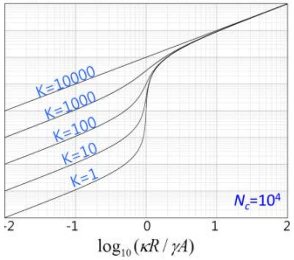
Thresholdless Quantum-Field Lasers

KW An’s Group

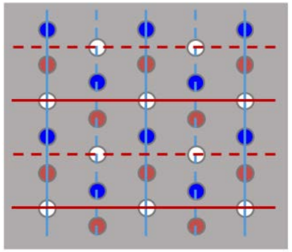
2015 INTRODUCTION TO RESEARCH PROGRAM

Thresholdless Quantum-Field Lasers

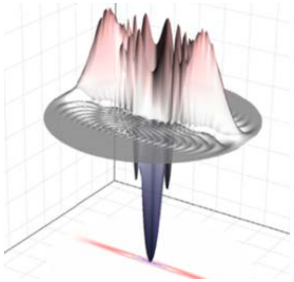
- Thresholdless lasing
  - Low pumping power for usable output
  - Below the shot noise (Mandel Q < 0)



- Multiple phase imprinting
  - More coding capacity than a classical field (of a single phase)

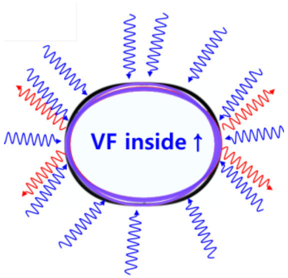


- Schrödinger-cat-like state generation
  - Quantum information processing
  - Foundation of quantum mechanics



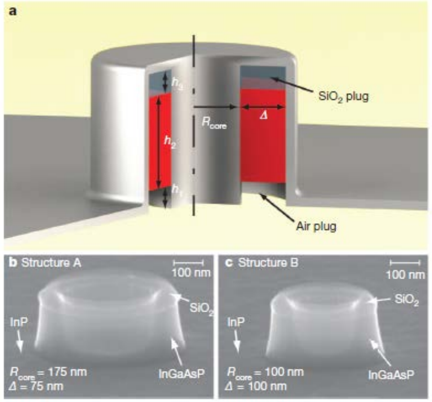
Our quantum-field laser

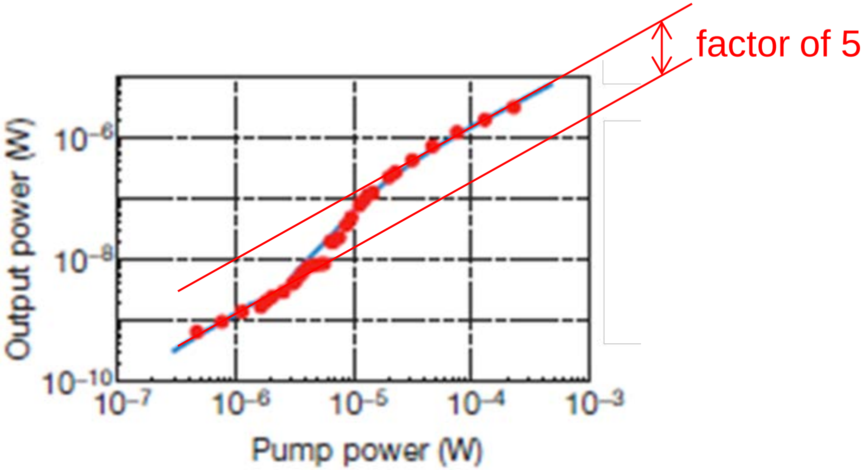
- Asymmetric vacuum energy flow
  - Better understanding of vacuum energy and perhaps the dark energy



Conventional Approach

- All thresholdless lasers are based on the Purcell factor: spontaneous emission enhancement due to a small mode volume and a high Q
- To achieve thresholdless lasing, the mode volume →λ^3
- Relatively low Q → high pump density → heat dissipation problems, short life time, low temp operation

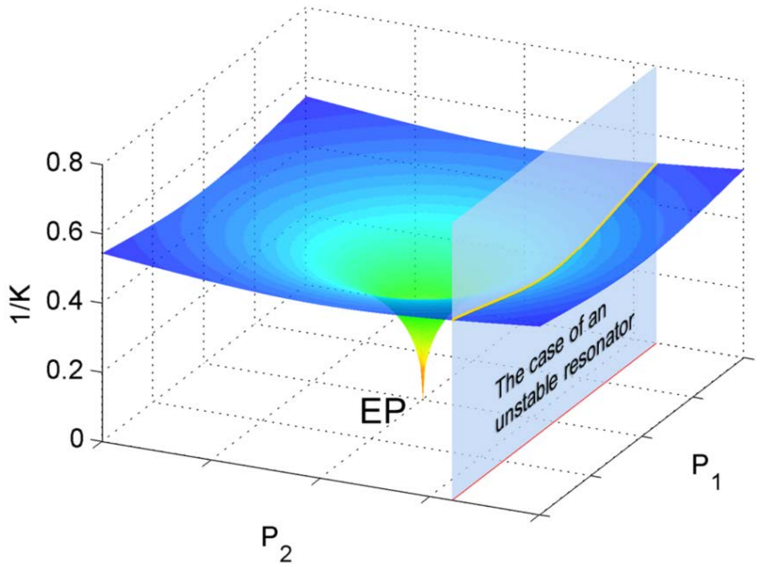




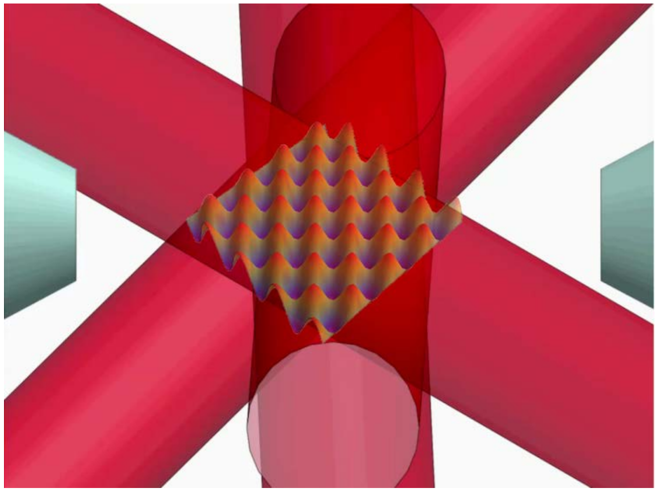
M. Khajavikhan *et al.*, Nature **482**, 204 (2012)

Our Approaches

- Cavity: diverging Petermann effect at an exceptional point (EP)



- Gain medium: quantum dipole material



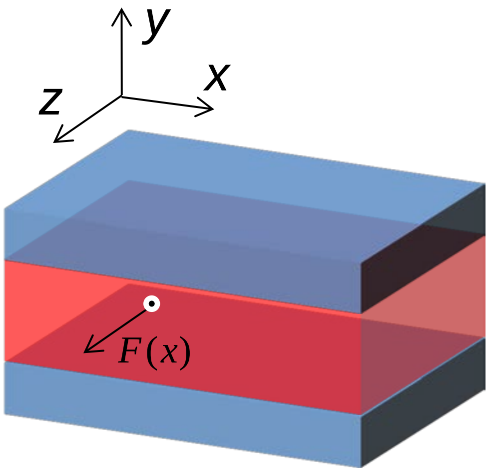
I. Petermann Effect

- Klaus Petermann reported that the spontaneous emission into a gain-guided mode is enhanced by a factor *K* :

Prof. Klaus Petermann
Technische Universität Berlin

$$K = \frac{\left(\int |F(x)|^2 dx\right)^2}{\left|\int F^2(x) dx\right|^2}$$

F(*x*): the electric field amplitude of the lasing mode with its *adjoint* being *F**(*x*)



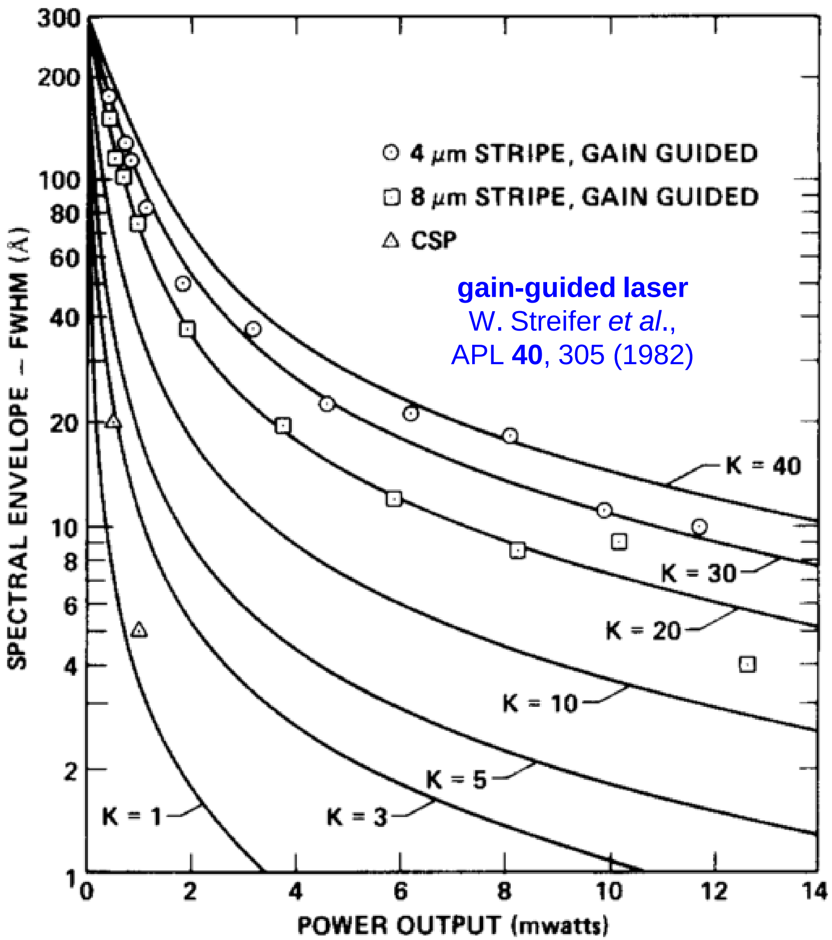
K. Petermann, IEEE J. Quantum Electron. **QE-15**, 566 (1979)

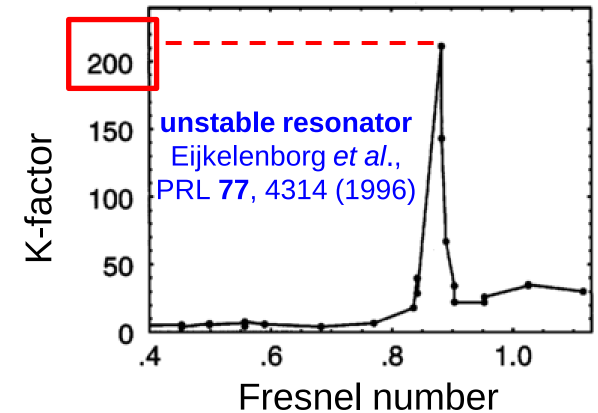
Purcell effect

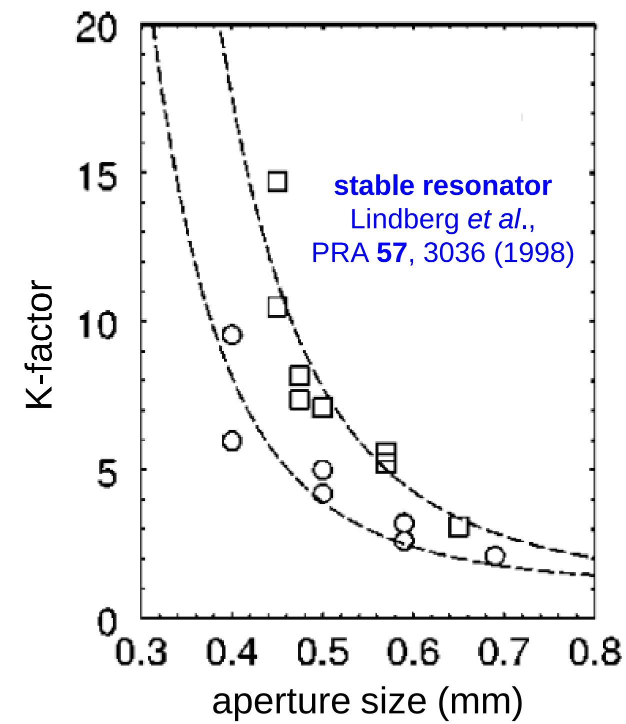
"The spontaneous emission factor not only increases with decreasing volume of the active layer but also increases with increasing astigmatism". – K. Petermann

Petermann effect

Petermann Factor in Experiments

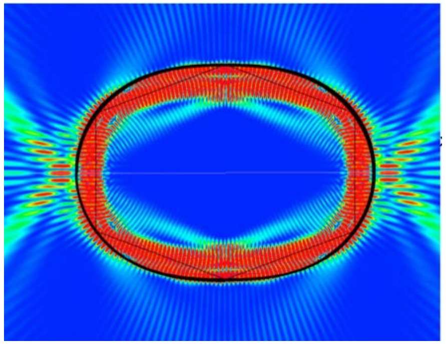




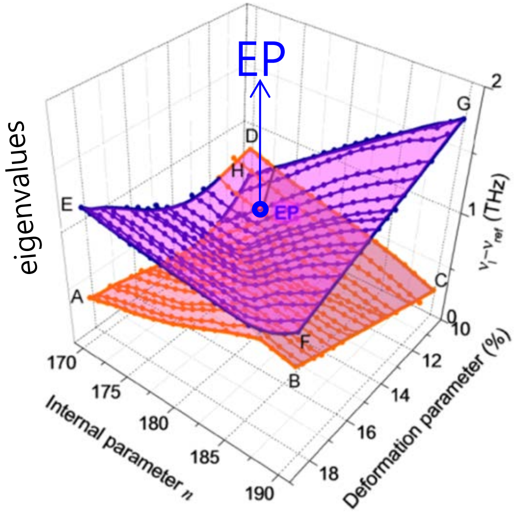


Exceptional Point (EP)

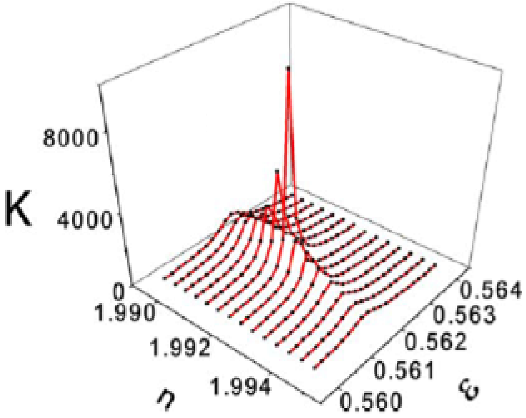
- In a deformed microcavity, two eigenmodes coalesce to a single eigenmode when the intermode coupling equals a combined decay rate. → EP
- Peterman factor *K* (∝ atomic spontaneous emission rate) diverges at an EP.



Deformed microcavity
S.-B. Lee *et al*., PRL **88**, 033903 (2002)



Experimental observation of an EP in a deformed microcavity
S.-B. Lee *et al*., PRL **103**, 134101 (2009)



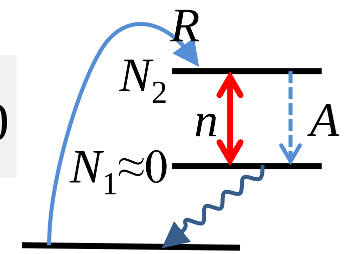
Diverging Petermann factor at an EP in a deformed microcavity
S.-Y. Lee *et al*., PRA **78**, 015805 (2008)

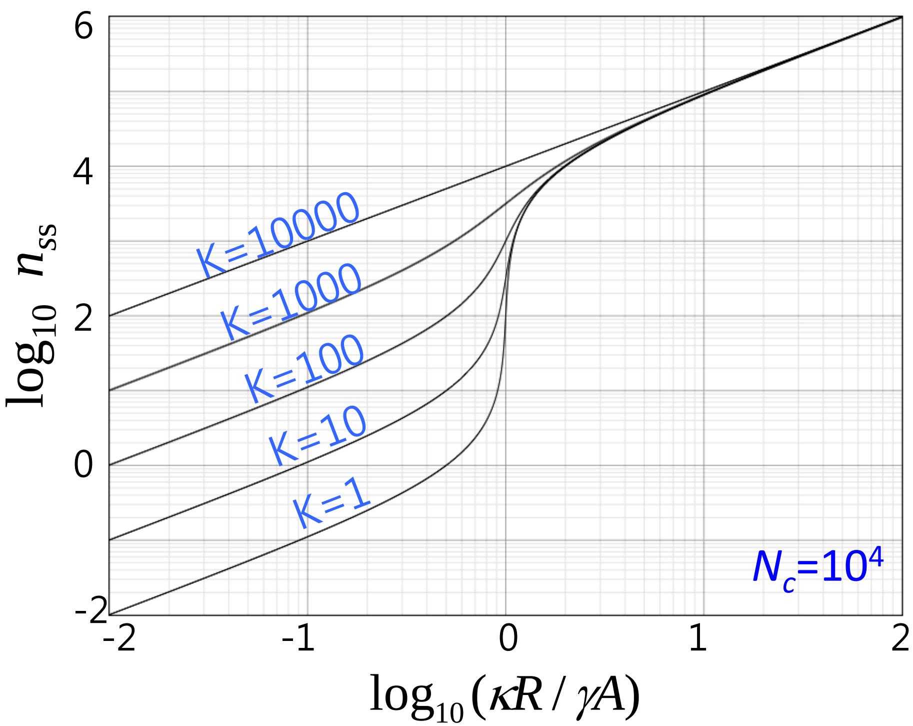
Thresholdless Lasing

- Steady-state solution of the laser rate equations including K ($N_1 \approx 0$ assumed)

Eijkelenborg *et al*., PRA **57**, 571 (1998)

$$\frac{dn}{dt} \simeq \kappa(n + K)N_2 - \gamma n = 0, \qquad \frac{dN_2}{dt} \simeq R - \kappa N_2 n - AN_2 = 0$$

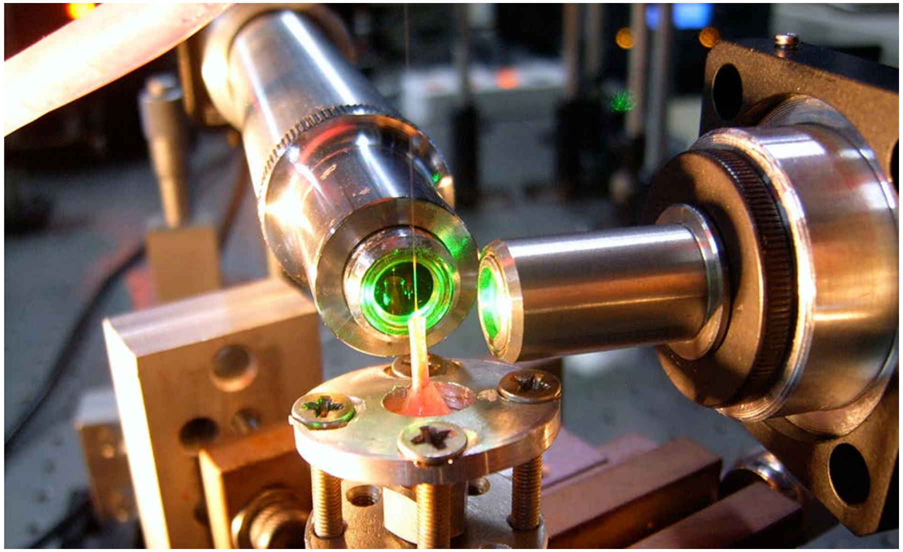


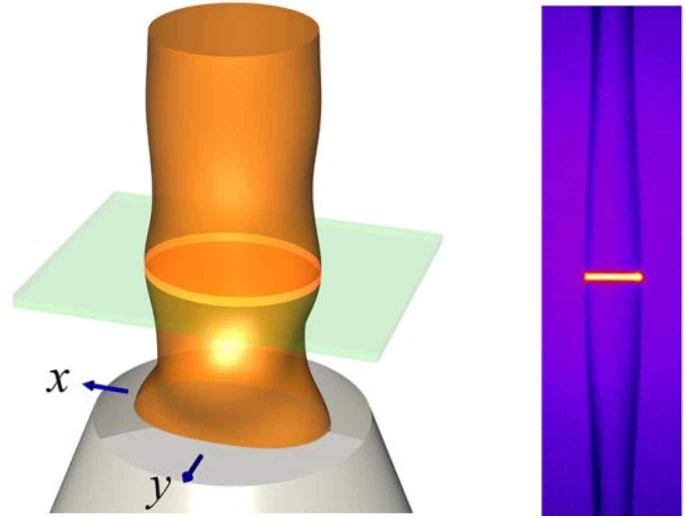


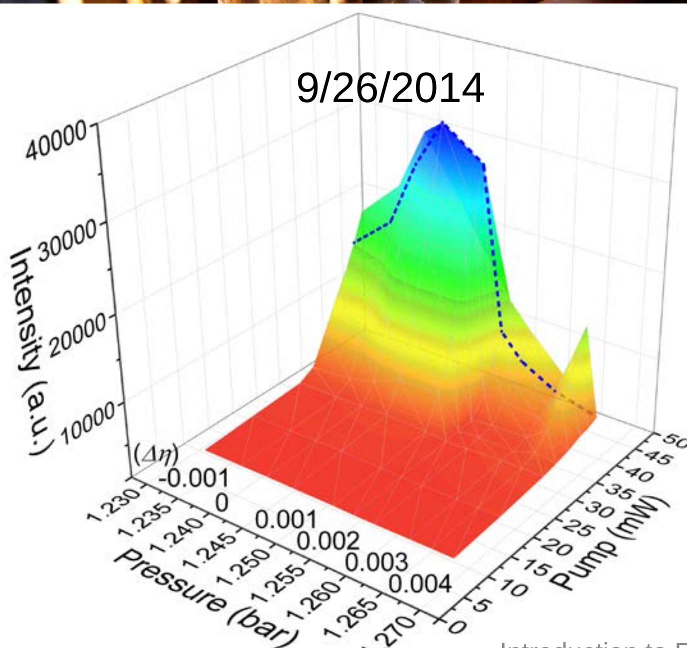
R : pumping power
A : decay rate of N_2
$\kappa = A/N_c$
N_c: # of cavity modes in the gain bandwidth

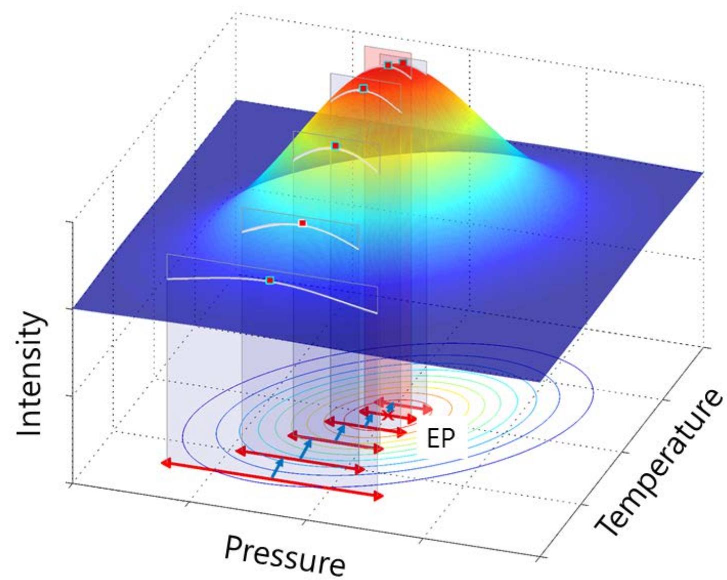
- The lasing threshold vanishes when $K = N_c$, so $\kappa K = A$, total spontaneous emission.

Preliminary Data



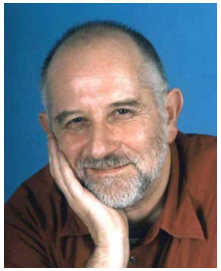






New Story

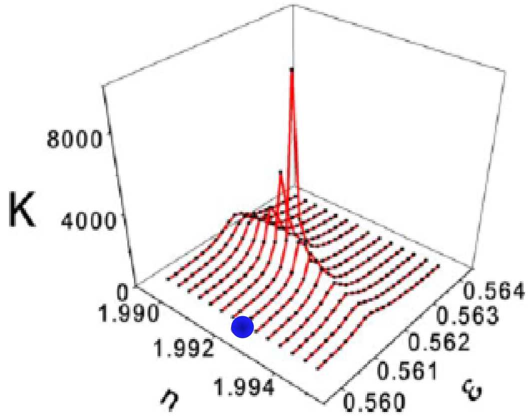
"New has given an excellent account of the physical meaning and origin of K." – M. V. Berry



M. V. Berry, J. Mod. Opt. **50**, 63 (2003)

"Excess noise can be attributed to a combination of spontaneous emission and vacuum fluctuations leaking into a lossy cavity from outside." – G. H. C. New

G. H. C. New, J. Mod. Opt. **42**, 799 (1995)



Diverging Petermann factor at an EP in a deformed microcavity
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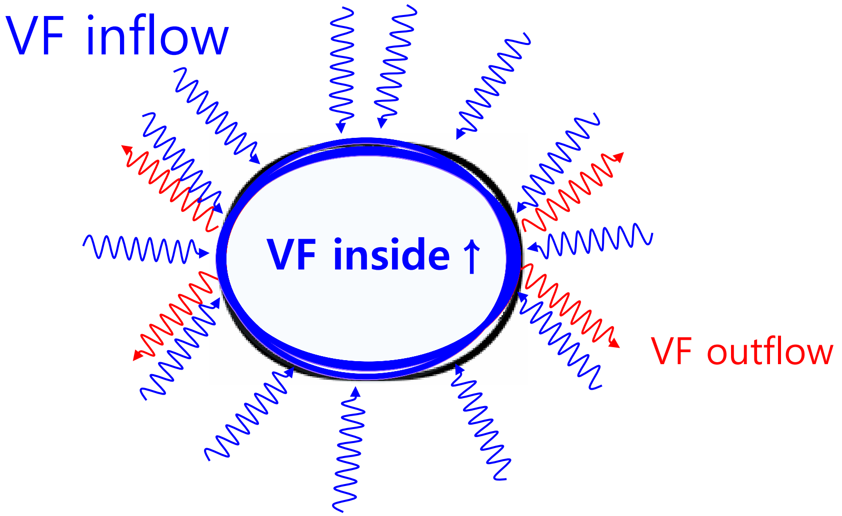
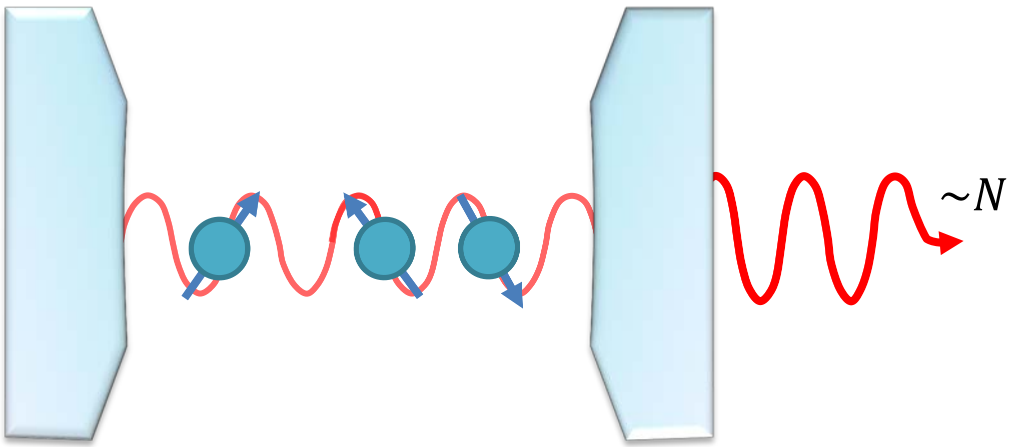


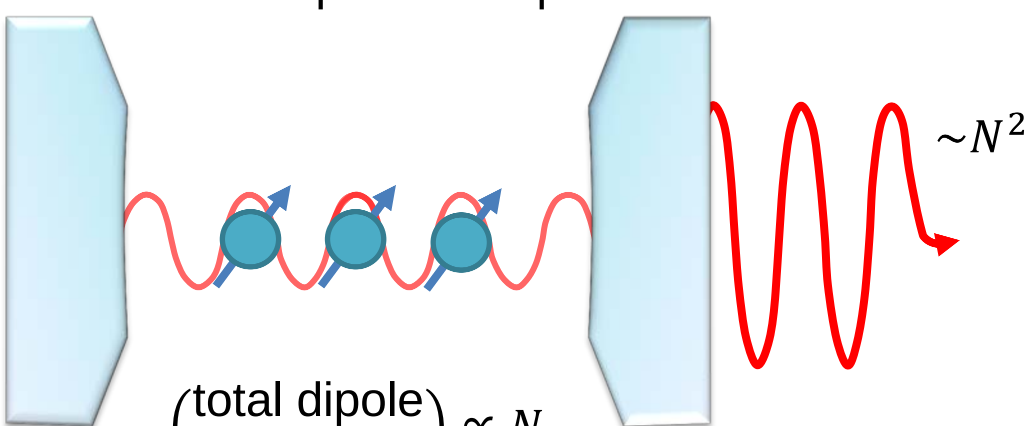
VF engineering

II. Quantum Dipole Material (QDM)

Incoherent quantum dipole



Coherent quantum dipole

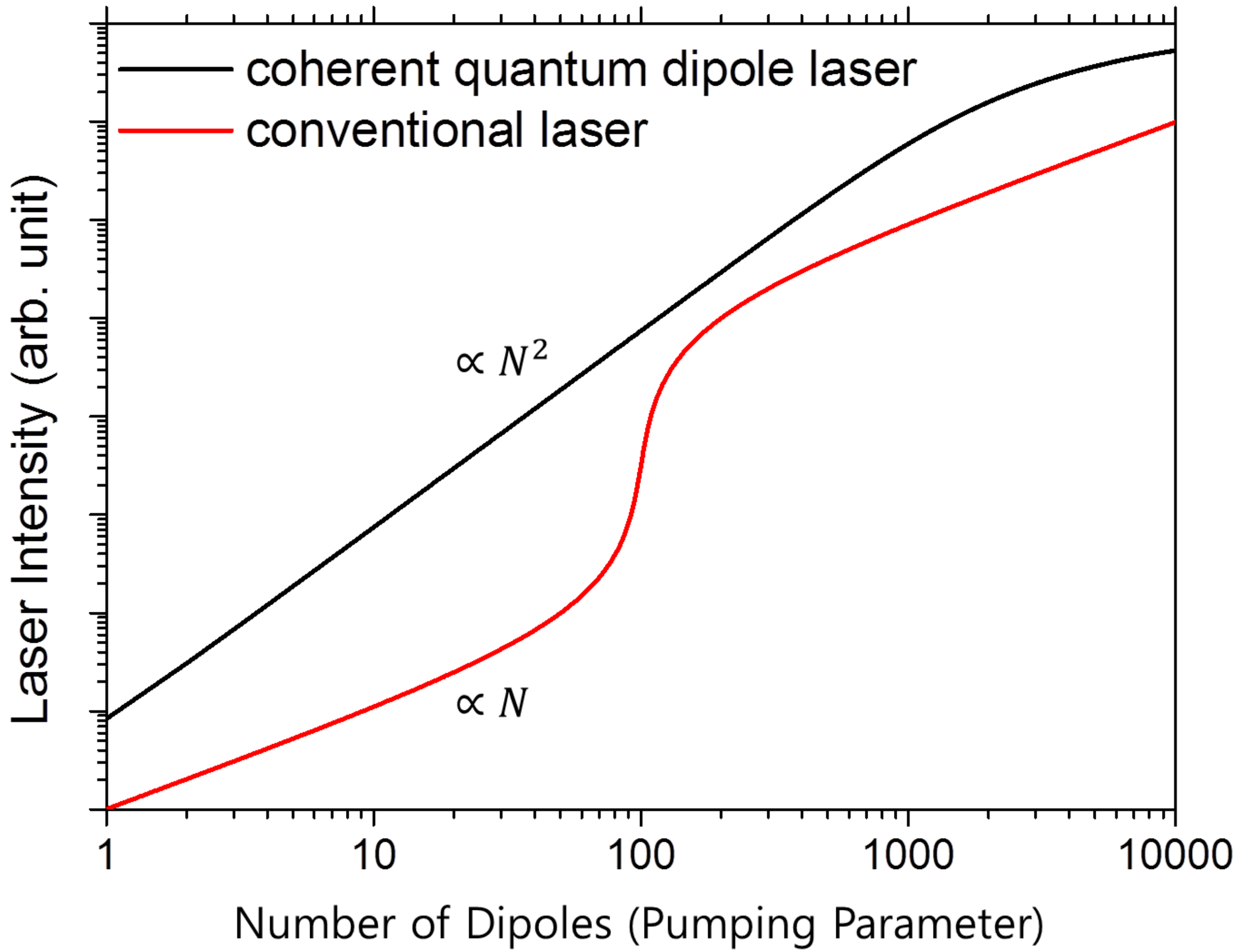


$\begin{pmatrix}\text{total dipole} \\ \text{moment}\end{pmatrix} \propto N$

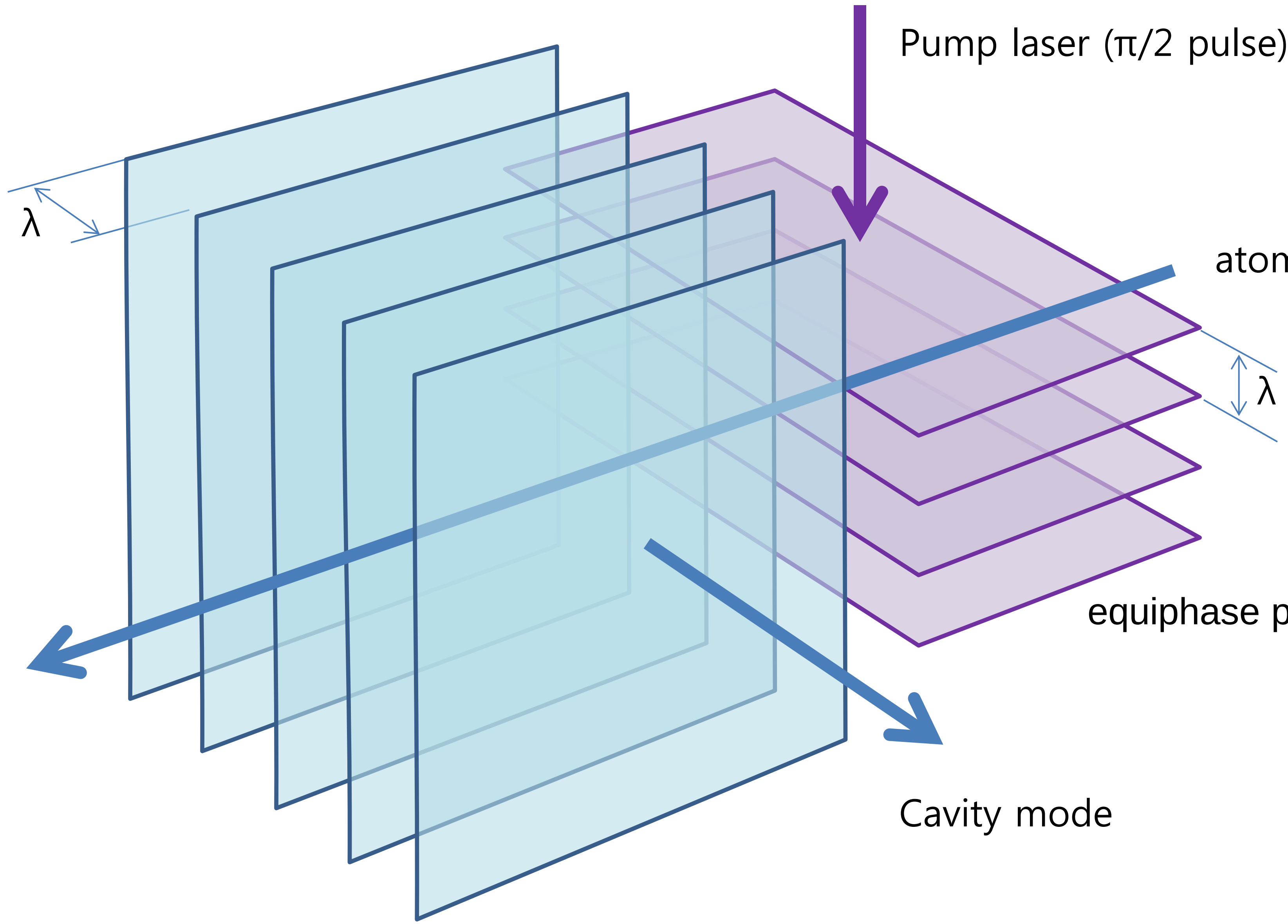
QDM:

A collection of coherent quantum dipoles prepared periodically in space with the same phase

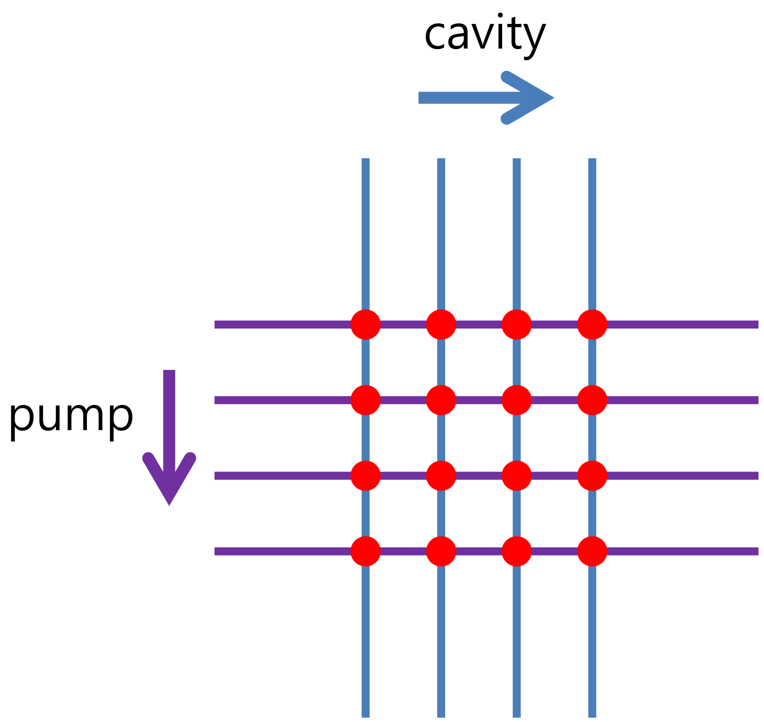
Thresholdless Lasing with QDM

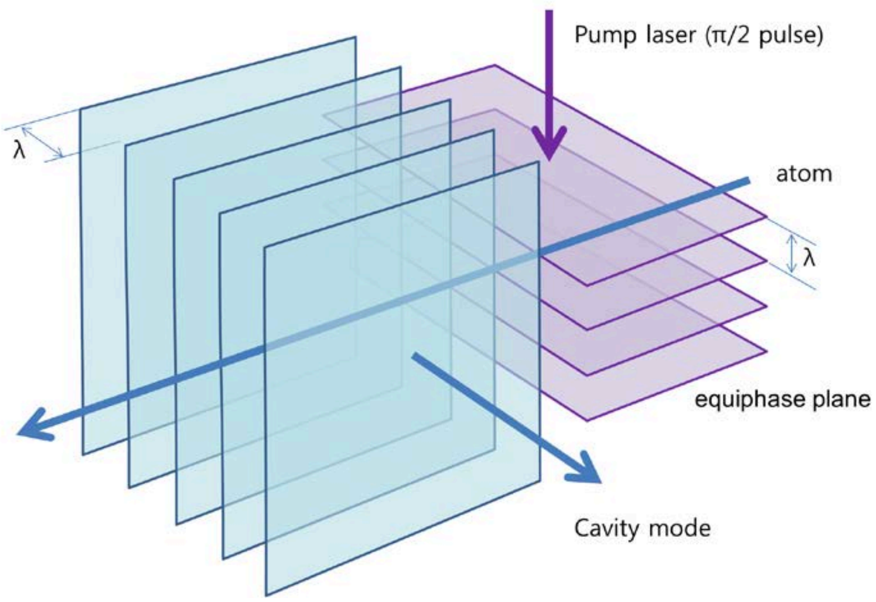


How to realize the same phase

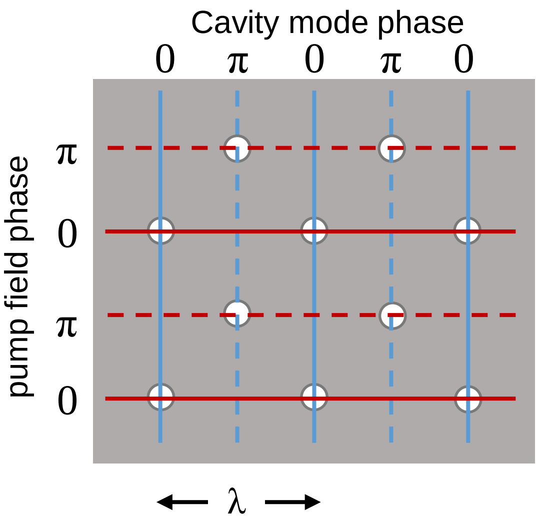


How to realize the same phase

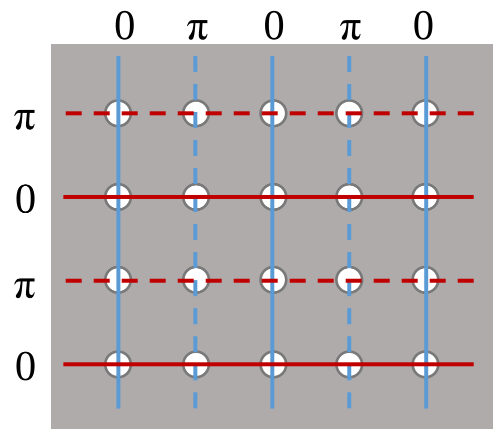




Multi-Phase Encoding

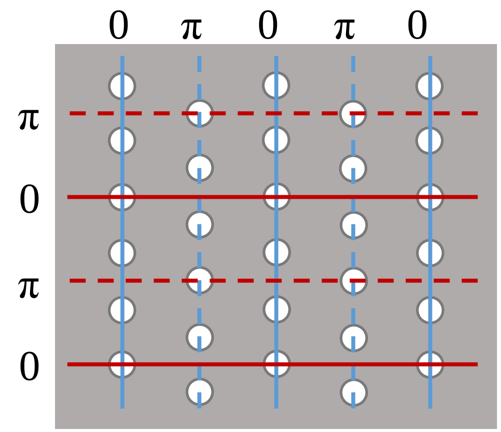


All the same phase



White : 0, black : π

Two phases



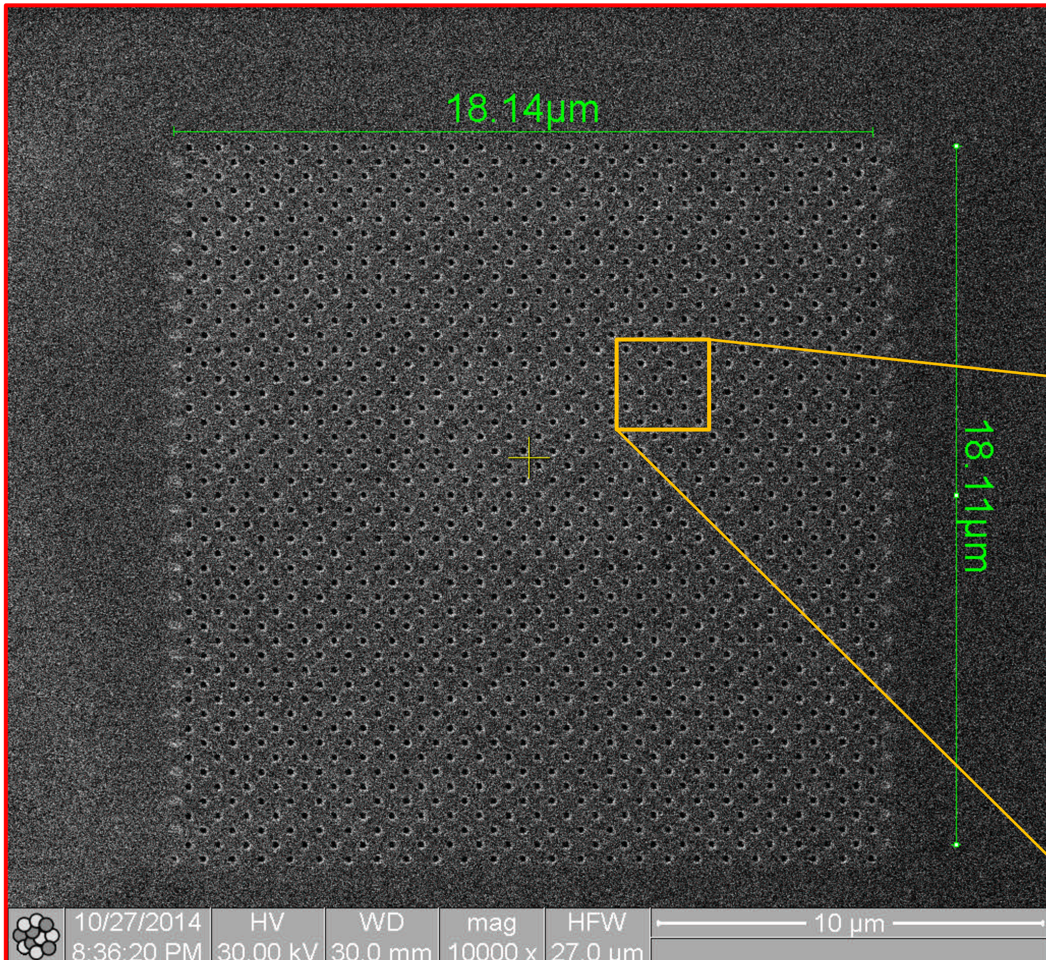
White : 0, red : 2π/3, blue : 4π/3

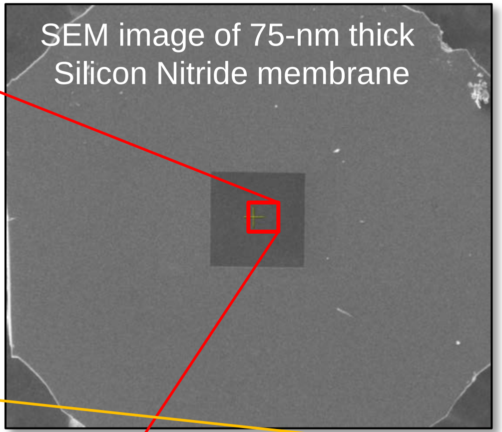
Three phases

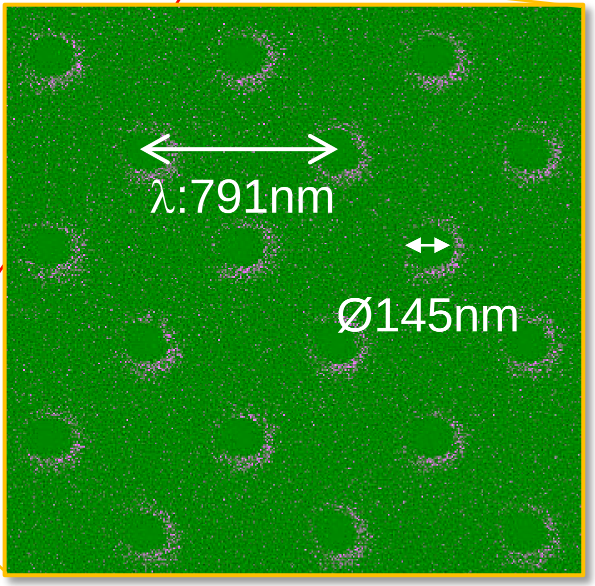
- The atom-cavity relative phases are determined by the hole structures.

Nanohole Array

- Machined by focused ion beam (FIB)

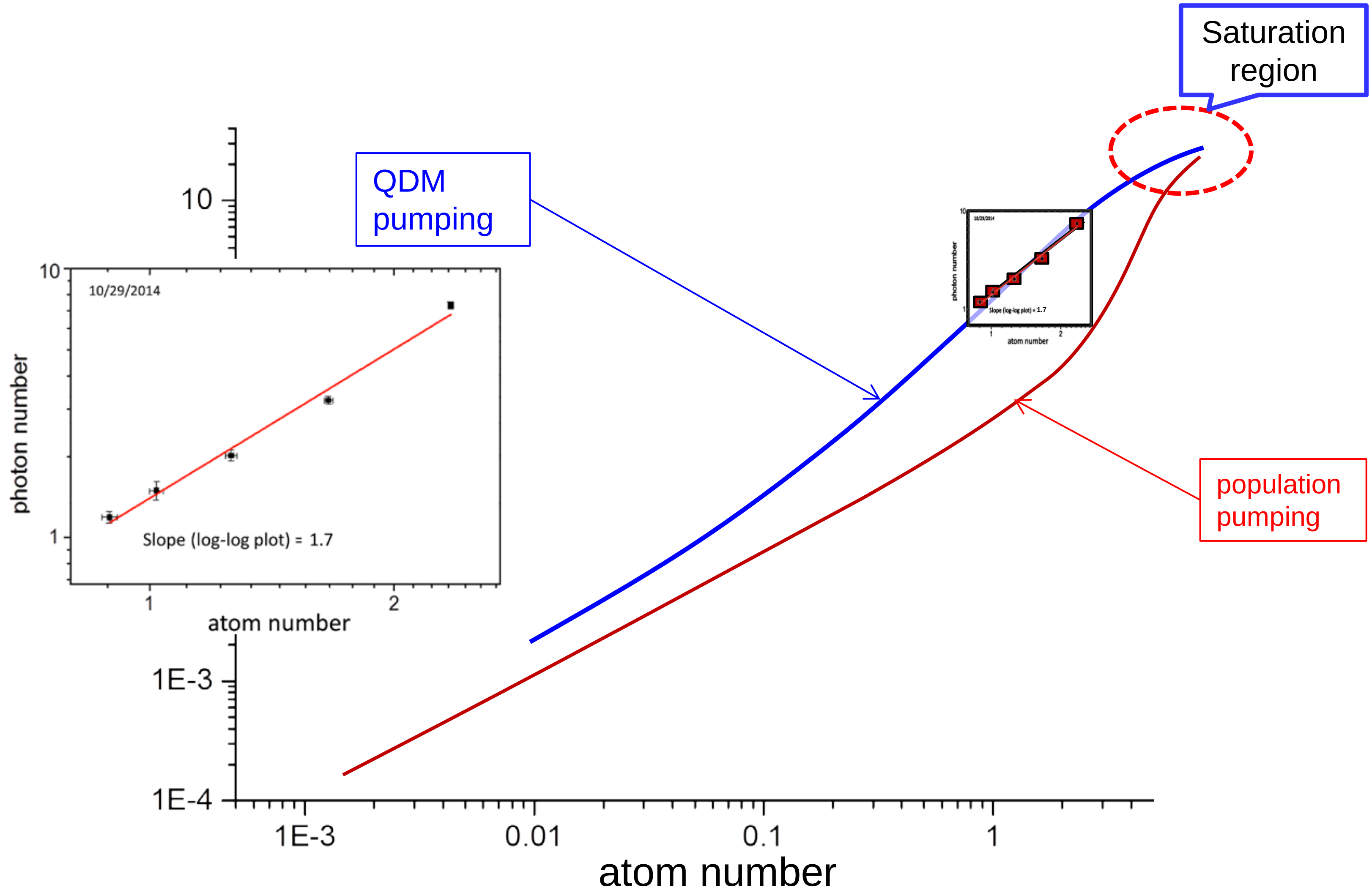






M. Lee *et al.*, Nat. Commun. **5**, 3144 (2014)

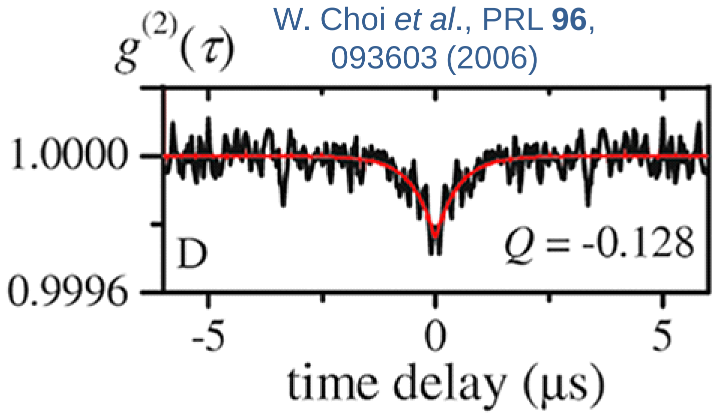
Preliminary Data of N^2 Emission



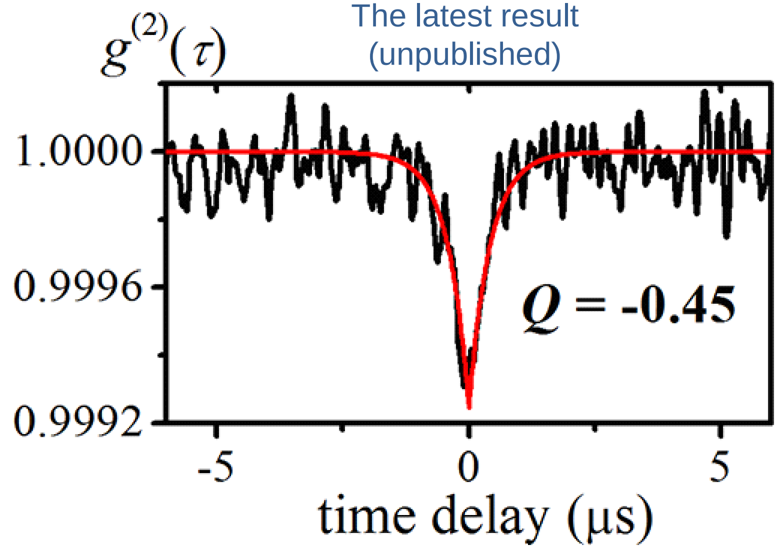
Sub-Poisson Light Generation

- Photon number stabilization occurs in the saturation region.
- Theoretical prediction, Mandel Q≈-0.7
  - variance $(\Delta n^2) = 0.3\langle n \rangle$, only 30% of the shot-noise variance.

W. Choi *et al.*, PRL **96**, 093603 (2006)



The latest result (unpublished)



$$g^{(2)}(t) = 1 + \frac{Q}{\langle n \rangle} e^{-t/\tau}$$

The second order correlation function

$$Q = \frac{\langle n^2 \rangle - \langle n \rangle^2}{\langle n \rangle} - 1$$

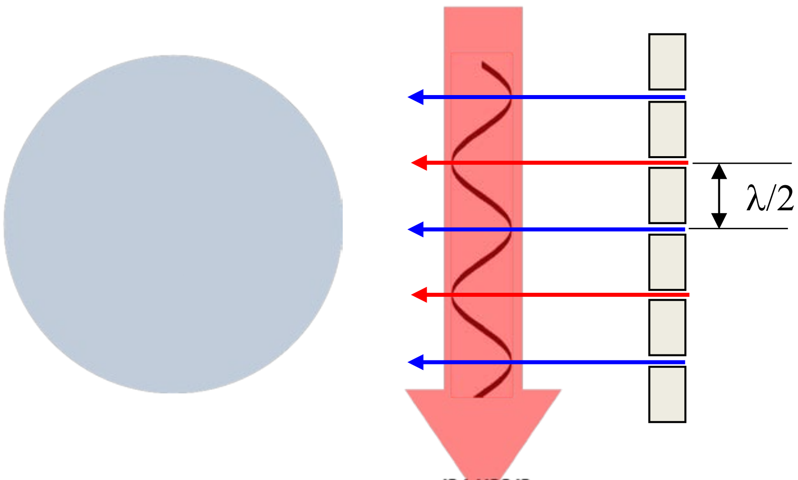
Mandel Q

$Q > 0$ super-Poisson
$Q = 0$ Poisson
$\boxed{Q < 0 \text{ sub-Poisson}}$

photon statistics

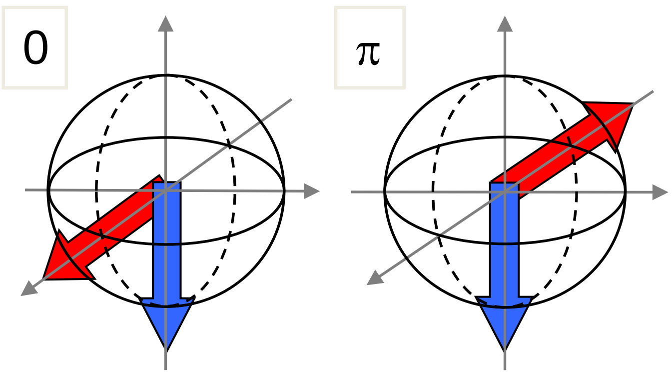
Opposite-phase Imprinting

The same phase is ensured with a nanohole array.



high-Q cavity mode

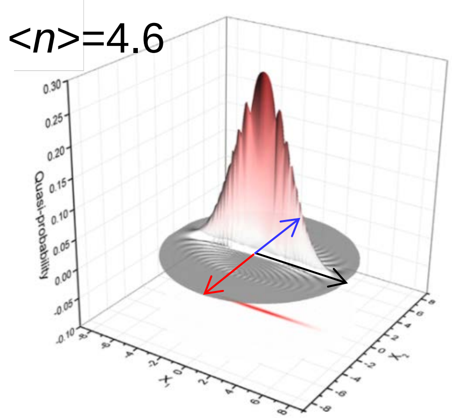
pump
(π/2 pulse)



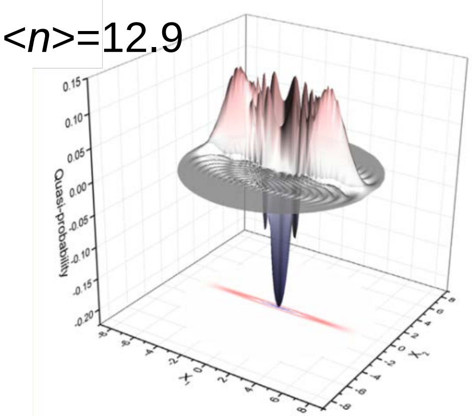
$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|e\rangle - i|g\rangle\right) \qquad |\psi\rangle = \frac{1}{\sqrt{2}}\left(|e\rangle + i|g\rangle\right)$$

Bloch Sphere

Wigner function of the cavity field



single-photon decay (herald)

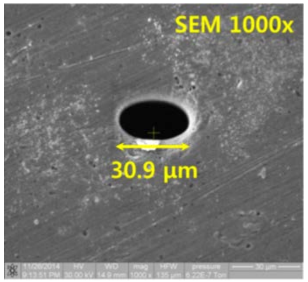


Squeezed vacuum

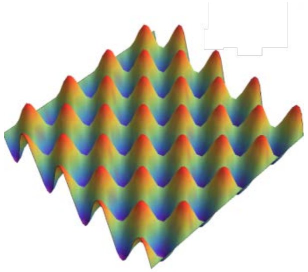
Schrödinger's-cat-like state

III. Extension to practical forms

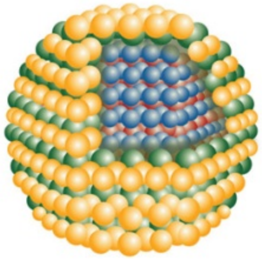
- Develop FIB technique for fabricating various microjet nozzles



- Simulate a stationary QDM by using an optical lattice in a cavity

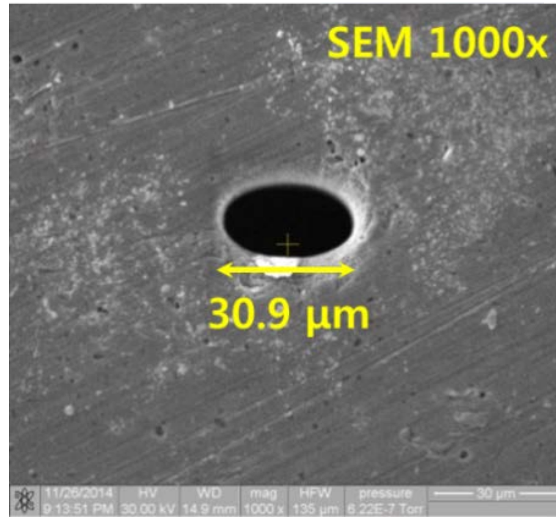


- Design a thresholdless quantum-field microlaser with artificial atoms (e.g., excitons, polaritons, surface plasmons, etc.)

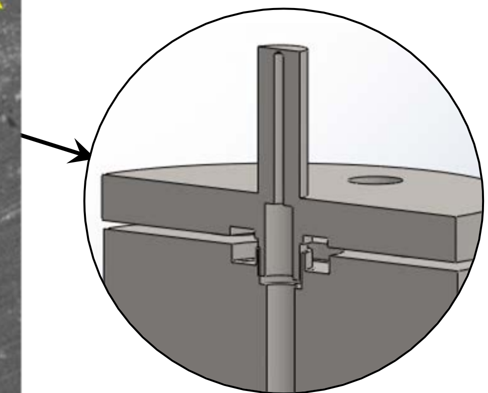


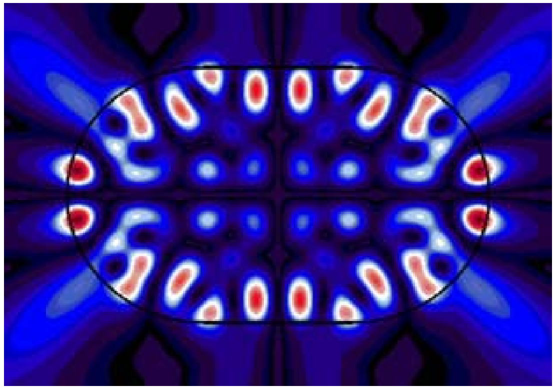
FIB technique for microjet nozzles

- FIB precision: 10nm
- Simulating various cavity shapes & array of cavities
- Compact optofluidic packaging possible

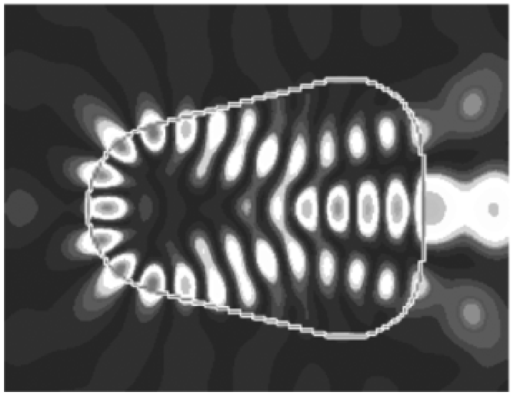


Sectional view

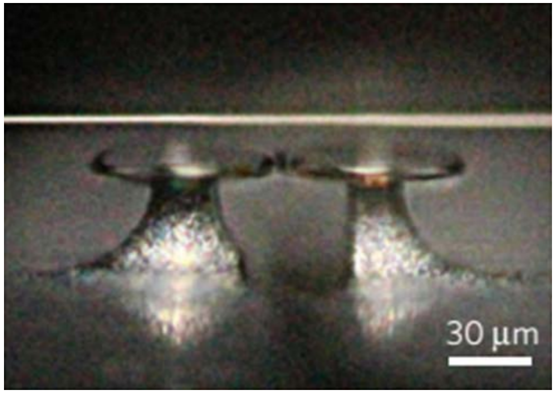




a stadium
Lee *et al*., Phys. Rev. A **78**, 015805 (2008)

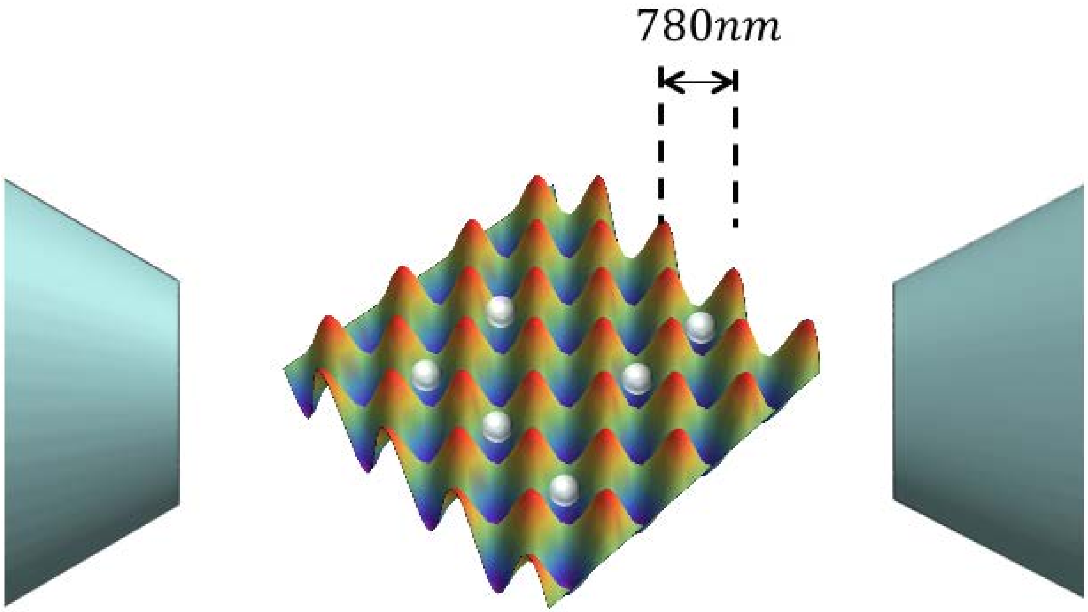


a rounded triangle
Kurdoglyan *et al.*, Opt. Lett. **29**, 2758 (2004)



coupled disks
Peng *et al.*, Nat. Phys. **10**, 394 (2014)

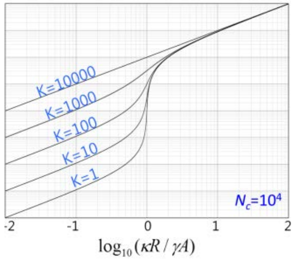
Stationary quantum dipole materials



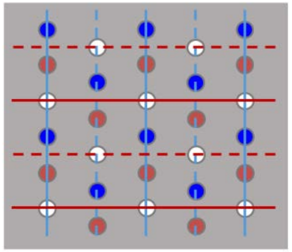
- ^{85}Rb Atoms are confined in a 2D optical lattice (pump in one direction). Along the cavity axis, the lattice spacing equals the Rb wavelength (equiphase to the cavity mode).
- Towards realizing solid-state QDM (e.g. quantum dots)

Thresholdless Quantum-Field Lasers

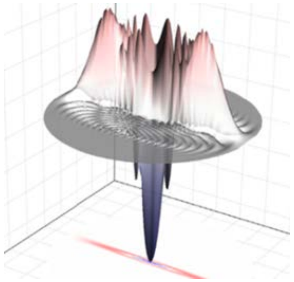
- Thresholdless lasing
  - Low pumping power for usable output
  - Below the shot noise (Mandel Q < 0)



- Multiple phase imprinting
  - More coding capacity than a classical field (of a single phase)



- Schrödinger-cat-like state generation
  - Quantum information processing
  - Foundation of quantum mechanics



- Asymmetric vacuum energy flow
  - better understanding of vacuum energy and perhaps the dark energy