All-optical cavity using atomic mirrors

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1. Dep. of Physics and Graduate Institute of Photonics, National Changhua University of Education, Taiwan
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3. MPI for the Physics of Complex Systems, Germany
4. Dep. of Physics, National Central University, Taiwan

2015 AMO Summer School

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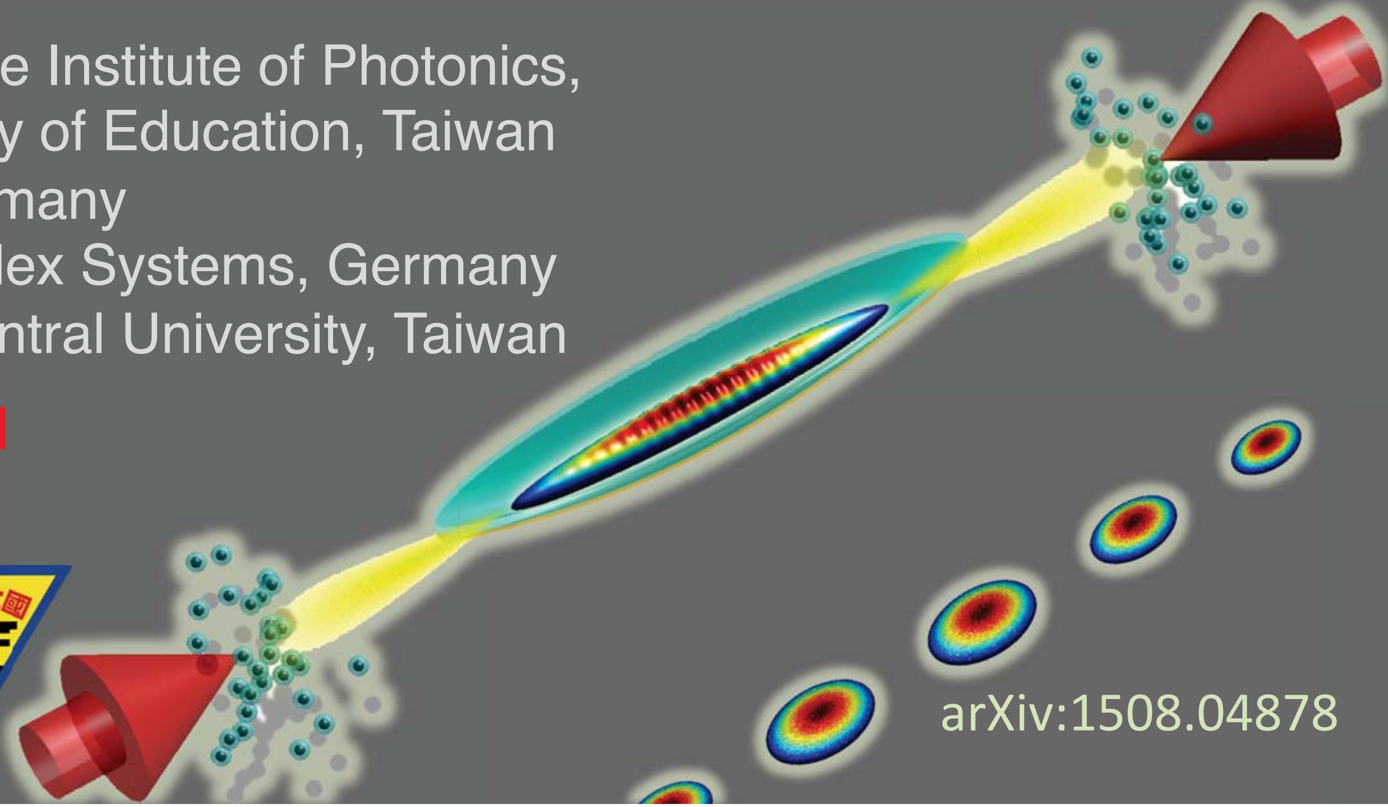
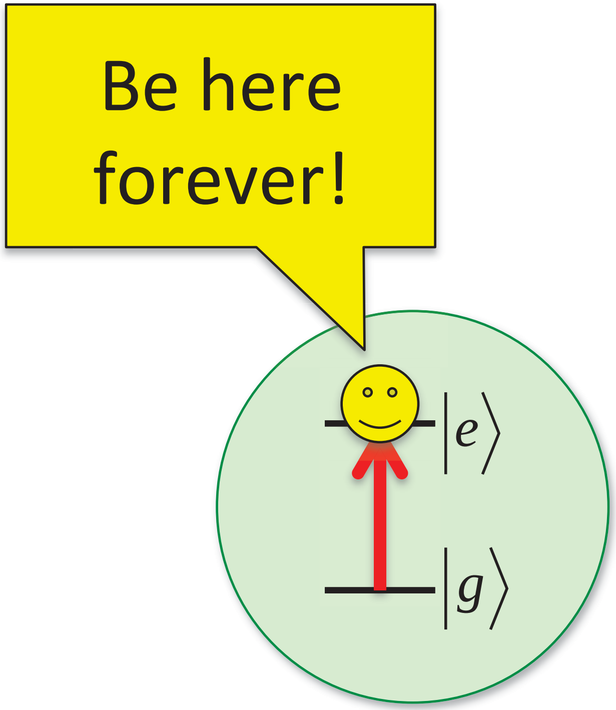


arXiv:1508.04878

Why Cavity?

Is eigenstate stationary?



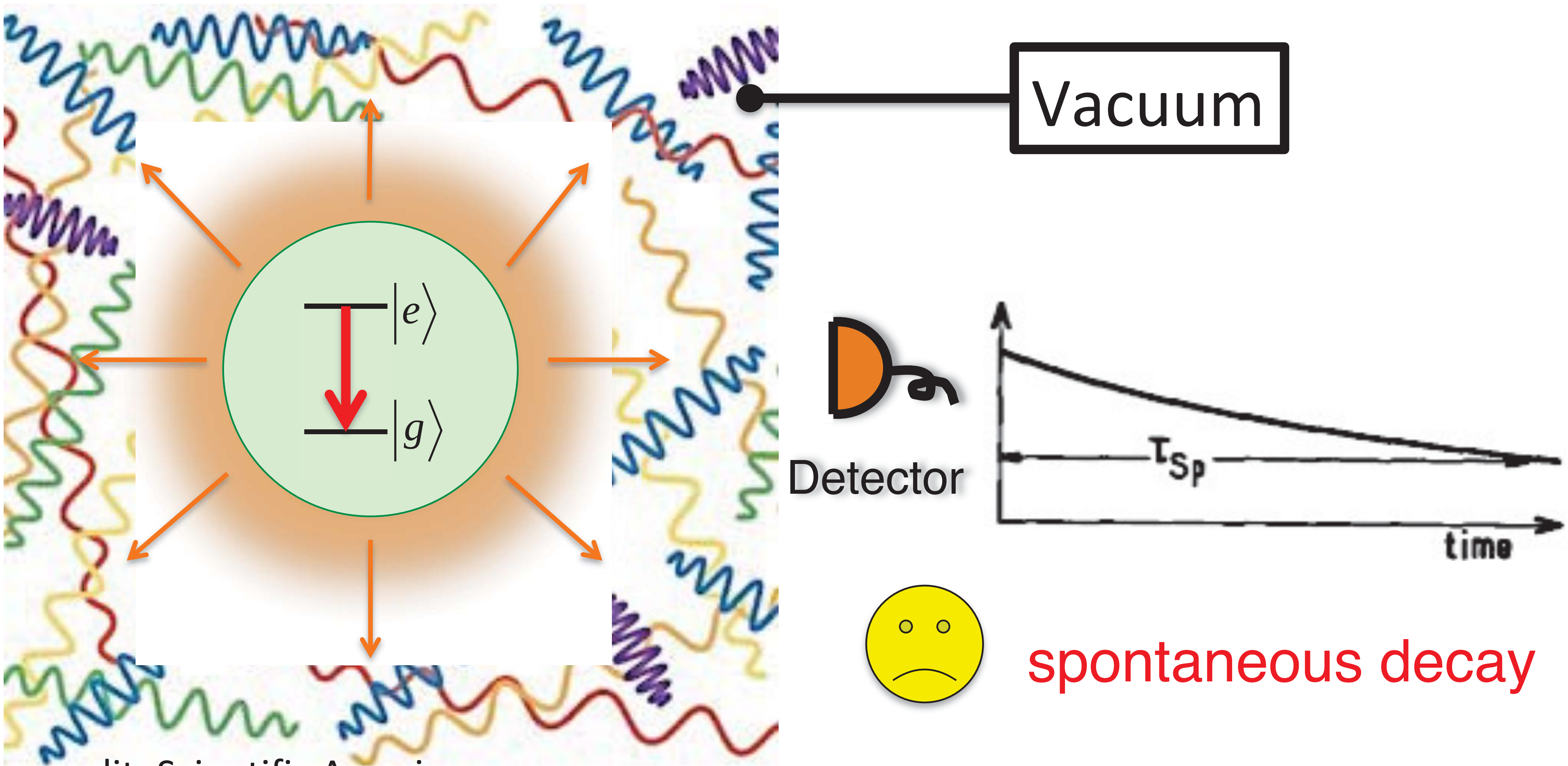
an atom

Schrödinger's Equation

$$i\hbar\frac{\partial}{\partial t}\psi(\mathbf{r},t) = -\frac{\hbar^2}{2m}\nabla^2\psi(\mathbf{r},t) + V(\mathbf{r},t)\psi(\mathbf{r},t)$$

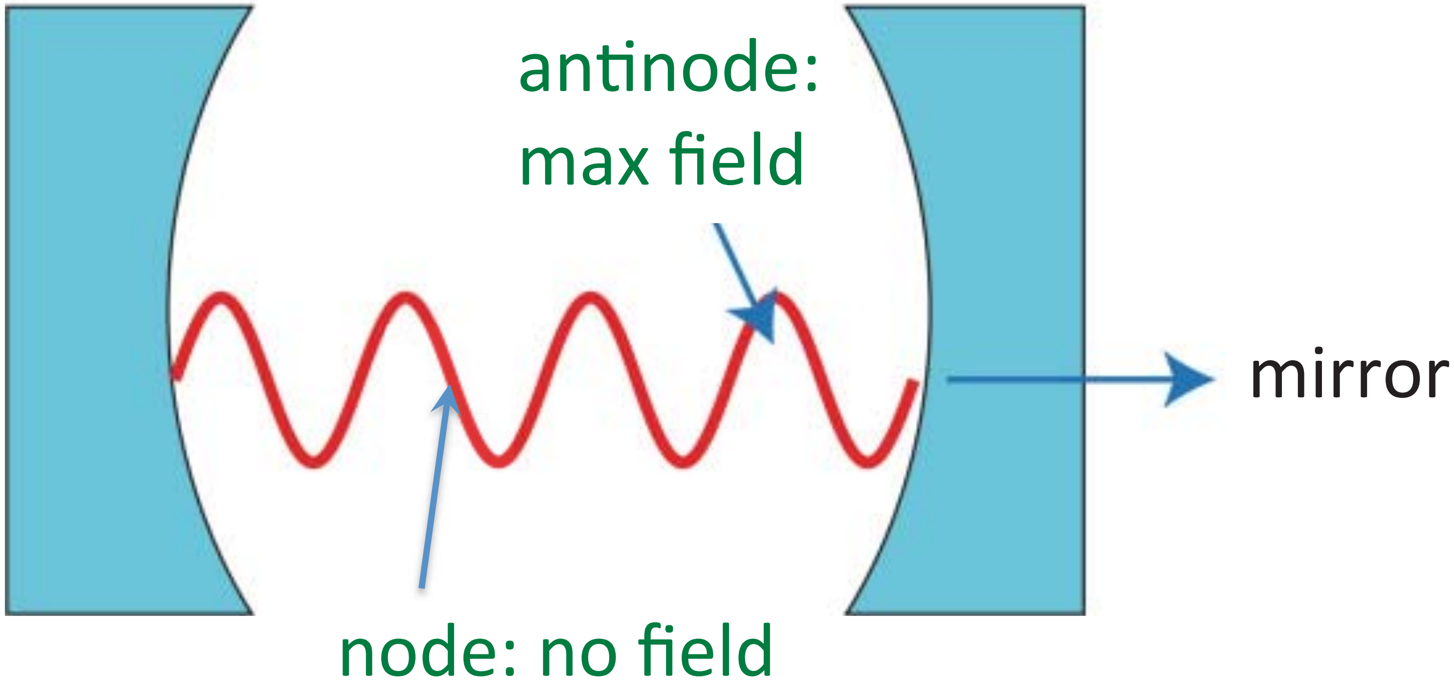
eigenstate???

something in vacuum

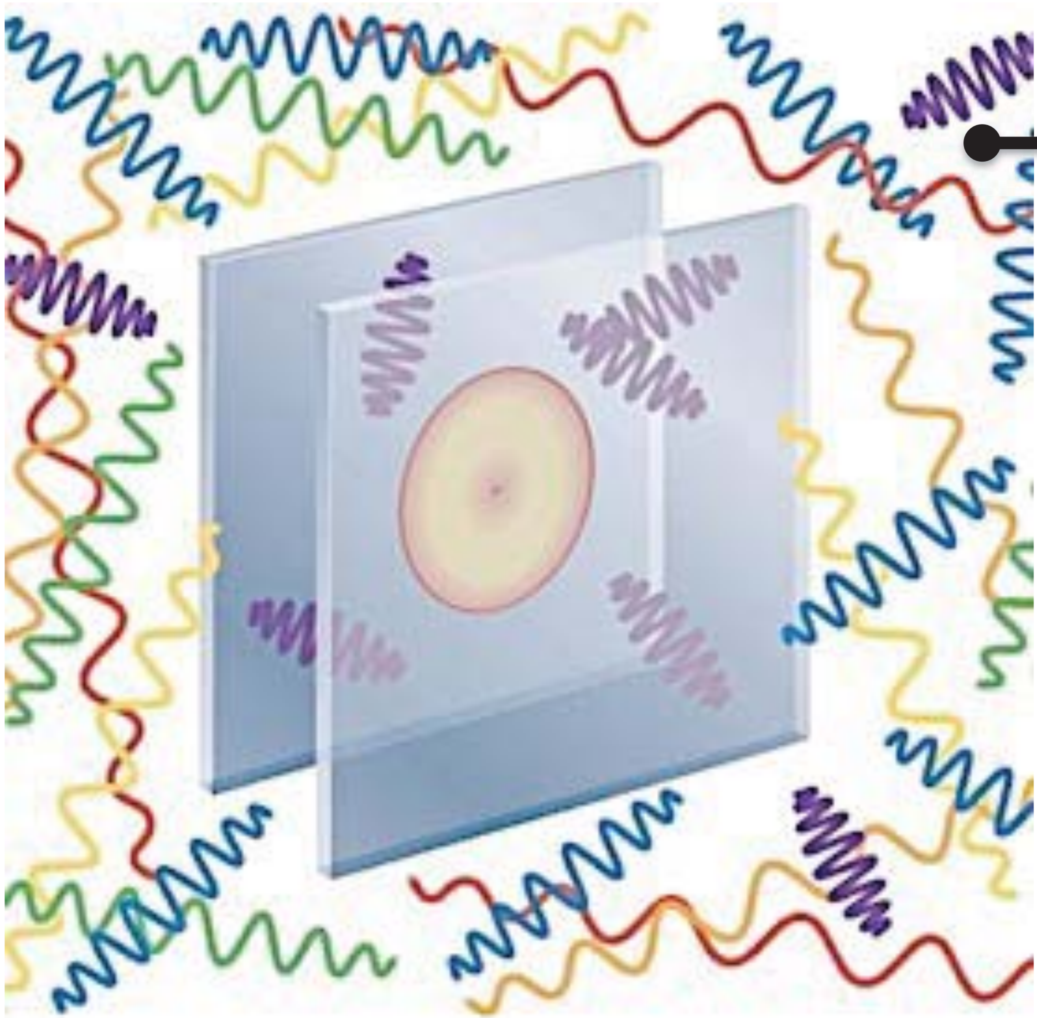


credit: Scientific American

Standing wave in a cavity



Interaction in a cavity



credit: Scientific American

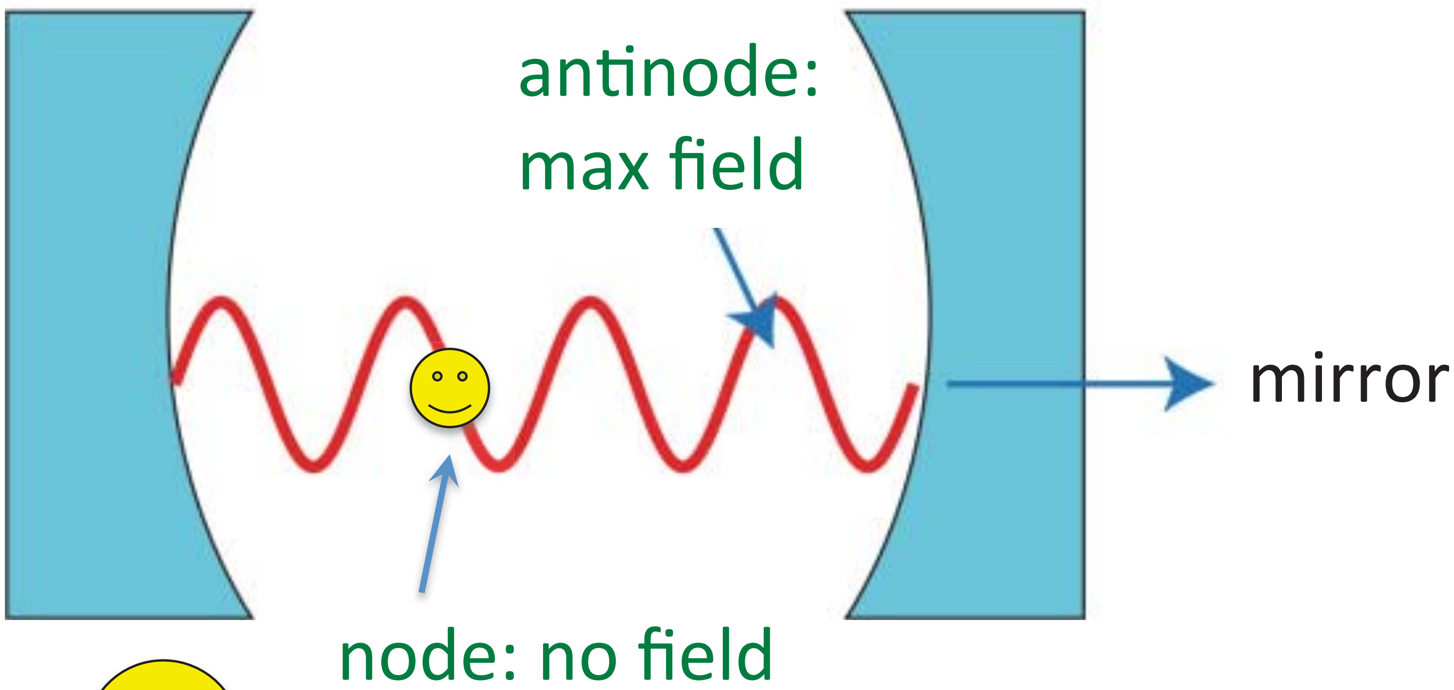
Vacuum outside

$$\hat{H}_{\text{JC}} = \hbar\omega_c \hat{a}^\dagger \hat{a} + \hbar\omega_a \frac{\hat{\sigma}_z}{2} + \frac{\hbar\Omega}{2} \left(\hat{a}\hat{\sigma}_+ + \hat{a}^\dagger \hat{\sigma}_- \right).$$

Jaynes–Cummings model

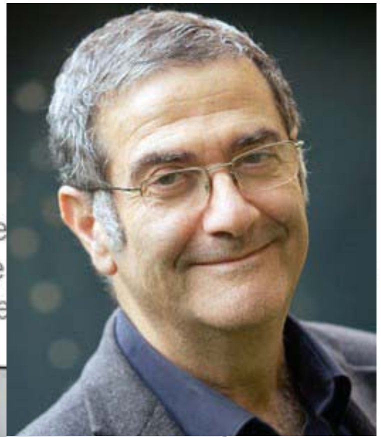
single mode photons v.s.
a single atom

Cavity modifies atom's behavior



NO spontaneous decay

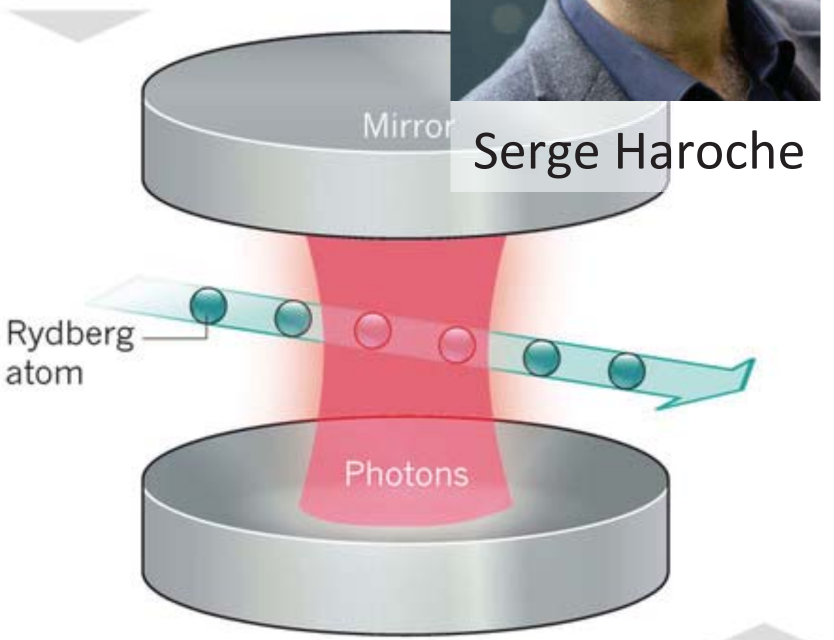
The Nobel Prize in Physics 2012



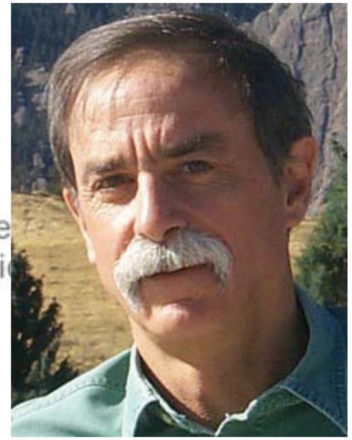
Serge Haroche

HAROCHE METHOD

Microwave photons are place
reflective mirrors that enable
bounce back and forth betwe



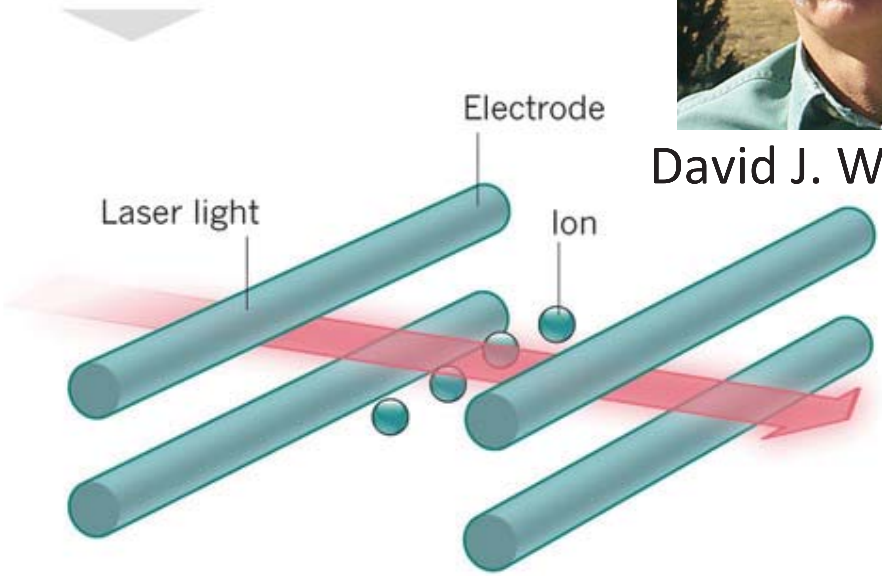
Rydberg atoms, which have one electron in a high-energy level, are sent through the system to measure and manipulate the photon's quantum state.



David J. Wineland

WINELAND METHOD

An electric field produced by an arrange
electrodes holds one or several ions insi

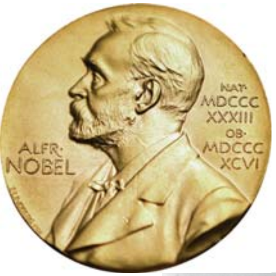


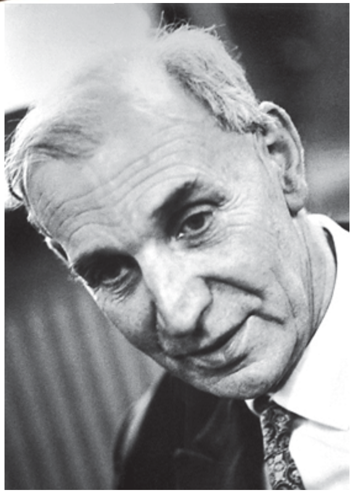
Laser light is shone on the ion, suppressing its thermal vibration and allowing its quantum state to be measured and controlled.

Ed Hinds & Rainer Blatt *Nature* 492, 55 (2012)

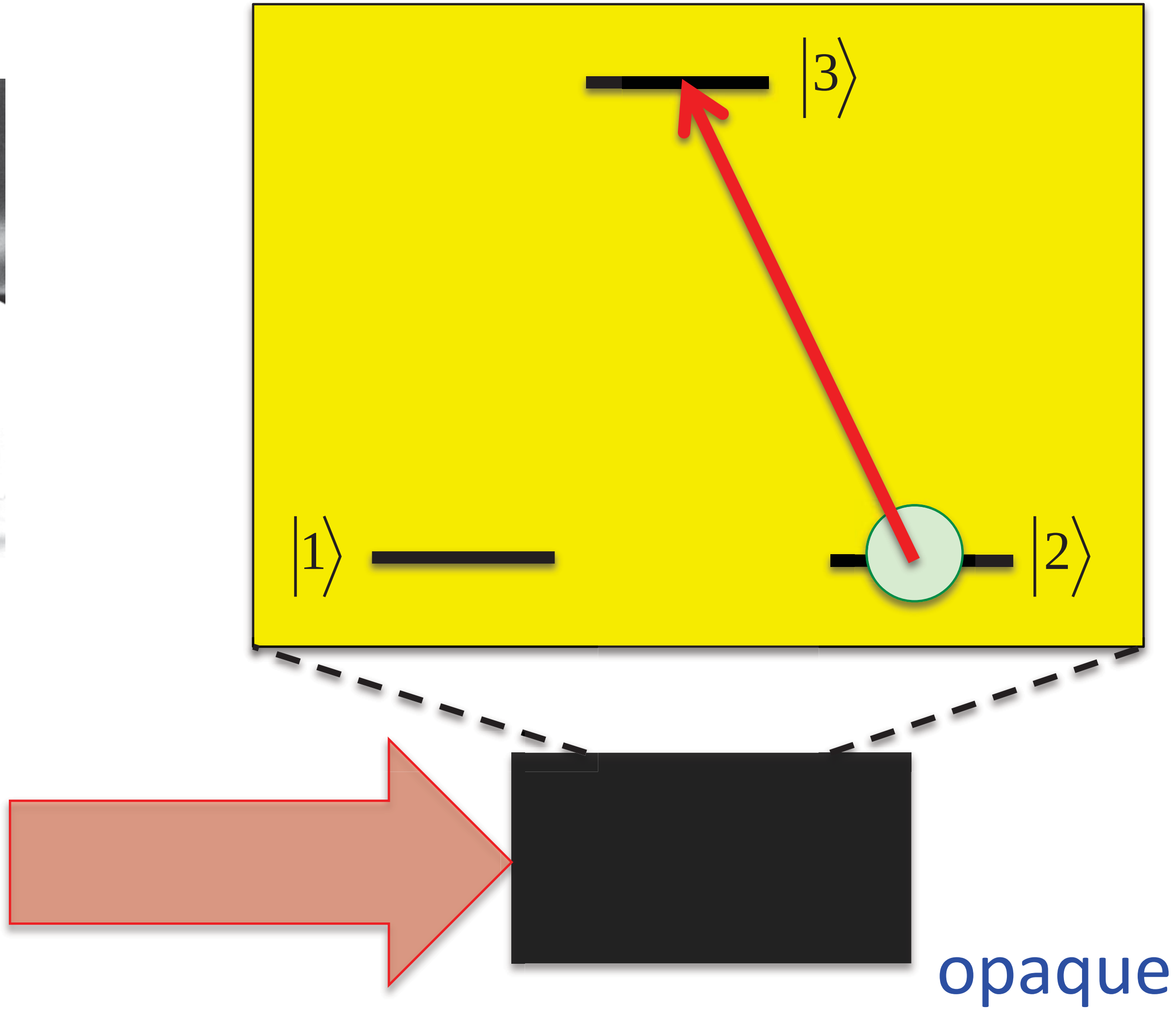
Control Matter with light

Optical pumping (1966 Nobel Prize)

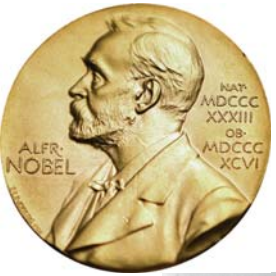


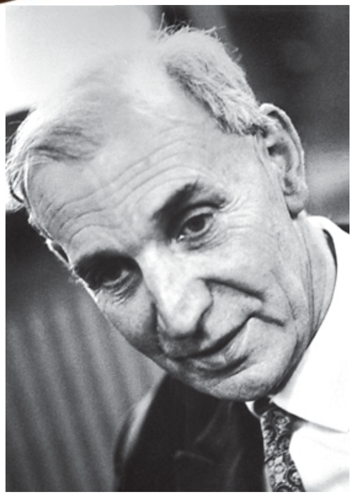


Alfred Kastler

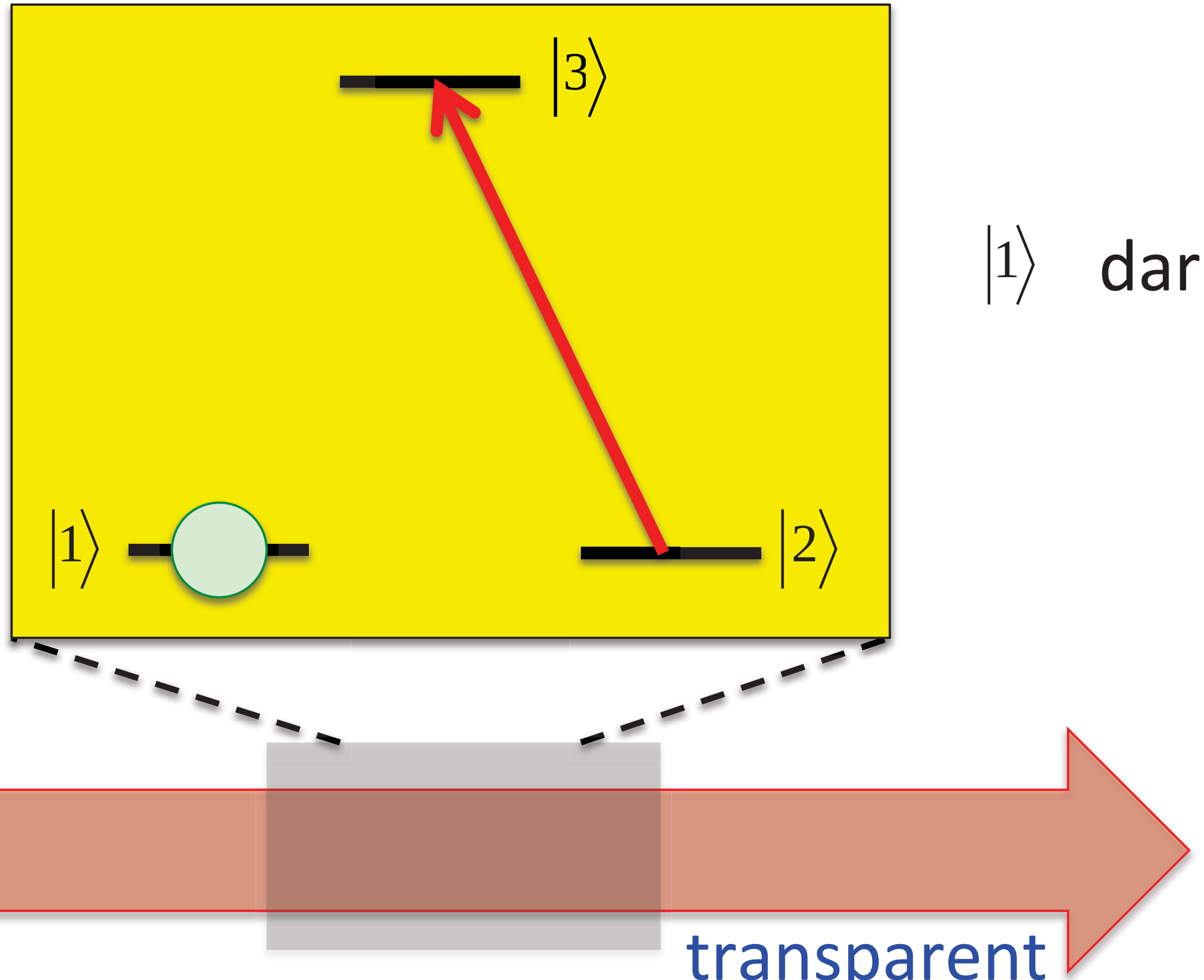


Optical pumping (1966 Nobel Prize)



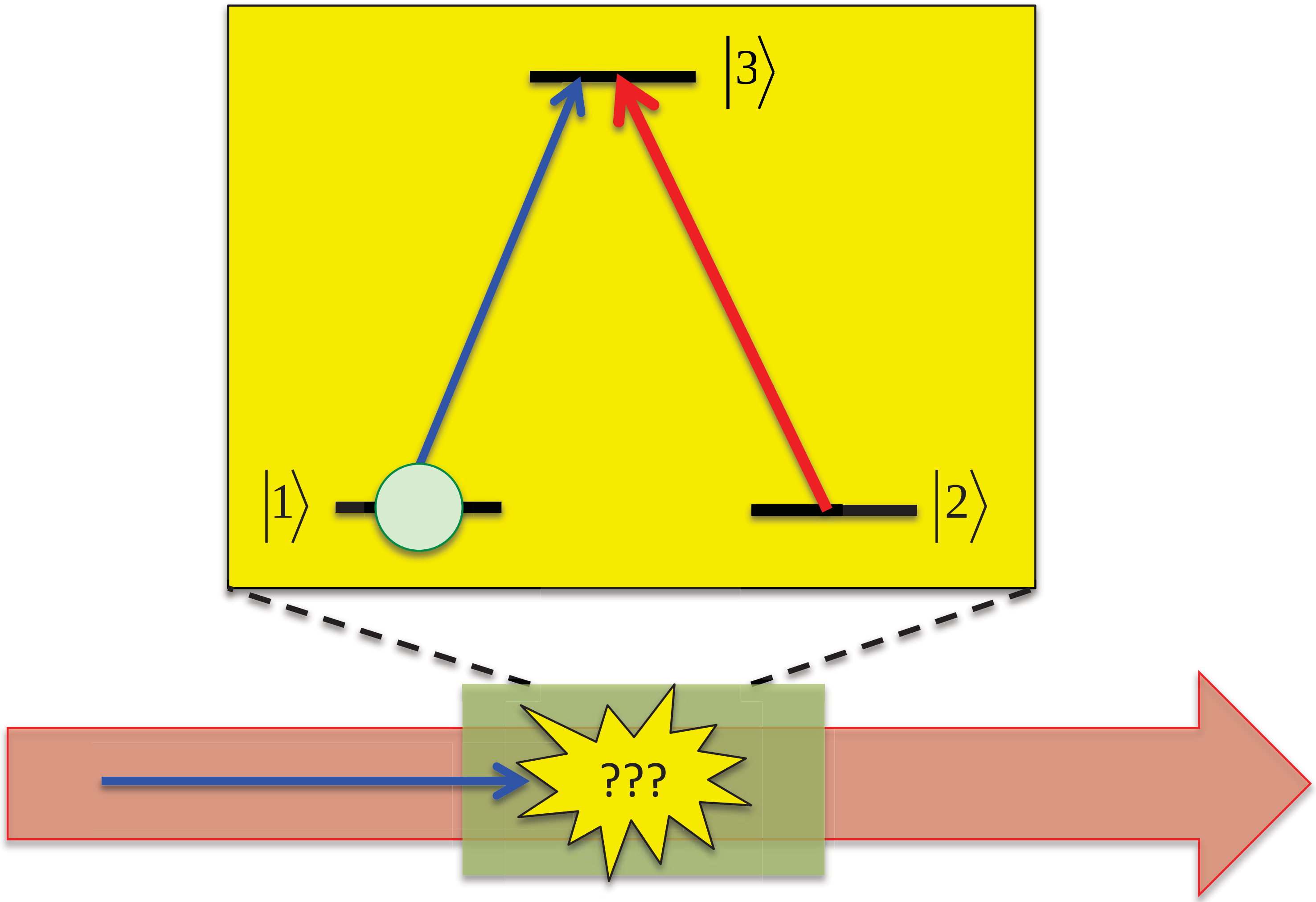


Alfred Kastler



$|1\rangle$ dark state

How about applying 2nd light?

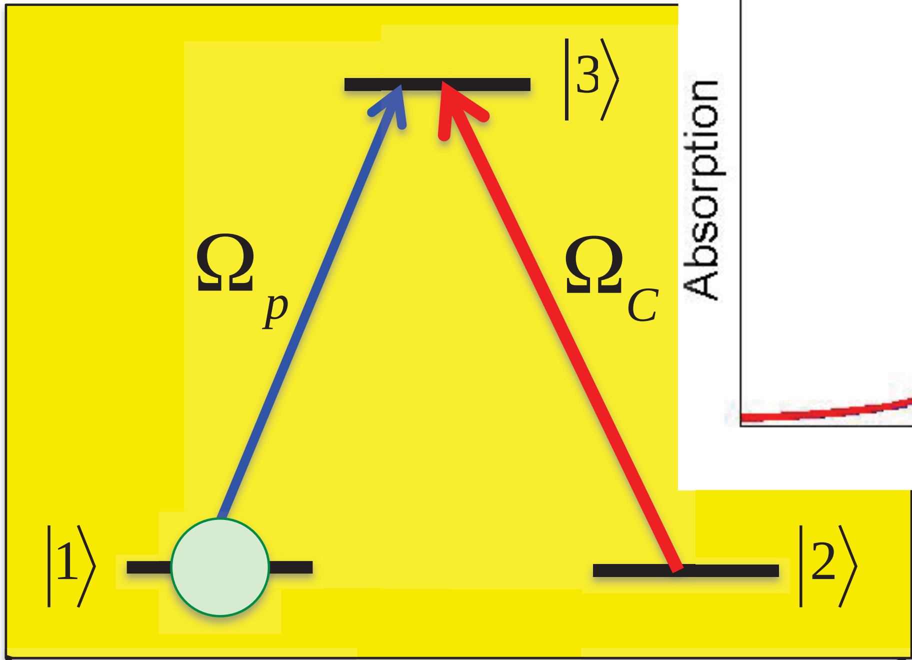


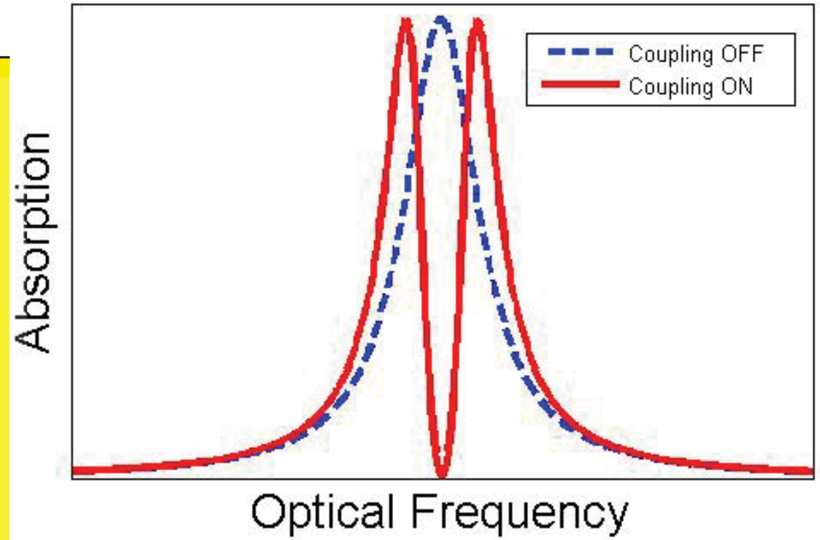
Electromagnetically induced transparency

$$|a^0\rangle = \cos\theta|1\rangle - \sin\theta|2\rangle$$

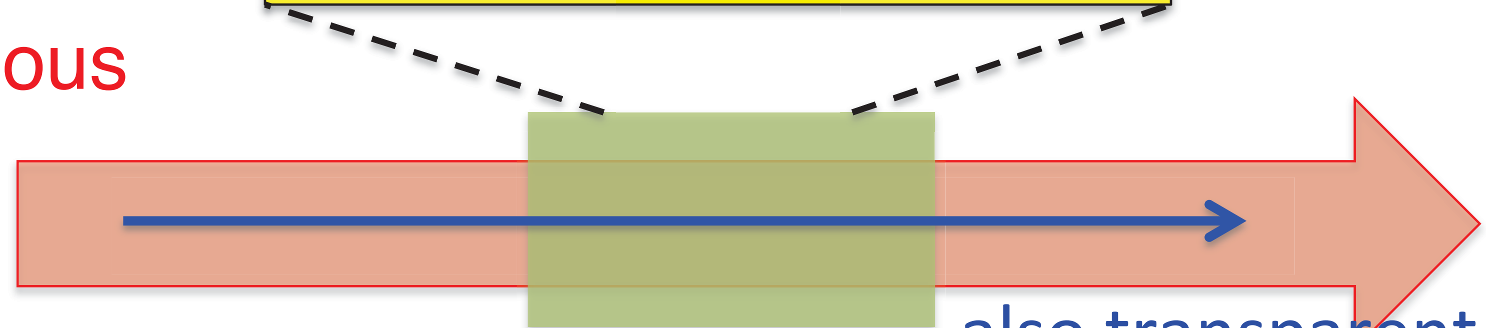
new dark state

$$\tan\theta = \frac{\Omega_p}{\Omega_c}$$





NO spontaneous decay



also transparent!!

O. Kocharovskaya and Y. I. Khanin, Sov. Phys. JETP 63, 945 (1986)

All-optical cavity using atomic mirrors

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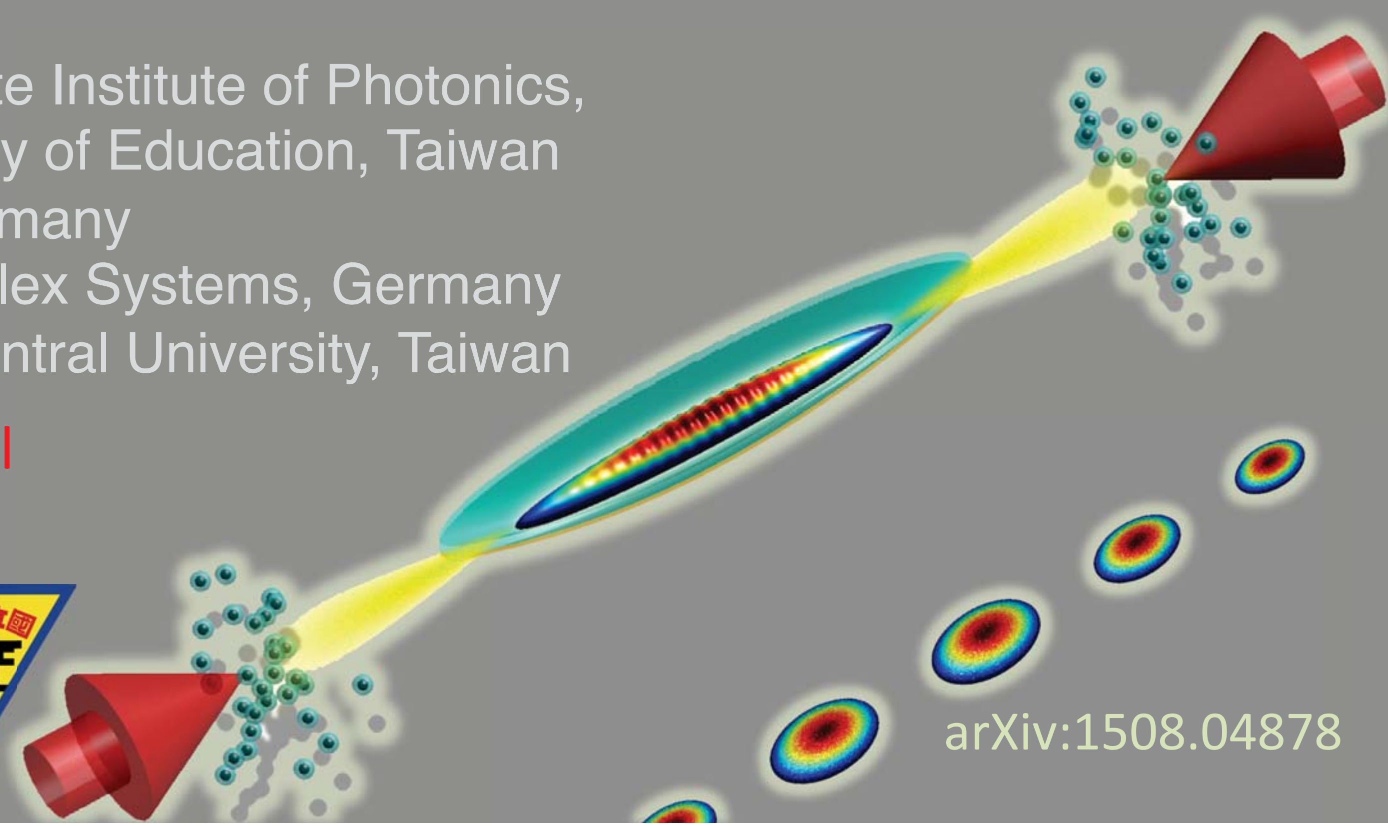
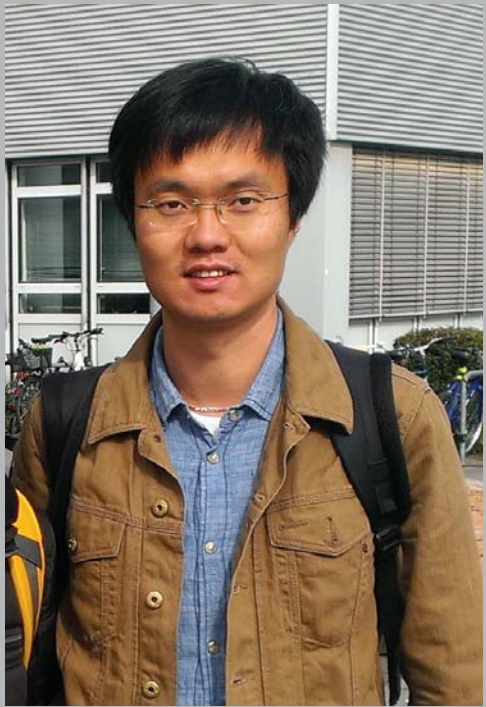


arXiv:1508.04878

Acknowledgement

Shih-Wei Su
(蘇士煒)

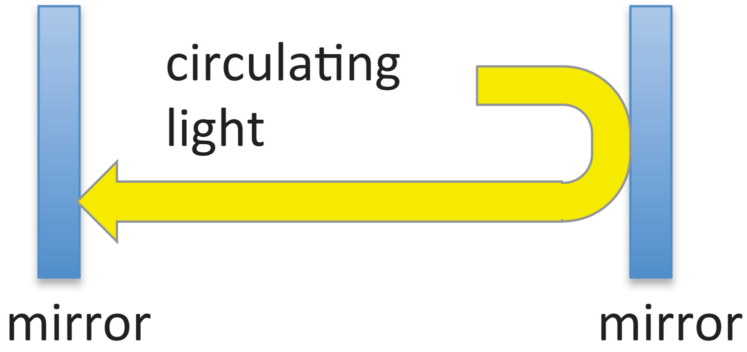


Zhen-Kai Lu
(呂振凱)

I-Kang Liu
(劉翼綱)

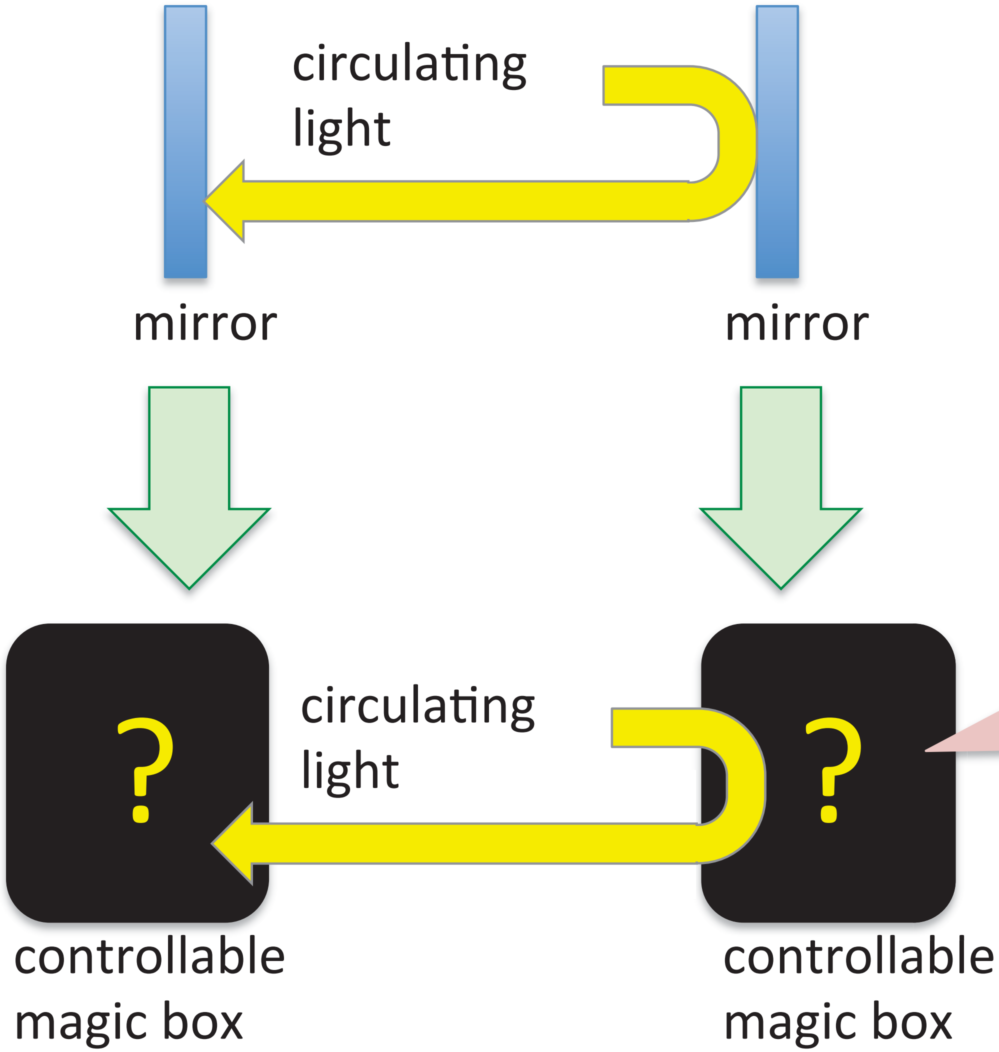
Shih-Chuan Gou
(郭西川)

What we want to do?



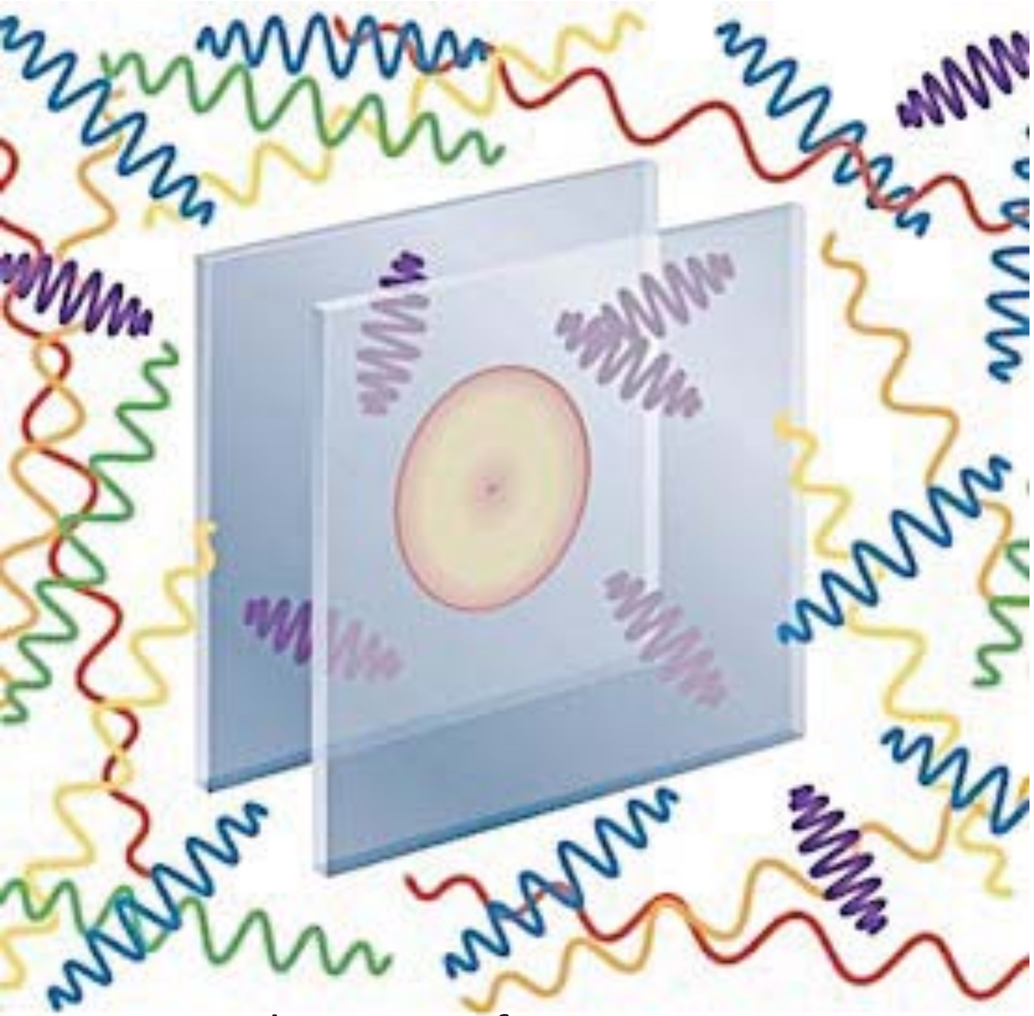
conventional cavity

What I want to do



reflection on/ off
whenever you
want

Motivation – different cavity QED



credit: Scientific American

conventional mirror is not controllable.

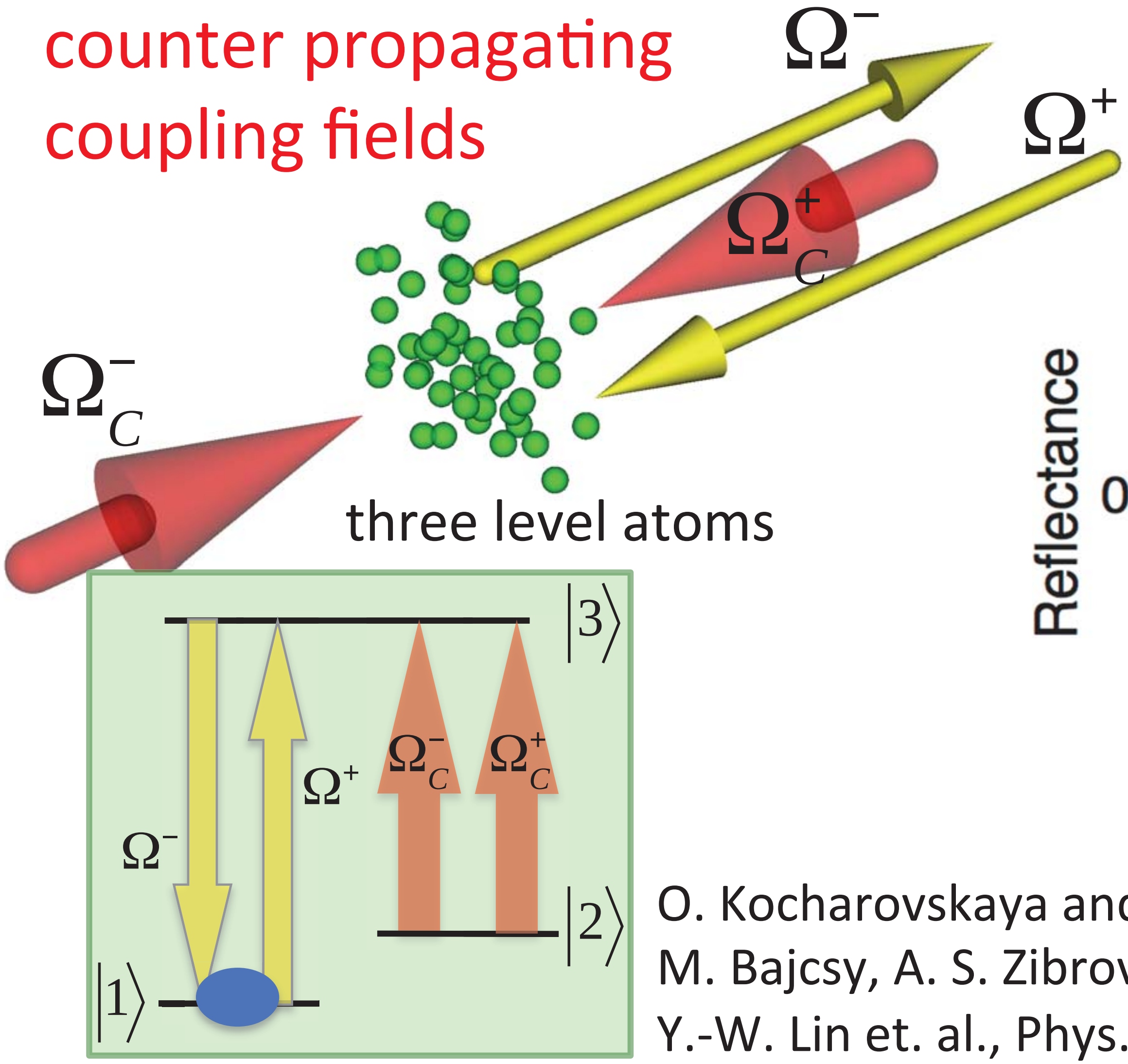
? Can fast control happen?

? can the mirror be as tiny as atom clouds in a cavity?

? any cavity effect different from vacuum Rabi oscillation?

? any novel way of controlling matter?

Dispersive Mirror



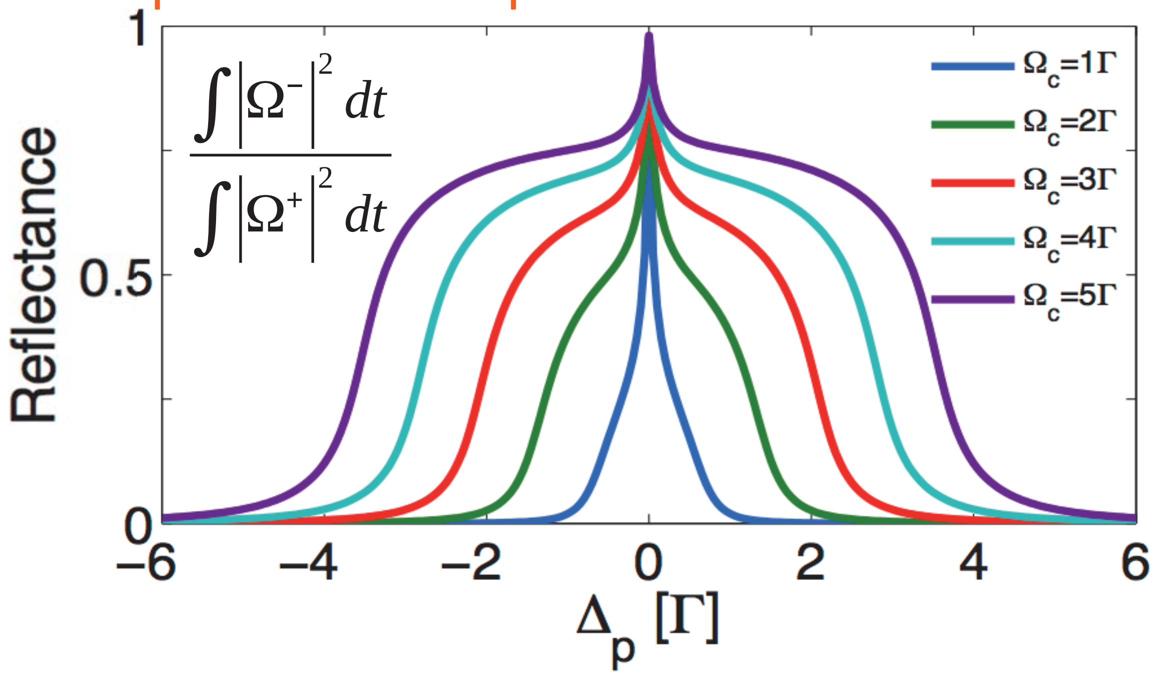
$$\partial_t\hat{\rho} = \frac{1}{i\hbar}\left[\hat{H},\hat{\rho}\right] + \hat{\rho}_{dec},$$

$$\left(\frac{1}{c}\partial_t \pm \partial_z\right)\Omega^{\pm} = i\eta_{EIT}\rho_{31}^{\pm}$$

Optical Bloch equation

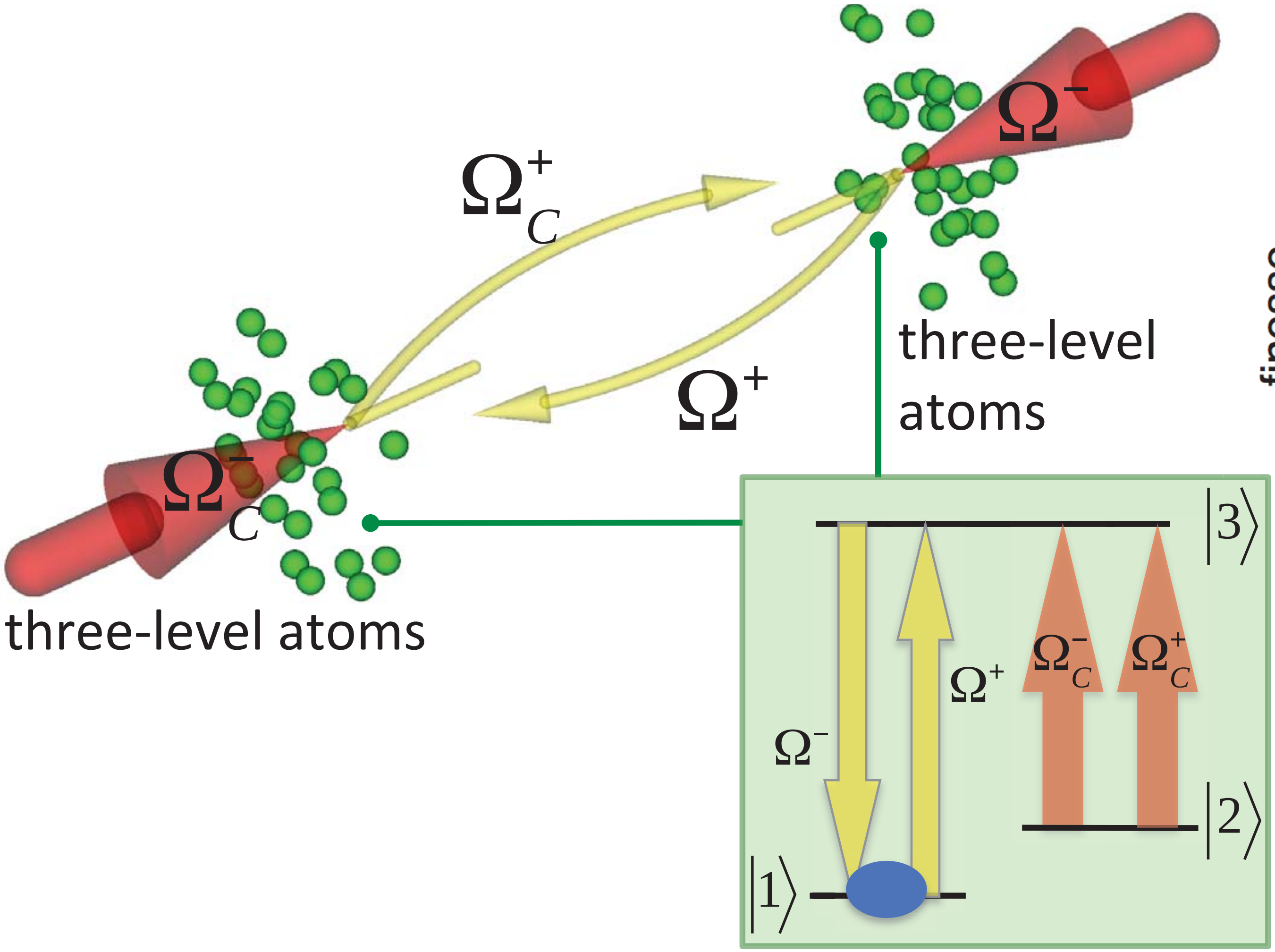
$$\eta_{EIT} = \Gamma d^{opt}/2L$$

optical depth (d^{opt}), linewidth (Γ), length (L)

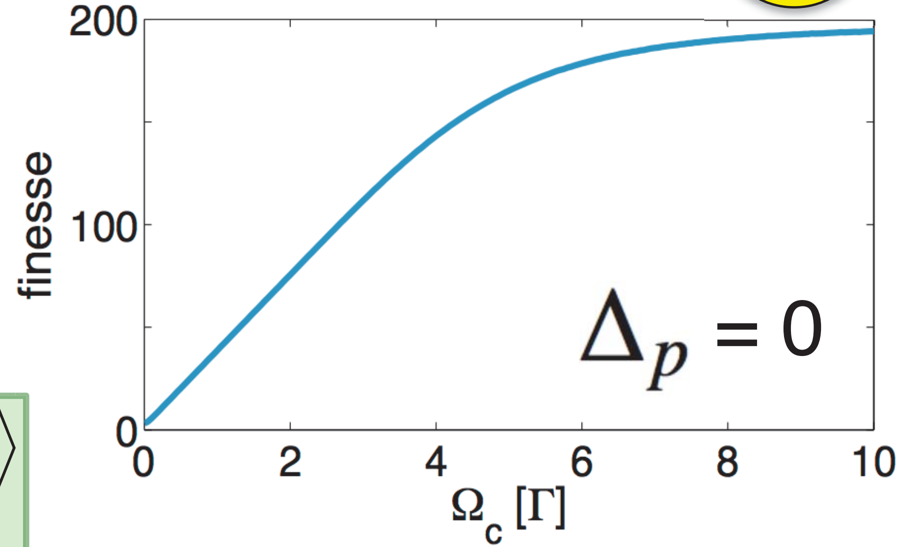


O. Kocharovskaya and Y. I. Khanin, Sov. Phys. JETP 63, 945 (1986).
M. Bajcsy, A. S. Zibrov, and M. D. Lukin, Nature 426, 638 (2003).
Y.-W. Lin et. al., Phys. Rev. Lett. 102, 213601 (2009).

Dispersive Cavity & its Finesse



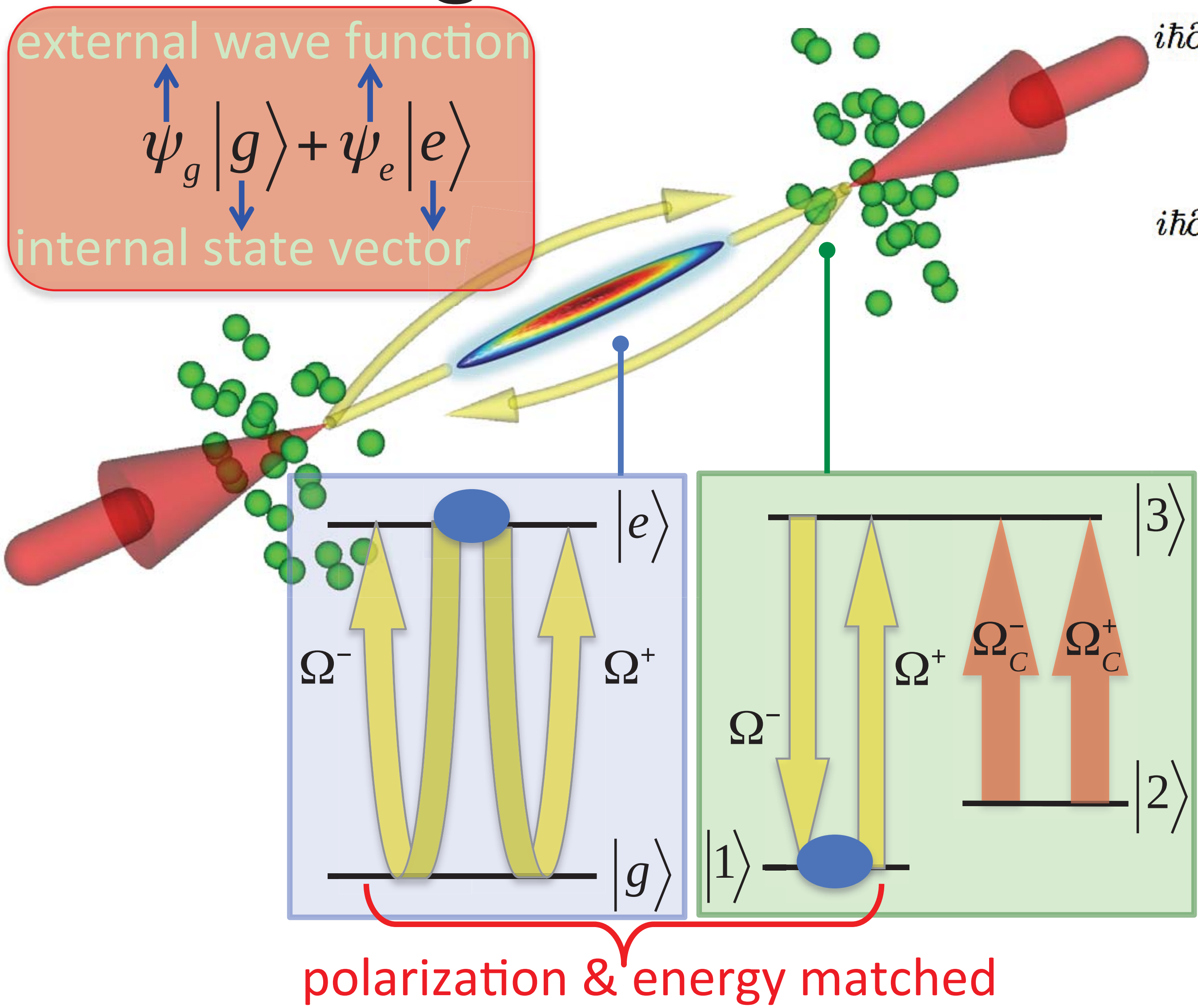
all-optical control



$$f(\Delta_p) = \frac{\pi}{1-R(\Delta_p)}$$

$R(\Delta_p)$ reflectance

Loading a 1D Bose-Einstein Condensate



$$i\hbar\partial_t\psi_g = \left(-\frac{\hbar^2}{2m}\partial_z^2 + V_{trap} + g_{gg}|\psi_g|^2 + g_{ge}|\psi_e|^2\right)\psi_g - \frac{\hbar}{2}\left(\Omega^{+*}e^{-ik_pz} + \Omega^{-*}e^{ik_pz}\right)\psi_e,$$

$$i\hbar\partial_t\psi_e = \left(-\frac{\hbar^2}{2m}\partial_z^2 + V_{trap} + g_{ee}|\psi_e|^2 + g_{ge}|\psi_g|^2\right)\psi_e - \frac{\hbar}{2}\left(\Omega^{+}e^{ik_pz} + \Omega^{-}e^{-ik_pz}\right)\psi_g,$$

Gross-Pitaevskii equation

$$\left(\frac{1}{c}\partial_t \pm \partial_z\right)\Omega^{\pm} = i\eta_{BEC}\sigma_{eg}^{(\pm1)}$$

wave equation in a cavity

$$\sigma_{eg} = \psi_e\psi_g^*$$

BEC coherence

particle number

$$\eta_{BEC} = 3\Gamma N_{BEC}\lambda^2/4\pi A$$

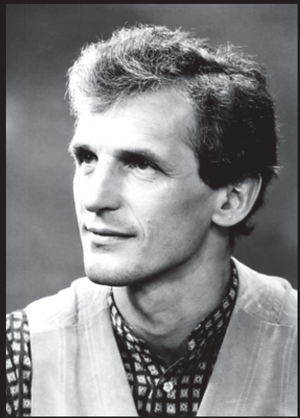
BEC's cross section

BEC-photon coupling constant

Bose-Einstein Condensate
video link
http://toutestquantique.fr/en/bose-einstein-condensate/

Bose-Einstein Condensate (2001 Nobel Prize)

Eric Cornell

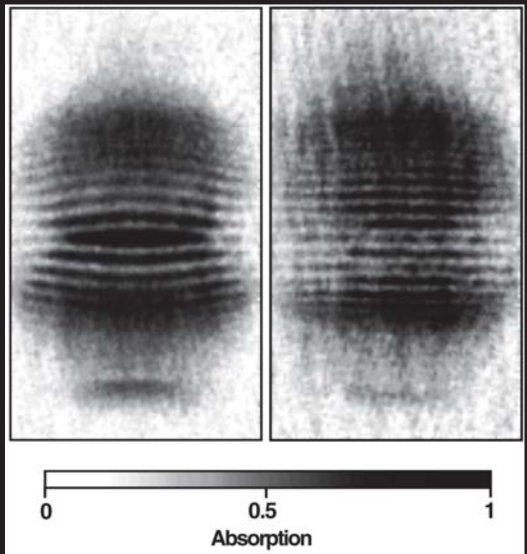


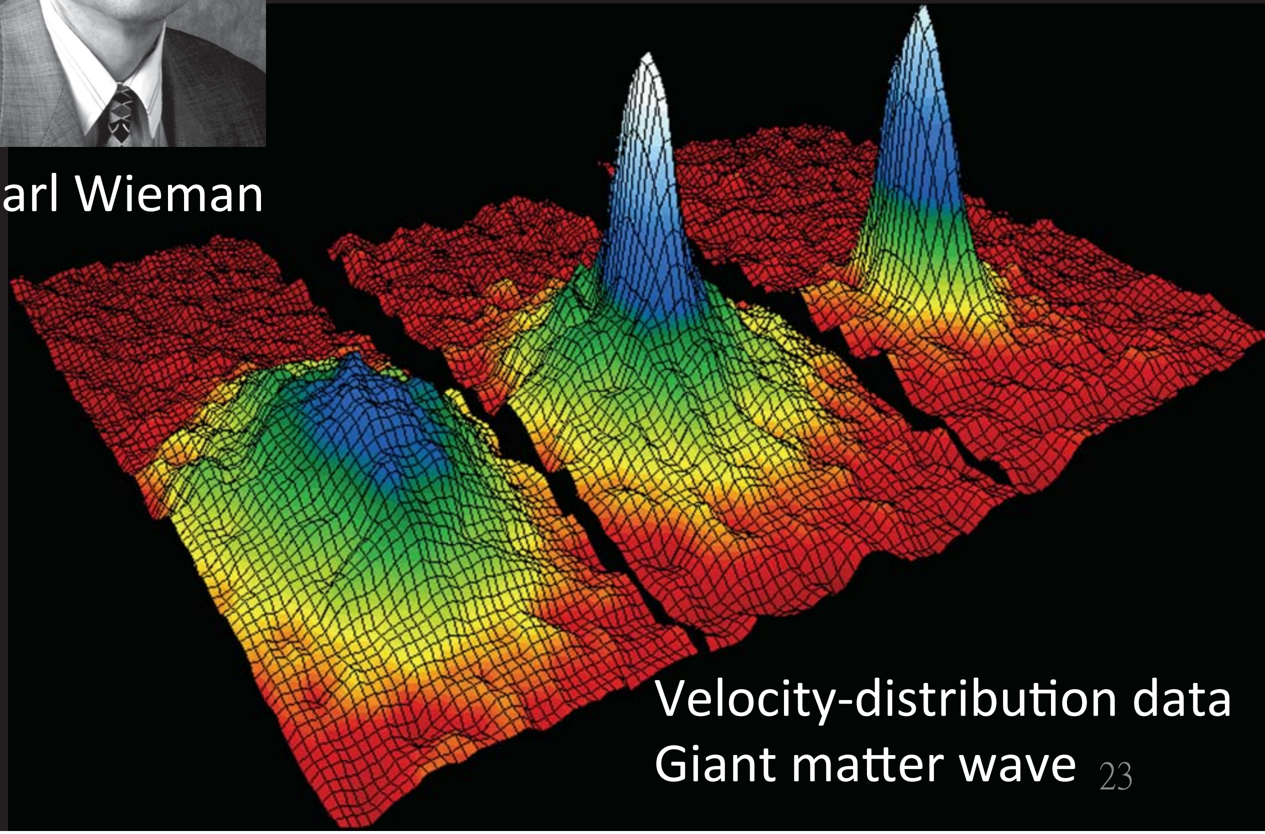
Wolfgang Ketterle

Carl Wieman

interference
between
2 BECs

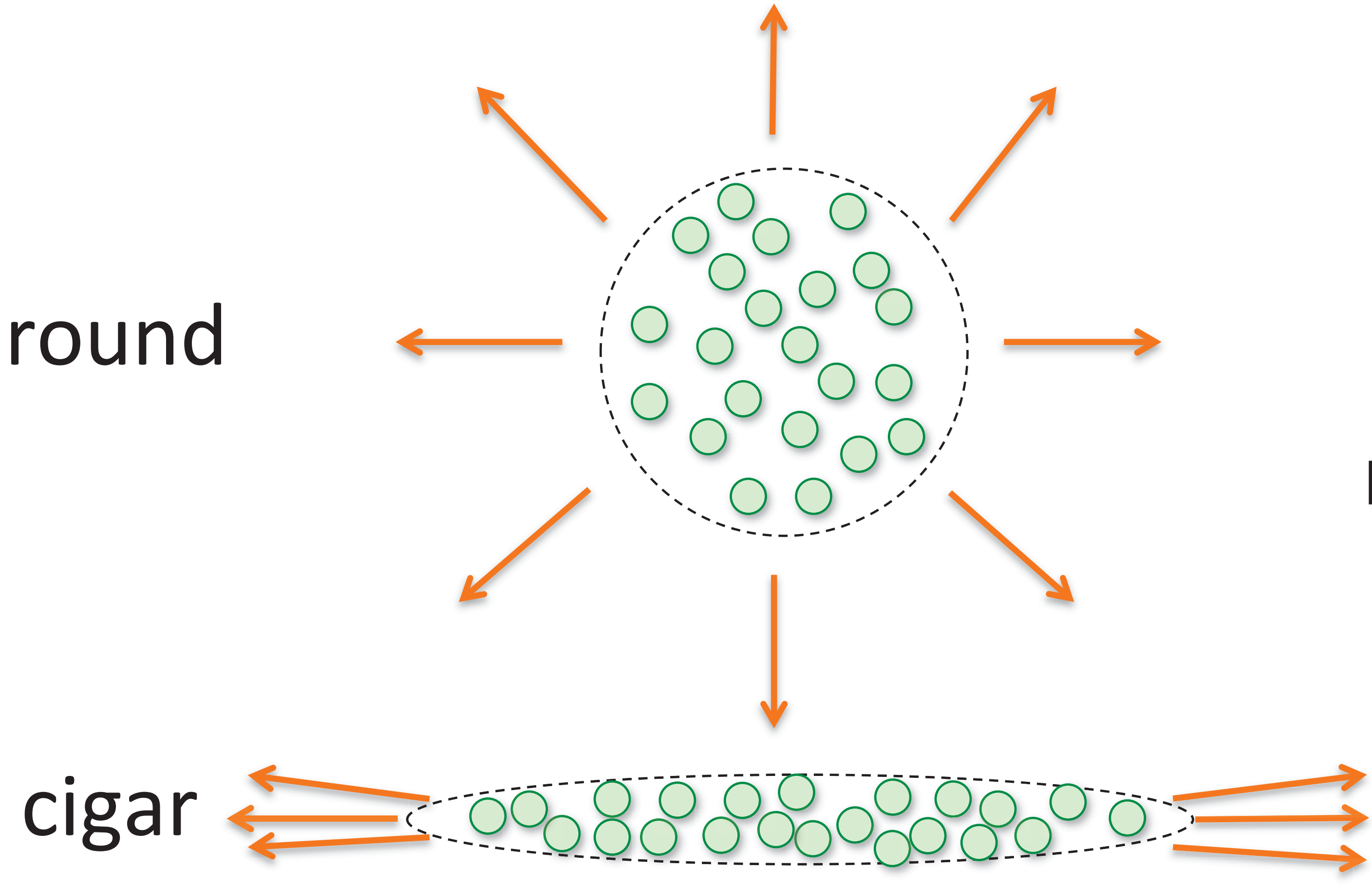
Coherent !!!

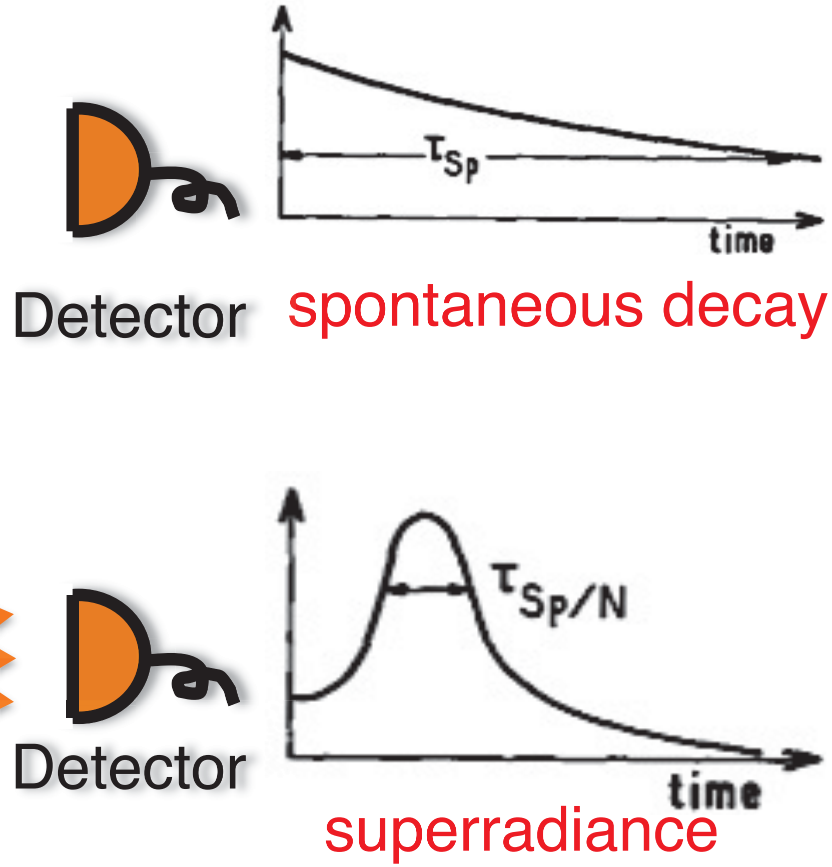




Velocity-distribution data
Giant matter wave

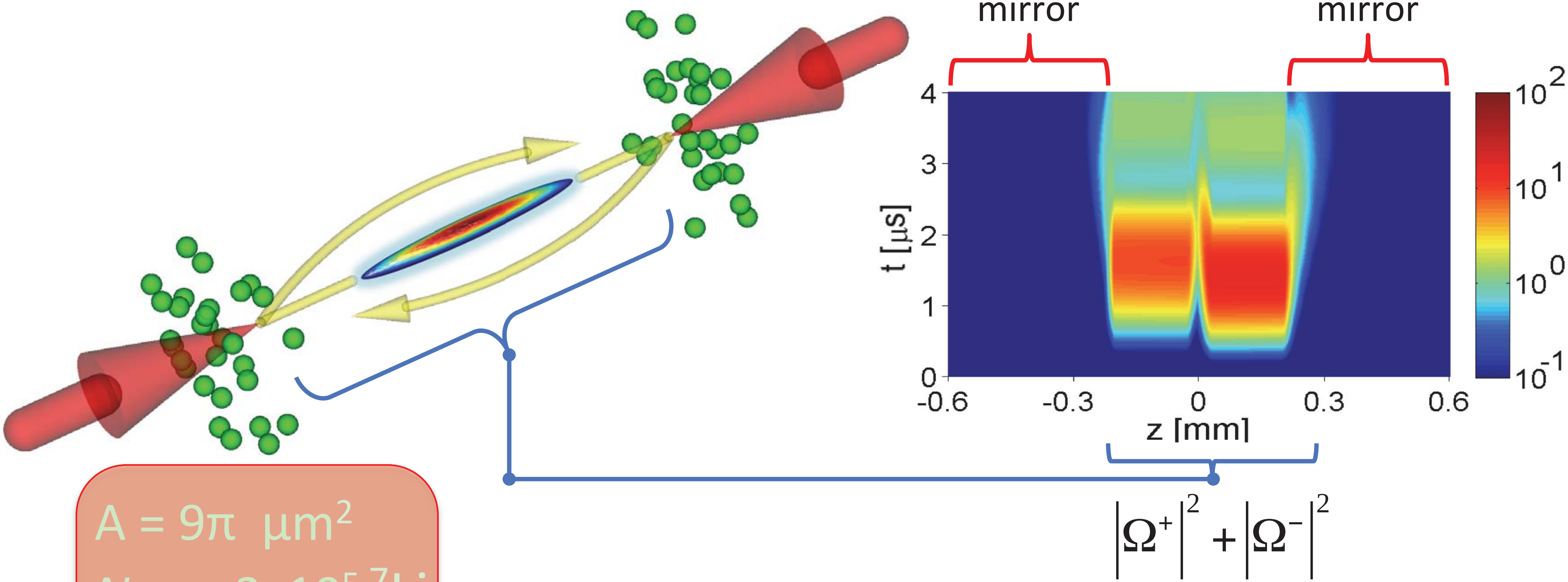
Superradiance from 1D gas





M. Gross, S. Haroche, Phys. Rep. 93, 301 (1982).
F. Haake et al., Phys. Rev. A 20,2047 (1979).
S. Inouye et al. Science 285, 571 (1999).

Confined superradiance from BEC



$A = 9\pi\ \mu m^2$

$N_{BEC} = 3x10^5\ ^7Li$

$d^{opt} = 500$

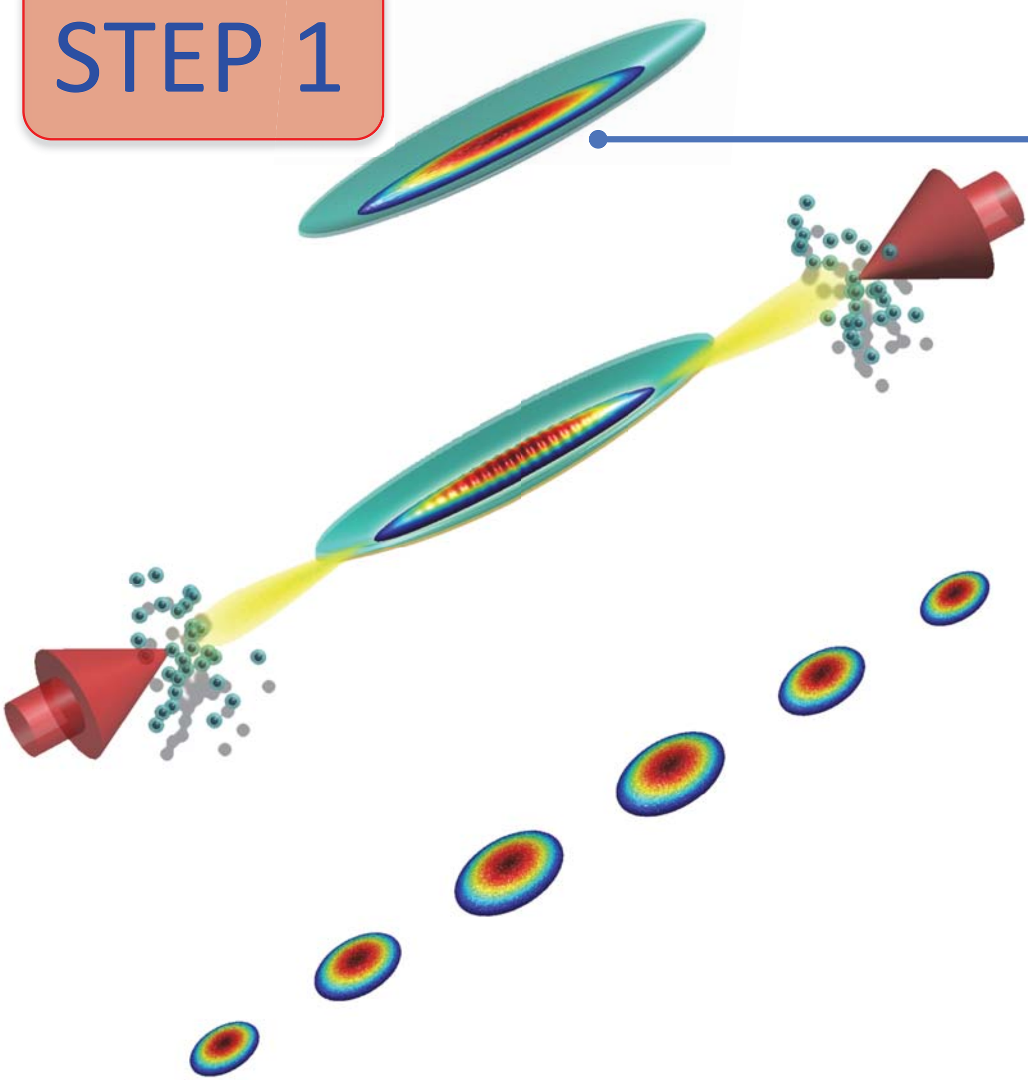
$\Omega c = 2\Gamma$

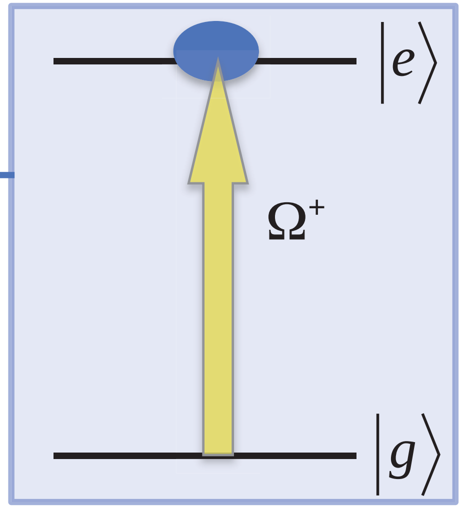
SR confined between two atomic mirrors.

Vacuum induced atomic diffraction

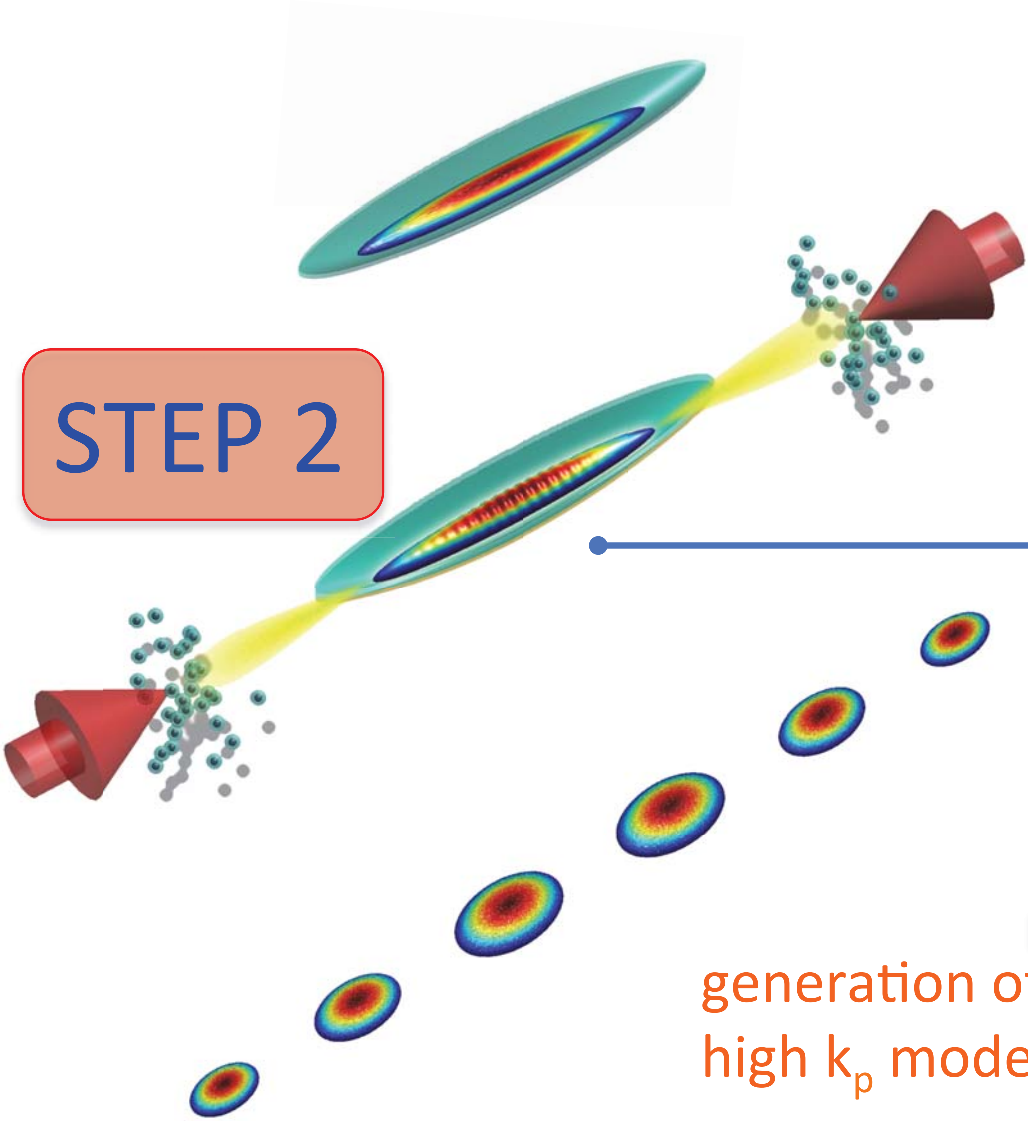
STEP 1

prepare and promote a binary BEC



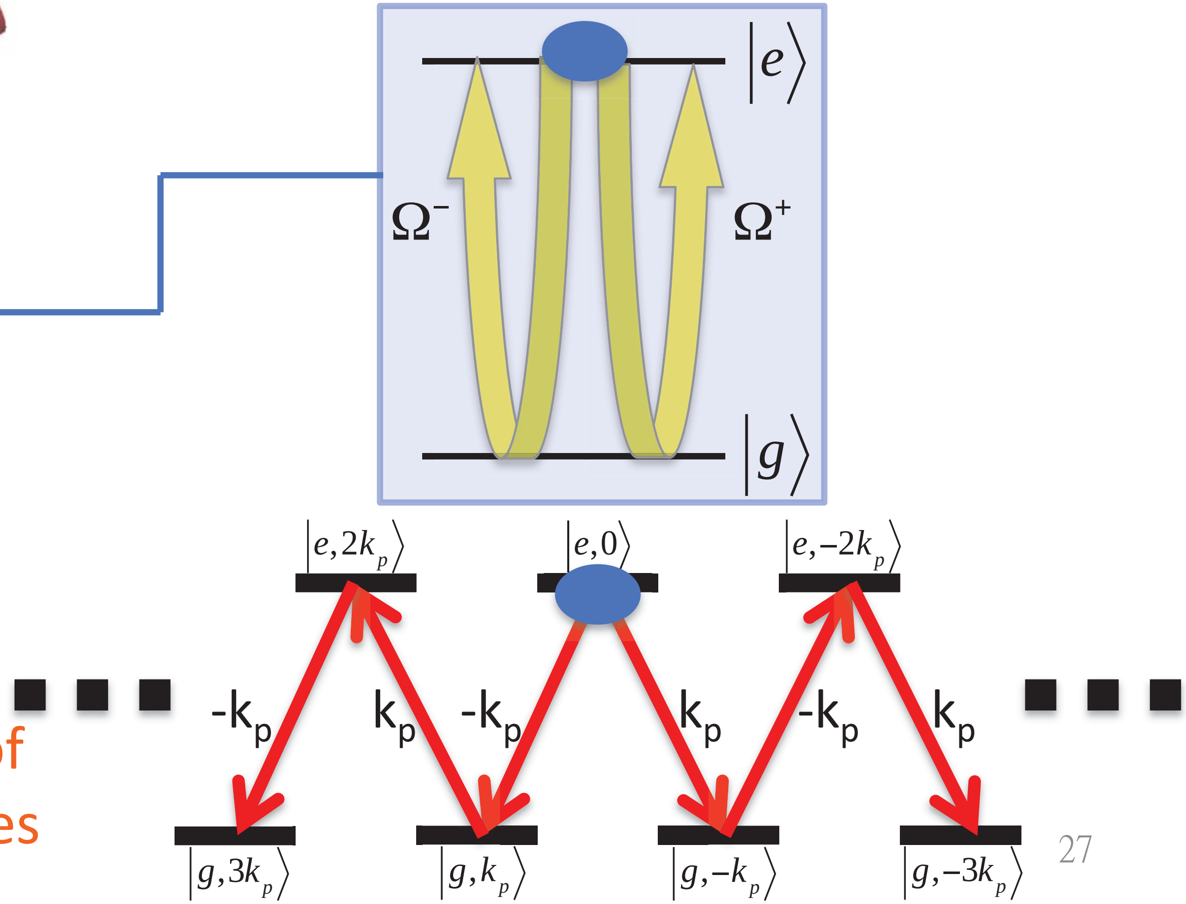


Vacuum induced atomic diffraction



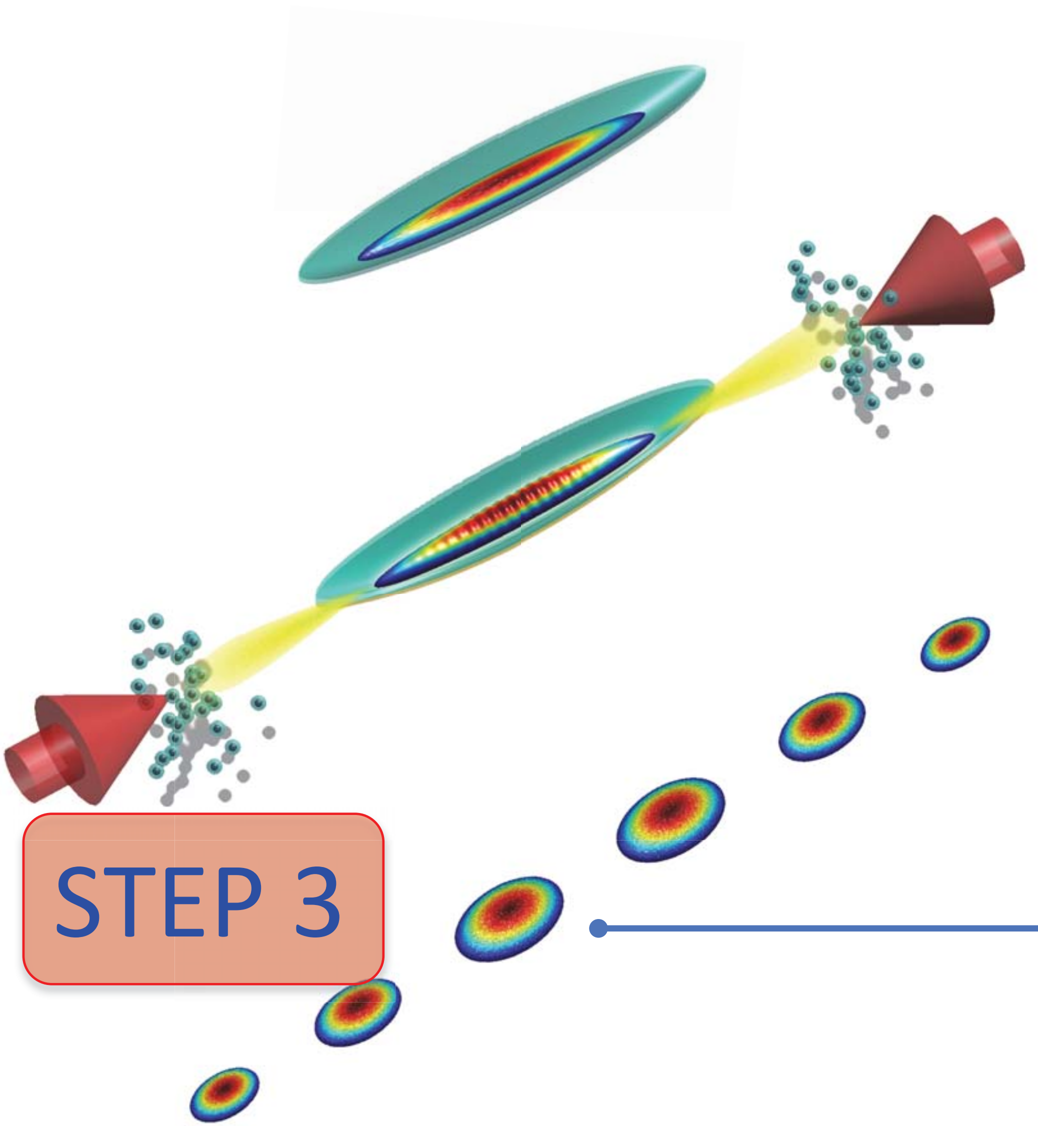
STEP 2

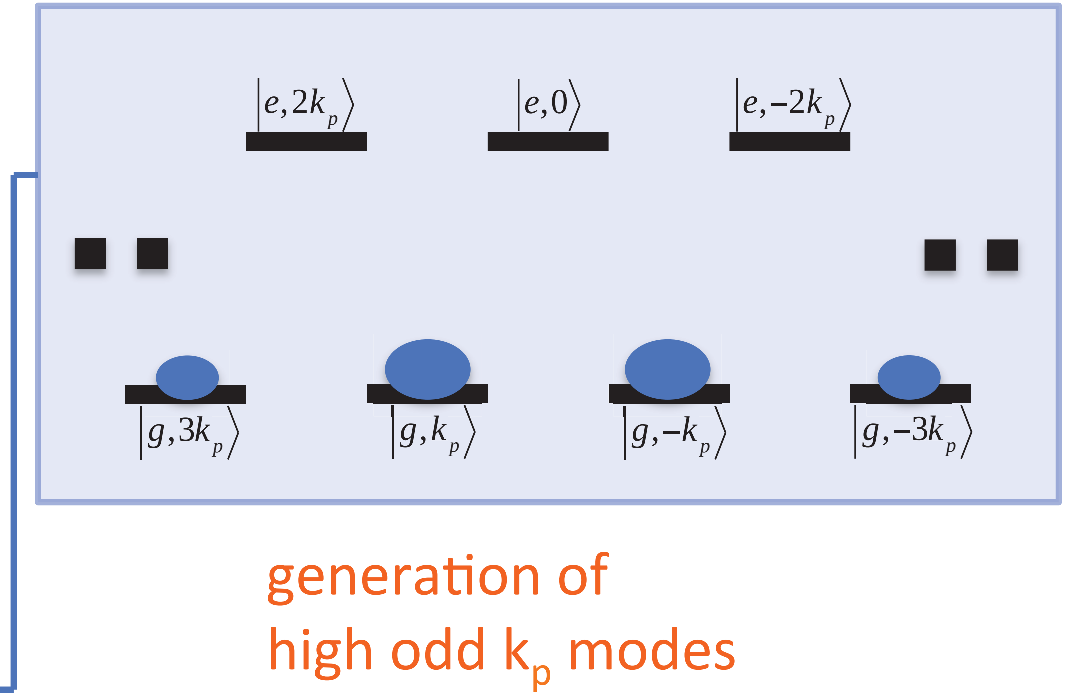
multiple scattering between BEC & circulating photons



generation of high k_p modes

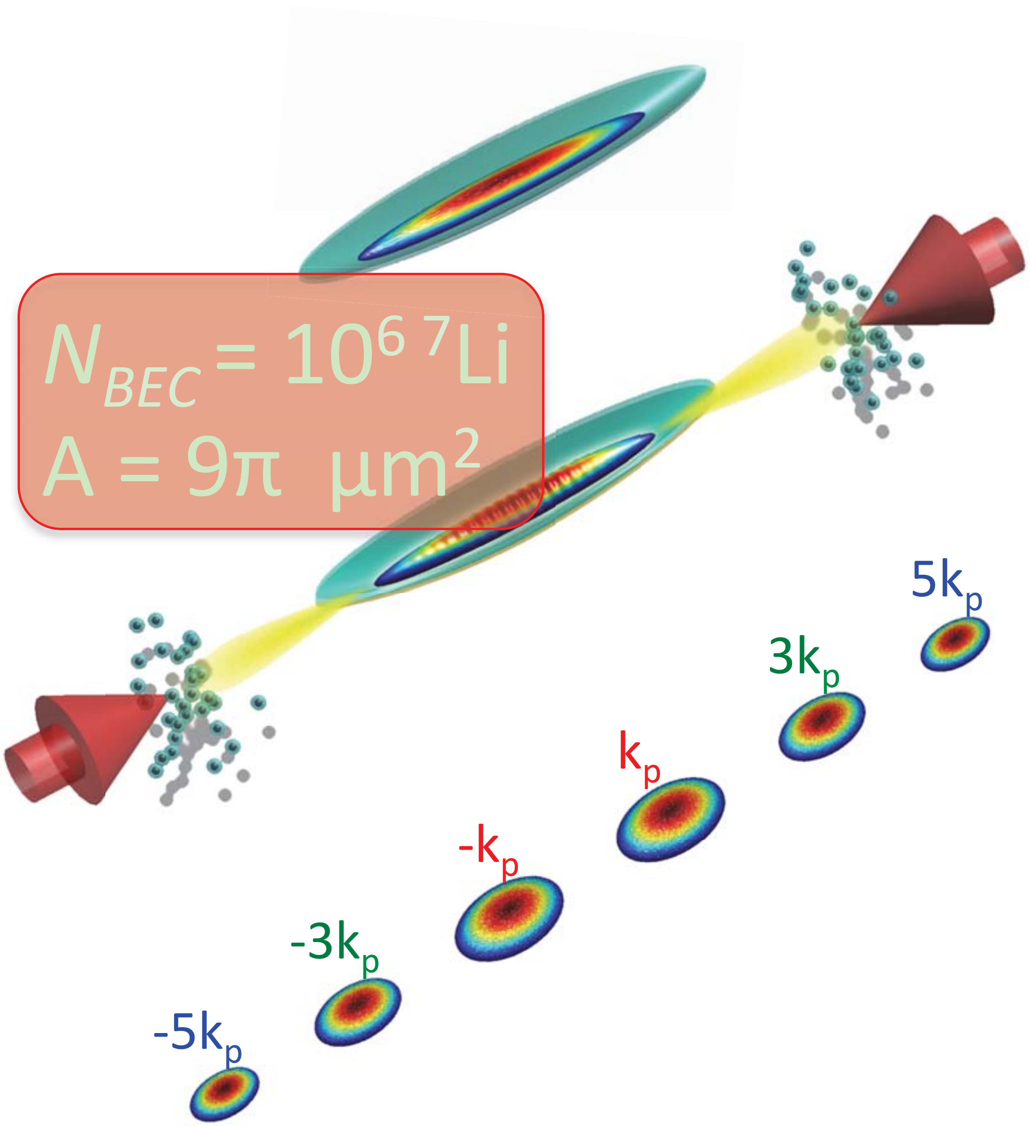
Vacuum induced atomic diffraction

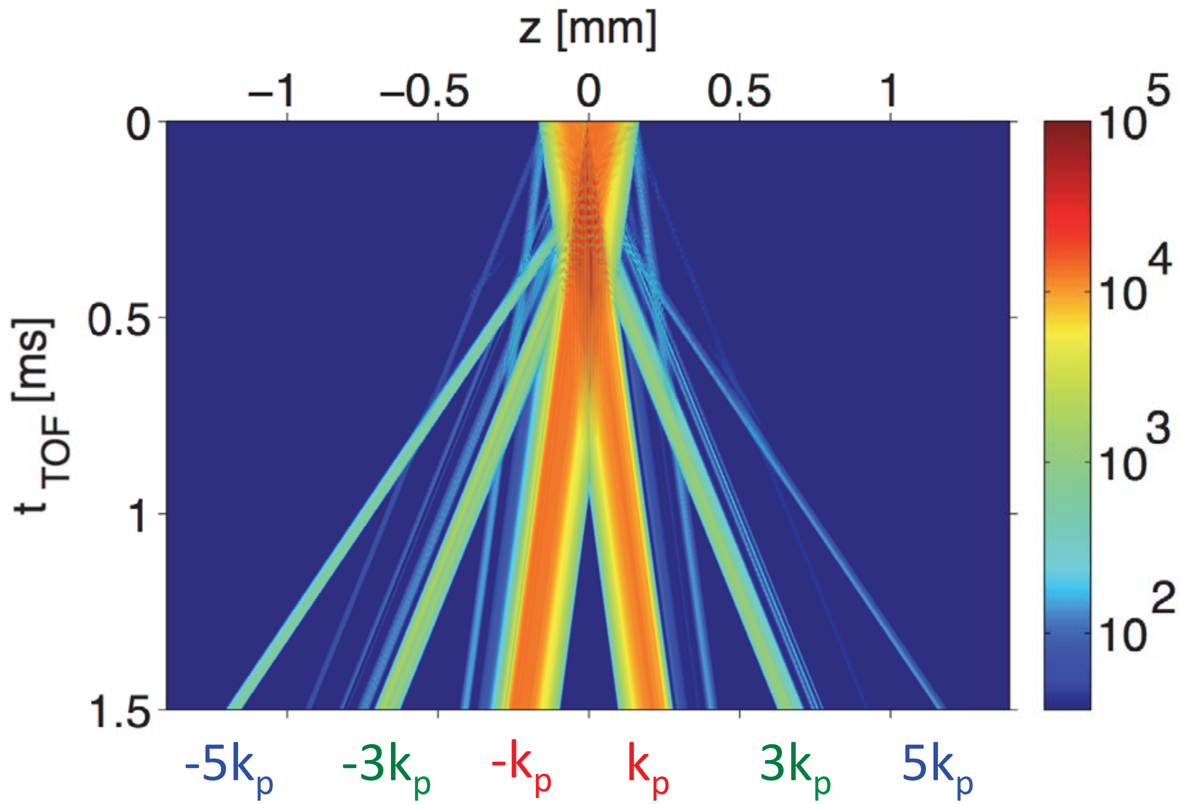




generation of
high odd k_p modes

Time of flight simulation

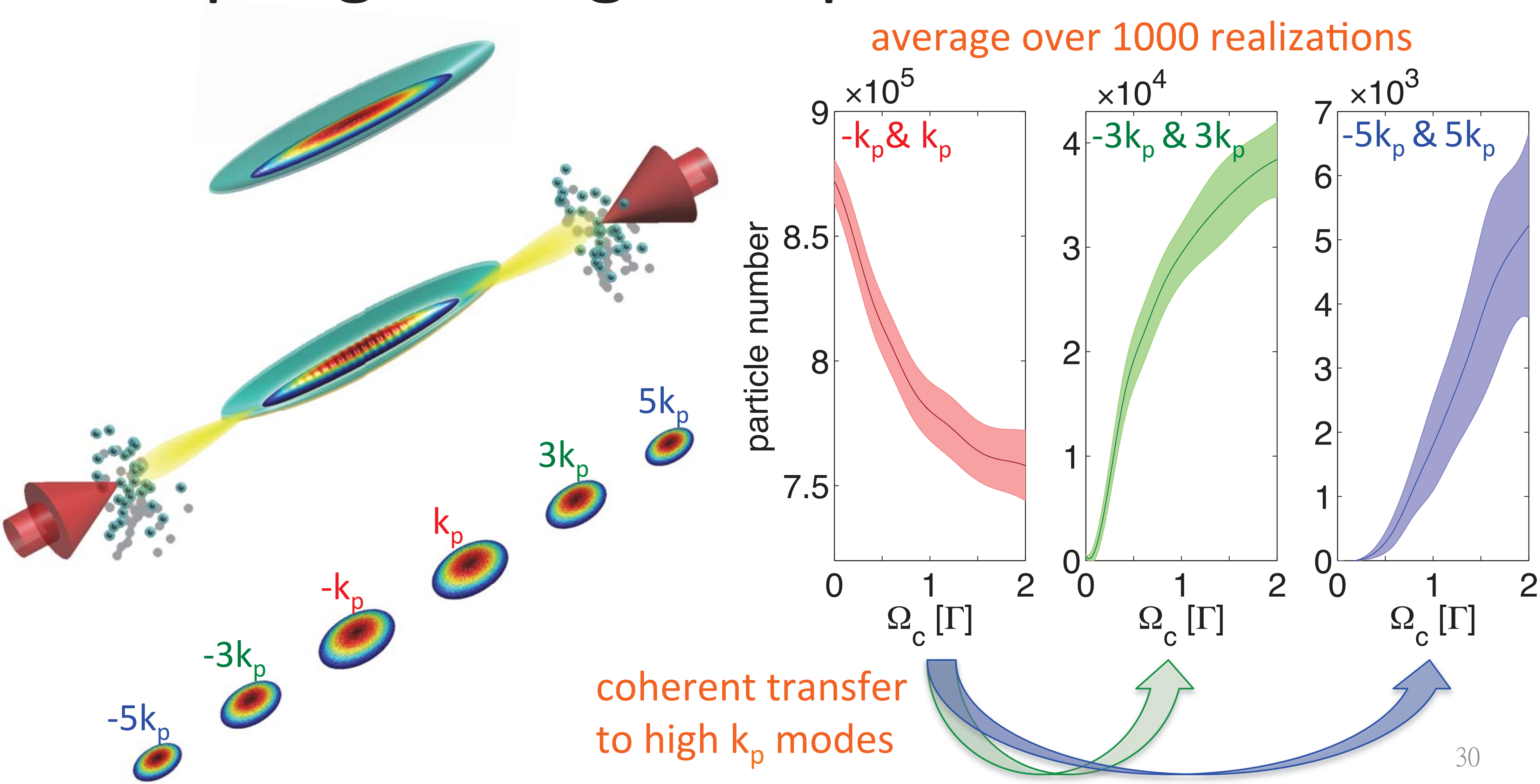




generation of
high odd k_p modes

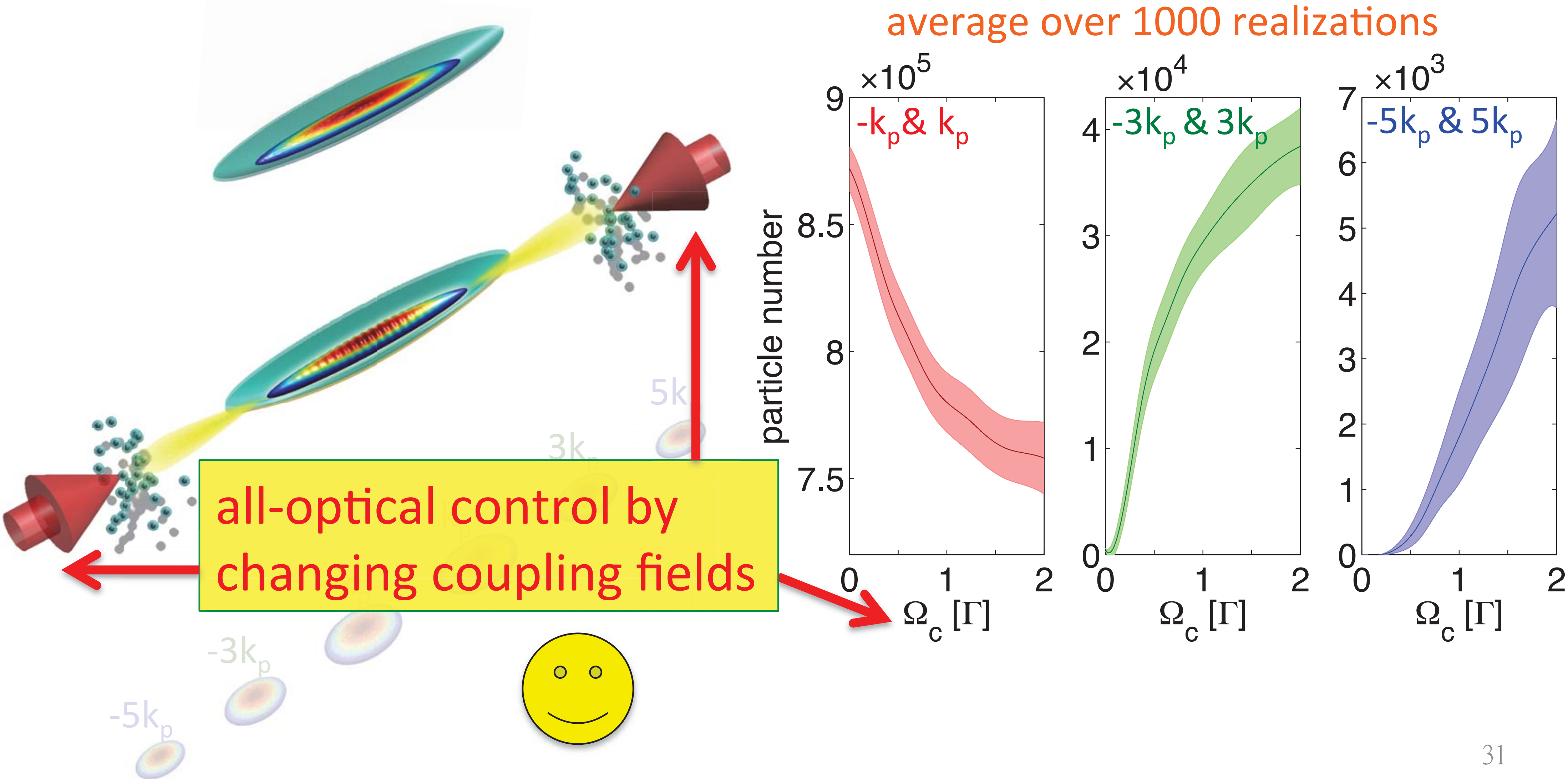
Coupling-strength-dependent diffraction

average over 1000 realizations

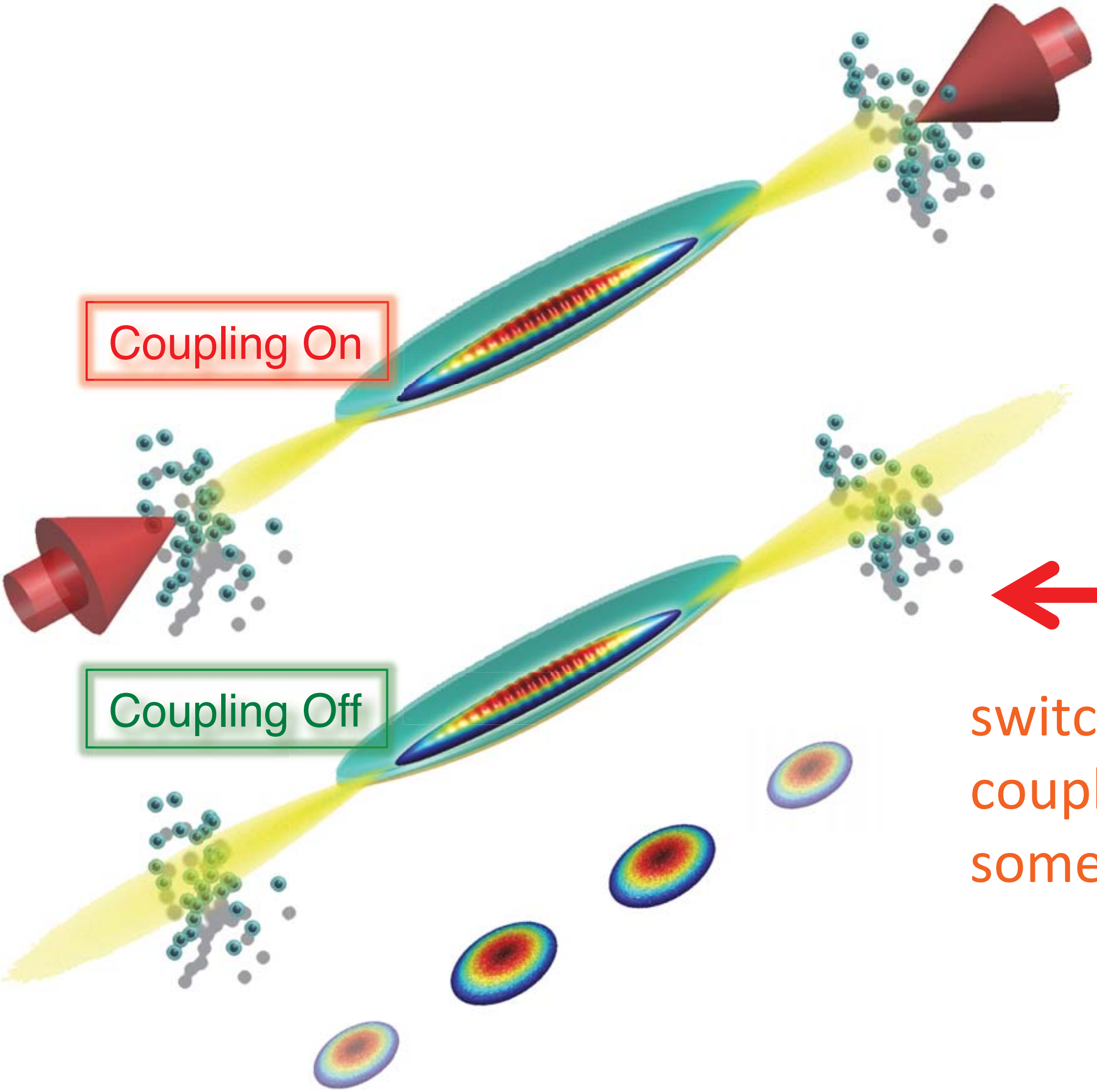


coherent transfer to high k_p modes

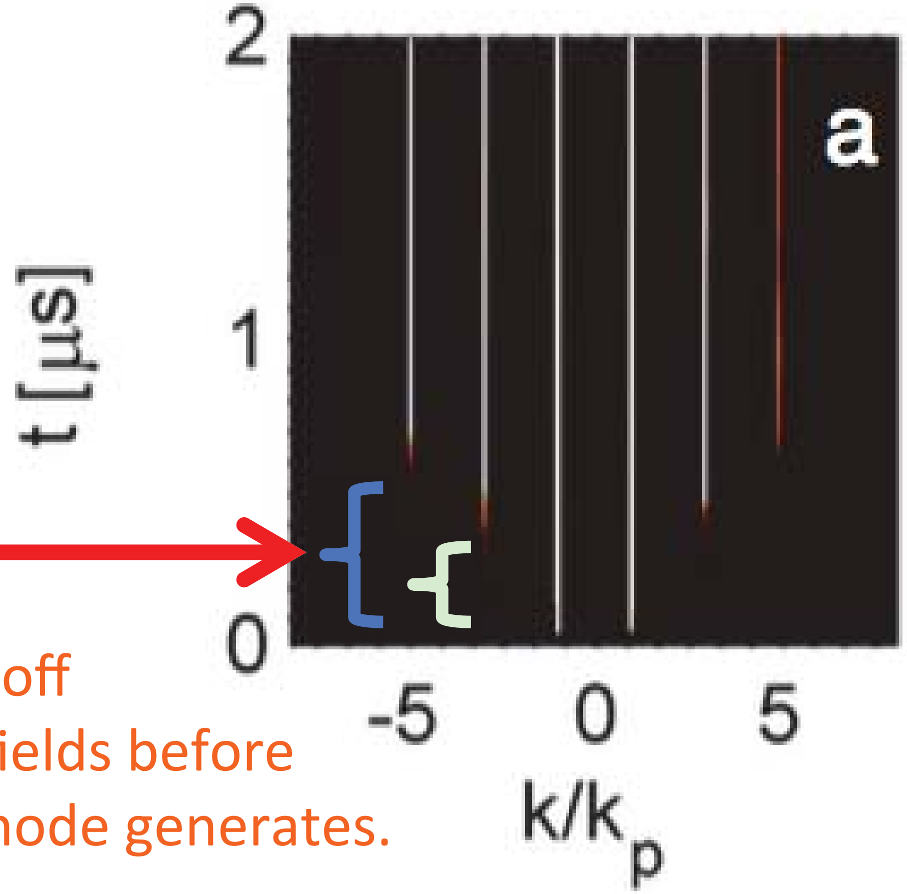
Coupling-strength-dependent diffraction



Dynamical control of diffraction

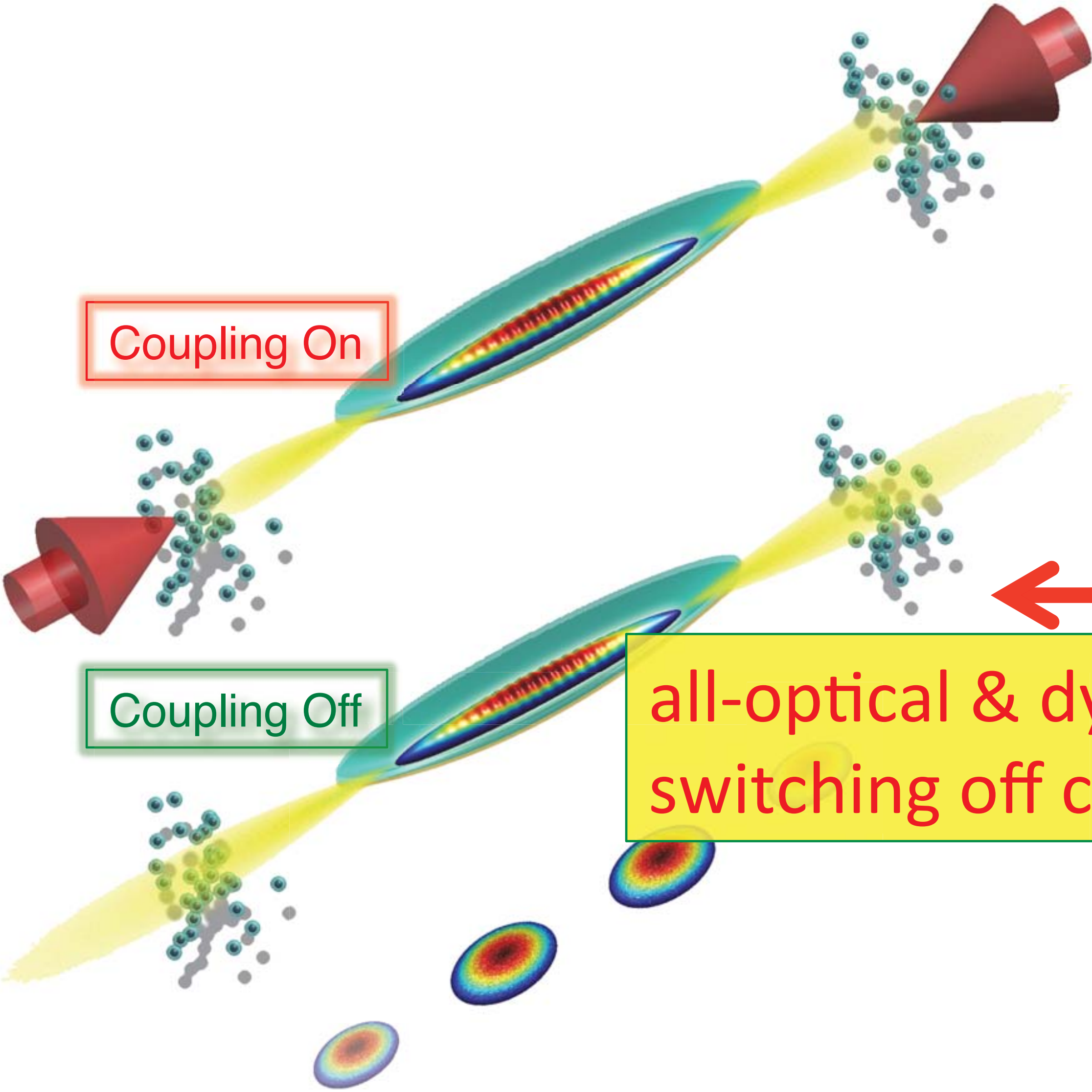


BEC density evolution in k-space

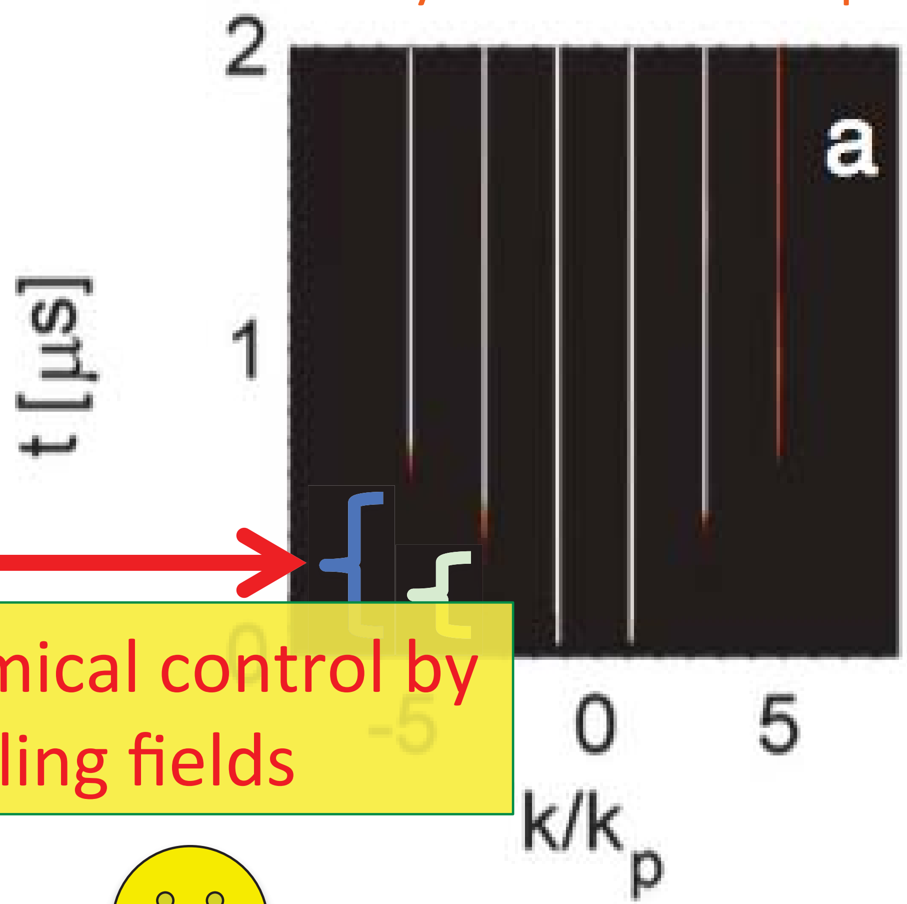


switching off coupling fields before some k_p mode generates.

Dynamical control of diffraction

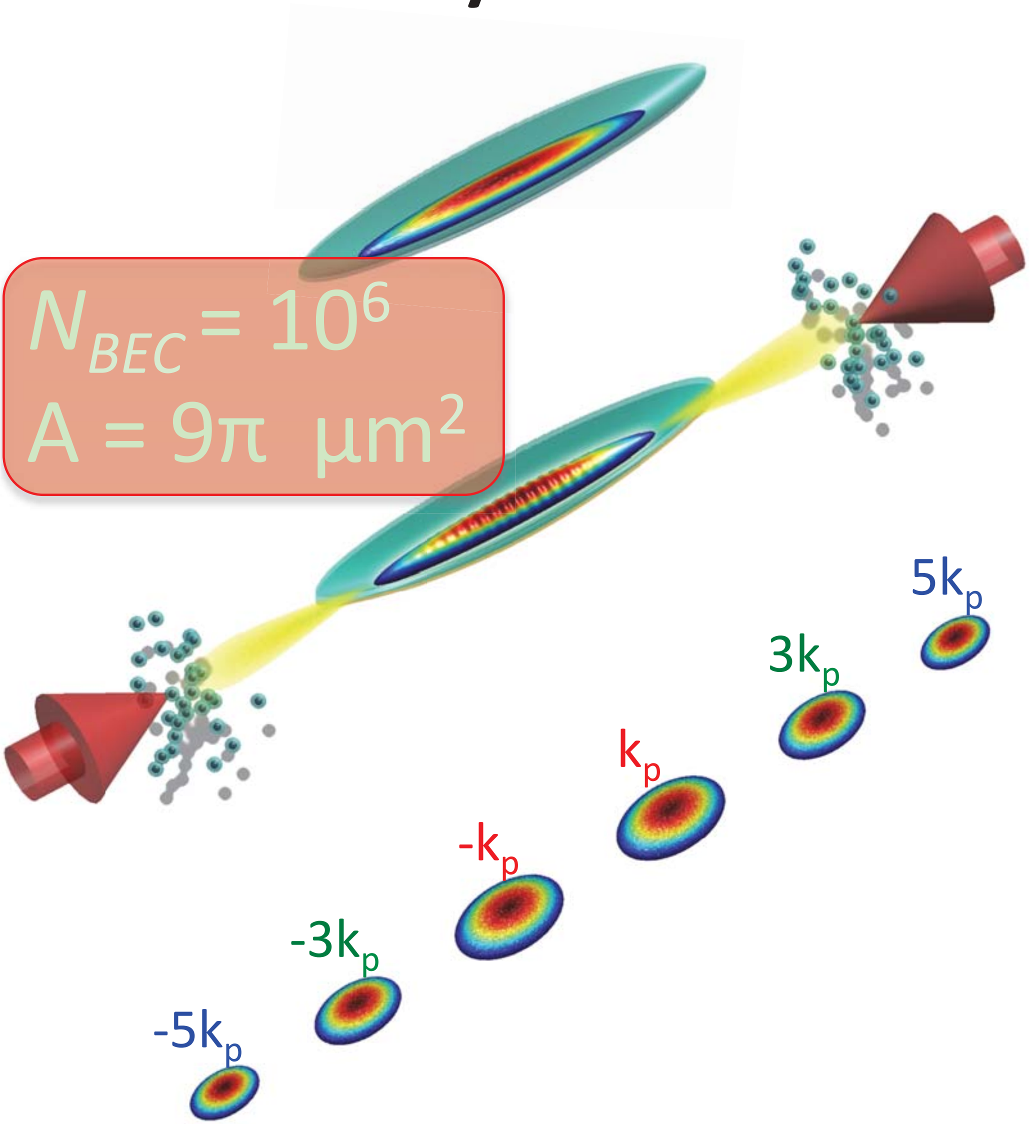


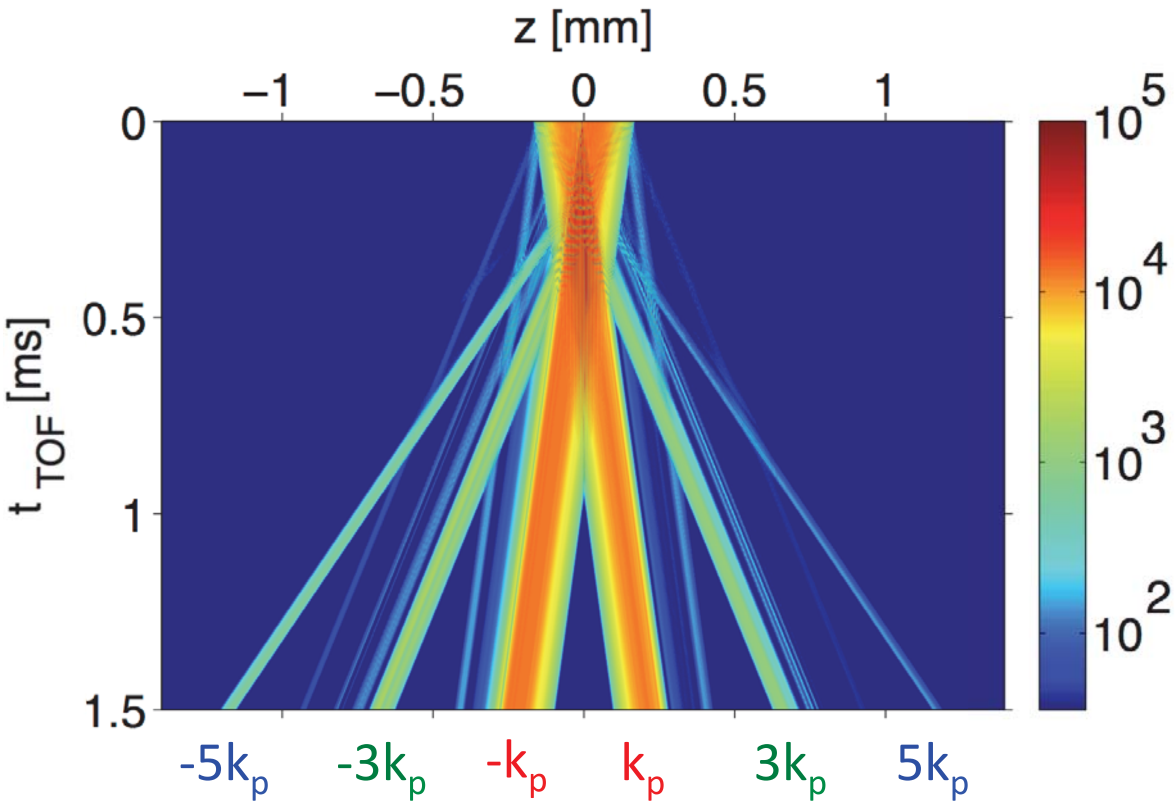
BEC density evolution in k-space



all-optical & dynamical control by switching off coupling fields

Dynamical control of diffraction

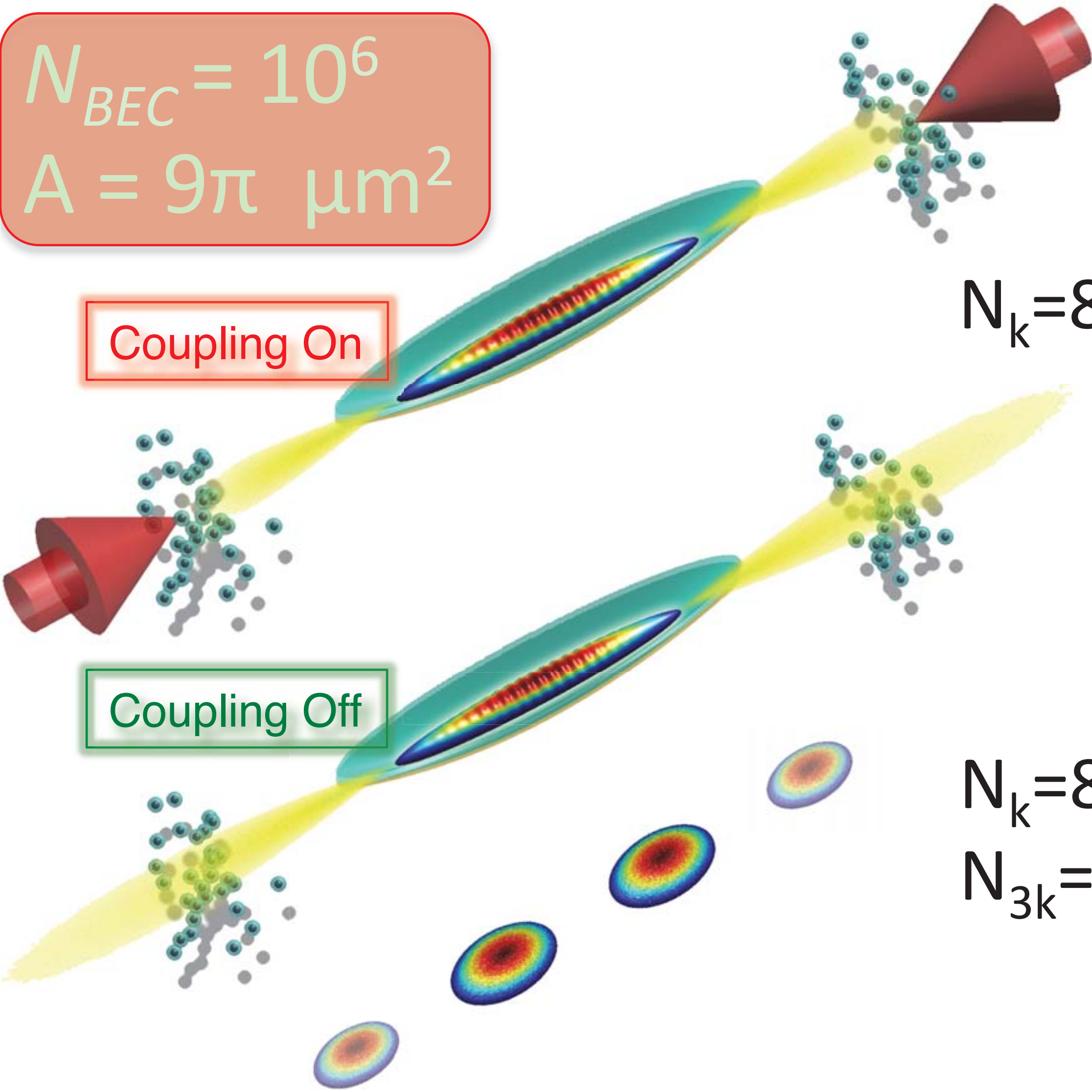




coupling always on

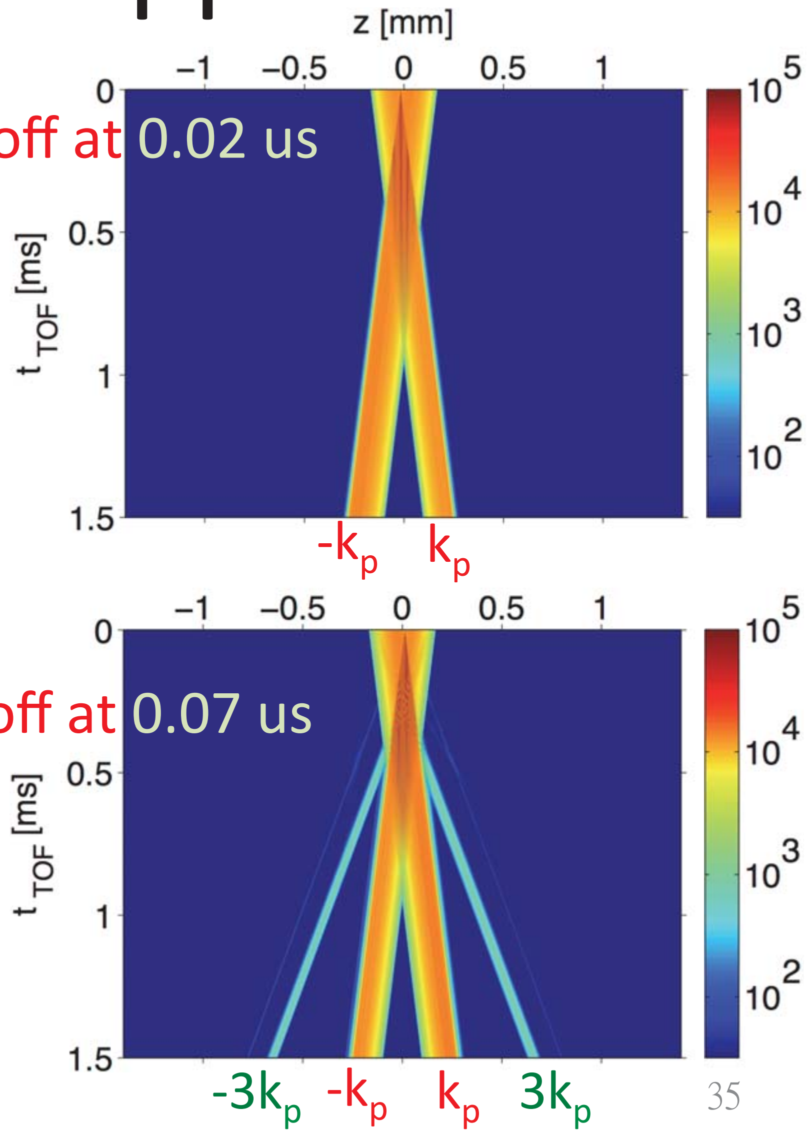
Specific mode can be suppressed

$N_{BEC} = 10^6$
$A = 9\pi\ \mu m^2$



coupling off at 0.02 us

$N_k = 8.5\times10^5$



coupling off at 0.07 us

$N_k = 8.2\times10^5$
$N_{3k} = 1.6\times10^4$

Summary

an all-optical and dynamically controllable cavity is demonstrated.

a dispersive cavity can be used to manipulate atomic diffraction by
1) changing the strength of coupling fields
2) dynamically switching off the coupling fields

arXiv:1508.04878