A Single Atom and the Radiation Field in Free Space

- an experimental study

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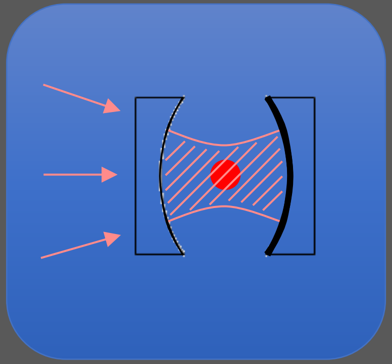
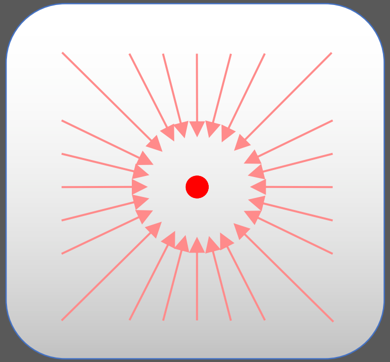
1 atom inside a cavity

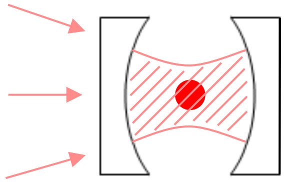


Haroche
Walther
Kimble
Rempe
…
Senellart
…

atom in free space



CQED



strong coupling

$\frac{g}{\gamma} \geq 1$ and $\frac{g}{\kappa} \geq 1$

$$\frac{g}{\gamma} \cdot \frac{g}{\kappa} = P_A \cdot N_{eff}$$

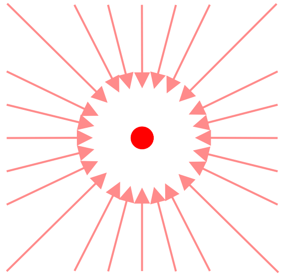
Sondermann et al.,
Appl.Phys.B 89, 489 (2007)

P. Pinkse, G. Rempe,
Exp.Meth.Phys.Sci. 40, 255 (2002)

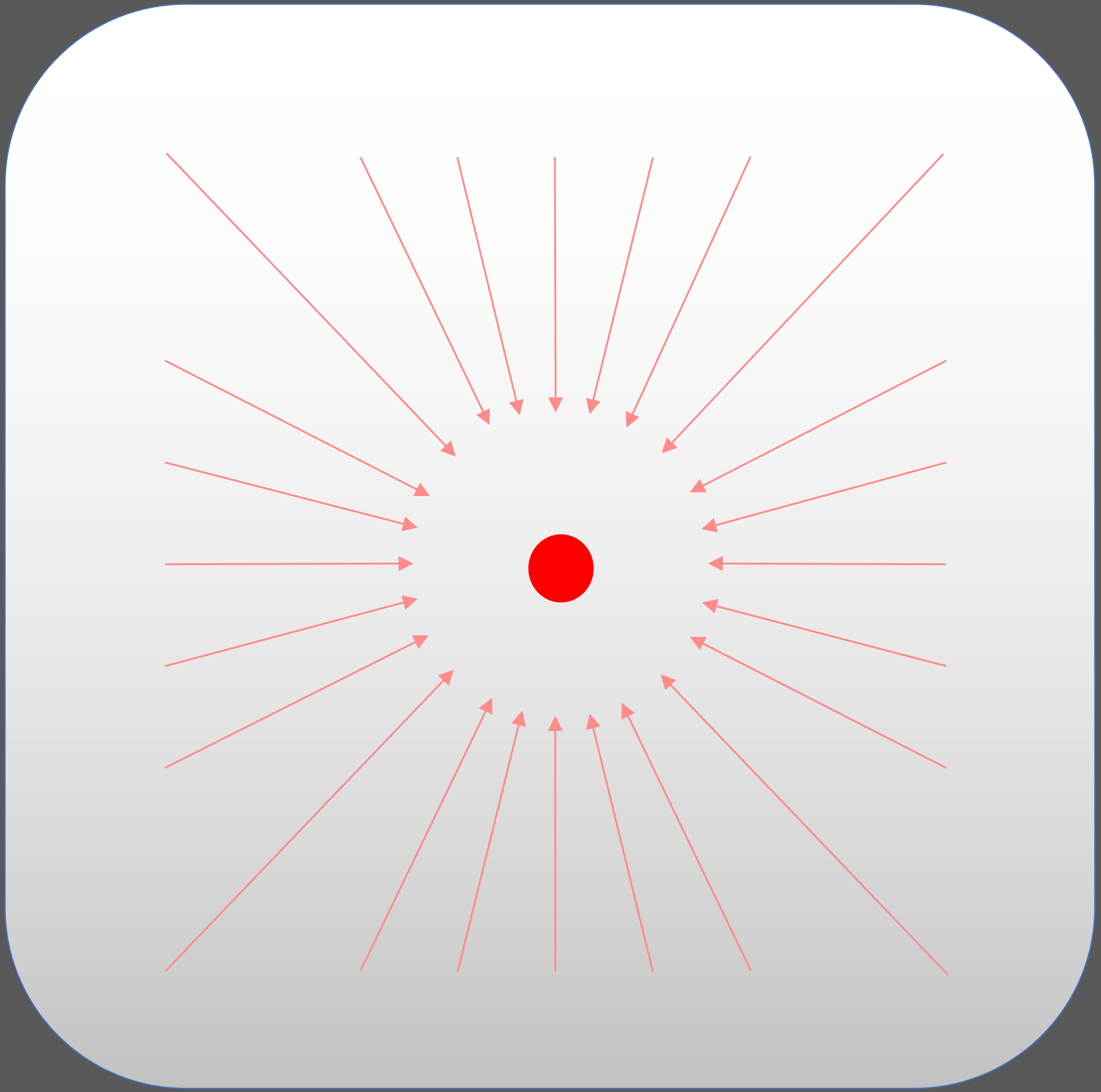
1

$$\frac{g^2}{\gamma \cdot \kappa}$$

free space coupling

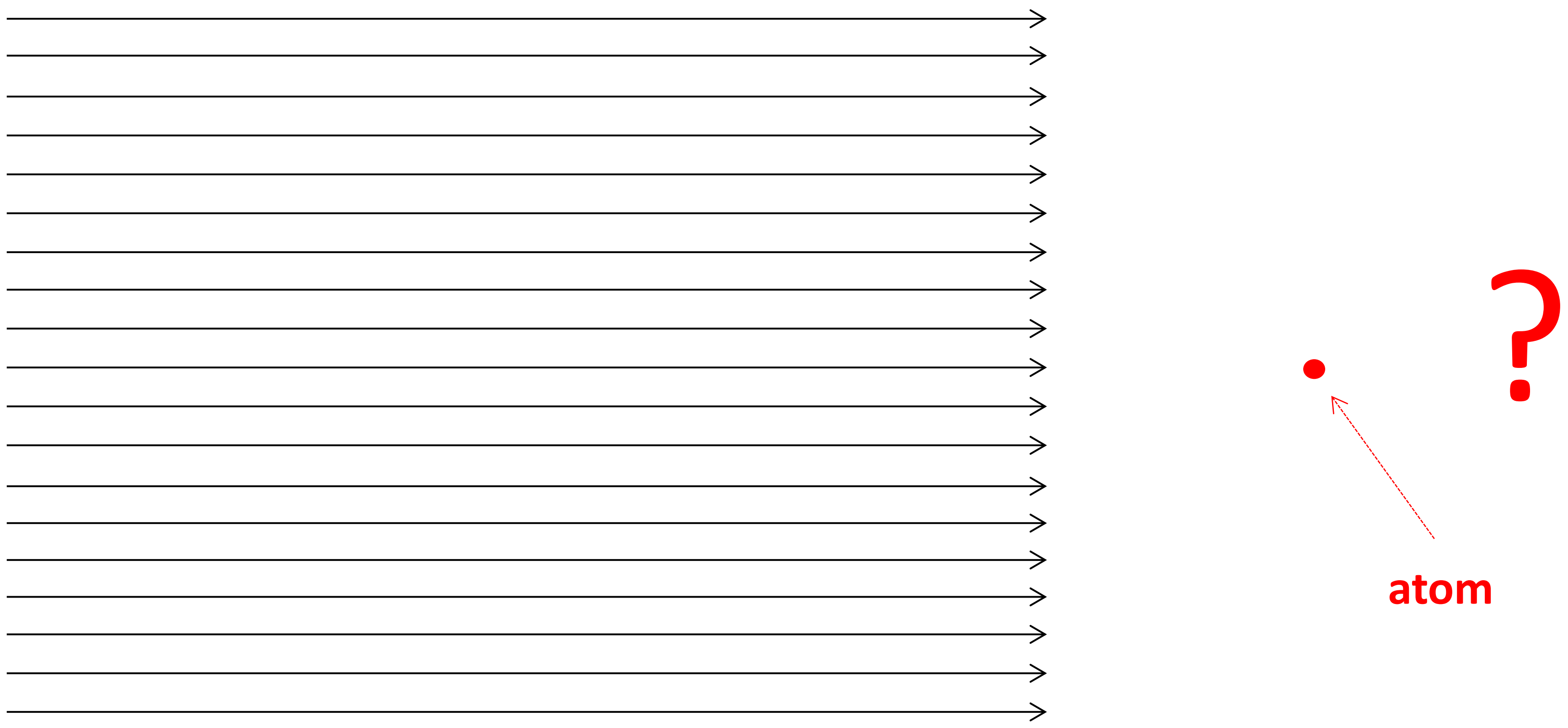


efficient &
broad band



focussing to an atom* ...

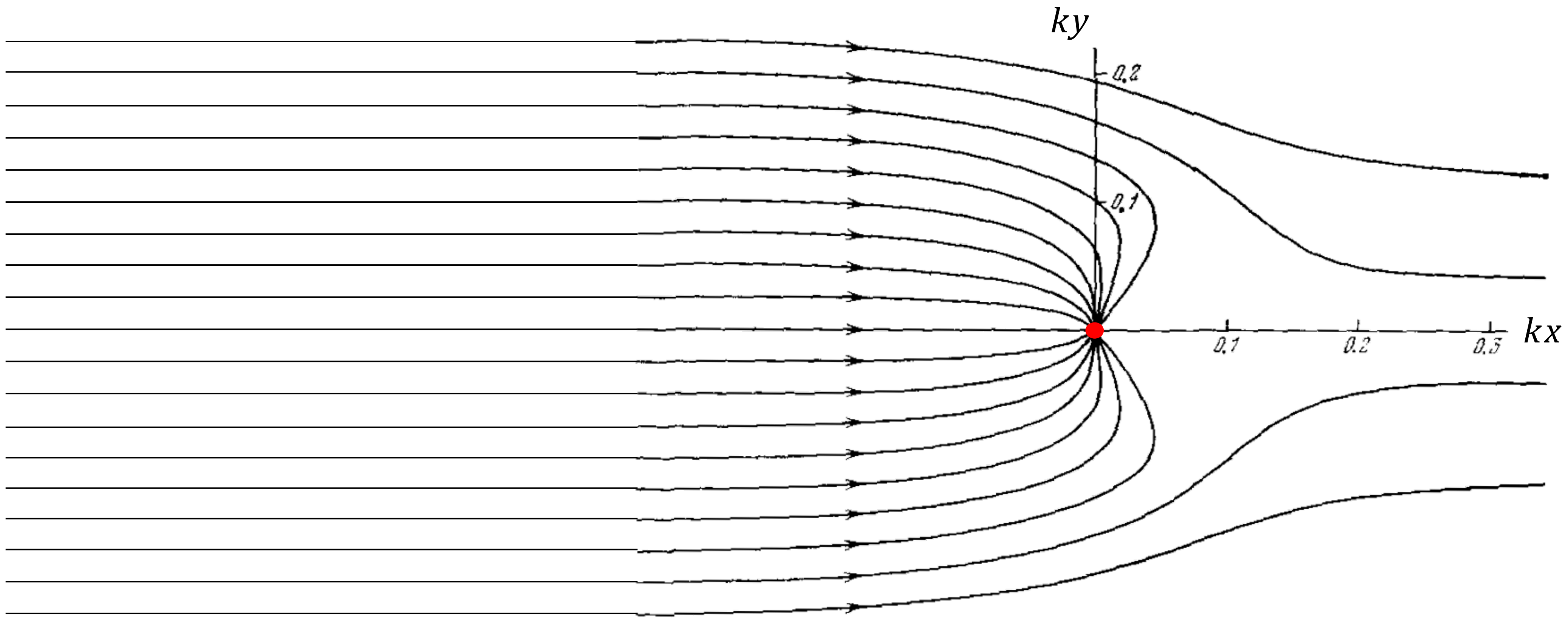
... without a lens or mirror ?



* dipole transition

focussing to an atom* ...

... without a lens or mirror !



dipole transition

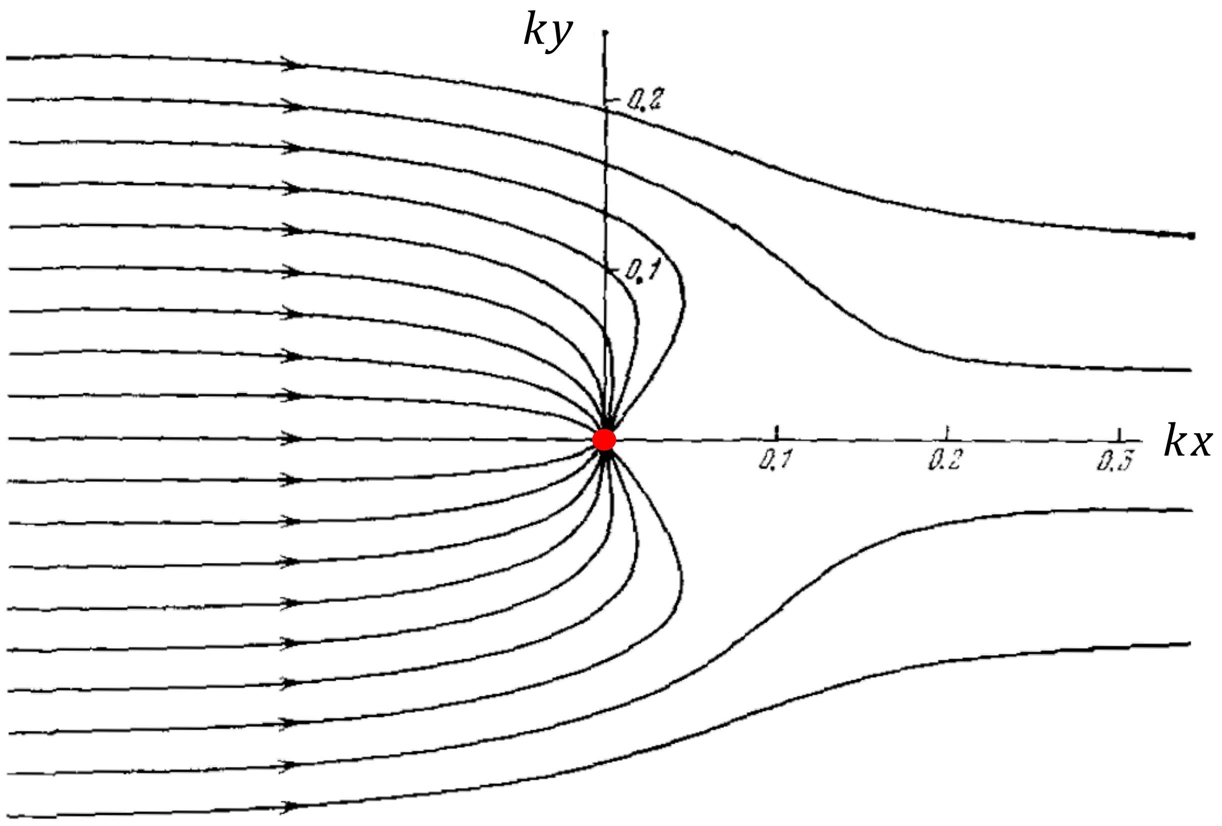
METHODOLOGICAL NOTES

Light absorption by a dipole

H. Paul and R. Fischer

Zentralinstitut für Optik und Spektroskopie, Berlin, DDR-1199

Usp. Fiz. Nauk **141**, 375–381 (October 1983)

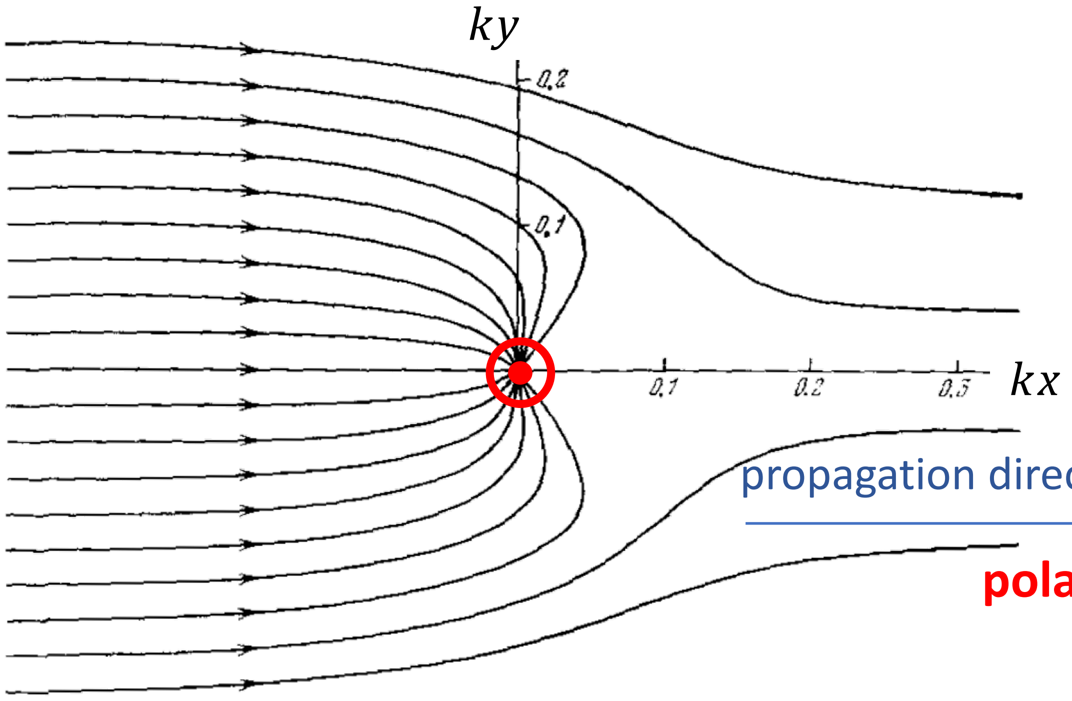


energy flux density <S>

$$\langle S \rangle = \frac{1}{2}\varepsilon_0 c E_0^2$$

→ **field enhancement**

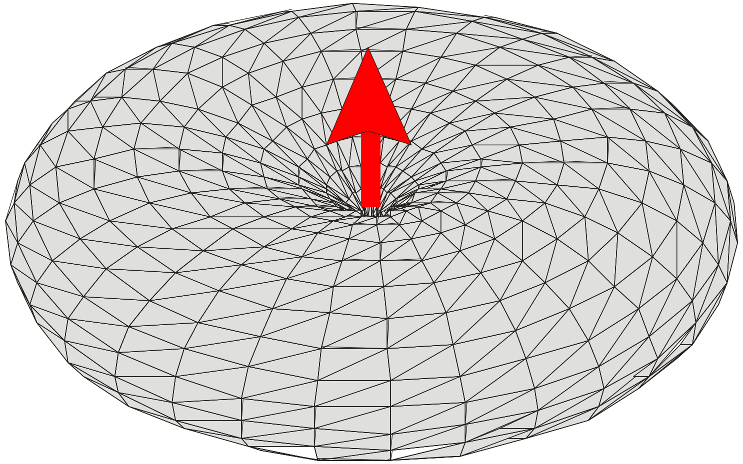
FIG. 1. Energy flux lines in the x, y-plane. The dipole located at $x = y = 0$, oscillates in the z direction. Incident (from the left) is a linearly polarized monochromatic plane wave.

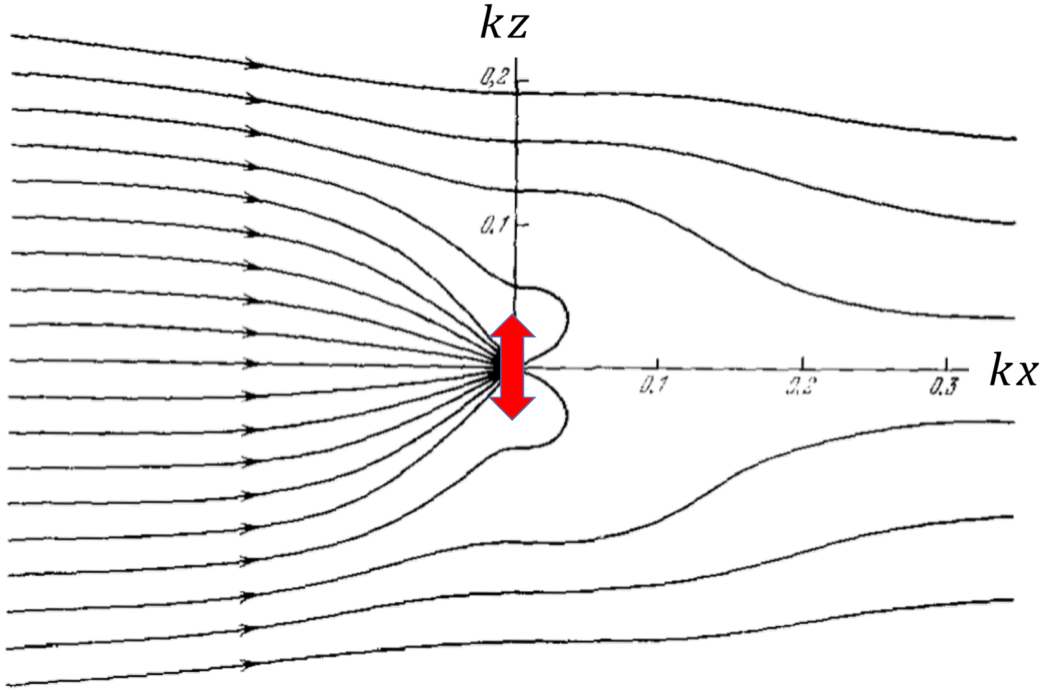


propagation direction

polarization

polar diagramm of a linear dipole wave

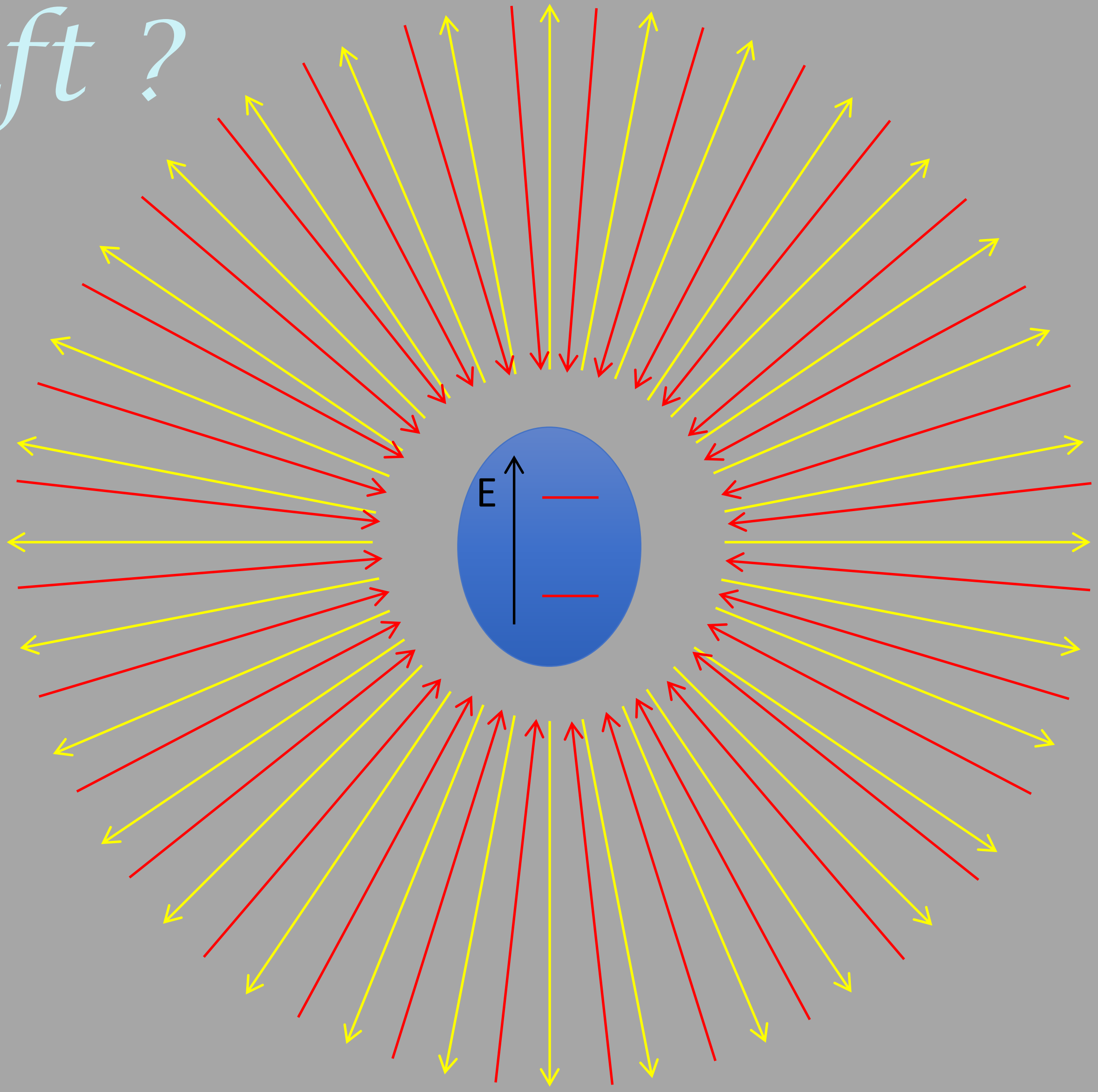




atom 'prefers'
dipole wave !!

$$\sigma = \frac{3\lambda^2}{4\pi}$$

phase shift ?



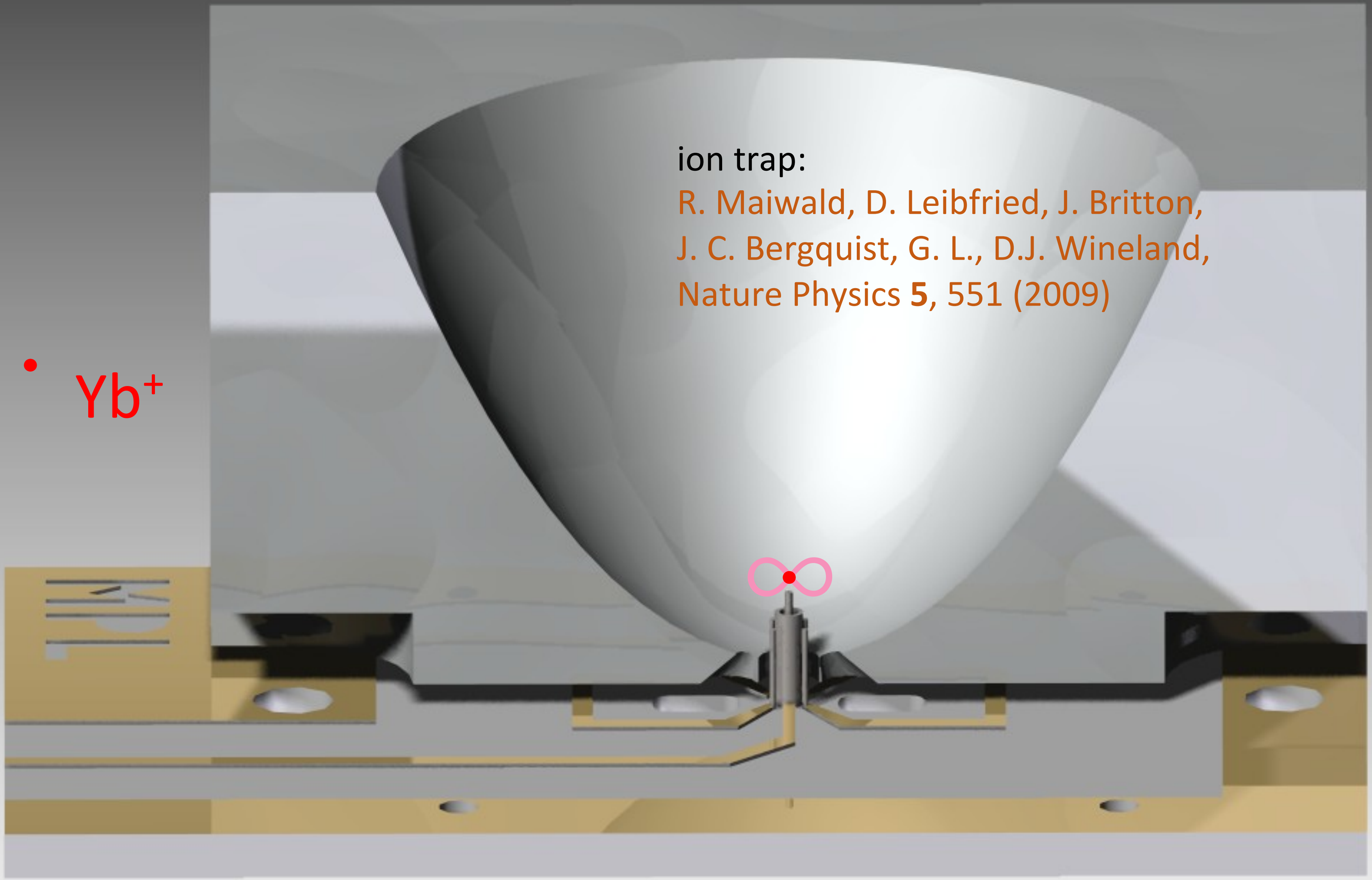
trivially:
all light
back reflected

with versus without
atom:

difference in
phase

max 180°

project plan: M. Sondermann et al., Appl. Phys. B 89, 489 (2007)



Yb^+

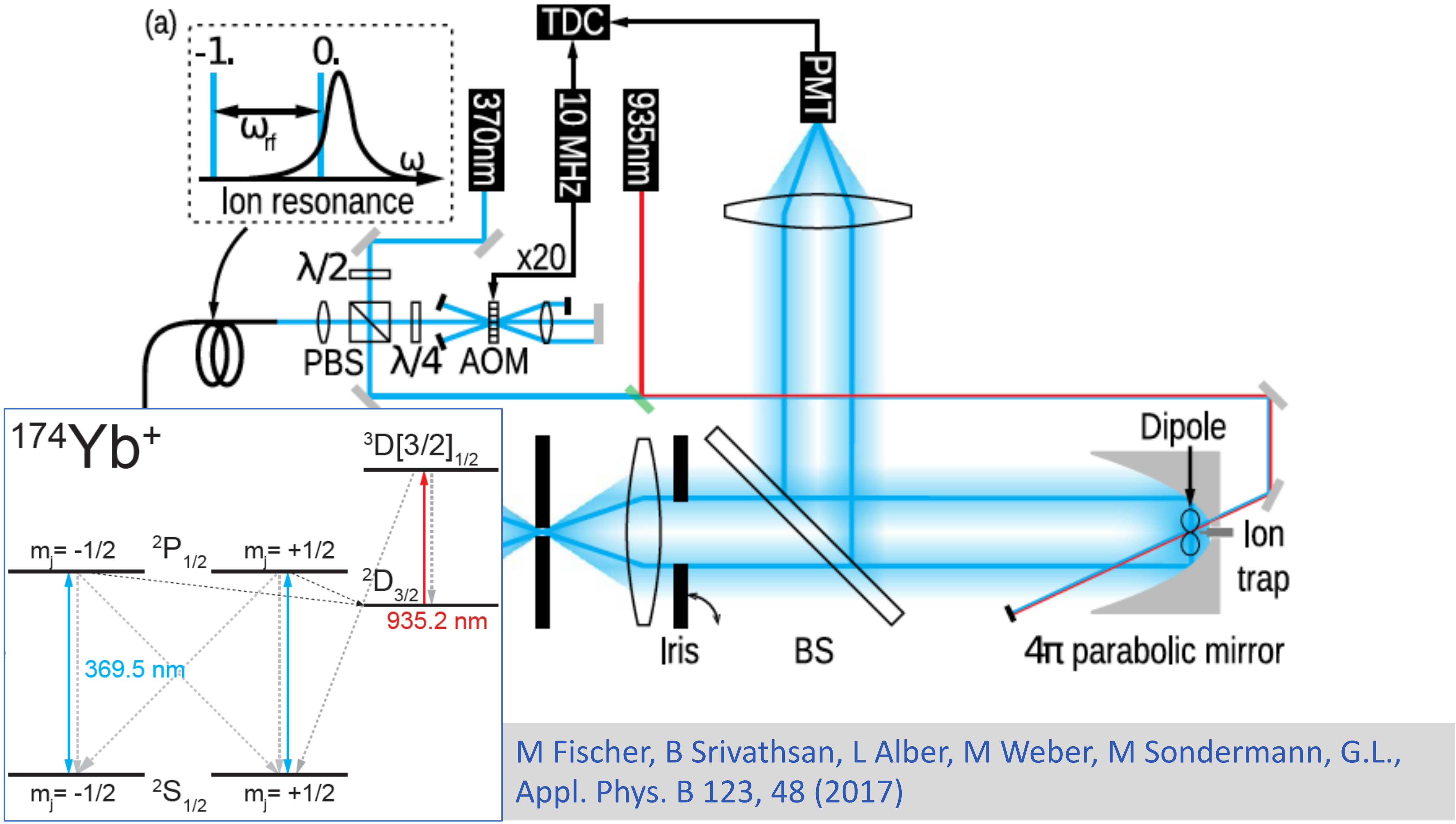
collected light:

- isotropic emission 80.5 %
- linear dipole ∞ (94 % coupling)

single atom weak light interaction in free space

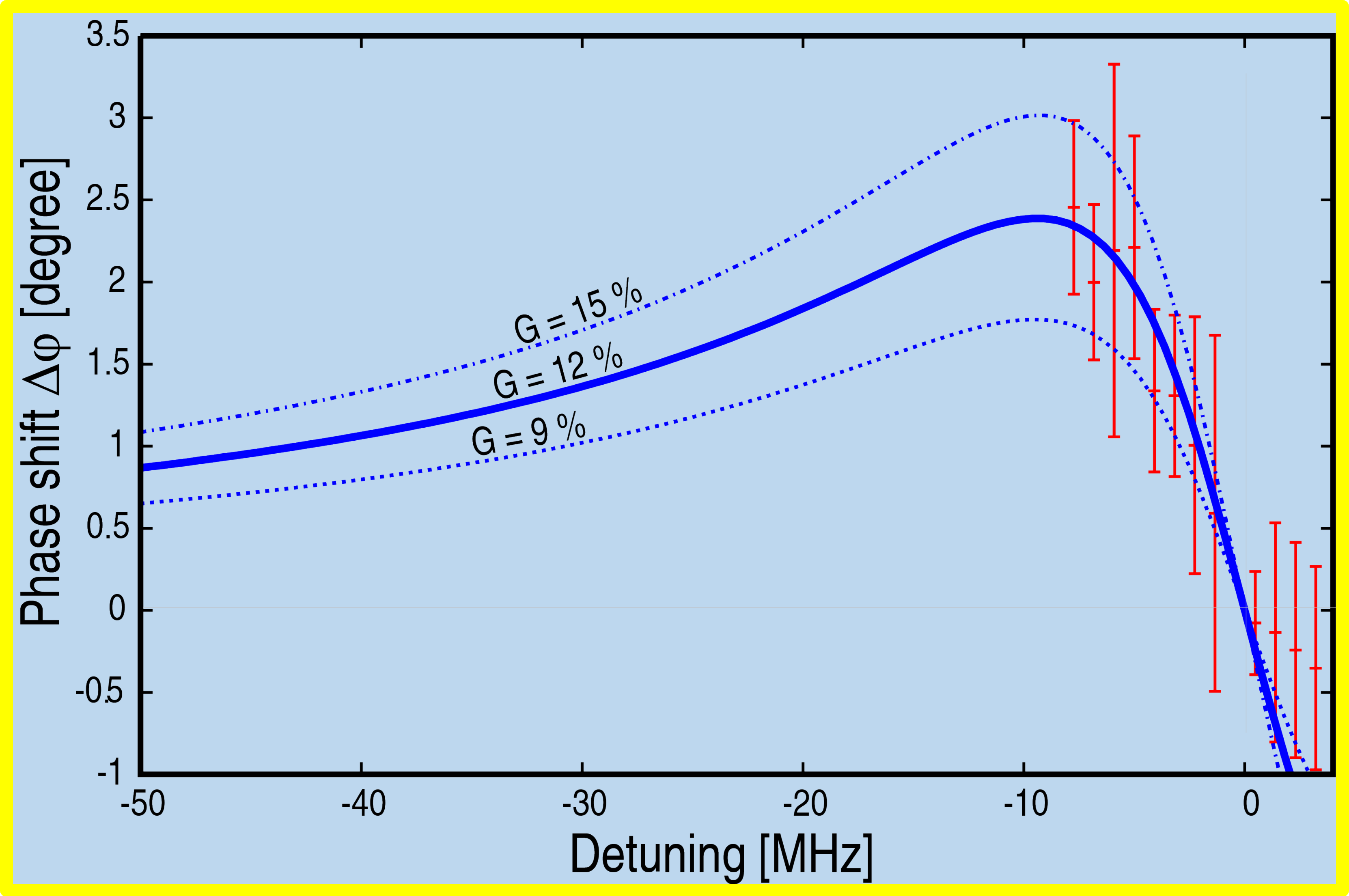
reference & experimental system	year	extinction max 100 %	reflection max 100 %	phase shift max 180°	absorption max 100 %
Wineland group # *trapped ion*	1987	≤ 0.1%			
Imamoglu group§ *quantum dot*	2007	12 %			
Sandoghdar group† *molecule in matrix*	since 2007	30 %		3°	
Kurtsiefer group‡ *trapped atom*	since 2008	18 %	0.61%	1°	2.8 %
Blatt group†† *single ion EIT*	since 2010	1.4 %	< 1%	0.3°	
Eschner group‡‡ *trapped ion*	2011				0.03 %
MPL Erlangen trapped ion				**2.5° ± 0.3°**	

a single ion shifts the phase of a laser beam ...

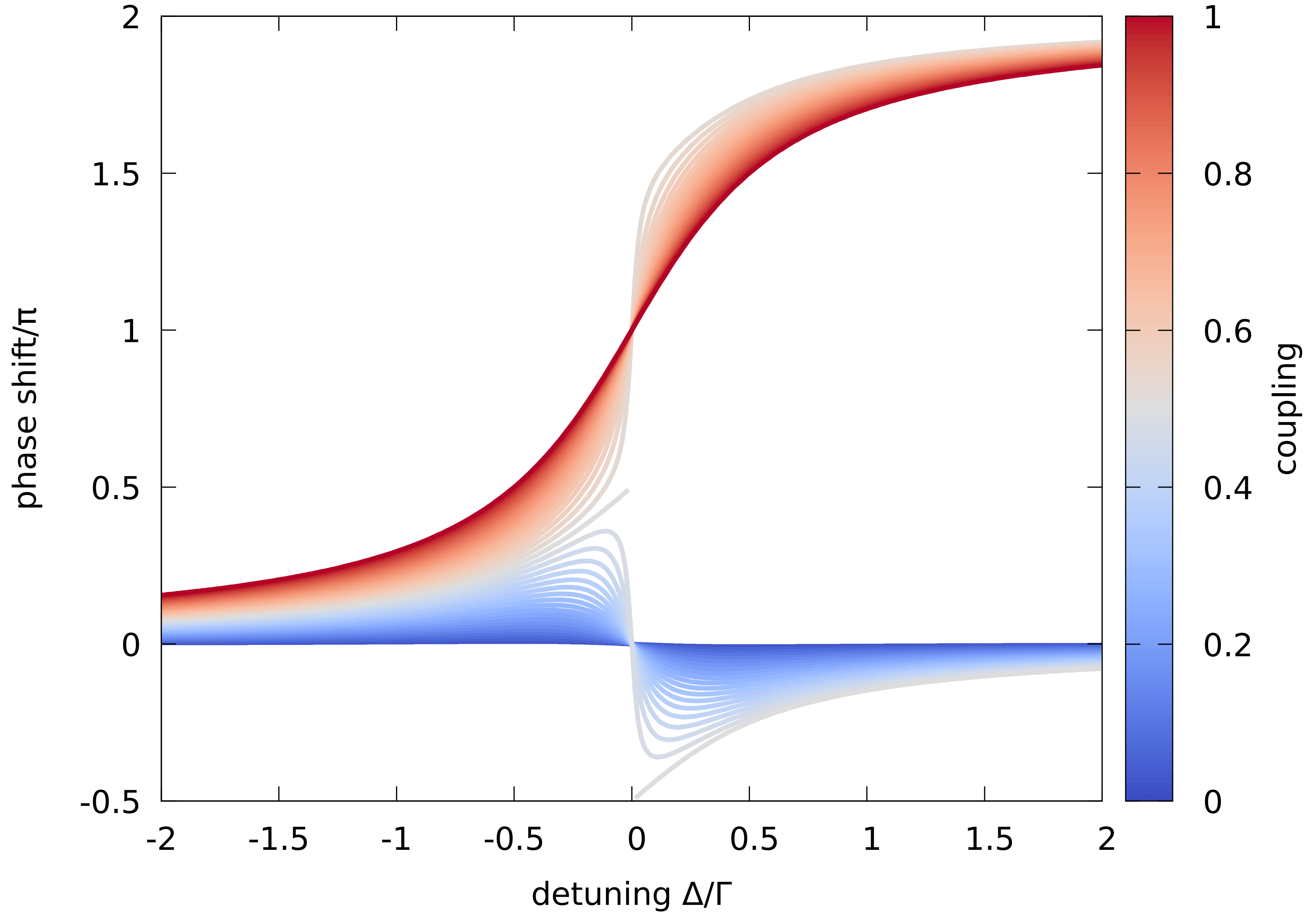


M Fischer, B Srivathsan, L Alber, M Weber, M Sondermann, G.L., Appl. Phys. B 123, 48 (2017)

... by 2.5 degrees



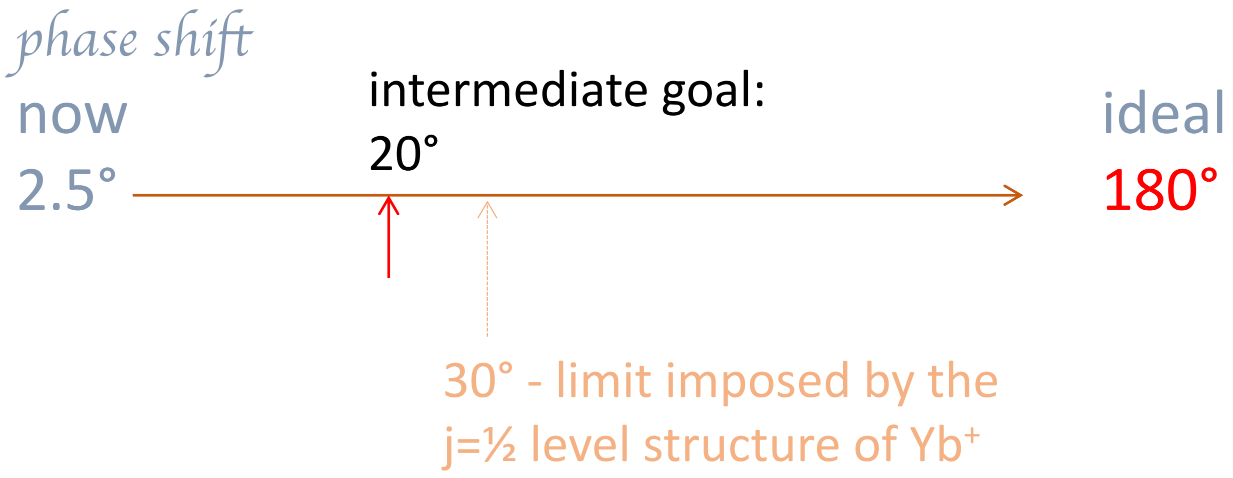
M Fischer et al., Appl. Phys. B 123, 48 (2017)



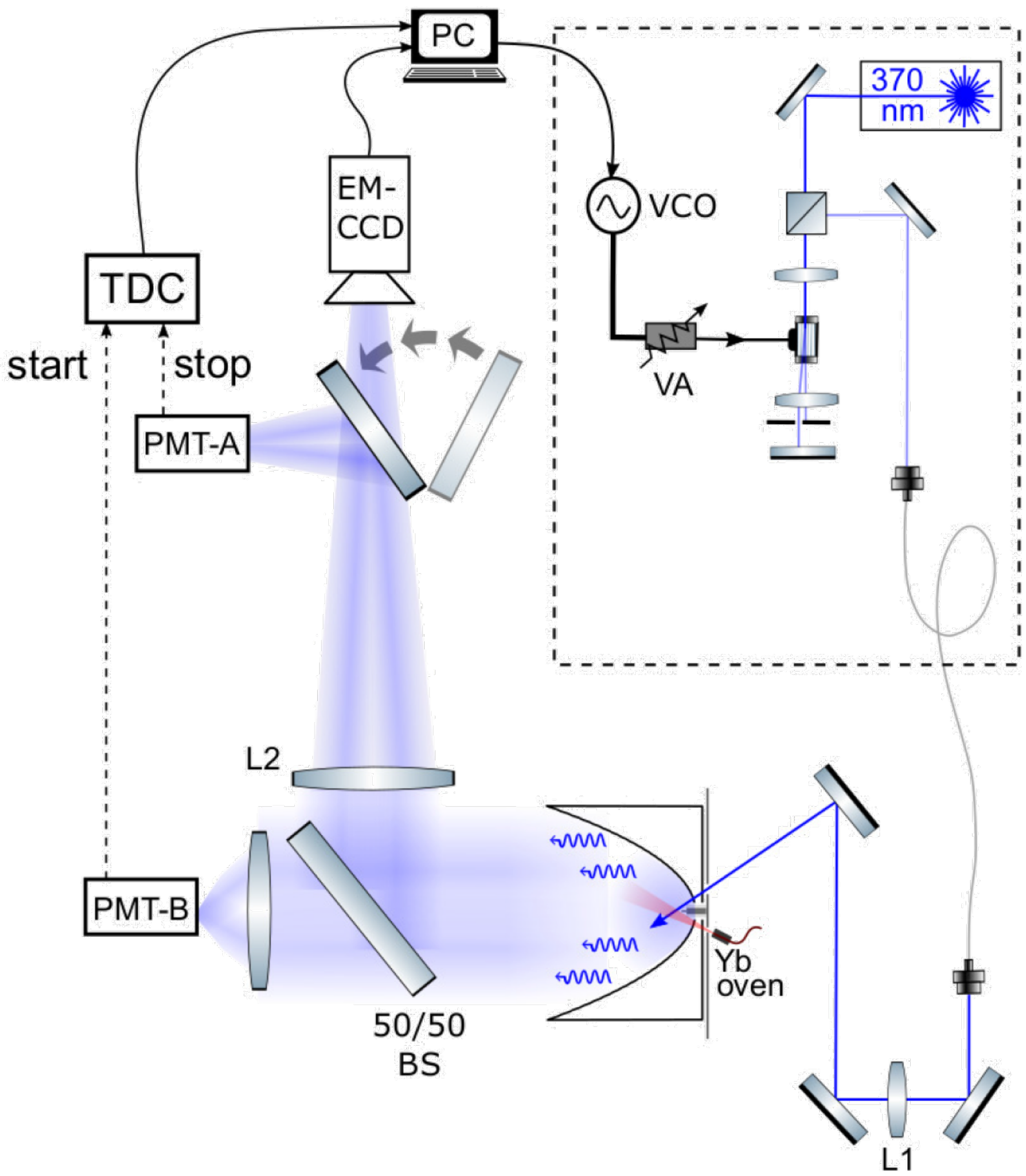
phase shift/π
2
1.5
1
0.5
0
-0.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
detuning Δ/Γ
coupling
1
0.8
0.6
0.4
0.2
0

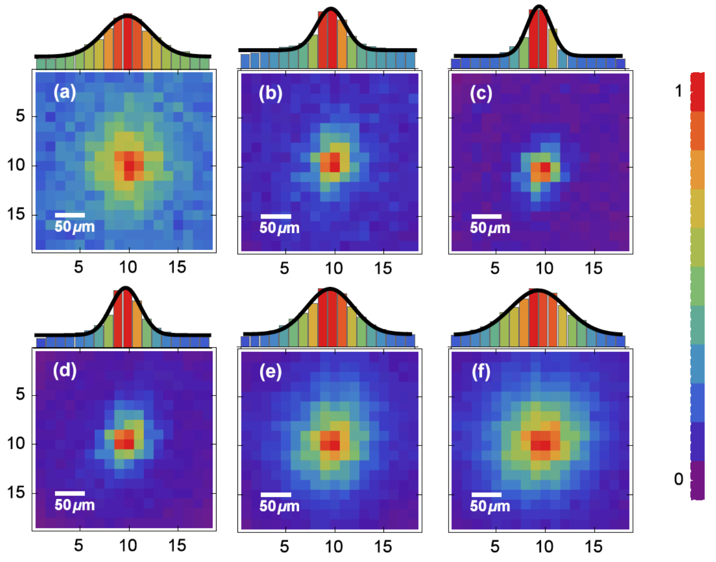
problems:

- residual motion of the ion
  - trap depth
  - limited cooling (short life time)
- residual aberrations of the mirror
- j=½ level structure of Yb^+



“imaging“ with parabolic mirror



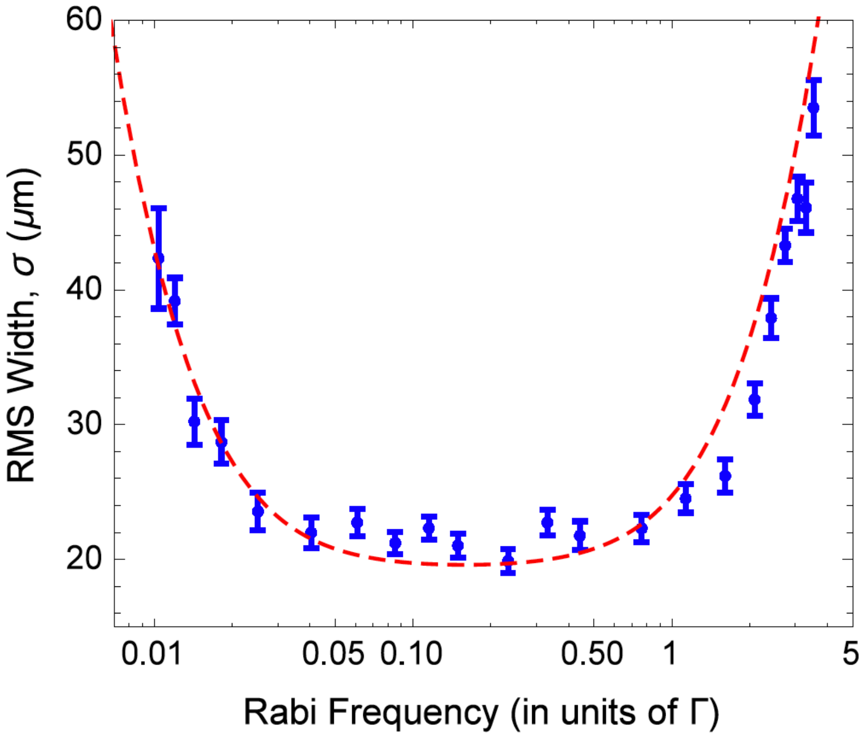


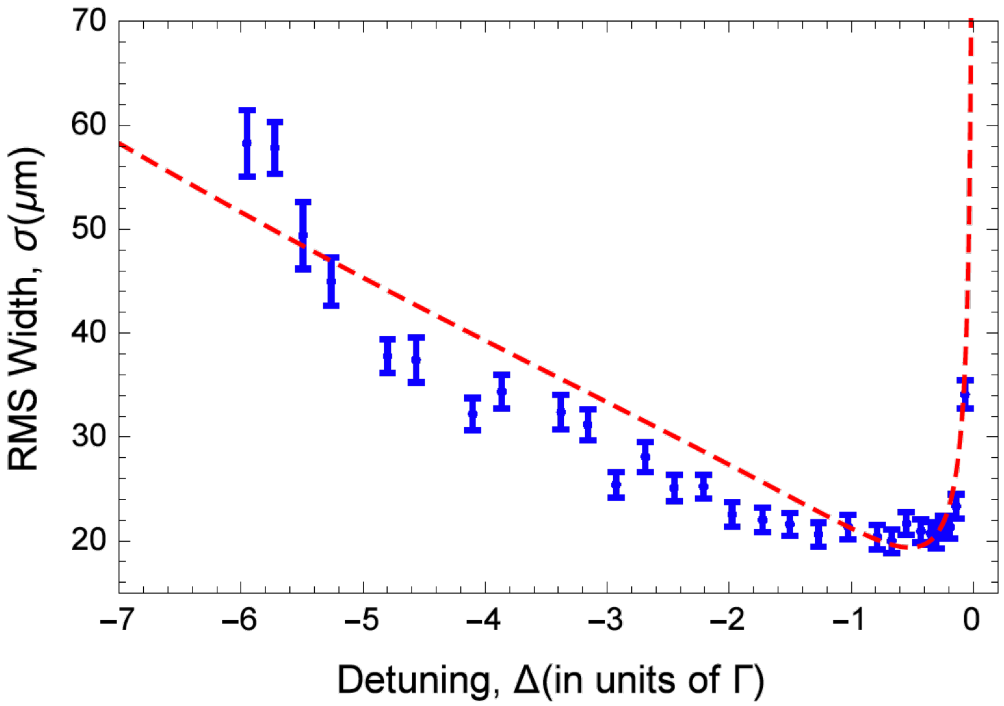
(a) – 0.012 Γ
(b) – 0.025 Γ
(c) – 0.23 Γ
(d) – 1.1 Γ
(e) – 2.4 Γ
(f) – 3.3 Γ

B Srivathsan, M Fischer, L Alber et al, arXiv:1905.09011

thermometry of trapped ion

deduced heating rate
0.38 +/- 0.07 quanta/ms





deduced heating rate
0.22 +/- 0.07 quanta/ms

B Srivathsan, M Fischer, L Alber et al, arXiv:1905.09011

- sooner:

  atom phase shifts a laser beam by 20°

- applications:

  broad band quantum gates; quantum repeater

- dream:

  demonstration of time reversal of spontaneous emission

  → linear dipole two level transition → $^{174}Yb^{2+}$

S. Quabis, R. Dorn, M. Eberler, O. Glöckl, G.L., Opt. Commun. 179, 1 (2000)

dream –

- *time reversal of spontaneous emission of an atom in free space*

time reversal of spontaneous emission

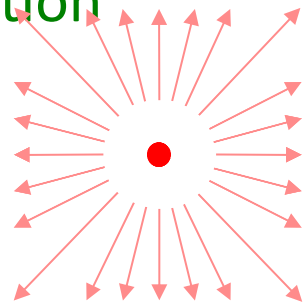
the dream

optimization:

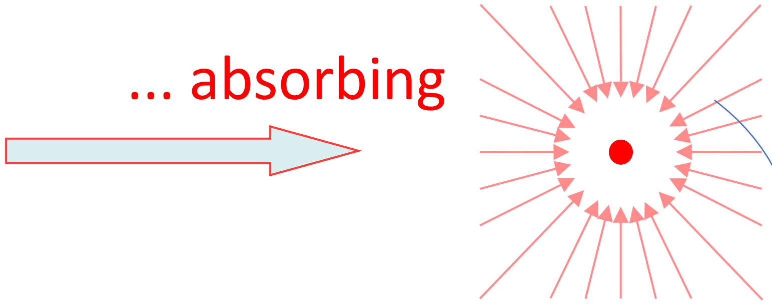
study free evolution of the desired state

... and then prepare time reversed situation

atom emitting photon



... absorbing



Problems

- geometry
- polarization
- temporal pulse shape

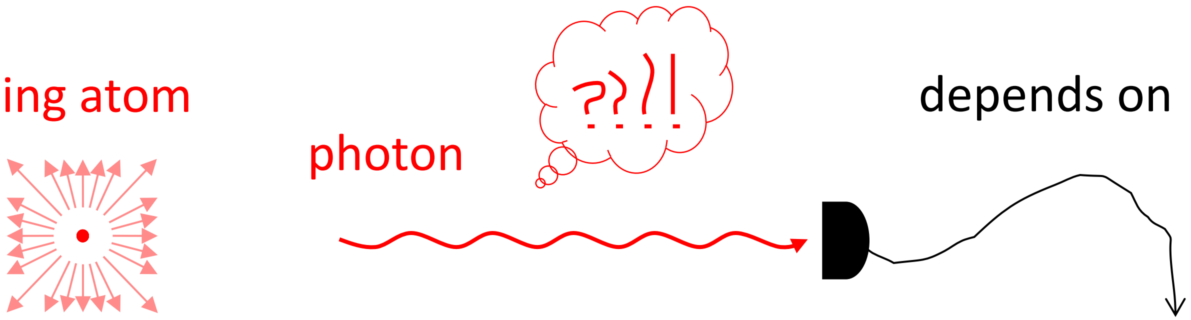
- n=1 Fock state
- 2-level system (Δm=0)
- no recoil

S. Quabis, R. Dorn,
M. Eberler, O. Glöckl, G.L.,
Opt.Commun. 179,1 (2000)

temporal pulse shape ?

radiating atom

photon

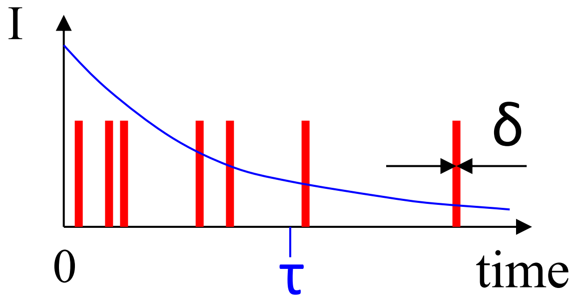


depends on

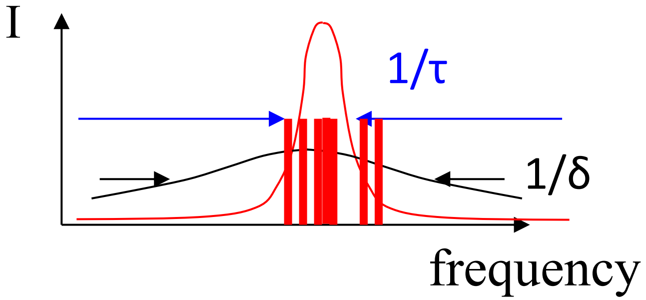
measurement result

type of measurement

time resolved detection



spectrally resolved detection



→ atom emits single photon wave packet with exponential shape *note*

time reversal - universal phase conjugating mirror ?

→ not a unitary operation

→ possible only with noise penalty

AL Gaeta, RW Boyd; Phys. Rev. Lett. 60, 2618 (1988)

A versatile source of single photons for quantum information processing

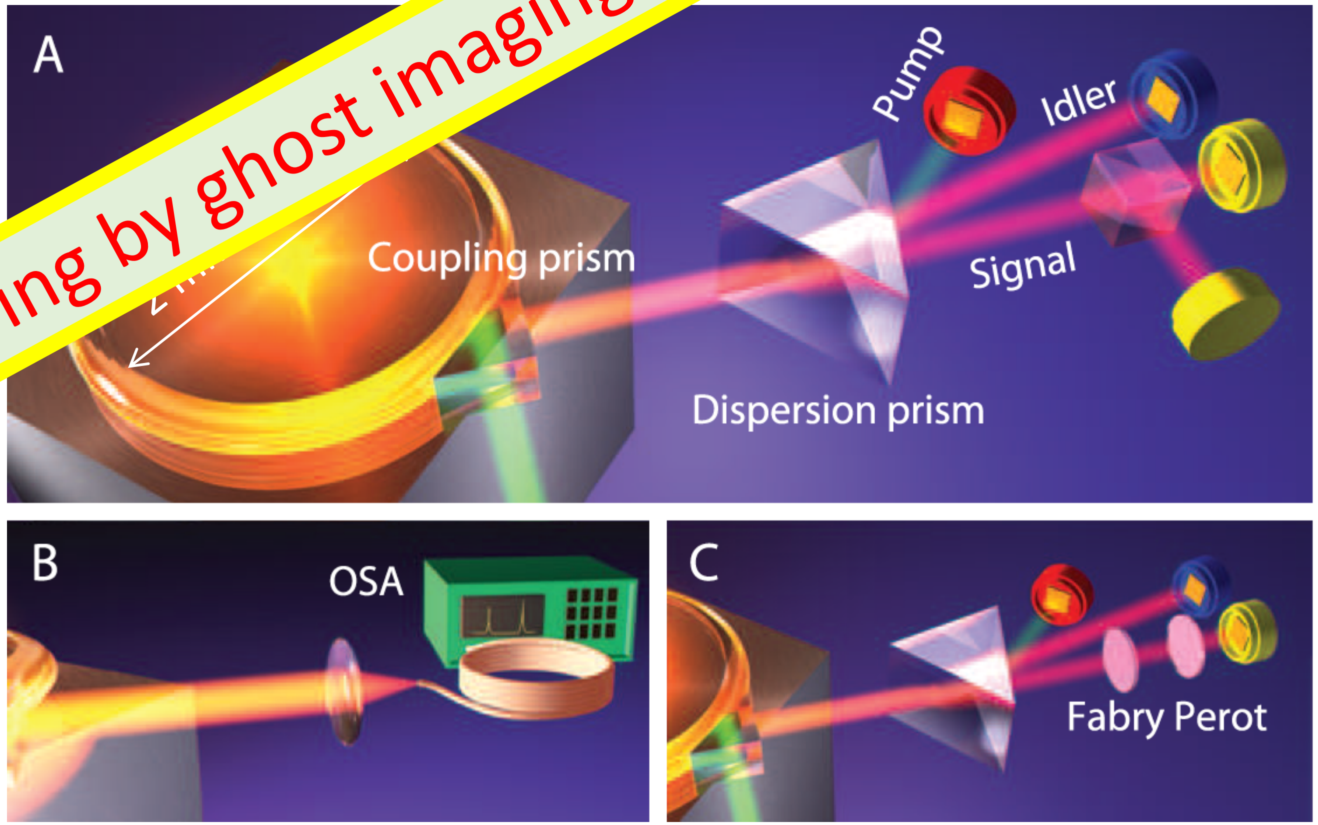
Michael Förtsch, Josef U. Fürst, Christoffer Wittmann, D... ...kalov, Andrea Aiello, Maria V. Chekhova, Christine Silbe... & Christoph Marquardt

Nature Commun. **4**, 1818 (2013)

- single photon
- narrow band
- efficient

... pairs per ...cond per mW pump power

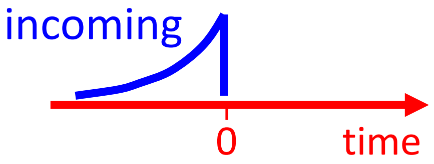
photon shaping by ghost imaging in the time domain



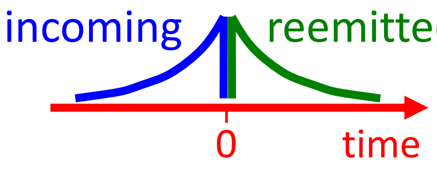
efficiency (theory)

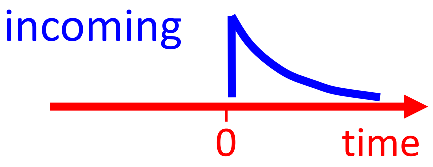
effect of shape --- same center frequency, same bandwidth

excitation probability

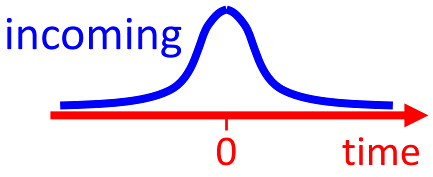


100%





54%



68%
(Gaussian)

see:

M. Stobinska, G. Alber, G.L., Euro Physics Letters 86, 14007 (2009)

Marianne Bader, Simon Heugel, Alexander Chekhov, Markus Sondermann, G.L., New J Phys 15, 1123008 (2013)

summary

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