

Experimental methods for Rydberg Atomtronics

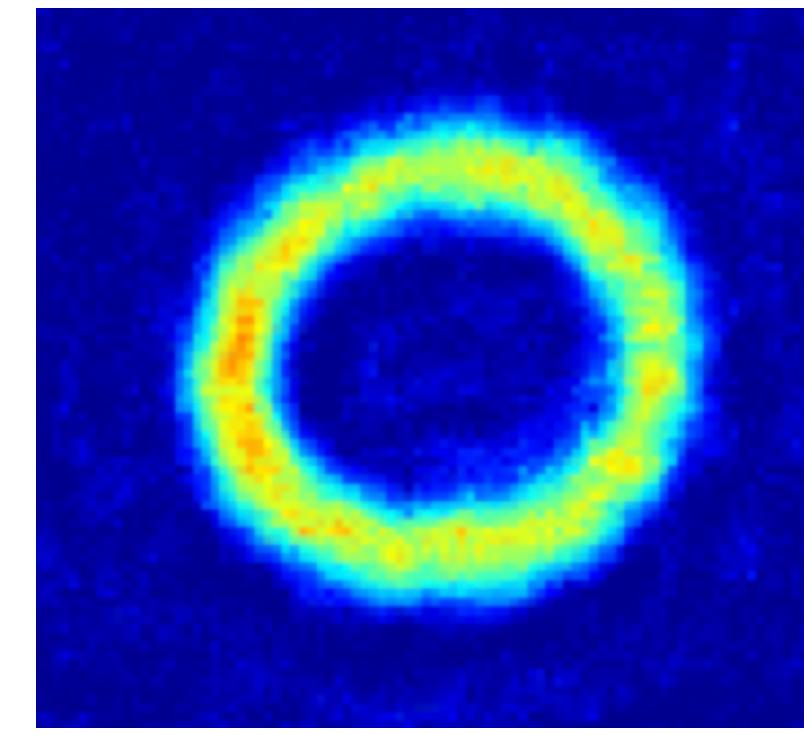
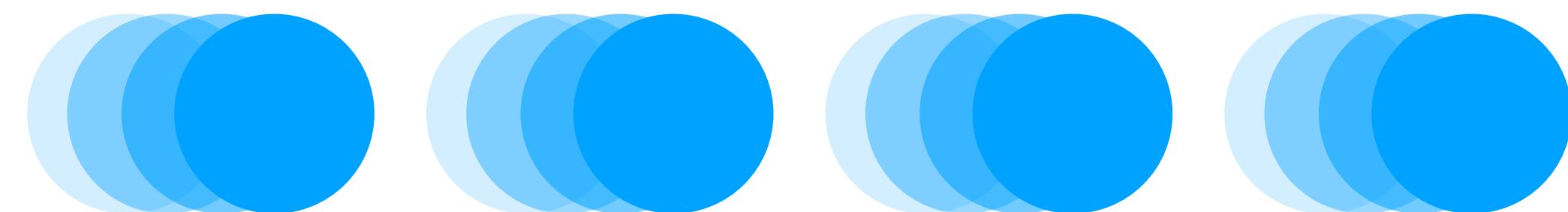
Valerio Amico. 05-2023.

Supervisor: Oliver Morsch

Cos'è l'Atomtronica?

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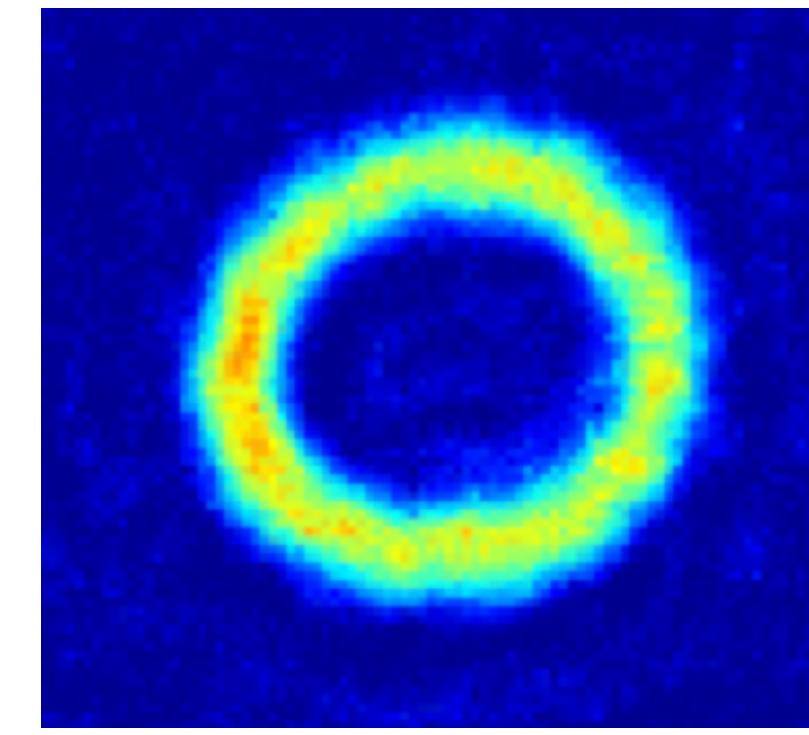
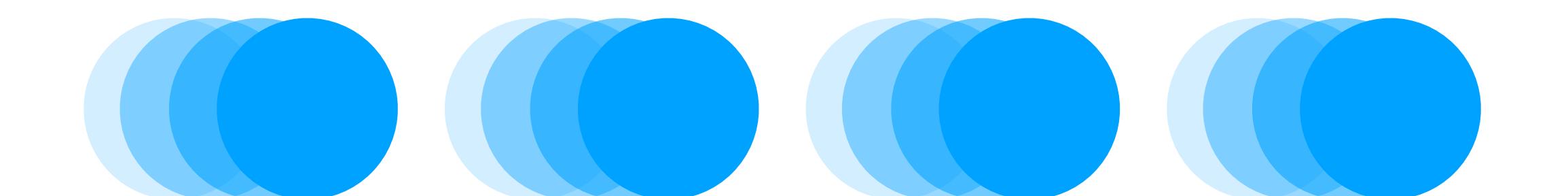
Atomtronica (atomi in movimento)



[arXiv:2008.04439](https://arxiv.org/abs/2008.04439)

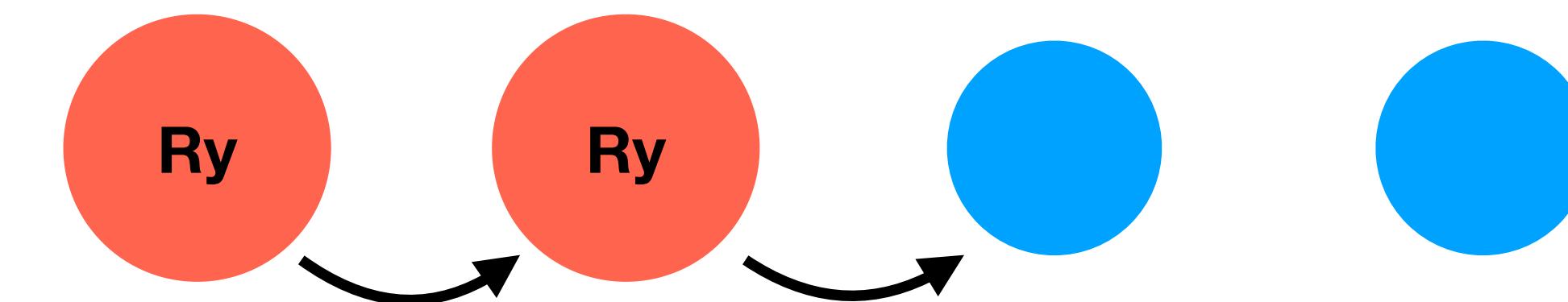
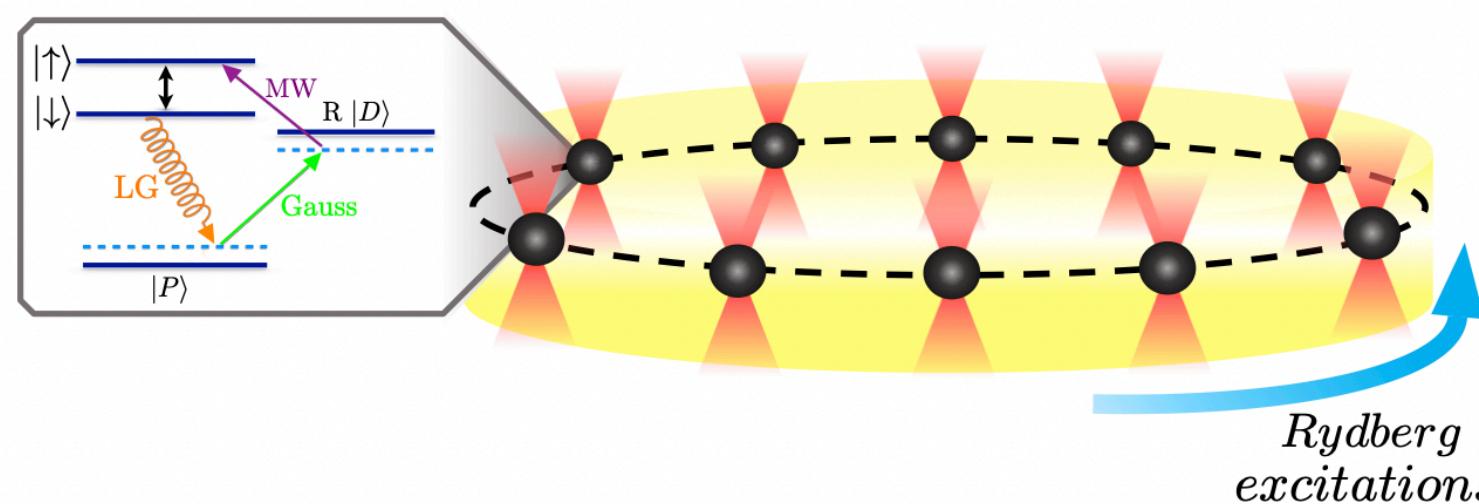
Cos'è l'Atomtronica?

Atomtronica (atomi in movimento)



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**Rydberg Atomtronica (eccitazioni in movimento)
“Rydbertronica”**



[arXiv:2212.12490](https://arxiv.org/abs/2212.12490)

Tabella di marcia

Tabella di marcia

Trappole ottiche

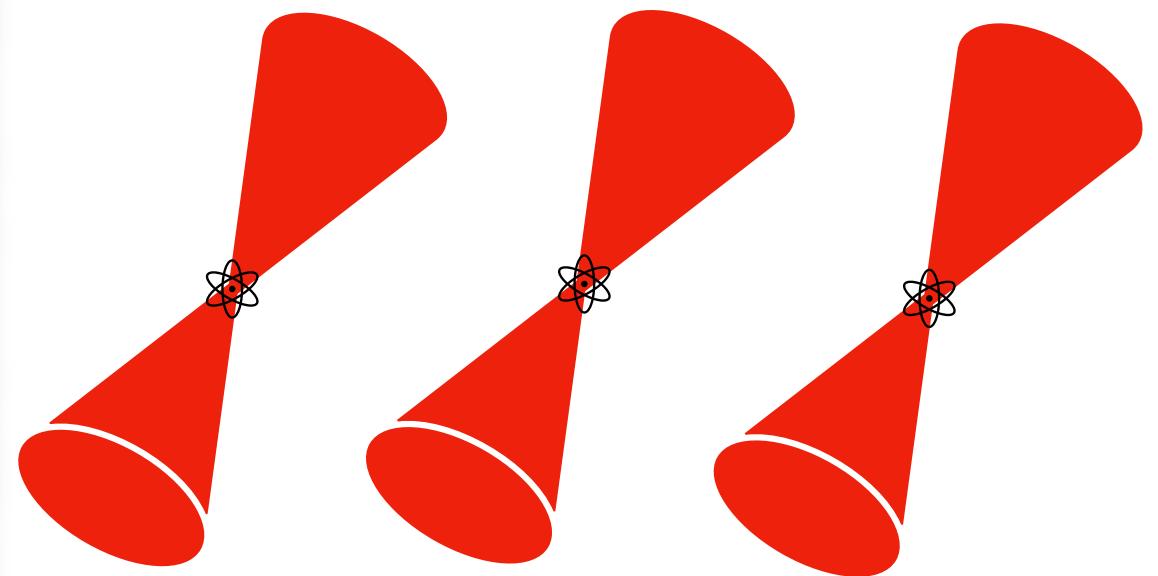
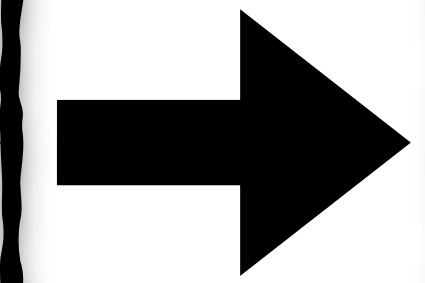
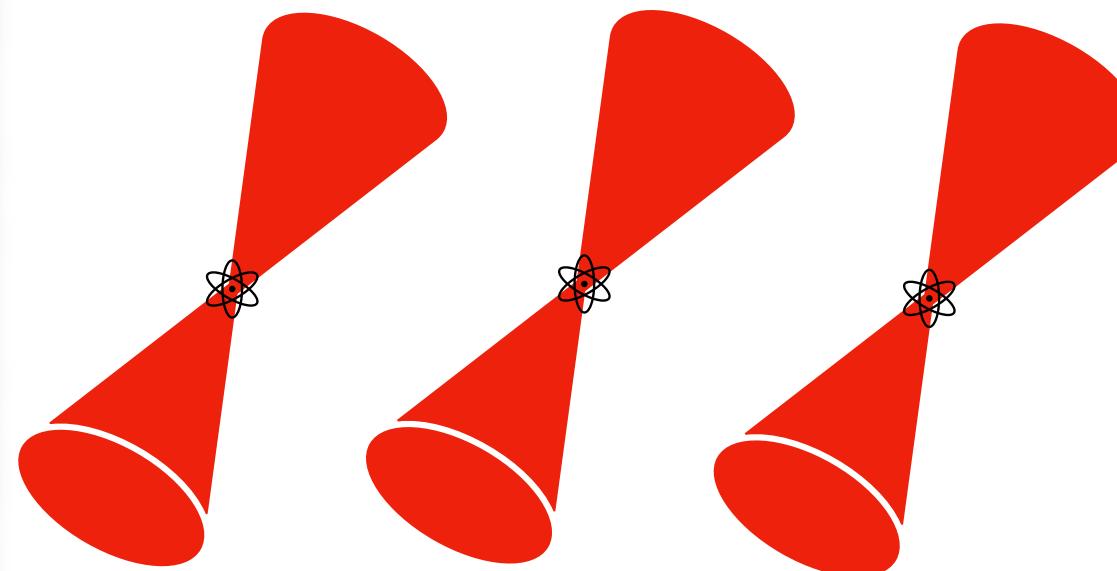


Tabella di marcia

Trappole ottiche



Controllo delle
interazioni

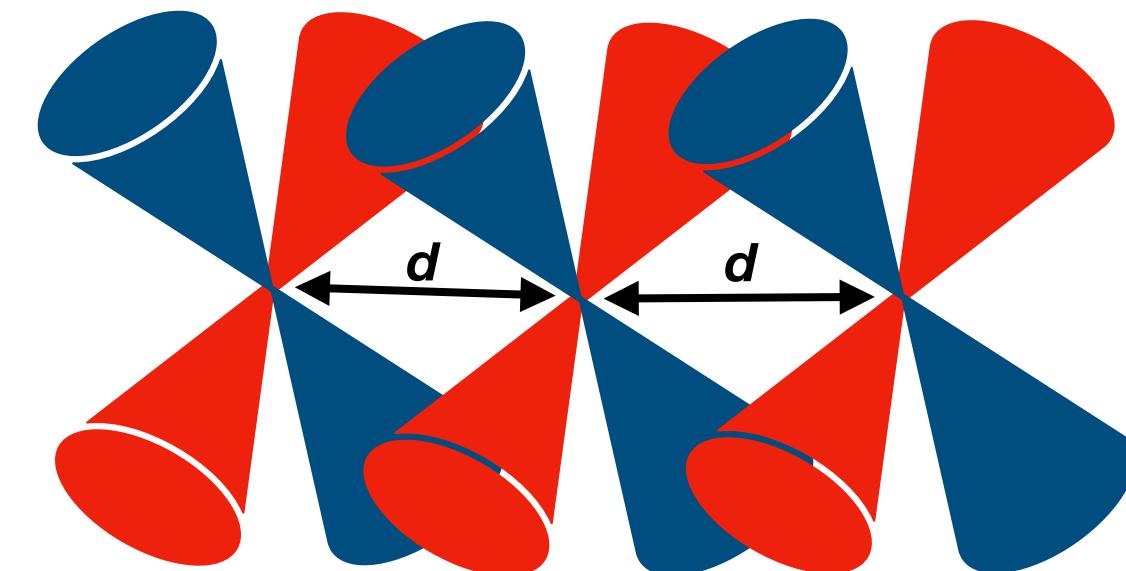


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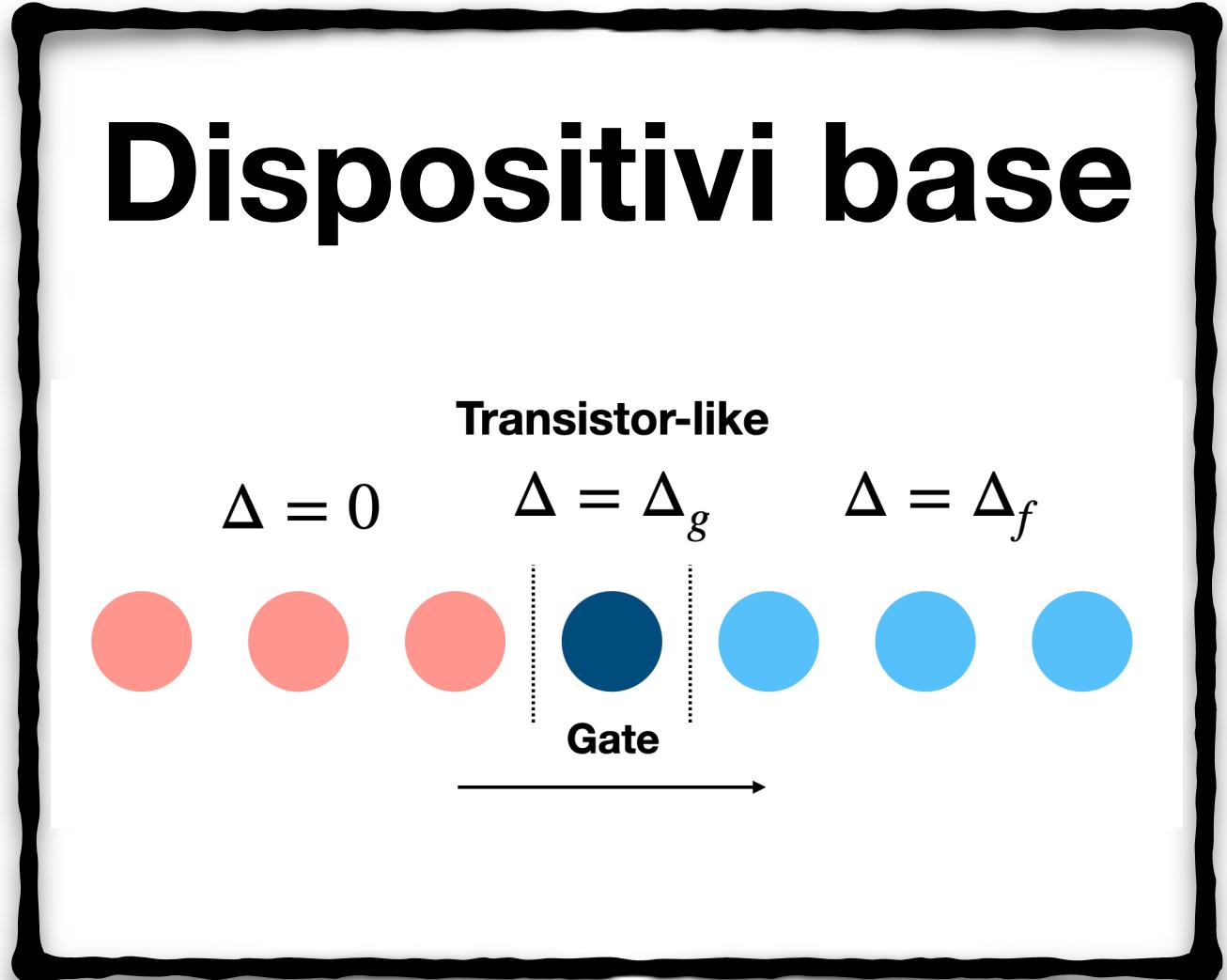
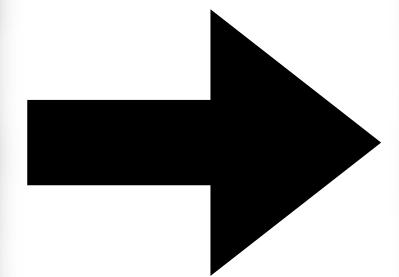
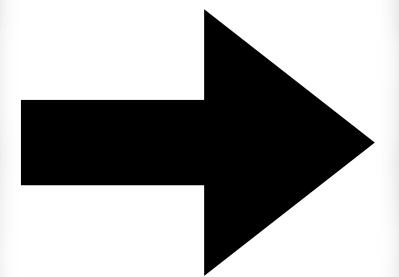
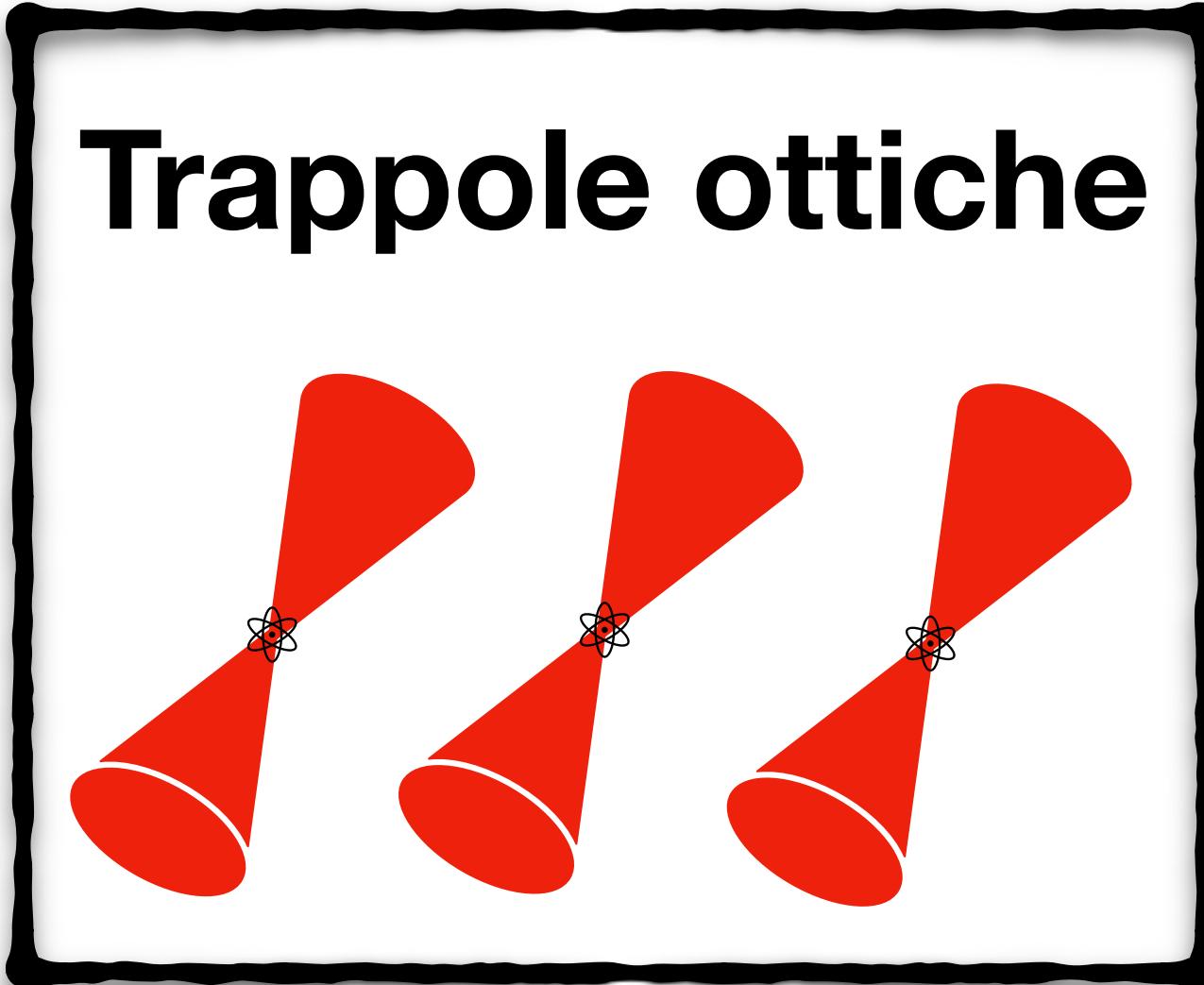


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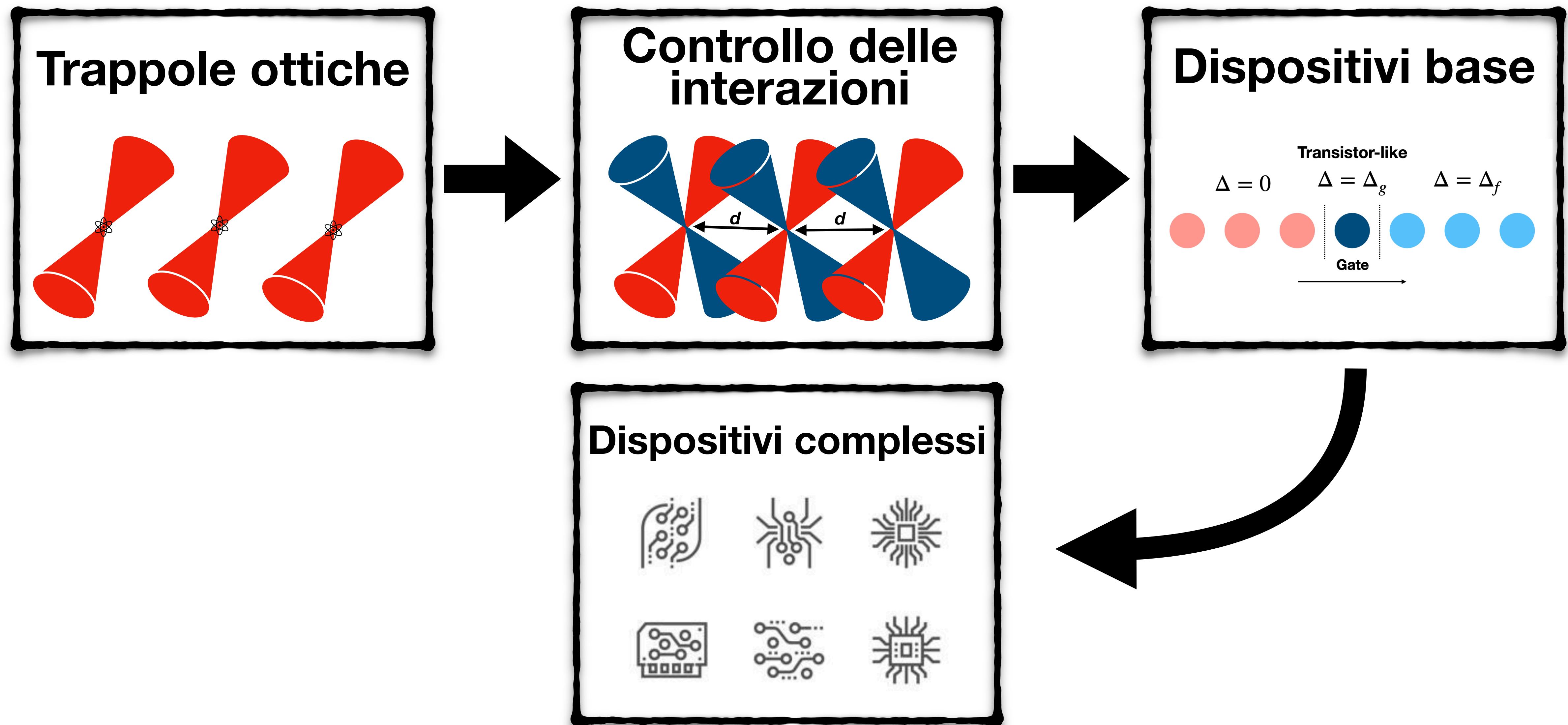
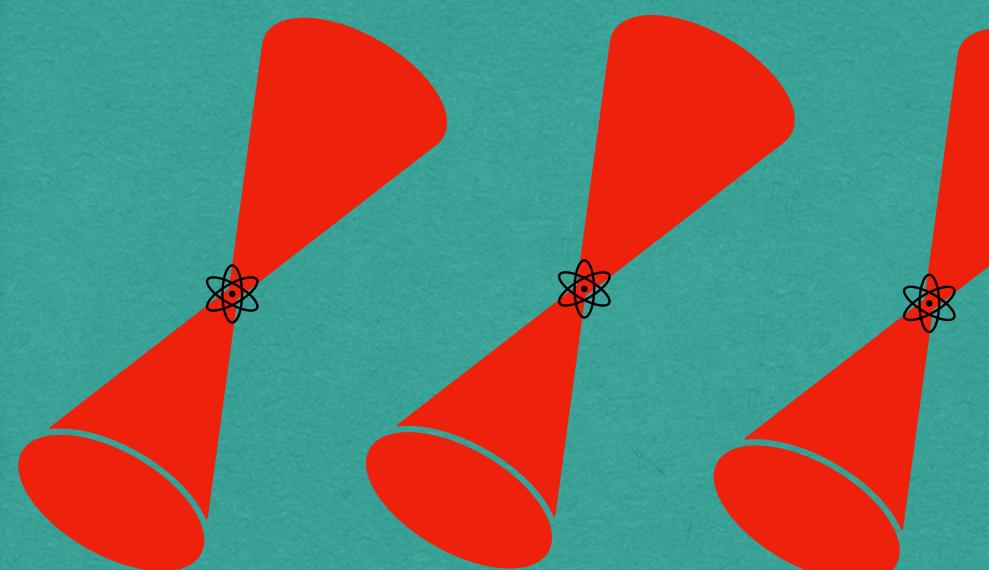
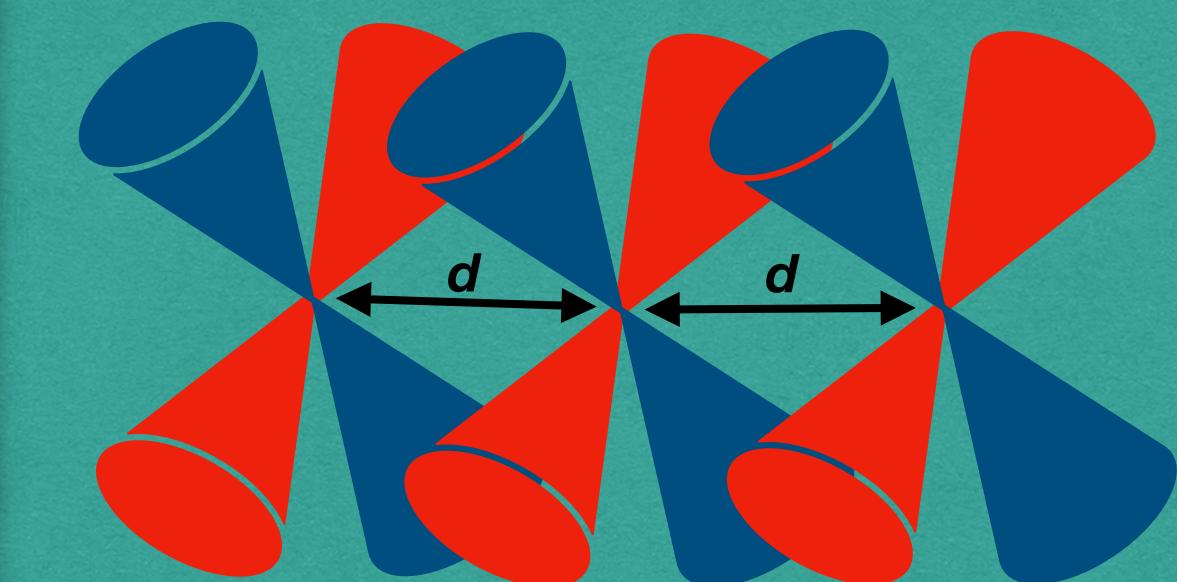


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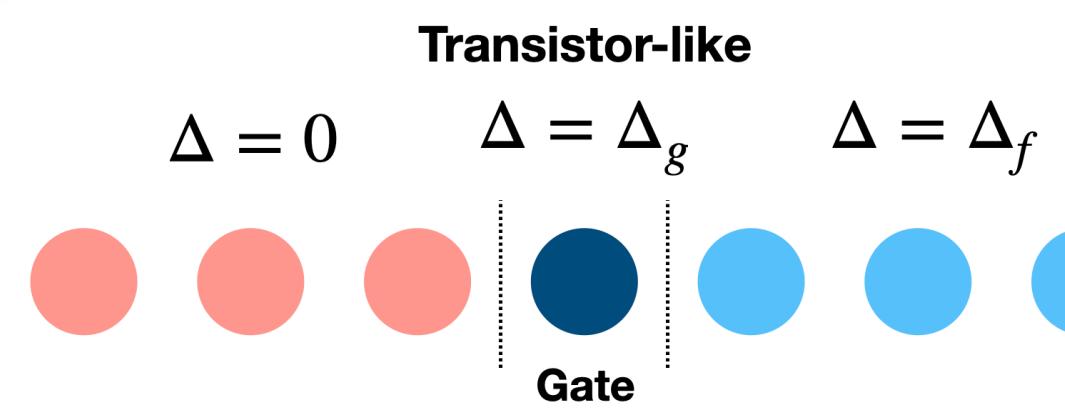
Trappole ottiche



Controllo delle interazioni



Dispositivi base



Dispositivi complessi

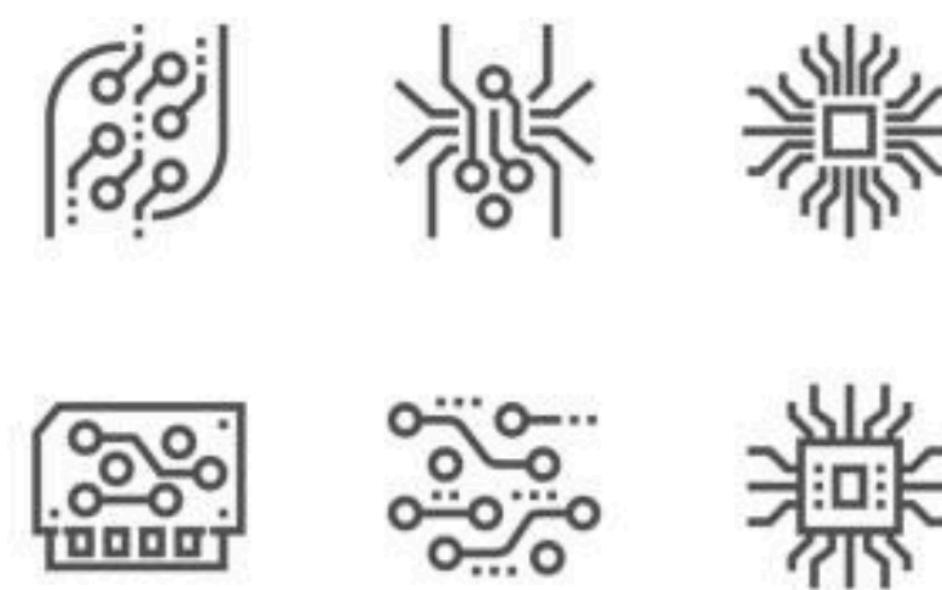
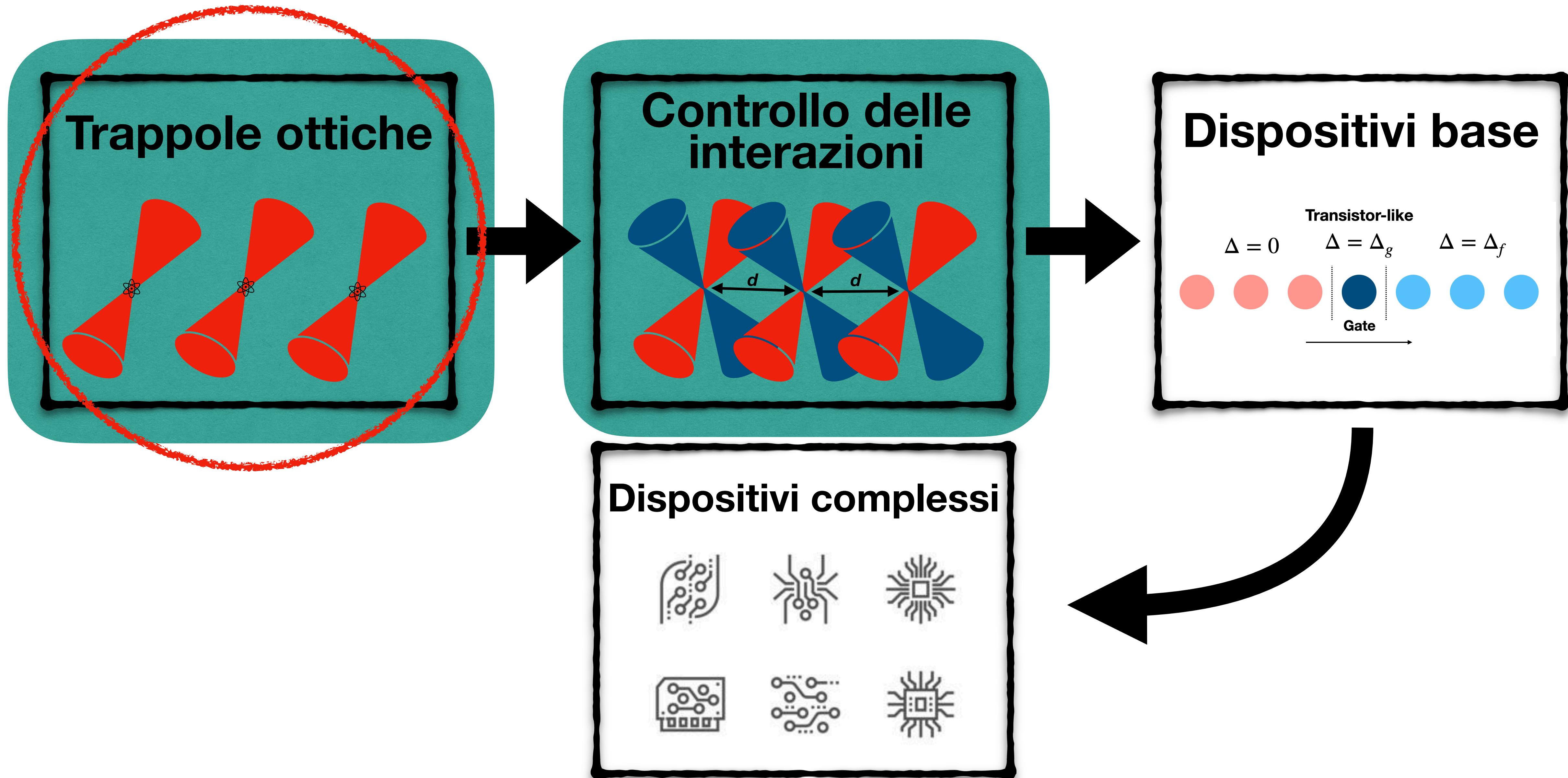
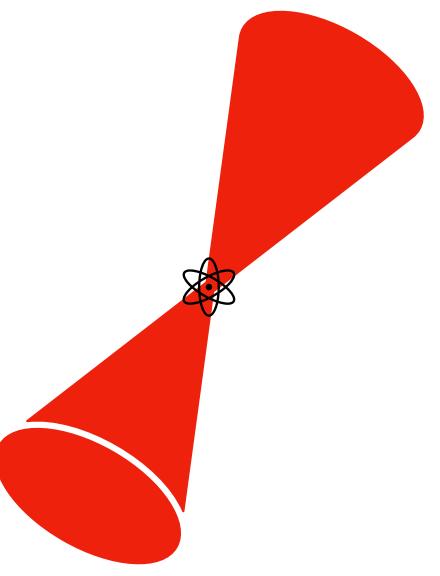
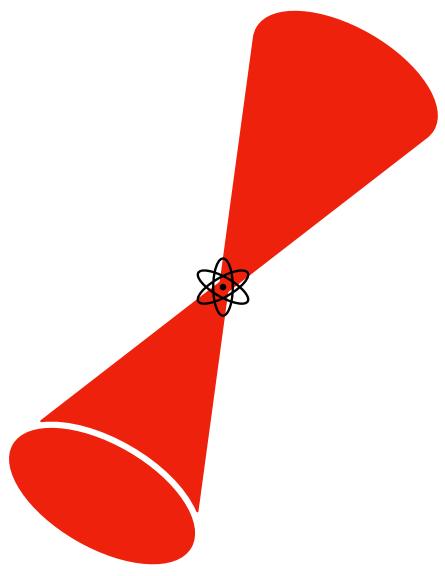


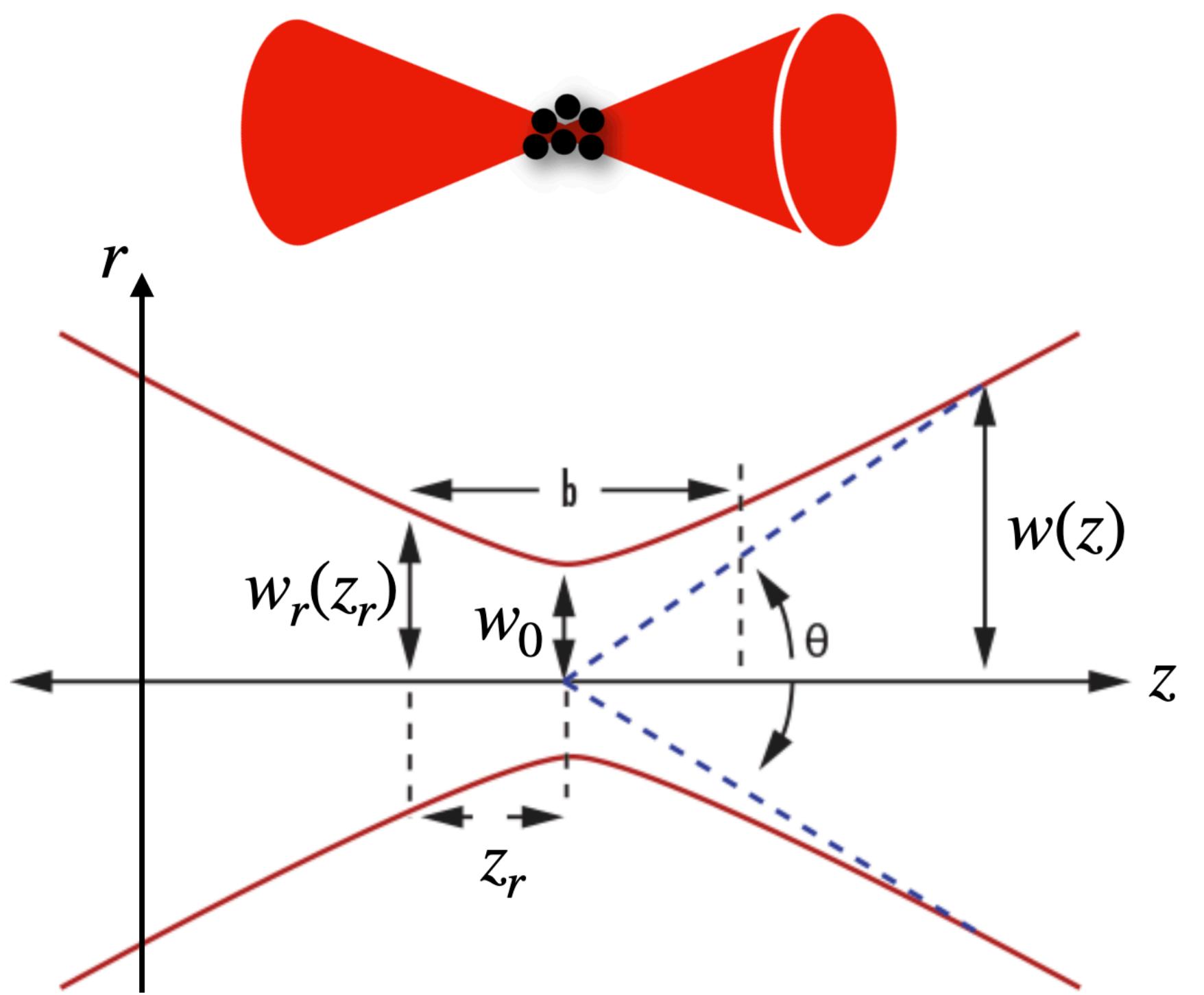
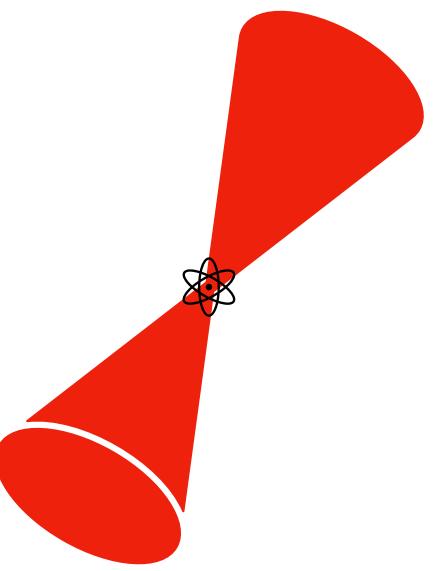
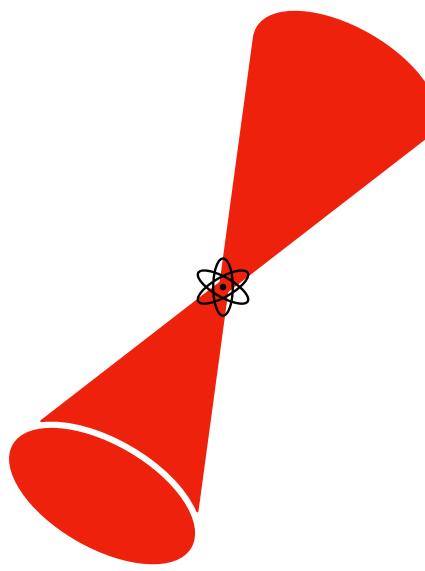
Tabella di marcia



Trappola dipolare

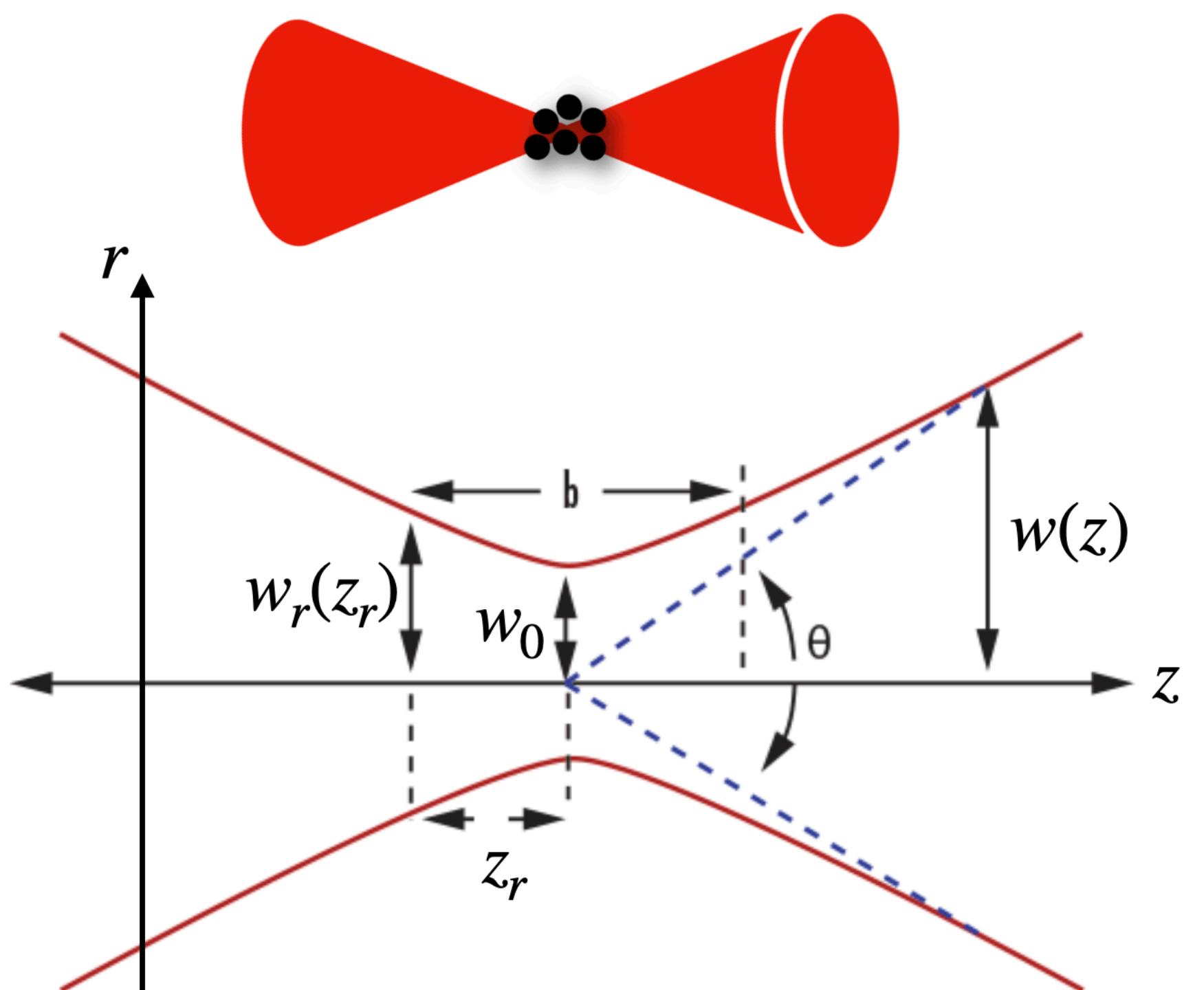
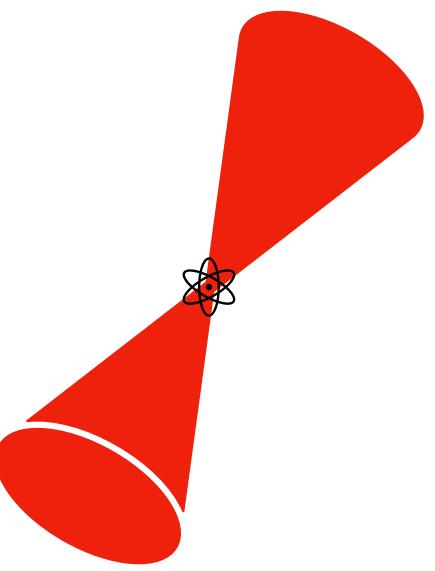
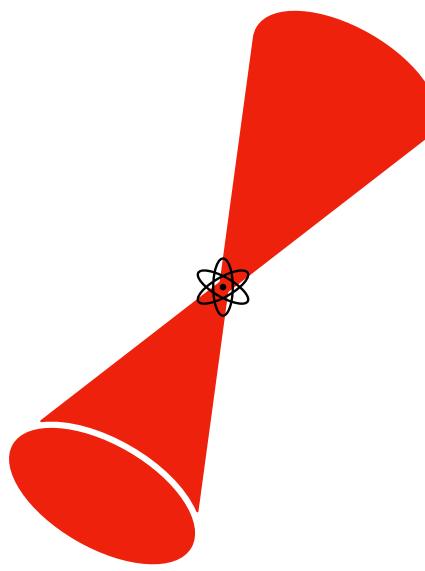


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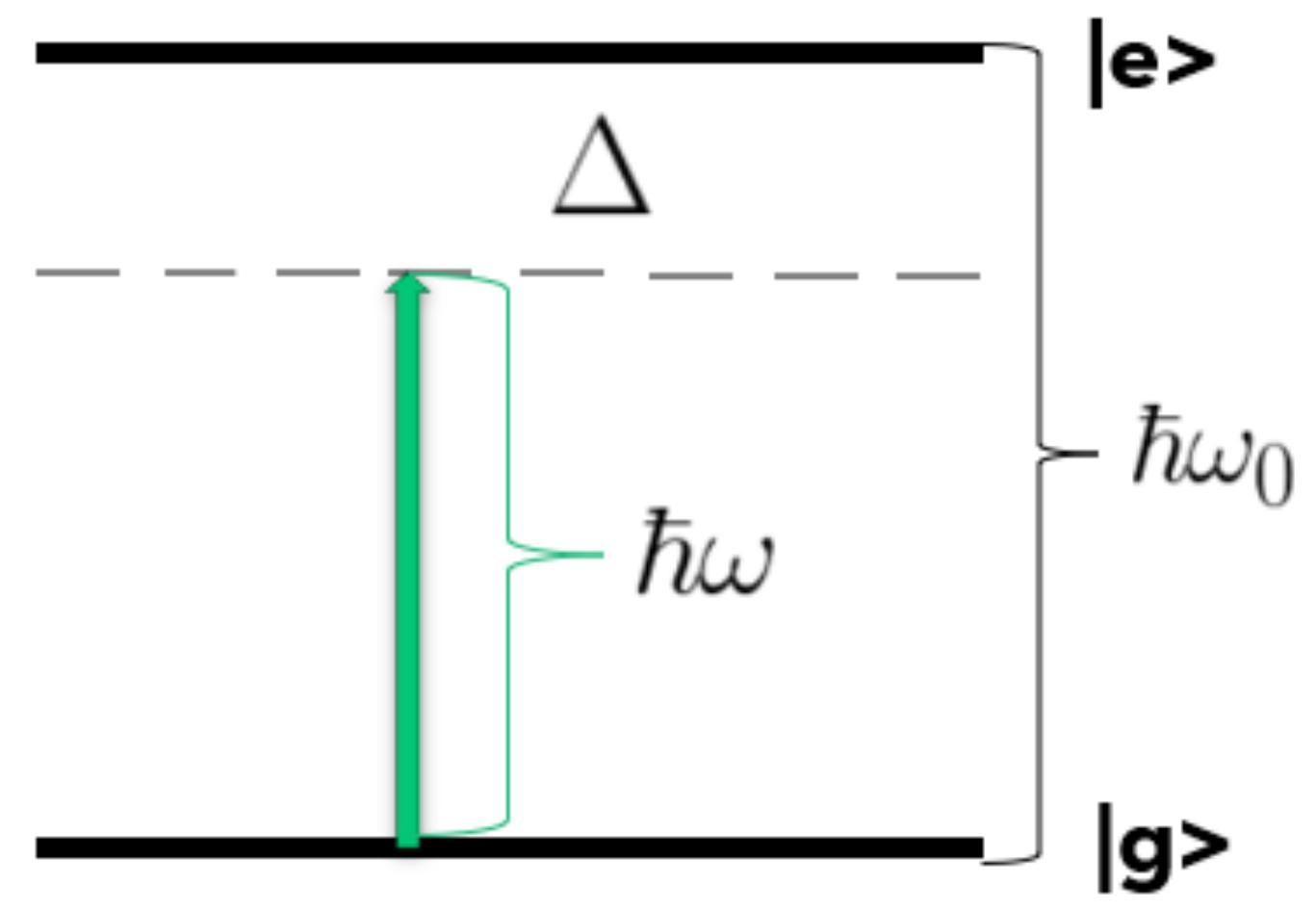


Laser

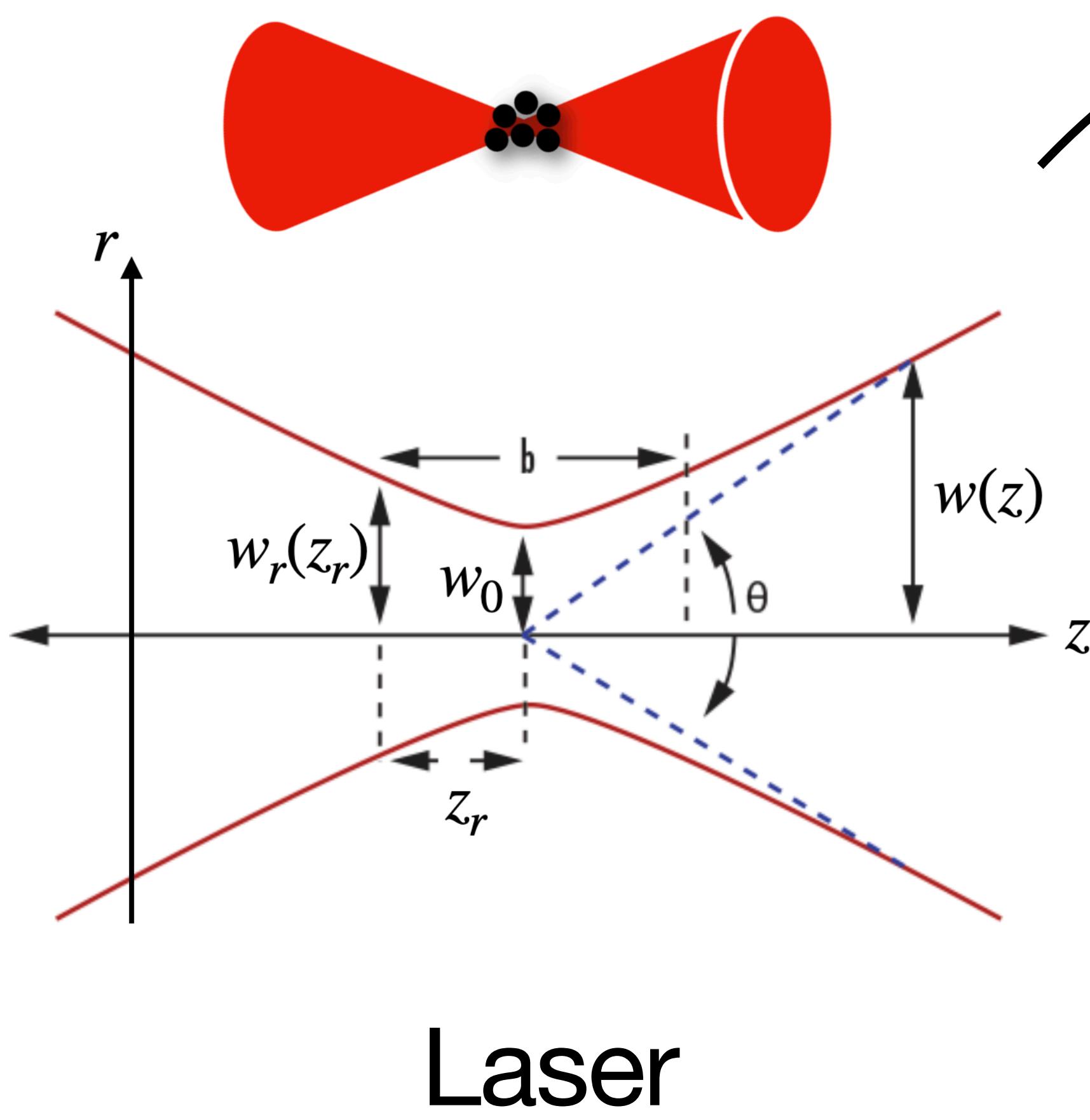
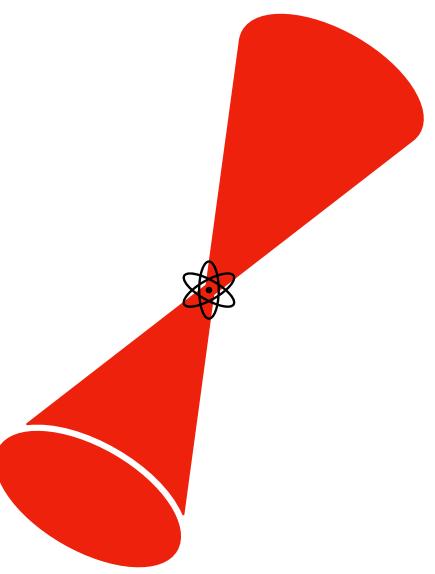
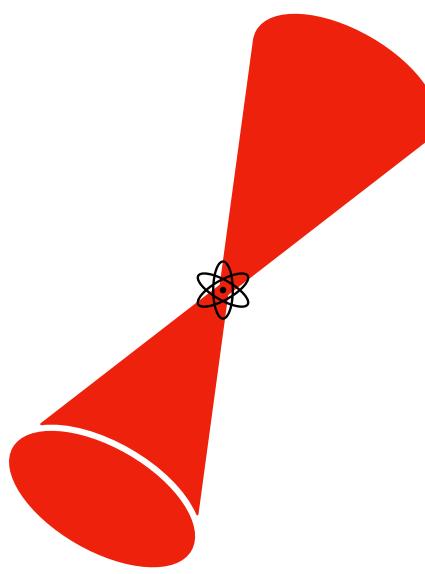
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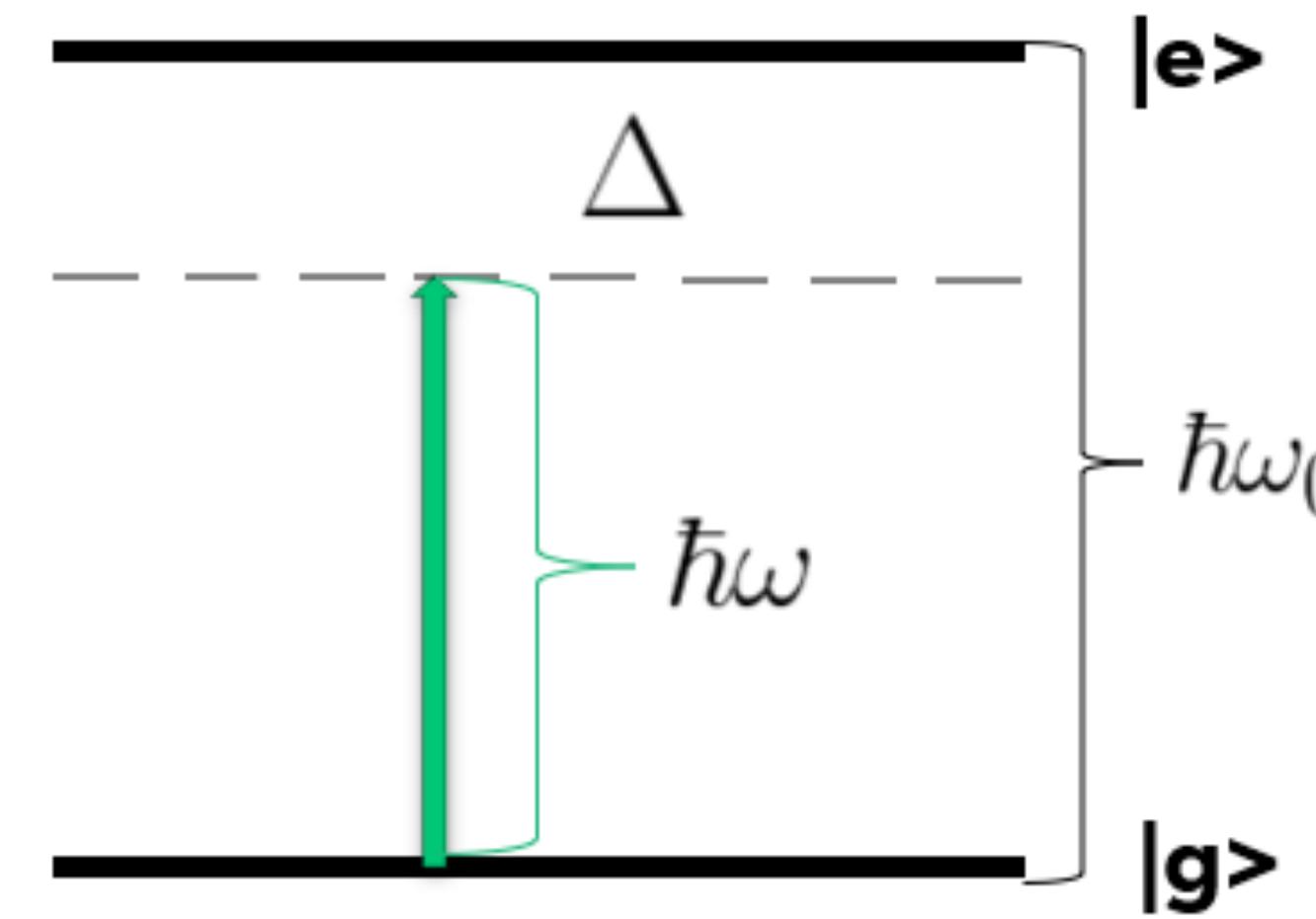
Laser



Trappola dipolare

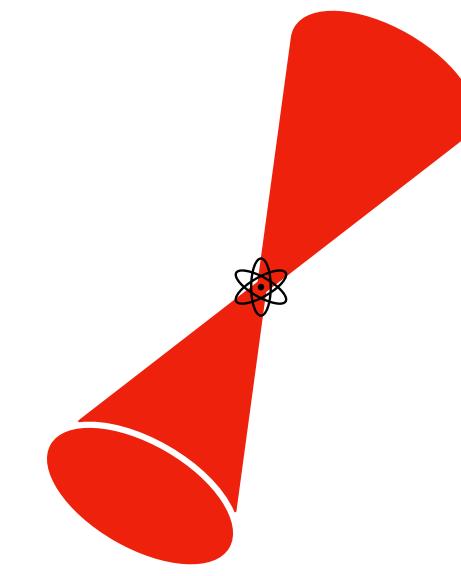
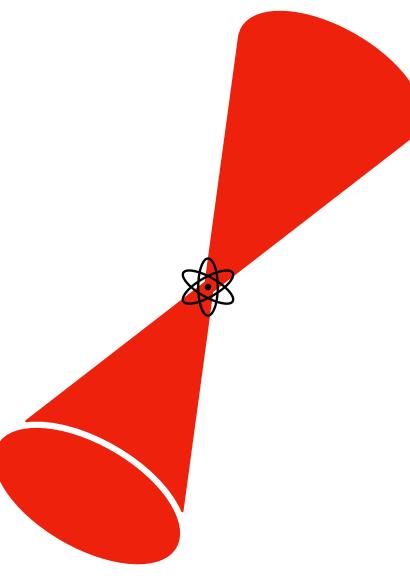


$$I(z, r) = \frac{2P}{\pi w(z)^2} e^{\frac{-2r^2}{w(z)^2}}$$



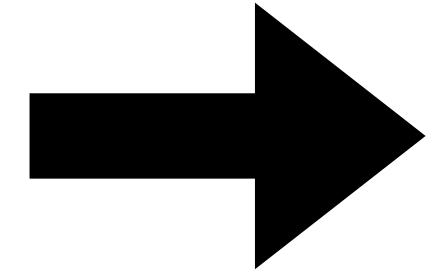
$$U_{dip}(z, r) = \frac{3\pi c^2}{2\omega_0^2} \frac{\Gamma}{\Delta} I(z, r)$$

$$\Gamma = \frac{e^2 \omega_0^2}{6\pi \epsilon_0 m_e c^3}$$



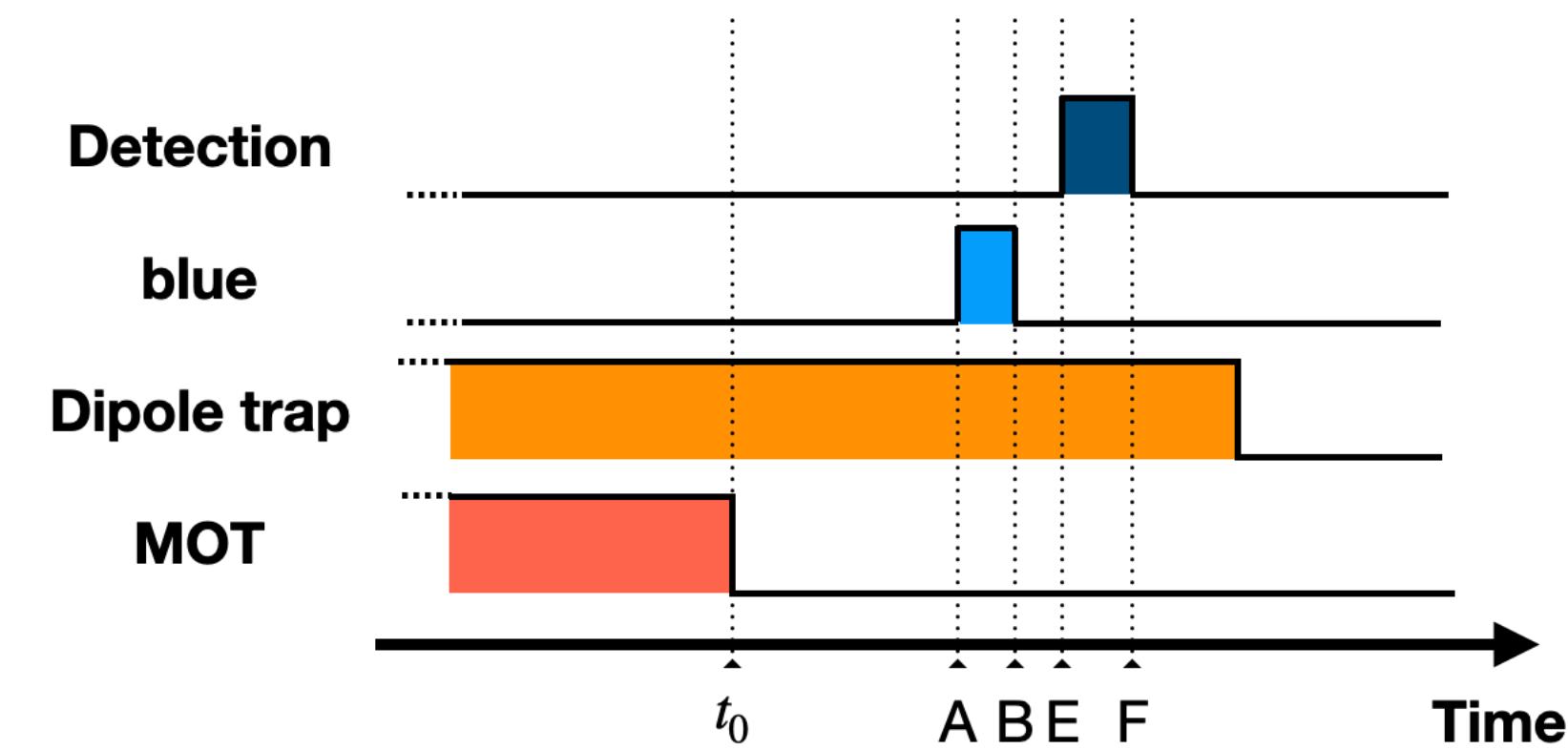
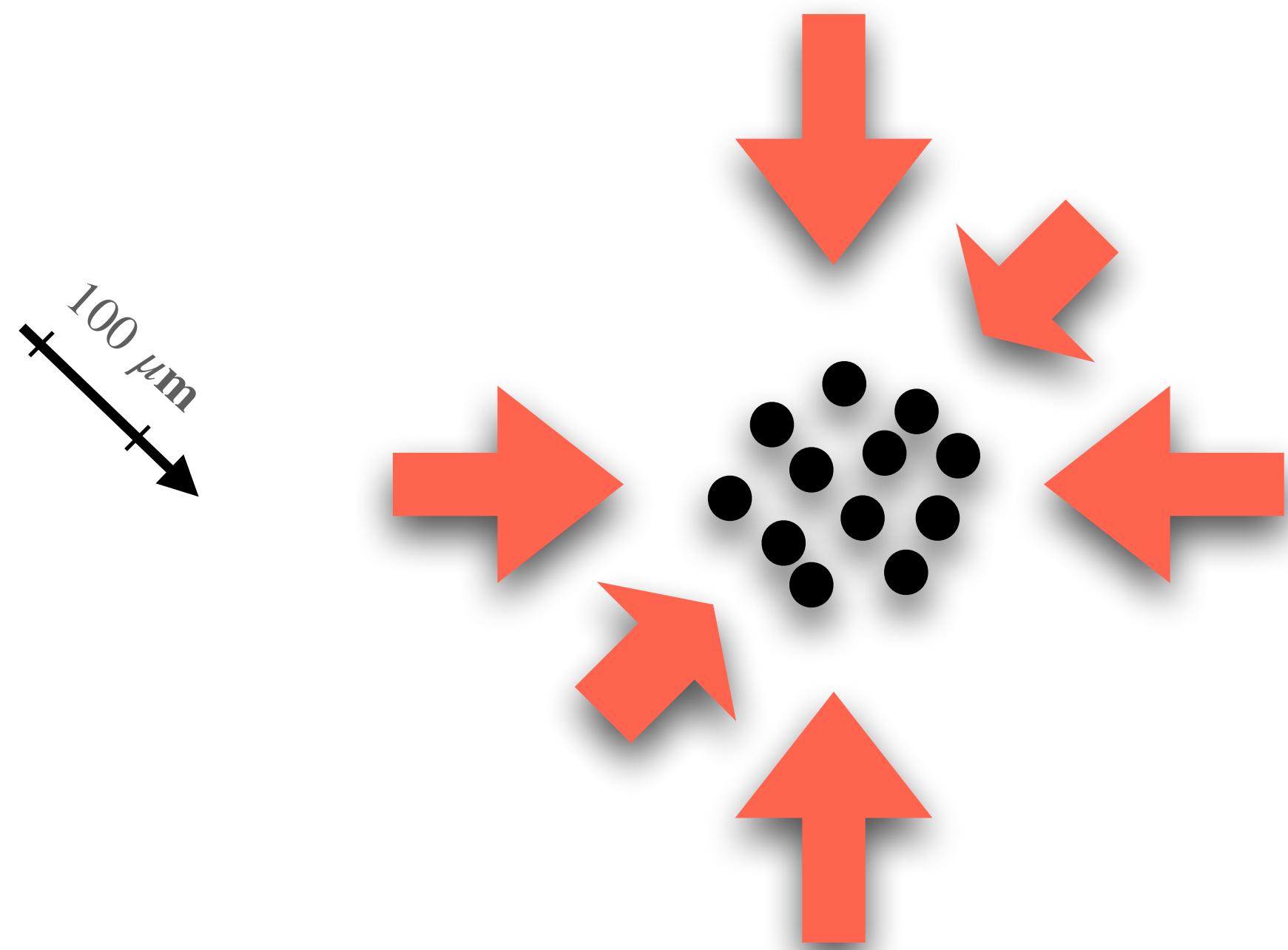
Caratterizzazione della Trappola Dipolare

Domande:



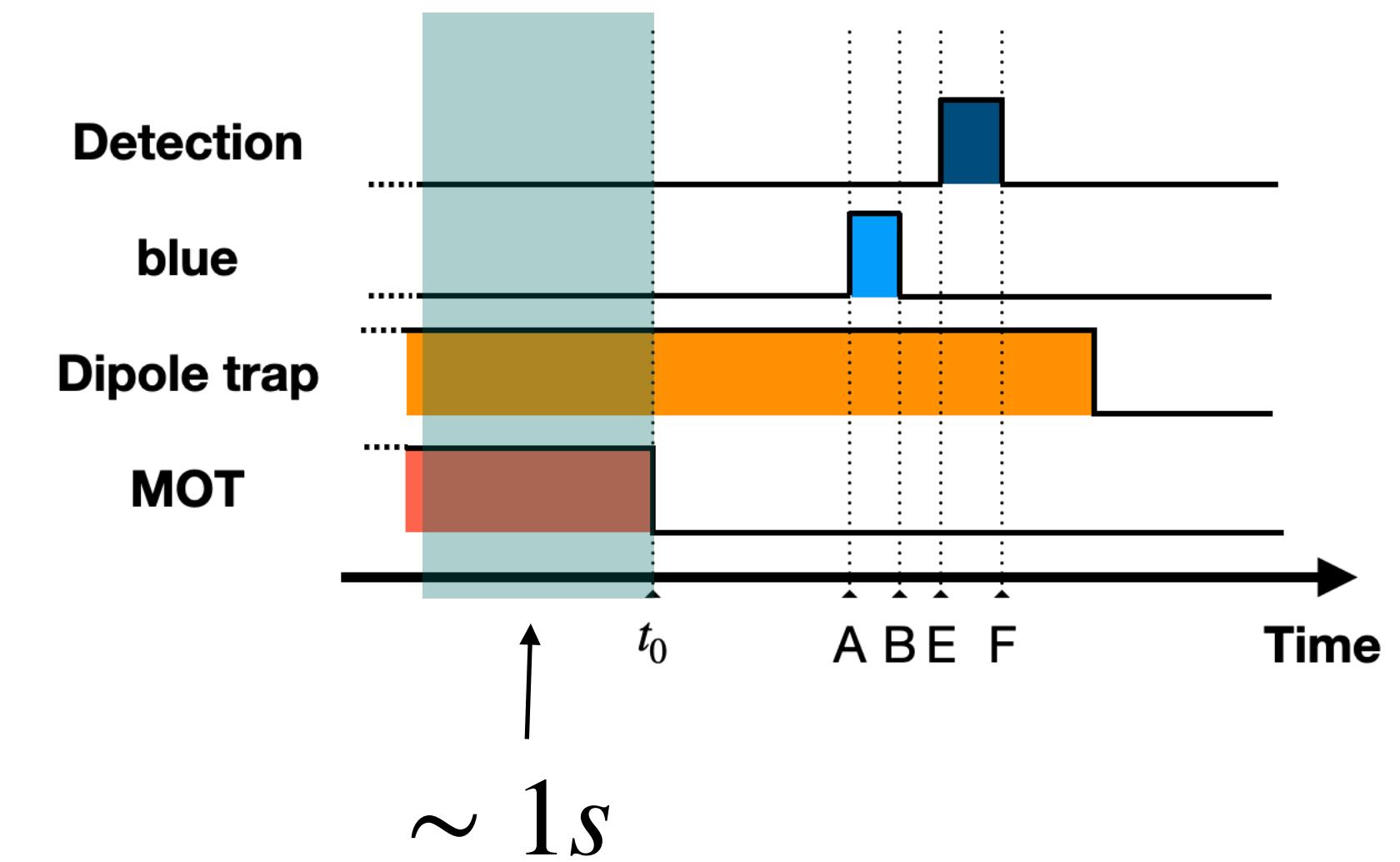
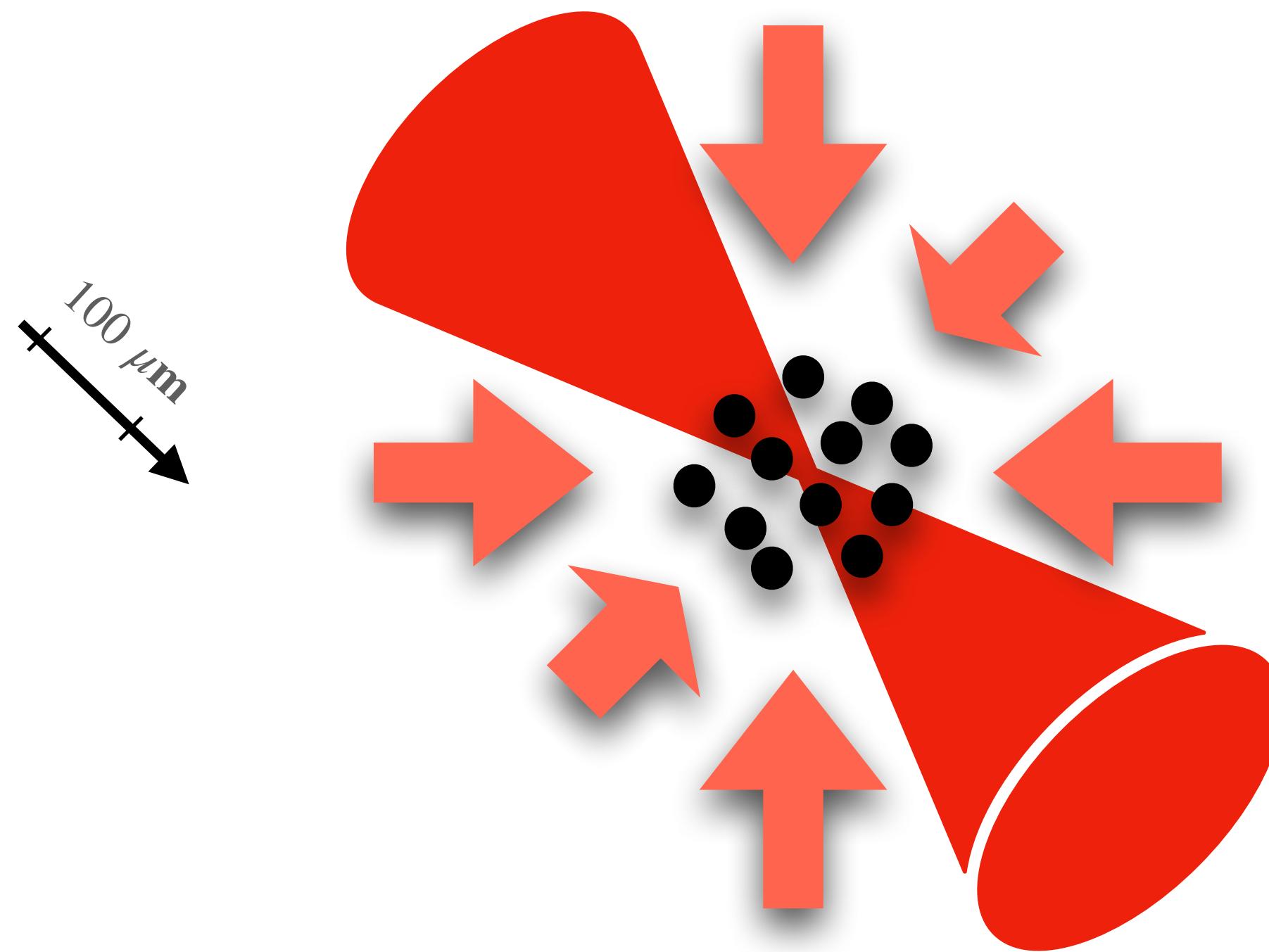
- Quanti atomi intrappoliamo?**
- Tempo di riempimento?**
- Come intrappolare un solo atomo?**

Come facciamo le misure?



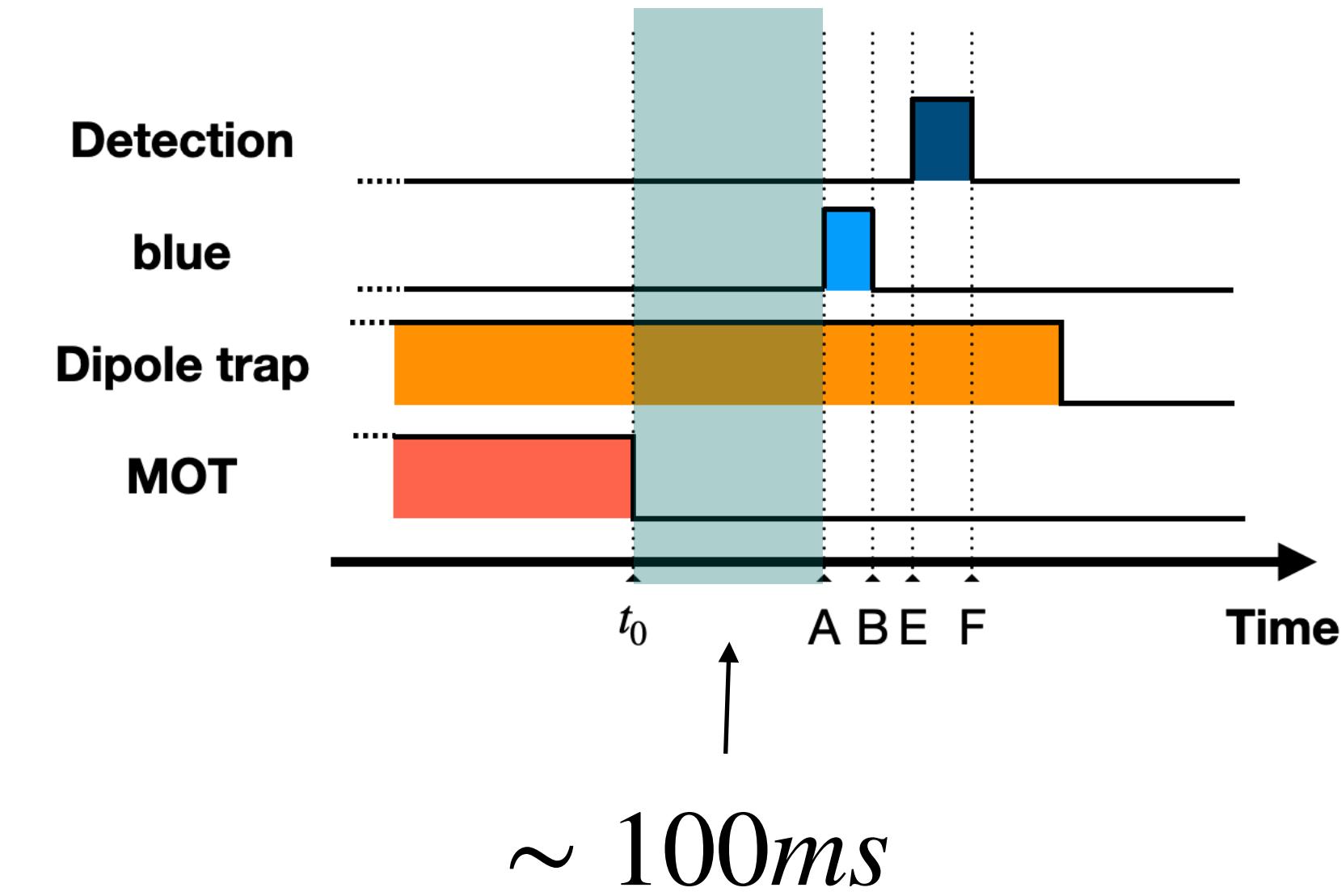
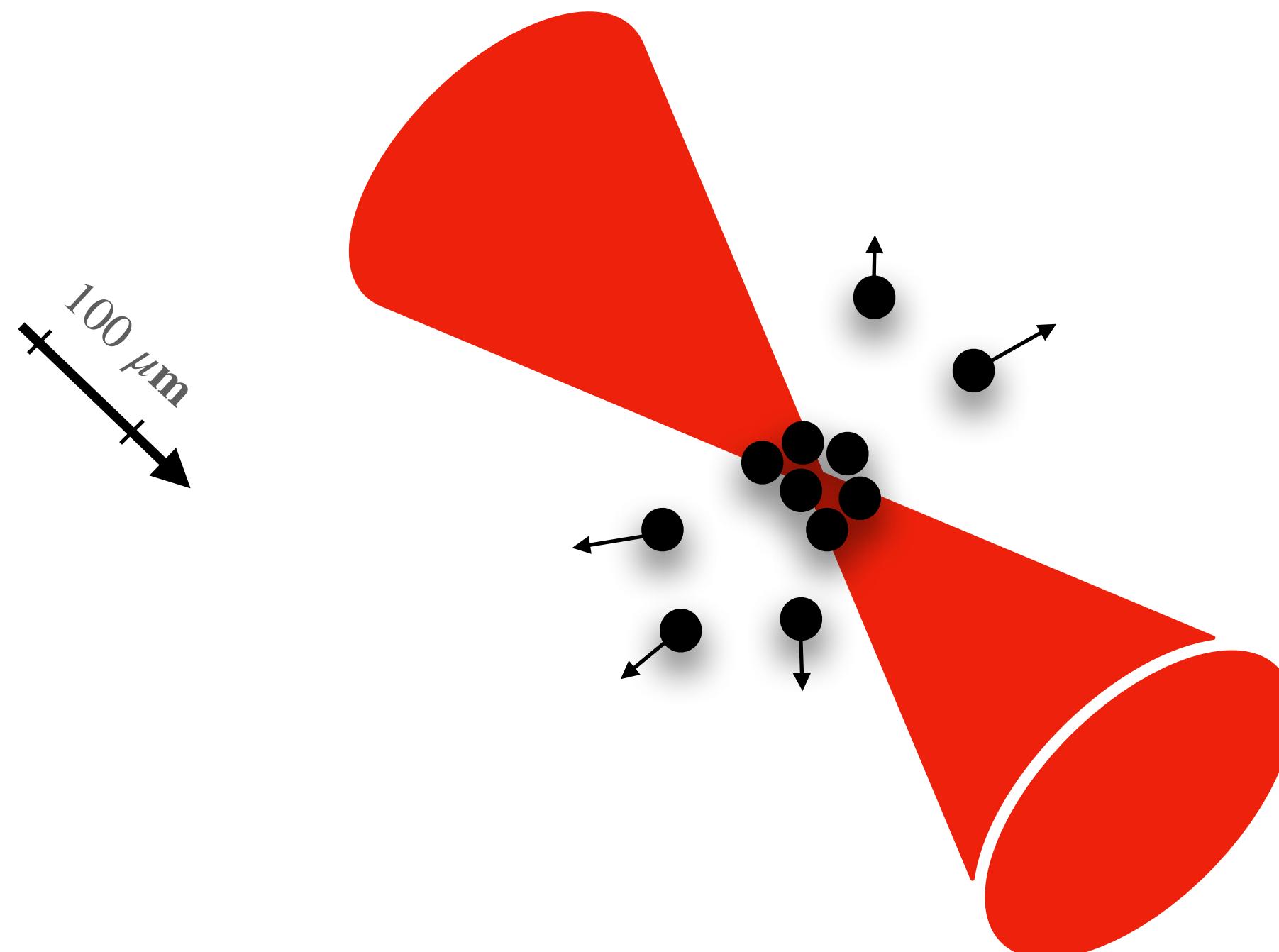
Raffreddamento
Magneto Optical Trap

Come facciamo le misure?



Intrappolamento nella
FORT

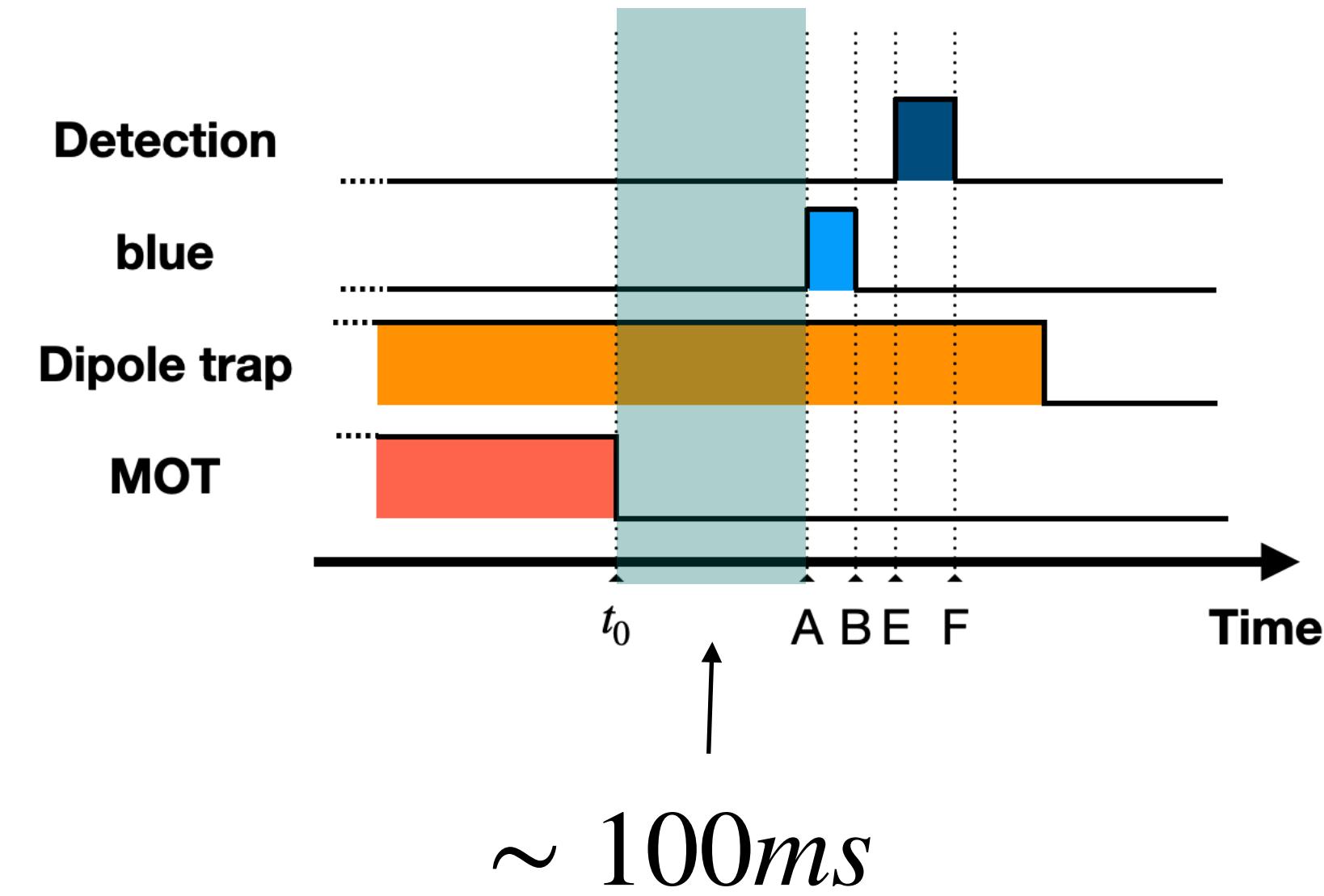
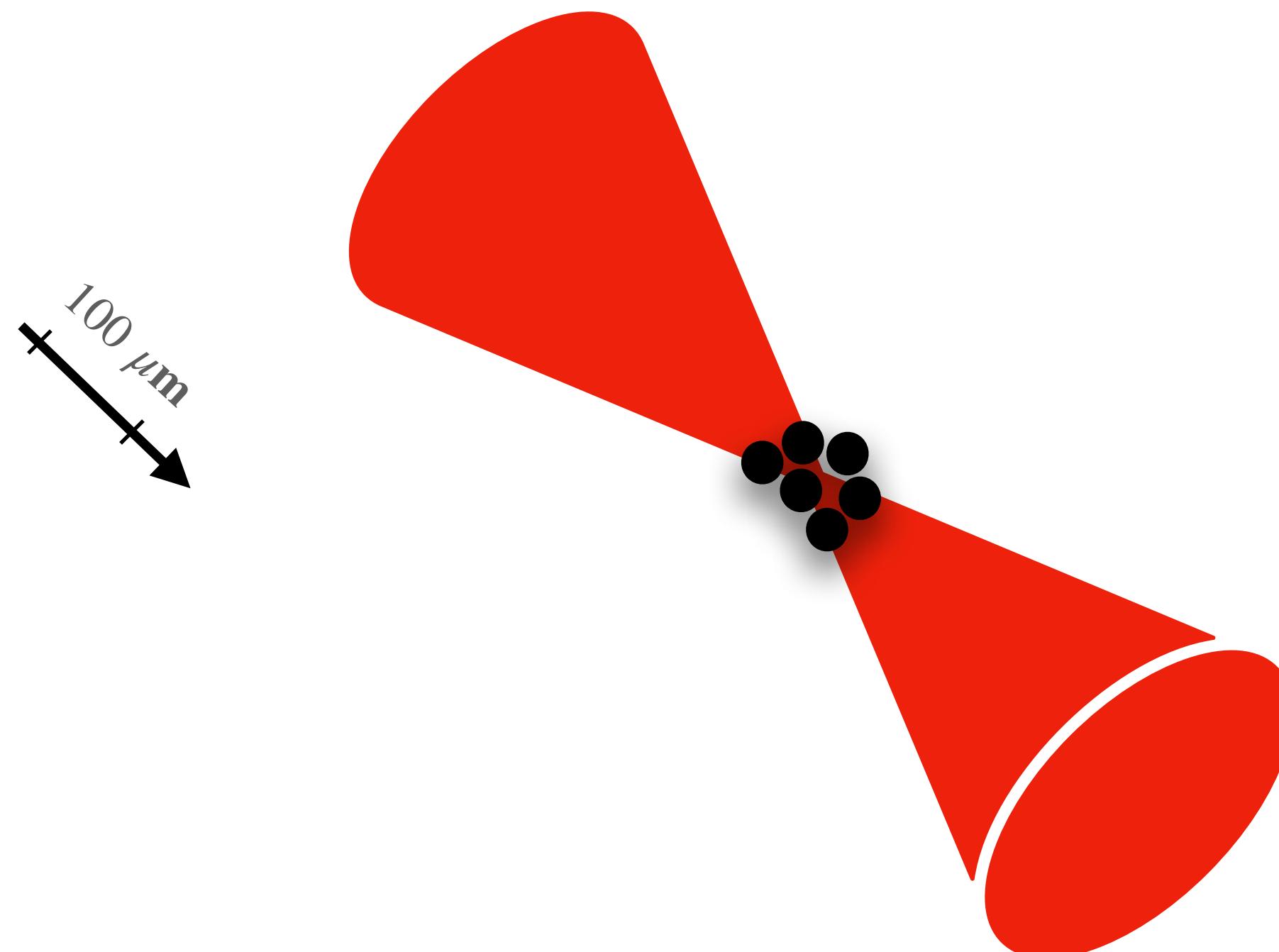
Come facciamo le misure?



Attesa

Gli atomi non intrappolati si allontanano
dalla regione di trappola

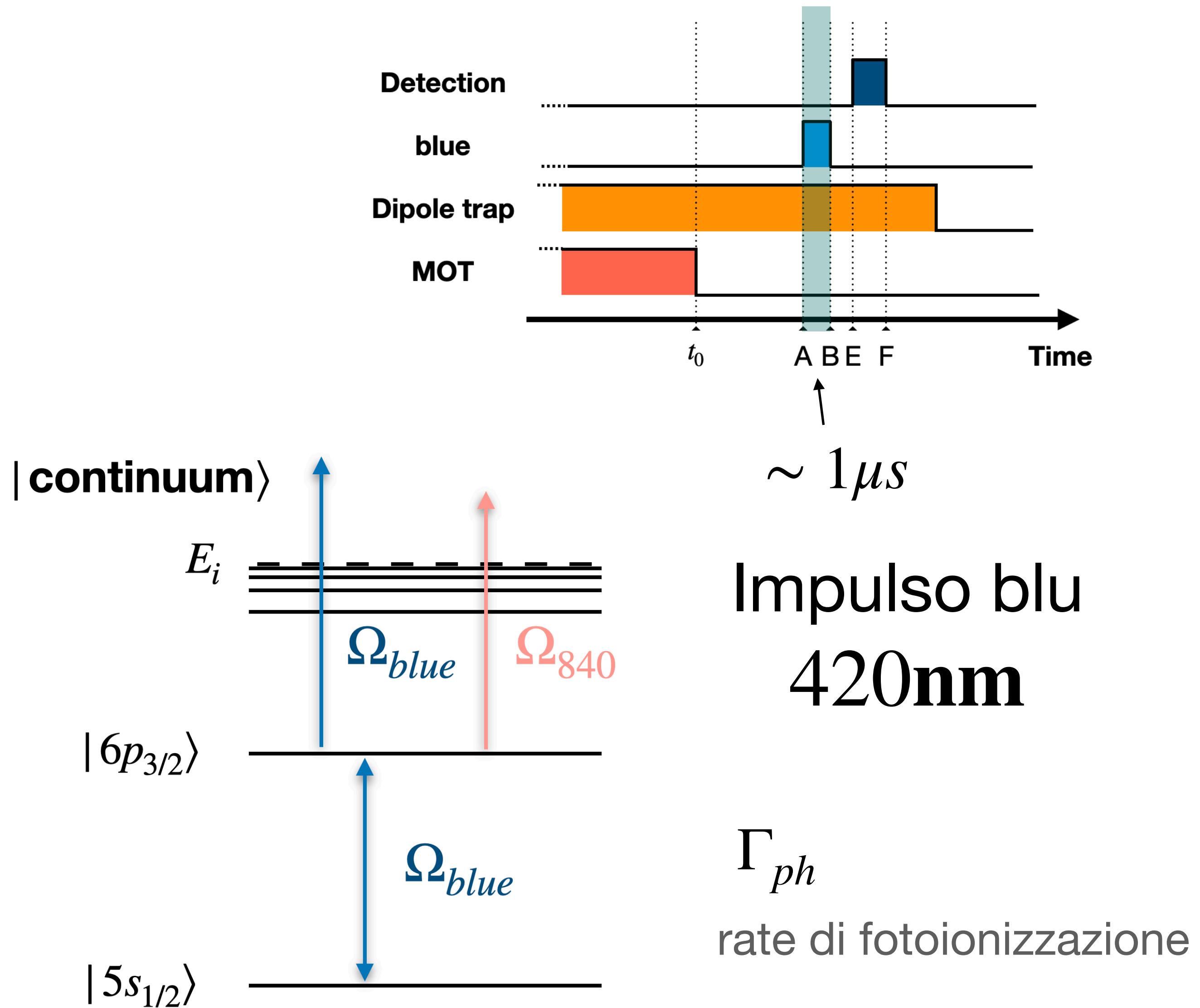
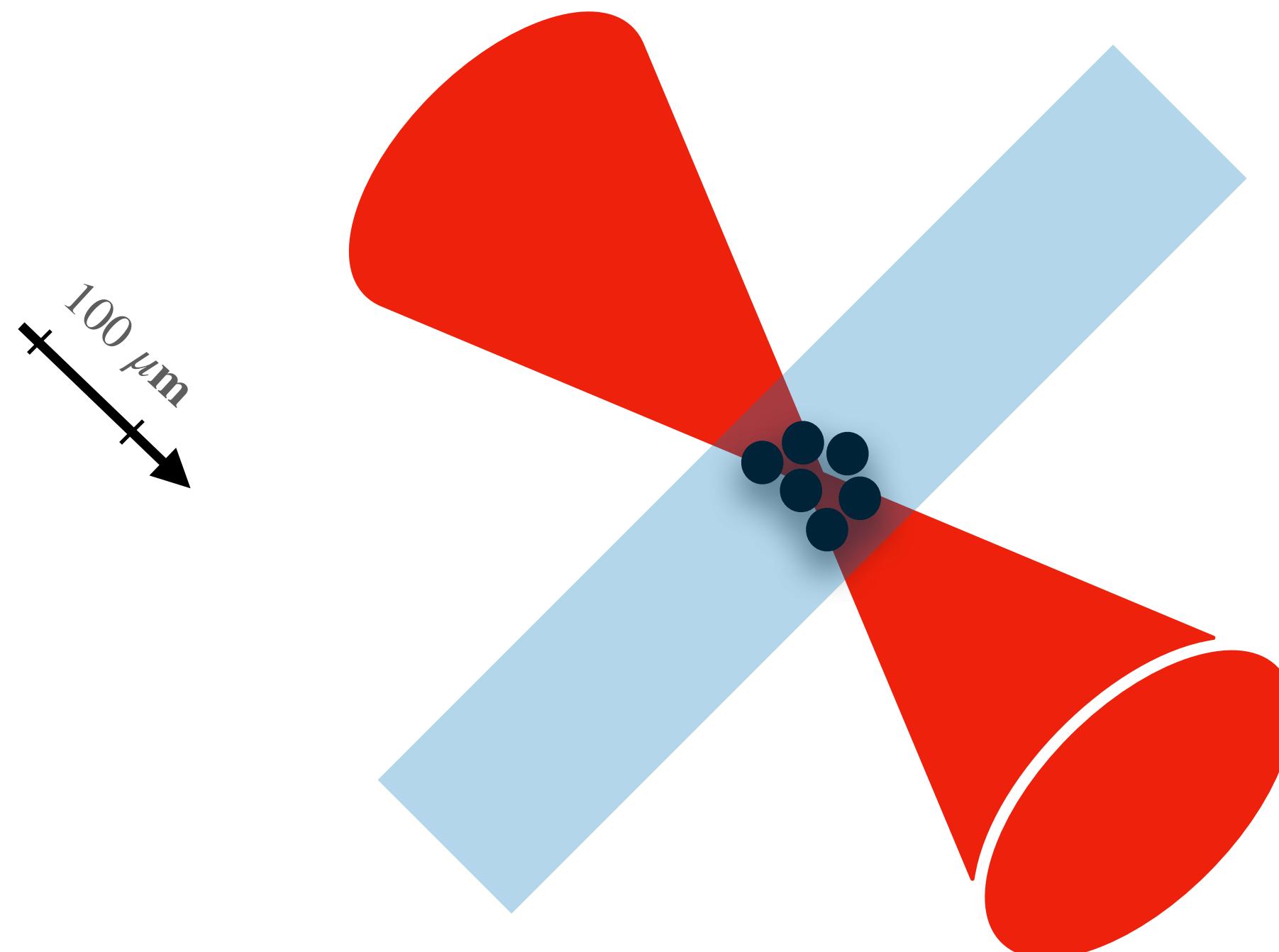
Come facciamo le misure?



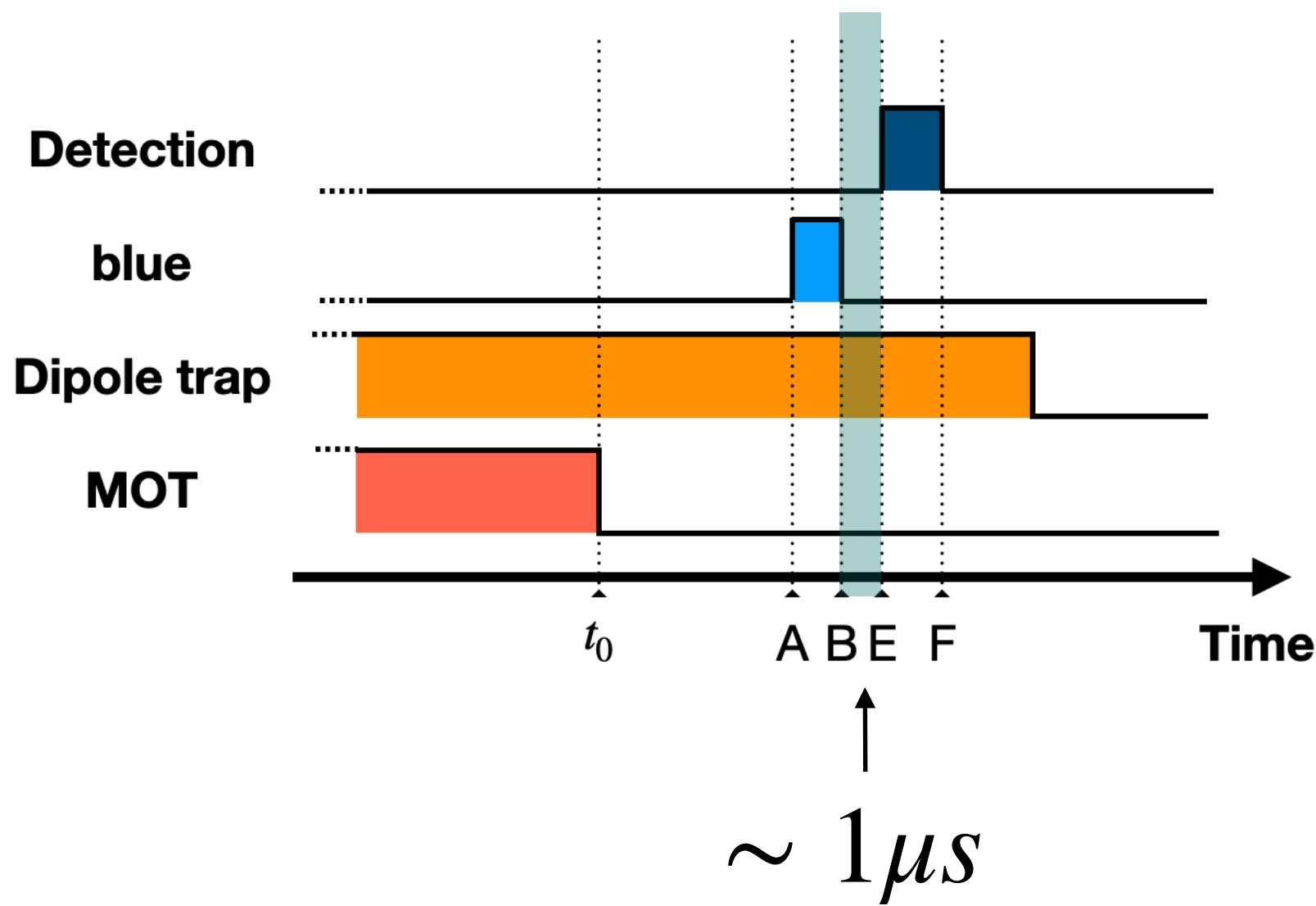
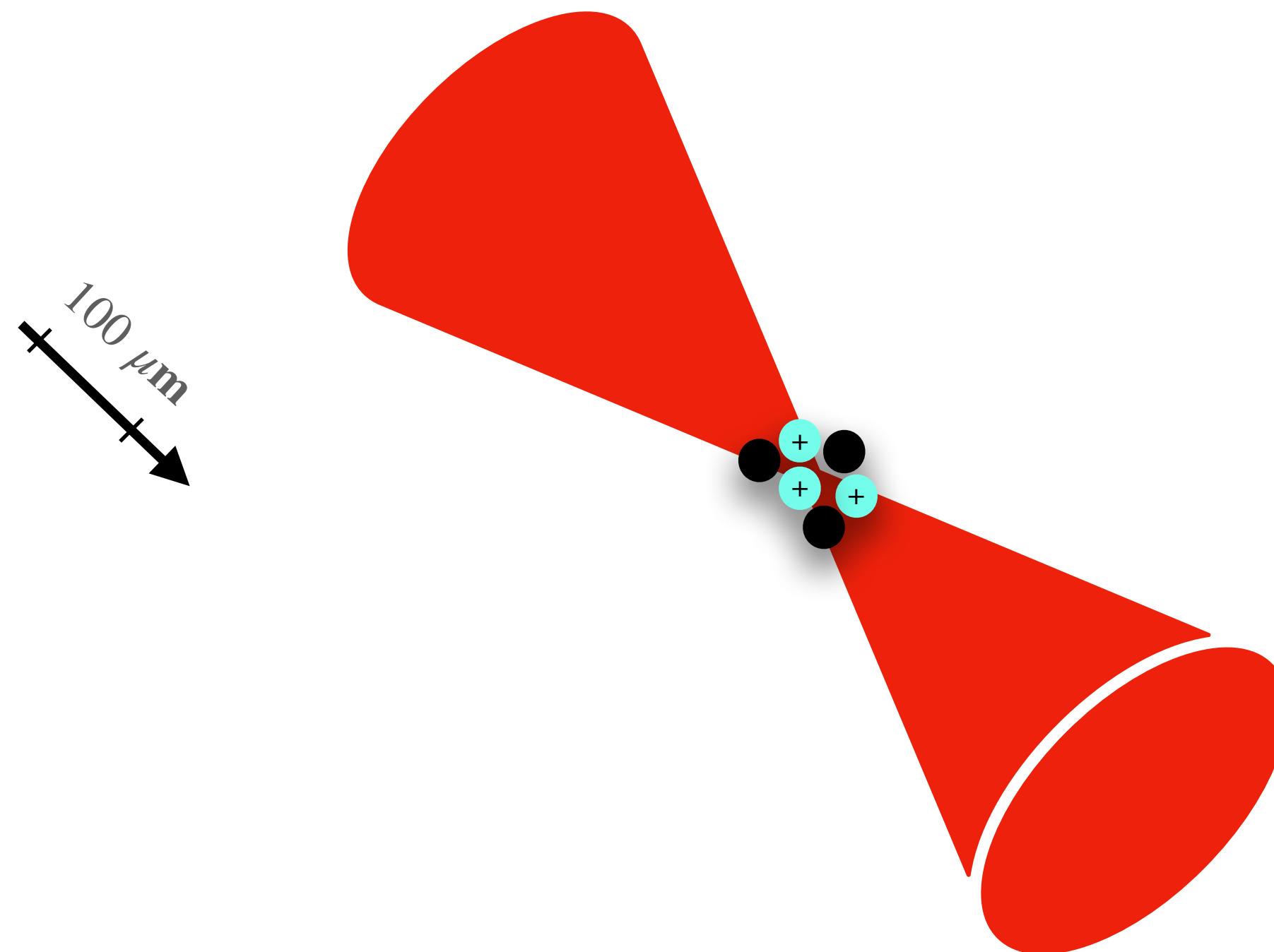
Attesa

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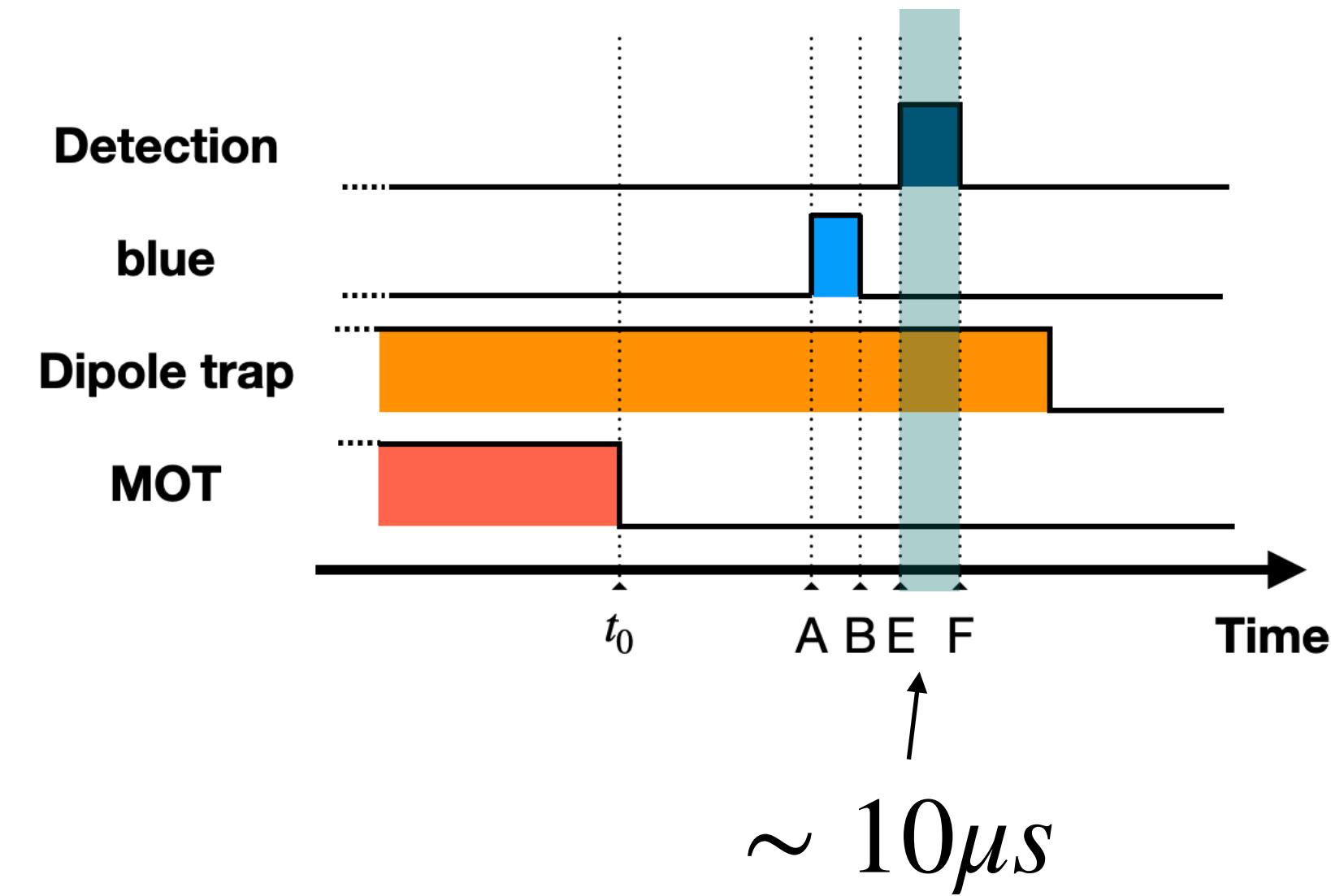
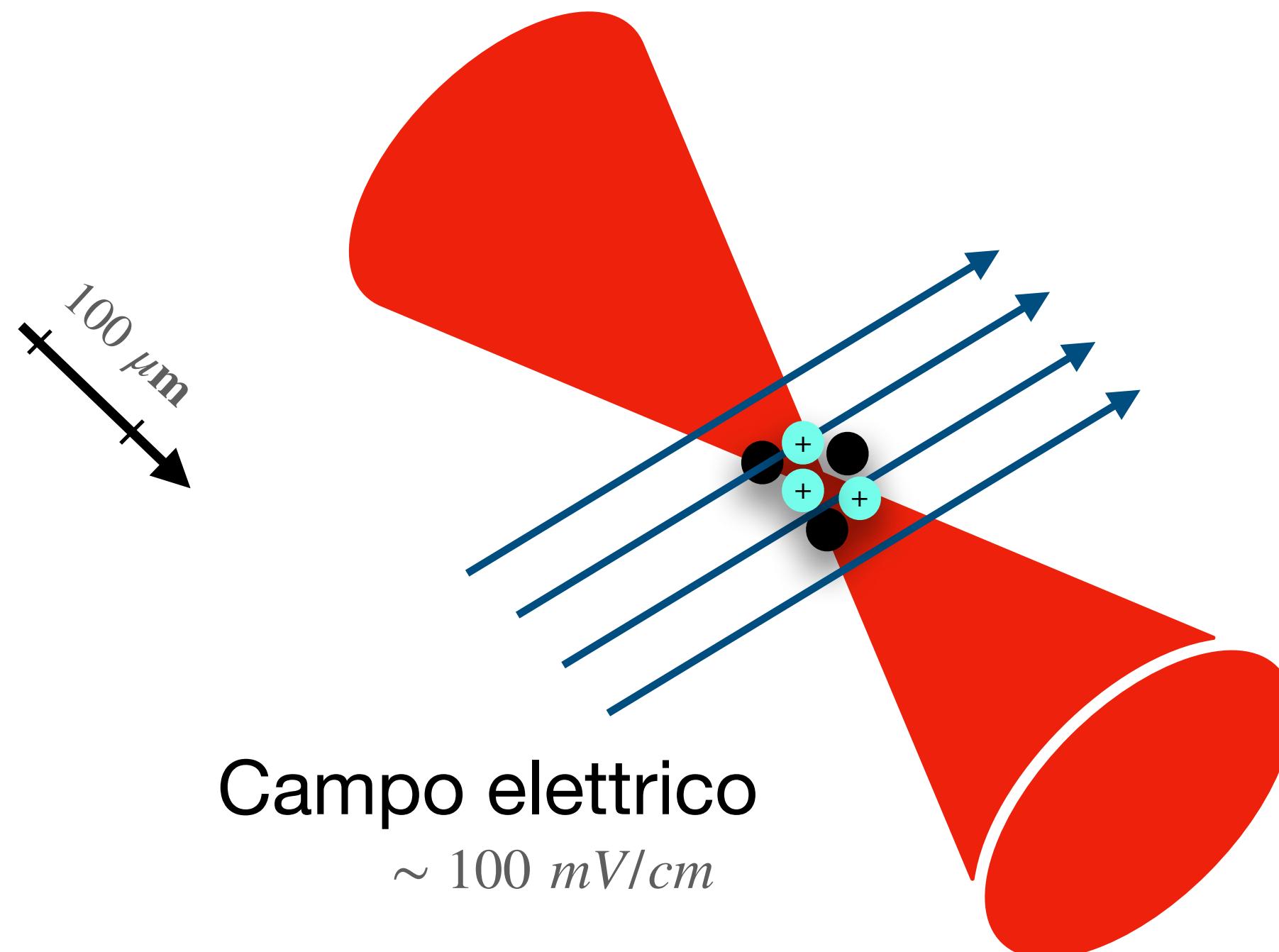


Come facciamo le misure?



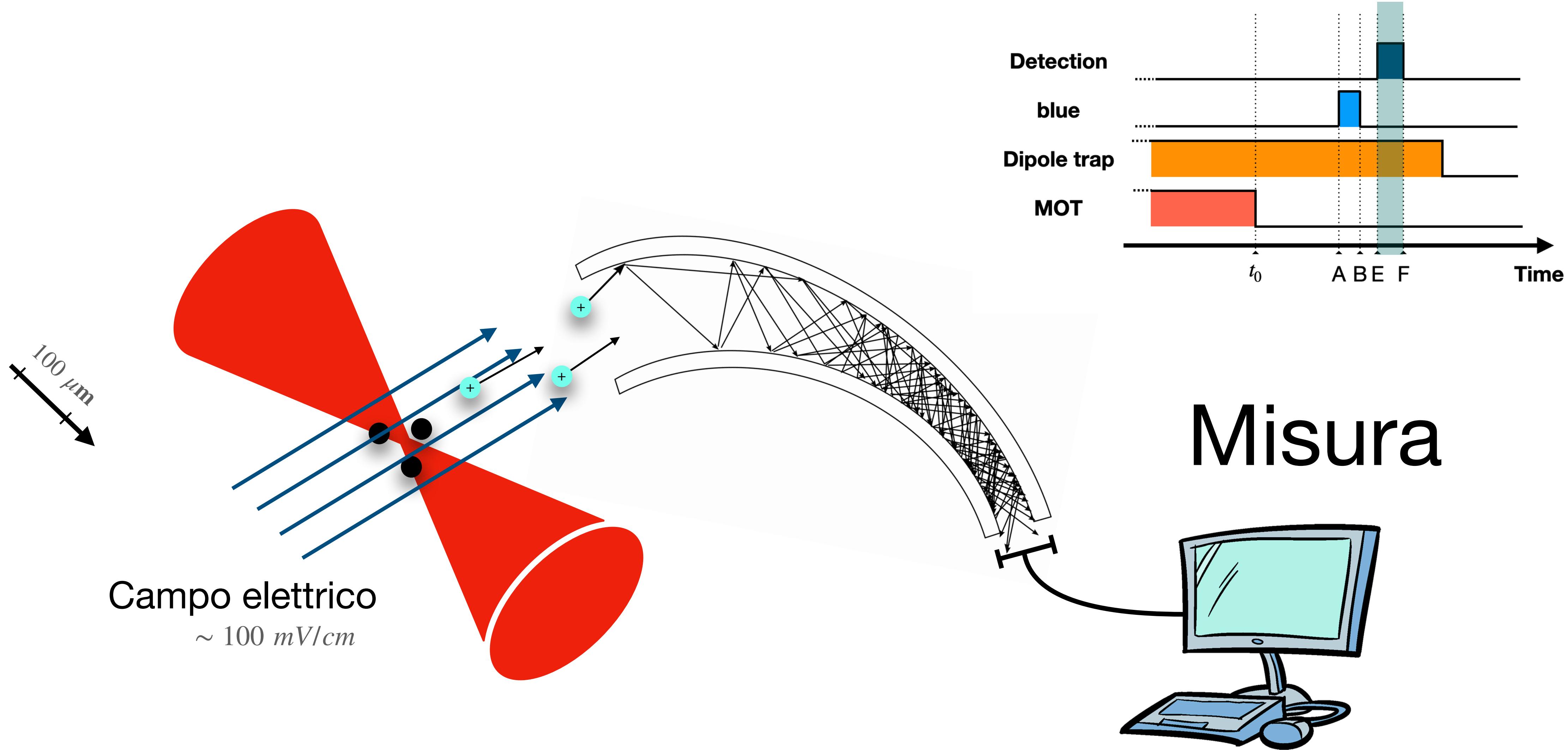
Attesa

Come facciamo le misure?

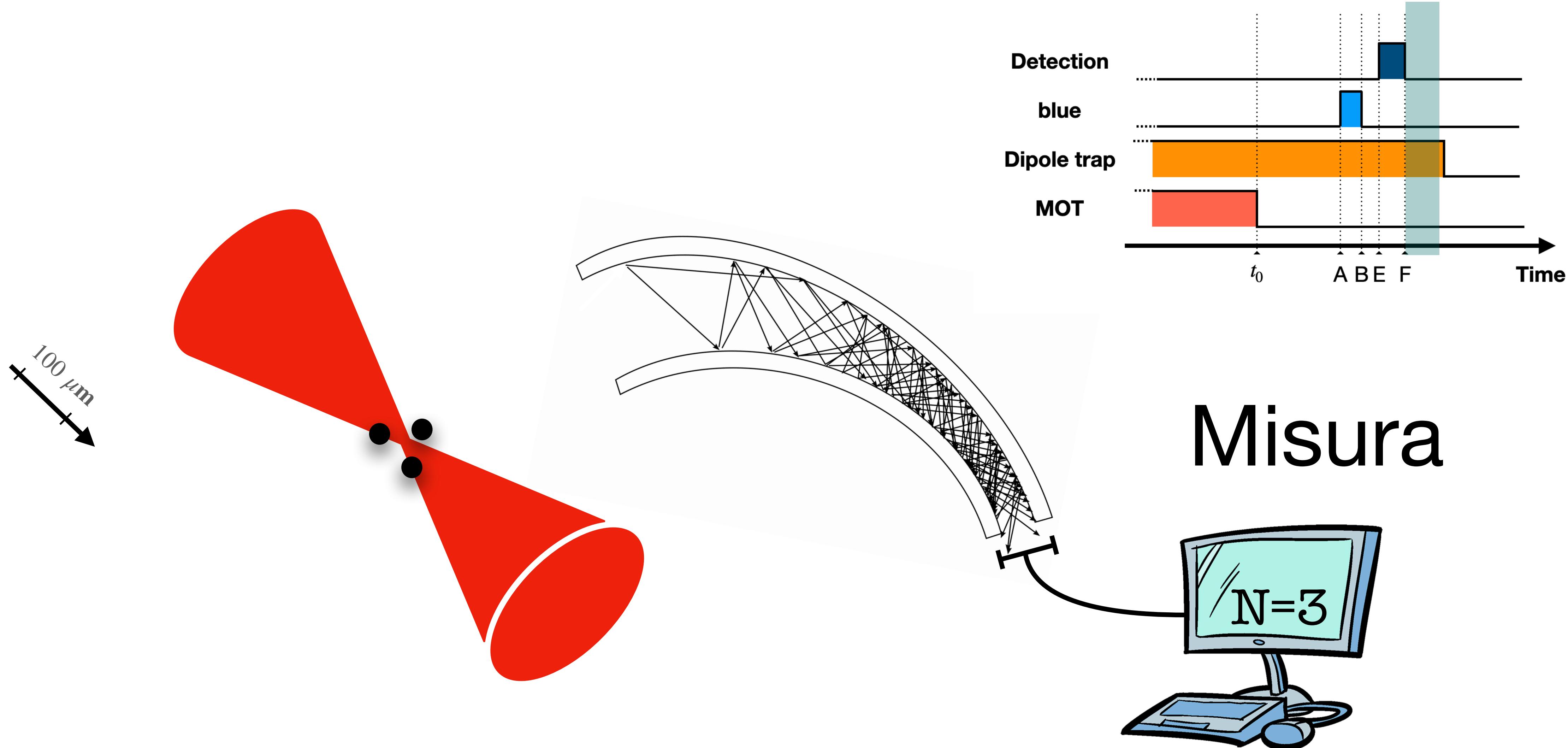


Campo elettrico per
accelerare gli ioni

Come facciamo le misure?

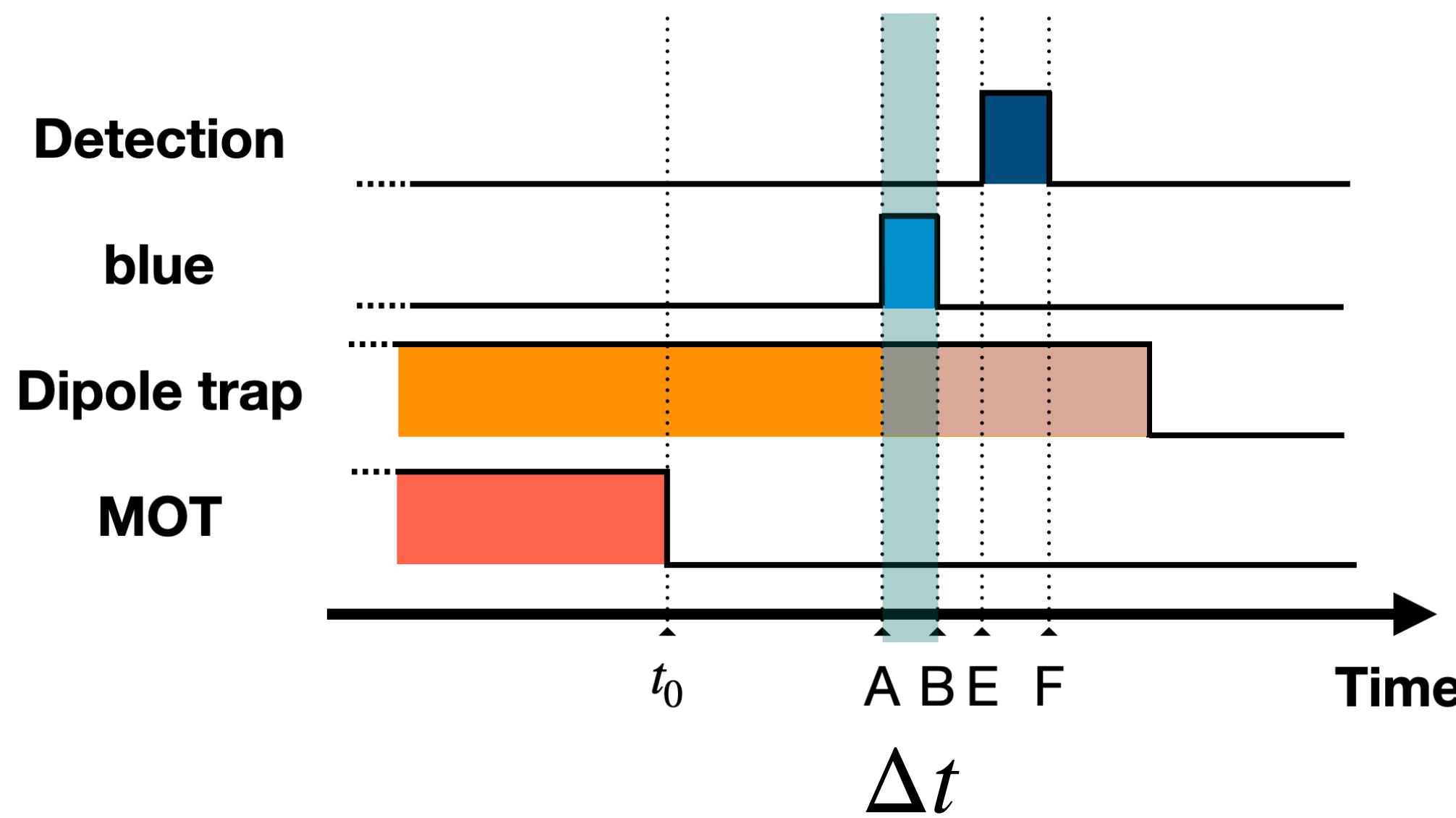
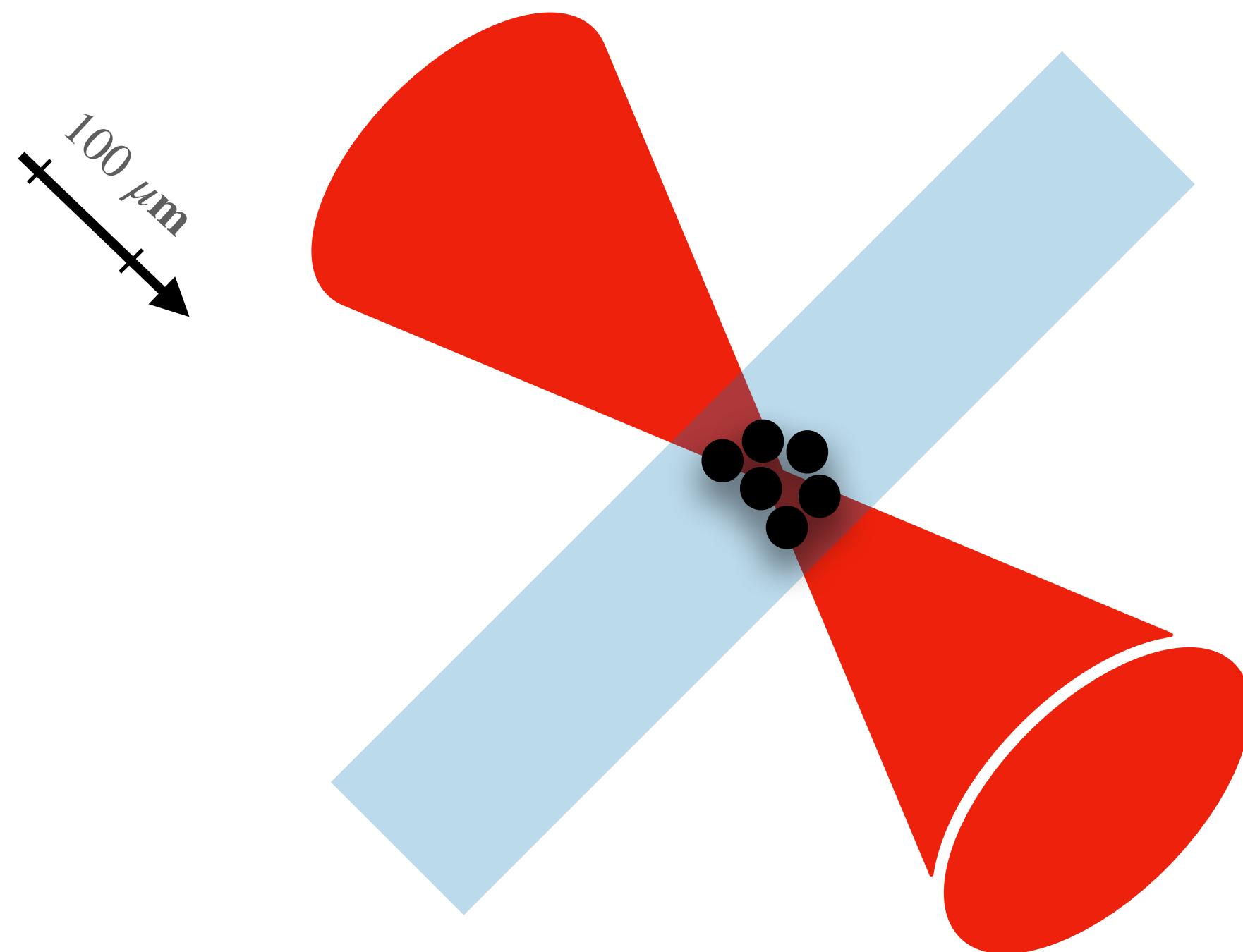


Come facciamo le misure?

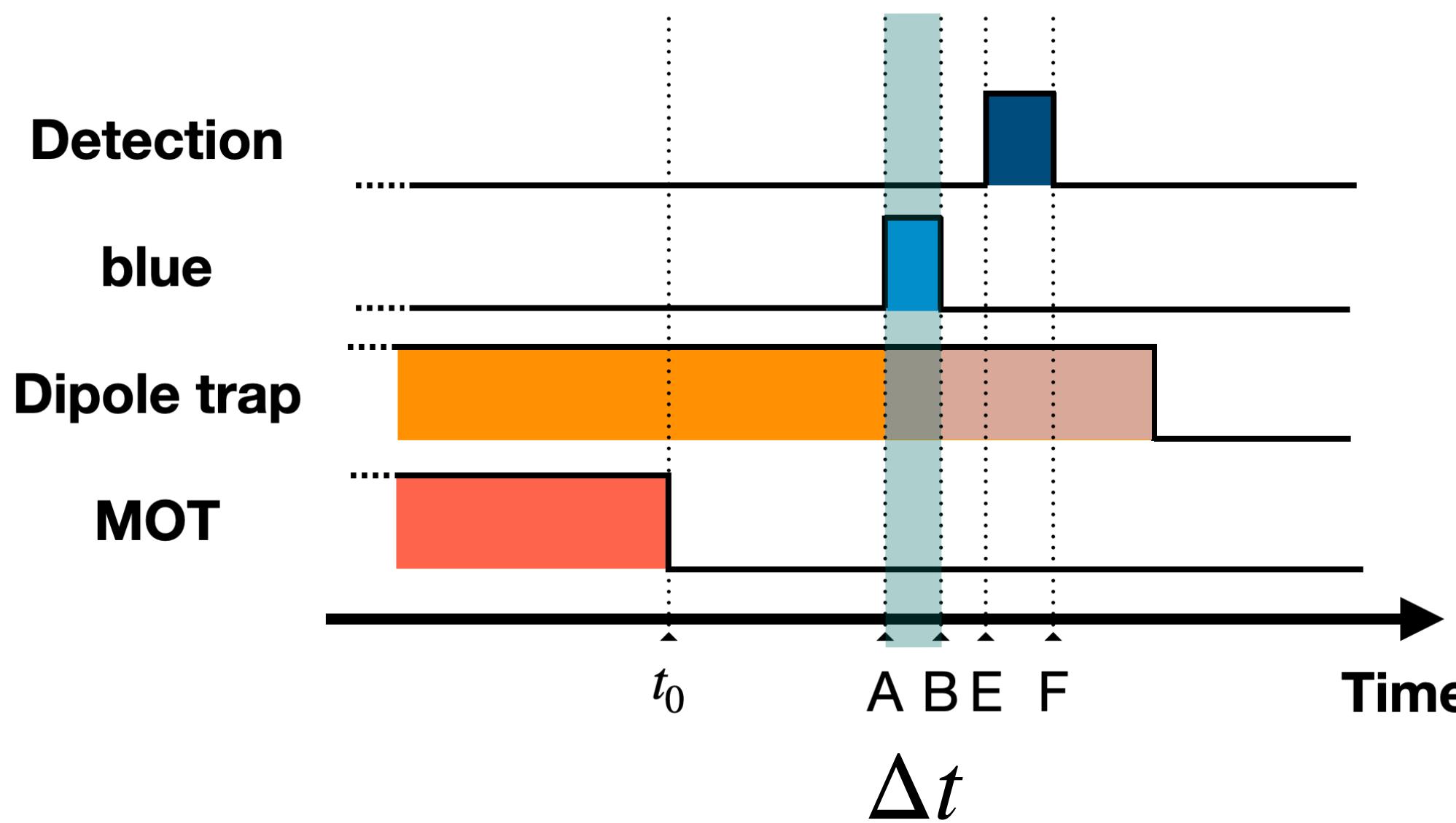
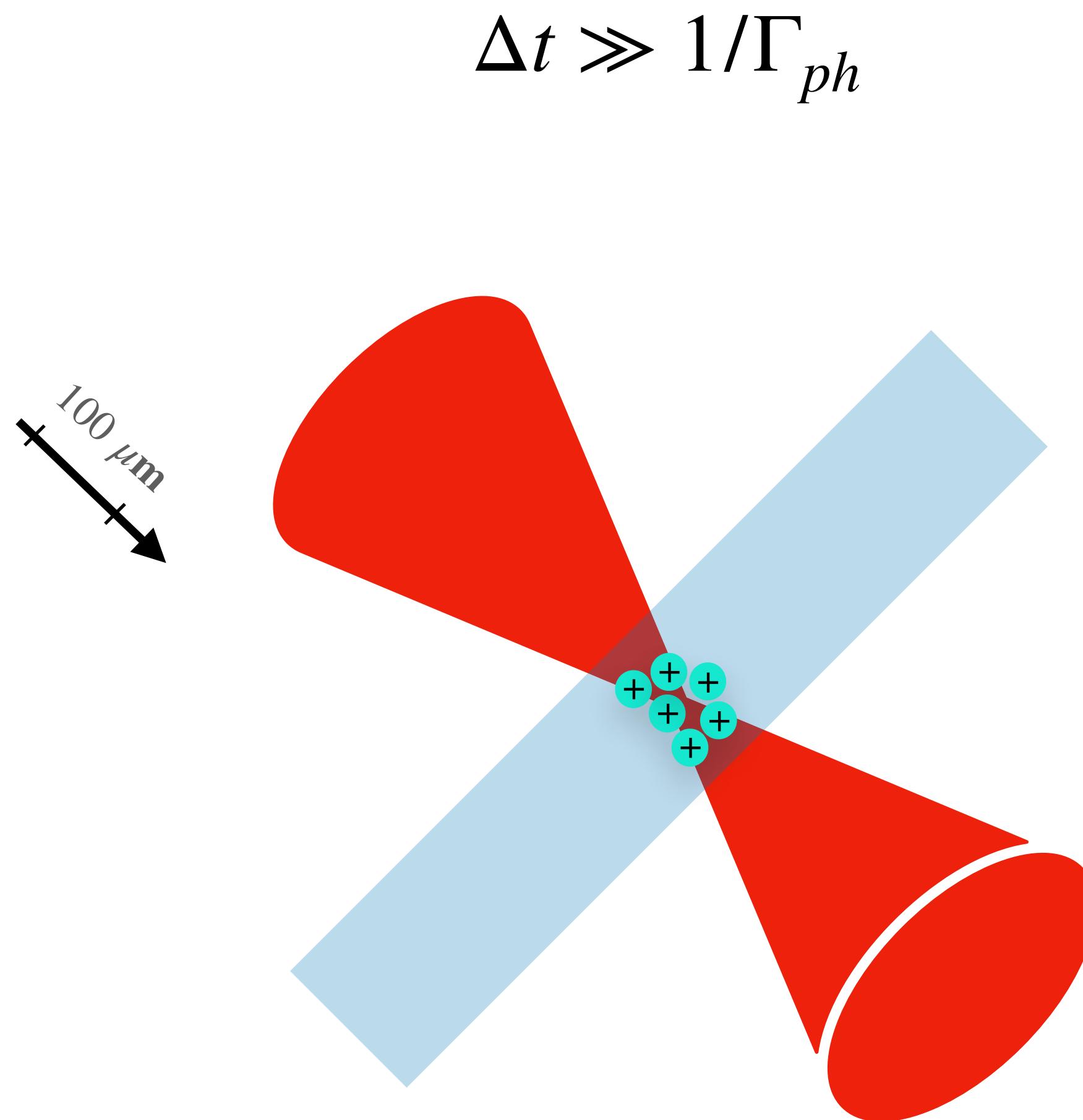


Quanti atomi intrappoliamo?

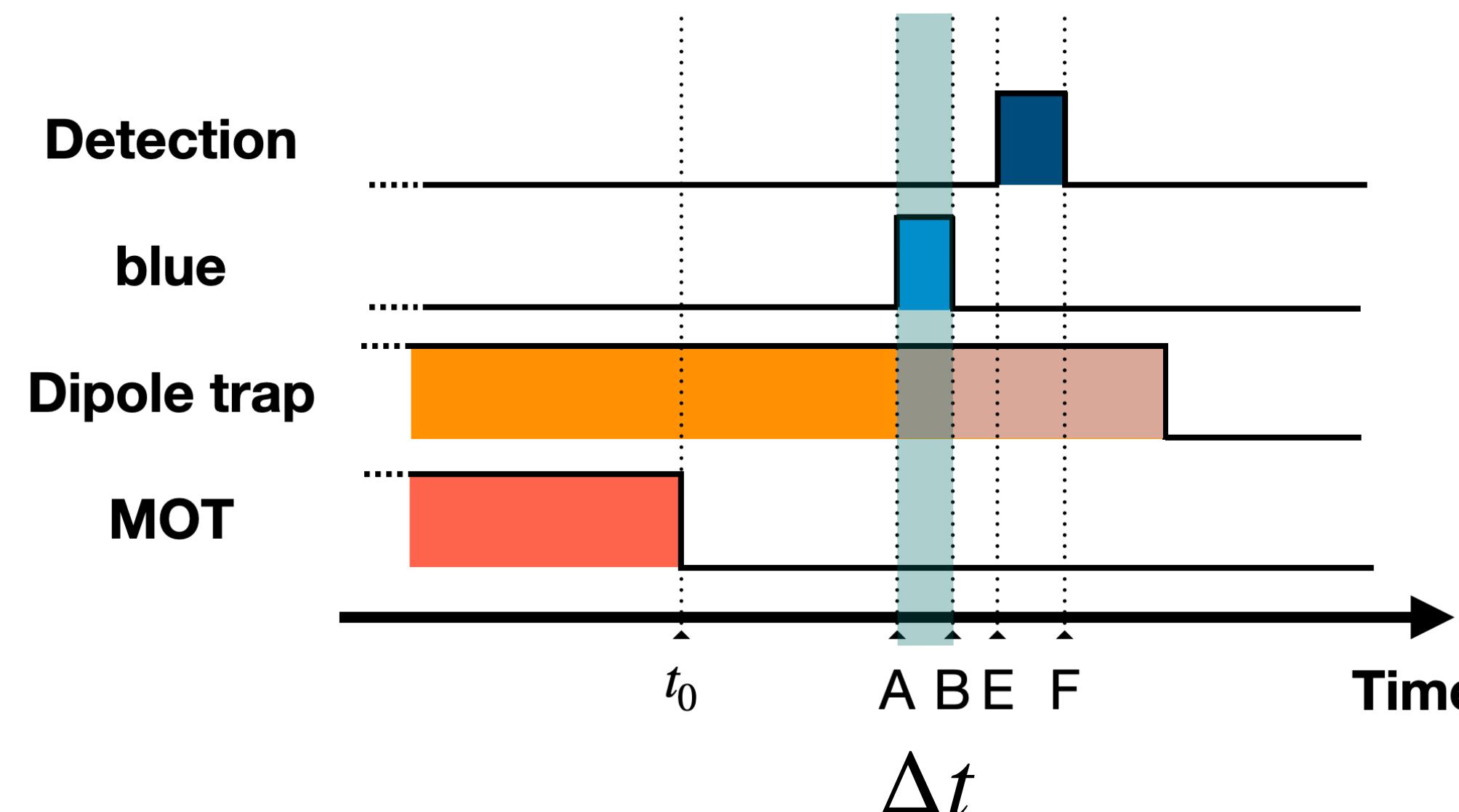
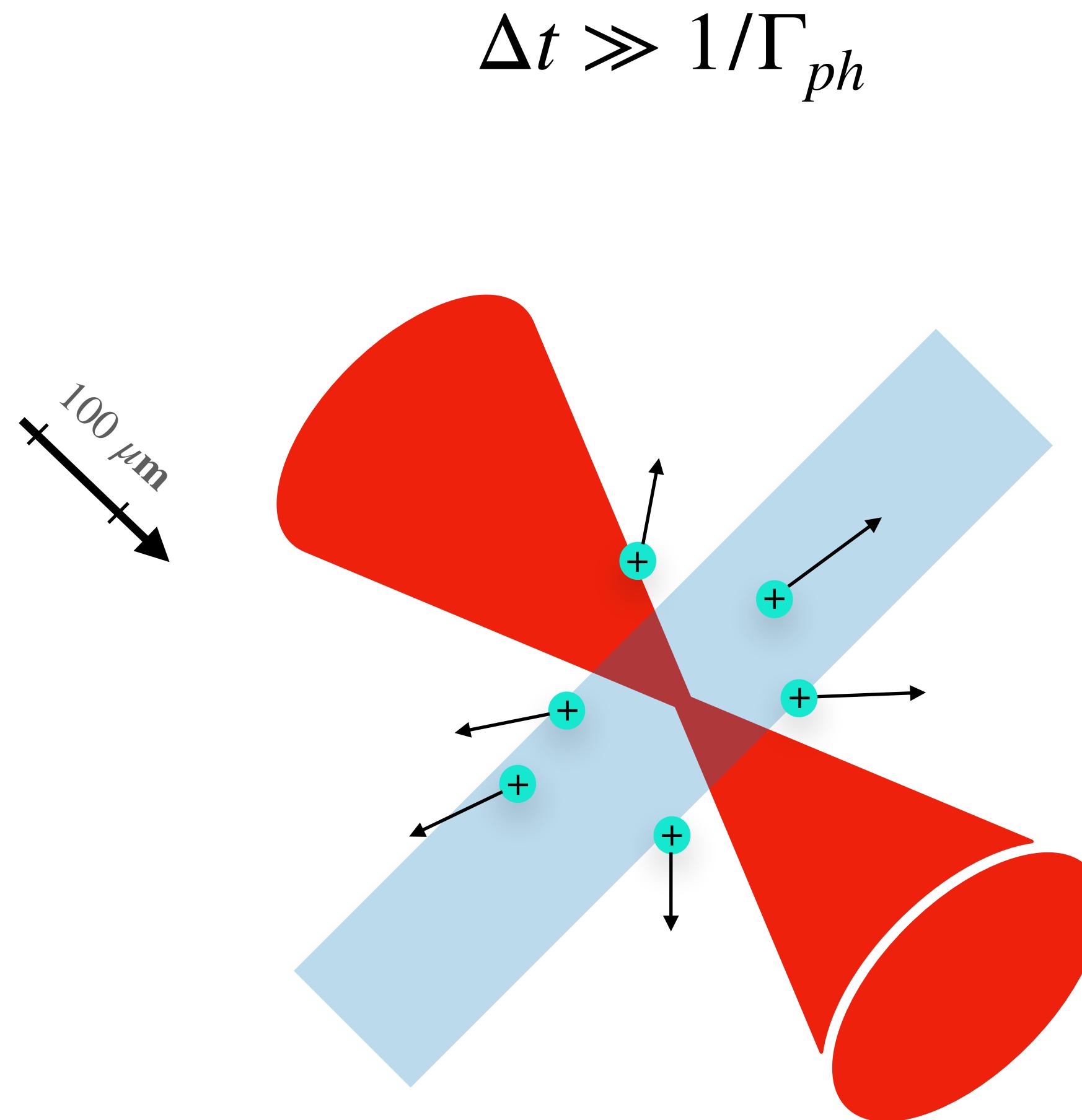
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Quanti atomi intrappoliamo?

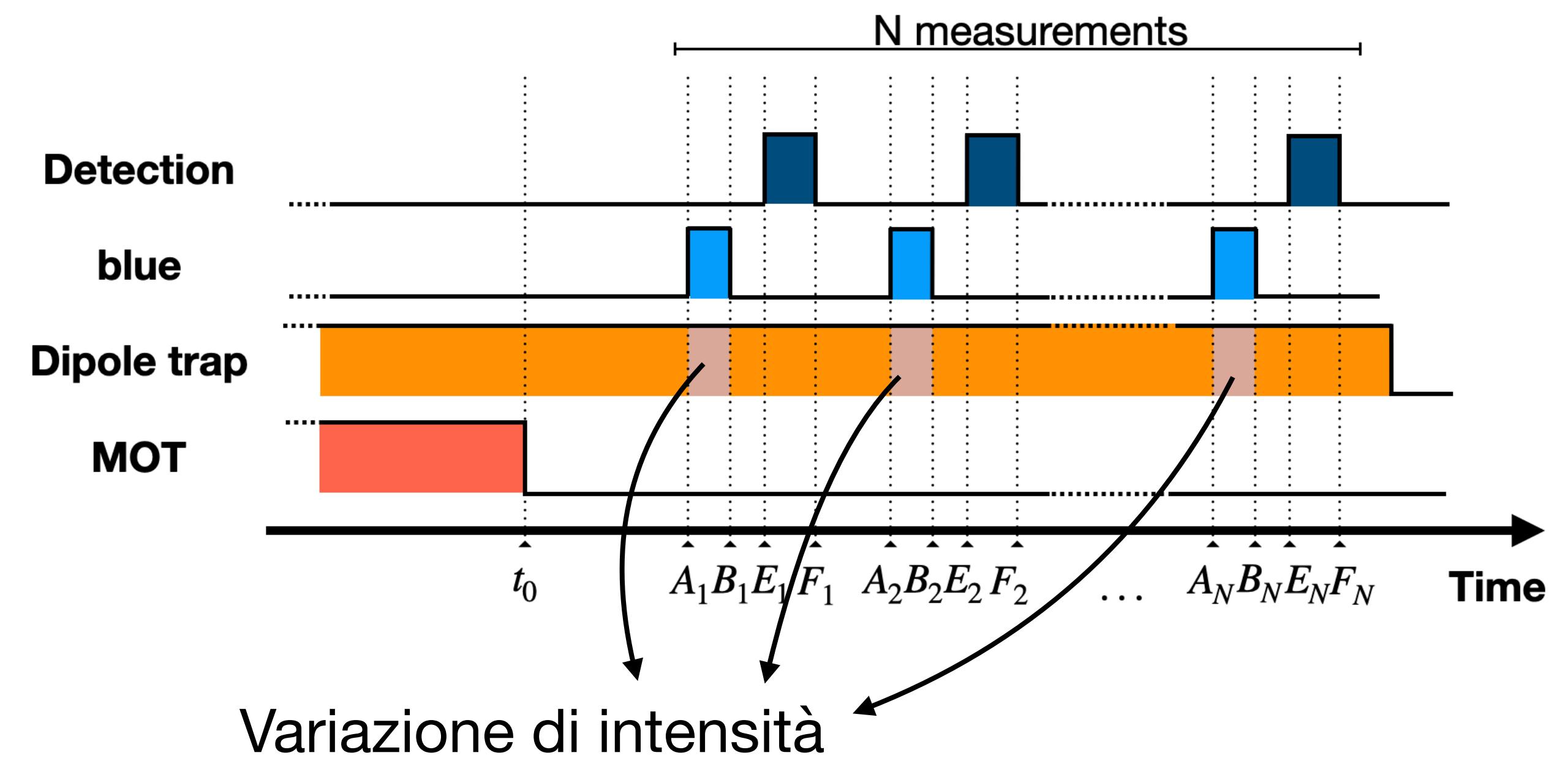
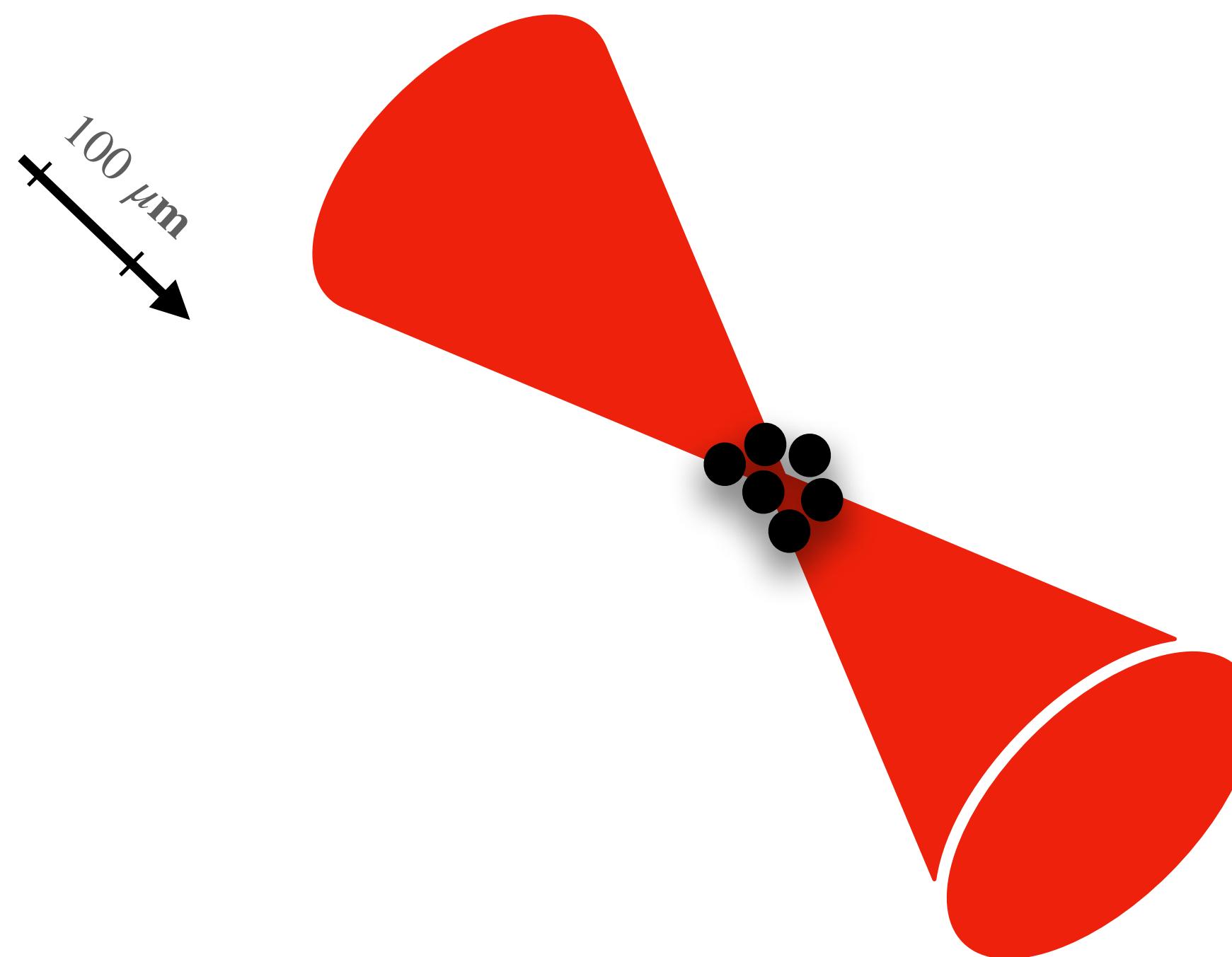


Problemi:

- Repulsione Coulombiana fra ioni
- Saturazione del rivelatore (*dead time*)

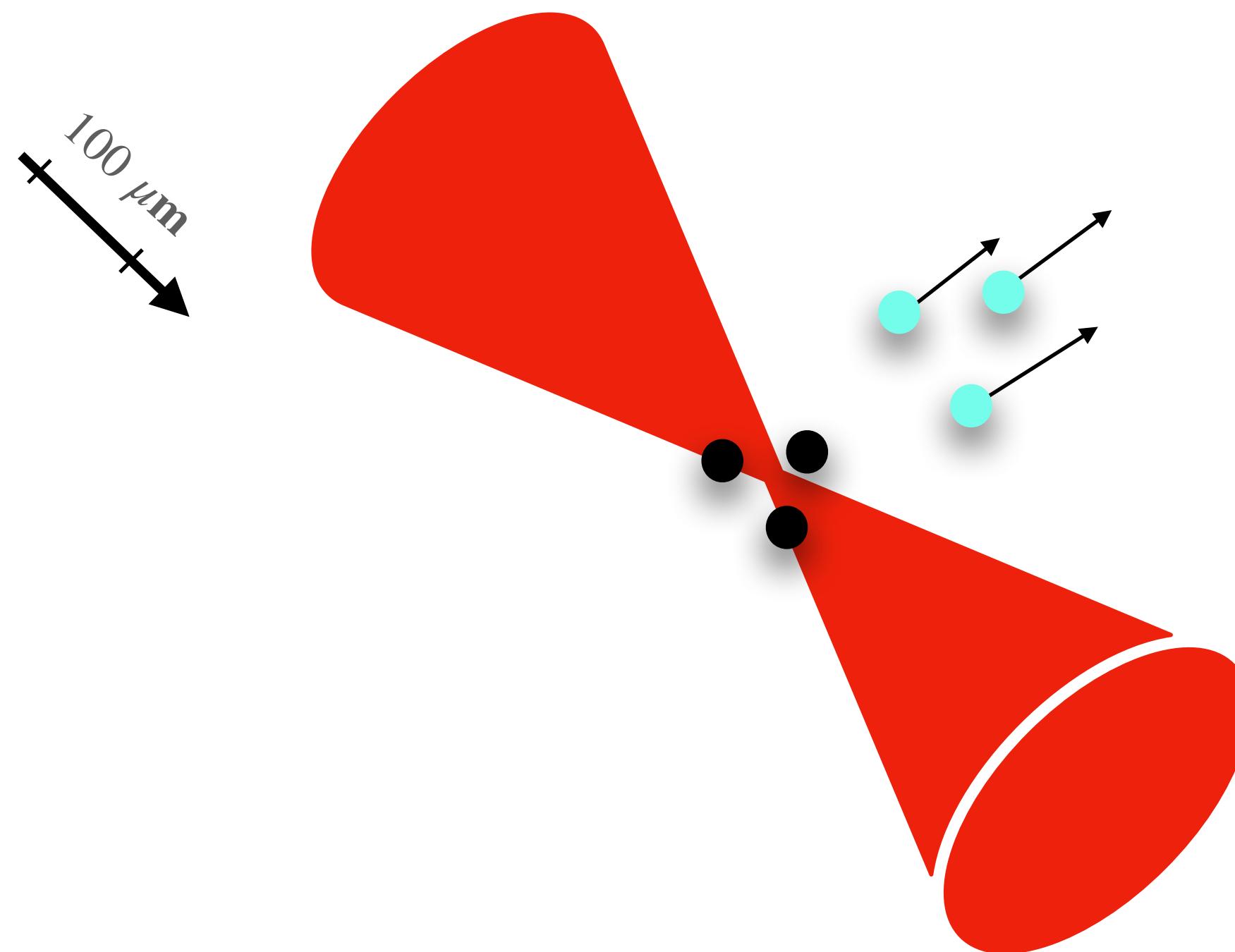
Quanti atomi intrappoliamo?

Soluzione: misure multiple dopo un solo ciclo di riempimento

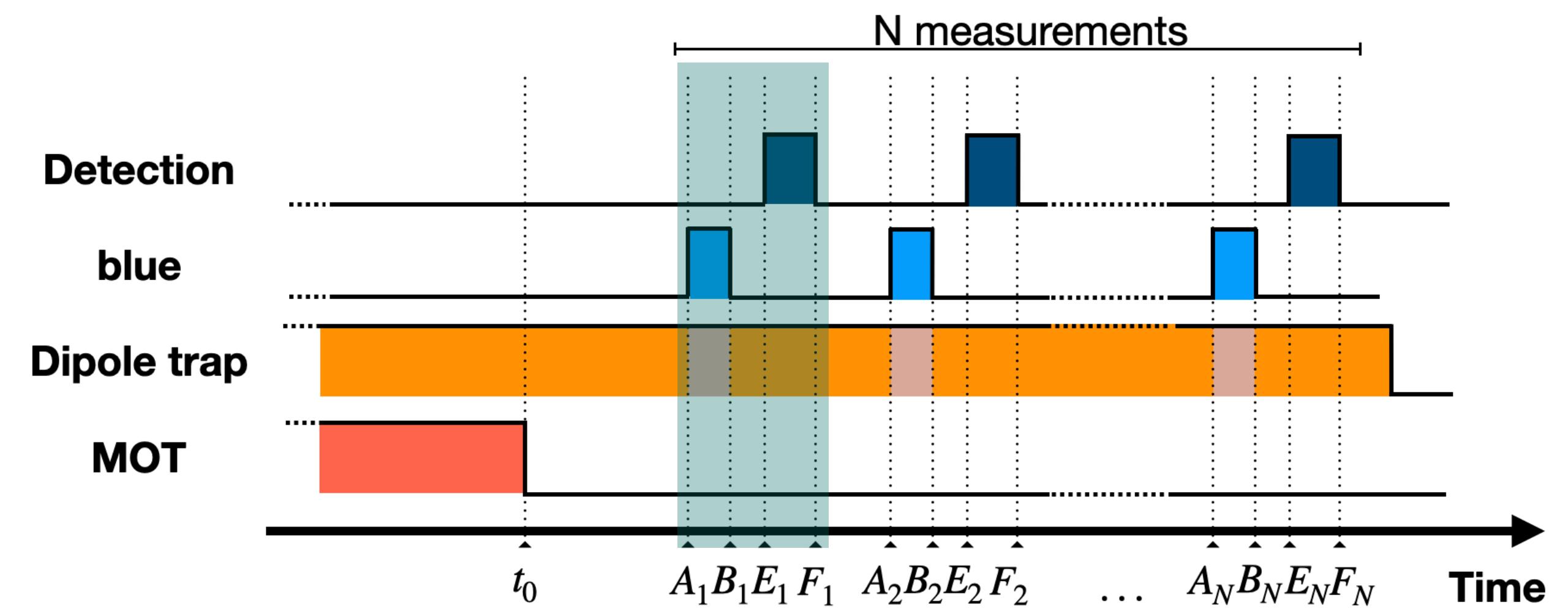


Quanti atomi intrappoliamo?

Soluzione: misure multiple dopo un solo ciclo di riempimento

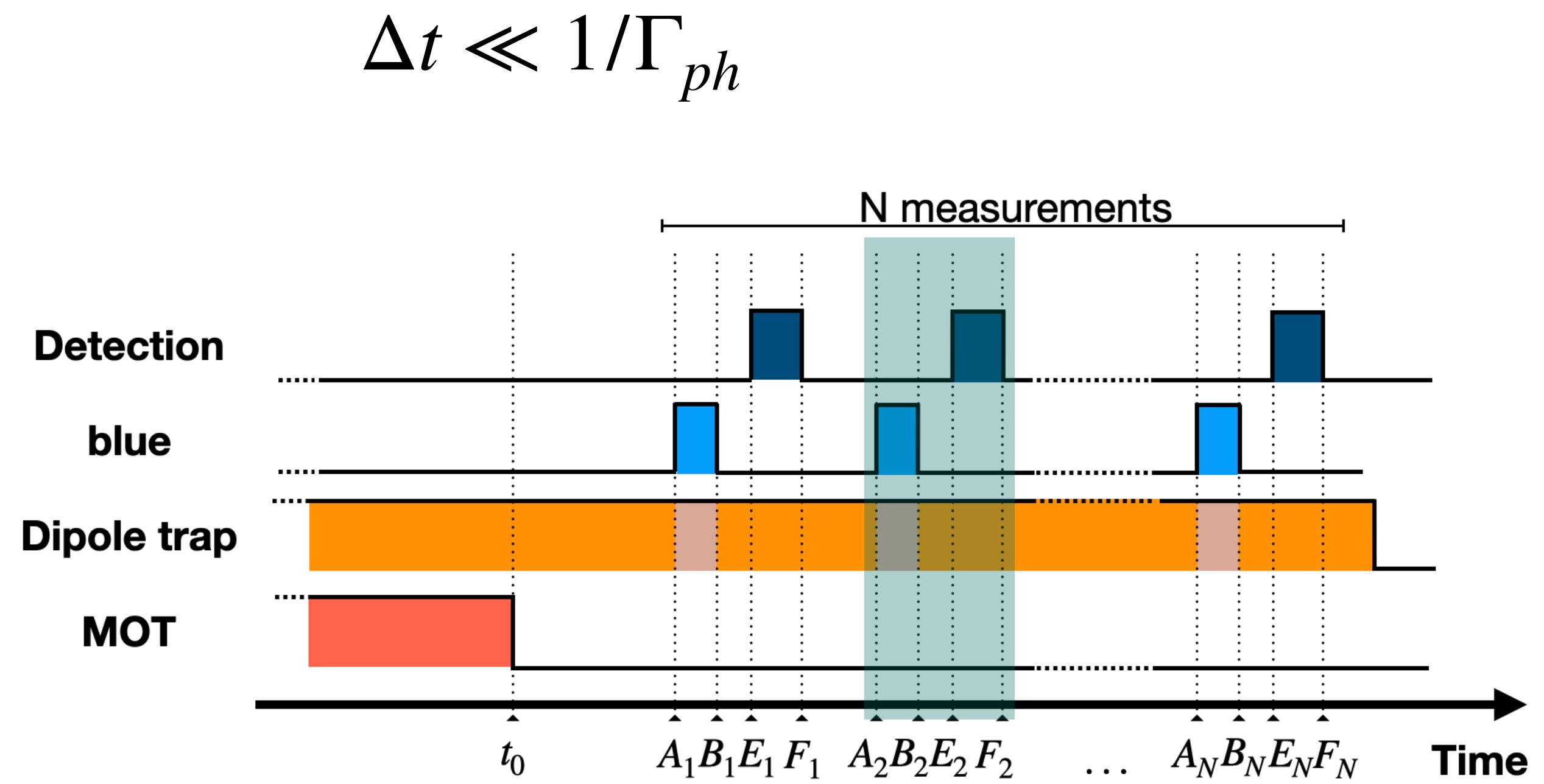
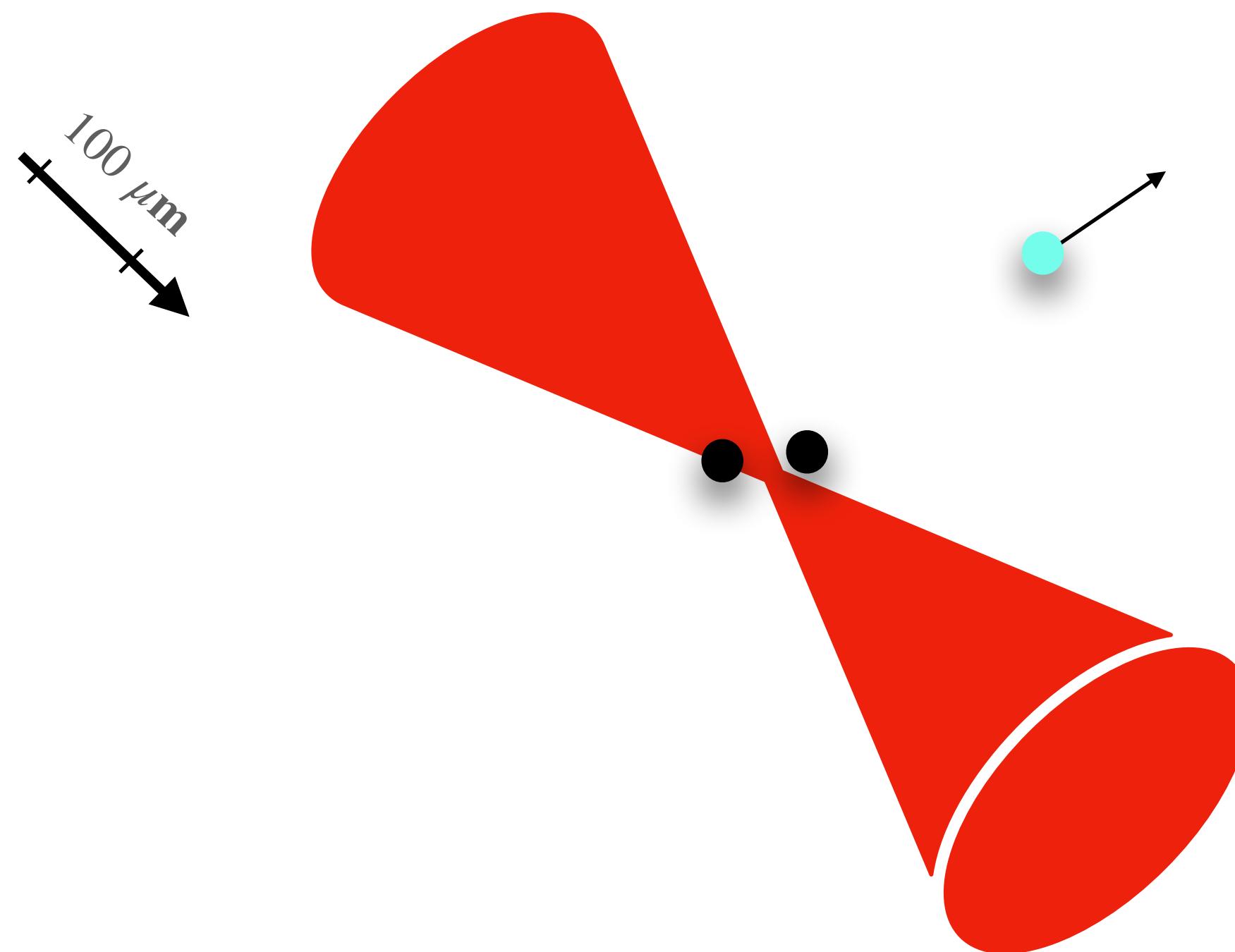


$$\Delta t \ll 1/\Gamma_{ph}$$



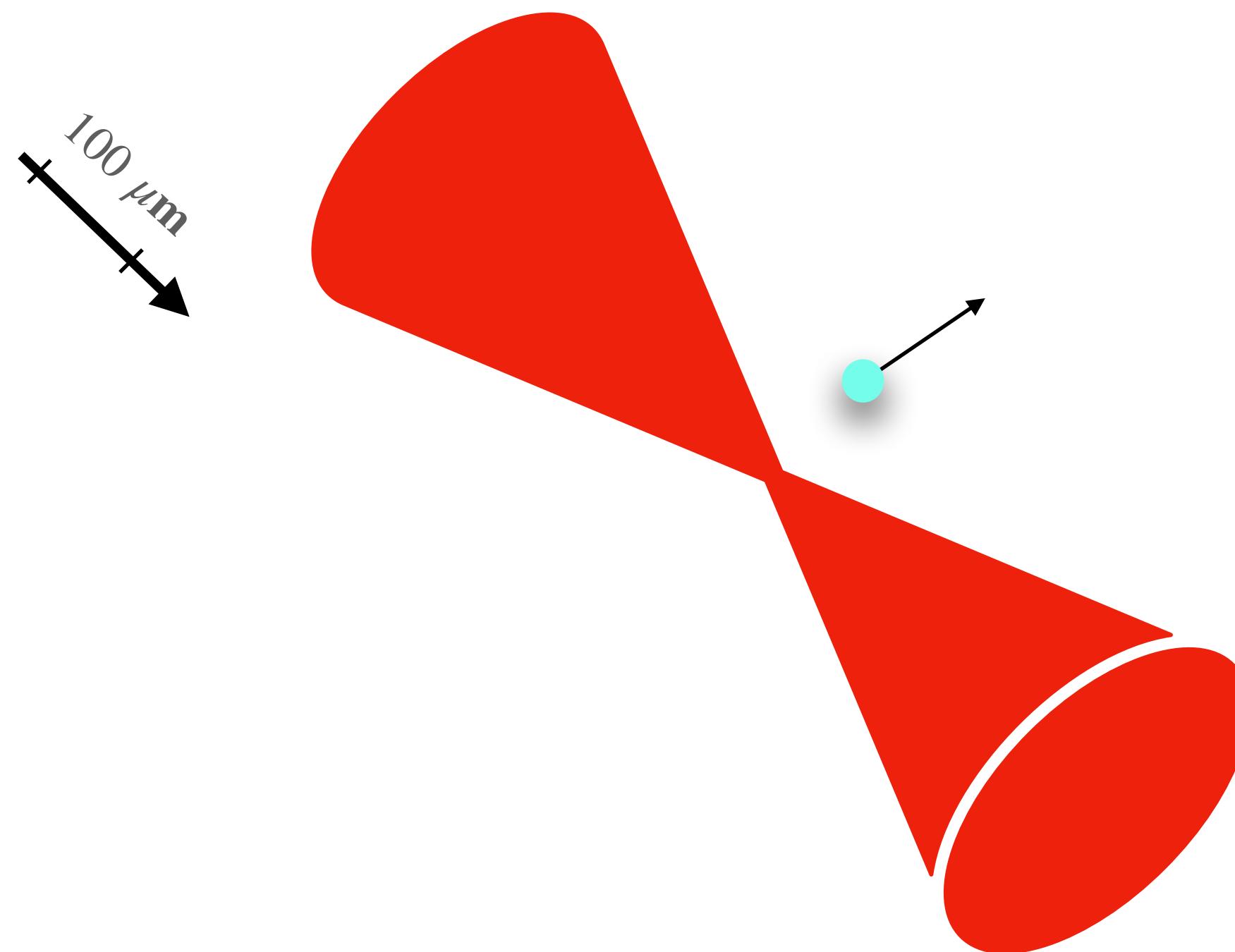
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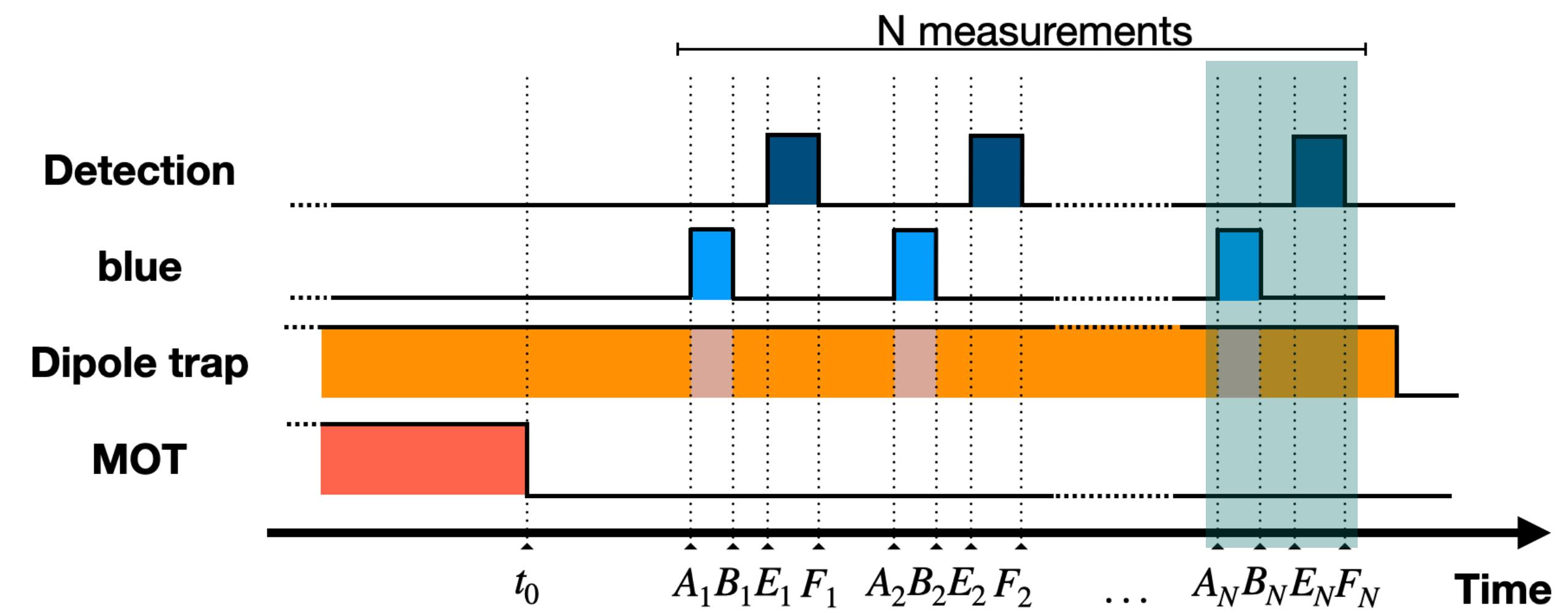


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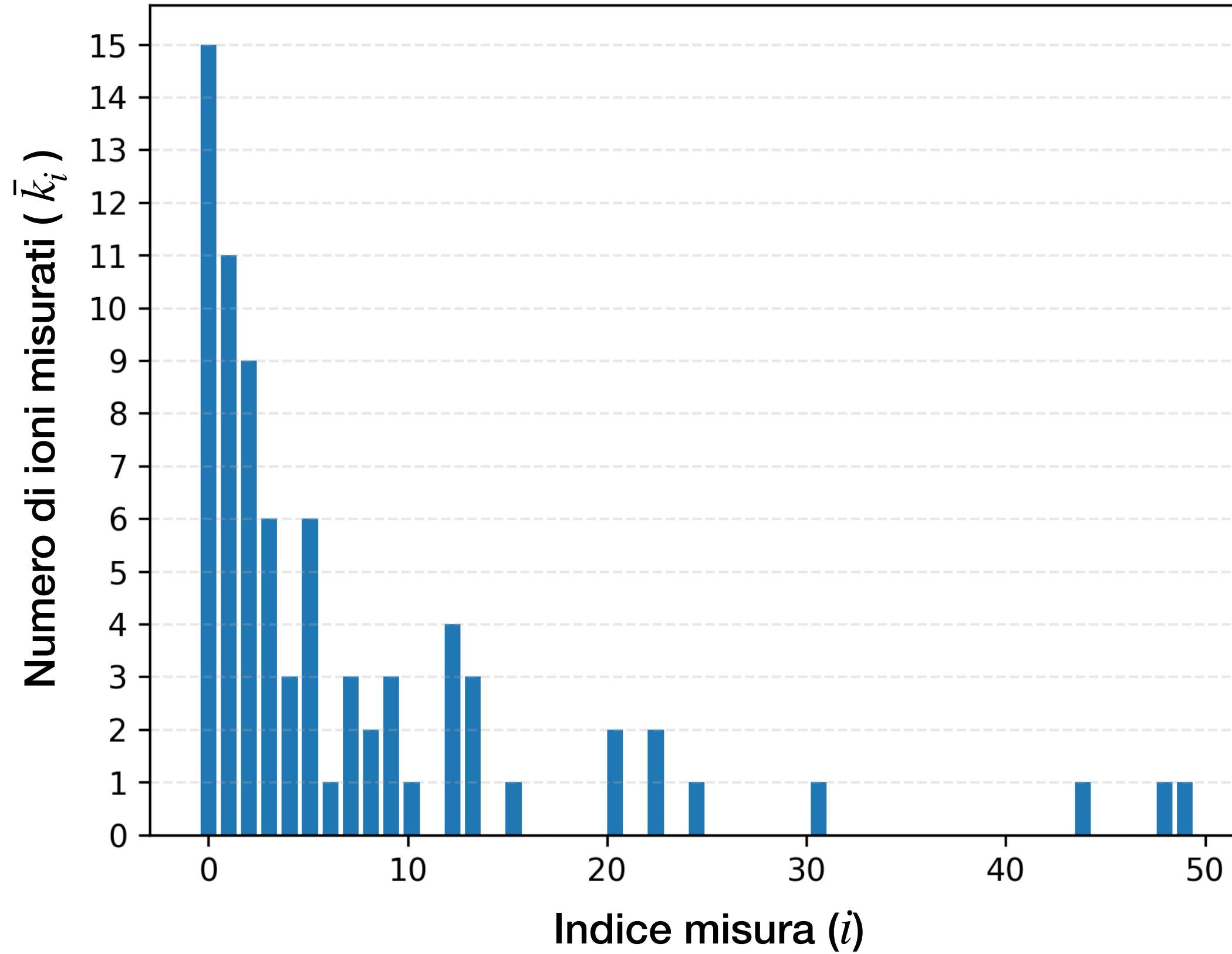
Soluzione: misure multiple dopo un solo ciclo di riempimento



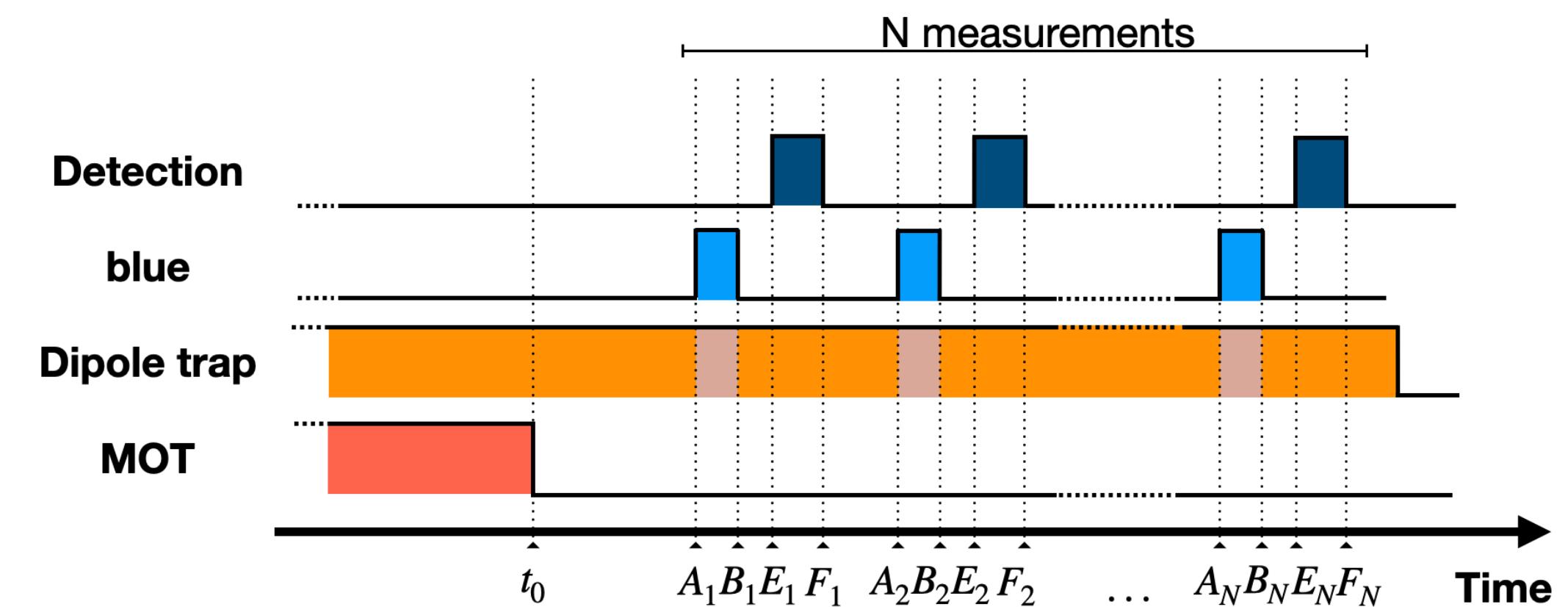
$$\Delta t \ll 1/\Gamma_{ph}$$



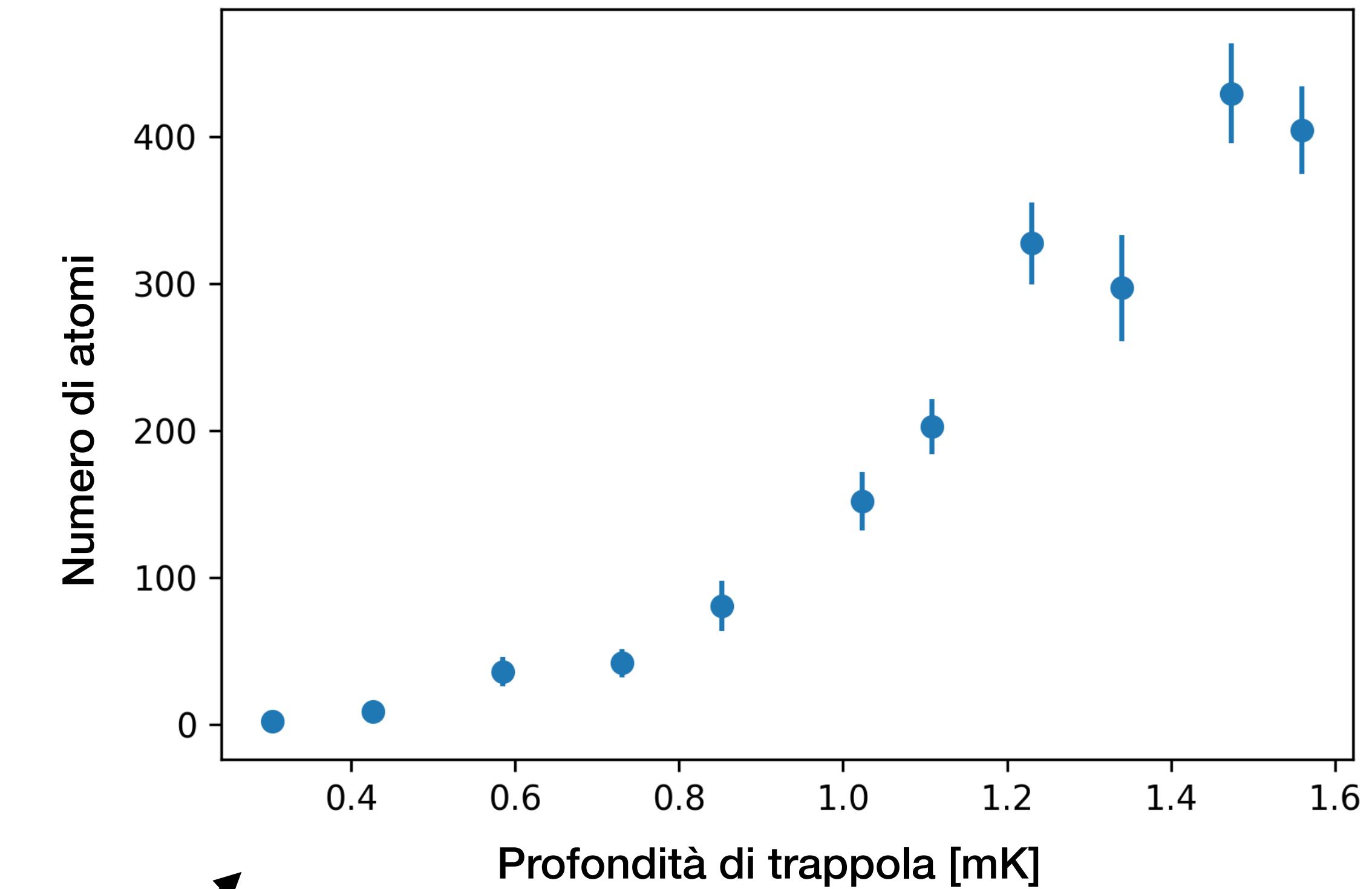
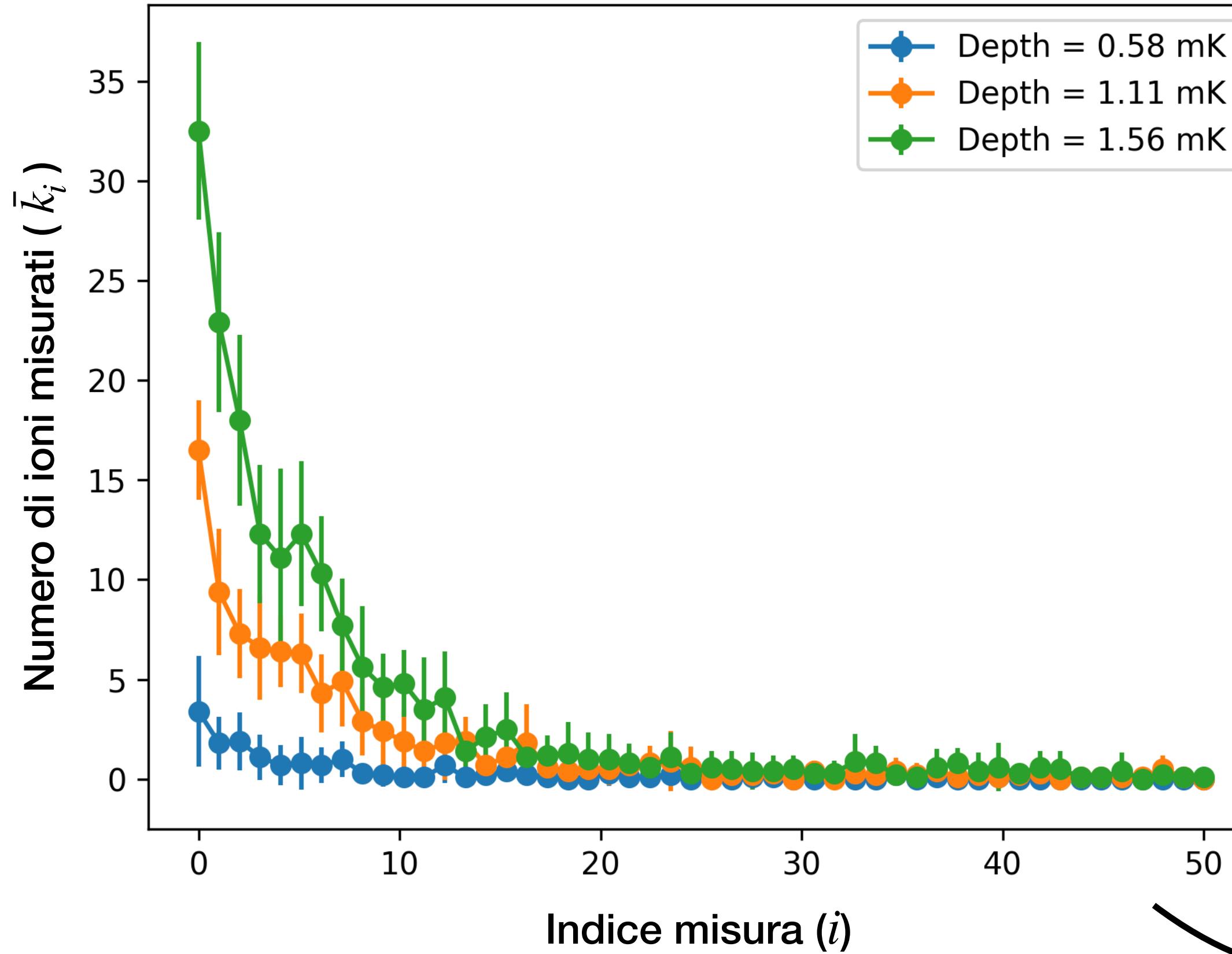
Quanti atomi intrappoliamo?



{ Una misura ogni 1 ms
Durata impulso di fotoionizzazione: 1 μ s



Quanti atomi intrappoliamo?



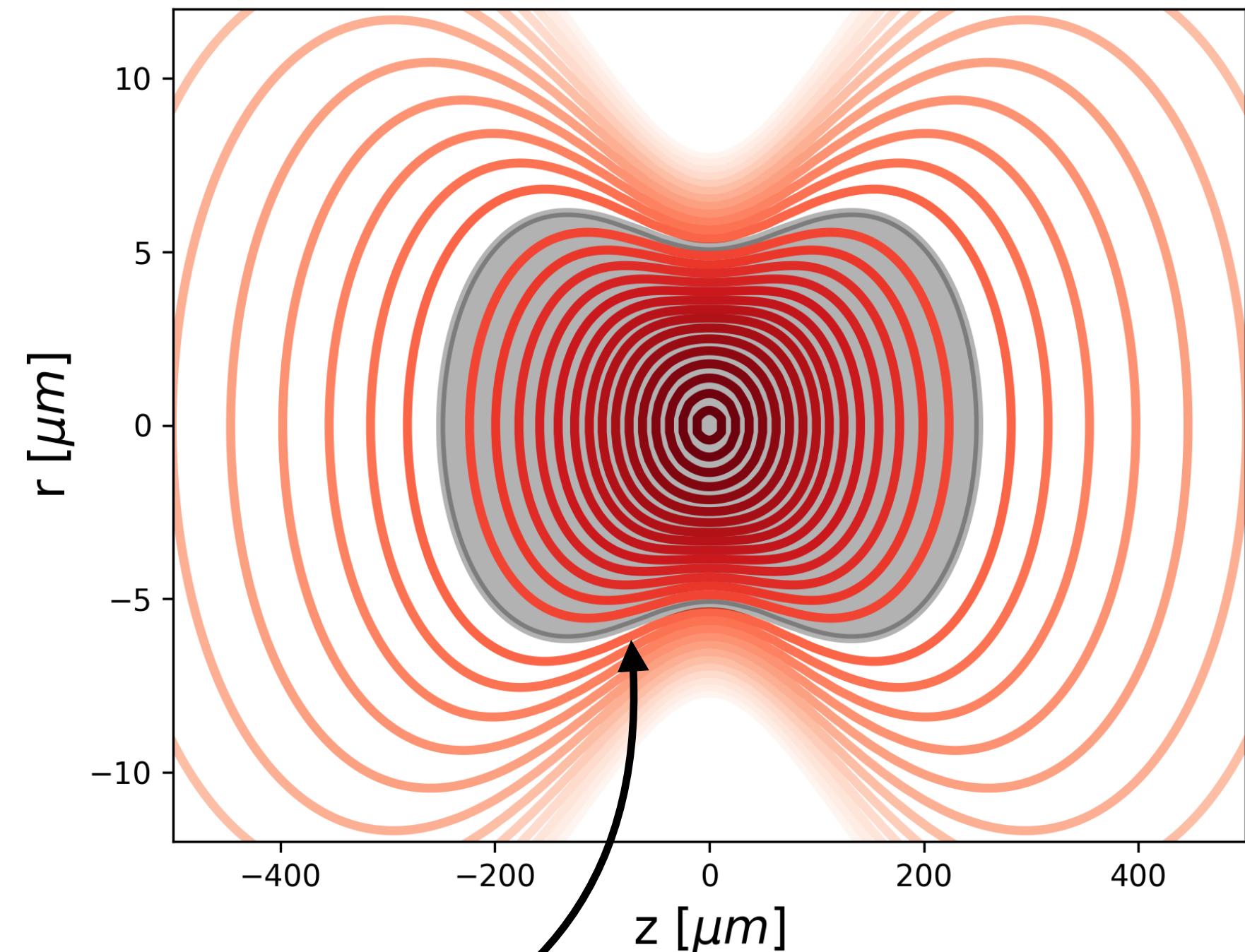
{ Una misura ogni 1 ms
Durata impulso di fotoionizzazione: 1 μ s

Sommando sulle misure consecutive
e ripetendo il tutto 10 volte

$\alpha = 0.4$
Efficienza di rivelazione

Quanti atomi intrappoliamo?

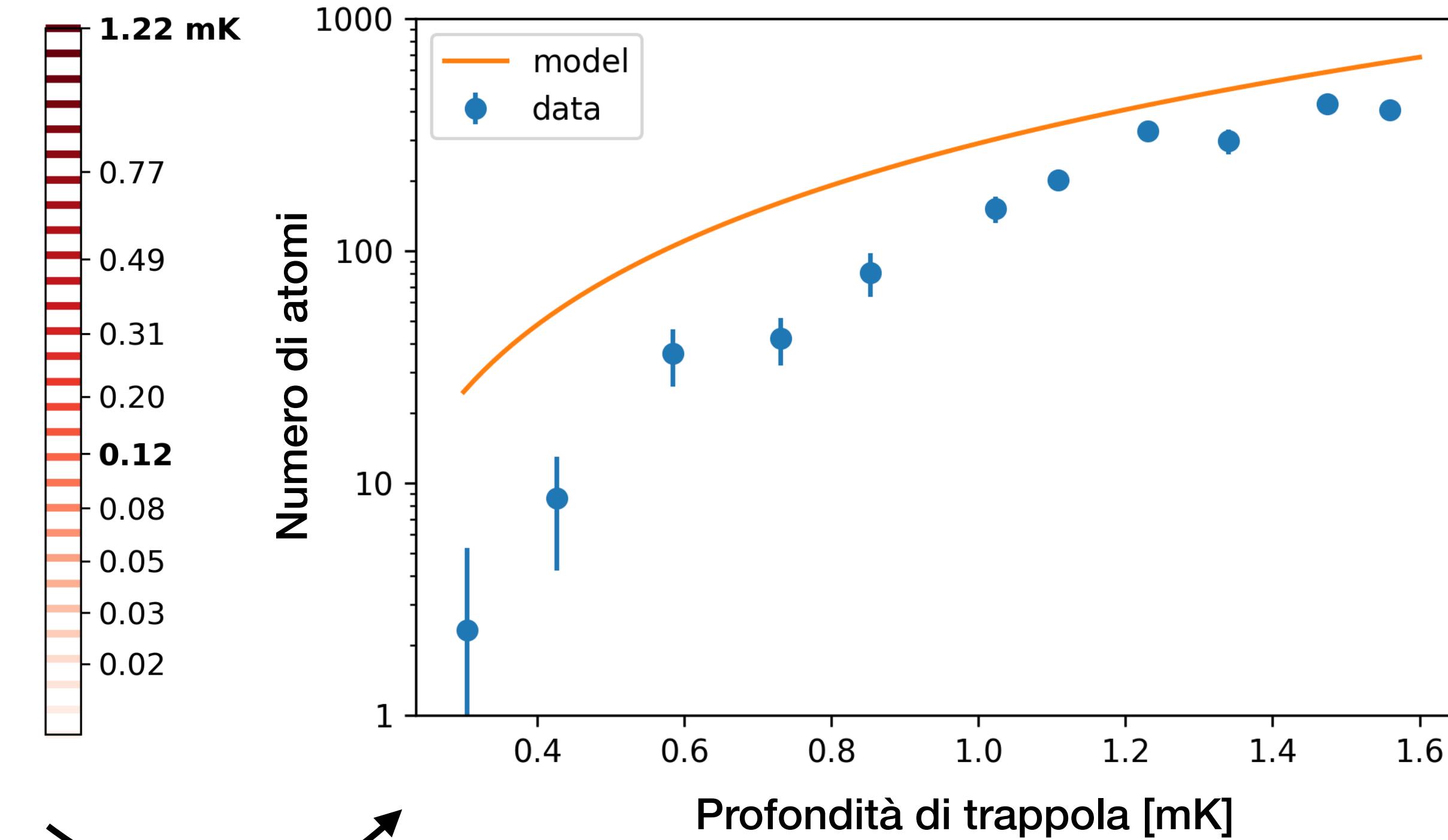
$$U_{dip}(z, r) = \frac{3\pi c^2}{2\omega_0^2} \frac{\Gamma}{\Delta} I(z, r)$$



Trapping volume for
 $T = 120 \mu K$
 $P = 100 mW$
 $\lambda = 840 nm$

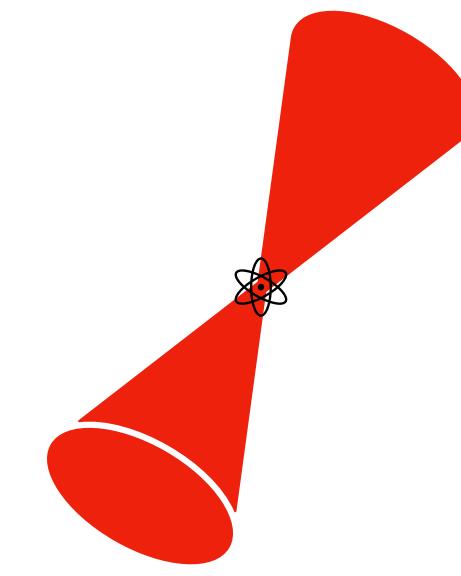
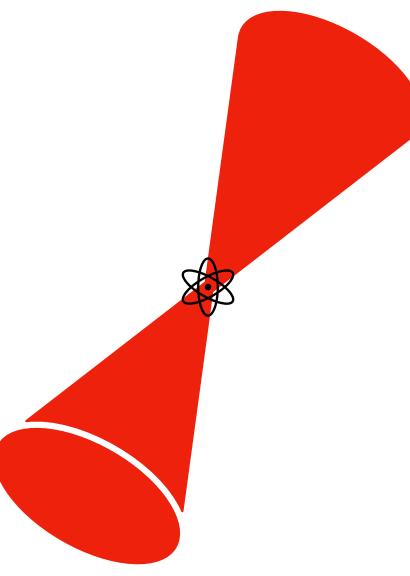
$$w_0 = 5 \mu m$$
$$\Delta = 30 \text{ THz}$$

Modello di densità limitata



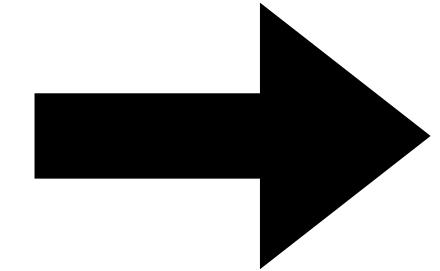
Integrando la regione grigia e moltiplicando
il risultato ottenuto per la densità della MOT

Densità MOT $\sim 10^9 \text{ cm}^{-3}$
Misurata con la CCD



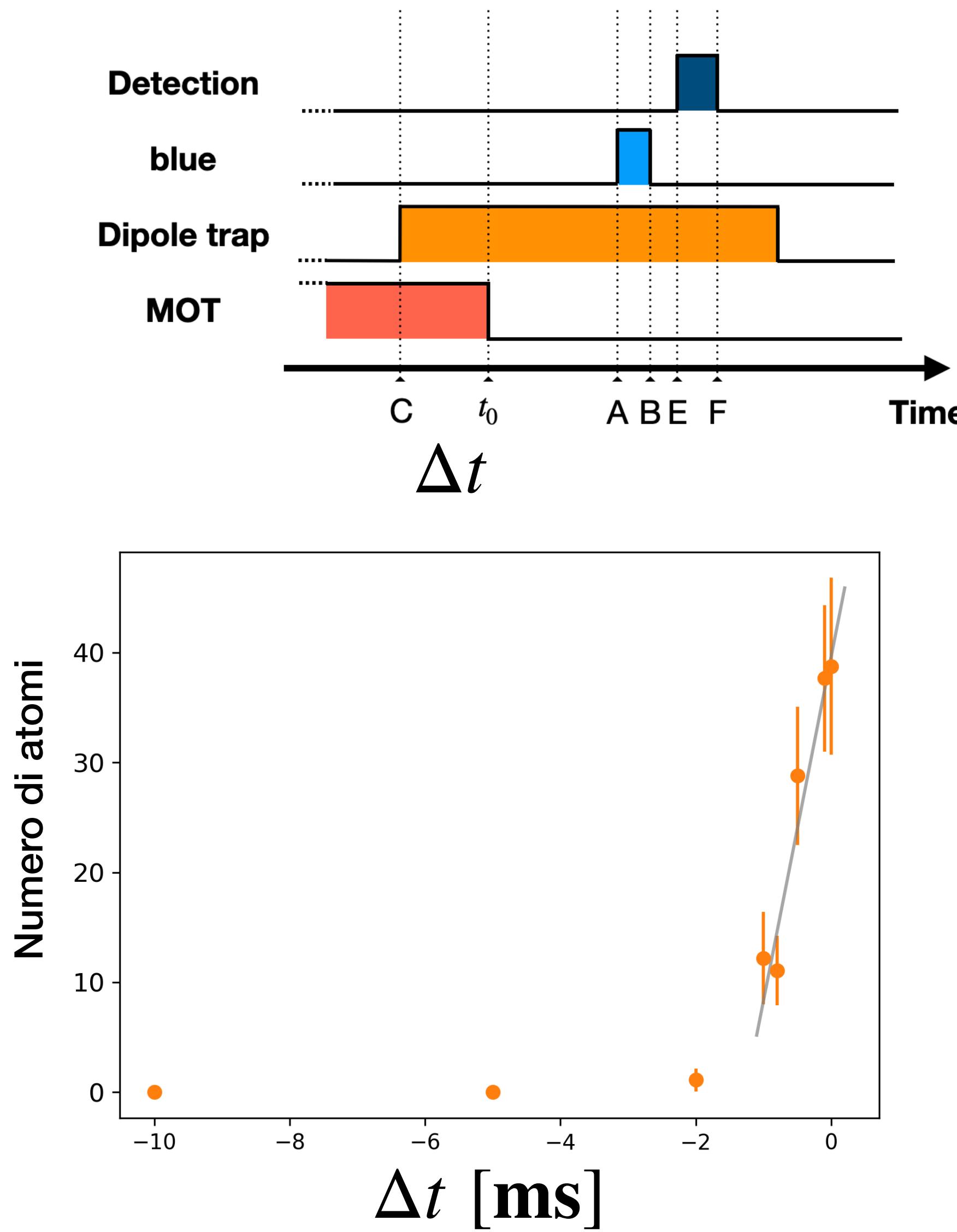
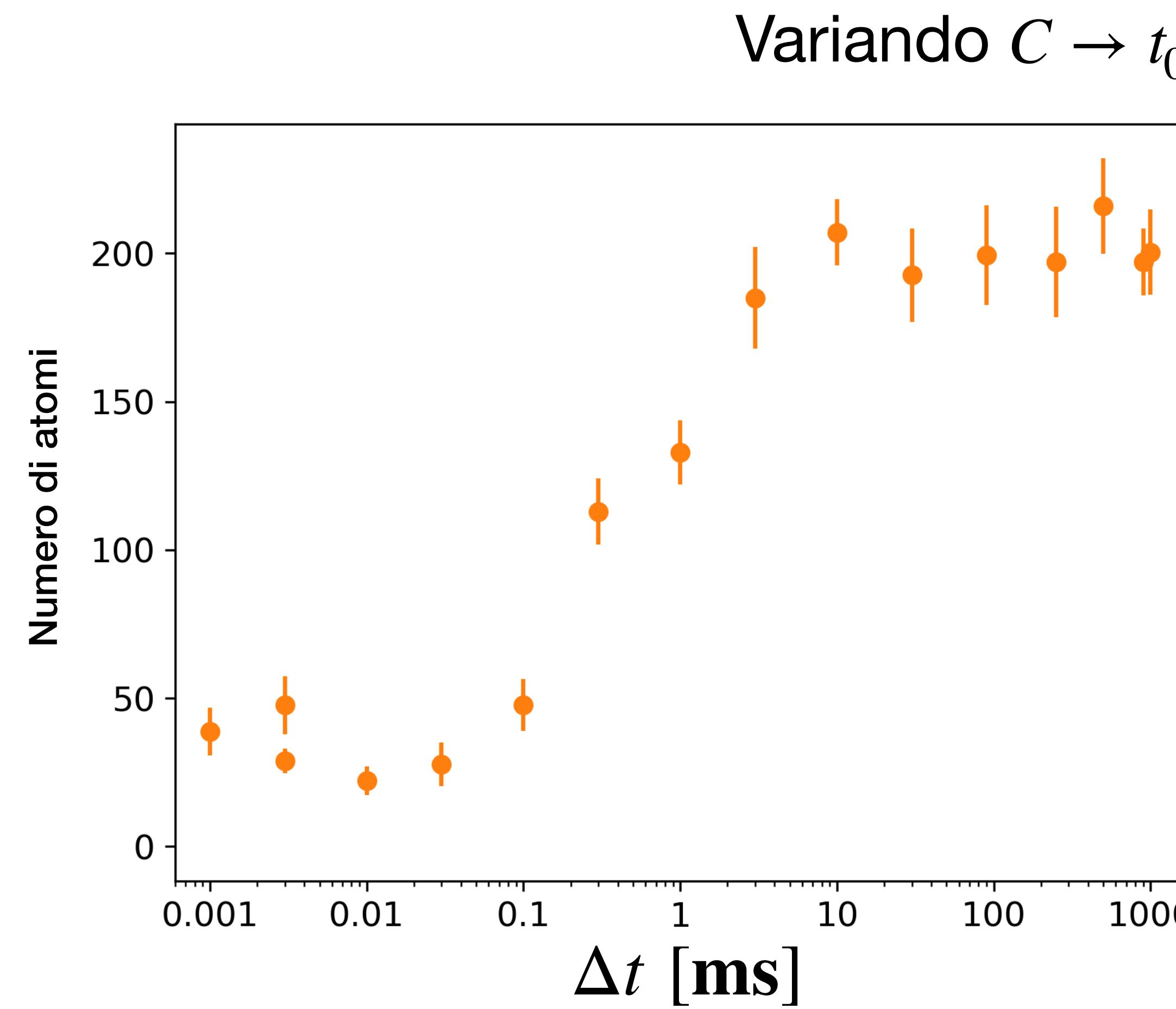
Caratterizzazione della Trappola Dipolare

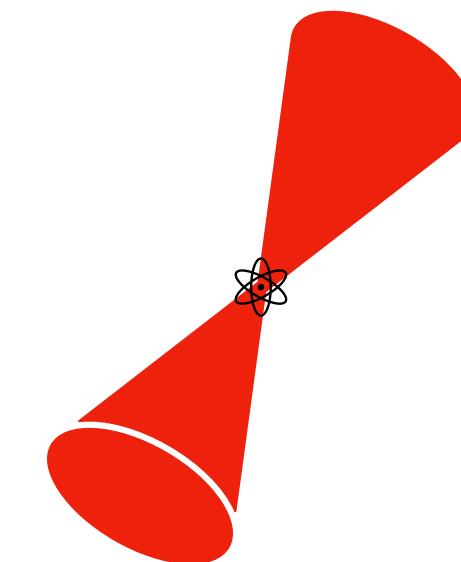
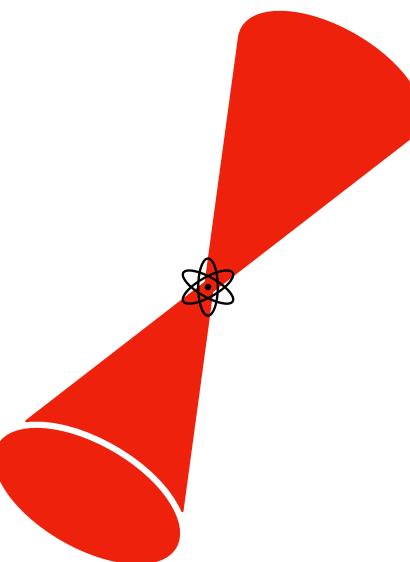
Domande:



- Quanti atomi intrappoliamo? 
- Tempo di riempimento?
- Come intrappolare un solo atomo?

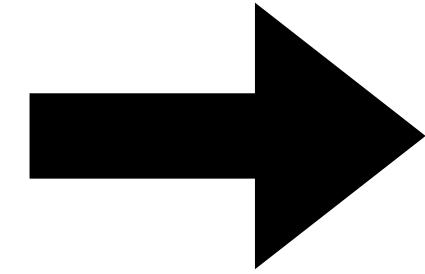
Tempo di riempimento





Caratterizzazione della Trappola Dipolare

Domande:



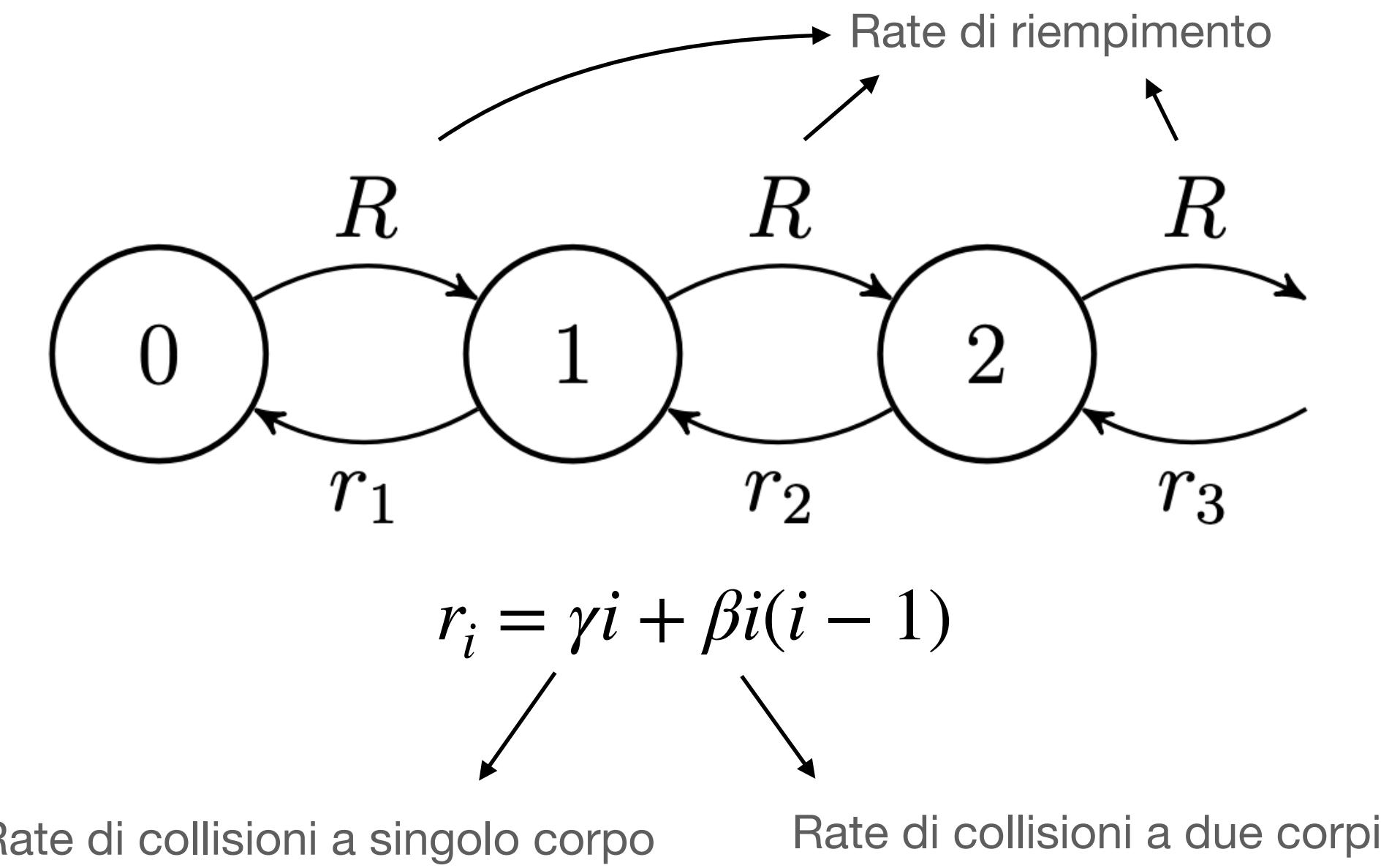
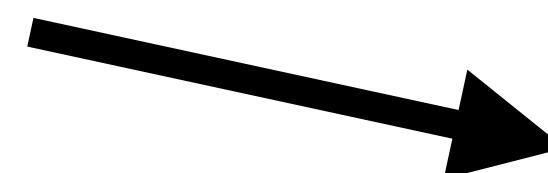
- Quanti atomi intrappoliamo? 
- Tempo di riempimento? 
- Come intrappolare un solo atomo?

Come intrappolare un singolo atomo?

Com'è distribuito il numero di atomi nello stato stazionario?

Nello stato stazionario:

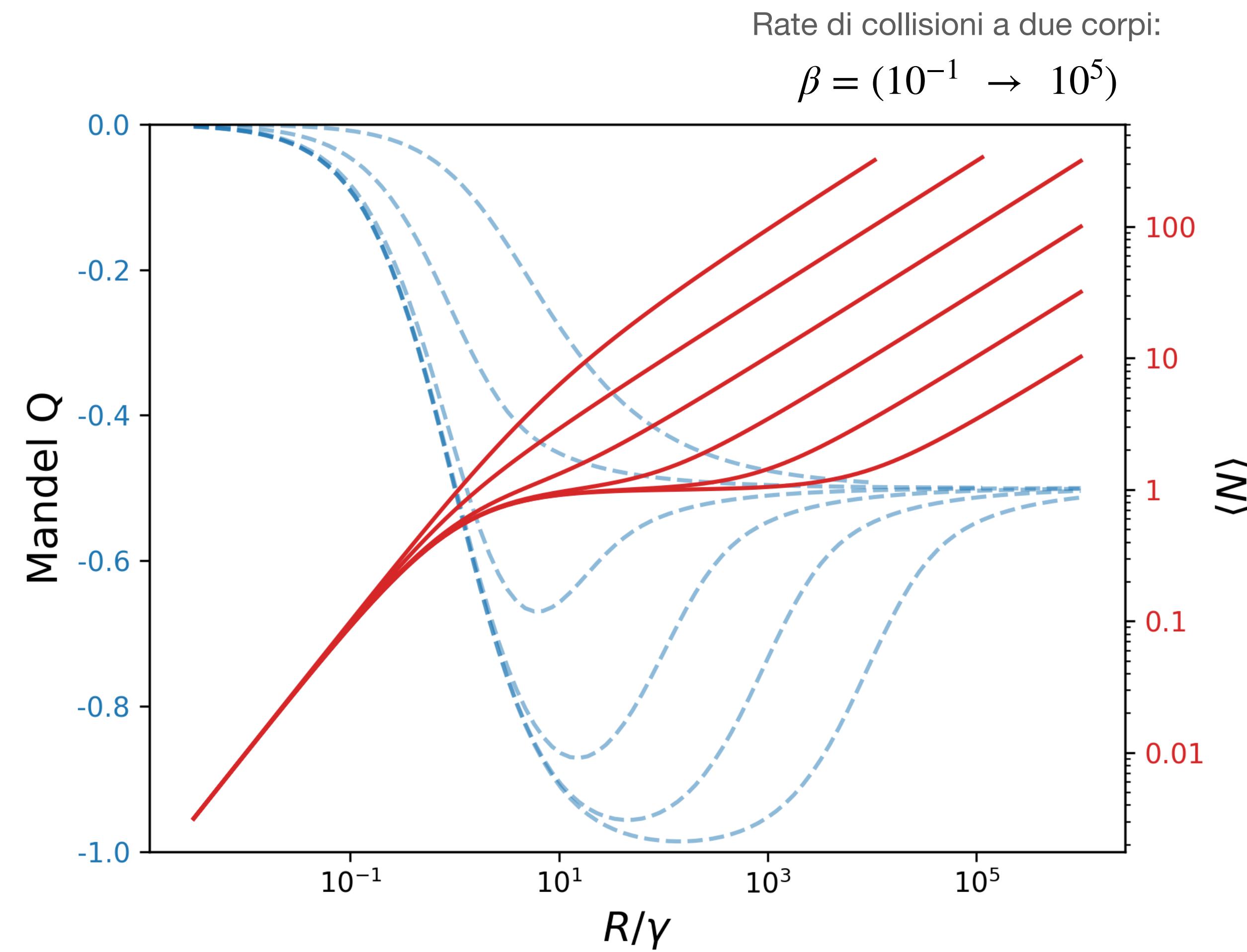
$$\frac{d}{dt} p_i = 0$$



$$p_i = \frac{\left(\sqrt{\frac{R}{\beta}}\right)^{2i+\gamma/\beta-1}}{\Gamma(i+1) \Gamma\left(\frac{\gamma}{\beta} + i\right) I_{\frac{\gamma}{\beta}-1}\left(2\sqrt{\frac{R}{\beta}}\right)}$$

Come intrappolare un singolo atomo?

$$\langle N \rangle = \sum_N N p_N$$



Rate di riempimento: R

Rate di collisioni a singolo corpo: γ

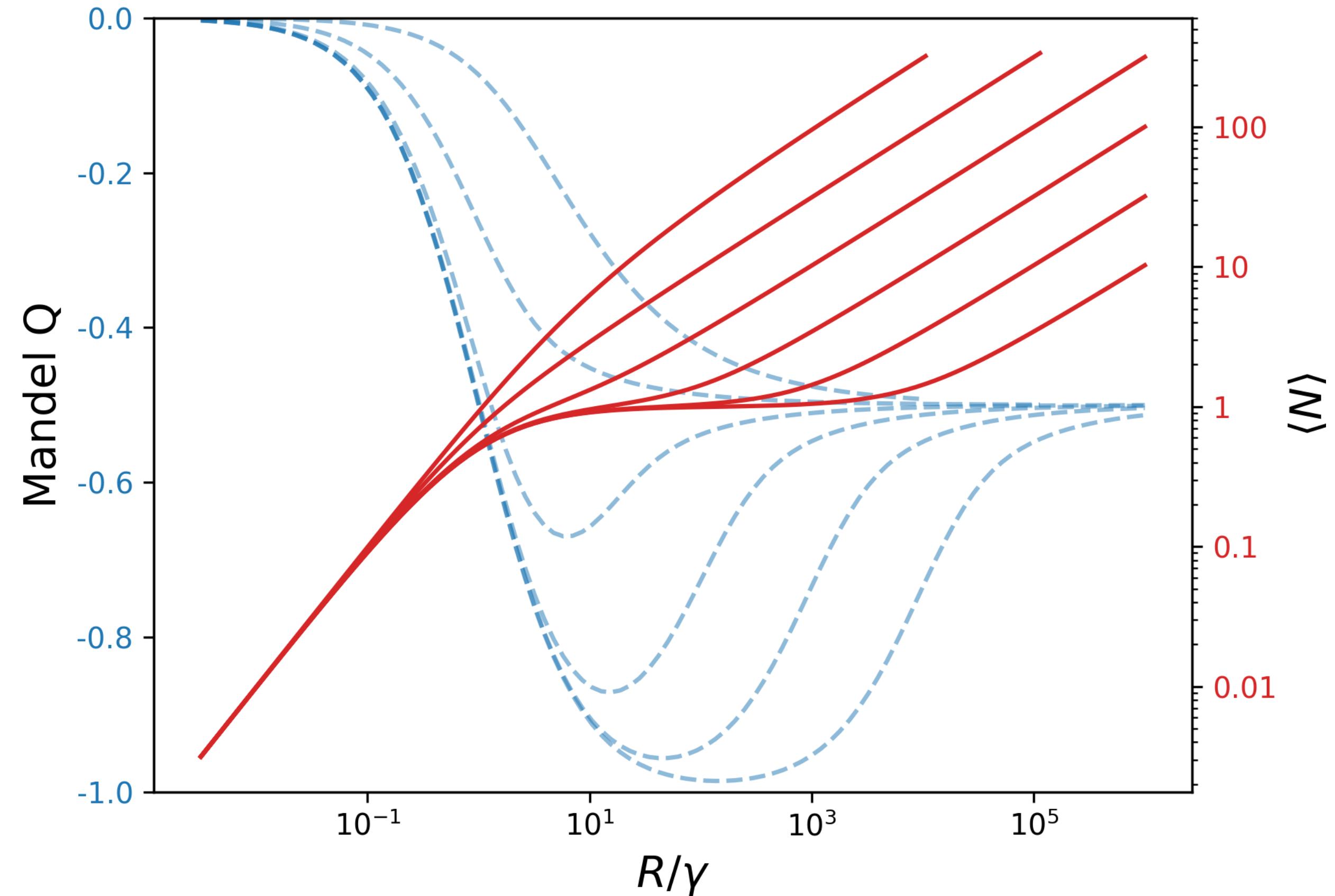
Come intrappolare un singolo atomo?

$$\langle N \rangle = \sum_N N p_N$$

$$\beta \propto w_0^{-4}$$

Rate di collisioni a due corpi:

$$\beta = (10^{-1} \rightarrow 10^5)$$



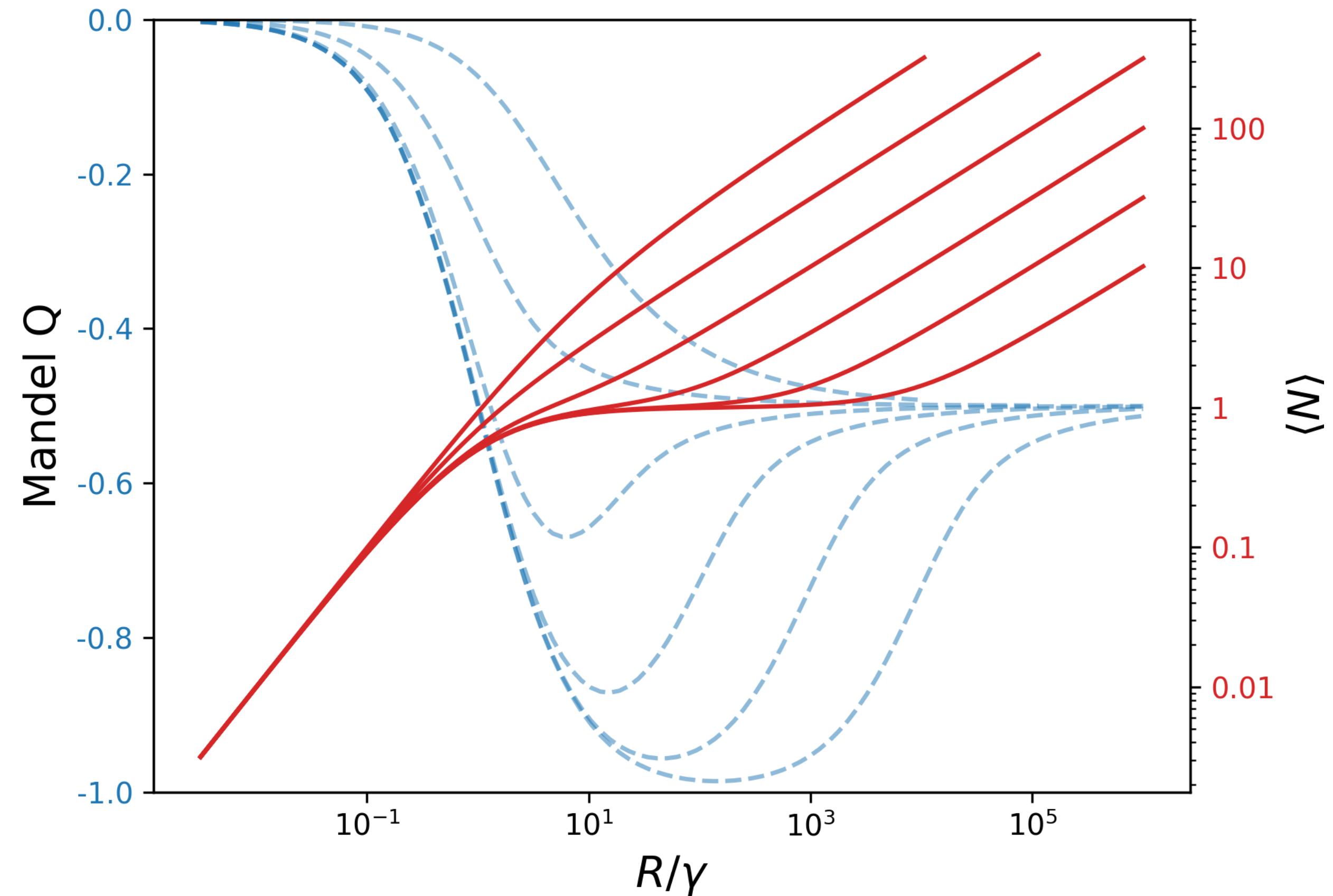
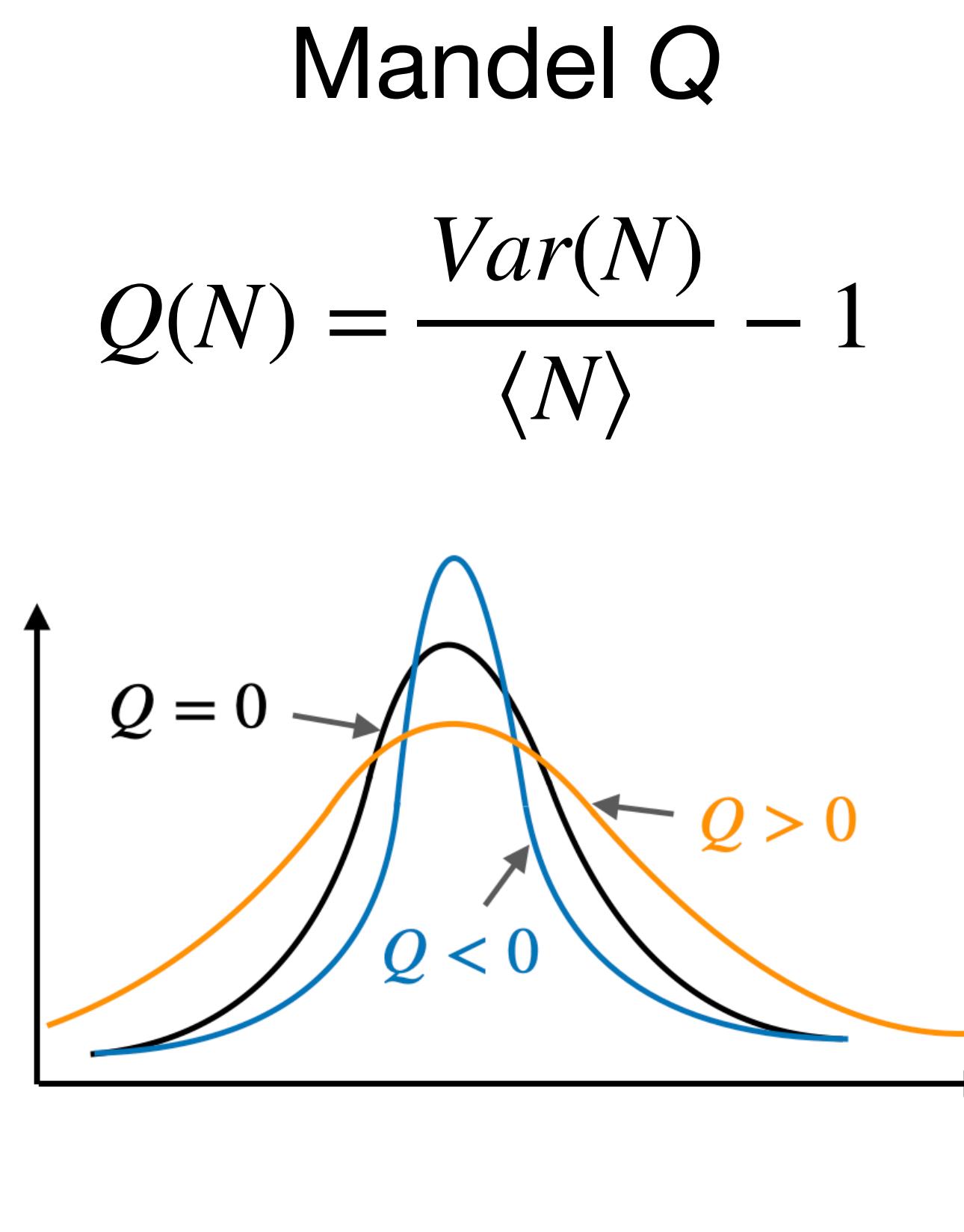
Rate di riempimento: R

Rate di collisioni a singolo corpo: γ

Come intrappolare un singolo atomo?

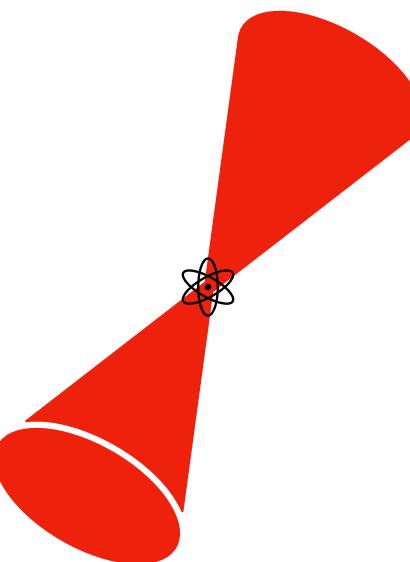
Rate di collisioni a due corpi:

$$\beta = (10^{-1} \rightarrow 10^5)$$

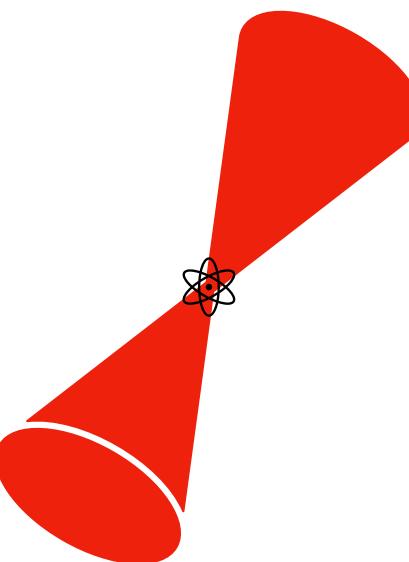


Rate di riempimento: R

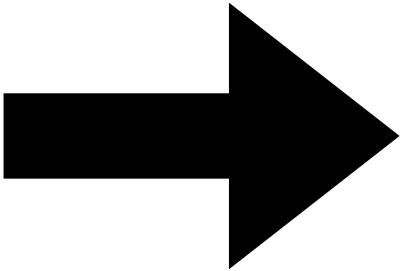
Rate di collisioni a singolo corpo: γ



Caratterizzazione della Trappola Dipolare

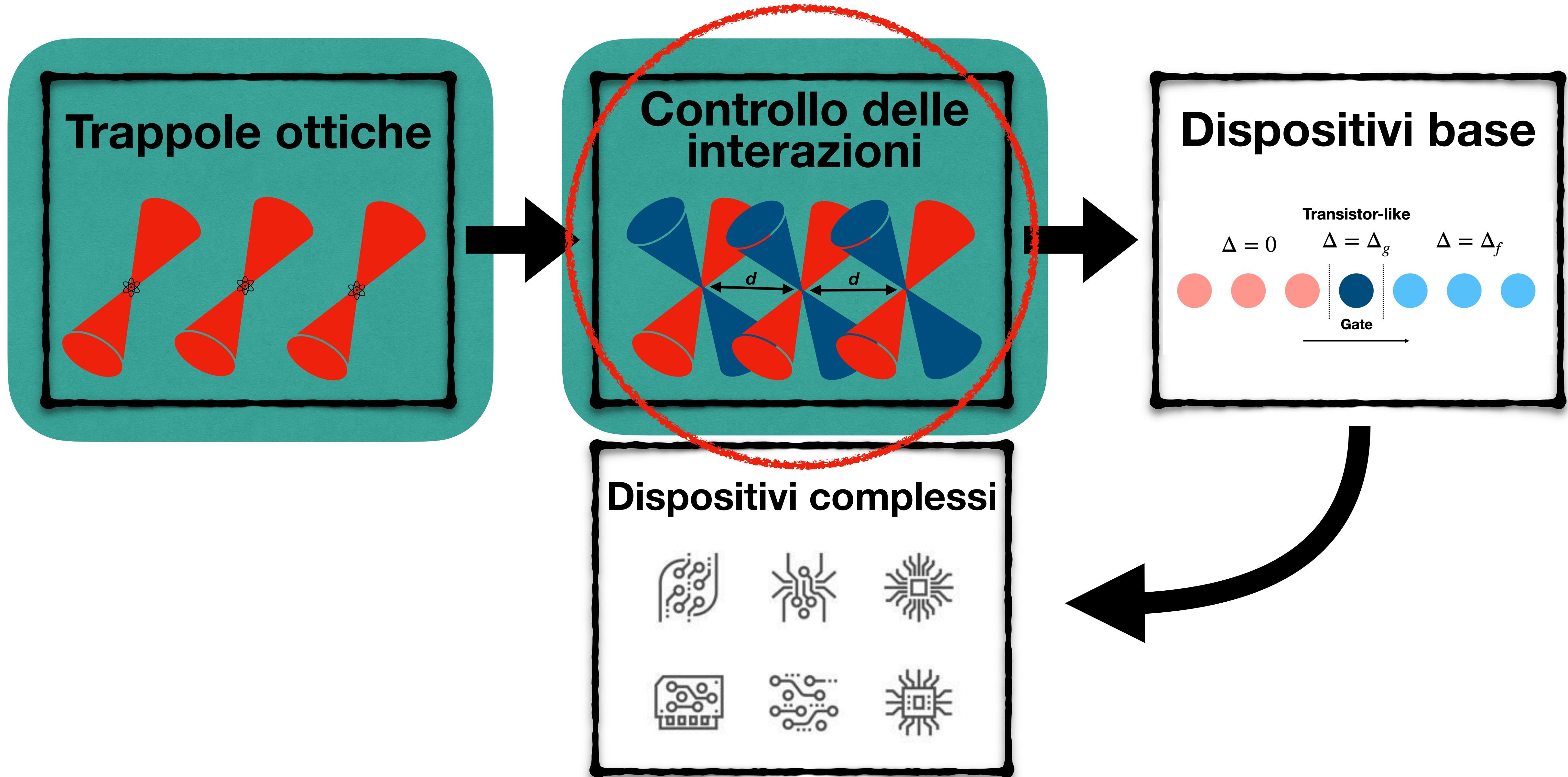


Domande:



- Quanti atomi intrappoliamo? 
- Tempo di riempimento? 
- Come intrappolare un solo atomo? 

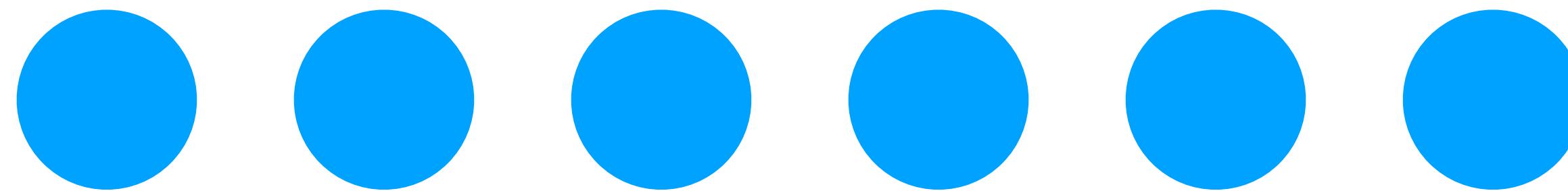
Tabella di marcia



Obiettivo

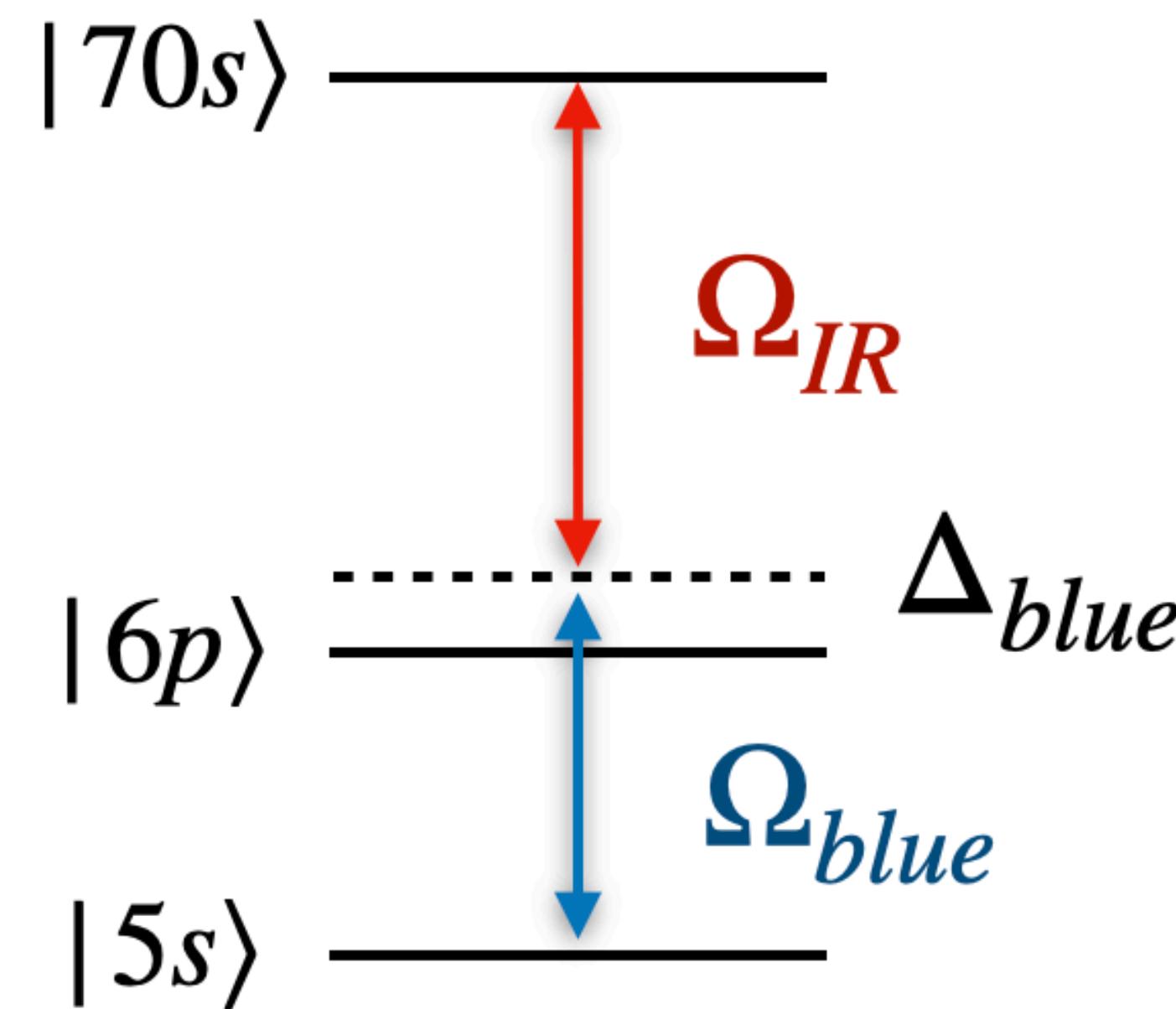
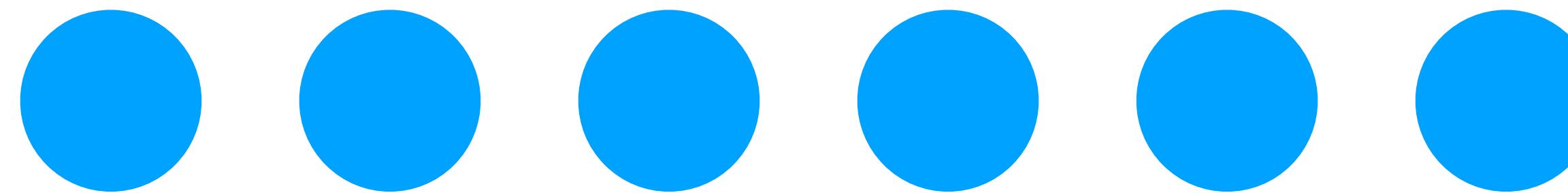
- 1) Realizzare il setup per il controllo dello stato interno
- 2) Testarlo sugli atomi

Controllo della propagazione dell'eccitazione



Controllo della propagazione dell'eccitazione

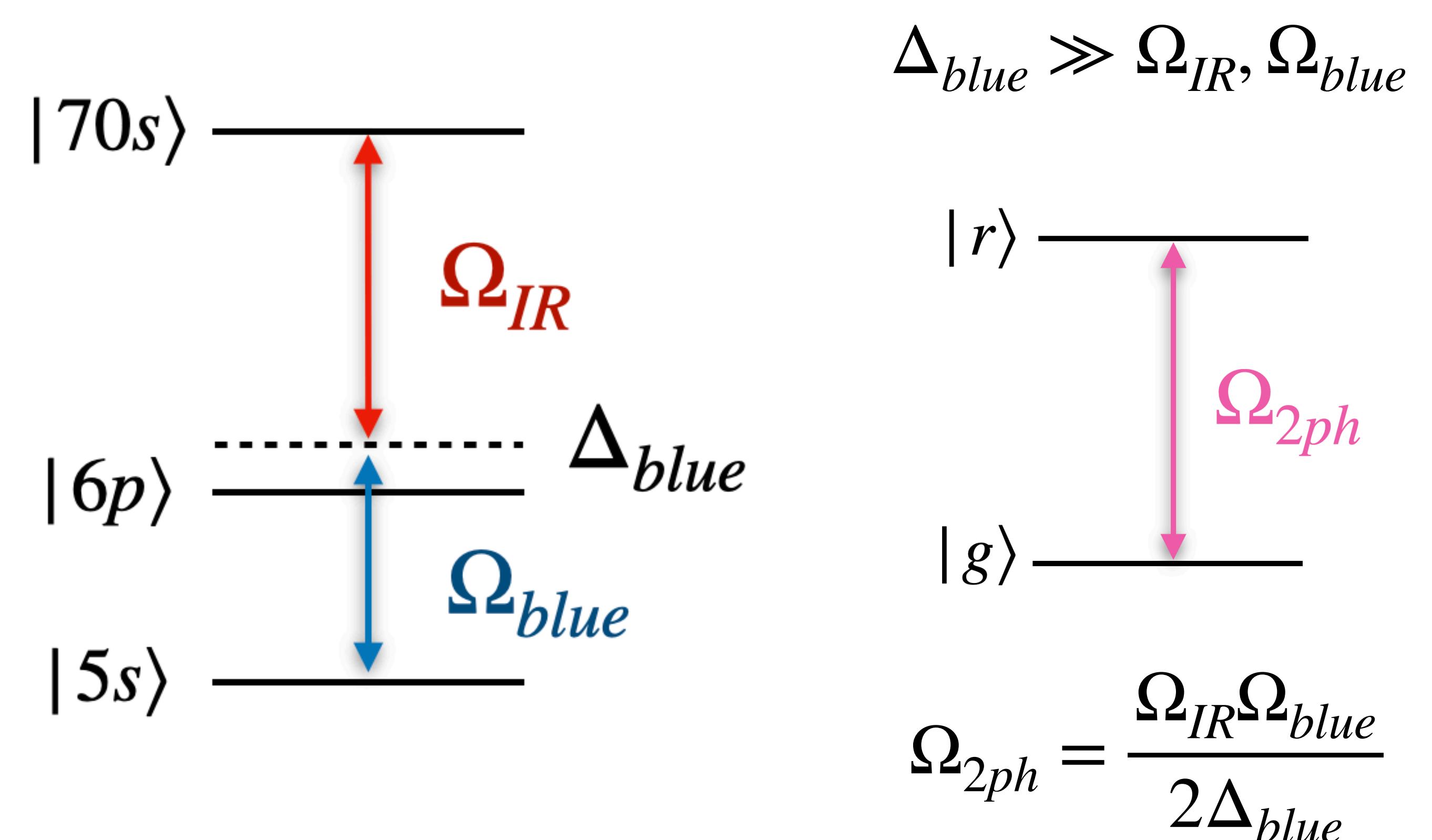
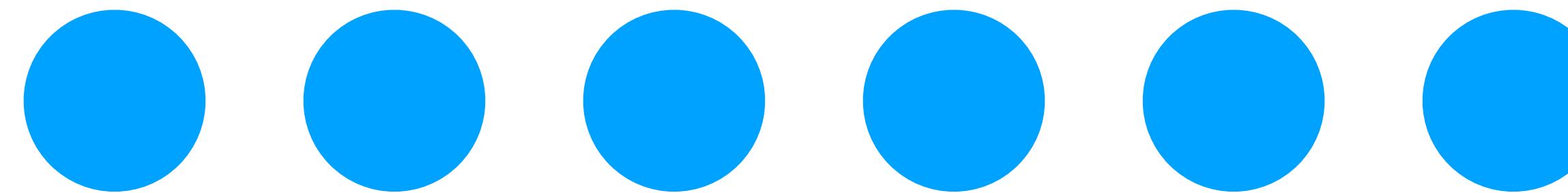
Canale di eccitazione
 $|5s\rangle \rightarrow |70s\rangle$



Controllo della propagazione dell'eccitazione

Canale di eccitazione

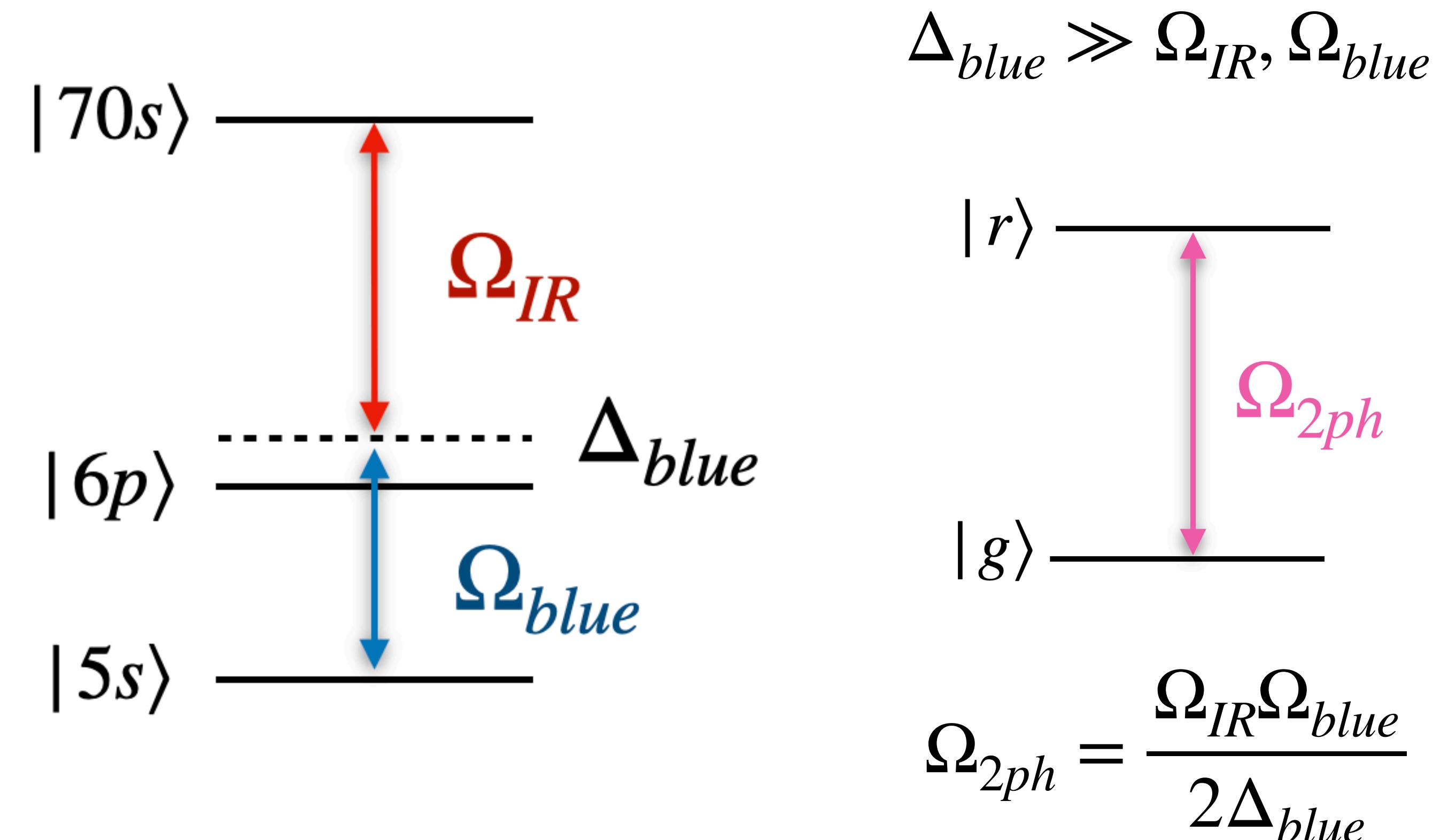
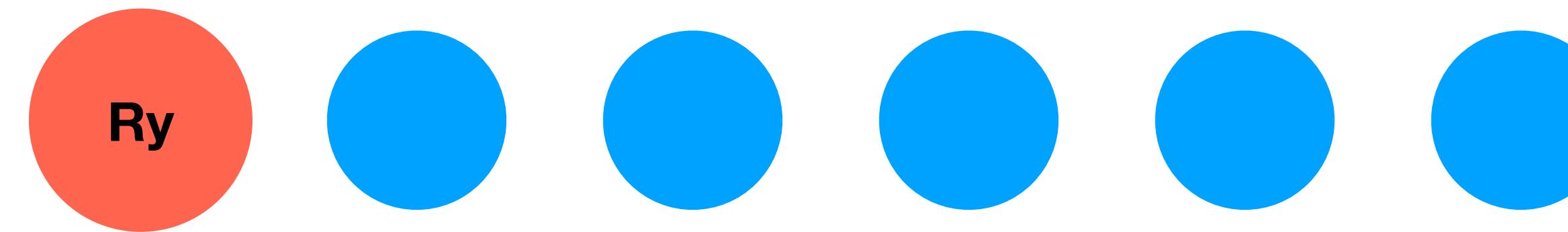
$$|5s\rangle \rightarrow |70s\rangle$$



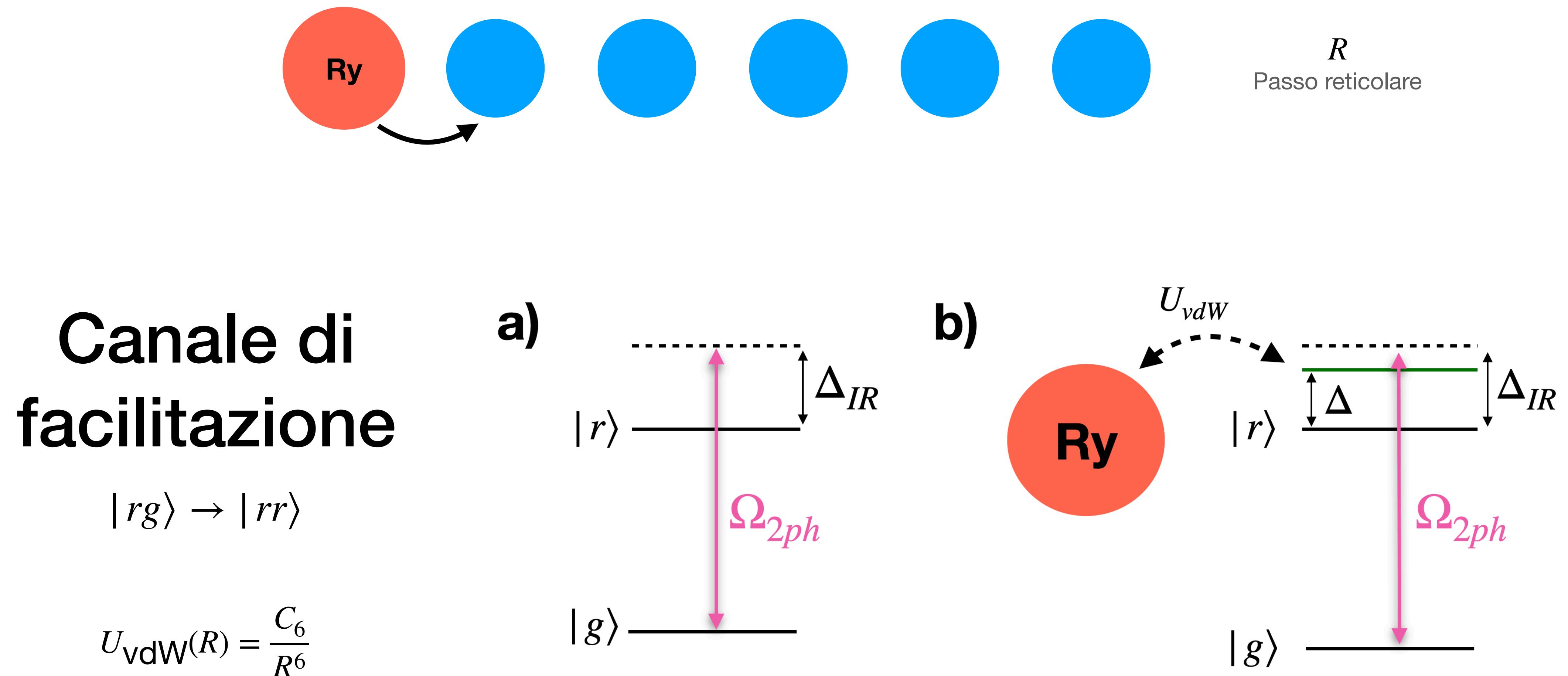
Controllo della propagazione dell'eccitazione

Canale di eccitazione

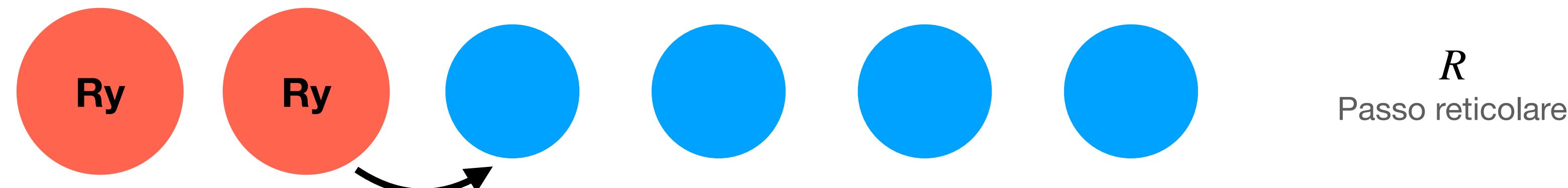
$$|5s\rangle \rightarrow |70s\rangle$$



Controllo della propagazione dell'eccitazione



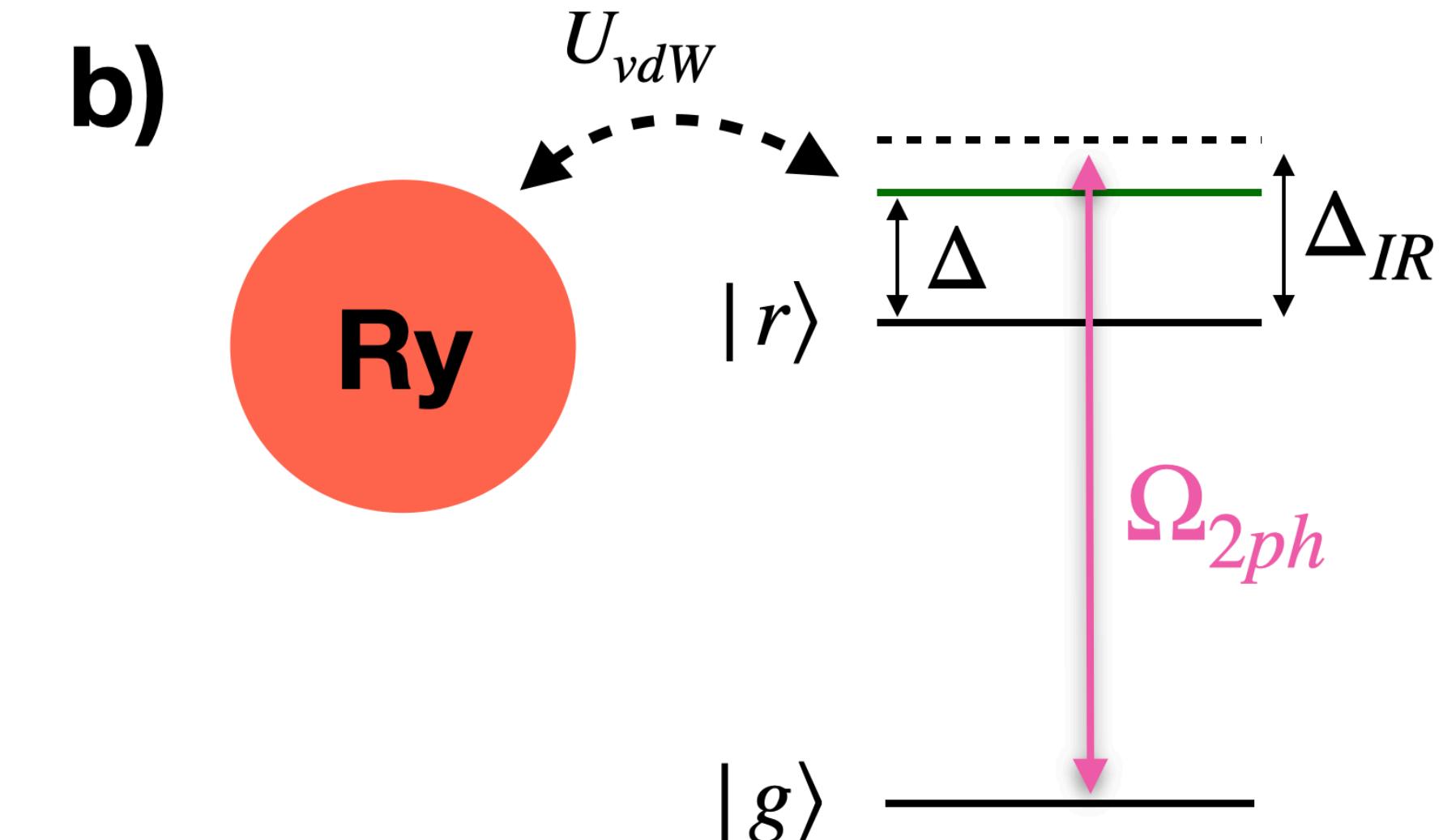
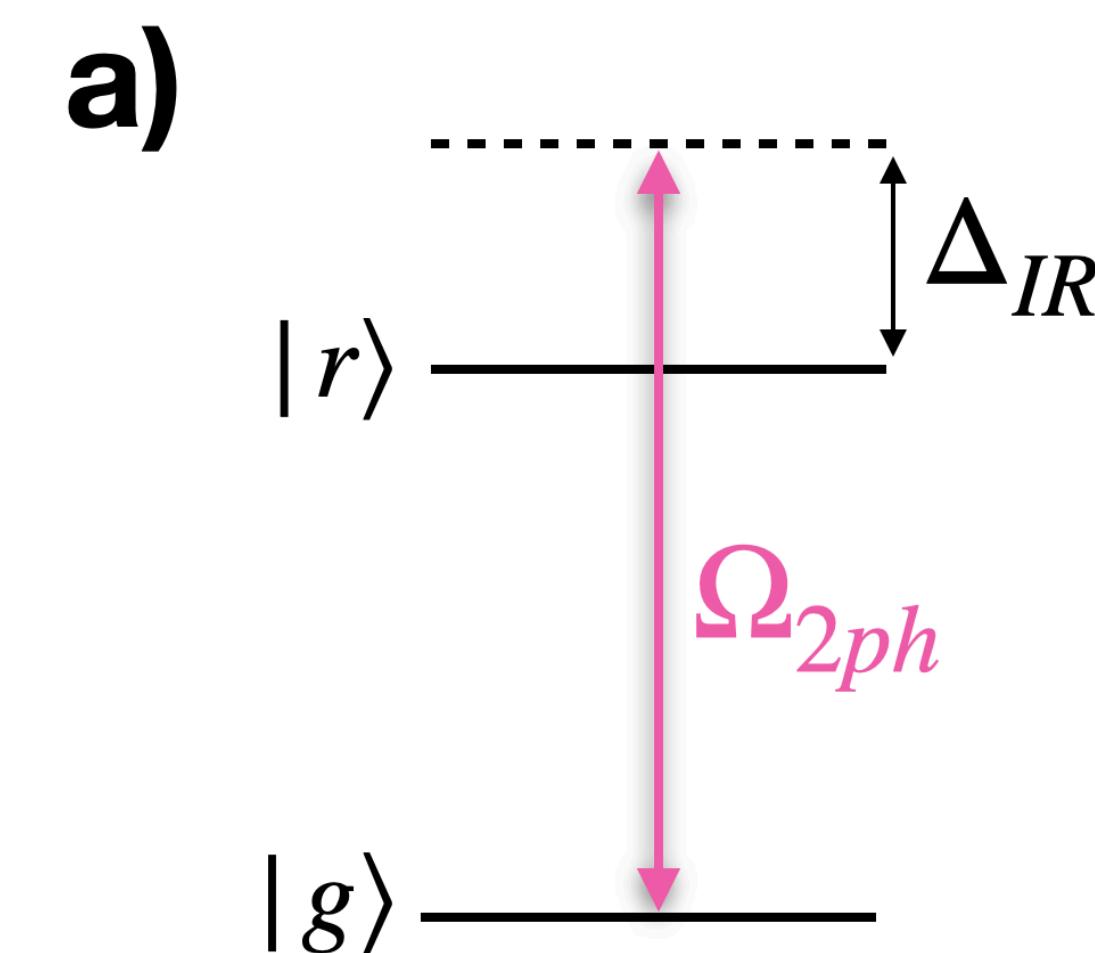
Controllo della propagazione dell'eccitazione



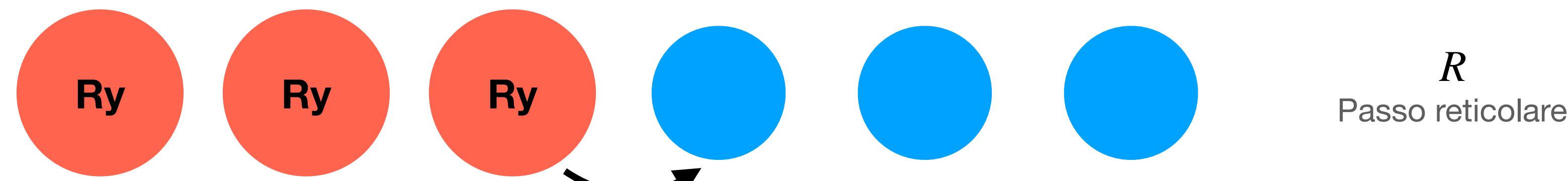
Canale di
facilitazione

$$|rg\rangle \rightarrow |rr\rangle$$

$$U_{vdW}(R) = \frac{C_6}{R^6}$$



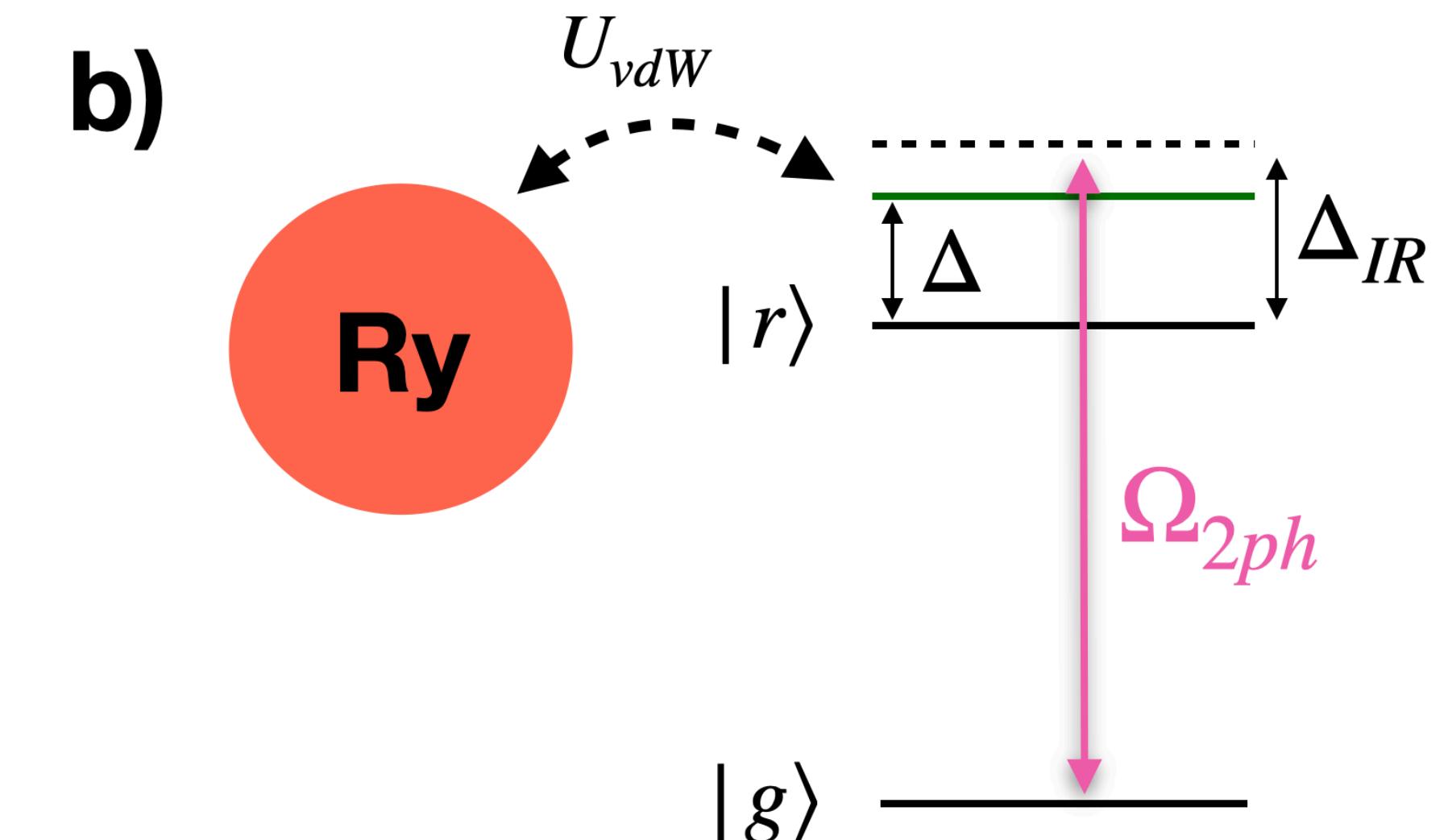
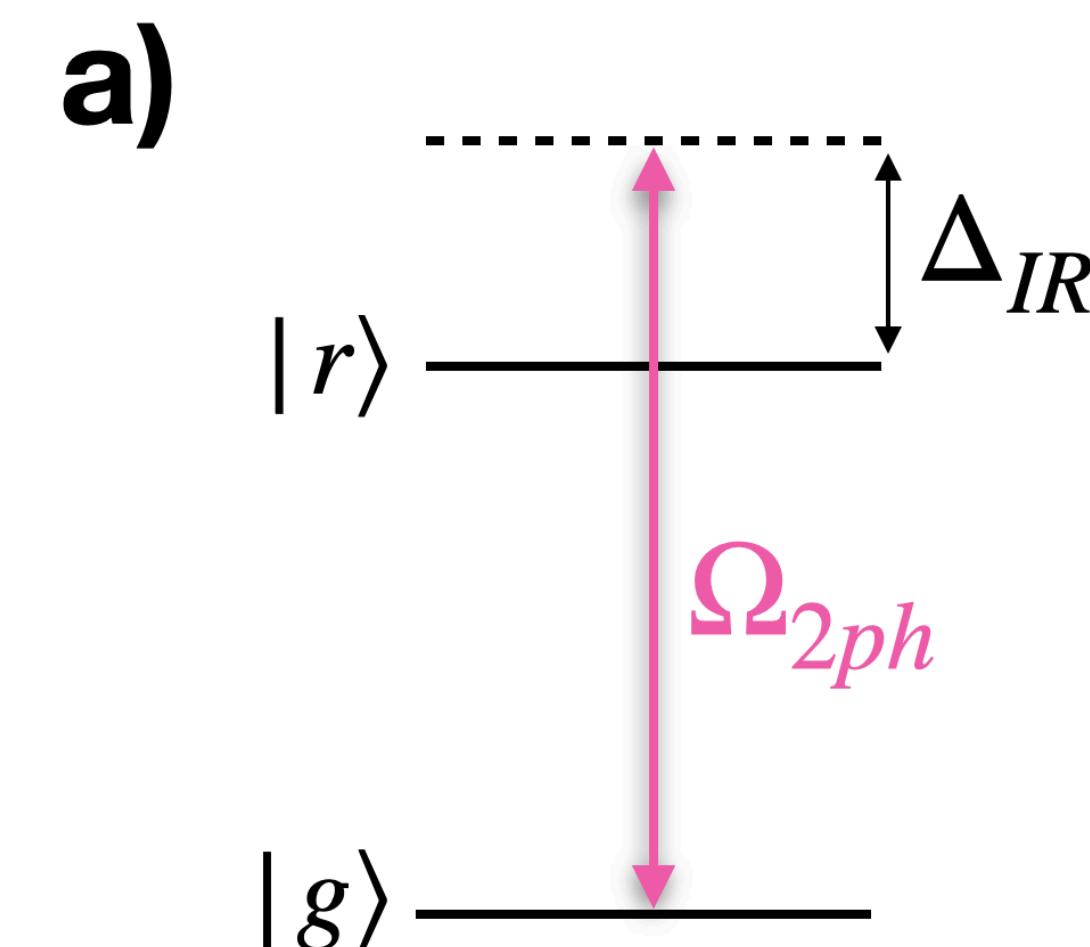
Controllo della propagazione dell'eccitazione



Canale di
facilitazione

$$|rg\rangle \rightarrow |rr\rangle$$

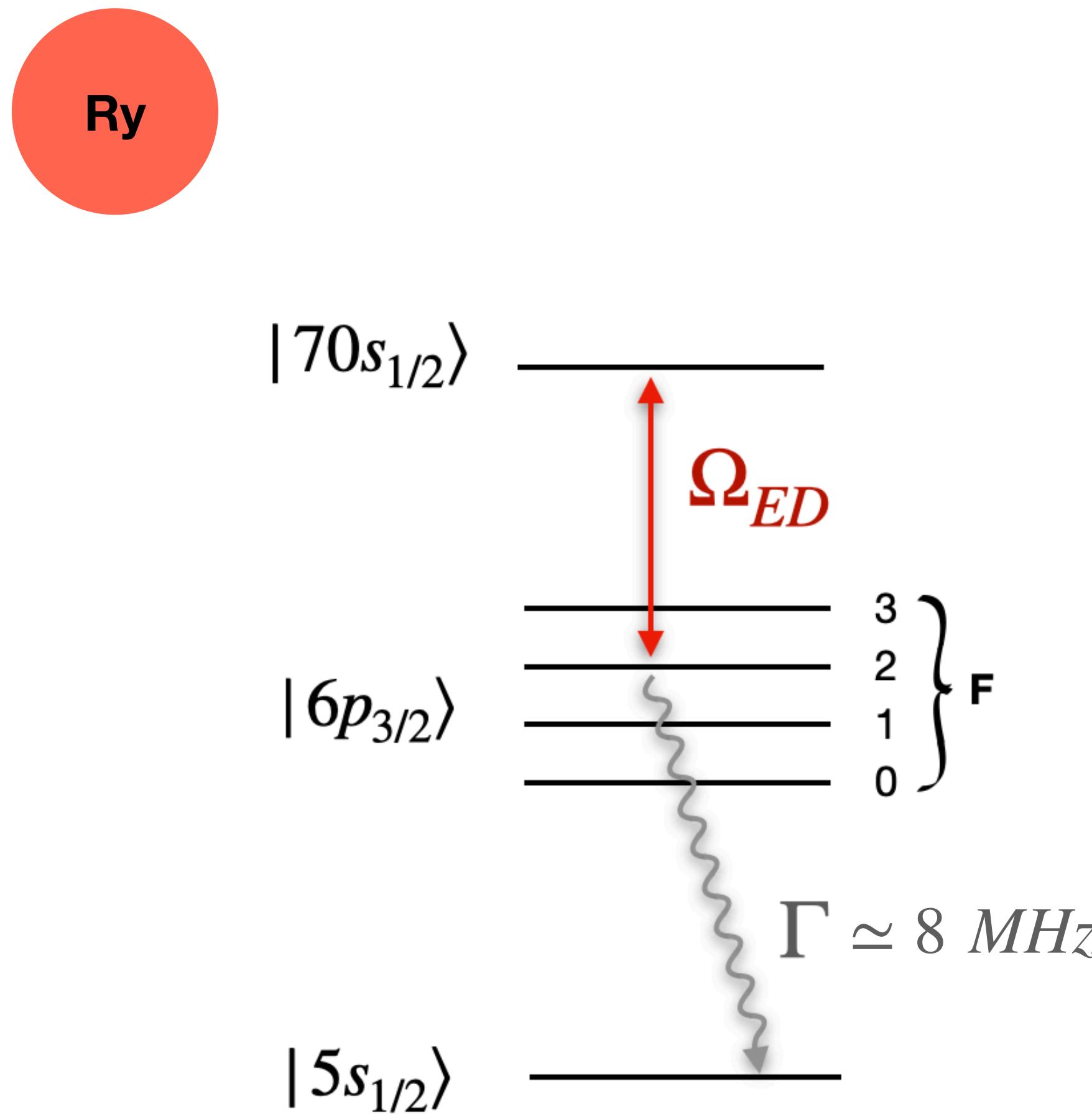
$$U_{vdW}(R) = \frac{C_6}{R^6}$$



Controllo della propagazione dell'eccitazione

Canale di dissipazione

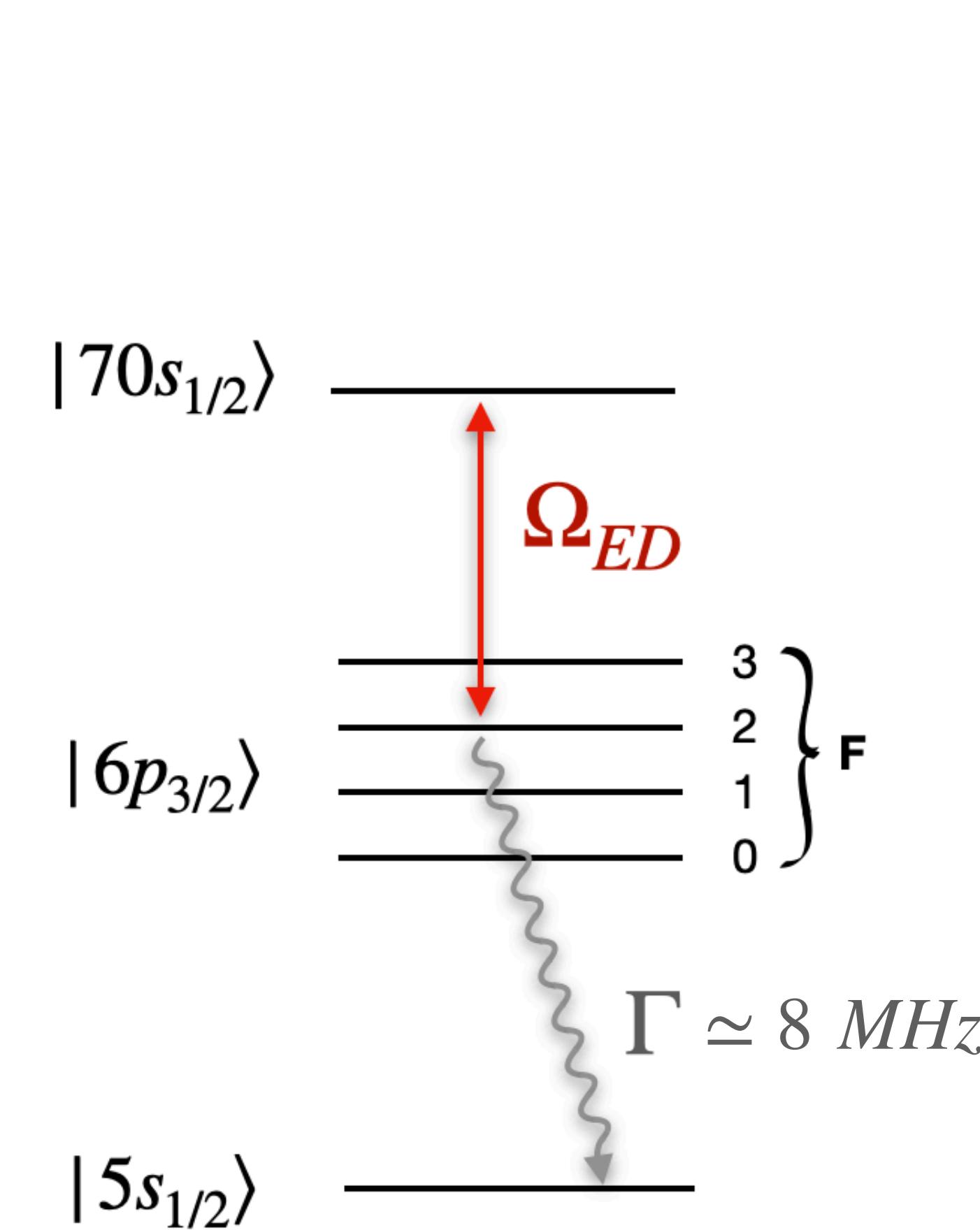
$$|70s\rangle \rightarrow |5s\rangle$$



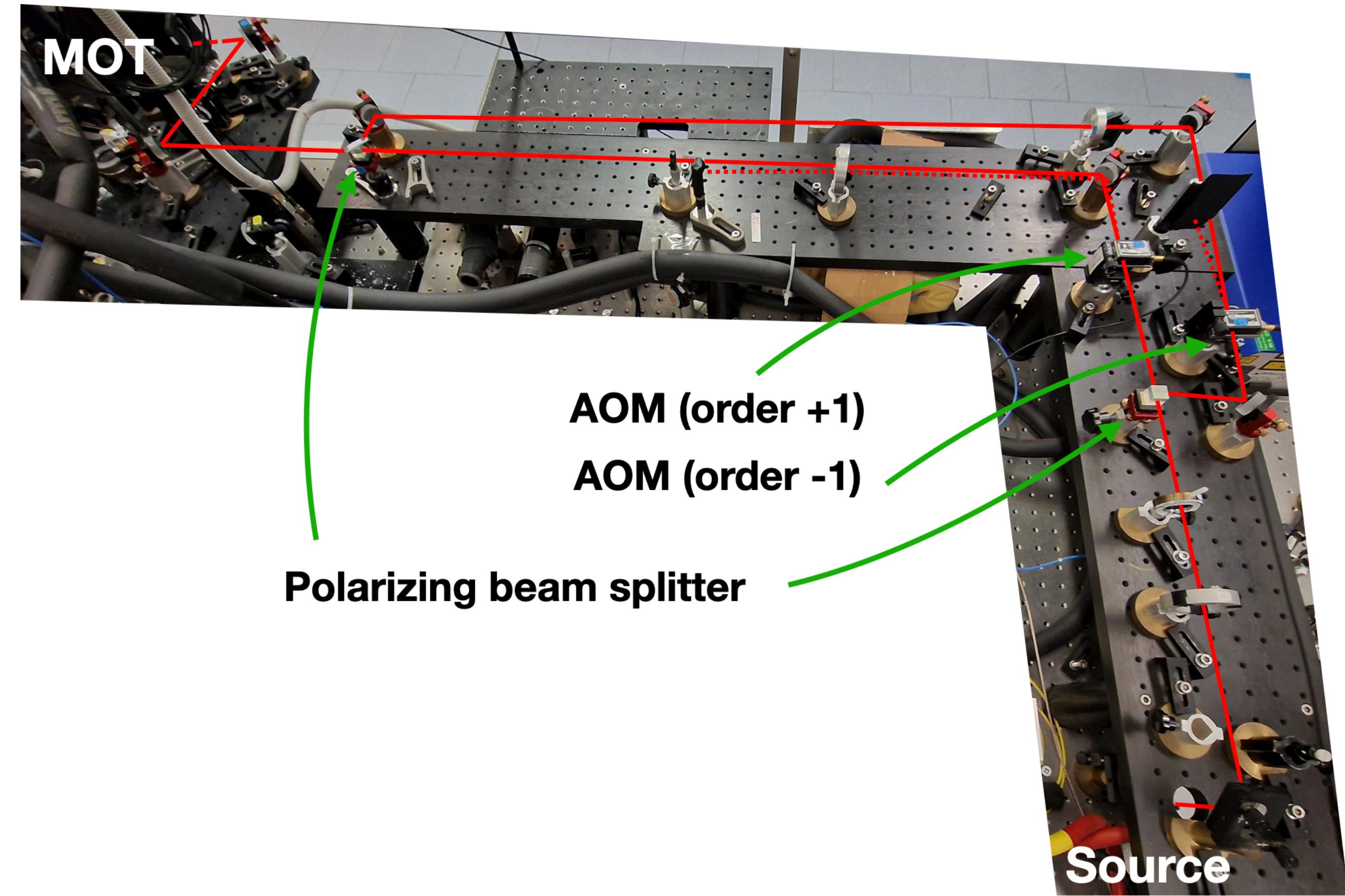
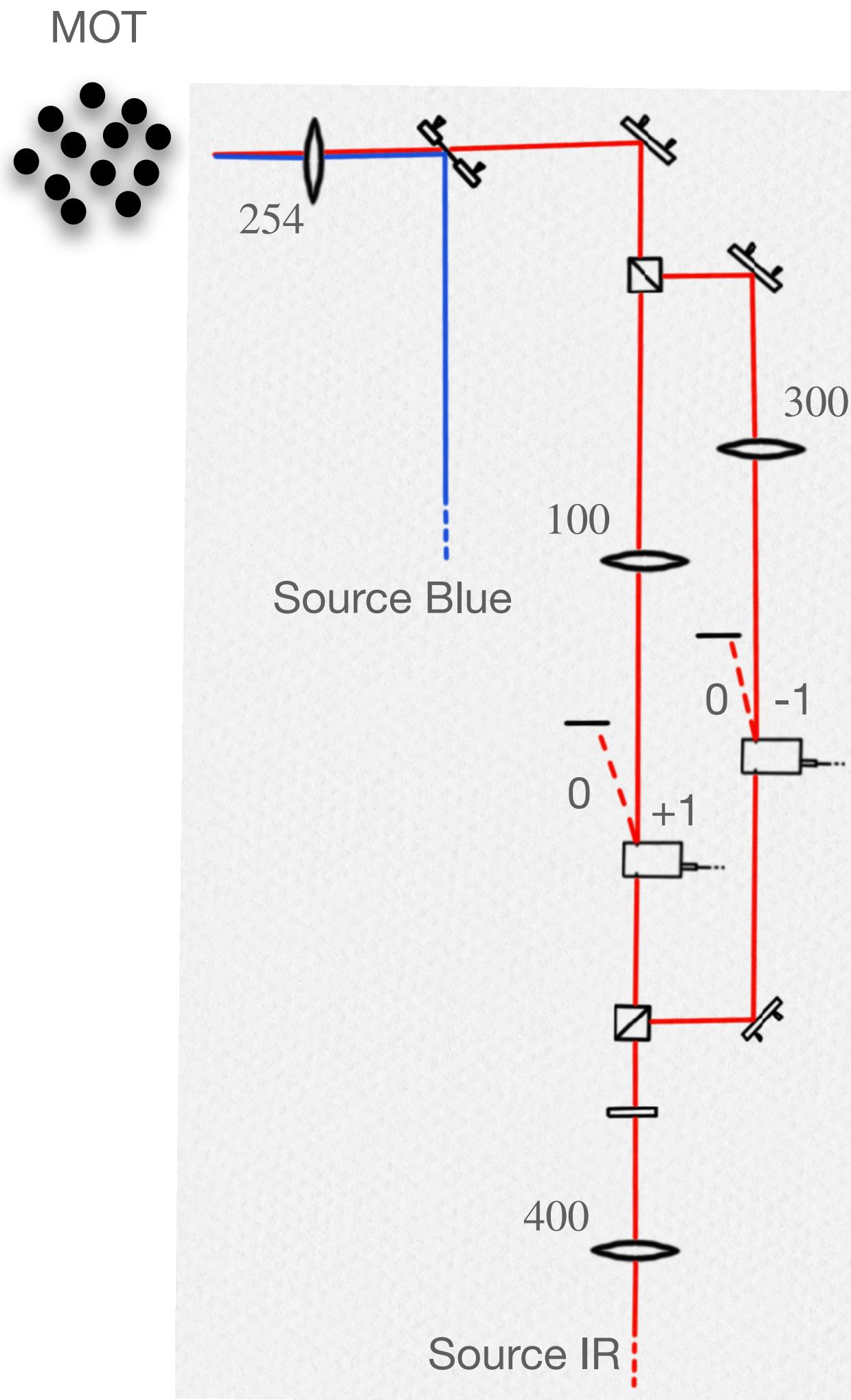
Controllo della propagazione dell'eccitazione

Canale di dissipazione

$$|70s\rangle \rightarrow |5s\rangle$$

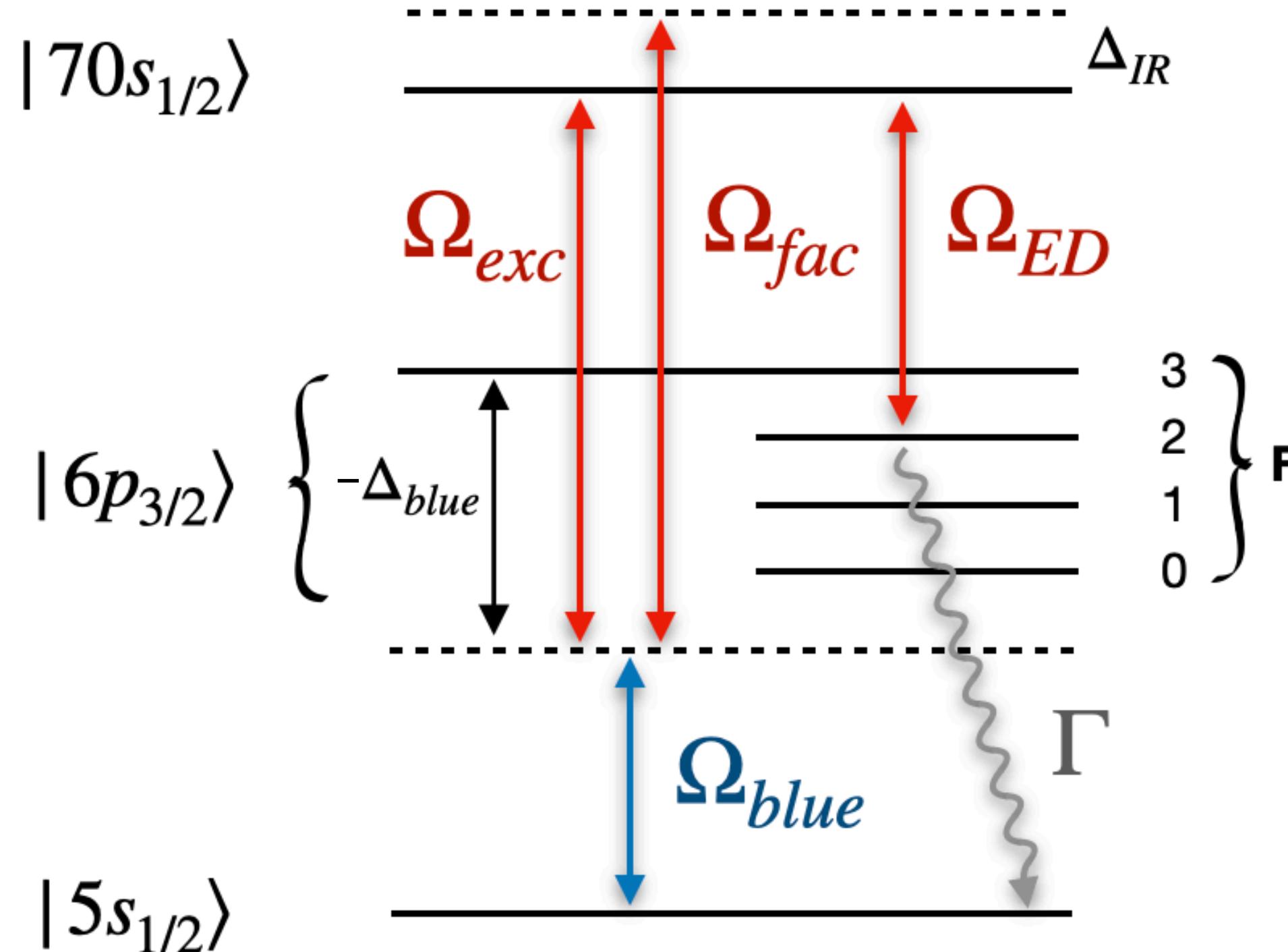
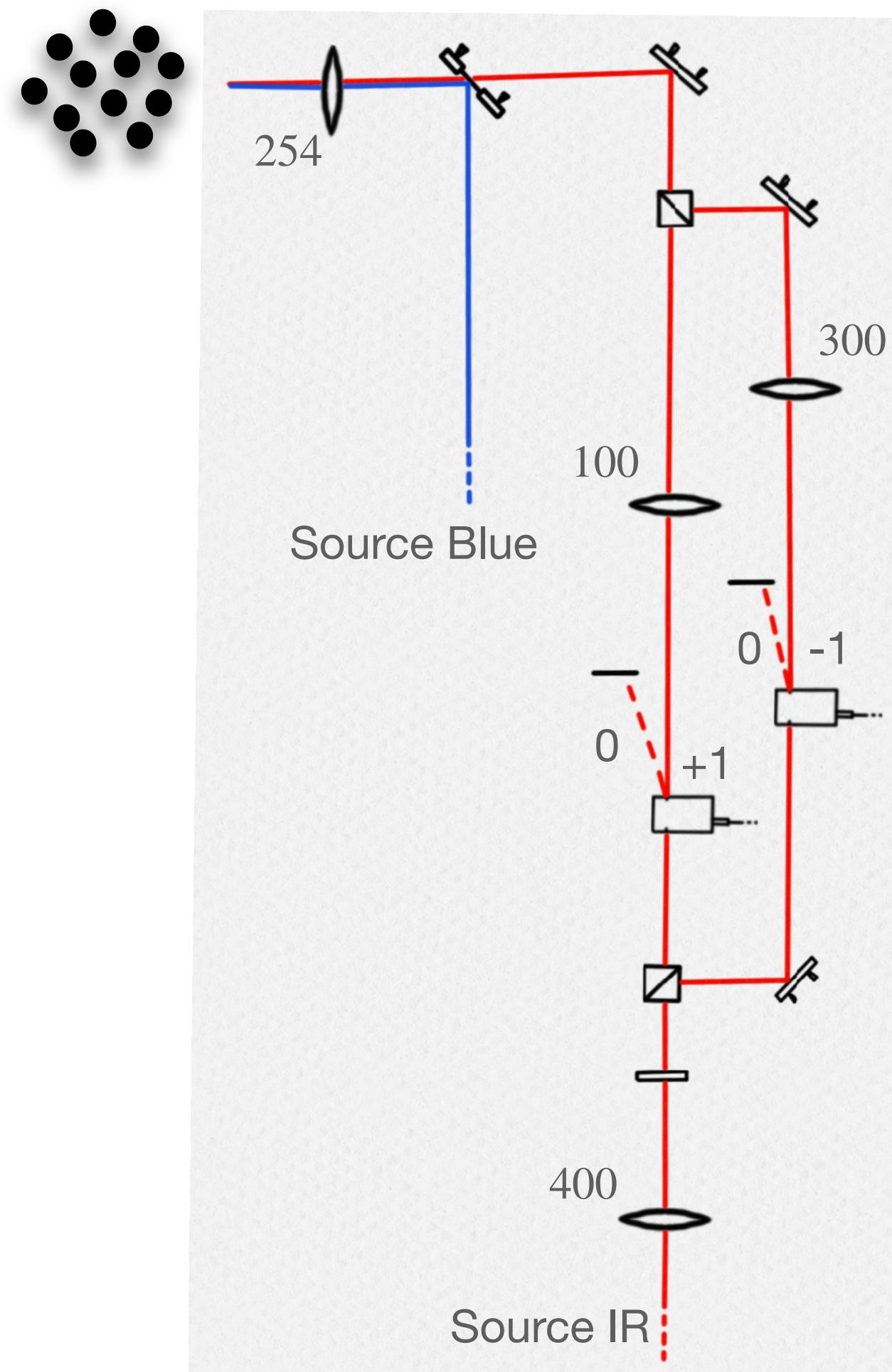


Set-up sperimentale



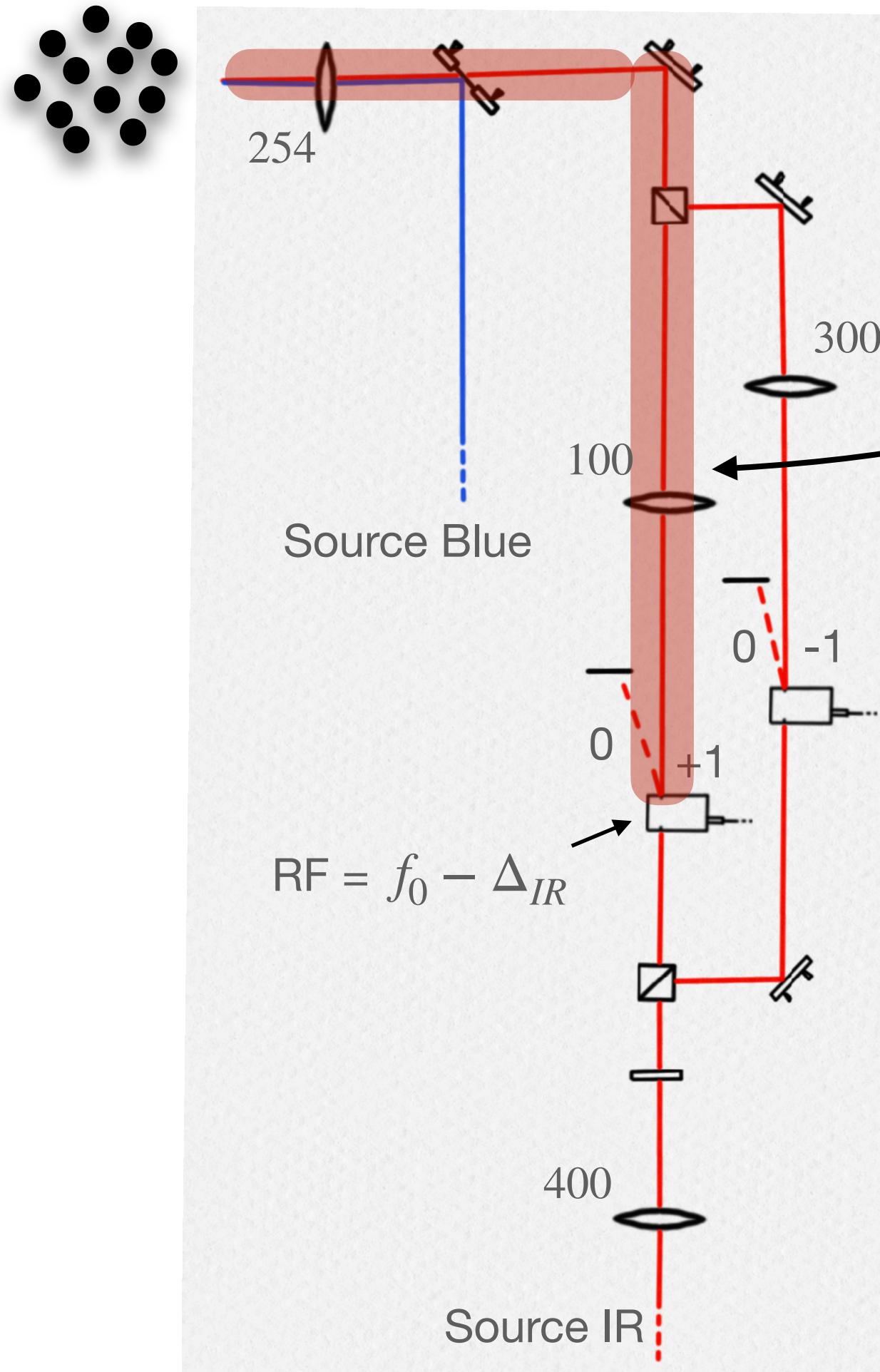
Set-up sperimentale

MOT

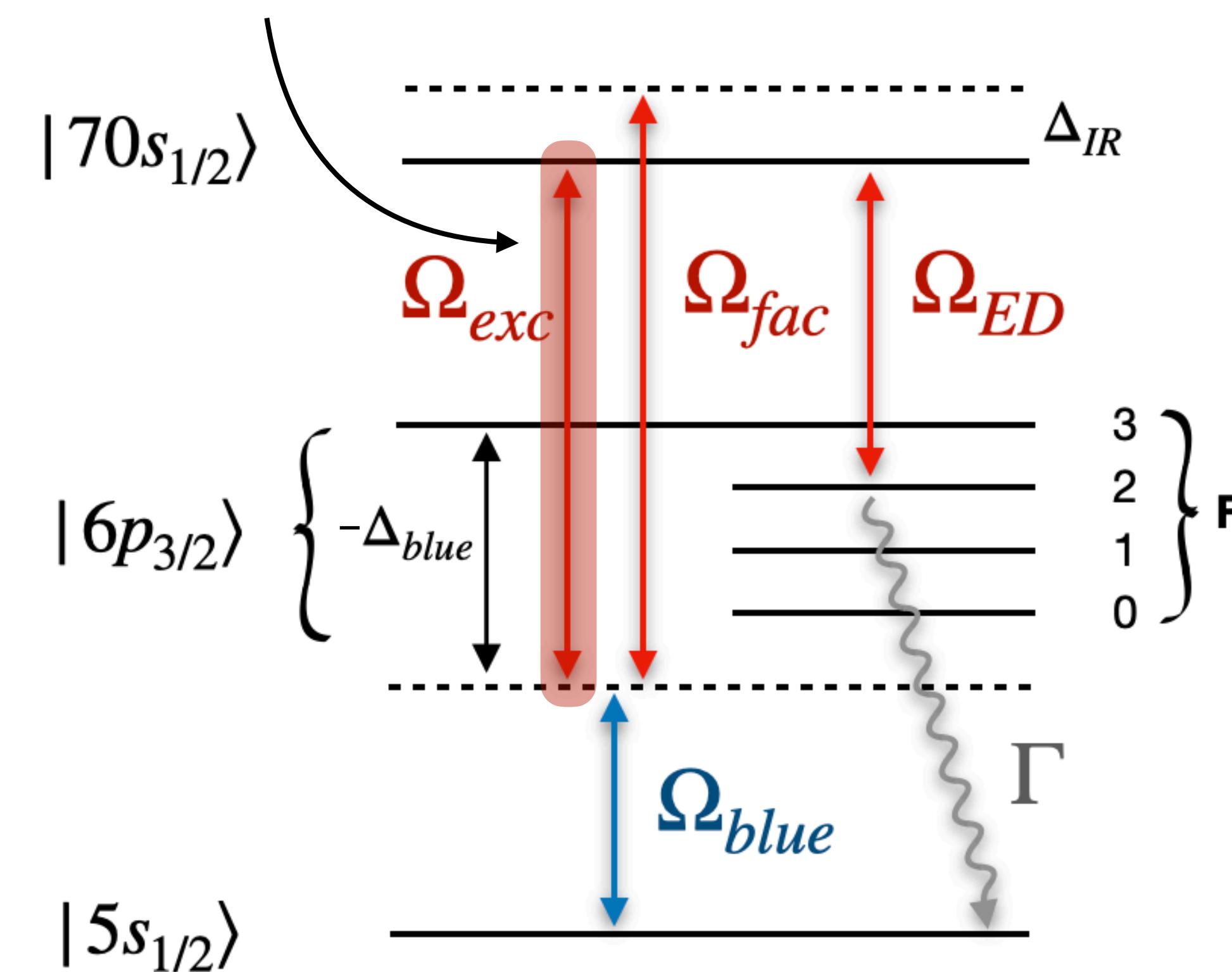


Set-up sperimentale

MOT

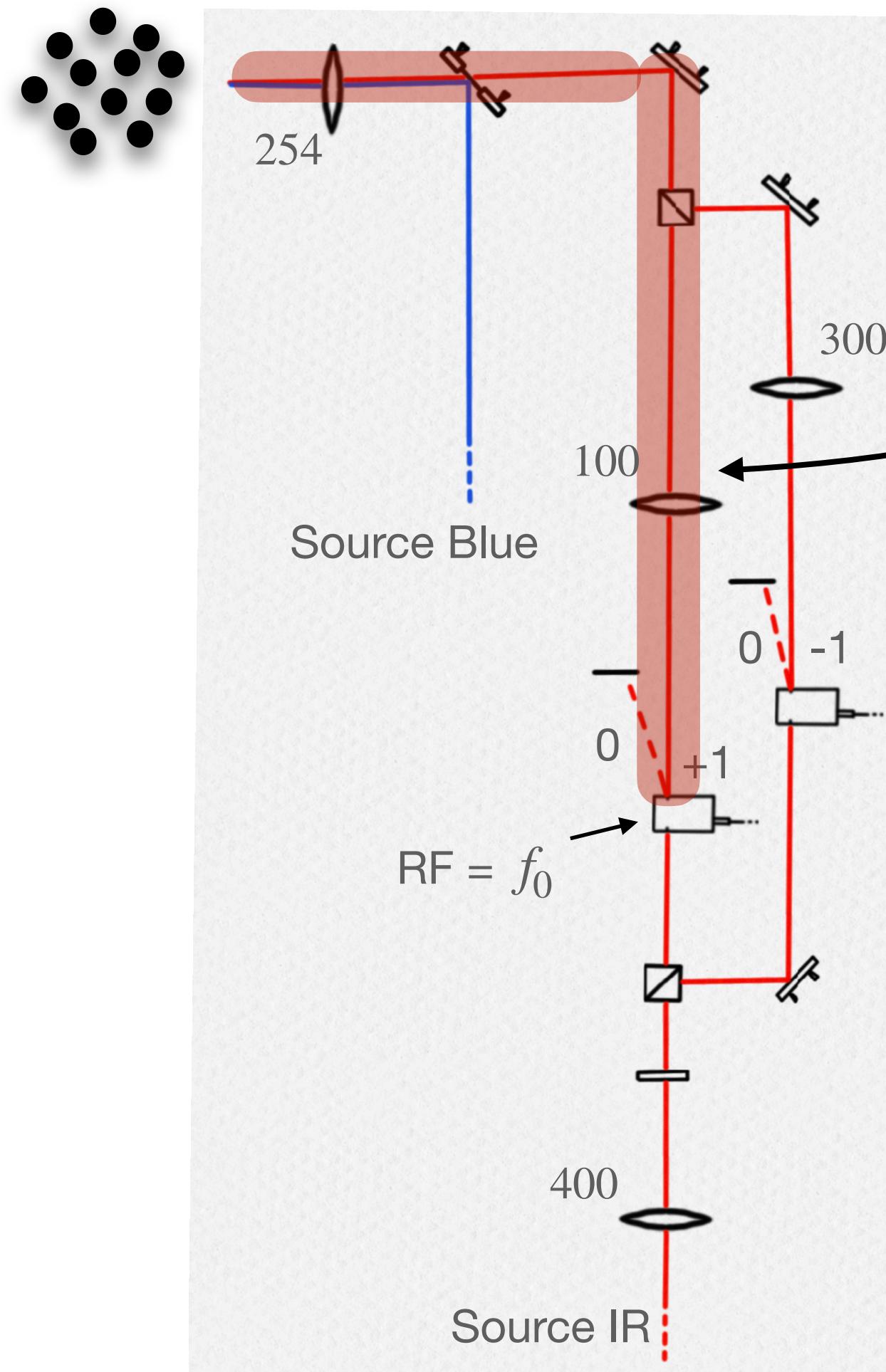


(f_0 is the AOMs central freq.)

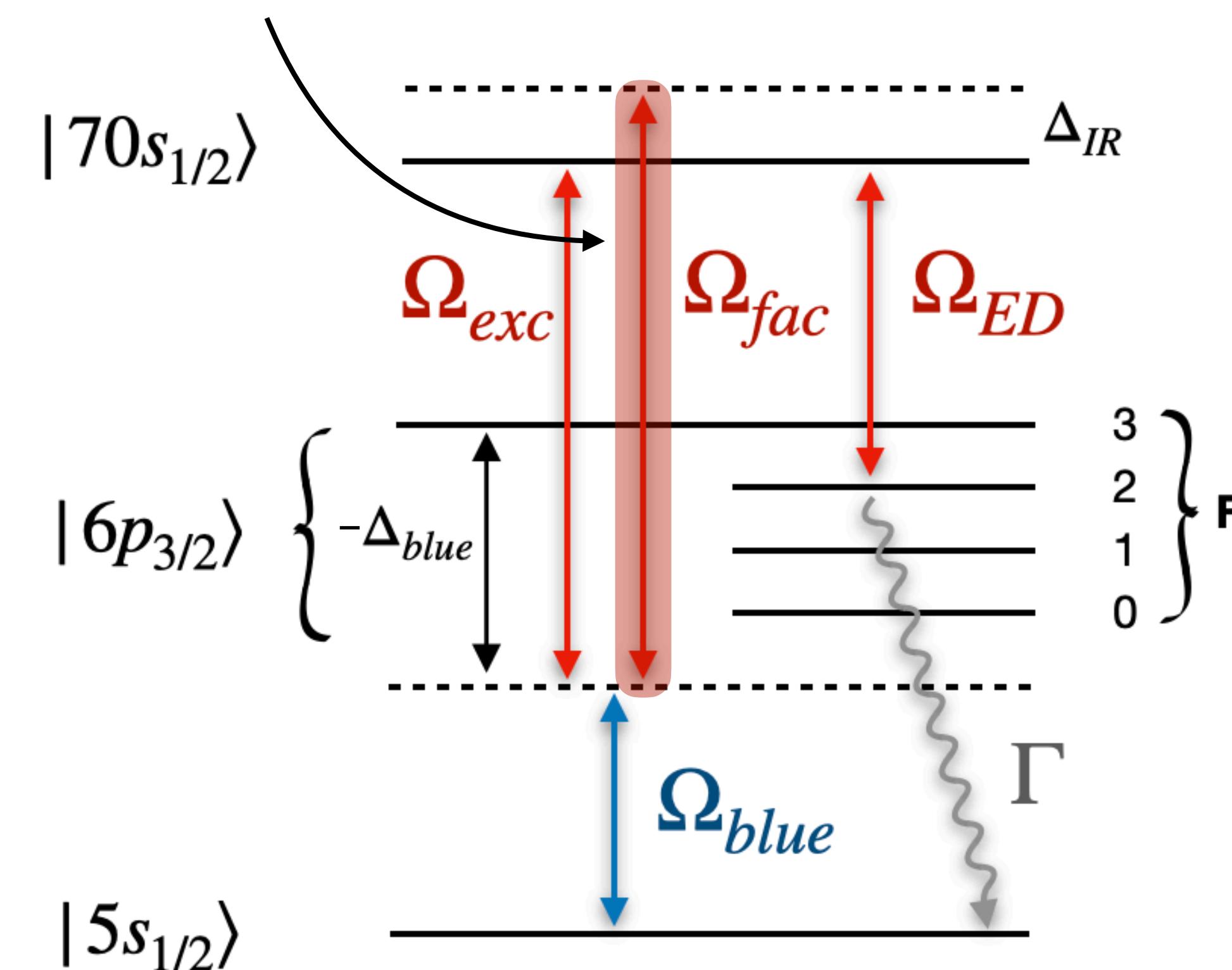


Set-up sperimentale

MOT

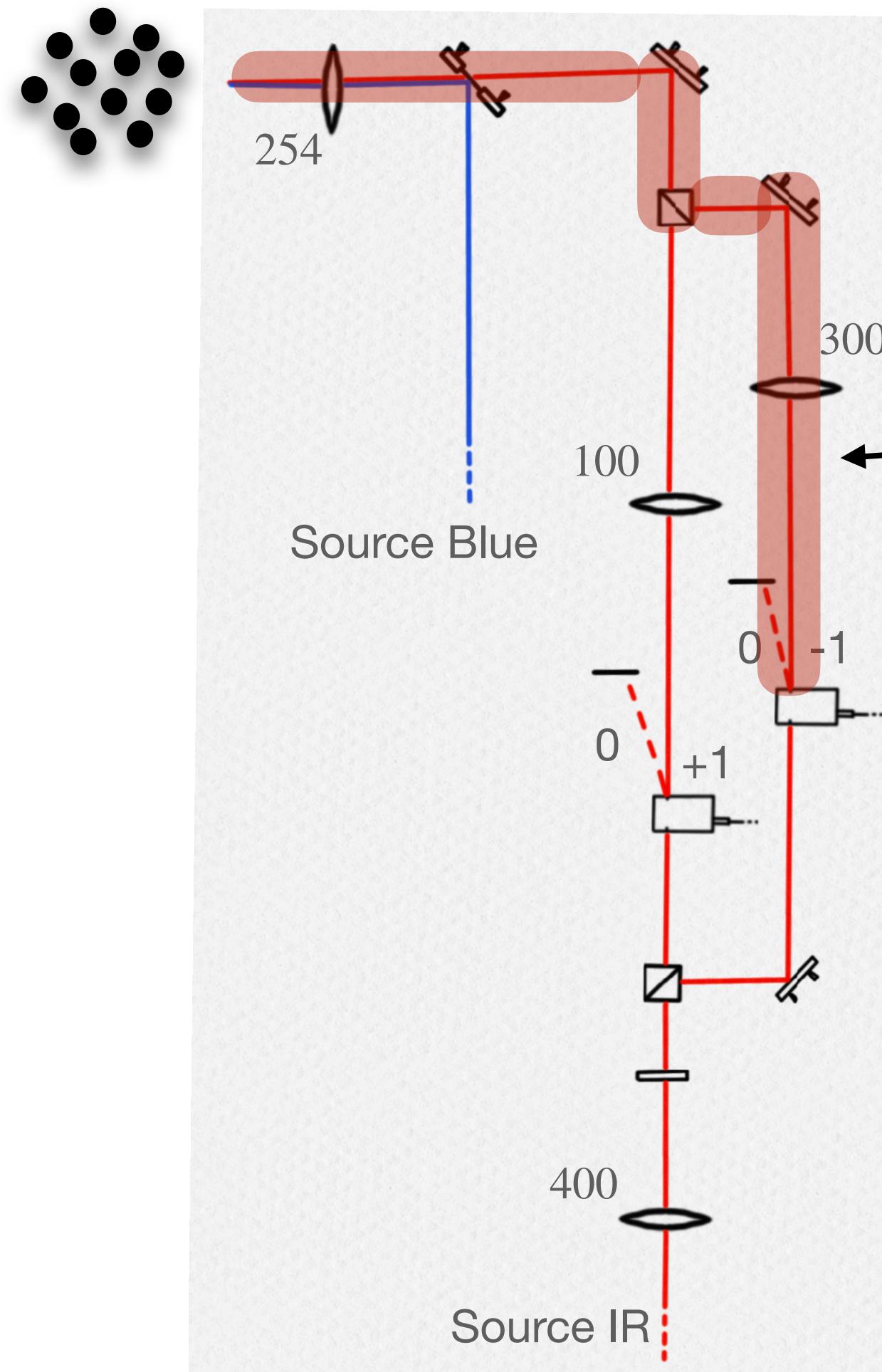


(f_0 is the AOMs central freq.)



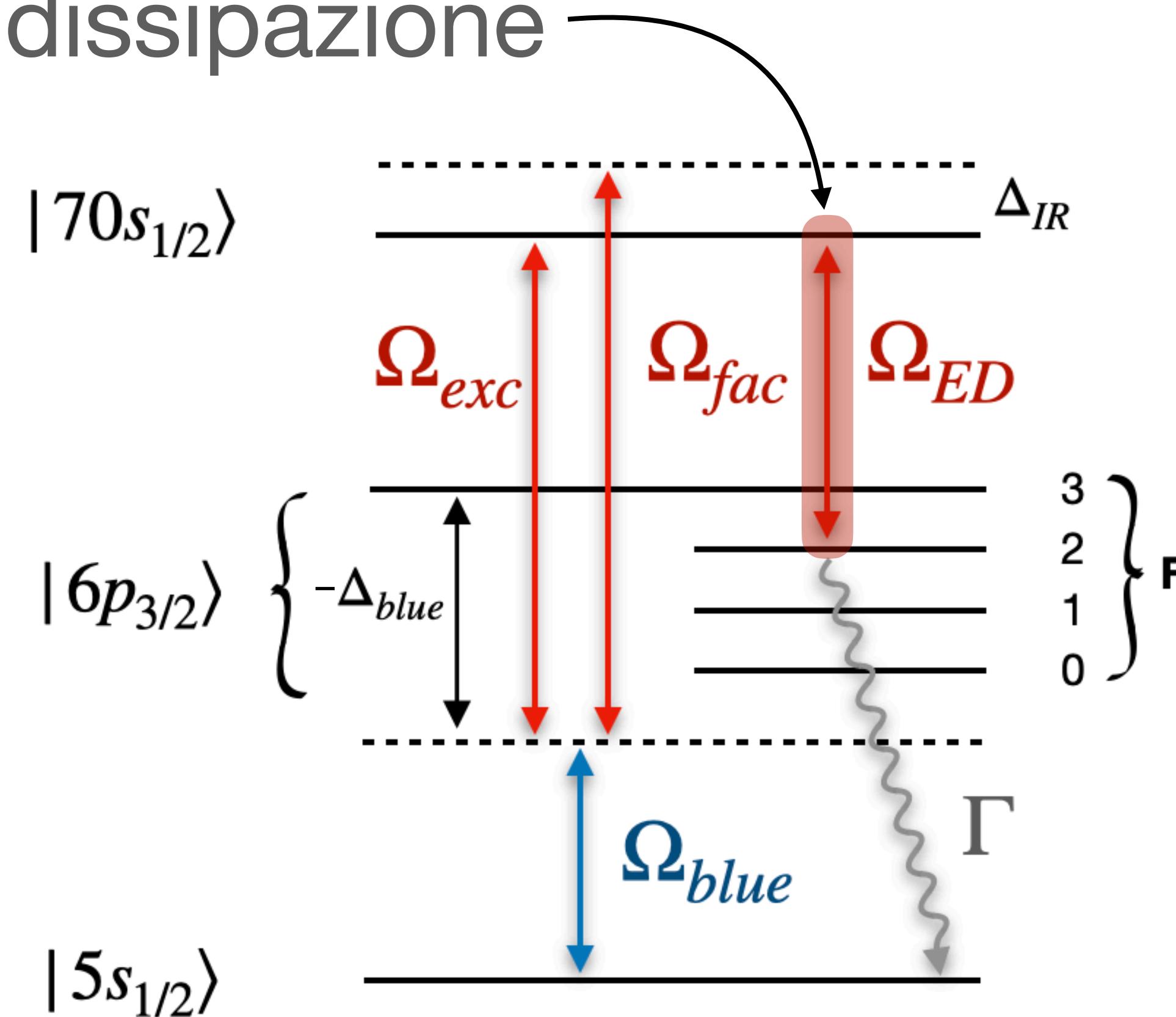
Set-up sperimentale

MOT



(f_0 is the AOMs central freq.)

Canale di dissipazione



Obiettivo

- 1) Realizzare il setup per il controllo dello stato interno
- 2) Testarlo sugli atomi



Obiettivo

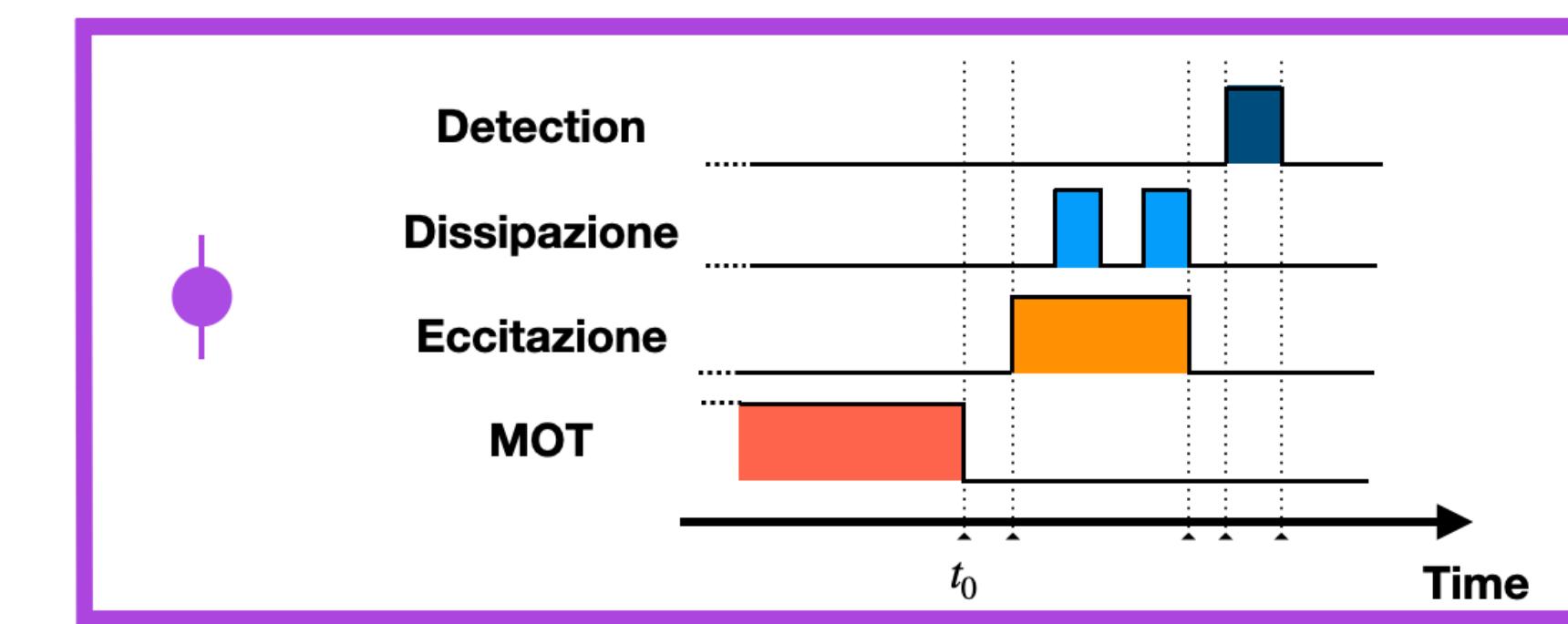
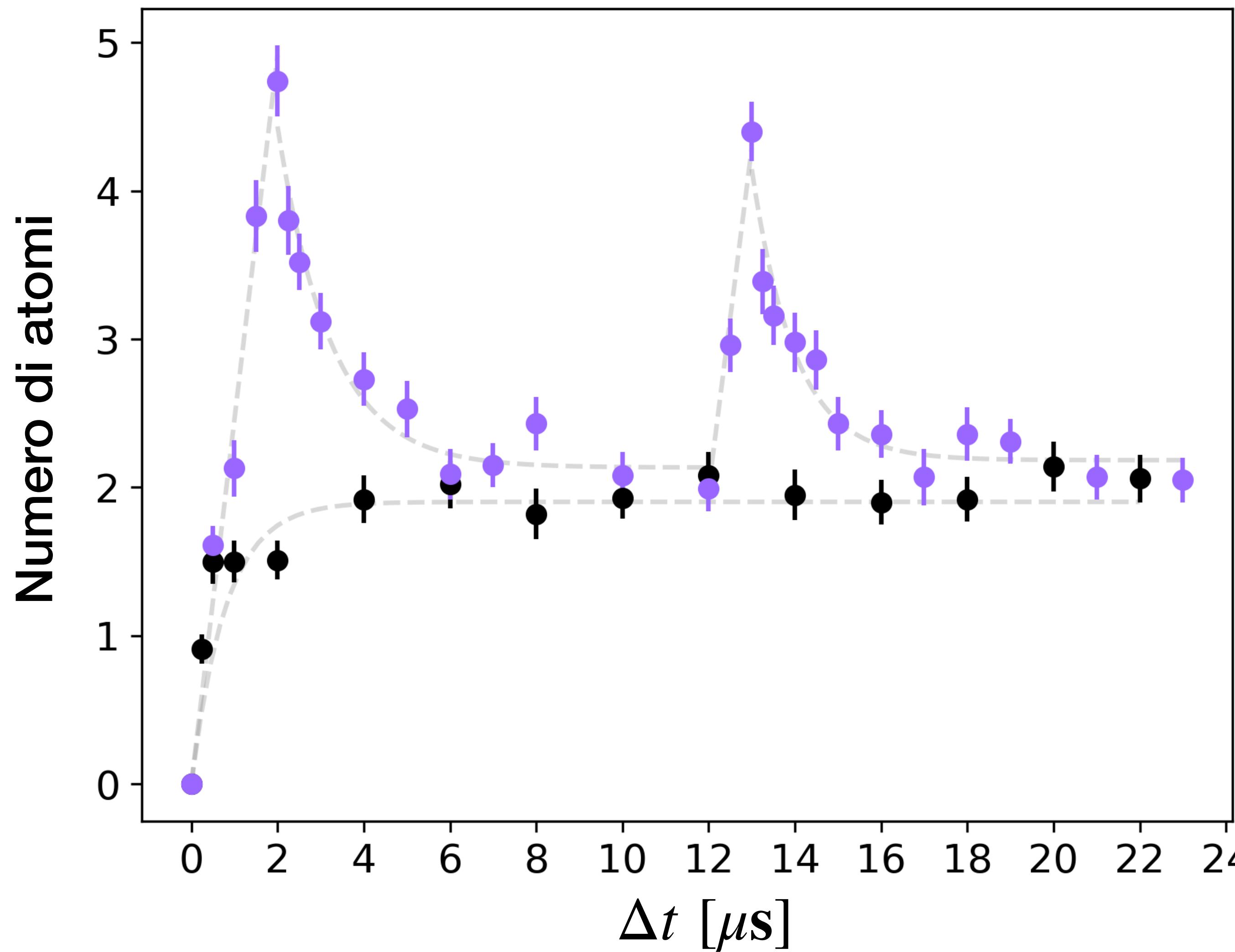
1) Realizzare il setup per il controllo dello stato interno



2) Testarlo sugli atomi

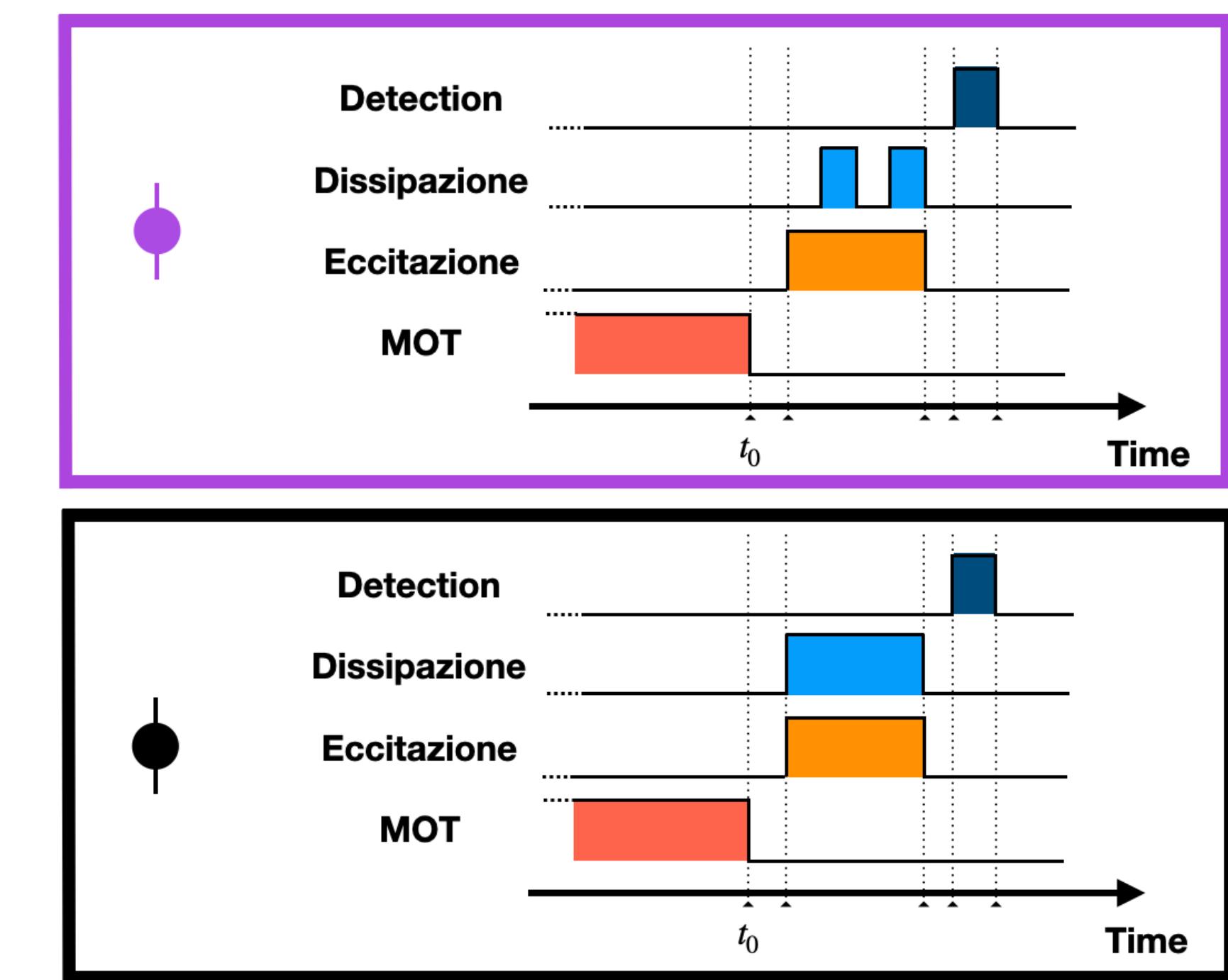
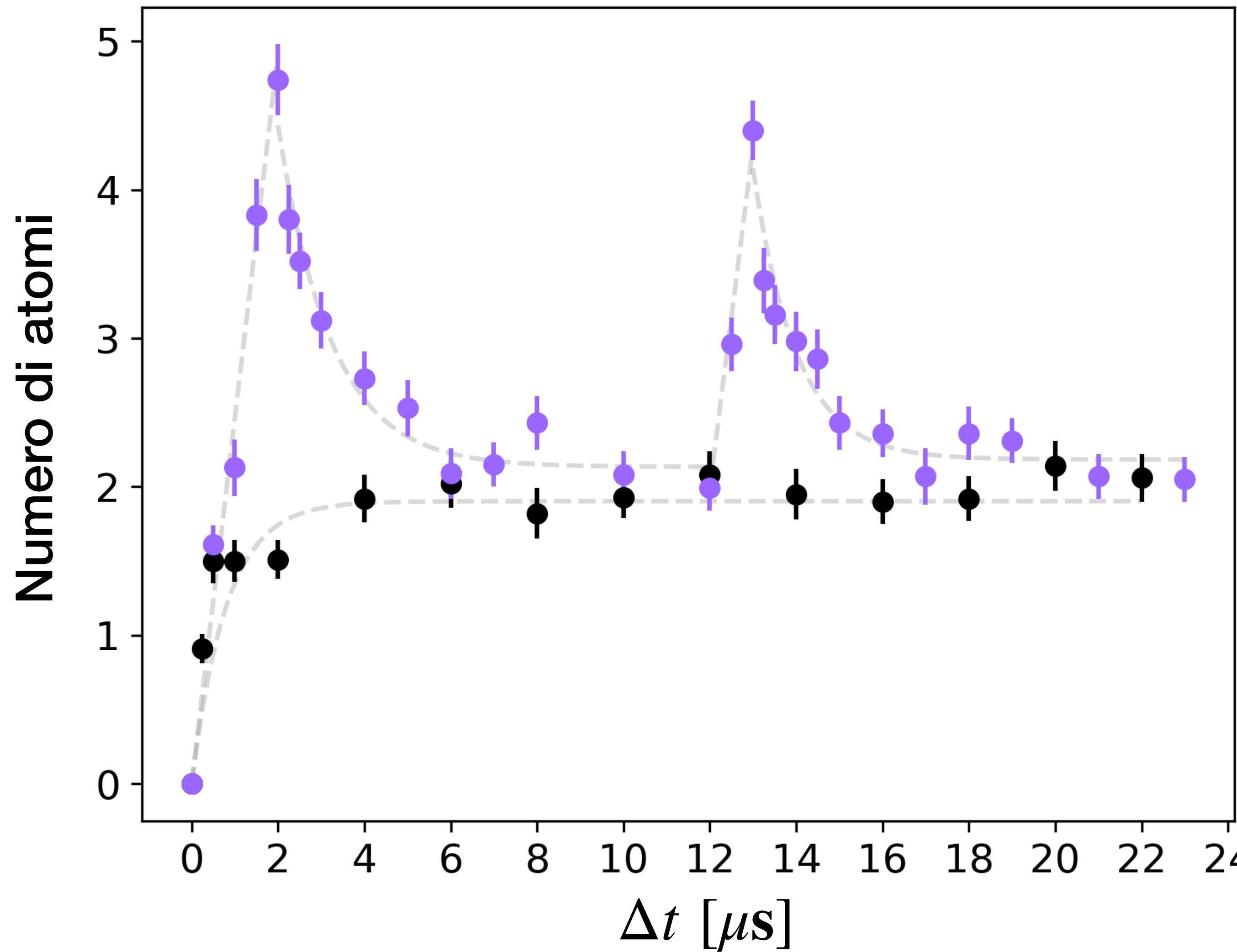
- Canale di eccitazione e dissipazione
- Canale di facilitazione
- Tutti insieme

Canali di eccitazione e dissipazione testati sulla MOT



$$\Gamma_{dep} \sim 1 \text{ MHz}$$

Canali di eccitazione e dissipazione testati sulla MOT



$$\Gamma_{dep} \sim 1 \text{ MHz}$$

Obiettivo

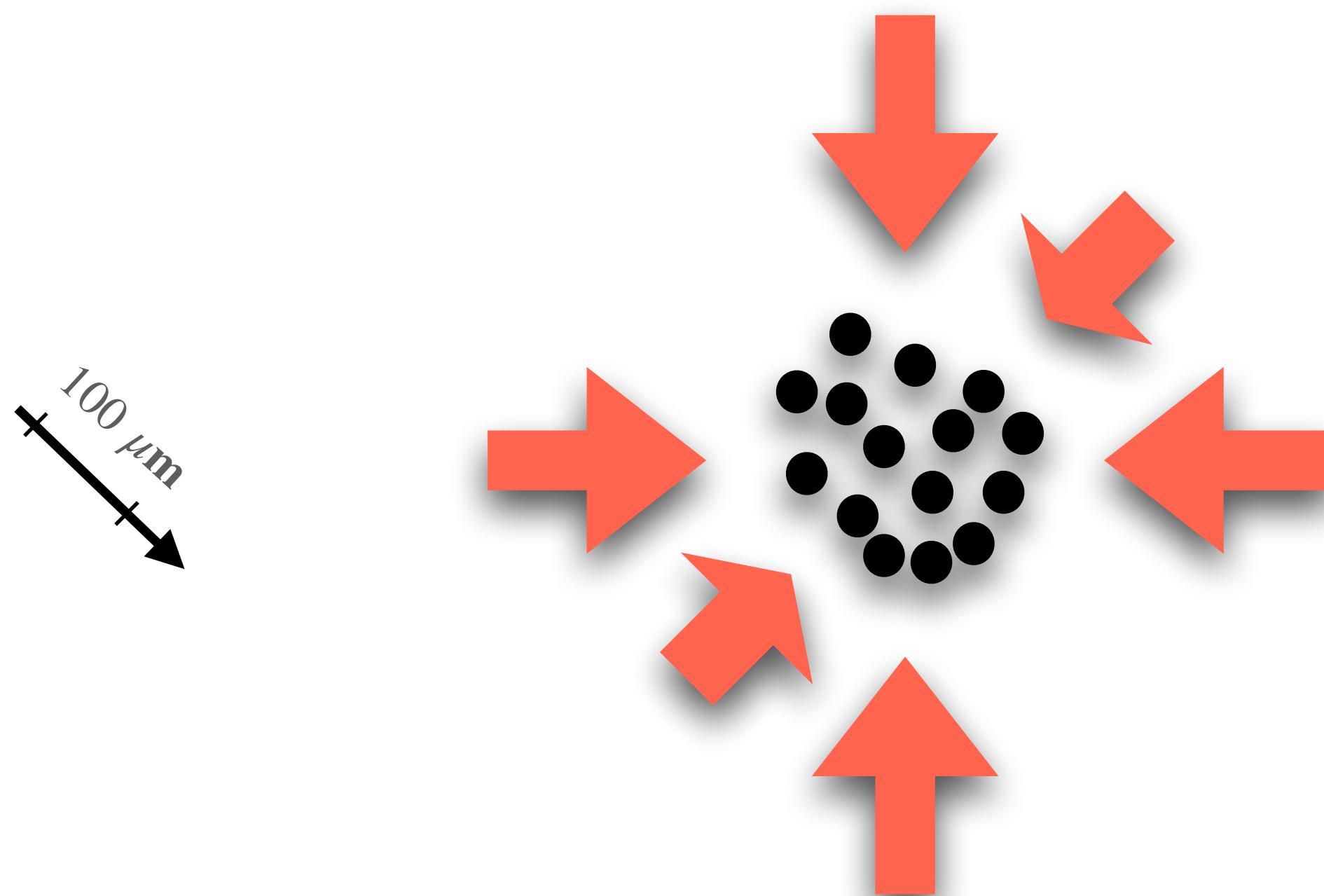
1) Realizzare il setup per il controllo dello stato interno



2) Testarlo sugli atomi

- Canale di eccitazione e dissipazione
- Canale di facilitazione
- Tutti insieme

Canale di facilitazione su un sistema multi corpi

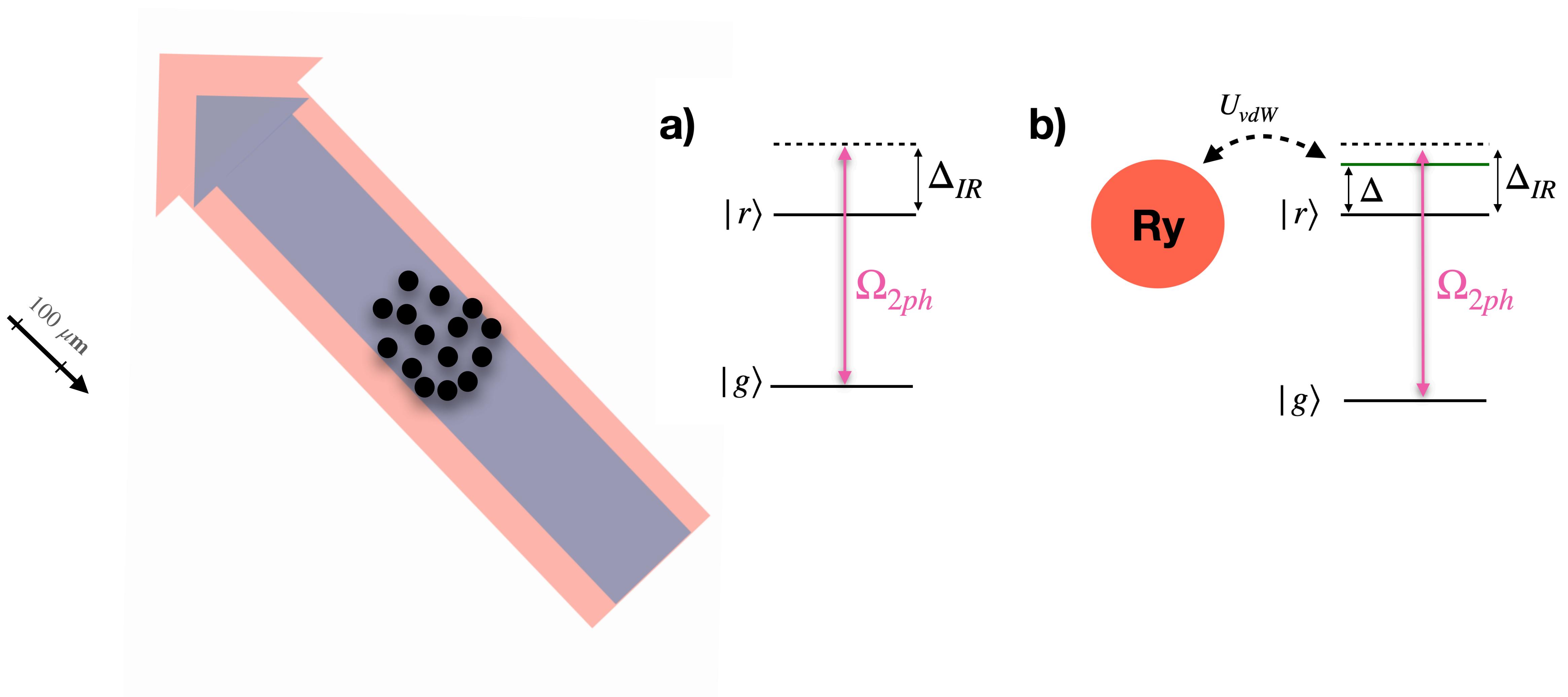


Raffreddamento
Trappola Magneto Ottica

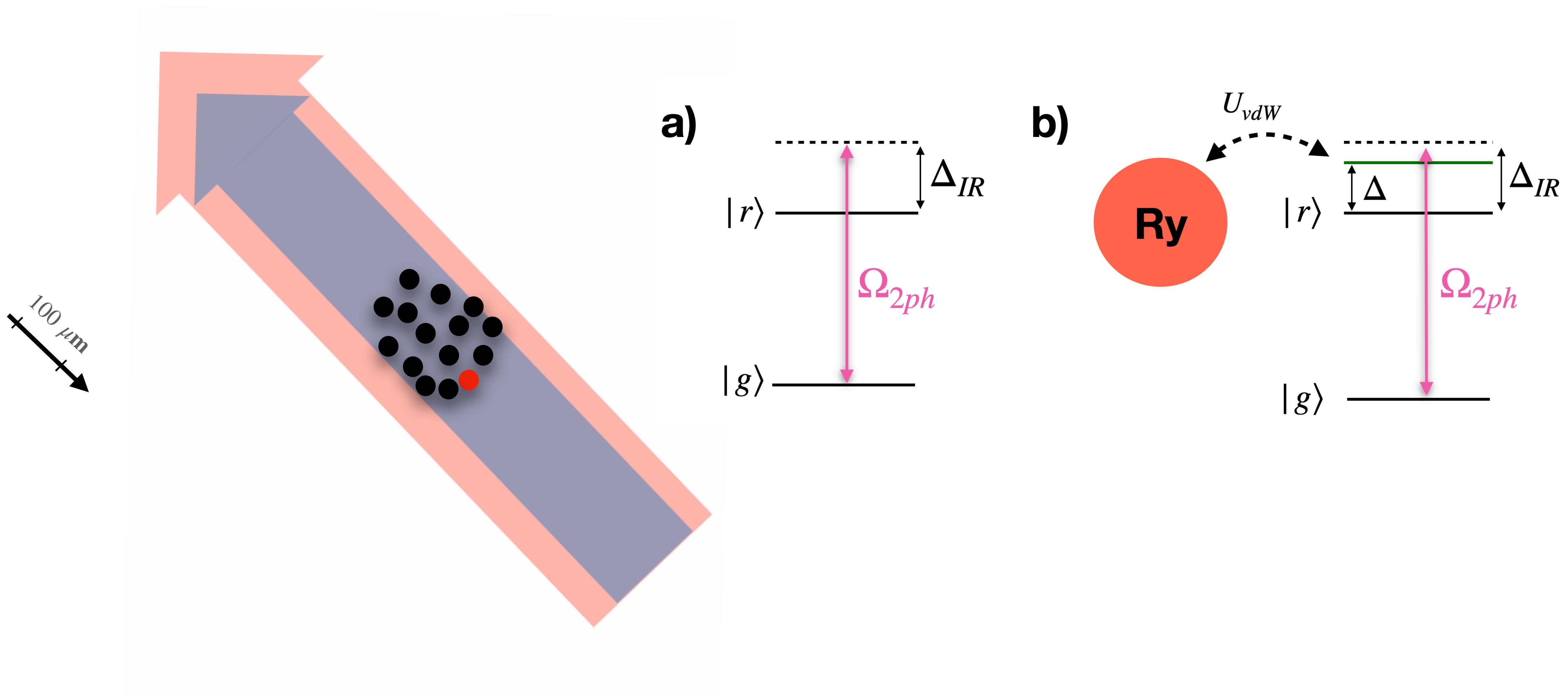
Canale di facilitazione su un sistema multi corpi



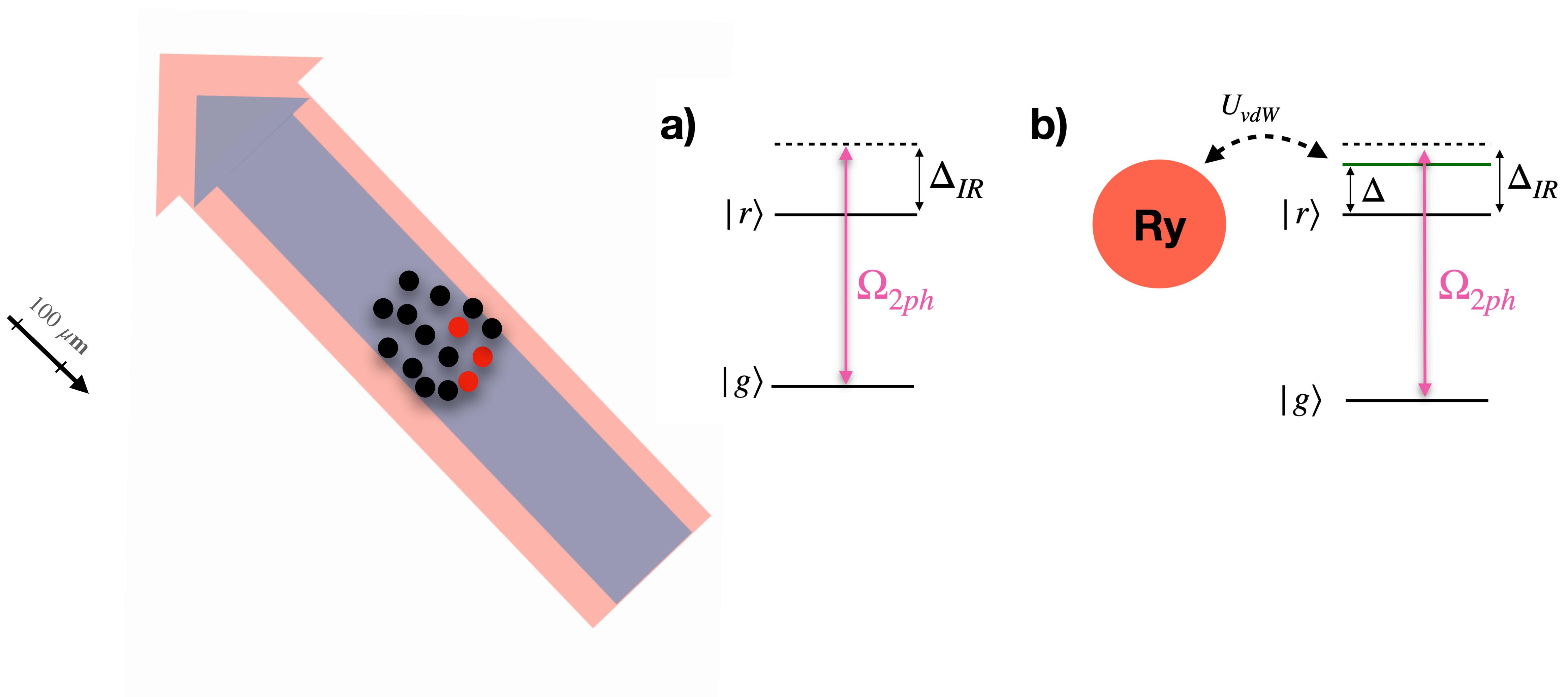
Canale di facilitazione su un sistema multi corpi



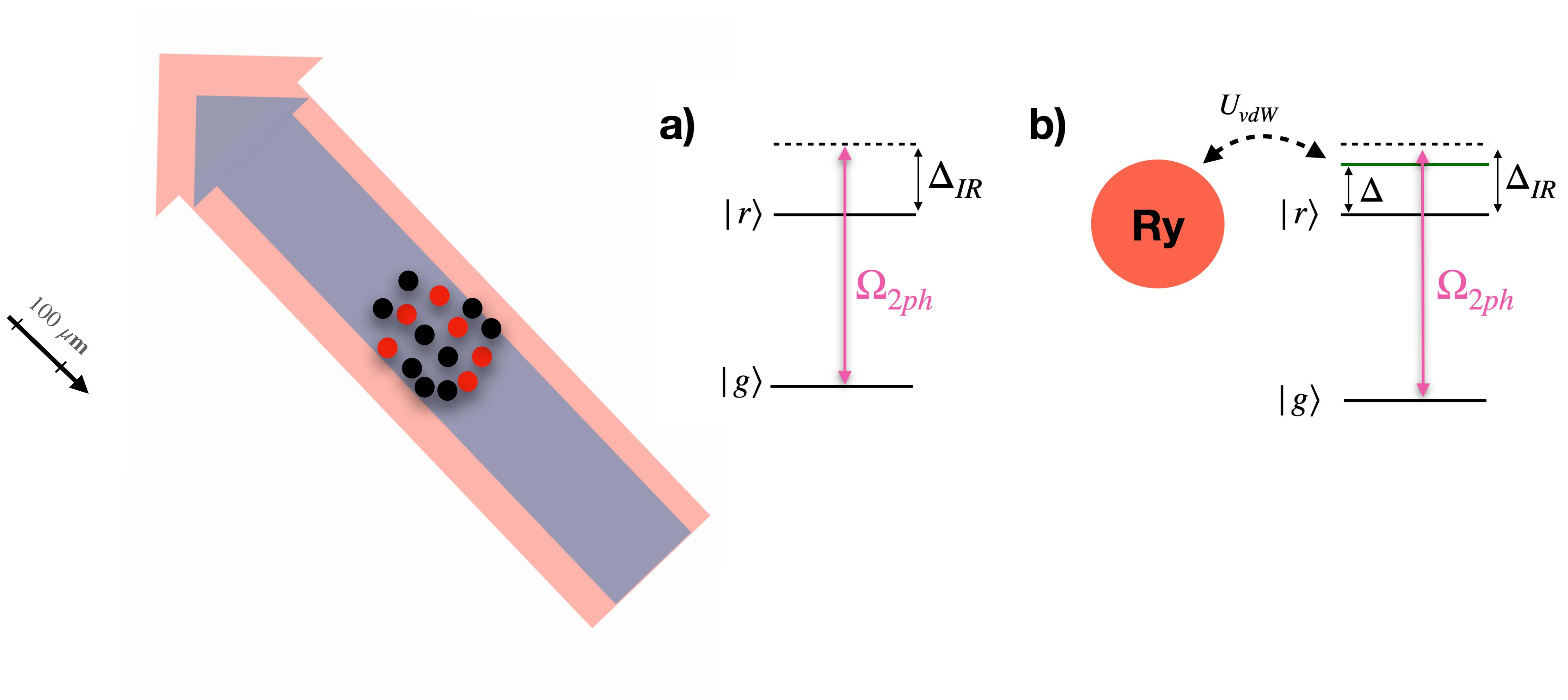
Canale di facilitazione su un sistema multi corpi



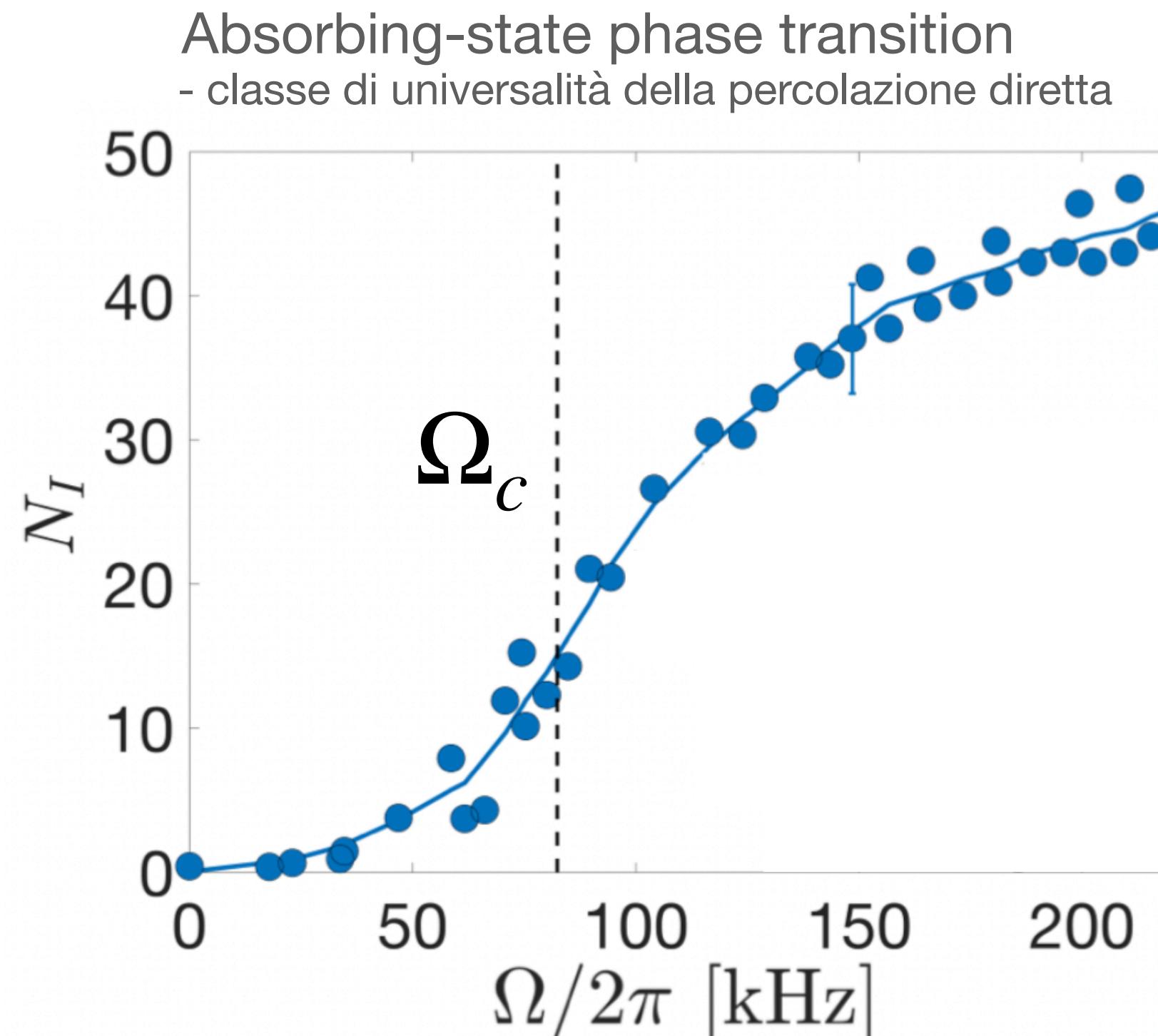
Canale di facilitazione su un sistema multi corpi



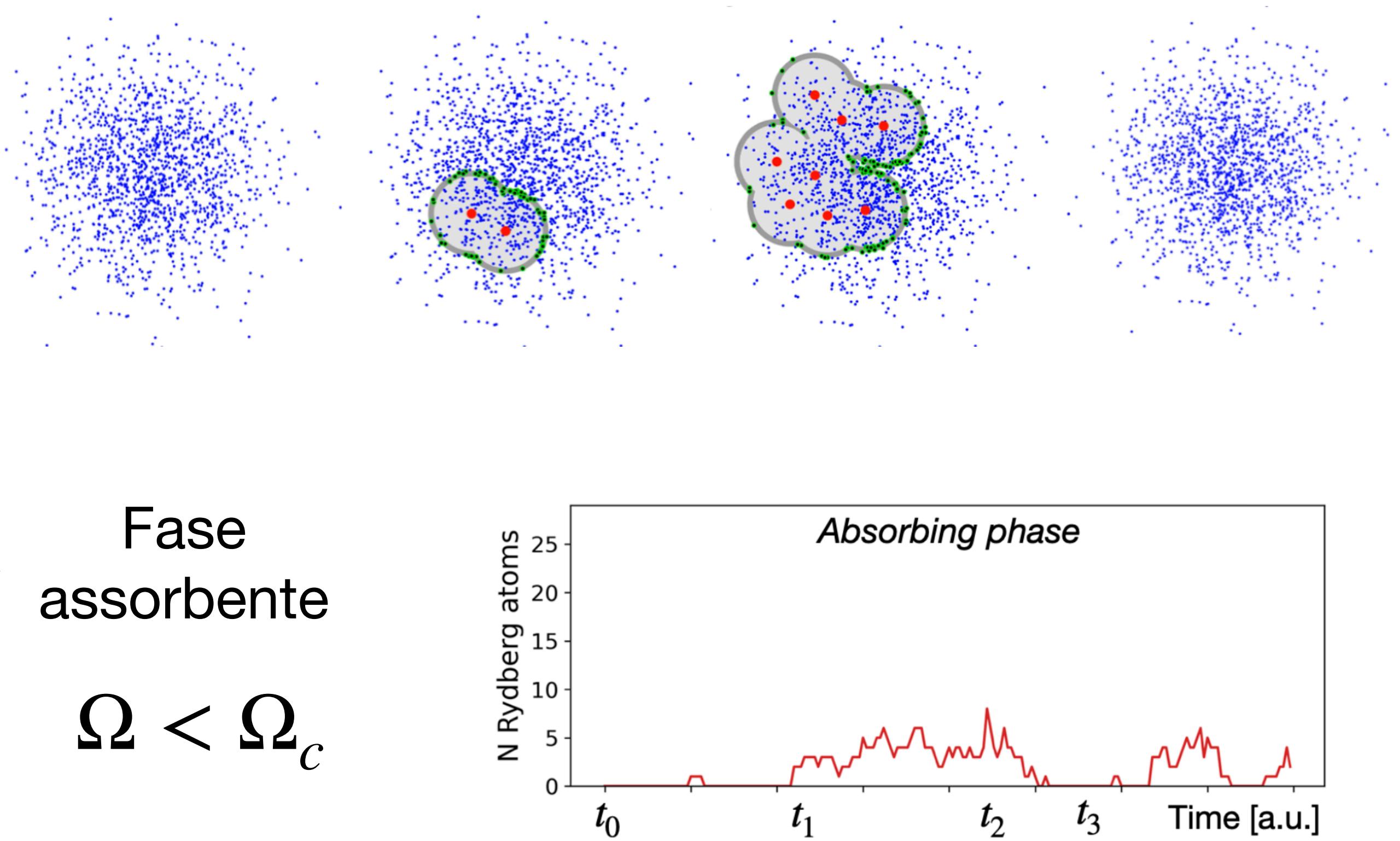
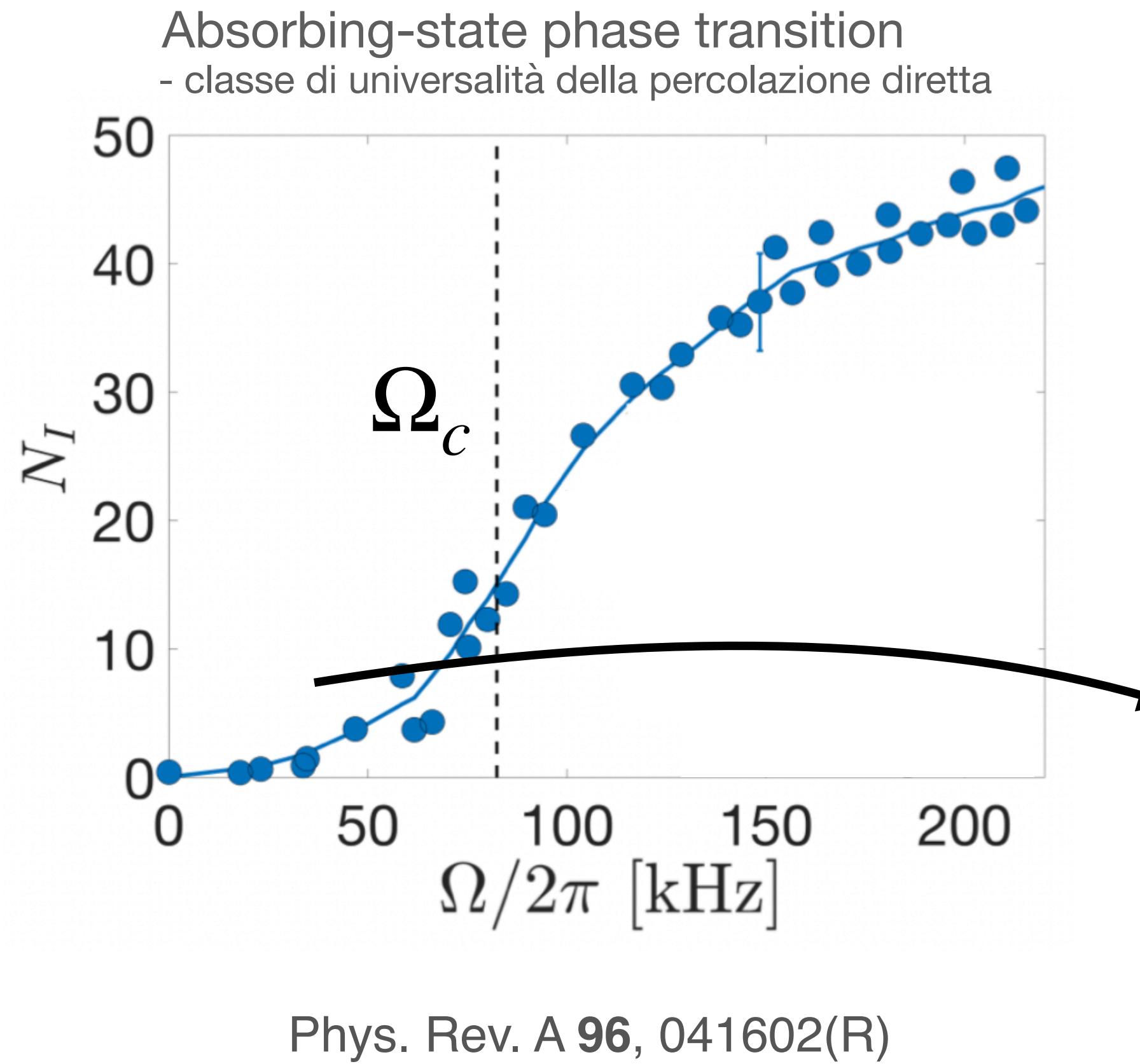
Canale di facilitazione su un sistema multi corpi



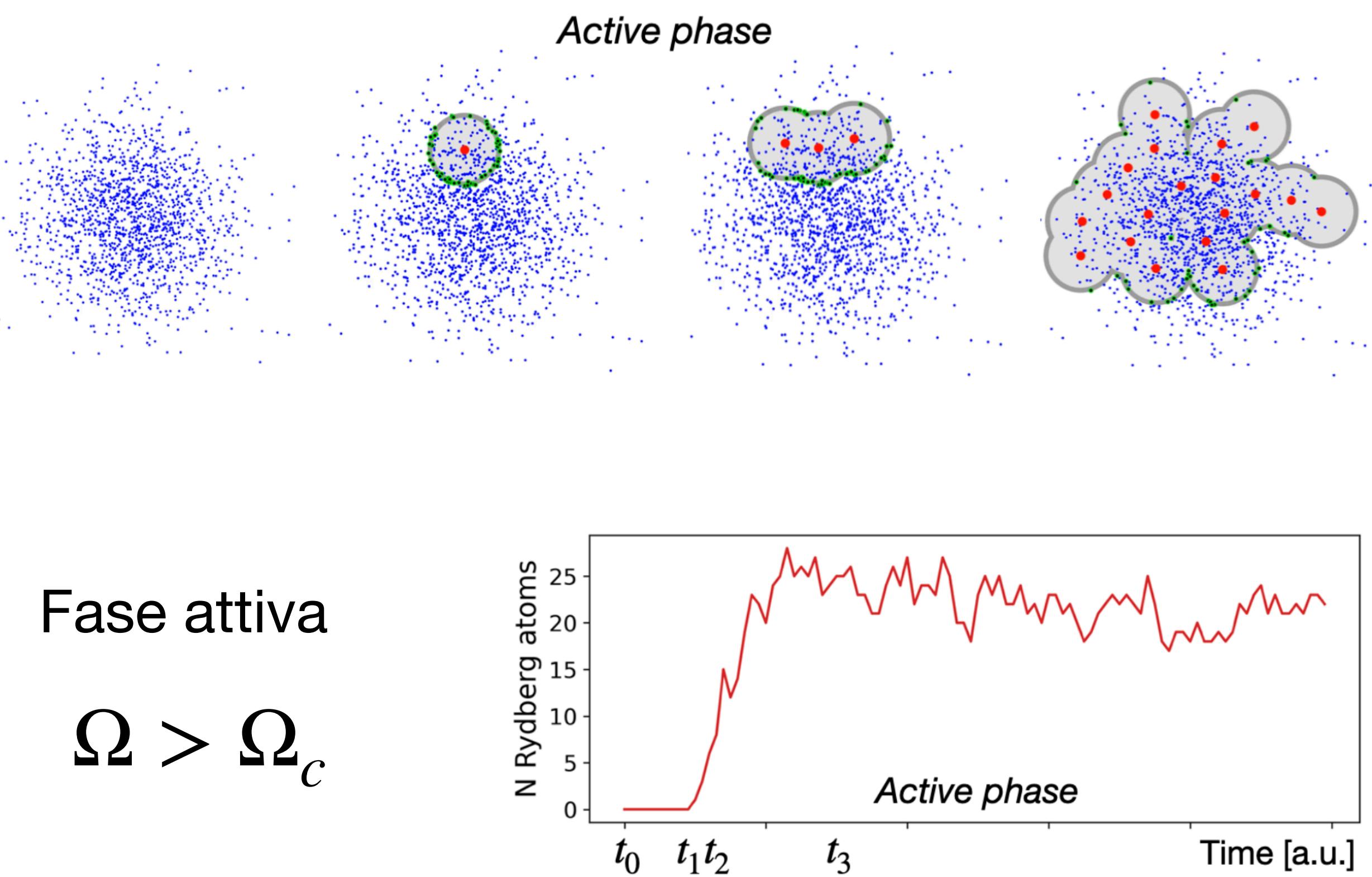
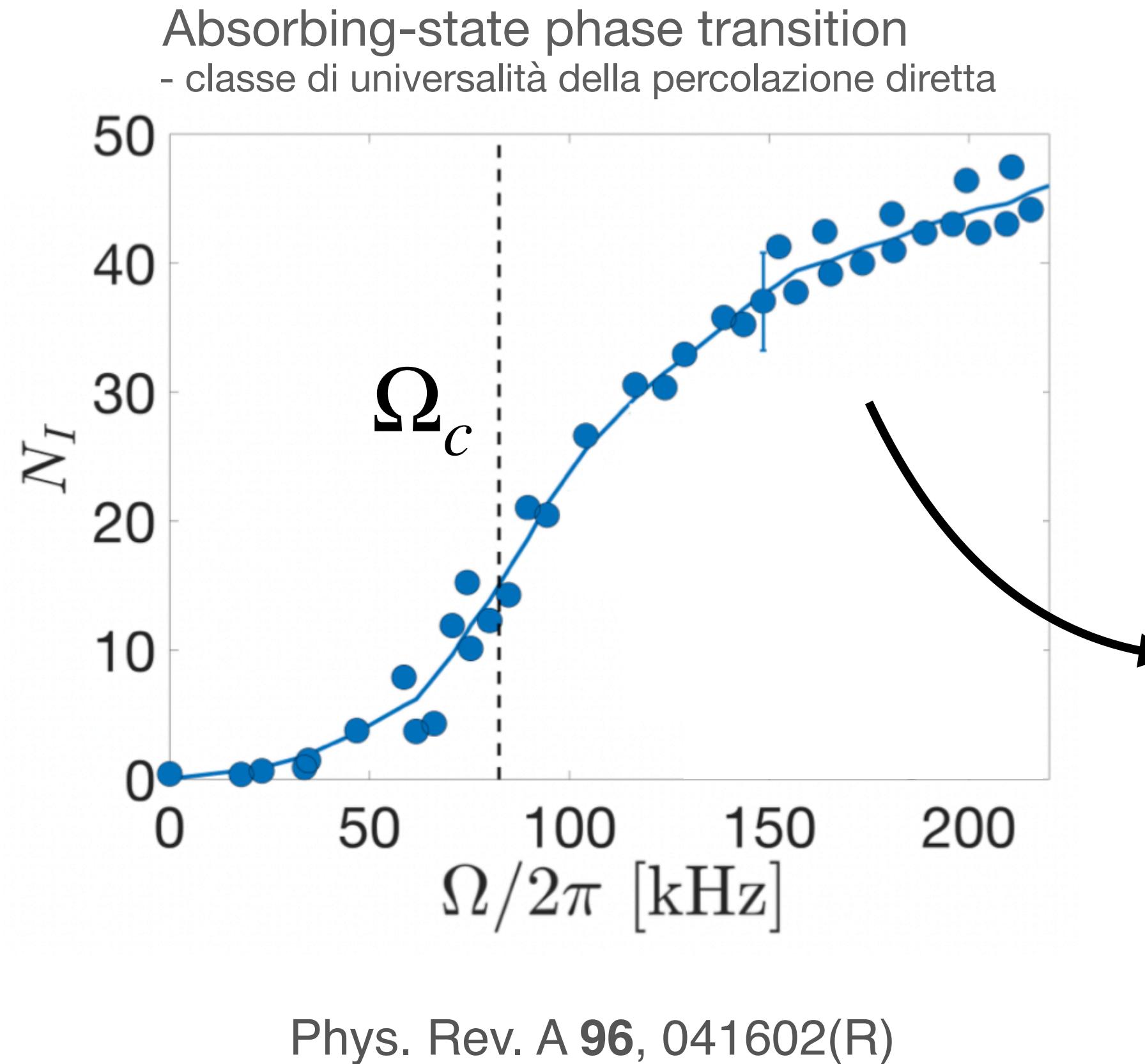
Competizione con l'emissione spontanea



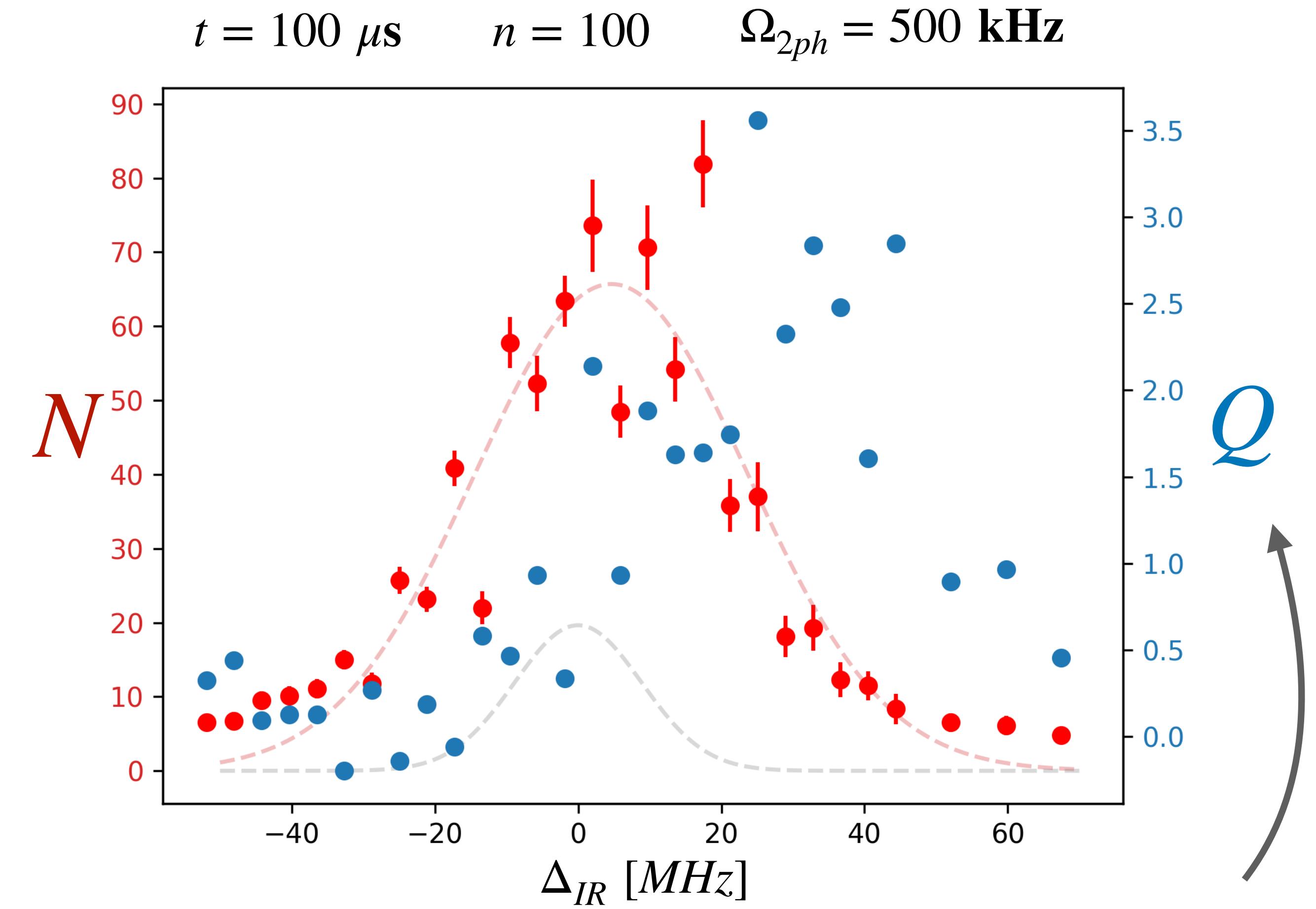
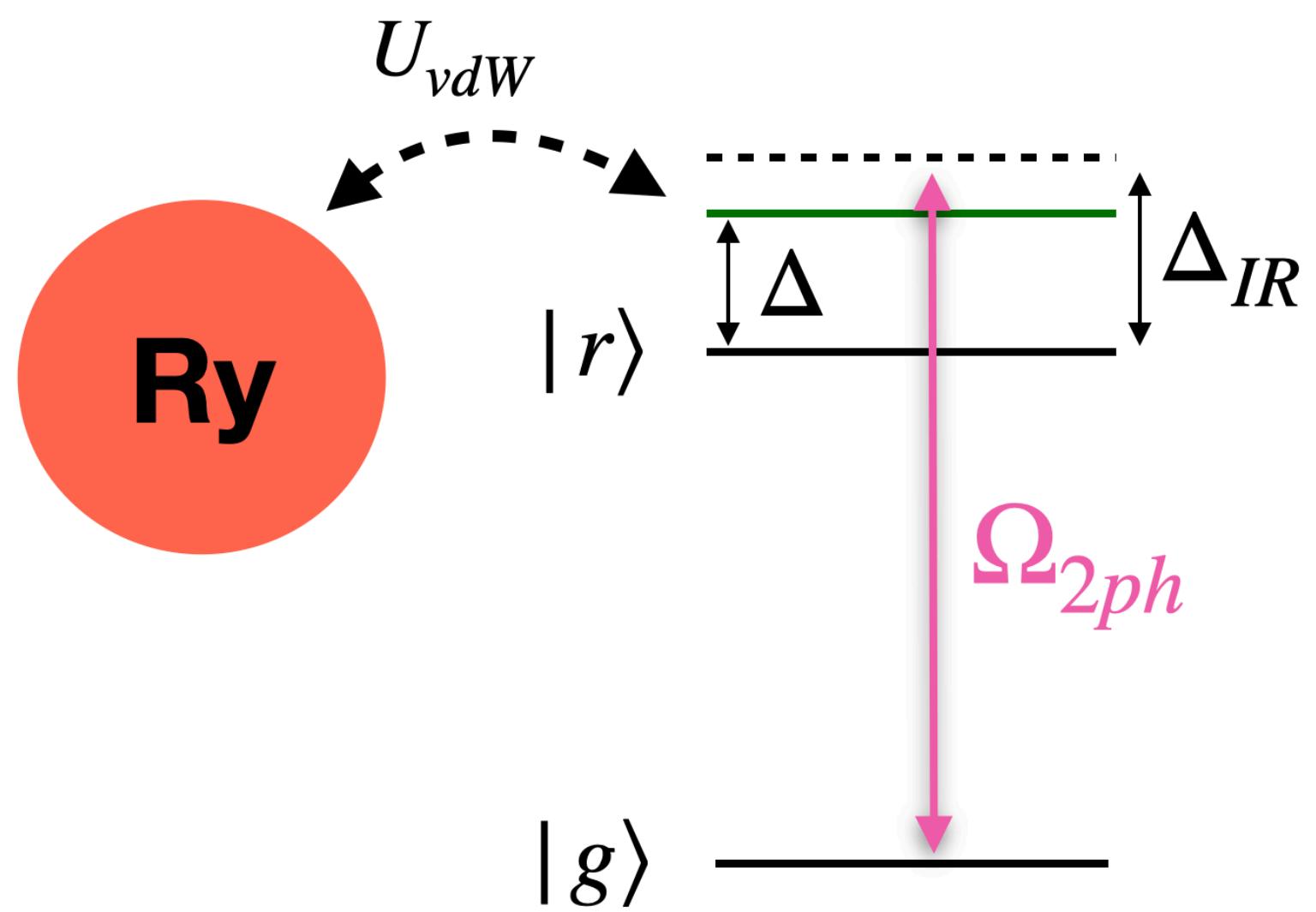
Competizione con l'emissione spontanea



Competizione con l'emissione spontanea



Evidenza di facilitazione nella MOT



$$Q(N) = \frac{\text{Var}(N)}{\langle N \rangle} - 1$$

Obiettivo

1) Realizzare il setup per il controllo dello stato interno



2) Testarlo sugli atomi

- Canale di eccitazione e dissipazione
- Canale di facilitazione
- Tutti insieme

Obiettivo

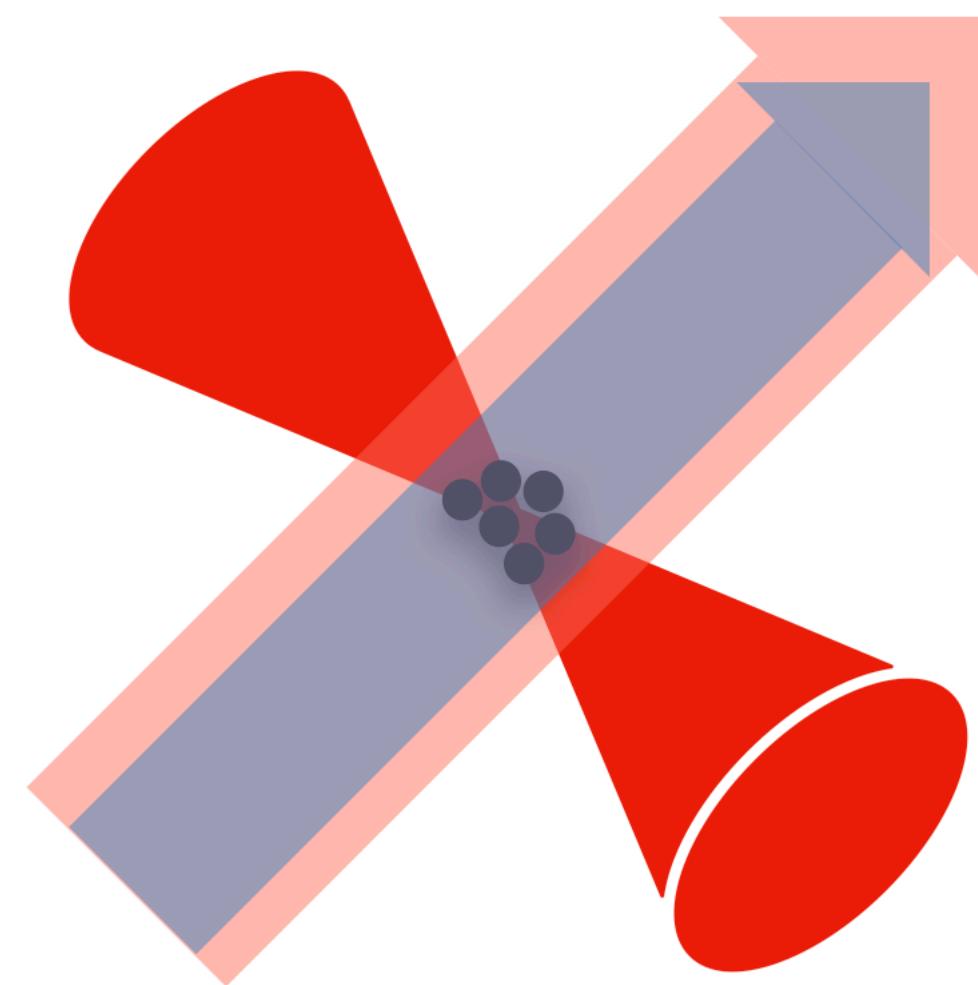
1) Realizzare il setup per il controllo dello stato interno



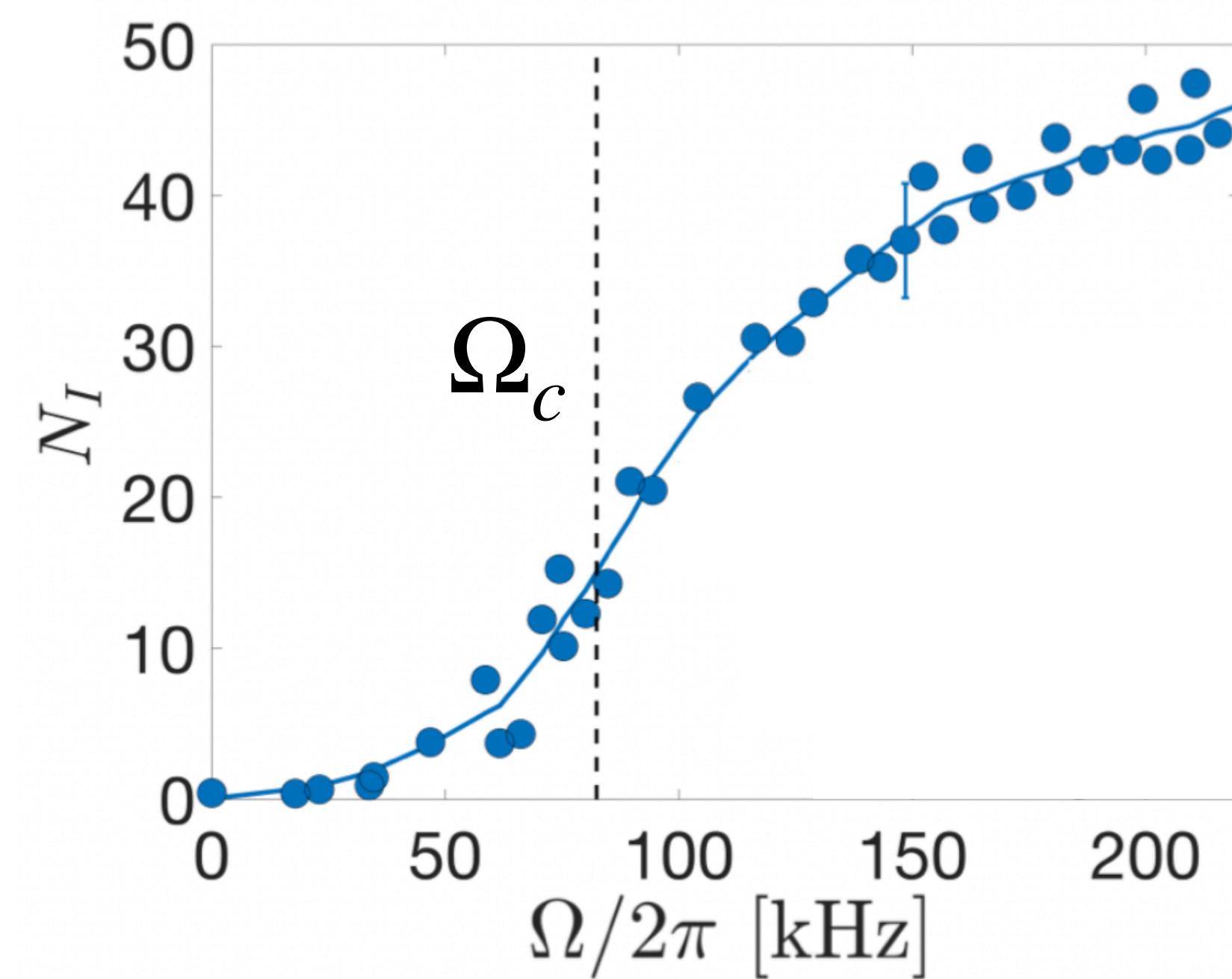
2) Testarlo sugli atomi

- Canale di eccitazione e dissipazione
- Canale di facilitazione
- Tutti insieme

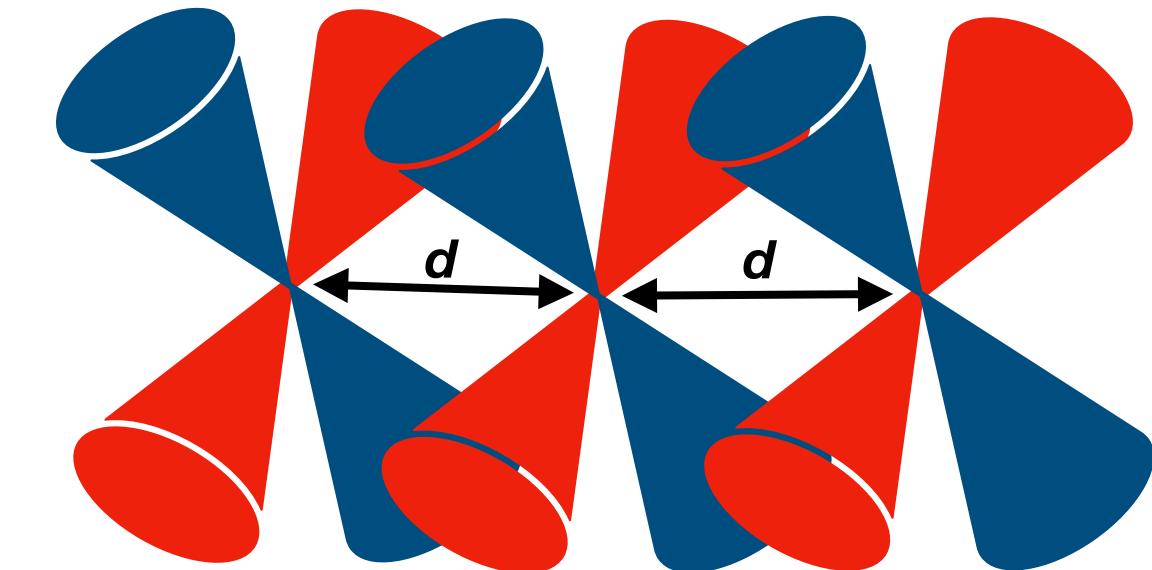
Esperimenti futuri



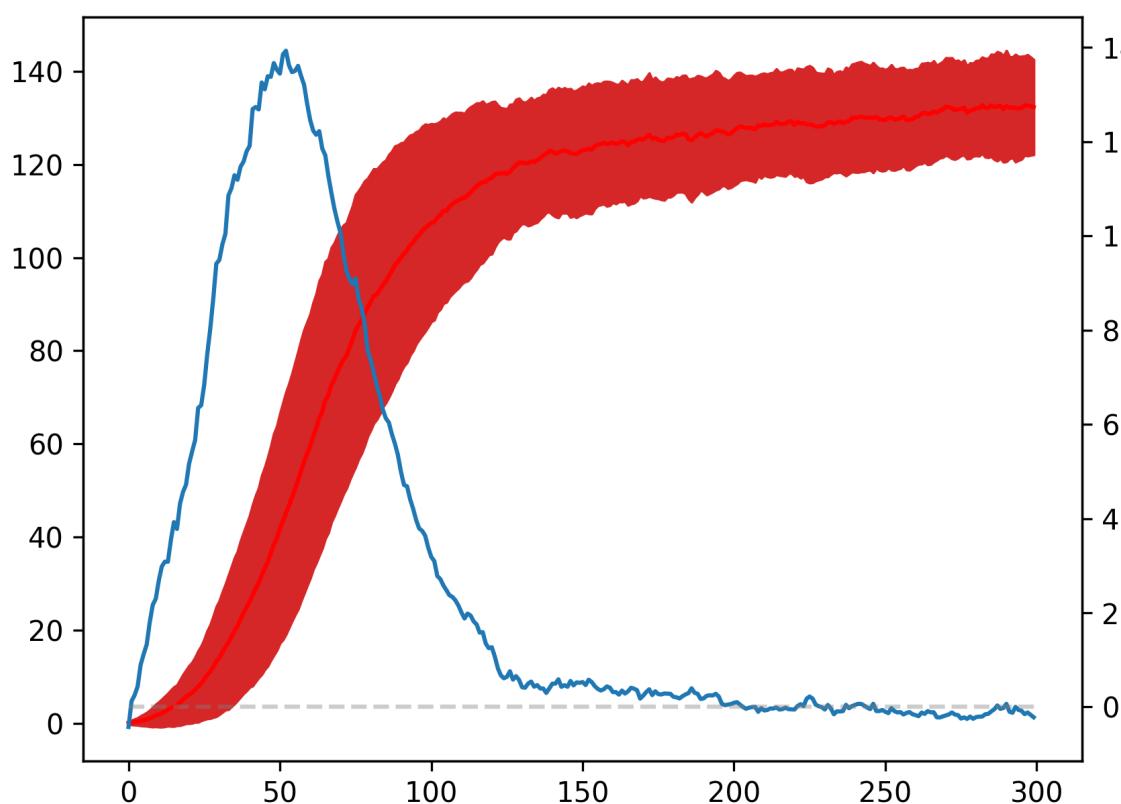
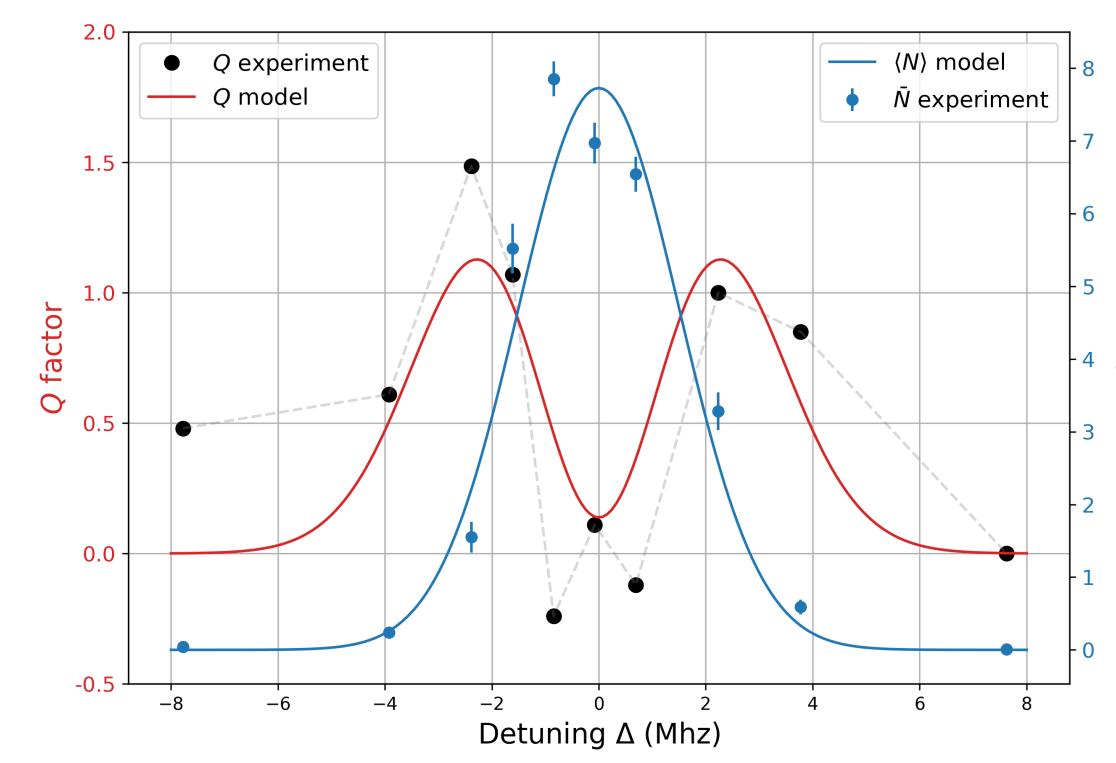
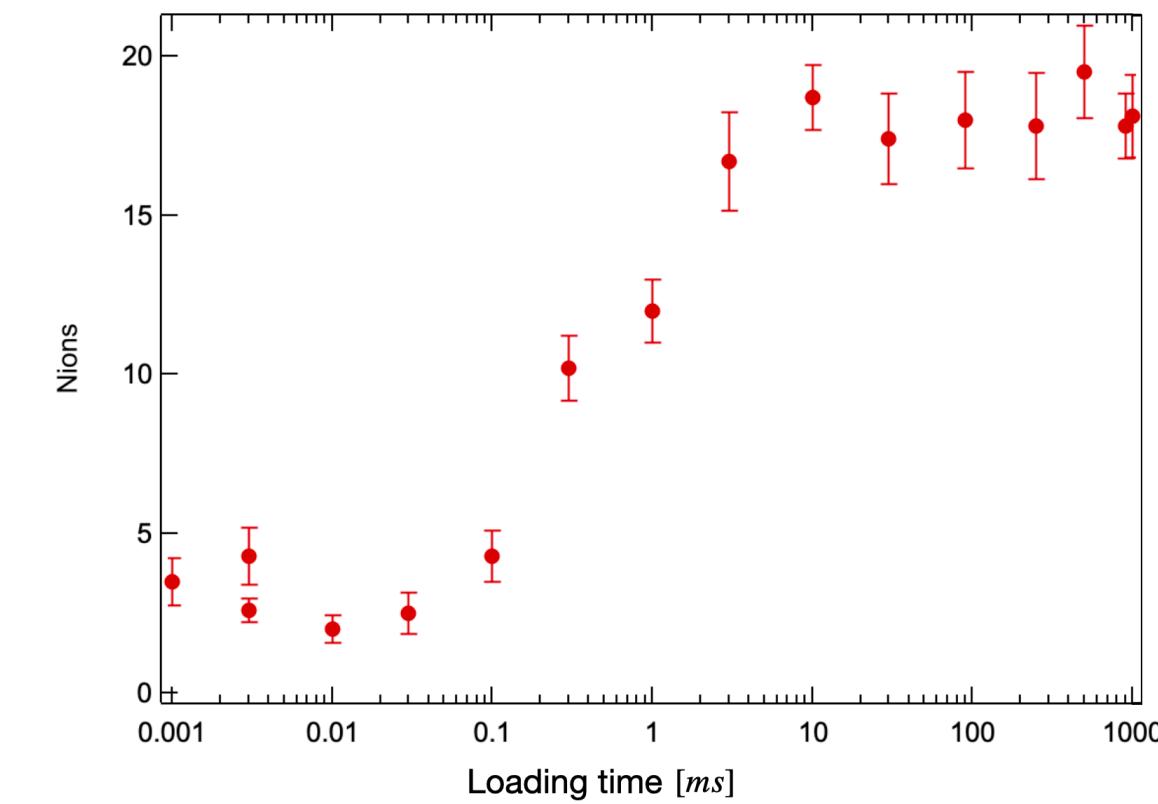
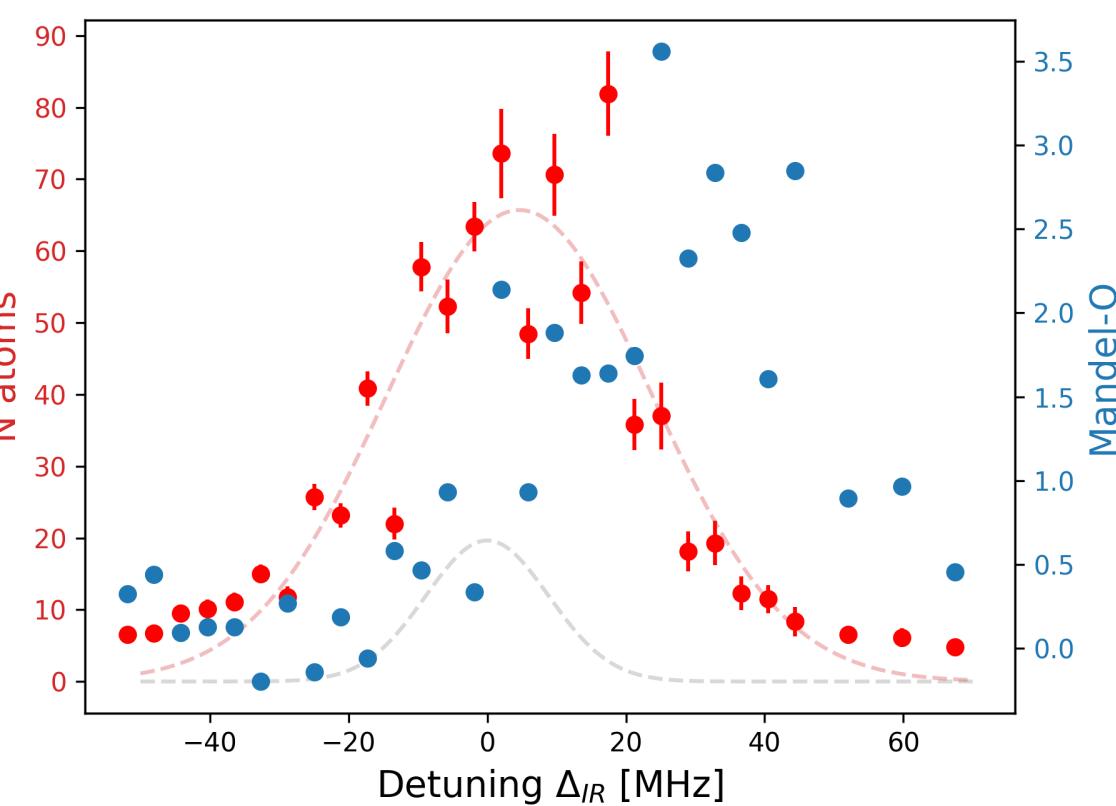
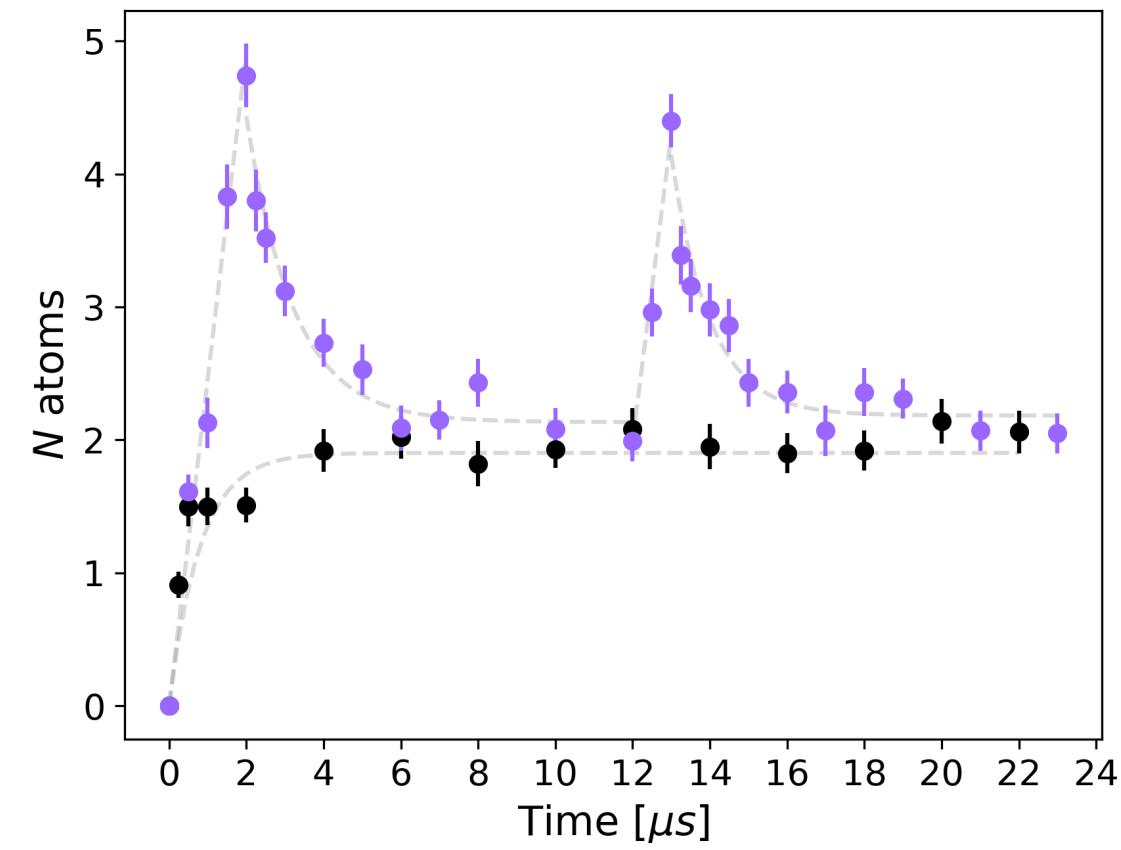
Facilitation and deexcitation on a dipole trap



Transizione di fase con dissipazione artificiale

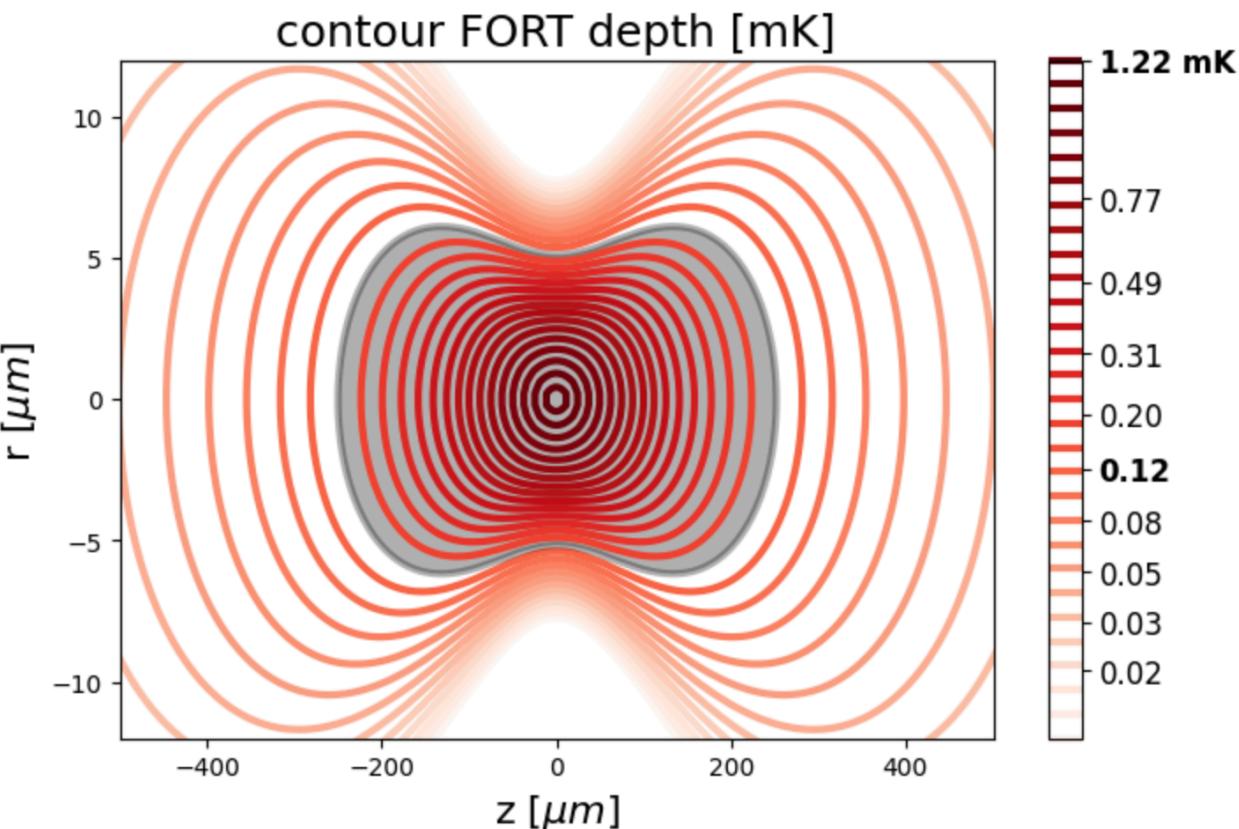
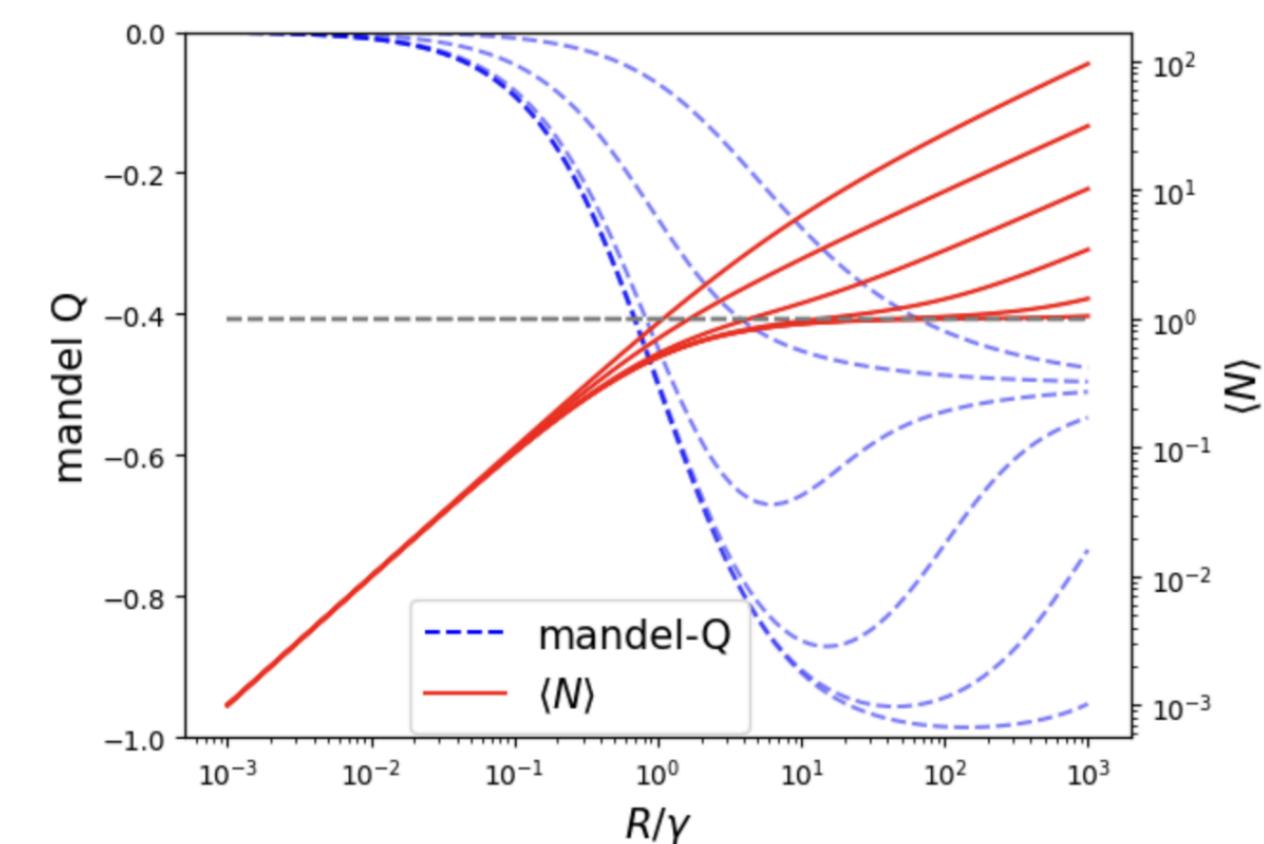
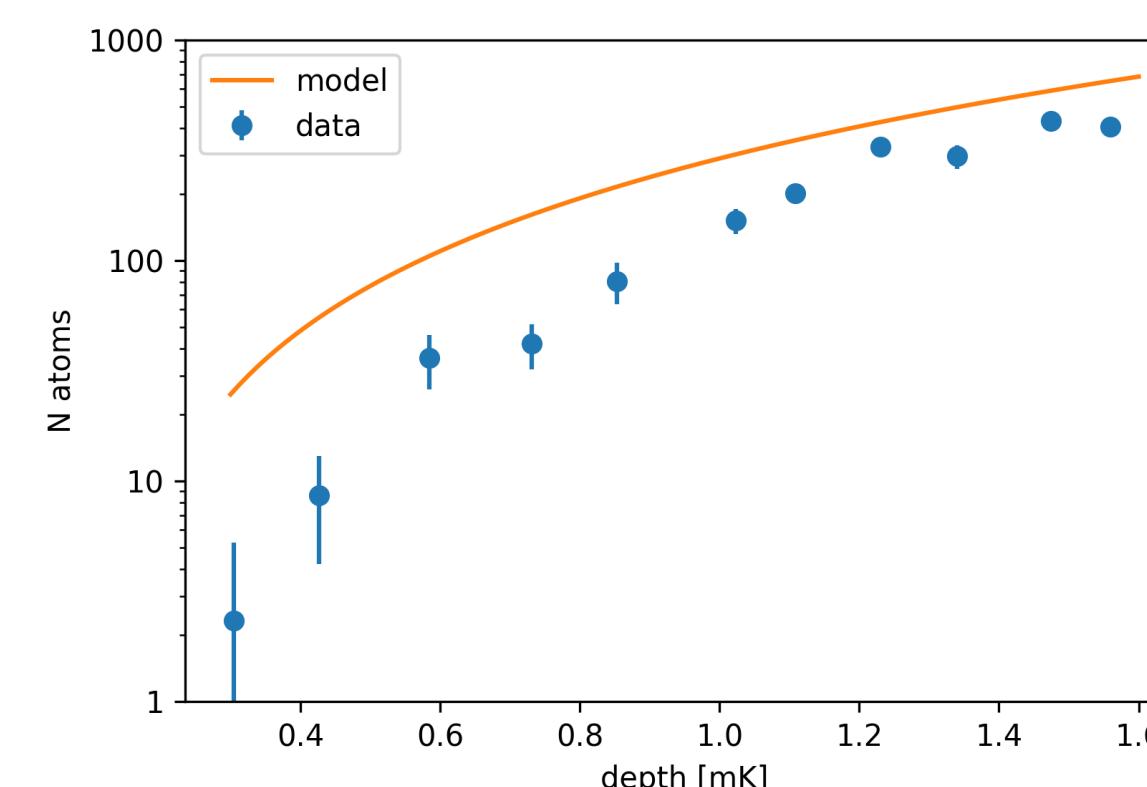
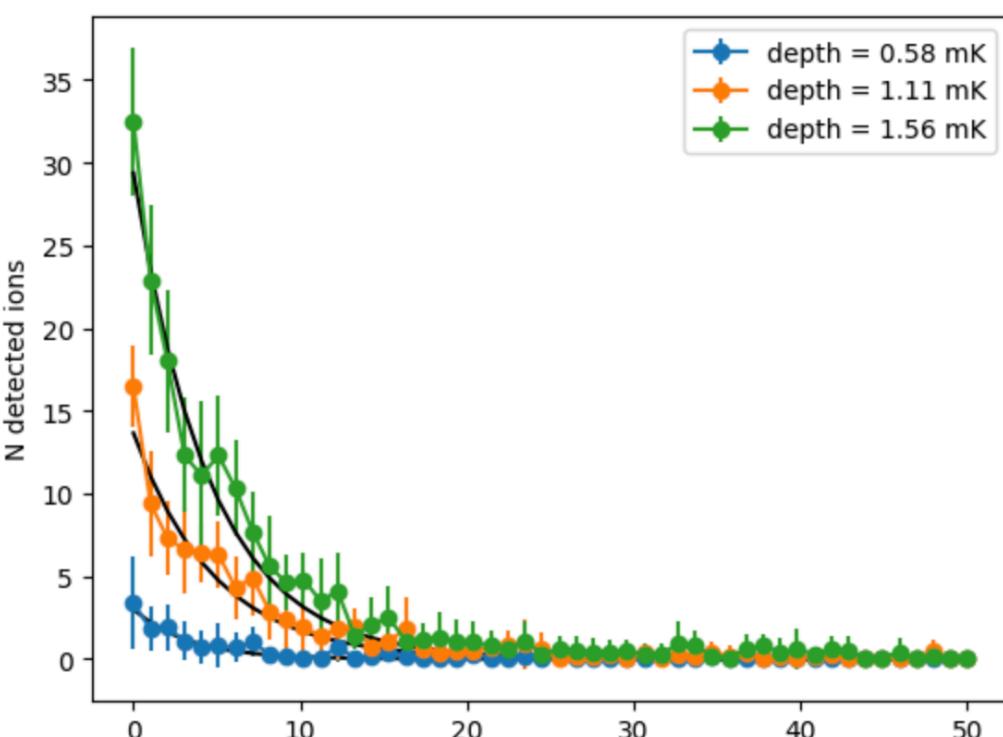
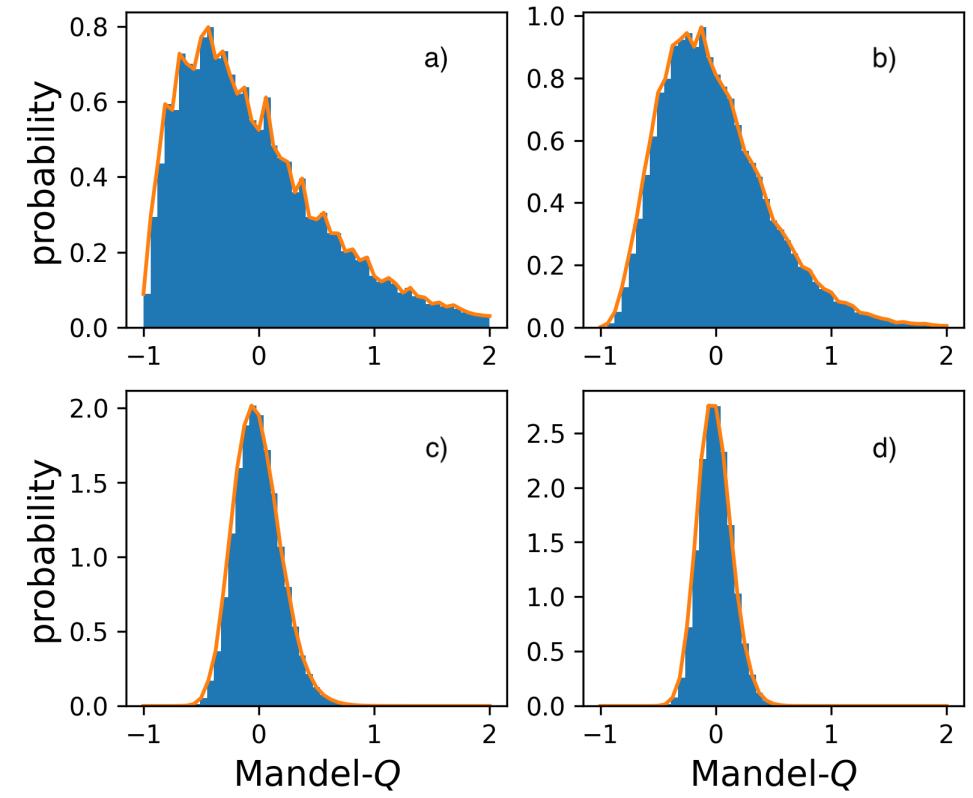


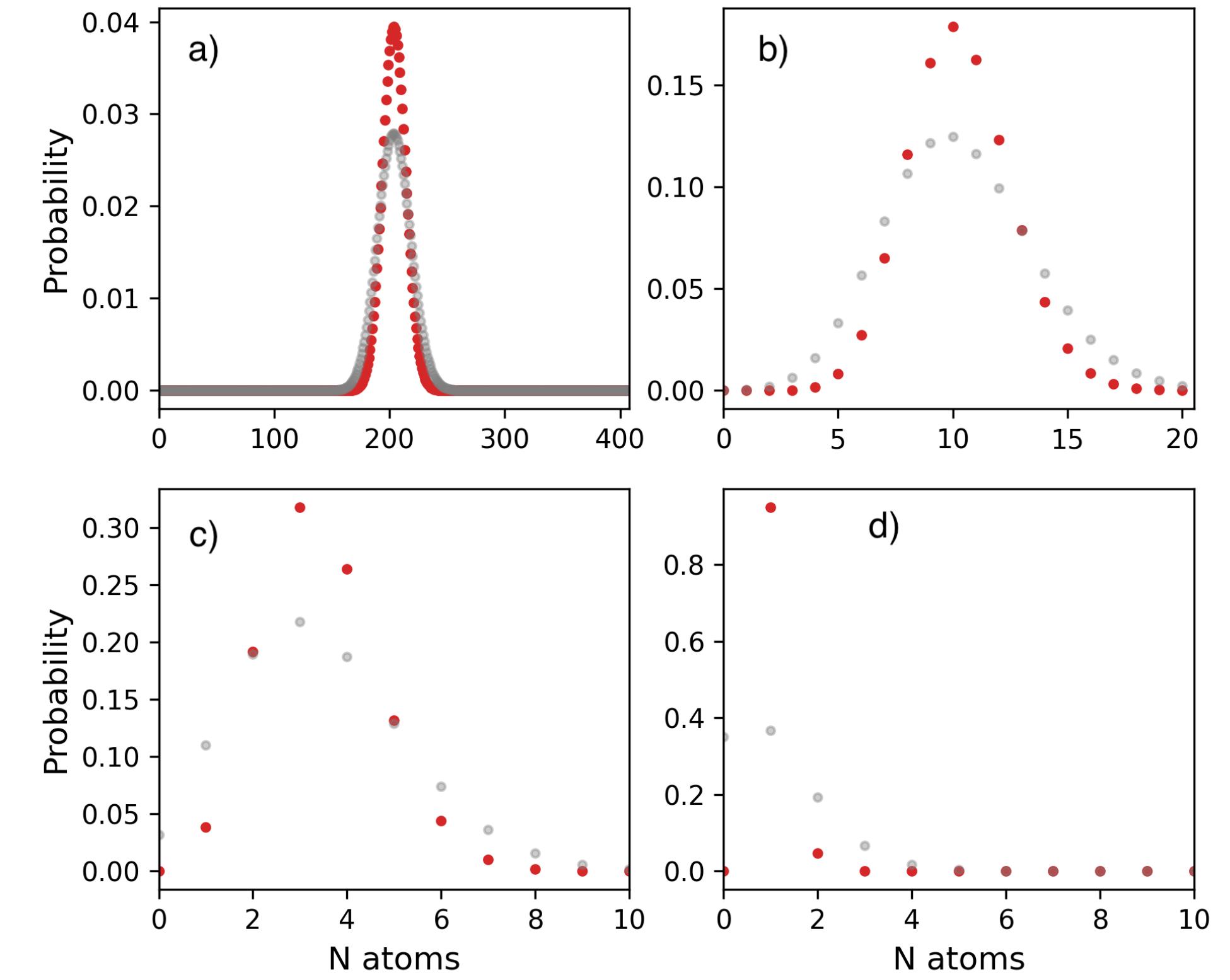
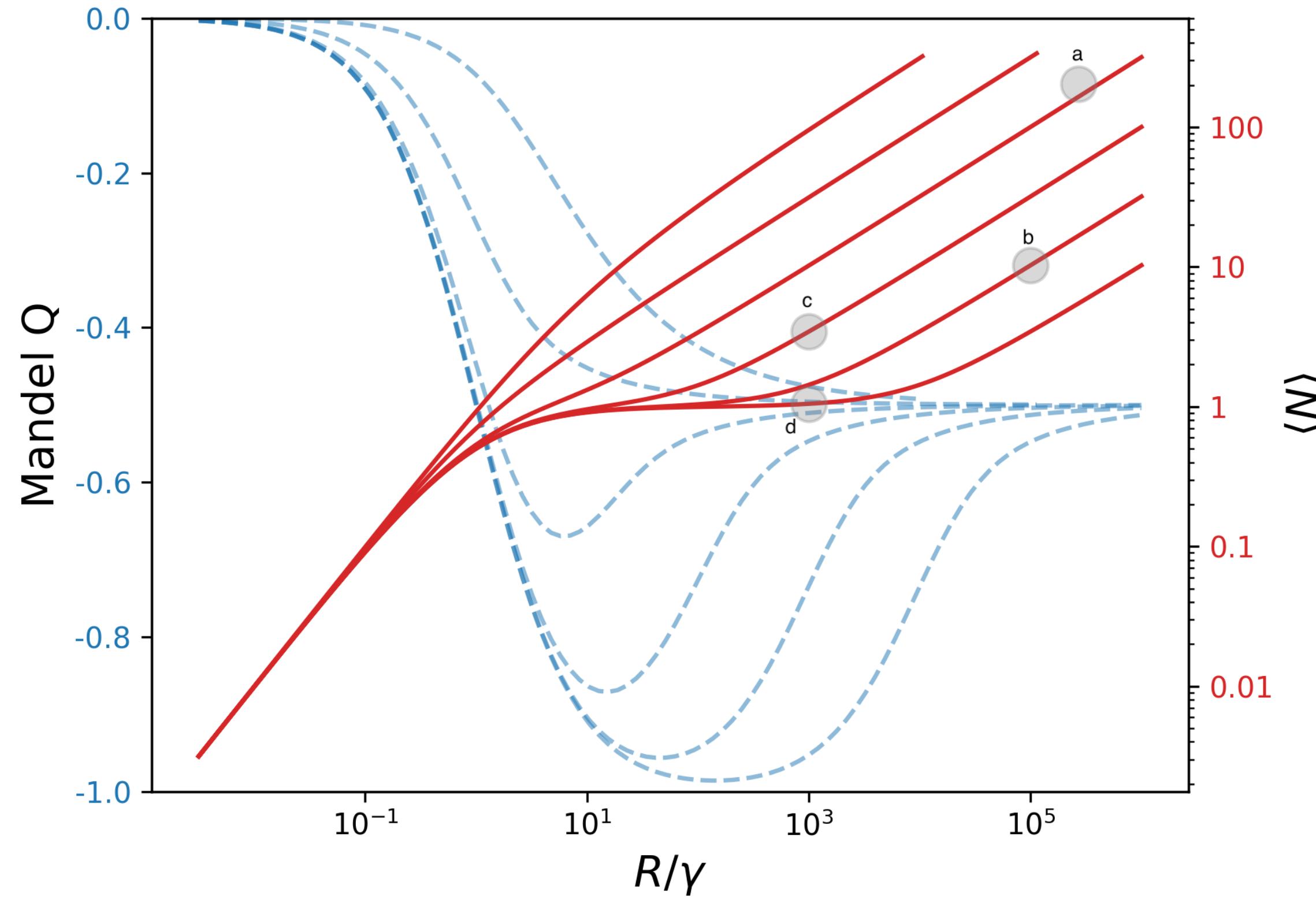
Pinsette ottiche multiple



Fine

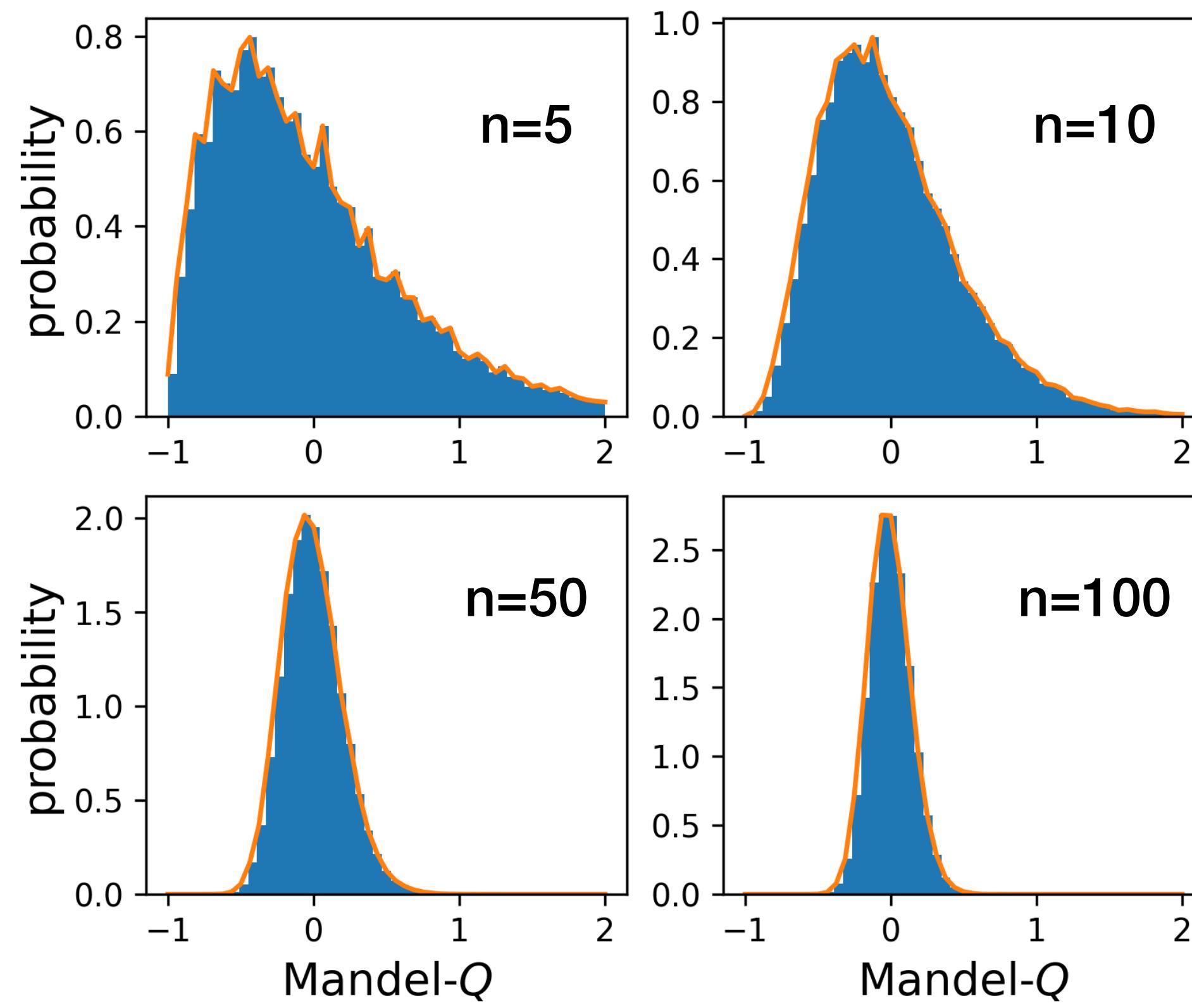
Grazie per l'attenzione



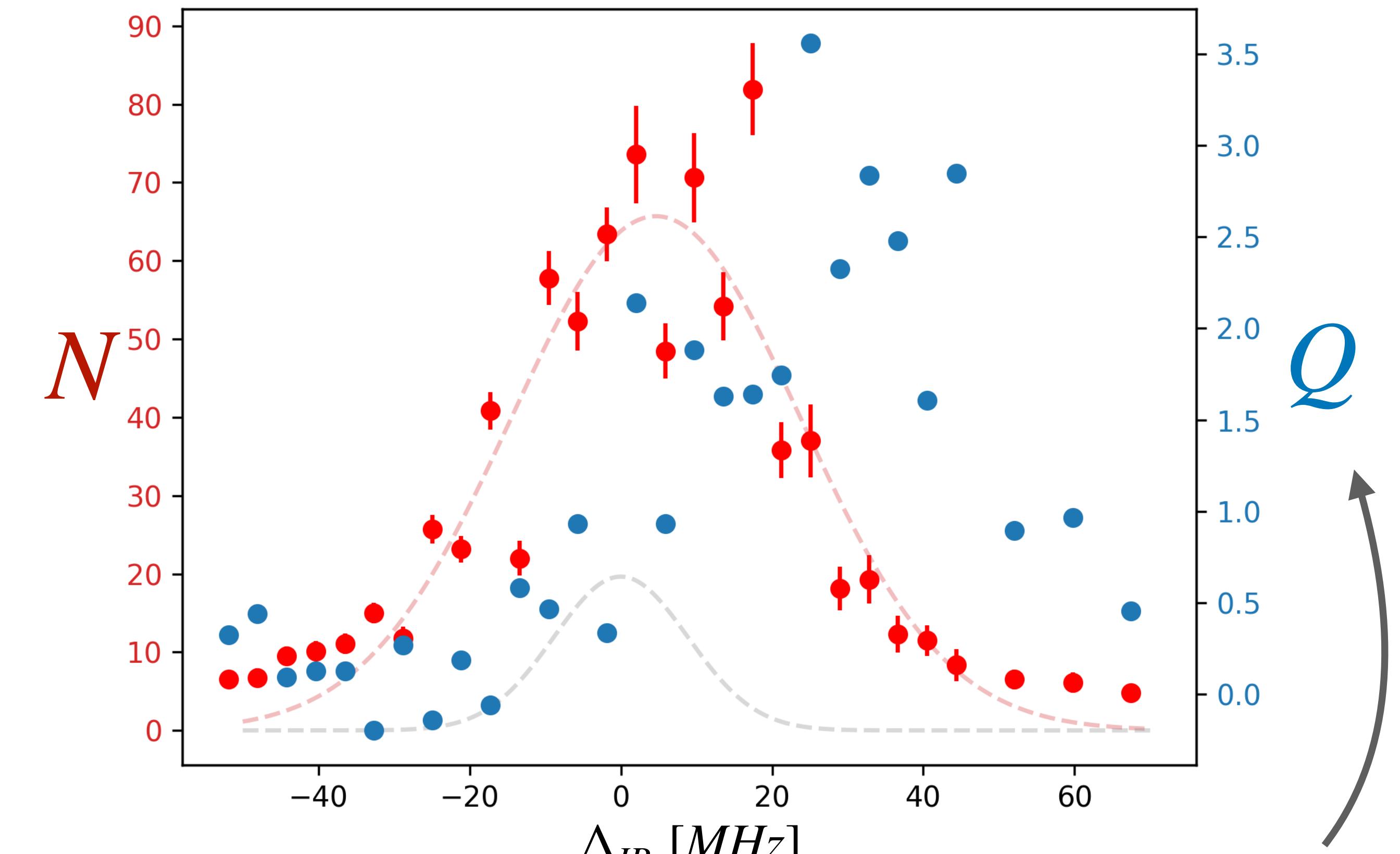


Evidenza di facilitazione nella MOT

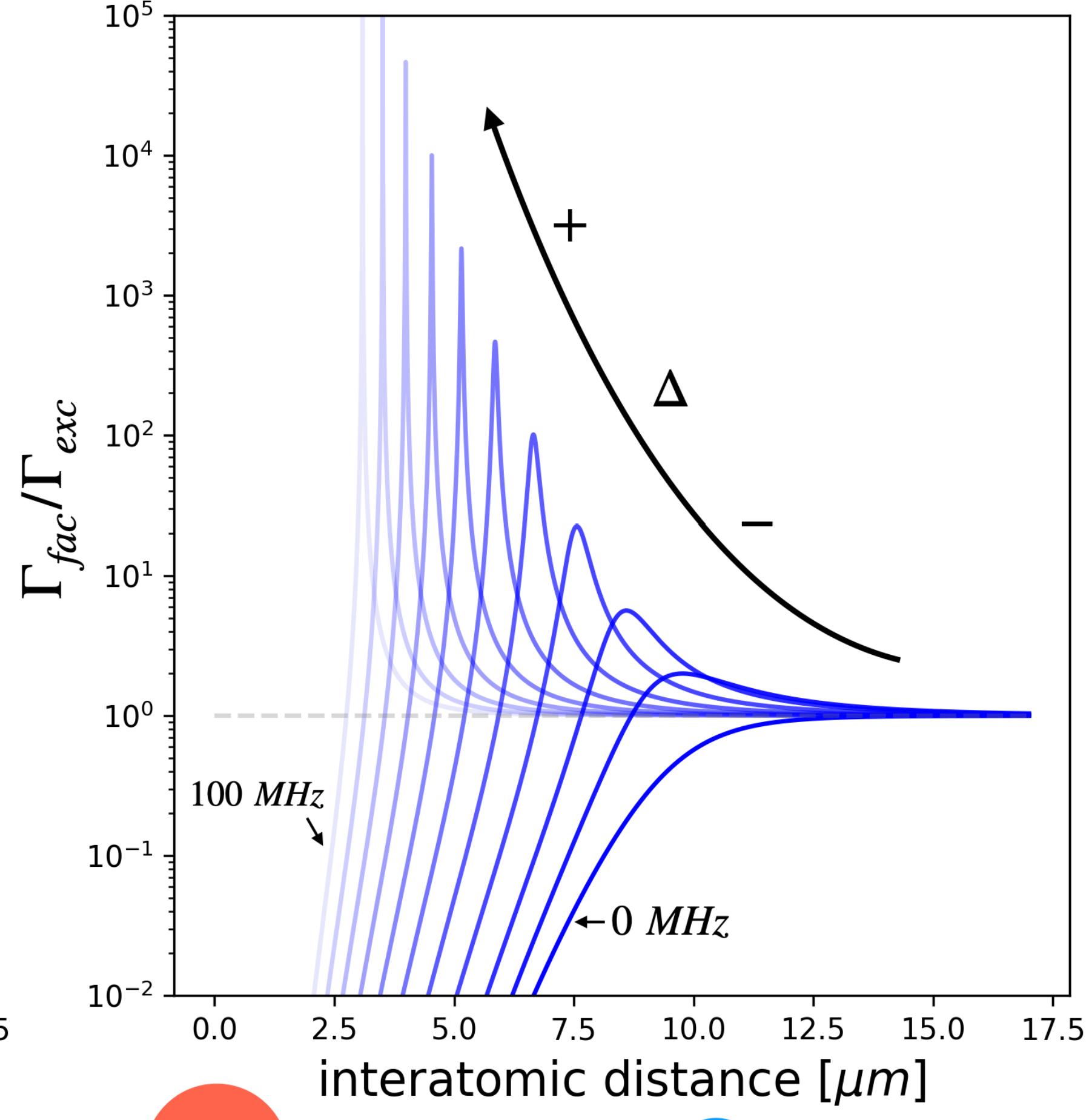
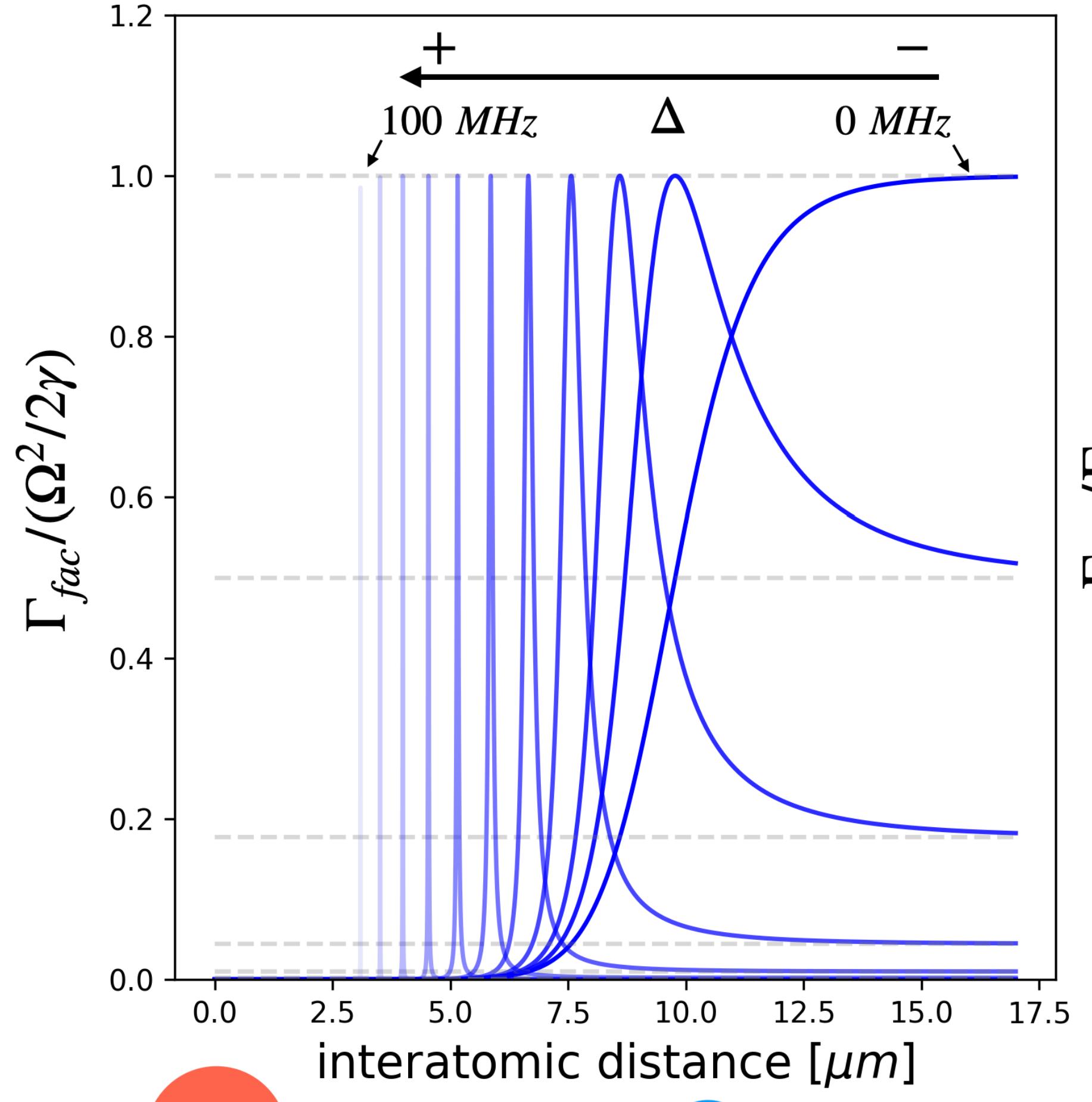
Distribuzione del Q per una distribuzione di Poisson



$t = 100 \mu s$ $\Delta_{blue} = -222 \text{ MHz}$ $\Omega_{2ph} = 500 \text{ kHz}$



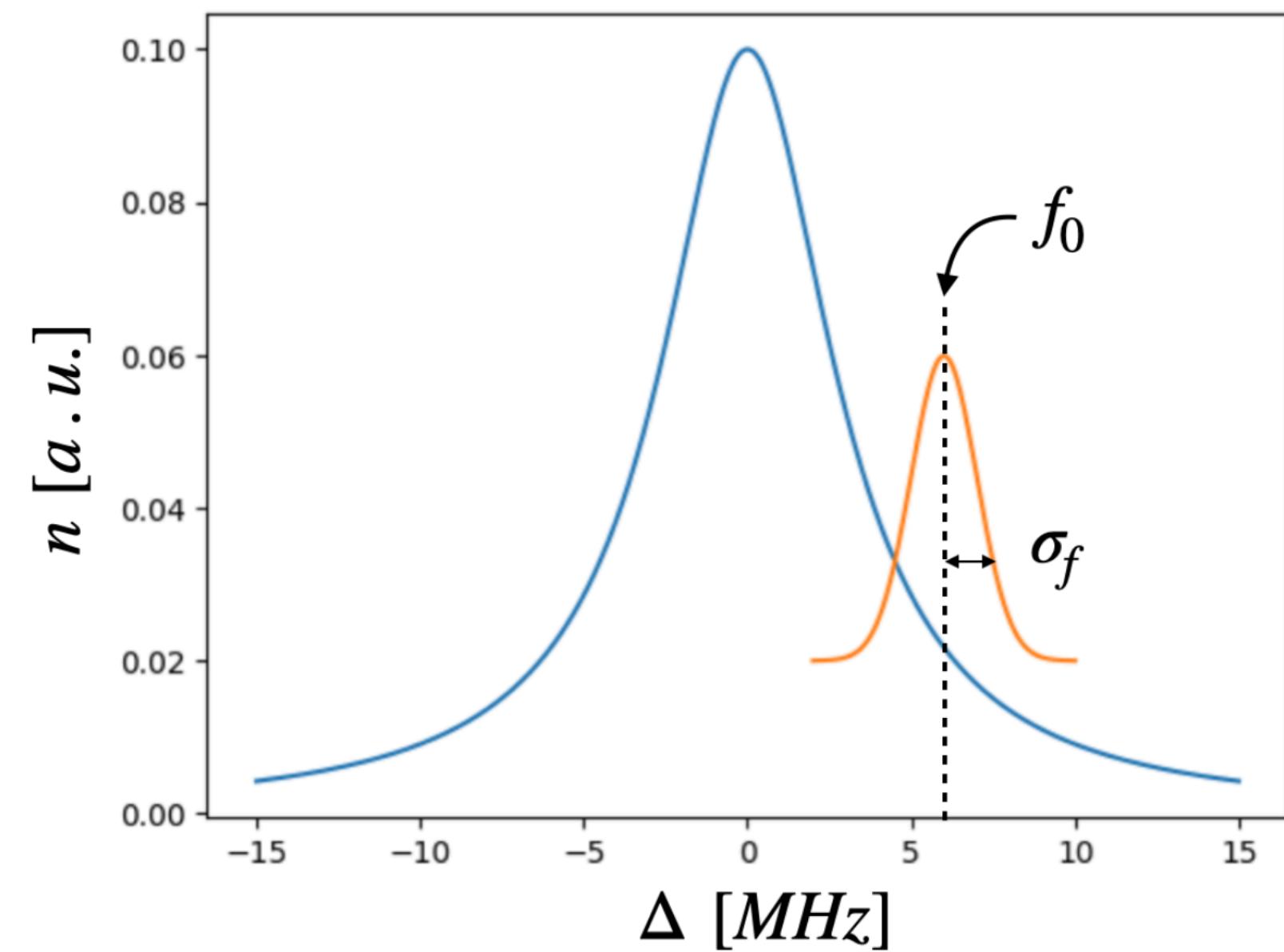
$$Q(N) = \frac{\text{Var}(N)}{\langle N \rangle} - 1$$



$$\Gamma_{fac} = \frac{\Omega^2}{2\gamma} \frac{1}{1 + \left(\frac{\Delta_{IR} - U_{vdW}(d)/\hbar}{\gamma} \right)^2}$$

$$\Gamma_{exc} = \frac{\Omega^2}{2\gamma} \frac{1}{1 + \left(\frac{\Delta_{IR}}{\gamma} \right)^2}$$

$$U_{vdW}(R) = \frac{C_6}{R^6}$$

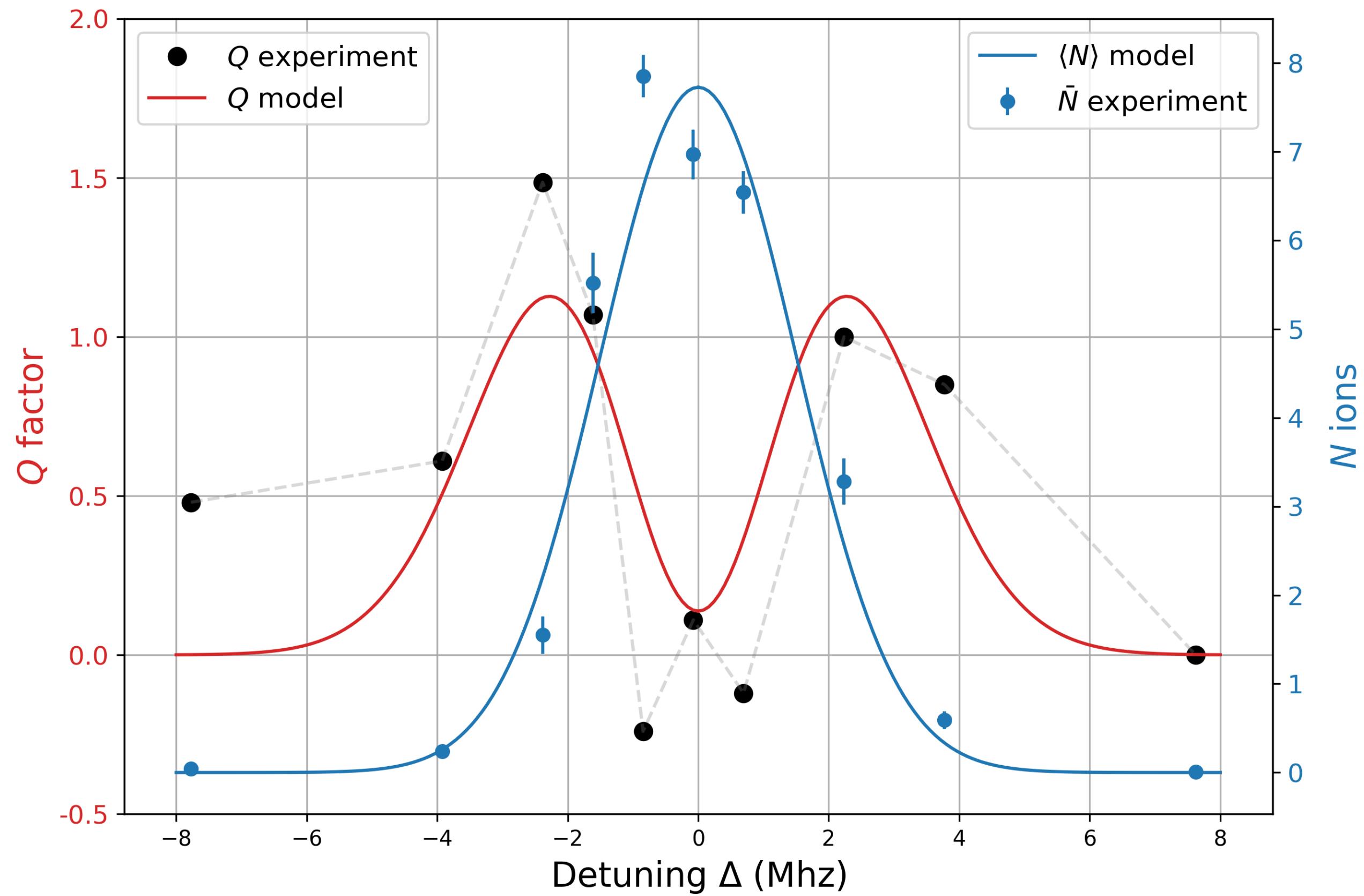


$$P(n; f_0) = \int_0^\infty P(n, f; f_0) df = \int_0^\infty P(n|f; f_0) P(f; f_0) df$$

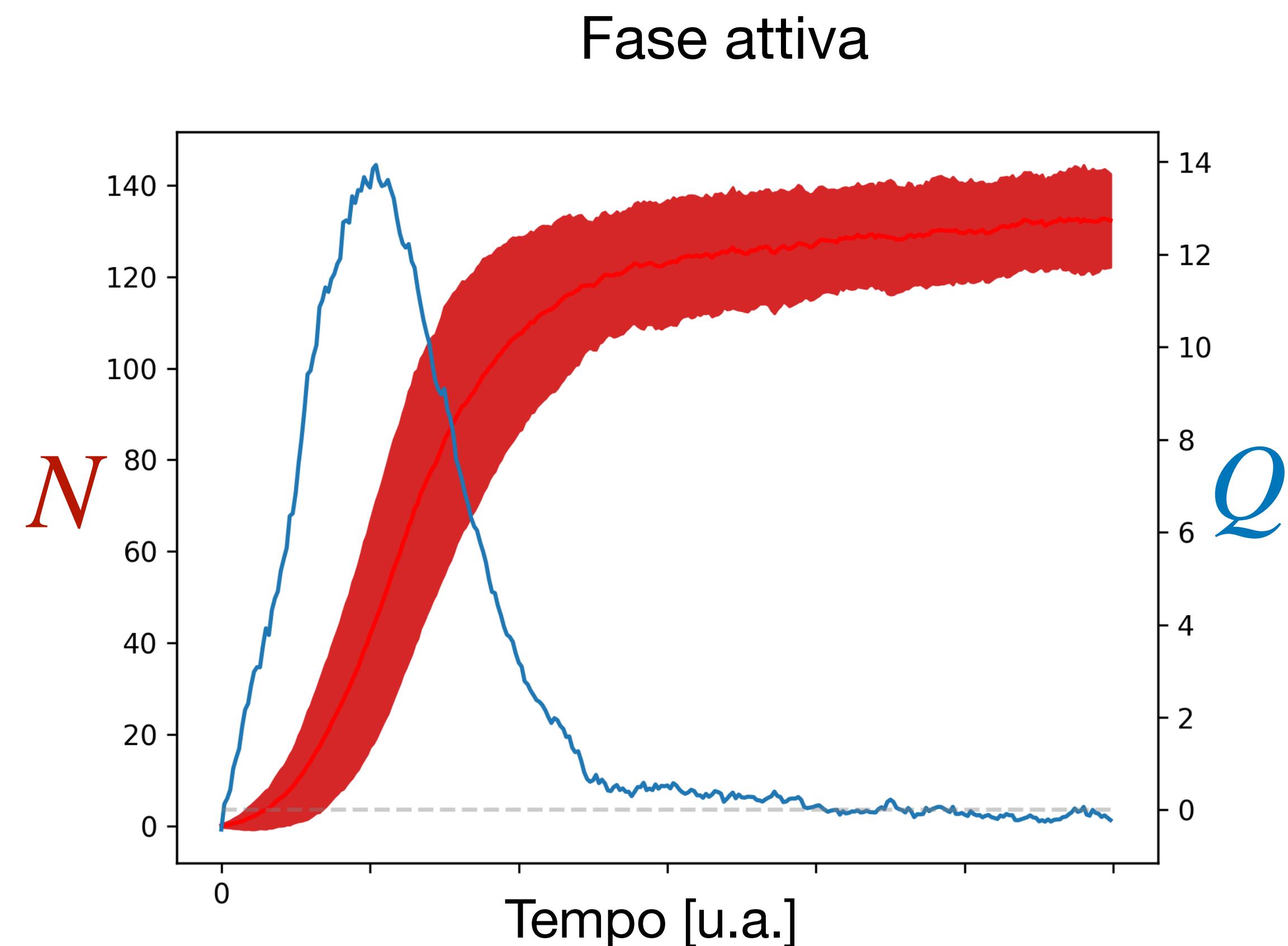
$$P(n; f_0) = \int_0^\infty \frac{e^{-\mu(f)} \mu(f)^n}{n!} \alpha e^{-\frac{(f-f_0)^2}{2\sigma_f^2}} df$$

$$\mu(f) = N_{max} e^{-\frac{(f-f_r)^2}{2\gamma^2}}$$

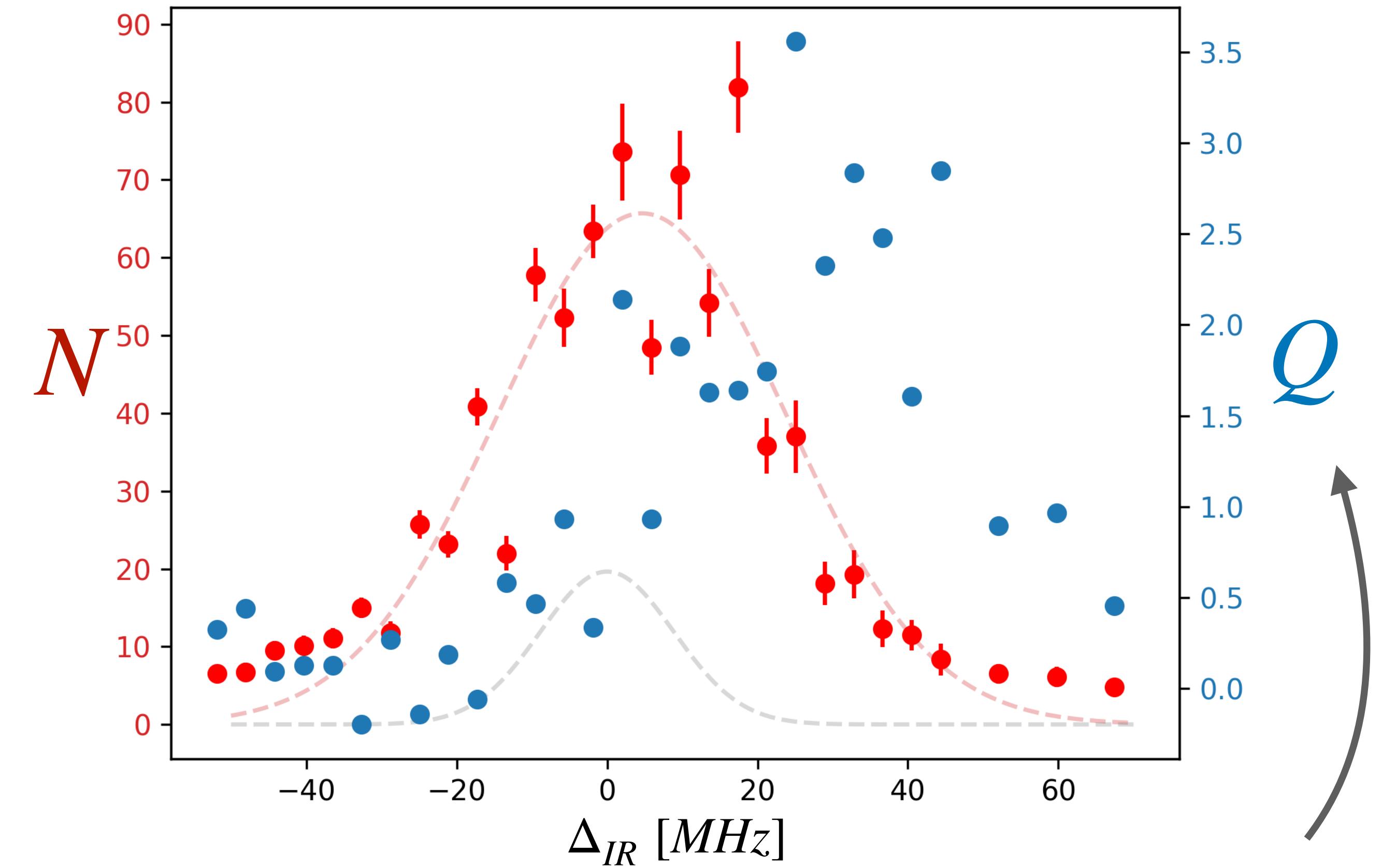
$\sigma_f = 0.7$ MHz
 $\gamma = 1.5$ MHz
 $N_{max} = 7.5$ atomi



Evidenza di facilitazione nella MOT

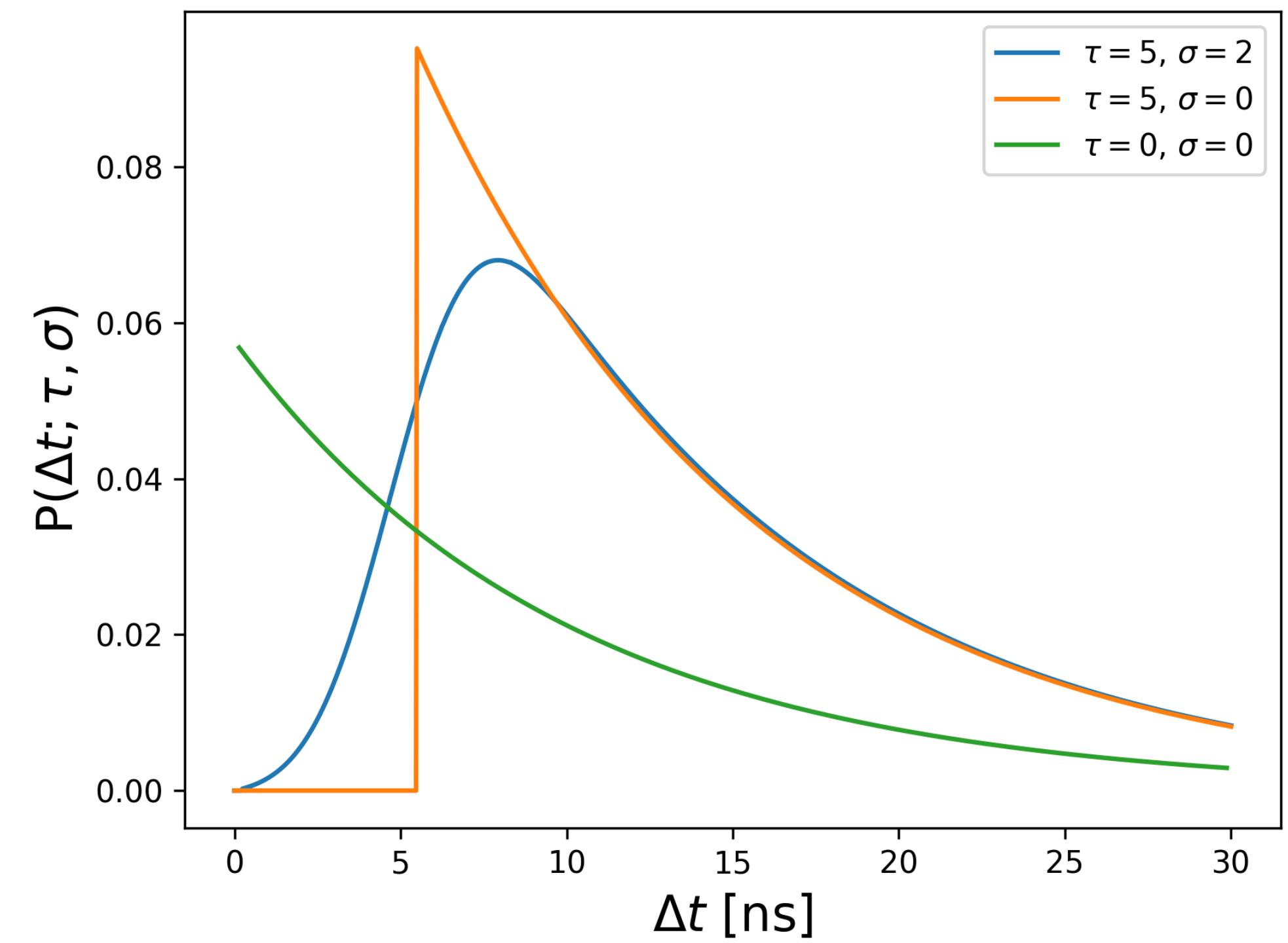


$t = 100 \mu\text{s}$ $\Delta_{blue} = -222 \text{ MHz}$ $\Omega_{2ph} = 500 \text{ kHz}$



$$Q(N) = \frac{\text{Var}(N)}{\langle N \rangle} - 1$$

$$n = \frac{N}{\sigma_0} \simeq 0.1 \text{ MHz}$$

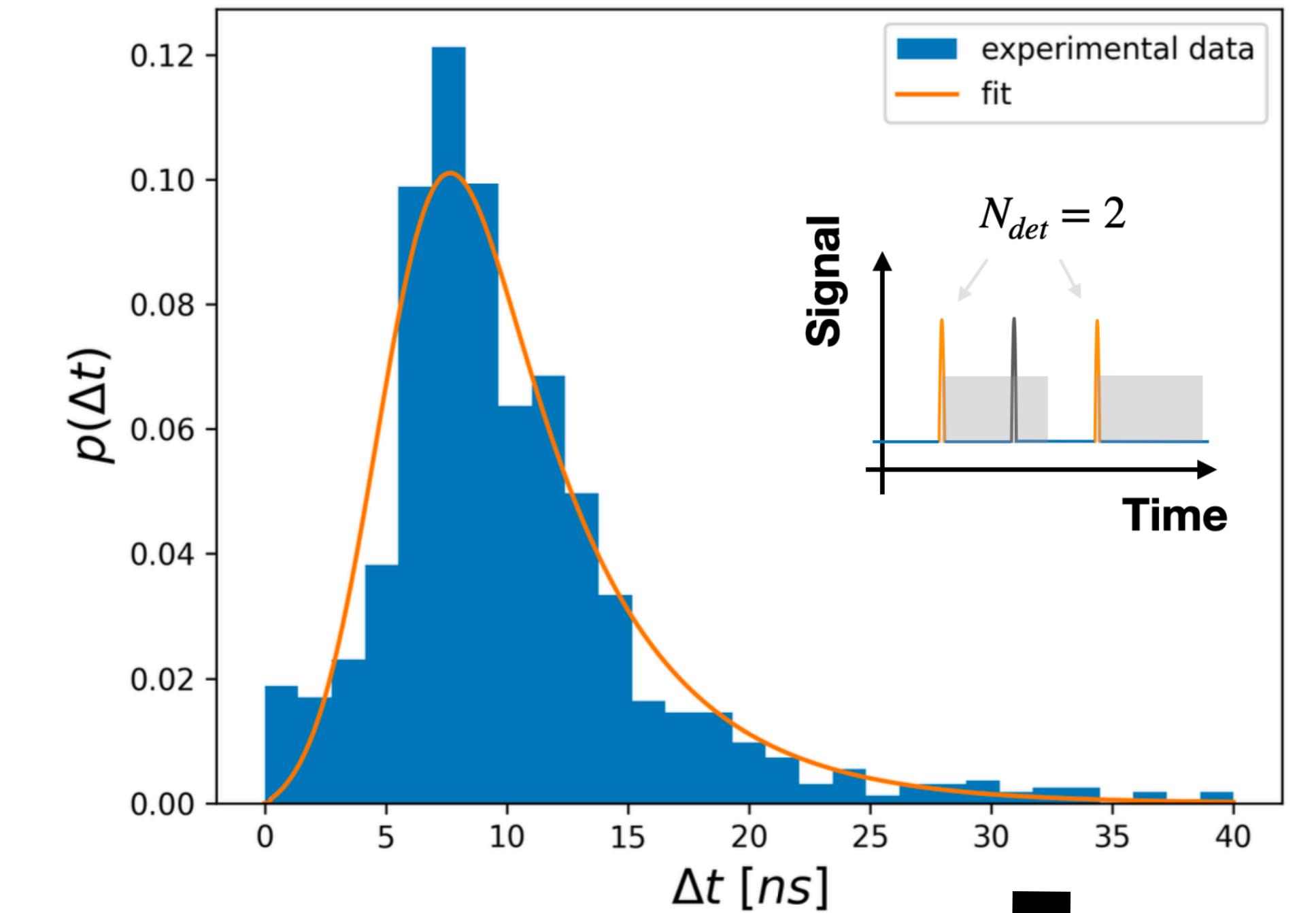


Senza jitter

$$p(\Delta t | n, \tau) = n e^{-n(\Delta t - \tau)} \quad (\Delta t > \tau)$$

Con jitter gaussiano

$$\left\{ \begin{array}{l} p(\Delta t | n, \hat{\tau}, \sigma_\tau) = \int_0^\infty p(\Delta t | n, \tau) p(\tau | \hat{\tau}, \sigma_\tau) d\tau \\ p(\Delta t | n, \hat{\tau}, \sigma_\tau) = \int_0^\infty n e^{-n(\Delta t - \tau)} \frac{1}{\sqrt{2\pi\sigma_\tau^2}} e^{-\frac{(\tau - \hat{\tau})^2}{2\sigma_\tau^2}} d\tau \end{array} \right.$$

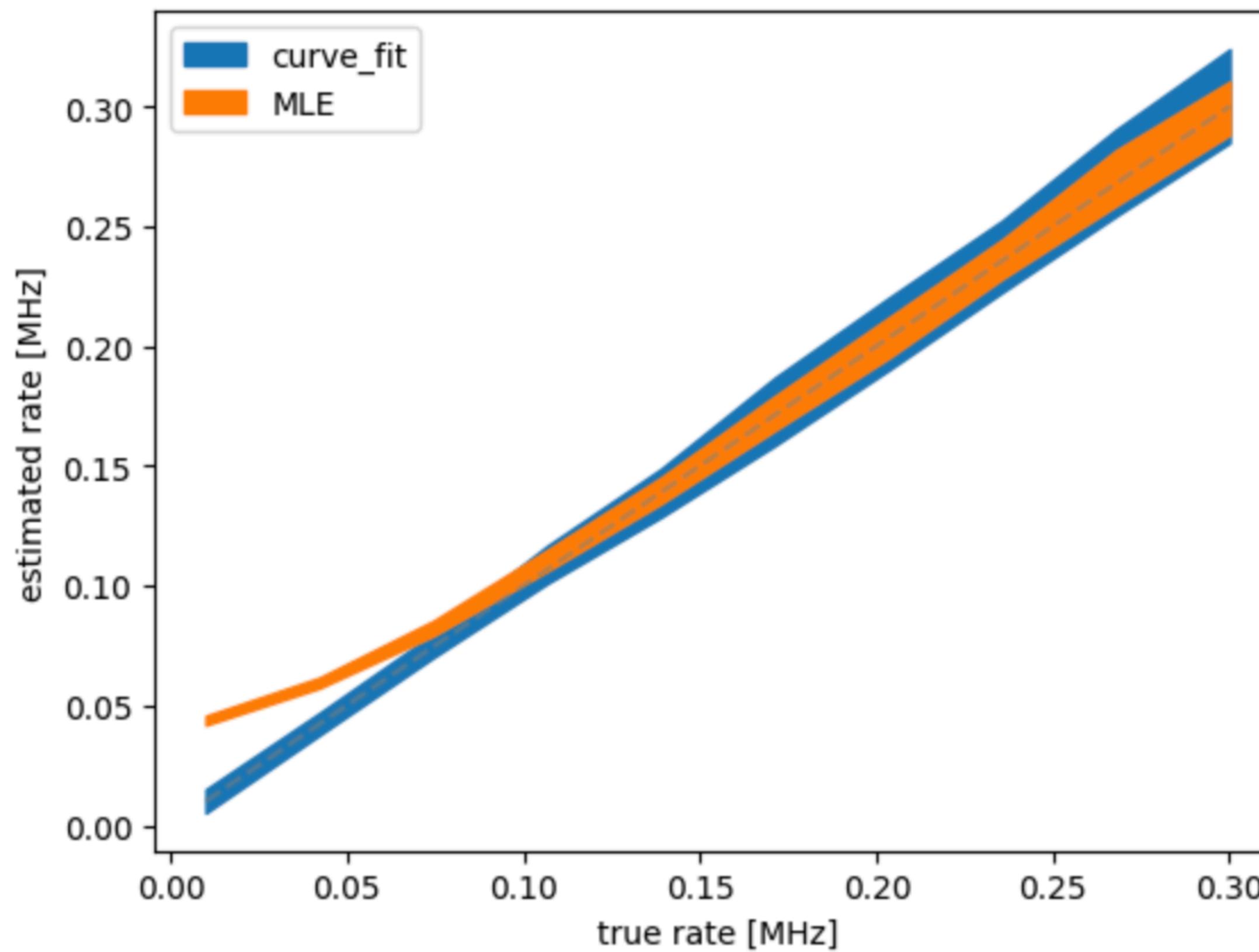


Fit di istogramma

$$\left\{ \begin{array}{l} n = 0.21 \pm 0.07 [\text{ns}^{-1}] \\ \hat{\tau} = 5.3 \pm 0.6 \text{ [ns]} \\ \sigma_\tau = 2.3 \pm 0.5 \text{ [ns]} \end{array} \right.$$

Numero di atomi : 200

Ripetizioni : 10



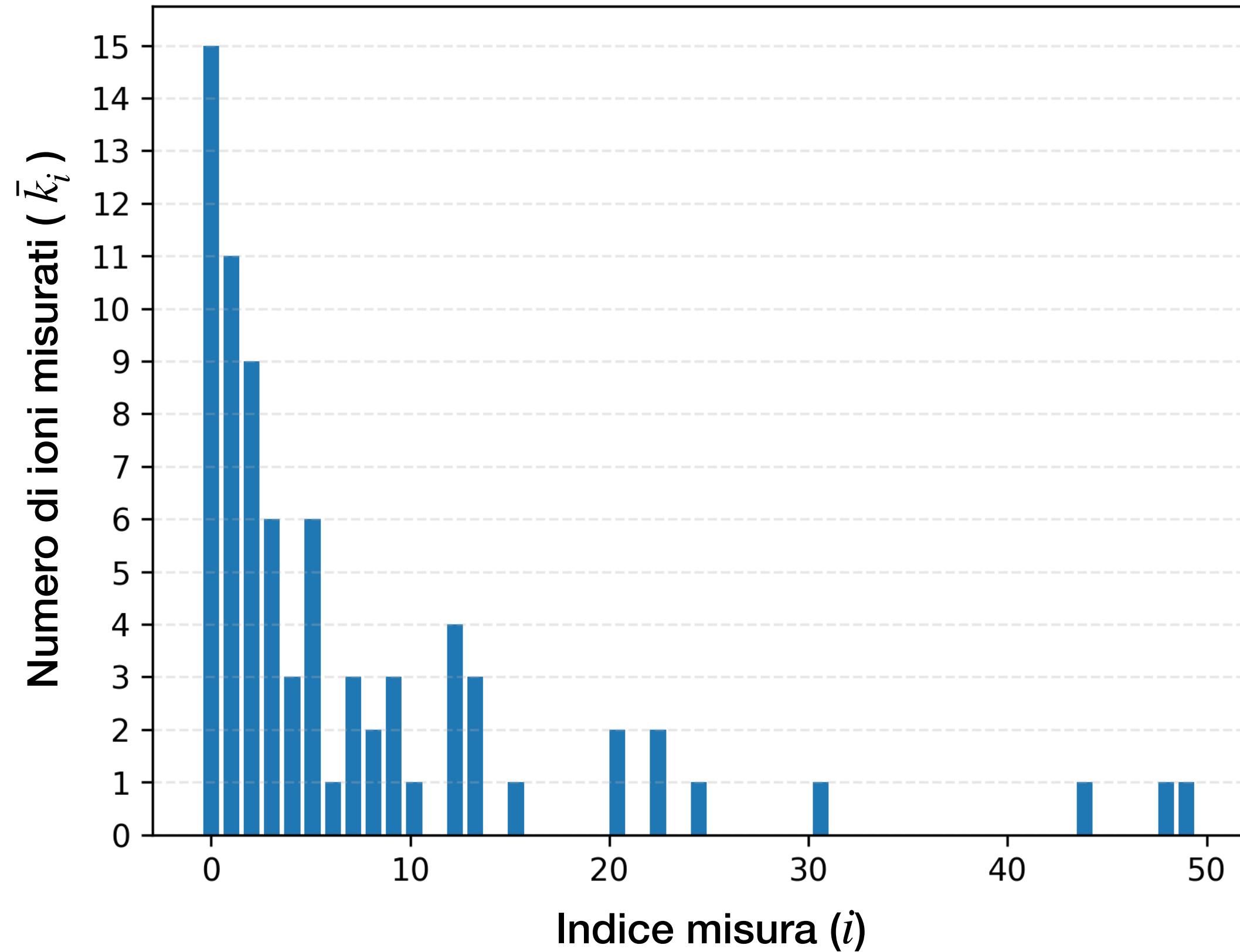
Rate di fotoionizzazione

$$P(\Delta t) = 1 - e^{-\Gamma_{ph}\Delta t}$$

Probabilità di fotoionizzare un
atomo con un impulso di durata Δt

Rate di fotoionizzazione

Fit di massima likelihood



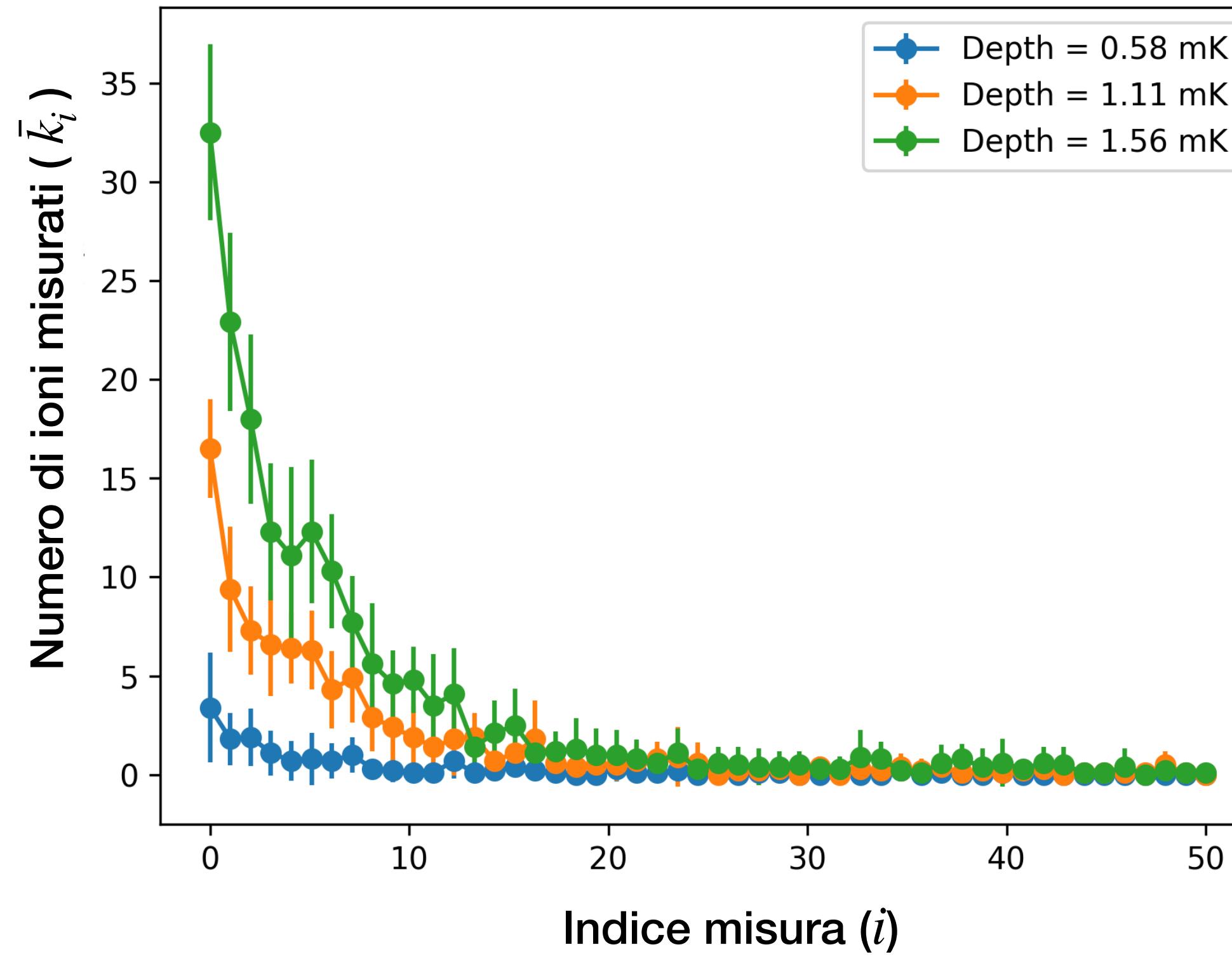
{ Una misura ogni 1 ms
{ Durata impulso di fotoionizzazione: 1 μ s

$$\frac{d}{d\Gamma} \log L = 0$$

$$\hat{\Gamma}_{ph} = \frac{1}{\Delta t} \log \left(\frac{N}{\sum_i i k_i} + 1 \right)$$

Rate di fotoionizzazione

Fit di massima likelihood



$\left\{ \begin{array}{l} \text{Una misura ogni 1 ms} \\ \text{Durata impulso di fotoionizzazione: } 1 \mu s \end{array} \right.$

$$\alpha < 1$$

$$P(\Delta t) = 1 - e^{-\Gamma_{ph}\Delta t} \quad \leftarrow \quad \text{Per un singolo impulso}$$

$$P_i = (1 - P(\Delta t))^i P(\Delta t) \quad \leftarrow \quad \text{Fotoionizzare un atomo nella misura } i$$

Supponendo di avere N atomi, e che il tempo complessivo di misura sia
Abbastanza grande ($n\Delta t \gg 1/\Gamma_{ph}$)

Experiment $\longrightarrow \{k_i\} ; i \in \{0, \dots, n-1\}$

$$L(\Gamma) = P(\{k_i\}_{0, \dots, n-1} | \Gamma) = N! \prod_i \frac{P_i^{k_i}}{k_i!} \quad \text{Multinomiale}$$

$$\frac{d}{d\Gamma} \log L = 0 \quad \longrightarrow \quad \hat{\Gamma}_{\text{MLE}} = \frac{1}{\Delta t} \log \left(\frac{N}{\sum_i ik_i} + 1 \right)$$

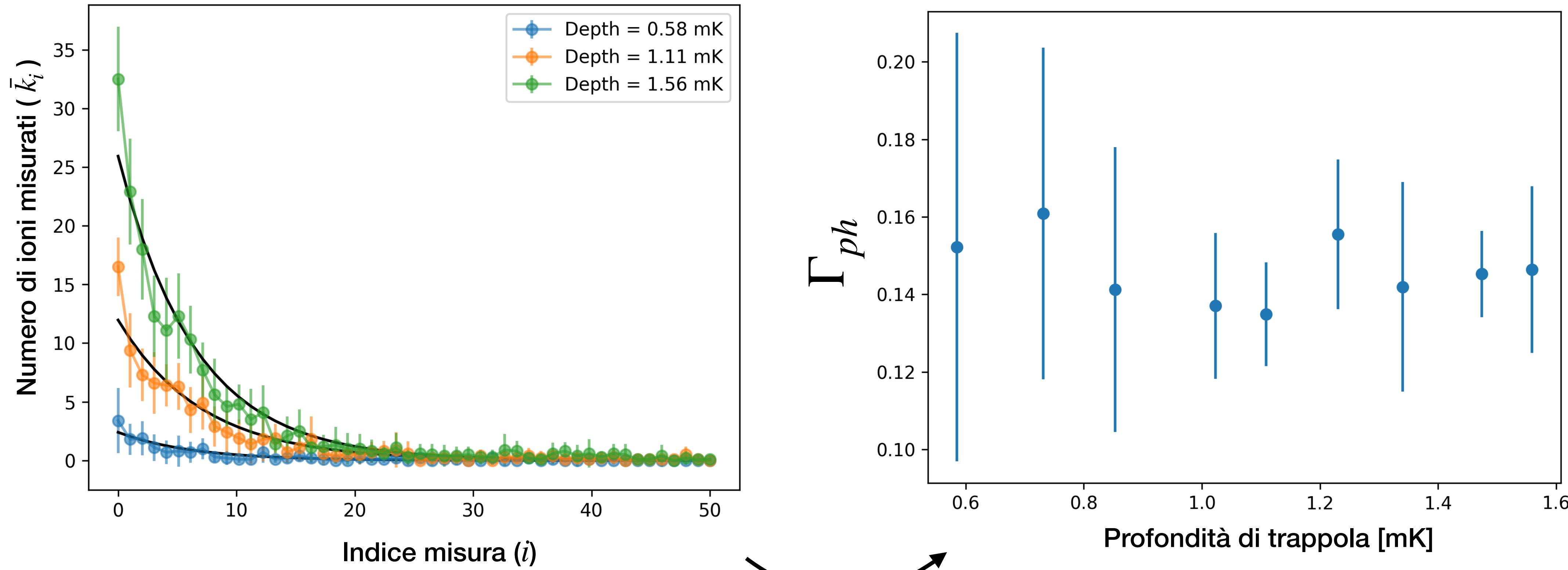
$$\xrightarrow[N \rightarrow \alpha N]{k_i \rightarrow \alpha k_i}$$

$$\hat{\Gamma}_{\text{MLE}} = \frac{1}{\Delta t} \log \left(\frac{\alpha N}{\alpha \langle k \rangle} - 1 \right)$$

$$\langle k \rangle = \sum_i ik_i$$

Rate di fotoionizzazione

Fit di massima likelihood



{ Una misura ogni 1 ms
Durata impulso di fotoionizzazione: 1 μ s

Media e deviazione standard
dell'MLE su 10 ripetizioni