Few photon photonics (in waveguides)

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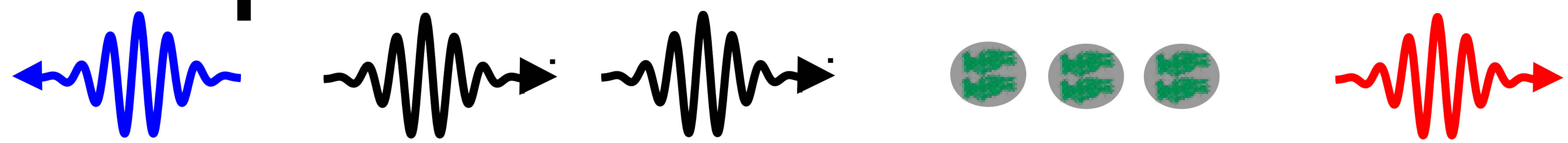
Few photon photonics



- Photons in 1D interact with discrete systems (qubits)
- Few mean 1, 2, 3, 4, 5, ...

✓ Strong coupling.   Experiments.

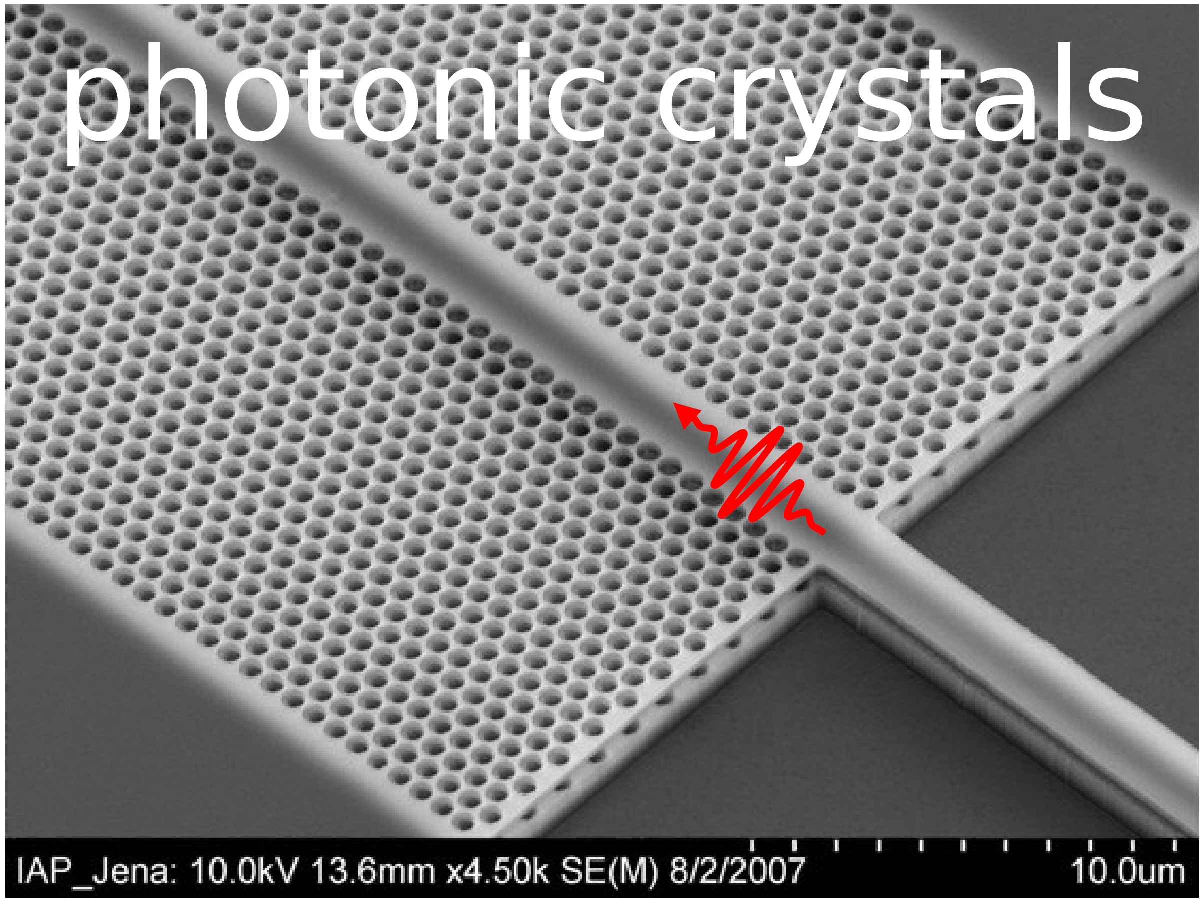
▸ performing tasks with minimum power:

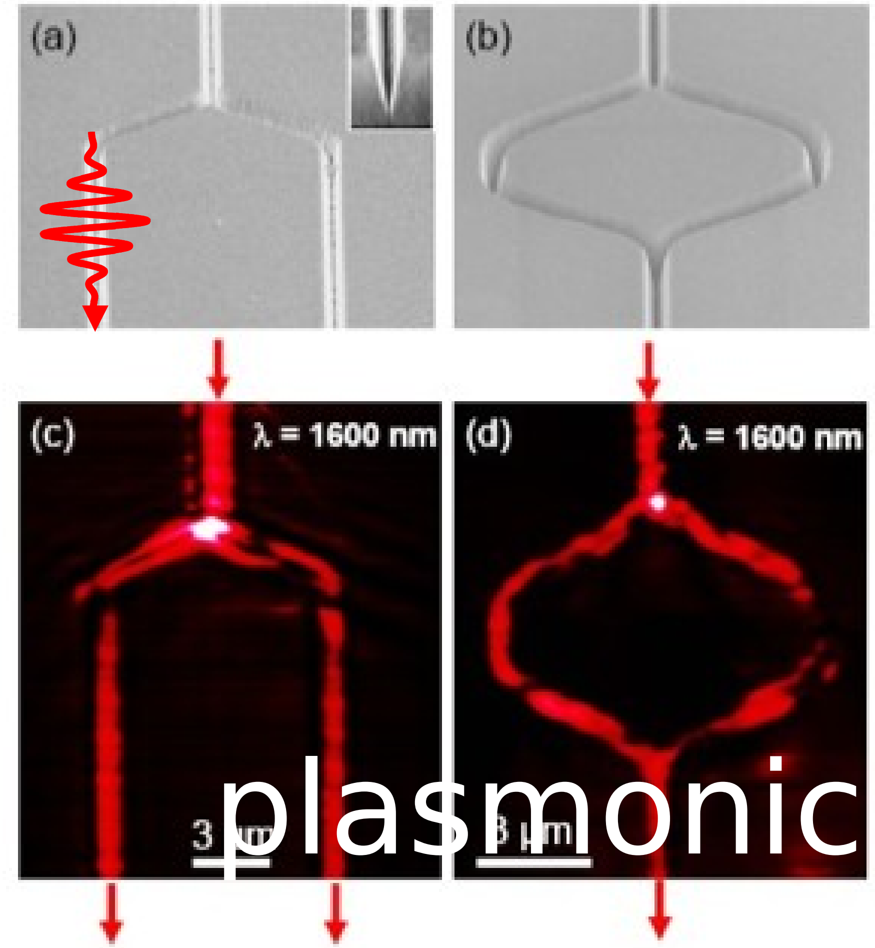
-single photon transistor / detector / emitter

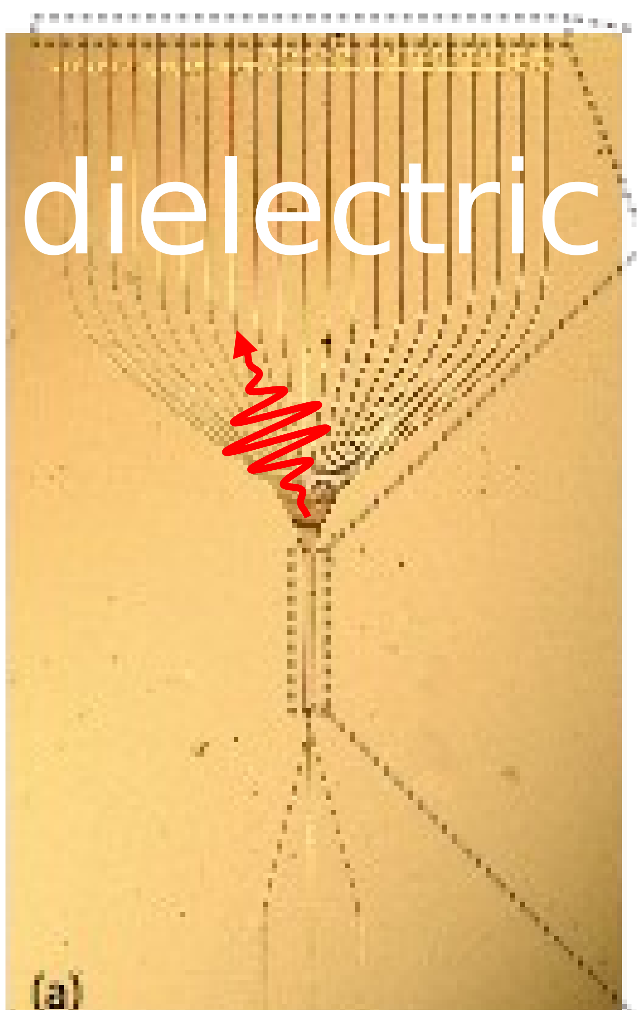
-spectroscopy

-nonlinear physics

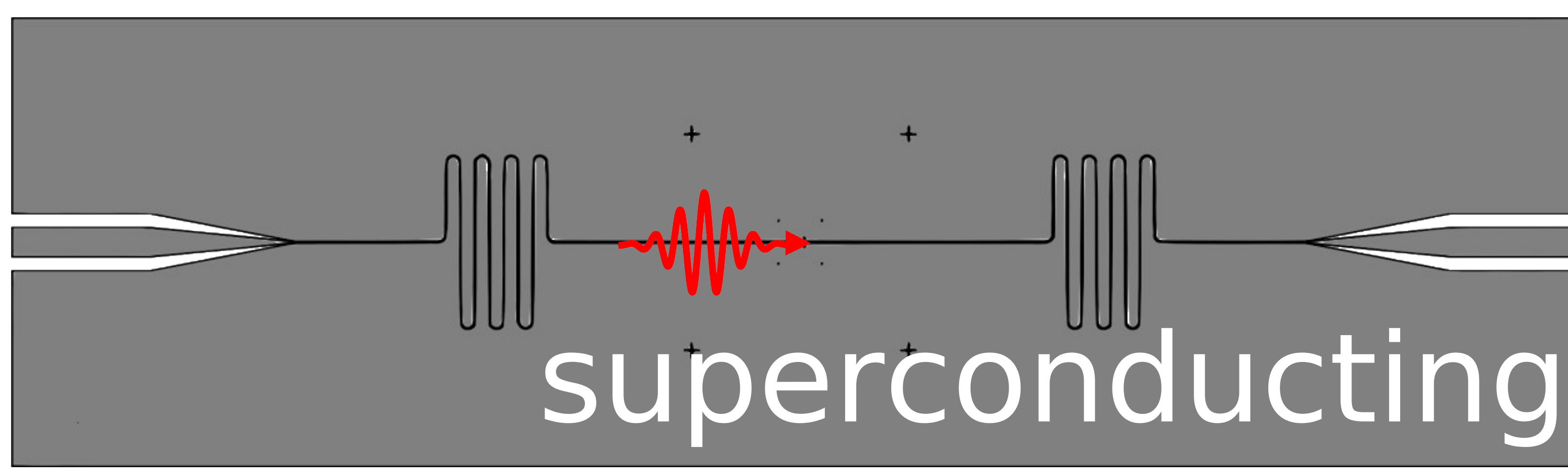
-q-gates (EIT ...) q-information processing


photonic crystals
IAP_Jena: 10.0kV 13.6mm x4.50k SE(M) 8/2/2007
10.0um

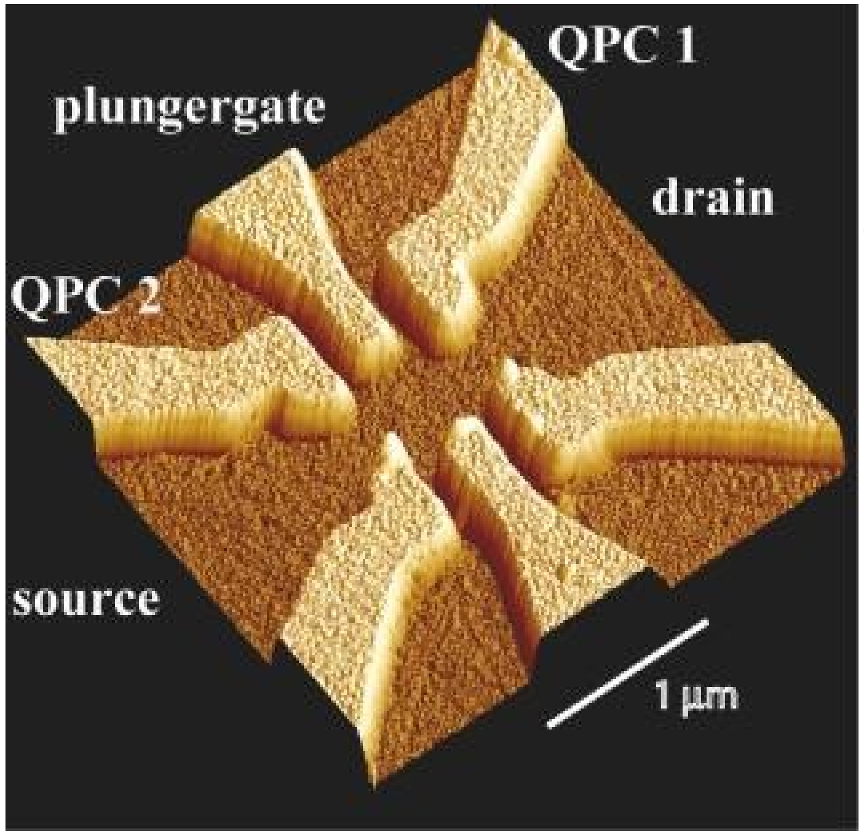

(a)
(b)
(c)
λ = 1600 nm
(d)
λ = 1600 nm
plasmonic


dielectric
(a)

waveguides

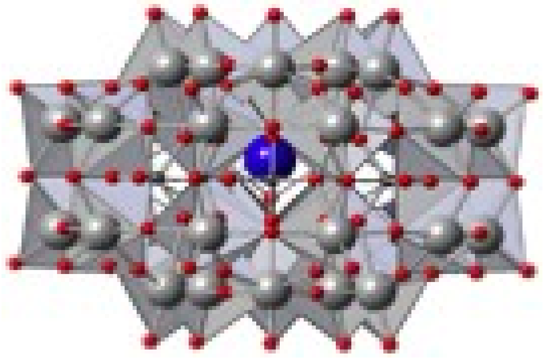

superconducting

qubits / emitters

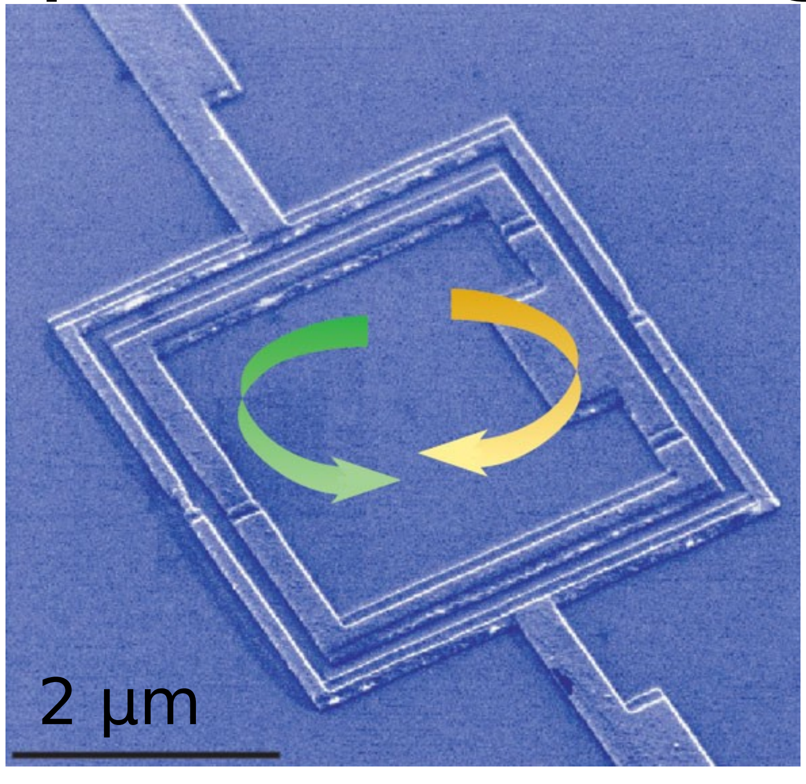


Q-dots

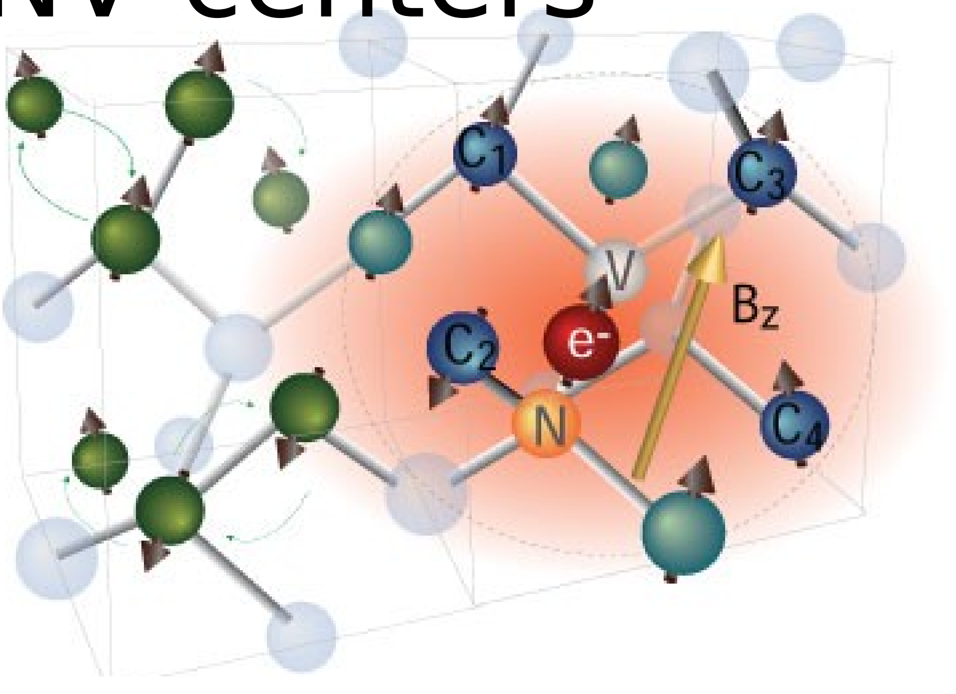
molecules



superconducting

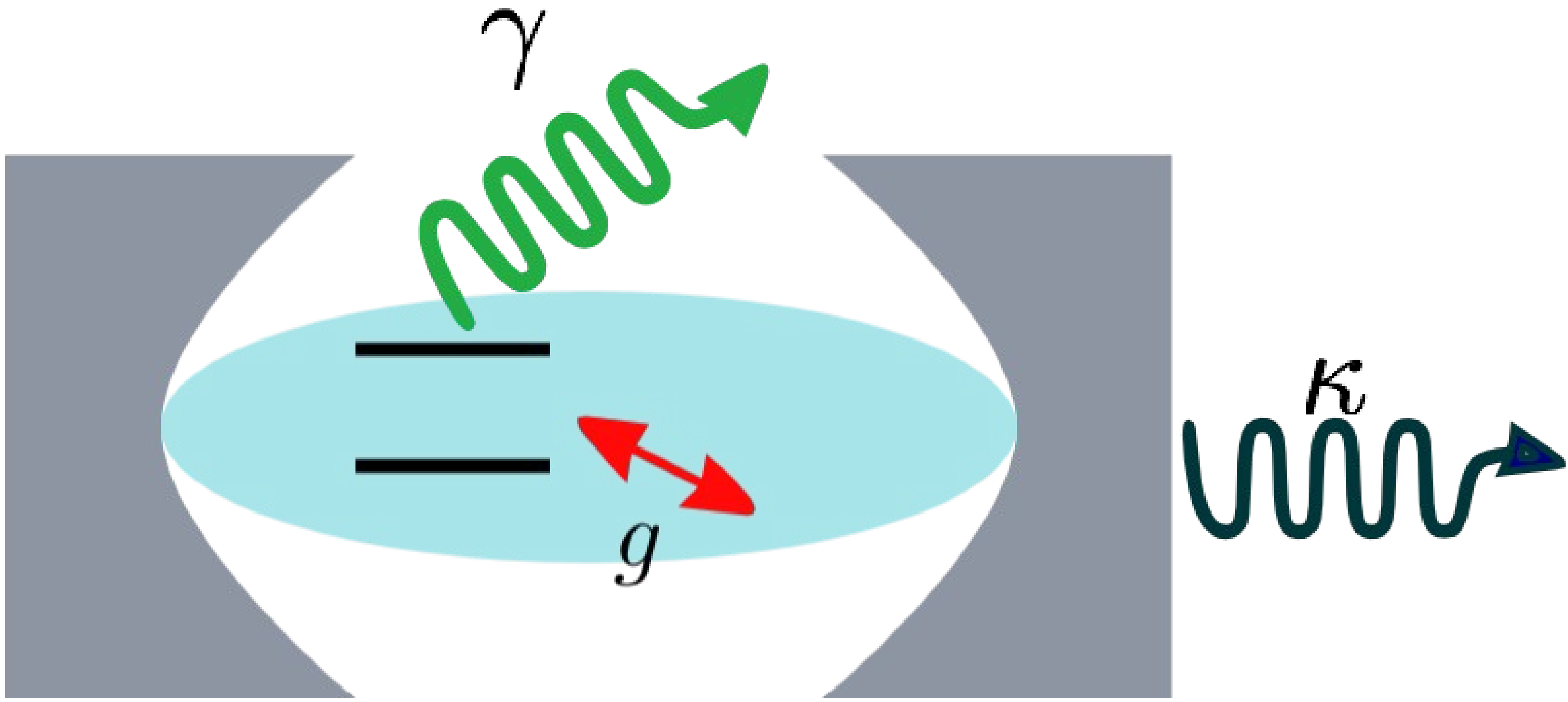


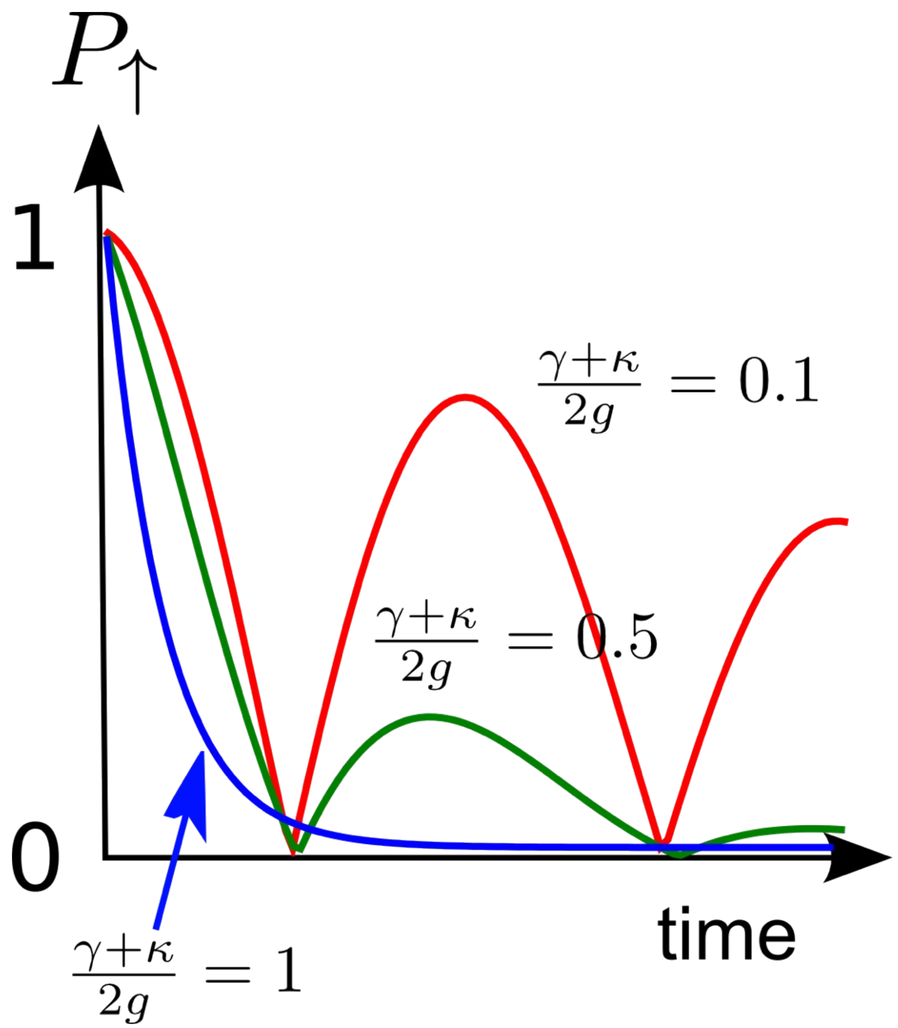
NV-centers



Strong coupling

g versus $\{\kappa, \gamma\}$





- Jaynes Cummings physics

$$H = \omega a^\dagger a + \frac{\Delta}{2}\sigma^z + \mathbf{g}(\sigma^+ a + \sigma^- a^\dagger)$$

- Today $\mathbf{g} \gg \{\gamma, \kappa\}$

Waveguides: two models

$$H = \int \mathrm{d}x \Pi(x)^2 + c(\partial_x \phi(x))^2$$

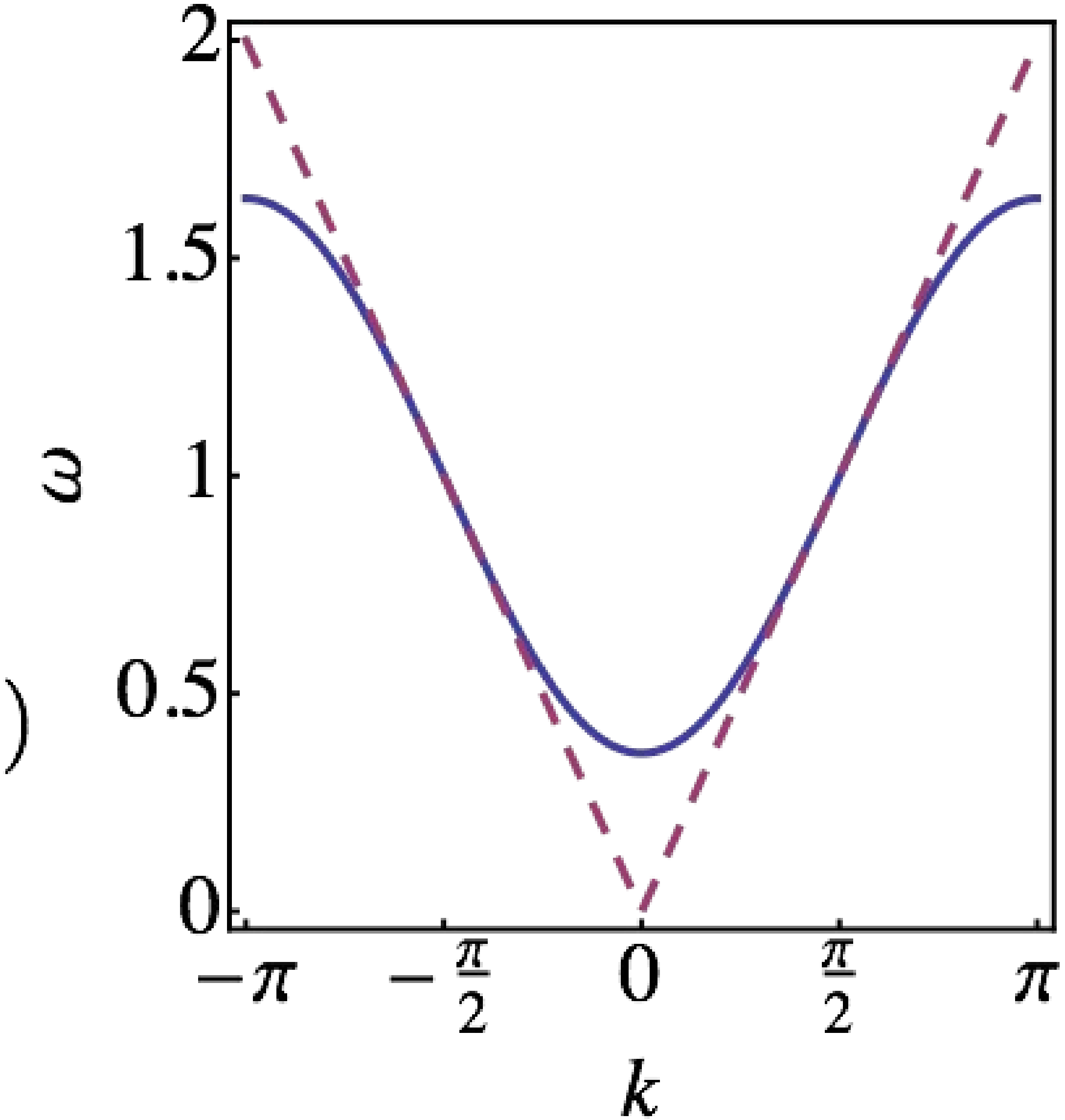
$\omega(k) = c|k|$

linear spectrum

$$H = \sum_j \omega_0 a_j^\dagger a_j + J(a_j^\dagger a_{j+1} + a_{j+1}^\dagger a_j)$$

$\omega(k) = \omega_0 + 2J\cos k$

non-linear spectrum / band gap



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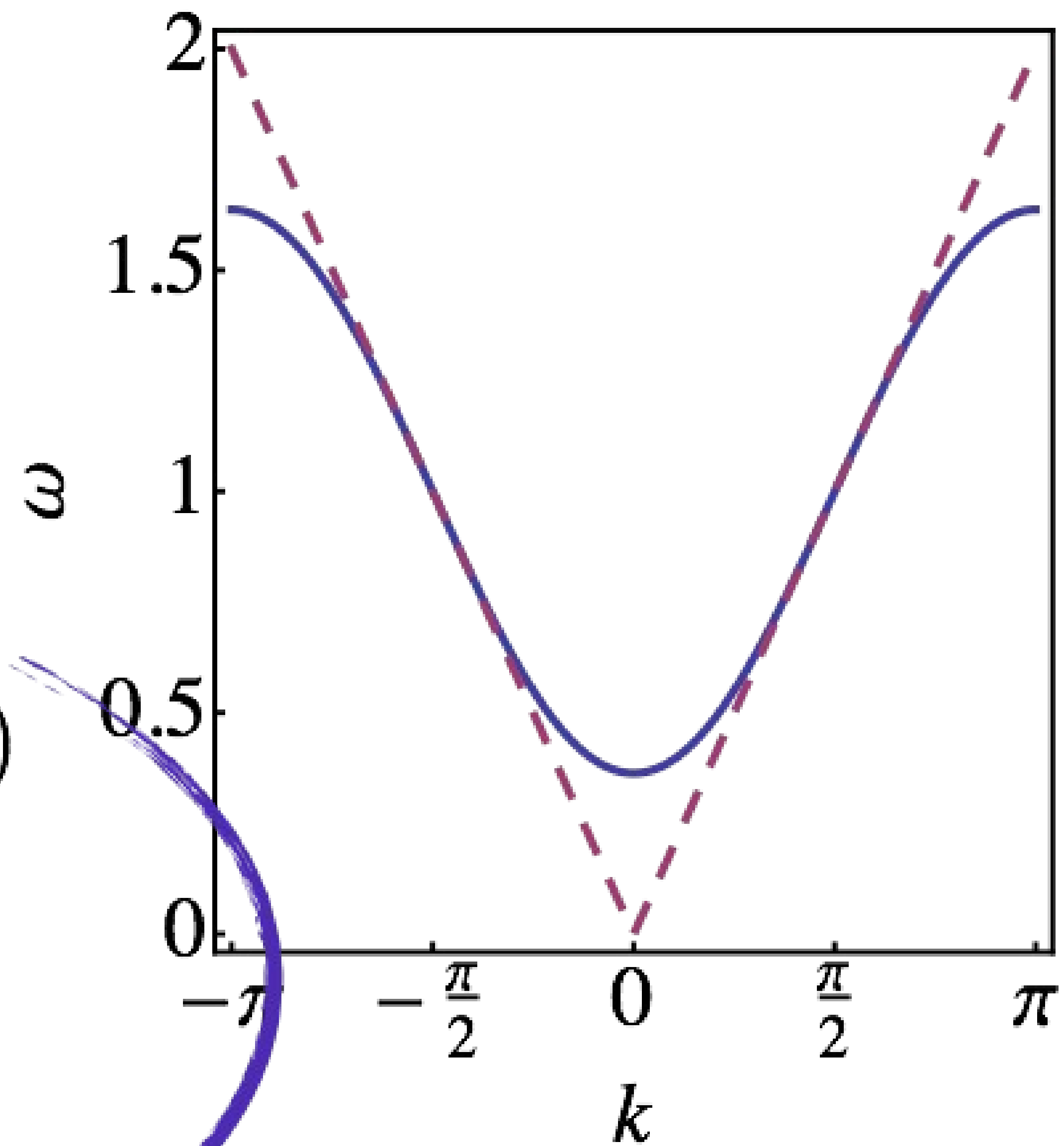
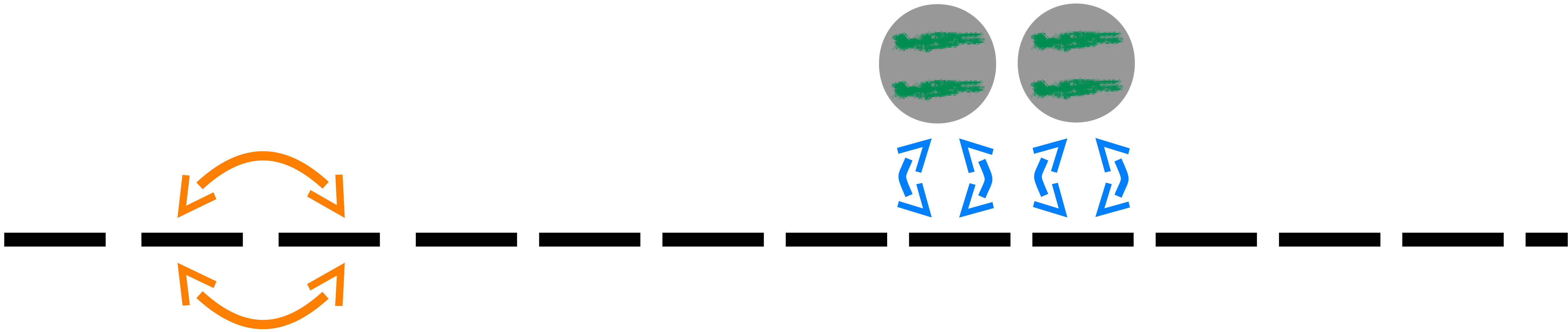


The model / scattering

$$H = H_{\text{guide}} + H_{\text{atom}} + H_{\text{coupling}}$$
$$= \sum_{j}^{L} \omega_0 a_j^\dagger a_j + J(a_j^\dagger a_{j+1} + a_{j+1}^\dagger a_j) + \sum_{m}^{M} \frac{\Omega_m}{2}\sigma_m^z + \mathbf{g}(\sigma_m^+ a_m + \sigma_m^- a_m^\dagger)$$



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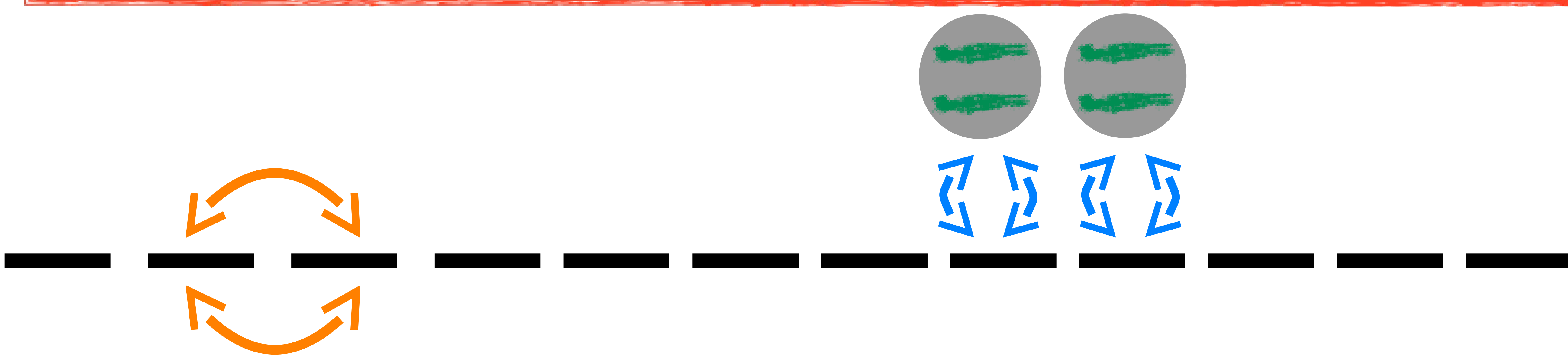
$N = \sum a_j^\dagger a_j + \sum \sigma_m^+ \sigma_m^-$ $\qquad [N, H] = 0$ $\qquad$ N is conserved



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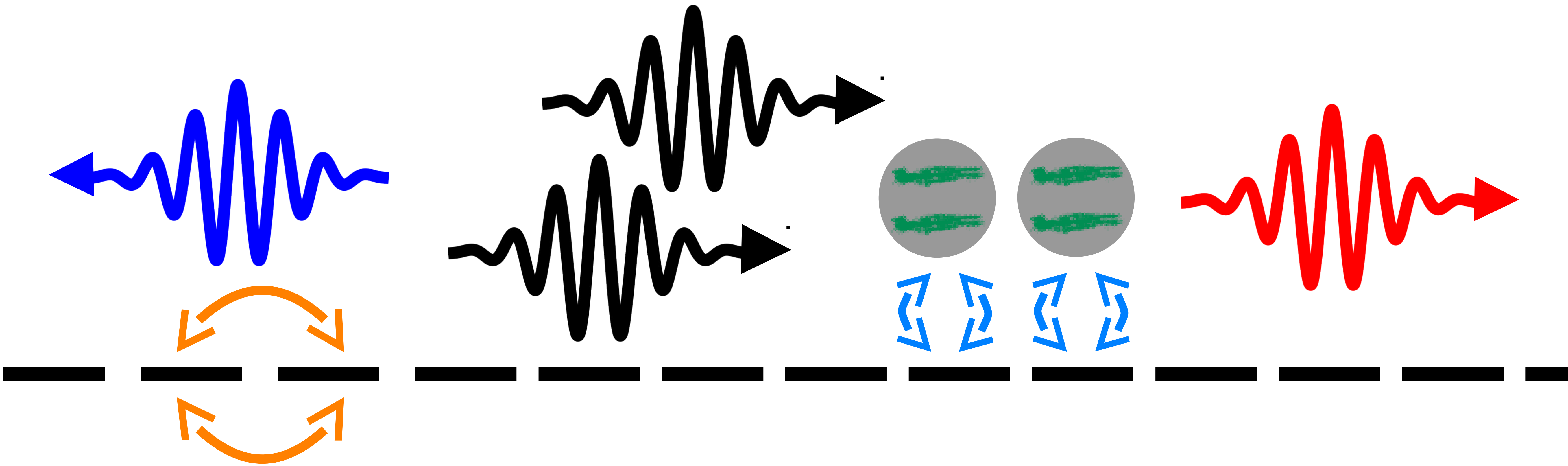
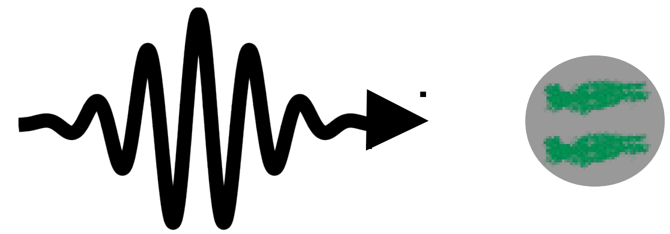
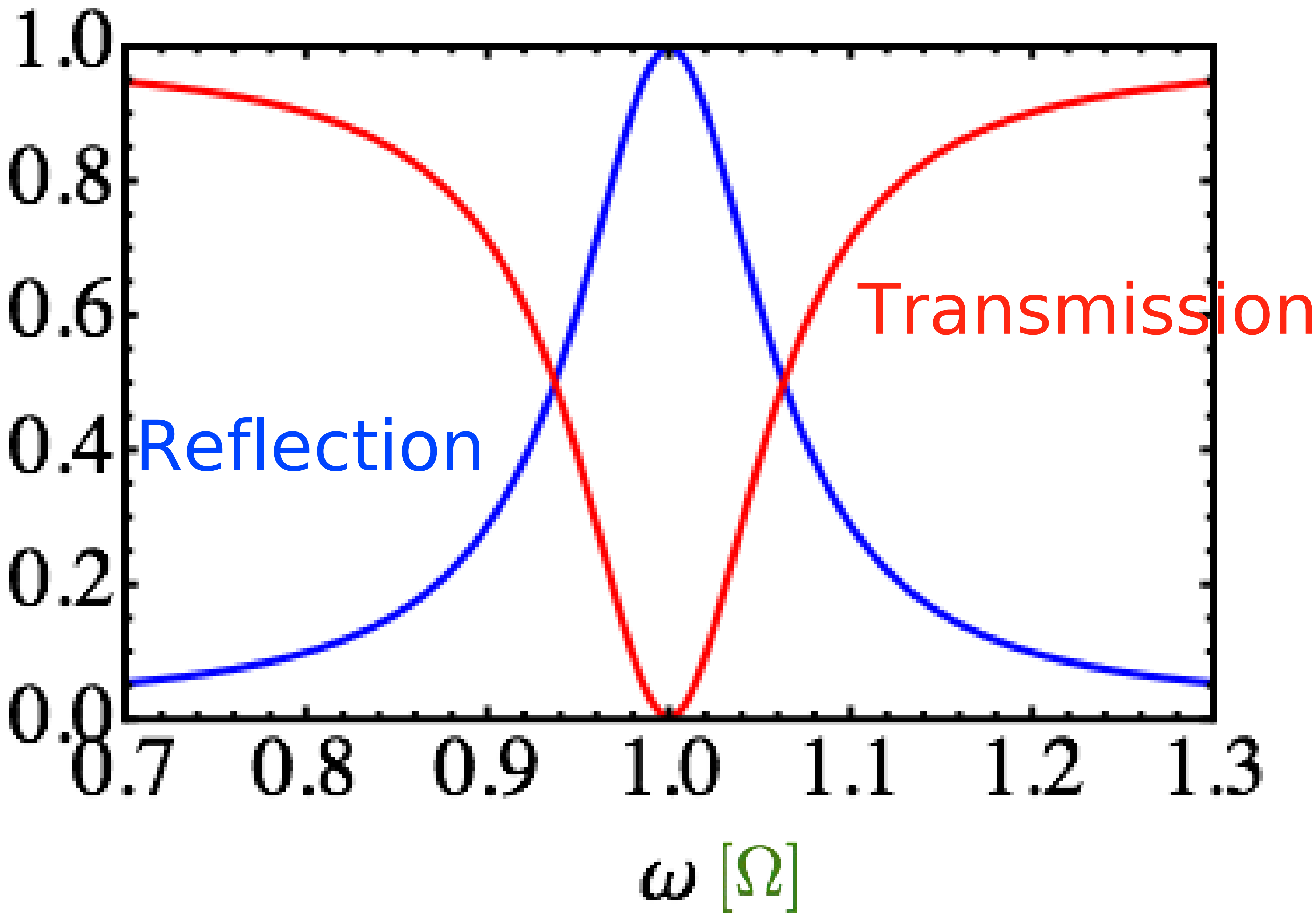


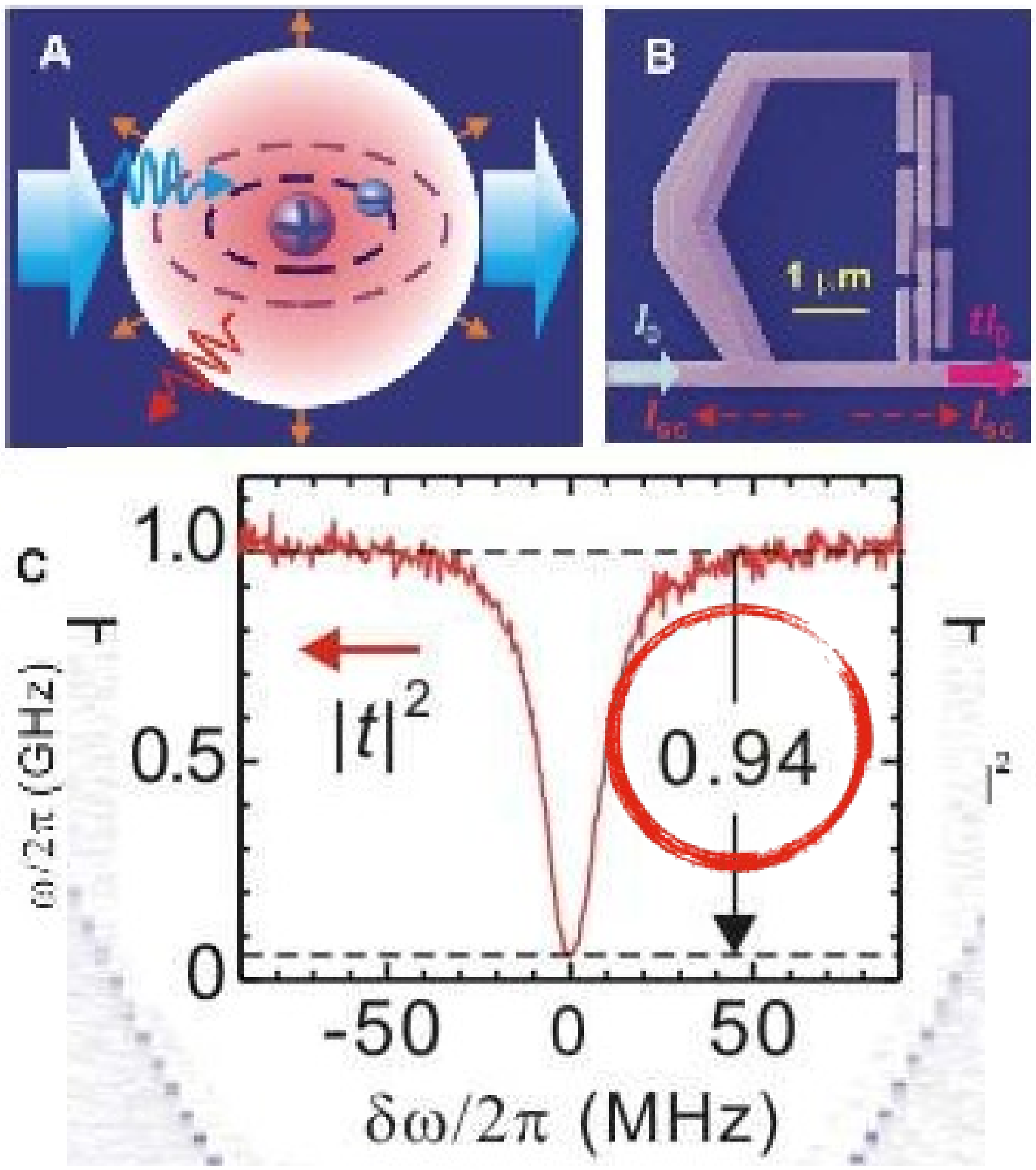
1 photon / 1 qubit



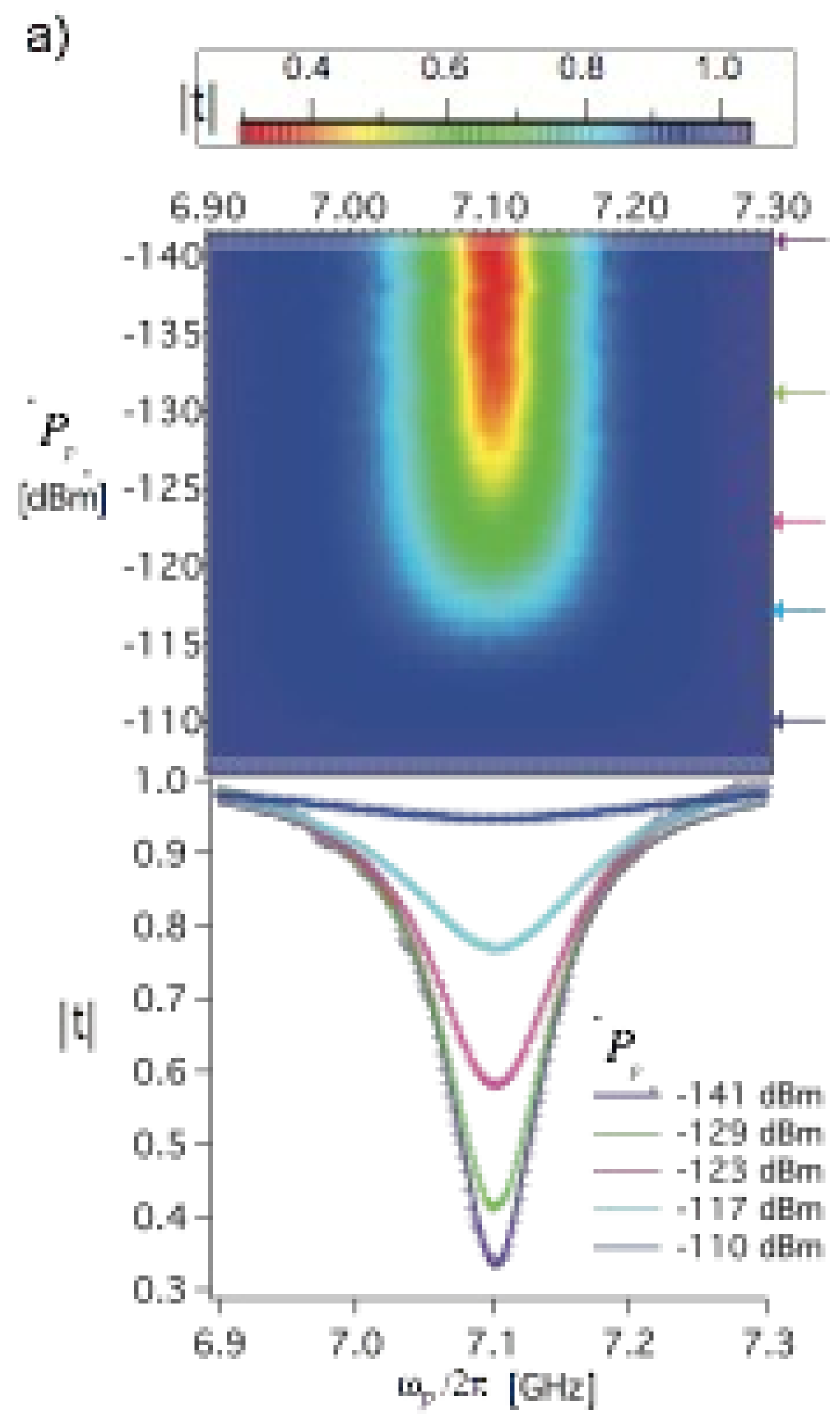
$$\psi(x) = \begin{cases} \sum_j (e^{ikj} a_j^\dagger + r e^{-ikj} a_j^\dagger)|vac\rangle & j < 0 \\ \sum_j t e^{ikj} a_j^\dagger |vac\rangle & j > 0 \end{cases}$$



Experiment(s)



[Astafiev et al Science 2010]



[Choi et al PRL 2011]

Theory

- 1 photon and classical (coherent) input is ok.
- 2 photons and 1 or 2 qubits doable.
- 3,4 photons is (very) hard.

Fan, Sun, Nori, Baranguer, Roy Groups, ...

- Numerical approach: 4 photons 1 qubit

Longo /Schmitteckert / Busch PRL 2010

A systematic tool ?

Theory

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Longo /Schmitteckert / Busch PRL 2010

A systematic tool ? YES

Quantum Scattering is many body

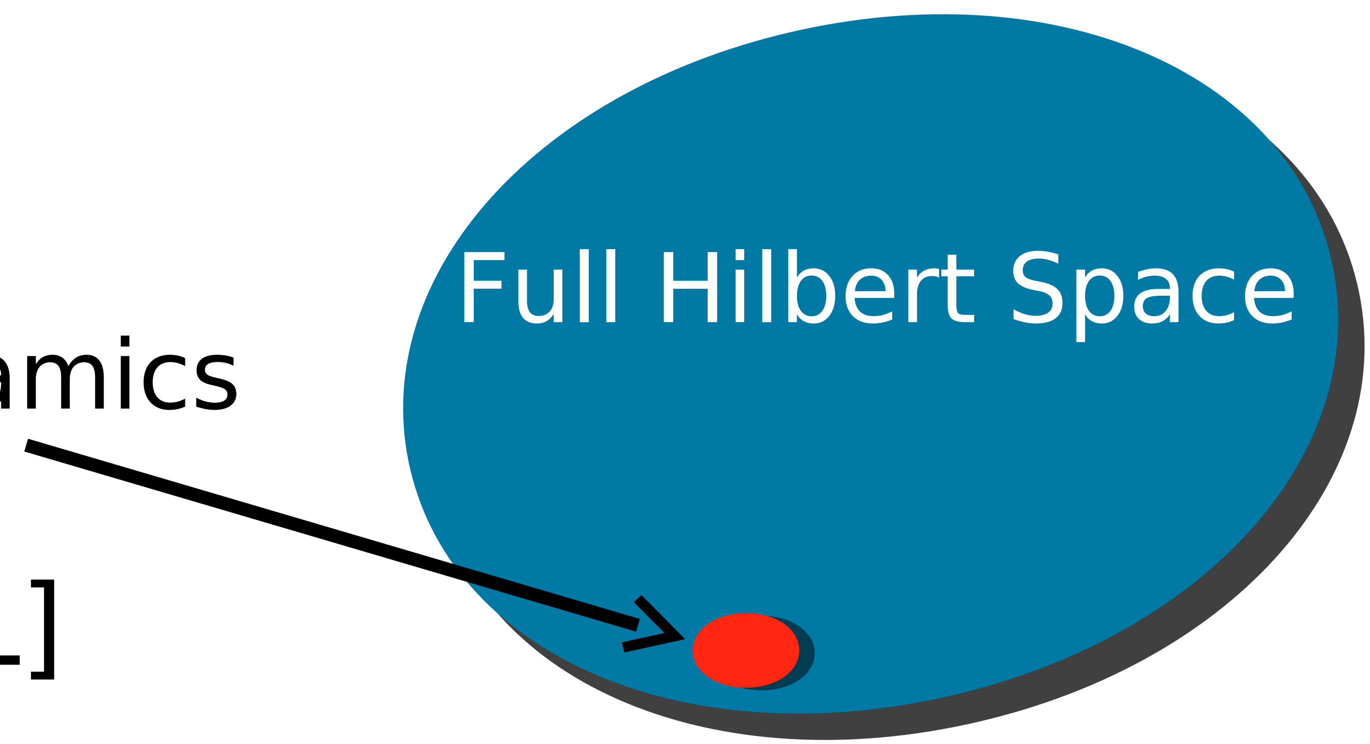
$$\dim \sim s^{L_{sites}}$$

- Simulating quantum mechanics is difficult

- Typically the evolution explores a small part: the

total Hilbert space is a **convenient illusion.**

- Identify the small part is hard. **Sometimes not.**



[David Poulin et al PRL]

Quantum Scattering is many body: finding the small part

- Assumptions: (i) the states belonging to the small part have some characteristic in common; (ii) the ground state (GS) belongs to the small part.
- The GS follows the area law: S ~ A
- So... we assume that those physical states are **slightly entangled**.

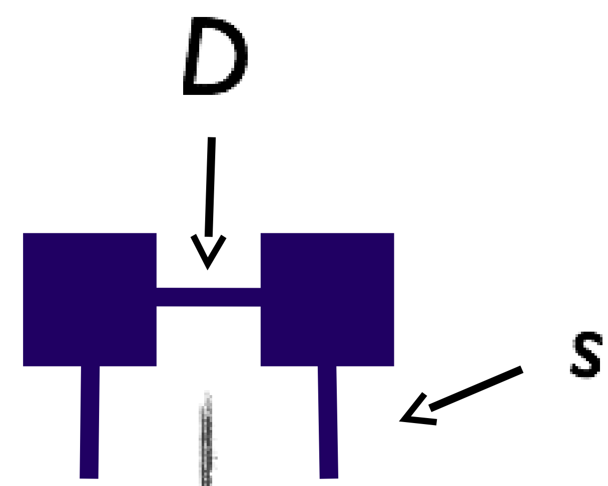
White, Vidal, Cirac, Verstraete...

MPS in a nutshell: two sites

$$\phi = \sum_{i_1 i_2}^{s} c_{i_1,i_2} |i_1\rangle |i_2\rangle = \sum_{k}^{D} \lambda_k |k_1\rangle |k_2\rangle$$ (Schmidt /SV)

Entanglement ~ $\log(D)$

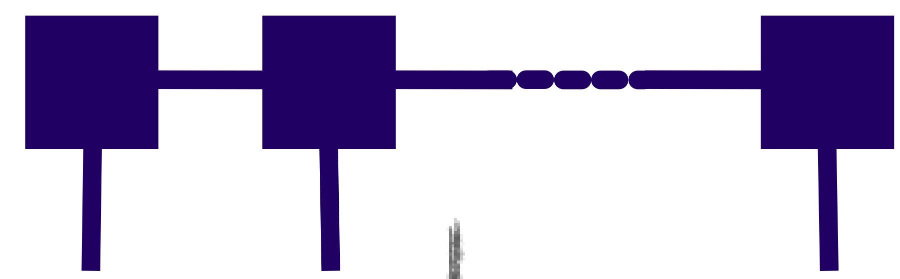
$$\hat{c} = \hat{U} \begin{pmatrix} \lambda_1 & 0 & 0 & \cdots & 0 \\ \vdots & \ddots & \ddots & \ddots & \vdots \\ 0 & \ddots & \lambda_D & \ddots & 0 \\ \vdots & \ddots & \ddots & \ddots & \vdots \\ 0 & \cdots & \cdots & \cdots & 0 \end{pmatrix} \hat{V} \equiv$$



s^2 numbers $\longrightarrow$ $2sD$ numbers

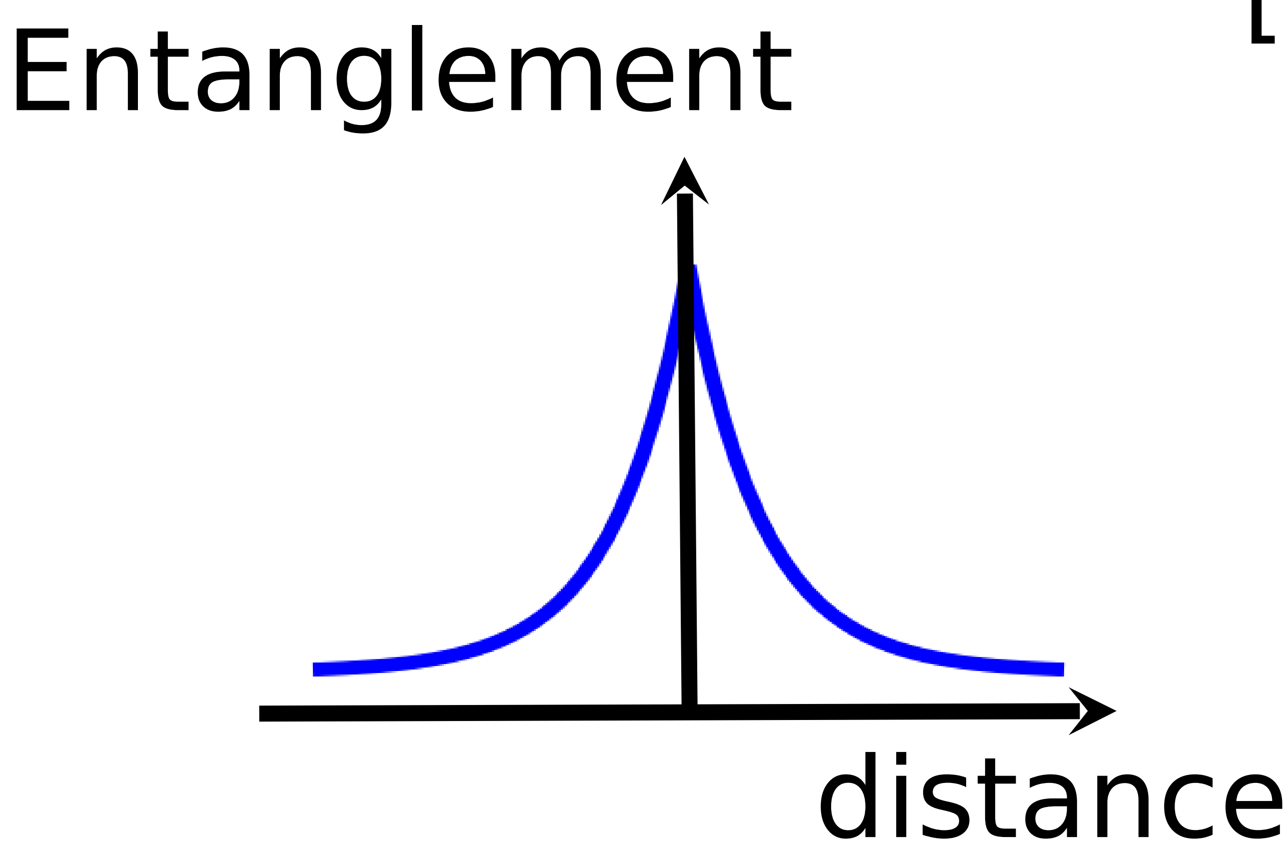
MPS in a nutshell: L sites

$$\phi = \sum_{i_1 i_2 \ldots i_L} c_{i_1 i_2 \ldots i_L} \left| i_1 i_2 \ldots i_L \right\rangle \equiv$$



s^L numbers $\longrightarrow$ LsD^2 numbers

[Guifré Vidal PRL]



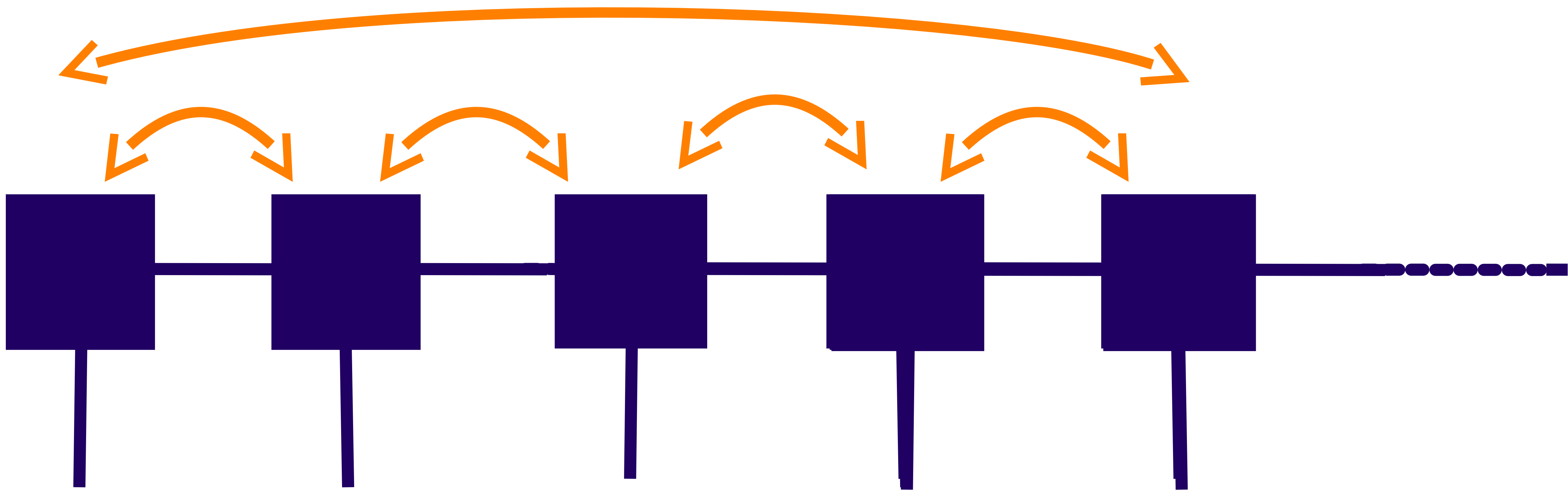
- As 1 dimension typical states are short correlated

$\downarrow$

D small

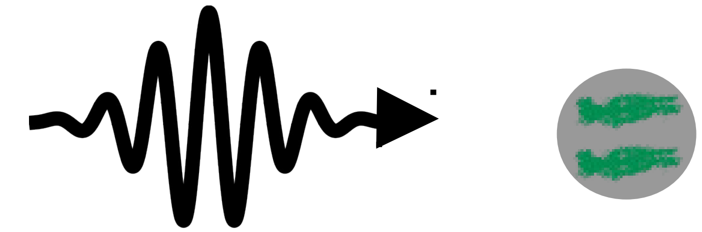
Be careful! MPS just for 1D

- It the system is higher dimensional:

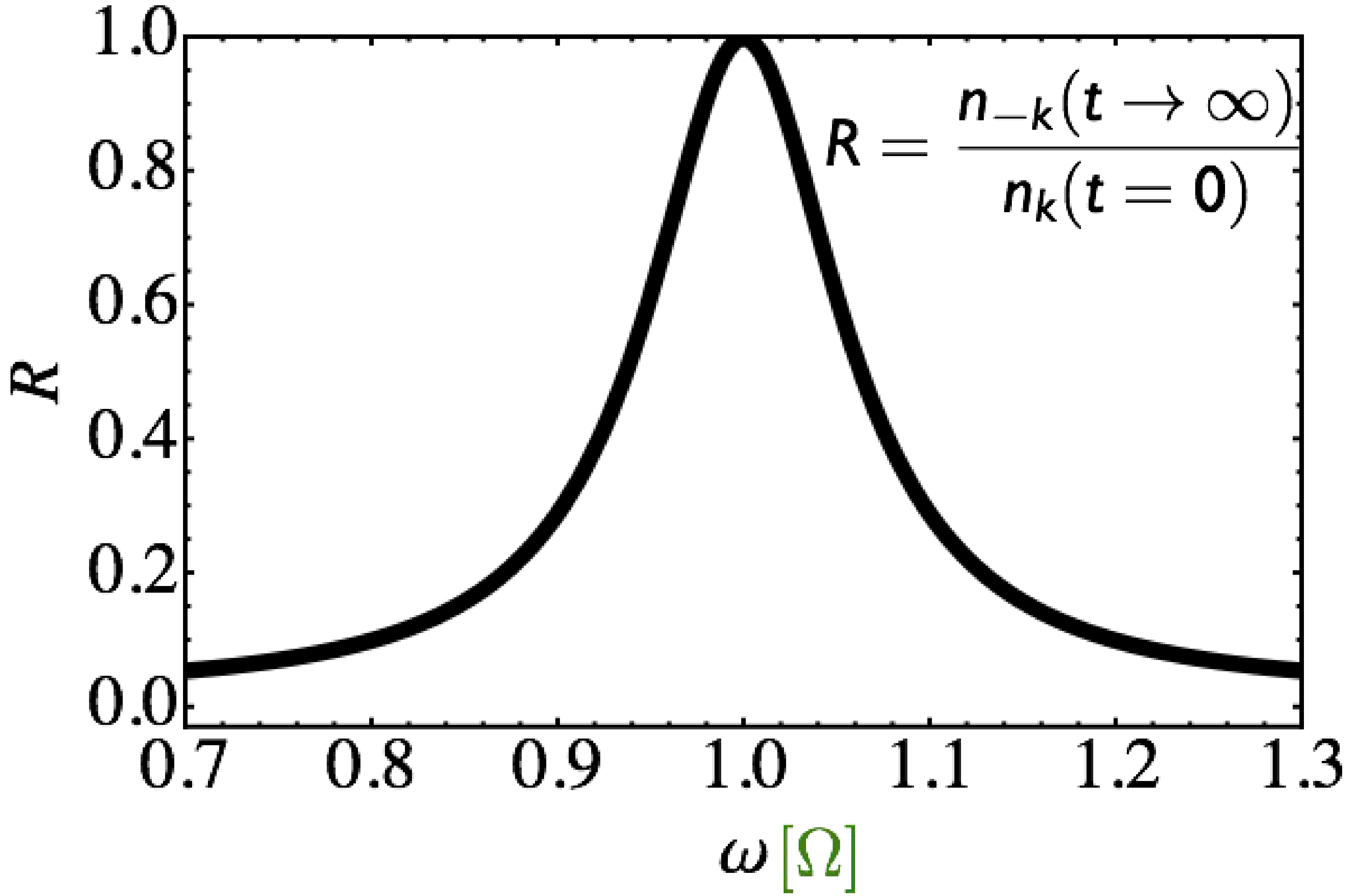


- The bipartition that MPS uses is not convenient for dimensions larger than one.

MPS at work

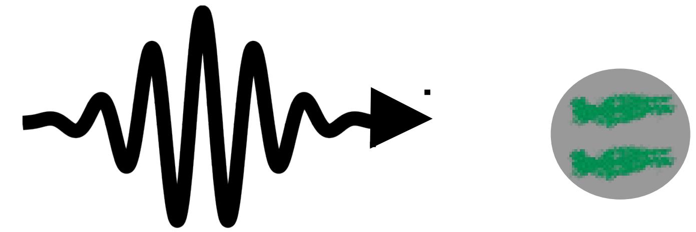


1 photon / 1 qubit (analytical)

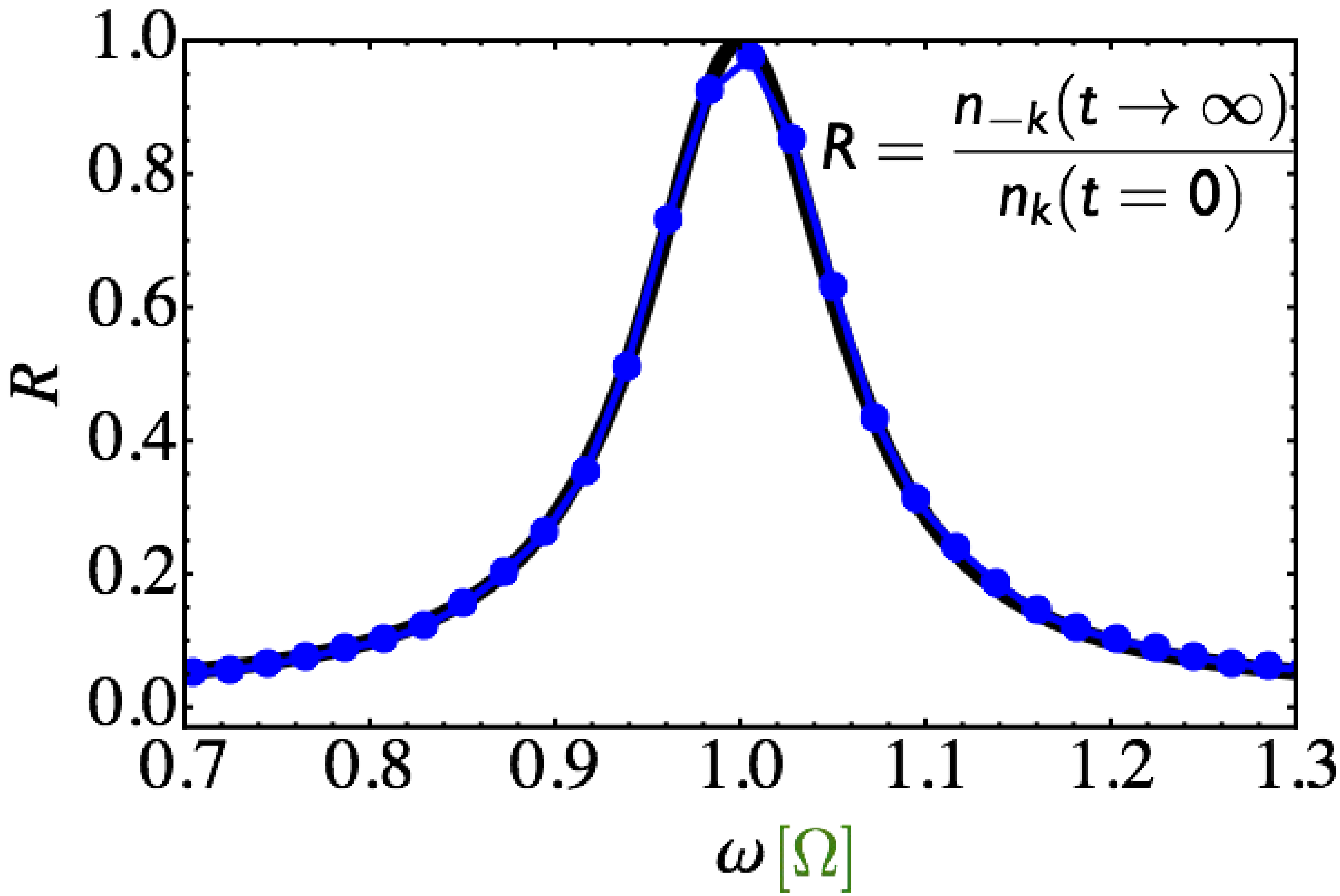


$g = 0.2$

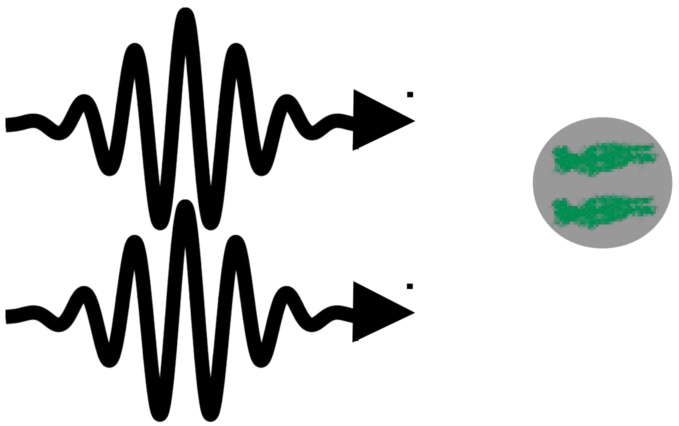
MPS at work



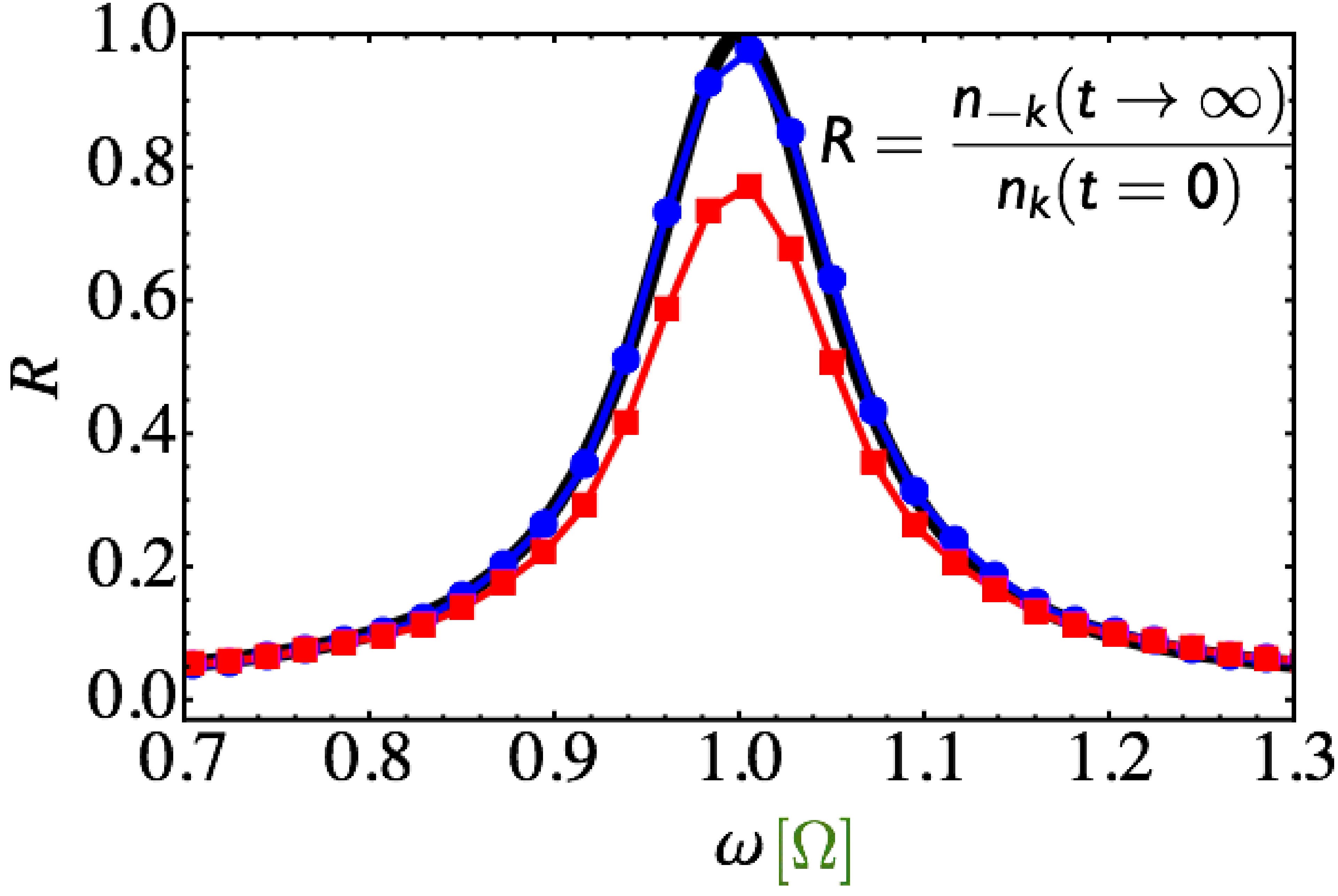
1 photon / 1 qubit (analytical vs numerical)



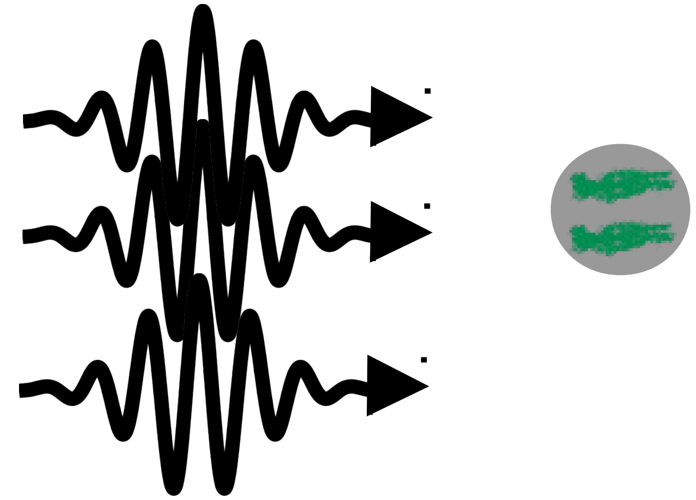
MPS at work



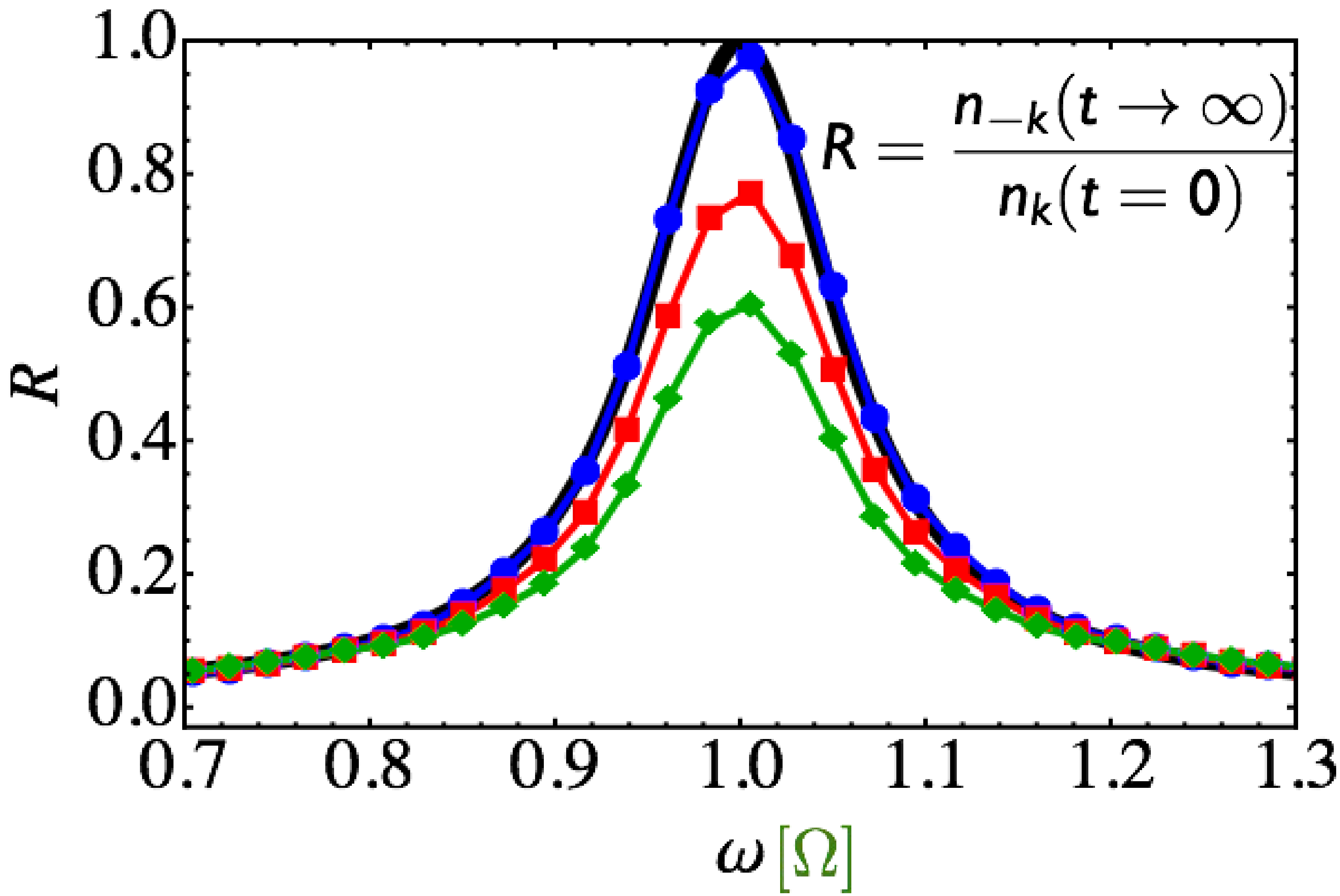
2 photon / 1 qubit



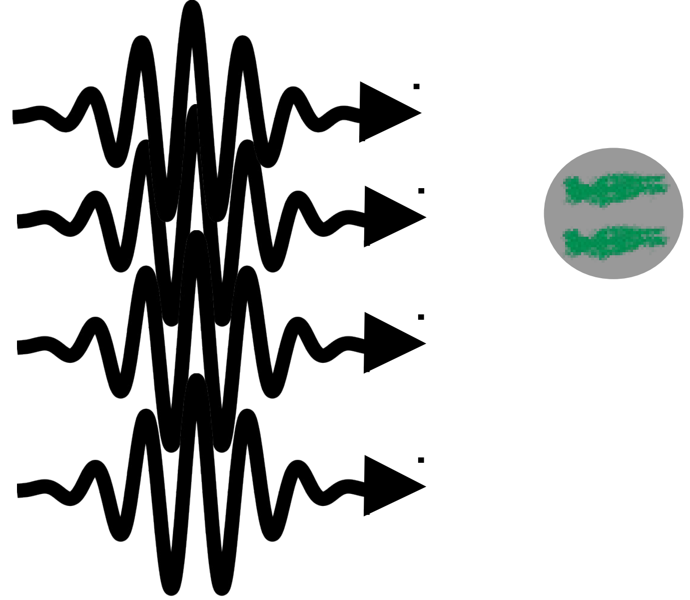
MPS at work



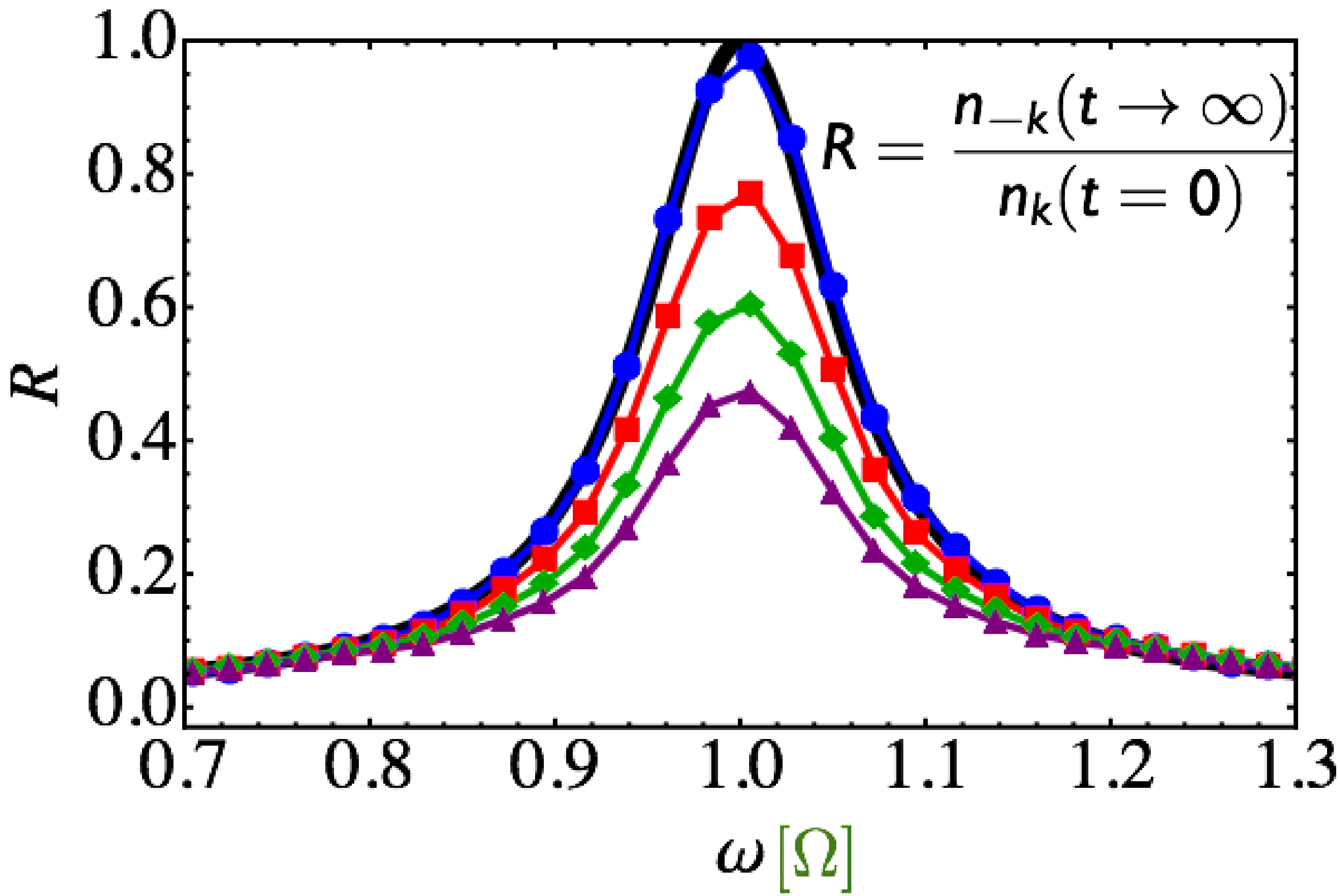
3 photon / 1 qubit



MPS at work

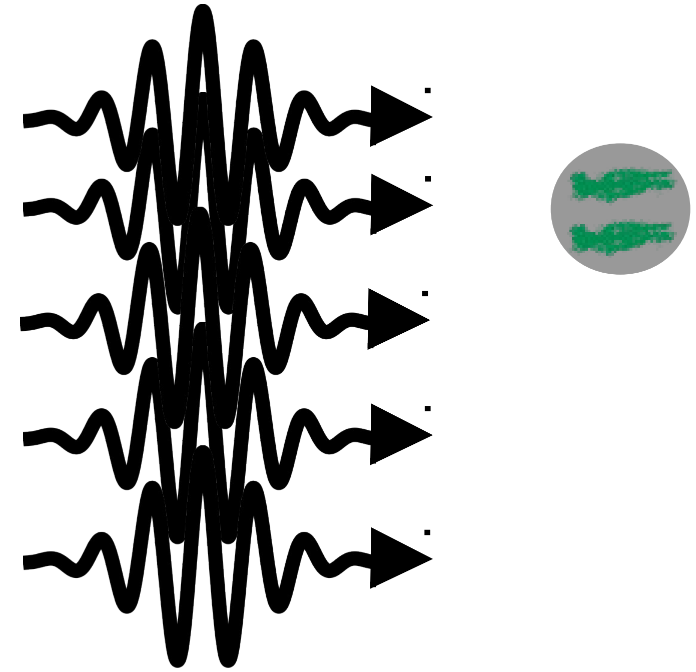


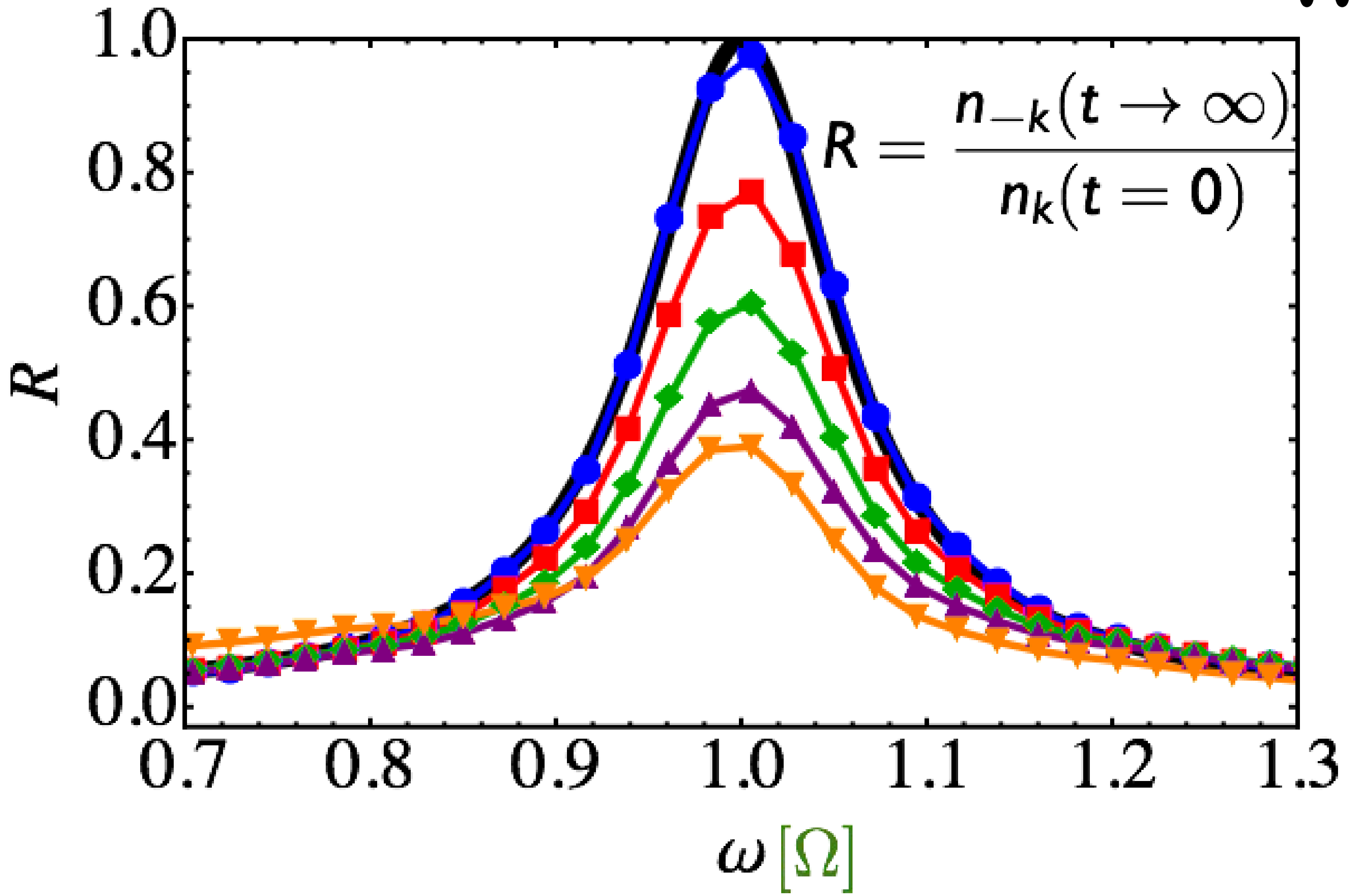
4 photon / 1 qubit



MPS at work

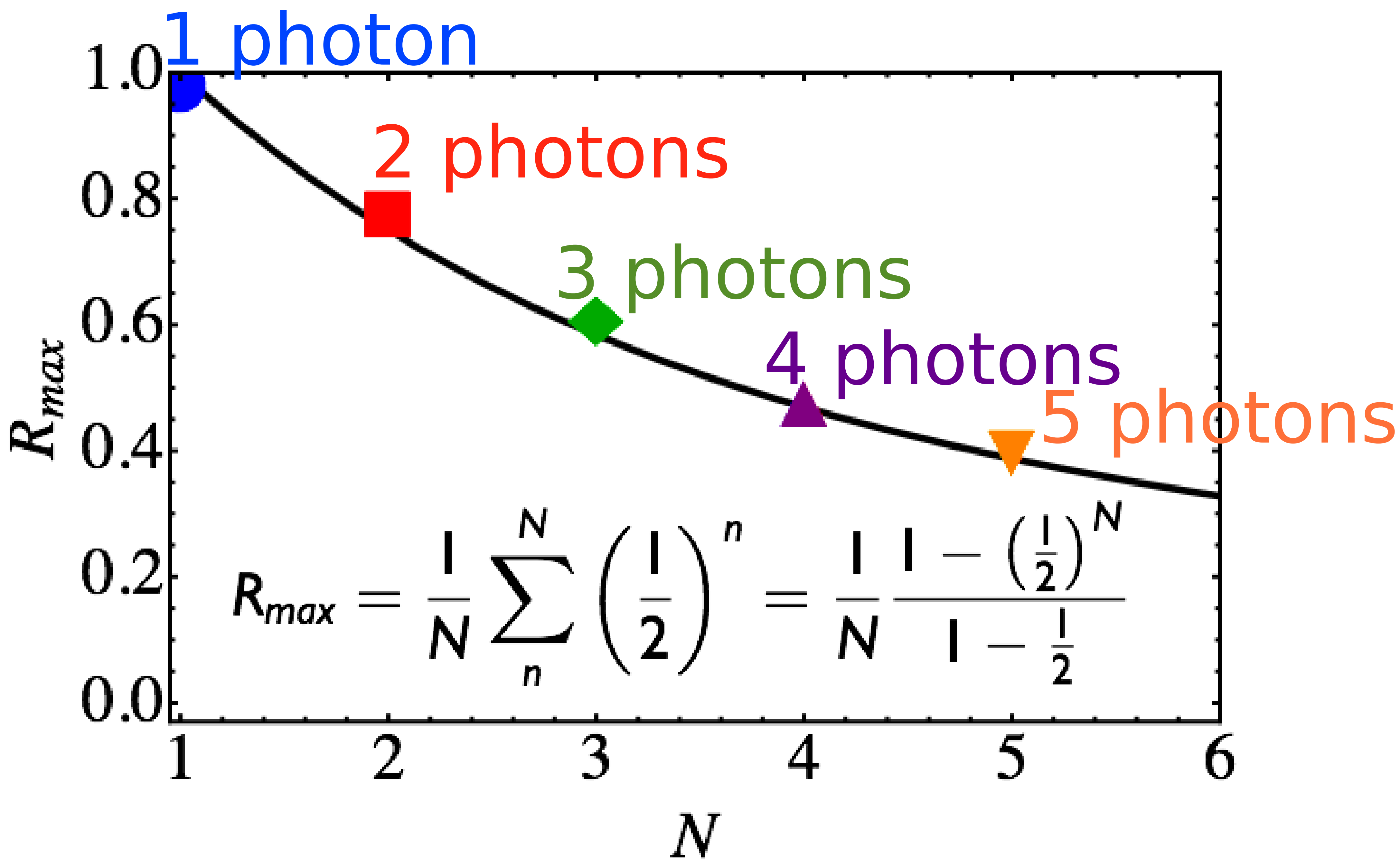
5 photon / 1 qubit



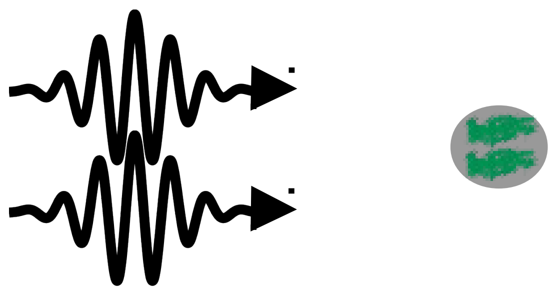


A few photon result

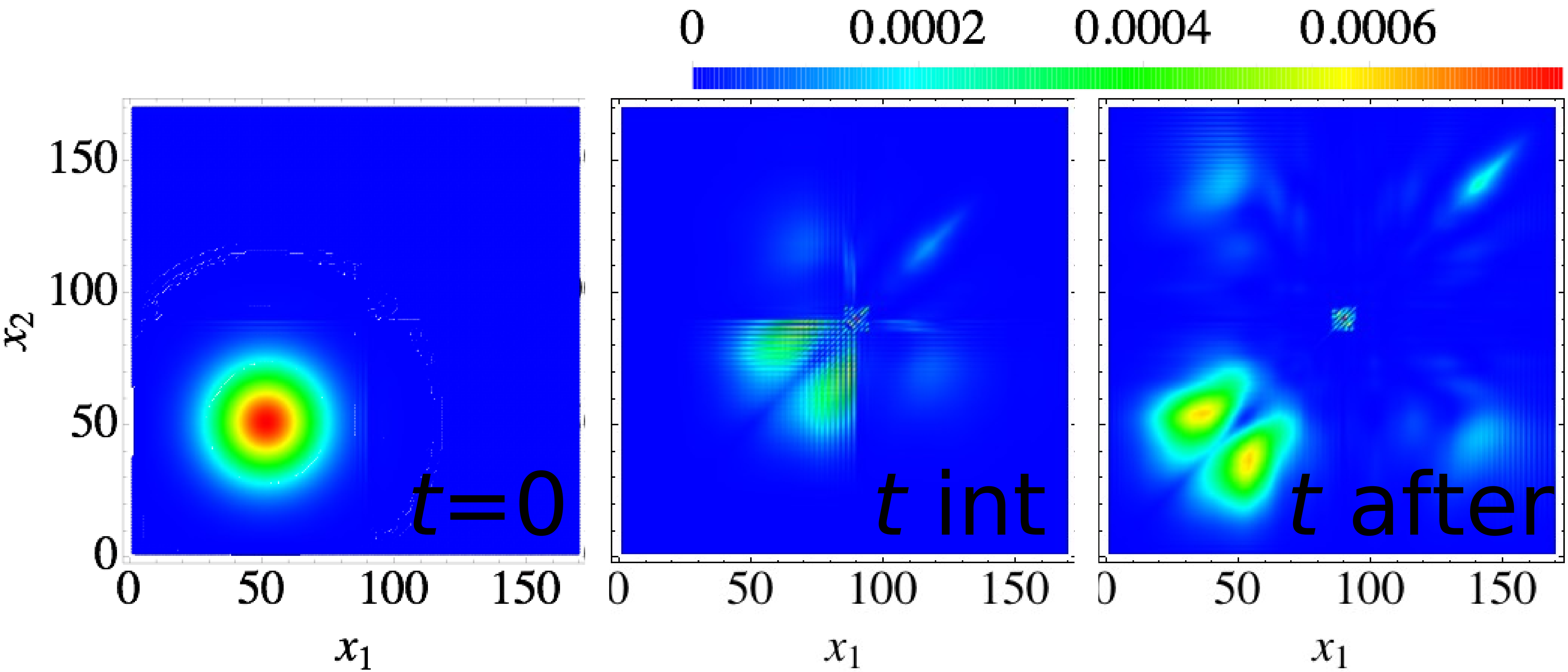
- Time evolution → Empirical formula
- $N \gg g/\omega$ we recover the coherent state result



Bunching (T) / Anti-bunching (R)



2 photon / 1 qubit $\langle n_{x_1} n_{x_2} \rangle$



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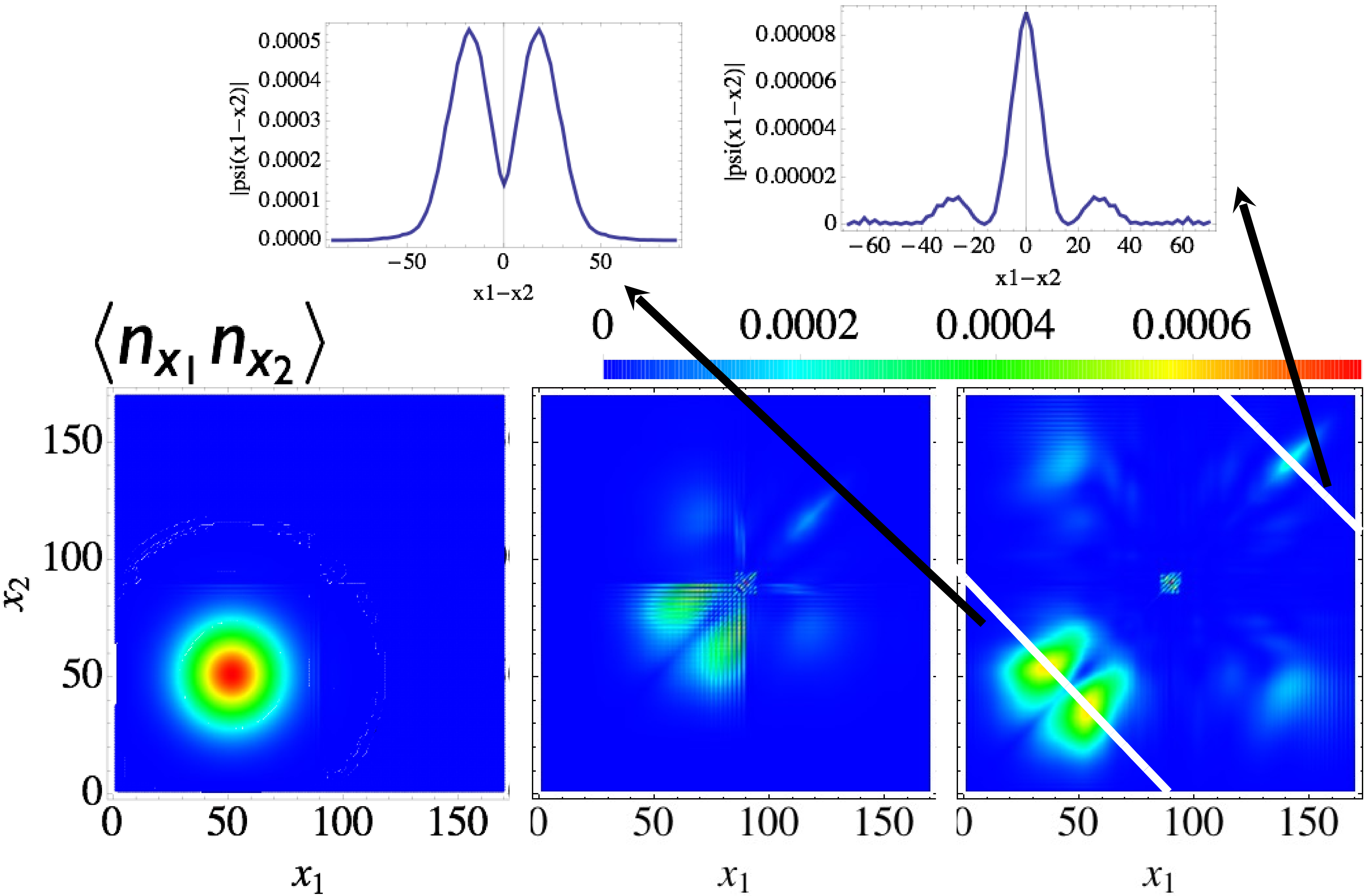


[Shen & Fan (2007)]

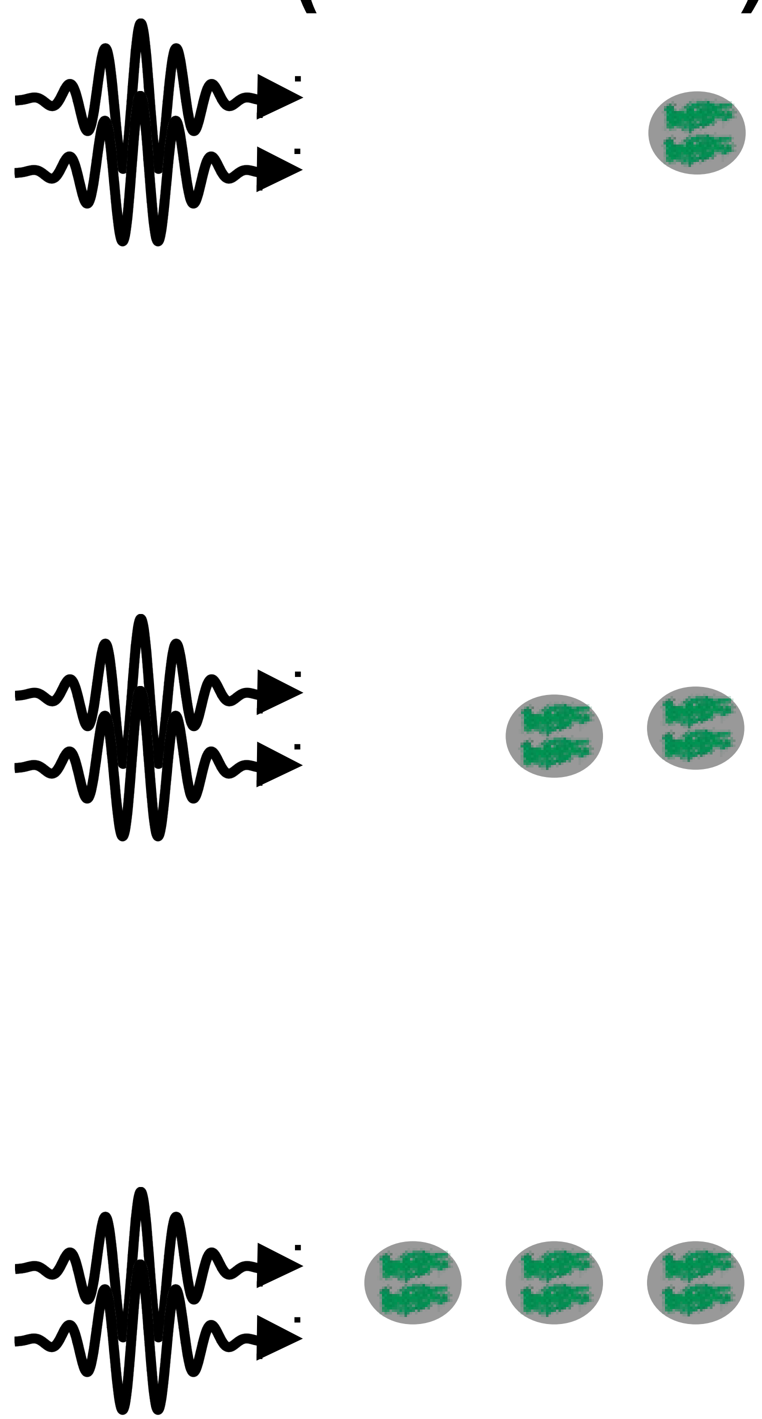
Anti-bunching → bunching

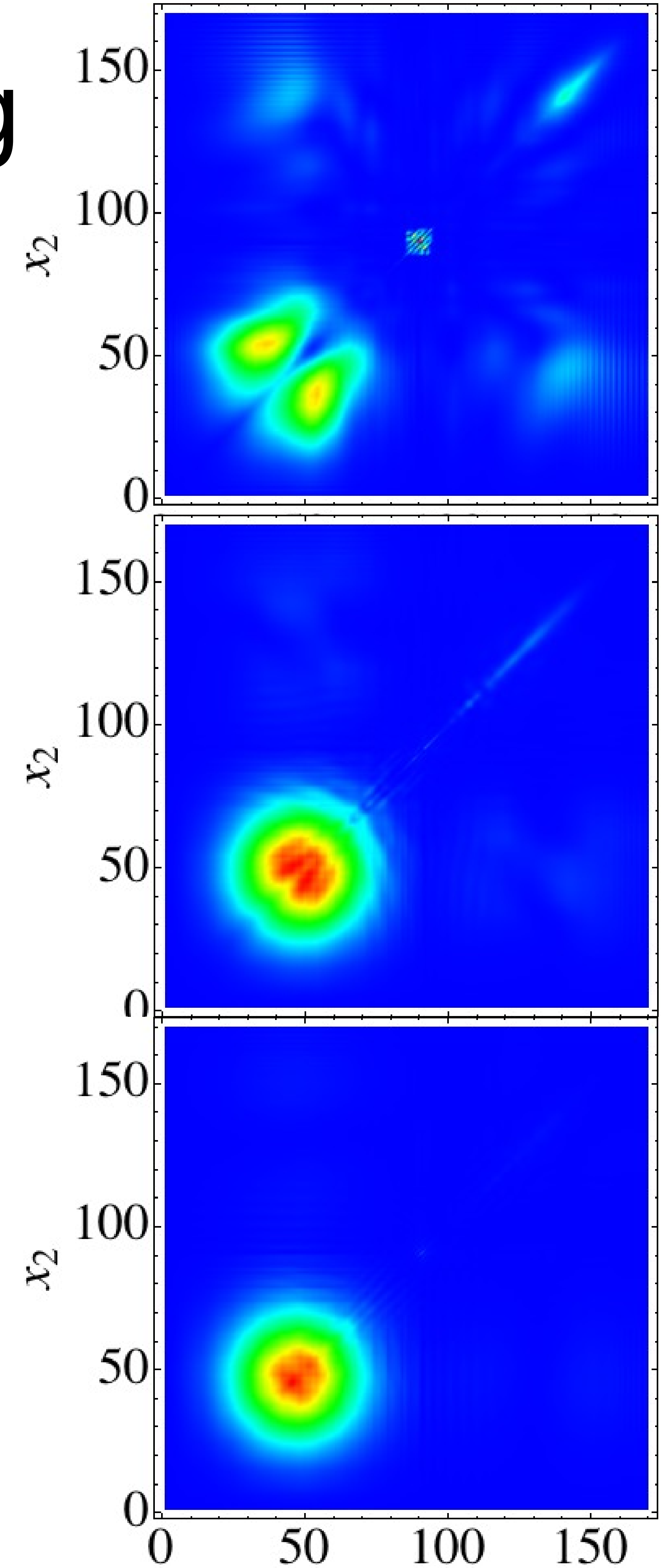
$\langle n_{x_1} n_{x_2} \rangle$ (t after)

2 ph → 1 qubit

2 ph → 2 qubit

2 ph → 3 qubit





ultra- strong coupling
and photonics

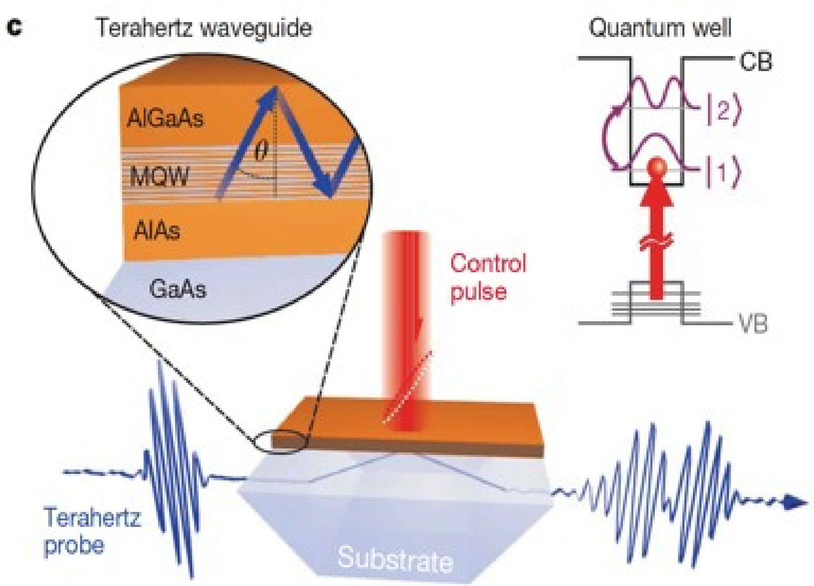
Ultrastrong / Beyond RWA. The definition

- JC / RWA $H = \omega a^\dagger a + \frac{\Delta}{2}\sigma^z + g(\sigma^+ a + \sigma^- a^\dagger)$
- However $H_{\rm dipole} = \vec{\mu}\vec{E}$ with $E \sim a^\dagger + a$ and $\vec{\mu} \sim \vec{\sigma}$
- Thus $H = \omega a^\dagger a + \frac{\Delta}{2}\sigma^z + g\sigma^x(a^\dagger + a)$

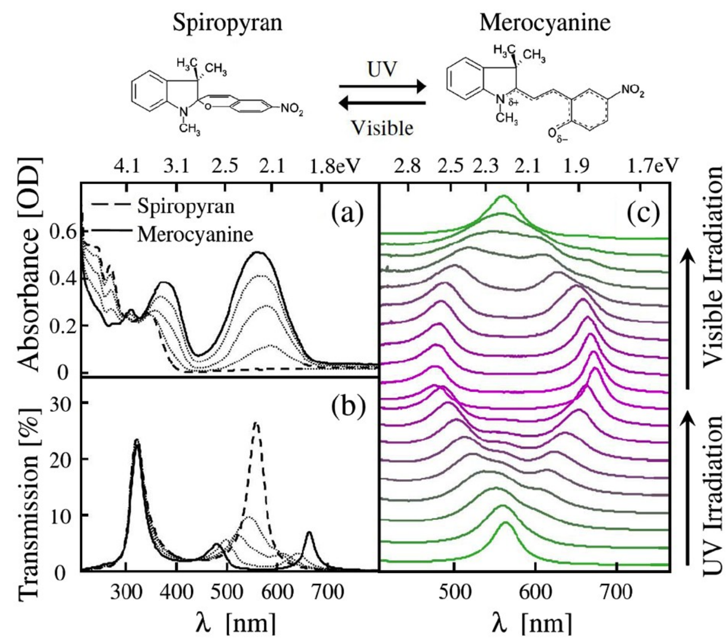
$$= \omega a^\dagger a + \frac{\Delta}{2}\sigma^z + g(\sigma^+ a + \sigma^- a^\dagger) + g(\sigma^+ a^\dagger + \sigma^- a)$$

Ultrastrong := The CR terms play a role

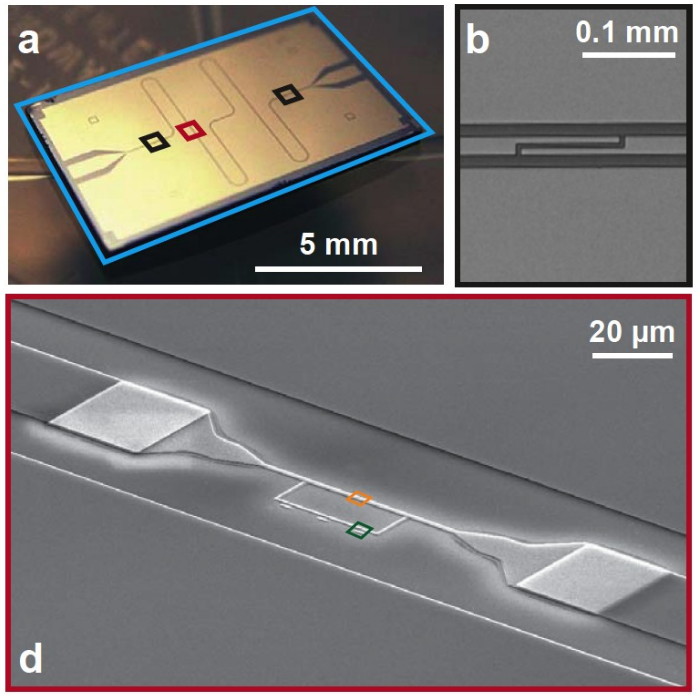
Gunter 2009 (g/ω =0.2 → g/ω=0.58)



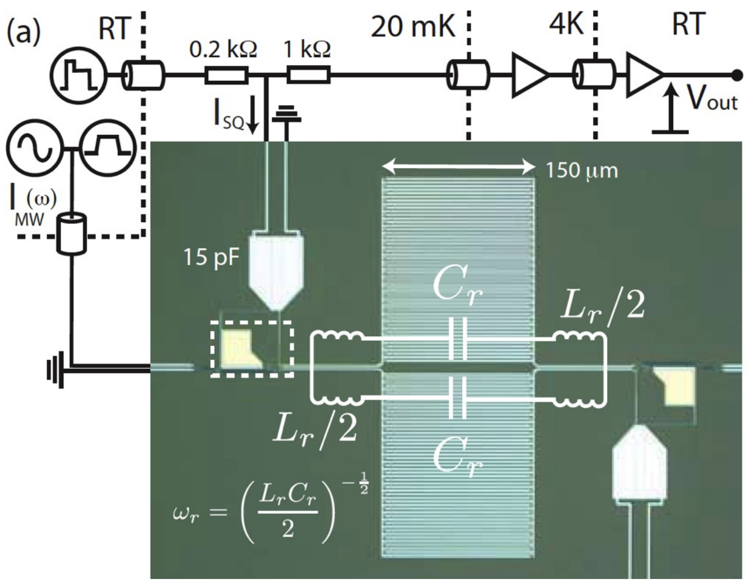
Schwartz 2011 (g/ω=0.16)



Experiments



Niemczyk 2010 (g/ω=0.12)

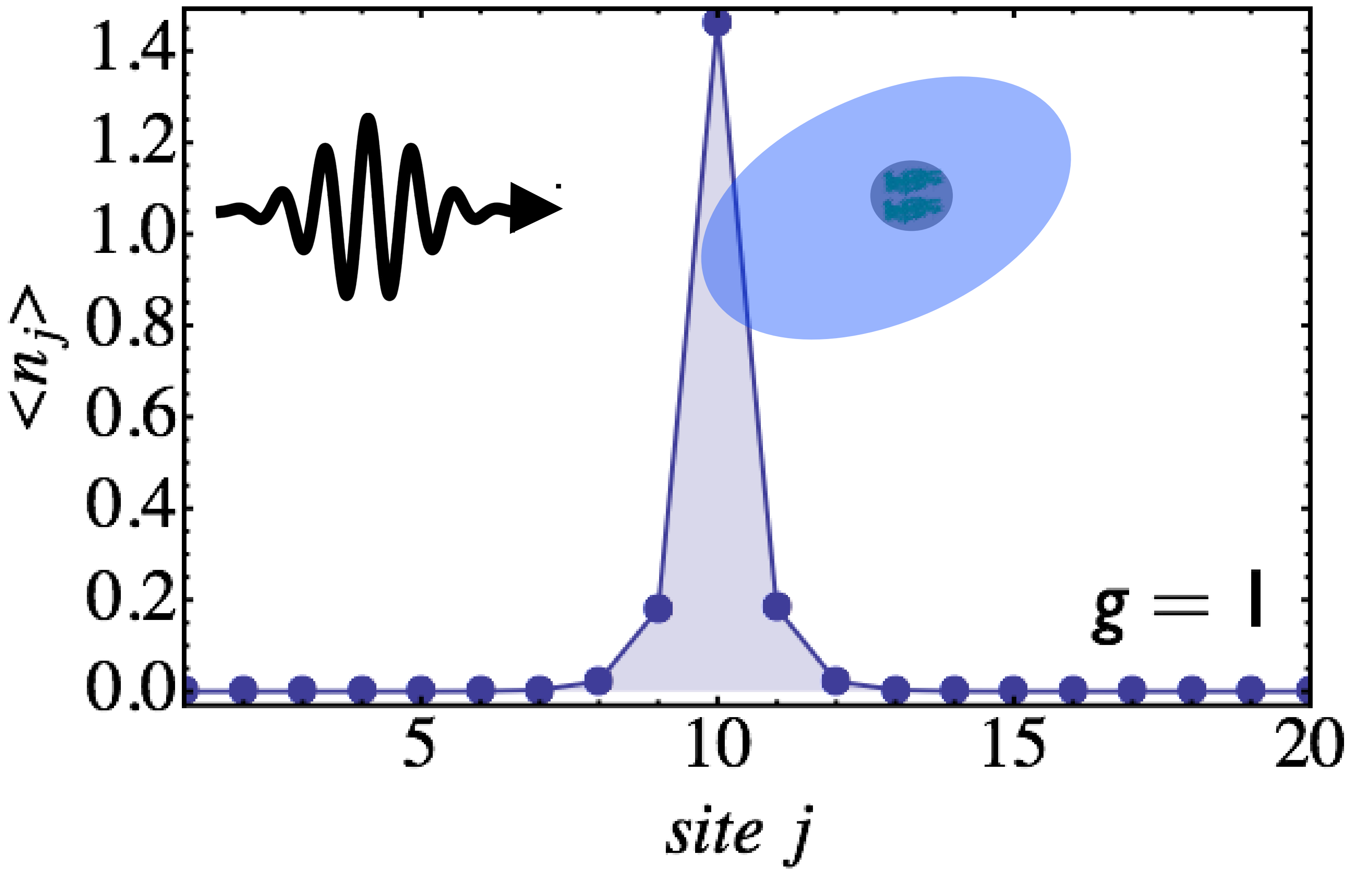


Forn Díaz 2010 (g/ω=0.1)

A consequence

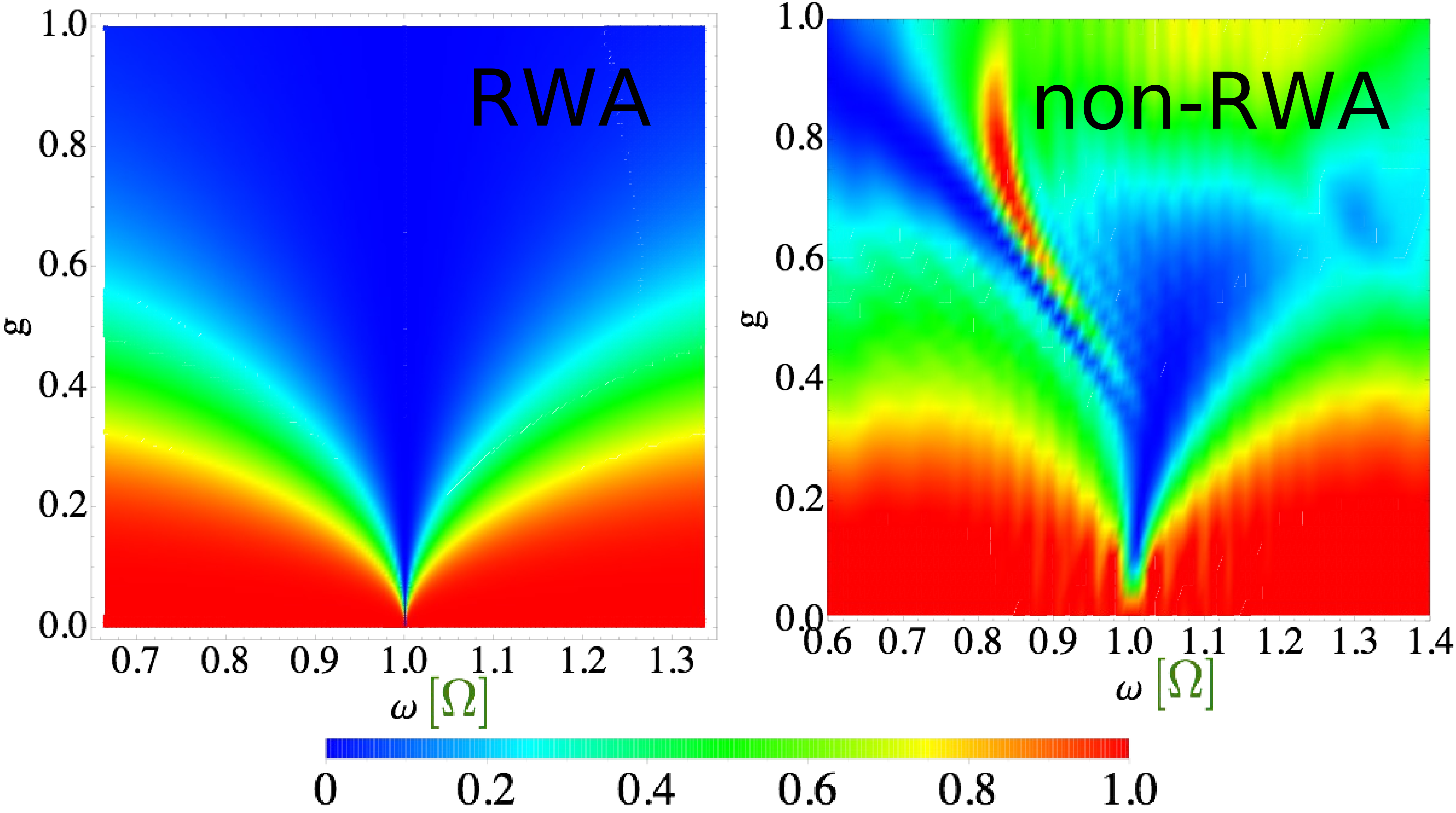
- $N = a^\dagger a + \sigma^+ \sigma^-$ is not a good quantum number
- The ground state is a dressed vacuum.

$$|\phi\rangle_{in} = (a_\phi)^N |GS\rangle \quad \text{where } a_\phi = \sum \phi_n a_n^\dagger$$

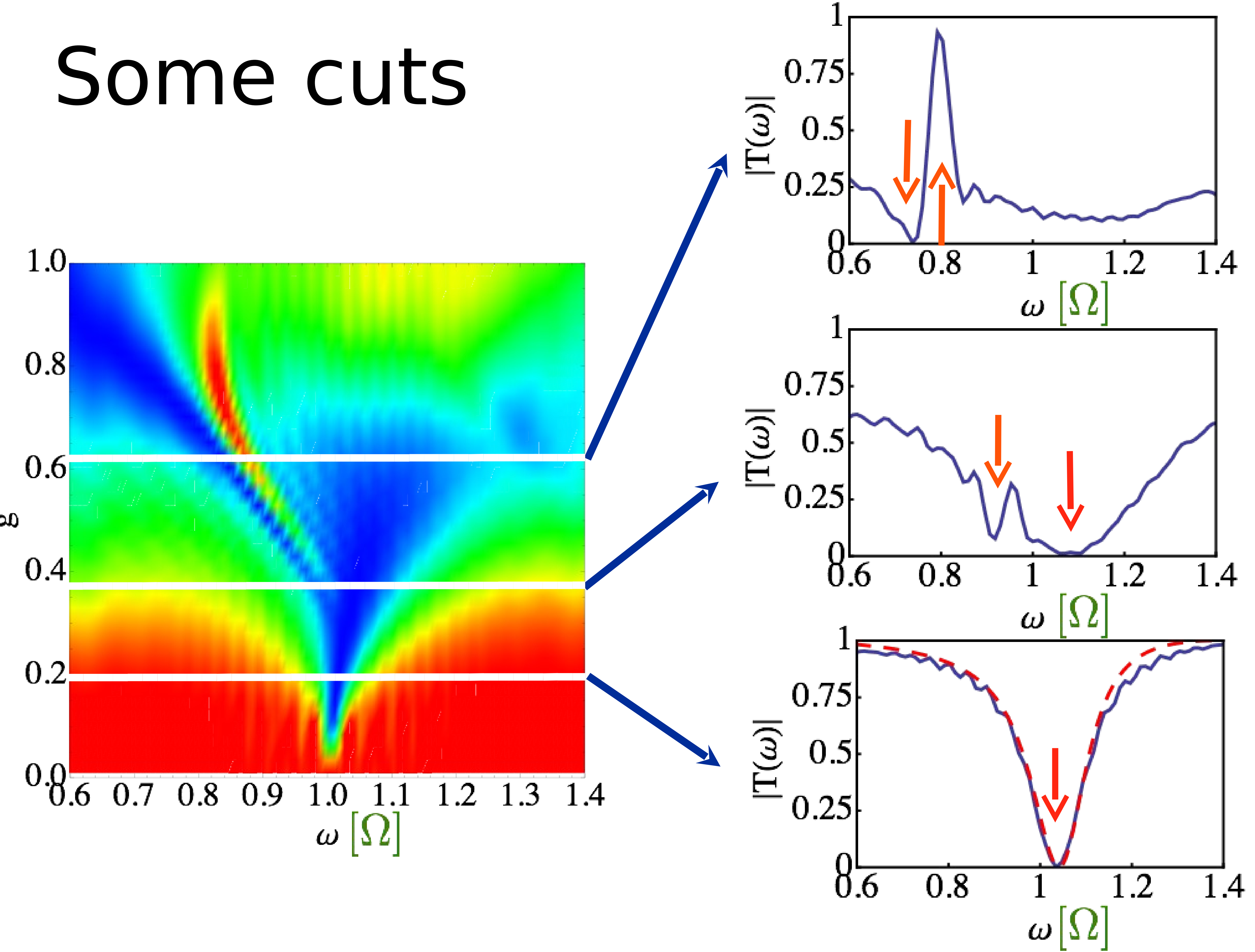


Full "single" photon scattering diagram

Transmission plots

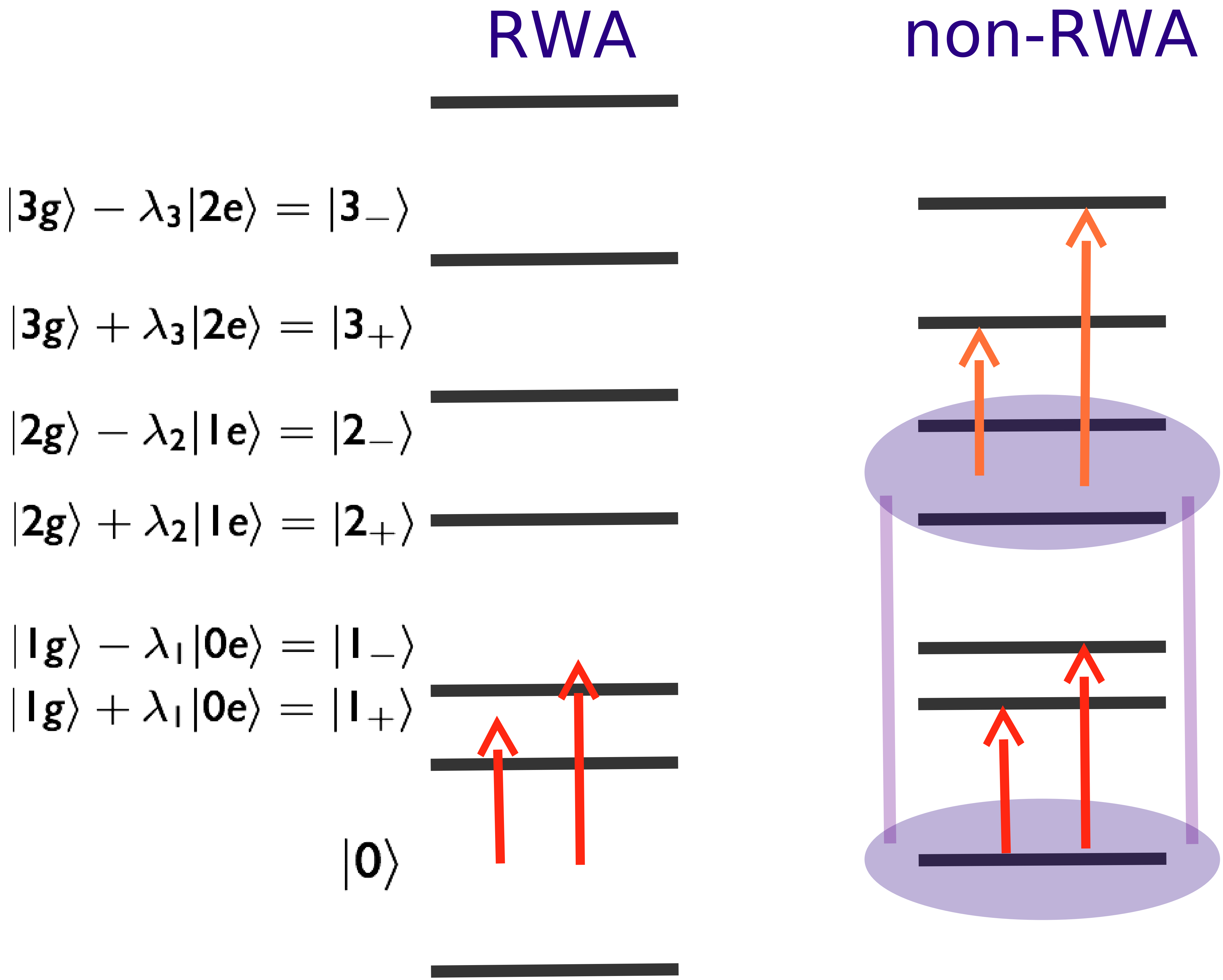


Some cuts



1.0
0.8
0.6
0.4
0.2
0.0
g
0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4
ω [Ω]
|T(ω)|
0 0.25 0.5 0.75 1
0.6 0.8 1 1.2 1.4
ω [Ω]
|T(ω)|
0 0.25 0.5 0.75 1
0.6 0.8 1 1.2 1.4
ω [Ω]
|T(ω)|
0 0.25 0.5 0.75 1
0.6 0.8 1 1.2 1.4
ω [Ω]

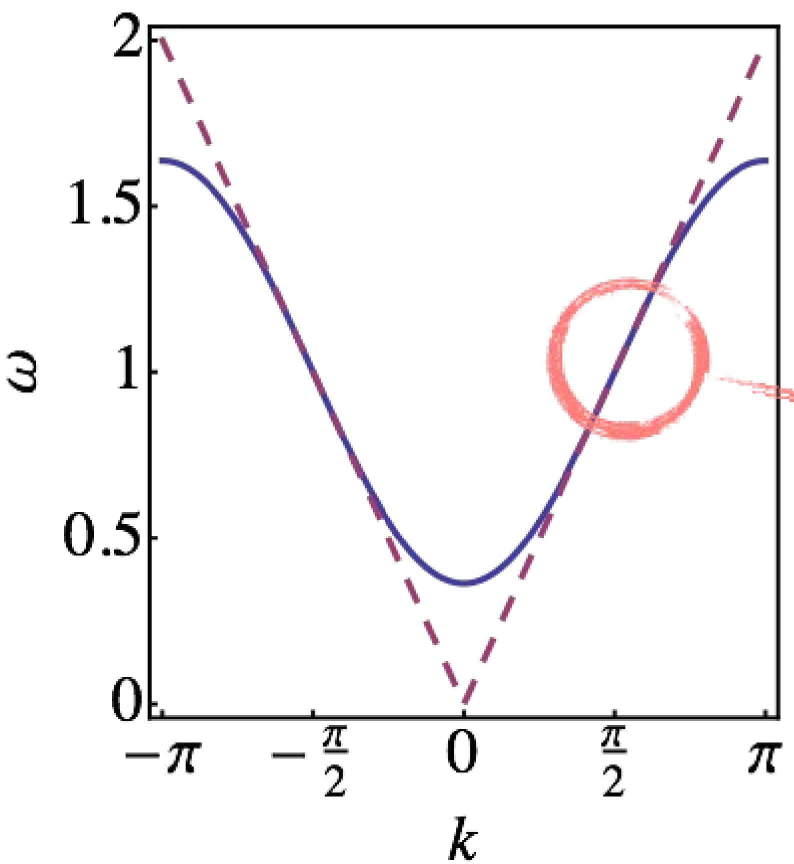
Preliminary interpretation



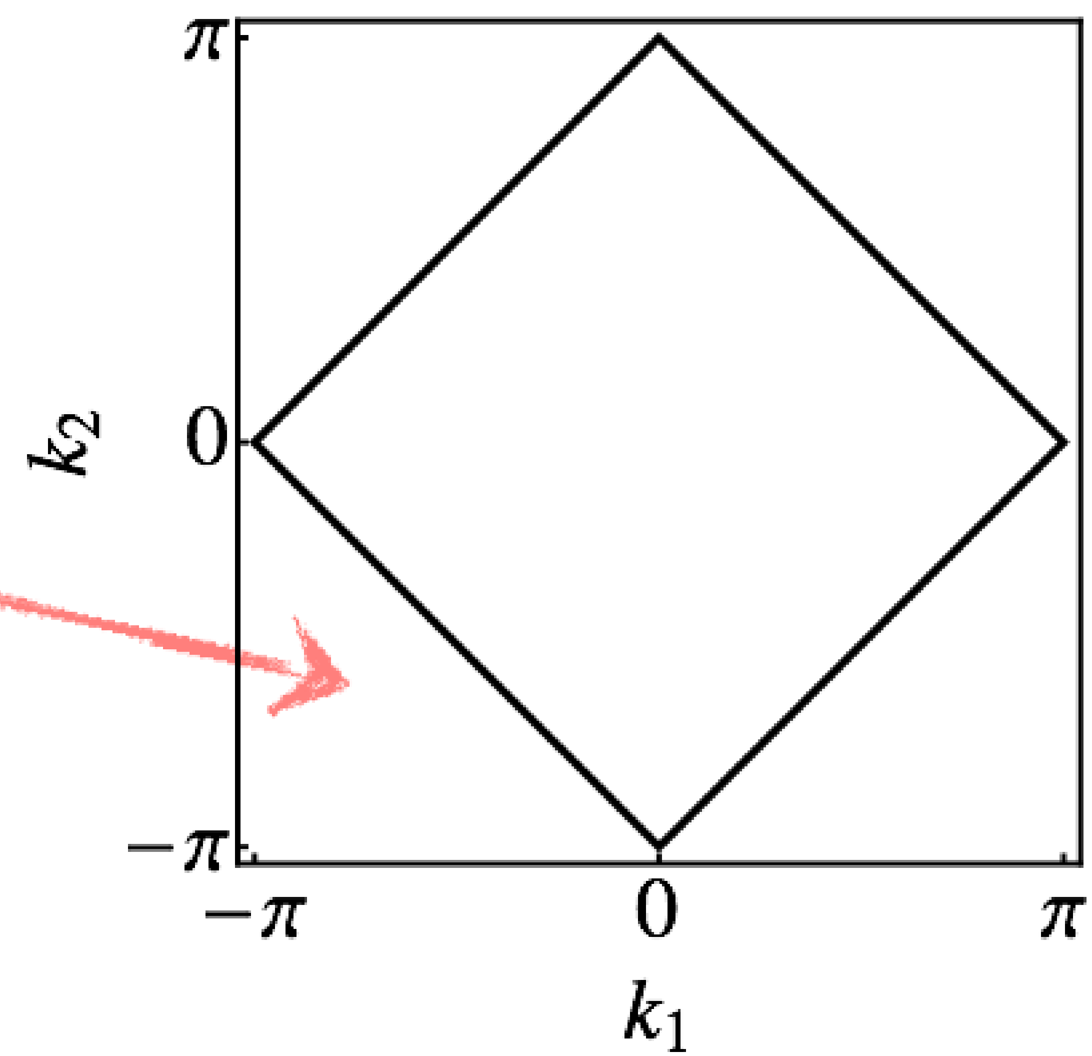
Resonance Fluorescence: RWA (strong) so far

- One photon: particle + energy conservation $\omega_{\rm in} = \omega_{\rm out}$
- Two photon chanel: $\omega_{1,\rm in} + \omega_{2,\rm in} = \omega_{1,\rm out} + \omega_{2,\rm out}$

iso-energy curve



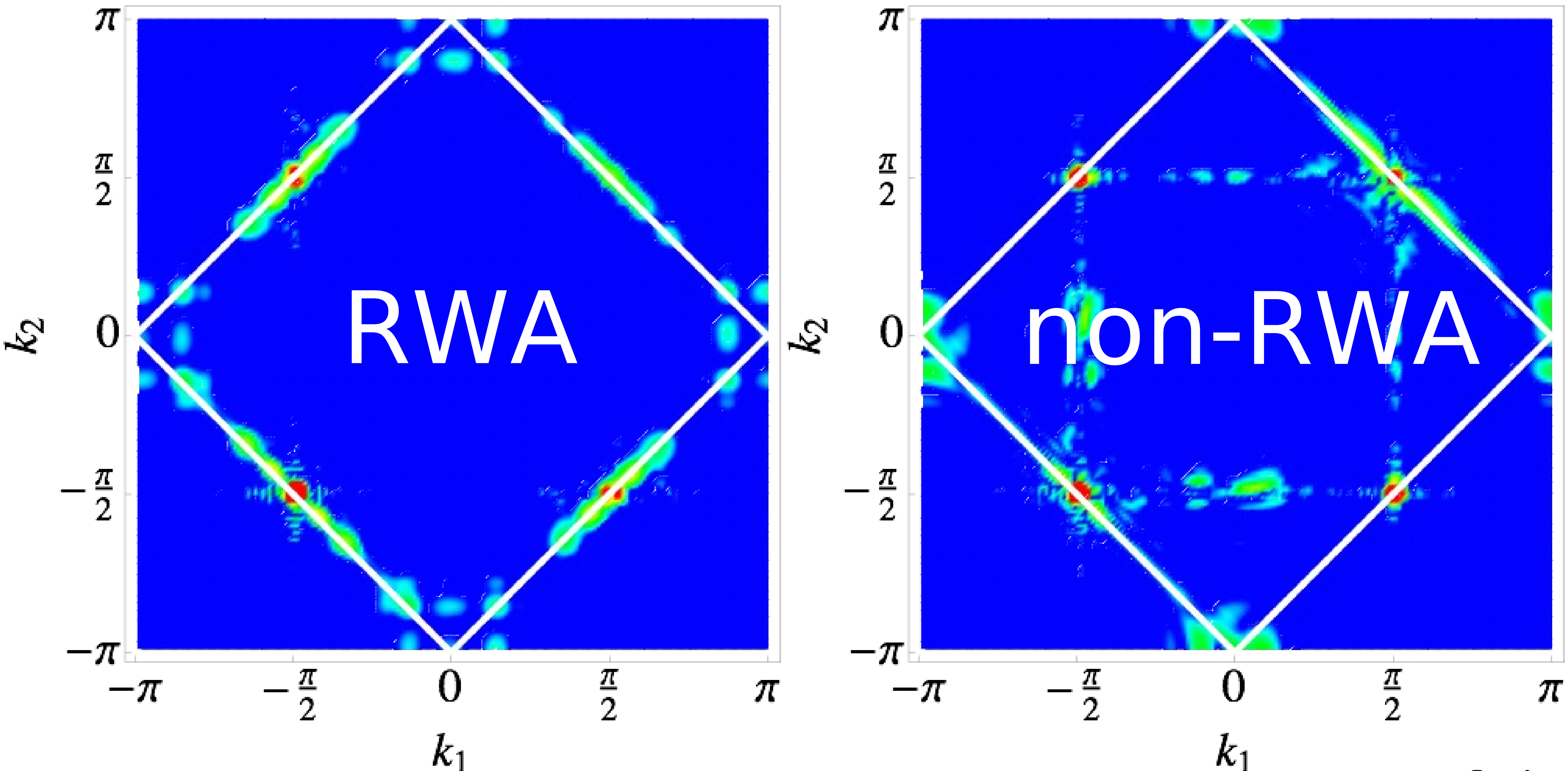
2 @ $k = \pi/2$



Resonance Fluerescence: RWA corrected

Suppression of the RF

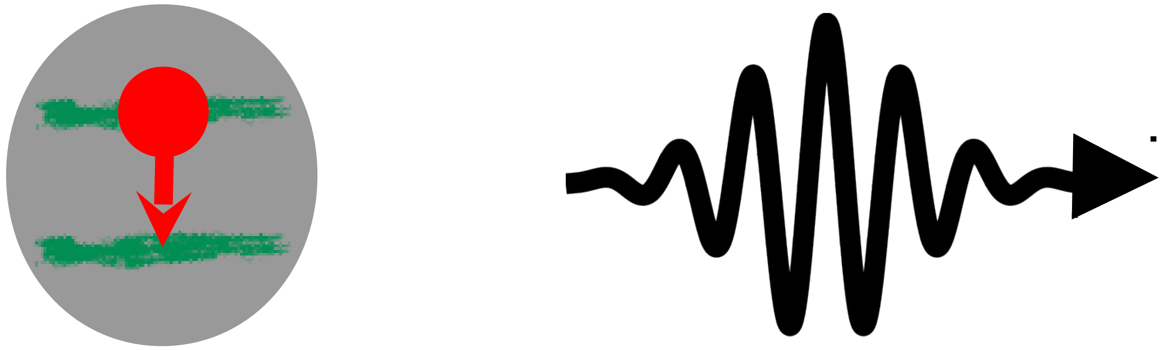
$\langle n_{k_1} n_{k_2} \rangle$ $\langle n_{k_1} n_{k_2} \rangle$

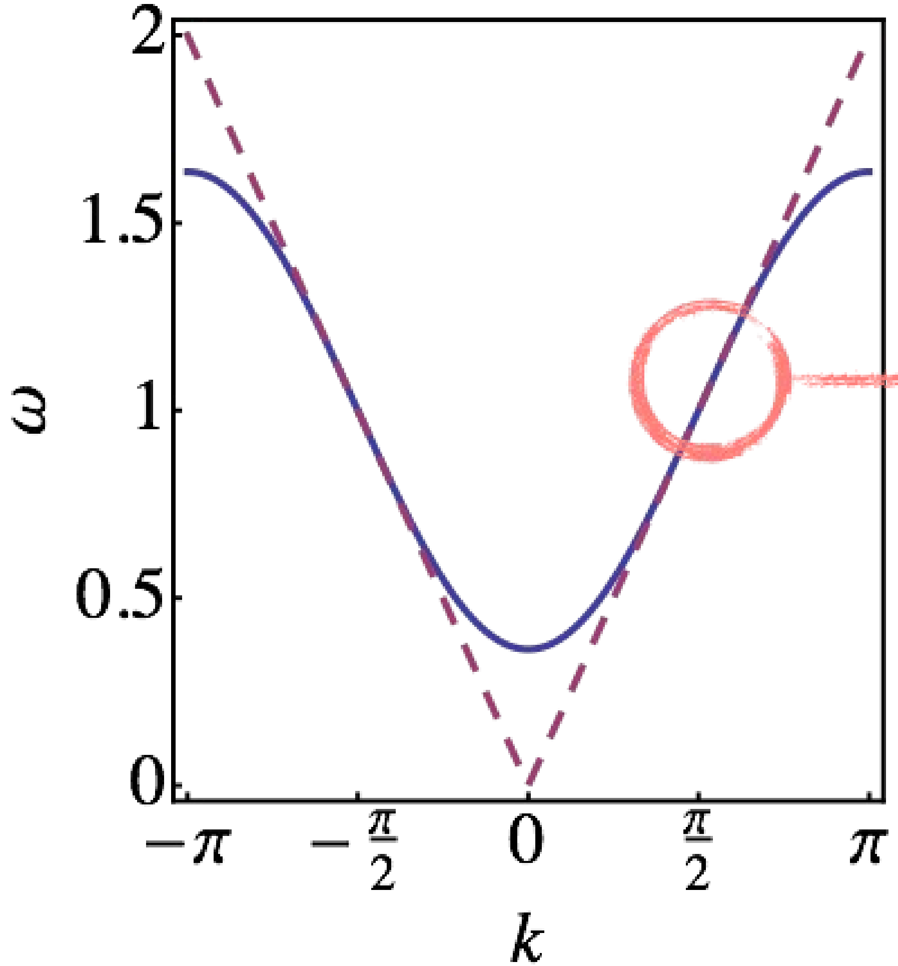


$g = 0.4$

[In RWA Rephaeli, Kocabas & Fan (2011)]

Spontaneous emission



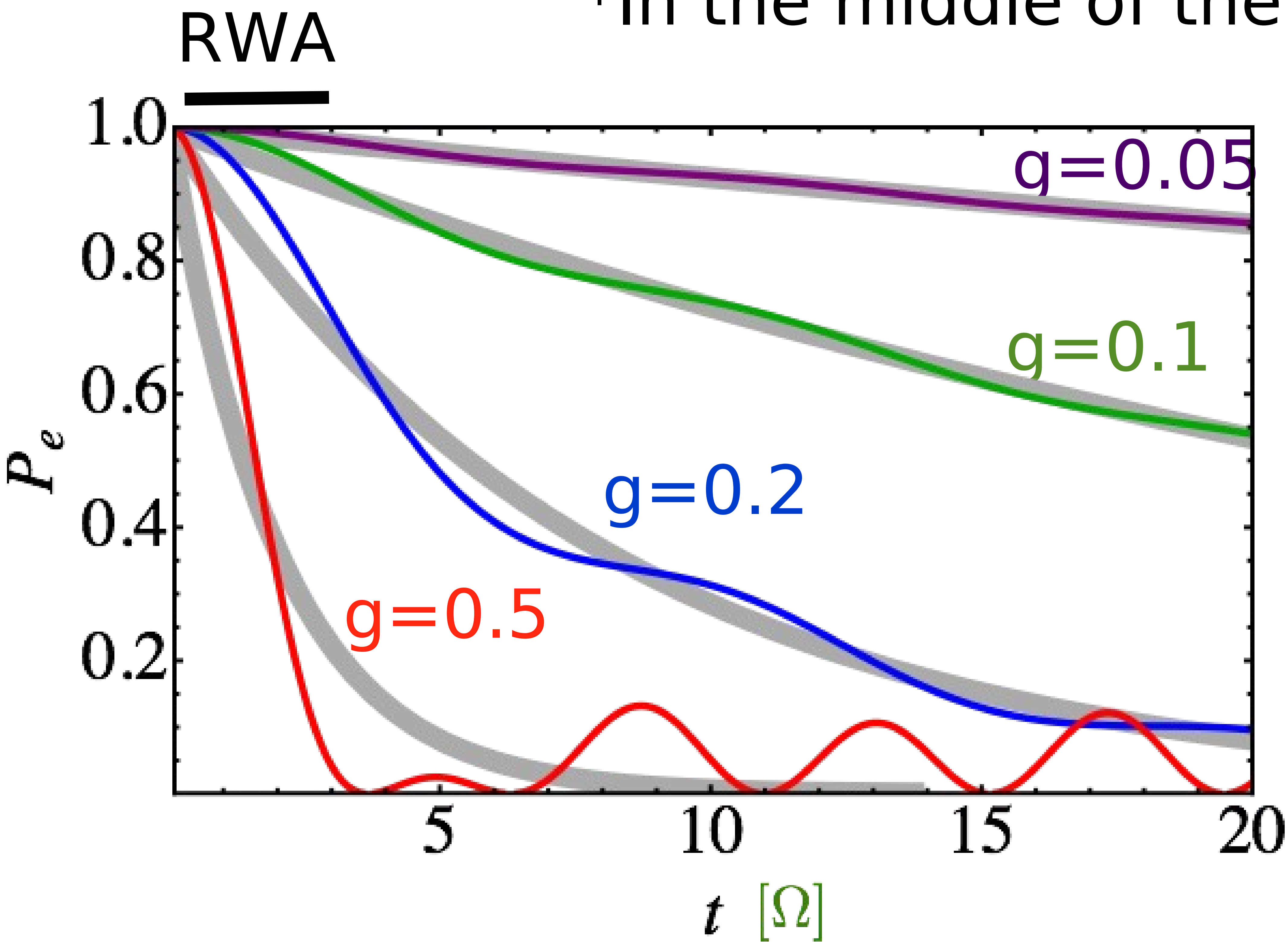


$$P_e = e^{-(g^2/J)t}$$

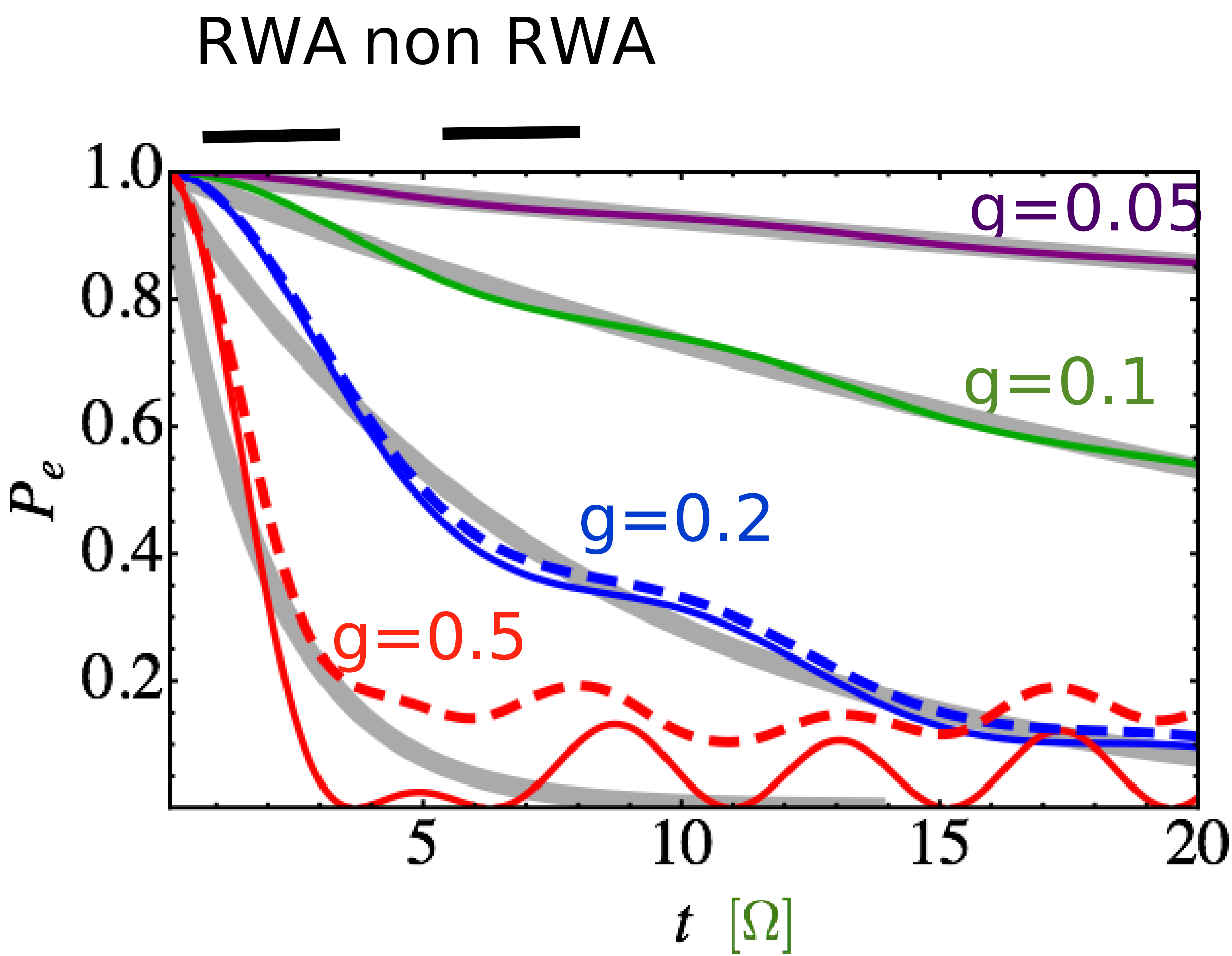
Fermi Golden Rule / Master Eq.

Testing the Markovianity*

*In the middle of the band!



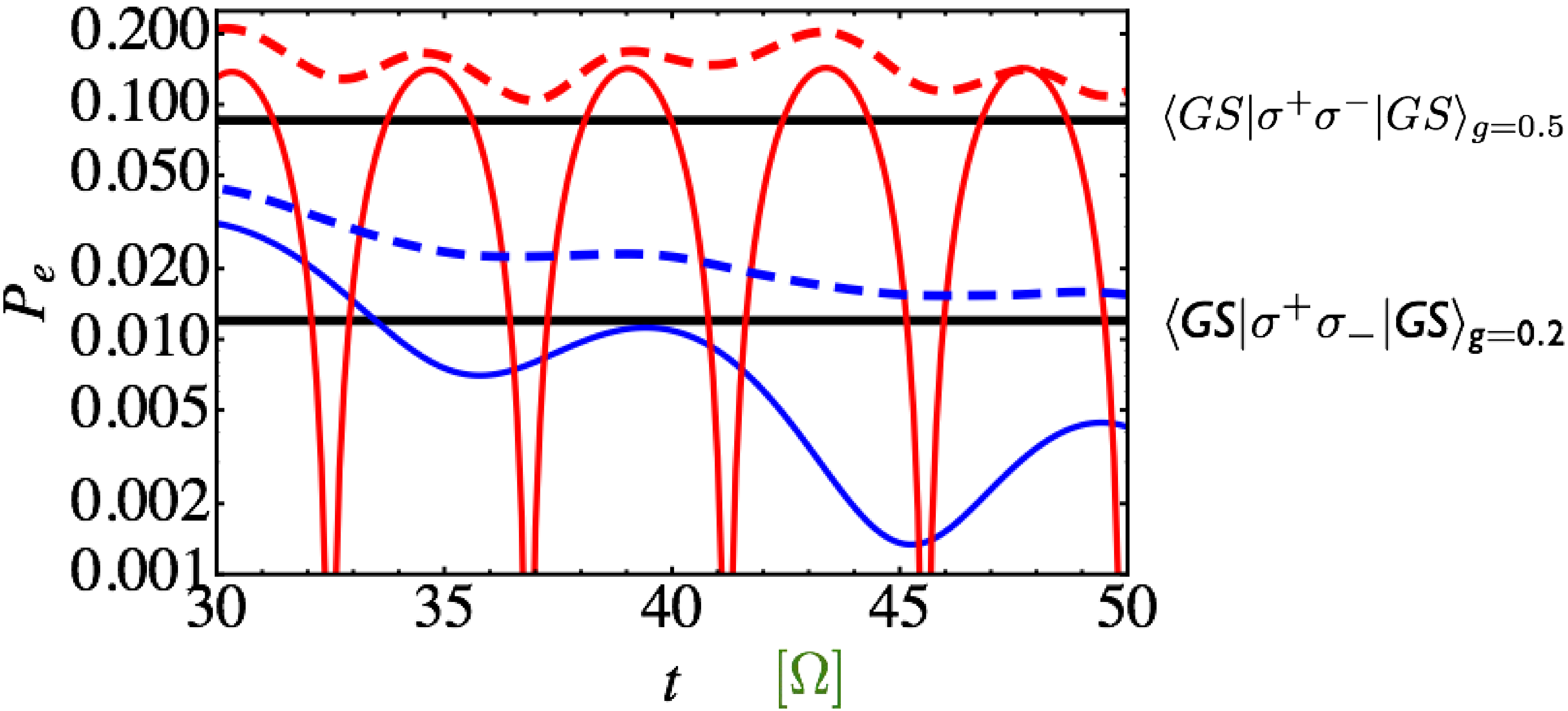
Testing the Markovianity*



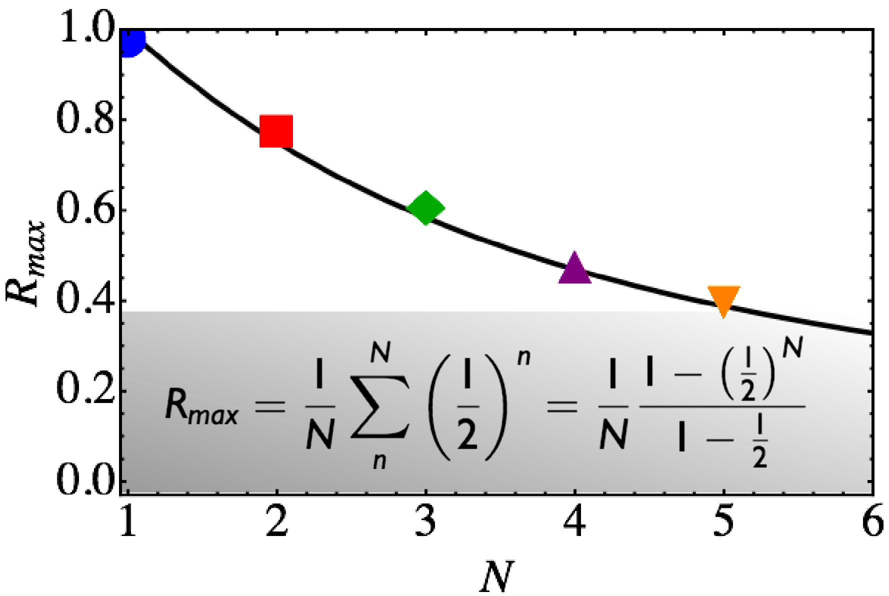
Testing the Markovianity*

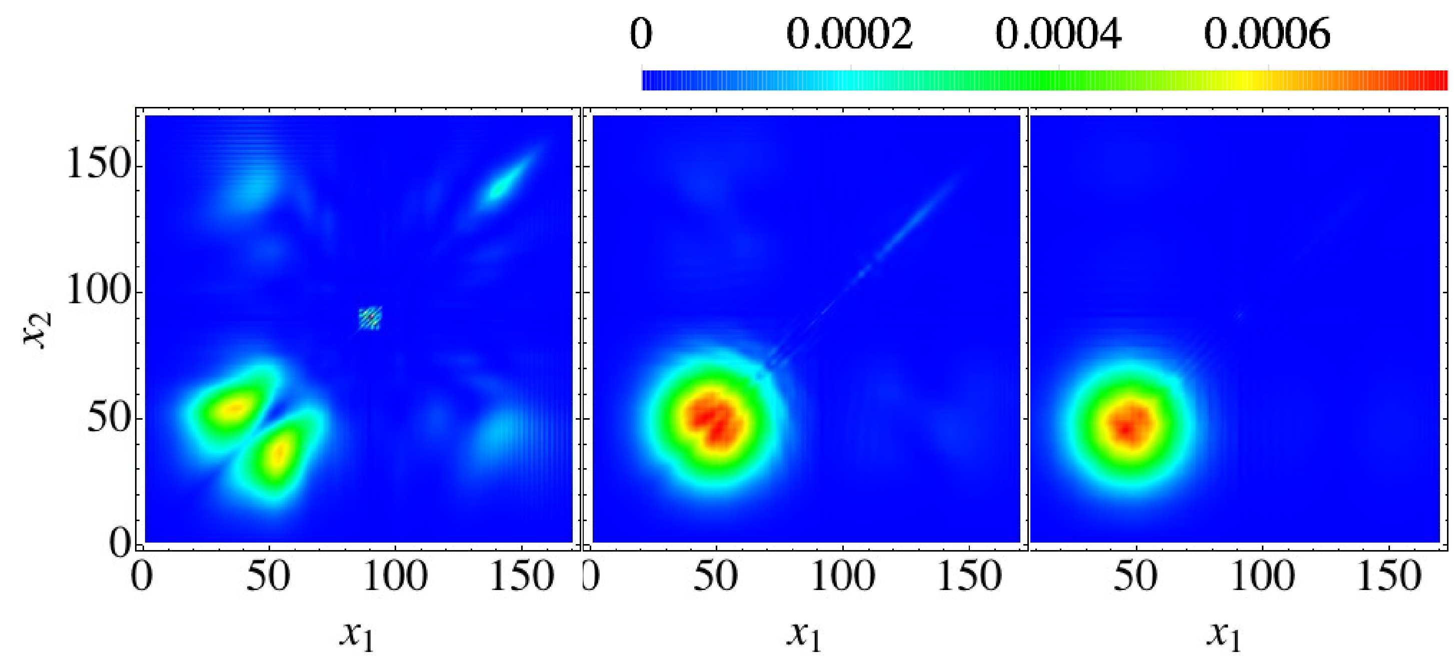
RWA non RWA

(Long times)

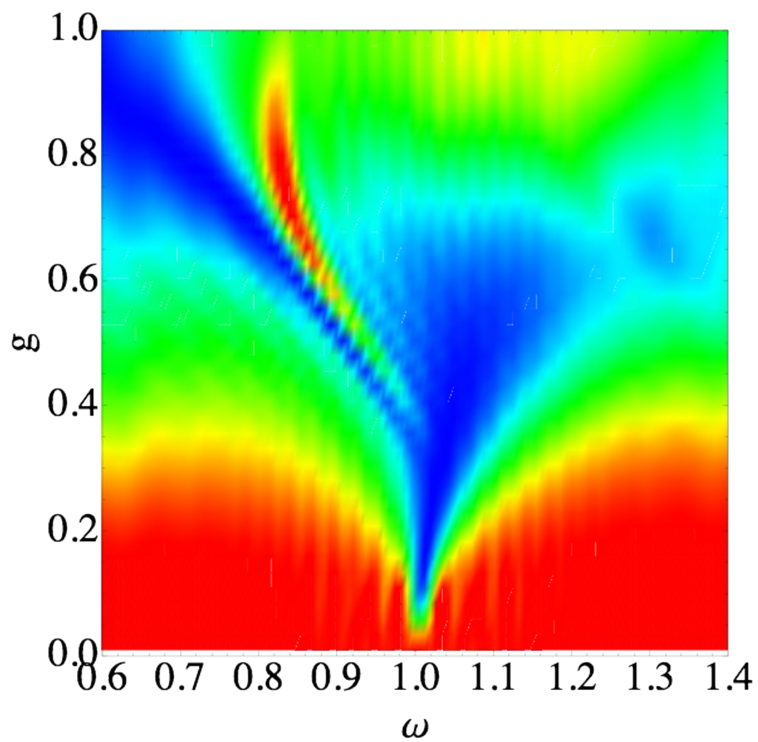


Conclusions

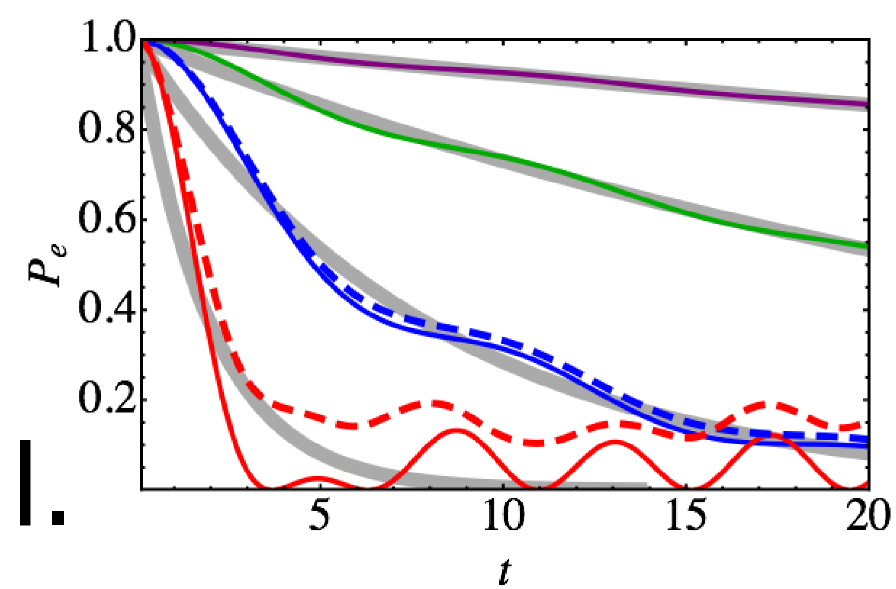




Numerical tool. N photons / M qubits / $O(LNM)$



Ultrastrong in scattering / $O(LNMg)$

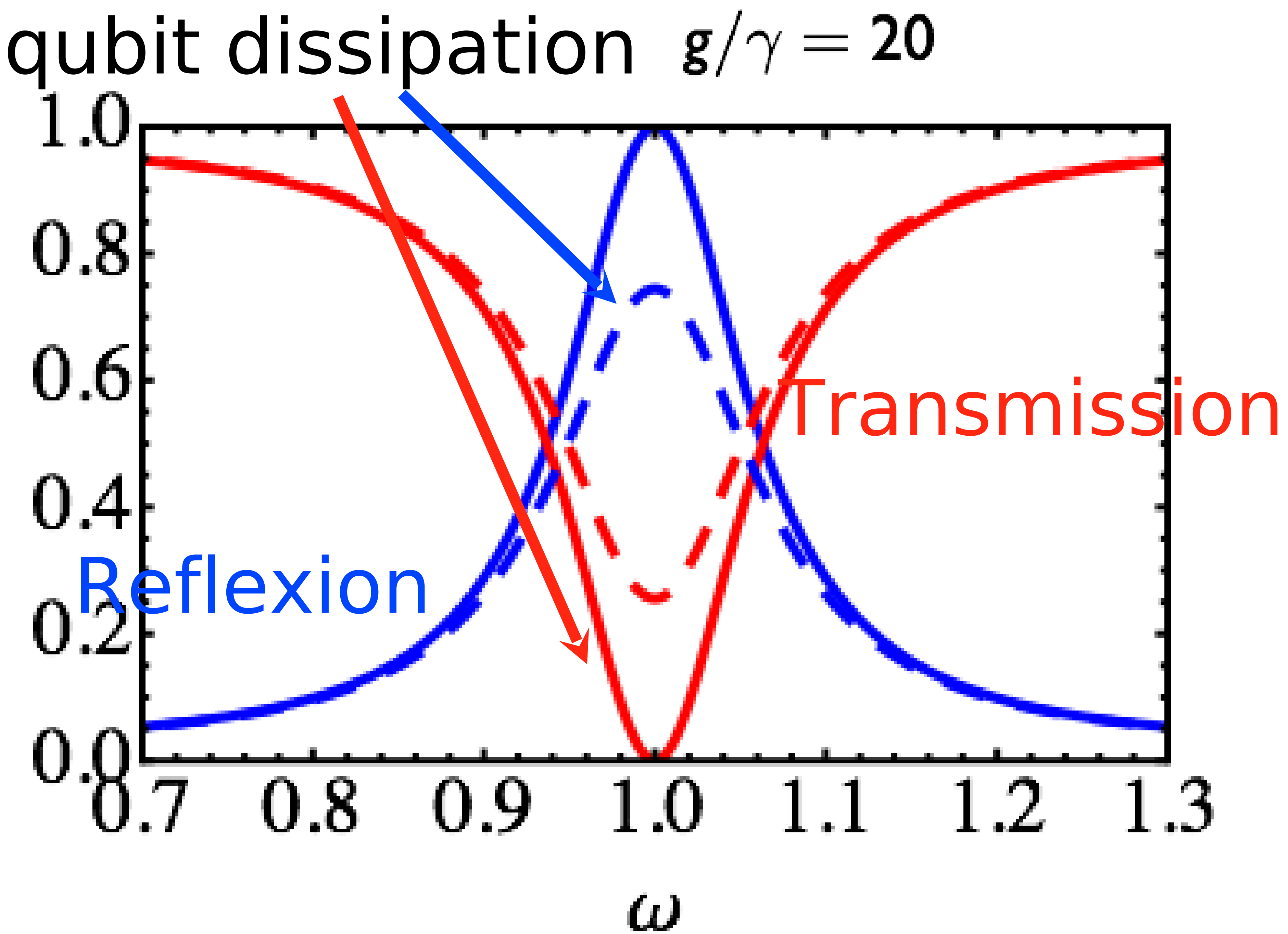


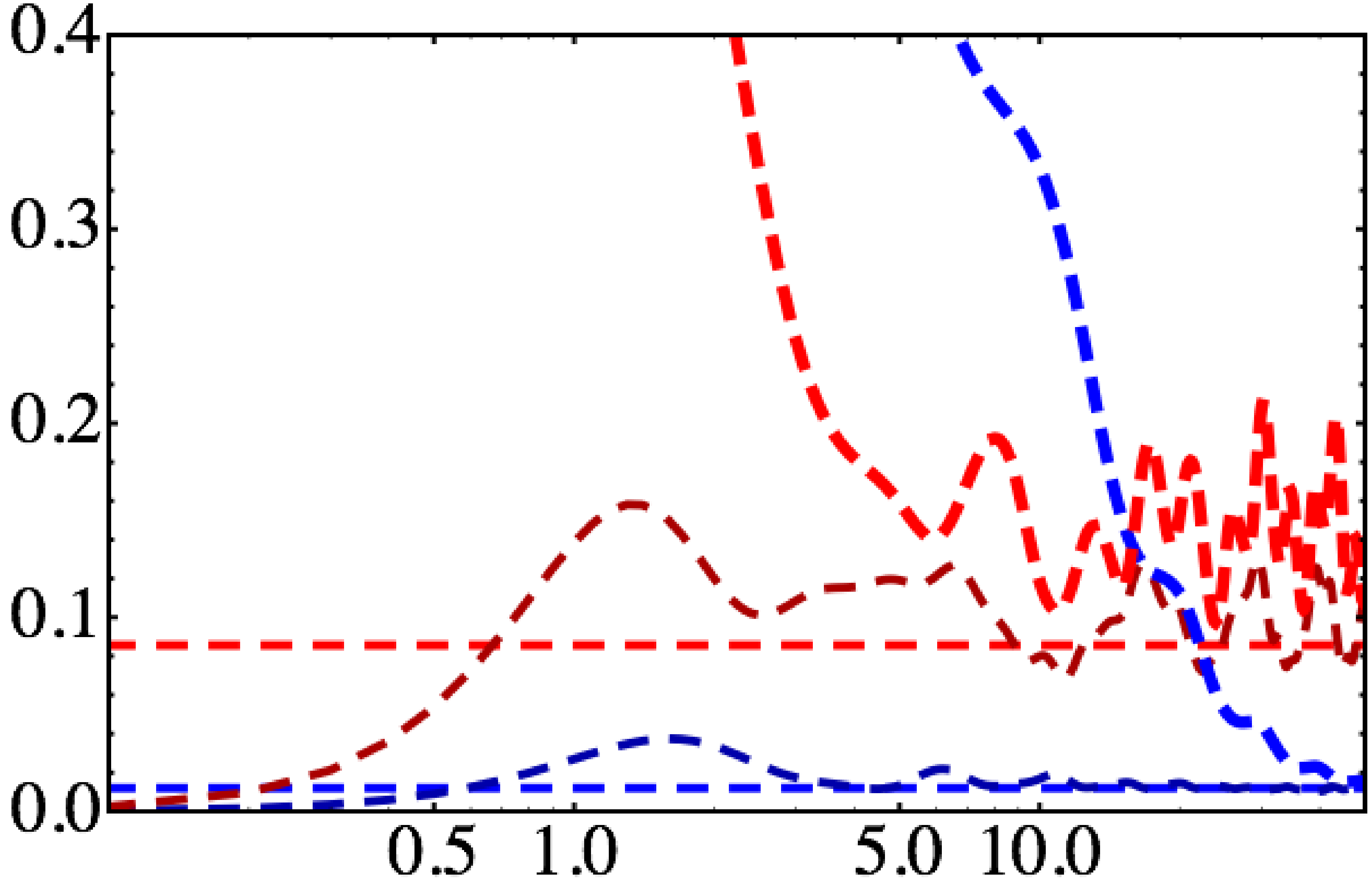
Non-equilibrium / Thermal.

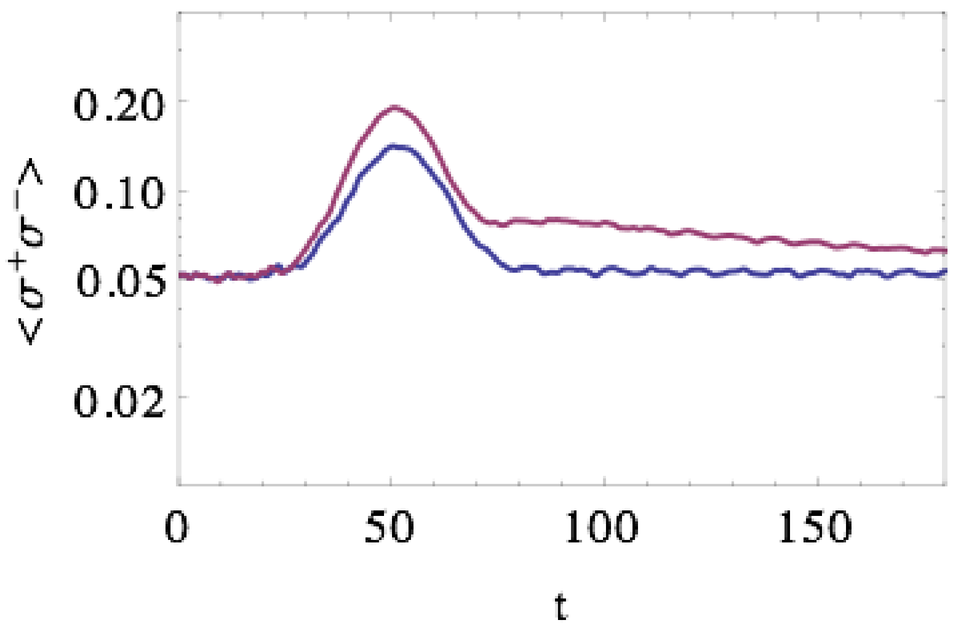
Thanks a lot !

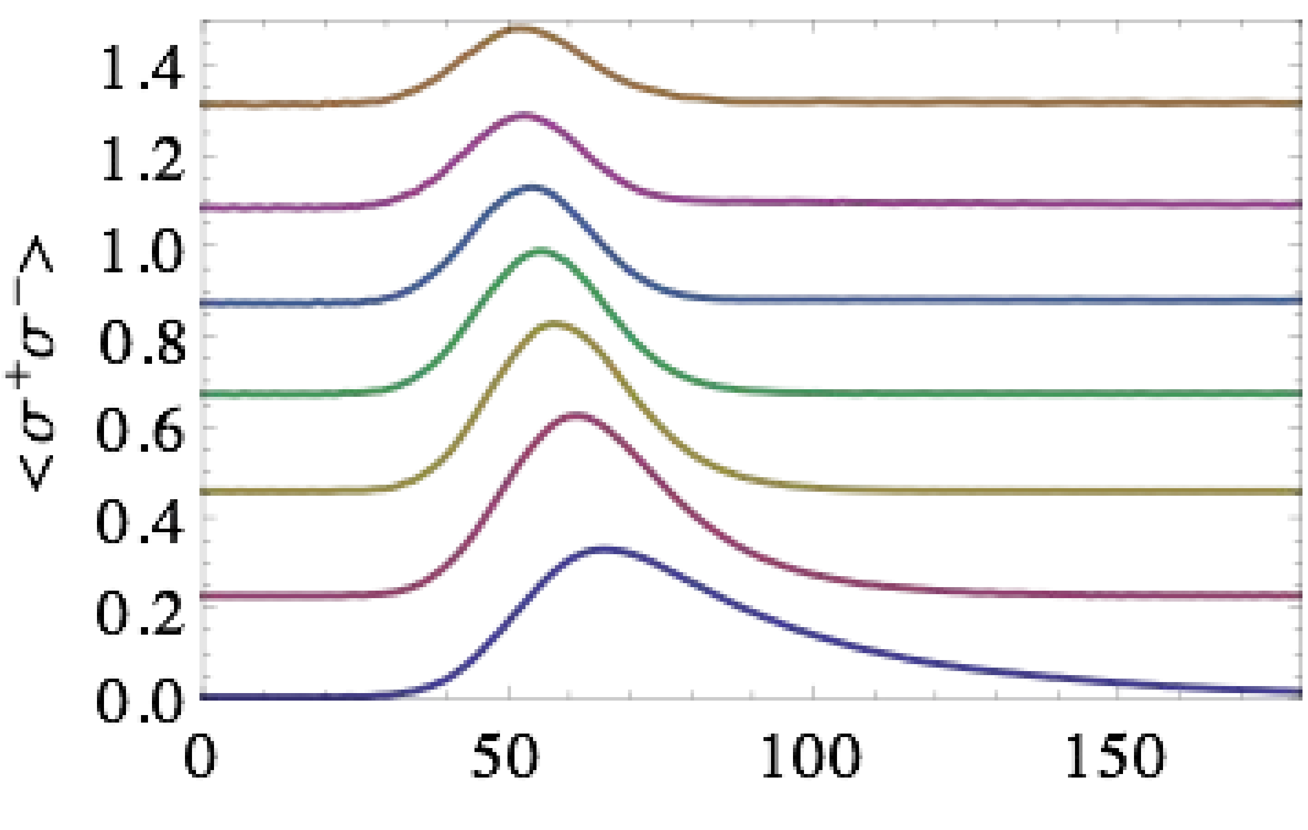
Appendices

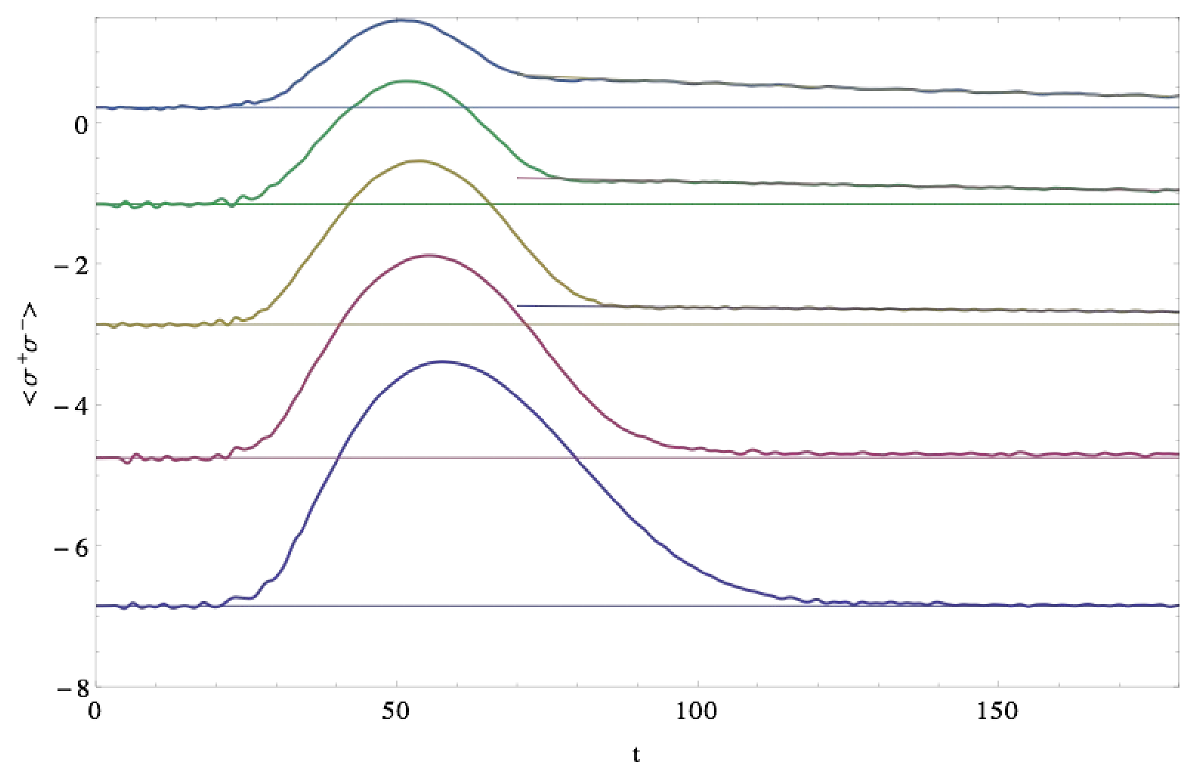
1 photon / 1 qubit

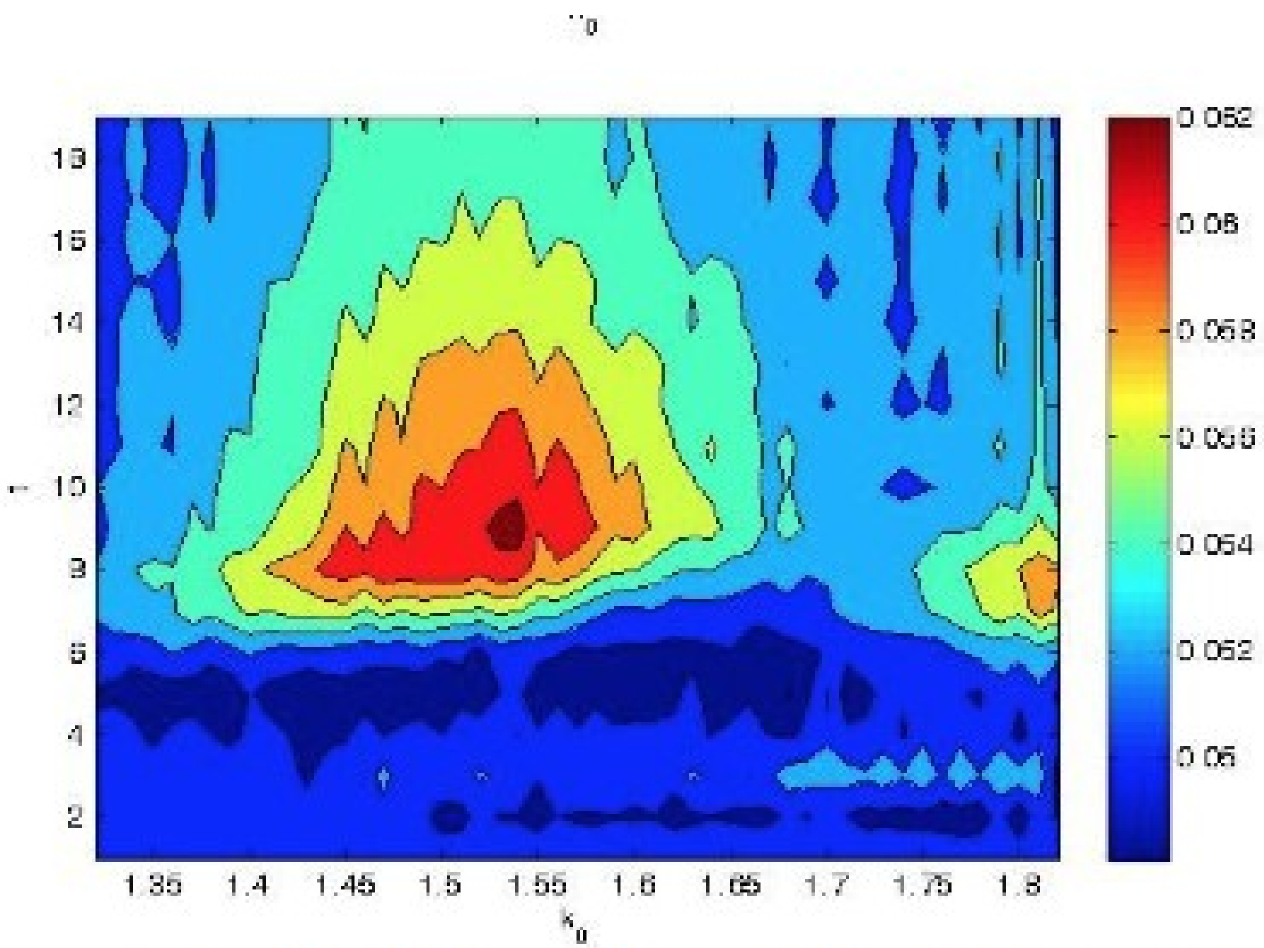



0.4
0.3
0.2
0.1
0.0
0.5
1.0
5.0
10.0


0.20
0.10
0.05
0.02
$<\sigma^+\sigma^->$
0
50
100
150
t

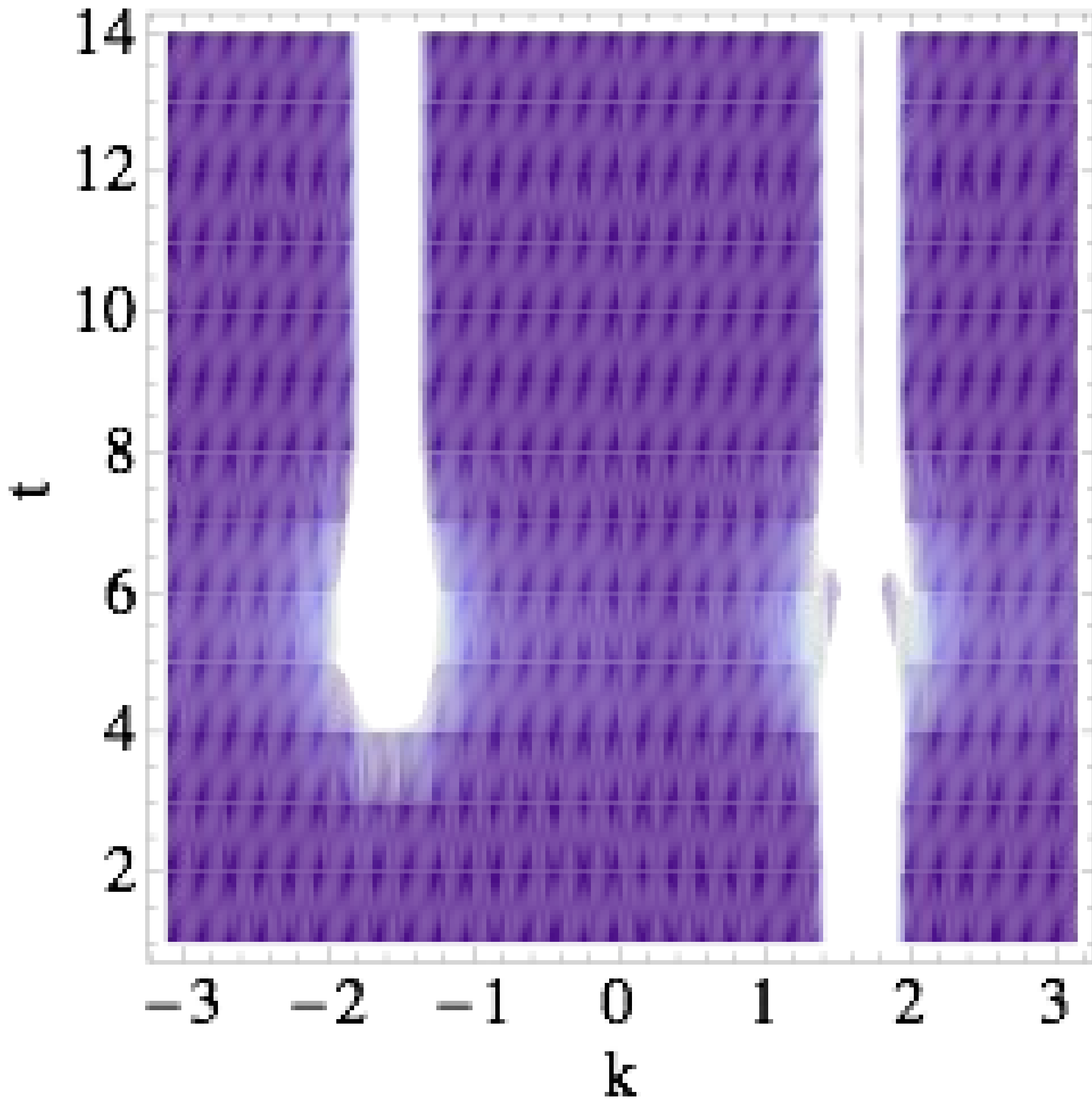

1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
$<\sigma^+\sigma^->$
0
50
100
150


0
−2
−4
−6
−8
$<\sigma^+\sigma^->$
0
50
100
150
t

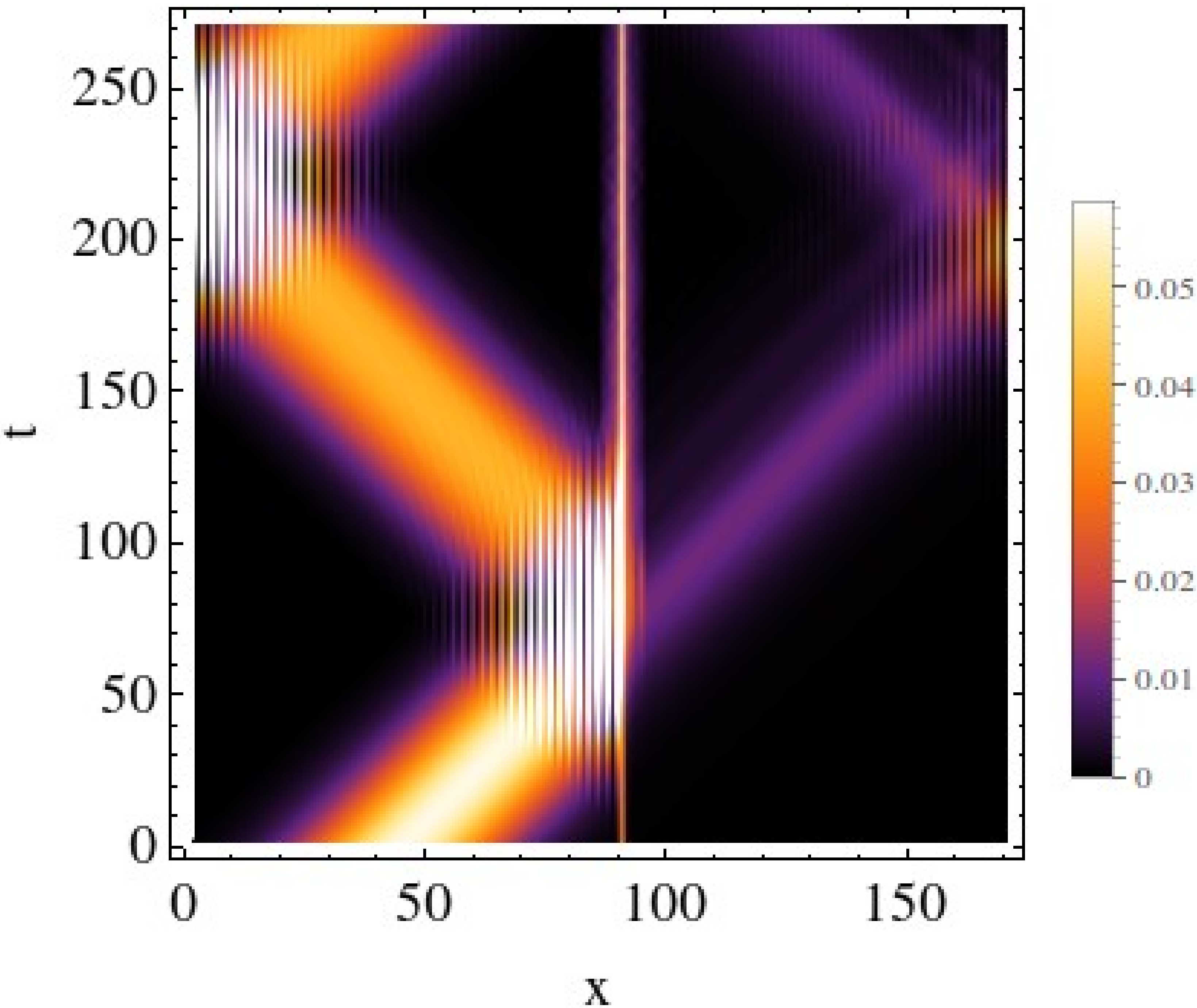


g=0.40

Overlap between the state and the subspace where the number of photons is two and the qubit is excited: \sum_nm |<0|a_n a_m \sigma^{-}|psi>/sqrt(2)|^{2}



t
14
12
10
8
6
4
2
−3
−2
−1
0
1
2
3
k



t
250
200
150
100
50
0
0
50
100
150
x
0.05
0.04
0.03
0.02
0.01
0