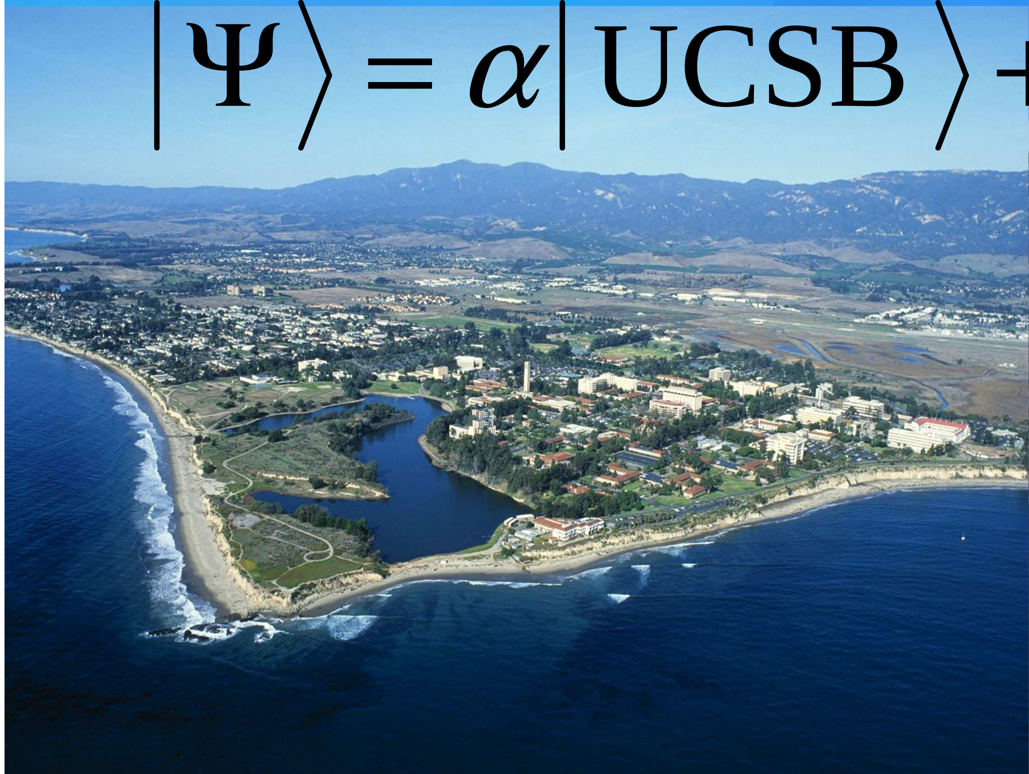
Dirk Bouwmeester

$$\left|\Psi\right\rangle = \alpha\left|\mathrm{UCSB}\right\rangle + \beta\left|\mathrm{Leiden}\right\rangle$$

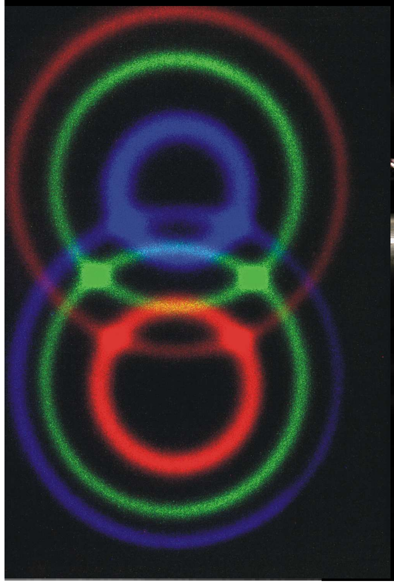


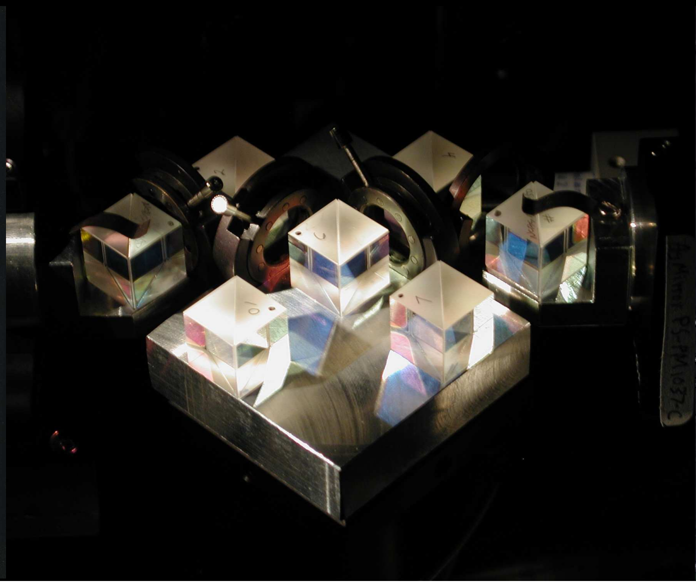
Glasgow, August 1, 2011

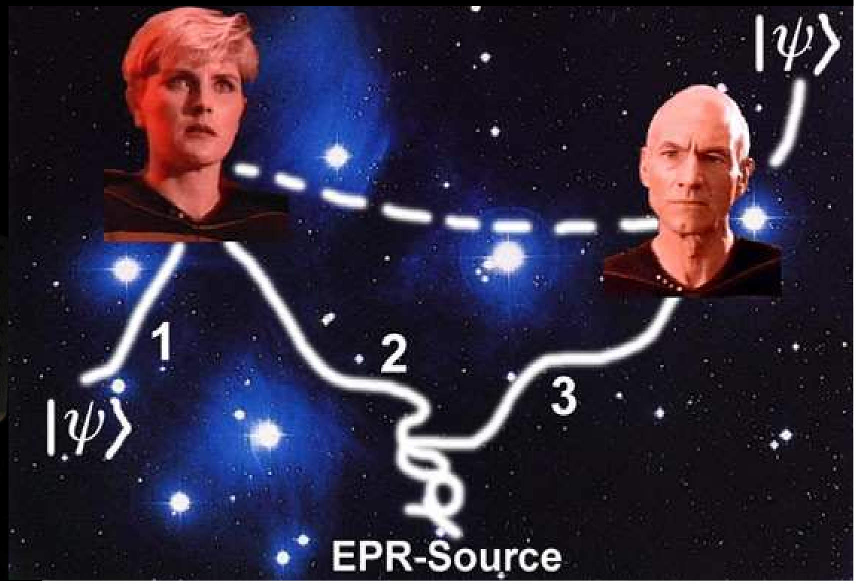
Quantum Optics
Solid-State Cavity QED

Lecture 1

Quantum Entanglement, Entangled Photons,
Quantum Cryptography, Hardy’s Thought Experiment,
Teleportation,



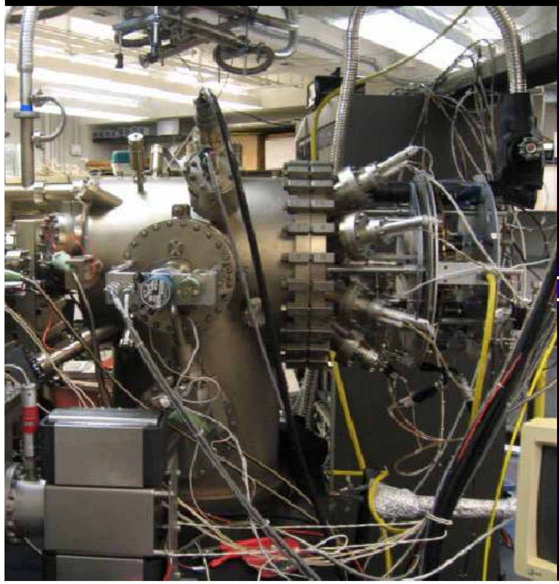


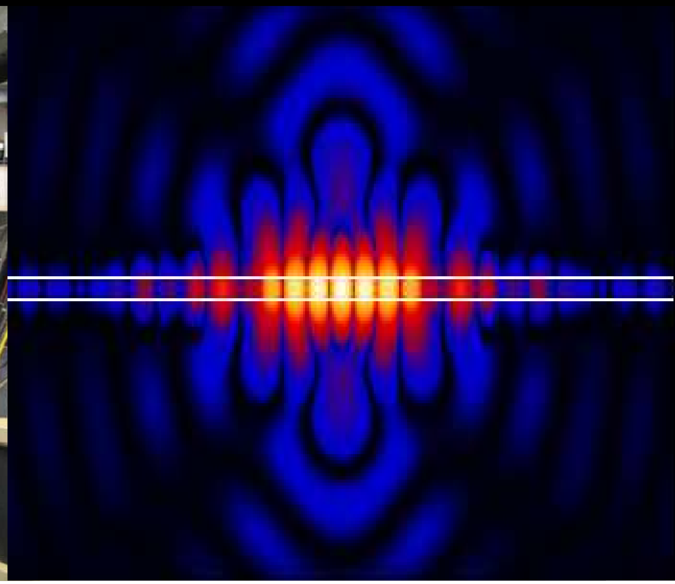


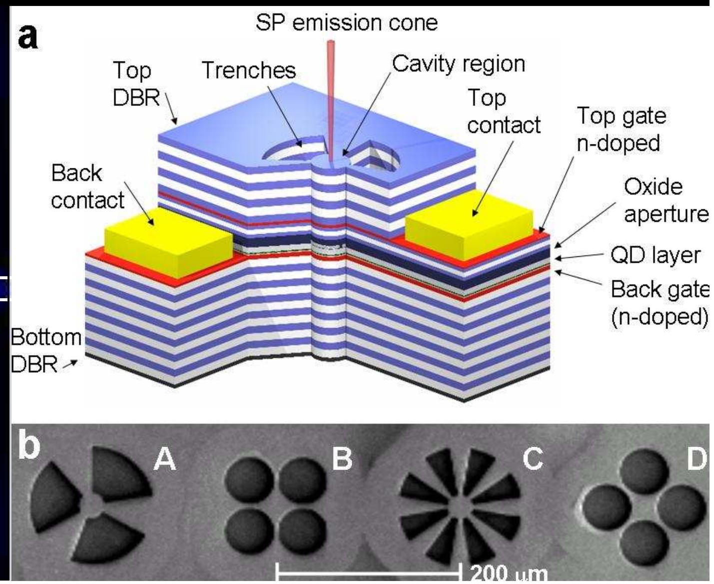
Quantum Optics
Solid-State Cavity QED

Lecture 1

Quantum Entanglement, Entangled Photons,
Quantum Cryptography, Hardy's Thought Experiment,
Teleportation, Quantum Dots, Photonic Crystals, Micropillars



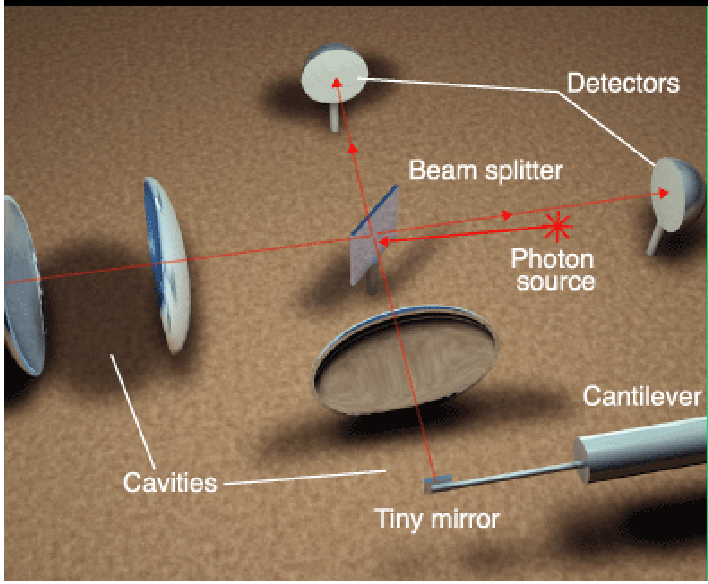


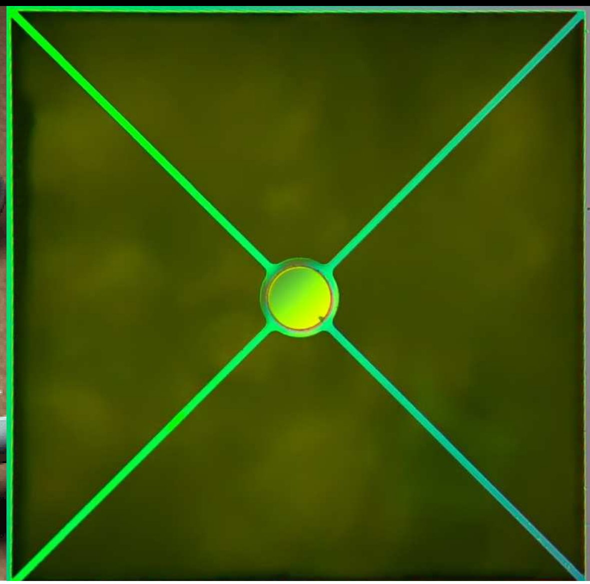


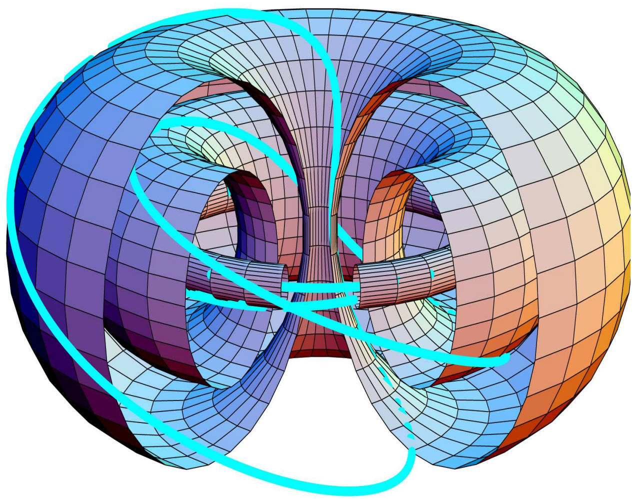
Macroscopic Quantum Superpositions

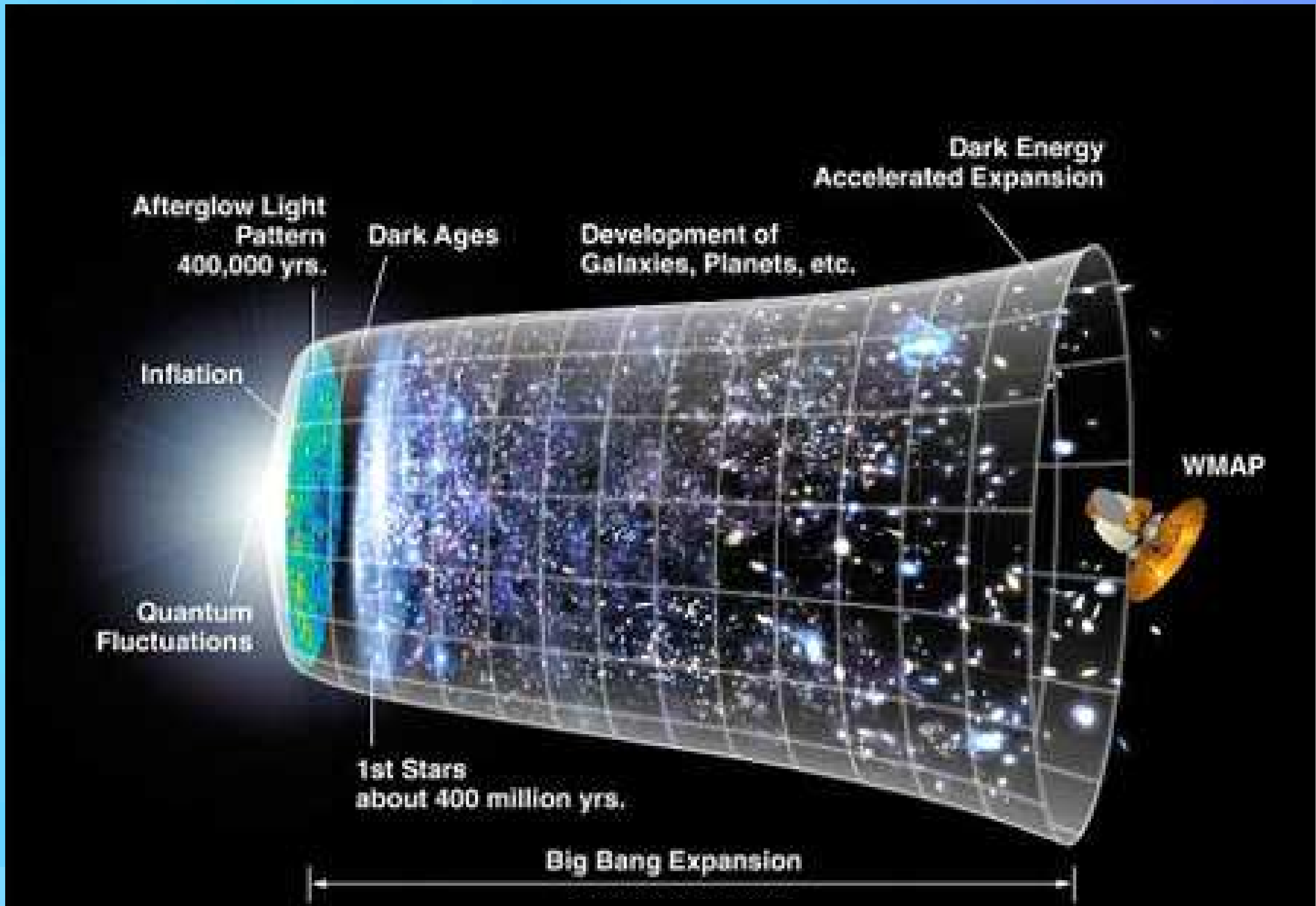
Lecture 2

Penrose's Arguments, Quantum Decoherence,
Optical Cooling, Knots of Light



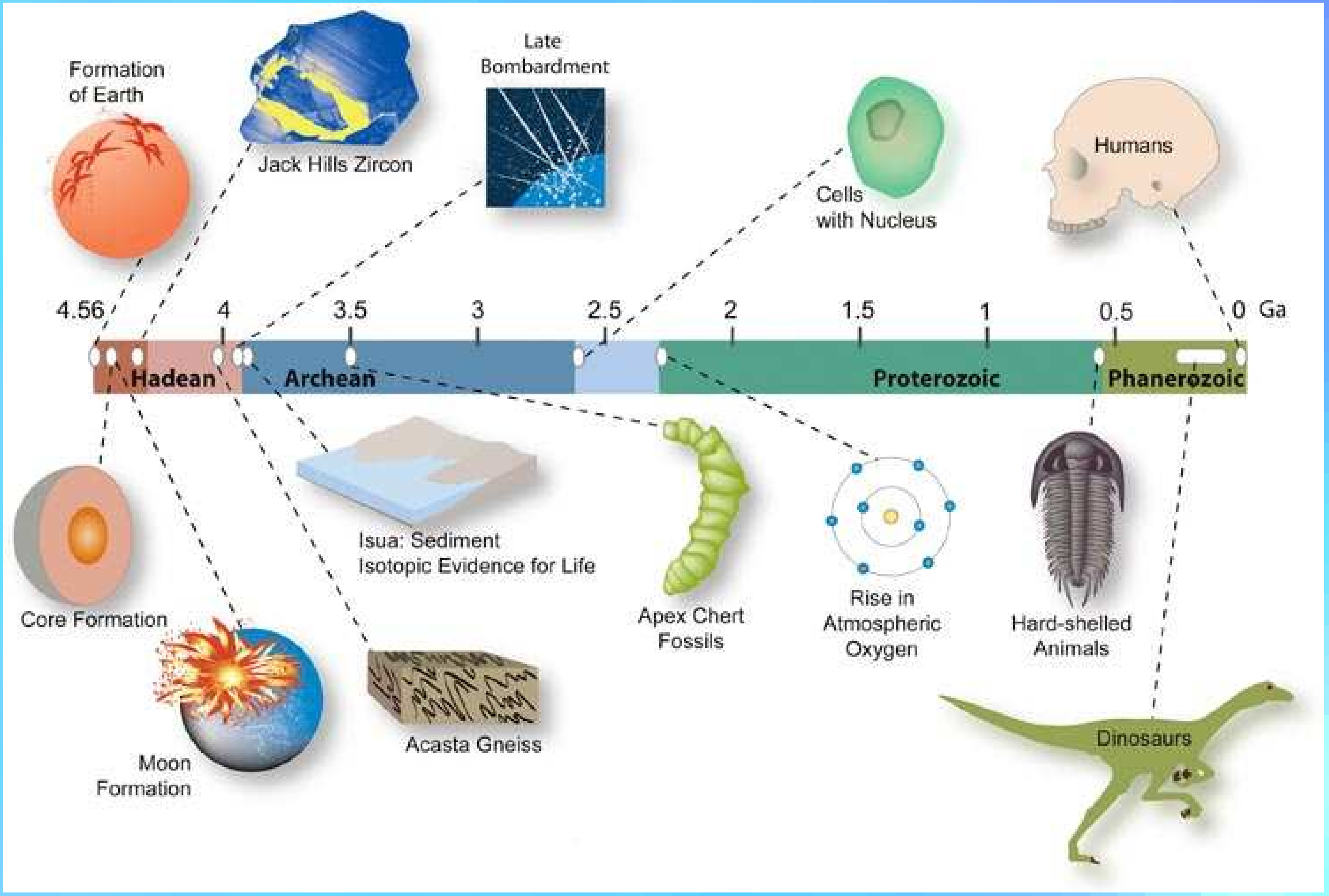




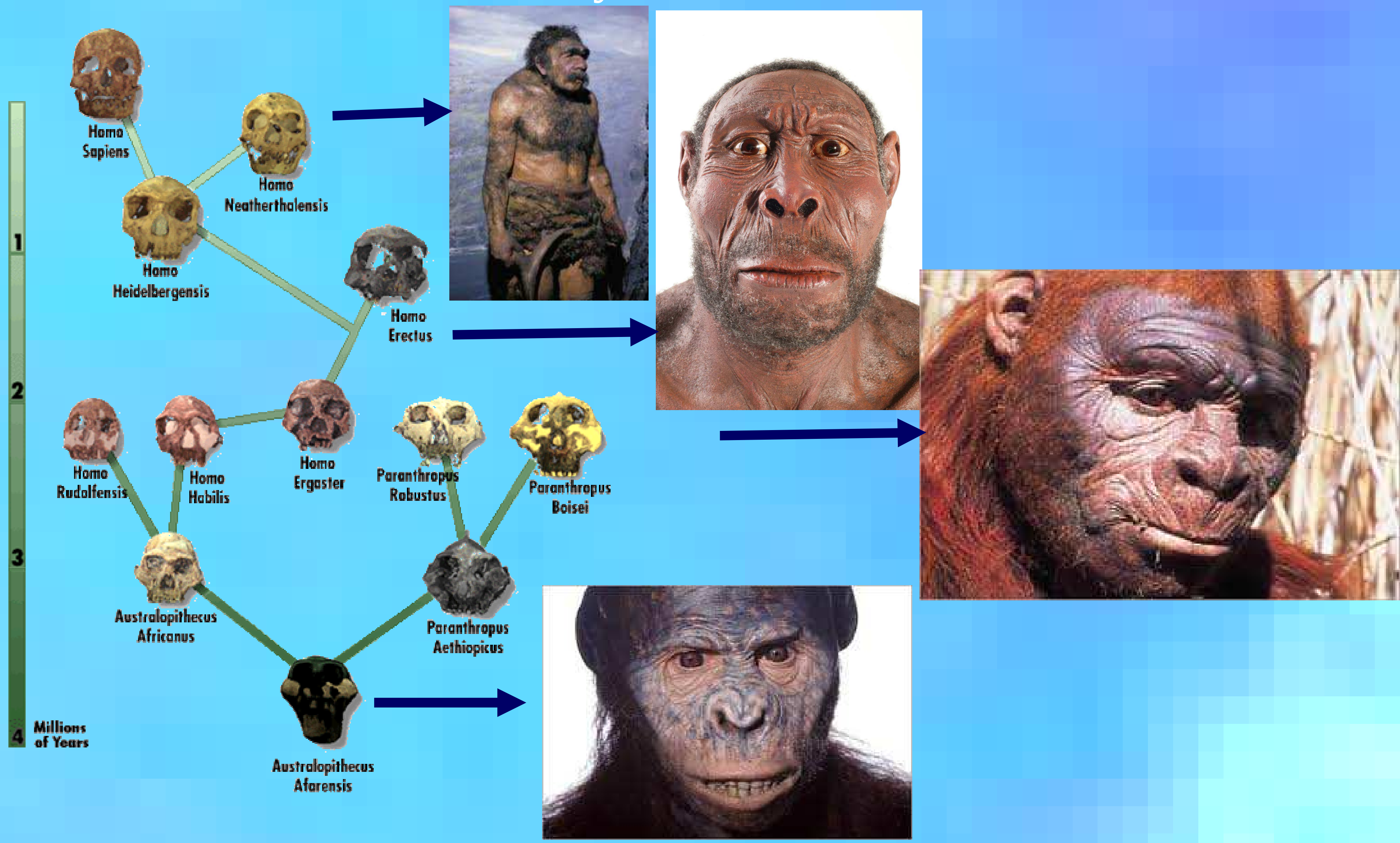


13.700.000.000 years

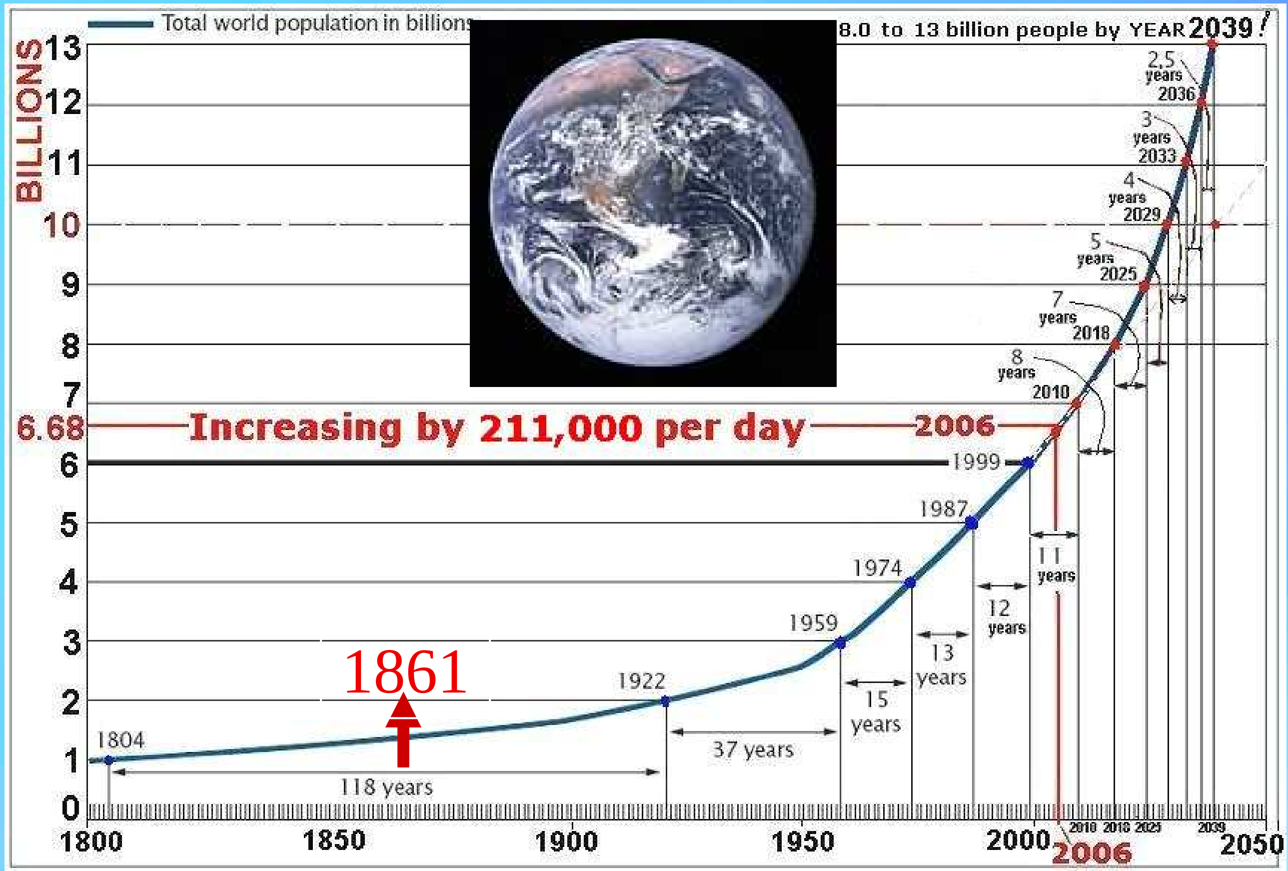
4.560.000.000 years



4.000.000 years

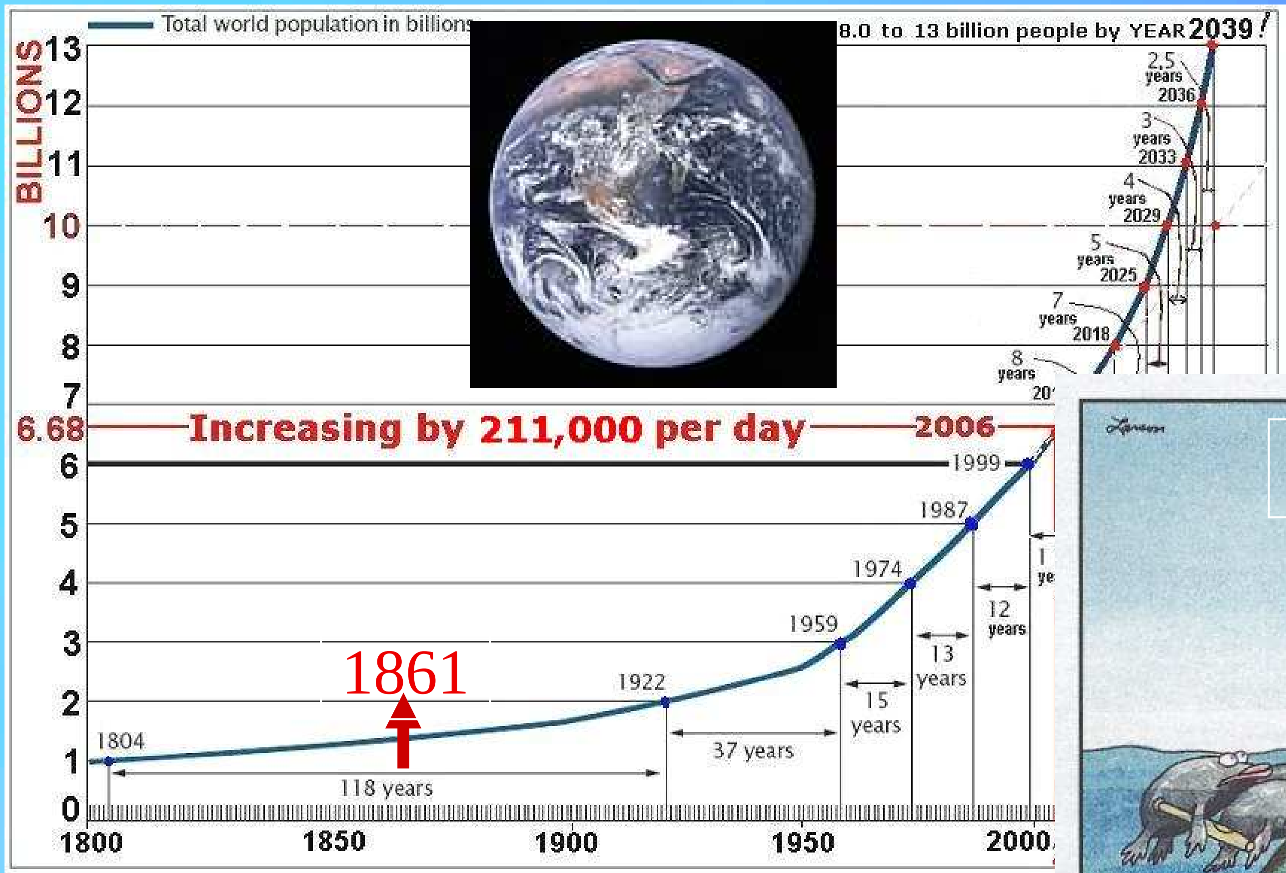


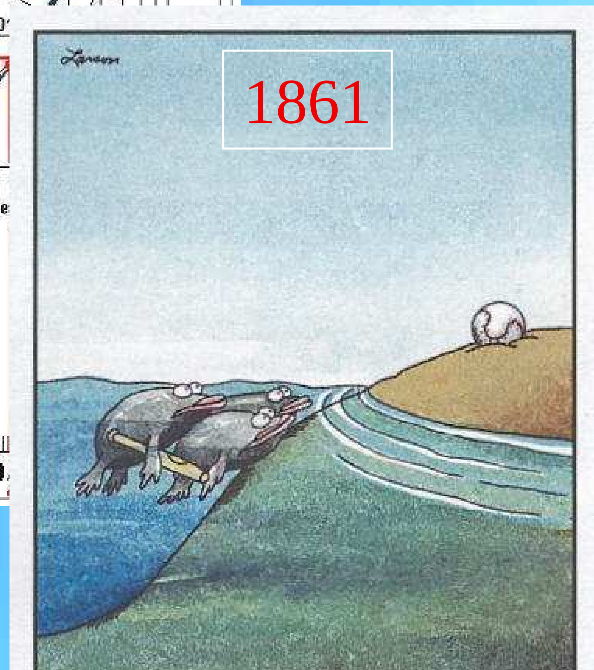
250 years



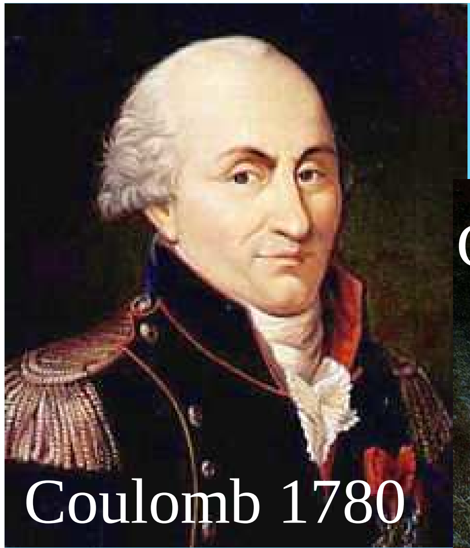
Total world population in billions
8.0 to 13 billion people by YEAR 2039!
BILLIONS
13
12
11
10
9
8
7
6.68
6
5
4
3
2
1
0
Increasing by 211,000 per day
2006
1999
1987
1974
1959
1922
1804
1861
118 years
37 years
15 years
13 years
12 years
11 years
8 years 2010
7 years 2018
5 years 2025
4 years 2029
3 years 2033
2.5 years 2036
1800
1850
1900
1950
2000
2006
2050

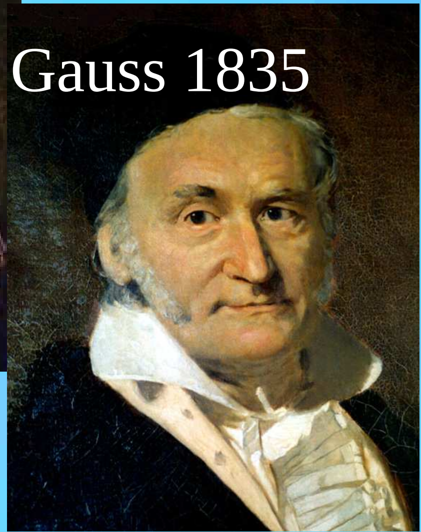
250 years

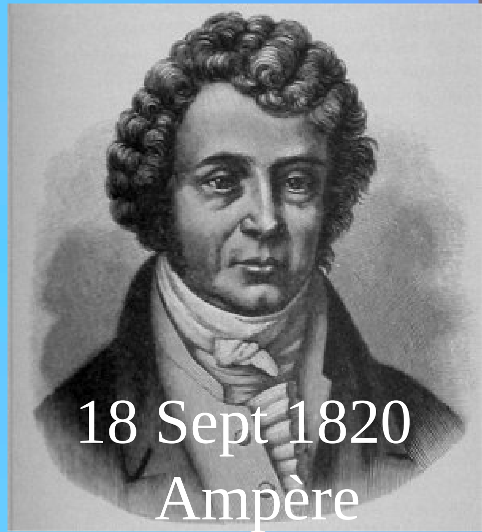


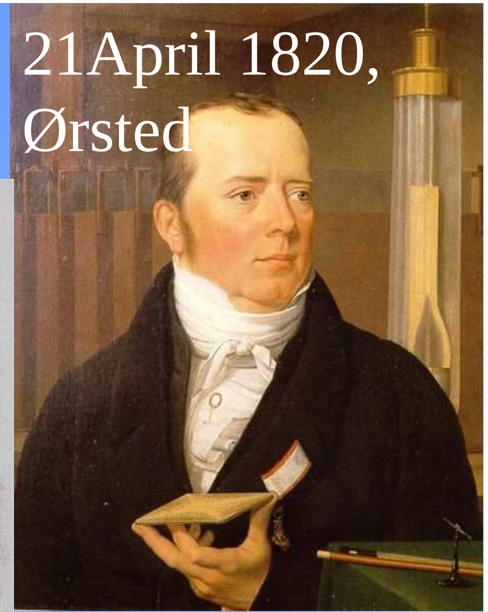


Great moments in evolution







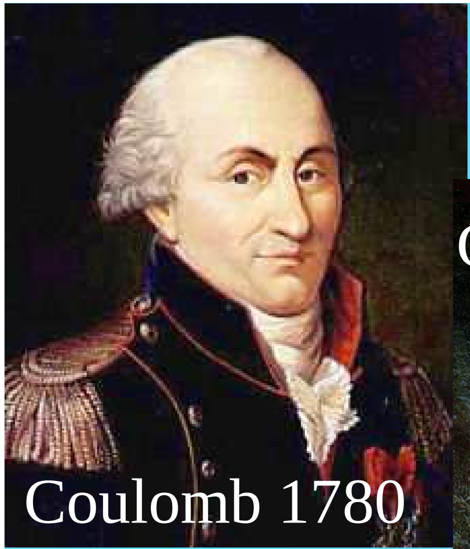


$$\vec{\nabla} \cdot \vec{E} = \frac{\rho}{\varepsilon_0}$$

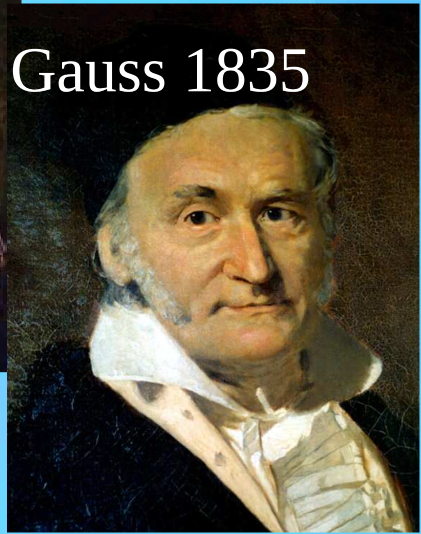
$$\vec{\nabla} \cdot \vec{B} = 0$$

$$\vec{\nabla} \times \vec{E} = 0$$

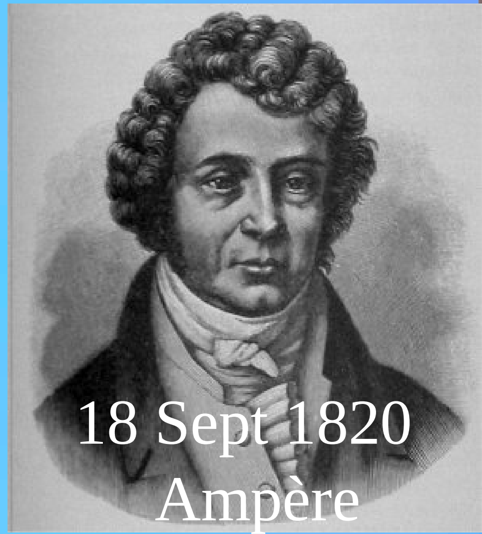
$$\vec{\nabla} \times \vec{B} = \mu_0 \vec{J}$$



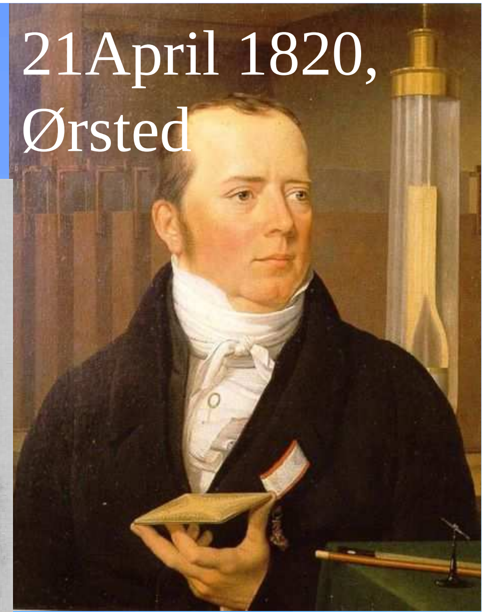
Coulomb 1780



Gauss 1835



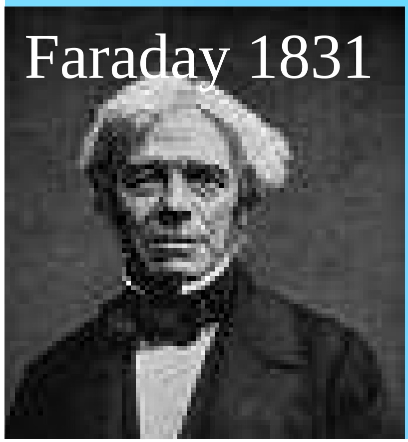
18 Sept 1820 Ampère



21April 1820, Ørsted

$$\vec{\nabla} \cdot \vec{E} = \frac{\rho}{\varepsilon_0}$$

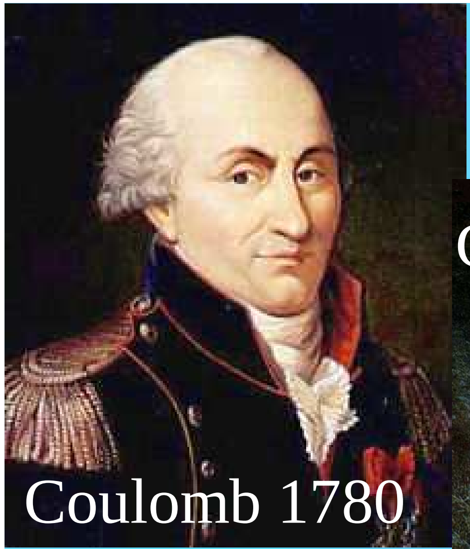
$$\vec{\nabla} \cdot \vec{B} = 0$$

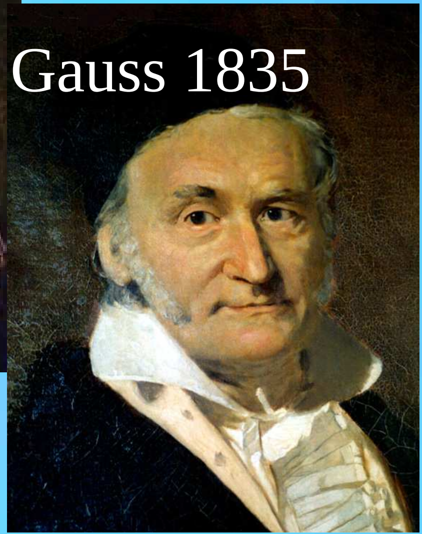


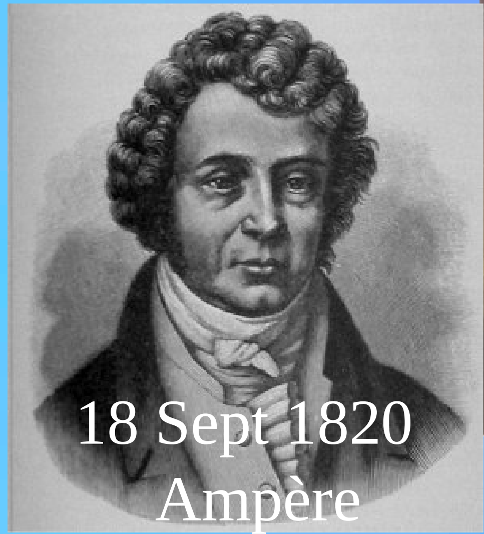
Faraday 1831

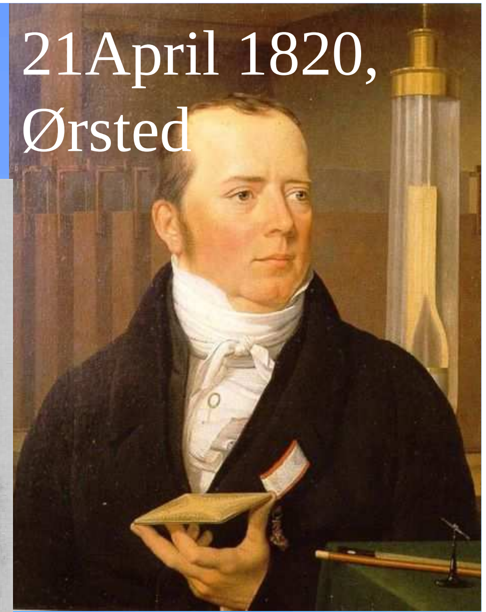
$$\vec{\nabla} \times \vec{E} = \boxed{-\frac{\partial \vec{B}}{\partial t}}$$

$$\vec{\nabla} \times \vec{B} = \mu_0 \vec{J}$$







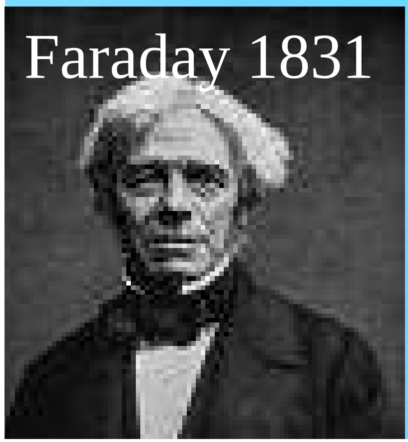


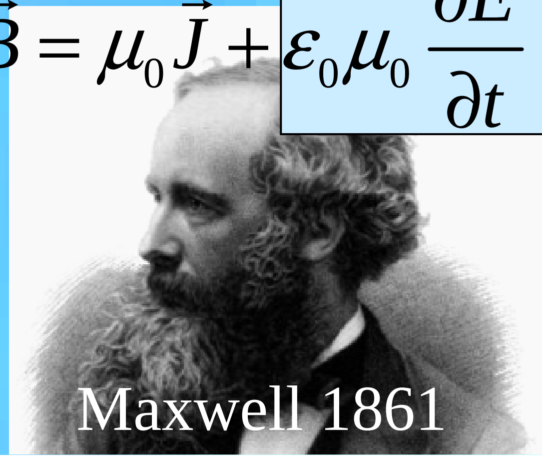
$$\vec{\nabla} \cdot \vec{E} = \frac{\rho}{\varepsilon_0}$$

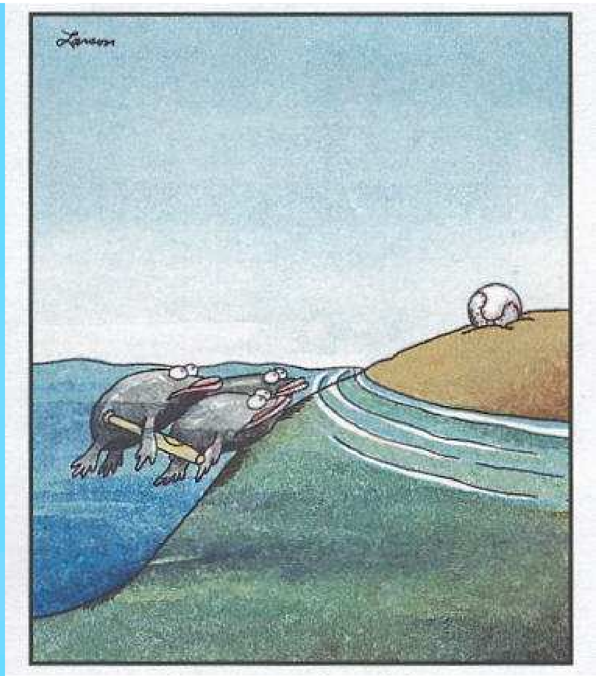
$$\vec{\nabla} \cdot \vec{B} = 0$$

$$\vec{\nabla} \times \vec{E} = \boxed{-\frac{\partial \vec{B}}{\partial t}}$$

$$\vec{\nabla} \times \vec{B} = \mu_0 \vec{J} + \boxed{\varepsilon_0 \mu_0 \frac{\partial \vec{E}}{\partial t}}$$

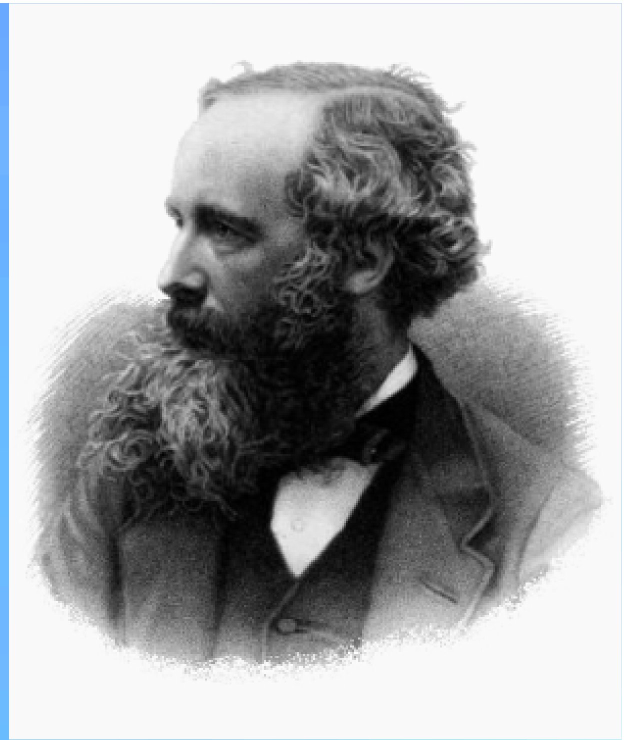






Great moments in evolution

1861

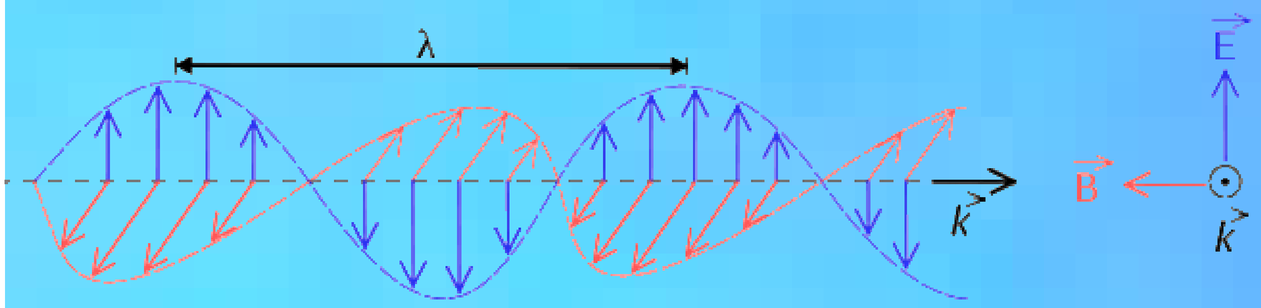


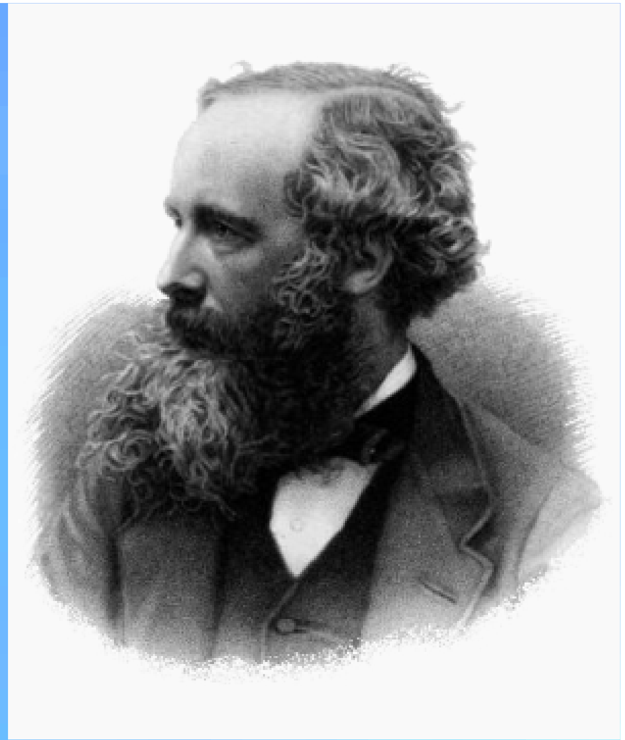
$$\vec{\nabla} \cdot \vec{E} = \frac{\rho}{\varepsilon_0}$$

$$\vec{\nabla} \cdot \vec{B} = 0$$

$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\vec{\nabla} \times \vec{B} = \mu_0 \vec{J} + \varepsilon_0 \mu_0 \frac{\partial \vec{E}}{\partial t}$$





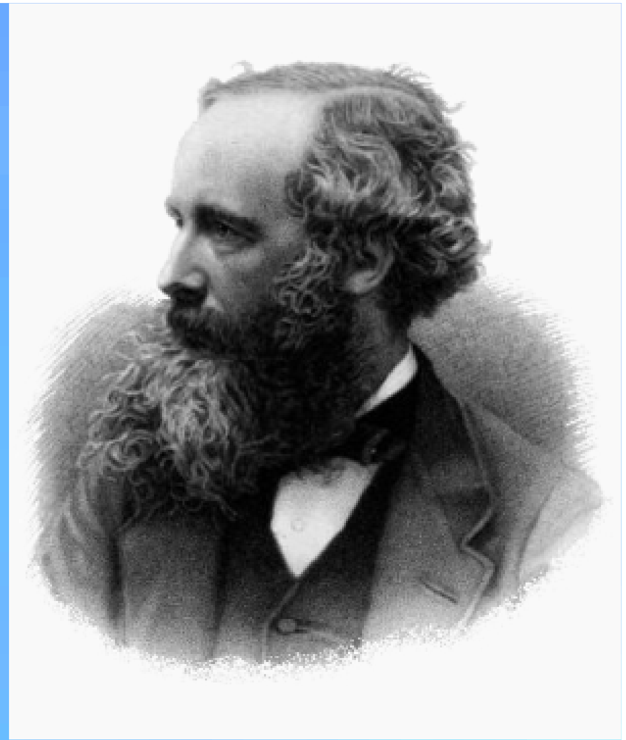
$$c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}}$$

LIGHT!!

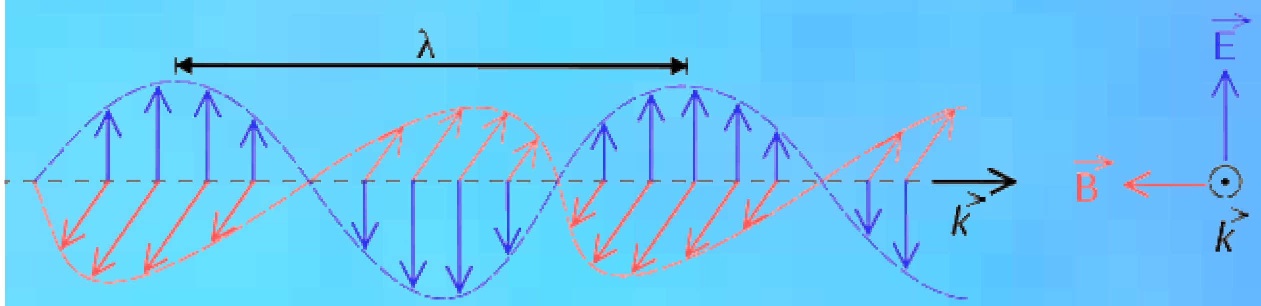
$$\vec{\nabla} \cdot \vec{E} = \cancel{\frac{\rho}{\varepsilon_0}} \qquad \vec{\nabla} \cdot \vec{B} = 0$$

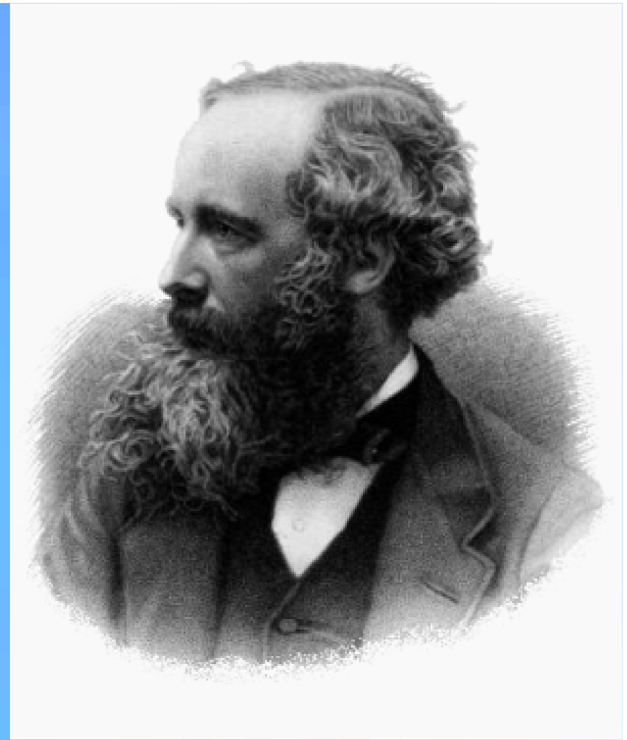
$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \qquad \vec{\nabla} \times \vec{B} = \cancel{\mu_0 \vec{J}} + \varepsilon_0 \mu_0 \frac{\partial \vec{E}}{\partial t}$$

1861



Experiment and Theory!!



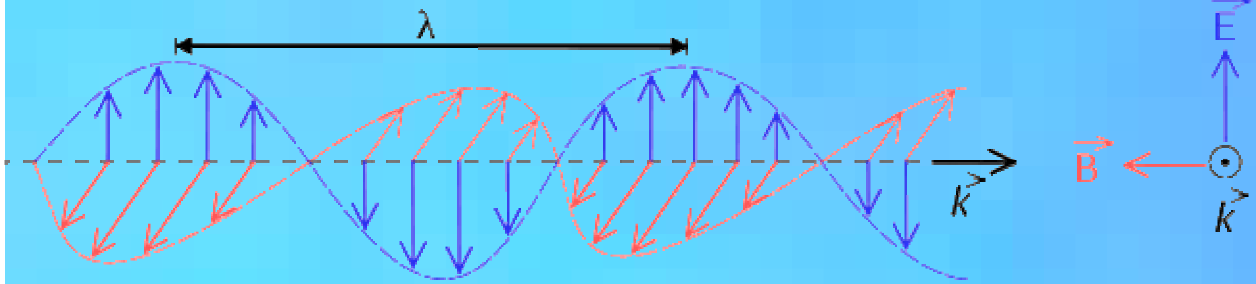


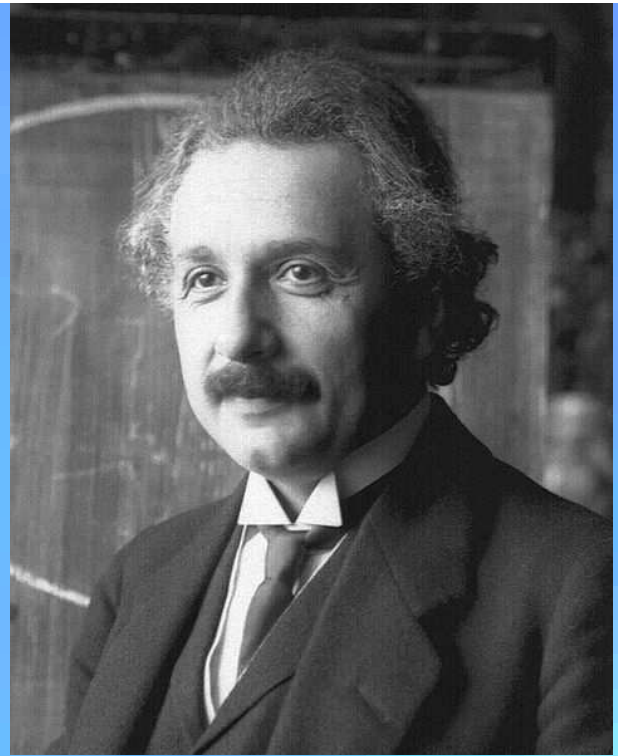
$$c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}}$$

LIGHT!!

$$\vec{\nabla} \cdot \vec{E} = \cancel{\frac{\rho}{\varepsilon_0}} \qquad \vec{\nabla} \cdot \vec{B} = 0$$

$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \qquad \vec{\nabla} \times \vec{B} = \cancel{\mu_0 \vec{J}} + \varepsilon_0 \mu_0 \frac{\partial \vec{E}}{\partial t}$$



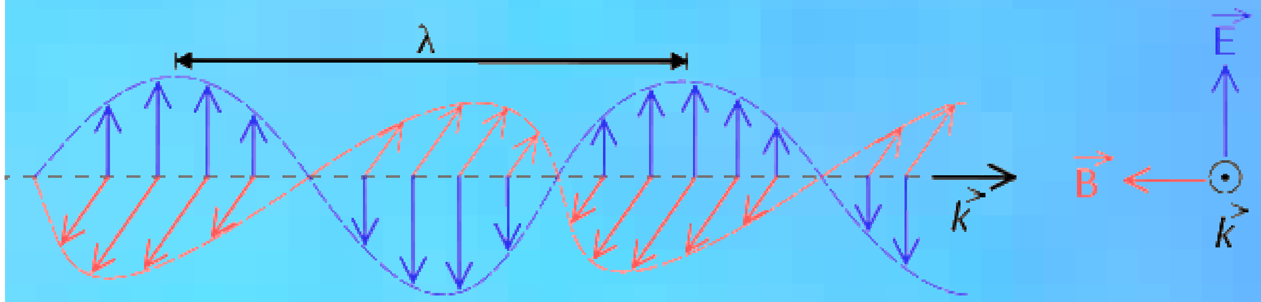


$$c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}}$$

LIGHT!!

Special Relativity

Albert Einstein: ***"The special theory of relativity owes its origins to Maxwell's equations of the electromagnetic field."***



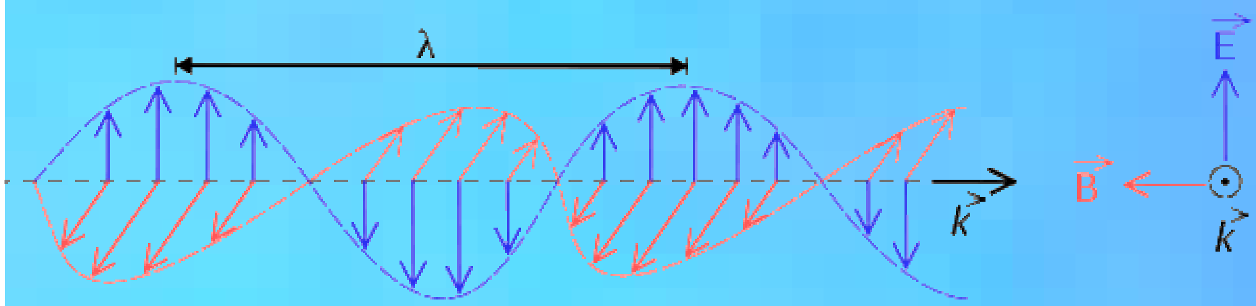
$$c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}}$$

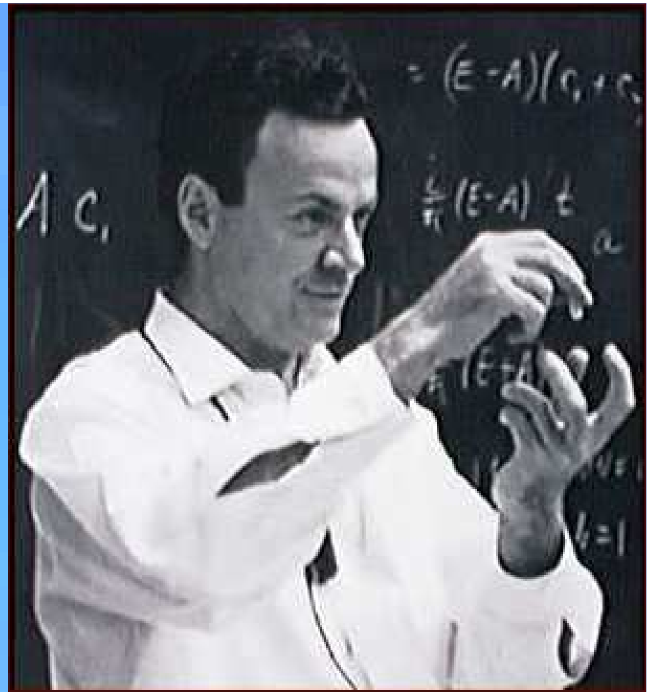
LIGHT!!

Special Relativity

Quantum Theory

Max Planck: ***“Maxwell achieved greatness unequalled"***





$$c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}}$$

LIGHT!!

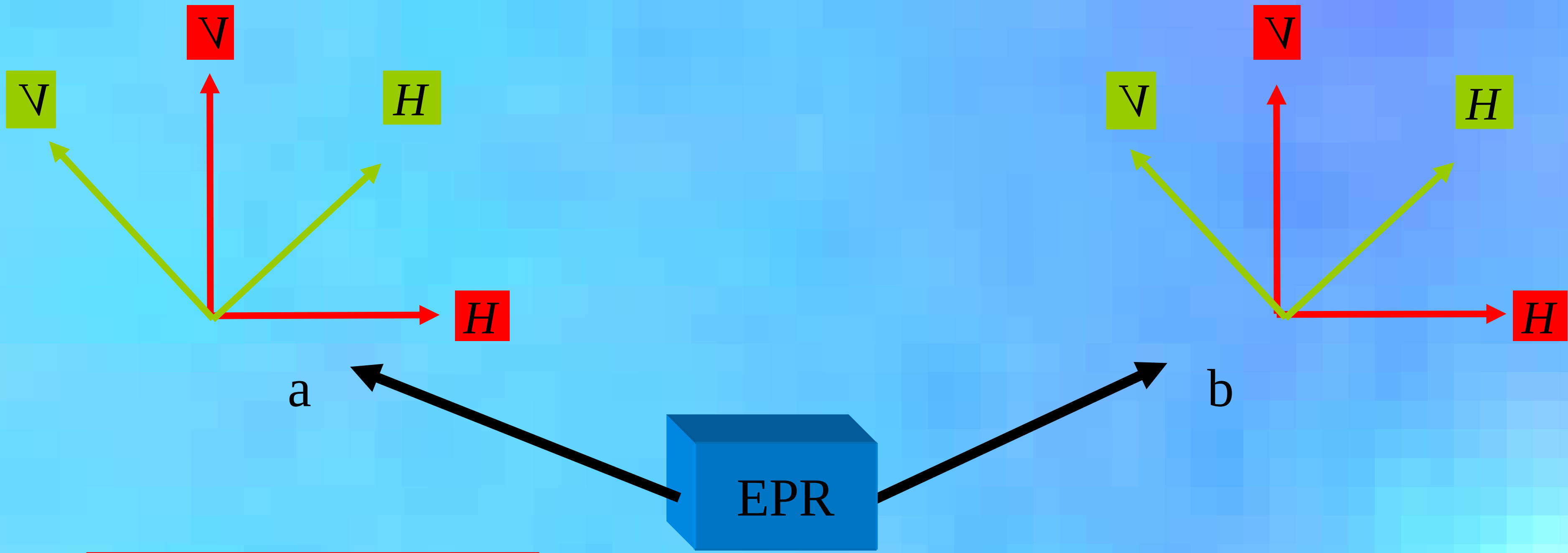
Special Relativity

Quantum Theory

Quantum Field Theory (Gauge theory)

Feynman ***"From a long view of the history of mankind there can be little doubt that the most significant event of the 19th century will be judged as Maxwell's discovery of the laws of electrodynamics"***

Entanglement



Einstein-Podolsky-Rosen

$$\psi_{ab} = \sqrt{\frac{1}{2}}\left(H_a V_b - V_a H_b\right)$$

$$= \sqrt{\frac{1}{2}}\left(\frac{1}{2}(H-V)_a(H+V)_b - \frac{1}{2}(H+V)_a(H-V)_b\right)$$

$$= \frac{1}{2\sqrt{2}}\left(H_a H_b + H_a V_b - V_a H_b - V_a V_b - H_a H_b + H_a V_b - V_a H_b + V_a V_b\right)$$

$$\psi_{ab} = \sqrt{\frac{1}{2}}\left(H_a V_b - V_a H_b\right)$$

Entanglement

Einstein:

"The Lord is subtle but not malicious."

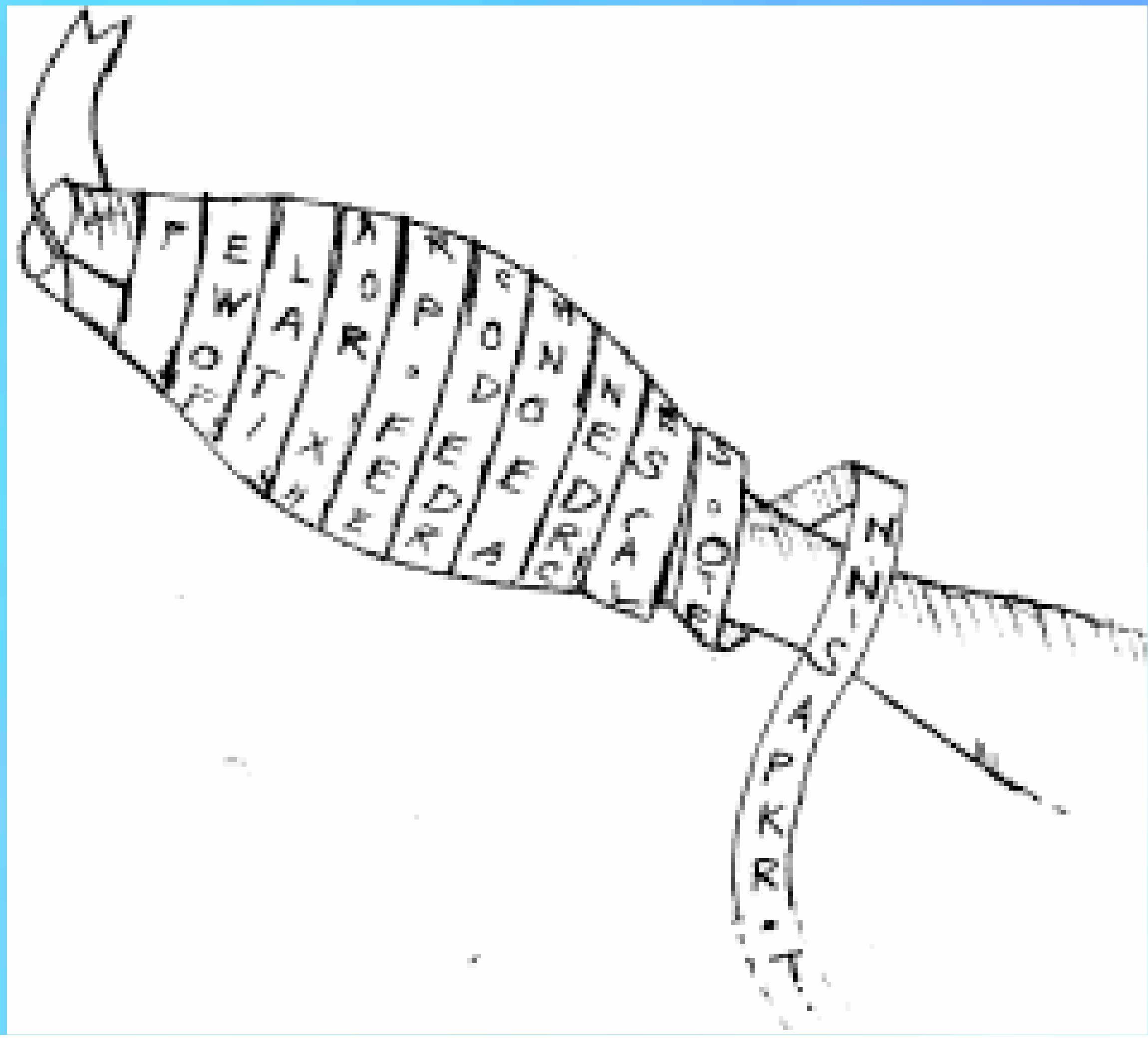
"God does not play dice."

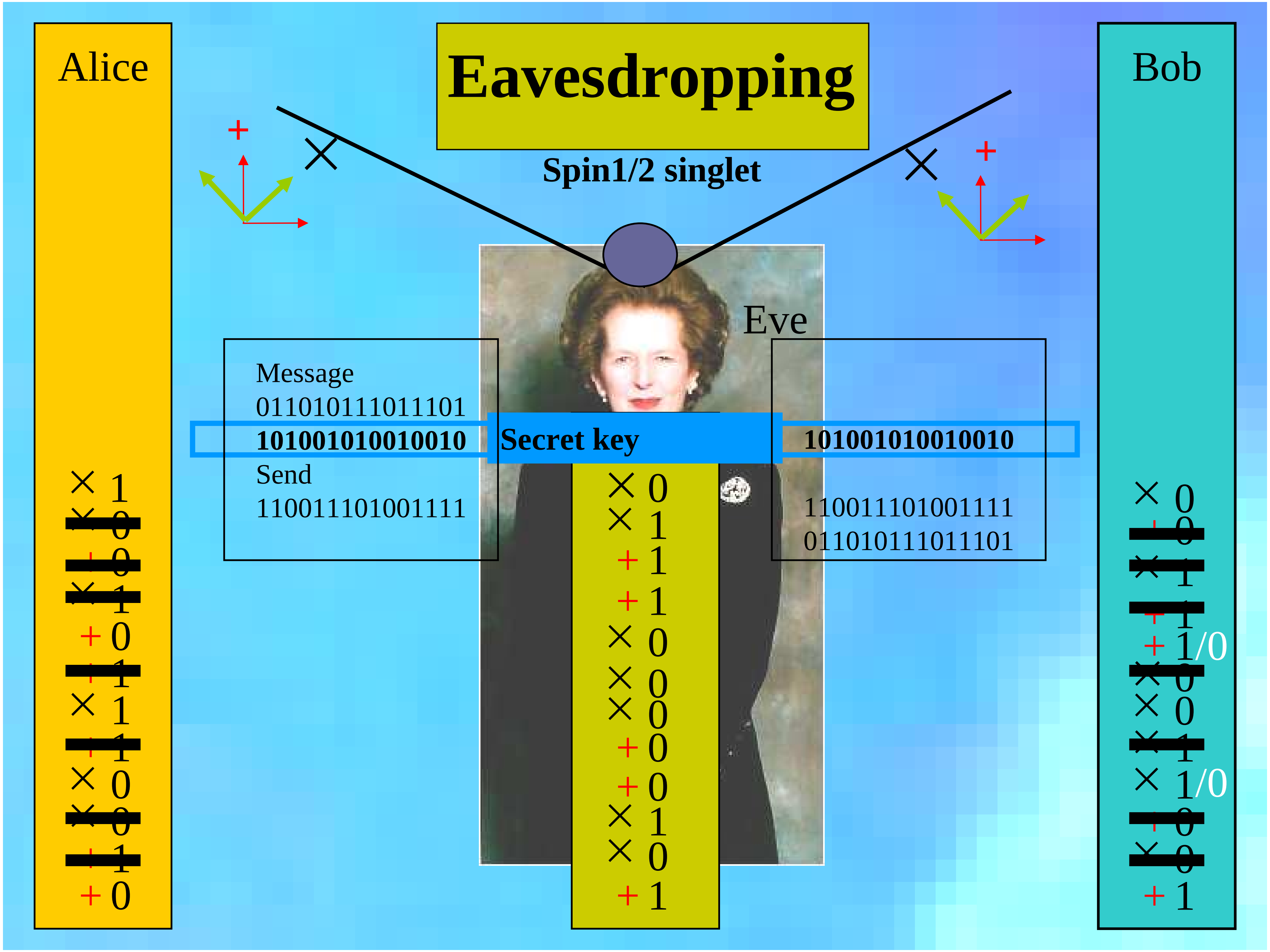
Bohr:

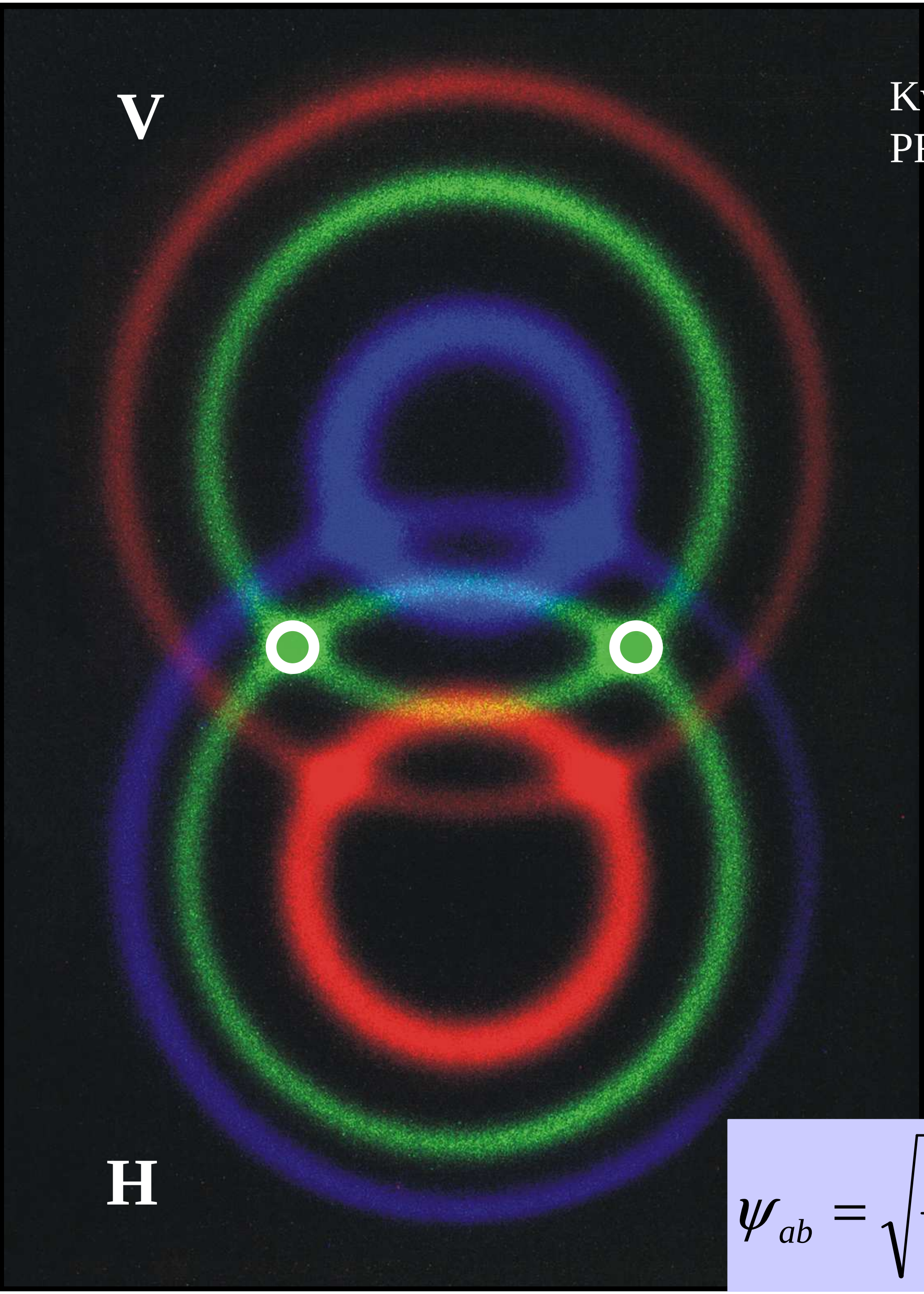
"Please stop telling God what to do."

Cryptography

Scytale: Spartans, 400 B.C.




Eavesdropping
Spin1/2 singlet
Alice
Bob
Eve
Message
011010111011101
101001010010010
Send
110011101001111
Secret key
101001010010010
110011101001111
011010111011101
× 1
~~× 0~~
~~+ 0~~
~~× 1~~
+ 0
~~+ 1~~
× 1
~~+ 1~~
× 0
~~× 0~~
~~+ 1~~
+ 0
× 0
× 1
+ 1
+ 1
× 0
× 0
× 0
+ 0
+ 0
× 1
× 0
+ 1
× 0
~~+ 0~~
~~× 1~~
~~+ 1~~
+ 1/0
~~× 0~~
× 0
~~× 1~~
× 1/0
~~+ 0~~
~~× 0~~
+ 1

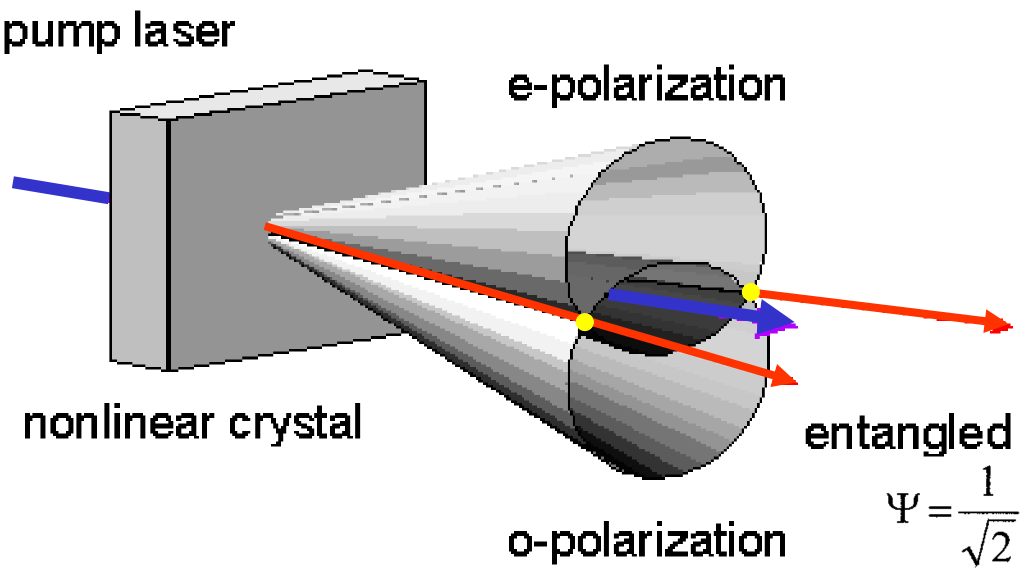


Kwiat et al.
PRL **74** 4763 (1995).

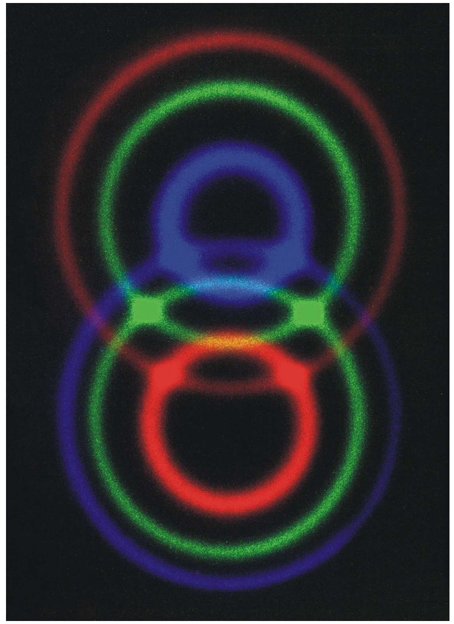
$$\psi_{ab} = \sqrt{\frac{1}{2}}\left(H_a V_b - V_a H_b\right)$$

Phase Matching and Entanglement

Degenerate case: $\omega_1 = \omega_2 = \omega_P/2$

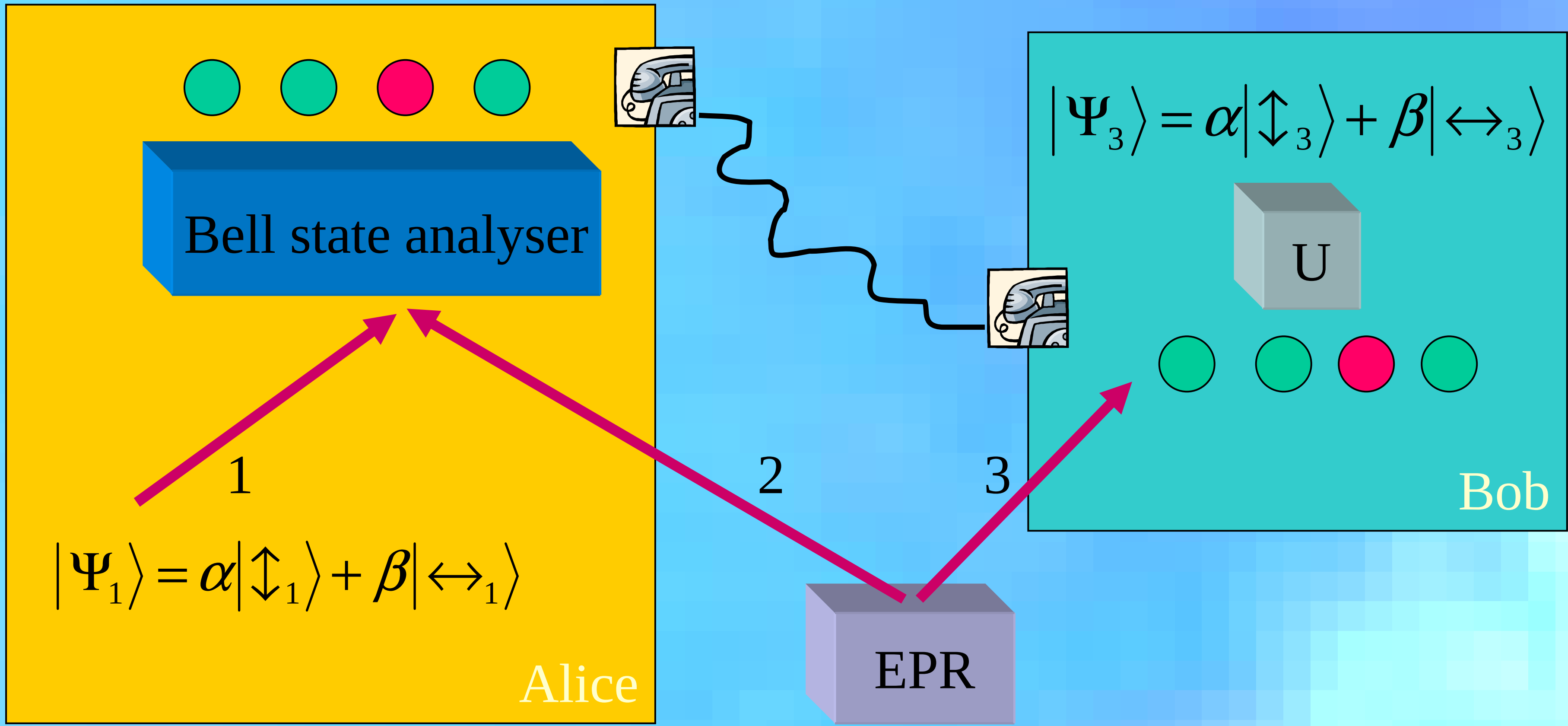


$$\Psi = \frac{1}{\sqrt{2}}\left(|H\rangle_1 |V\rangle_2 + |V\rangle_1 |H\rangle_2 \right)$$



Birefringence needed for phase matching

Teleportation Scheme



$$|\Psi_{23}\rangle = \sqrt{\frac{1}{2}}\left(|\updownarrow_2\rangle|\leftrightarrow_3\rangle - |\leftrightarrow_2\rangle|\updownarrow_3\rangle\right)$$

Basis of Bell States

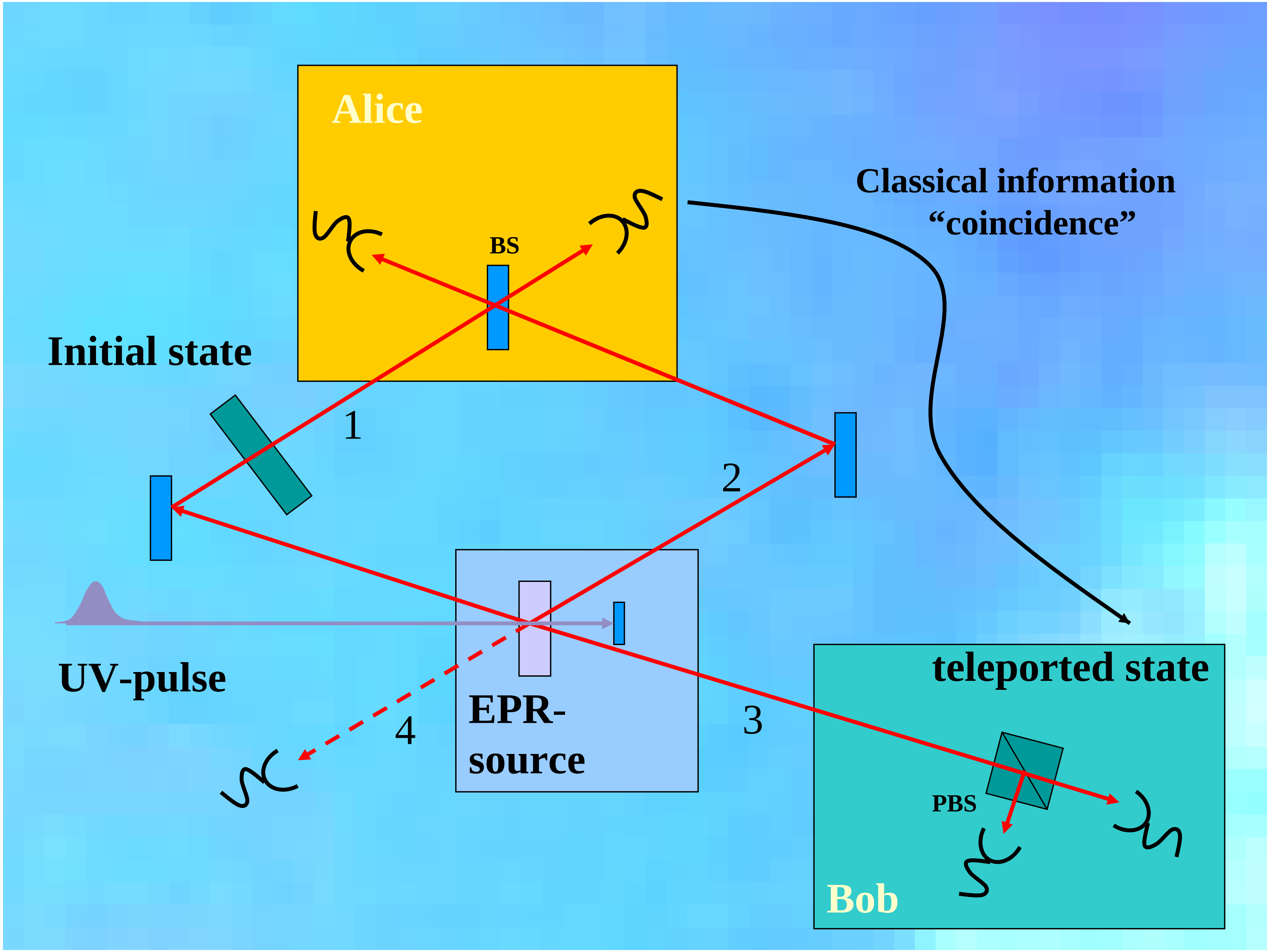
$$\left|\Psi_{12}^{\pm}\right\rangle = \sqrt{\frac{1}{2}}\left(\left|\updownarrow_1\right\rangle\left|\leftrightarrow_2\right\rangle \pm \left|\leftrightarrow_1\right\rangle\left|\updownarrow_2\right\rangle\right)$$

$$\left|\Phi_{12}^{\pm}\right\rangle = \sqrt{\frac{1}{2}}\left(\left|\updownarrow_1\right\rangle\left|\updownarrow_2\right\rangle \pm \left|\leftrightarrow_1\right\rangle\left|\leftrightarrow_2\right\rangle\right)$$

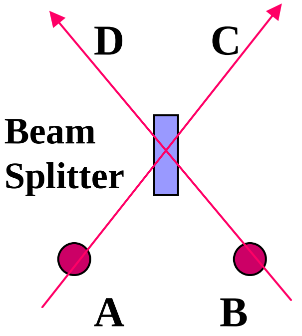
$$\begin{aligned}\left|\Psi_{123}\right\rangle = \left|\Psi_1\right\rangle \otimes \left|\Psi_{23}\right\rangle = \frac{1}{2}\Big[&\left|\Psi_{12}^{-}\right\rangle\left(-\alpha\left|\updownarrow_3\right\rangle - \beta\left|\leftrightarrow_3\right\rangle\right) + \\ &\left|\Psi_{12}^{+}\right\rangle\left(-\alpha\left|\updownarrow_3\right\rangle + \beta\left|\leftrightarrow_3\right\rangle\right) + \\ &\left|\Phi_{12}^{-}\right\rangle\left(-\alpha\left|\leftrightarrow_3\right\rangle + \beta\left|\updownarrow_3\right\rangle\right) + \\ &\left|\Phi_{12}^{-}\right\rangle\left(-\alpha\left|\leftrightarrow_3\right\rangle - \beta\left|\updownarrow_3\right\rangle\right)\Big]\end{aligned}$$

Known unitary transformation of particle 3 gives the initial state of particle 1:

$$\left|\Psi_3\right\rangle \overset{U}{\Rightarrow} \left|\Psi_1\right\rangle$$


Alice
BS
Classical information
"coincidence"
Initial state
1
2
UV-pulse
EPR-
source
4
3
teleported state
PBS
Bob

2-Photon Interference



$$\begin{pmatrix} C \\ D \end{pmatrix} = \frac{1}{\sqrt{2}} \underbrace{\begin{pmatrix} 1 & i \\ i & 1 \end{pmatrix}}_{\text{unitary}} \begin{pmatrix} A \\ B \end{pmatrix} \qquad U^{\dagger}U = 1$$

$$\left|\Phi_{12}^{+}\right\rangle \Psi_S$$

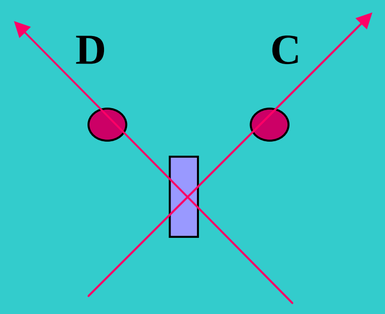
$$\left|\Phi_{12}^{-}\right\rangle \Psi_S$$

$$\left|\Psi_{12}^{+}\right\rangle \Psi_S$$

$$\left|\Psi_{12}^{-}\right\rangle \Psi_A$$

$$\Psi_S = \frac{1}{2}\left(A_1 B_2 + A_2 B_1\right) \rightarrow \frac{i}{2}\left(C_1 C_2 + D_2 D_1\right)$$

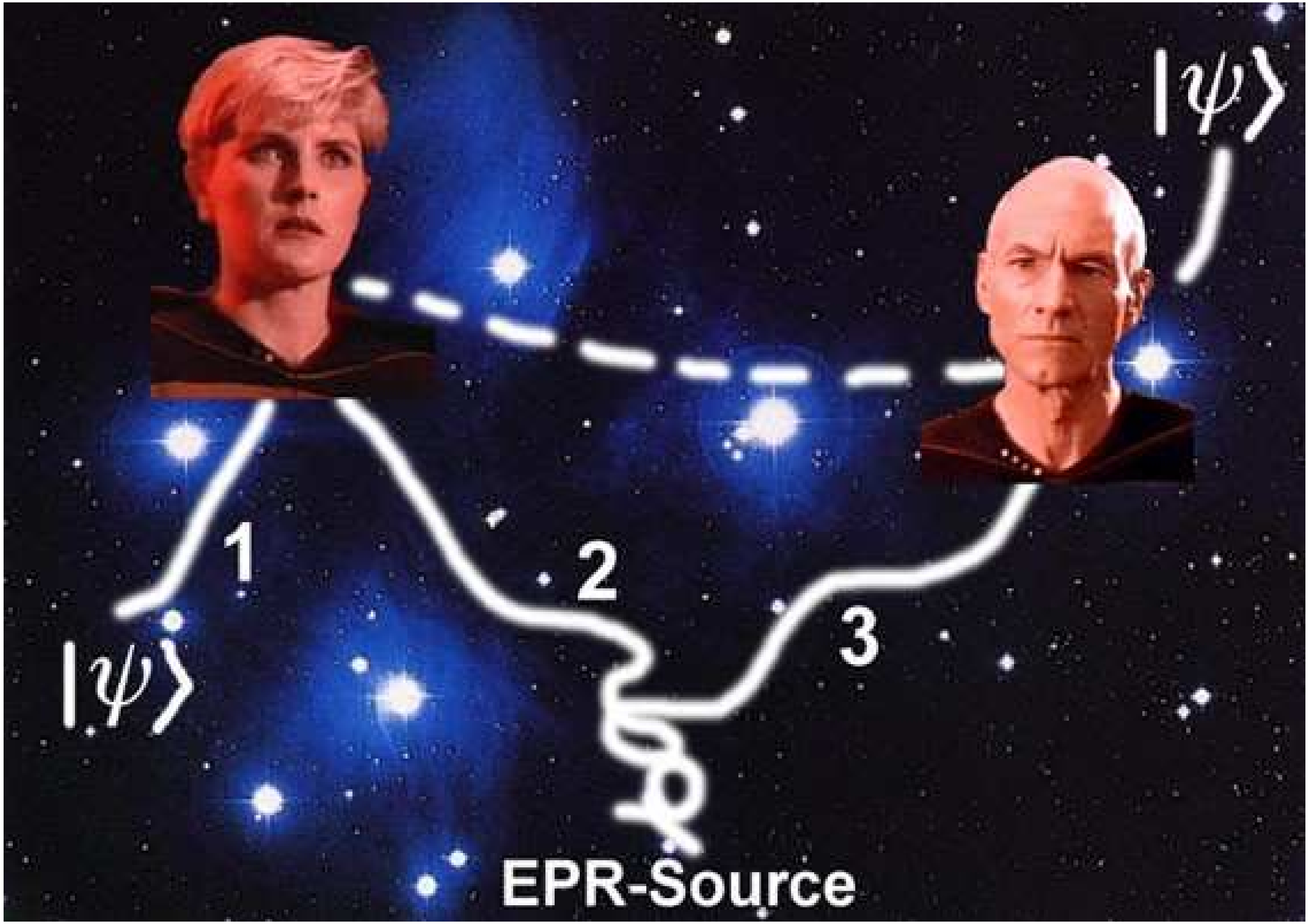
$$\Psi_A = \frac{1}{2}\left(A_1 B_2 - A_2 B_1\right) \rightarrow \frac{1}{2}\left(C_1 D_2 - C_2 D_1\right)$$



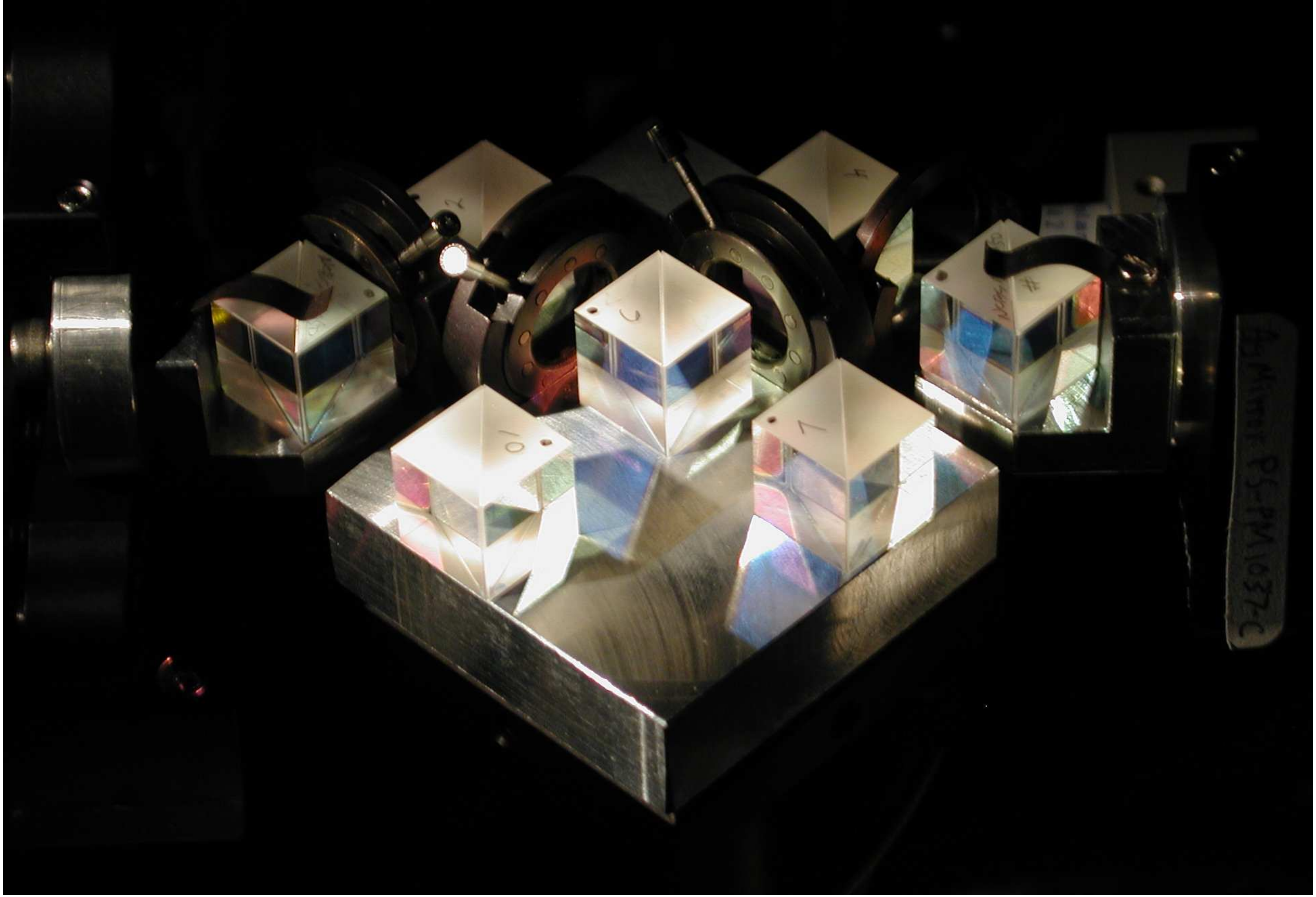
$$\left|\Psi_{12}^{-}\right\rangle$$

Nature 390, 575 (1997)
Phys. Rev. Lett. 80, 3891 (1998)

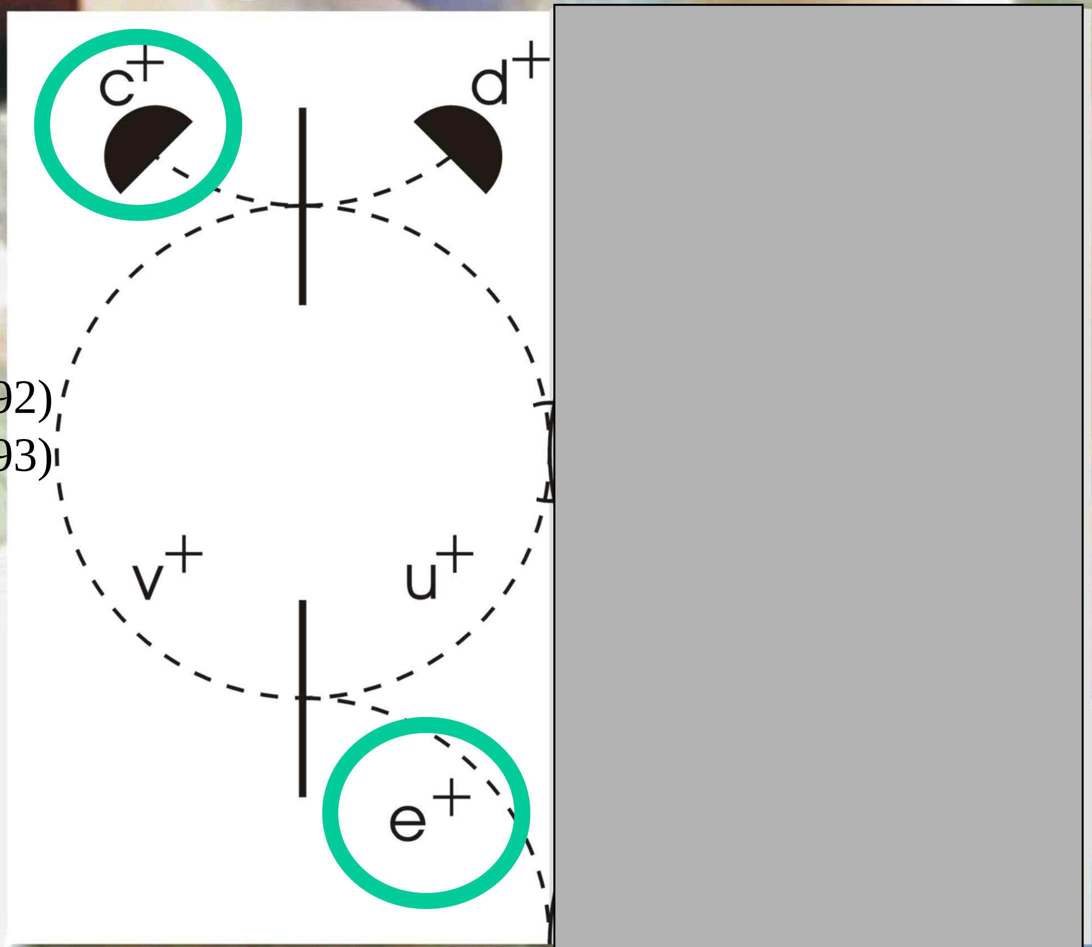
Quantum Internet



Hardy's Thought Experiment



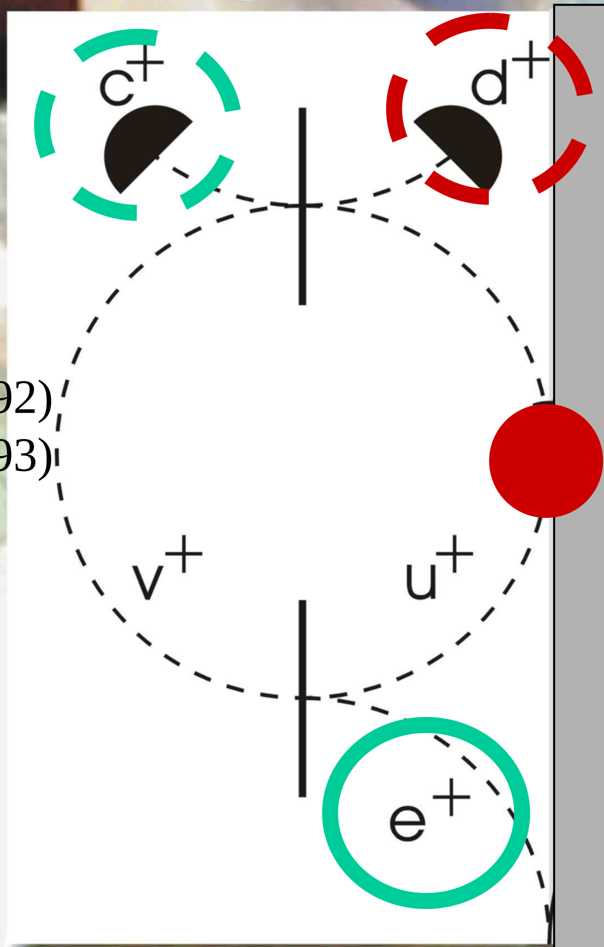
Hardy’s Thought Experiment



PRL **68**, 2981 (1992)
PRL **71**, 1665 (1993)

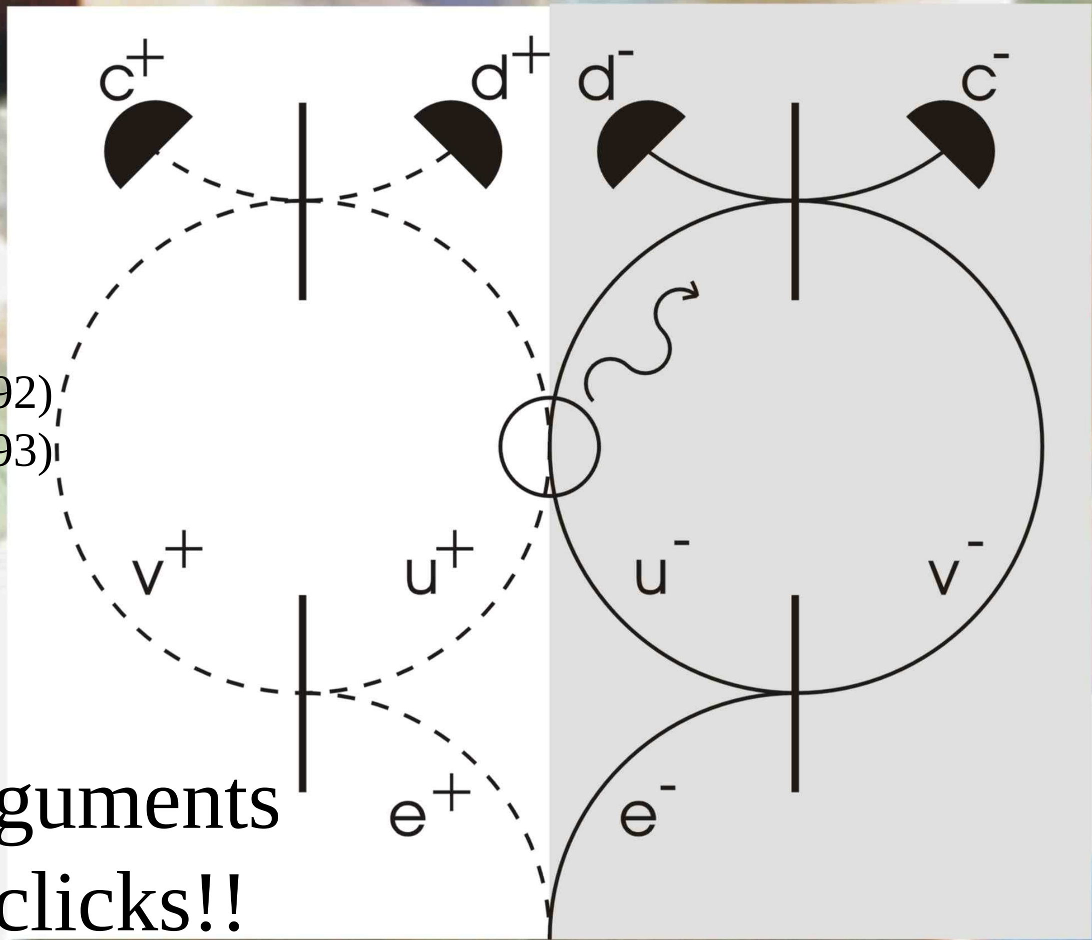
Hardy's Thought Experiment

PRL **68**, 2981 (1992)
PRL **71**, 1665 (1993)



Interaction-free measurement

Hardy's Thought Experiment

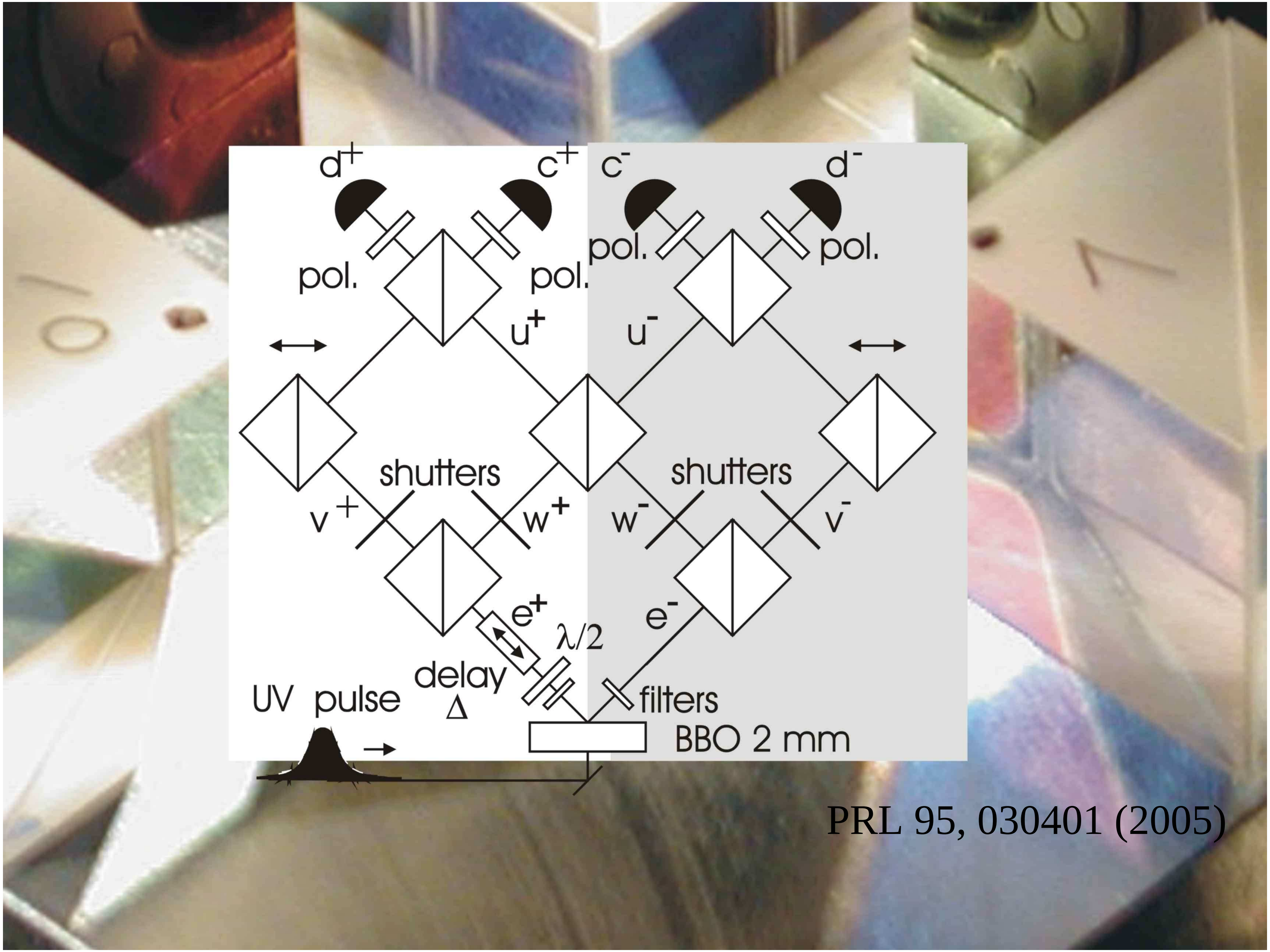


PRL **68**, 2981 (1992)
PRL **71**, 1665 (1993)

Local arguments
No d^+d^- clicks!!

$$|e^+\rangle|e^-\rangle \rightarrow \frac{1}{2}\left(|v^+\rangle + i|u^+\rangle\right)\left(|v^-\rangle + i|u^-\rangle\right) \rightarrow \frac{1}{2}\left(|v^+\rangle|v^-\rangle + i|u^+\rangle|v^-\rangle + i|v^+\rangle|u^-\rangle - |\gamma\rangle\right)$$

$$\rightarrow \frac{1}{4}\left(-3|c^+\rangle|c^-\rangle + i|c^+\rangle|d^-\rangle + i|d^+\rangle|c^-\rangle - \underline{|d^+\rangle|d^-\rangle} - 2|\gamma\rangle\right)$$



PRL 95, 030401 (2005)

Quantum Computation

Bit 0 or 1 $\rightarrow$ Quantum bit $|\Psi\rangle_1 = \alpha|0\rangle_1 + \beta|1\rangle_1$

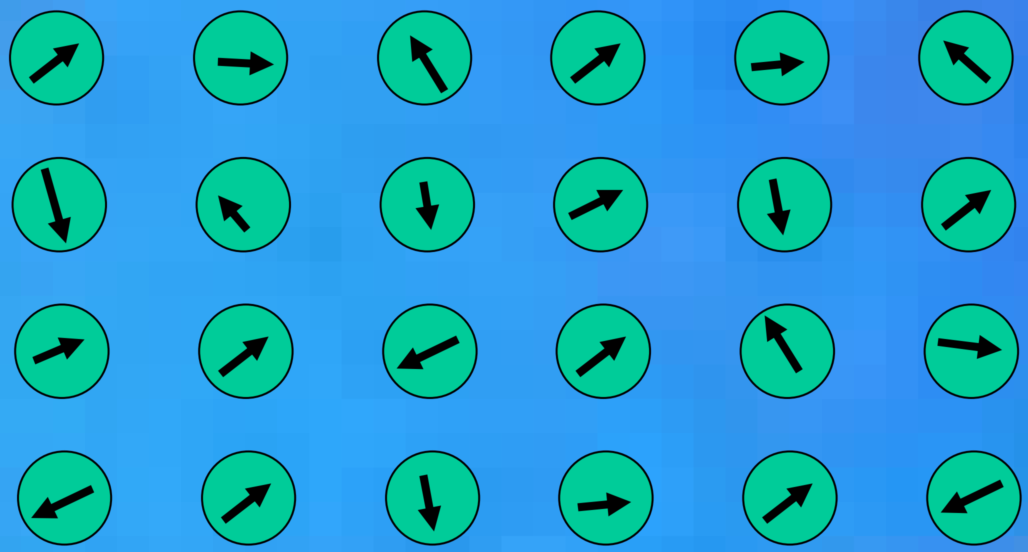
0110100 $\rightarrow |\Psi\rangle_1 \otimes |\Psi\rangle_2 \otimes |\Psi\rangle_3 \otimes |\Psi\rangle_4 \otimes \cdots$

CNOT $\rightarrow$ Quantum CNOT (approach 1)

Generate Cluster Entangled State (approach 2)

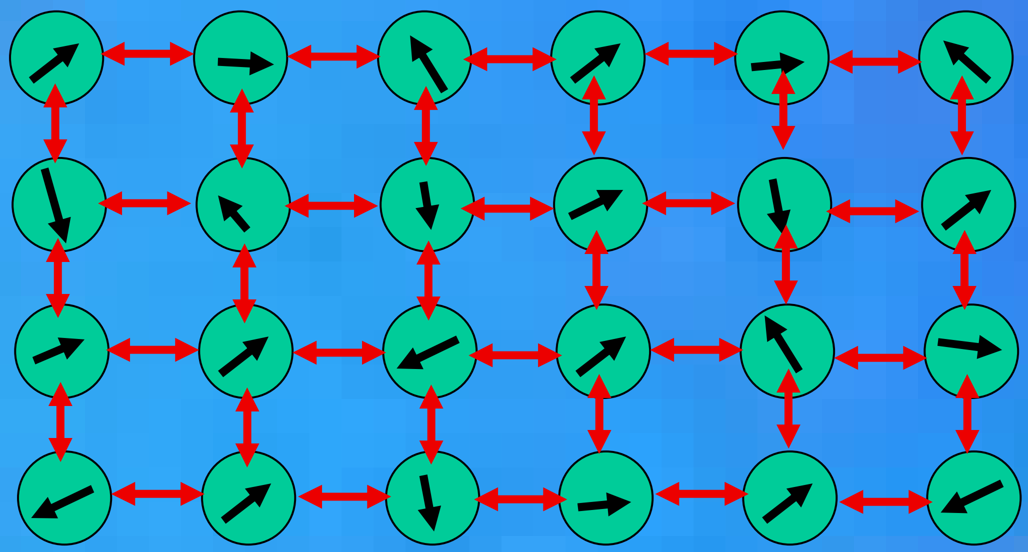
Quantum Computation

Cluster Entangled State



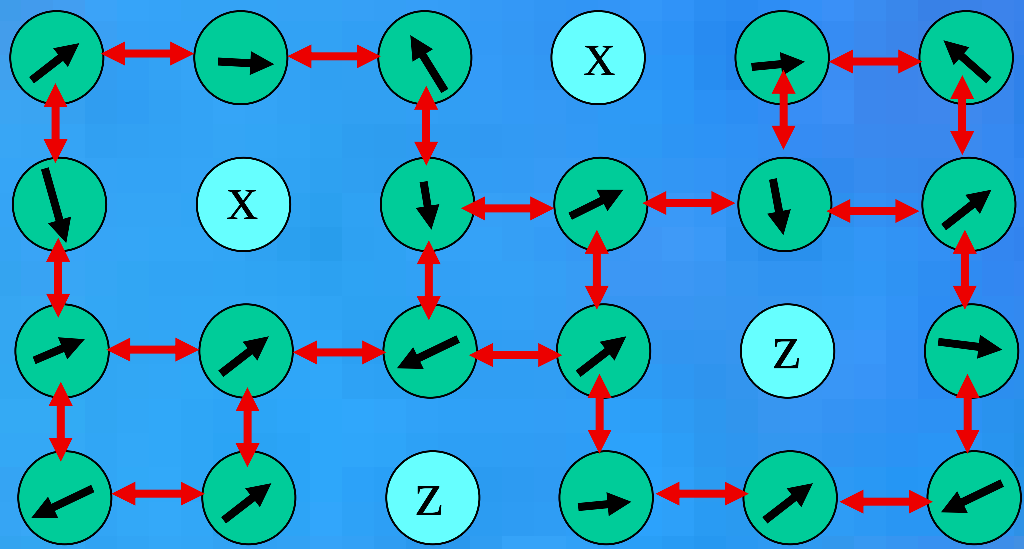
Quantum Computation

Cluster Entangled State



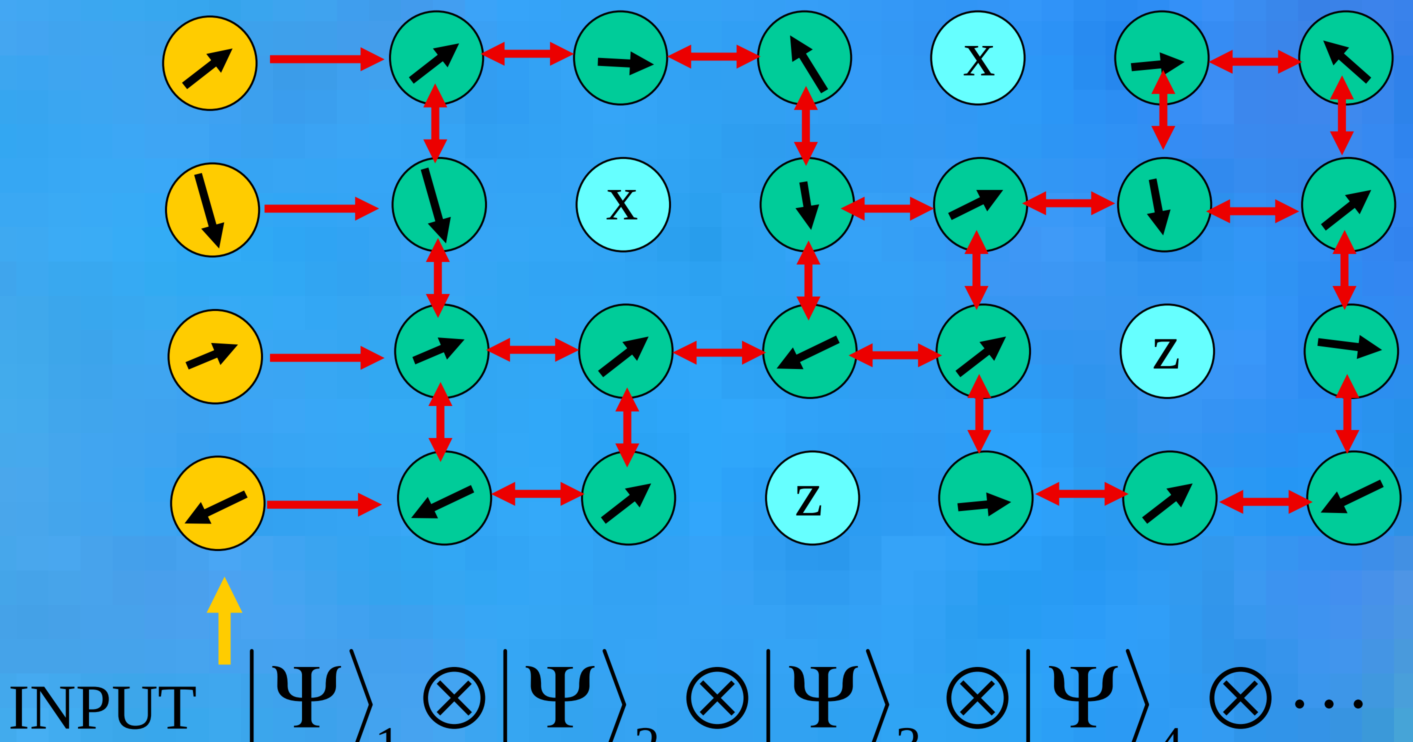
Quantum Computation

Cluster Entangled State



Quantum Computation

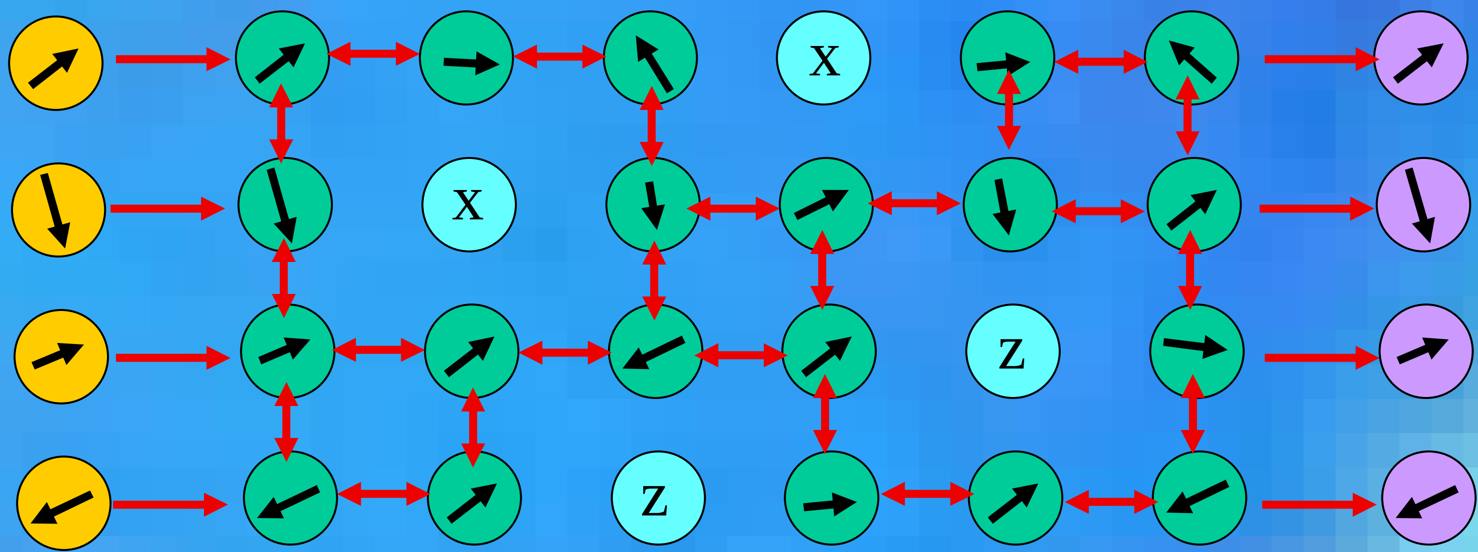
Cluster Entangled State



$$|\Psi\rangle_1 \otimes |\Psi\rangle_2 \otimes |\Psi\rangle_3 \otimes |\Psi\rangle_4 \otimes \cdots$$

Quantum Computation

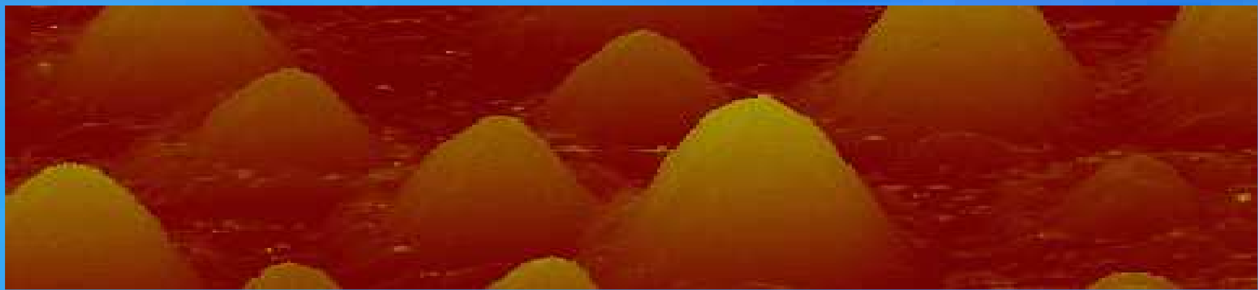
Cluster Entangled State

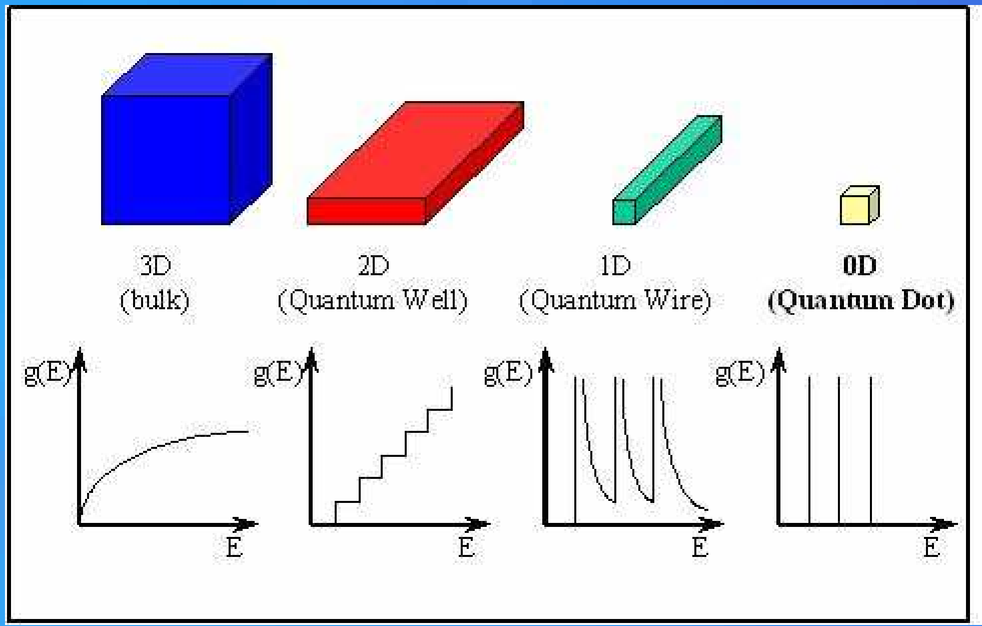


Output → Superposition of outputs ←

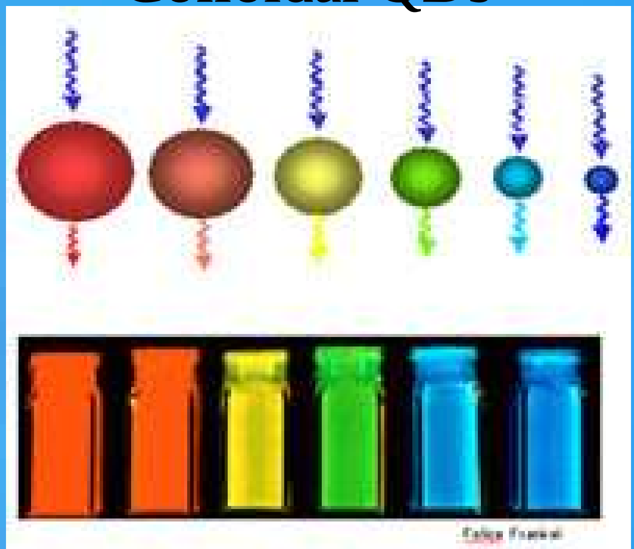
+ projection measurement

Self-assembled Quantum Dots



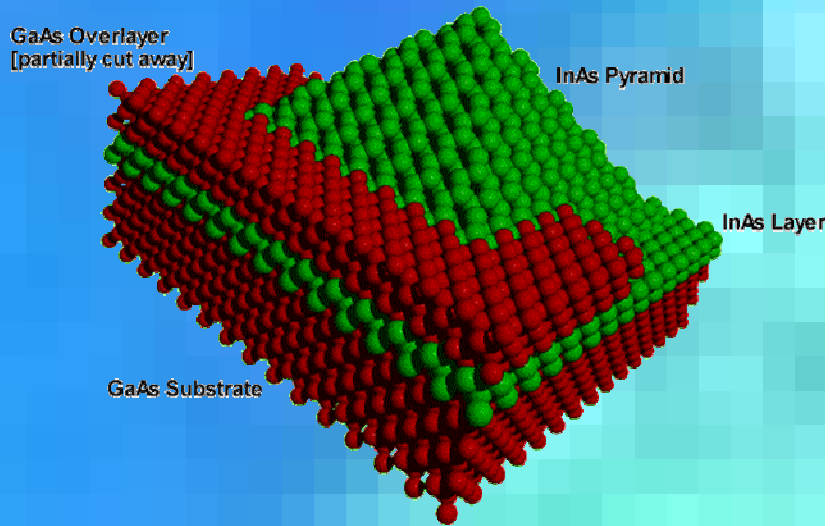


Colloidal QDs

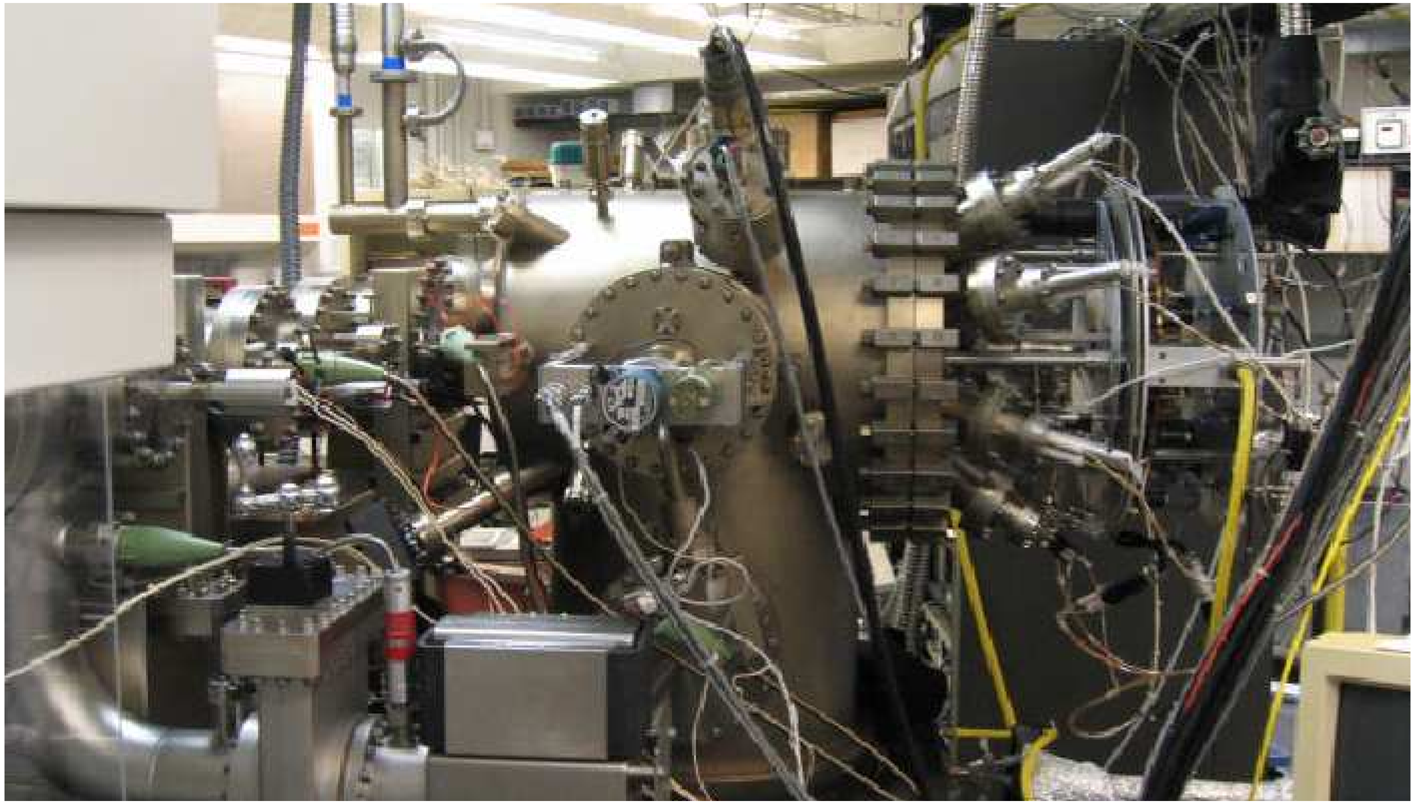


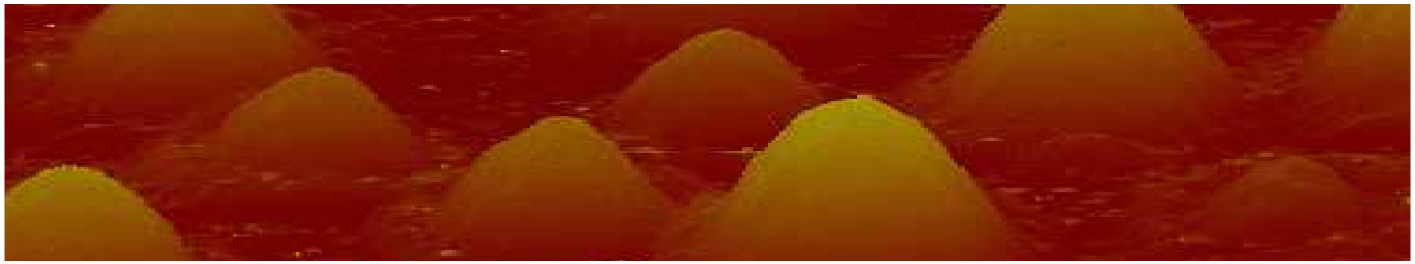
Size
1-20 nm

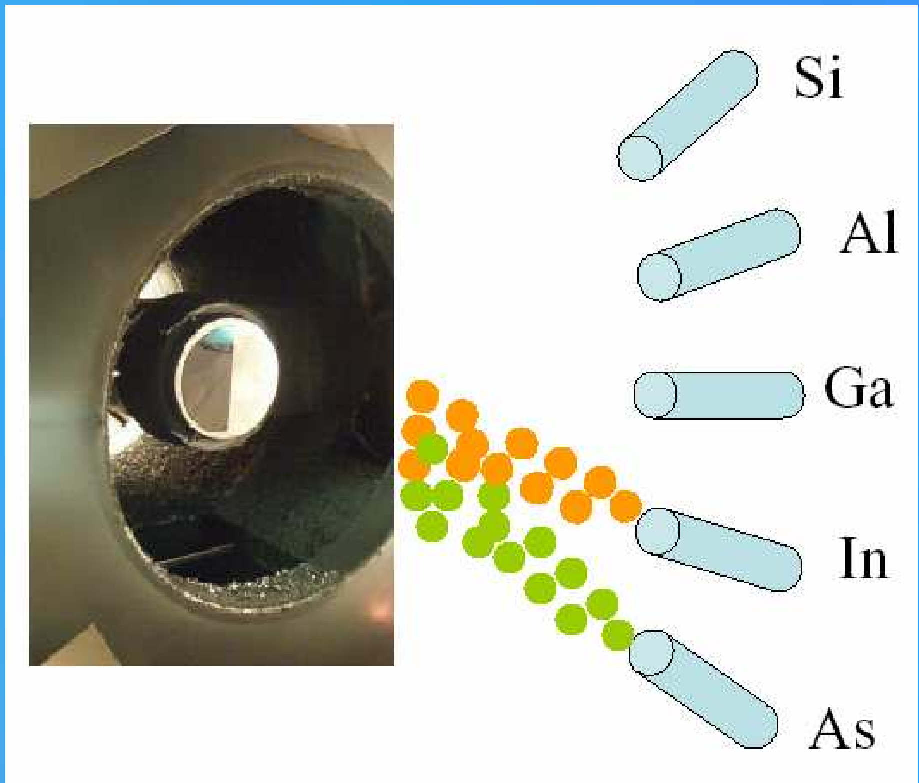
Epitaxial QDs

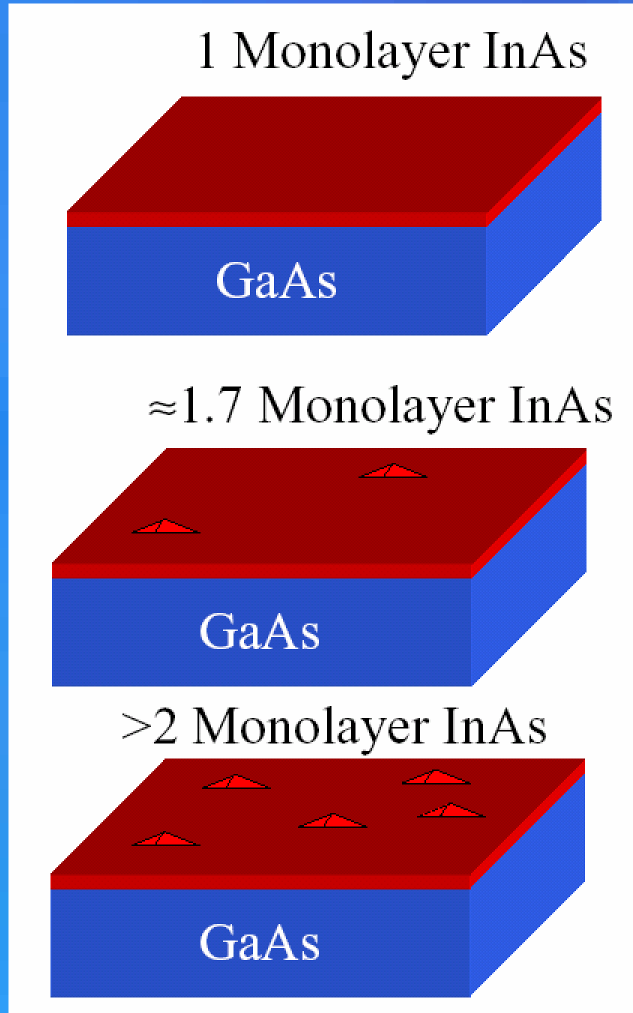


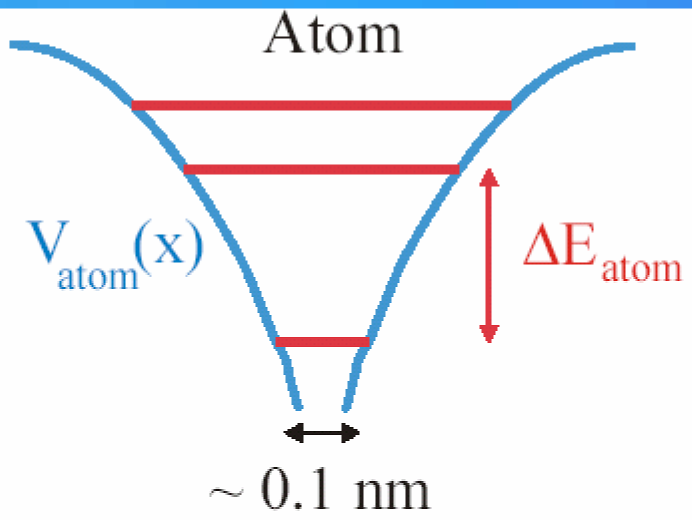
Molecular Beam Epitaxy (MBE) grown quantum dots (Petroff)

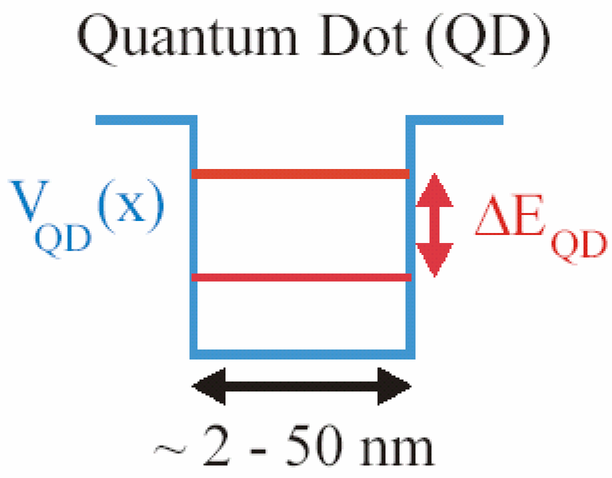


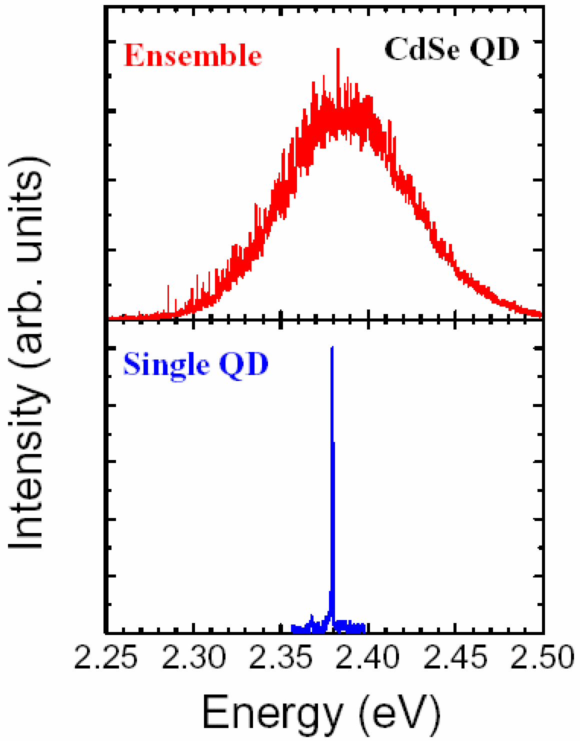


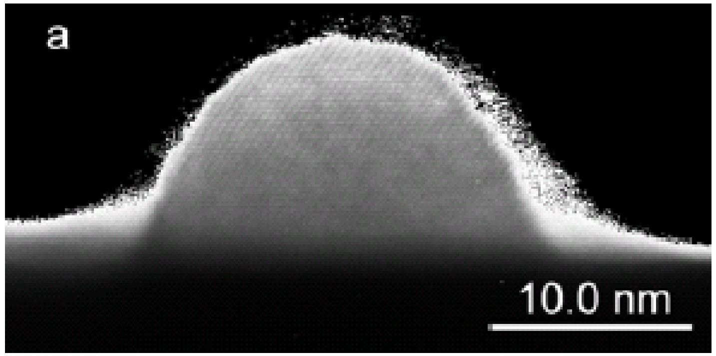

Si
Al
Ga
In
As


1 Monolayer InAs
GaAs
≈1.7 Monolayer InAs
GaAs
>2 Monolayer InAs
GaAs


Atom
$V_{atom}(x)$
ΔE_{atom}
~ 0.1 nm

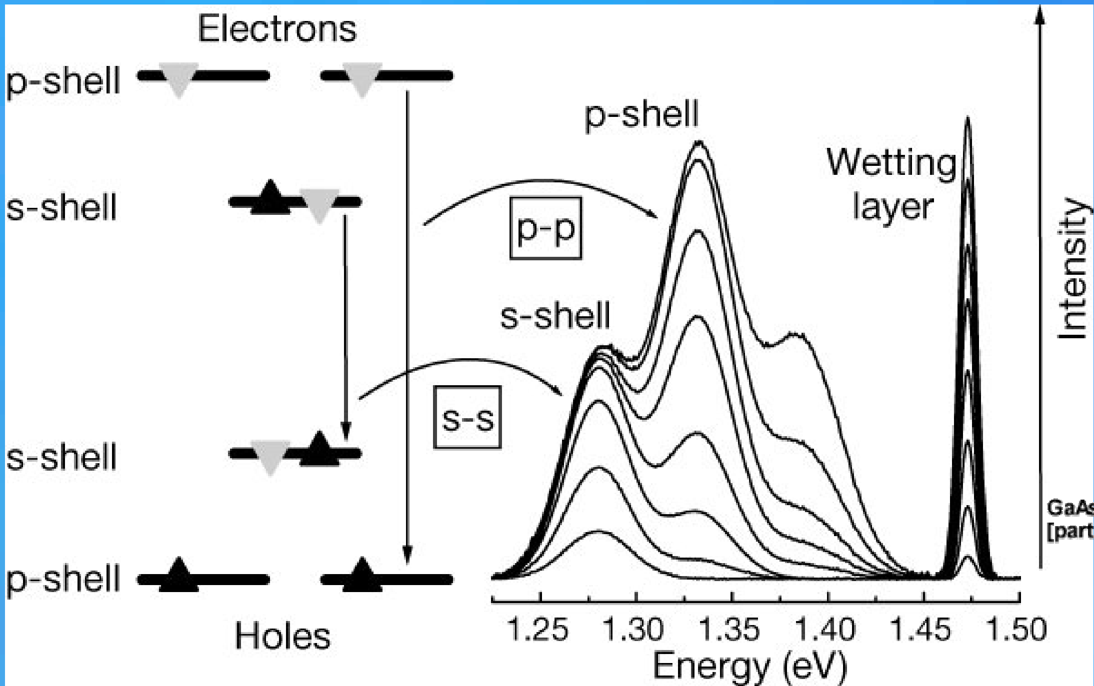

Quantum Dot (QD)
$V_{QD}(x)$
ΔE_{QD}
~ 2 - 50 nm


Ensemble
CdSe QD
Single QD
Intensity (arb. units)
2.25
2.30
2.35
2.40
2.45
2.50
Energy (eV)


a
10.0 nm

Quantum dots – artificial atoms

Ensemble emission

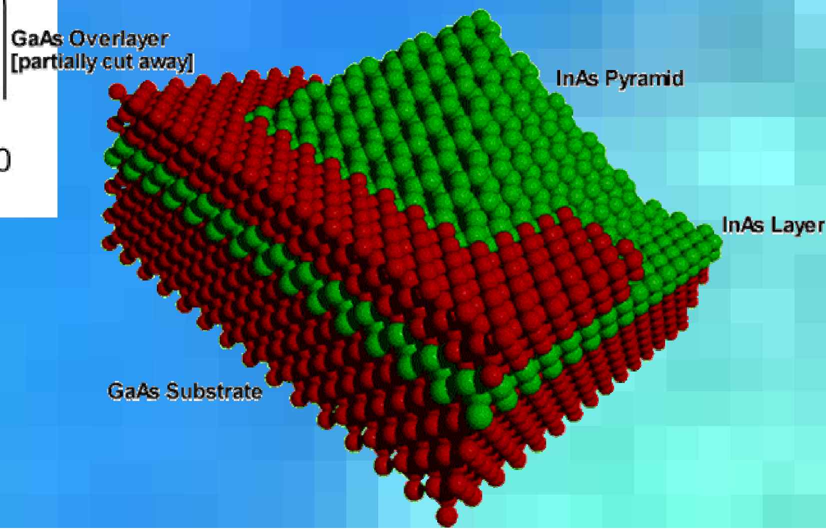


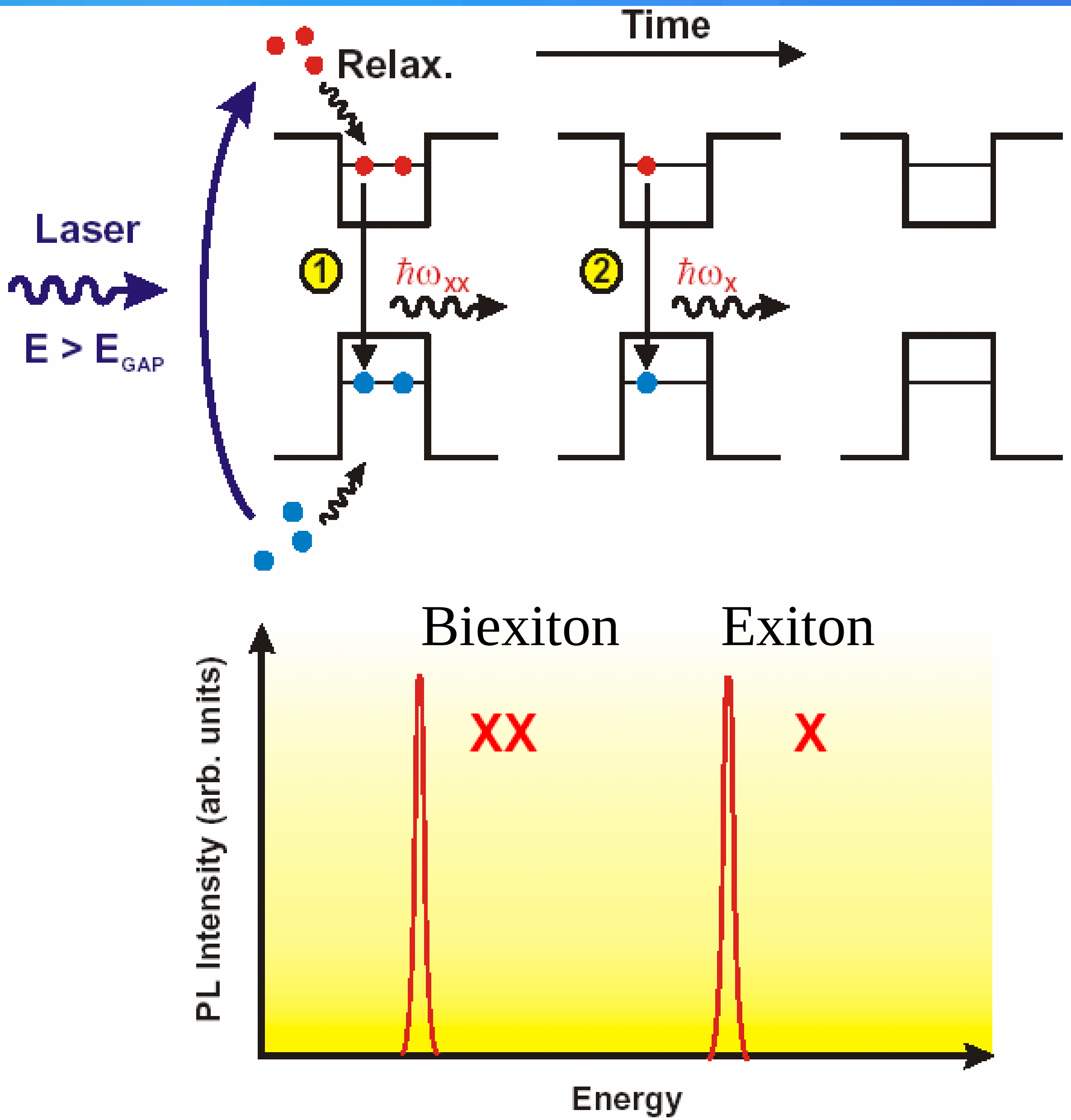
M. Bayer et al. Nature **405**, 923 (2000)

R. Warburton et al. Nature **405**, 927 (2000)

K. Karrai et al. Nature **427**, 135 (2004)

Epitaxial QDs





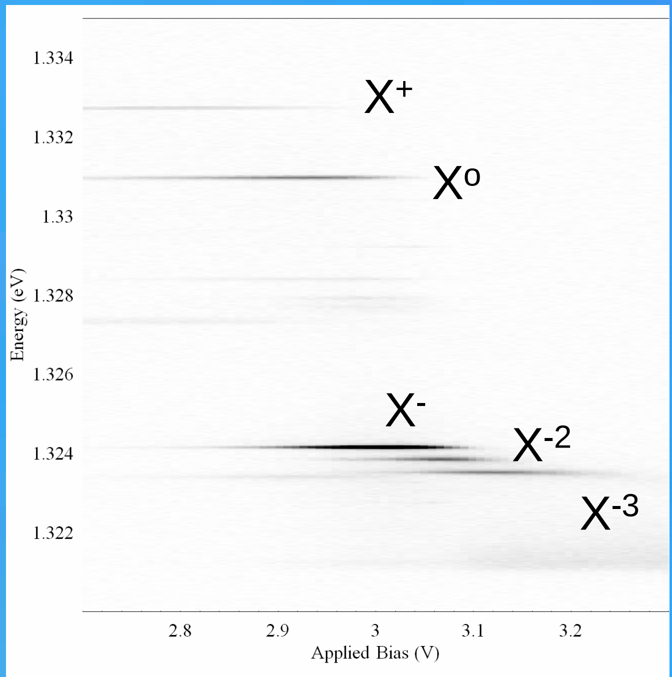
due to Coulomb interaction:

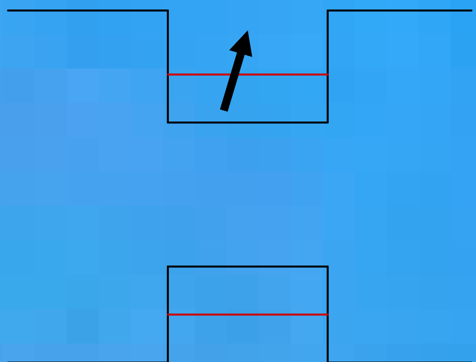
$$\hbar\omega_{XX} \neq \hbar\omega_{X}$$

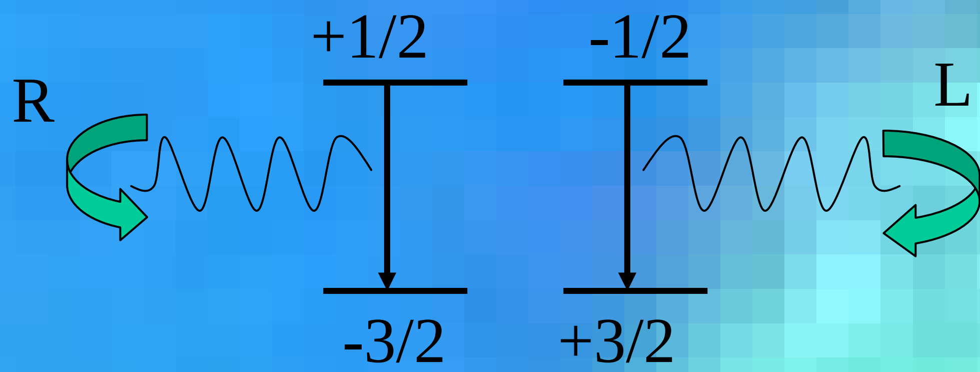
Self-assembled GaAs/InGaAs QUANTUM DOTS

add extra electron to QD

Spin of extra electron is qubit (0.1ms?)
coupled to excitons (gates ns)







Hybrid QP schemes

$$\langle \Phi | \Psi \rangle_{12} = \alpha |\uparrow\uparrow\rangle + \beta |\uparrow\downarrow\rangle + \gamma |\downarrow\uparrow\rangle - \delta |\downarrow\downarrow\rangle$$

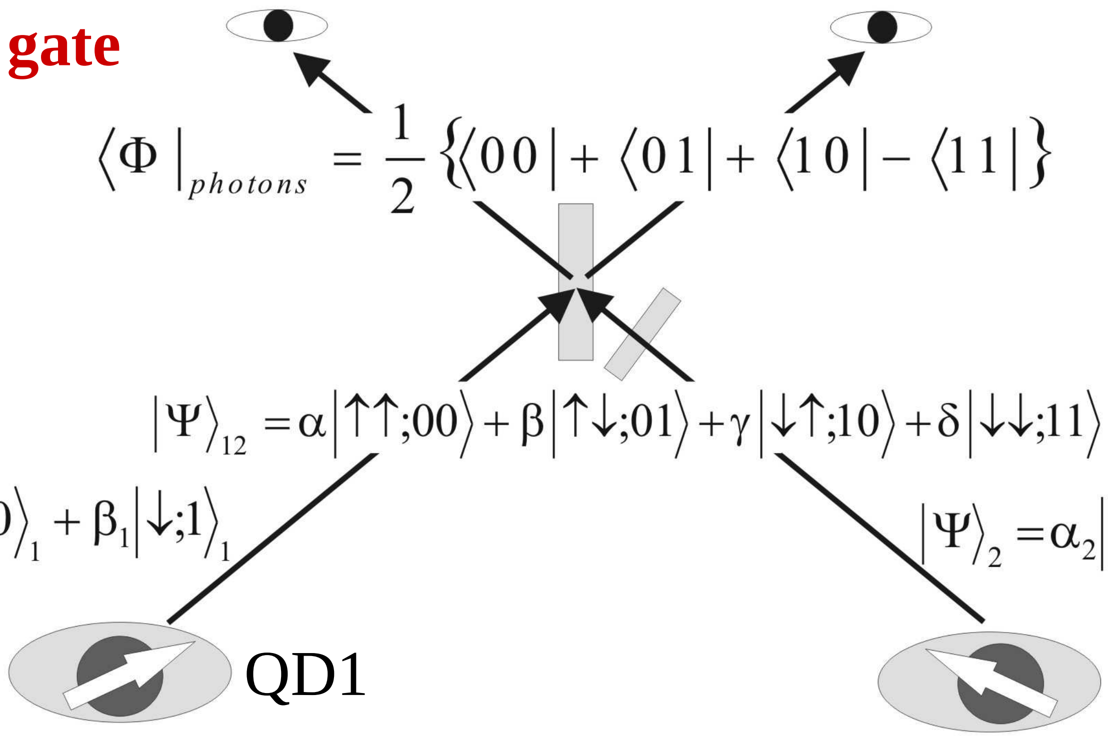
2 qubit gate

$$\langle \Phi |_{photons} = \frac{1}{2} \{ \langle 00| + \langle 01| + \langle 10| - \langle 11| \}$$

$$|\Psi\rangle_{12} = \alpha |\uparrow\uparrow;00\rangle + \beta |\uparrow\downarrow;01\rangle + \gamma |\downarrow\uparrow;10\rangle + \delta |\downarrow\downarrow;11\rangle$$

$$|\Psi\rangle_1 = \alpha_1 |\uparrow;0\rangle_1 + \beta_1 |\downarrow;1\rangle_1$$

$$|\Psi\rangle_2 = \alpha_2 |\uparrow;0\rangle_2 + \beta_2 |\downarrow;1\rangle_2$$



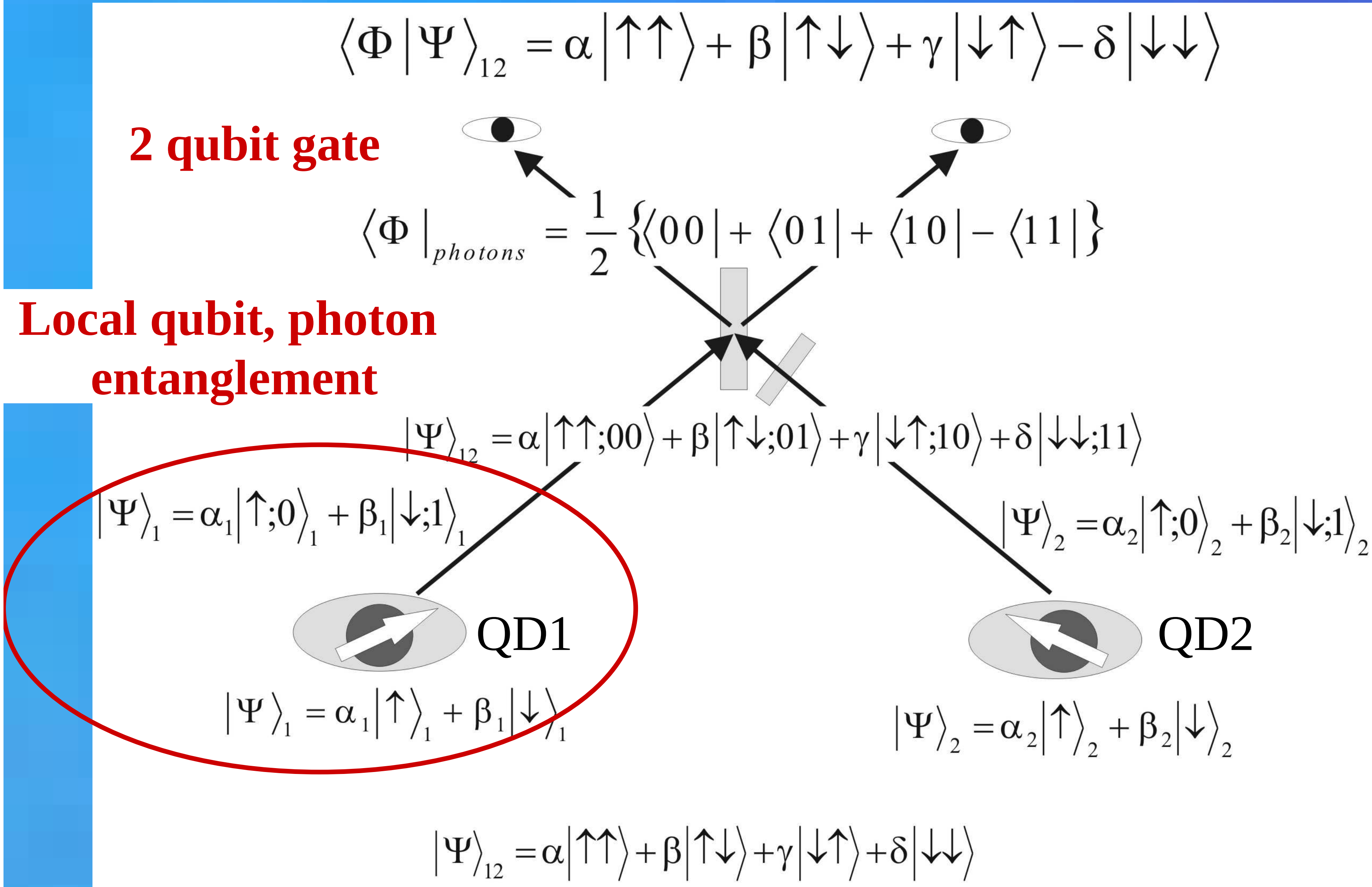
$$|\Psi\rangle_1 = \alpha_1 |\uparrow\rangle_1 + \beta_1 |\downarrow\rangle_1$$

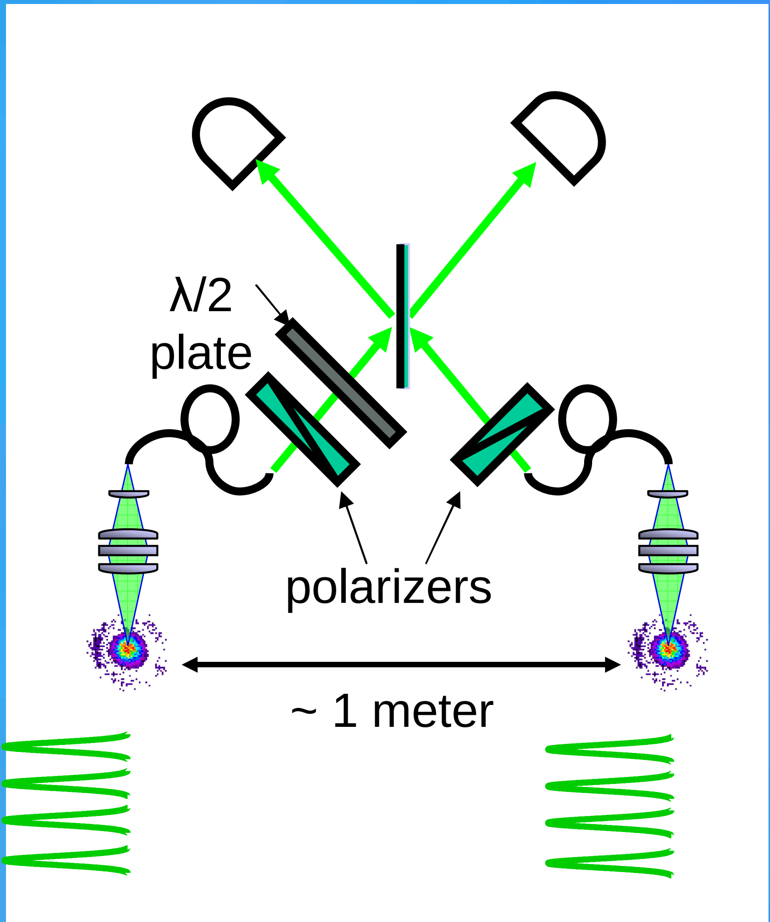
$$|\Psi\rangle_2 = \alpha_2 |\uparrow\rangle_2 + \beta_2 |\downarrow\rangle_2$$

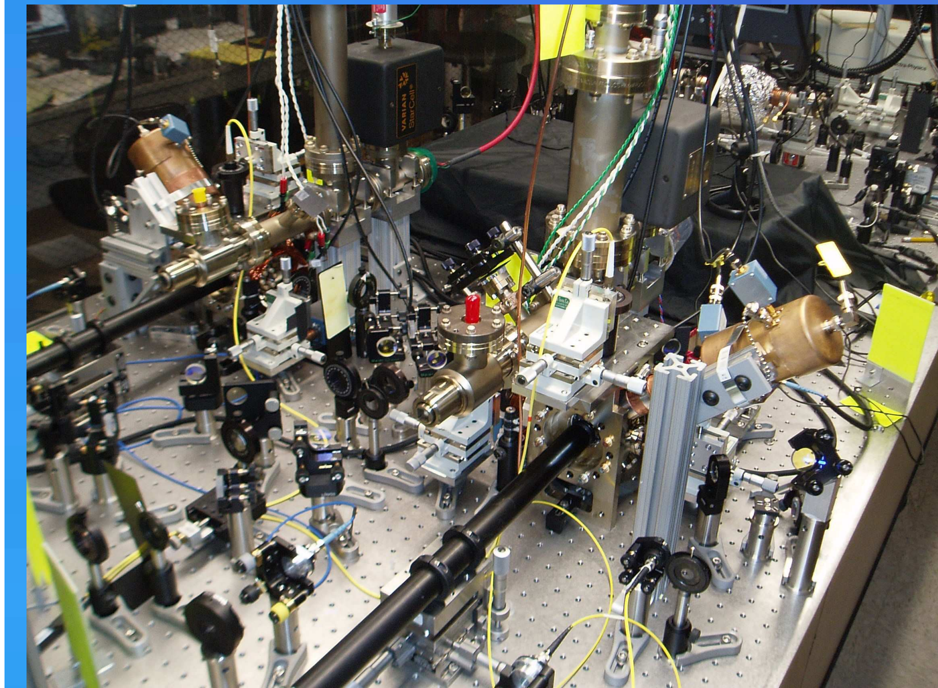
$$|\Psi\rangle_{12} = \alpha |\uparrow\uparrow\rangle + \beta |\uparrow\downarrow\rangle + \gamma |\downarrow\uparrow\rangle + \delta |\downarrow\downarrow\rangle$$

Linear optics distributed quantum computation, PRL **95**, 030505

Hybrid QP schemes







Fidelities good (~0.8)

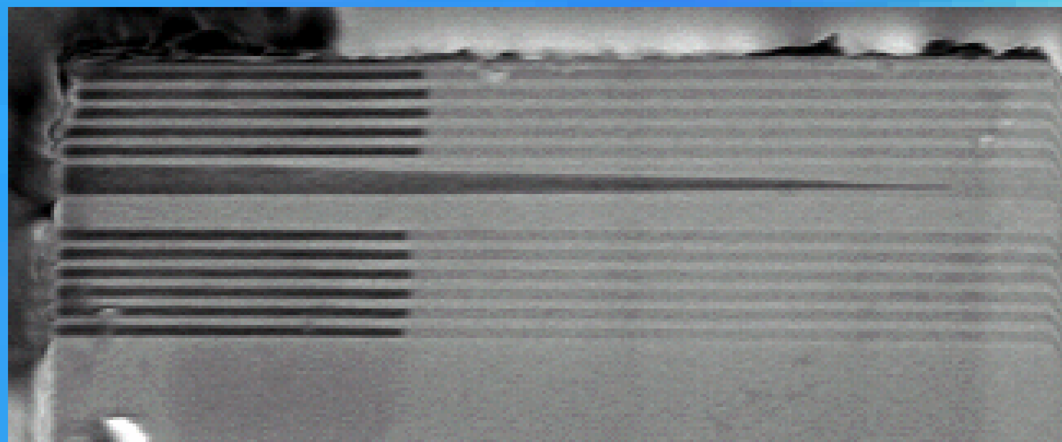
Probability of success 10^{-8}

Nature **449**, 68 (2007); PRL **100**, 150404 (2008) **Monroe group**

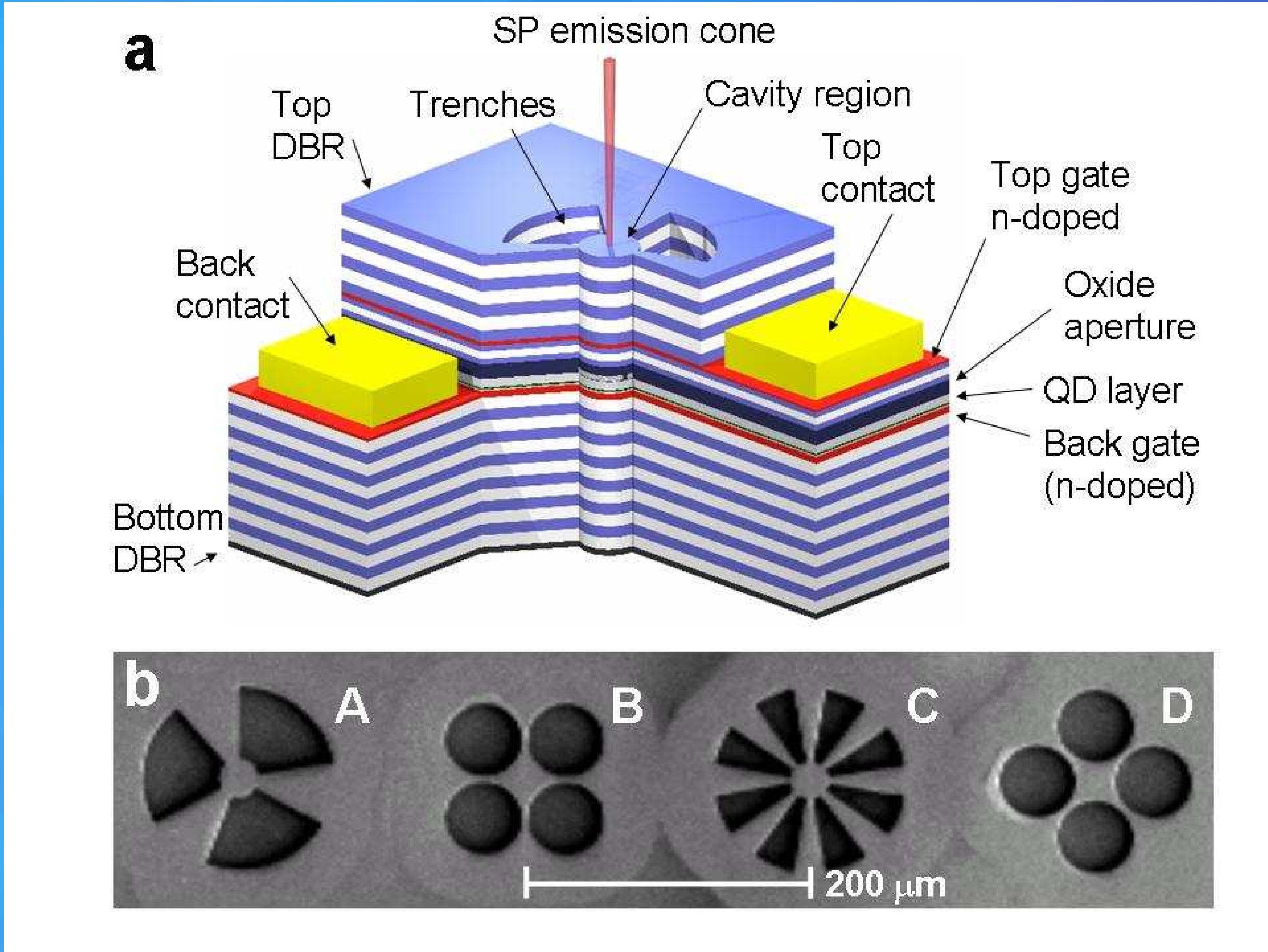
Electron spins coupled to photons using micropillars

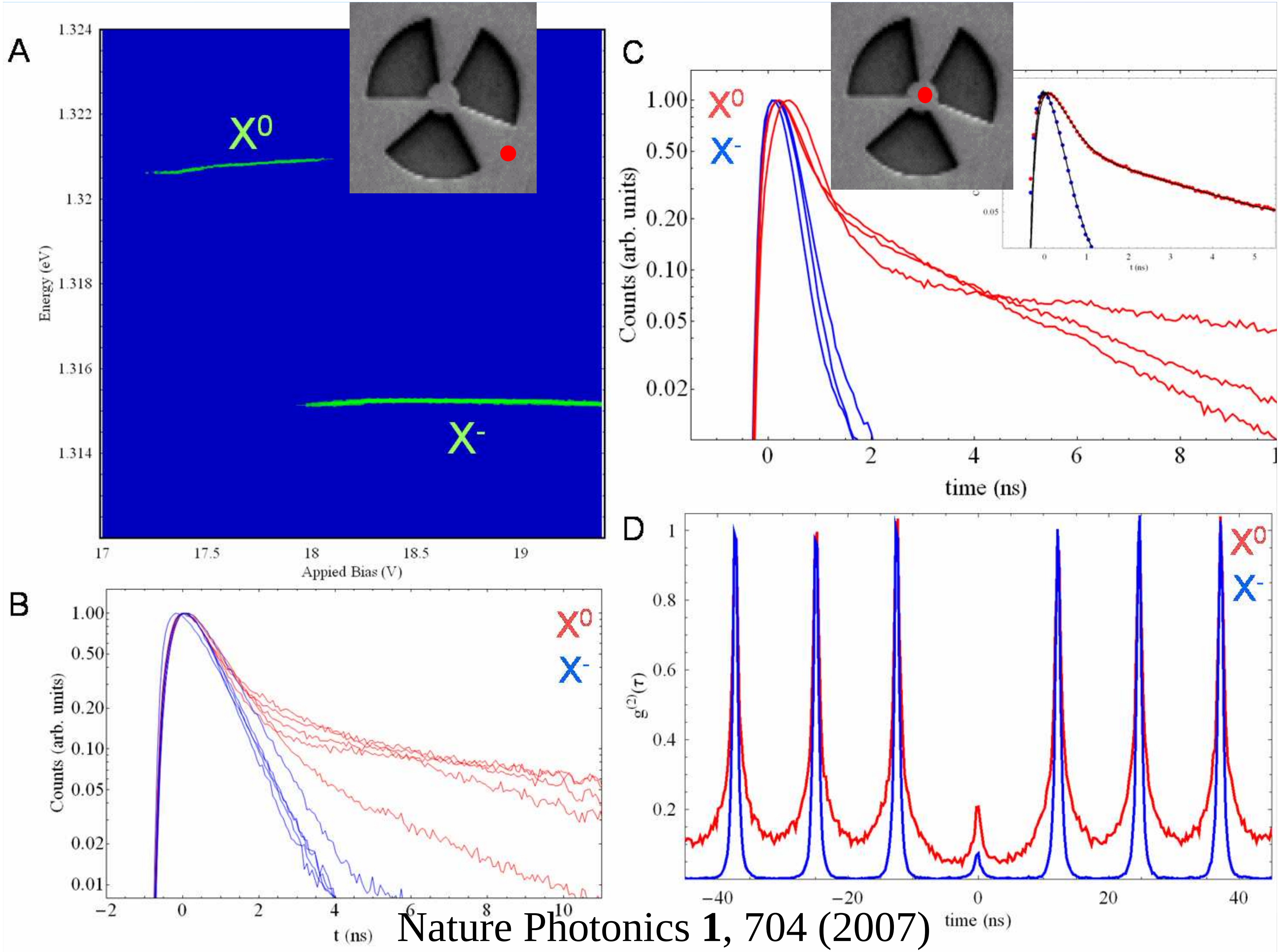
Oxide apertured micropillars

M. Pelton et al.,
PRL 2002



N. G. Stoltz, et al.,
Appl. Phys. Lett. **87**,
031105 (2005)

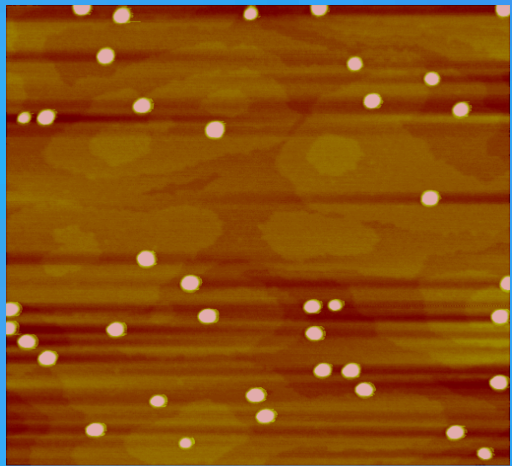

a
SP emission cone
Top DBR
Trenches
Cavity region
Top contact
Top gate n-doped
Back contact
Oxide aperture
QD layer
Back gate (n-doped)
Bottom DBR
b
A
B
C
D
200 μm



Nature Photonics **1**, 704 (2007)

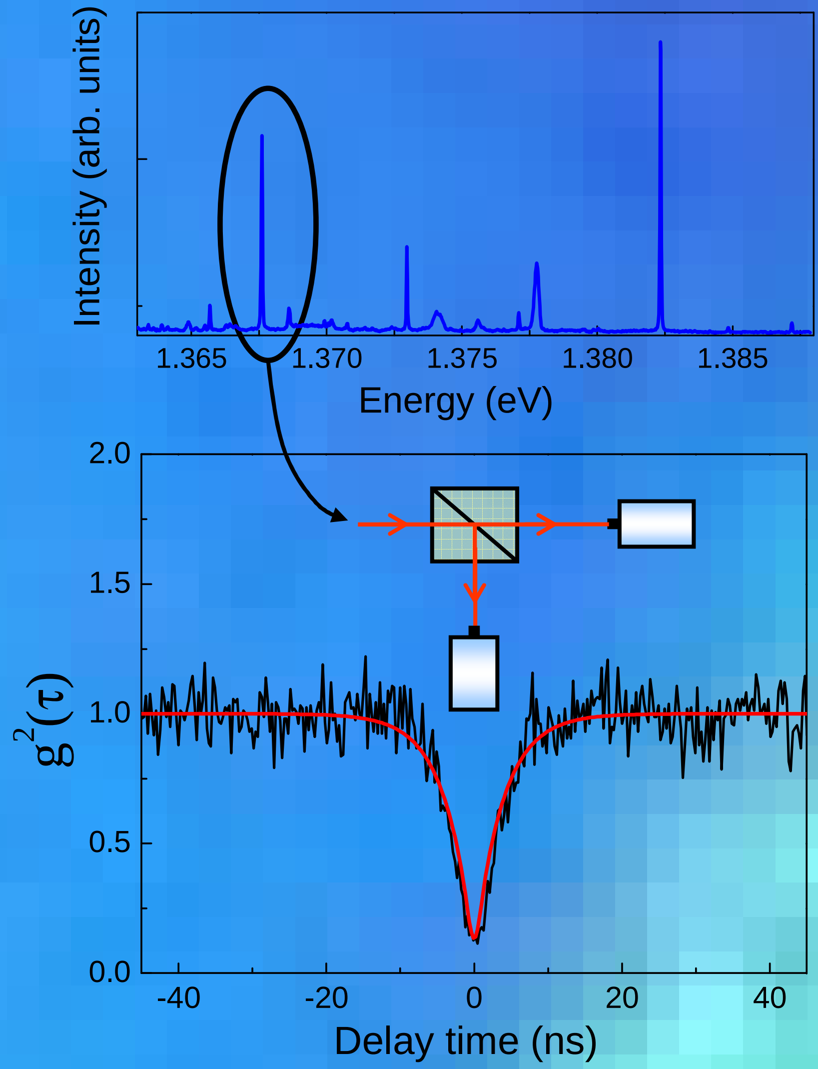
Individual quantum dots

InAs quantum dots
embedded in **GaAs** matrix

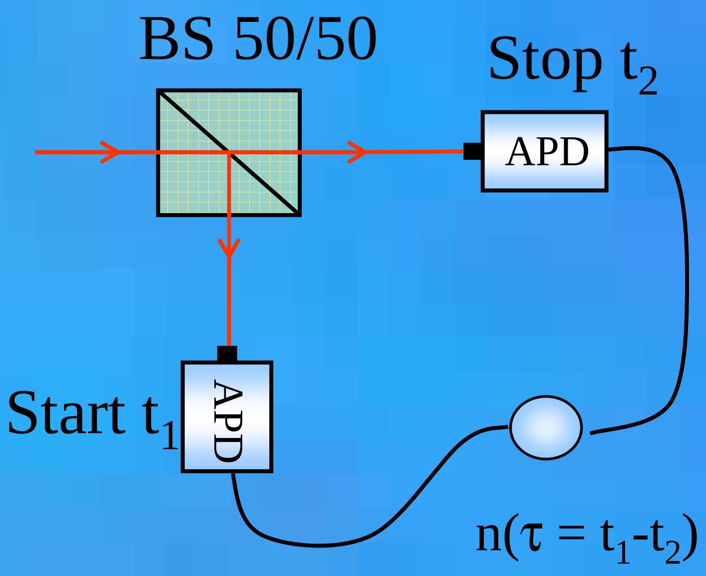


1μm x 1μm AFM

- Dot size: 10-20 nm
- Emission: 900-950 nm
- Density gradient



Photon antibunching



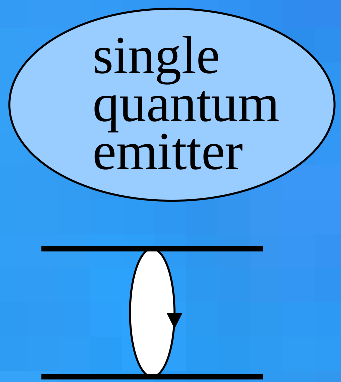
chaotic light
(laser below threshold):
$g^{(2)}(\tau) = 2$

classical light (laser):

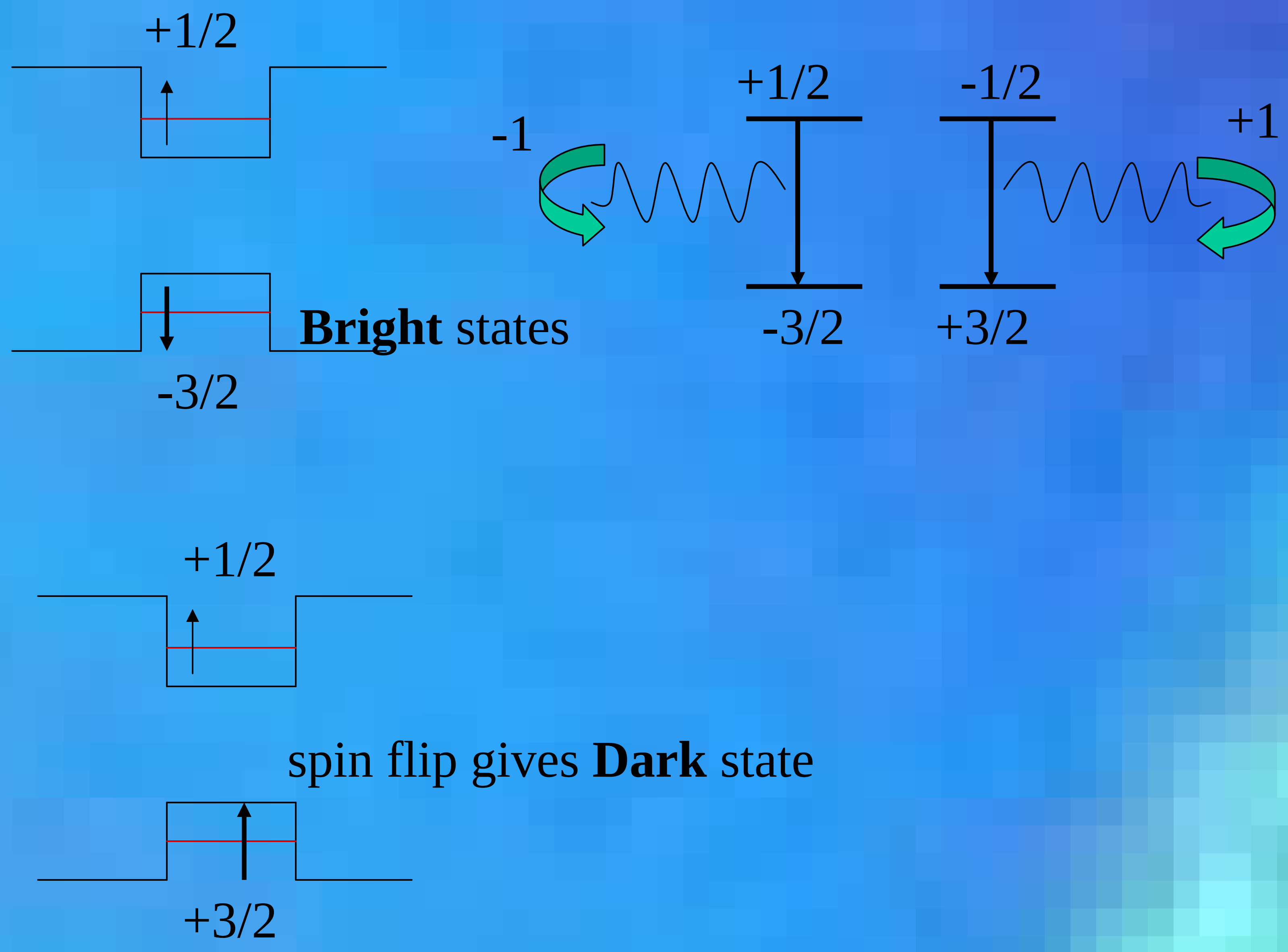
$g^{(2)}(\tau) = 1$

photon correlation function

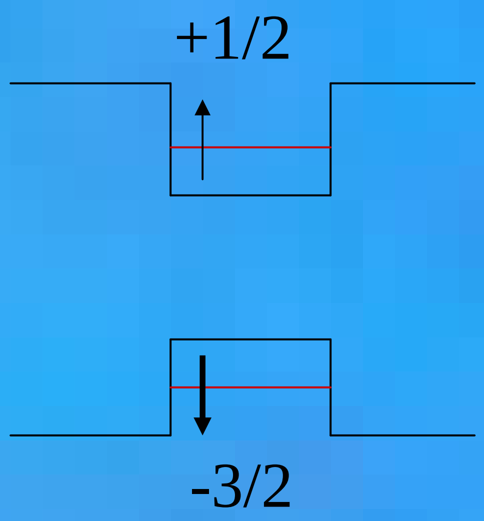
$$g^{(2)}(\tau) = \frac{\langle I(t)\, I(t+\tau)\rangle}{\langle I(t)^2 \rangle}$$

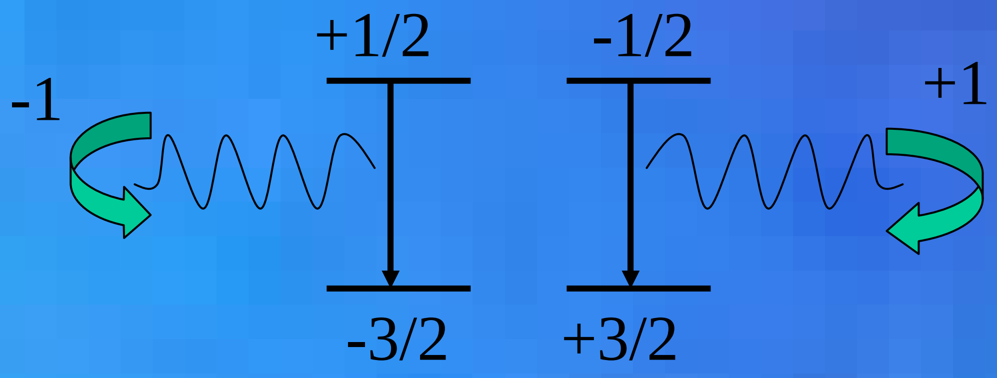


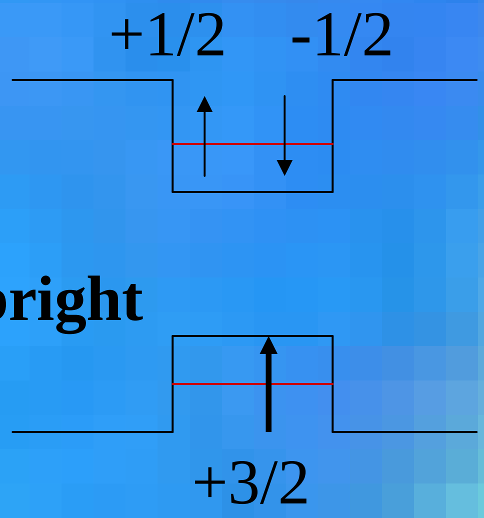
nonclassical light
(photon antibunching):
$g^{(2)}(\tau=0) = 0$



+1/2
-3/2
Bright states
+1/2
-1/2
-1
+1
-3/2
+3/2
+1/2
spin flip gives Dark state
+3/2

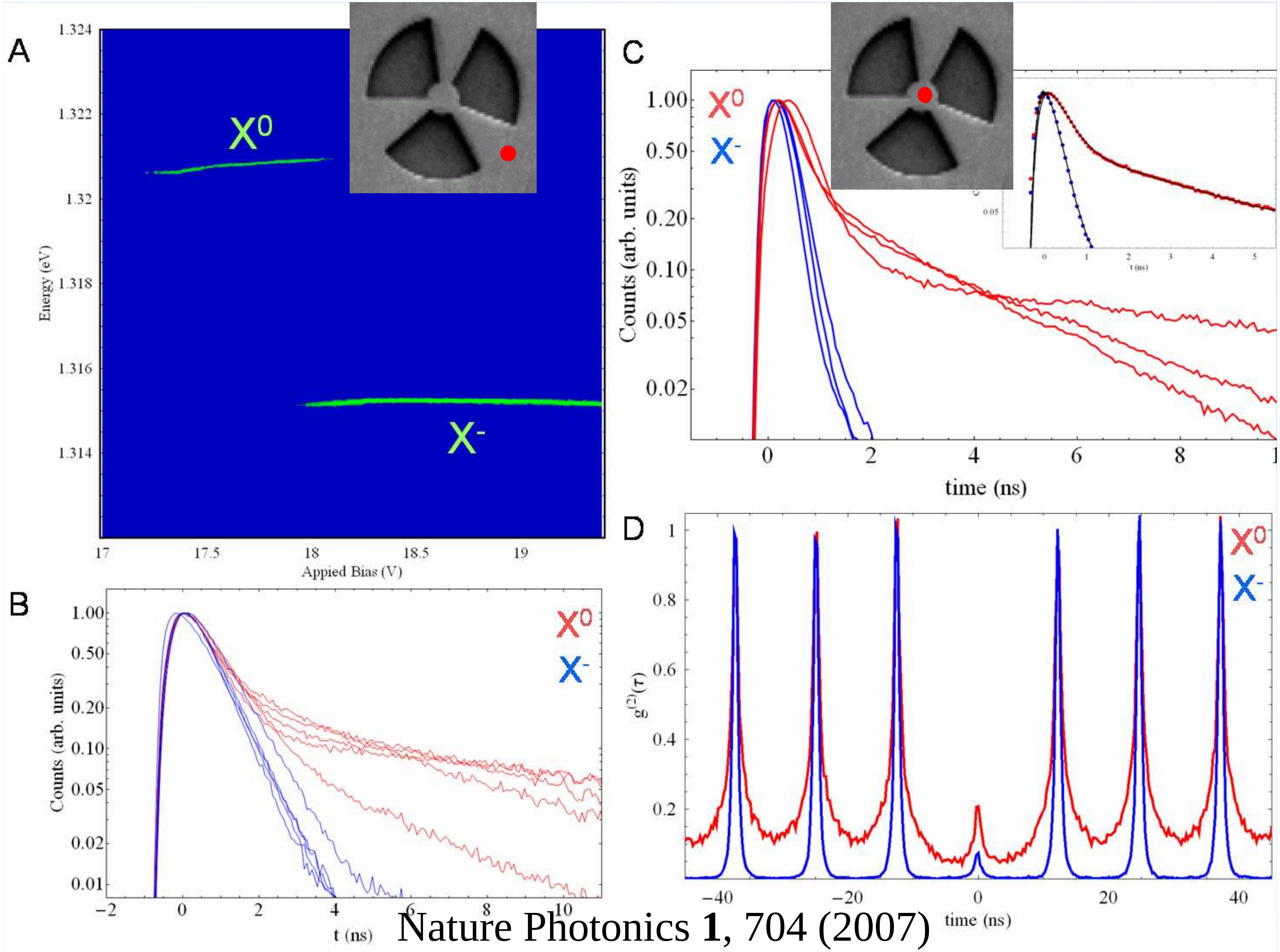






Add single electron

Trion state, always **bright**



Nature Photonics **1**, 704 (2007)

Jaynes-Cummings Hamiltonian

$$\mathcal{H} = \frac{1}{2}\hbar\omega_a\sigma_z + \hbar\omega_c a^\dagger a + \hbar g\left(\sigma_+ a + \sigma_- a^\dagger\right)$$

$$\hbar\omega_a = E_a - E_b \qquad \hbar g = \left|\langle\vec{\wp}\cdot\vec{E}\rangle\right|$$

$$\sigma_z = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}, \quad \sigma_+ = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}, \quad \sigma_- = \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix}$$

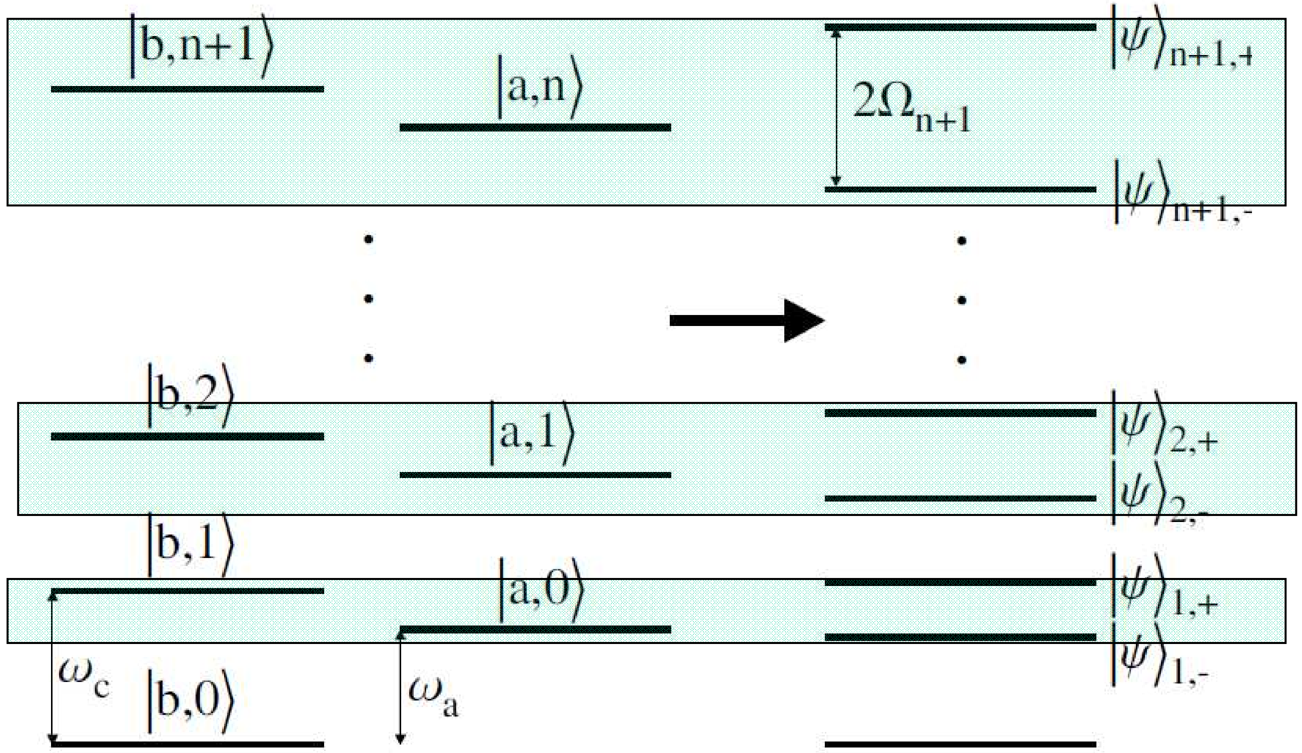
$$|E_{max}| = \sqrt{\frac{\hbar\omega_c}{2n_{eff}^2\epsilon_o V_{eff}}}.$$

$$g \sim 1/\sqrt{V_{eff}}$$

$$V_{eff} = \frac{1}{Max[n^2(\vec{r})|\vec{E}(\vec{r})|^2]}\int d^3\vec{r}\, n^2(\vec{r})|\vec{E}(\vec{r})|^2$$

$$\mathcal{H} = \frac{1}{2}\hbar\omega_a\sigma_z + \hbar\omega_c a^\dagger a + \hbar g\left(\sigma_+ a + \sigma_- a^\dagger\right)$$

Dressed states



$$|\,\psi\rangle_{n+1,\pm} = \frac{1}{\sqrt{2}}\left\{\,|\,a,n\rangle \pm |\,b,n+1\rangle\,\right\}$$

for, $\Delta = \omega_c - \omega_a = 0$

$$E_{n+1,\pm} = (n+\tfrac{1}{2})\hbar\omega_c \pm \hbar g\sqrt{n+1}$$

Now include losses

$$\dot{O} = \frac{\imath}{\hbar}[\mathcal{H}, O] + \mathcal{L}(O)$$

$$\dot{a} = -\imath\omega_c a - \imath g \sigma_- - \kappa a$$

$$\dot{\sigma}_- = -\imath\omega_a \sigma_- + \imath g a \sigma_z + \gamma \sigma_z \sigma_-$$

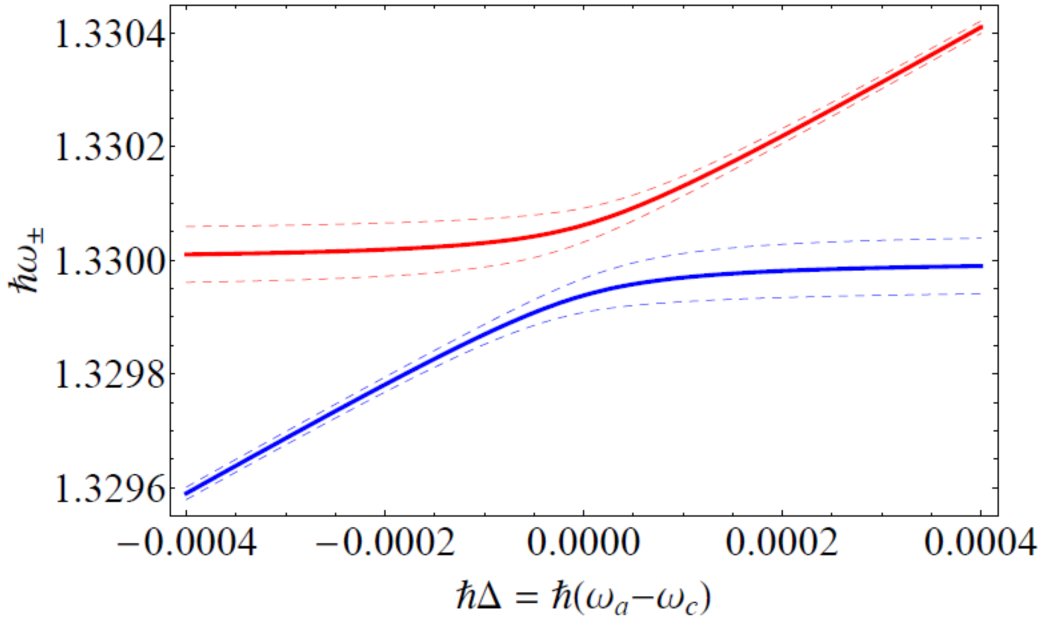
$$\dot{a}^\dagger = \imath\omega_c a^\dagger + \imath g \sigma_+ - \kappa a^\dagger$$

$$\dot{\sigma}_+ = \imath\omega_a \sigma_+ - \imath g a^\dagger \sigma_z + \gamma \sigma_z \sigma_+$$

$Q = \omega_c / 2\kappa$, with κ the electric field amplitude loss rate, γ is dipole decay rate

Strong coupling ($g >> \kappa, \gamma$)

$$\Delta E = 2\hbar \sqrt{g^2 - \frac{1}{4}(\kappa - \gamma)^2}$$



Now include losses

$$\dot{O} = \frac{\imath}{\hbar}[\mathcal{H}, O] + \mathcal{L}(O)$$

$$\dot{a} = -\imath\omega_c a - \imath g\sigma_- - \kappa a$$

$$\dot{\sigma}_- = -\imath\omega_a\sigma_- + \imath g a\sigma_z + \gamma\sigma_z\sigma_-$$

$$\dot{a}^\dagger = \imath\omega_c a^\dagger + \imath g\sigma_+ - \kappa a^\dagger$$

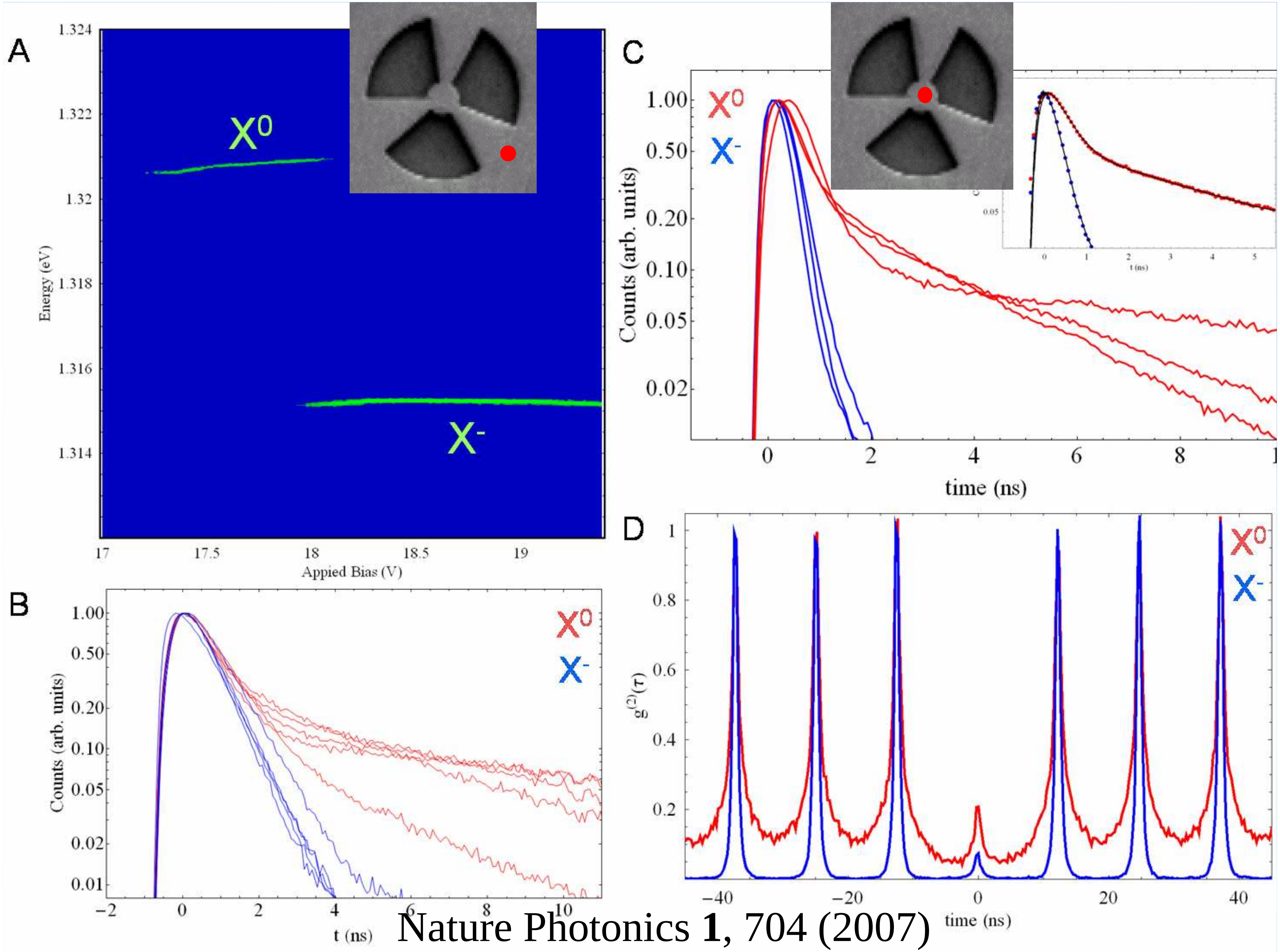
$$\dot{\sigma}_+ = \imath\omega_a\sigma_+ - \imath g a^\dagger\sigma_z + \gamma\sigma_z\sigma_+$$

$Q = \omega_c/2\kappa$, with κ the electric field amplitude loss rate, γ is dipole decay rate

Weak coupling (κ>>g>>γ)

Purcell Factor

$$F_p = \frac{\Gamma_{cav}}{\Gamma_o} = \frac{3}{4\pi^2}\frac{Q}{V_{eff}}\left(\frac{\lambda}{n}\right)^3$$



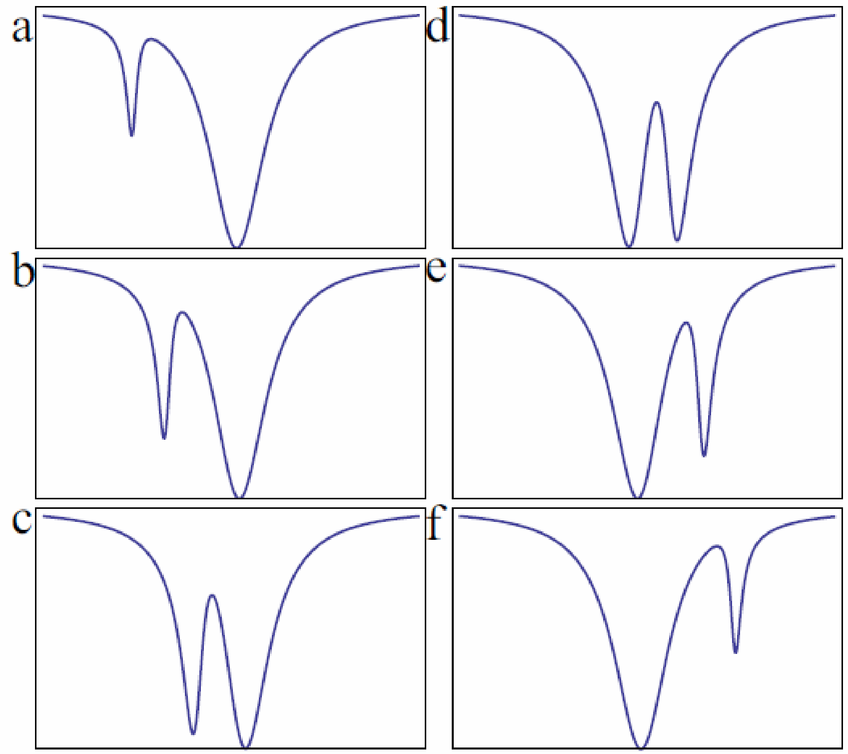
Nature Photonics **1**, 704 (2007)

Interaction with weak probe field: Input-Output formalism

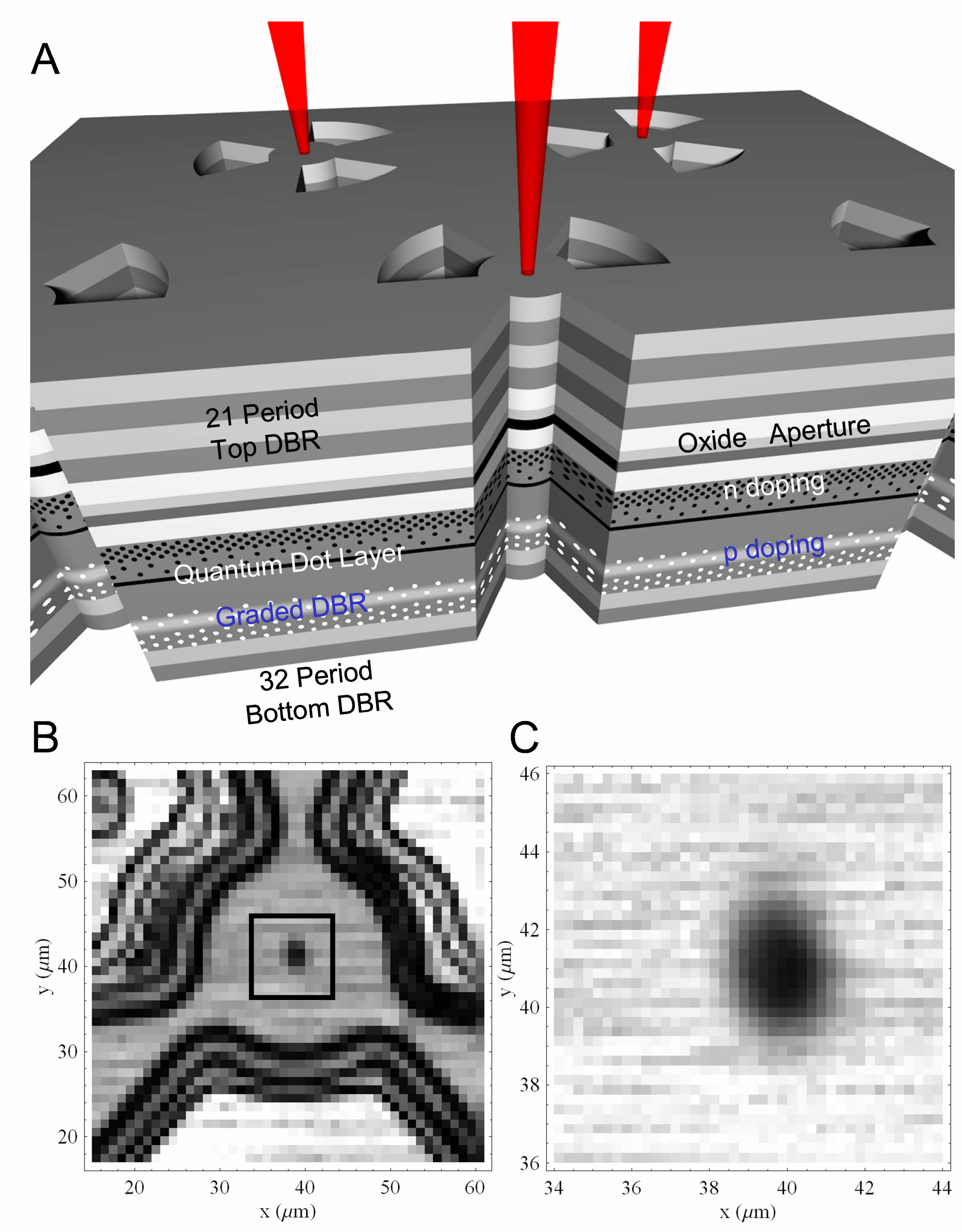
Collett and Gardiner, Physical Review A **31**, 3761 (1985).

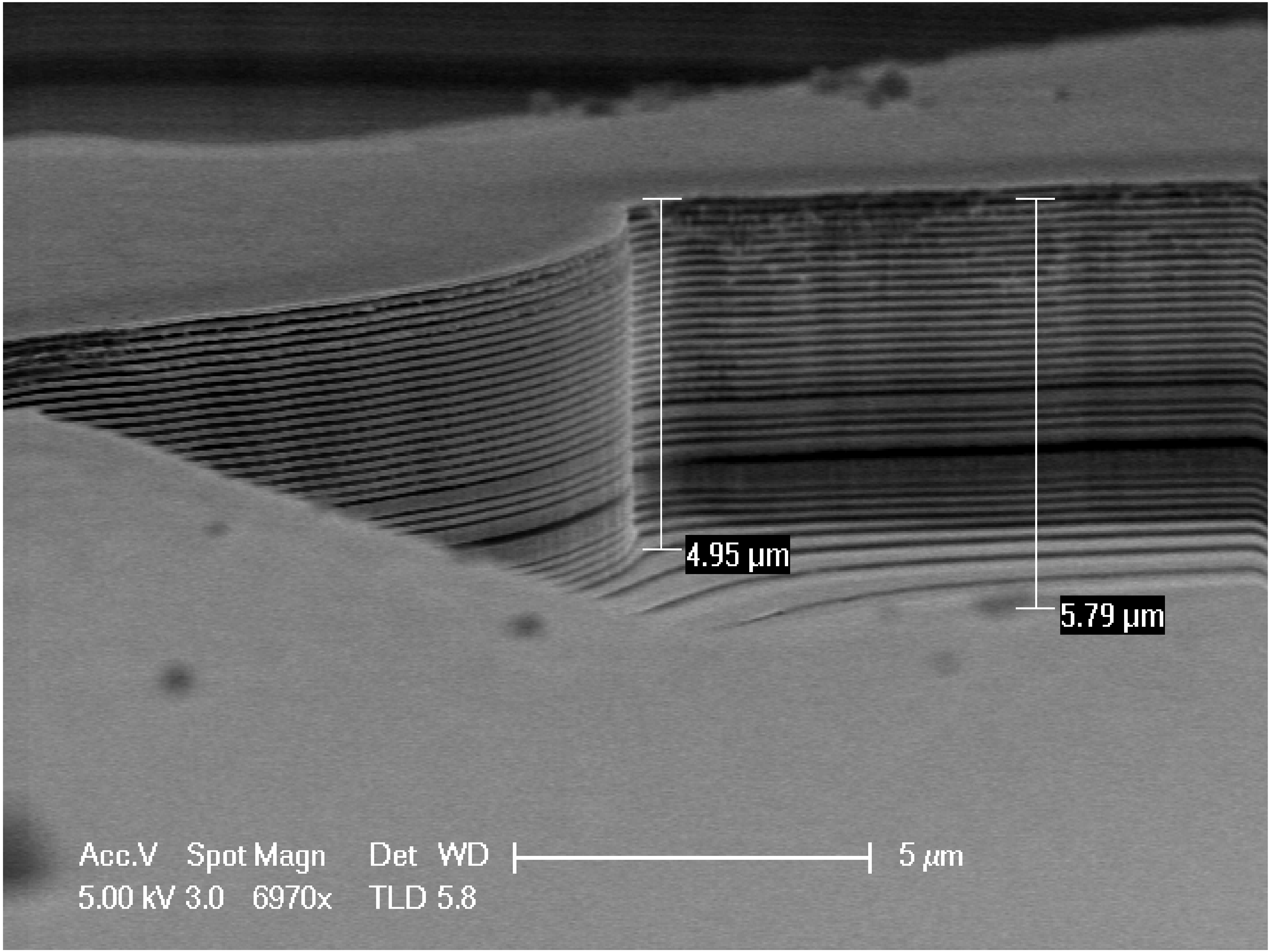
$$\dot{a} = -\imath\omega_c a - \imath g\sigma_- - \kappa a - \sqrt{2\kappa_1}a_{1,in} - \sqrt{2\kappa_2}a_{2,in},$$

$$\dot{\sigma}_- = -\imath\omega_a\sigma_- - \imath g a - \gamma\sigma_- - \sqrt{2\gamma}b_{in},$$

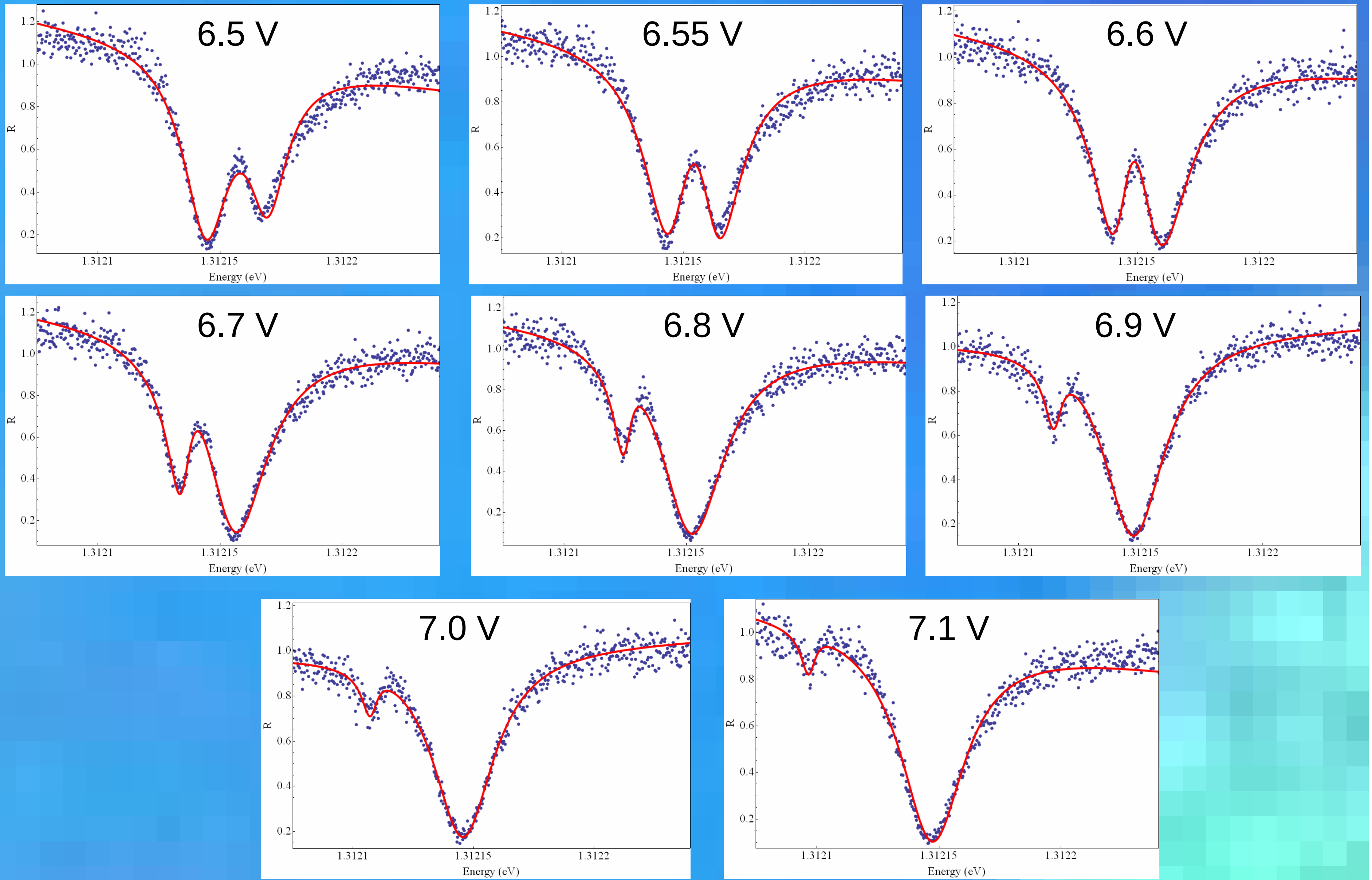


Plots of various detuning of two-level system form cavity resonance

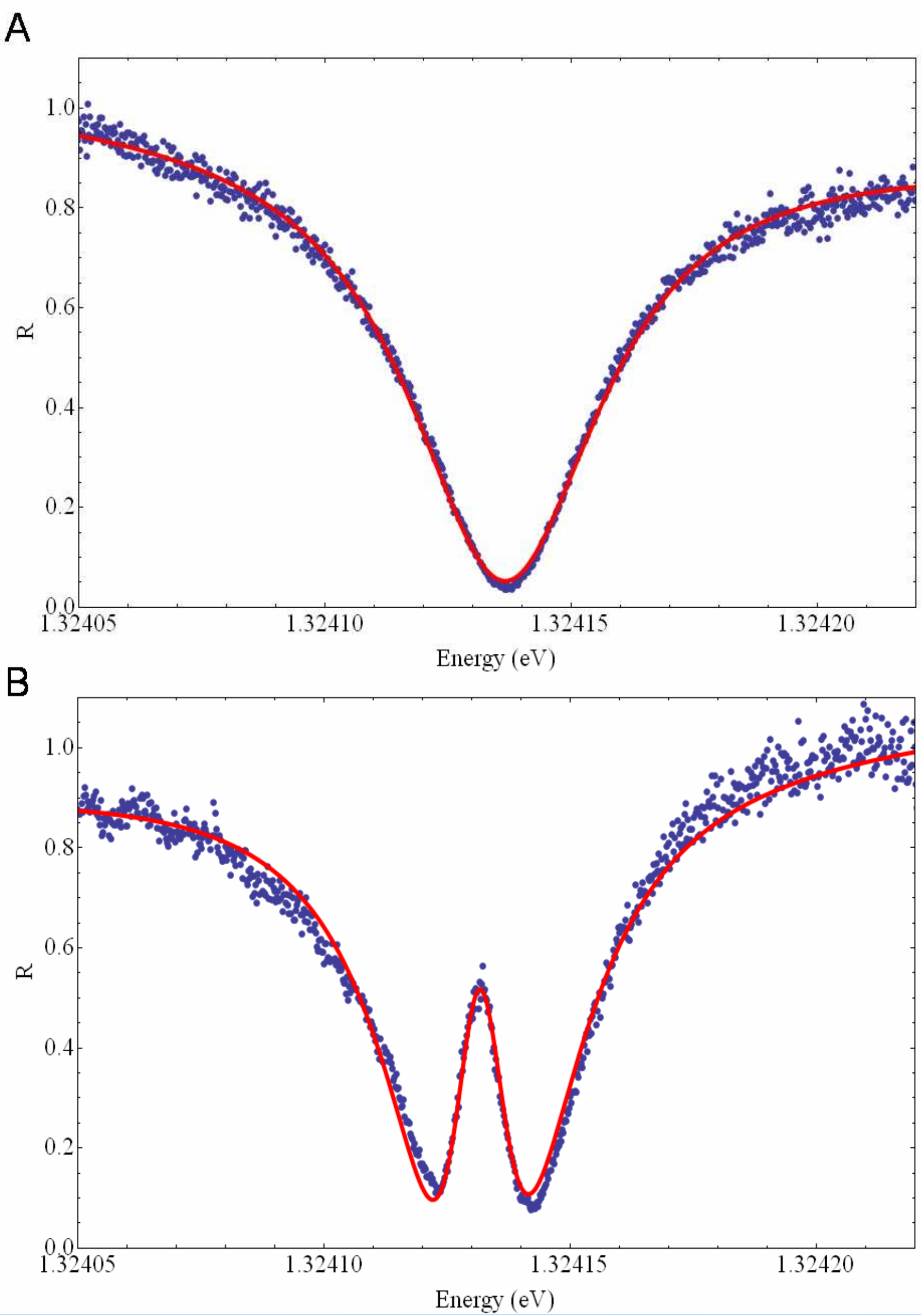

A
21 Period
Top DBR
Oxide Aperture
n doping
p doping
Quantum Dot Layer
Graded DBR
32 Period
Bottom DBR
B
C
y (μm)
x (μm)
y (μm)
x (μm)


4.95 µm
5.79 µm
Acc.V Spot Magn Det WD
5.00 kV 3.0 6970x TLD 5.8
5 µm

Stark shift QD frequency tuning



Reflection Spectroscopy



Jaynes-Cummings model

$$R(\omega) = \left| 1 - \frac{\kappa(\gamma - i(\mu\omega - \omega_{QD}))}{(\gamma - i(\omega - \omega_{QD})\kappa) - i(\omega - \omega_c) + g^2} \right|^2$$

κ is cavity field decay rate:

κ = 24.1μeV, corresponding to Q =27,000,

g is emitter-cavity coupling

g = 9.7μ eV,

γ is emitter decay rate:

γ = 1.9μ eV,

$\frac{g}{\kappa} = 0.40$, deep in Purcell (weak-coupling) regime,

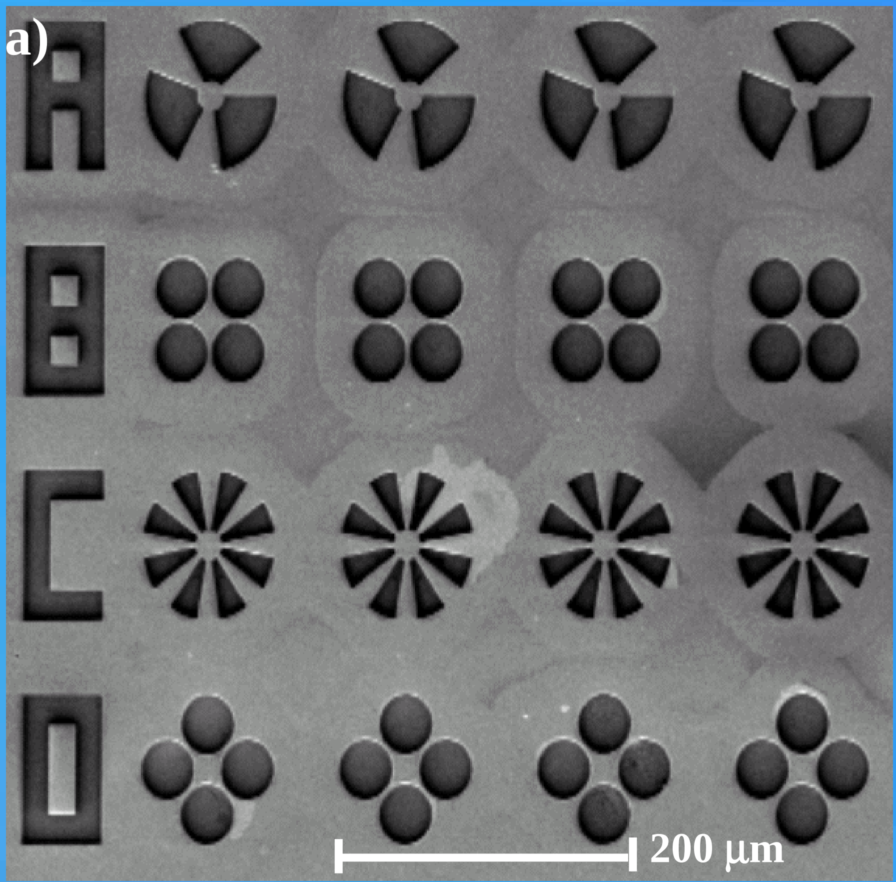
$\frac{g}{\kappa} > 0.5$ is strong coupling

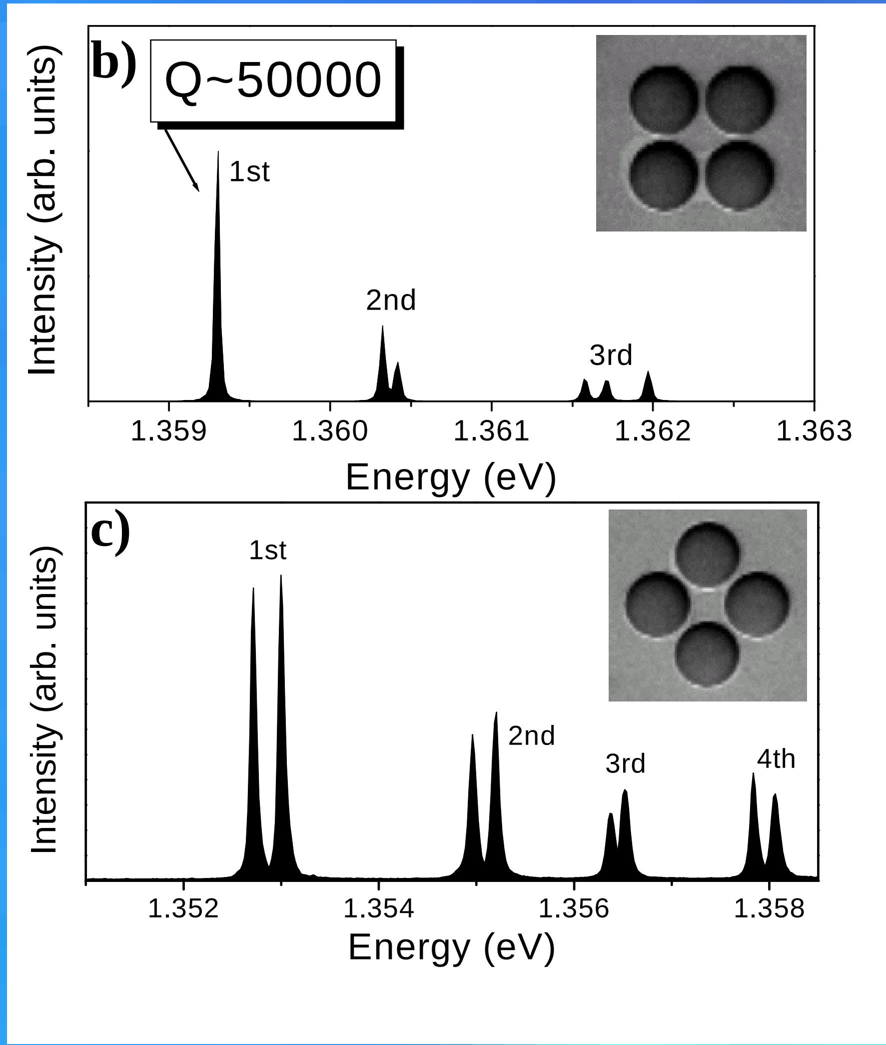
96% mode matched!!!

Ideal for hybrid QIP schemes

PRL Rakher et al. ‘09

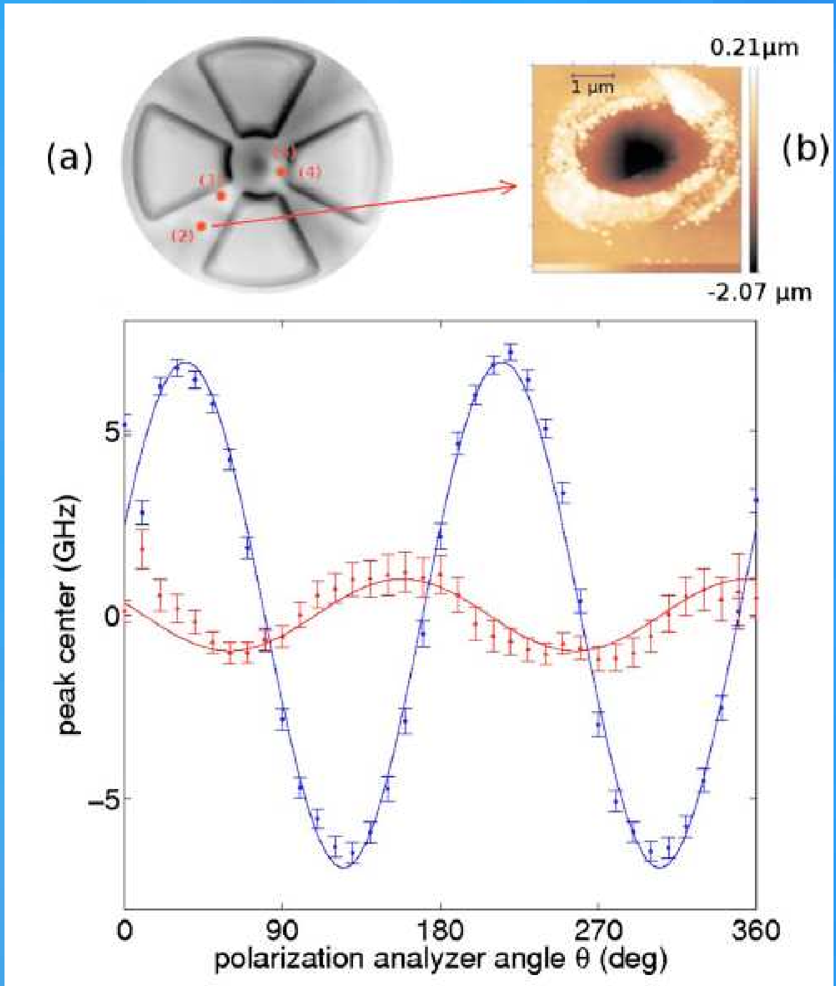
Mode polarization tuning

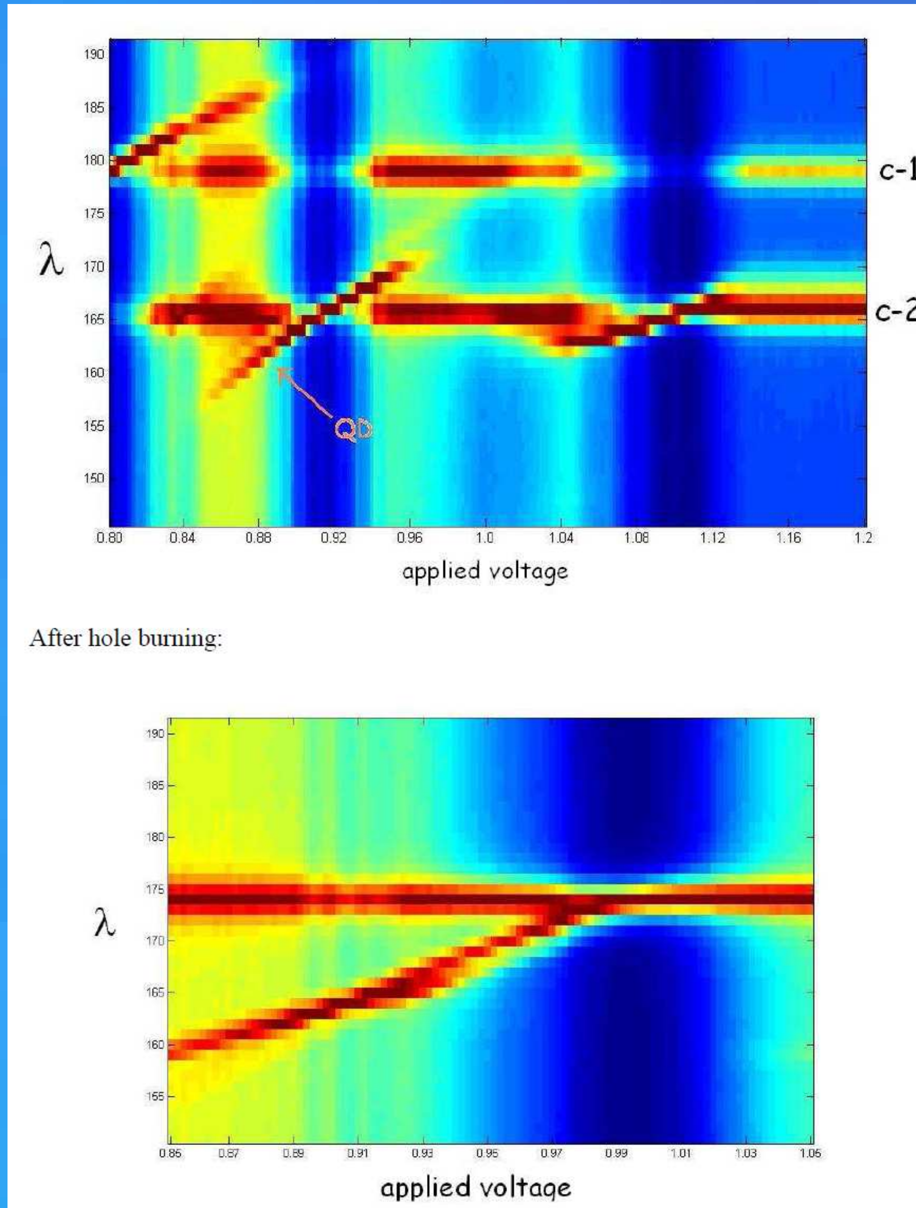




- Fine tuning by hole burning
- Fibre coupling (two sided)

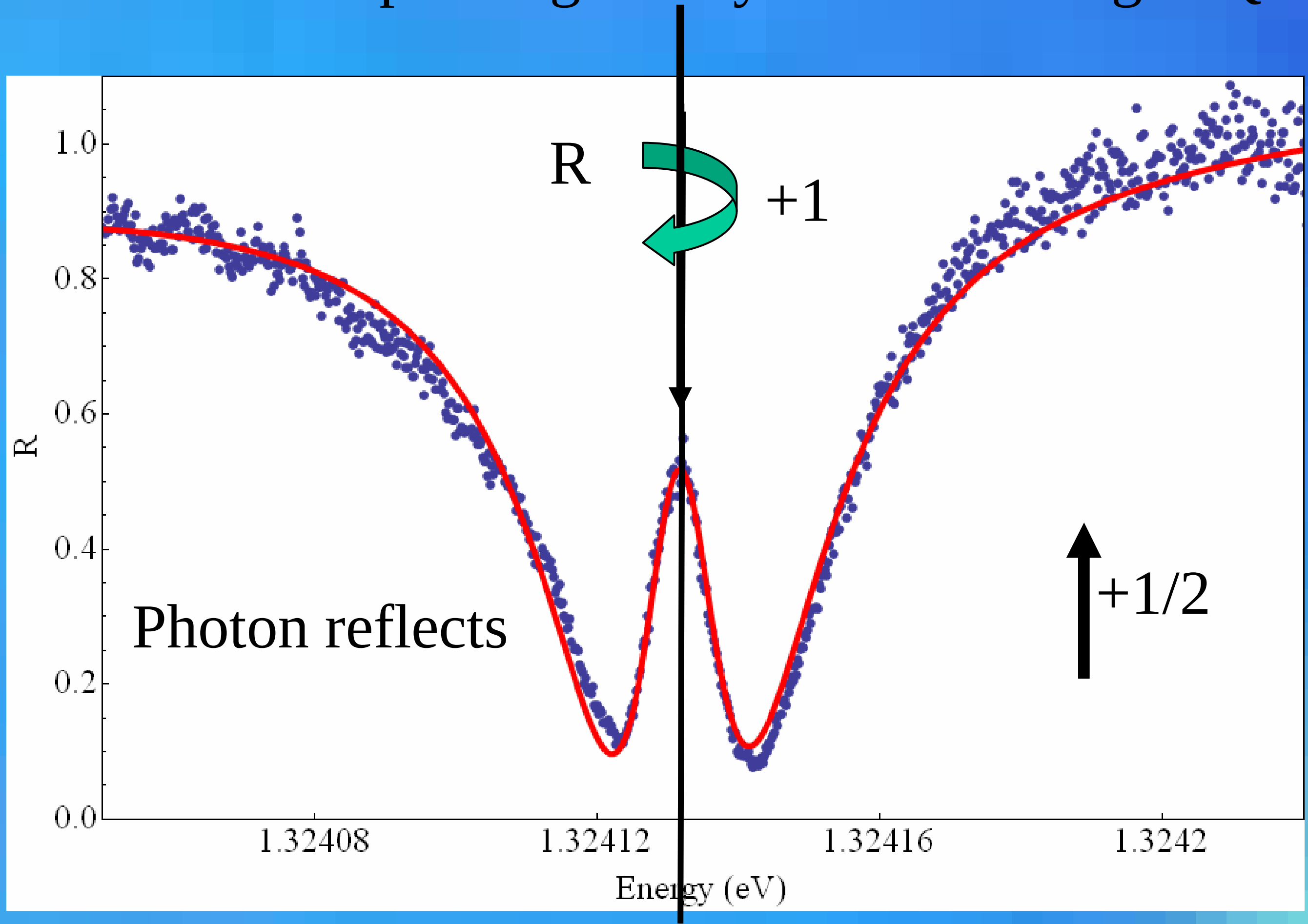
Birefringence fine tuning by hole burning



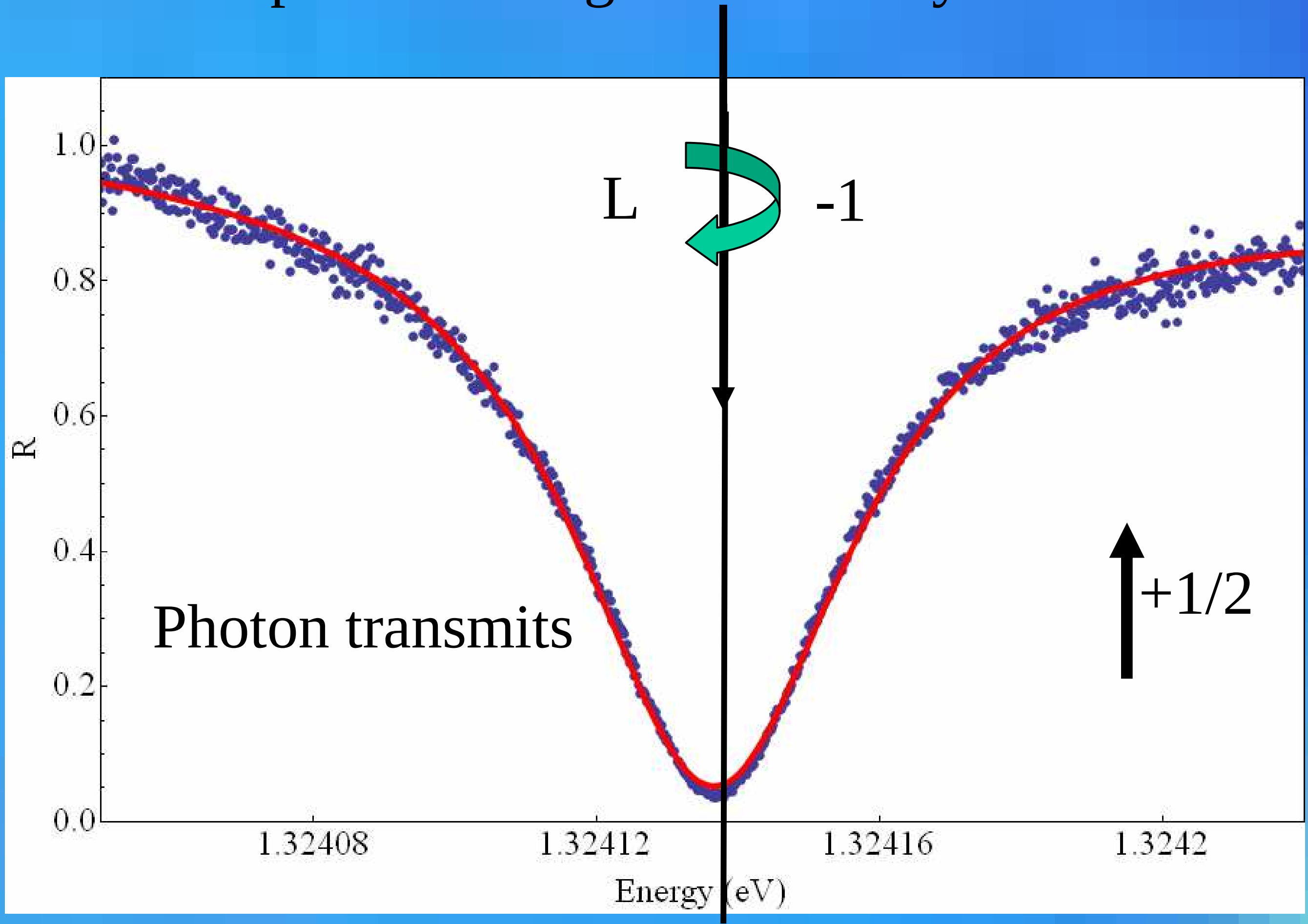


APL **95**, 251104 (2009)

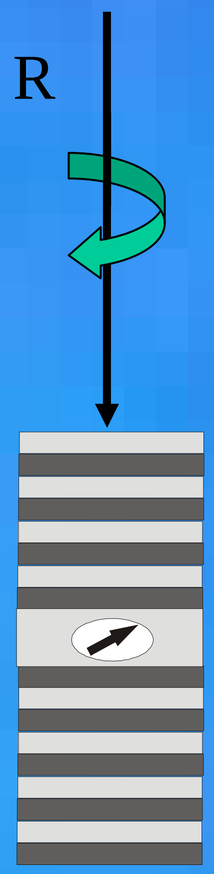
Prediction: For pol. deg. cavity and a X^- charged QD

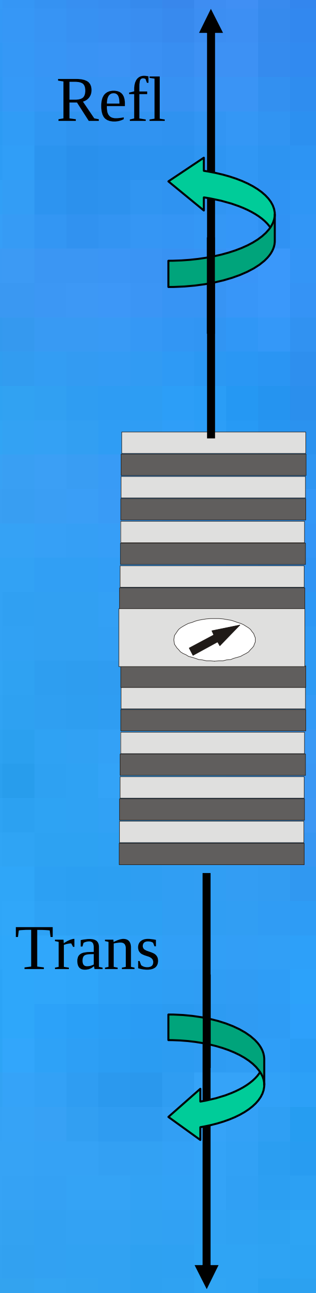


Prediction: For polarization generate cavity and a X^- charged QD



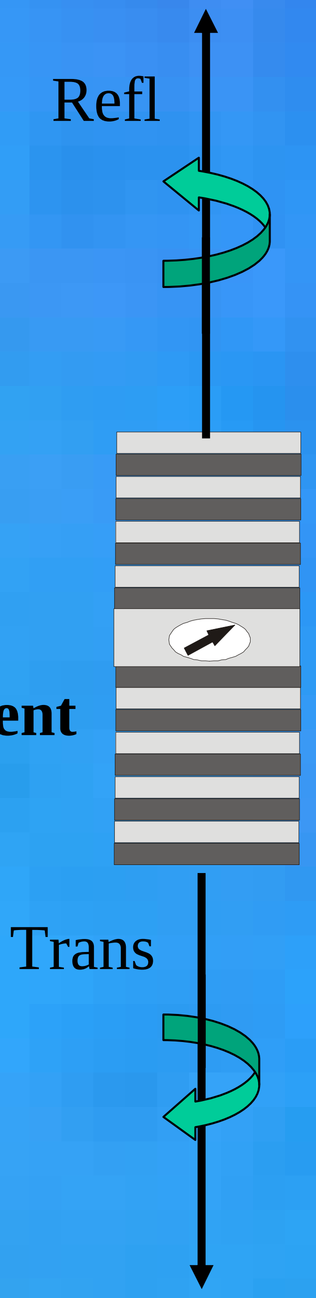
$$|\Psi\rangle = \alpha|\uparrow\rangle + \beta|\downarrow\rangle$$



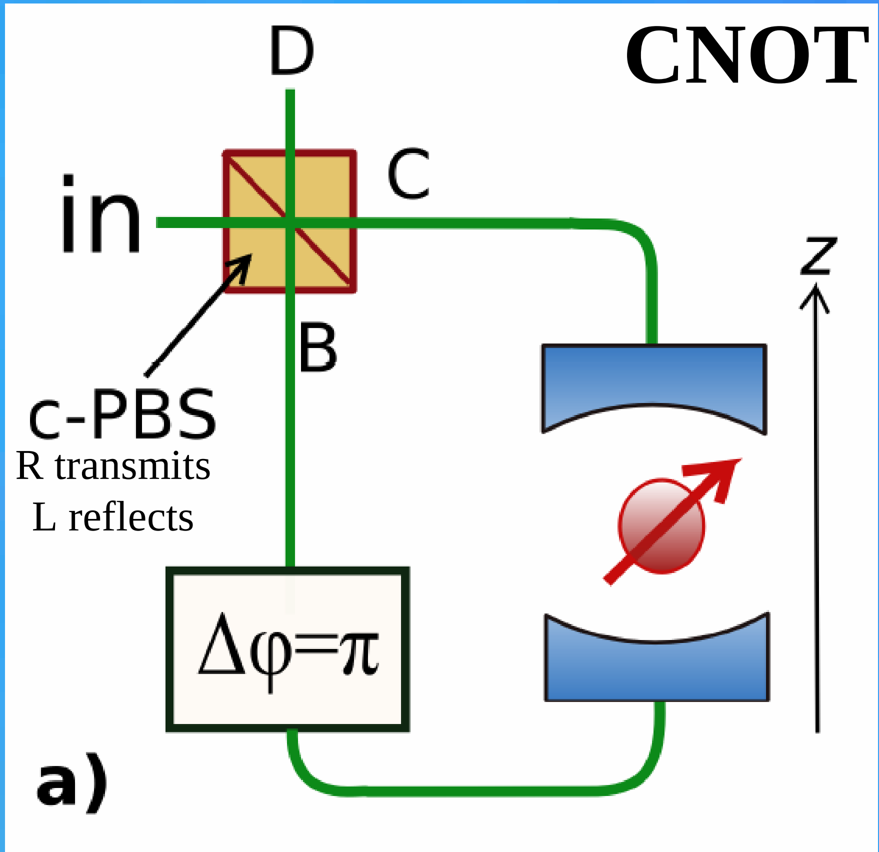


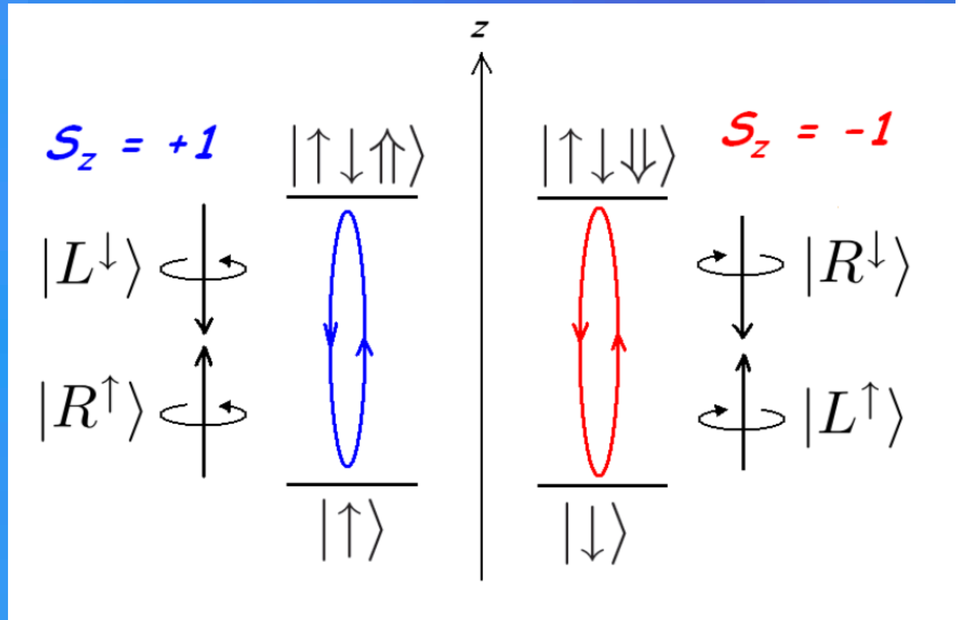
$$|\Psi\rangle = \alpha|\uparrow;\mathrm{Refl}\rangle + \beta|\downarrow;\mathrm{Trans}\rangle$$

Single photon
"interaction free"
single electron spin
entanglement/measurement



$$|\Psi\rangle = \alpha|\uparrow;\mathrm{Refl}\rangle + \beta|\downarrow;\mathrm{Trans}\rangle$$





Transmission π mod2π
with respect to reflection

PRL Bonato et al
2010

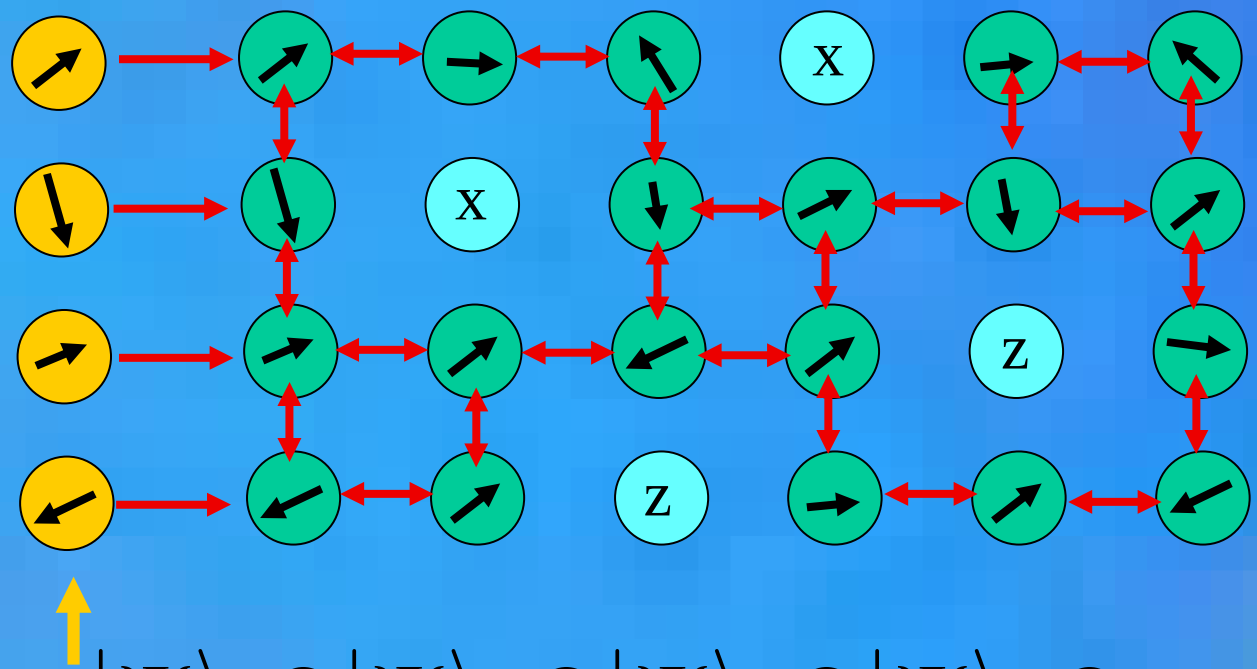
$$\left|\psi_{ph}\right\rangle = \alpha\left|R\right\rangle + \beta\left|L\right\rangle, \quad \left|\psi_{el}\right\rangle = \gamma\left|\uparrow\right\rangle + \delta\left|\downarrow\right\rangle$$

$$\left|\psi\right\rangle_{in} = \left|\psi_{ph}\right\rangle \otimes \left|\psi_{el}\right\rangle$$

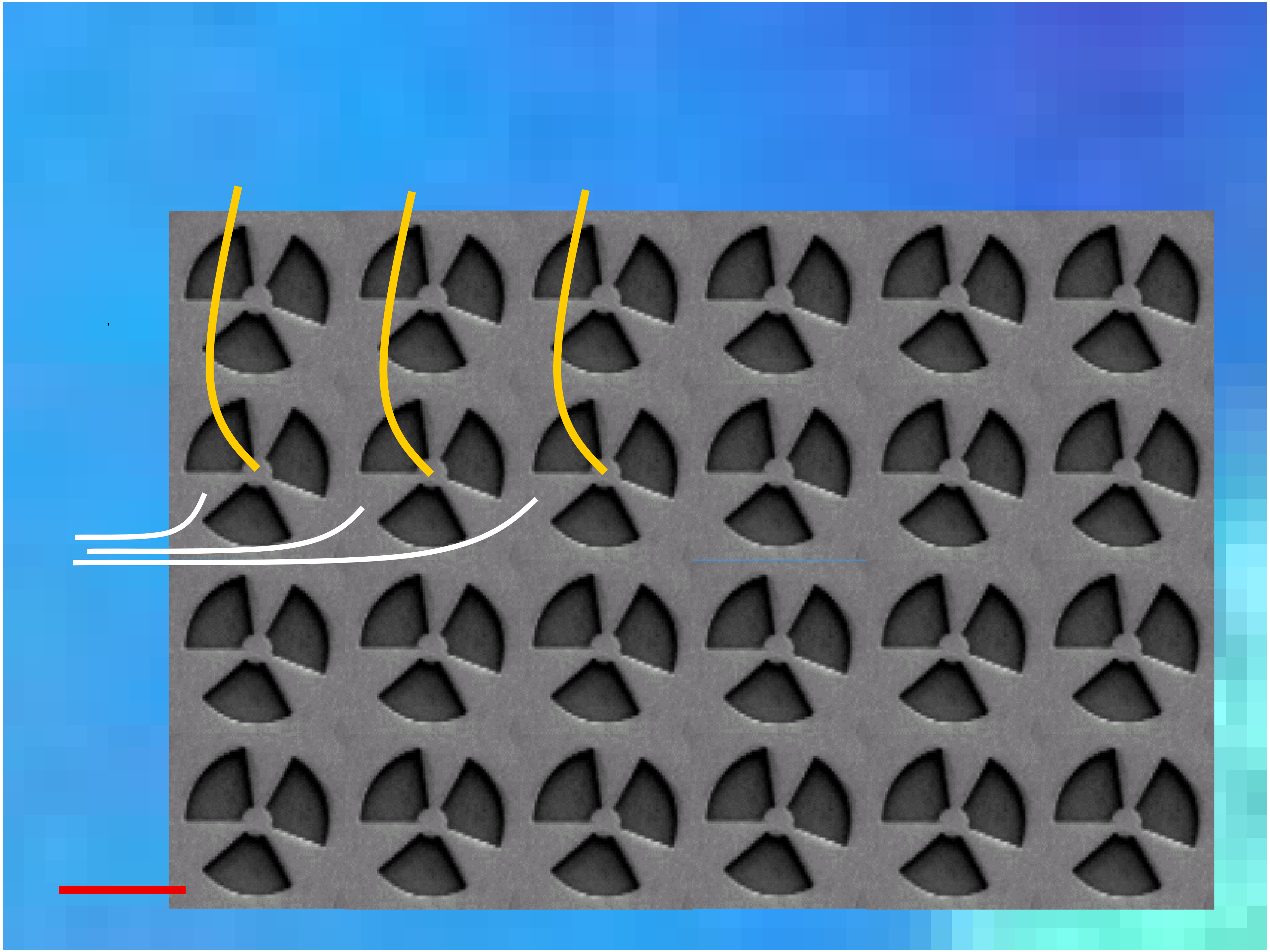
$$\left|\psi\right\rangle_{out} = \gamma\left|\uparrow\right\rangle\left[\alpha\left|R\right\rangle + \beta\left|L\right\rangle\right] + \delta\left|\downarrow\right\rangle\left[\alpha\left|L\right\rangle + \beta\left|R\right\rangle\right]$$

Quantum Computation

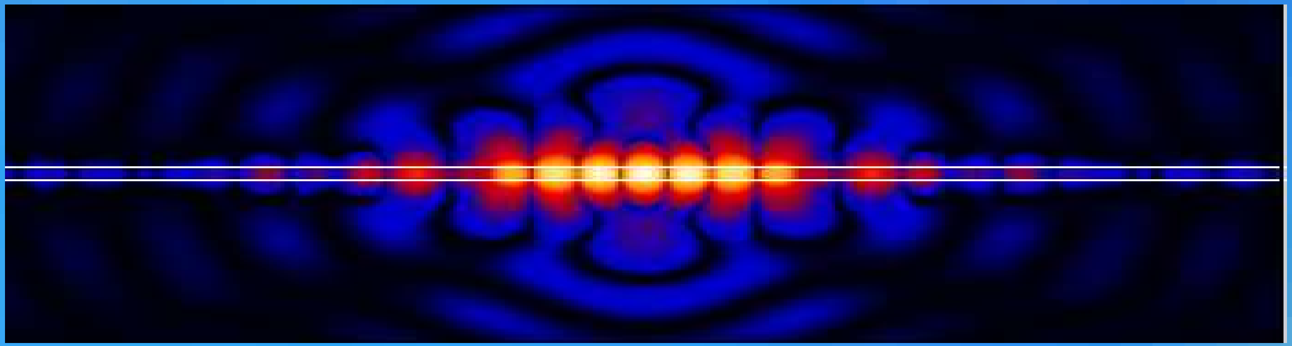
Cluster Entangled State



INPUT $|\Psi\rangle_1 \otimes |\Psi\rangle_2 \otimes |\Psi\rangle_3 \otimes |\Psi\rangle_4 \otimes \cdots$

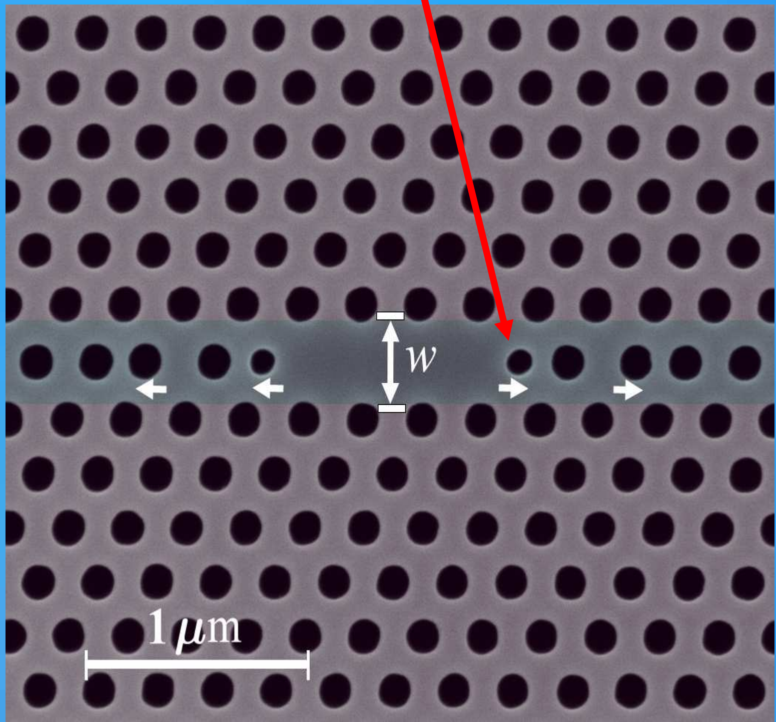


Photonic Crystals



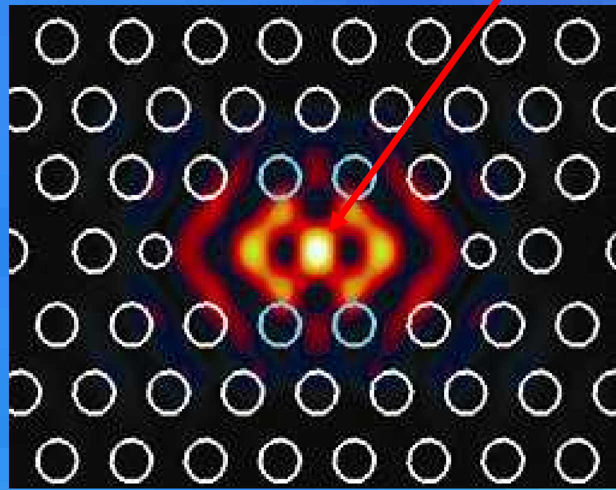
Q dot L3 photonic crystal cavity coupling

Size and position optimized for high **Q** and high $\mathbf{n_{eff}}$

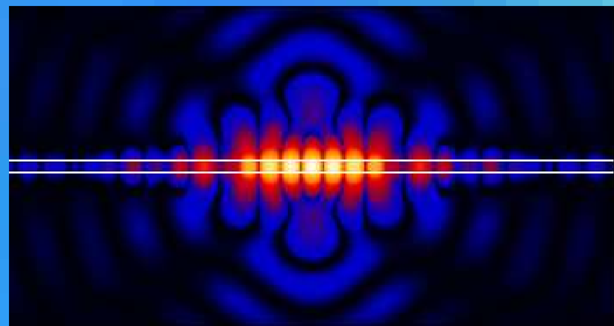


Field stays away from interface

Top View



Side View



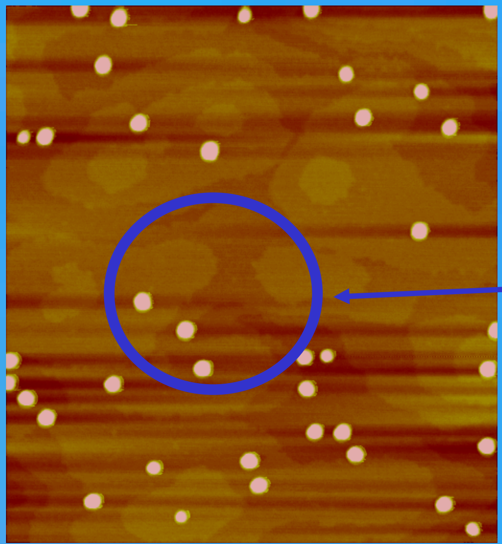
Mode volume	**V ~ 0.68(λ/n)³**
Effective index	$\mathbf{n_{eff}}$ **~ 2.9**
Q-factor (in theory)	**> 200000**

Measured Q ~ **18000**

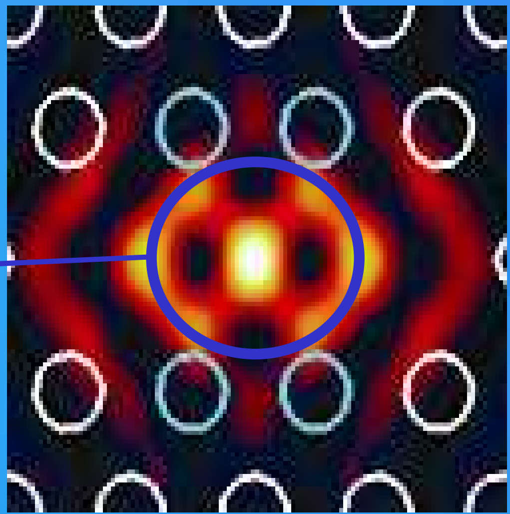
GaAs !

Low density of QDs

QD density
5-50 μm^{-2}
from AFM



Mode volume
from FDTD



QDs are spectrally distributed over 50-100 nm

Sharp exciton resonance

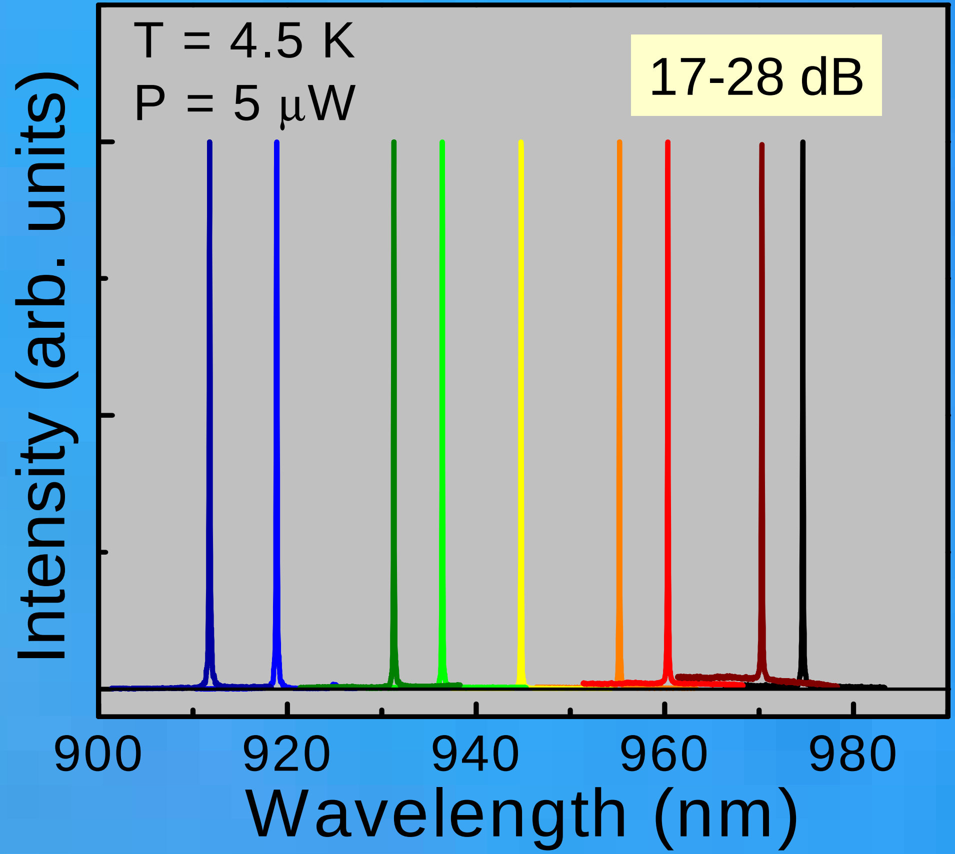
Chance of **~ 1%** for both spatial and spectral coupling

Only **1-3 QDs** are within the mode !

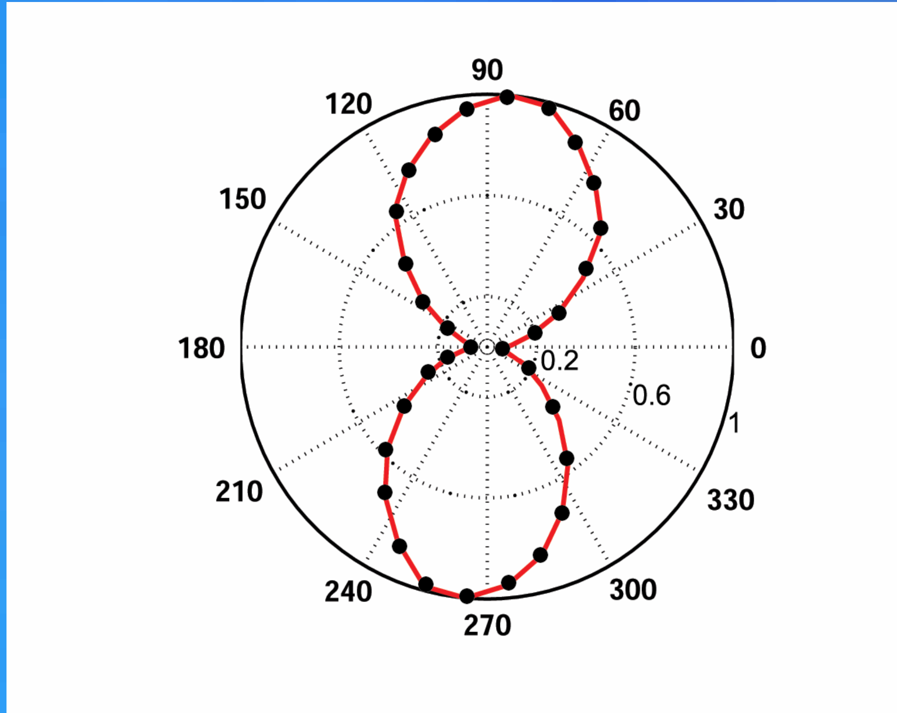
No pronounced coupling is expected

Lasing!?!?

Single mode lasing spectra



Nondegenerate lasing mode



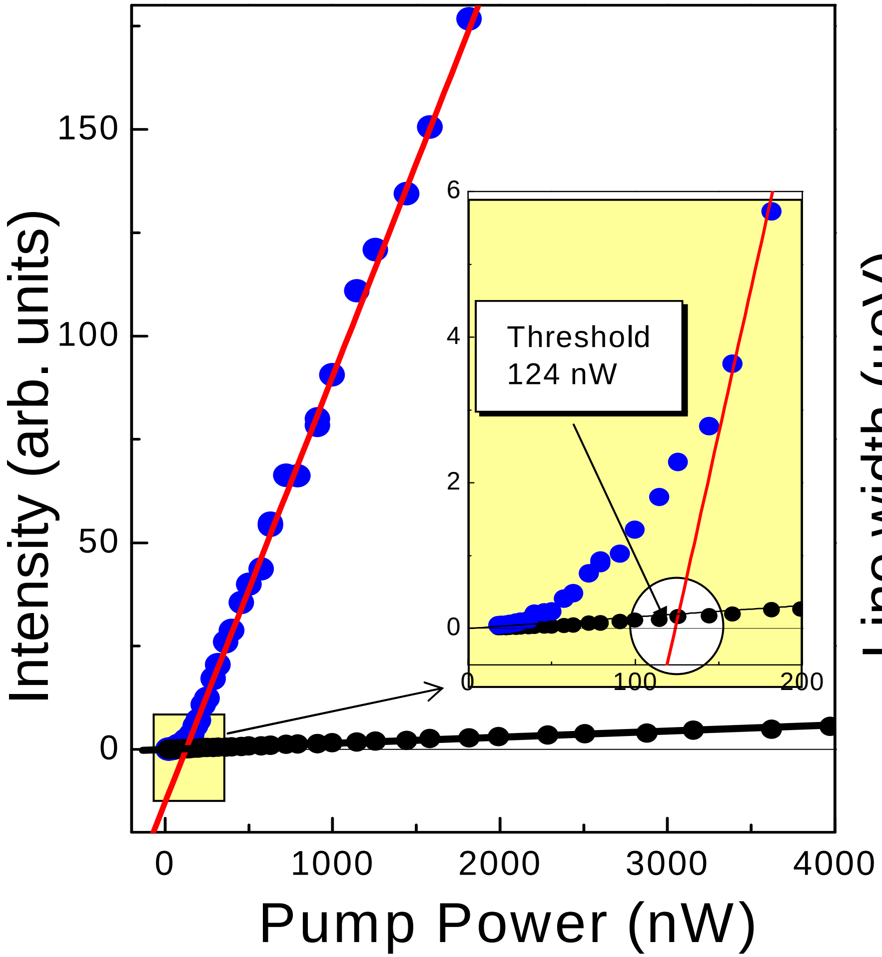
β~1 expected

No QDs – no mode decoration

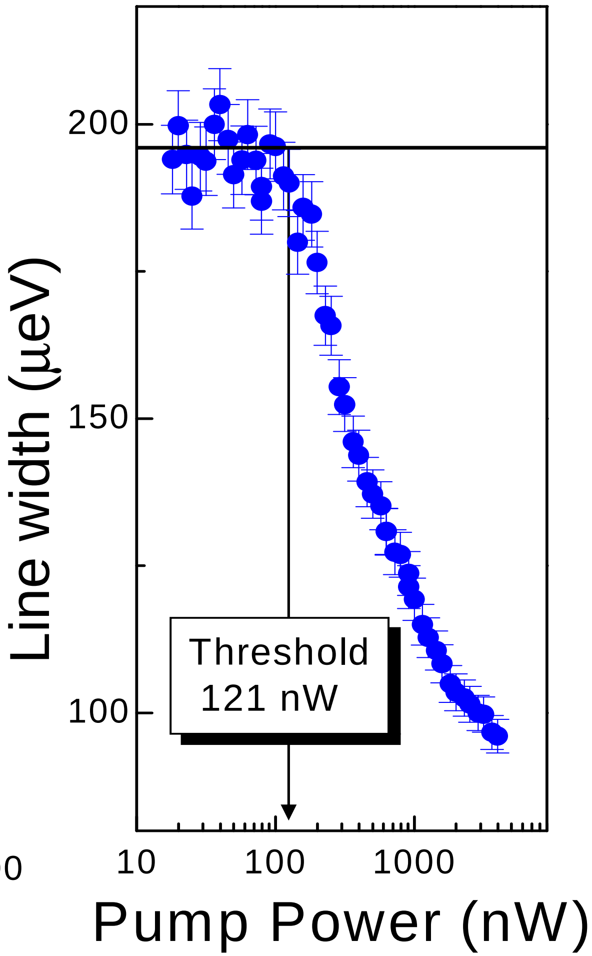
PRL **96**, 127404 (2006), S. Strauf et al., APL 2007

Lasing threshold behavior

Vanishing-threshold



Linewidth narrowing

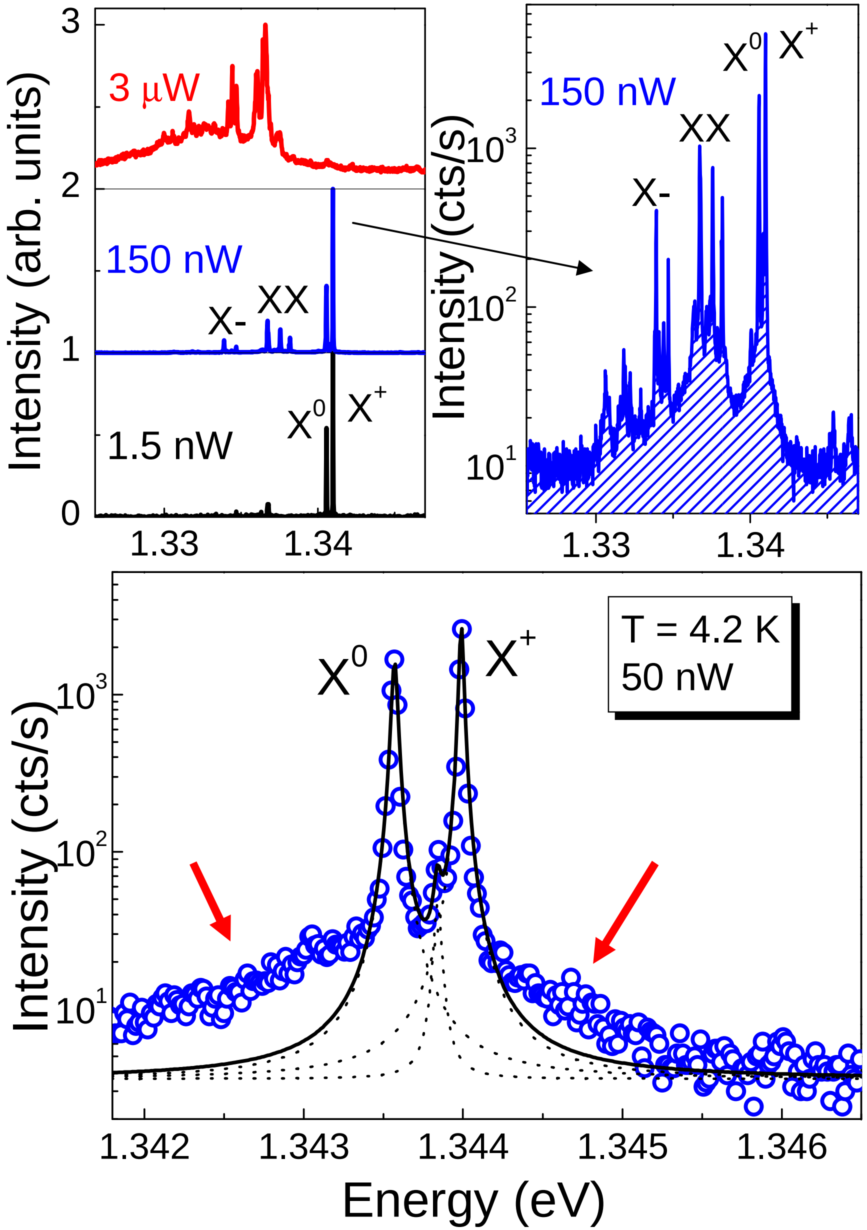


Conventional cw-threshold:
~100 nW

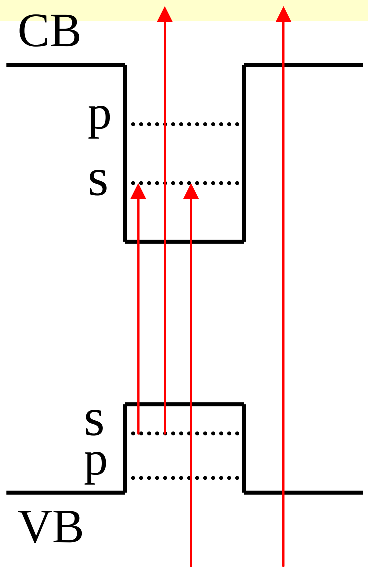
Absorbed power:
~4 nW

~ 10^2 -10^3 times lower than previous reports

Single QDs are broadband emitters



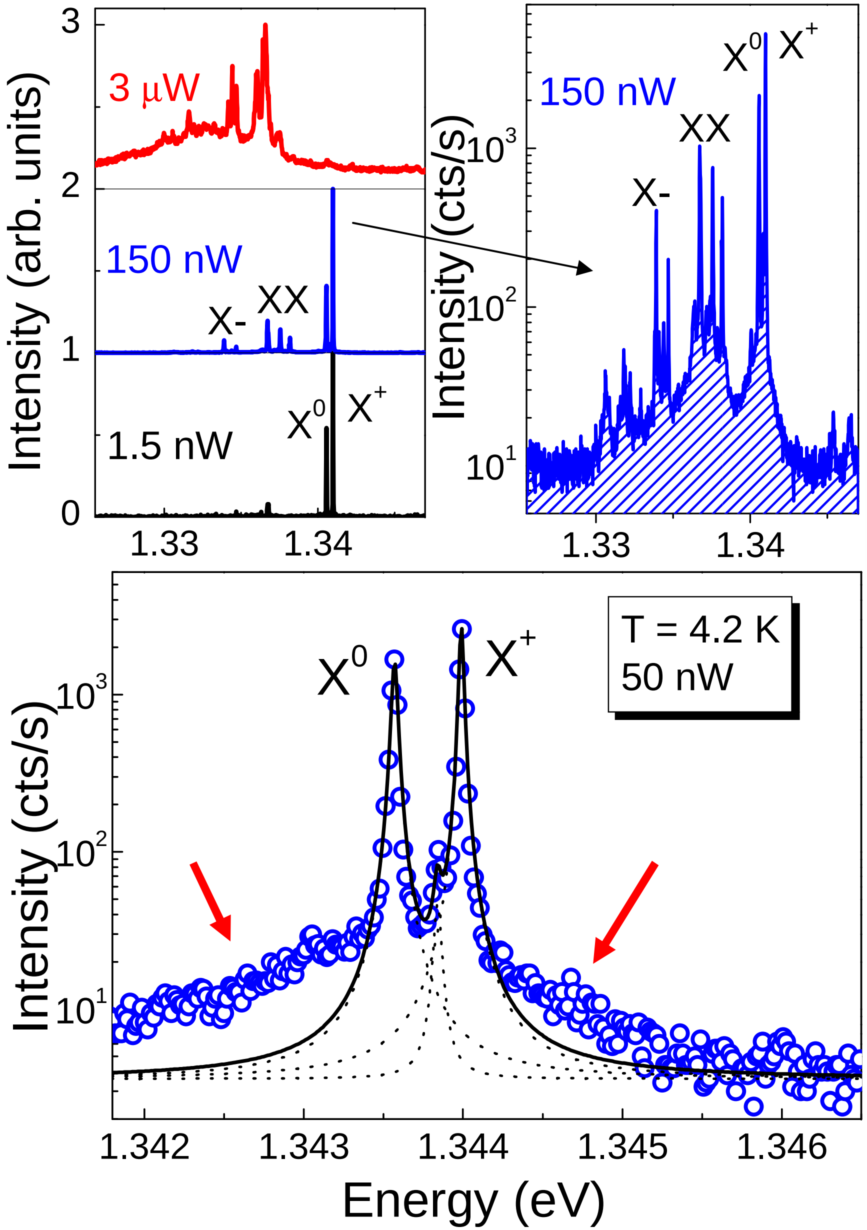
- charged states X^+, X^0, X^-
- bi- and multi Xs
- Extended state

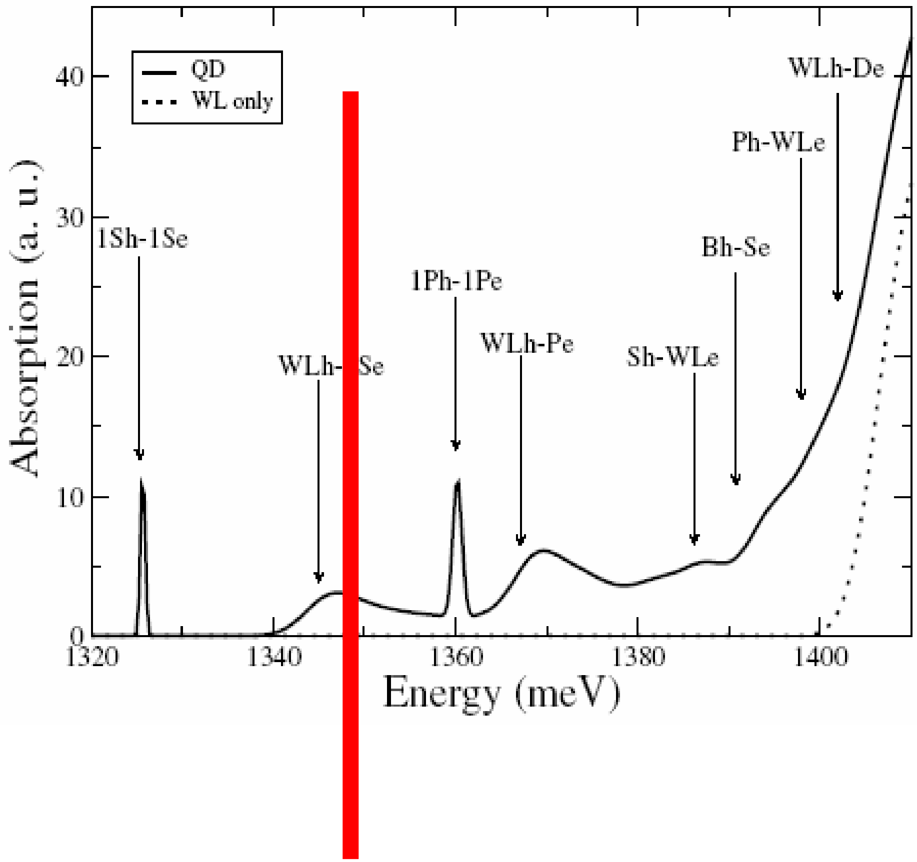


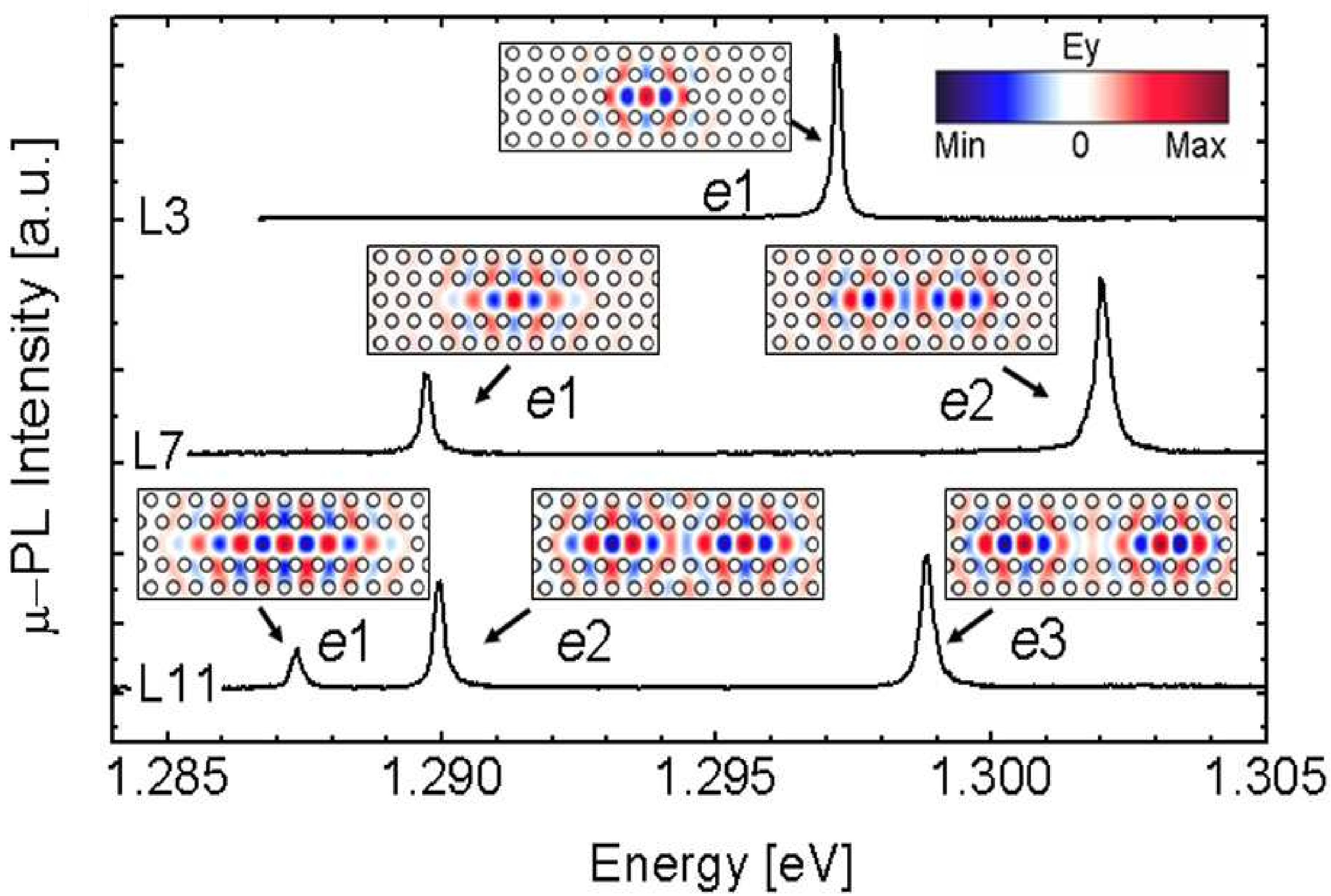
- acoustic phonon coupling

QD interaction with surrounding matrix provides **indirect** and **efficient** coupling

(our) single QDs are broadband emitters

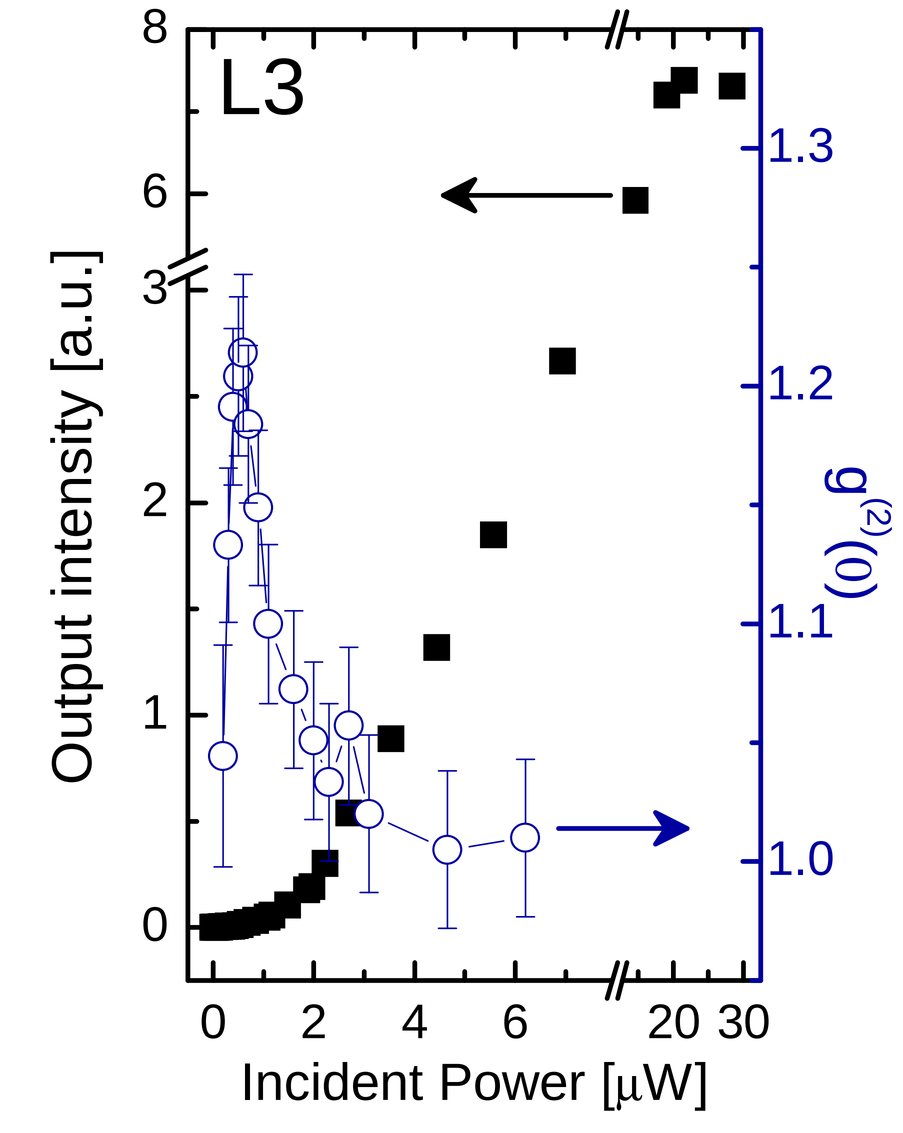


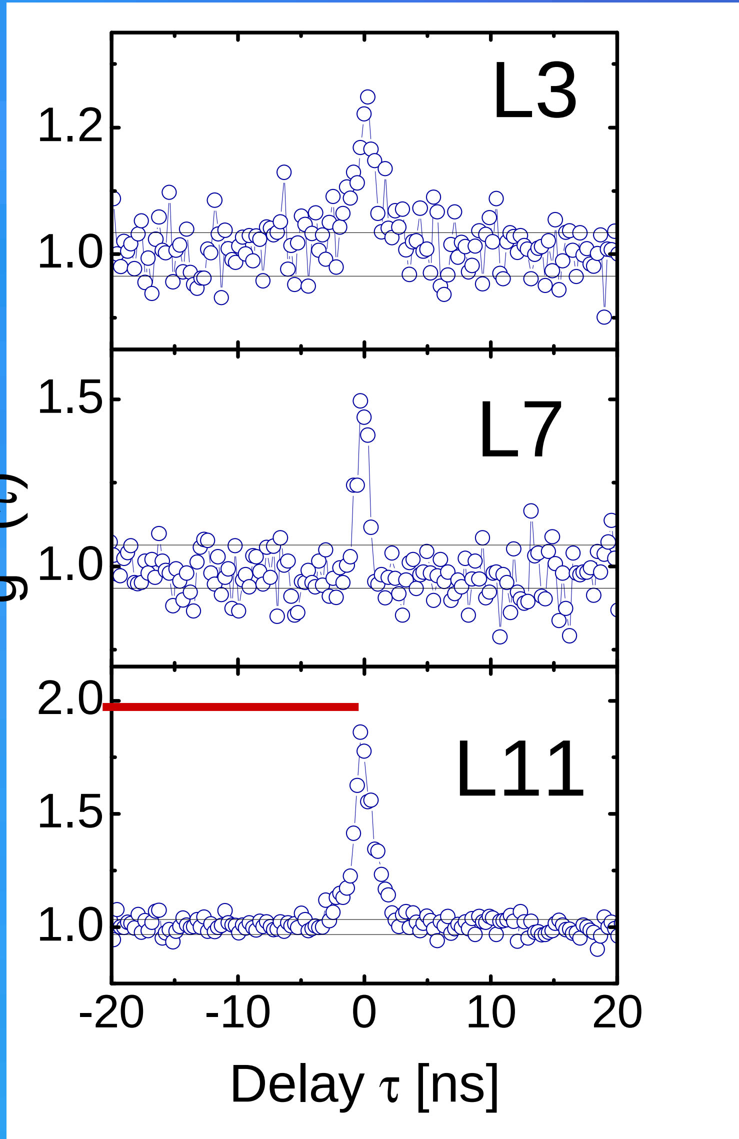




Ey
Min
0
Max
L3
e1
L7
e1
e2
L11
e1
e2
e3
μ–PL Intensity [a.u.]
1.285
1.290
1.295
1.300
1.305
Energy [eV]

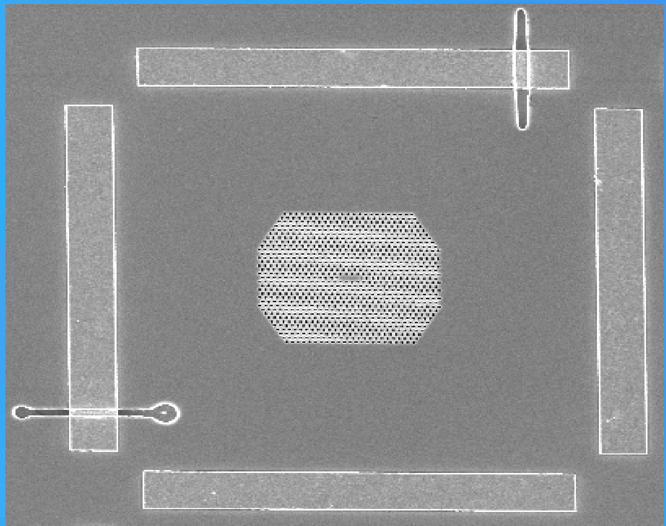
Proof lasing, Fano peak

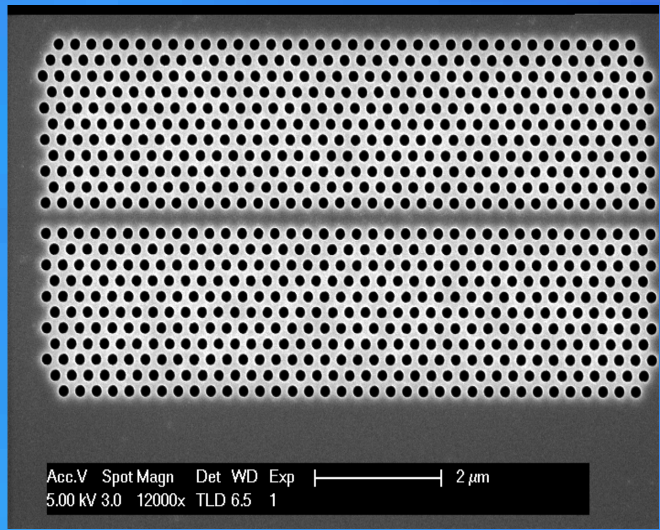




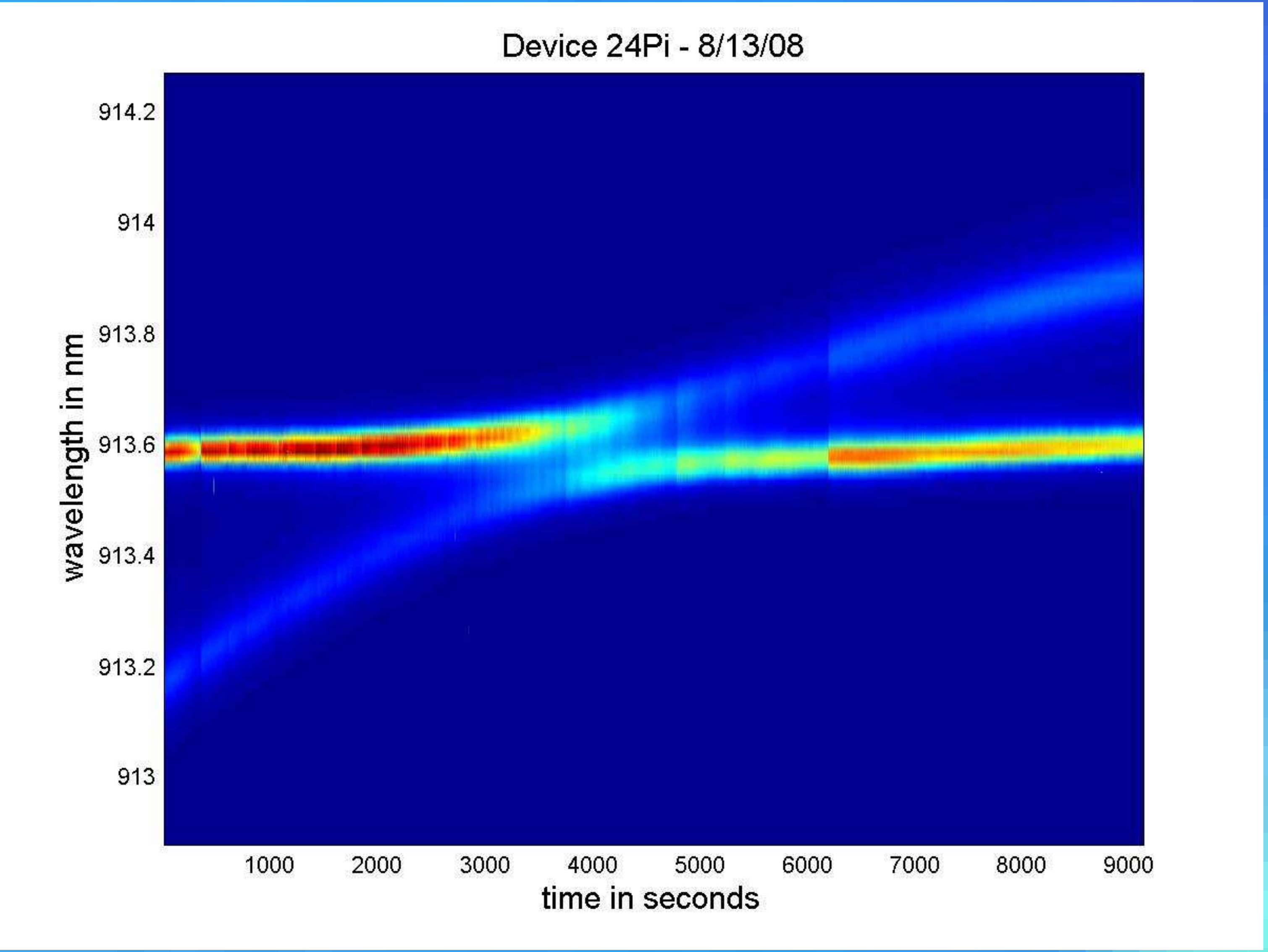
Appl. Phys. Lett. 91, 031108 (2007).

Strong coupling by optical positioning (10nm resolution in positioning PC)



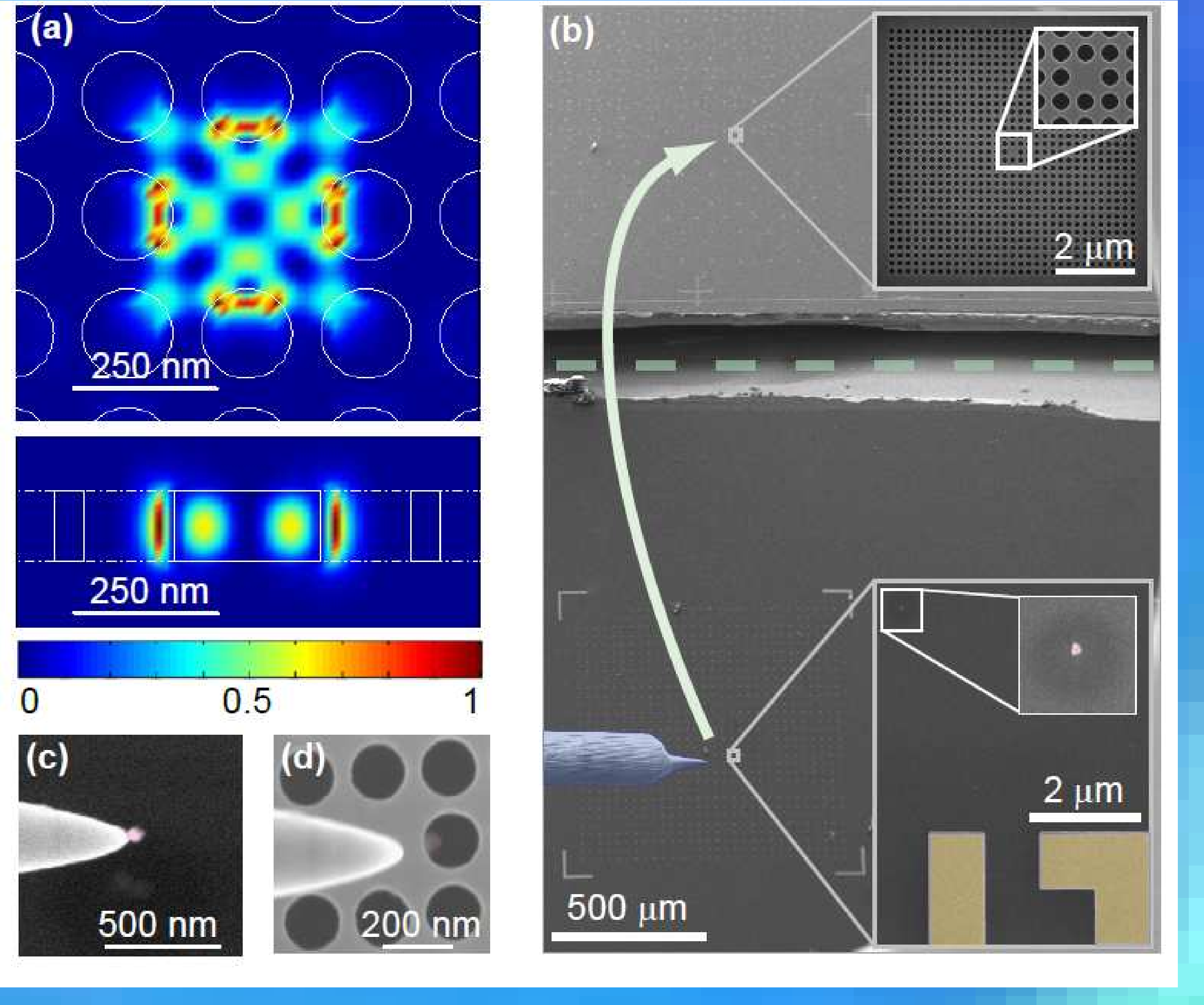


Strong coupling by optical positioning
(10nm resolution in positioning PC)



APL '09 Thon et al.

NV centers in diamond and photonic crystals



van der Sar et al. APL 2011