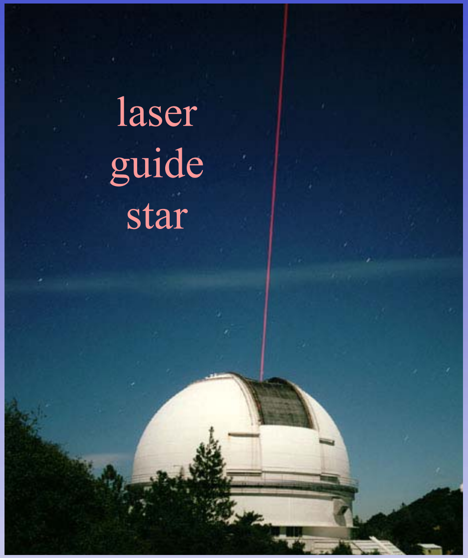
When Quantum States Grow Macroscopic

Hui Deng

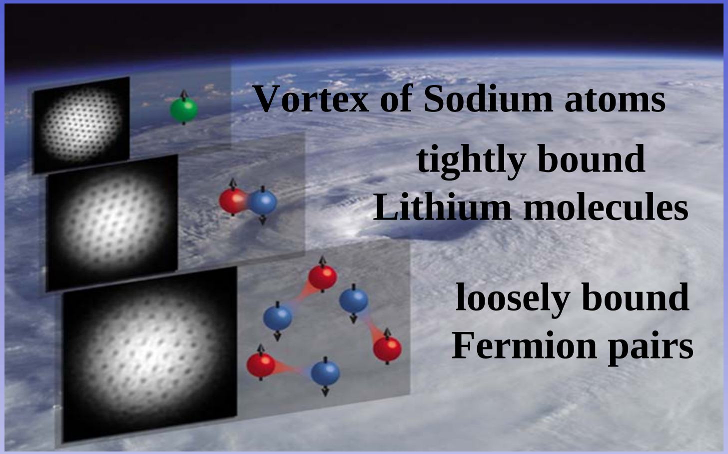
Mini-Colloquium, Sept 26, 2008

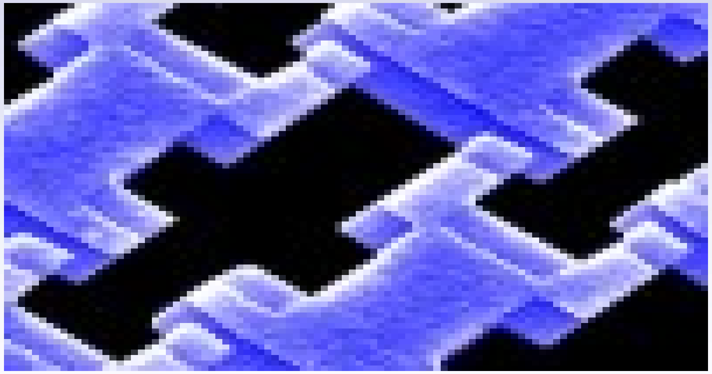
When Quantum States Grow Macroscopic

Laser,
Lick
observatory
California

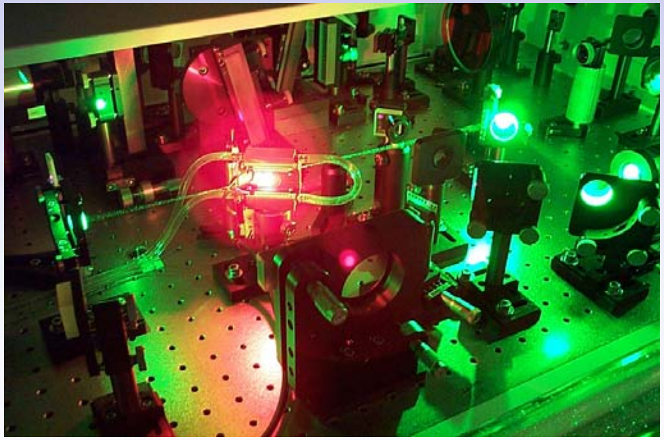


Vortex, MIT, Massachusetts





Josephson array, Mooij group, Delft



An Optical Parametric Amplifier
at Univ. Alberta

When, where, how, and what about it?

1. Can quantum coherence exist in many-body systems, either spontaneously acquired or externally induced and preserved?
2. How does that happen, how do we measure, manipulate, and utilize the macroscopic coherence?

Spontaneous Macroscopic Order in Quantum Phases

- Superfluidity in liquid He^4
- Superconductivity, BCS state of cooper pairs
- High Tc superconductivity
- Atomic BEC

… …

Fundamental Physics &
Technology Innovation

Induced Coherence and ‘Macro-sized’ Quantum Control

- Quantum memories
- Quantum processors

… …

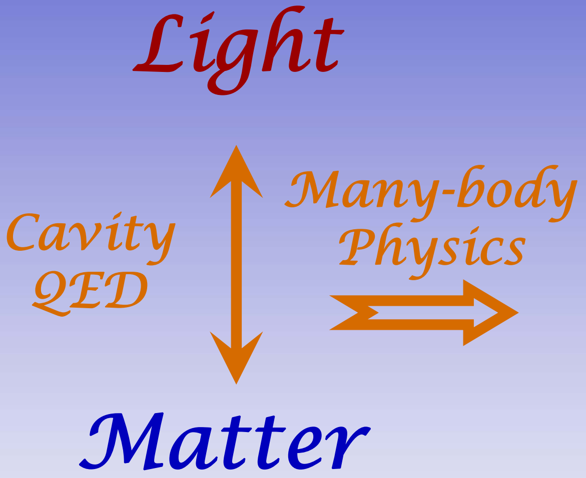
Quantum Information &
Quantum Technology

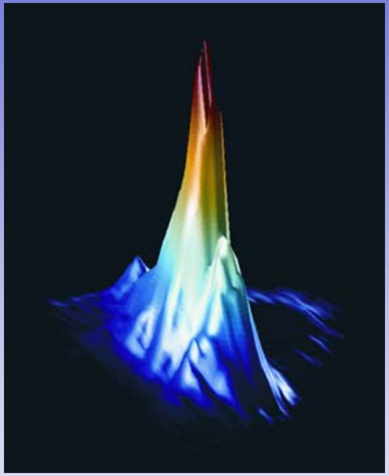
←

Many-body Physics, Emergence (vs. Reductionism)
“More is different” P. Anderson
“A Different Universe’ R. Laughlin

Macroscopic Quantum Coherence in
Matter-Light Systems

Spontaneous Macroscopic Order of Microcavity Polaritons

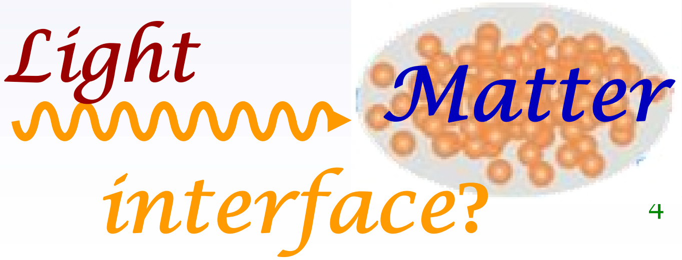




- What are polaritons?
  What's special about them?
- What quantum phases may they possess? How to realized them?
- What have we found?
  What I am looking for?
- What potential applications?

Scalable Quantum Memories and Processors -- Electron Spin Ensembles

- Why quantum information?
- Why quantum memory?
- Why/which ensembles and solid state systems?
- How to establish coherent Light Matter interface?



Spontaneous Macroscopic Order of Microcavity Polaritons

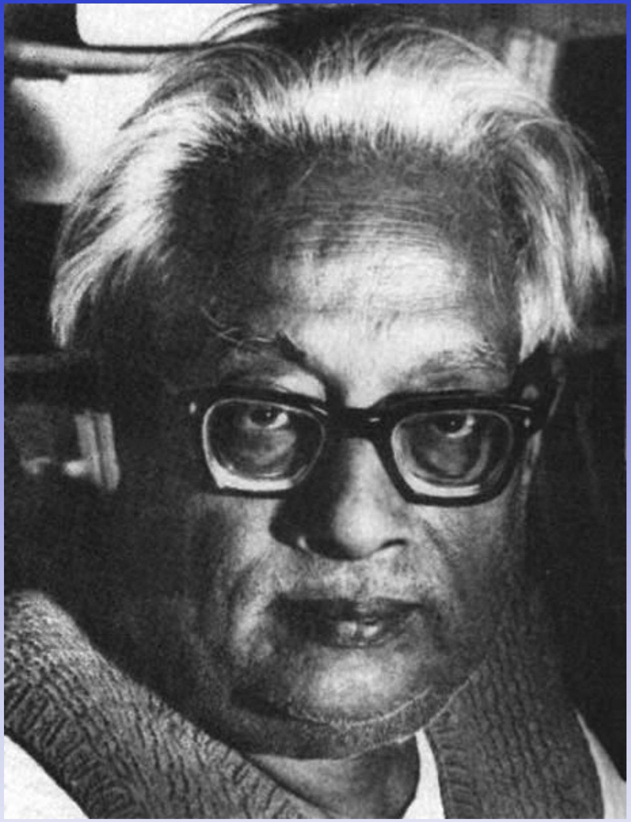
- Introduction to Bose-Einstein Condensation (BEC)
- Introduction to Microcavity Polariton
- Experiments on Polariton BEC and beyond

Light

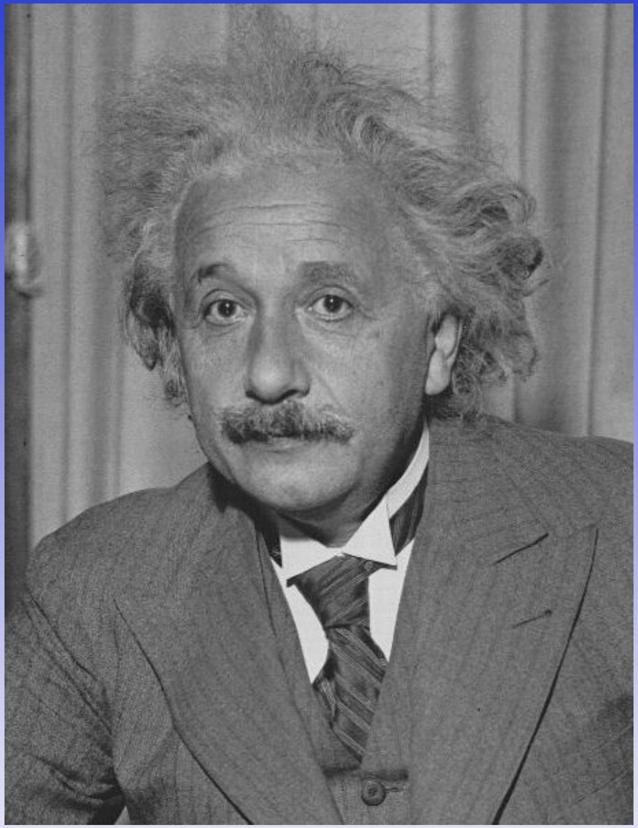
Cavity QED

Matter

polariton condensation



Satyendra Nath Bose (1894-1974)



Albert Einstein (1879-1955)

Introduction to Bose-Einstein Condensation

S.N. Bose, Zeitschrift für Physik 26:178-181 (1924).
A. Einstein, Sitz. Ber. Preuss. Akad. Wiss. (Berlin) 1, 3 (1925)

Simplified Definition of BEC

A uniform infinite system of non-interacting particles of mass m, total number N, the occupation numbers are:

Bosons	Fermions	a classical gas
$n_k = \frac{1}{e^{\beta(\varepsilon_k - \mu)} - 1}$	$n_k = \frac{1}{e^{\beta(\varepsilon_k - \mu)} + 1}$	$n_k \propto e^{-\beta\varepsilon_k}$

$$\varepsilon_k = \hbar^2 k^2/2m, \quad \beta = (k_B T)^{-1}$$

μ given by: $\sum_k n_k = N = \int d\varepsilon \nu(\varepsilon) \frac{1}{e^{\beta(\varepsilon-\mu)} \pm 1}, \; \nu(\varepsilon)^{(d)} \sim L^d m^{d/2} \varepsilon^{d/2-1}$

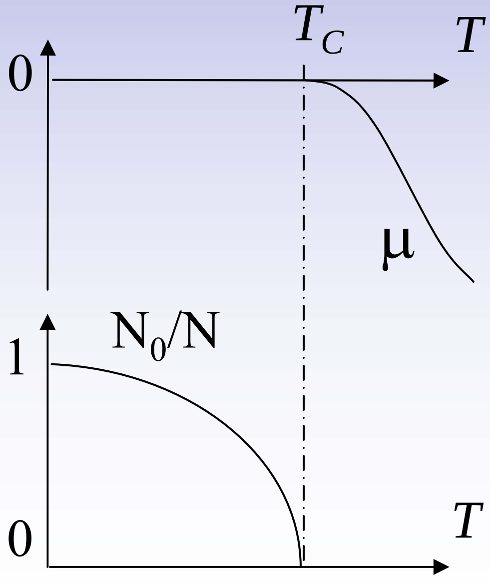
for BOSONS, and ONLY for BOSONS:

$$n_k, \varepsilon_k \geq 0 \rightarrow \mu \leq 0$$

If $d > 2$, T_c exists where: $\mu = 0, \int d\varepsilon \nu(\varepsilon) \frac{1}{e^{\beta_c \varepsilon} - 1} = N_c$

at $T < T_c$, μ pinned at 0, $N_0 = N - N'(T, \mu = 0)$, N_0/V finite

e.g. $d=3$, $k_B T_C = 2.612^{-2/3} 2\pi\hbar^2 m^{-1} (N/V)^{2/3}$



Essential Features of BEC

1. Macroscopic population in a *single* state

2. The condensed state becomes a ‘classical state’ (coherent state)

Hamiltonian of free boson gas: $H = \sum_k \left(\frac{\hbar^2 k^2}{2m} - \mu\right) a_k^\dagger a_k$

In BEC: $\lim_{N,V\to\infty} \left[\frac{a_0}{\sqrt{V}}, \frac{a_0^+}{\sqrt{V}}\right] = \frac{1}{V} \xrightarrow{V\to\infty} 0$ $\qquad \frac{<a_0^+ a_0>}{V} = \frac{N_0}{V} \to \mathit{finite}$

$$\Longrightarrow \quad a_0 \sim \sqrt{N_0}\, e^{-i\phi}, \quad a_0^+ \sim \sqrt{N_0}\, e^{i\phi} \qquad \Longrightarrow \quad a_0 |\Omega> \sim \sqrt{N_0}\, e^{-i\phi} |\Omega>$$

3. BEC has off-diagonal long range order ➔ Macroscopic coherence

Order Parameter for BEC: $\Psi(r) = \frac{1}{\sqrt{V}} \sum_k a_k e^{ikr} = \frac{a_{k_0}}{\sqrt{V}} + \frac{1}{\sqrt{V}} \sum_{k \neq k_0} a_k e^{ikr} \sim \underline{\sqrt{n_0}\, e^{i\phi}}$

finite in BEC

1st Reduced density matrix

$$\rho_1(r, r') =< \Psi^+(r')\Psi(r) >= \boxed{\frac{N_{k_0}}{V}} e^{ik_0(r-r')} + \underline{\frac{1}{V} \sum_{k \neq k_0} < a_k^+ a_k > e^{ik(r-r')}}$$

Condensate Fraction

non-condensed part →0 when $|r - r'| \to \infty$

Where 'Quantum' Grows 'Macroscopic'

-- Parameters of atomic and semiconductor BEC systems

systems	atomic gas	exciton	**polariton**
	realized in 1995	proposed in 1962	proposed in 1968
effective mass m^*/m_e	10^3	10^{-1}	$\mathbf{10^{-5}}$
Bohr radius a_B (A)	10^{-3}	10^2	$\mathbf{10^2}$
particle spacing $n_c^{-1/d}$ (nm)	10^2	10^3	$\mathbf{10^3}$
critical temperature T_c	1nK~1mK	1mK~1K	**1K~300K**
$\frac{\text{thermalization time}}{\text{lifetime}}$	1ms/1s ~10^{-3}	10ps/1ns $= 10^{-2} \sim 1$	$\mathbf{\frac{(1\sim10\text{ ps})}{(1\sim10\text{ps})} = 10^{-1} \sim 10^{1}}$

← extremely light m* (mixing with photons)

← extremely high T_c

$T_C \propto m^{-1}$

← dynamic

1. Why such small mass?
2. Why such short lifetime?

What is a Microcavity Polariton?

strong coupling of semiconductor
exciton and microcavity photon

What is Exciton: bound-state of an electron and a hole

Semiconductor crystal ground state $|vac>$: filled valence band, empty conduction band

Lowest energy elementary excitation from $|vac>$:

an exicton → an electron and hole pair bound by attractive Coulomb interaction

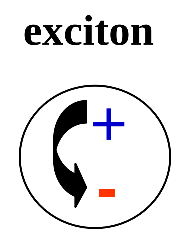
Exciton creation operator

electron hole

$$e^{\dagger}_{\nu,K} = |\nu, K\rangle\langle vac| = \sum_k f_\nu(k,K)\, c^{\dagger}_k b^{\dagger}_{K-k}$$

mode index

envelope function of relative motion
(analogous to Hydrogen atom)



$$m^*_h/m^*_e < 10$$

$$a_B = \frac{\hbar^2}{e^2}\frac{\epsilon}{m_r} \sim 100\mathring{A}$$

$$E_b = \frac{e^4}{2\hbar^2}\frac{m_r}{\epsilon^2} \sim 10\text{meV}$$

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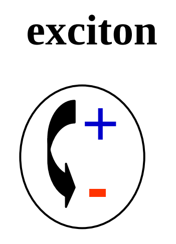
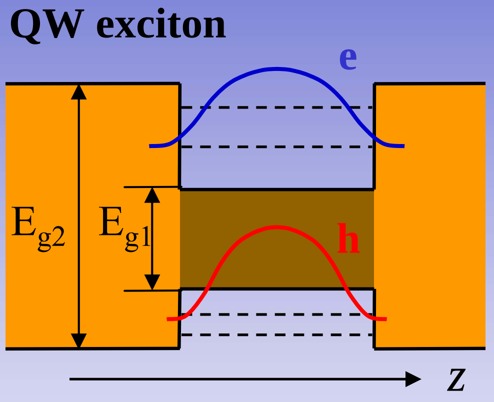


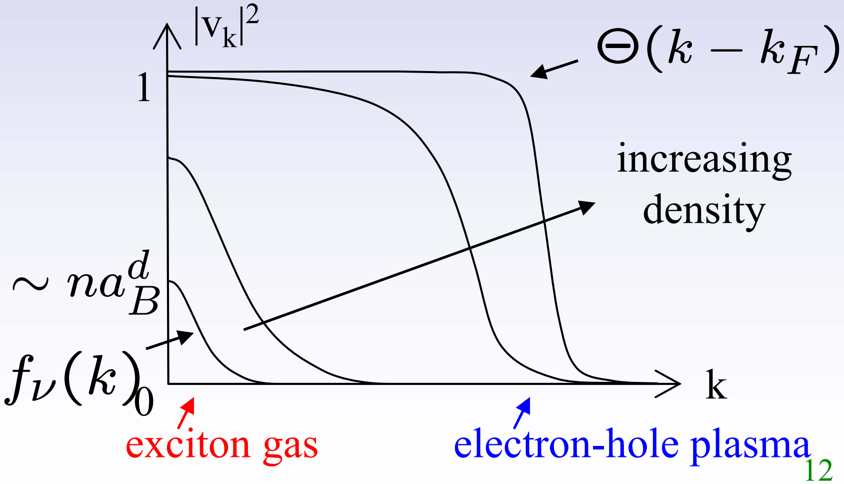


$$\langle[e_{\nu,0}, e^{\dagger}_{\nu,0}]\rangle = 1 - O(n a_B^{*d})$$

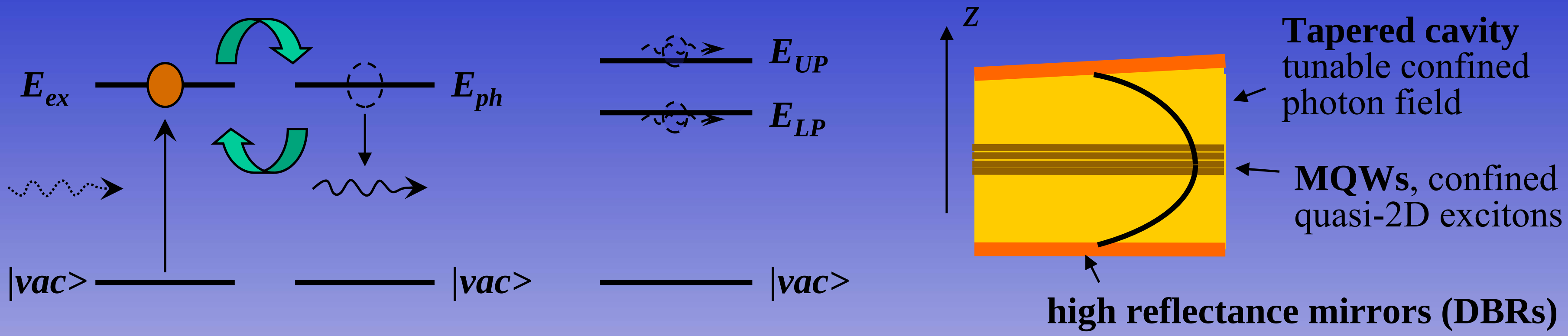
composite boson at low densities

at high densities: electron-hole plasma

- laser (high T, large decoherence)
- BCS (low T, low decoherence)



What is Polariton: strong coupling of exciton & photon



Tapered cavity tunable confined photon field

MQWs, confined quasi-2D excitons

high reflectance mirrors (DBRs)

polariton is the elementary excitation of a semiconductor microcavity, when the energy exchange rate between the coupled photon and exciton is faster than their decay and decoherence rates

Hamiltonian of coupled cavity photon-QW exciton

$$H=\sum_k[E_{ph}(k)a_k^\dagger a_k+E_{ex}(k)e_k^\dagger e_k+g_0(a_k^\dagger e_k+a_k e_k^\dagger)]$$

polariton operator $P_k = u_k e_k + \nu_k a_k$

linear superposition of a microcavity-photon and a QW-exciton with the same $k_{||}$

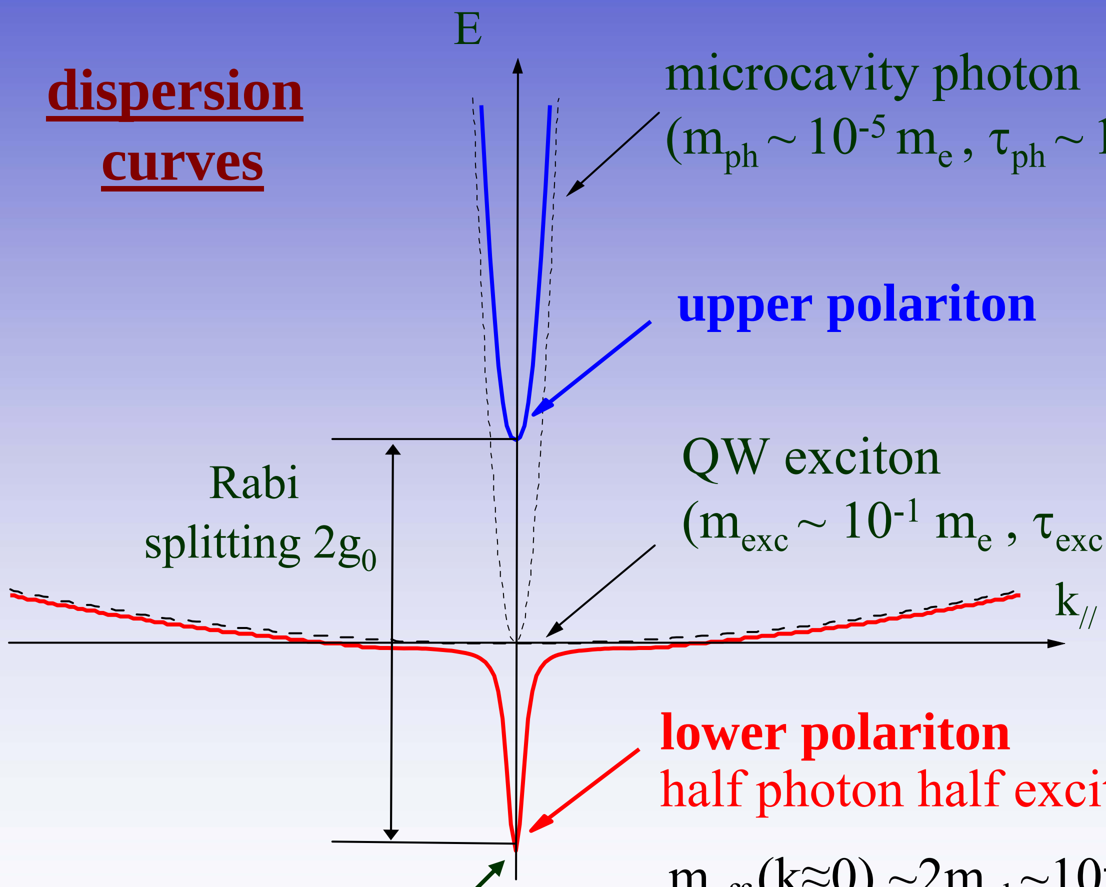
$$H=\sum_k E_{pol}(k)P_k^\dagger P_k,$$

$$E_{pol}(k)=\frac{1}{2}[E_{ph}(k)+E_{ex}(k)\pm\sqrt{4g_0^2+(E_{ph}-E_{ex})^2}]$$ $\Delta E_{pol}=2g_0$, when $E_{ph}=E_{ex}$

Properties of Polaritons

$$E_{pol}(k) = \frac{1}{2}[E_{ph}(k)+E_{ex}(k)\pm\sqrt{4g_0^2+(E_{ph}-E_{ex})^2}]$$

dispersion curves



microcavity photon
($m_{ph} \sim 10^{-5}\, m_e$, $\tau_{ph} \sim 10$ ps)

upper polariton

Rabi splitting $2g_0$

QW exciton
($m_{exc} \sim 10^{-1}\, m_e$, $\tau_{exc} \sim 1$ ns)

lower polariton
half photon half exciton at k=0

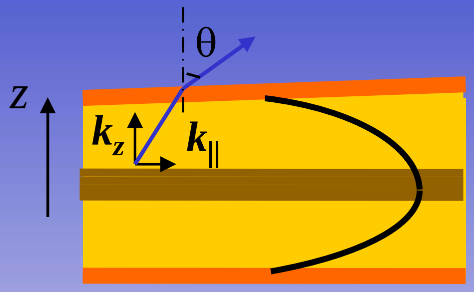
$m_{eff}(k\approx 0) \sim 2m_{ph} \sim 10^{-4}\, m_{exc} \sim 10^{-8}\, m_H$

$\tau_0(k\approx 0) \sim 2\tau_{ph} \sim 10^{-2}\tau_{exc}$

bottom of LP branch: ‘ground state’

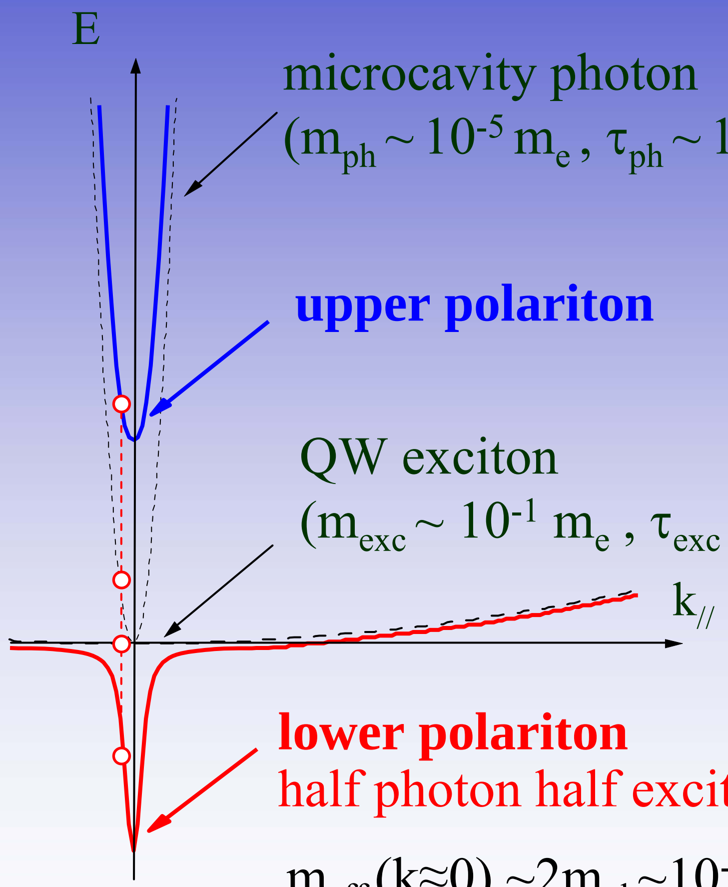
Experimental Access of Polaritons

$$E_{pol}(k) = \frac{1}{2}\left[E_{ph}(k) + E_{ex}(k) \pm \sqrt{4g_0^2 + (E_{ph} - E_{ex})^2}\right]$$



one-to-one correspondence
between each LP at certain $k_{||}$
and each external photon
emitted at certain angle θ
with the same $k_{||}$ and $E_{LP}(k_{||})$

The out-coupled photon carries direct information of the internal LP
e.g. dispersion, statistics,
population $I(k_{||})=N(k_{||})/\tau_{LP}$,
k-distribution…



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$\tau_0(k \approx 0) \sim 2\tau_{ph} \sim 10^{-2} \tau_{exc}$

Polariton for BEC

- BEC critical temperature

$$T_C \propto m^{-1}$$

⇨ **Very high critical temperature (>4K)**

- Polaritons mass ~10^{-4} m_{exc}~10^{-8} m_H

- BEC originates from quantum statistics

⇨ **Can directly measure quantum statistics**

- convenient experimental access by one-to-one mapping between out-coupled photon and internal POL

- Exciton suffer localization and inhomogeneous broadening due to disorders in solids

⇨ **Extended coherence** in the combined excitation when excitons dressed by the microcavity vacuum field

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- Avoid exciton saturation

⇨ **Use multiple, narrow QWs**

$$g_0 \propto \sqrt{N_{\mathrm{QW}}},\quad n_{exc} \propto n_{LP} / N_{\mathrm{QW}}$$

- Spontaneous coherence needs efficient cooling

⇨ **Pronounced stimulated scattering** into states at k~0 due to small DOS

How to study polariton condensation in experiment?

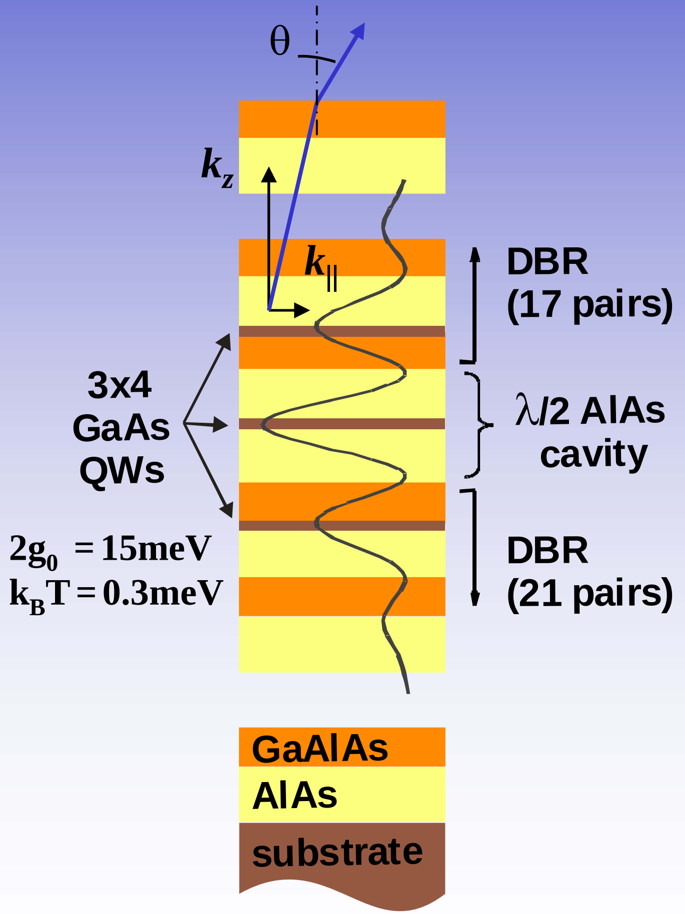
1. **Macroscopic population in the ground state**
    - **quantum degeneracy threshold**

2. **Thermodynamic properties**
    - **momentum distribution**

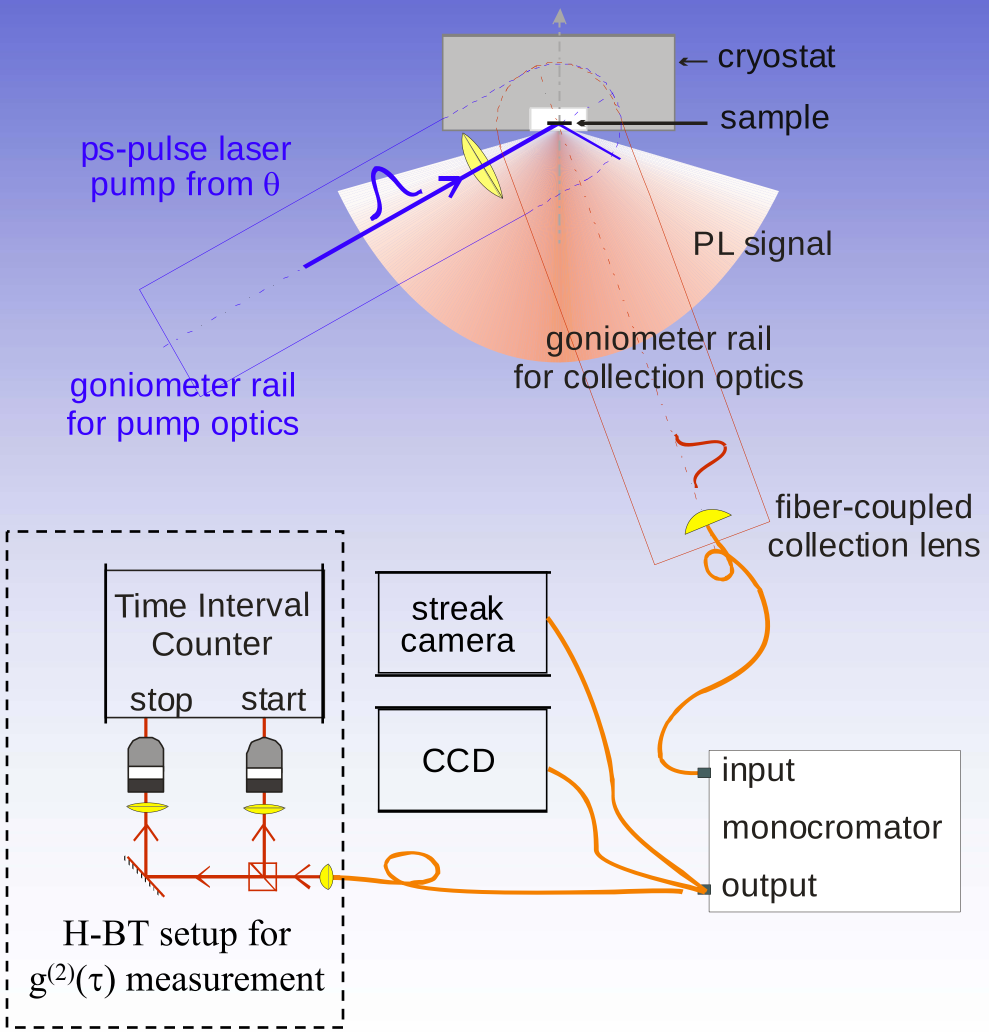
3. **Coherence properties**
    - **second order coherence function**
    - **first order coherence function**

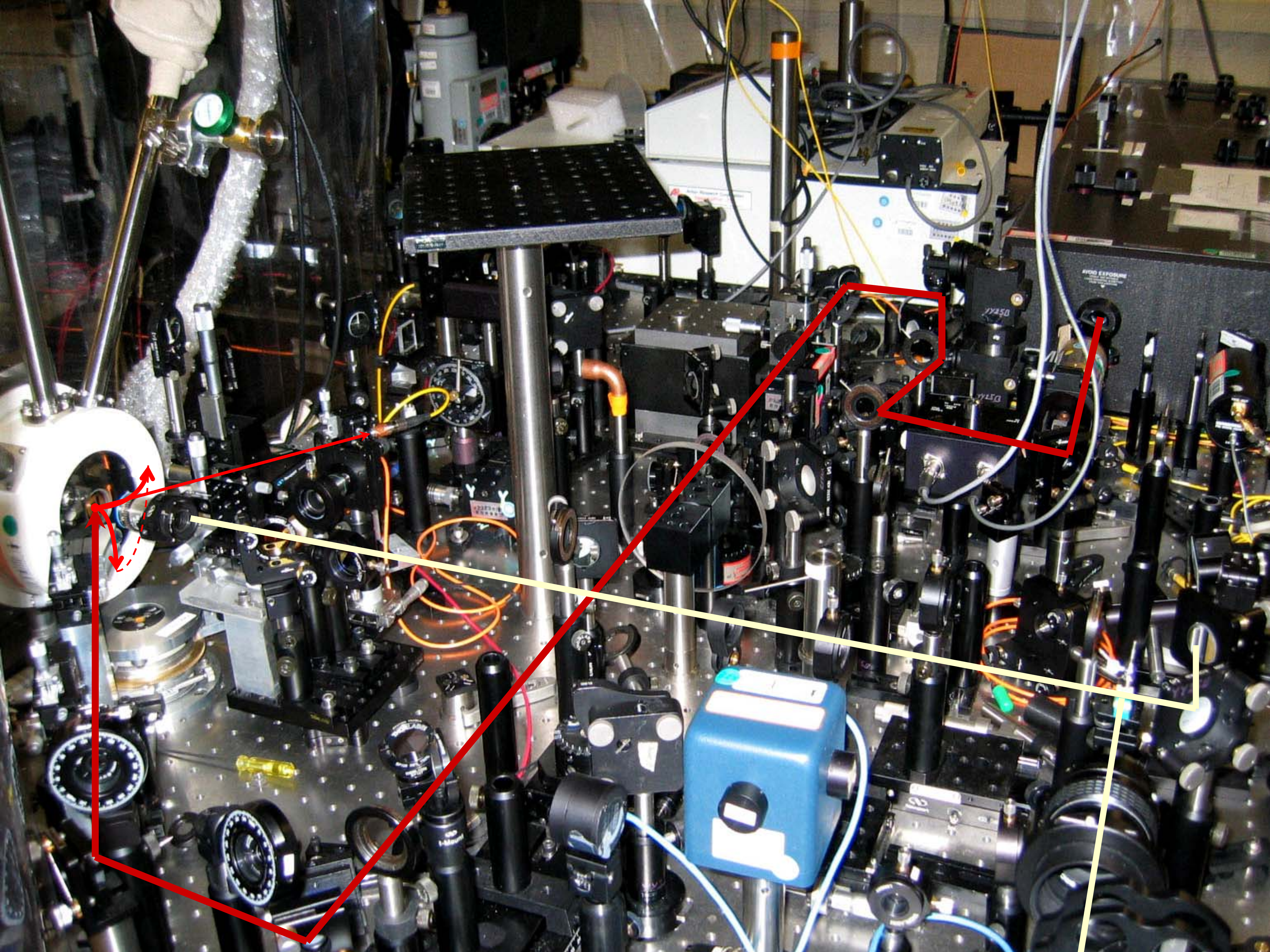
Sample and Setup

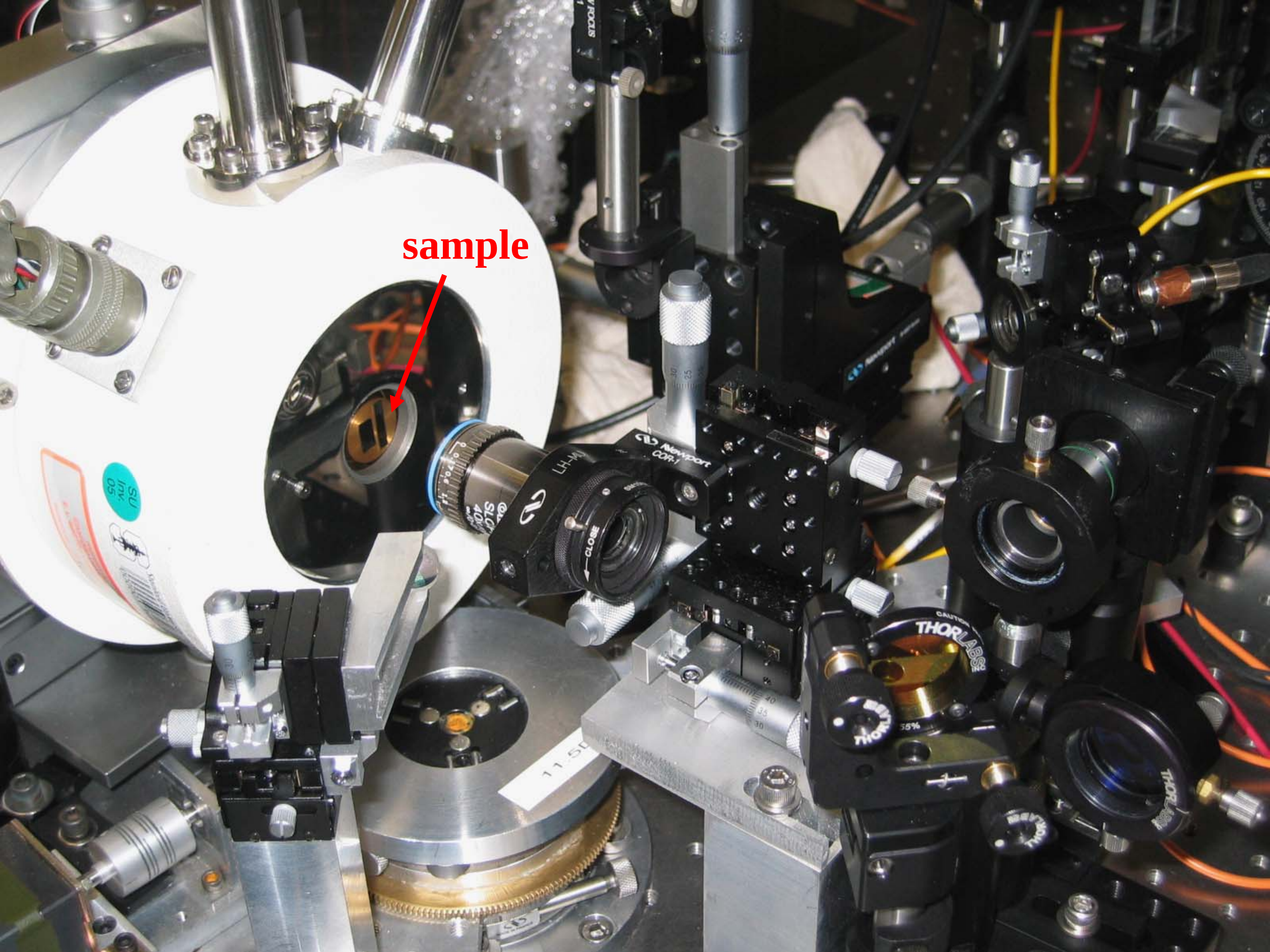
a λ/2 microcavity cavity with 12 GaAs/AlAs QWs



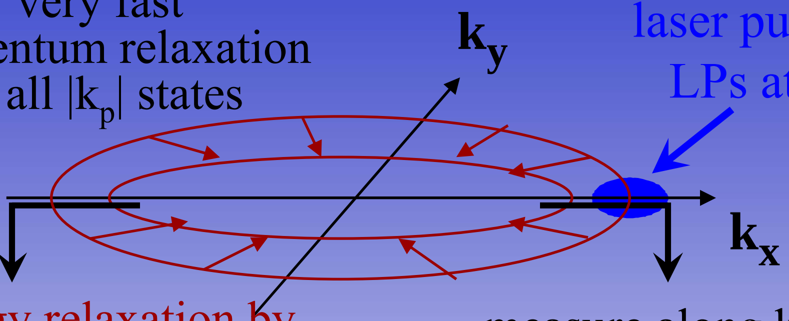
angle-resolved photoluminescence setup






sample

Experimental Scheme

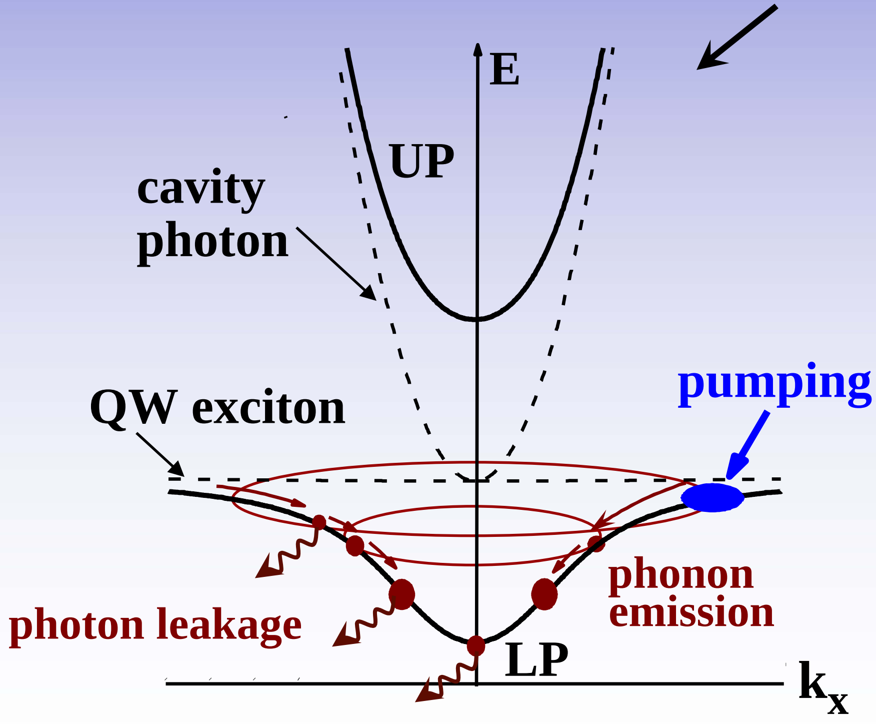


very fast momentum relaxation to all $|k_p|$ states

laser pump creates LPs at large $\mathbf{k_p}$

energy relaxation by phonon scattering

measure along k_x by scanning the emission angle θ



cavity photon

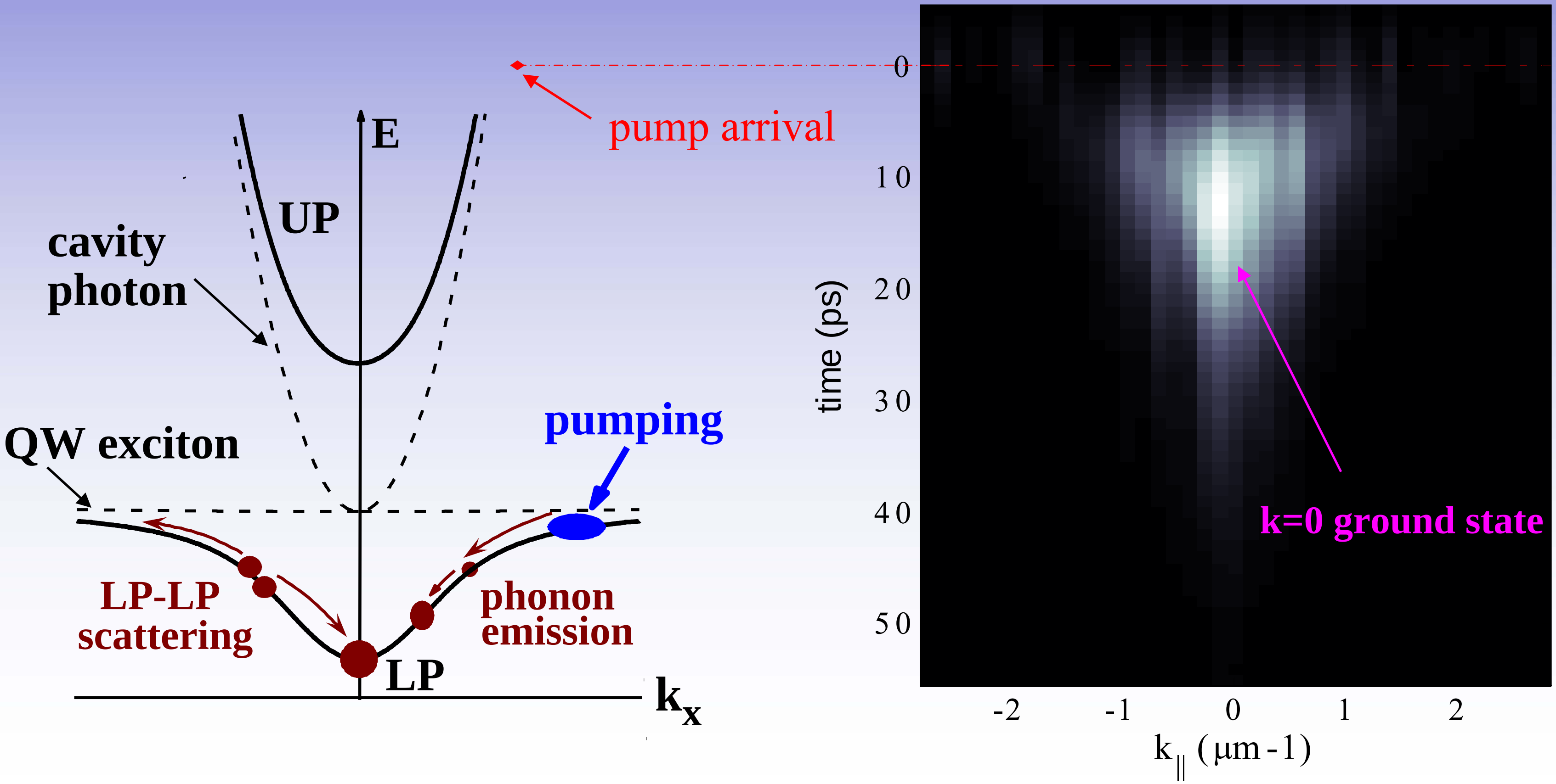
QW exciton

pumping

phonon emission

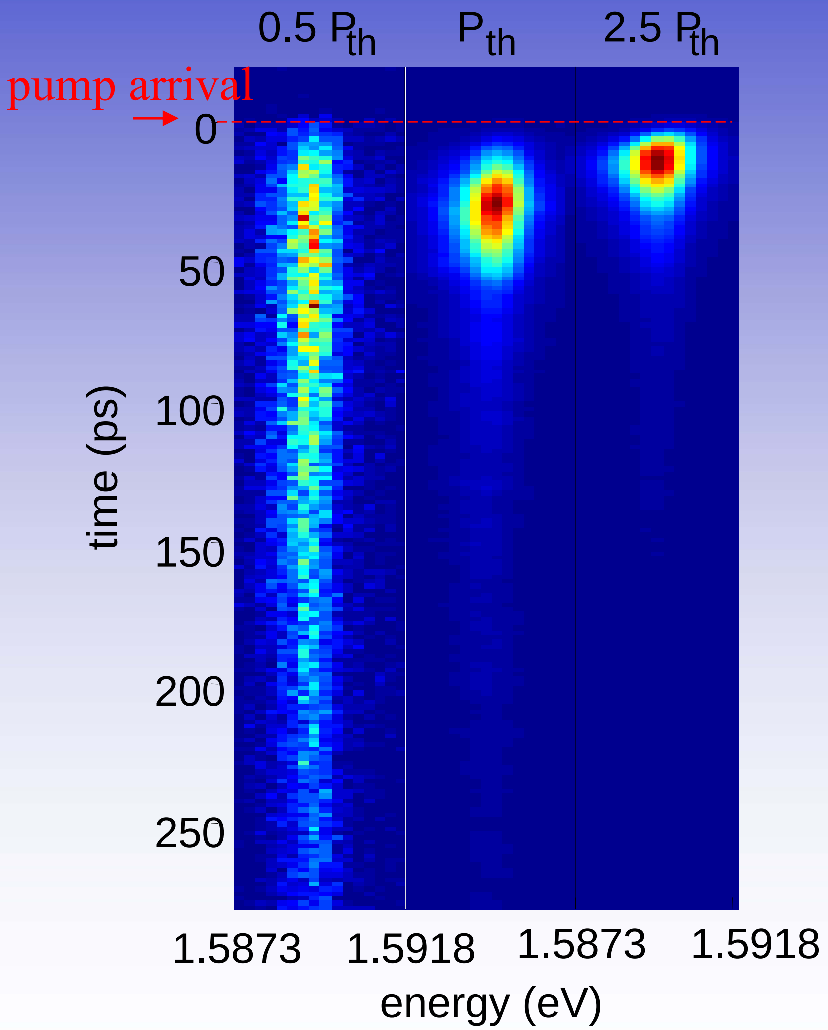
photon leakage

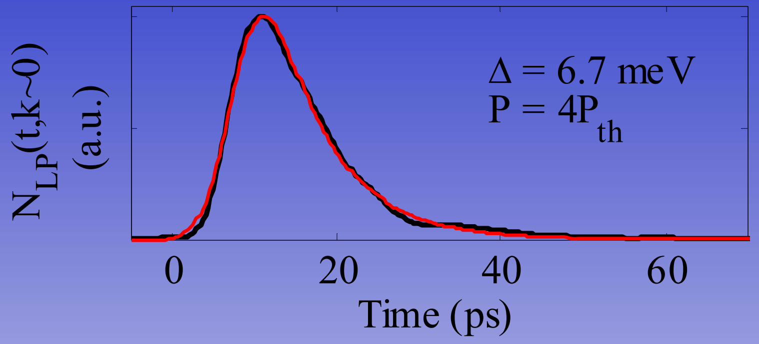
Experimental Scheme



Time Resolved Measurements

streak camera images of $k_{\|}=0$ LP

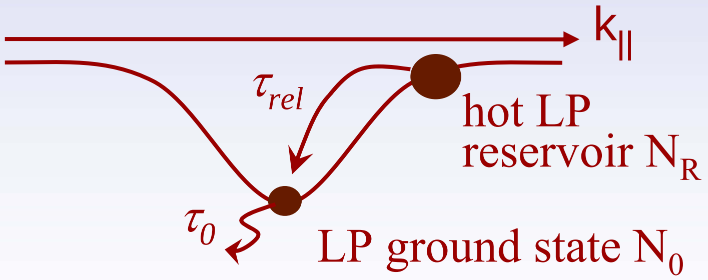




2-mode rate equation model:

$$\frac{\partial N_R}{\partial t} = P(t) - \frac{N_R}{\tau_R} - \frac{N_R}{\tau_{rel}}$$

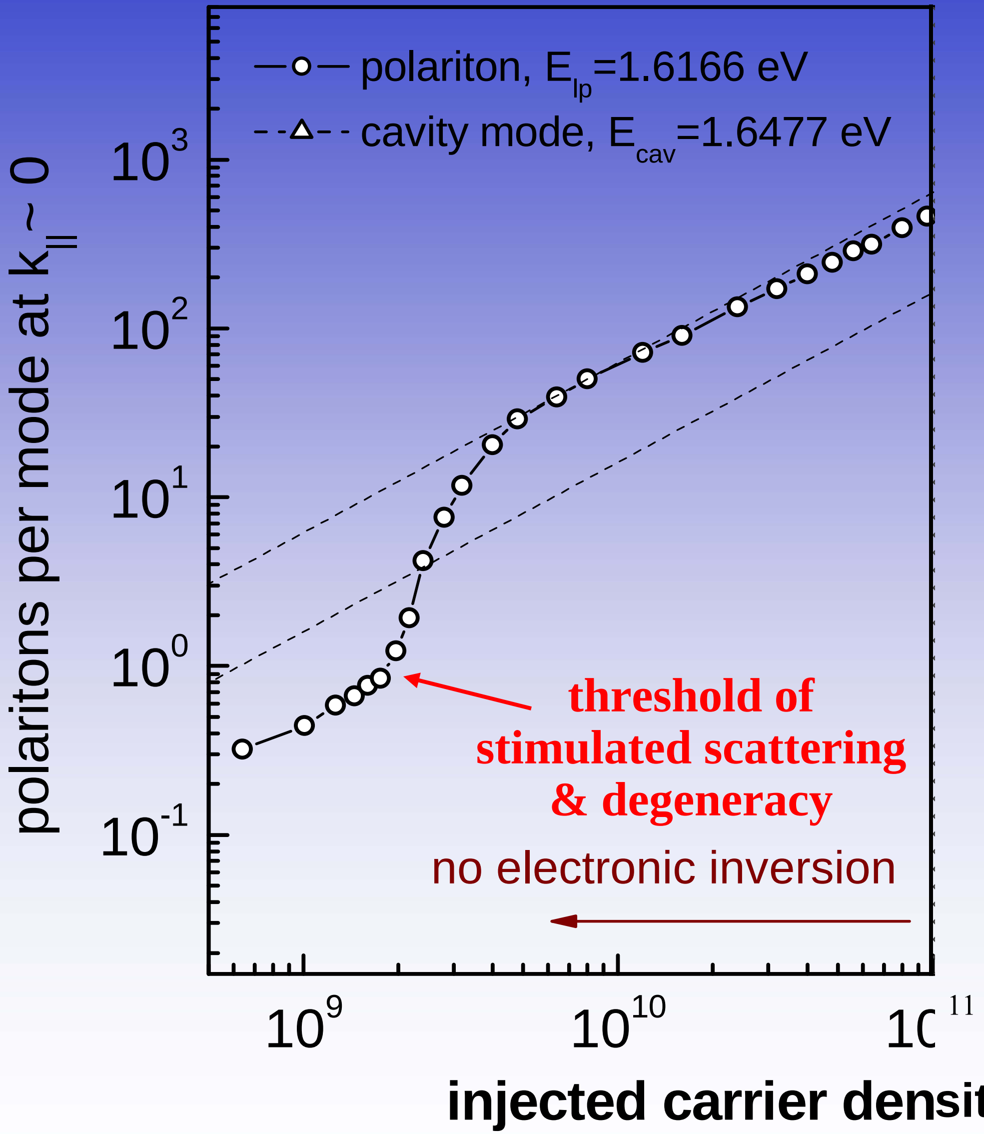
$$\frac{\partial N_0}{\partial t} = -\frac{N_0}{\tau_0} + \frac{N_R}{\tau_{rel}}$$

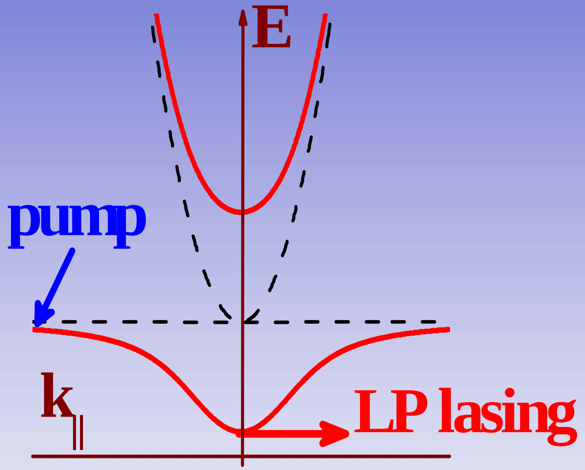


$\tau_R \sim inf$, τ_0 is inferred from linewidth

P(t) is a Gaussian pump centered at t=0

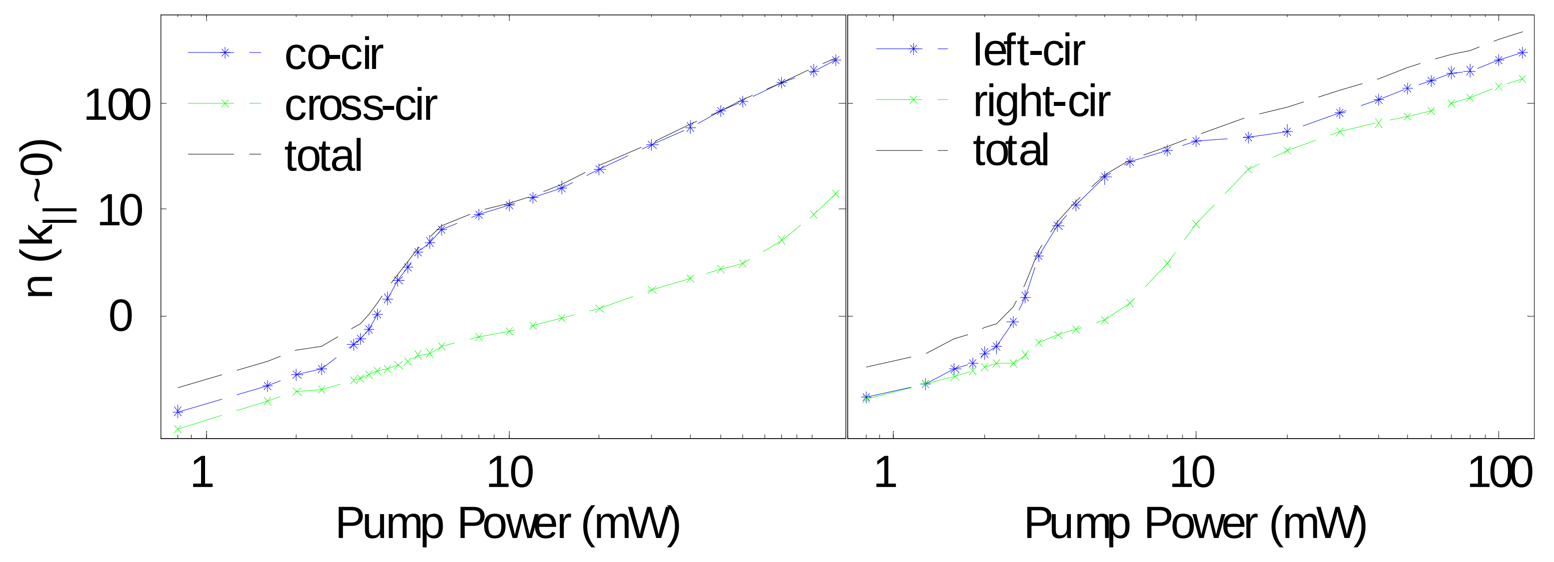
Polariton Quantum Degeneracy Threshold

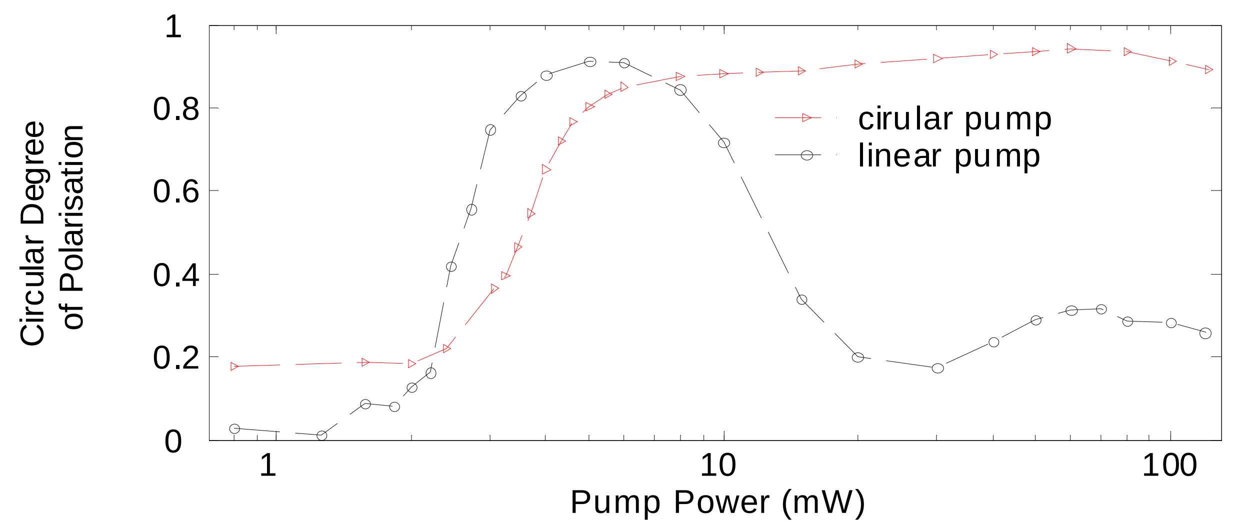




H. Deng, *et. al.*, *Proc. Natl. Acad. Sci.* **100**, 15318 (2003)

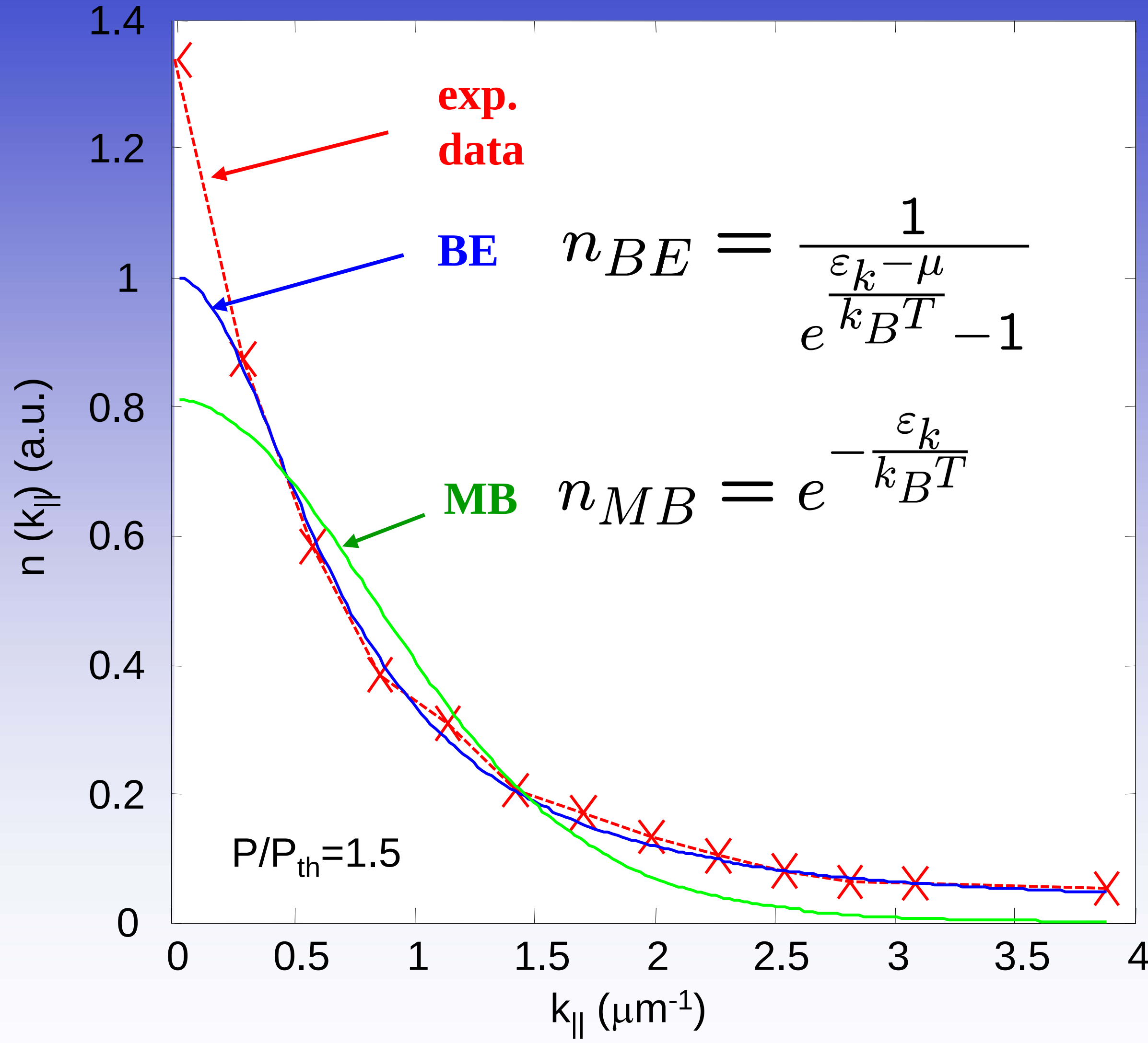
Spin Dynamics and Spontaneous Polarization





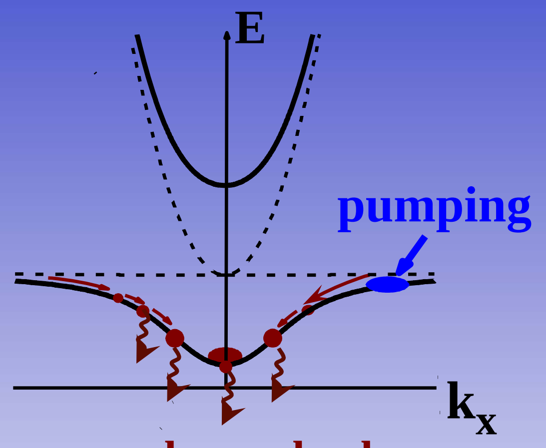
H. Deng, G. Weihs, *et. al.*, *Proc. Natl. Acad. Sci.* **100**, 15318 (2003)

Bose-Einstein Momentum Distribution



$$n_{BE} = \frac{1}{e^{\frac{\varepsilon_k - \mu}{k_B T}} - 1}$$

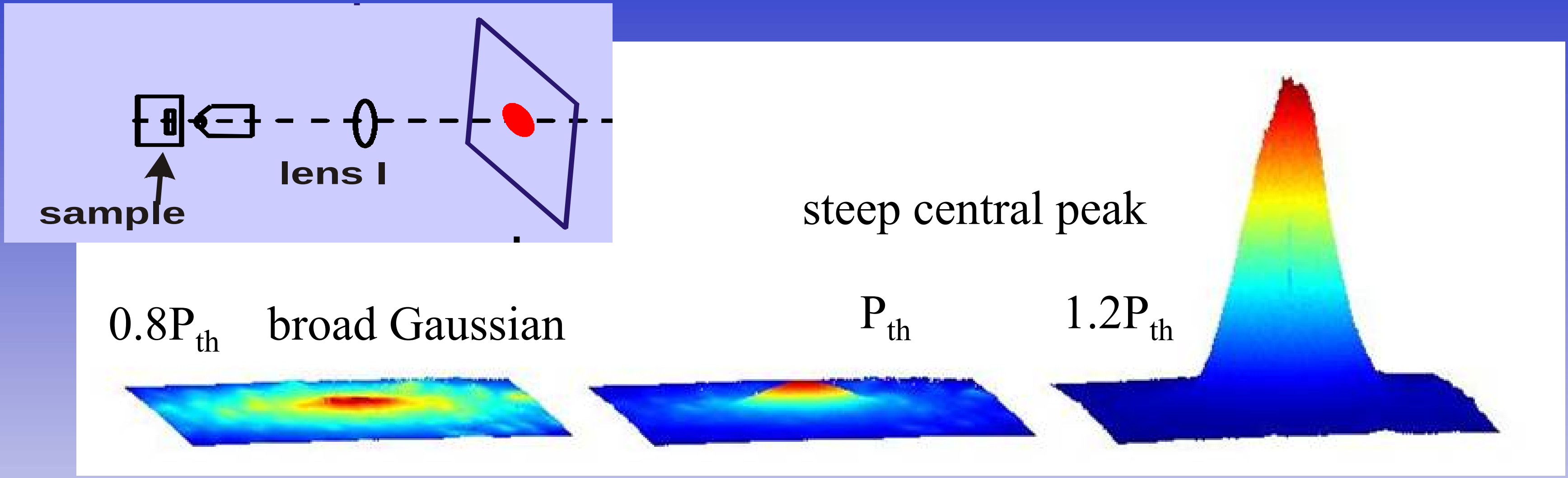
$$n_{MB} = e^{-\frac{\varepsilon_k}{k_B T}}$$



A degenerate Bose gas of polaritons!

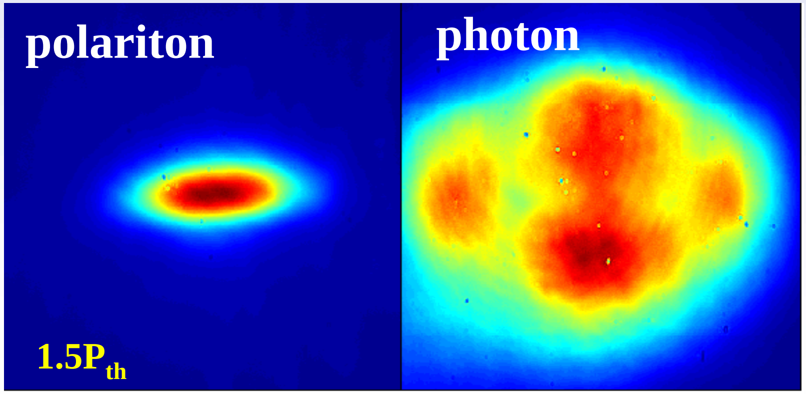
H. Deng, G. Weihs, et. al., Proc. Natl. Acad. Sci. 100, 15318 (2003)
H. Deng et al., Phys. Rev. Lett. **97**, 146402 (2006).

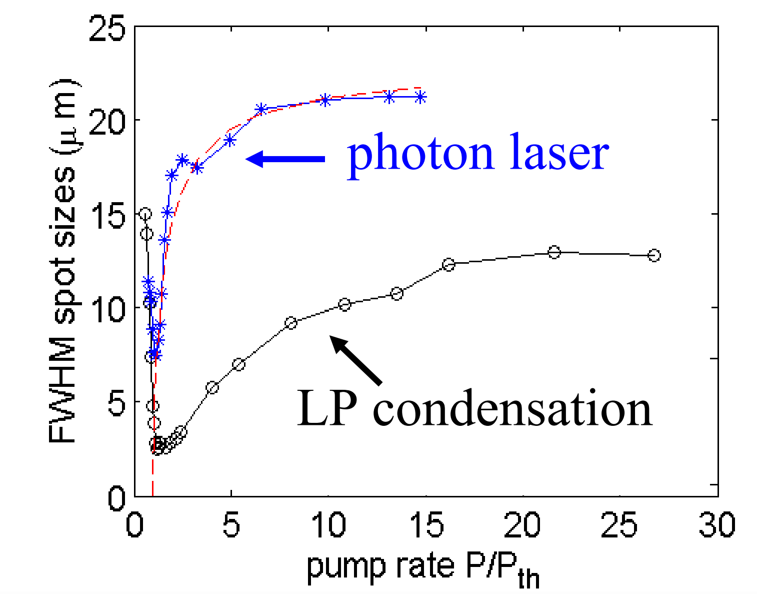
Spatial Distribution



Compare with a photon laser

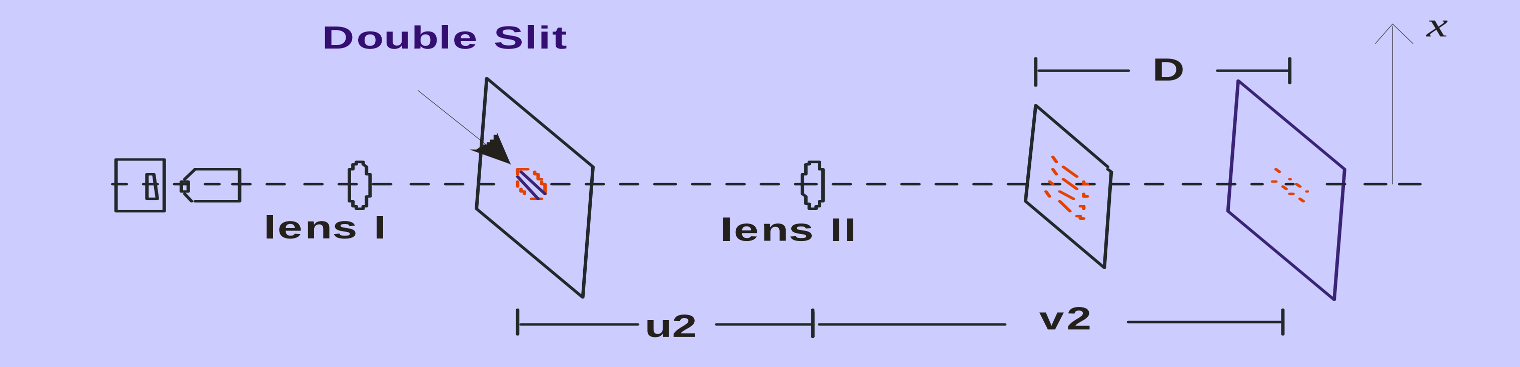
- homogeneous spatial mode
- anomalous shrinkage of spatial size

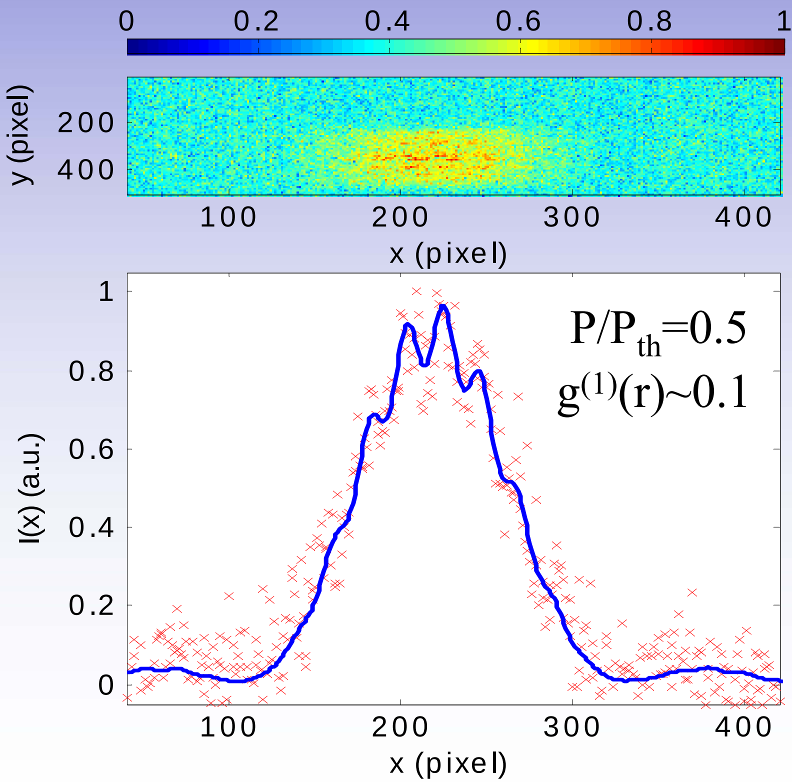


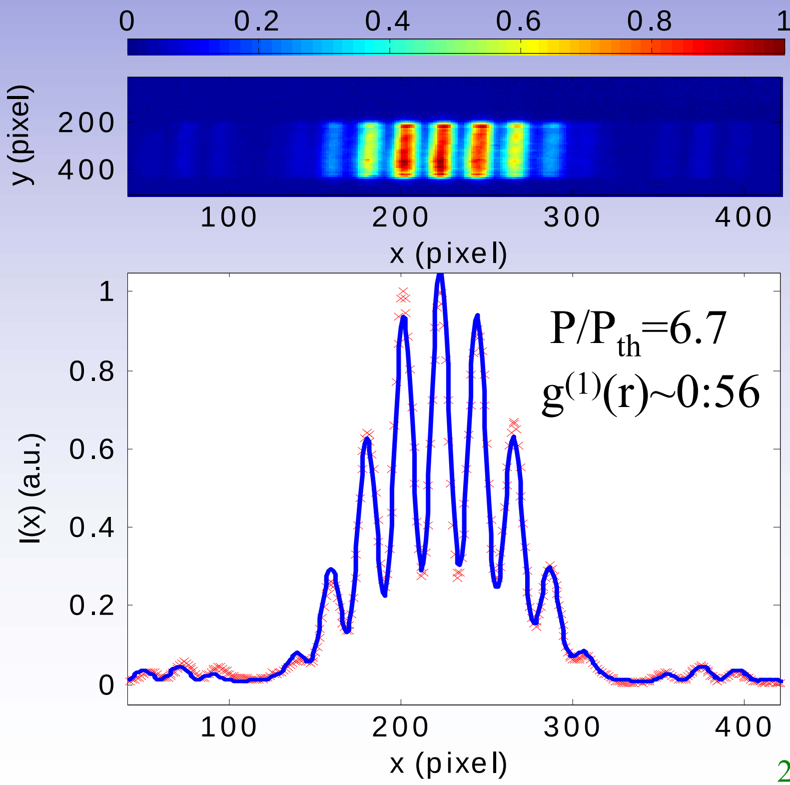


H. Deng, et. al., Proc. Natl. Acad. Sci. 100, 15318 (2003)

Spatial Coherence by Double-Slit Interference







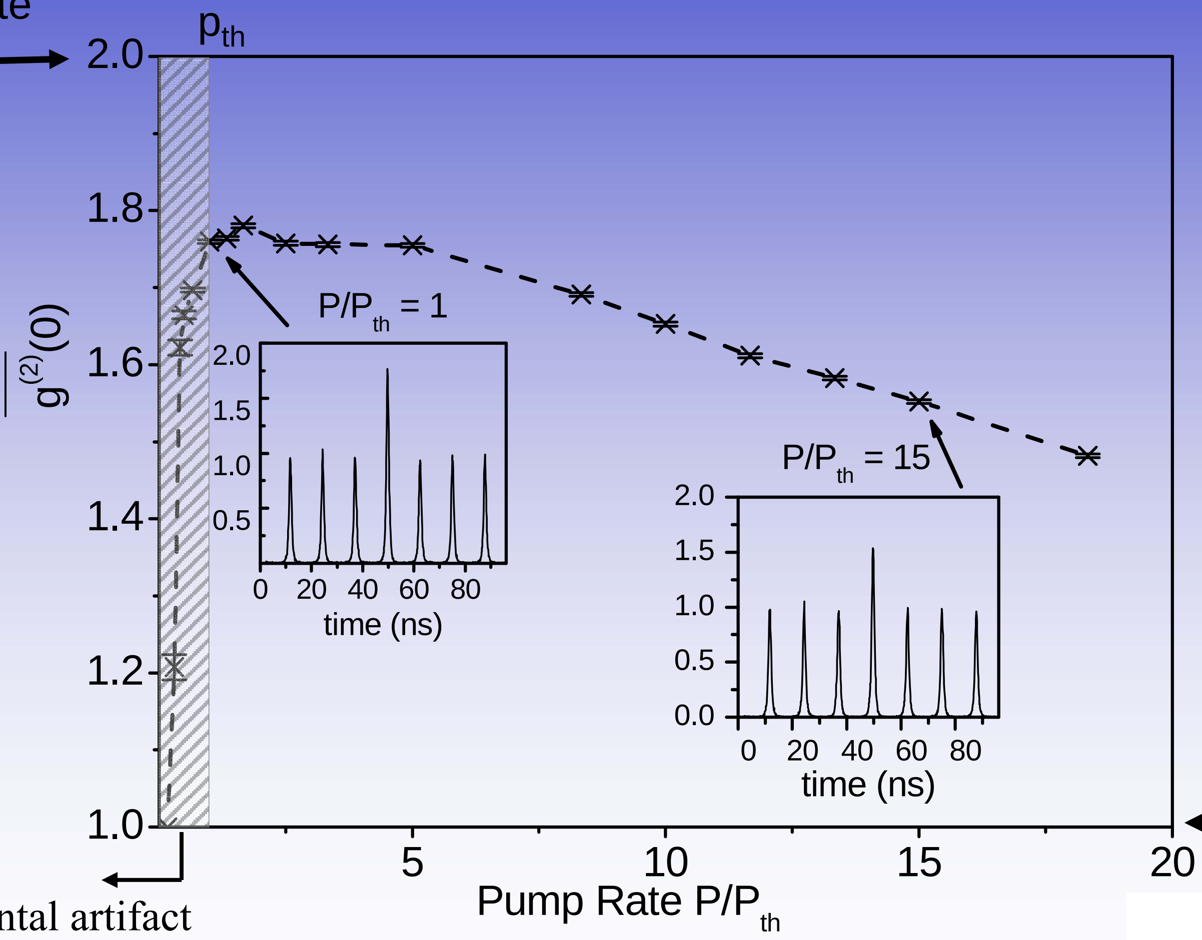
H. Deng, et al., Phy. Rev. Lett. 99, 126403 (2007)

Second Order Coherence Function

$$g^{(2)}(\tau)=\frac{\left\langle \hat{E}^{(-)}(t)\hat{E}^{(-)}(t+\tau)\hat{E}^{(+)}(t+\tau)\hat{E}^{(+)}(t)\right\rangle}{\left\langle \hat{E}^{(-)}(t)\hat{E}^{(+)}(t)\right\rangle^{2}}=\frac{\langle :n(t)n(t+\tau):\rangle}{\langle n\rangle^{2}}\approx\frac{\langle n_1(i)n_2(i+j)\rangle_i}{\langle n_1\rangle\langle n_2\rangle}=\overline{g^{(2)}}(jT)$$

thermal state

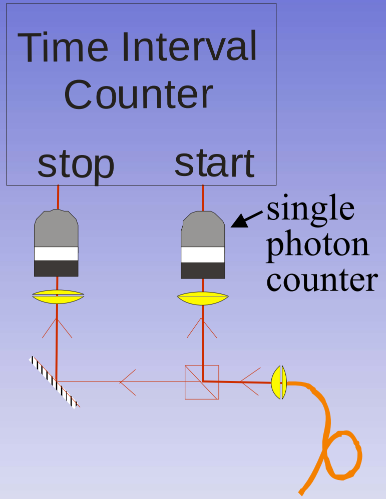
$g^{(2)}(0)\approx 2$ →



← single-mode coherent state

$g^{(2)}(0)\approx 1$

experimental artifact
due to slow dynamics and
limited time resolution



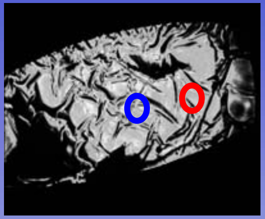
H. Deng, et. al., Science 298, 199 (2002)

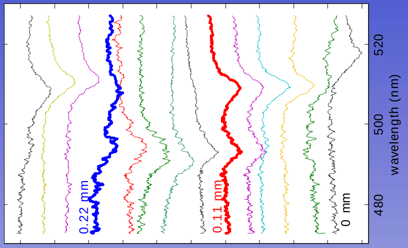
Multitudes of Open Questions and Opportunities

Practicalities:

- Room temperature polariton condensation

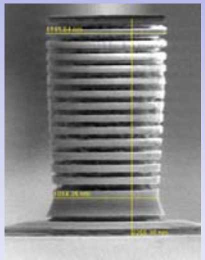
  using material with large binding energy, e.g. ZnSe, GaN, organics …

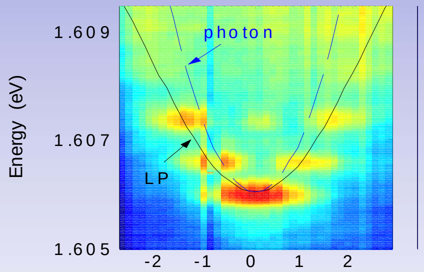




- Electrical injection

- In-plane confinement potential
  - – single-mode coherent light source
  - – better defined system size to facilitate theoretical understanding





- Device applications: huge nonlinearity and very fast response time
  - – ultra-low threshold source of coherent light
  - – resonant parametric appliifer
  - – spintronics devices

Multitudes of Open Questions and Opportunities

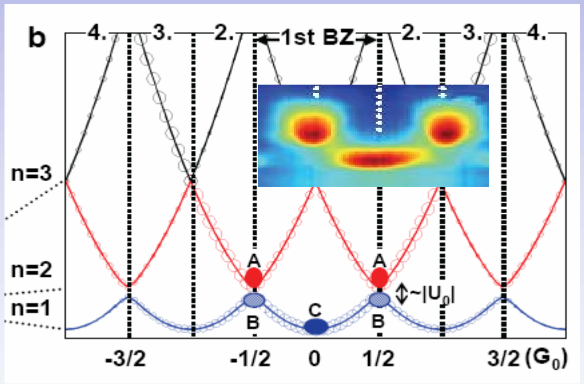
Fundamentals:

Properties of the 2D condensate

- Exact quantum state of the condensed ground state
- Superfluidity and vortices
- Excitation spectra – Goldstone mode, roton mode?
- Critical exponent of the phase transition
- Magnetic field responses

Other quantum phases

- Kosterlitz-Thouless transition in larger systems
- BEC to BCS crossover at high densities
- Lattice potential and a polariton quantum simulator



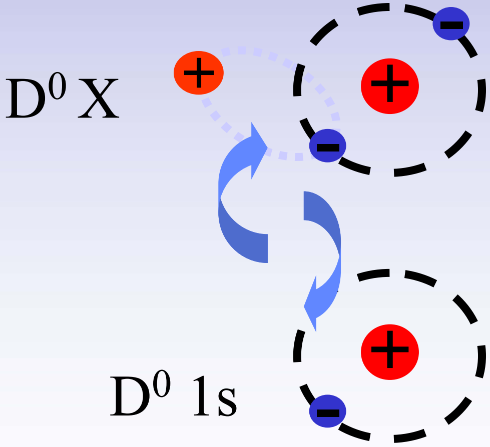
Lai et al, Nature, 2007

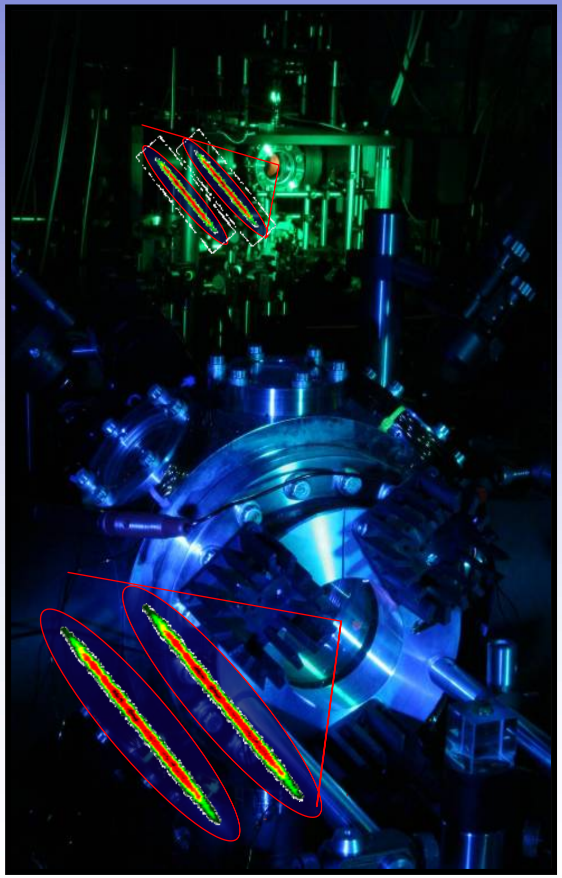
Other dimensions and structures

- One-dimensional polaritons in quantum wires
- Polaritons in quantum disks, in flat band photonic crystals, …

Scalable Quantum Information Processing

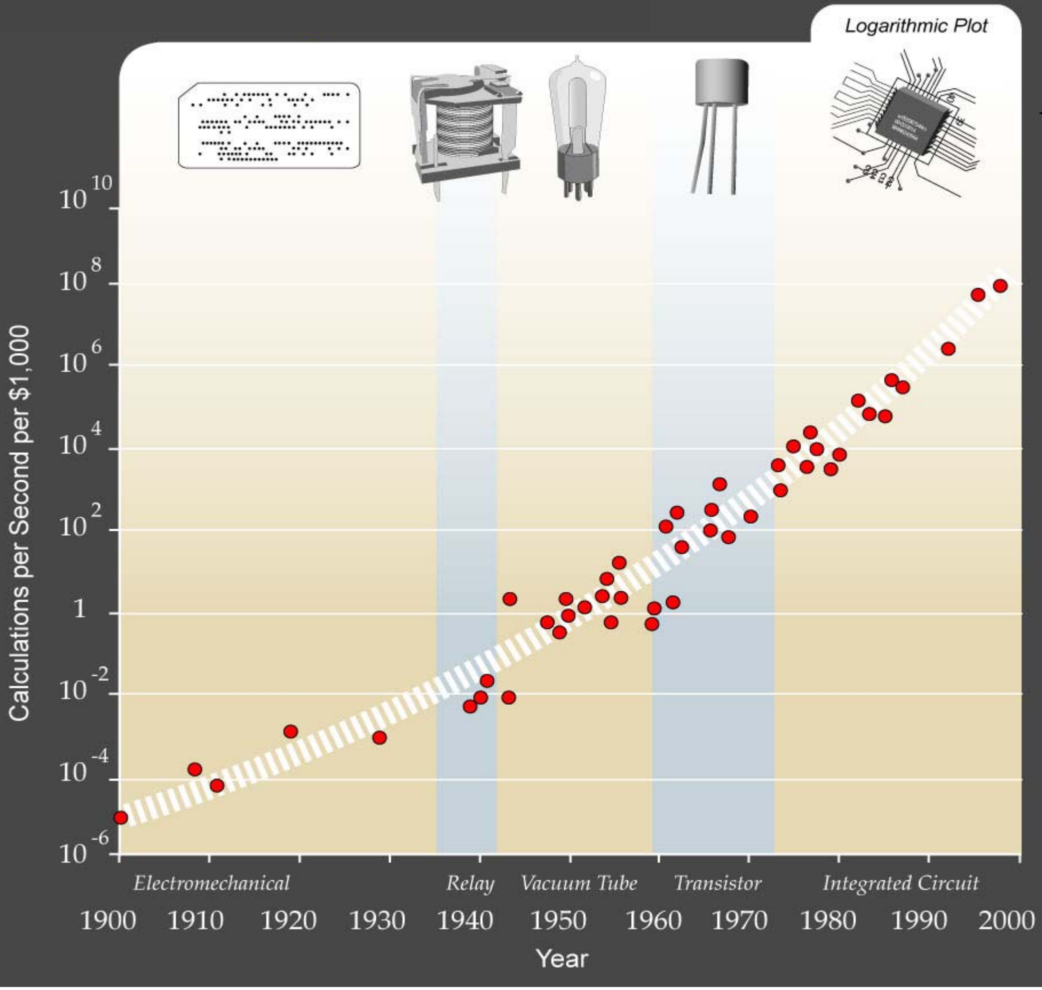
- Why Quantum Information, What's in it?
- An example of atom-light quantum interface
- A solid-state candidate





Why Quantum Information

The Moore's Law



Fundamental Scientific Questions & New Paradigms in Modern Technologies

What is “Quantum Information”?

Quantum Communication
Wiesner (1970)

Information theory
information is physical!
channel capacity,
super-dense coding …

Quantum teleportation

Information reconciliation & privacy amplification: Bennet (1992)

Quantum cryptography
non-local & perfectly secure
Bennett & Brassard (1984)
Ekert (1991)

Quantum Simulation
Feynman (1982)

Q…

Q…

Q…

Quantum Computation

Computer science
Turing (1936)
Deutsch (1985)

Quantum algorithms
Deutsch (1992)
Shor (1994)
Grove (1996)

Quantum error-correction
Shor, Steane (1995)

Quantum Metrology

Quantum Cosmology

Q…

What is “Quantum Information”?

“Quantum Technology”

generation, storage, manipulation, transportation, and application of quantum systems

Info
information is physical:
channel capacity,
super-dense coding …

Quantum teleportation

Information reconciliation & privacy amplification: Bennet (1992)

Quantum cryptography
non-local & perfectly secure
Bennett & Brassard (1984)
Ekert (1991)

Quantum Computation

Computer science
Turing (1936)
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Quantum algorithms
Deutsch (1992)
Shor (1994)
Grove (1996)

Quantum error-correction
Shor, Steane (1995)

Quantum Metrology

Quantum Cosmology

Q…

The Real World Challenge

“Quantum Technology”

How to generate, store, manipulate, transport and use quantum systems

Quantum Communication

Entangled states (& single photons), and their faithful transportation

- Quantum teleportation
  photon: Bouwmeester *et al.* (1997)
  atom: Riebe *et al*., Barrett *et al.* (2004)
- Quantum cryptography
  photon: Bennett *et al.* (1990)
- Commercial quantum cryptography!
  MagiQ Technologies (New York)
  id Quantique (Geneva)

Record distance: 150 km with photonic systems

Quantum Computation

Qubits, and their initialization, controlled interactions and read-out

- a variety of matter qubits
  nulcear spins, electron spins, charge qubits, flux qubits, phase qubits …
- Diverse matter systems
  ions, neutral atoms, molecules, semiconductors, super-conductors …
  single particle systems & ensemble systems …

Biggest QC: 12-qubit Negrevergne et al. (2006)

The Real World Challenge

“Quantum Technology”

How to generate, store, manipulate, transport and use quantum systems

Quantum

Entangled sta
and their

- Qua
  photon
  atom:
- Quantu
  photon: Bennett
- Commercial quantum cryptography!
  MagiQ Technol York)
  id Quantique (Geneva)

Record distance: 150 km with photonic systems

ge
nts …

ral s, molecules,
onductors, super-conductors …
single particle systems & ensemble systems …

Biggest QC: 12-qubit Negrevergne et al. (2006)

Quantum Networks

(that combine matter and light systems)

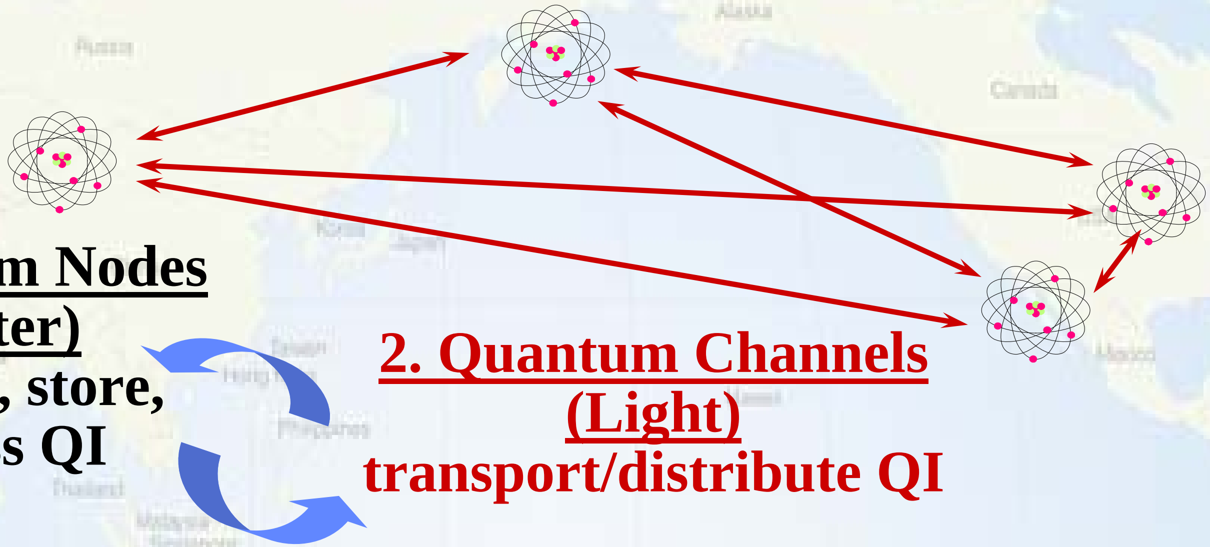
for Scalable Quantum Communication and Computing

Bennett (1996), Cirac et al. (1997)

Quantum Networks

Building blocks of a Quantum Network?

1. Quantum nodes (Matter)
2. Quantum channels (Light)
3. Quantum interfaces (Matter ←→ Light)

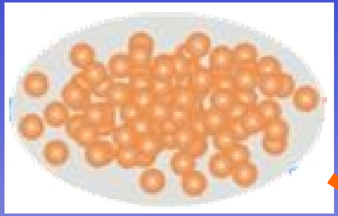


1. Quantum Nodes (Matter)
generate, store, process QI

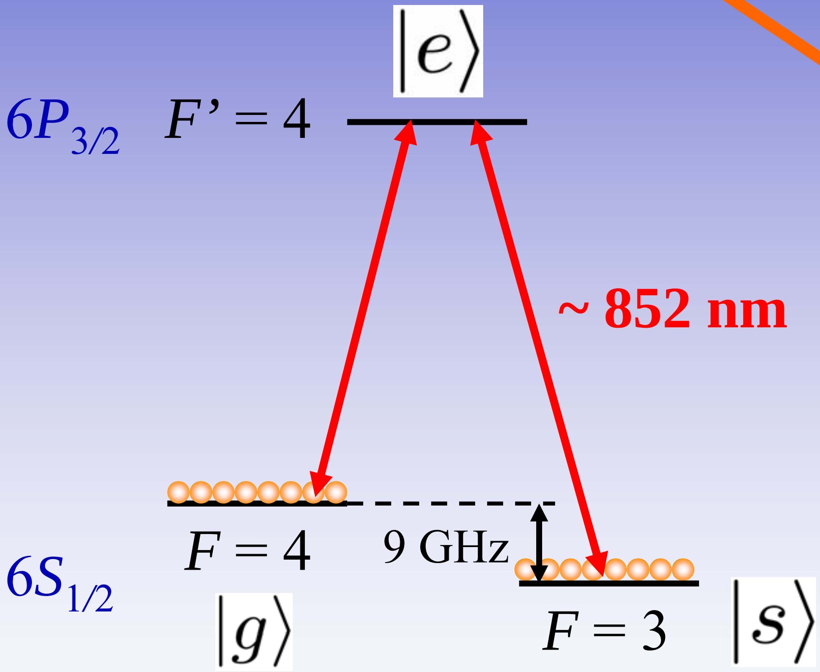
2. Quantum Channels (Light)
transport/distribute QI

3. Quantum Interface
map QI between matter – light

Quantum Memory of Atomic Ensembles



Quantum Memory: a cloud of cesium atoms confined by a magneto-optical trap (MOT)



$|e\rangle$

$6P_{3/2}$ $F' = 4$

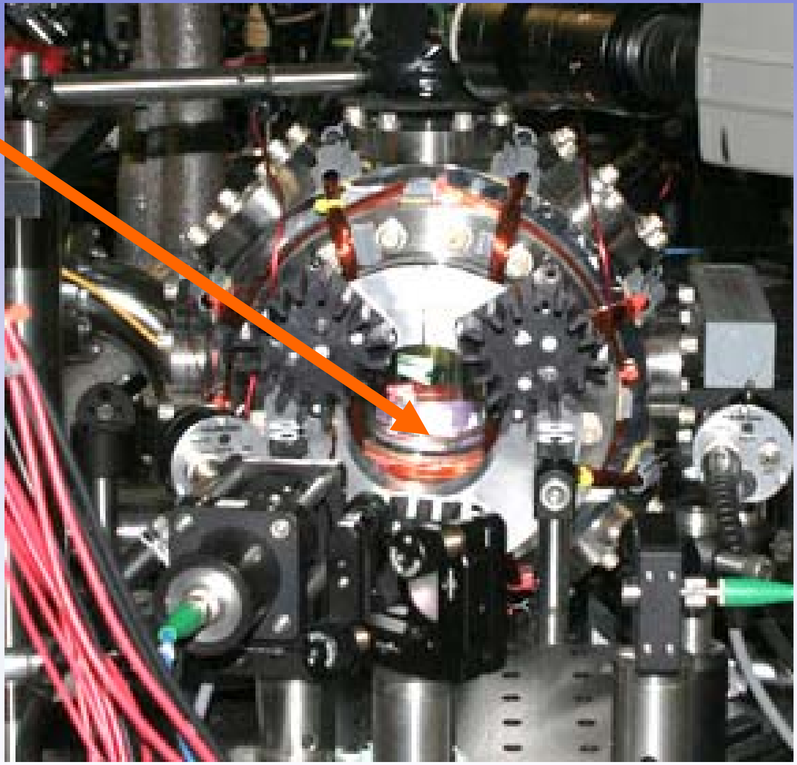
~ 852 nm

$6S_{1/2}$ $F = 4$ $|g\rangle$

9 GHz

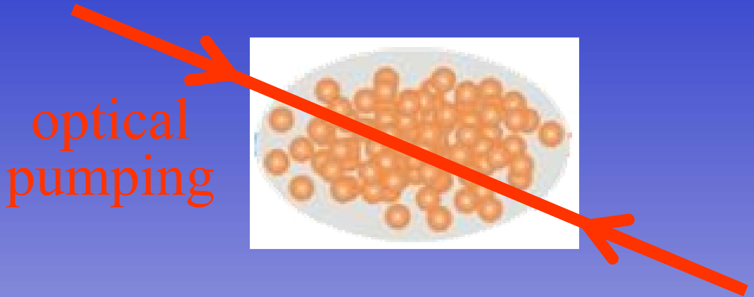
$F = 3$ $|s\rangle$

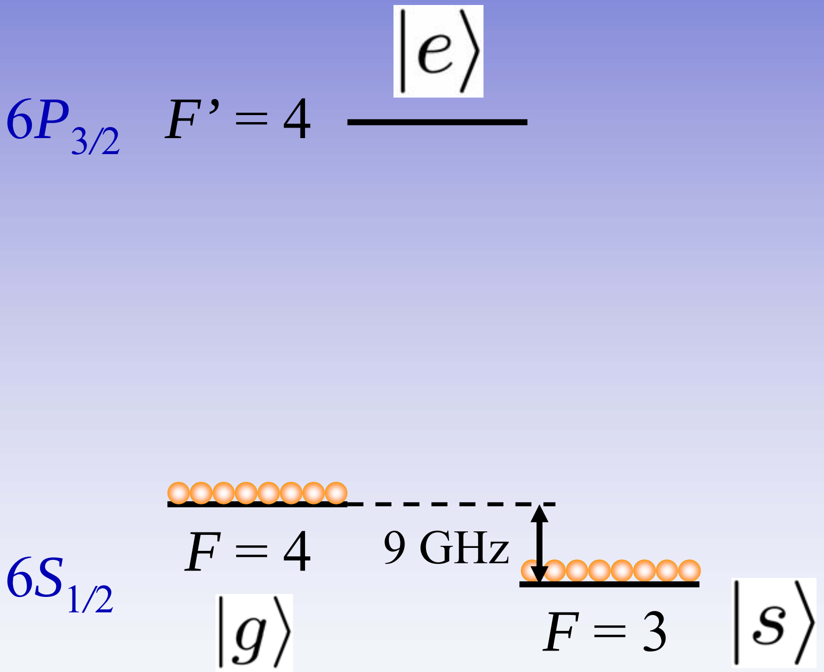
Λ-type energy levels, $\gamma_{gs} \sim 0$



an ultra high vacuum chamber
– the host of our quantum nodes

Quantum Memory – Atomic Ensembles





Quantum Information Processing with Atomic Ensembles

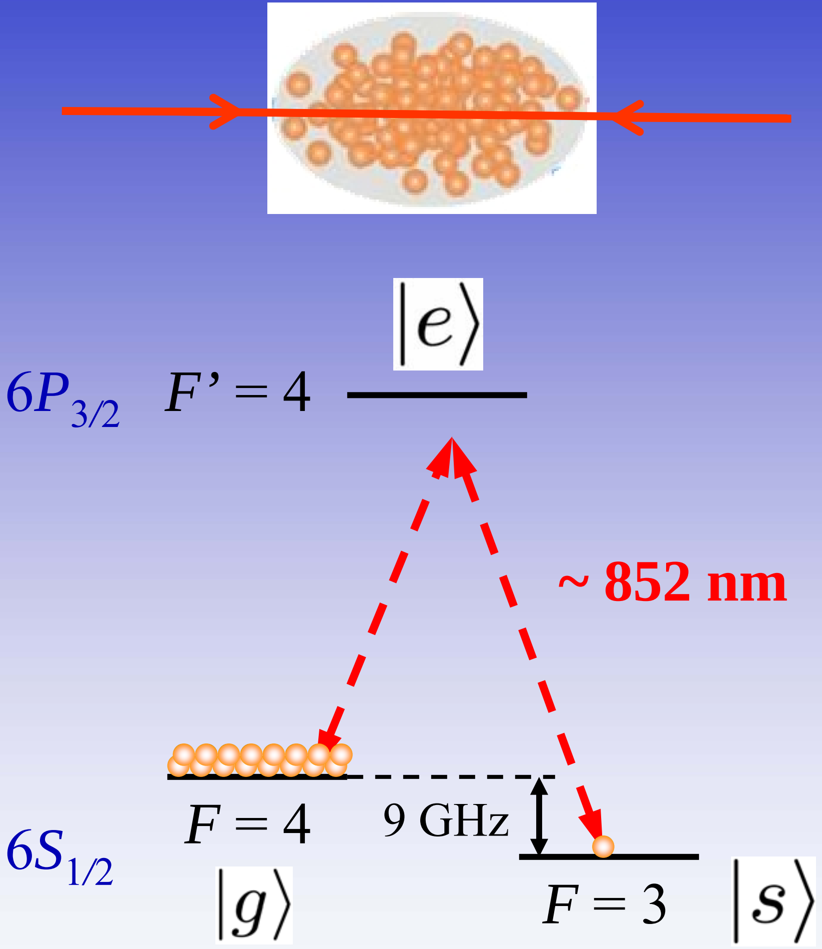
all atoms in g (by optical pumping)

no photon

Initialize: $\bigotimes_i |g\rangle_i \otimes |0_p\rangle$

Λ-type energy levels, $\gamma_{gs} \sim 0$

Quantum Memory – Atomic Ensembles



Λ-type energy levels, $\gamma_{gs} \sim 0$

Quantum Information Processing with Atomic Ensembles

all atoms in g (by optical pumping)

no photon

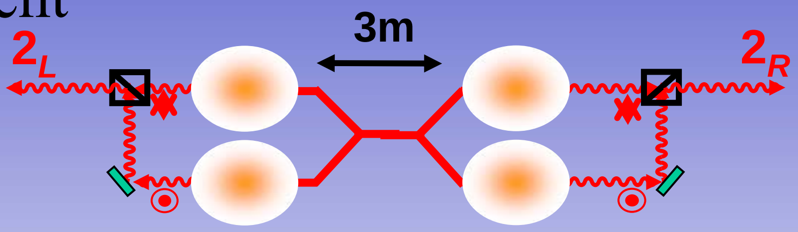
Initialize:	$\bigotimes_i |g\rangle_i \bigotimes |0_p\rangle$
Generate QI:	Single excitations in $|s>$ via laser manipulations
Store QI:	in $|s>$, memory time by coherence time of $|s>$
Retrieve QI:	map single excitations into single photonic state, & restore atomic states

Probabilistic Quantum Interface by DLCZ Protocol

Duan, Lukin, Cirac, Zoller, Nature, 414, 413 (2001)

- Heralded Single photons and entanglement
- Distribution of Polarization Entanglement for Scalable Quantum Cryptography

  Chou *et al.*, Science 316, 1316 (2007)

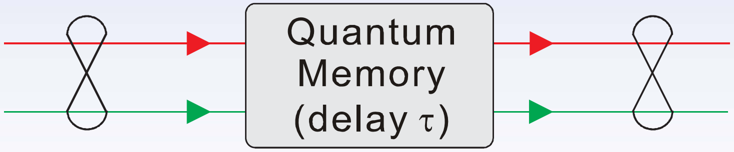


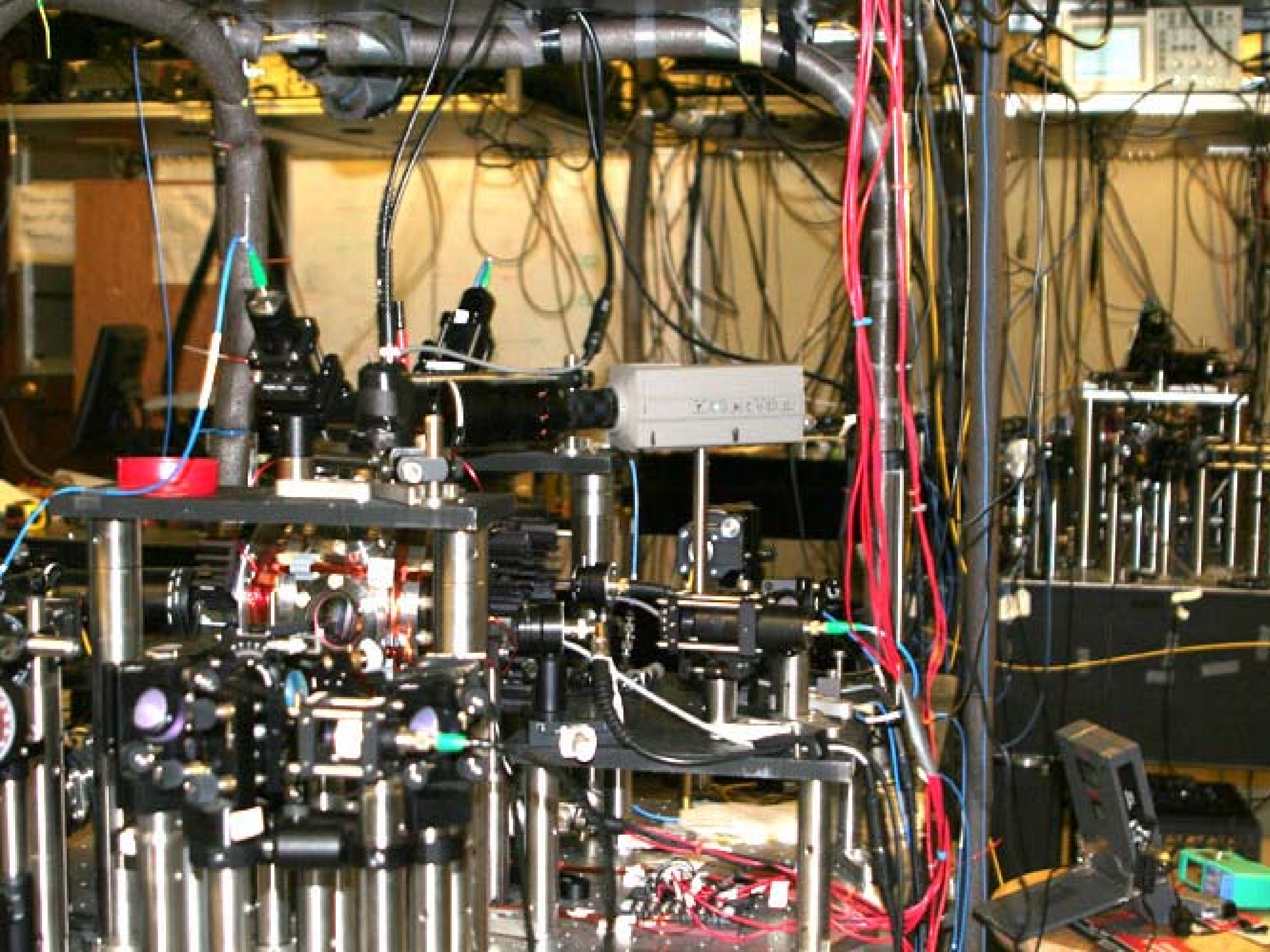
Deterministic Quantum Interface by Dynamic EIT

- Entanglement mapping IN and OUT of quantum memories

  Choi *et al.*, Nature 452, 66 (2008)

  - ✓ Reversible and coherent mapping
  - ✓ Entanglement transfer efficiency 20(2)%





From Atomic Gasses to Solids State Chips

- Compact, integrable, scalable
- Versatile
- New technologies, new physics
  - Can we pick out the ‘right’ systems, and the ‘right’ interactions?
  - Can we understand and control the interactions?
  - And manipulate the system the way we want?
  - How are they similar to, and different form atomic systems?

Why quantum information …

Why solid state …

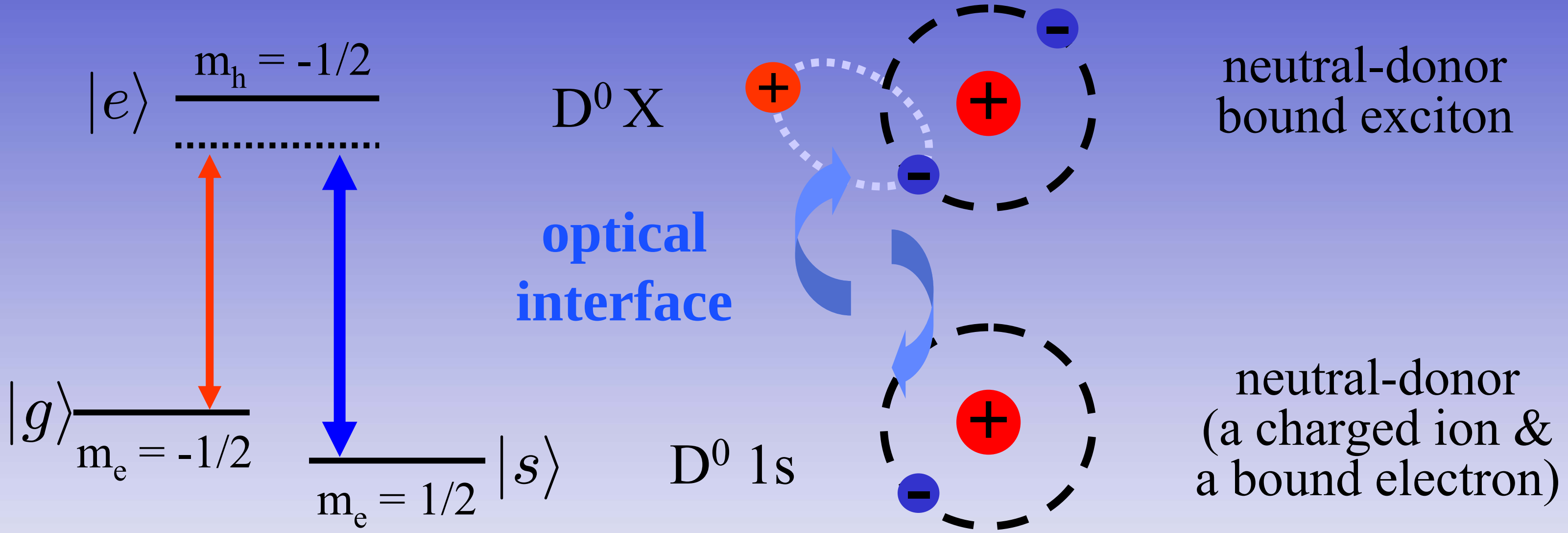
Which Solid State Systems and How

- Nuclear spin
  - long decoherence time
  - slow, no convenient optical interface, limited control techniques
- Single electron spins
  - could have long decoherence time and optical interface
  - fragile, difficult to isolate, difficult to make identical and scale up
- Superconductor qubits
  - Macroscopic, integrated on-chip microwave circuitry
  - no optical access, extremely complicated microwave circuitry

- **Donor-bound electron spin ensemble**
  - **robust, all identical, convenient optical access**
  - material properties and control techniques less studied

Electron Spin Ensembles

Bulk GaAs with neutral donor (Si) impurities



$|e\rangle$ $m_h = -1/2$

$|g\rangle$ $m_e = -1/2$

$|s\rangle$ $m_e = 1/2$

D^0 X

optical interface

D^0 1s

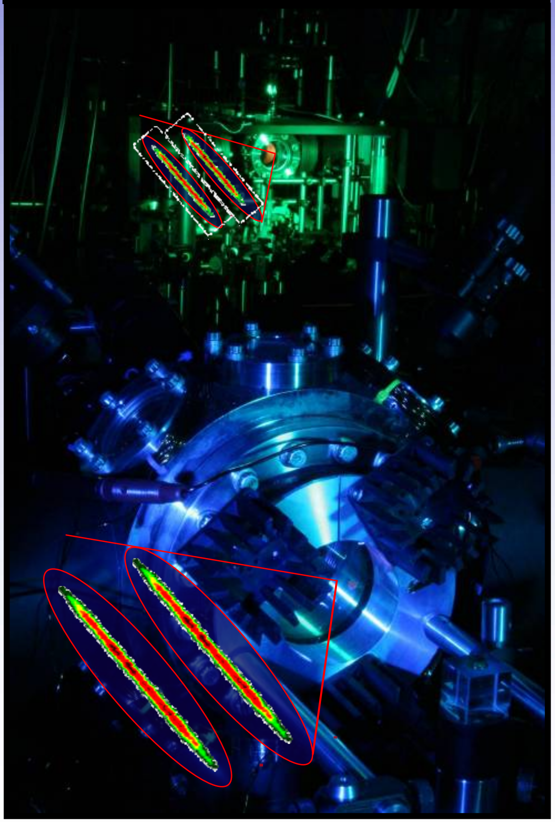
neutral-donor
bound exciton

neutral-donor
(a charged ion &
a bound electron)

- Λ-type energy levels with very long decay and homogeneous dephasing times
- Store quantum information in one lower level
- Manipulate quantum information by light through coupling to the upper level
- As an ensemble system, very robust against loss and noise
- Easy to scale up and integrate

Macroscopic Coherence in Matter-Light Systems

Quantum Control
of Matter by Light
in
e Spin Ensembles



Matter

Quantum Physics
Collective Phenomena
Cavity QED

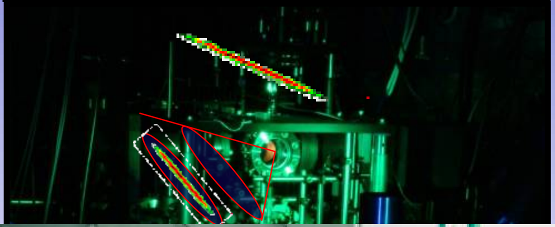
Quantum Information
Processing
Novel Devices

Light

Spontaneous
Macroscopic
Coherent
in
a polariton
condensate

Macroscopic Coherence in Matter-Light Systems

Quantum Control of Matter by Light in e Spin Ensembles



Matter

Quantum Physics
Collective Phenomena
Cavity QED

Quantum Information Processing
Novel Devices

Light

Material Science
Fabrication Technology

Novel Mesoscopic Systems

- New Structures
- New Materials
- New Types of Ensembles