Atomtronics: connecting AMO and semiconductor physics

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What is atomtronics?

Similarities to optoelectronic engineering

Examples

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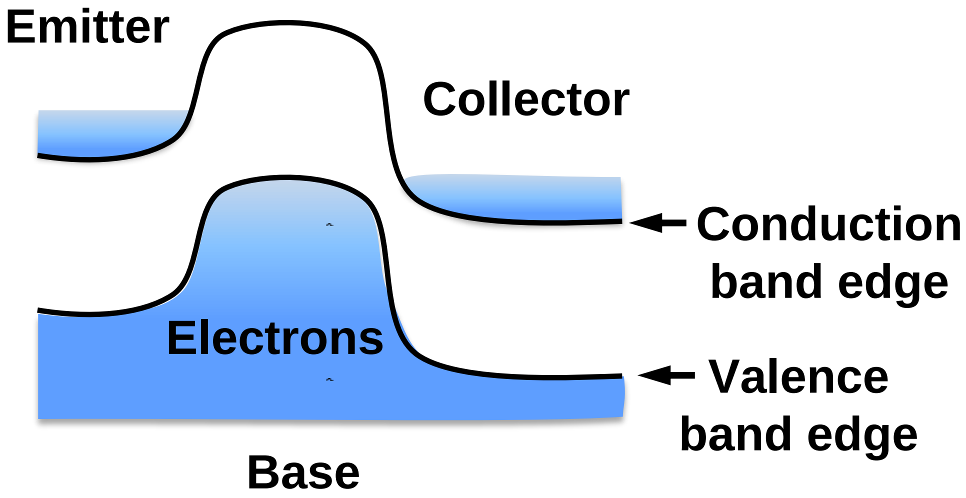
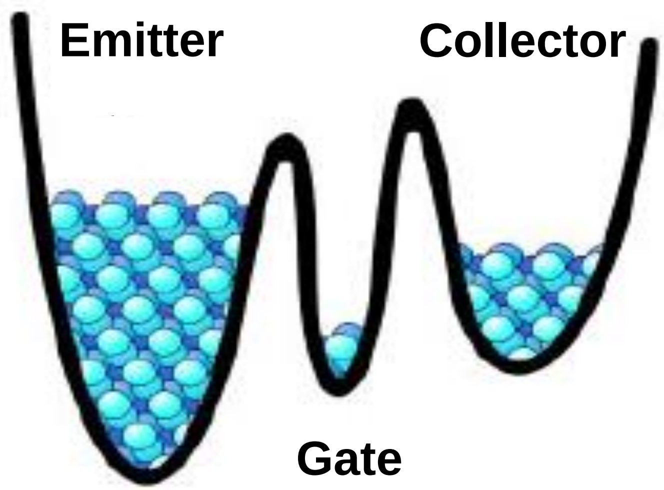
What is Atomtronics?

Electronic transistor



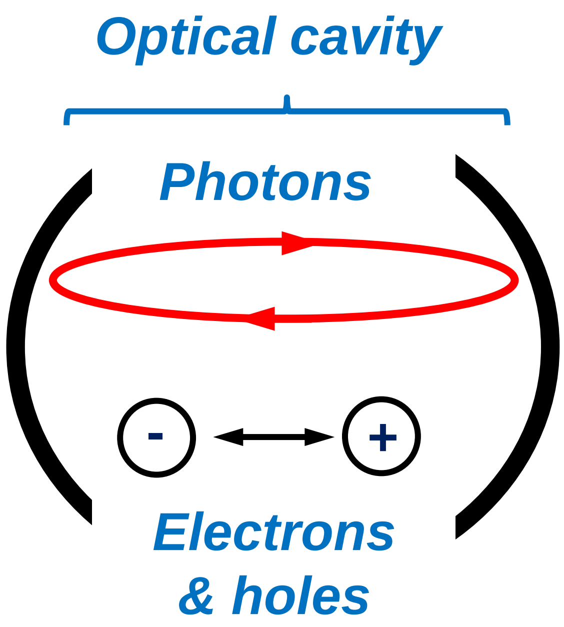
Bose-Einstein-Condensate (BEC) transistor



Stickney, Anderson, Zozulya: PRA75, 013608 (2007)

Why Atomtronics?

Example: Optoelectronics



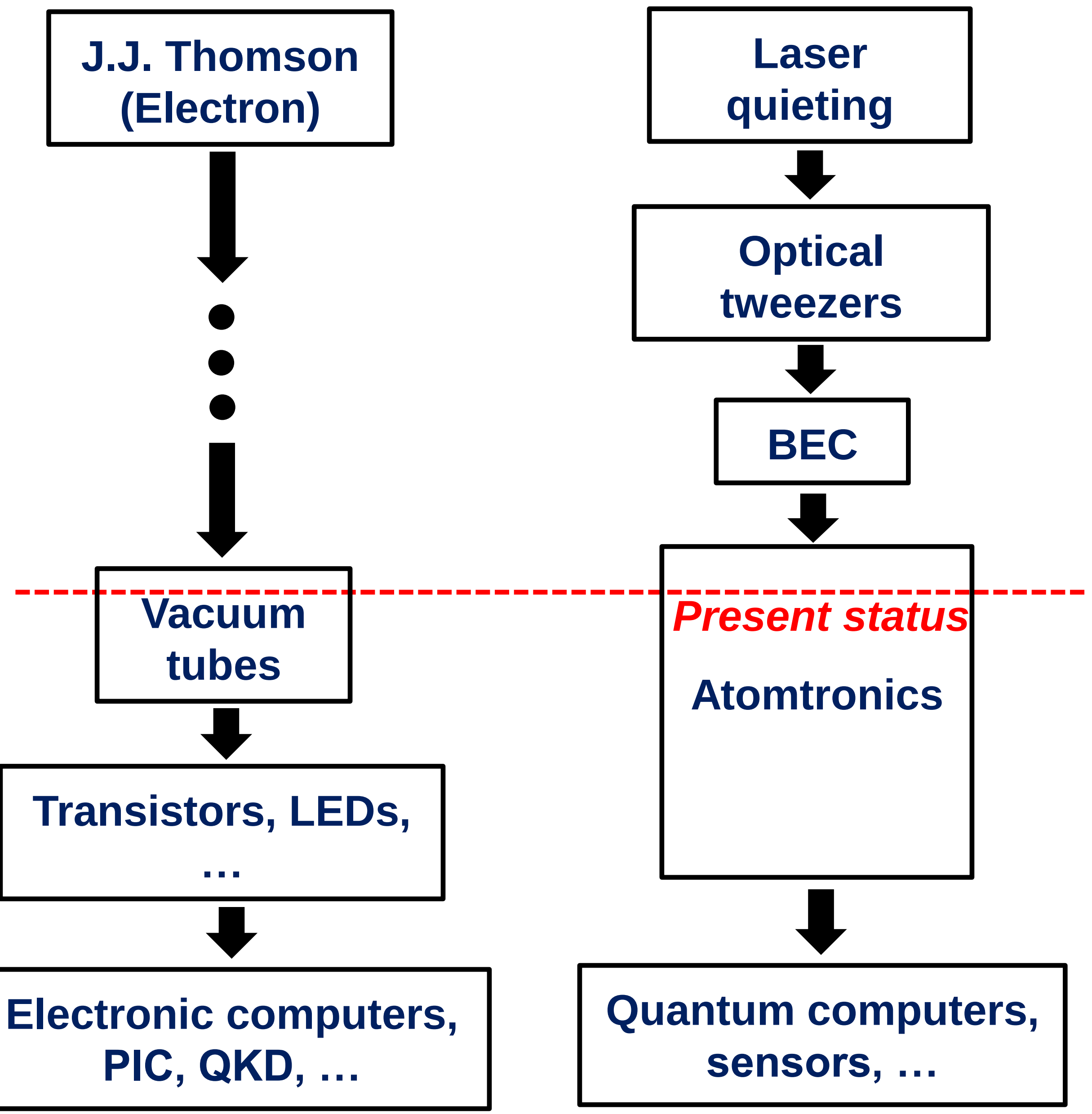
- **Cold atoms doing jobs of charge carriers and photons**

- $\lambda_{deBroglie}^{Atom} \ll \lambda_{Photon}$

  $\ll \lambda_{deBroglie}^{Electron,hole}$

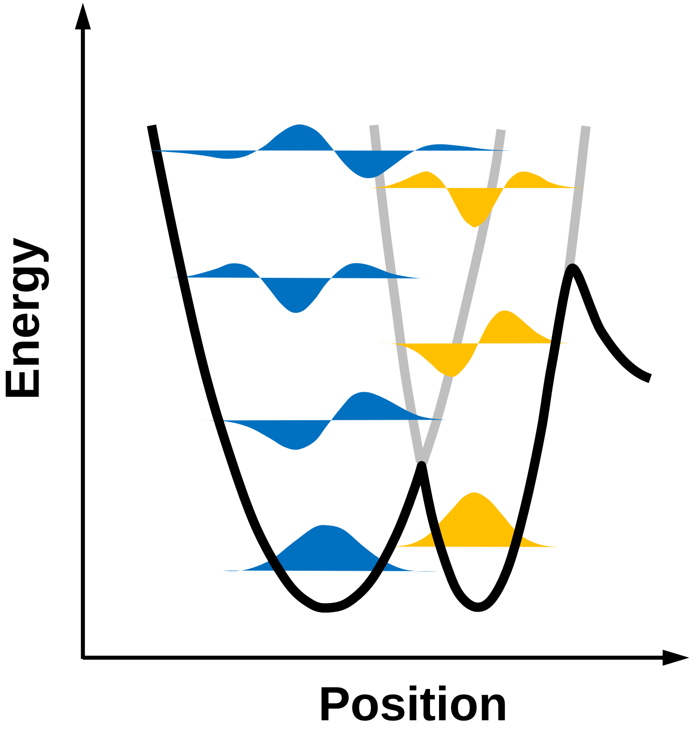
- **Significantly reduced footprint and increased precision -- beyond present fundamental limit**

Developmental stage of Atomtronics -- early infancy



Basic atomtronic component

Double-potential well



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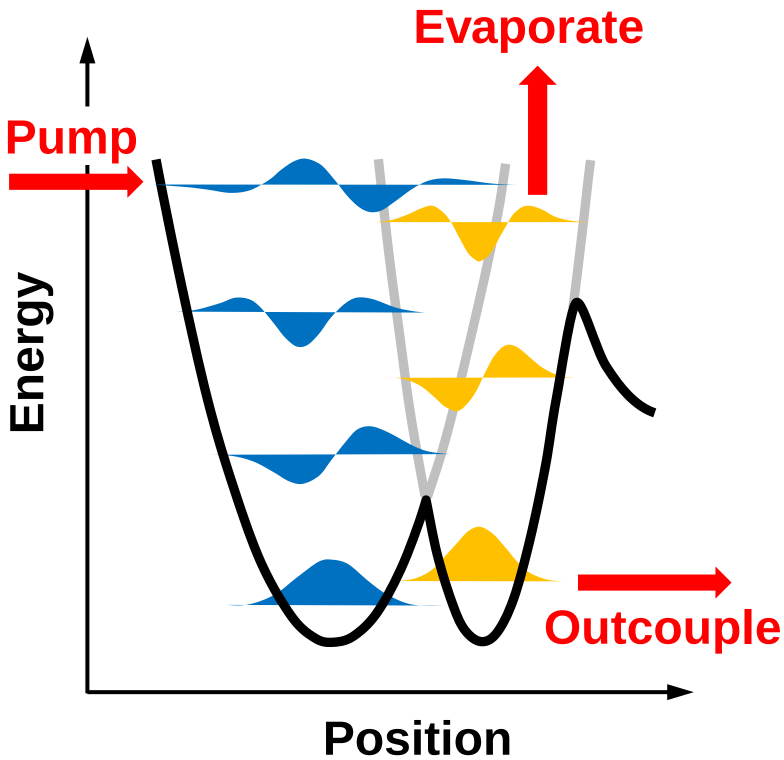

Need engineering design tool to transition BEC from laboratory to devices

Basic atomtronic component

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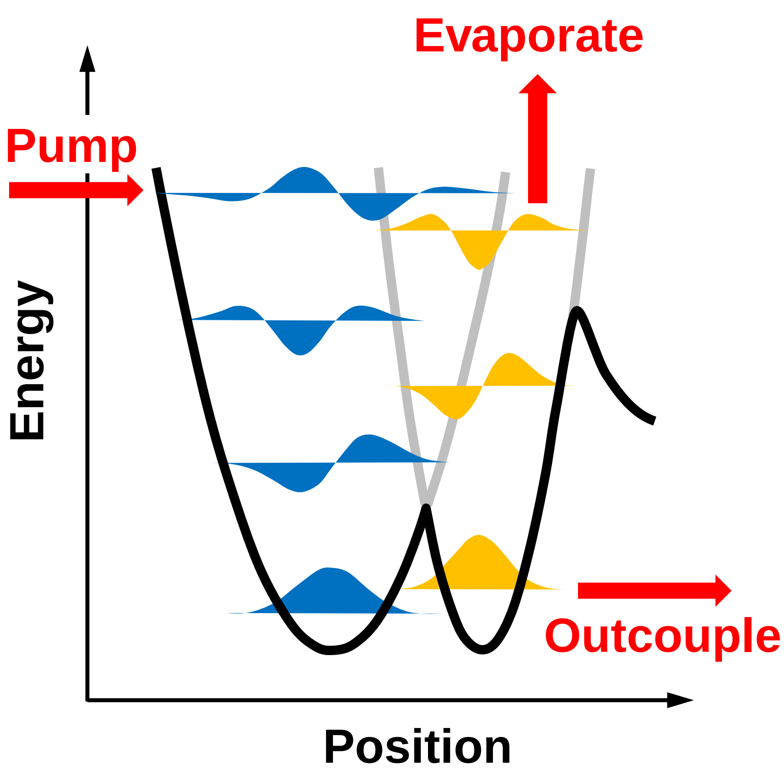
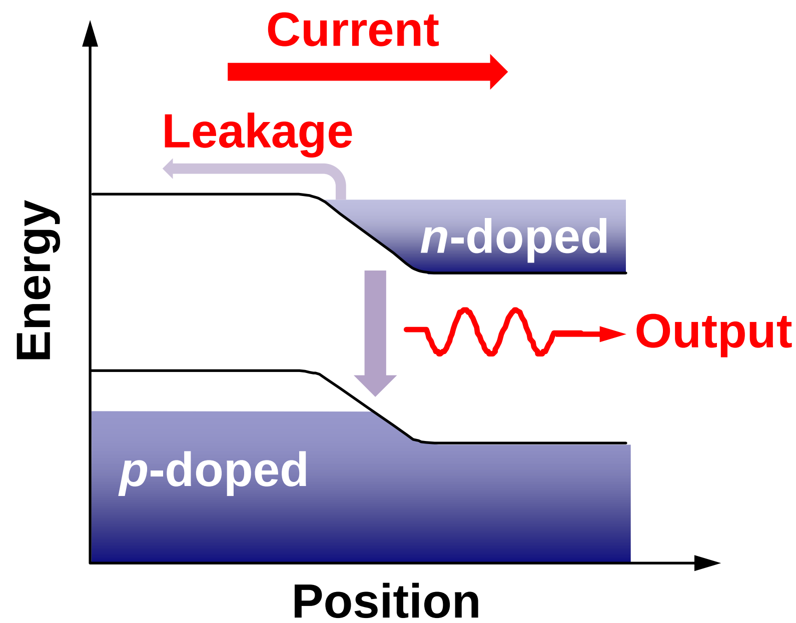


Semiconductor laser diode



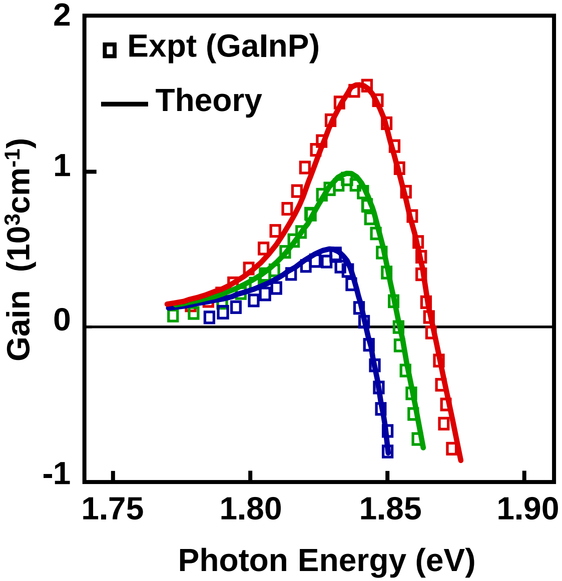
Need engineering design tool to transition BEC from laboratory to devices

- **Pump, extraction and relaxation**
- **Nonequilibrium**
- **Dynamical range**

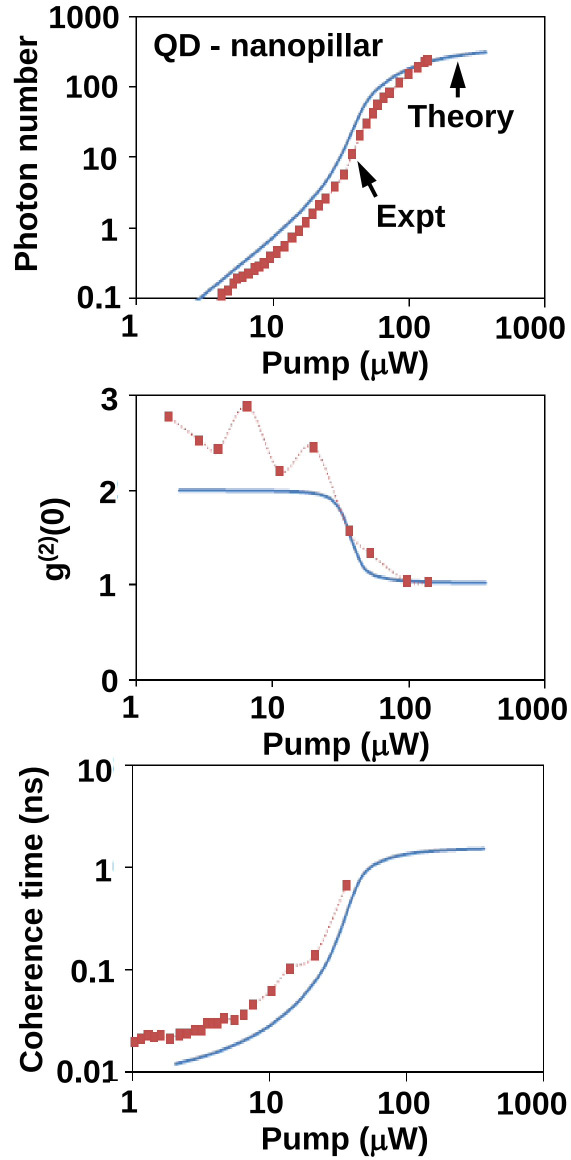
  – collisions (fast), operation (slow)
- **Large parameter space for engineering optimization**
- **Long-lived coherences**
- **Phonons**

Results possibly convertible for atomtronics use

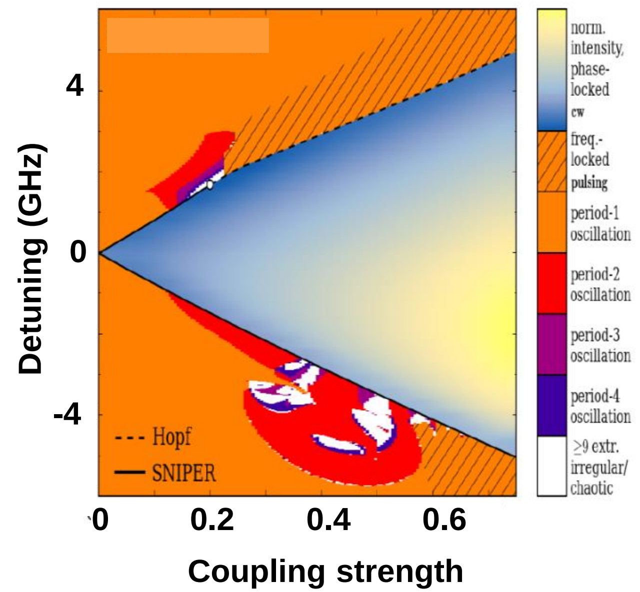
Collisions



Coherences and statistics



Bifurcation-continuation tools for parametric studies



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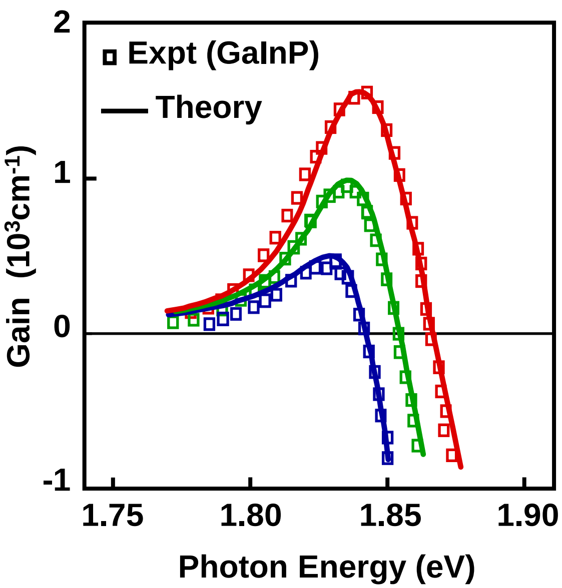

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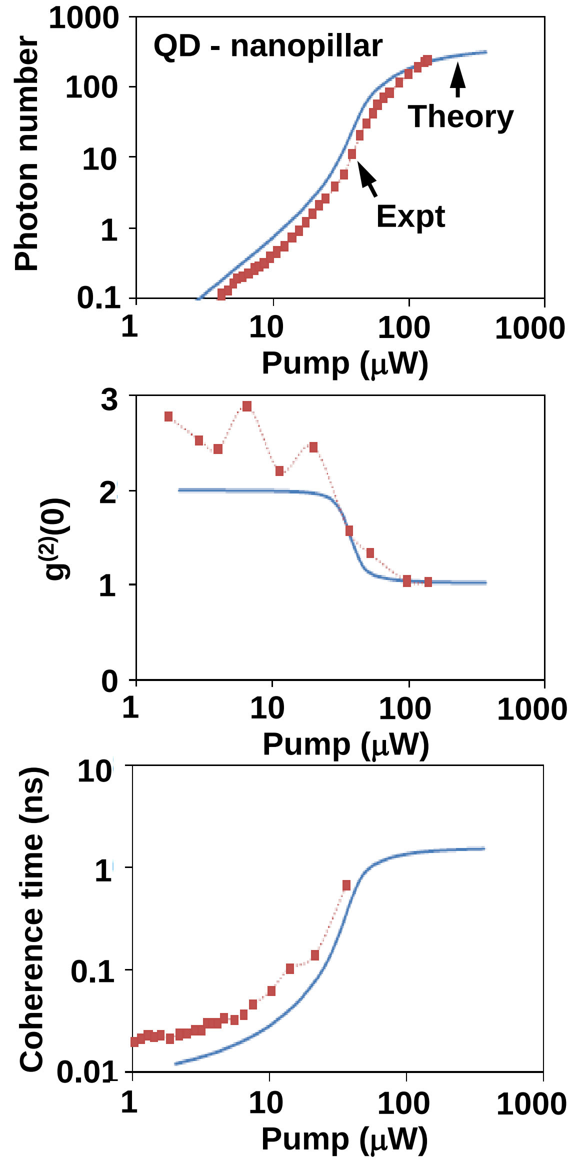

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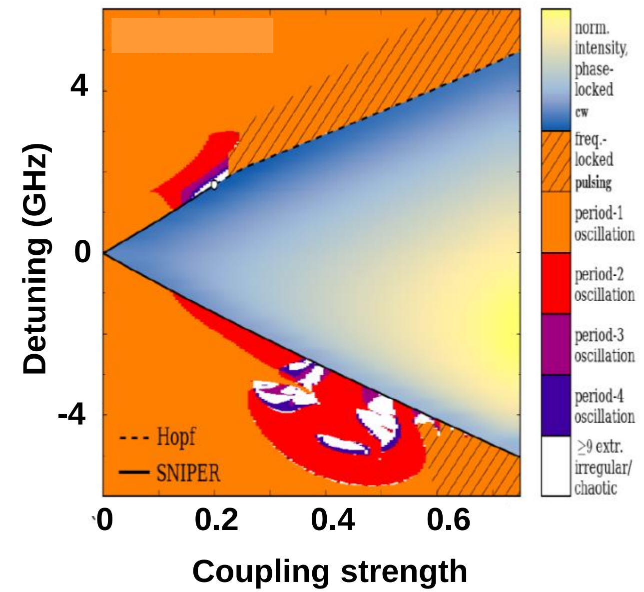
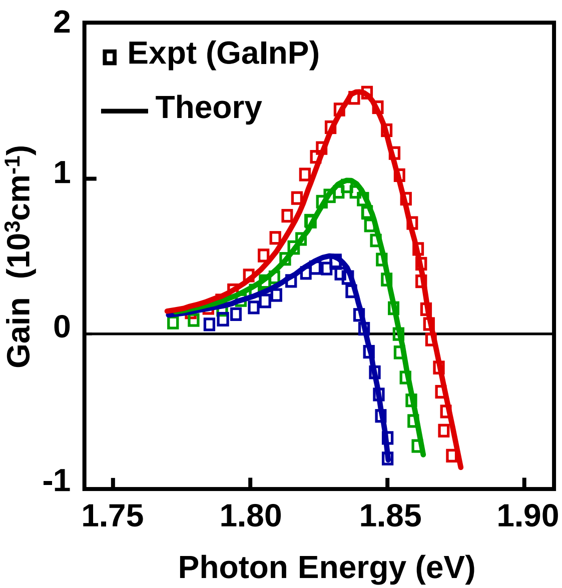


Stephan Reitzenstein's sessions on semiconductor quantum optics

Results possibly convertible for atomtronics use

Collisions



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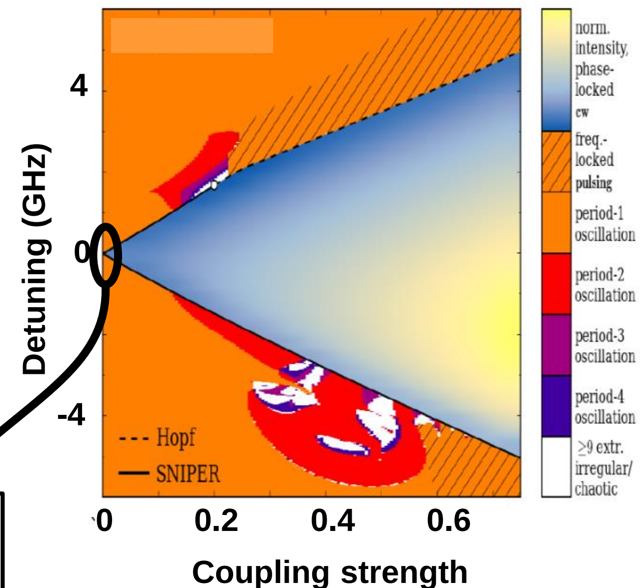
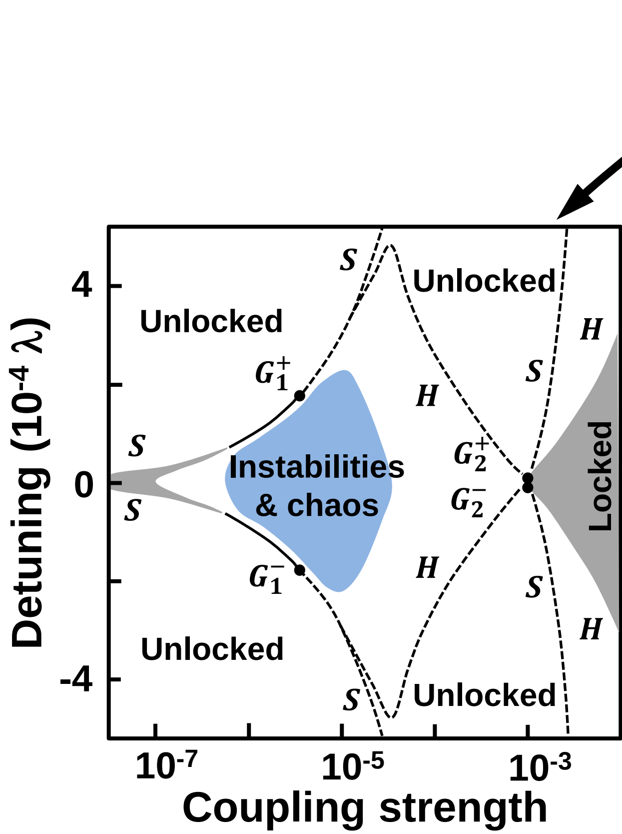
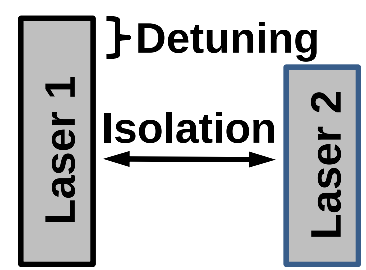
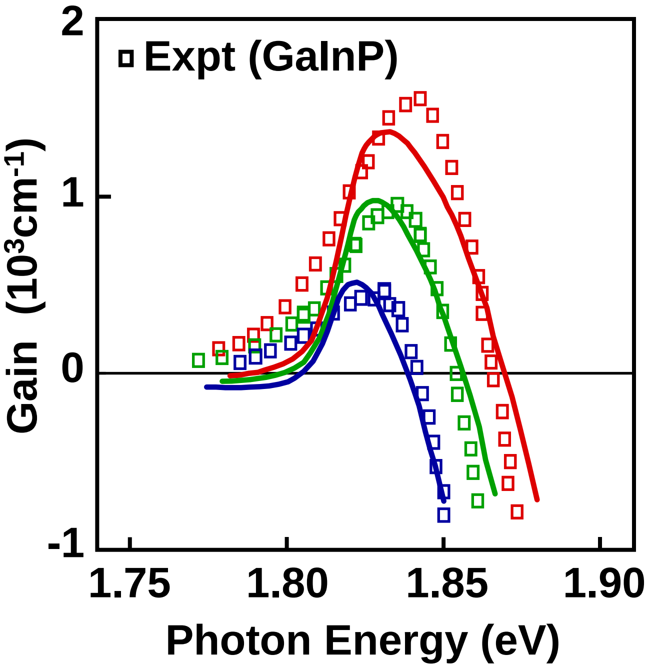




Coupled lasers



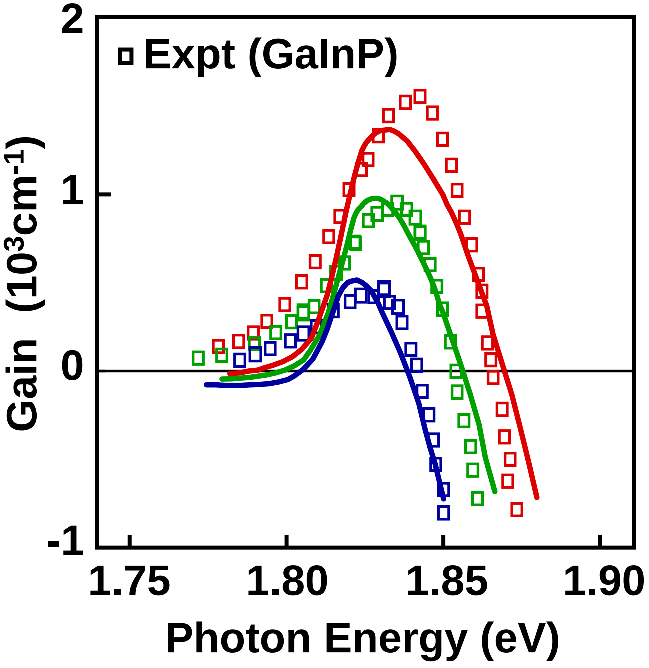
Results possibly convertible for atomtronics use



Treatment of collisions

Using T_1 , T_2

Results possibly convertible for atomtronics use

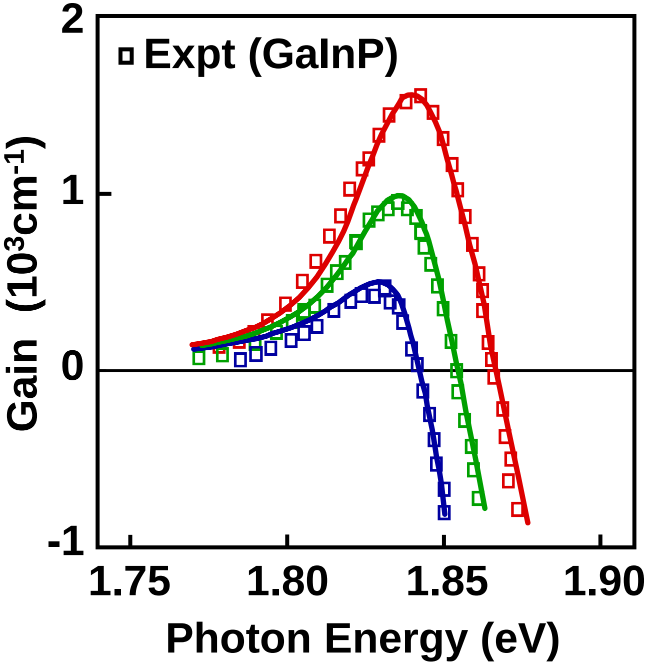


<u>Treatment of collisions</u>

Using T_1 , T_2

Compute carrier correlations
- **2^{nd} order perturbation theory**
- **Markov approx.**

Results possibly convertible for atomtronics use



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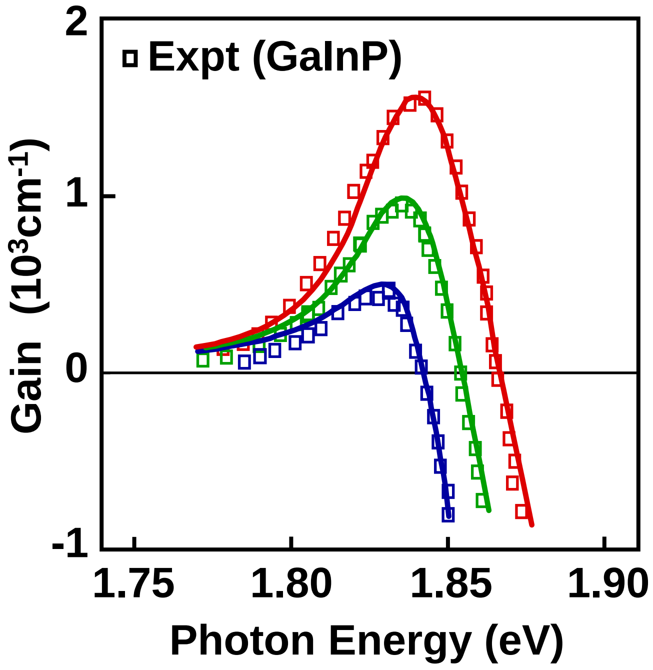
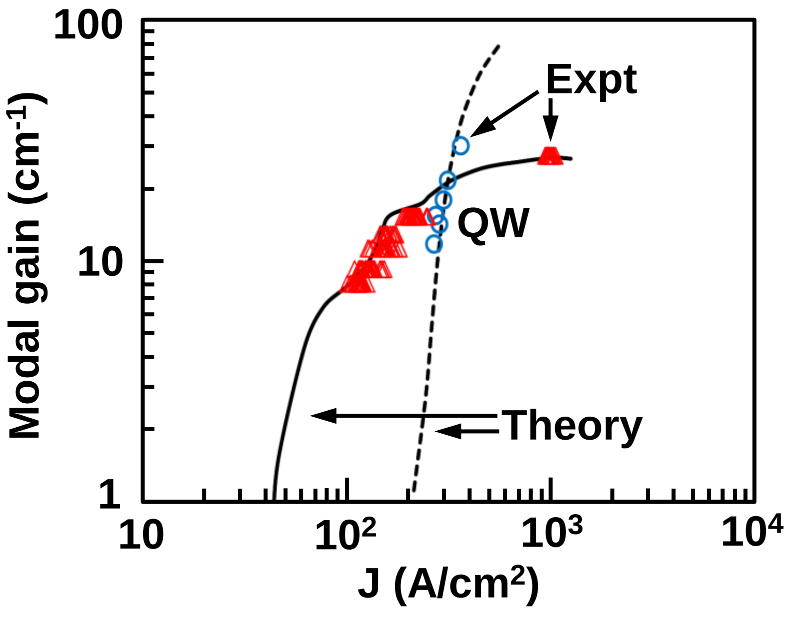


<u>Treatment of collisions</u>

Using T_1 , T_2

Compute carrier correlations
2nd order perturbation theory
Markov approx.

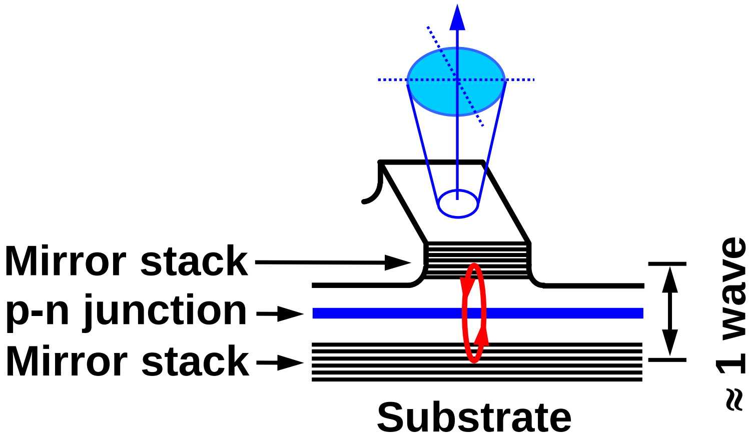
Now: Non-perturbative treatment
Memory effects

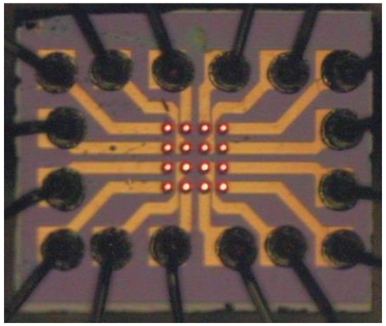


Extraction of difficult to measure parameters in quantum-dot lasers for silicon photonics

Semiconductor systems studied and developed

Microlasers





10^8 VCSELs produced/year

> 2 billion in use

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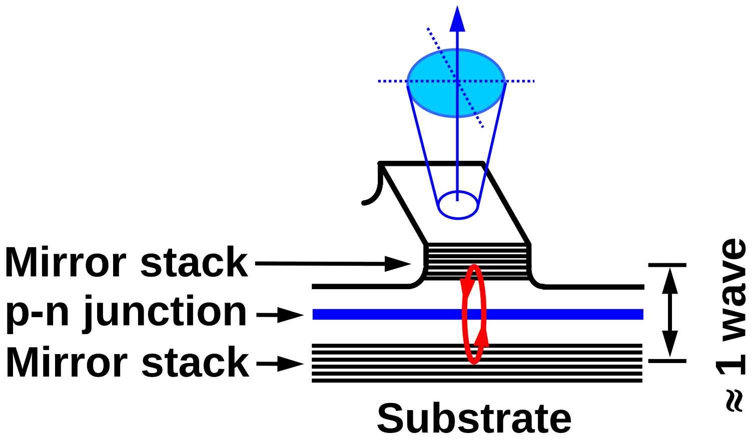

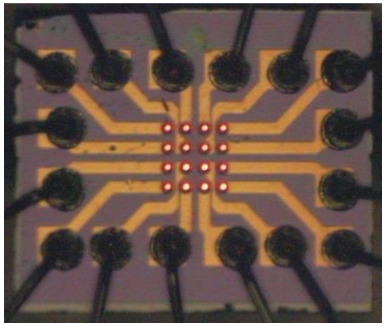

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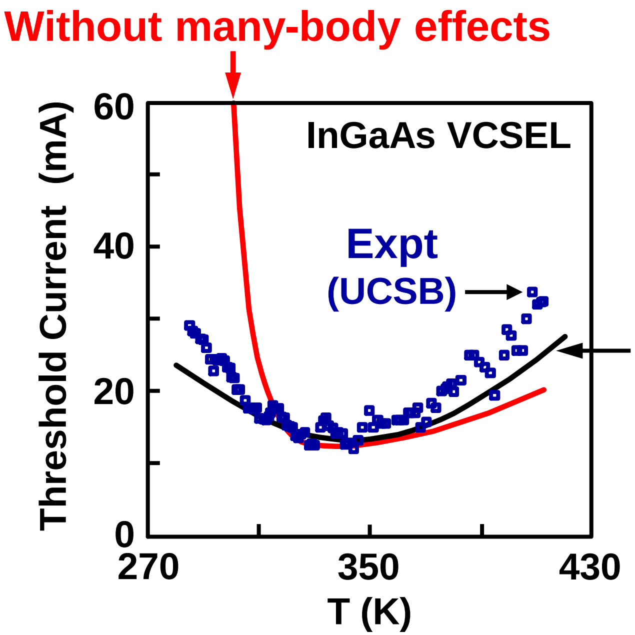

Similar to exchange shift in Gross-Pitaevskii equation for BEC

With many-body effects

Semiconductor systems studied and developed

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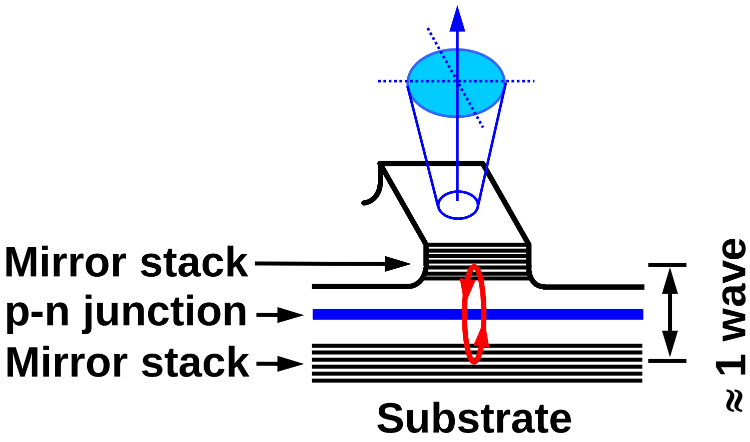
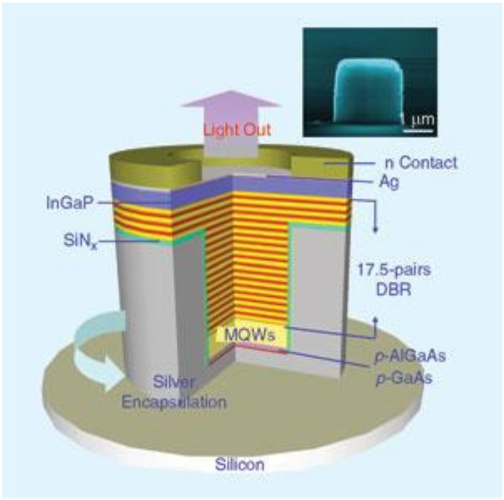
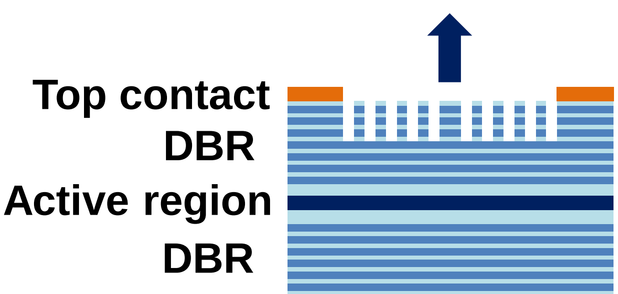


Nanolasers

Plasmonic-cavity lasers



Photon crystal lasers



Semiconductor systems studied and developed

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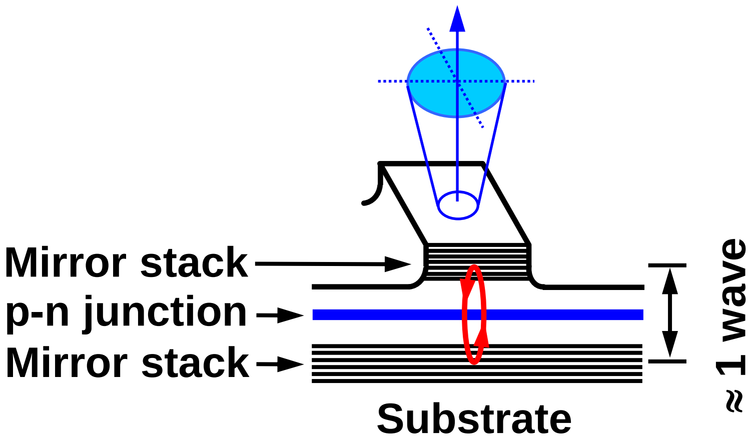
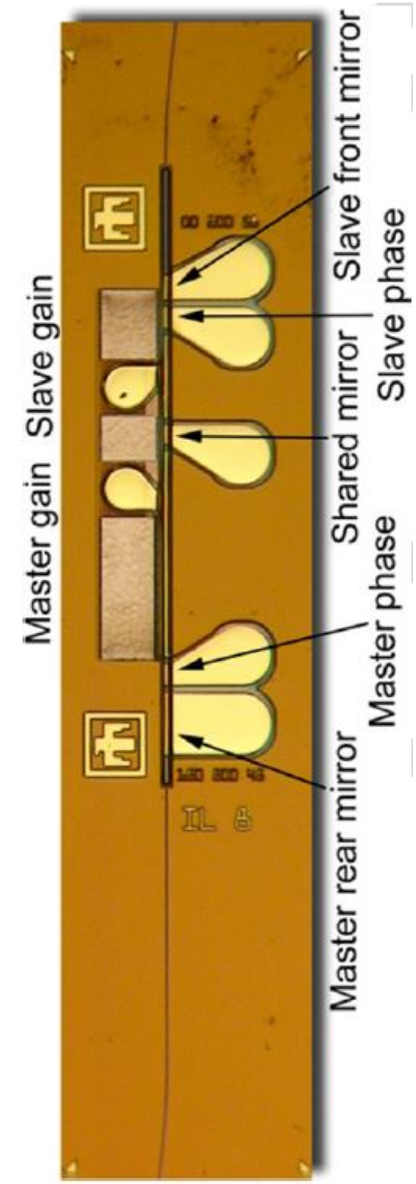


Coupled-cavity PIC



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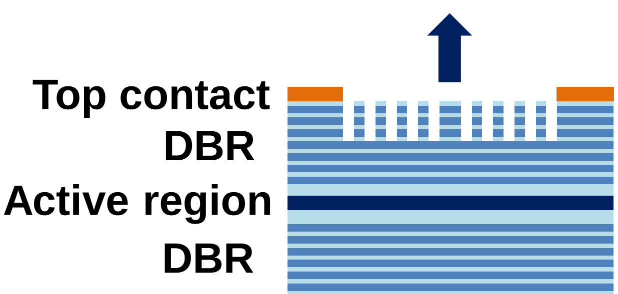

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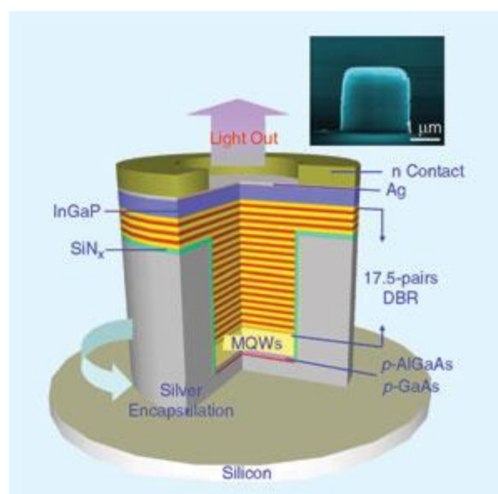

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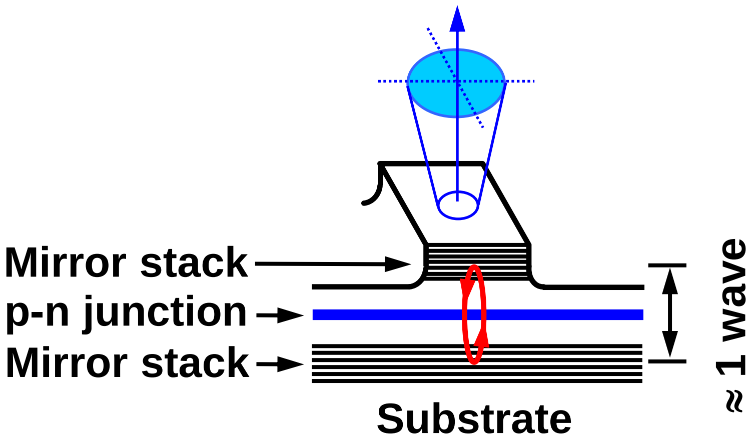
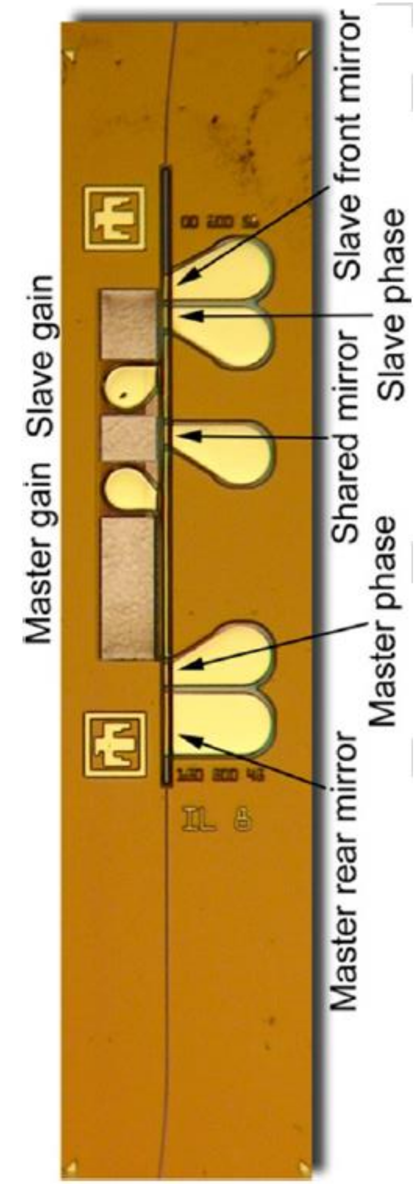


LED lights

Coupled-cavity PIC



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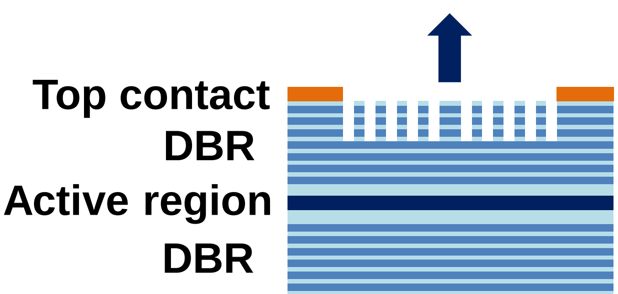

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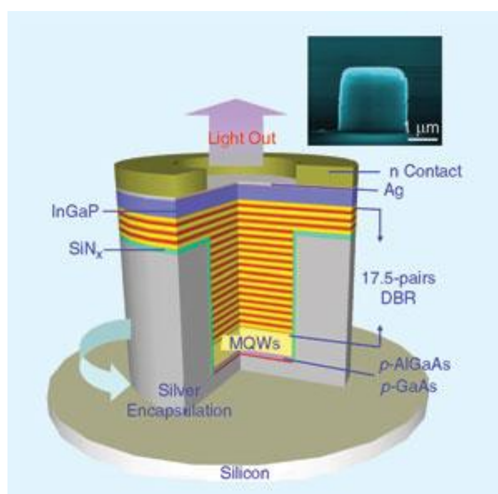

UNITE TO LIGHT

The Problem:

1.5 billion people rely on kerosene for light

The Solution:

Over 80,000 solar lights distributed

Global Impact

80,000 lights have been distributed to over 64 countries on 4 continents.

Atomtronics circuit description

System Hamiltonian

$$H = \underbrace{\sum_i \left[\frac{p_i^2}{2m} + V(r_i)\right]}_{\text{Single-particle}} + \sum_{i<j} \underbrace{V(r_i, r_j)}_{\text{Interatomic interaction}}$$

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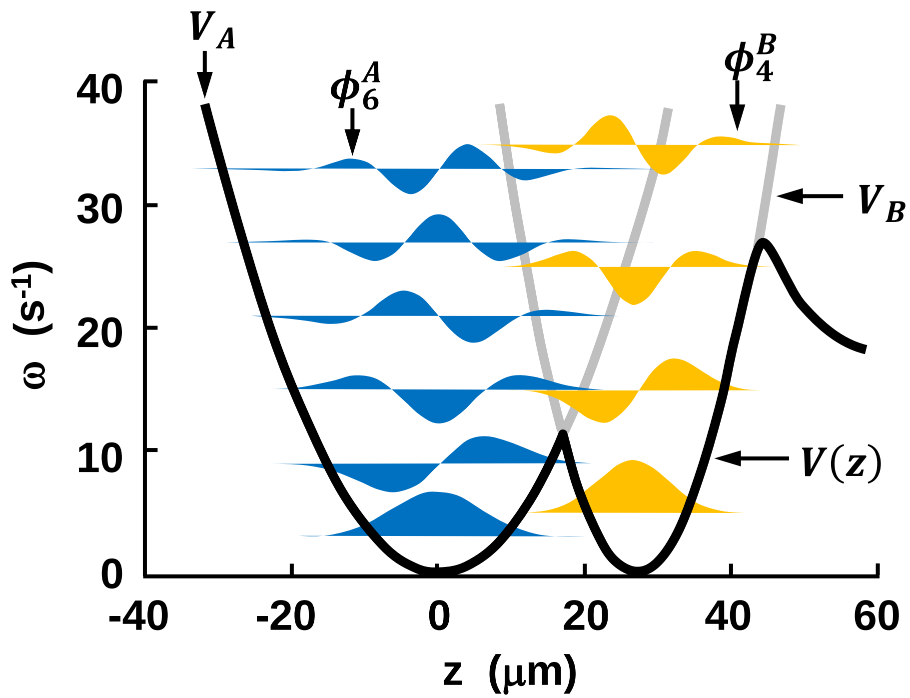
Basis

$$\left[\frac{p^2}{2m} + V_A(r)\right]\phi_n^A(r) = \varepsilon_n^A\,\phi_n^A(r)$$

$$\left[\frac{p^2}{2m} + V_B(r)\right]\phi_n^B(r) = \varepsilon_n^B\,\phi_n^B(r)$$

Double-potential well



2nd-quantize

$$\hat{\psi}(r) = \sum_i a_i\,\phi_i^A(z) + \sum_i b_i\,\phi_i^B(z)$$

Atomtronics circuit description

Two-site Bose Hubbard Hamiltonian

$$H = \sum_i \varepsilon_i^A \, a_i^\dagger a_i + \sum_i \varepsilon_i^B \, b_i^\dagger b_i$$

$$+ \sum_{i,j} \left(g_{ij} \, a_i^\dagger b_j + g_{ji}^* \, b_j^\dagger a_i \right) \longleftarrow \text{Hopping}$$

$$+ \sum_{i,j,k\neq 0} \left(v_{ijk}^{AA} \, a_{i-k}^\dagger a_{i+k}^\dagger a_j a_i + v_{ijk}^{BB} \, b_{i-k}^\dagger b_{i+k}^\dagger b_j b_i \right) \longleftarrow \text{Interatomic interactions}$$

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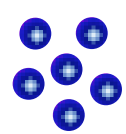
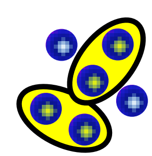
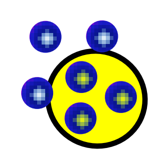
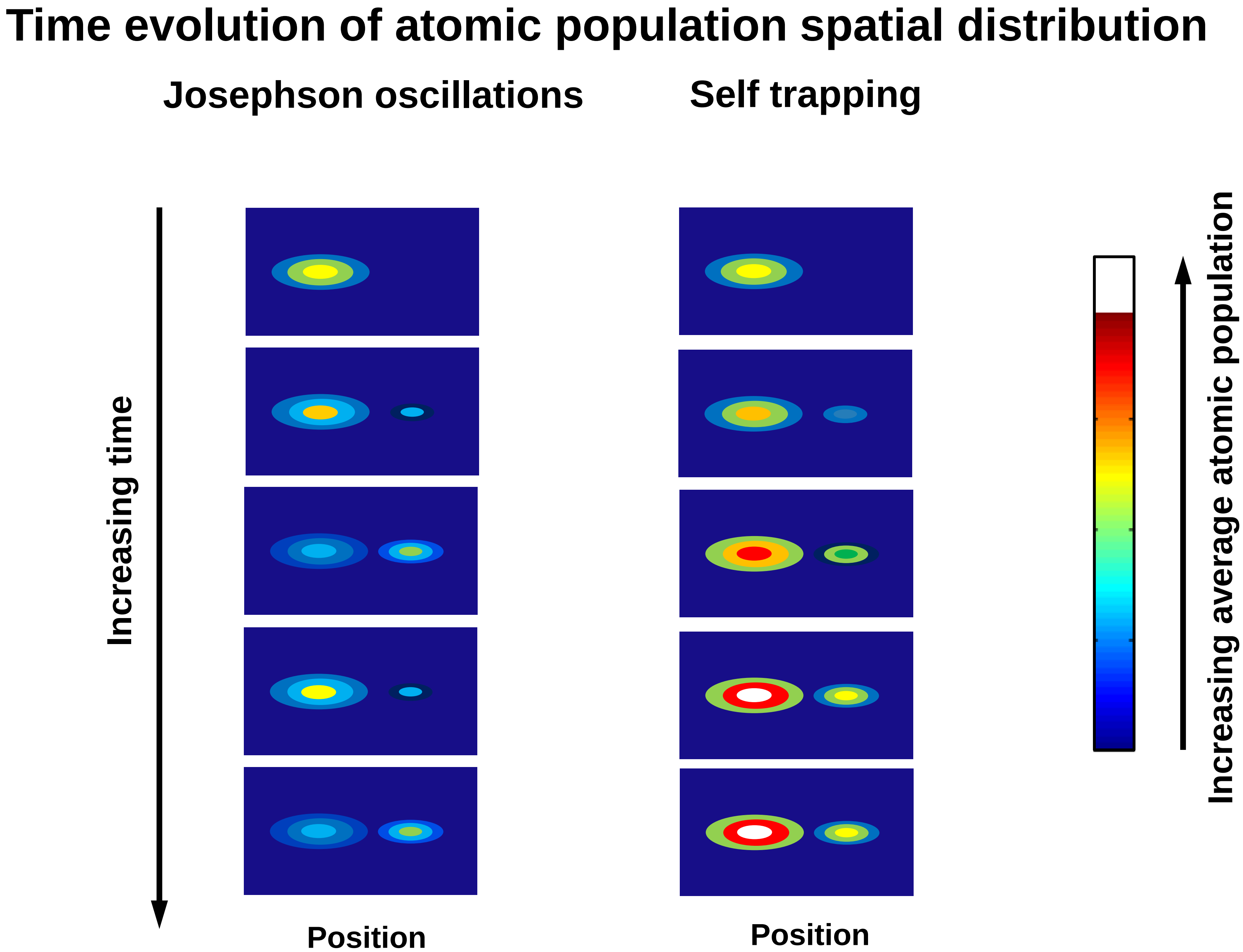
Heisenberg Picture

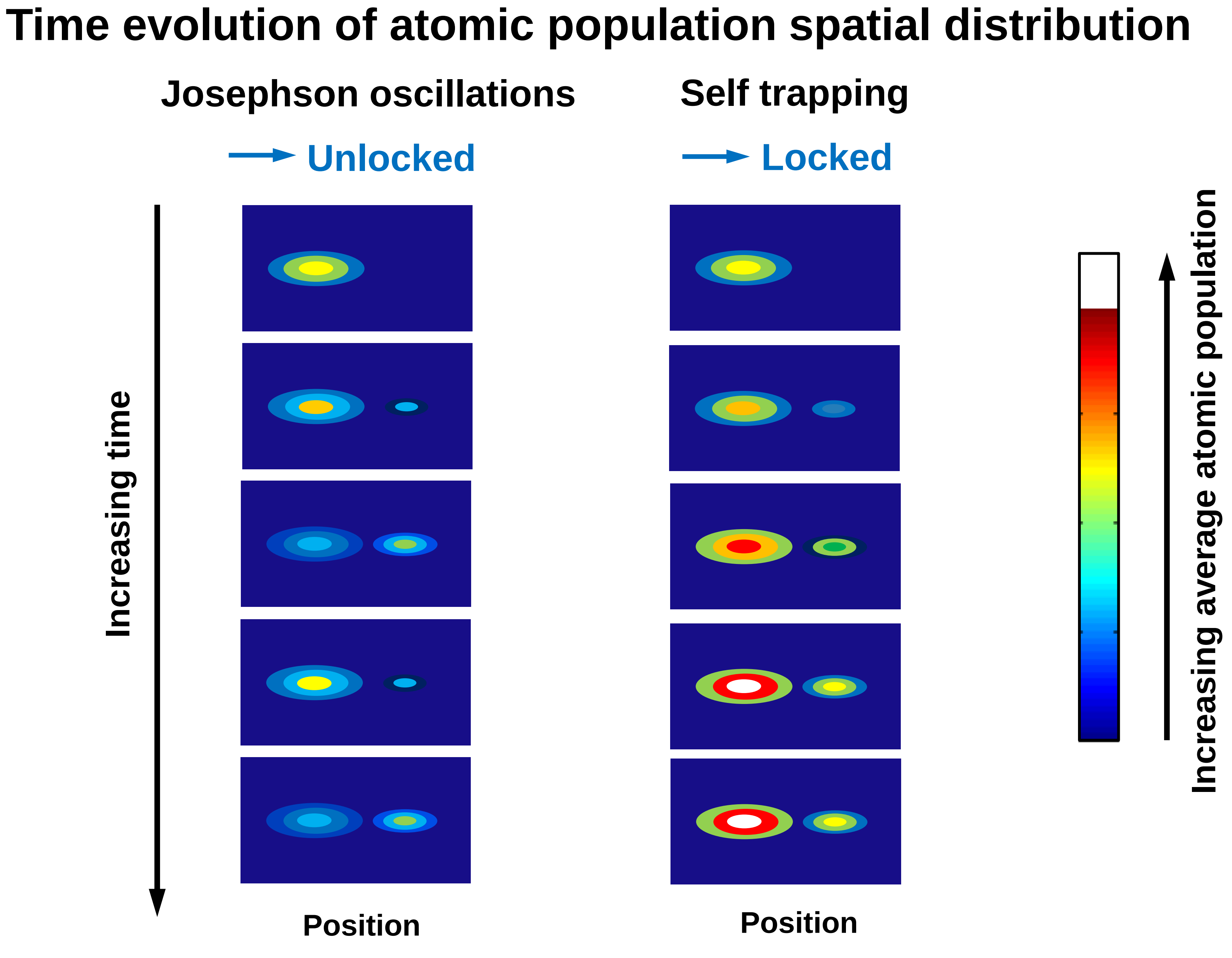
$$\frac{\partial}{\partial t} A = -\frac{i}{\hbar} [A, H]$$

Populations and polarizations: $\langle a_i^\dagger a_i \rangle, \left\langle b_j^\dagger b_j \right\rangle, \langle a_i^\dagger b_j \rangle$

Single particles | **Correlated pairs** | **Correlated 3-particle clusters**

Cluster expansion: $\langle \widehat{N} \rangle =$  +  +  + ...


Time evolution of atomic population spatial distribution
Josephson oscillations
Self trapping
Increasing time
Position
Position
Increasing average atomic population


Time evolution of atomic population spatial distribution
Josephson oscillations
Self trapping
Unlocked
Locked
Increasing time
Increasing average atomic population
Position
Position

Phase locking picture of system dynamics

Average left-well population : $\langle a_i^\dagger a_i \rangle = n_i^A$

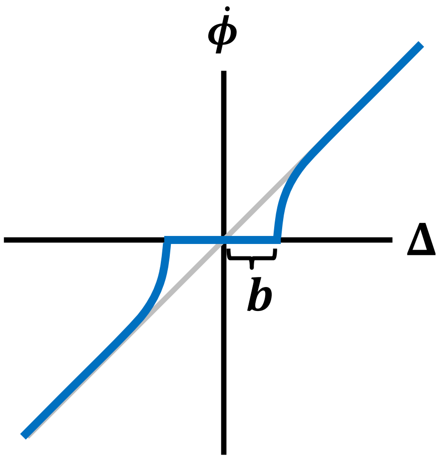
Average right-well population : $\langle b_i^\dagger b_i \rangle = n_i^B$

Polarization : $\langle a_1^\dagger b_1 \rangle = \sqrt{n_1^A n_1^B}\, exp(-i\phi)$

$$\frac{d\phi}{dt} = \underbrace{\frac{1}{\hbar}\left[\Delta_{11} - \sum_k \left(\sigma_{1,k}^A n_{1+k}^A + \sigma_{1,k}^B n_{1+k}^B\right)\right]}_{\text{Detuning, }\Delta} + \underbrace{\frac{g_{11}}{\hbar}\frac{(n_1^A - n_1^B)}{\sqrt{n_1^A n_1^B}}}_{\text{Locking coefficient}} cos\phi$$

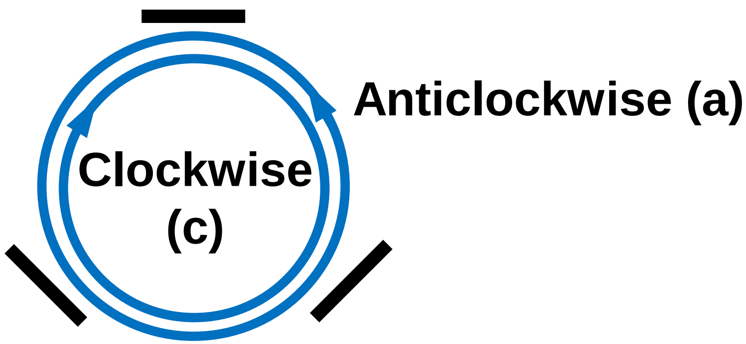
Locking

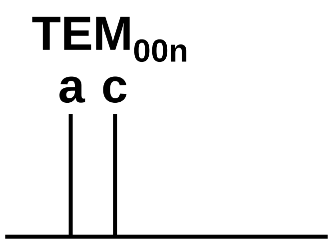
$$\frac{d\phi}{dt} = \Delta + b\, cos\phi$$

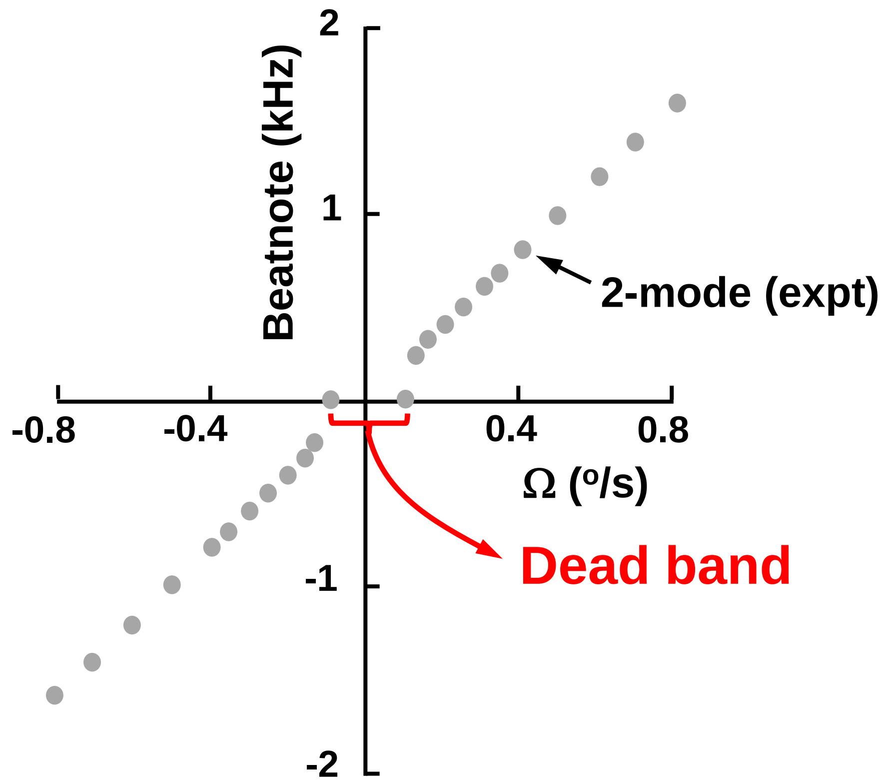


Atomtronics analog?

Laser gyroscope







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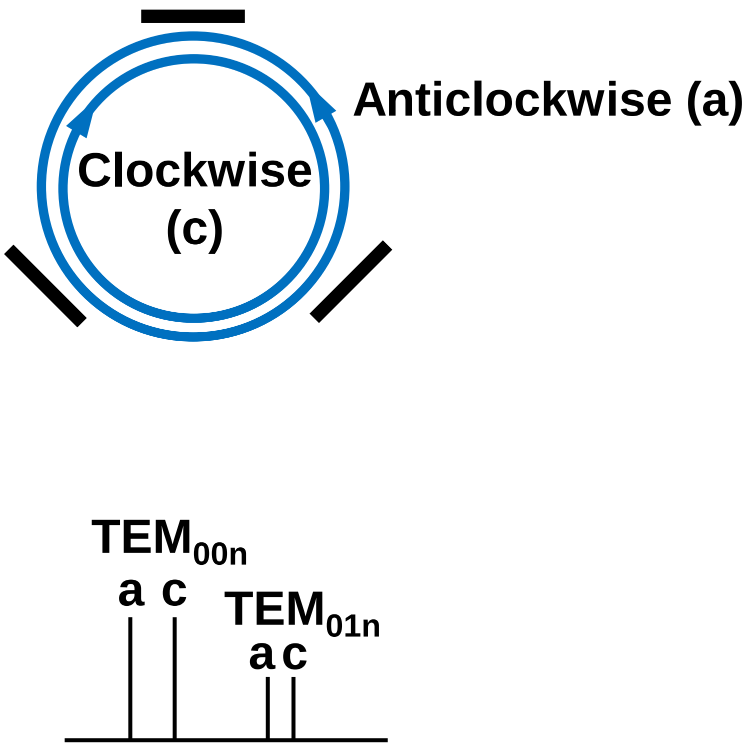

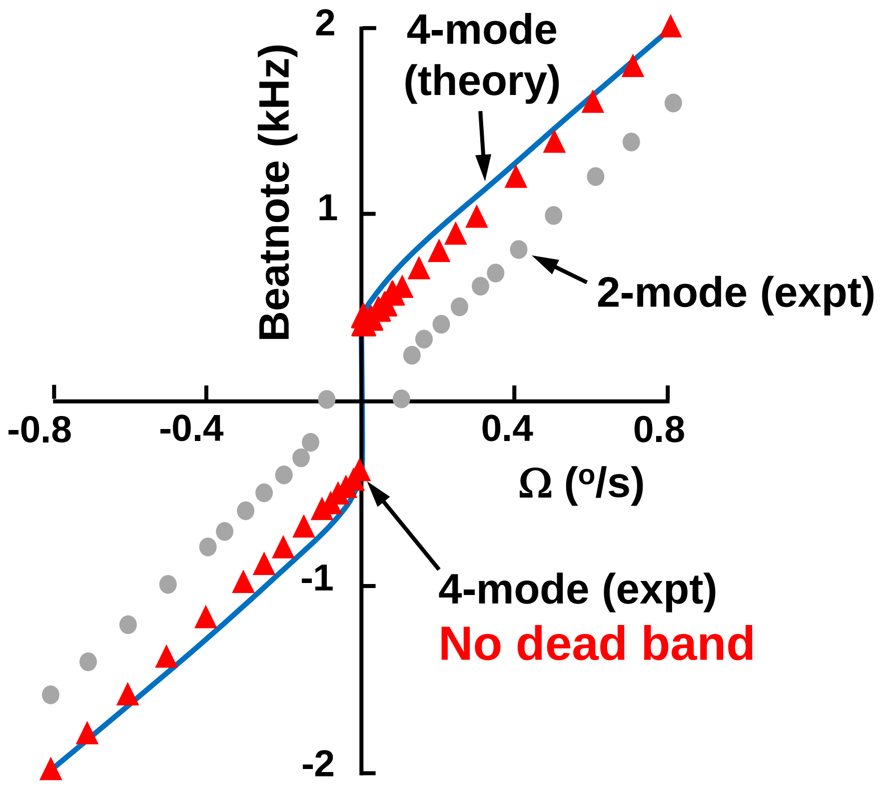

Anderson, Chow, Scully & Sanders, Opt. Lett. 5 413 (1980)

Elimination of dead band with 4-mode gyro.
Is the same possible with atomic sensor?

Summary: Atomtronics

Weng Chow, Cameron Straatsma & Dana Z. Anderson

Sandia National Laboratories, JILA & University of Colorado

Motivation: BEC from laboratory to devices

Atomtronics versus electronics:

- Commutator versus anticommutators – BEC versus exclusion principle

Summary: Atomtronics

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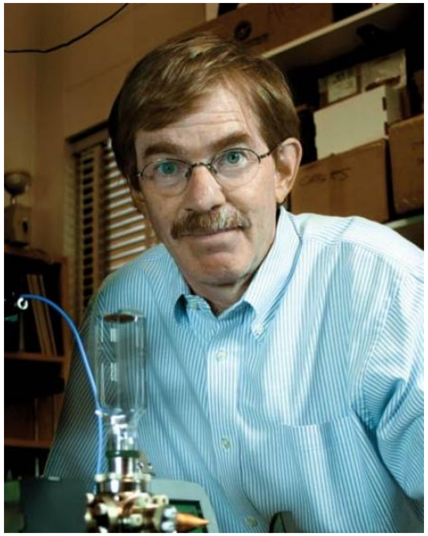


JILA, Physics Dept. Colorado
ColdQuanta

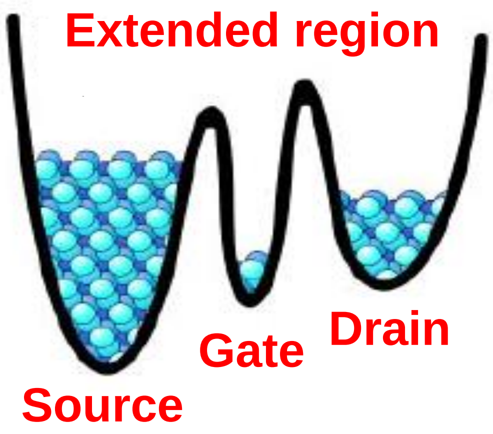
<u>Motivation:</u> **BEC from laboratory to devices**

<u>Atomtronics versus electronics:</u>

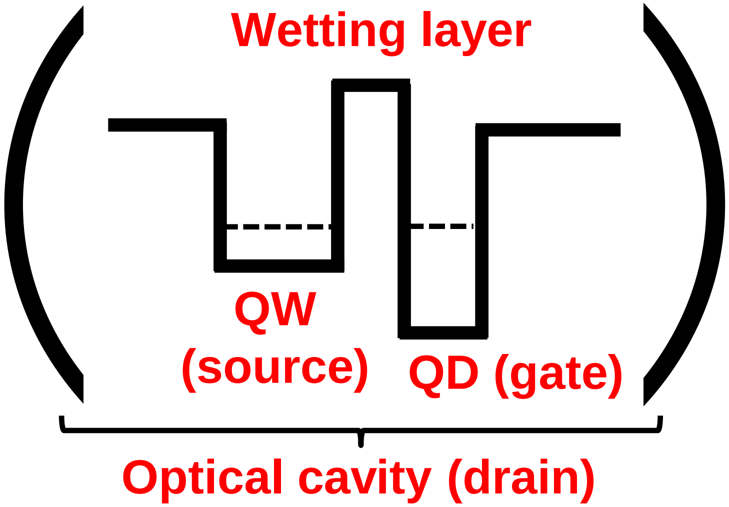
- **Commutator versus anticommutators – BEC versus exclusion principle**

Future atomtronics and optoelectronics

Atom transistor



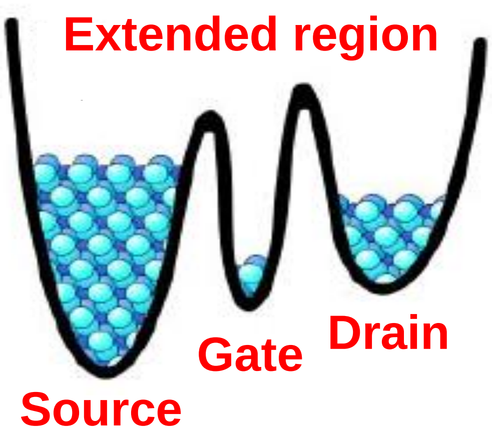
Tunnel-injection laser



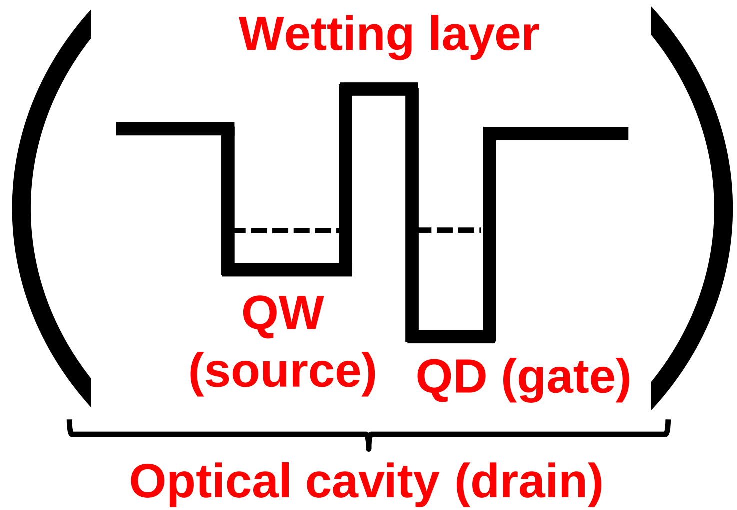
PQE talks: Gadi Eisenstadt & Hans-Peter Reithmaier
Record high modulation speeds

Future atomtronics and optoelectronics

Atom transistor



Tunnel-injection laser



PQE talks: Gadi Eisenstadt & Hans-Peter Reithmaier
Record high modulation speeds