Delocalization in the light matter interaction

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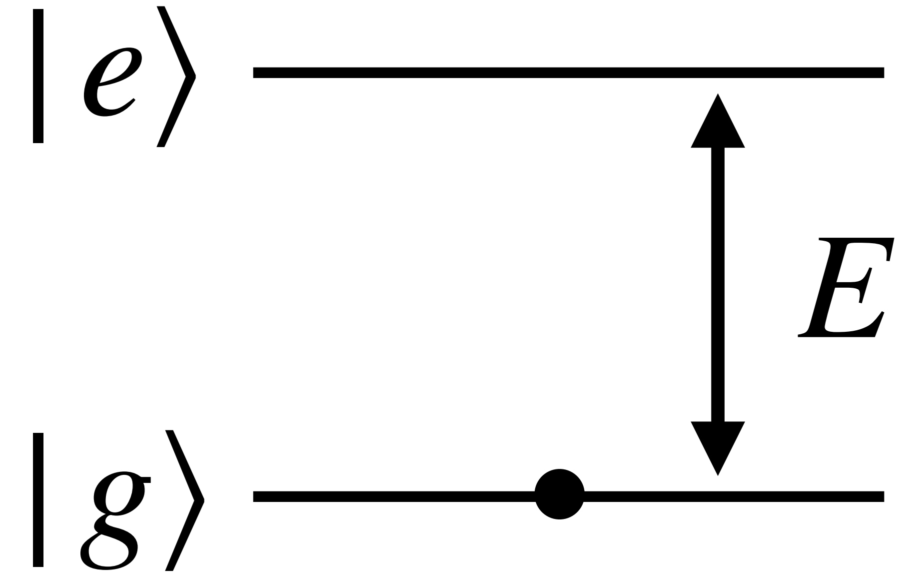

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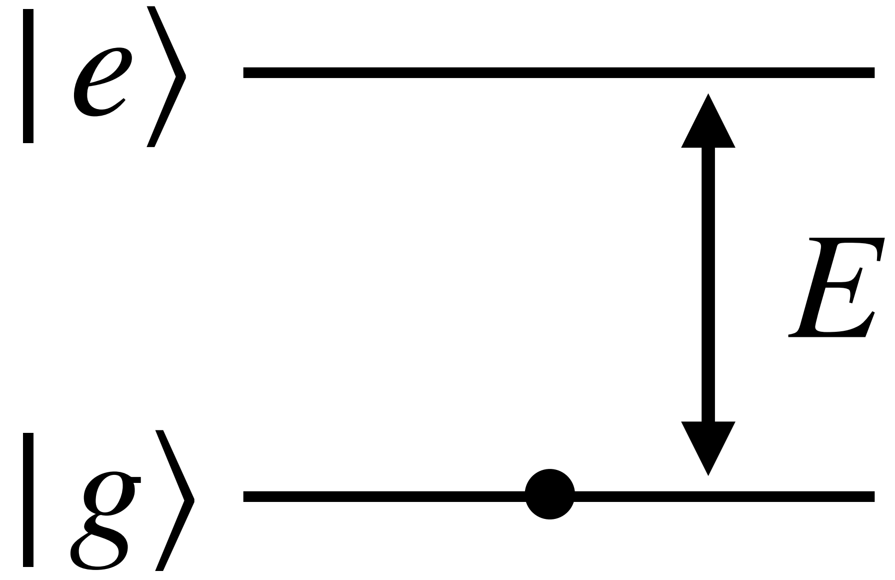

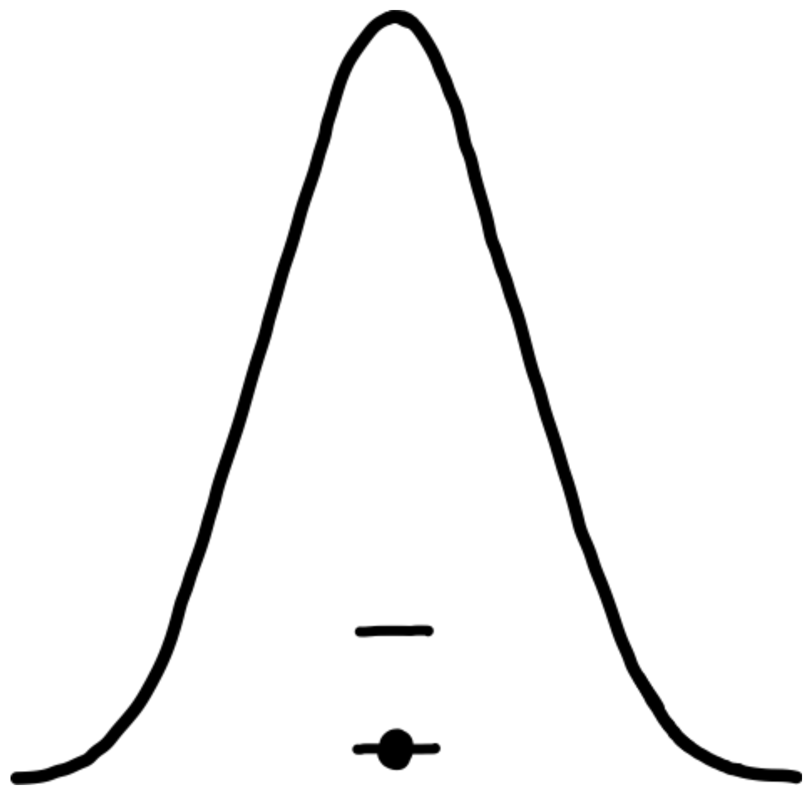

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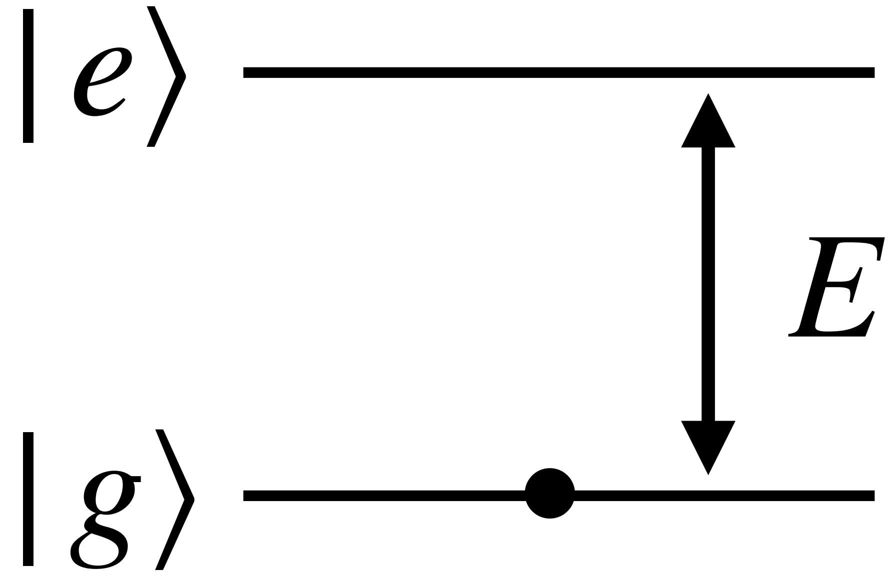
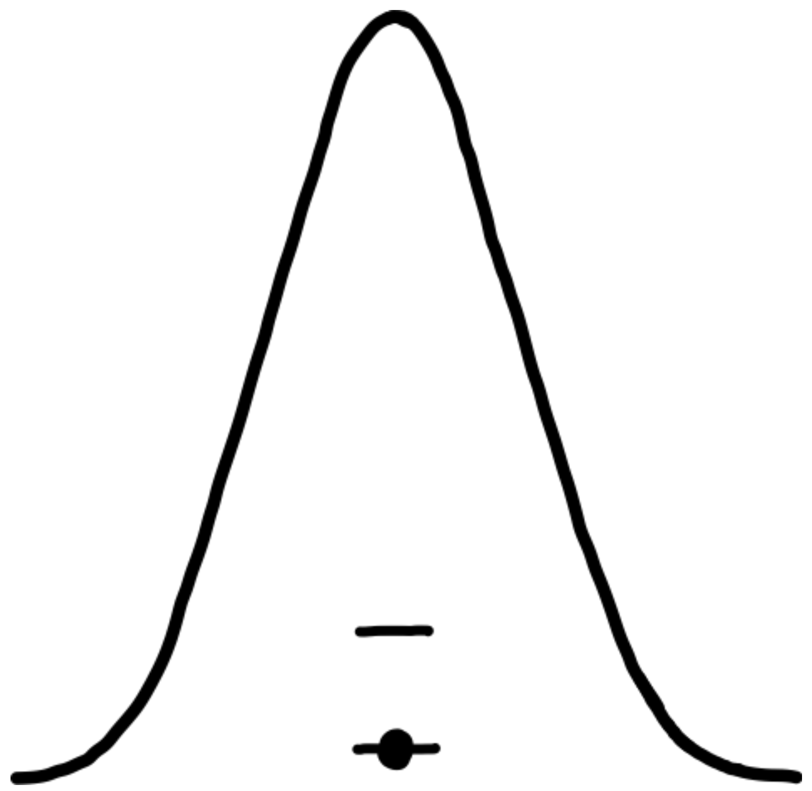
Incorporate delocalization into detector model?

$$\mathscr{H}_{total} = \mathscr{H}_{external} \otimes \mathscr{H}_{internal} \otimes \mathscr{H}_{field}$$





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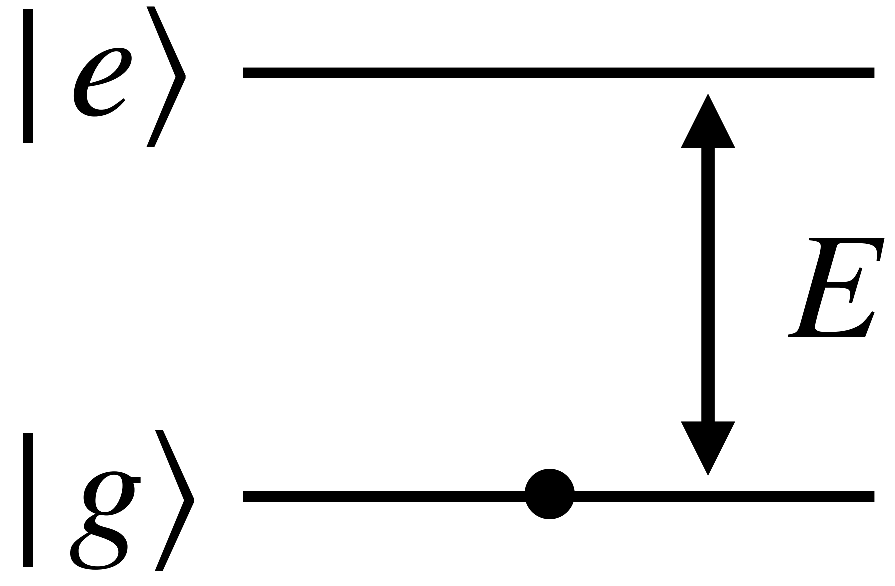

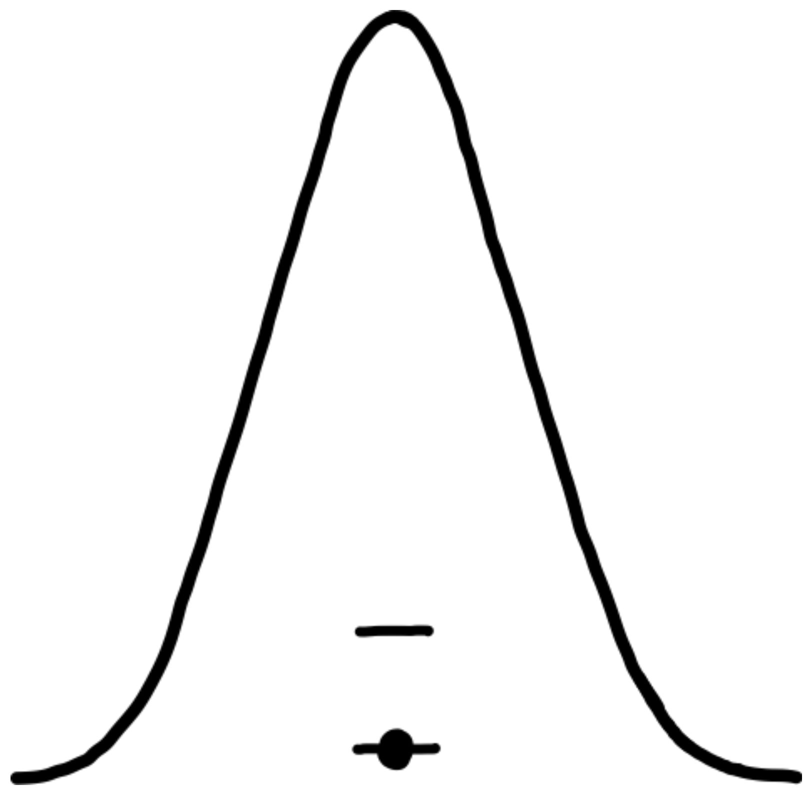

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Spectral theorem: $$\hat{X}\,|x\rangle = x\,|x\rangle\,, \quad f(\hat{X}) = \int dx\, f(x)\,|x\rangle\langle x|$$

For operator valued functions: $$\hat{f}(\hat{X}) = \int dx\, \hat{f}(x) \otimes |x\rangle\langle x|$$

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More realistic model:

$$\hat{H}^{(total)} = \frac{\left(\hat{\mathbf{p}}_p + e\hat{\mathbf{A}}(\hat{\mathbf{x}}_p)\right)^2}{2m_p} + \frac{\left(\hat{\mathbf{p}}_e - e\hat{\mathbf{A}}(\hat{\mathbf{x}}_e)\right)^2}{2m_e} - \frac{e^2}{4\pi\epsilon_0 |\hat{\mathbf{x}}_p - \hat{\mathbf{x}}_e|} + \int \frac{d^3k}{(2\pi)^{3/2}} |\mathbf{k}| \sum_{s=1}^{2} a_{\mathbf{k}}^{s\dagger} a_{\mathbf{k}}^{s}$$

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CM + $\Downarrow$ relative d.o.f.

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CM + $\Downarrow$ relative d.o.f.

$$\hat{H}^{(free)} := \frac{\hat{\mathbf{p}}_{CM}^2}{2M} + \frac{\hat{\mathbf{p}}_{rel}^2}{2\mu} - \frac{e^2}{4\pi\epsilon_0 |\mathbf{x}_{rel}|} + \int \frac{d^3k}{\sqrt{2\pi}^3} |\mathbf{k}| \sum_{s=1}^{2} a_{\mathbf{k}}^{s\dagger} a_{\mathbf{k}}^{s}$$

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... qualitatively similar results. Go back to detector model.

Do e.g. the spontaneous emission rates differ?

$$\hat{H}^{(int)} = \lambda \int d^3x \, |\mathbf{x}\rangle\langle\mathbf{x}| \otimes \hat{\mu} \otimes \hat{\phi}(\mathbf{x}) \qquad \text{vs.} \qquad \hat{H}^{(int)} = \lambda\hat{\mu} \otimes \hat{\phi}(\mathbf{x})$$

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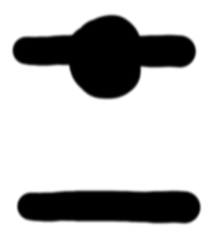
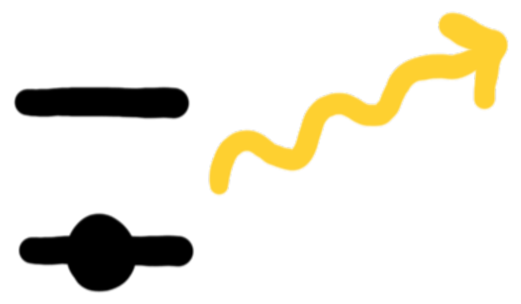


$\longrightarrow$



$|\Psi_{in}\rangle = |e\rangle \otimes |0\rangle$

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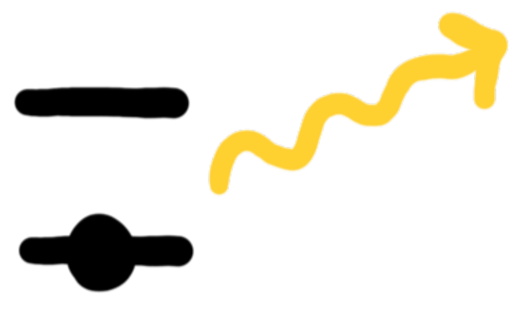

$$|\Psi_{in}\rangle = |e\rangle \otimes |0\rangle \qquad\qquad |\Psi_{out}\rangle = |g\rangle \otimes |1_{\mathbf{k}}\rangle$$

Spontaneous emission rate (tracing over field) : $\mathscr{R}_{e\to g} = \dfrac{\lambda^2 E}{c^3\hbar^3}$

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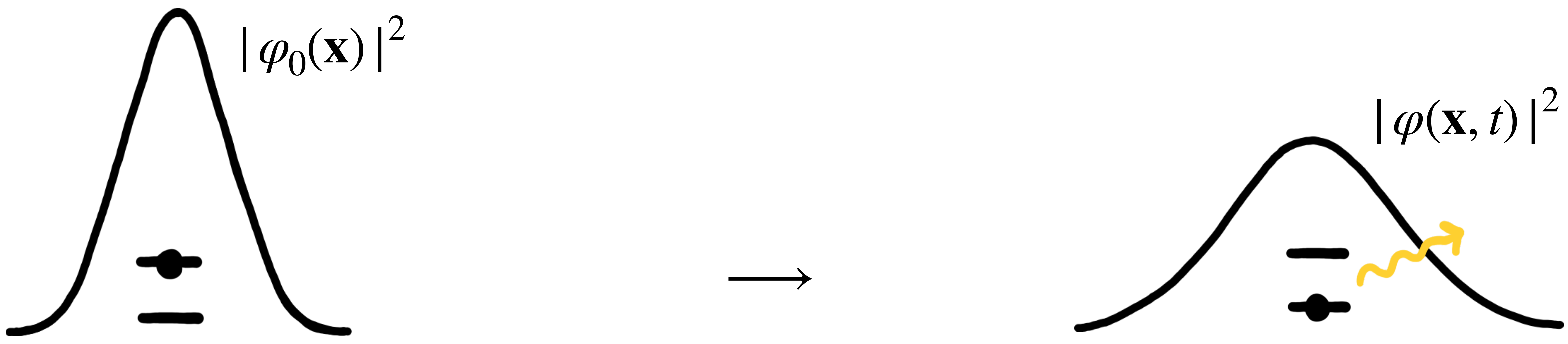

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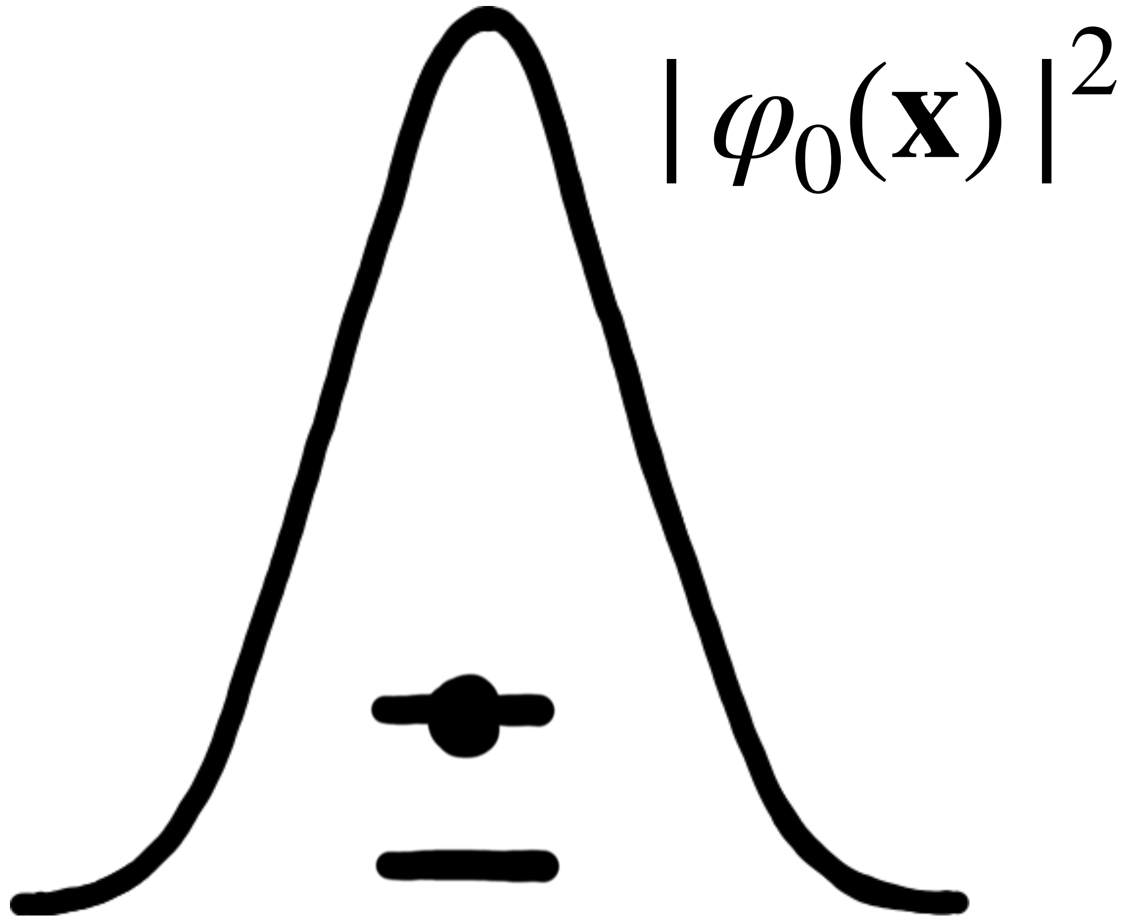

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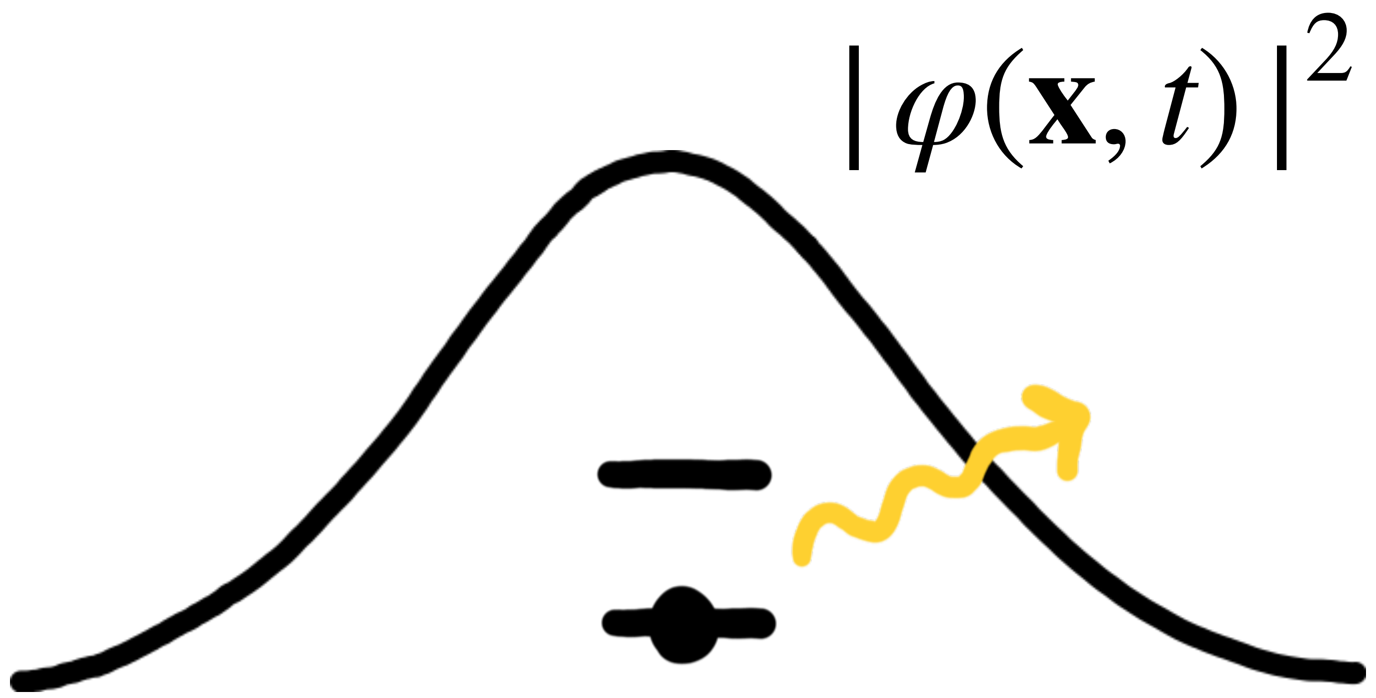

$$|\Psi_{in}\rangle = \int d^3p\, \varphi_0(\mathbf{p})\, |\mathbf{p}\rangle \otimes |e\rangle \otimes |0\rangle$$

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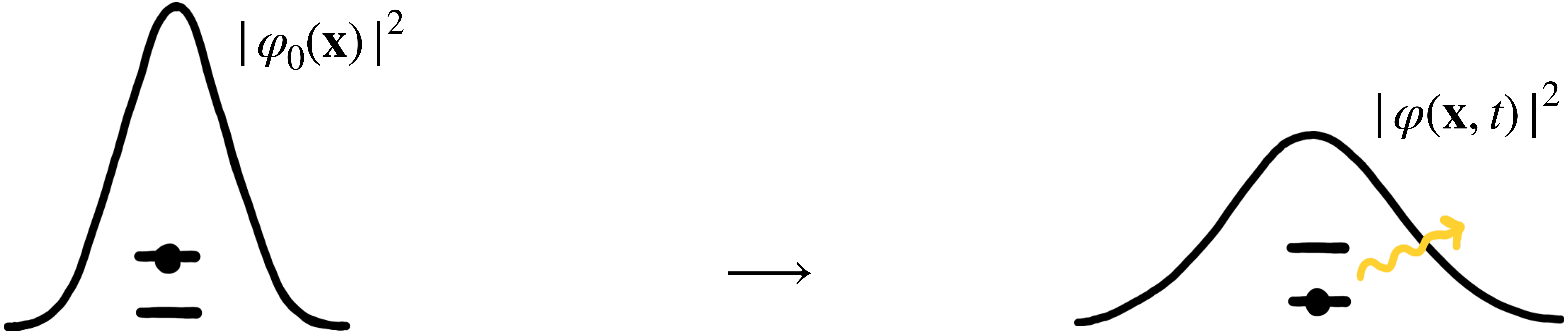

Spontaneous emission rate (tracing over field and recoil momentum):

$$\mathscr{R}_{e\to g} = \frac{\lambda^2}{2c\hbar^3}\int d^3p\,|\varphi_0(\mathbf{p})|^2 \left(2M - \frac{M^2}{|\mathbf{p}|}\sqrt{\left(\frac{|\mathbf{p}|}{M}+c\right)^2+\frac{2E}{M}} + \frac{M^2}{|\mathbf{p}|}\sqrt{\left(\frac{|\mathbf{p}|}{M}-c\right)^2+\frac{2E}{M}} \right)$$

Delocalization affects spontaneous emission!

$$\mathscr{R}_{e\to g} = \frac{\lambda^2}{2c\hbar^3}\underbrace{\int d^3p\,|\varphi_0(\mathbf{p})|^2}_{\text{initial CM wave function}}\underbrace{\left(2M - \frac{M^2}{|\mathbf{p}|}\sqrt{\left(\frac{|\mathbf{p}|}{M}+c\right)^2+\frac{2E}{M}} + \frac{M^2}{|\mathbf{p}|}\sqrt{\left(\frac{|\mathbf{p}|}{M}-c\right)^2+\frac{2E}{M}}\right)}_{\text{template function}}$$

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$$= \frac{2E}{c^2} + \mathcal{O}\left(\frac{1}{M}\right)$$

Limit of infinite detector mass:

$$\lim_{M\to\infty}\mathscr{R}_{e\to g} = \frac{\lambda^2 E}{c^3\hbar^3}$$

= decay rate for standard UdW detector!

$$\mathscr{R}_{e\to g} = \frac{\lambda^2}{2c\hbar^3}\underbrace{\int d^3p\,|\varphi_0(\mathbf{p})|^2}_{}\left(2M - \frac{M^2}{|\mathbf{p}|}\sqrt{\left(\frac{|\mathbf{p}|}{M}+c\right)^2+\frac{2E}{M}} + \frac{M^2}{|\mathbf{p}|}\sqrt{\left(\frac{|\mathbf{p}|}{M}-c\right)^2+\frac{2E}{M}}\right)$$

assume $|\mathbf{p}| \ll Mc$

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$$A_1 := 1 - \frac{c\sqrt{M}}{\sqrt{c^2M+2E}}$$

$$A_2 := \frac{Ec}{\sqrt{M}}\frac{1}{(c^2M+2E)^{5/2}}$$

Spontaneous emission rate (with delocalization):

$$\mathcal{R}_{e\to g} = \frac{\lambda^2}{c\hbar^3}\int d^3p\,|\varphi_0(\mathbf{p})|^2\left(A_1 + A_2|\mathbf{p}|^2 + \mathcal{O}(|\mathbf{p}|^4)\right)$$

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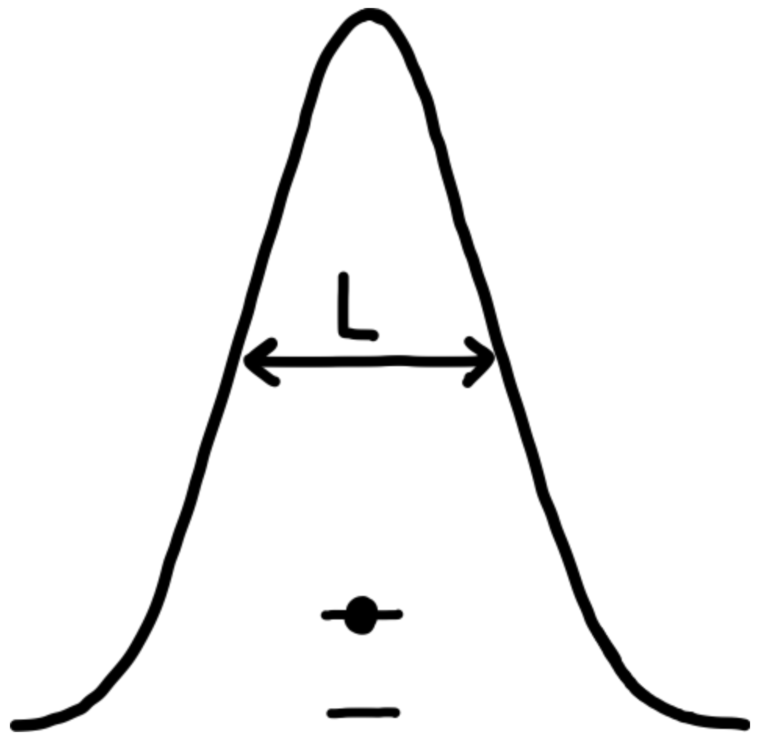
Gaussian wave packet state:

$$\varphi_0(\mathbf{p}) \sim e^{-\frac{|\mathbf{p}|^2 L^2}{4}}$$



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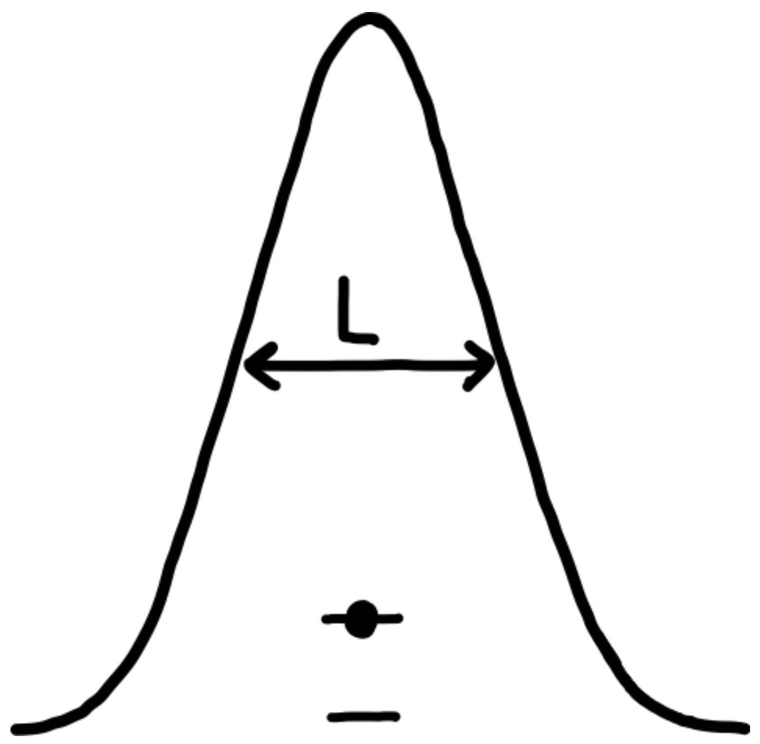

$$\mathscr{R}_{e\to g} \approx \frac{\lambda^2 M}{c\hbar^3}\left(A_1 + \frac{3\hbar^2}{L^2}A_2\right)$$

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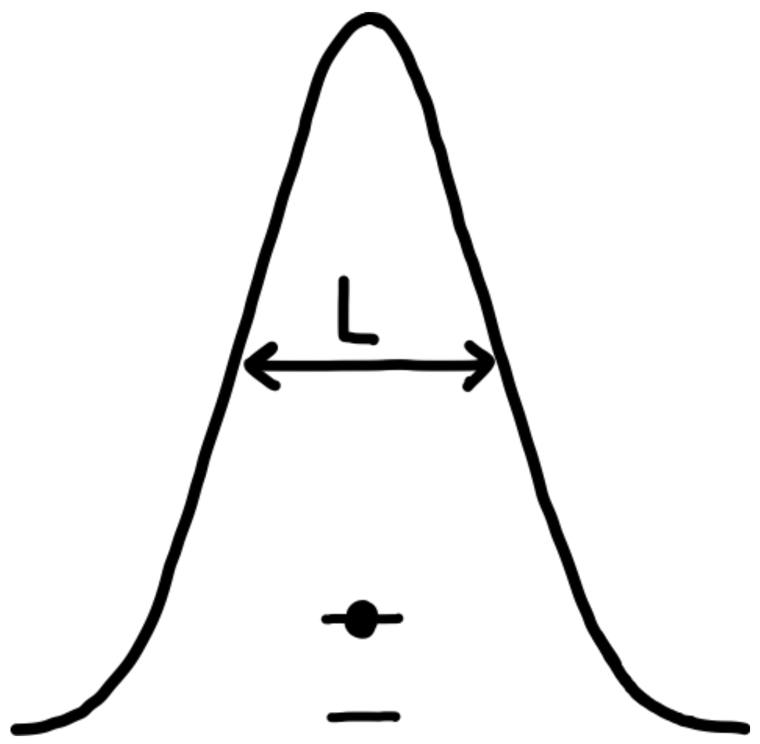

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Faster delocalization
$\Longrightarrow$ Faster decay

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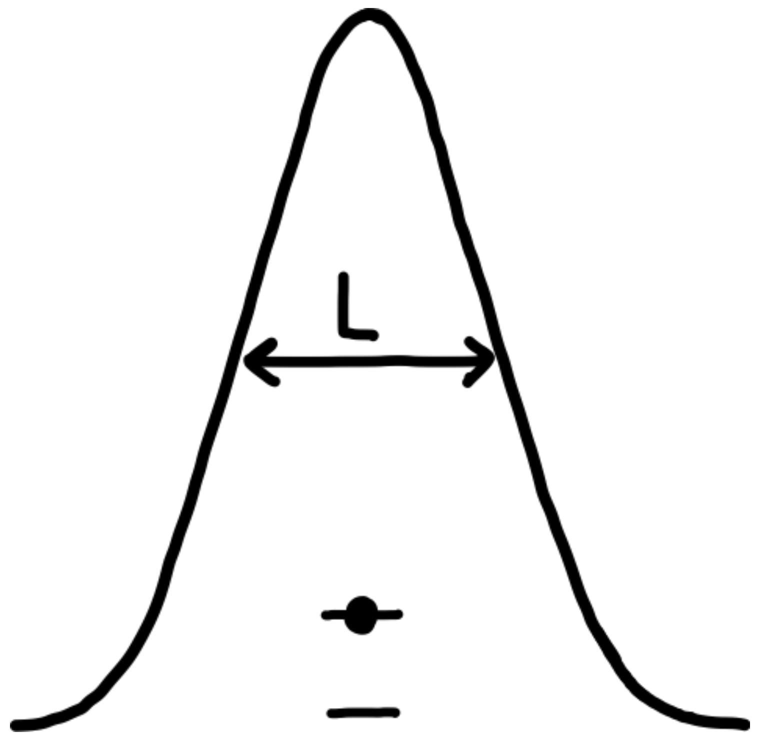

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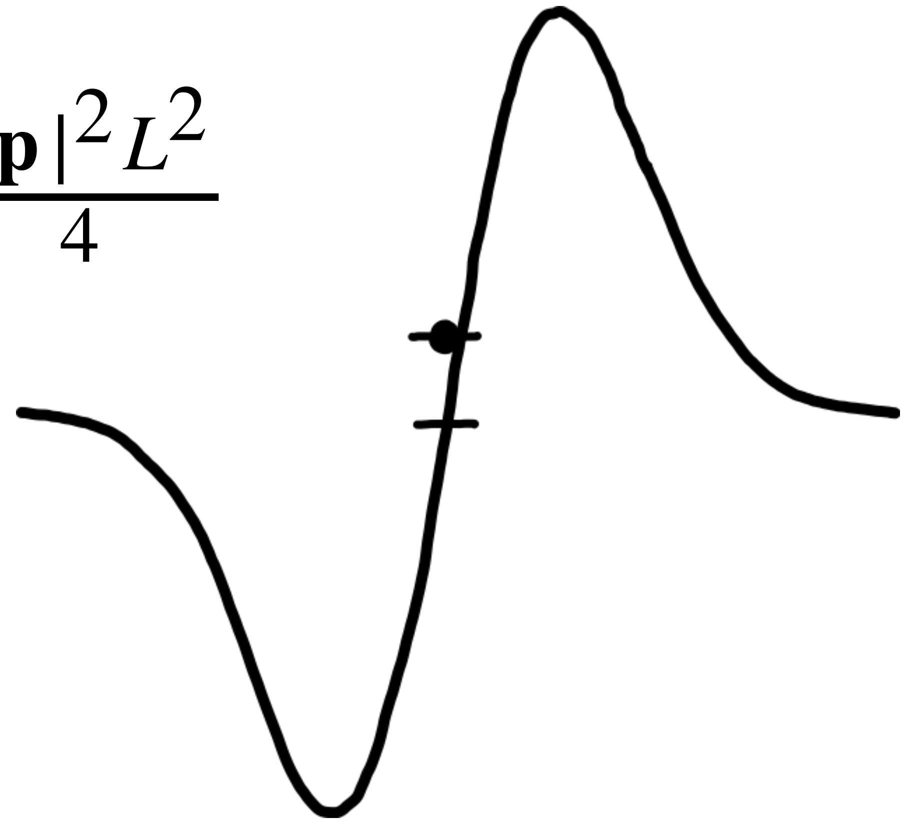

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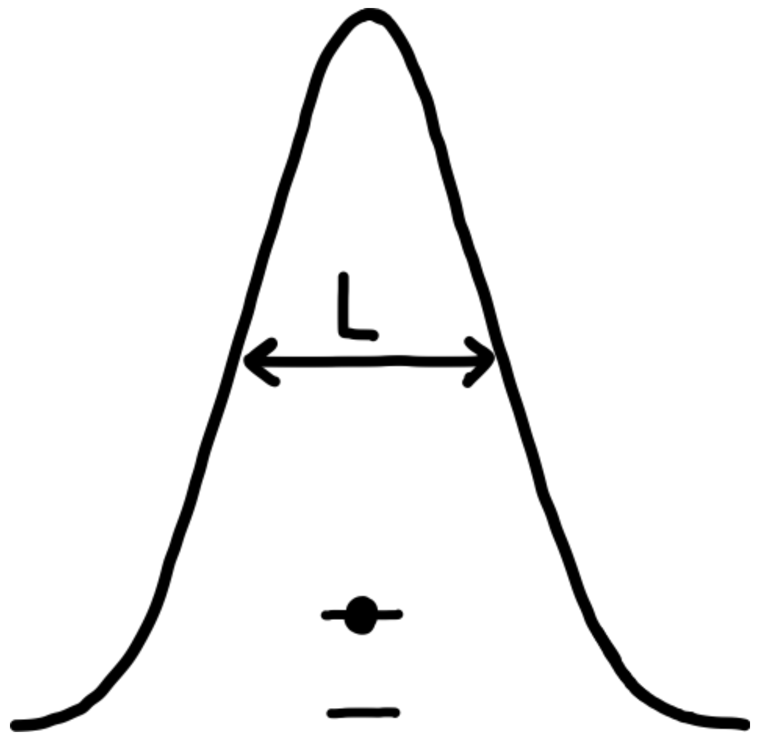

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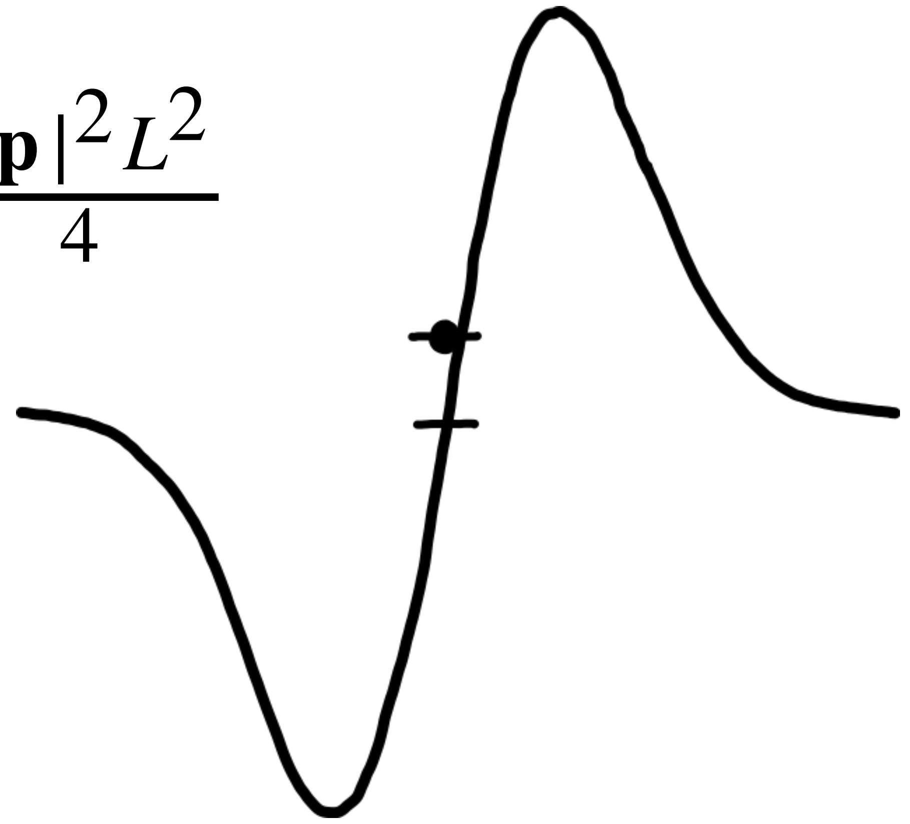

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Spontaneous emission affected by delocalization process

Decay rates affected differently by incoherent vs. coherent delocalization?

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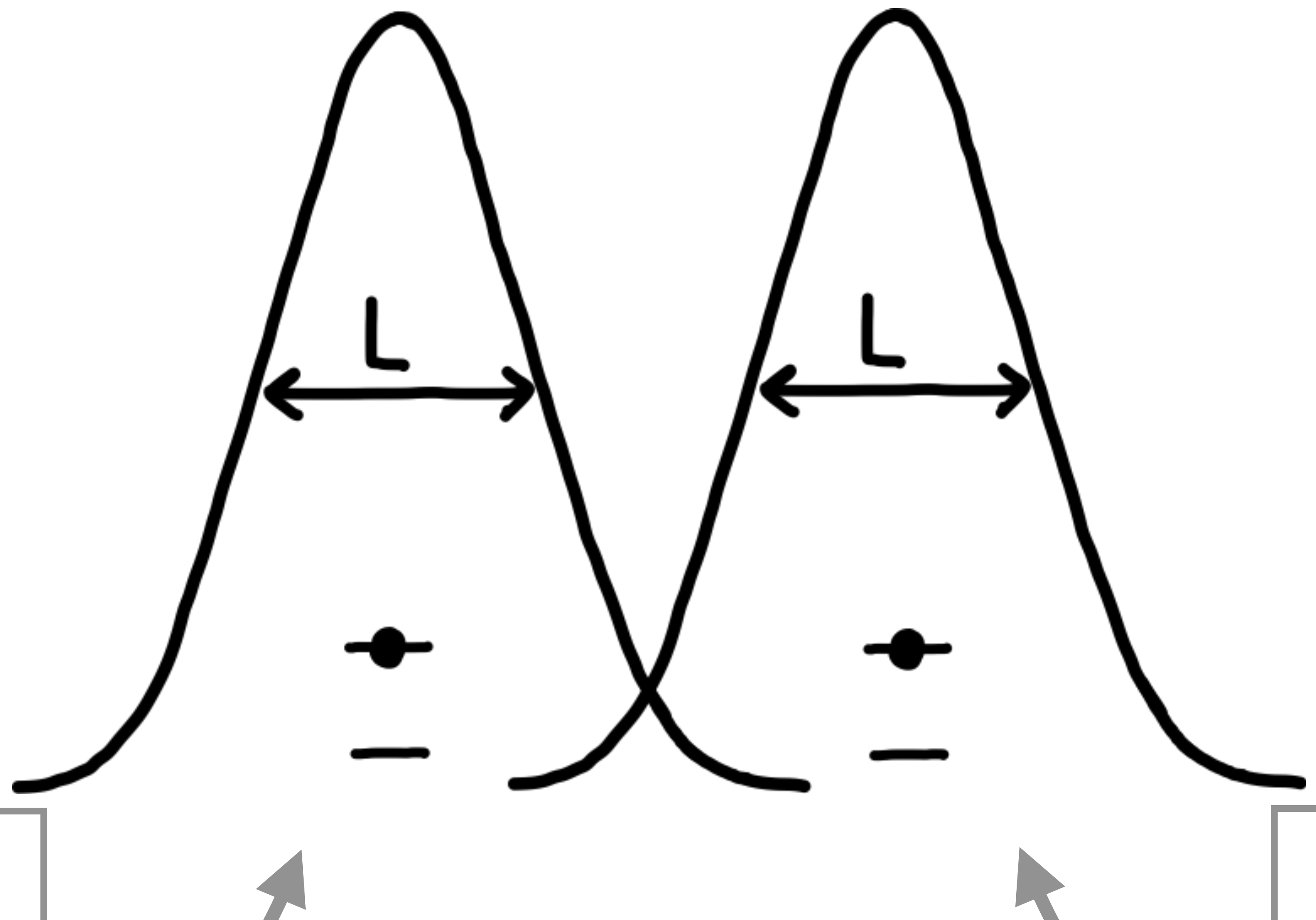

$$\varphi_0^{(1)}(\mathbf{x}) \sim \exp\left(-\frac{|\mathbf{x}+\mathbf{x}_0|^2}{L^2} \right)$$

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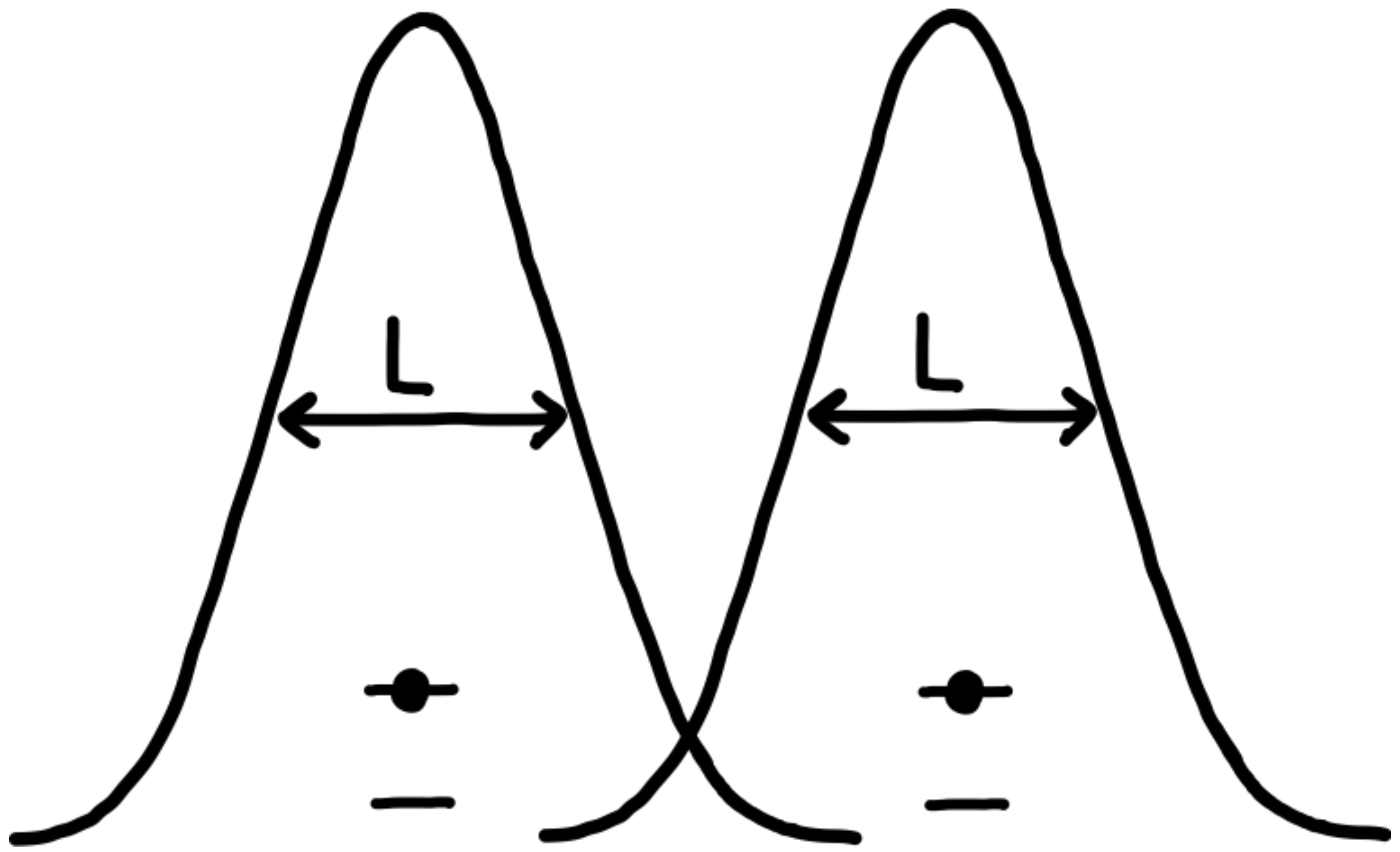
Decay rates affected differently by incoherent vs. coherent delocalization?

Incoherent superposition

$$\rho_0 = \tfrac{1}{2}\left(|\varphi_0^{(1)}\rangle\langle\varphi_0^{(1)}| + |\varphi_0^{(2)}\rangle\langle\varphi_0^{(2)}| \right)$$



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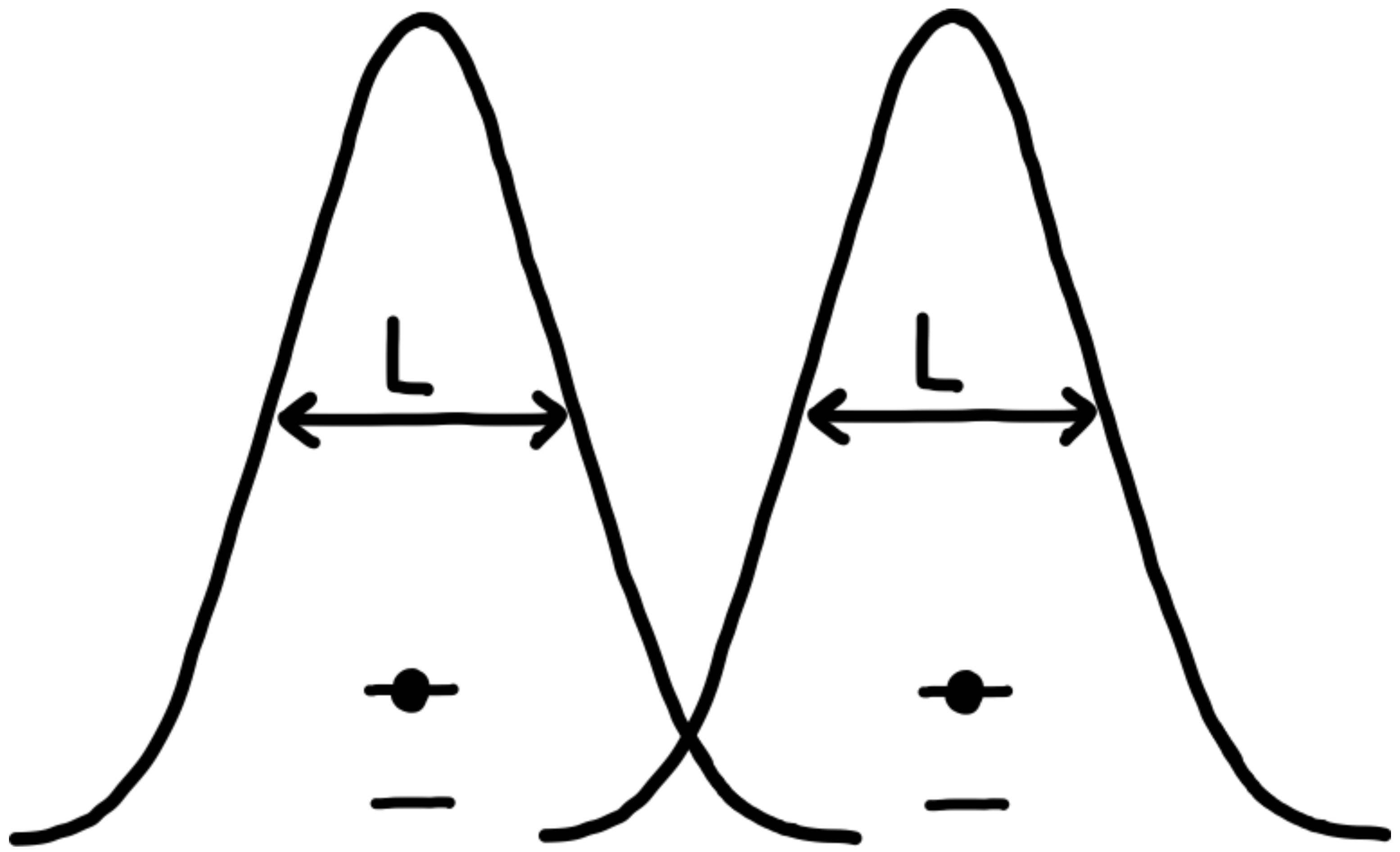

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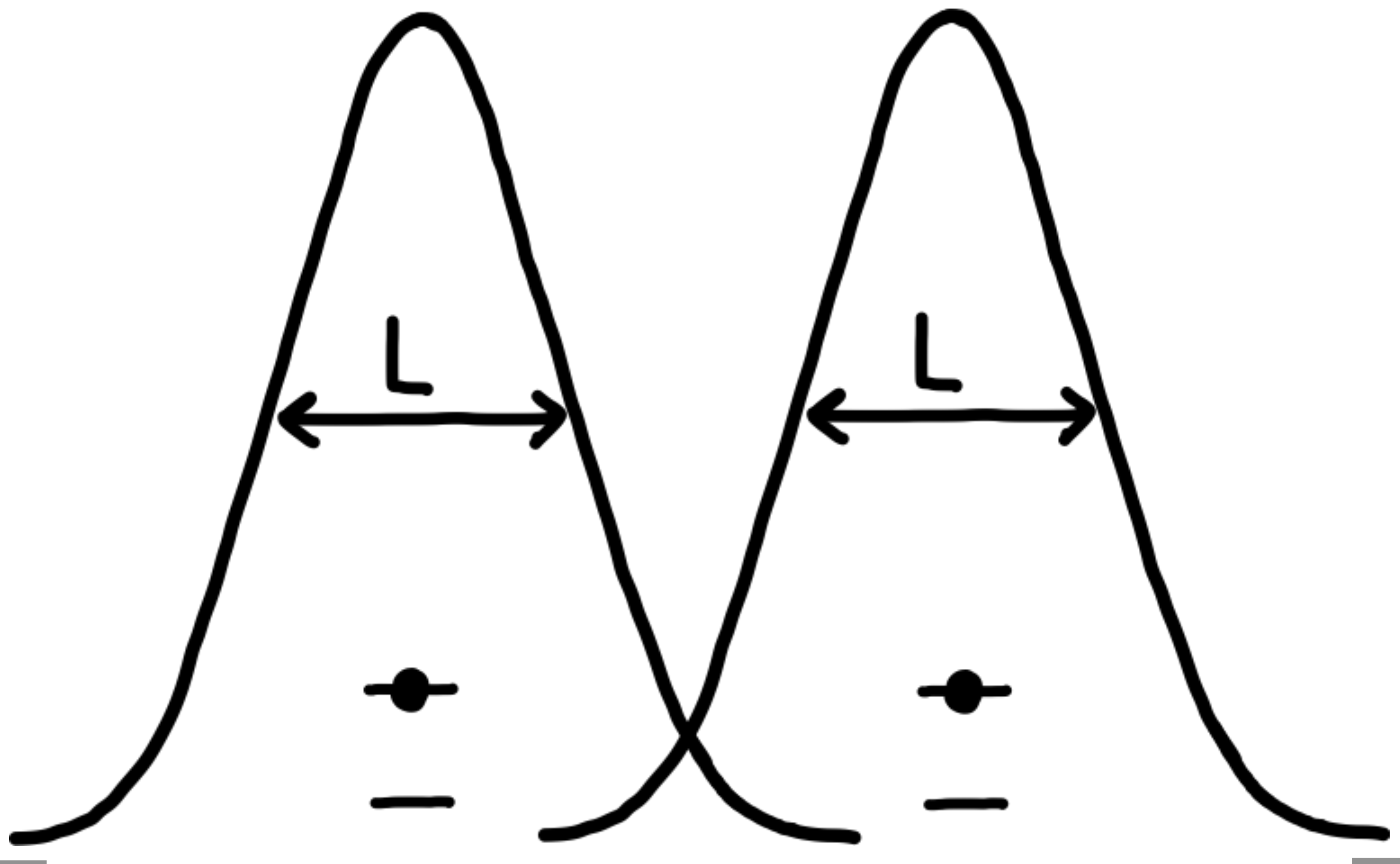

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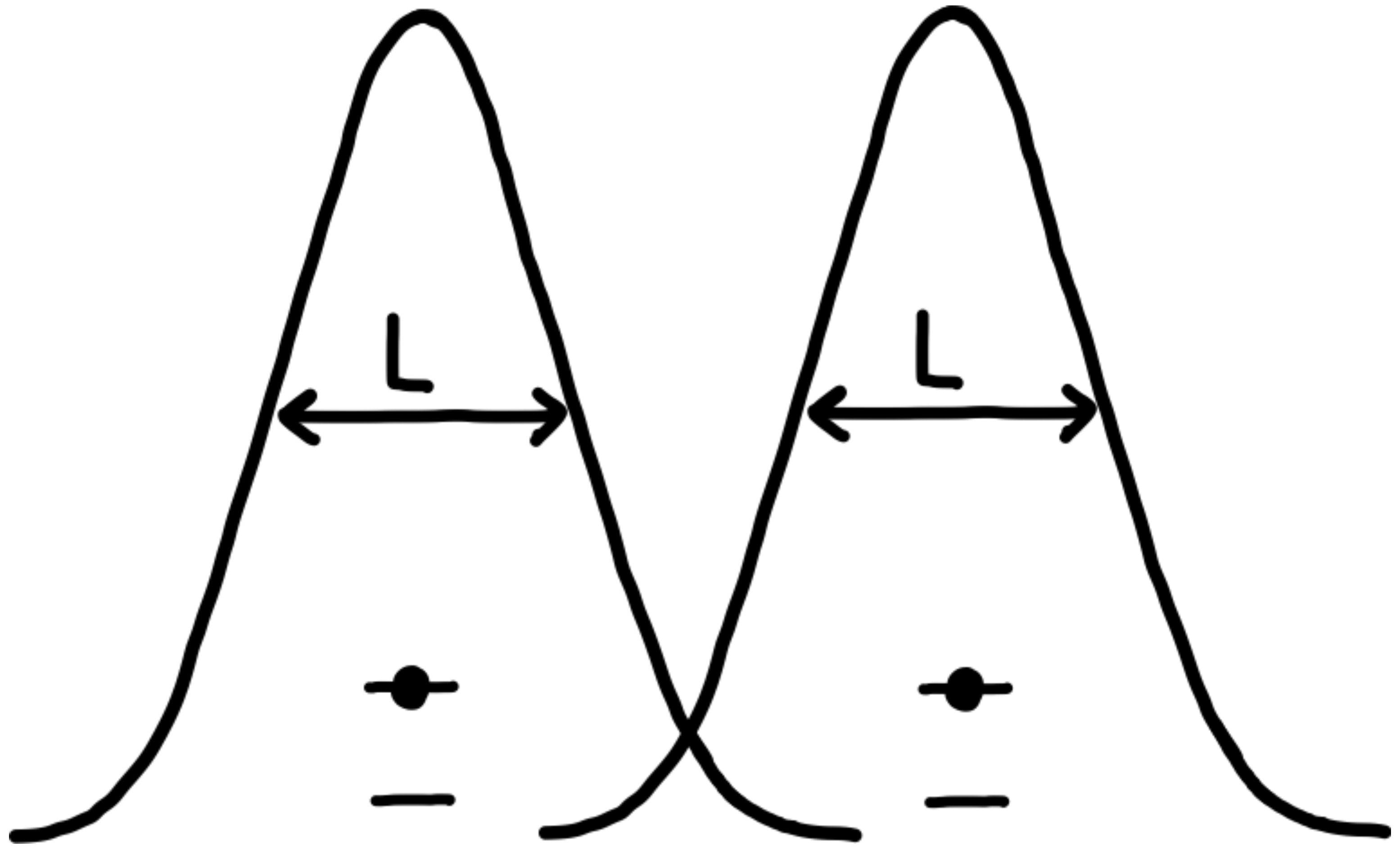
Coherent superposition

$$\varphi_0(\mathbf{x}) \sim \varphi_0^{(1)}(\mathbf{x}) + \varphi_0^{(2)}(\mathbf{x})$$

$$\mathscr{R}_{e\to g} \approx \frac{\lambda^2 M}{c\hbar^3}\left(A_1 + \frac{3}{L^2}A_2\left(1 - \frac{4|\mathbf{x}_0|^2}{3L^2}\frac{e^{-2|\mathbf{x}_0|^2/L^2}}{1+e^{-2|\mathbf{x}_0|^2/L^2}}\right)\right)$$



$$\varphi_0^{(1)}(\mathbf{x}) \sim \exp\left(-\frac{|\mathbf{x}+\mathbf{x}_0|^2}{L^2}\right)$$

$$\varphi_0^{(1)}(\mathbf{x}) \sim \exp\left(-\frac{|\mathbf{x}-\mathbf{x}_0|^2}{L^2}\right)$$

Decay rates affected differently by incoherent vs. coherent delocalization!

Can delocalization trigger excitation of atoms?

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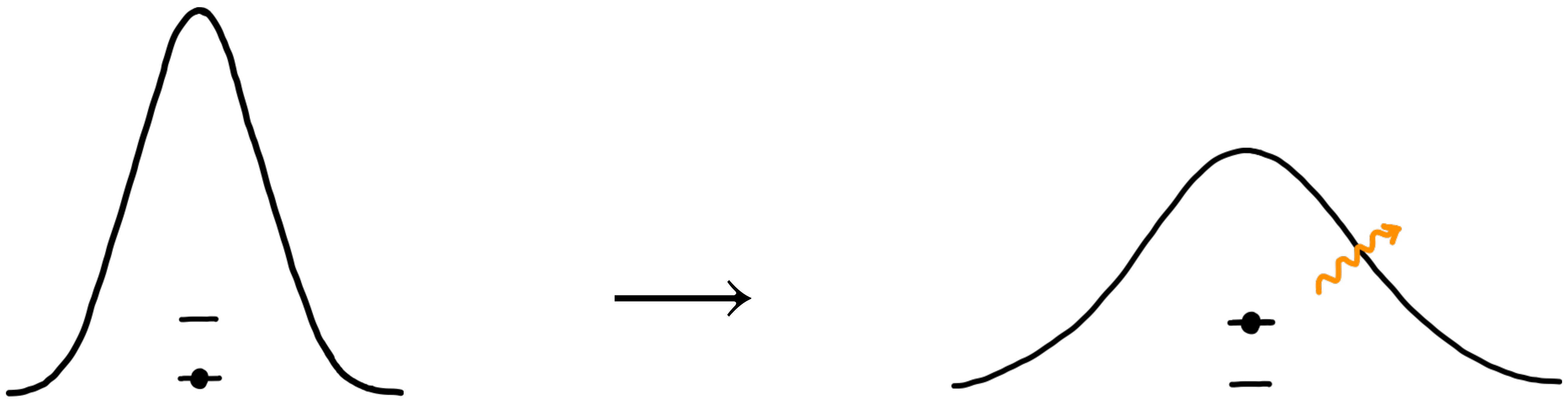
$$|\Psi_{in}\rangle = \int d^3p\, \varphi_0(\mathbf{p})\,|\mathbf{p}\rangle \otimes |g\rangle \otimes |0\rangle \quad \longrightarrow \quad |\Psi_{out}\rangle = |\mathbf{p}'\rangle \otimes |e\rangle \otimes |1_{\mathbf{k}}\rangle$$



Can delocalization trigger excitation of atoms?

... delocalization implies kinetic energy uncertainty!

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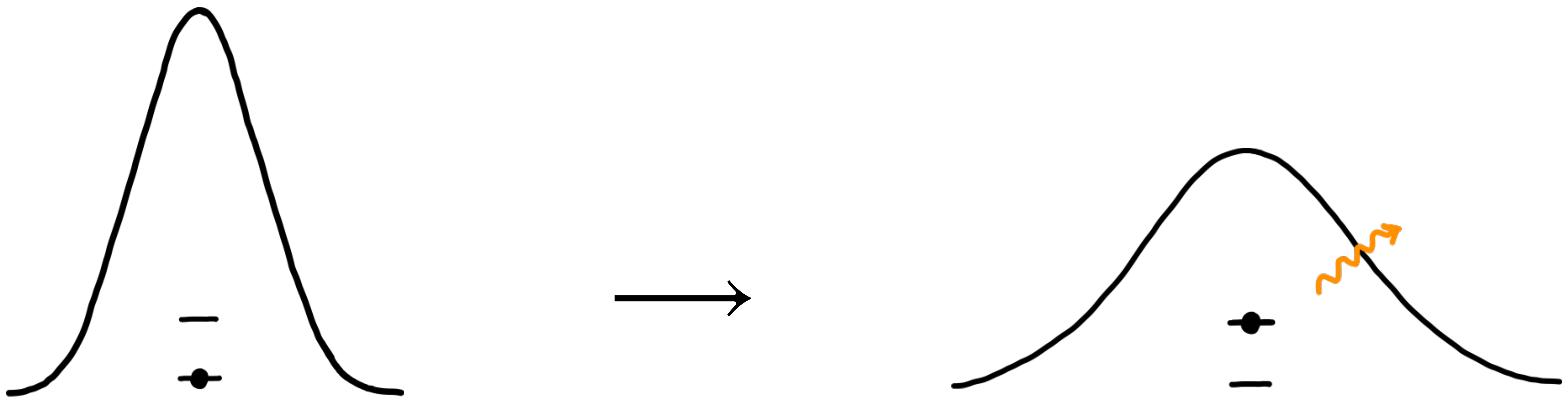
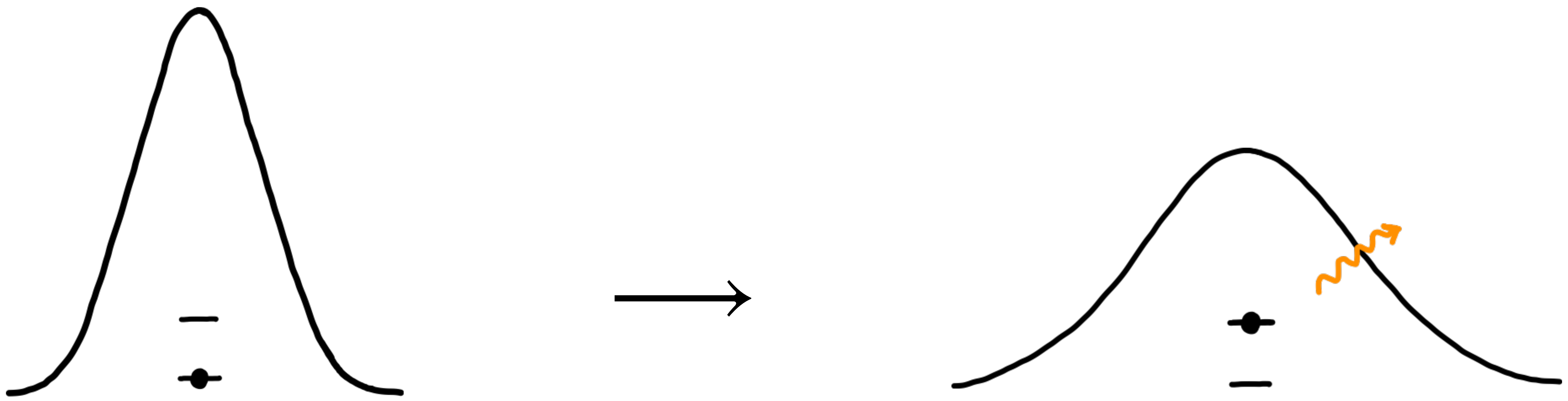


Can delocalization trigger excitation of atoms?

$$\mathscr{R}_{g\to e} = \frac{\lambda^2}{2c\hbar^2}\underbrace{\int d^3p\,|\varphi_0(\mathbf{p})|^2}_{\text{initial CM wave function}}\int_0^\infty dk\int_{-1}^{1} dz\,\frac{M}{|\mathbf{p}|}\,\delta\left(z-\frac{M}{|\mathbf{p}|k}\left(\frac{\hbar k^2}{2M}+\frac{E}{\hbar}+ck\right)\right)$$



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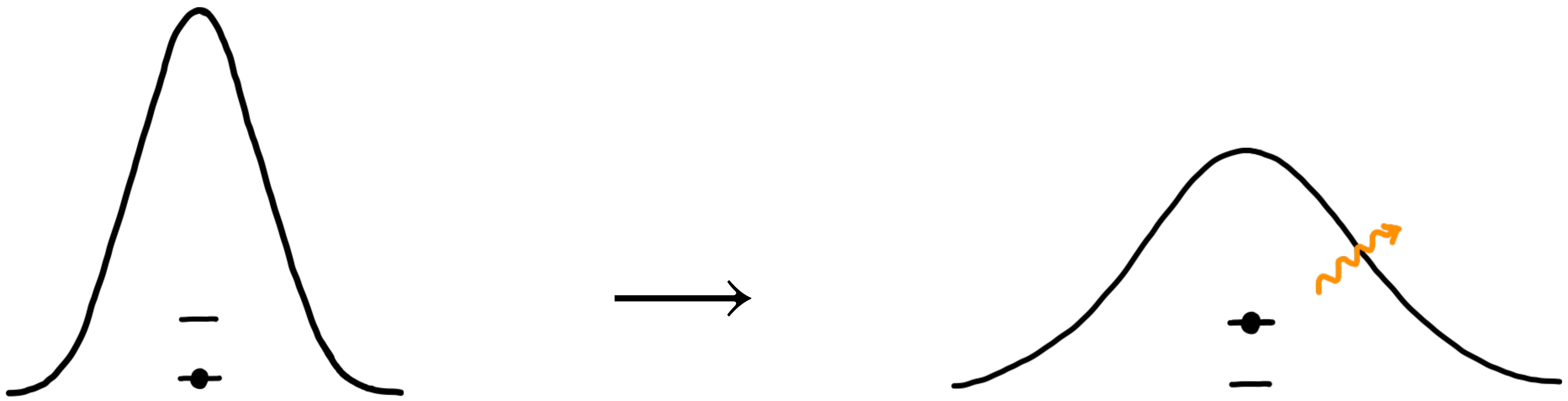

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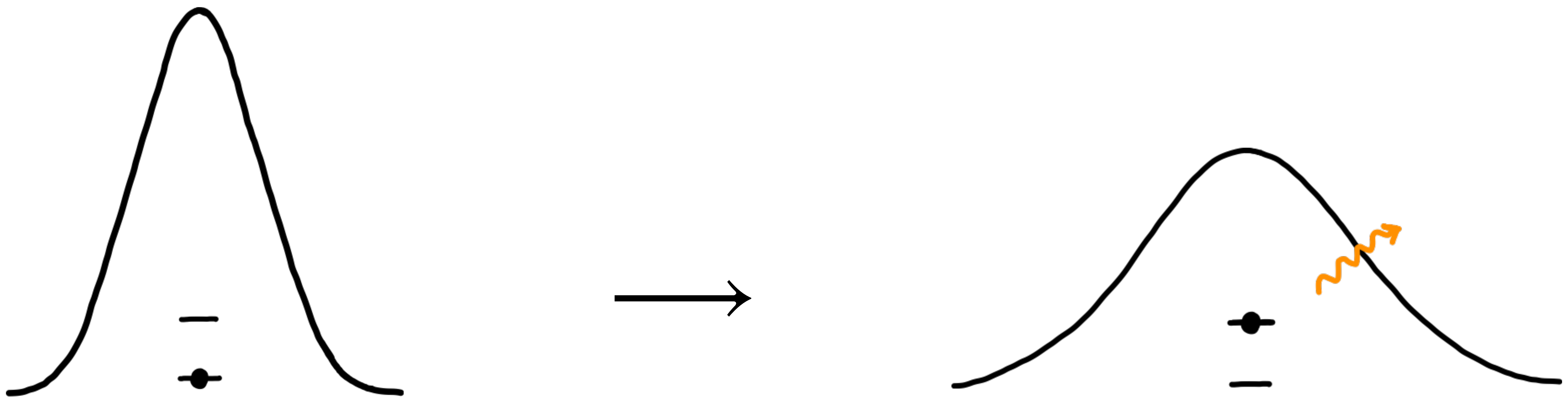

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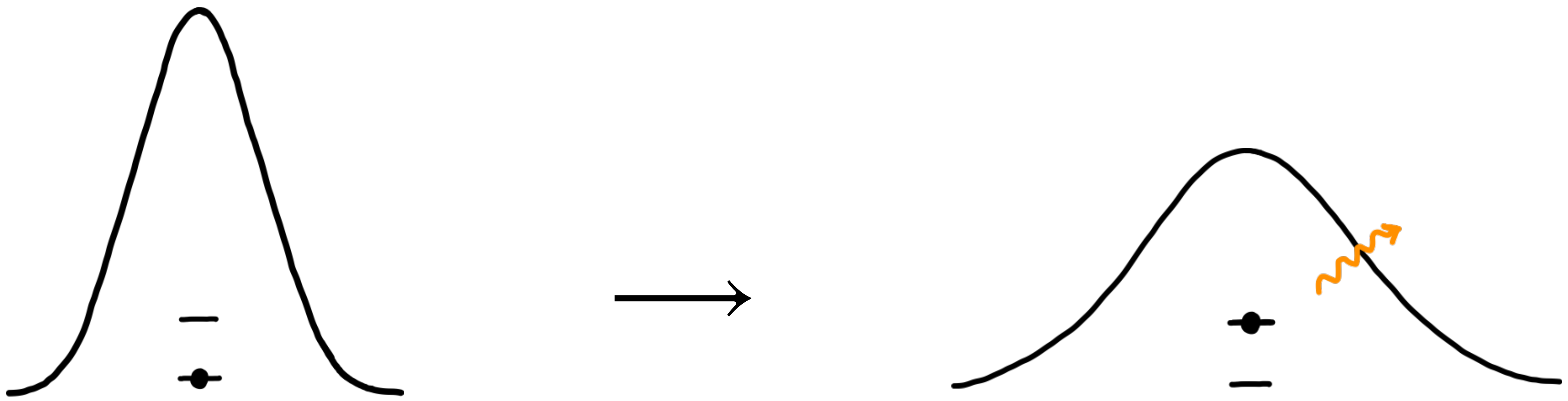

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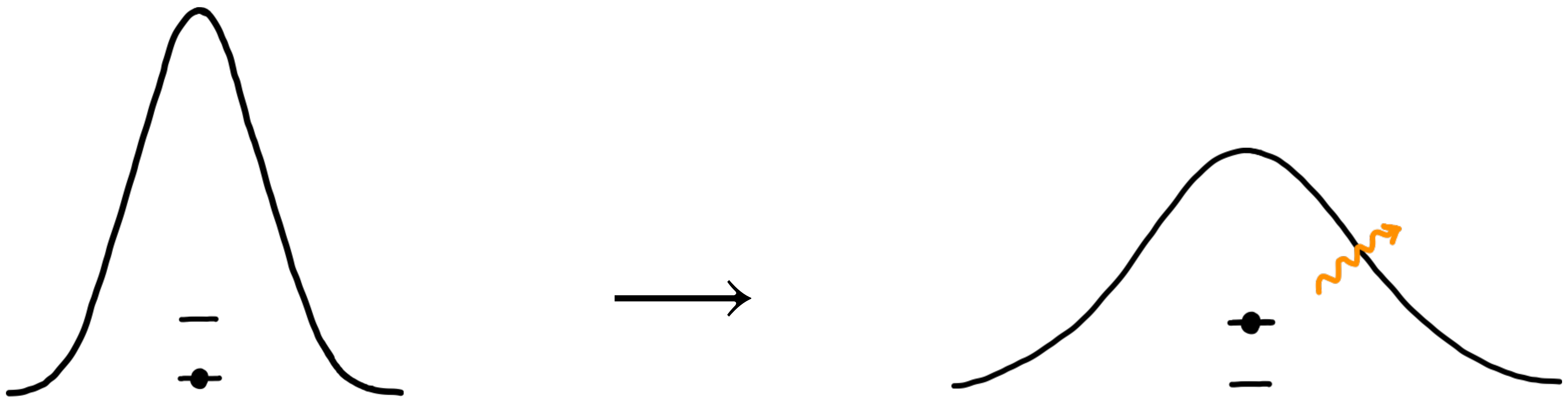
- But: could occur for light in medium, or for collective excitations, e.g. phonons
- Virtual-motion-induced Cherenkov-like radiation

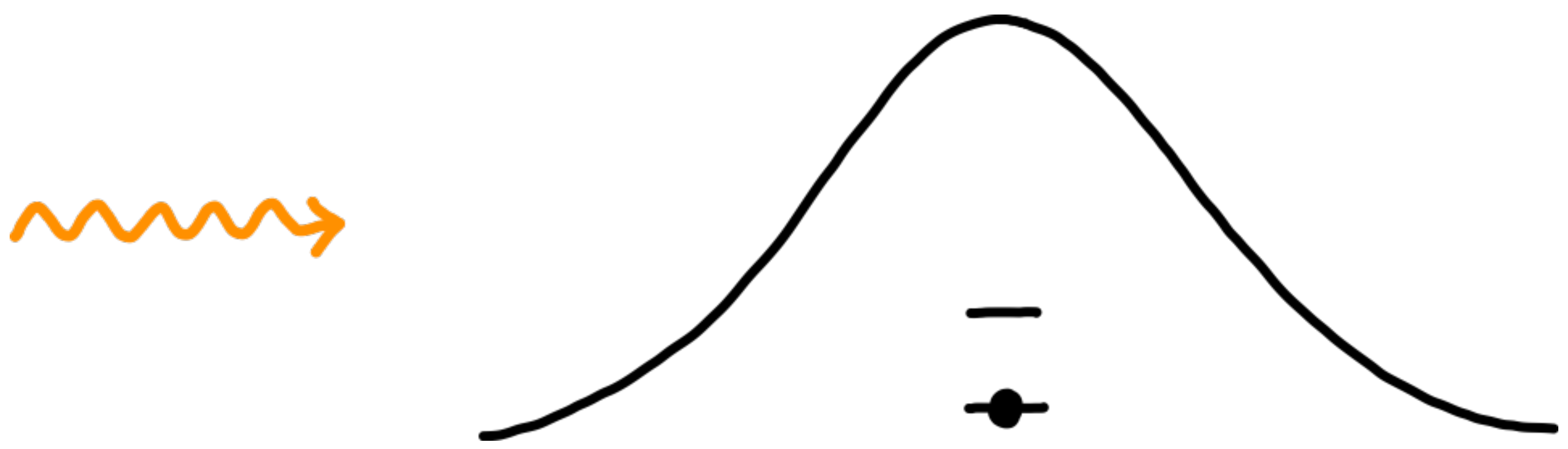


Delocalization can trigger excitation of atoms in a medium!

Quantum channel capacities of the light matter interaction

Quantum channel capacities of the light matter interaction

- Assume input (e.g. to-be-absorbed photon) entangled with ancilla



Quantum channel capacities of the light matter interaction

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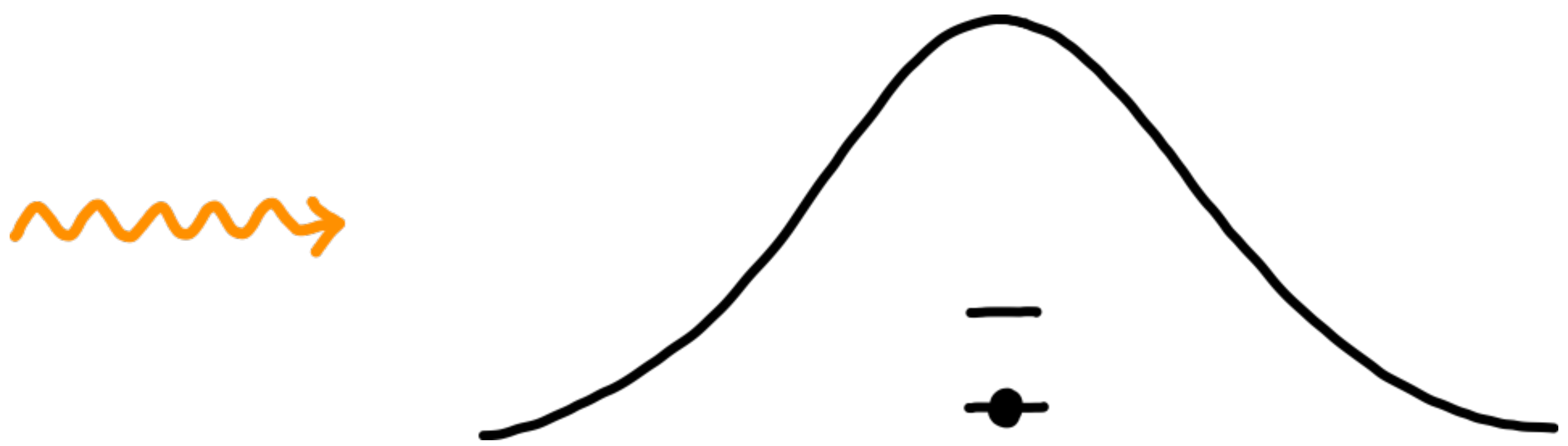
- How much is output (e.g. atom) entangled with ancilla?



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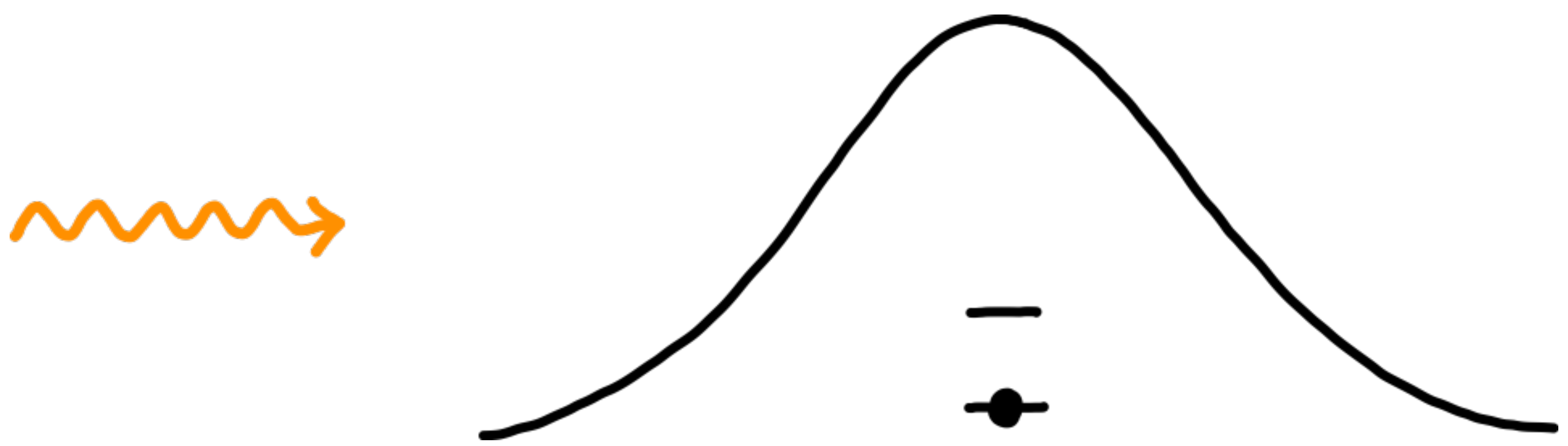

Which part of the atom received quantum information — internal or external d.o.f.?

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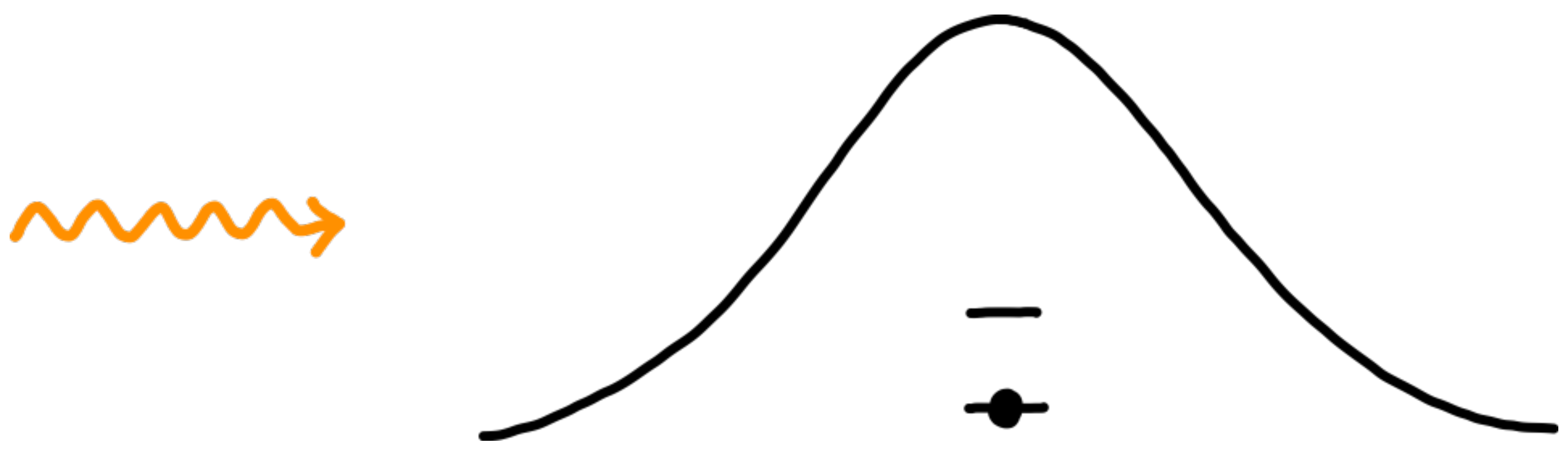

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E.g. for ion trap based quantum computing

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    - Coherent delocalization different from incoherent delocalization
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- Prepared to study quantum channel capacities of the light matter interaction





Thank you! Questions?