K. Bergmann

TECHNISCHE UNIVERSITÄT
KAISERSLAUTERN

STIRAP
a Powerful Coherent Population Transfer Scheme

the basics ..... and
phase-controlled superpositions
of degenerate state

Toronto, August 10, 2006

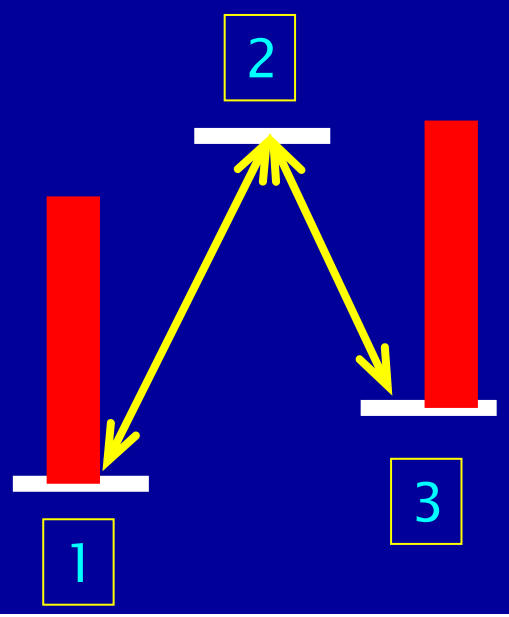
Stimulated **R**aman **A**diabatic **P**assage

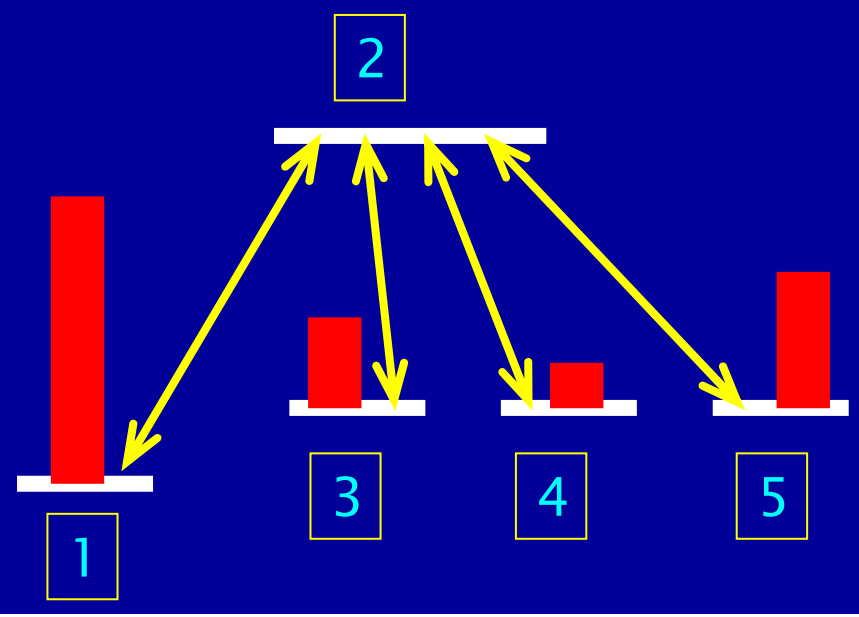
preparing tools for quantum information

controlling q-bits and higher dimensional objects

.... not only population

.... but also amplitude





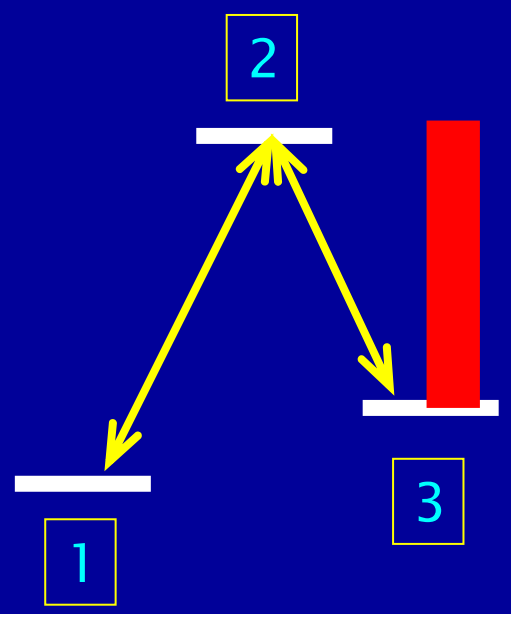
Stimulated **R**aman **A**diabatic **P**assage

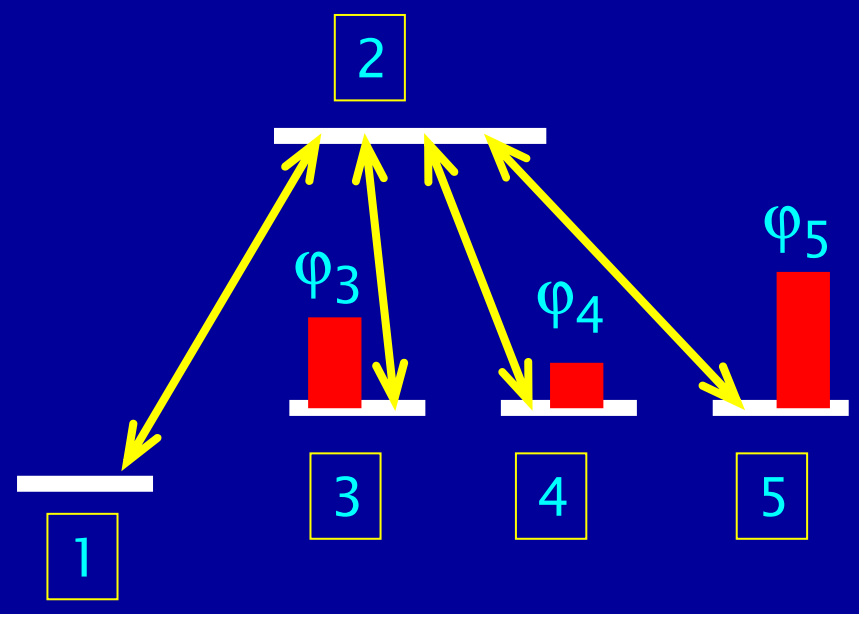
preparing tools for quantum information

controlling q-bits and higher dimensional objects

.... not only population

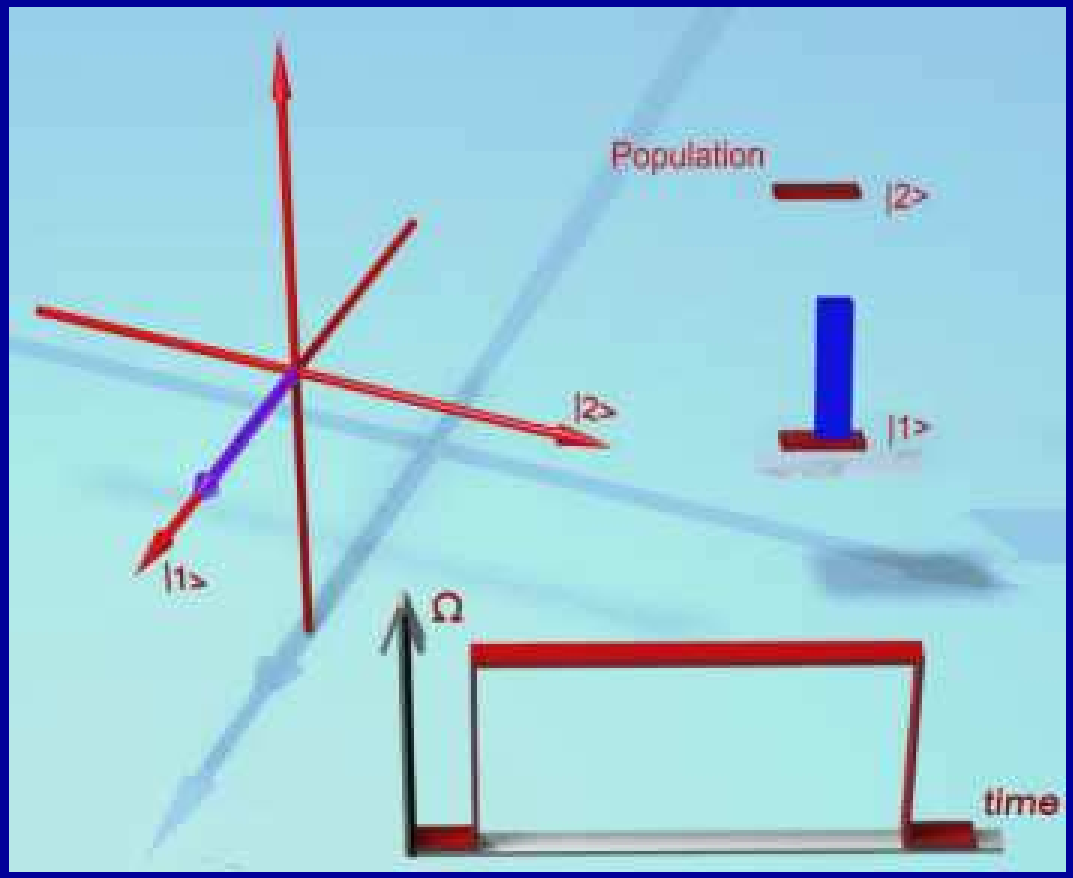
.... but also amplitude and phase

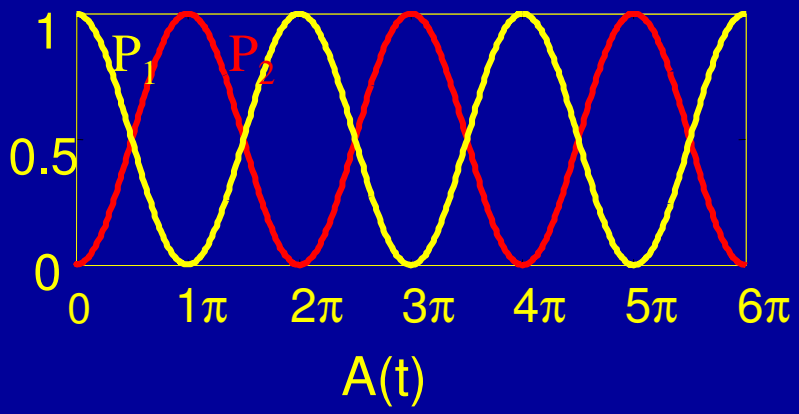




for reference: a traditional transfer scheme

Rabi-Oscillations in two-level-systems, (2n +1) π - puls





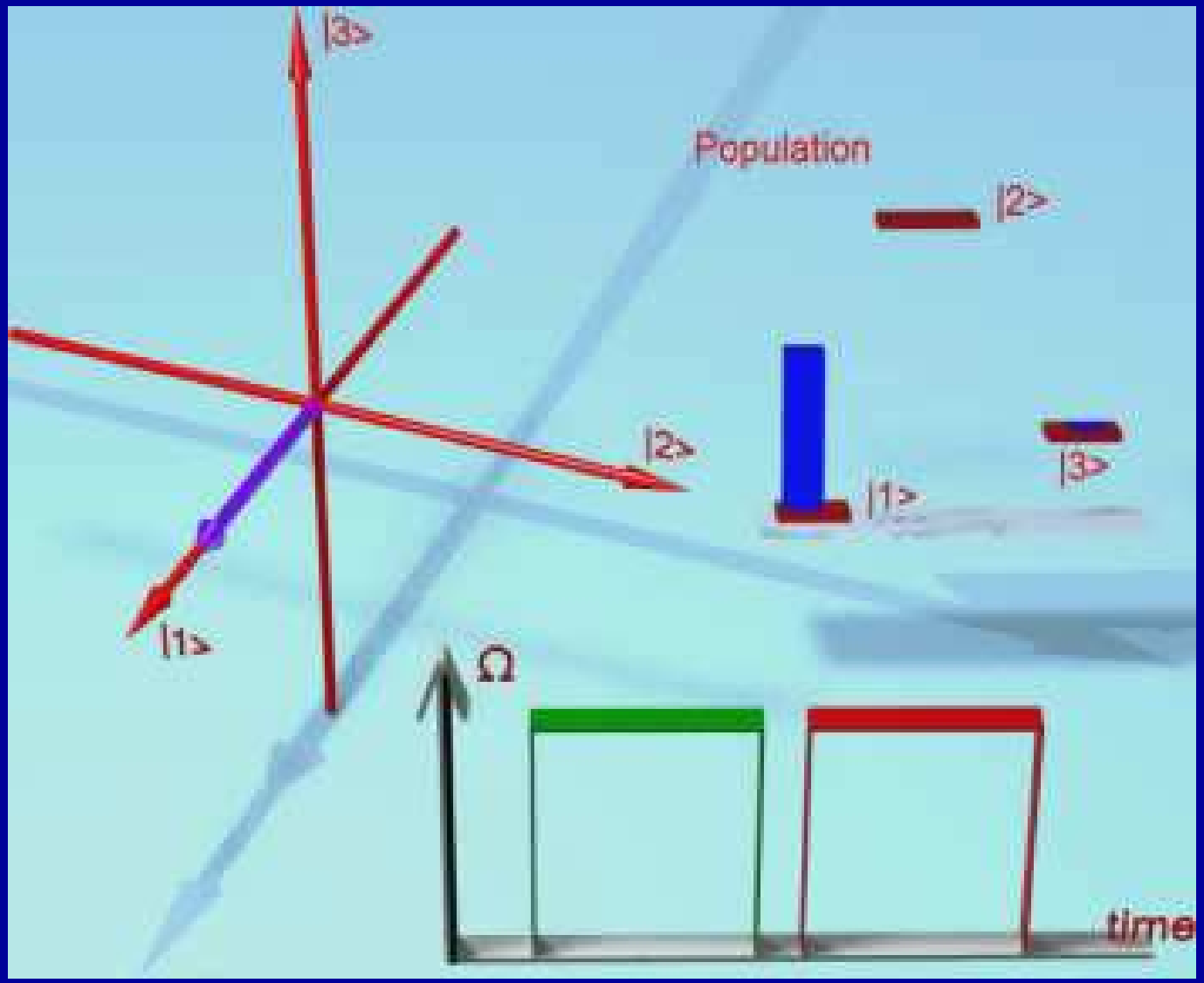
$\Omega(t) = \mu\, E(t) / \hbar$ Rabifrequency

$A(t) = \int \Omega(t')dt'$ Pulse Area

$P_2(t) = 0.5\,[\,1\text{-}\cos A(t)\,]$

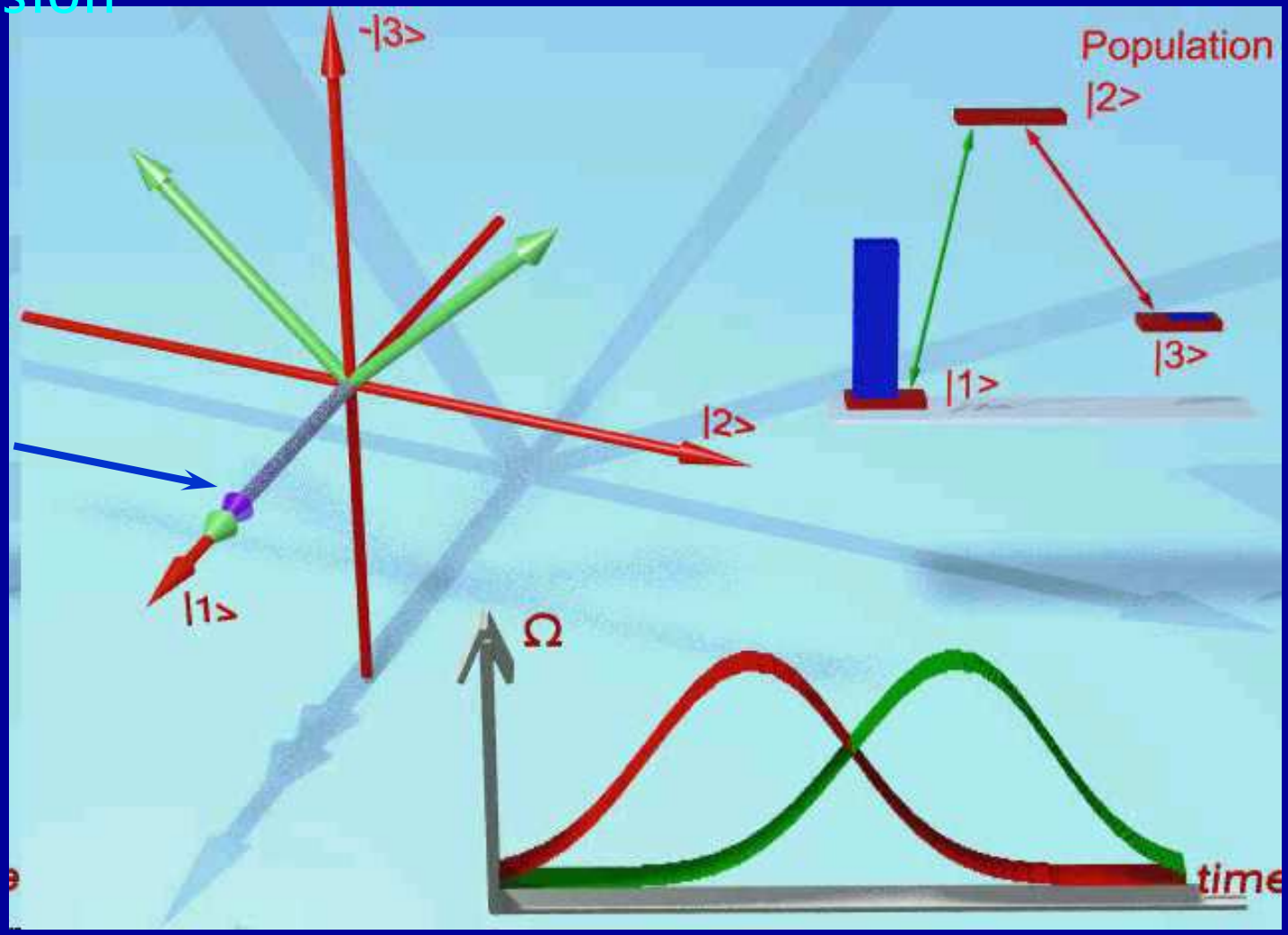
Population in |2>

Population transfer by a double π-pulse



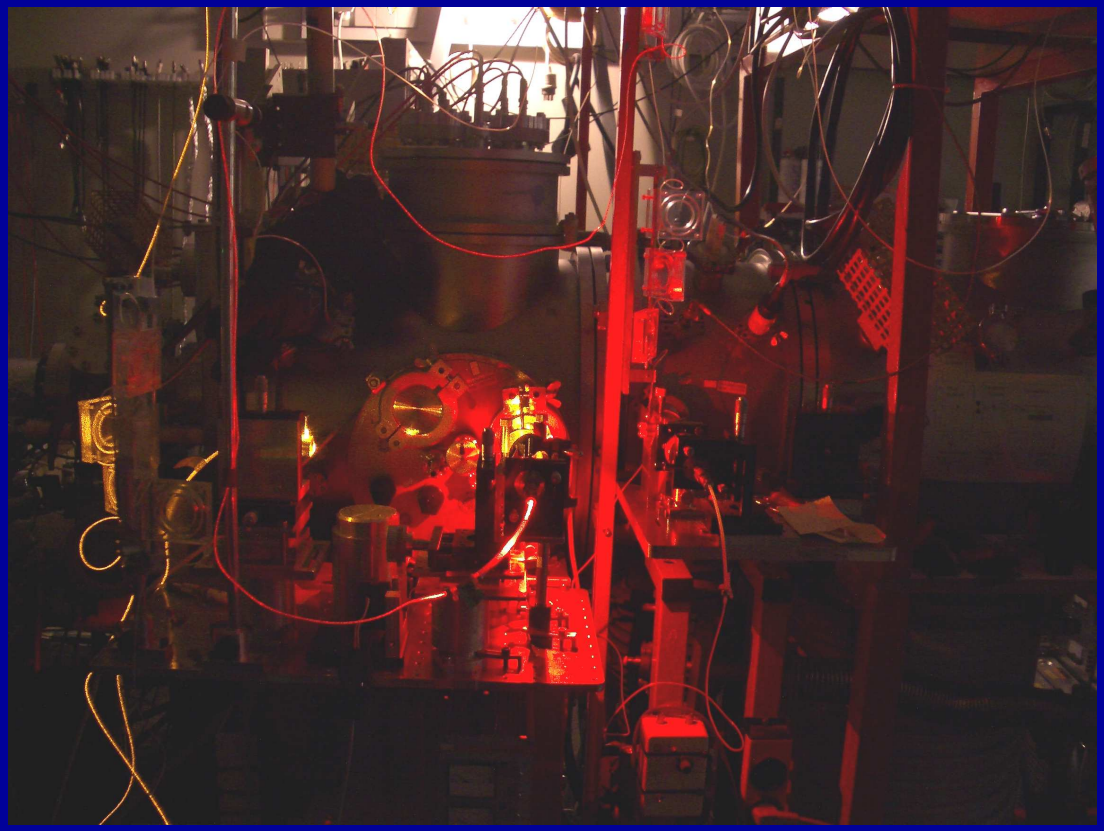
the goal of the STIRAP process
transfer **without loss** due to spontaneous emission

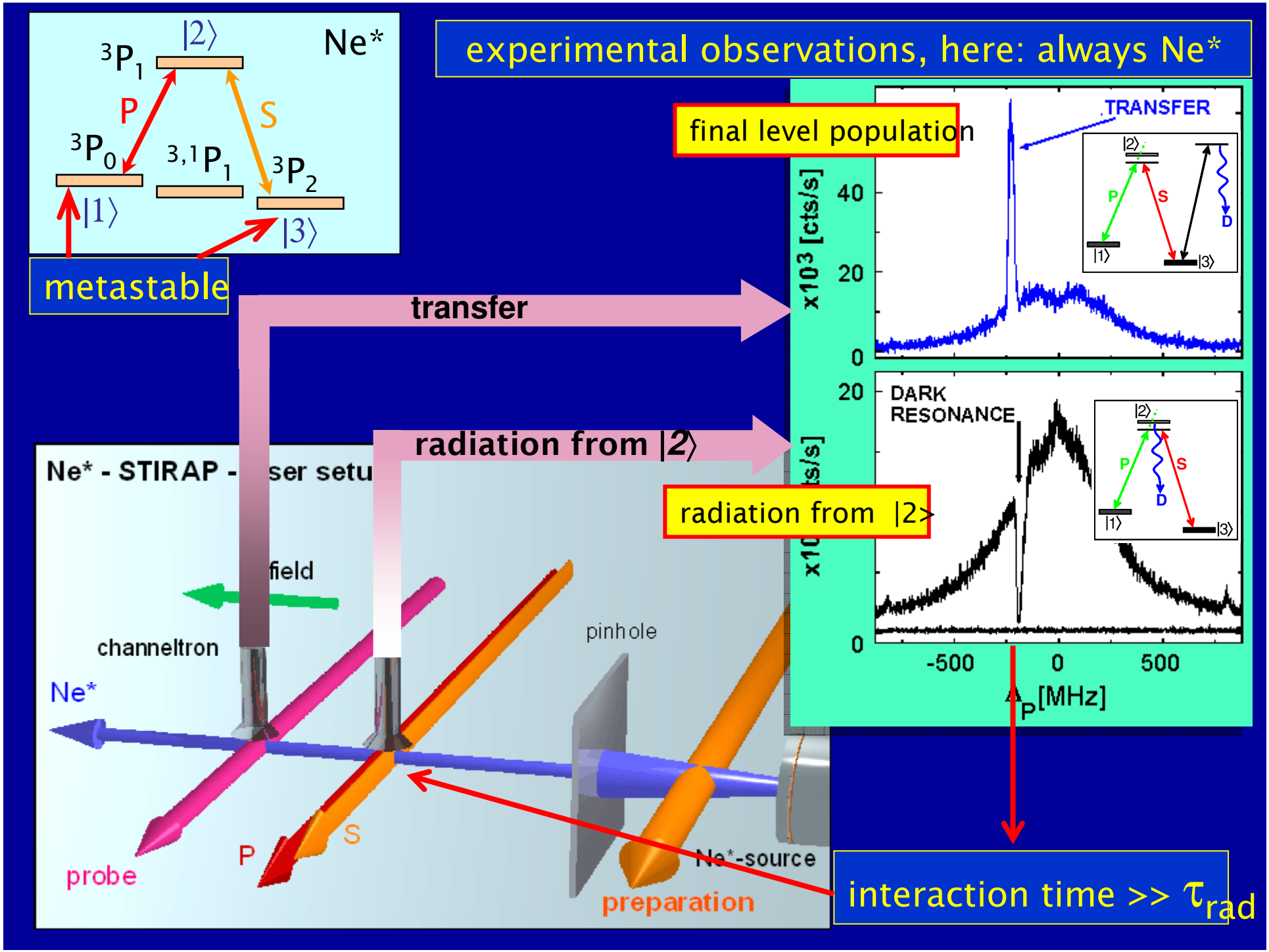
observe the blue arrow



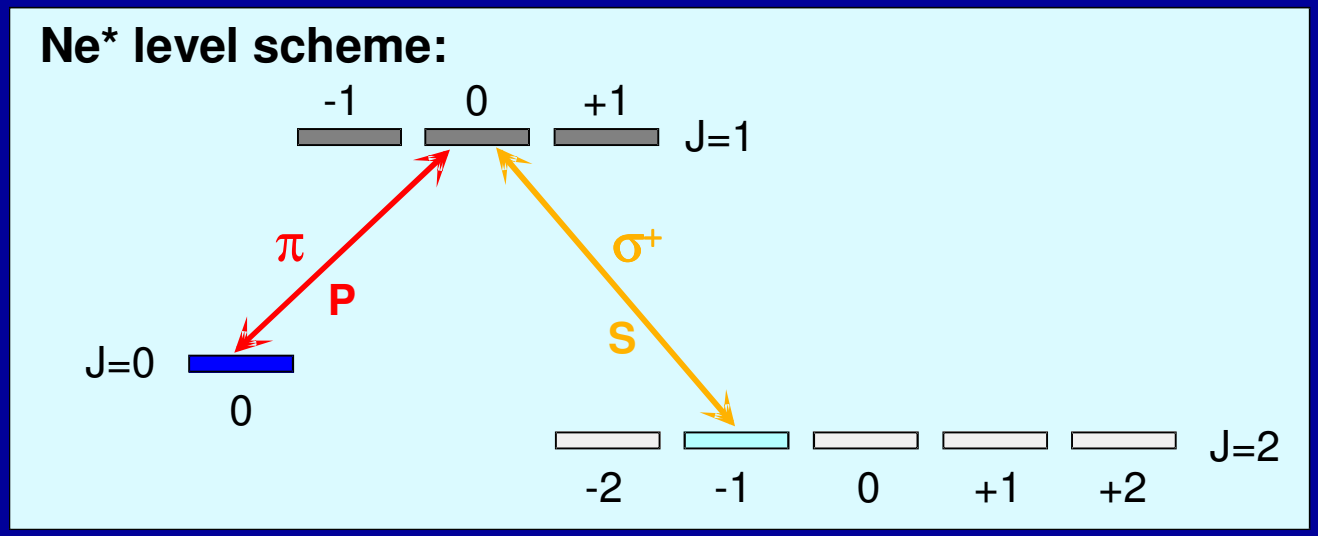
basic STIRAP:

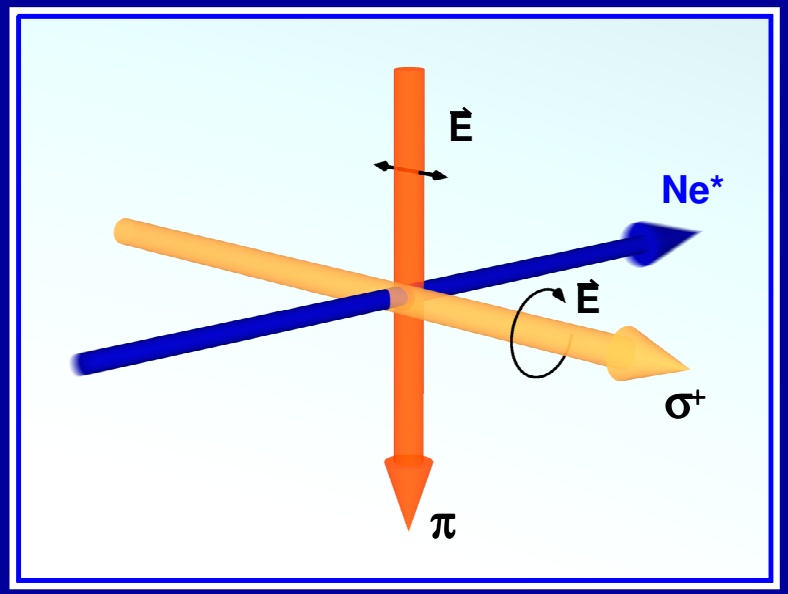
experimental observations

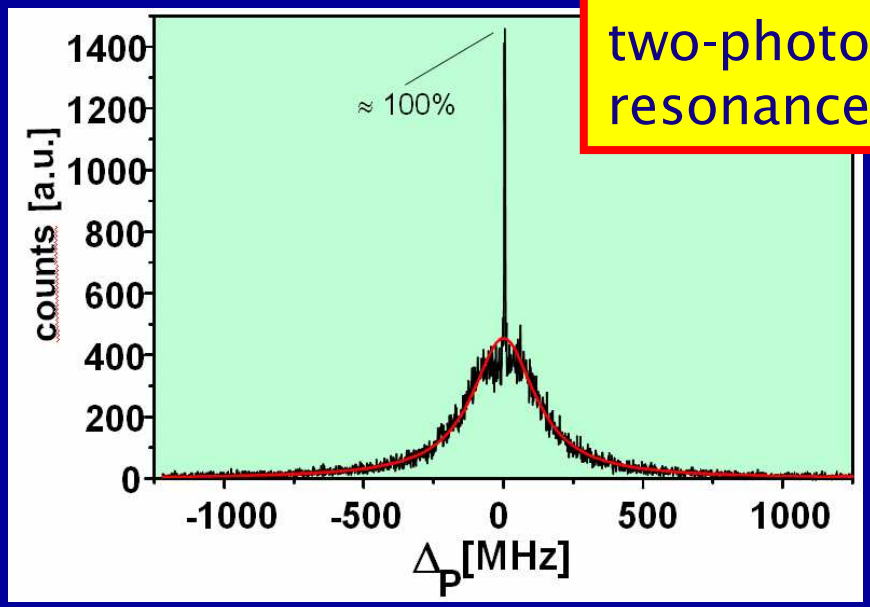



Ne*
$^3P_1$
|2⟩
P
S
$^3P_0$
$^{3,1}P_1$
$^3P_2$
|1⟩
|3⟩
metastable
experimental observations, here: always Ne*
final level population
TRANSFER
x10³ [cts/s]
40
20
0
DARK RESONANCE
radiation from |2⟩
-500
0
500
Δ_P[MHz]
transfer
radiation from |2⟩
Ne* - STIRAP - ser setu
field
channeltron
Ne*
pinhole
probe
P
S
Ne*-source
preparation
interaction time >> τ_{rad}

σ / π three - level - STIRAP







transfer at two-photon resonance

the physics behind the STIRAP process

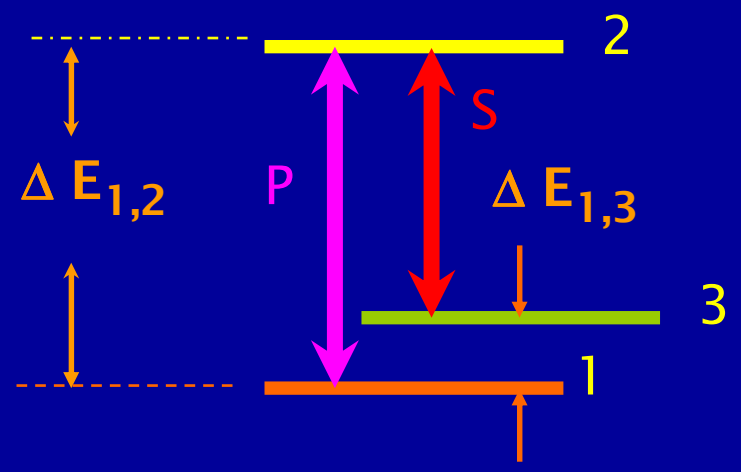
the essential elements:

- Autler-Townes splitting →
  - supression of absorption (EIT)
  - adiabatic passage

some basic facts

Rabi frequency $\hbar \quad \Omega_{ik} = \mu_{ik} E_L$

μ_{ik} = transition dipole moment



$\Omega_{ik} \ll \Delta E_{1,3}$

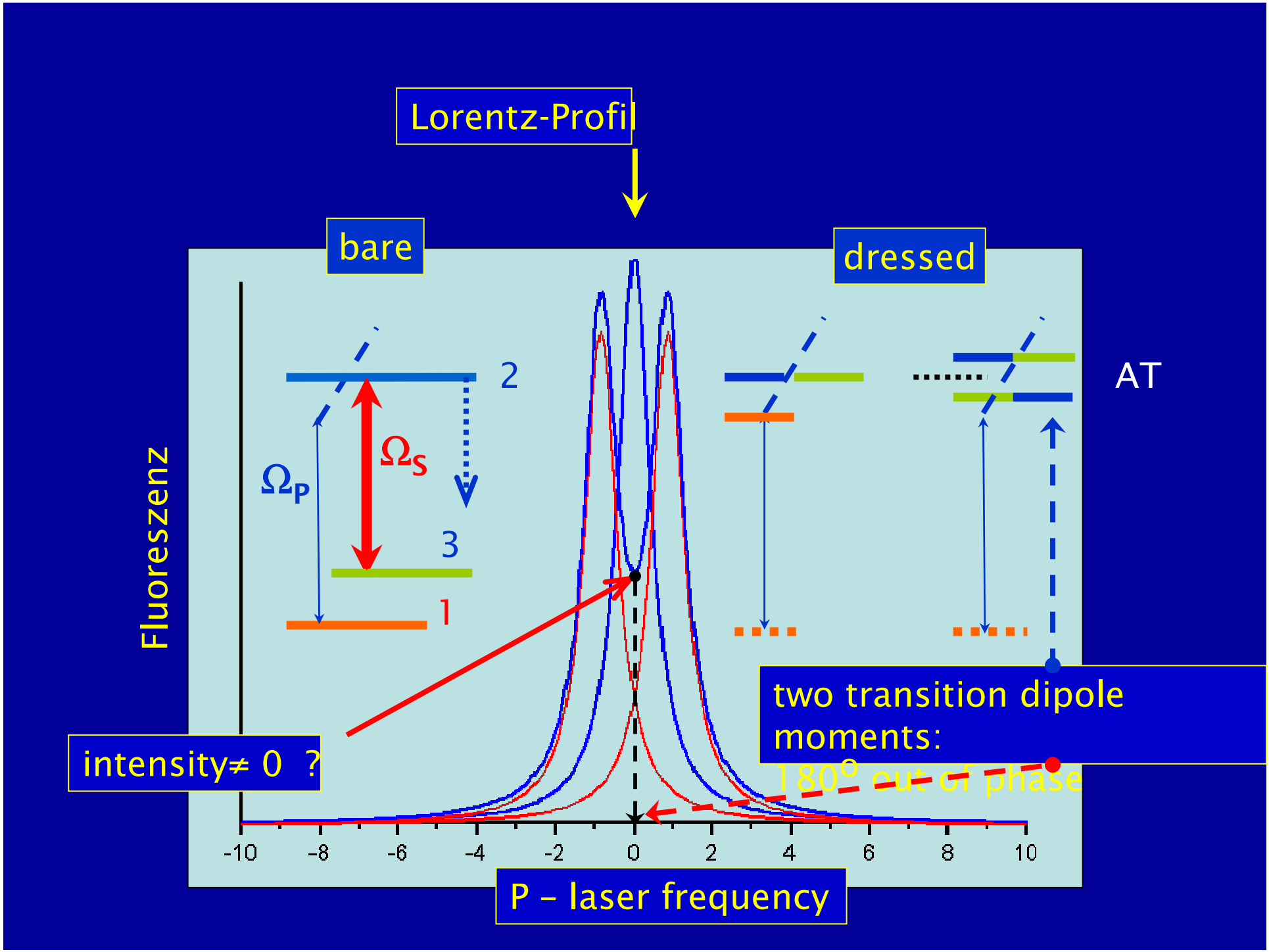
each field couples to one pair of levels only

selectivity by frequency and/or polarization

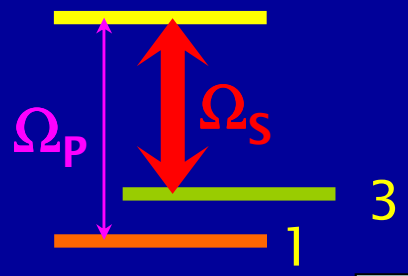
large pulse area: $\Omega \Delta T > \pi$

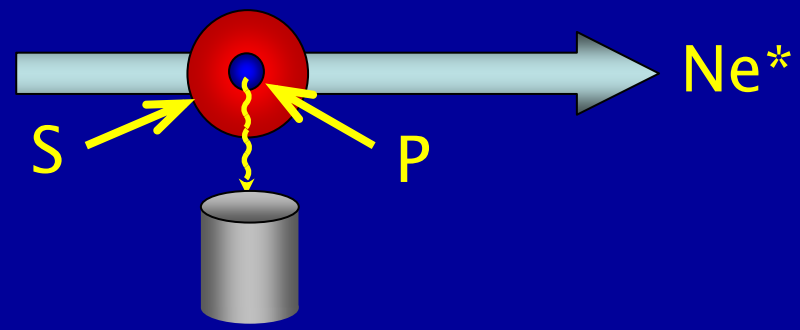
many Rabi cycles in two-level systems

adiabatic evolution

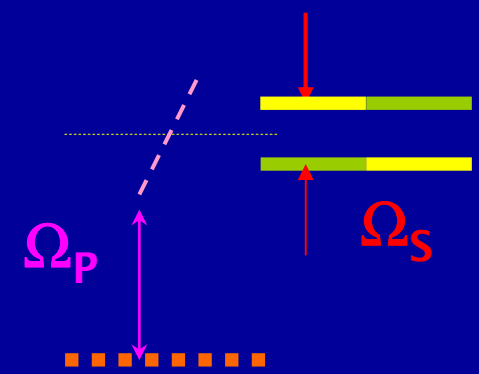

Lorentz-Profil
bare
dressed
AT
2
3
1
Ω_P
Ω_S
Fluoreszenz
intensity≠ 0 ?
two transition dipole moments:
180° out of phase
-10
-8
-6
-4
-2
0
2
4
6
8
10
P – laser frequency

bare states

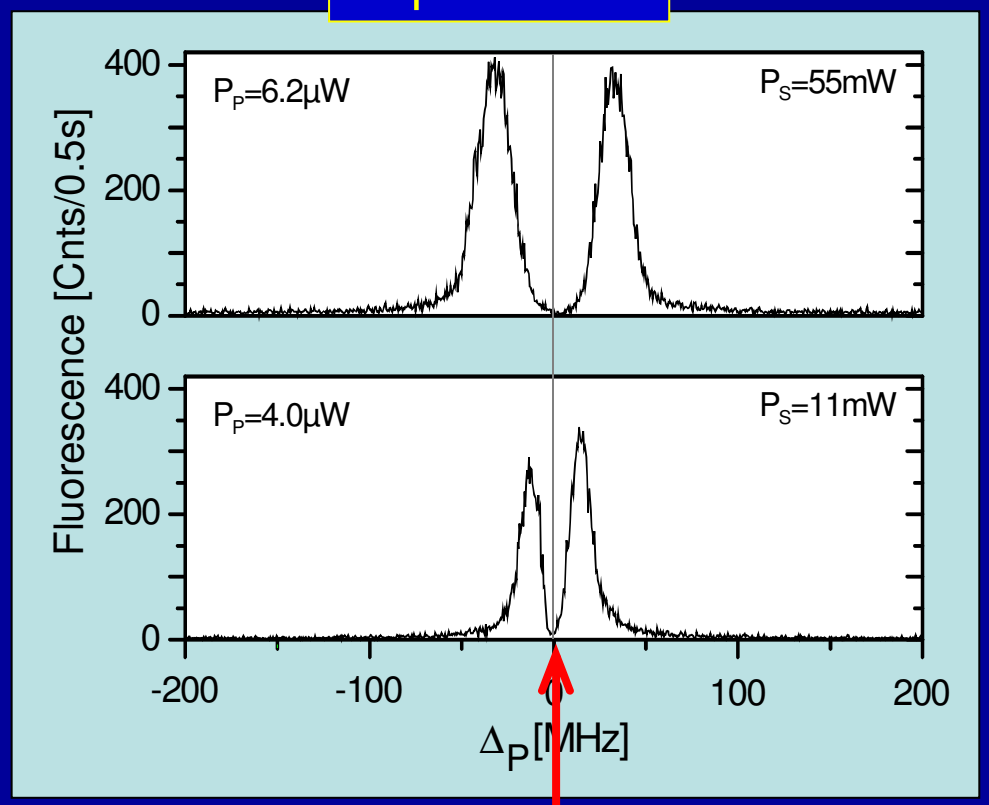




dressed states



Experiment

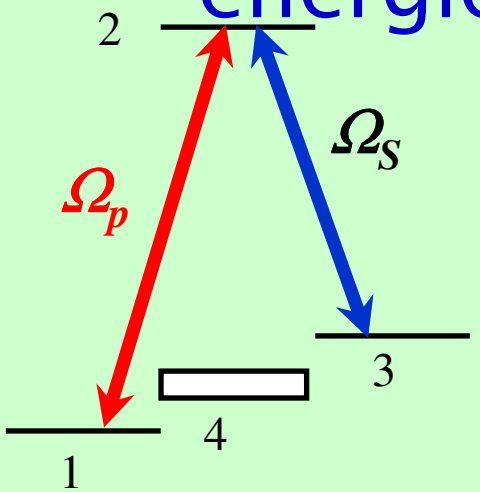


exactly zero

putting the pieces together.....

$$H = \frac{\hbar}{2}\begin{bmatrix} 0 & \Omega_P(t) & 0 \\ \Omega_P{}^*(t) & 0 & \Omega_S(t) \\ 0 & \Omega_S{}^*(t) & 0 \end{bmatrix}$$

Dressed states and dressed energies



$$H = \frac{\hbar}{2}\begin{bmatrix} 0 & \Omega_P(t) & 0 \\ \Omega_P{}^*(t) & 0 & \Omega_S(t) \\ 0 & \Omega_S{}^*(t) & 0 \end{bmatrix}$$

include laser phases

here shown for:

$\Delta_P = \Delta_S = 0$

$$|\Phi_+(t)\rangle = \frac{1}{\sqrt{2}}\left[\sin\theta(t)|\psi_1\rangle + |\psi_2\rangle + \cos\theta(t)|\psi_3\rangle\right]$$

$$|\Phi_0(t)\rangle = \cos\theta(t)|\psi_1\rangle - \sin\theta(t)|\psi_3\rangle$$

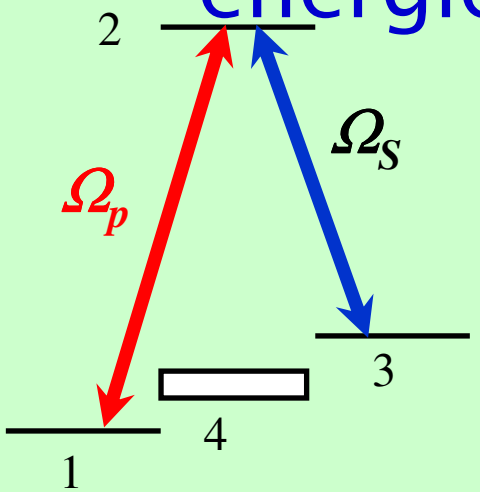
$$|\Phi_-(t)\rangle = \frac{1}{\sqrt{2}}\left[\sin\theta(t)|\psi_1\rangle - |\psi_2\rangle + \cos\theta(t)|\psi_3\rangle\right]$$

$\tan\Theta = \Omega_P / \Omega_S$

$\Omega_P = 0 \rightarrow \Theta = 0$

$\Omega_S = 0 \rightarrow \Theta = \pi/2$

Dressed states and dressed energies



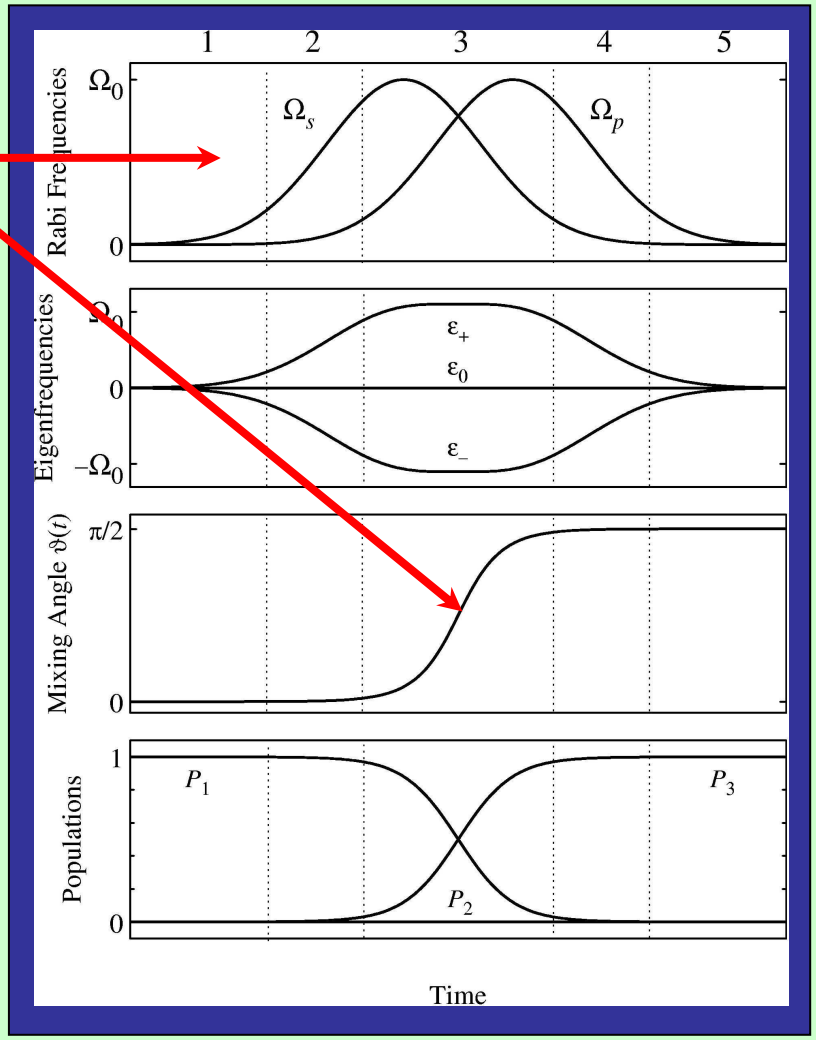
$\tan\Theta = \Omega_P / \Omega_S$

$$H = \frac{\hbar}{2}\begin{bmatrix} 0 & \Omega_P(t) & 0 \\ \Omega_P{}^*(t) & 0 & \Omega_S(t) \\ 0 & \Omega_S{}^*(t) & 0 \end{bmatrix}$$

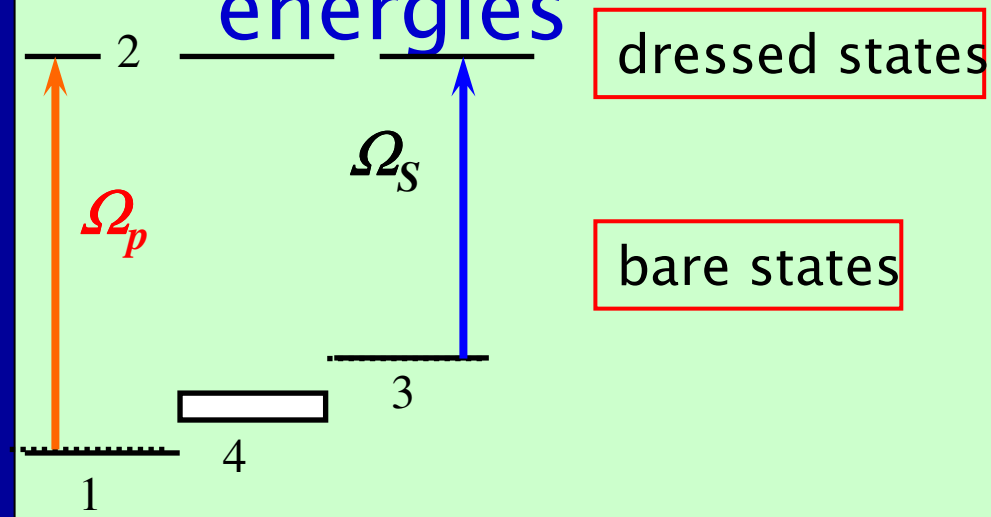
$$|\Phi_+(t)\rangle = \frac{1}{\sqrt{2}}\left[\sin\theta(t)|\psi_1\rangle + |\psi_2\rangle + \cos\theta(t)|\psi_3\rangle\right]$$

$$|\Phi_0(t)\rangle = \cos\theta(t)|\psi_1\rangle - \sin\theta(t)|\psi_3\rangle$$

$$|\Phi_-(t)\rangle = \frac{1}{\sqrt{2}}\left[\sin\theta(t)|\psi_1\rangle - |\psi_2\rangle + \cos\theta(t)|\psi_3\rangle\right]$$



Dressed states and dressed energies

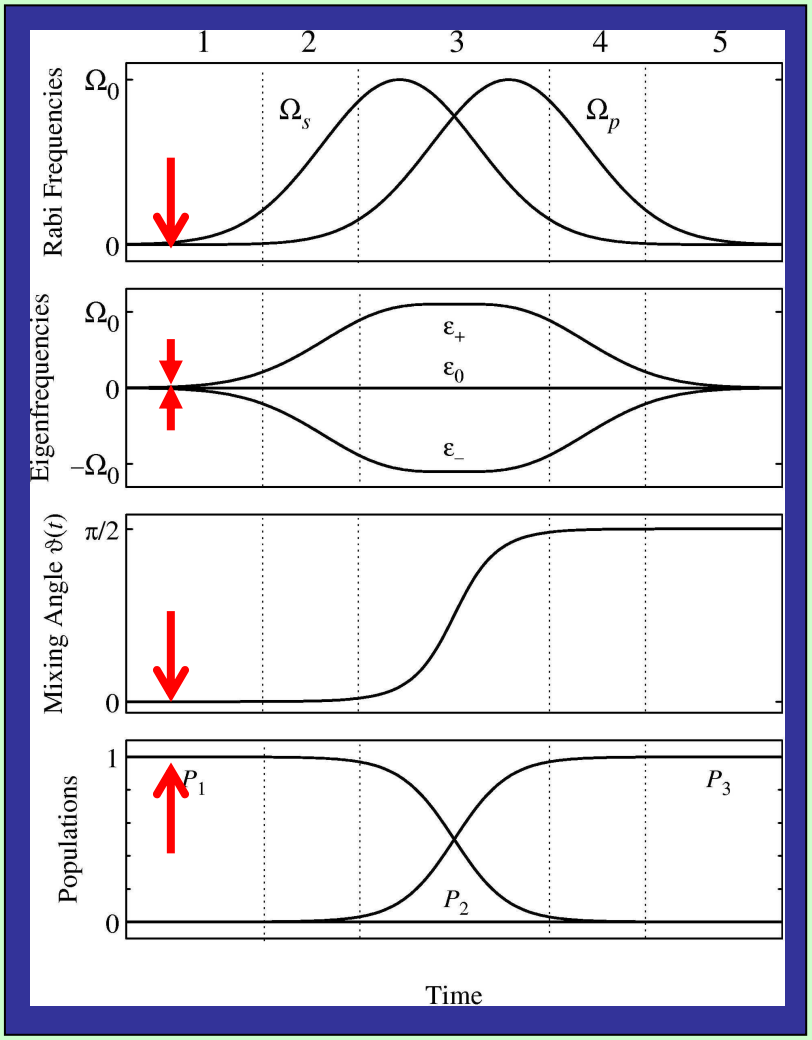


$$H = \frac{\hbar}{2}\begin{bmatrix} 0 & \Omega_P(t) & 0 \\ \Omega_P{}^*(t) & 0 & \Omega_S(t) \\ 0 & \Omega_S{}^*(t) & 0 \end{bmatrix}$$

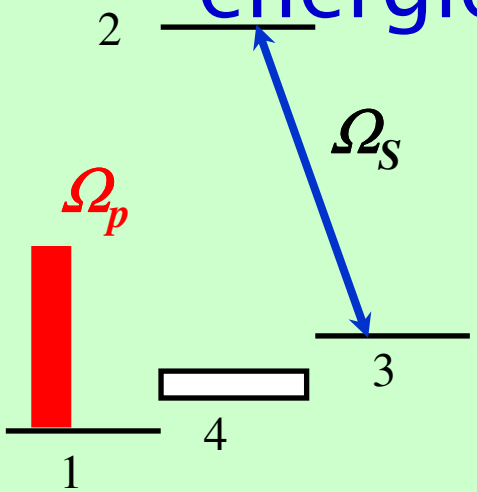
$$|\Phi_+(t)\rangle = \frac{1}{\sqrt{2}}\left[\sin\theta(t)|\psi_1\rangle + |\psi_2\rangle + \cos\theta(t)|\psi_3\rangle\right]$$

$$|\Phi_0(t)\rangle = \cos\theta(t)|\psi_1\rangle - \sin\theta(t)|\psi_3\rangle$$

$$|\Phi_-(t)\rangle = \frac{1}{\sqrt{2}}\left[\sin\theta(t)|\psi_1\rangle - |\psi_2\rangle + \cos\theta(t)|\psi_3\rangle\right]$$



Dressed states and dressed energies



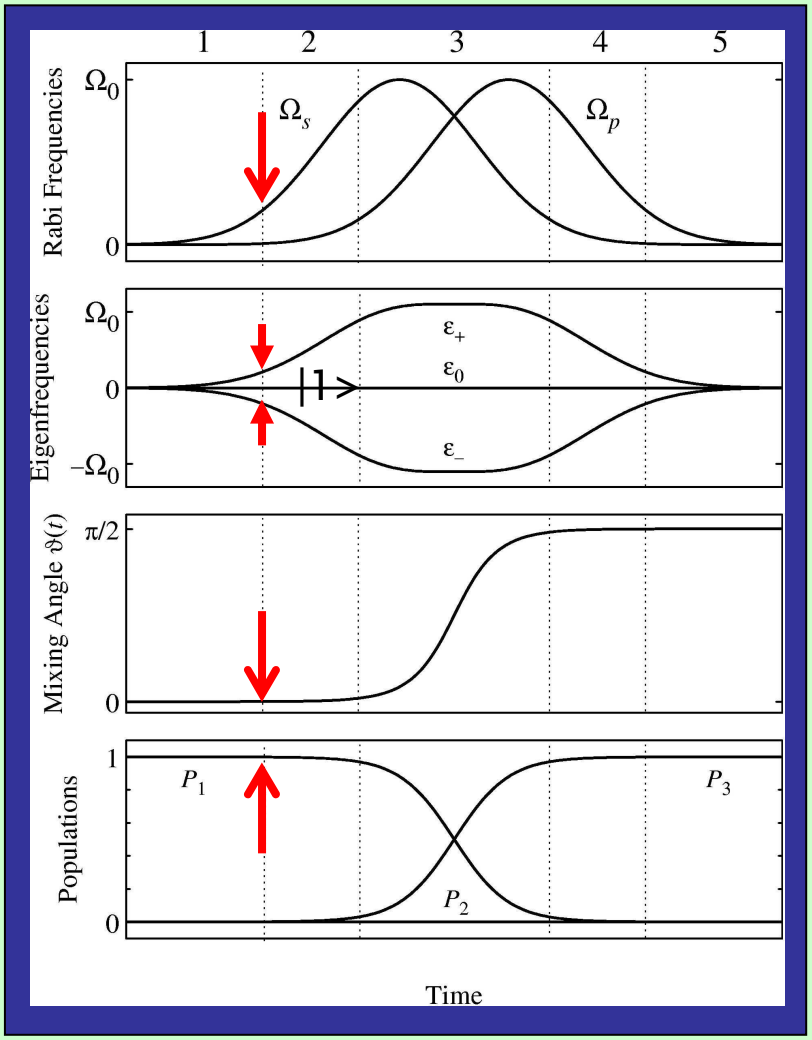
$\Omega_p = 0$

$$H = \frac{\hbar}{2}\begin{bmatrix} 0 & \Omega_P(t) & 0 \\ \Omega_P{}^*(t) & 0 & \Omega_S(t) \\ 0 & \Omega_S{}^*(t) & 0 \end{bmatrix}$$

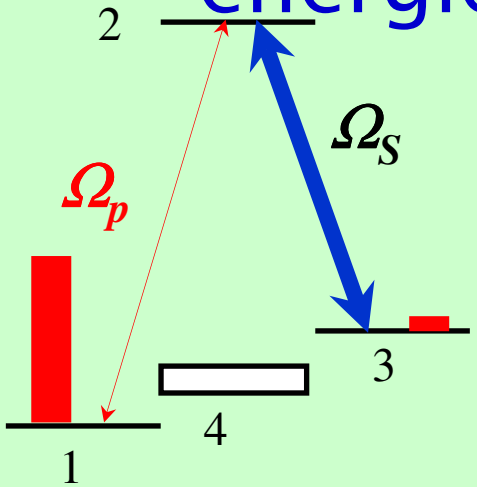
$$|\Phi_+(t)\rangle = \frac{1}{\sqrt{2}}\left[\sin\theta(t)|\psi_1\rangle + |\psi_2\rangle + \cos\theta(t)|\psi_3\rangle\right]$$

$$|\Phi_0(t)\rangle = \cos\theta(t)|\psi_1\rangle - \sin\theta(t)|\psi_3\rangle$$

$$|\Phi_-(t)\rangle = \frac{1}{\sqrt{2}}\left[\sin\theta(t)|\psi_1\rangle - |\psi_2\rangle + \cos\theta(t)|\psi_3\rangle\right]$$



Dressed states and dressed energies



$\Omega_p \neq 0$

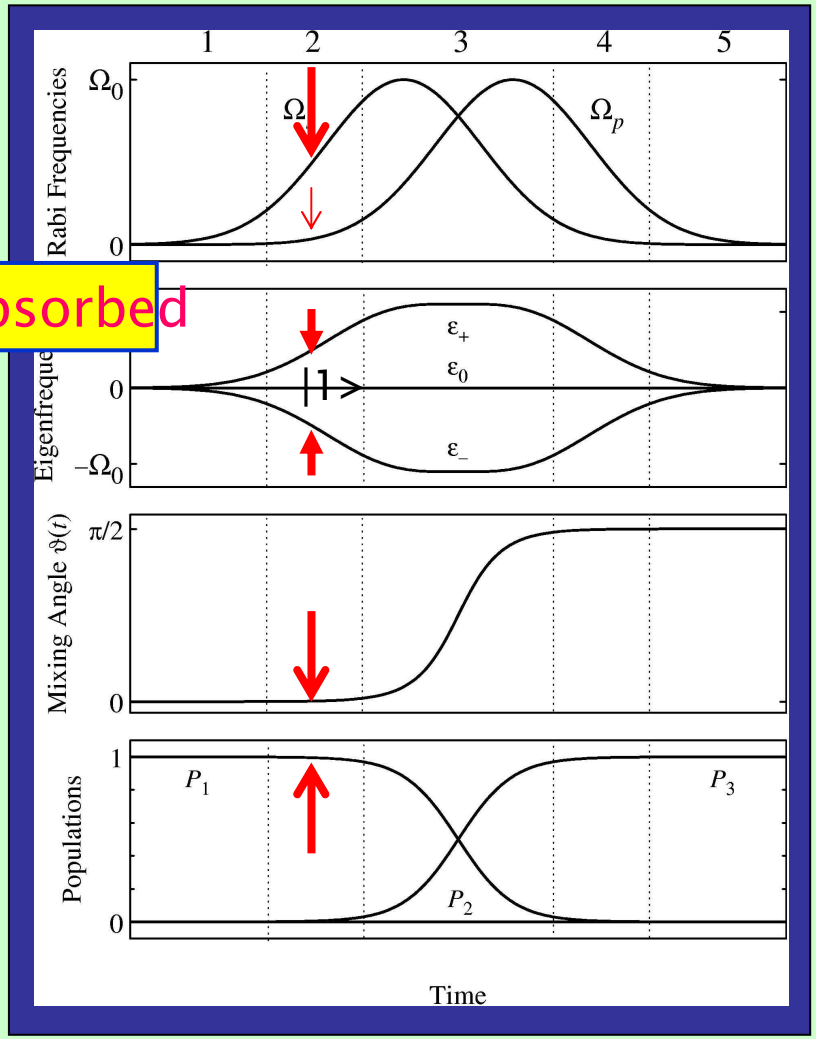
P radiation **NOT** absorbed

$$H = \frac{\hbar}{2}\begin{bmatrix} 0 & \Omega_P(t) & 0 \\ \Omega_P{}^*(t) & 0 & \Omega_S(t) \\ 0 & \Omega_S{}^*(t) & 0 \end{bmatrix}$$

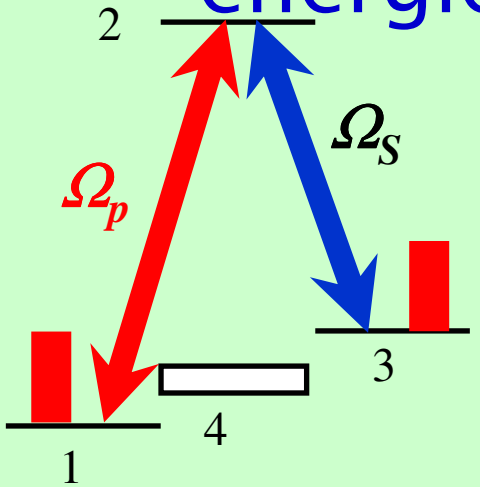
$$|\Phi_+(t)\rangle = \frac{1}{\sqrt{2}}\left[\sin\theta(t)|\psi_1\rangle + |\psi_2\rangle + \cos\theta(t)|\psi_3\rangle\right]$$

$$|\Phi_0(t)\rangle = \cos\theta(t)|\psi_1\rangle - \sin\theta(t)|\psi_3\rangle$$

$$|\Phi_-(t)\rangle = \frac{1}{\sqrt{2}}\left[\sin\theta(t)|\psi_1\rangle - |\psi_2\rangle + \cos\theta(t)|\psi_3\rangle\right]$$



Dressed states and dressed energies

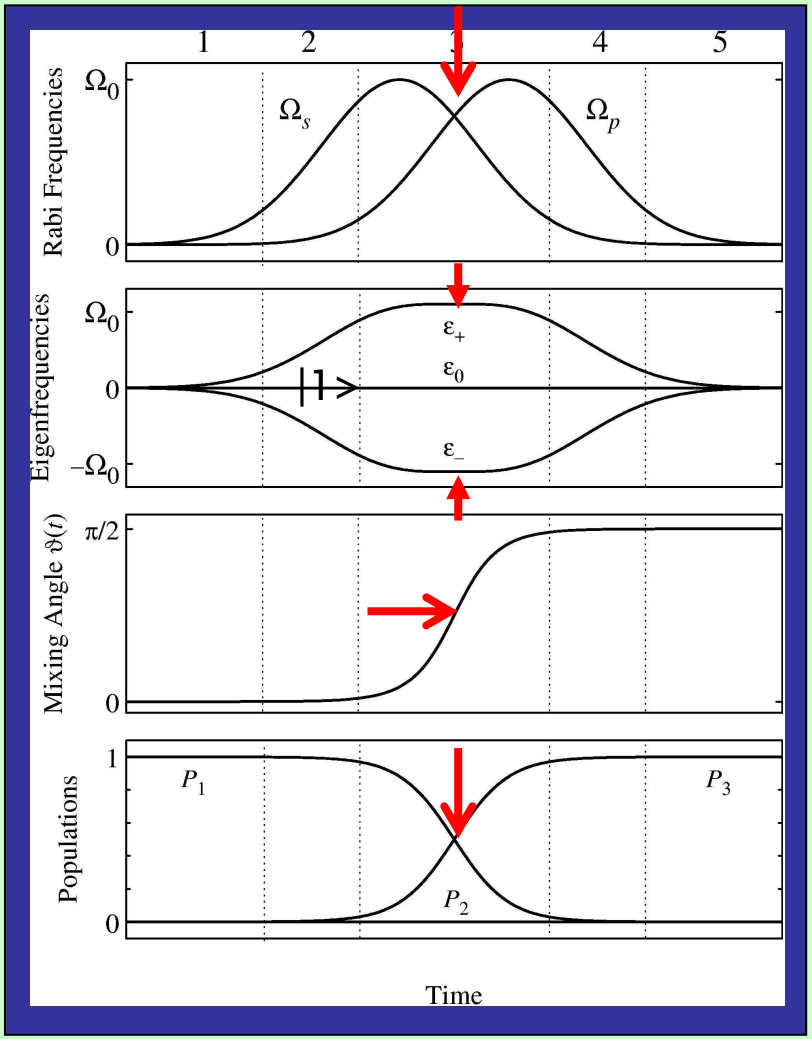


$$H = \frac{\hbar}{2}\begin{bmatrix} 0 & \Omega_P(t) & 0 \\ \Omega_P{}^*(t) & 0 & \Omega_S(t) \\ 0 & \Omega_S{}^*(t) & 0 \end{bmatrix}$$

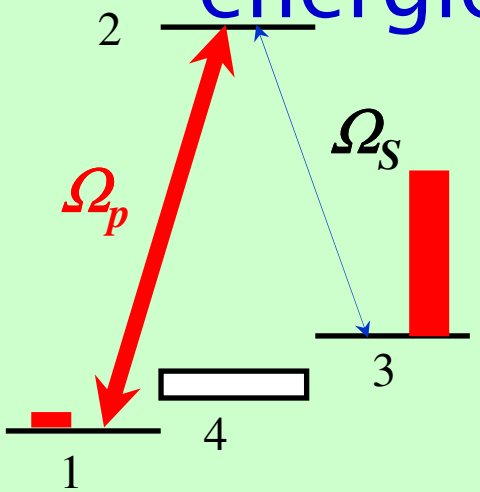
$$|\Phi_+(t)\rangle = \frac{1}{\sqrt{2}}\left[\sin\theta(t)|\psi_1\rangle + |\psi_2\rangle + \cos\theta(t)|\psi_3\rangle\right]$$

$$|\Phi_0(t)\rangle = \cos\theta(t)|\psi_1\rangle - \sin\theta(t)|\psi_3\rangle$$

$$|\Phi_-(t)\rangle = \frac{1}{\sqrt{2}}\left[\sin\theta(t)|\psi_1\rangle - |\psi_2\rangle + \cos\theta(t)|\psi_3\rangle\right]$$



Dressed states and dressed energies



$\Omega_S \neq 0$

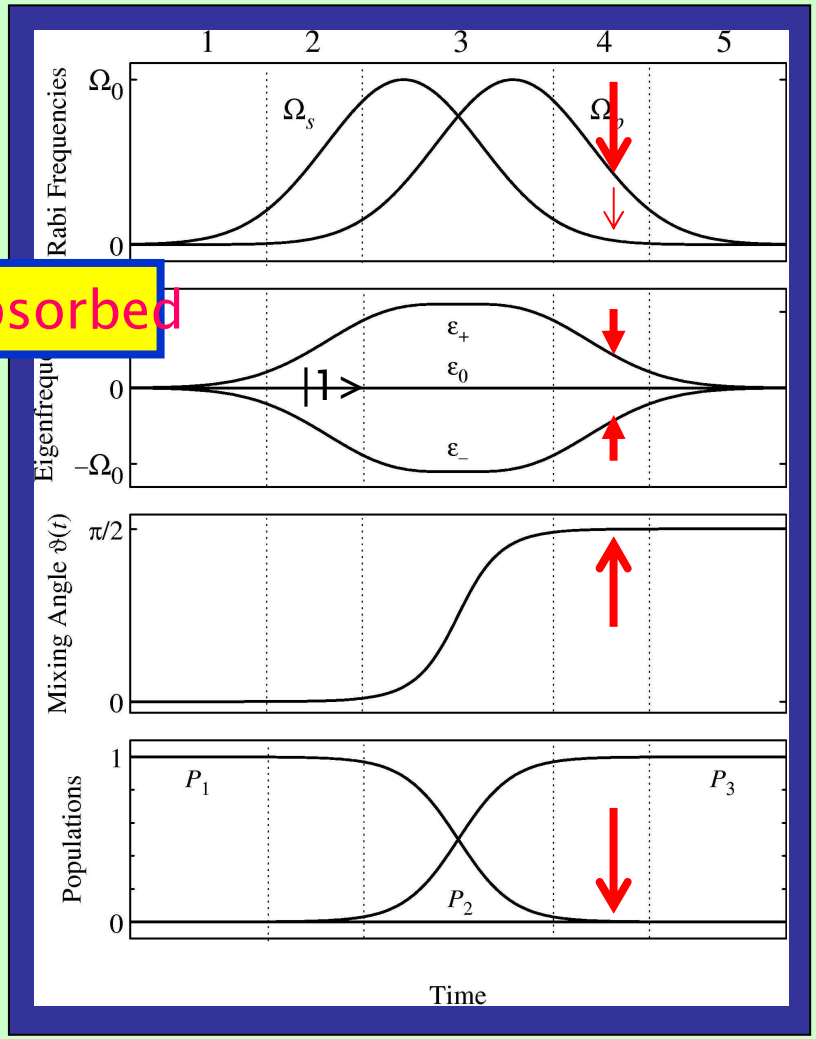
S radiation NOT absorbed

$$H = \frac{\hbar}{2}\begin{bmatrix} 0 & \Omega_P(t) & 0 \\ \Omega_P{}^*(t) & 0 & \Omega_S(t) \\ 0 & \Omega_S{}^*(t) & 0 \end{bmatrix}$$

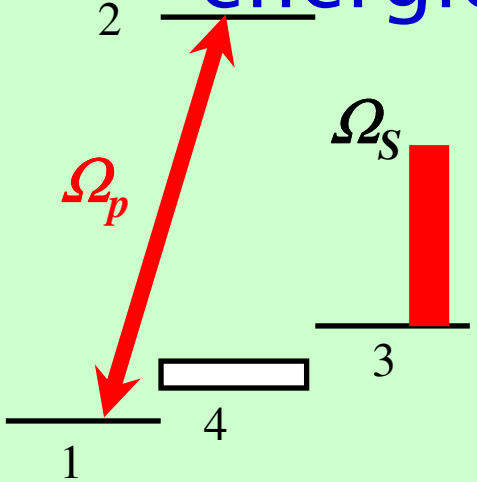
$$|\Phi_+(t)\rangle = \frac{1}{\sqrt{2}}\left[\sin\theta(t)|\psi_1\rangle + |\psi_2\rangle + \cos\theta(t)|\psi_3\rangle\right]$$

$$|\Phi_0(t)\rangle = \cos\theta(t)|\psi_1\rangle - \sin\theta(t)|\psi_3\rangle$$

$$|\Phi_-(t)\rangle = \frac{1}{\sqrt{2}}\left[\sin\theta(t)|\psi_1\rangle - |\psi_2\rangle + \cos\theta(t)|\psi_3\rangle\right]$$



Dressed states and dressed energies



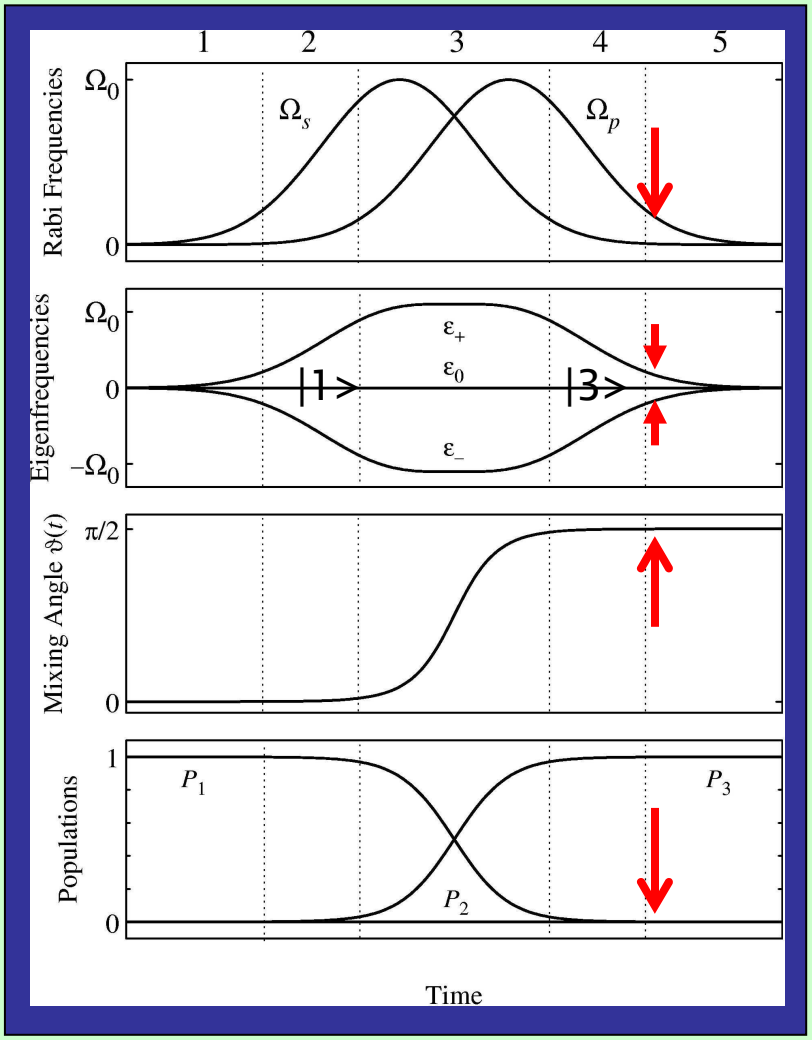
$\Omega_S = 0$

$$H = \frac{\hbar}{2}\begin{bmatrix} 0 & \Omega_P(t) & 0 \\ \Omega_P{}^*(t) & 0 & \Omega_S(t) \\ 0 & \Omega_S{}^*(t) & 0 \end{bmatrix}$$

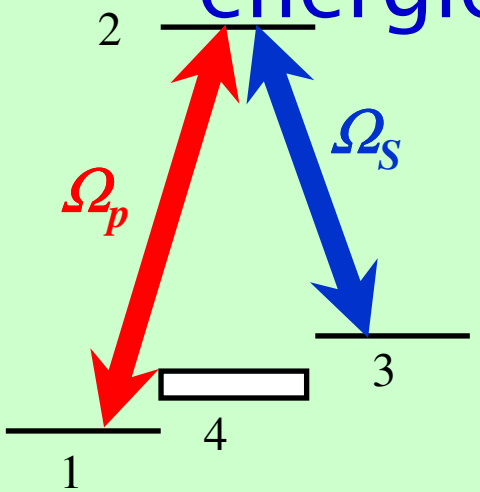
$$|\Phi_+(t)\rangle = \frac{1}{\sqrt{2}}\left[\sin\theta(t)|\psi_1\rangle + |\psi_2\rangle + \cos\theta(t)|\psi_3\rangle\right]$$

$$|\Phi_0(t)\rangle = \cos\theta(t)|\psi_1\rangle - \sin\theta(t)|\psi_3\rangle$$

$$|\Phi_-(t)\rangle = \frac{1}{\sqrt{2}}\left[\sin\theta(t)|\psi_1\rangle - |\psi_2\rangle + \cos\theta(t)|\psi_3\rangle\right]$$



Dressed states and dressed energies



zero-energie eigenvalue, trapped stat

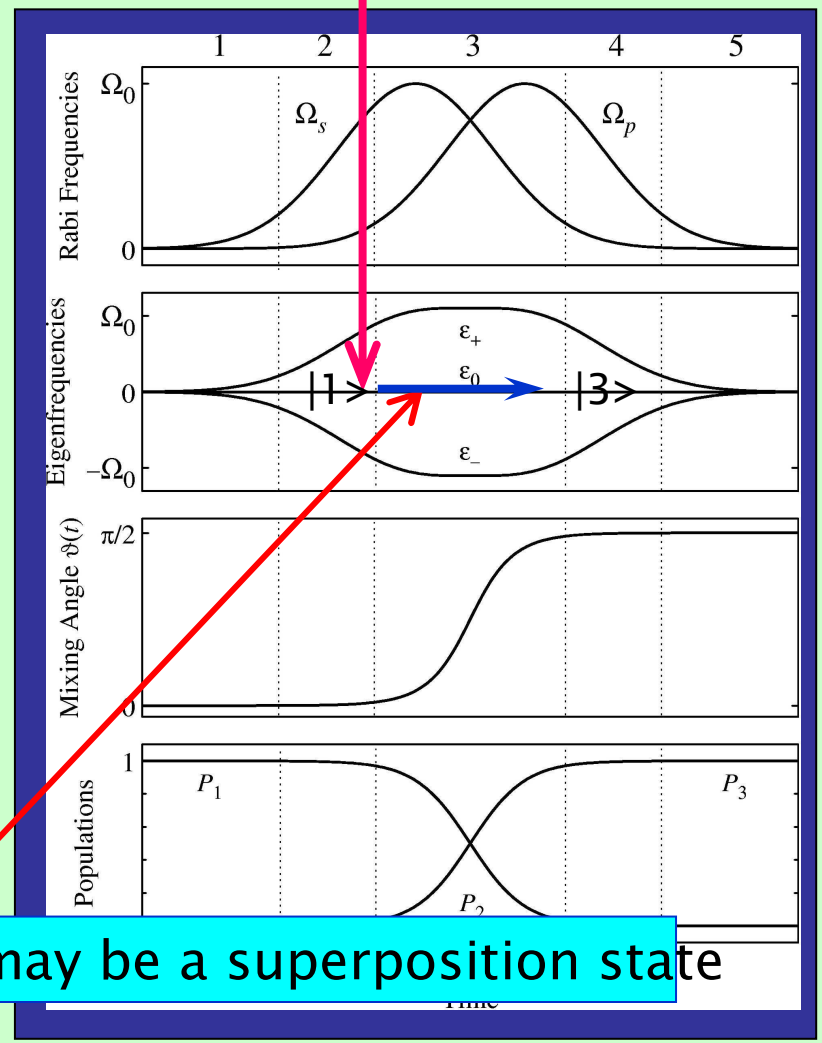
$\tan\Theta = \Omega_P / \Omega_S$

$$H = \frac{\hbar}{2}\begin{bmatrix} 0 & \Omega_P(t) & 0 \\ \Omega_P{}^*(t) & 0 & \Omega_S(t) \\ 0 & \Omega_S{}^*(t) & 0 \end{bmatrix}$$

$$|\Phi_+(t)\rangle = \frac{1}{\sqrt{2}}\left[\sin\theta(t)|\psi_1\rangle + |\psi_2\rangle + \cos\theta(t)|\psi_3\rangle\right]$$

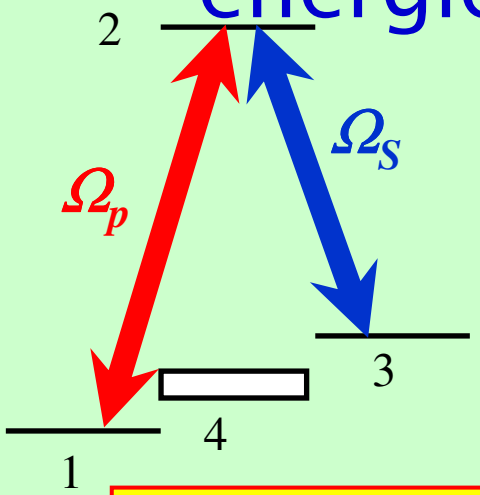
$$|\Phi_0(t)\rangle = \cos\theta(t)|\psi_1\rangle - \sin\theta(t)|\psi_3\rangle$$

$$|\Phi_-(t)\rangle = \frac{1}{\sqrt{2}}\left[\sin\theta(t)|\psi_1\rangle - |\psi_2\rangle + \cos\theta(t)|\psi_3\rangle\right]$$

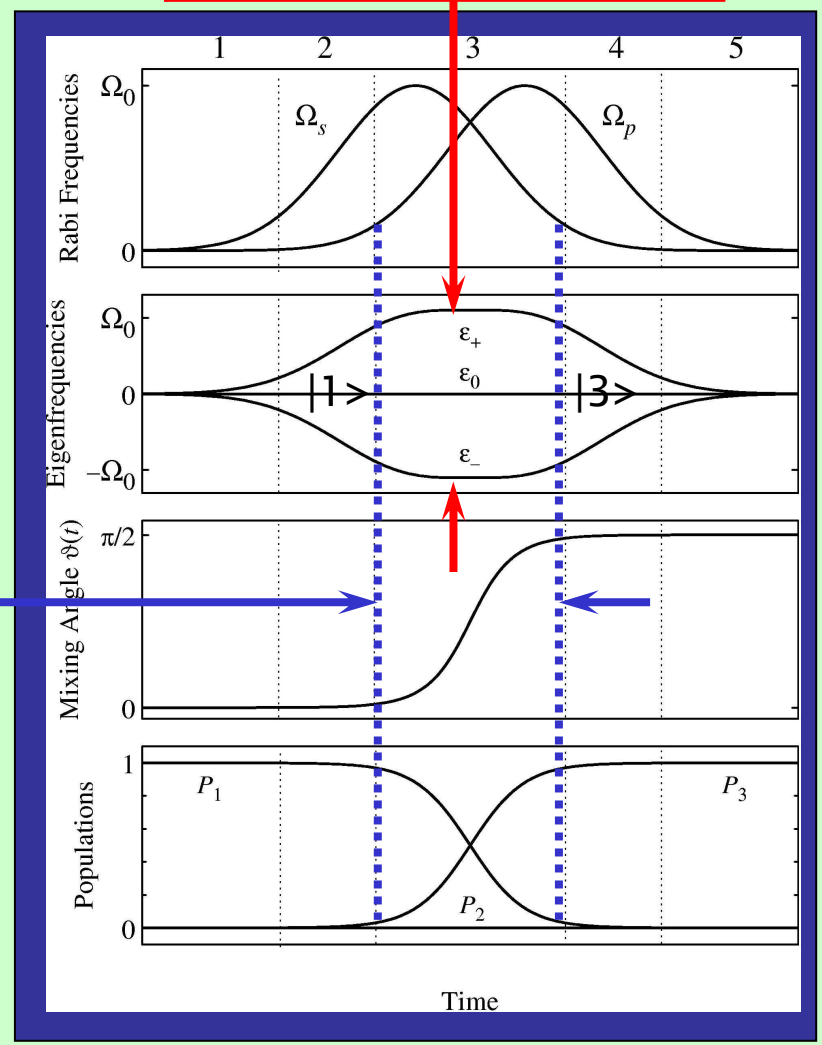


may be a superposition state

Dressed states and dressed energies



$$\Omega_{eff} = \sqrt{\Omega_P^2 + \Omega_S^2}$$



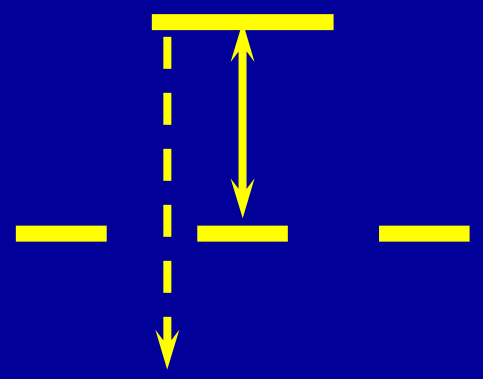
$\Delta\tau$

population trapping
coherent superposition
dark state

adiabatic evolution
if:

$$\Omega_{eff}\,\Delta\tau \gg 1$$

comment on dark states

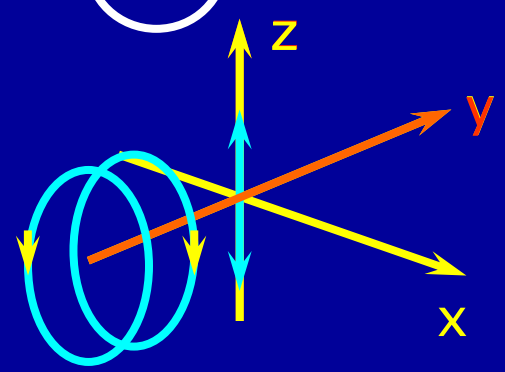


$J = 1 \rightarrow J = 0$ transition

induced by linearly polarized light

decay $\rightarrow$ depletion by optical pumping

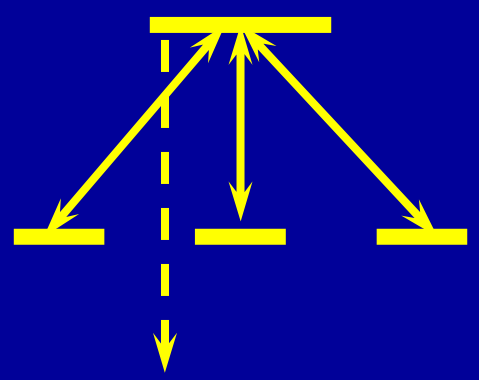
2/3 of population remains in initial level



change of quantization axis

decomposition: linear polarizati

$\rightarrow$ circular-right + circular-le



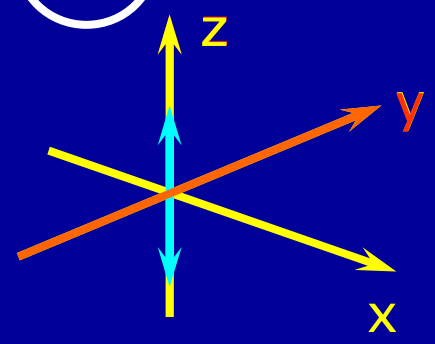
still: $J = 1 \rightarrow J = 0$ transition

still: decay $\rightarrow$ depletion by optical pumping

but now: 1/3 of population remains in initial leve

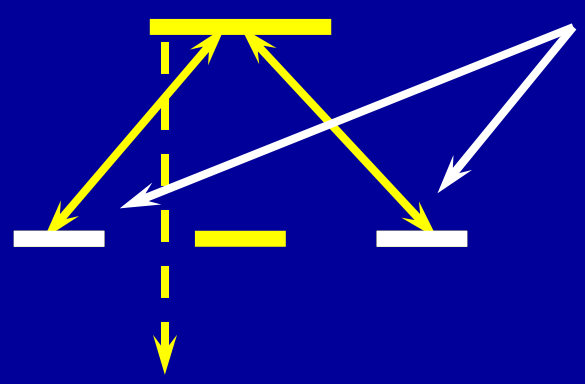
comment on dark states

2/3 of population remains in initial level



change of quantization axis

decomposition: linear polarizati
→ circular-right + circular-le

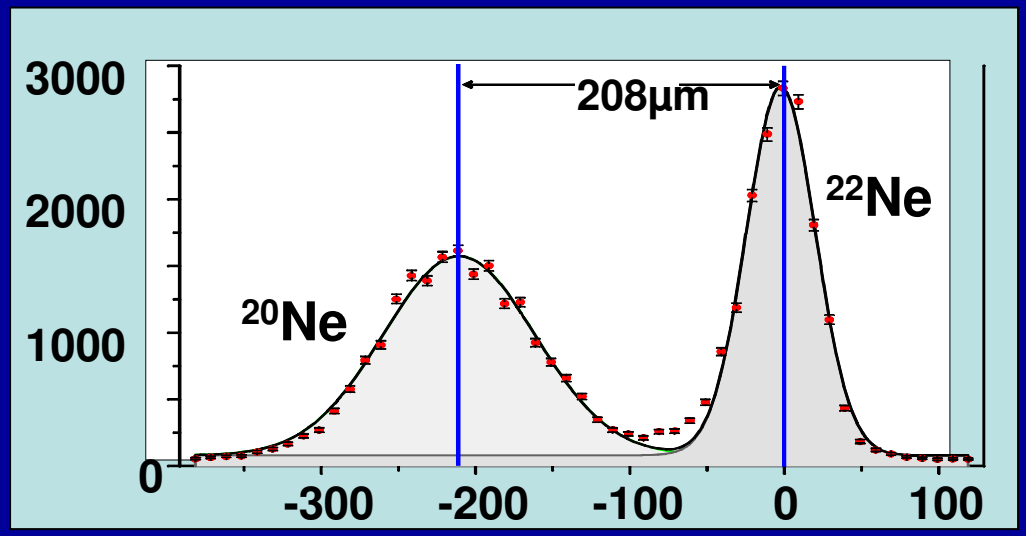


coherent superposition of two states
50 % in „bright“ state -- 50% in „dark state“

but now: 2/3 of population remains in initial leve

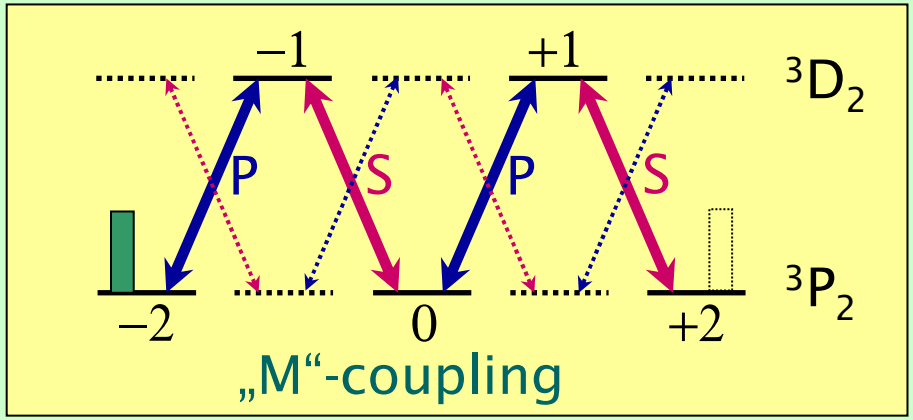
two applications – out of many:

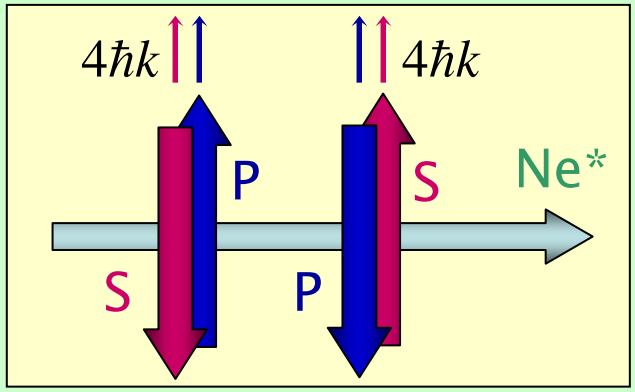
multiphoton processes
and
tailored momentum transfer

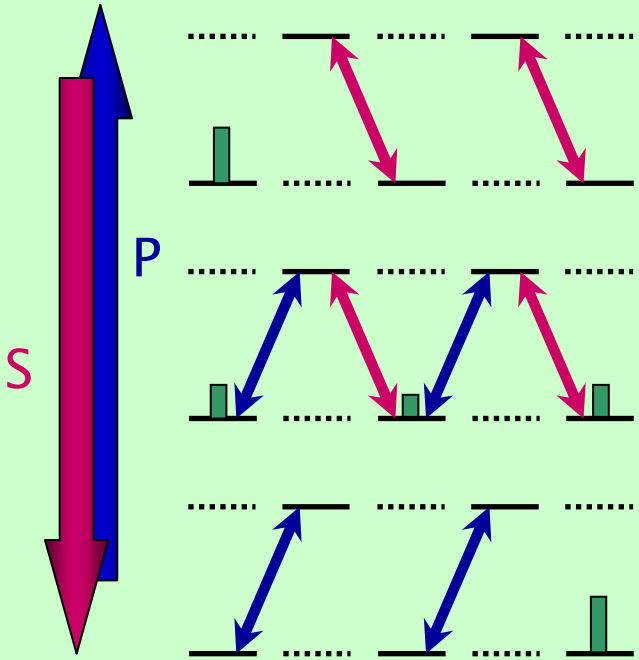


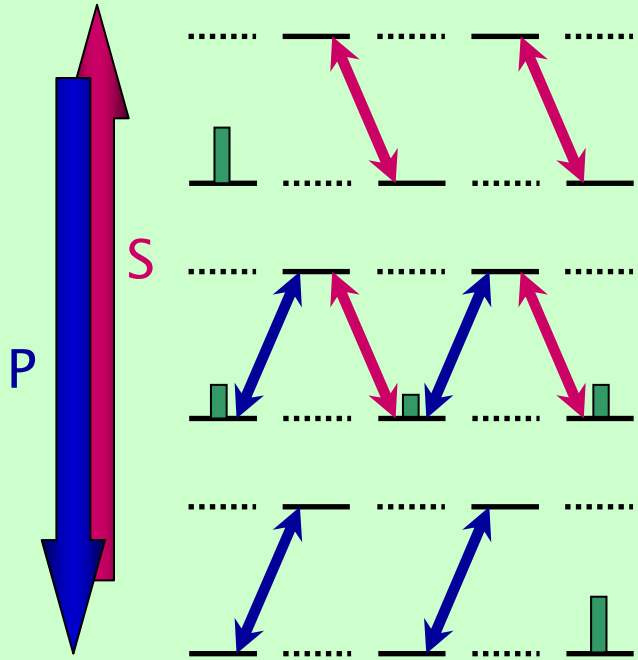
example: extension to multi-level systems

coherence-preserving mirror for particles

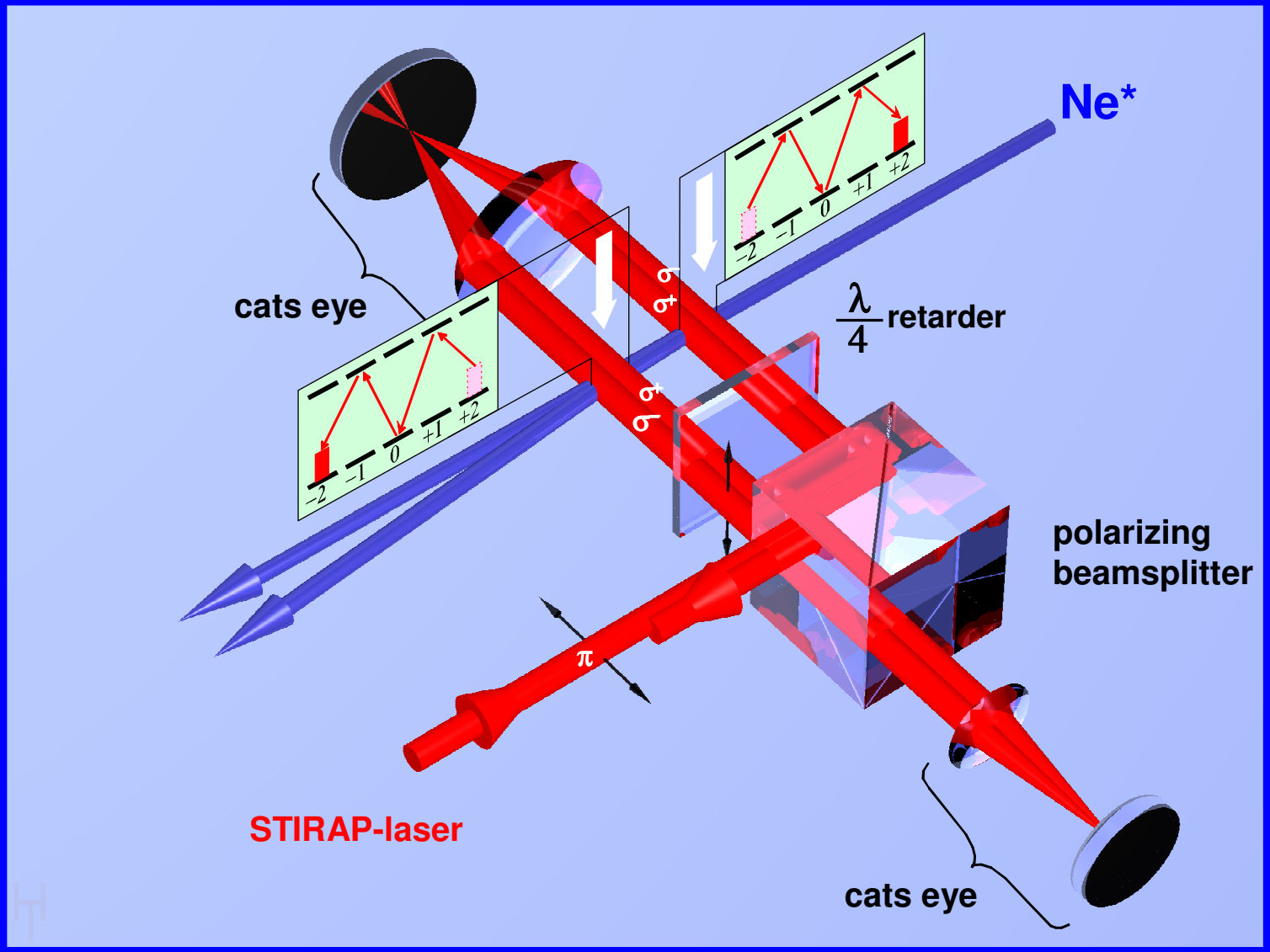




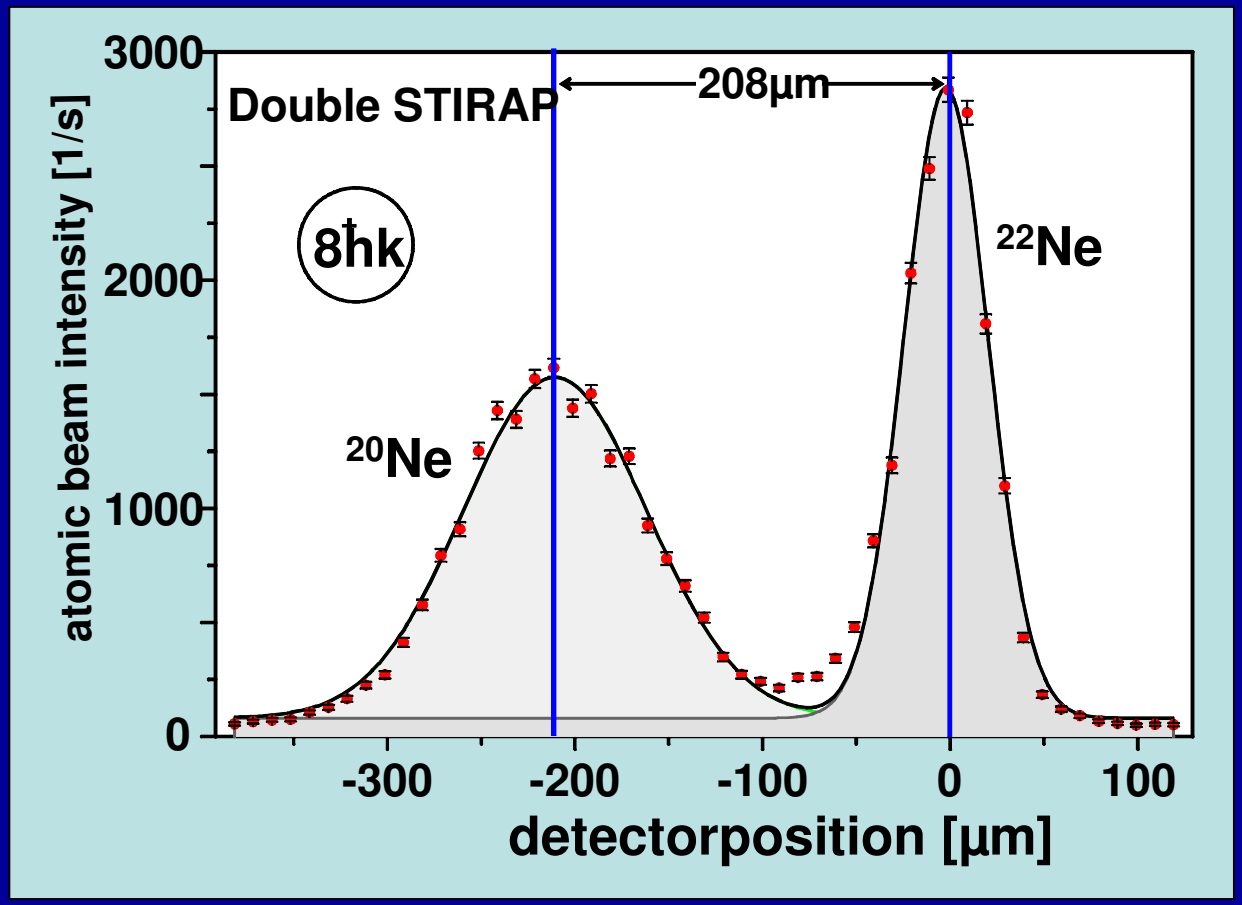




experimental realization of „double - STIRAP“

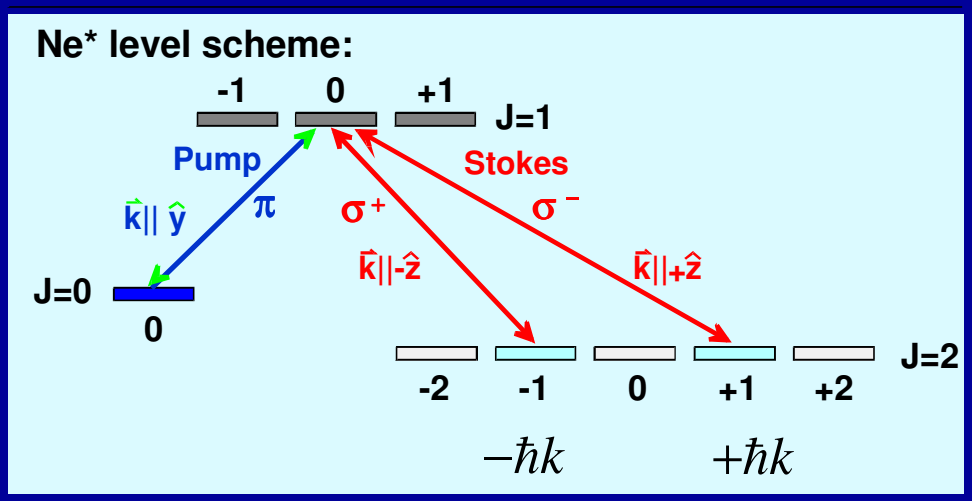


deflection of Ne* using „double-STIRAP“

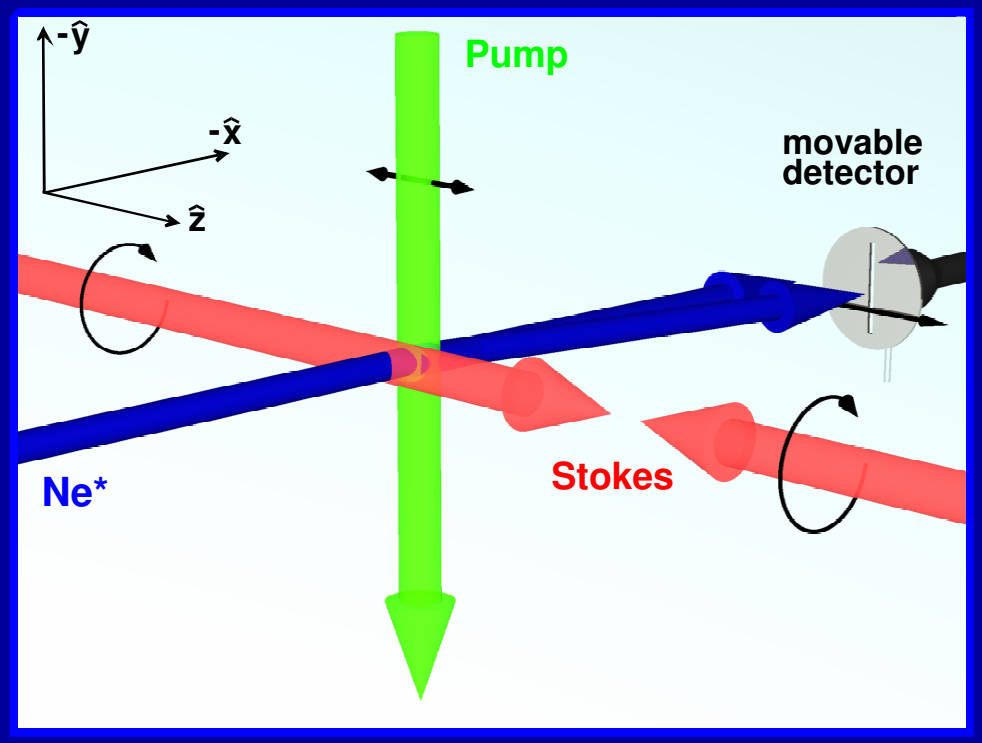


matter wave mirror

beam splitters for matterwaves: the tripod - coupling

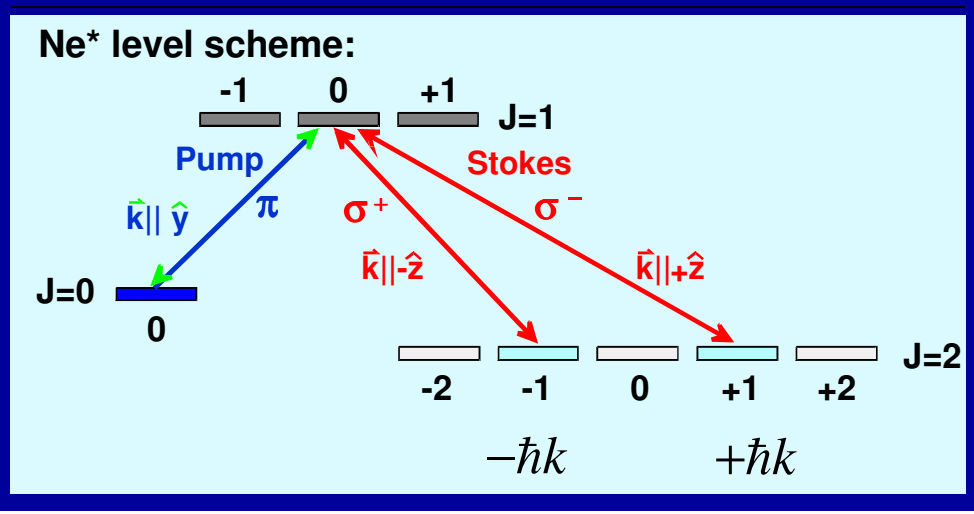


tripod-STIRAP: beamsplitter for atoms

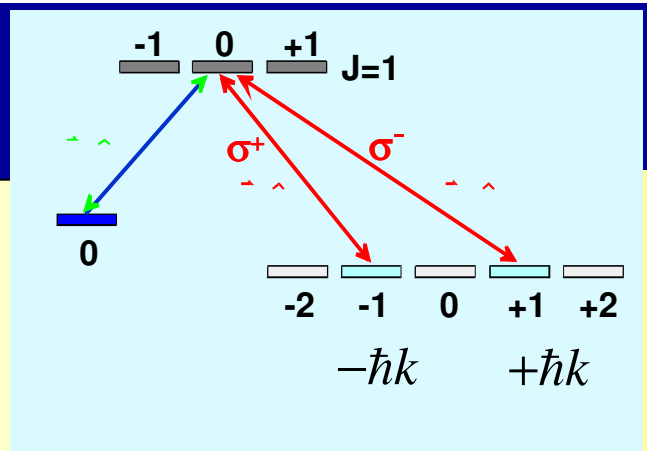


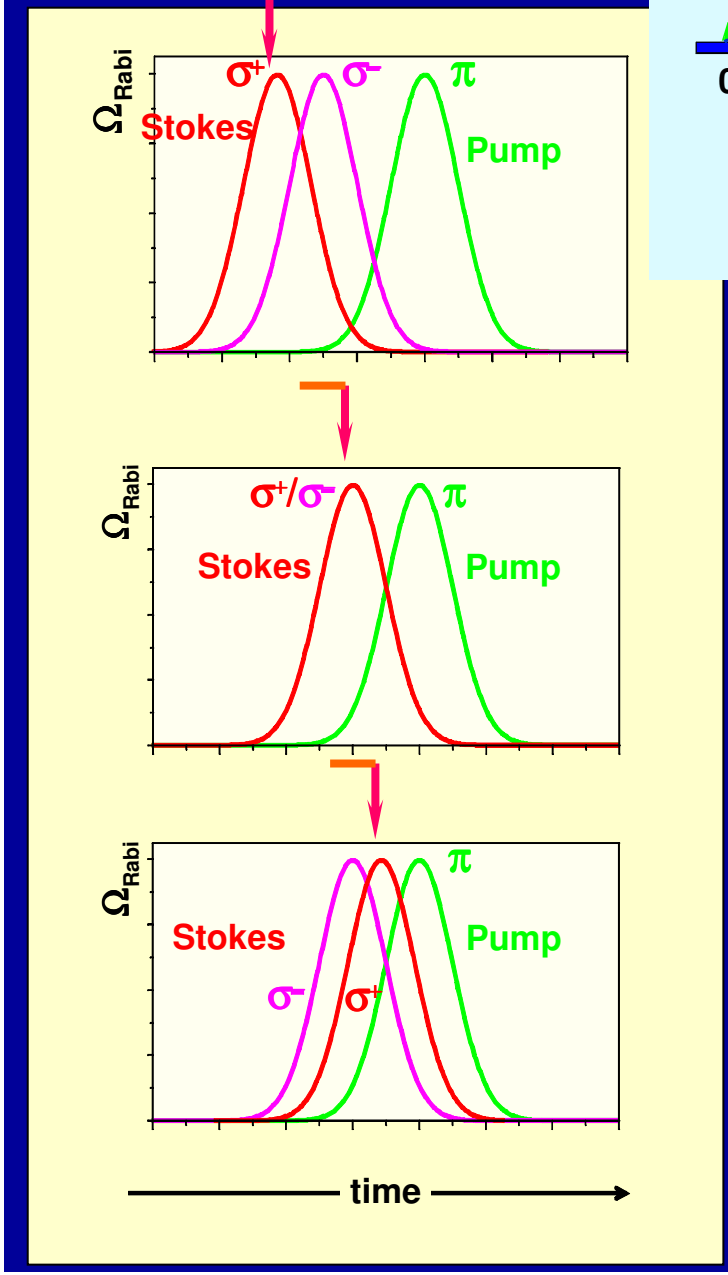
experimental arrangement

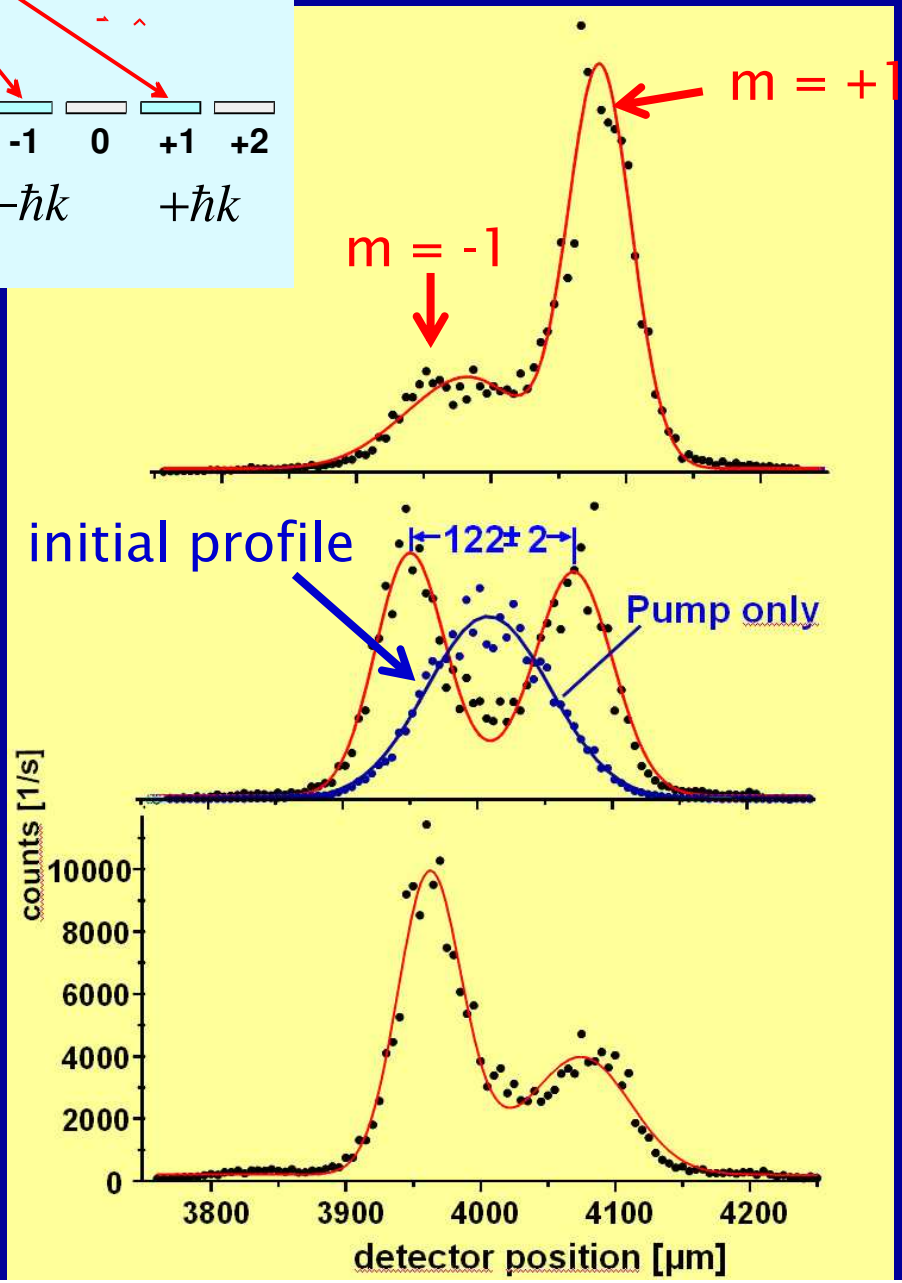
level scheme and coupling



variable beam







full control of (multi-component) superposition state

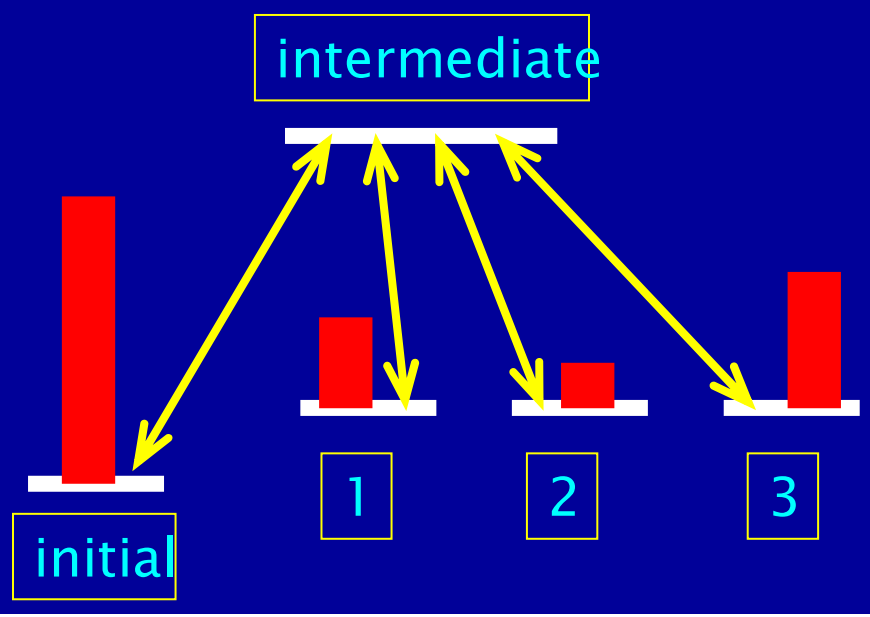
with cw lasers !

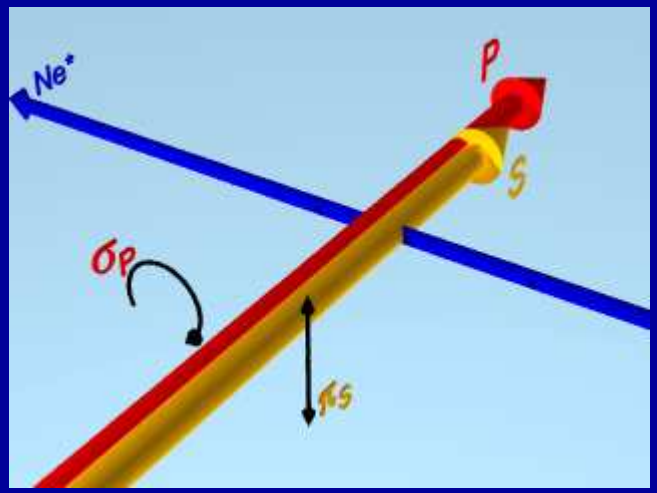
$$|\Psi\rangle = \alpha_1 |1\rangle + \alpha_2 e^{i\Phi_2} |2\rangle + \ldots\ldots + \alpha_5 e^{i\Phi_5} |5\rangle$$

control of amplitude | and phase

stream of identically prepared particles

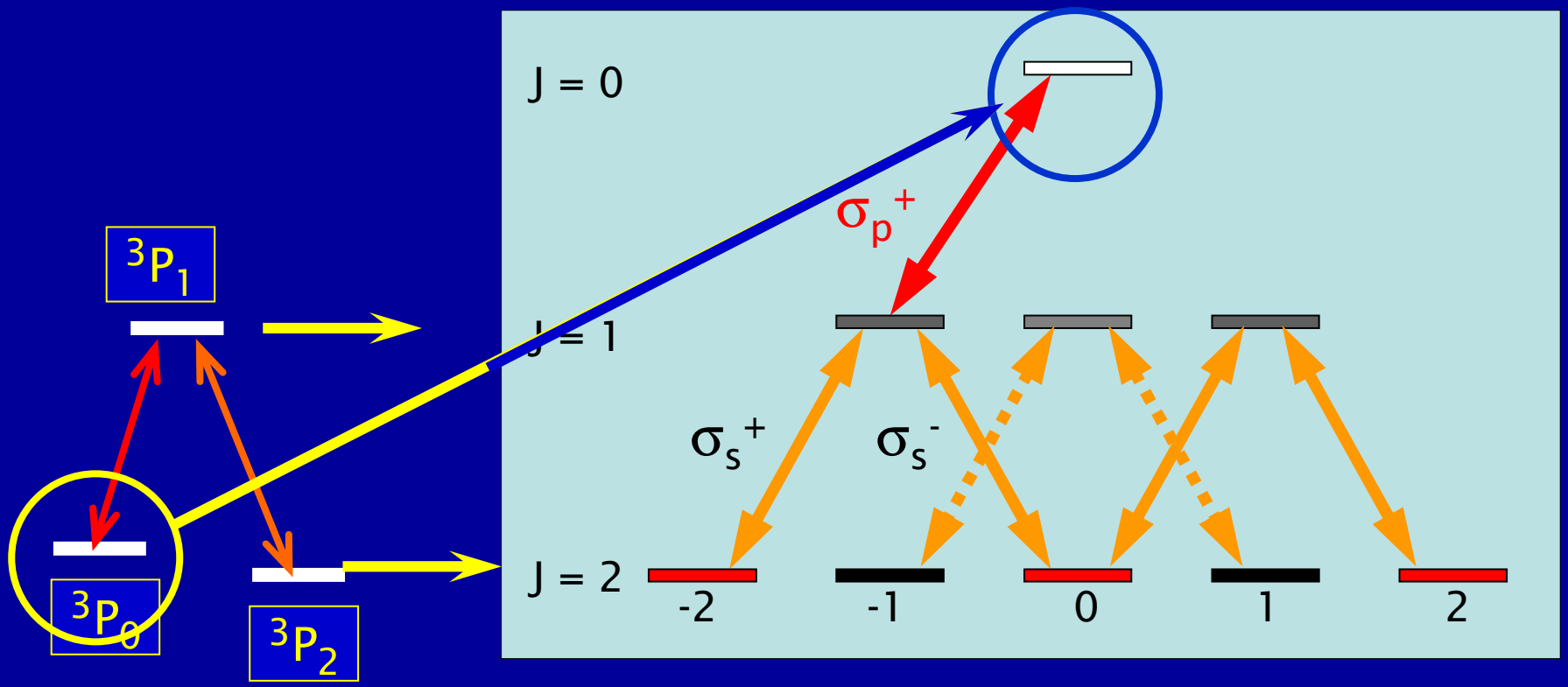
degenerate states
→ no dynamic phase





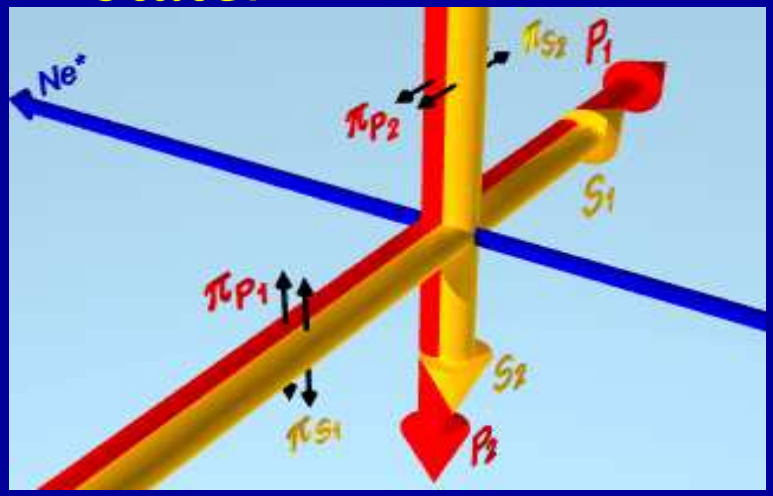
radiative coupling
example of linkage
pattern

extended Tripod-STIRAP



complete control of 5 - component superposition state:

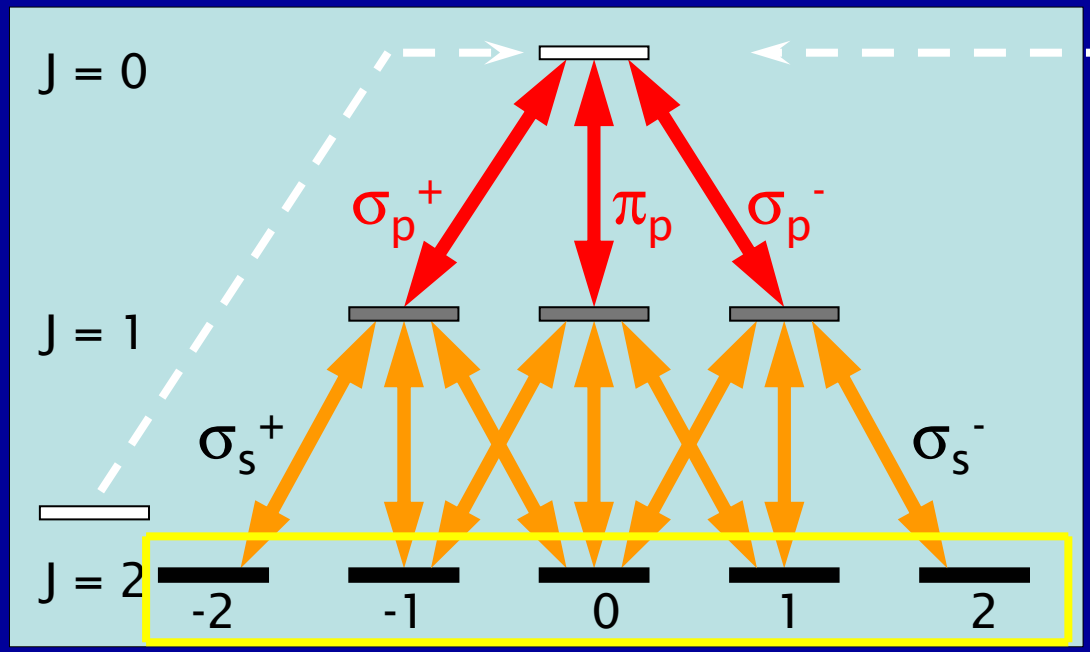
the making



8 parameters available:

2 per laser field ($R_{\perp\parallel}$, $\varphi_{\perp\parallel}$)

4 laser fields



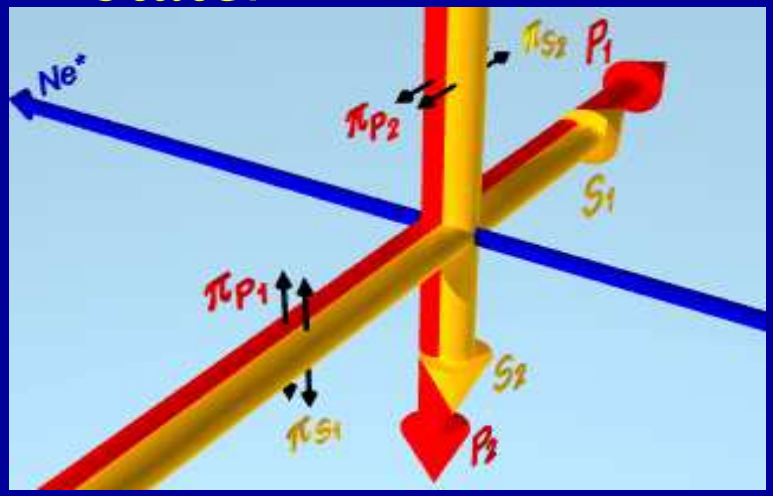
Initial state shown on top (for convenient display)

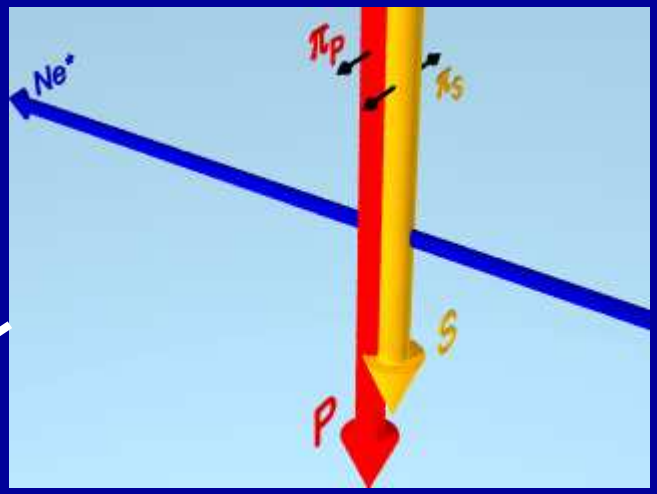
8 parameters wanted:

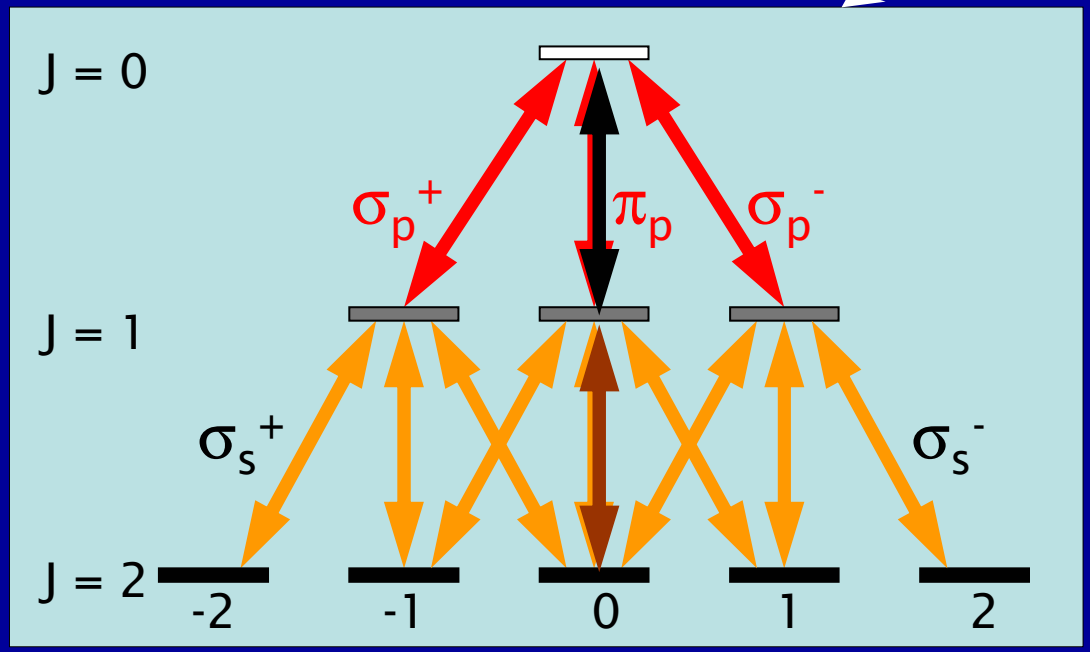
4 ratios of amplitudes

4 relative phases

complete control of 5 - component superposition state:

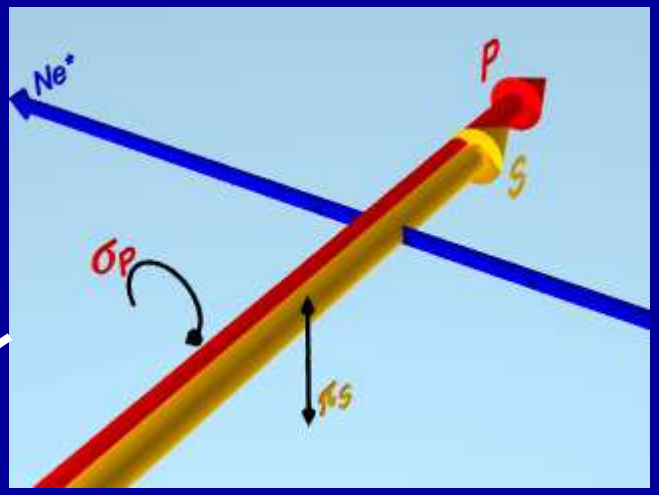


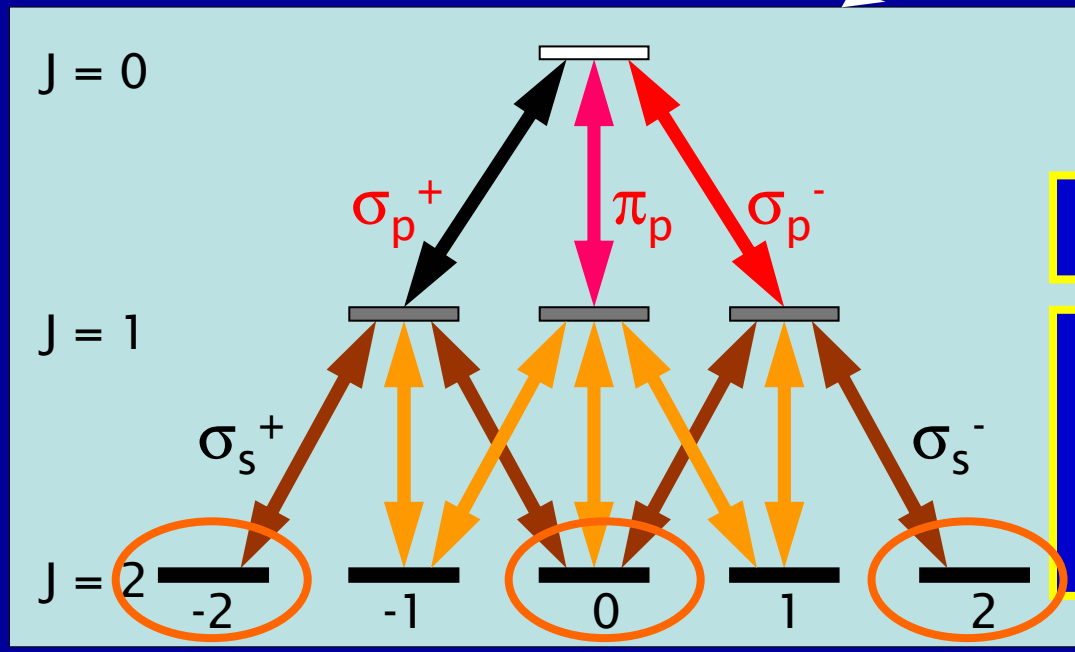




3-level STIRAP

complete control of 5 - component superposition state:



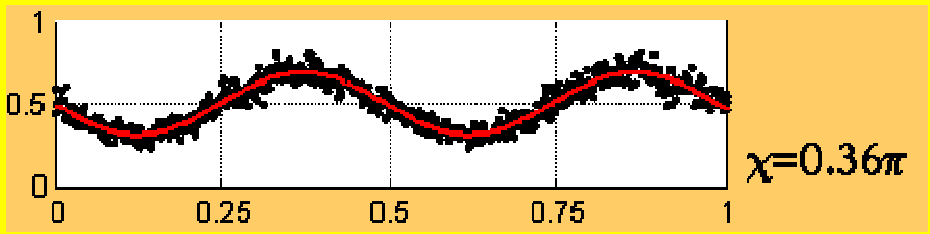


multi-level STIRAP

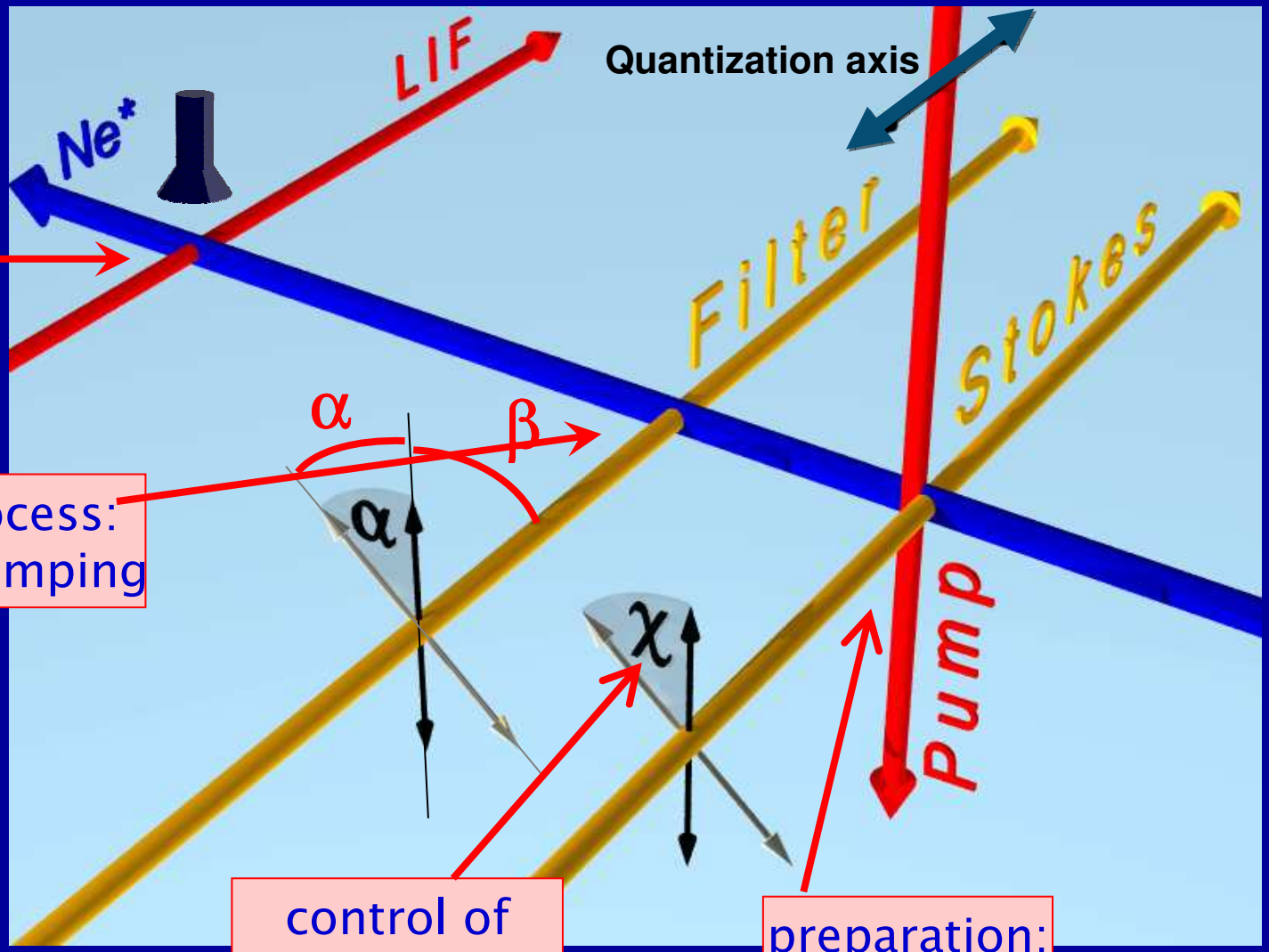
extended tripod - STIRAP

phase of σ_S^+ vs σ_S^- controlled by direction of π - polarization

measuring the relative phase between components



phase-to-population mapping – the principle



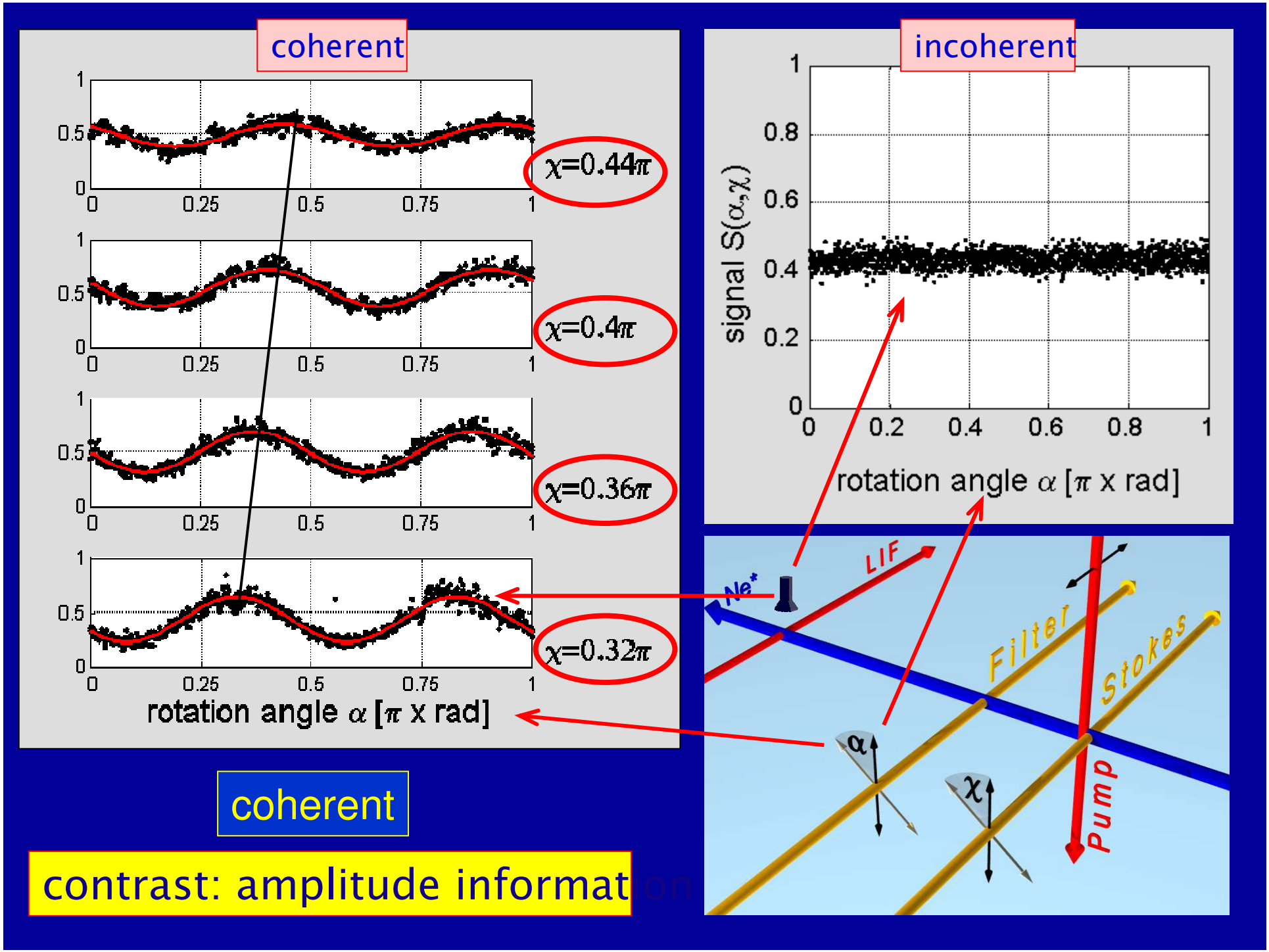
detection: laser-induced fluorescence

filter process: optical pumping

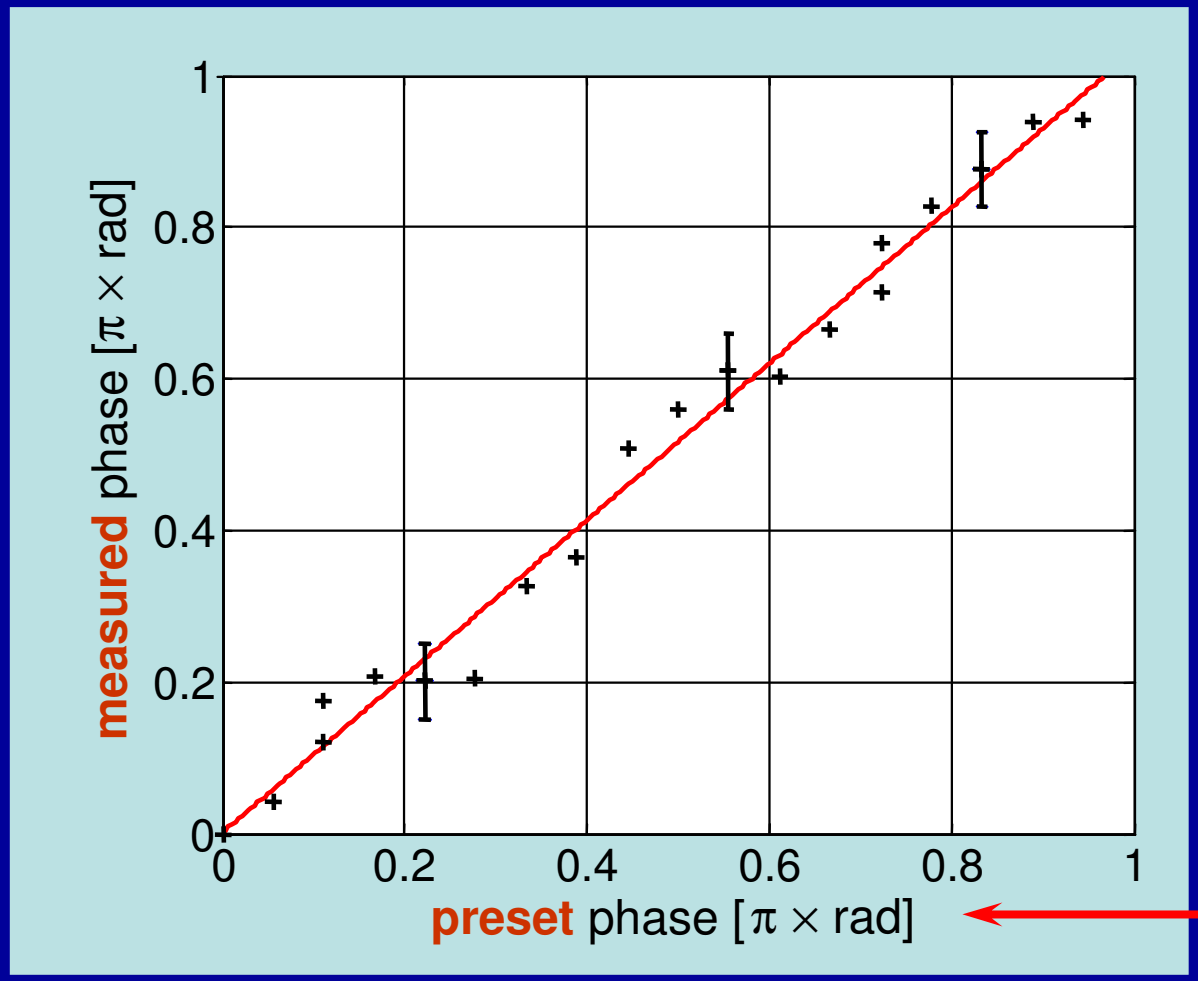
control of $\varphi_S(\sigma^+) - \varphi_S(\sigma^-)$

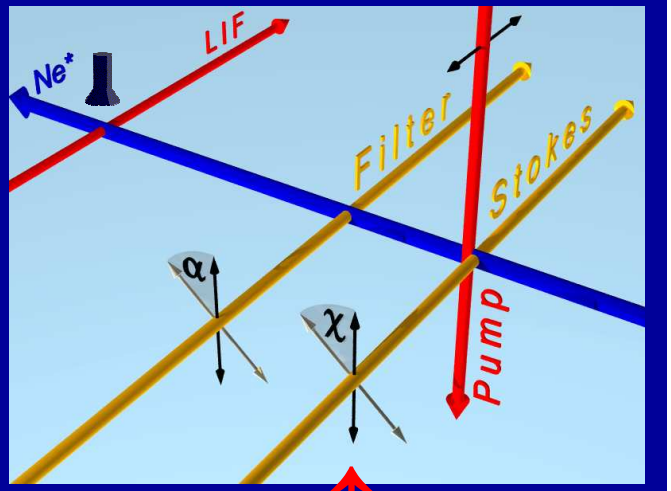
preparation: STIRAP

to be shown: equivalence to interferometer


coherent
χ=0.44π
χ=0.4π
χ=0.36π
χ=0.32π
rotation angle α [π x rad]
incoherent
signal S(α,χ)
rotation angle α [π x rad]
Ne*
LIF
Filter
Stokes
Pump
α
χ
coherent
contrast: amplitude information

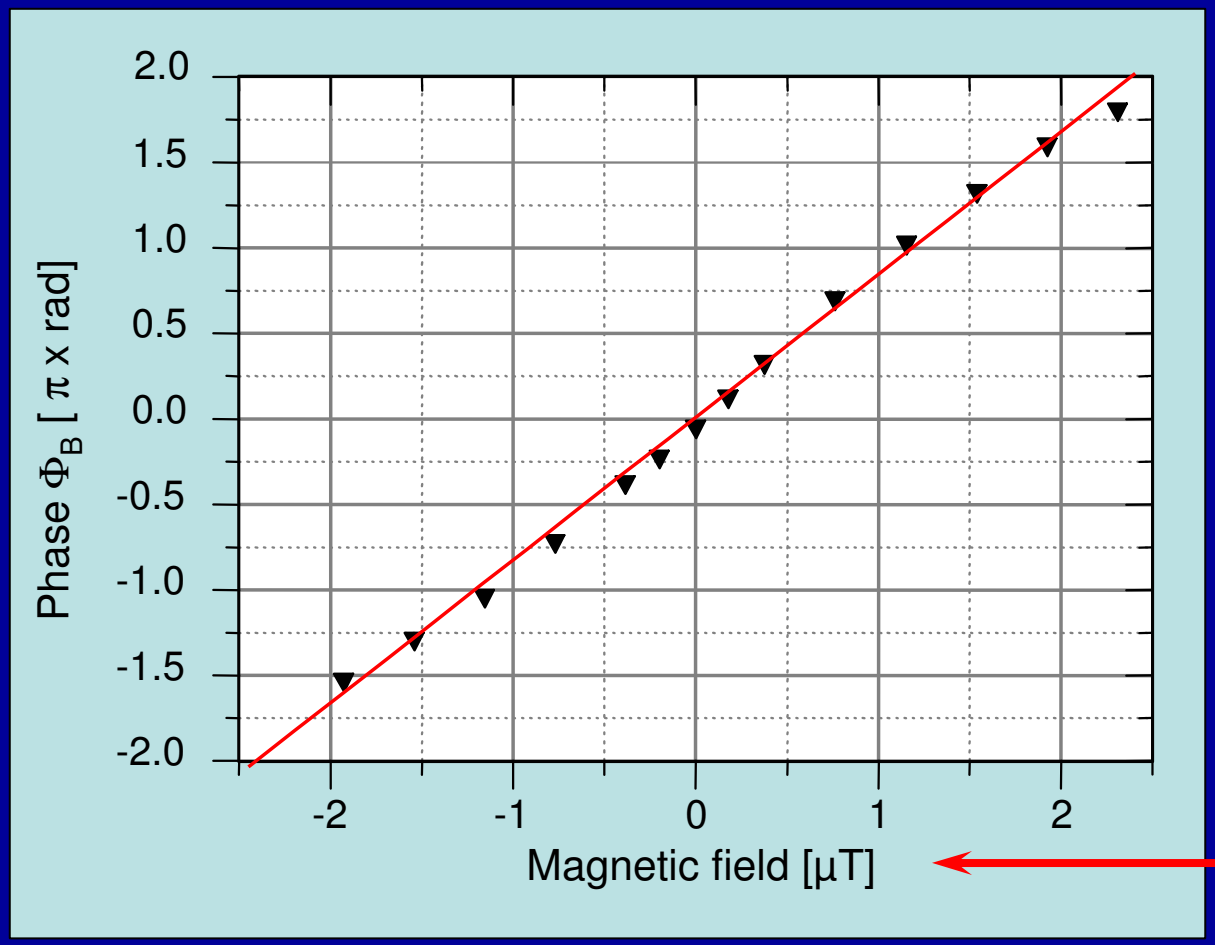
verifying : retrieval of preset phase

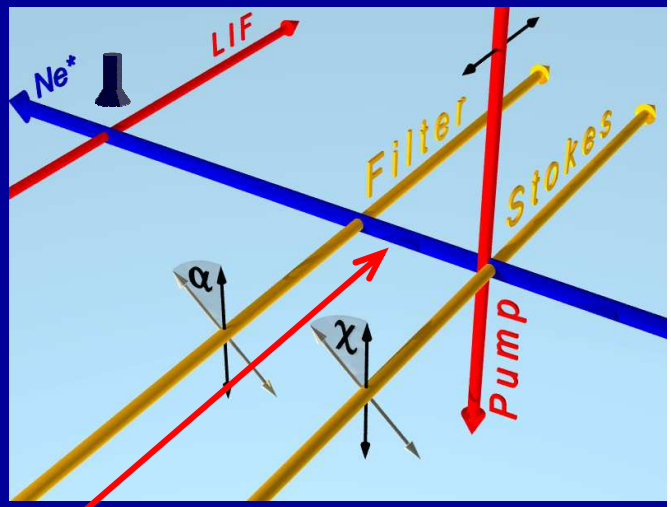




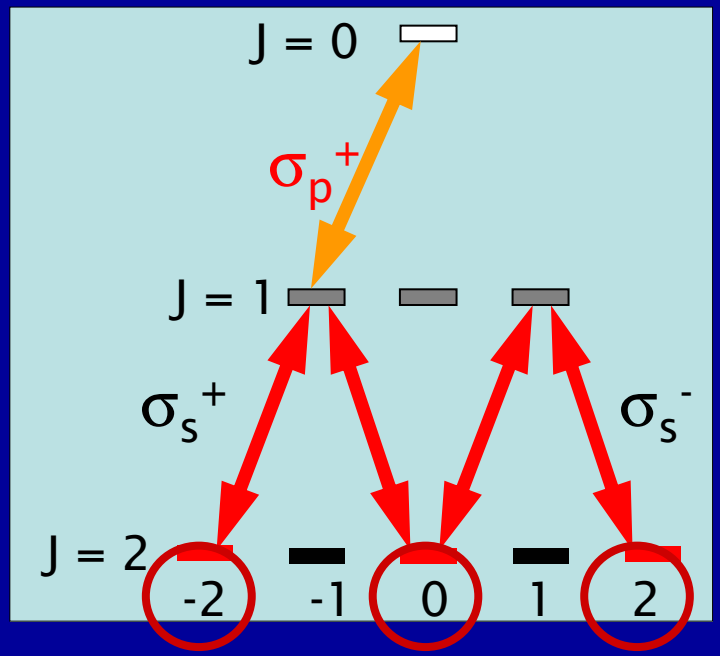
preset phase

verifying : control of phase by a B-field (Zeeman-splitting)





controlled B-field parallel to the direction of Stokes-laser propagation

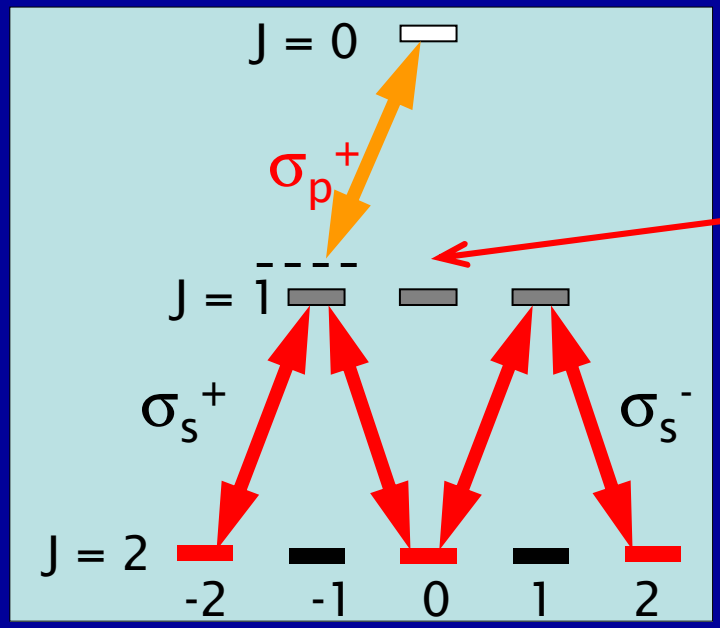


„phase manipulation"

3-level superposition sta

$$|a2(on)\rangle = e^{-i\chi}\left[c_{-2}|2,-2\rangle + c_0 e^{+i2\chi}|2,0\rangle + c_{+2}e^{+i4\chi}|2,+2\rangle\right]$$

on two-photon resonance (STIRAP)



„phase manipulation"

pump laser **detuned (Δ)** from resonance

3-level superposition sta

$$|a2(on)\rangle = e^{-i\chi}\left[c_{-2}|2,-2\rangle + c_0 e^{+i2\chi}|2,0\rangle + c_{+2}e^{+i4\chi}|2,+2\rangle\right]$$

on two-photon resonance (STIRAP)

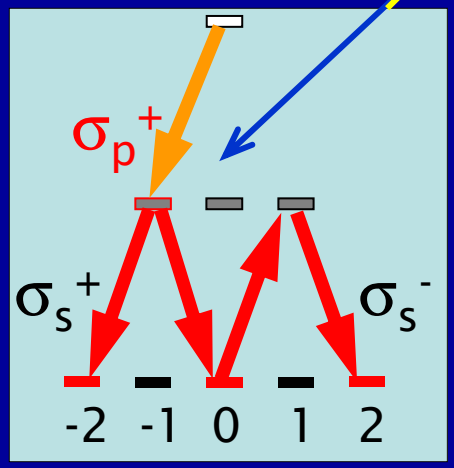
$$|a2(off)\rangle = e^{-i\chi}\left[c'_{-2}|2,-2\rangle + c'_0 e^{+i(2\chi+\pi)}|2,0\rangle + c'_{+2}e^{+i4\chi}|2,+2\rangle\right]$$

off two-photon resonance

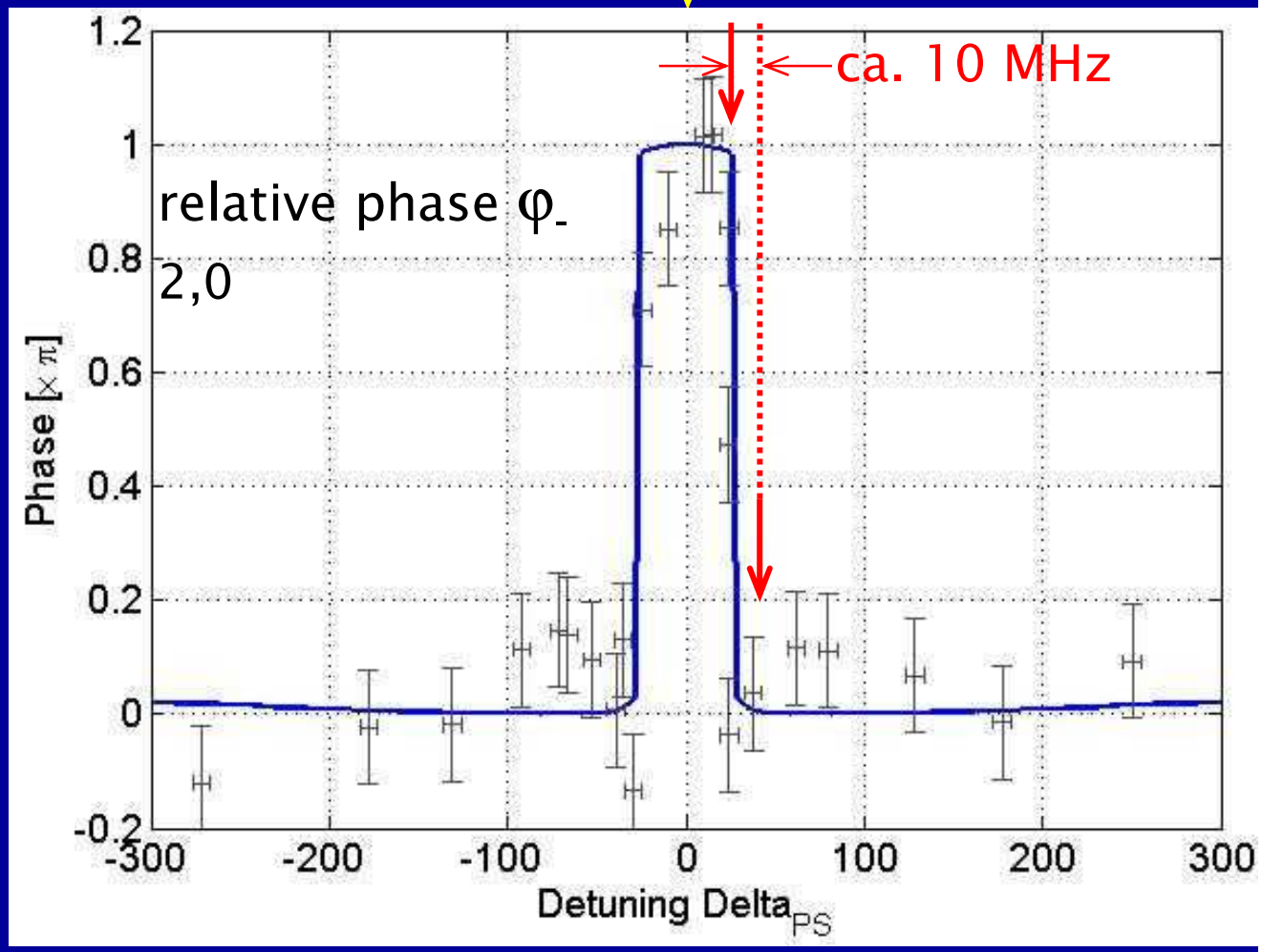
phase control by frequency control

detectable ?

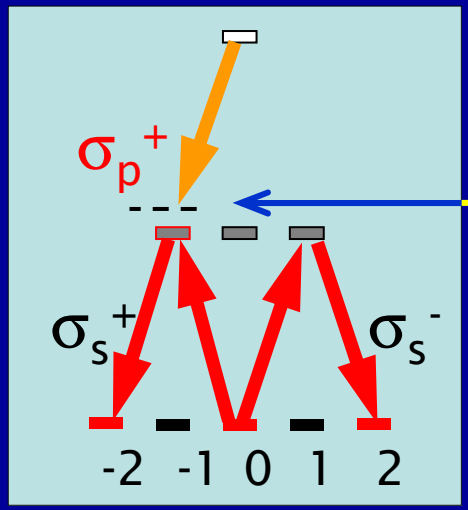
STIRAP:



pump laser on resonance

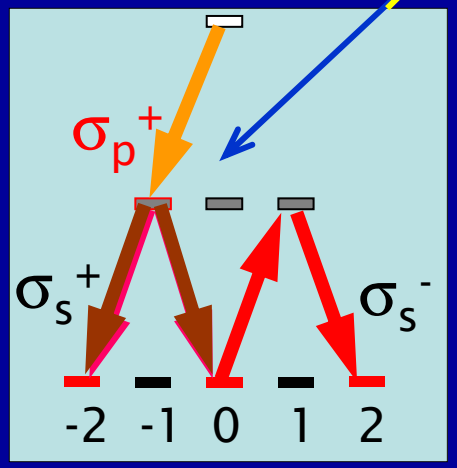


Coh.Pop.Trap.:

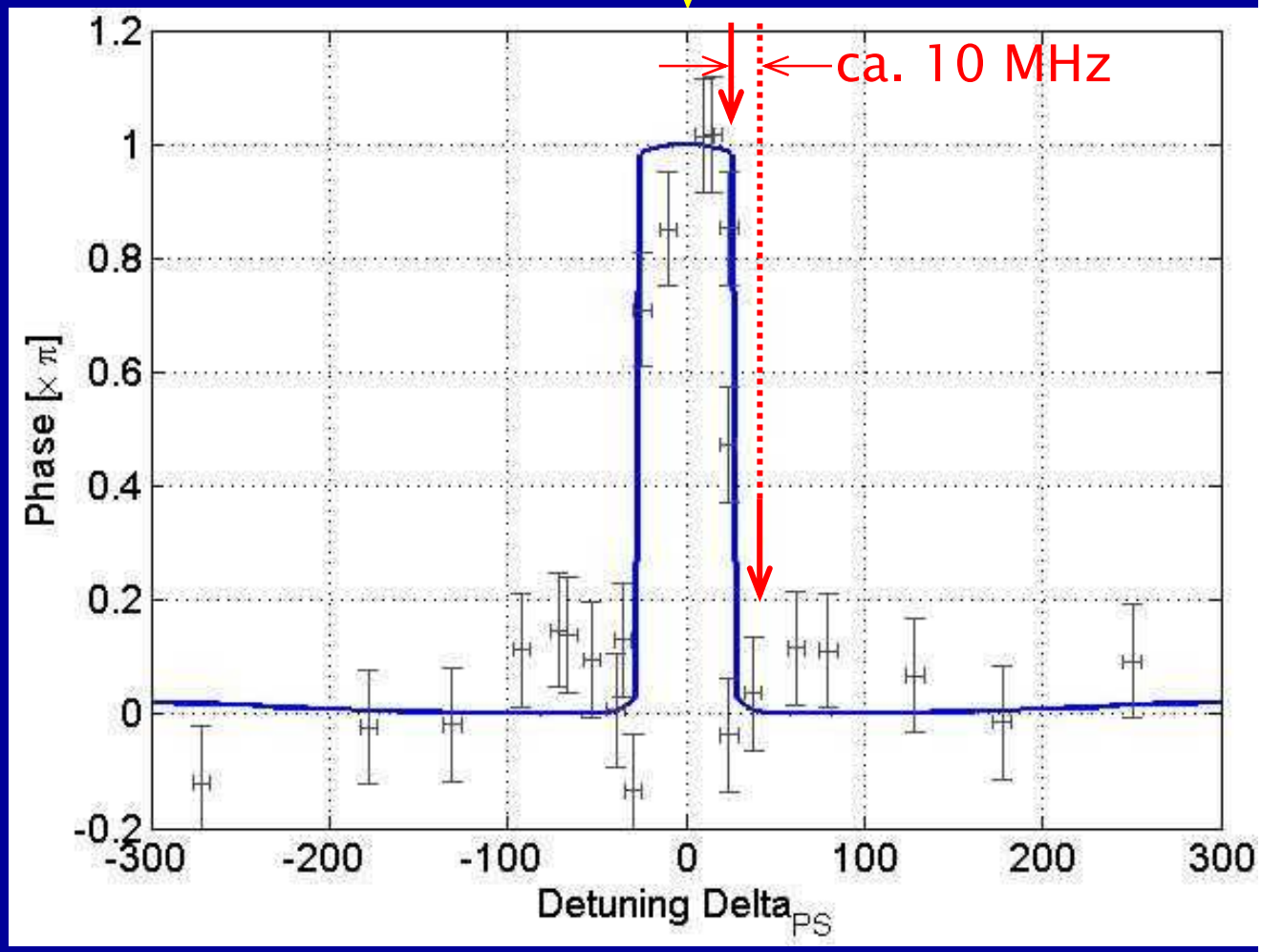


pump laser off resonance

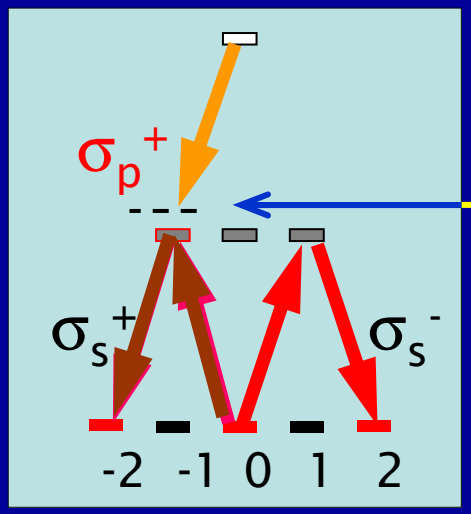
STIRAP:



pump laser on resonance



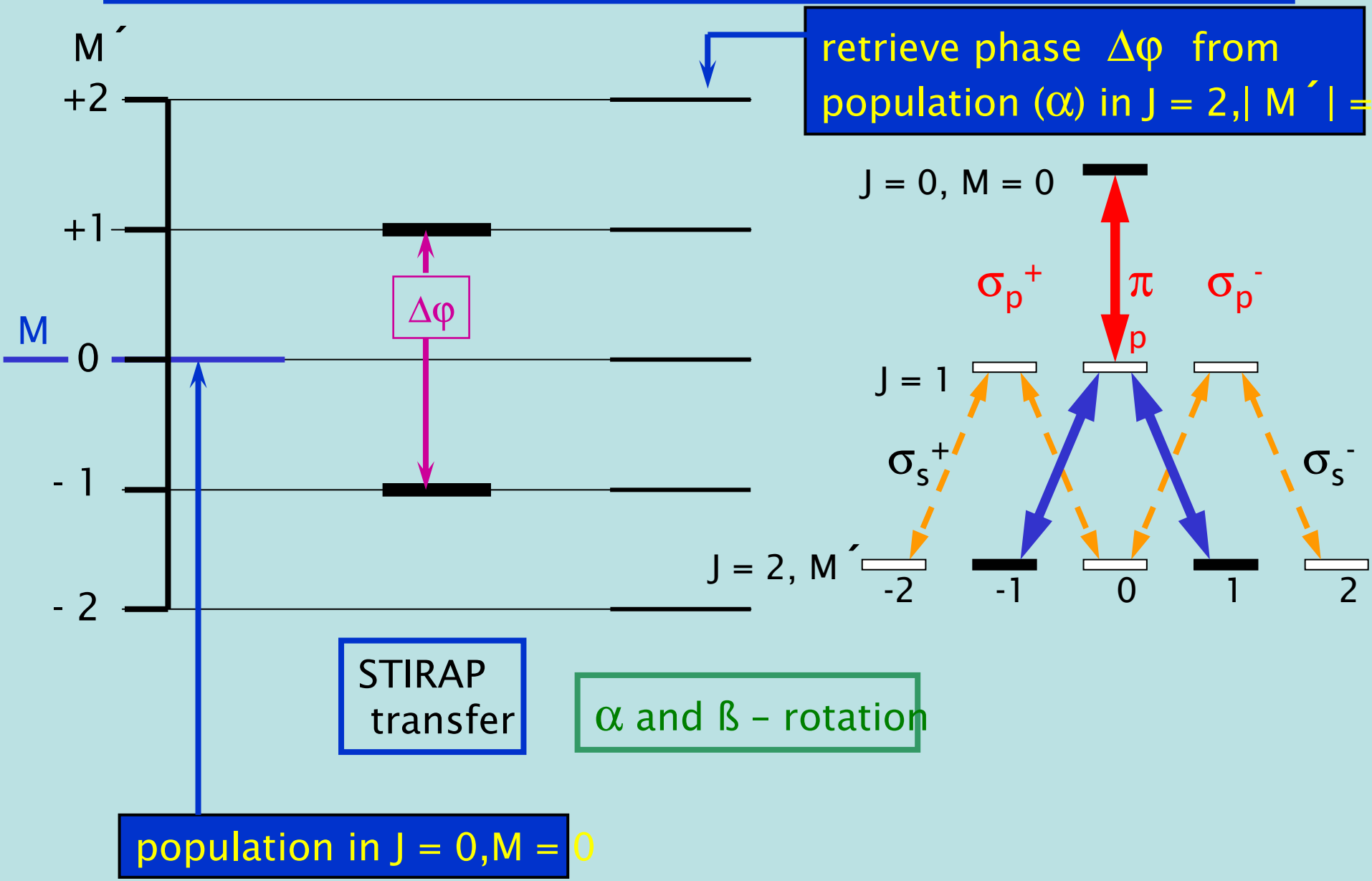
Coh.Pop.Trap.:

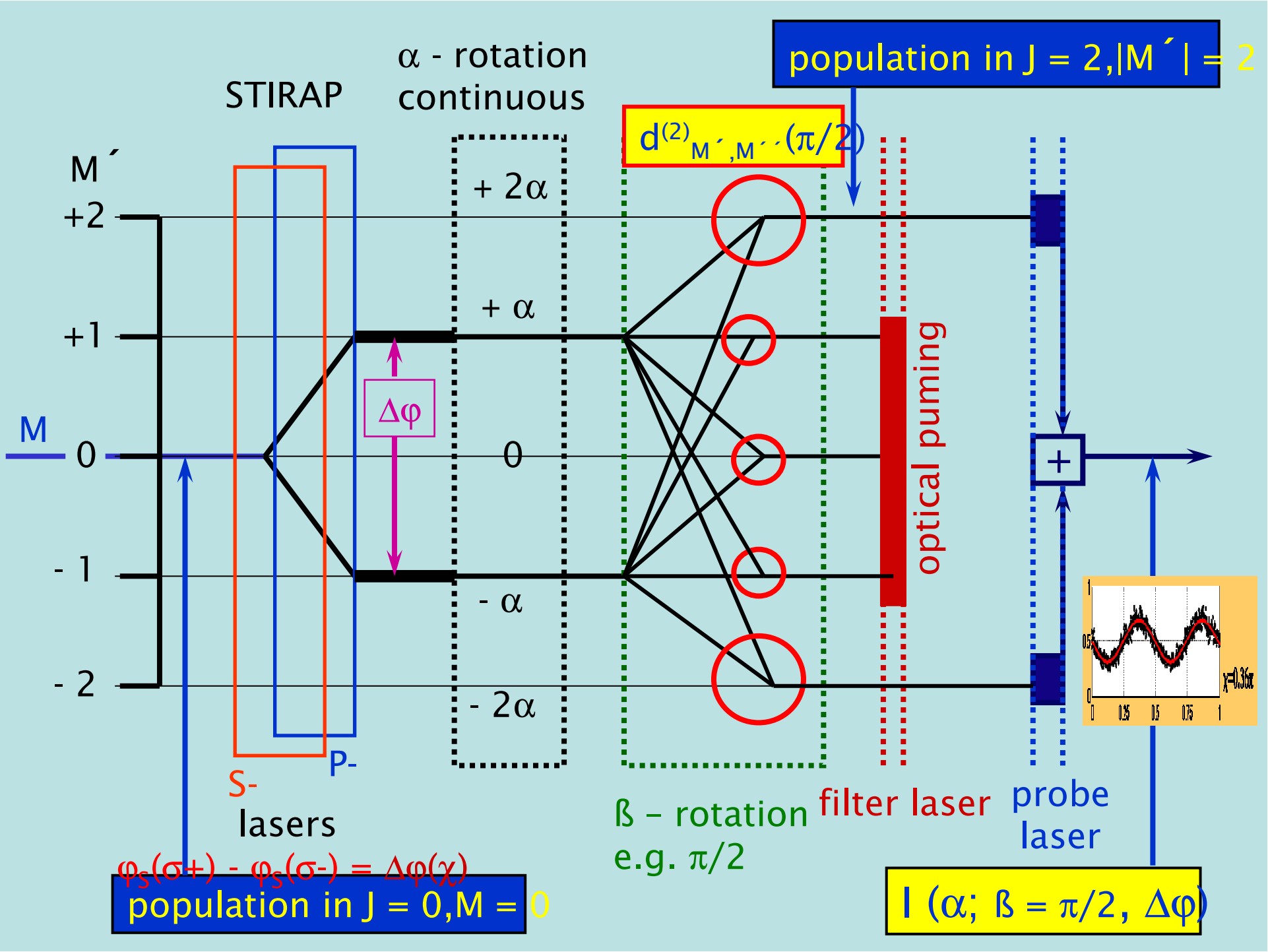


pump laser off resonance

measurement of the relative phase $\Delta\varphi$ (in the interferometry picture)

example: superposition of M´ = -1 and M´ = +1




population in J = 2,|M´| = 2
STIRAP
α - rotation
continuous
d(2)M´,M´´(π/2)
M´
+2
+1
M
0
- 1
- 2
+ 2α
+ α
0
- α
- 2α
Δφ
optical puming
+
S-
P-
lasers
ß – rotation
e.g. π/2
filter laser
probe
laser
φs(σ+) - φs(σ-) = Δφ(χ)
population in J = 0,M = 0
I (α; ß = π/2, Δφ)

STIRAP
a Powerful Coherent Population Transfer Scheme

provides high flexibility for the control of

- population and momentum
- amplitude and phases of components of superpositio

applications, e.g.

- collision dynamics and coherent con
- matter wave mirrors and beam splitters
- preparation of Fock states and superpositions thereo
- storage and retrieval of phase information
- transfer of phase information between laser beams

see poster by
C.Arango
P.Brumer
M.Shapiro

..... and many more .....

the Bergmann - Halfmann - Group
Frank Vewinger
Leonid Yatsenko
UAS, Kiev
Bruce Shore
LLNL
Manfred Heinz
previous graduate students
Uli Gaubatz
Jürgen Martin
Axel Kuhn
Heiko Theuer

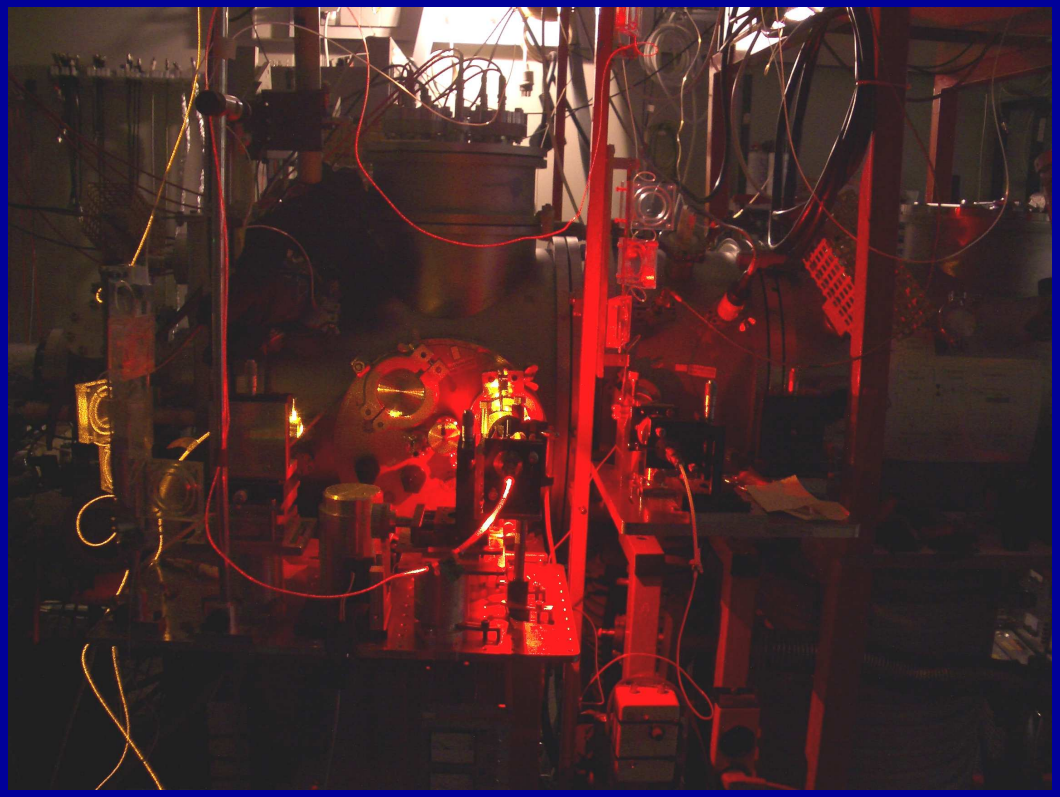
the end

TECHNISCHE UNIVERSITÄT
KAISERSLAUTERN

STIRAP - reviews:

Rev.Mod.Phys. **70**, 1003 – 1026 (1998)

Adv.At.Mol.Opt.Phys **46**, 55 – 190 (2001)



phase control

Phys. Rev. Lett. **91** 213001 (2003)

Opt. Commun. **264**, 248 - 255 (August 15, 2006)

funding: DFG, EU

Max-Planck Research Prize