Dark matter detection via atomic spectroscopy

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in collaboration with Jack D. Shergold (Liverpool University) and Martin Bauer (Durham University)

Based on [2407.12913] and [2507.14287]

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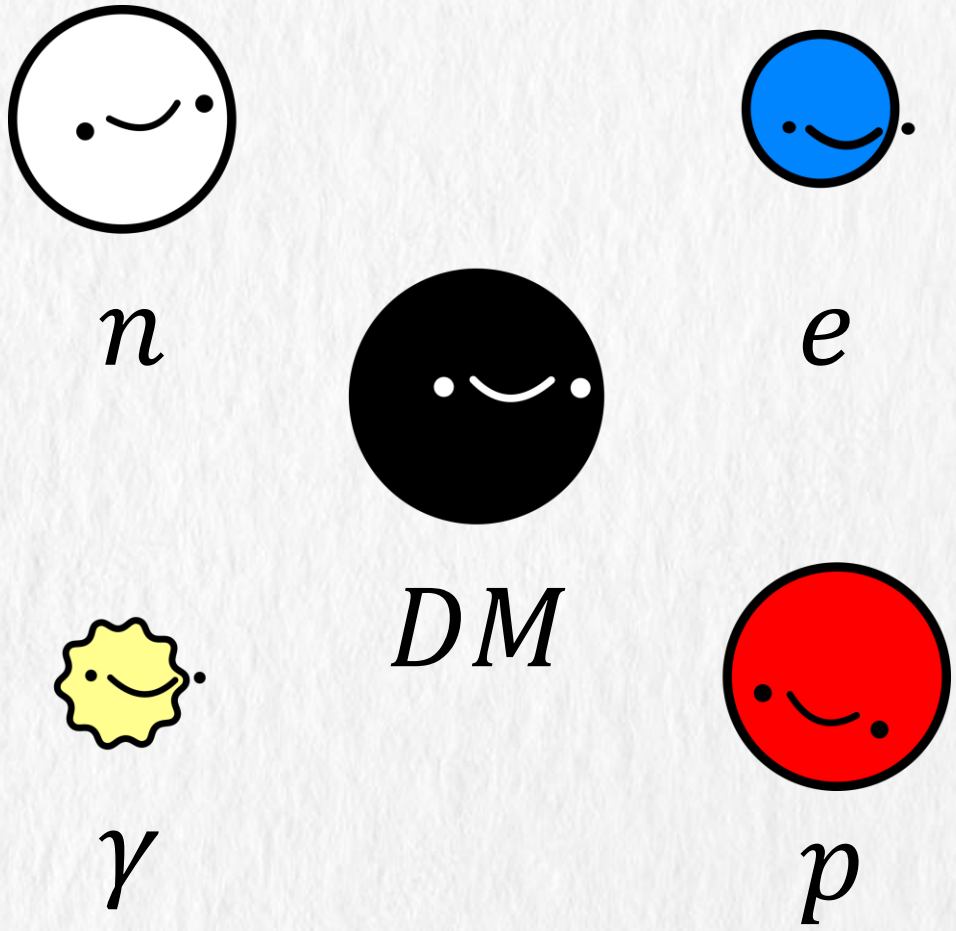
What's this about?

- Atomic scattering experiments are the realm of **heavy DM**



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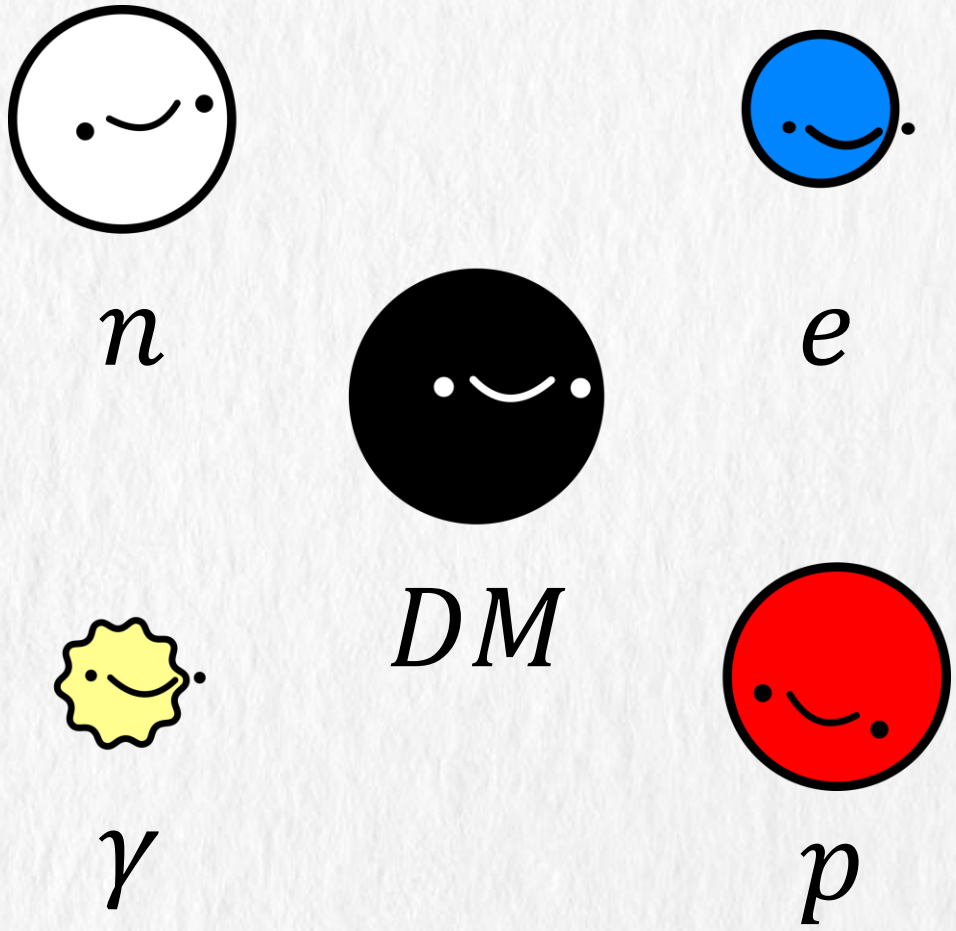
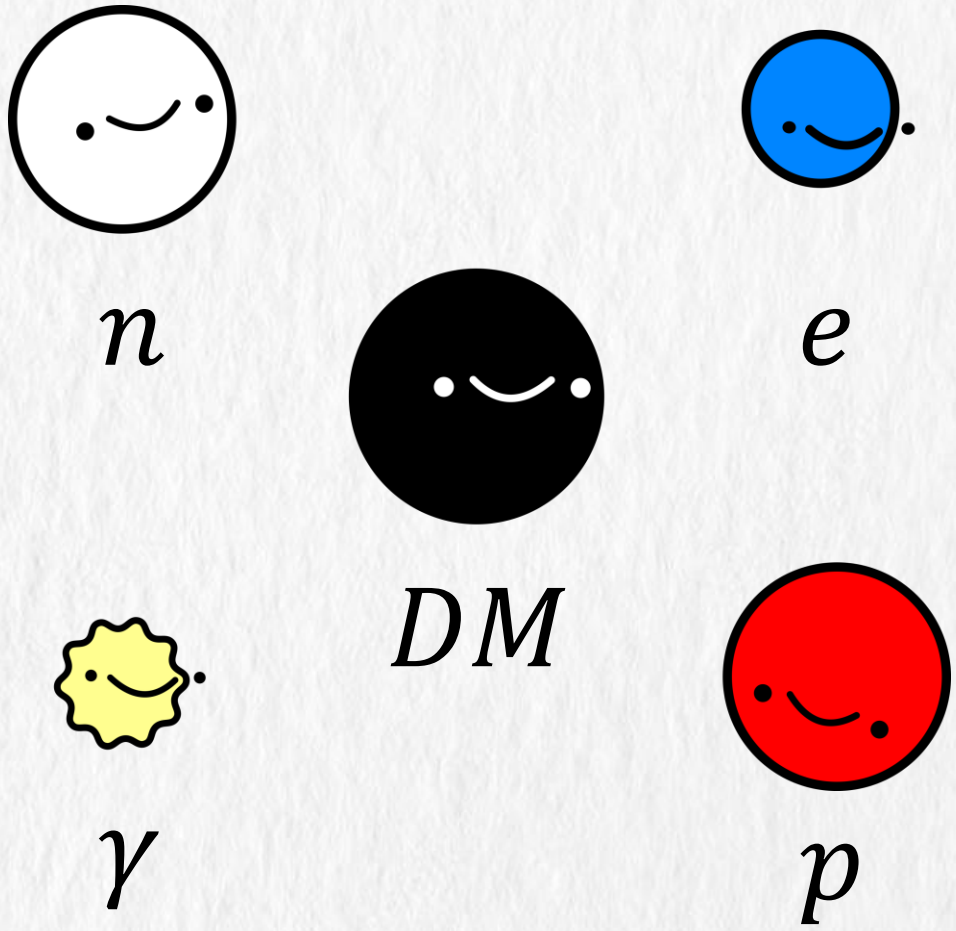
- For **light DM**, small momentum transfer makes detection via scattering hard



What's this about?

- Atomic scattering experiments are the realm of **heavy DM**
- For **light DM**, small momentum transfer makes detection via scattering hard
- Any other way of **detecting light DM?**



Atomic transitions

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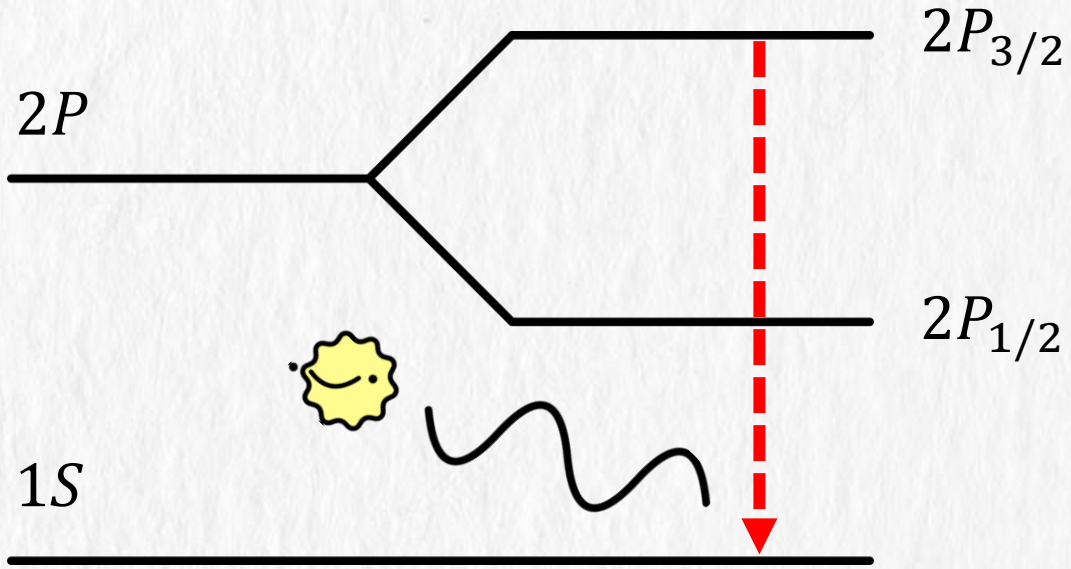

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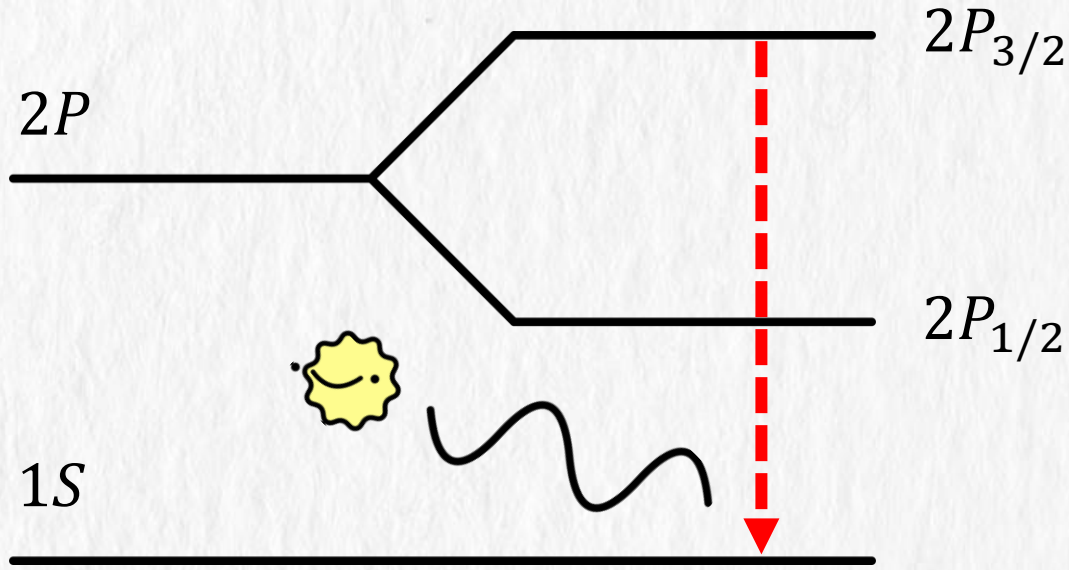

Atomic transitions

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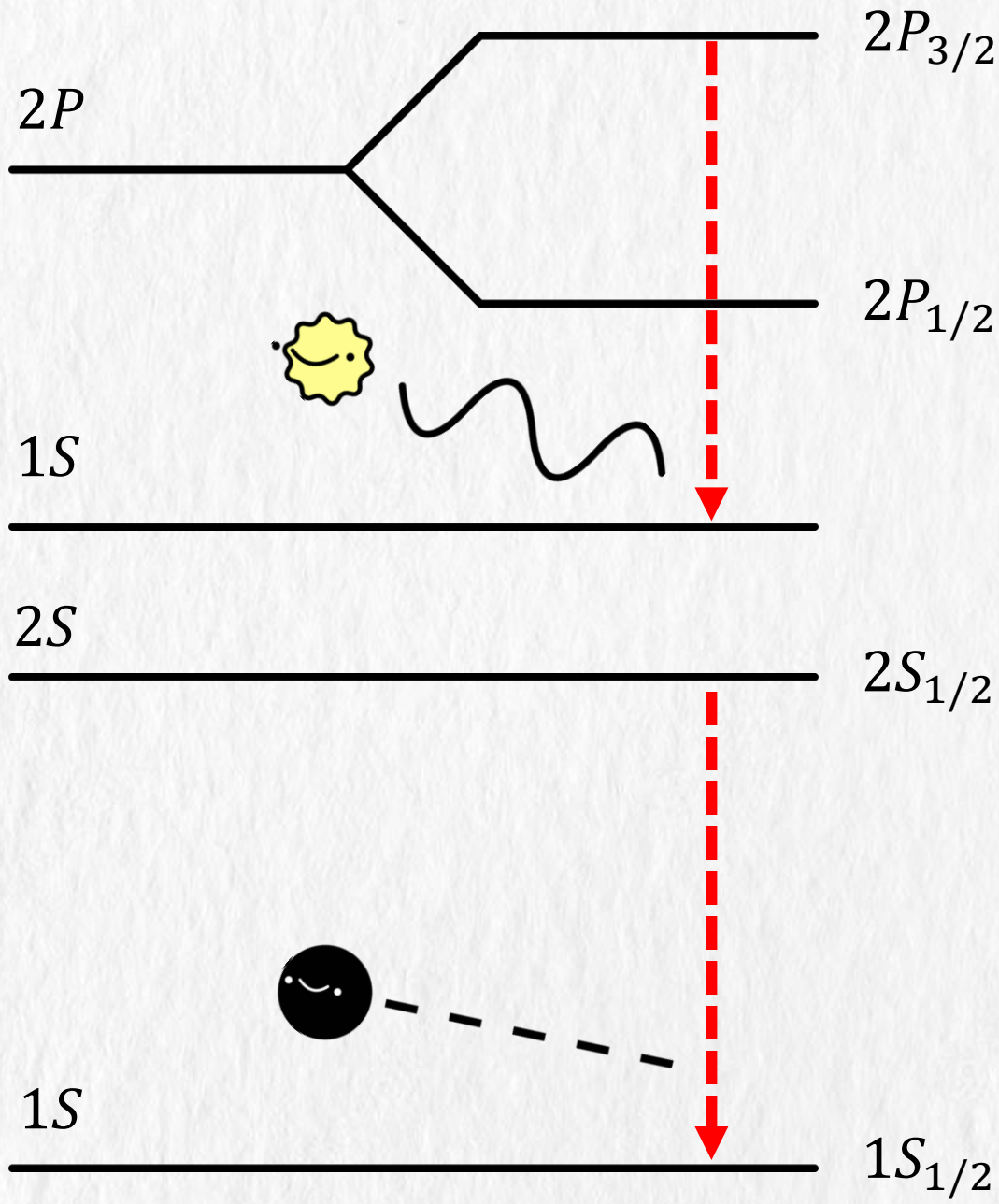
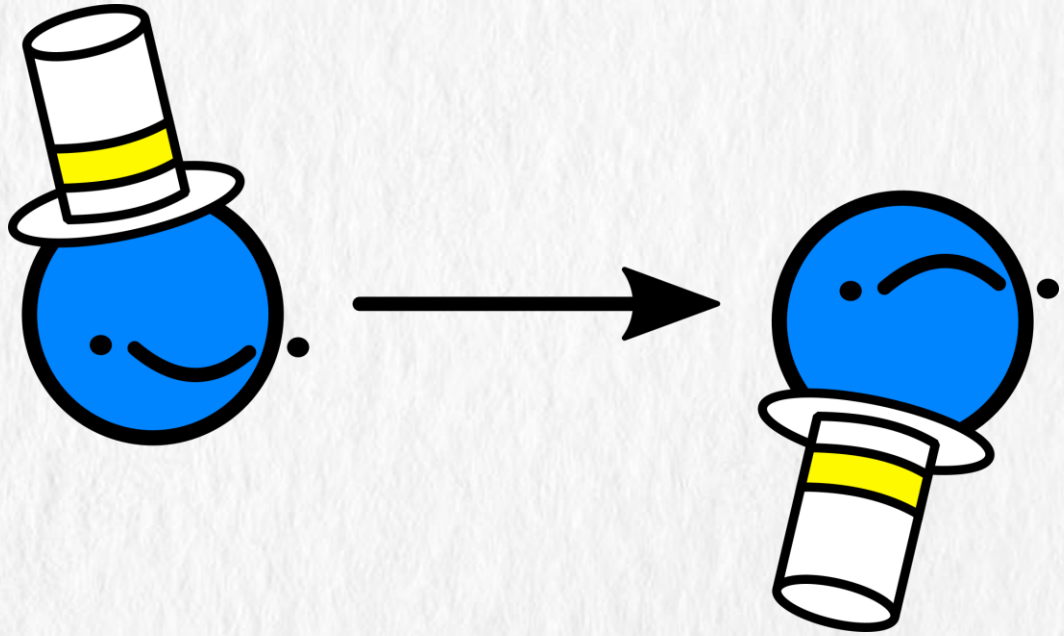
- These are dominated by photons… **or are they?**
- **Some transitions are heavily suppressed** for photons (vector couplings with SM) but not for DM (any coupling a priori)



Spin flip transition

- In this talk I'll use **electronic spin flip** as an example



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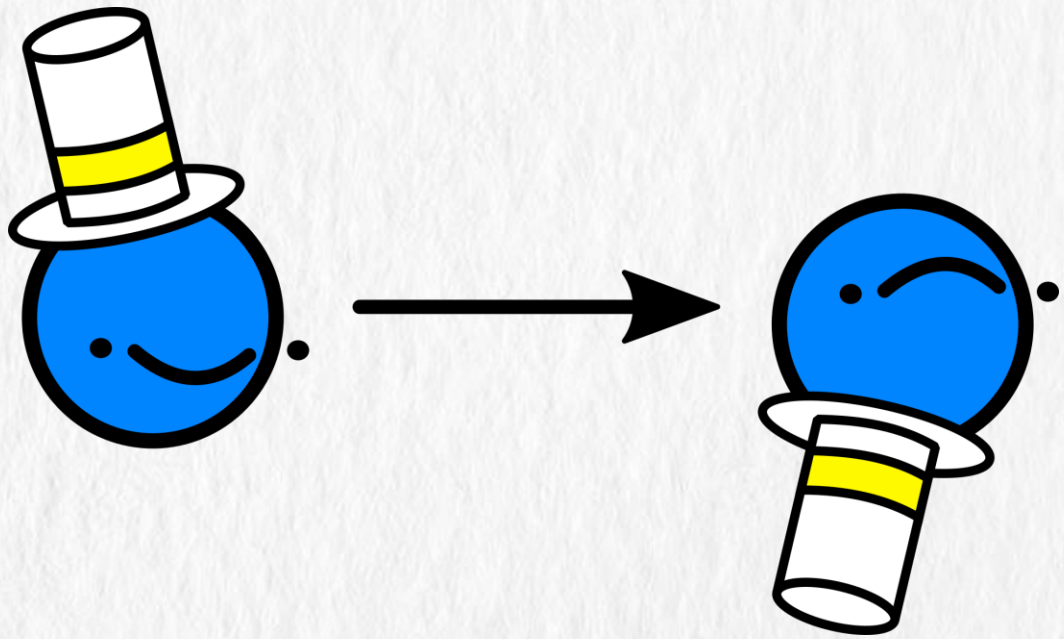
- **Suppressed for photons** but leading order for axial-vector couplings (like axions!)



Spin flip transition

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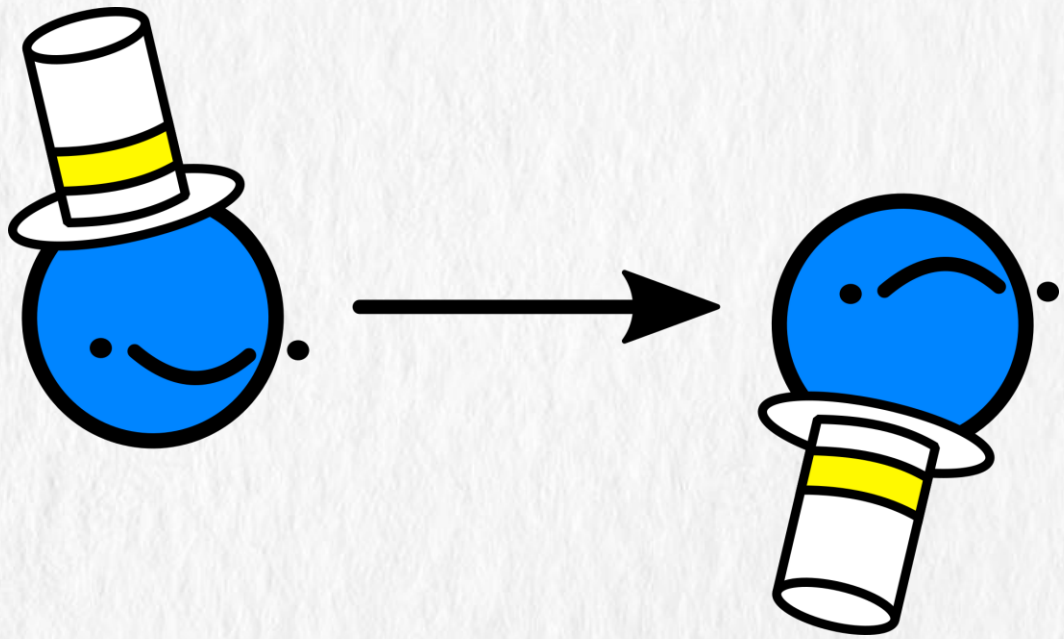
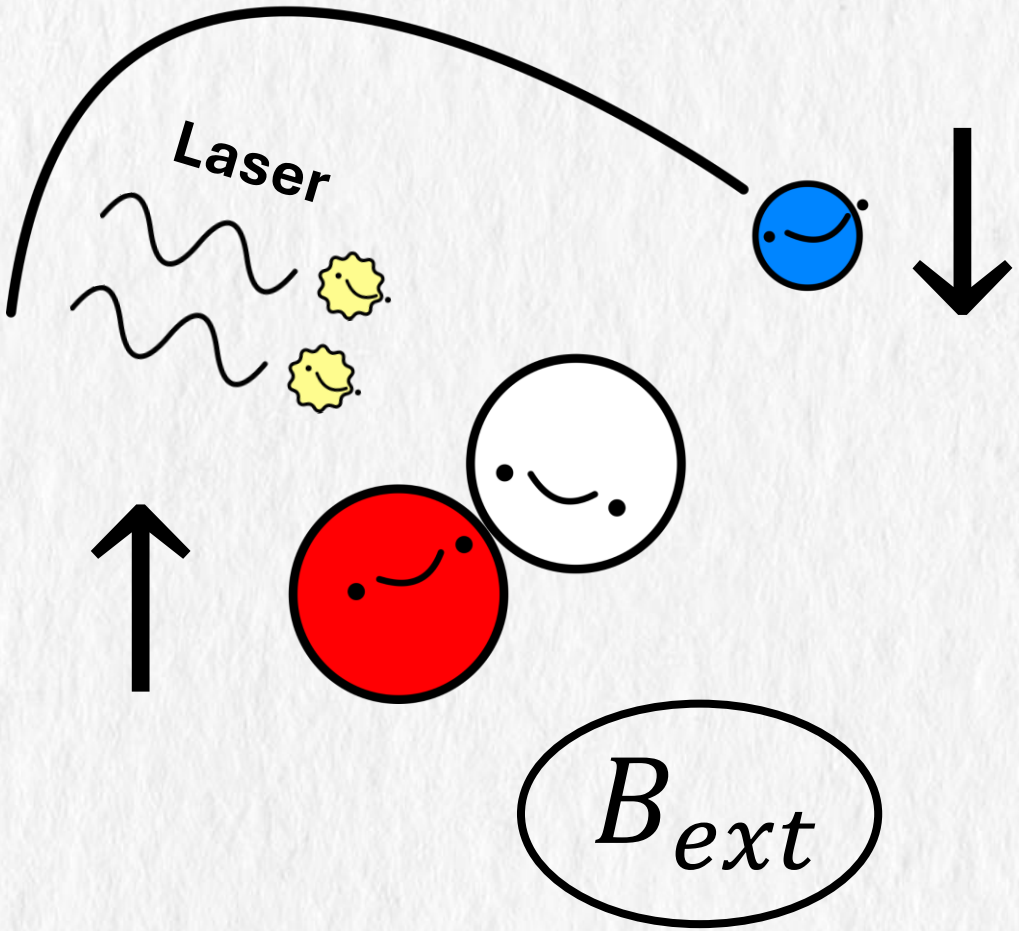
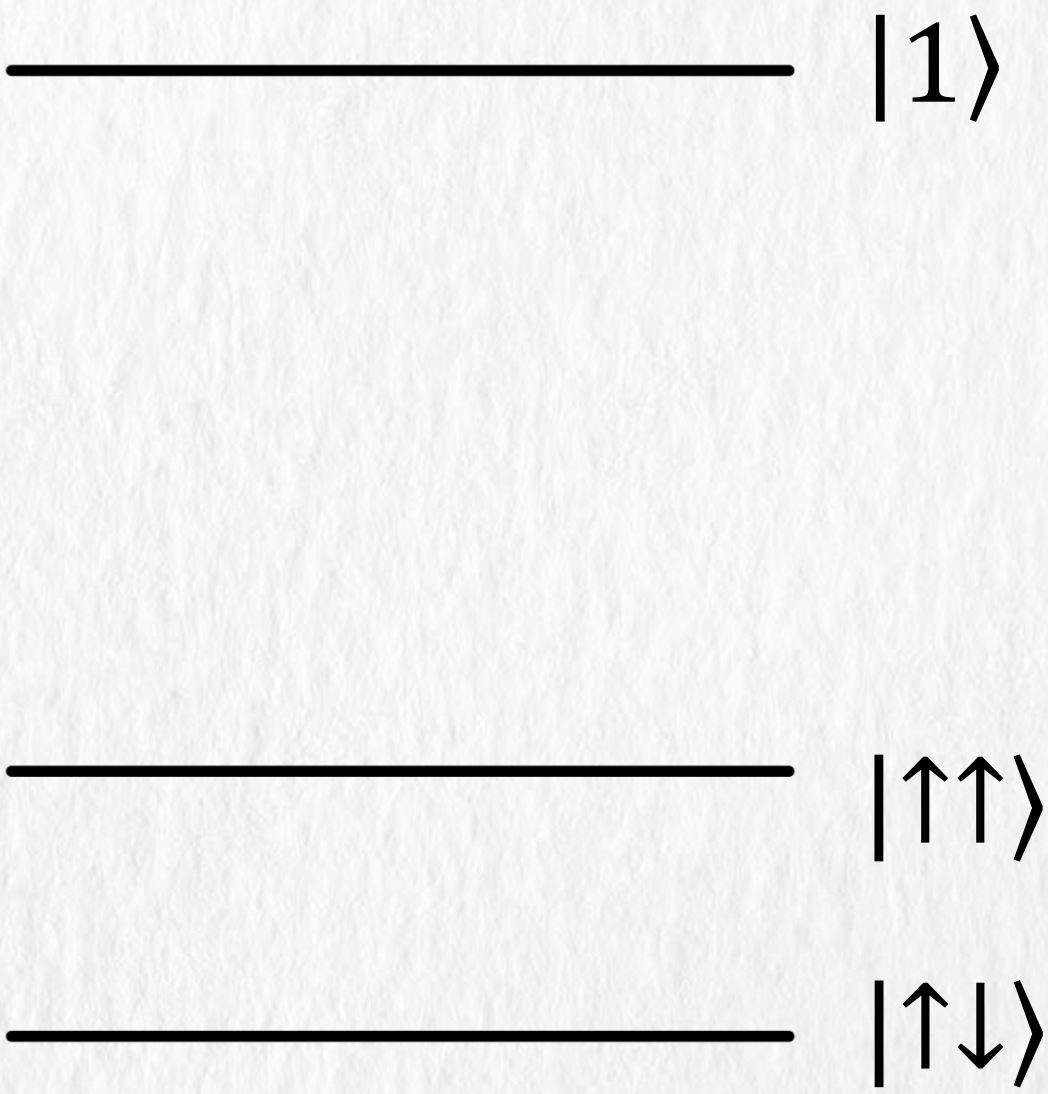
- **Suppressed for photons** but leading order for axial-vector couplings (like axions!)

- We can make a **super simple experimental setup** with these [1409.2806]



Atomic system with an **external magnetic field and a laser**





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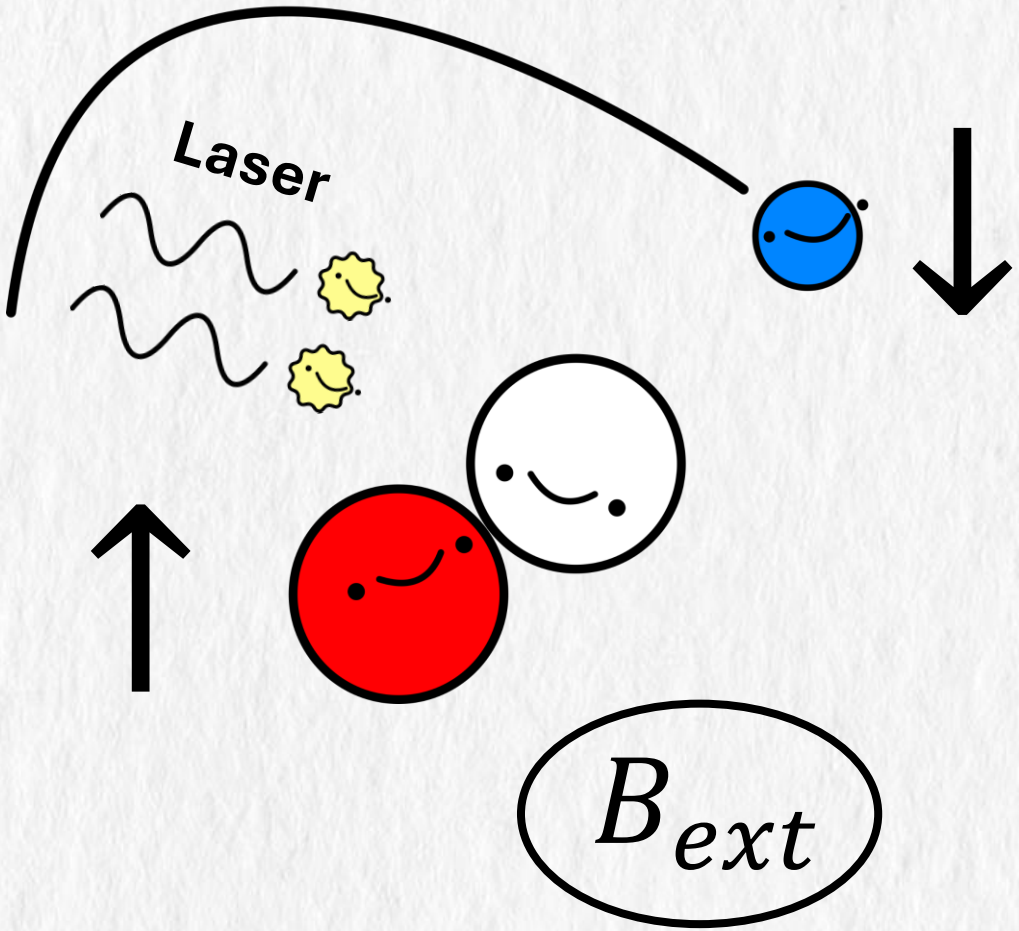

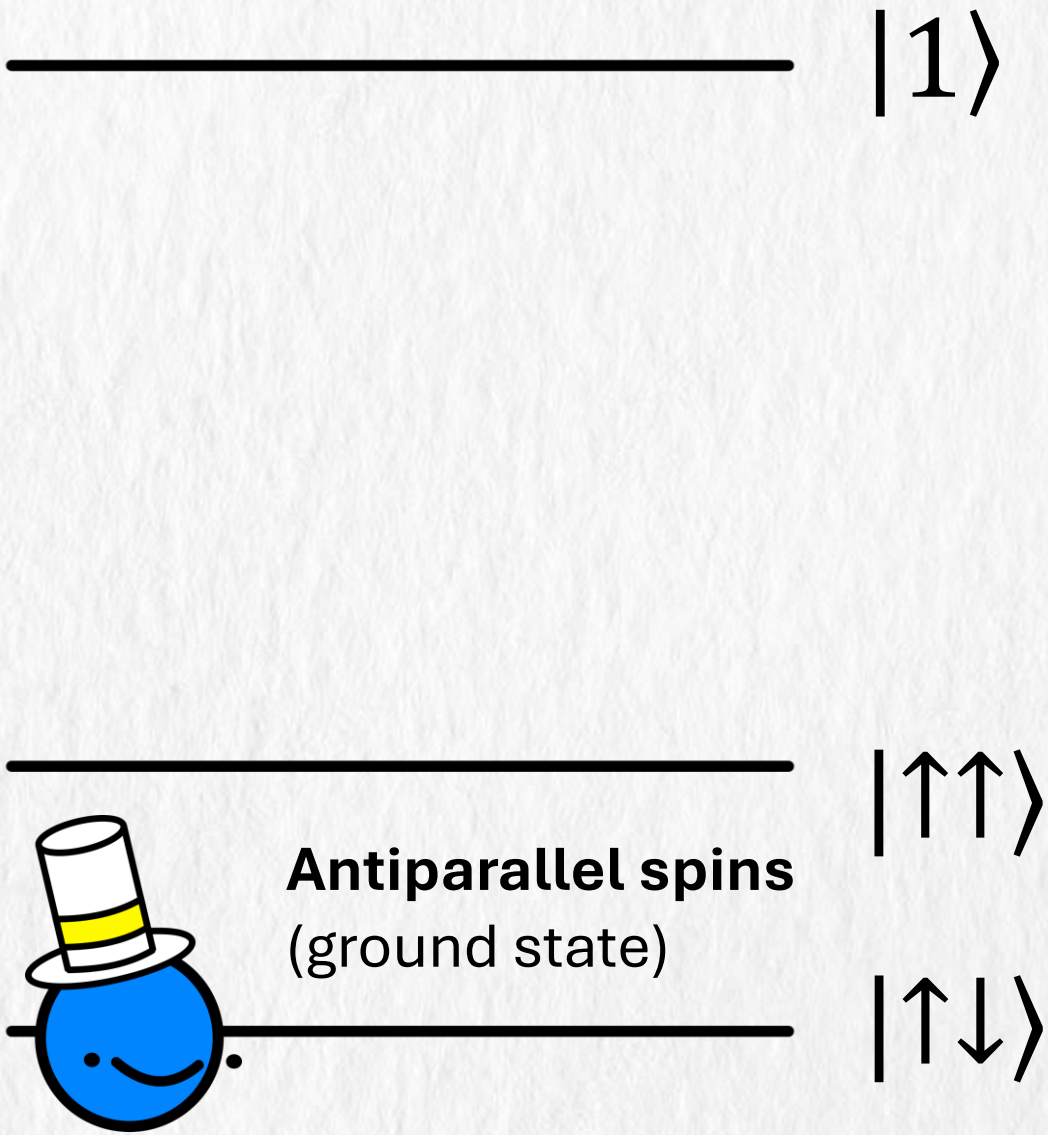

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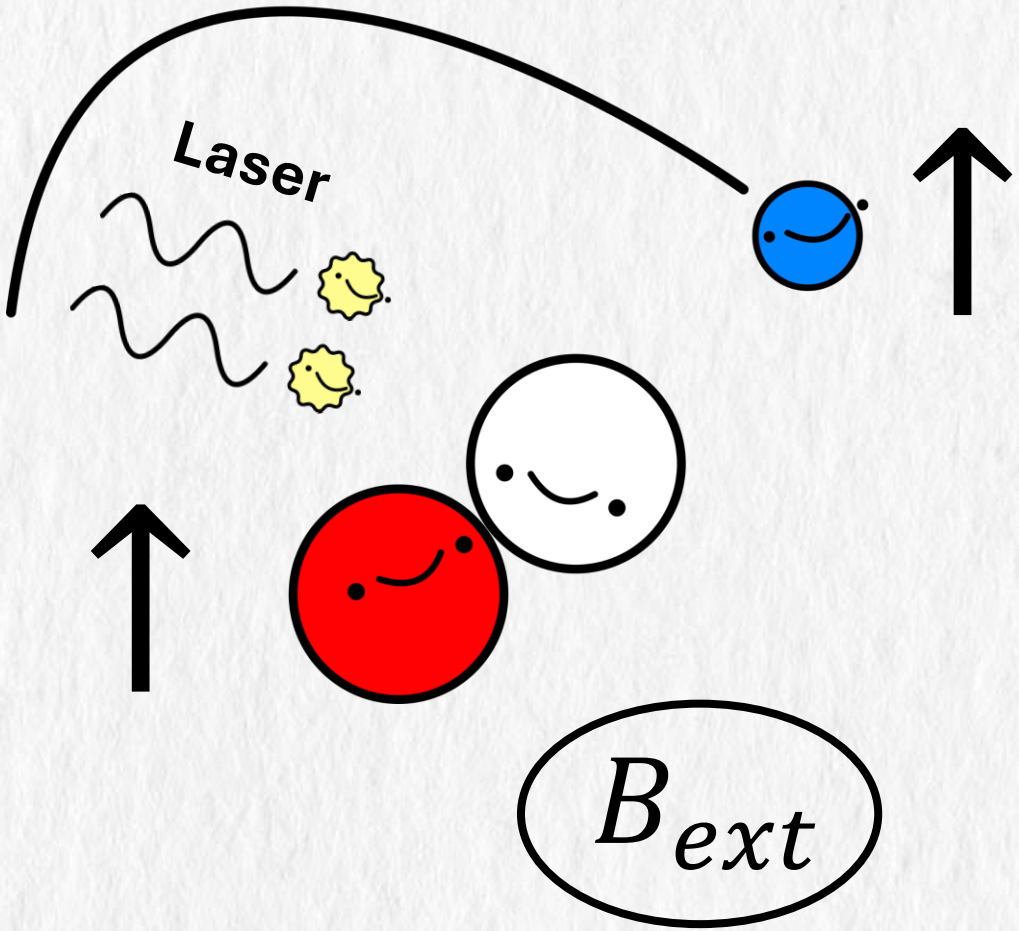

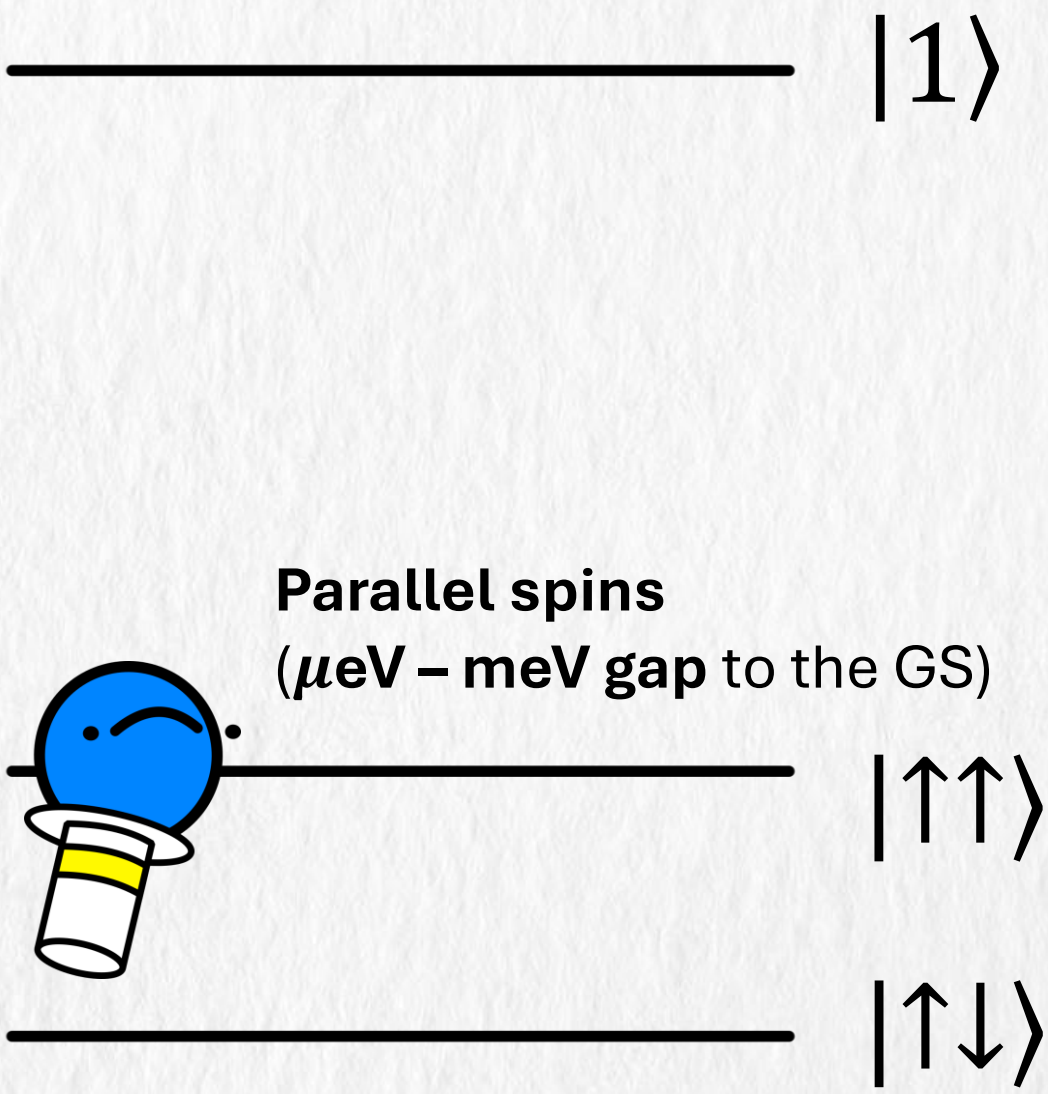

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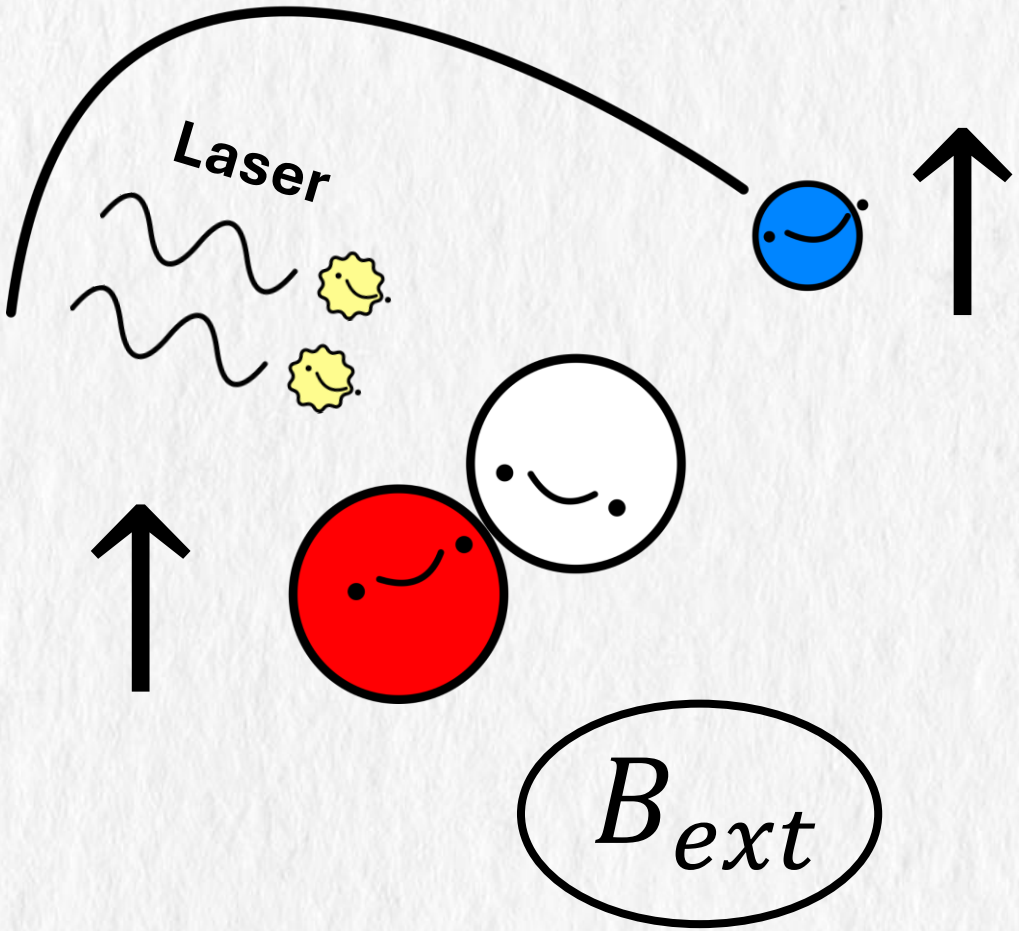
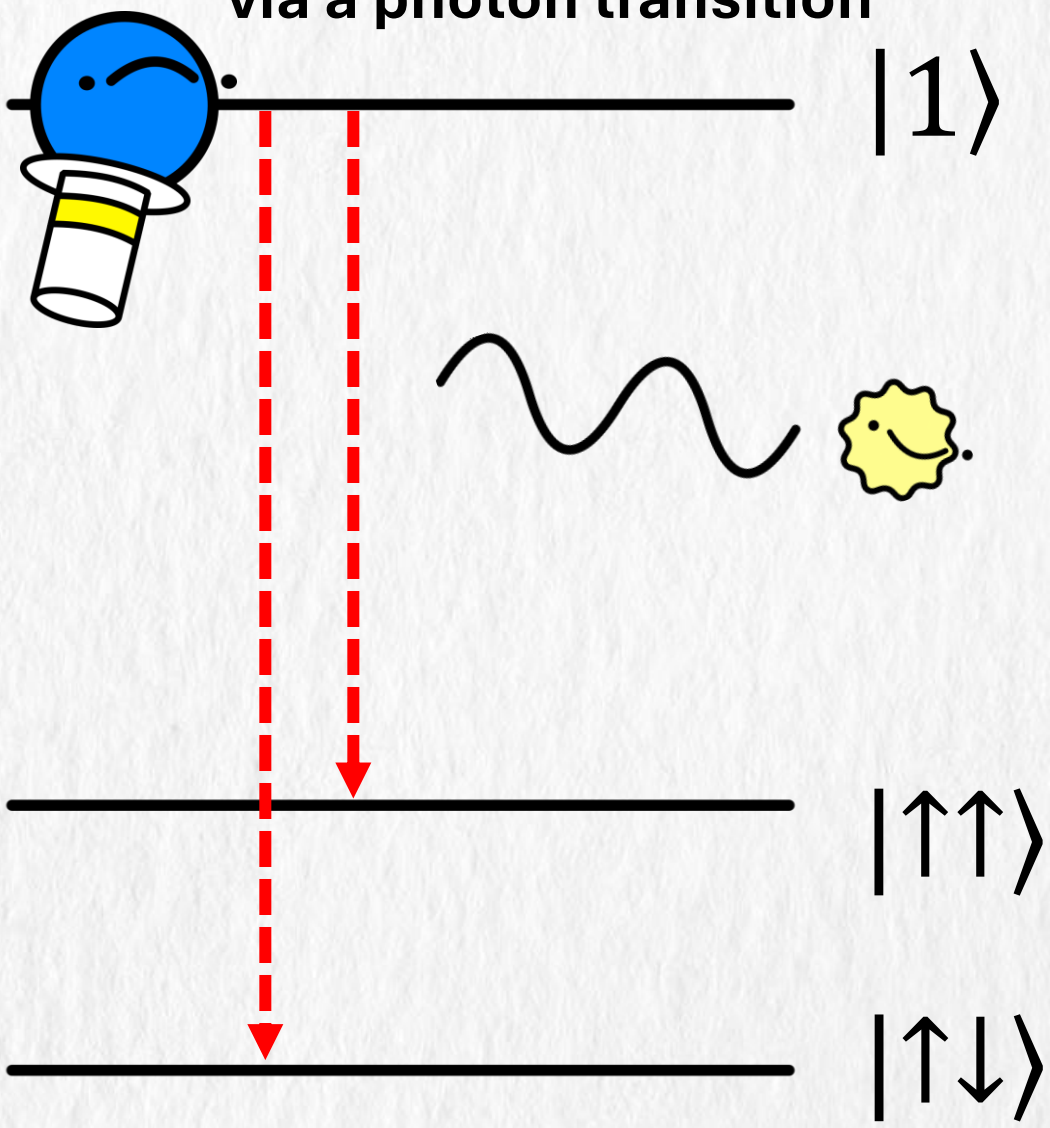
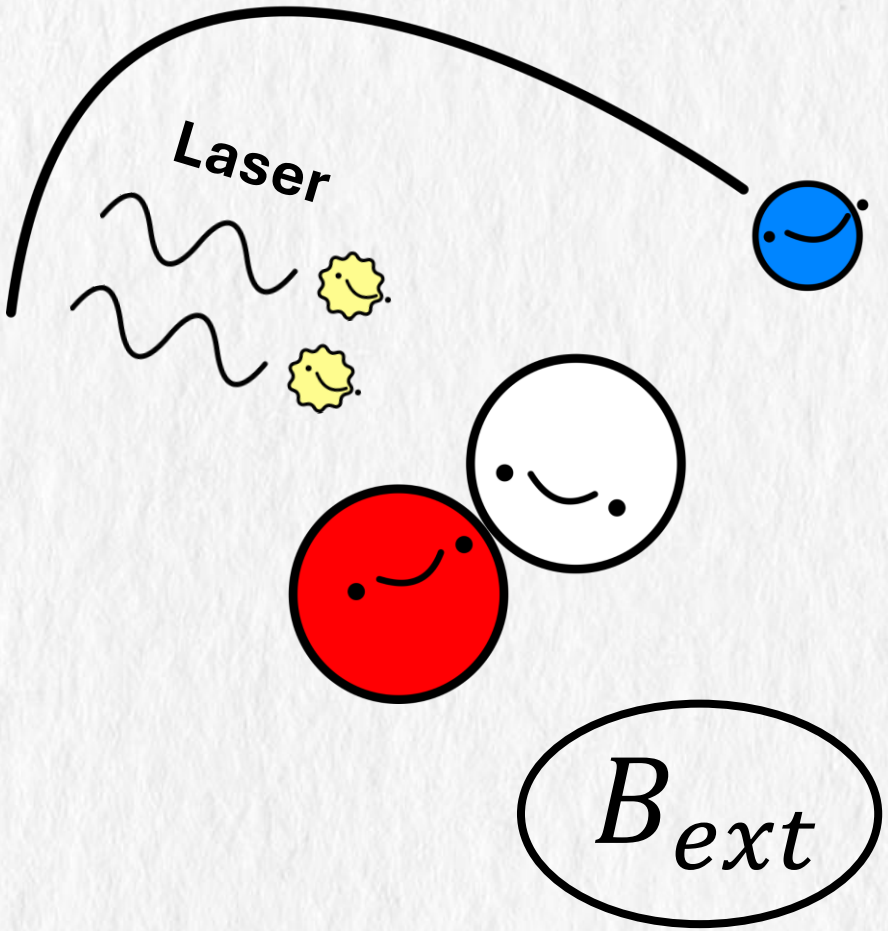
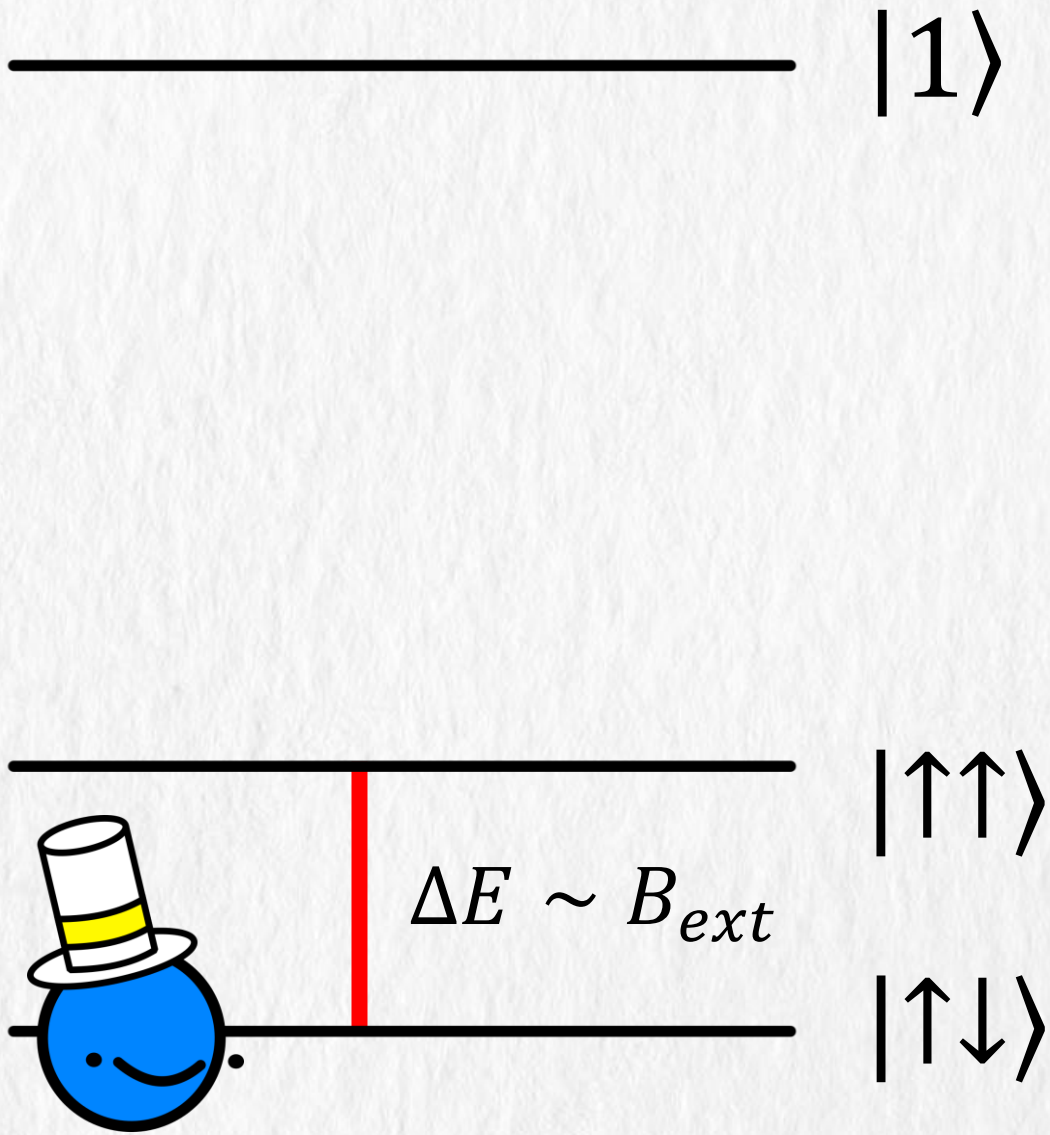


State connected to the other states **via a photon transition**

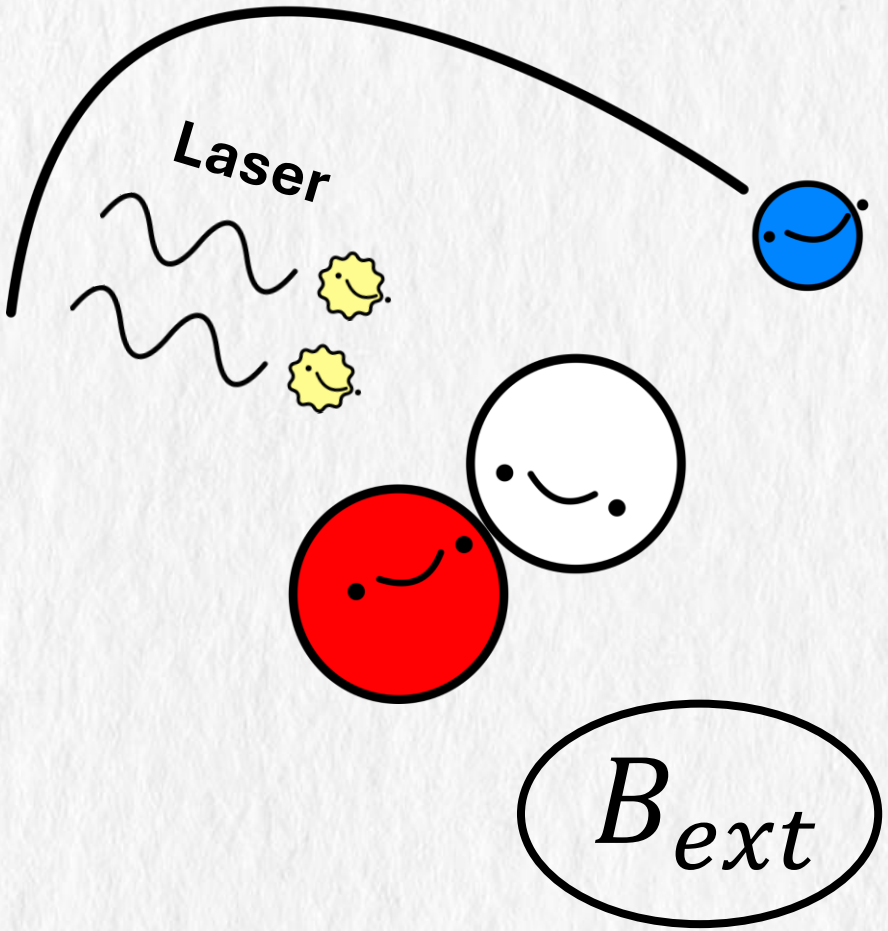


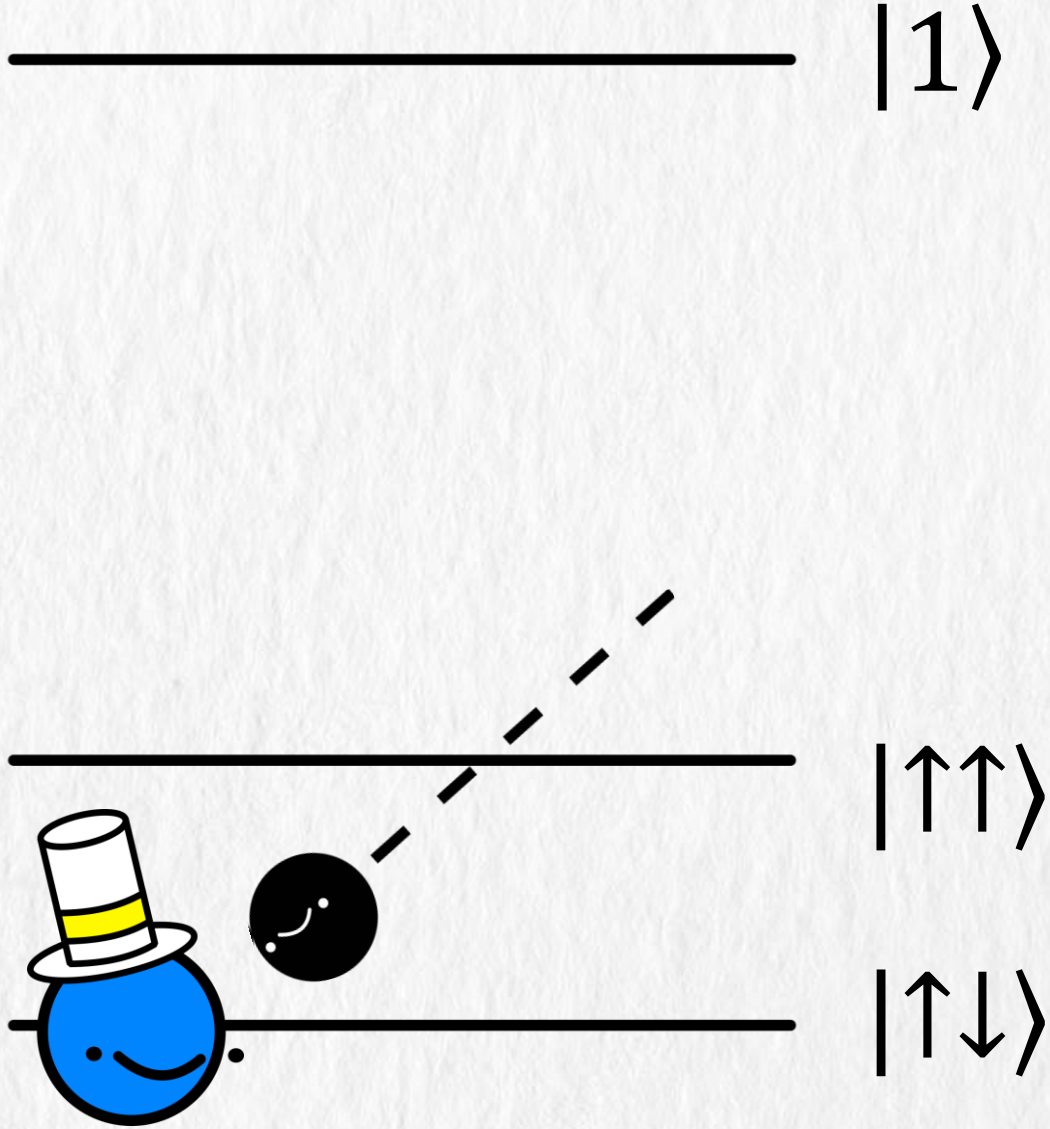
The spin flip transition **can be modulated** with B_{ext}





Some DM particle is **absorbed by the electron**...





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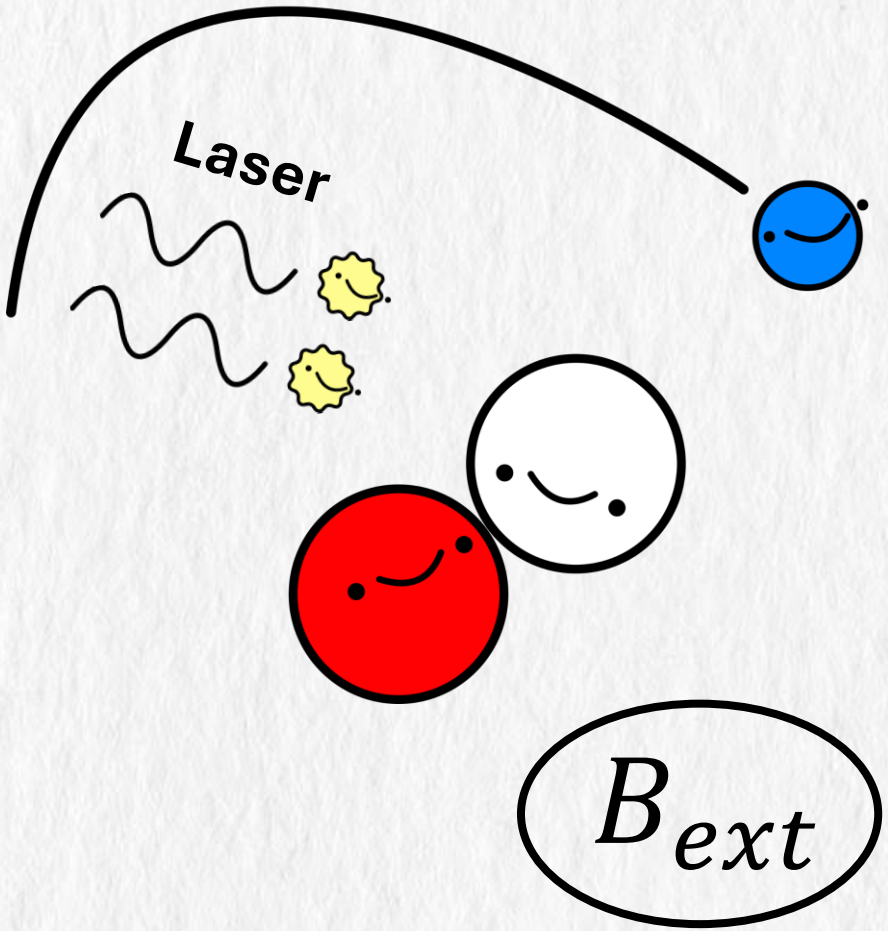
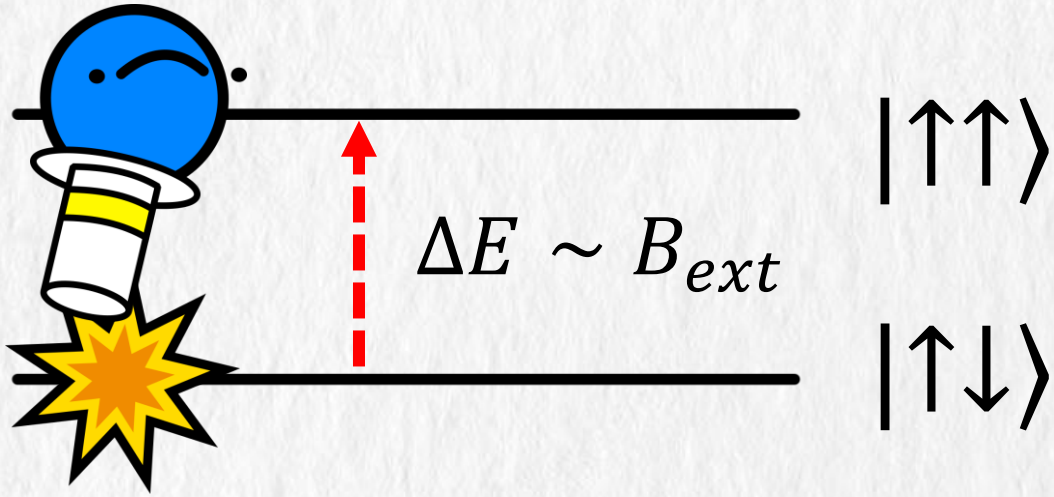


...and it **gets to the first excited state**

For **non-relativistic DM** $\Delta E \sim m_{DM}$



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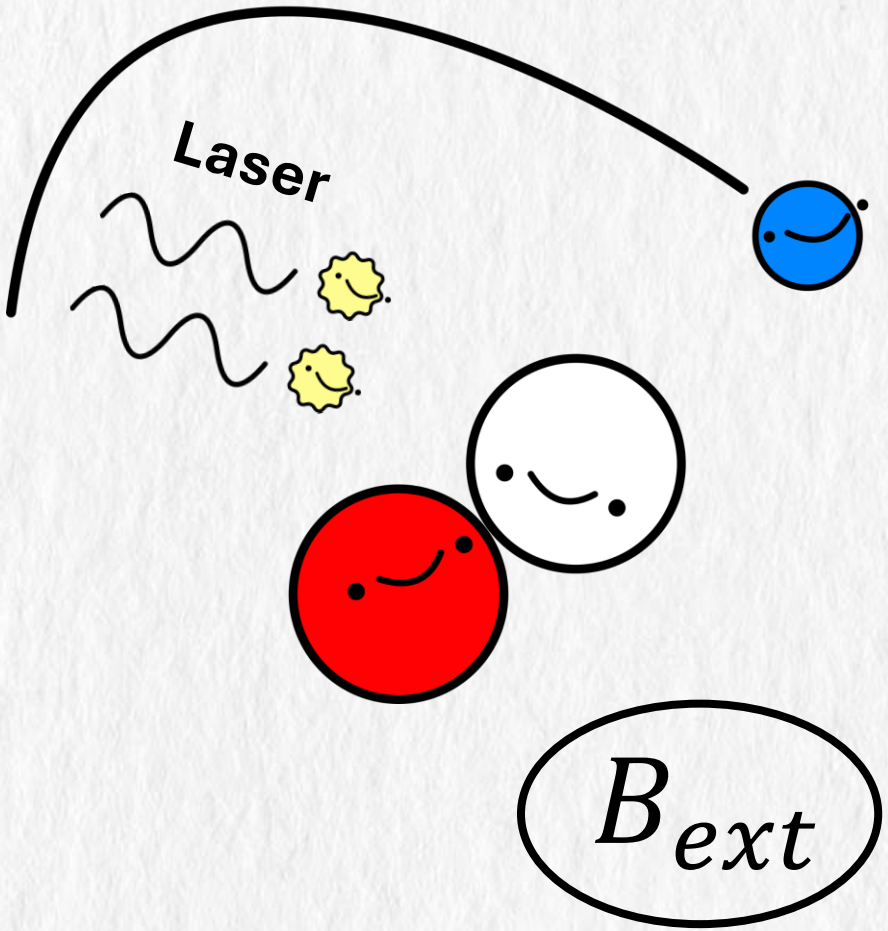

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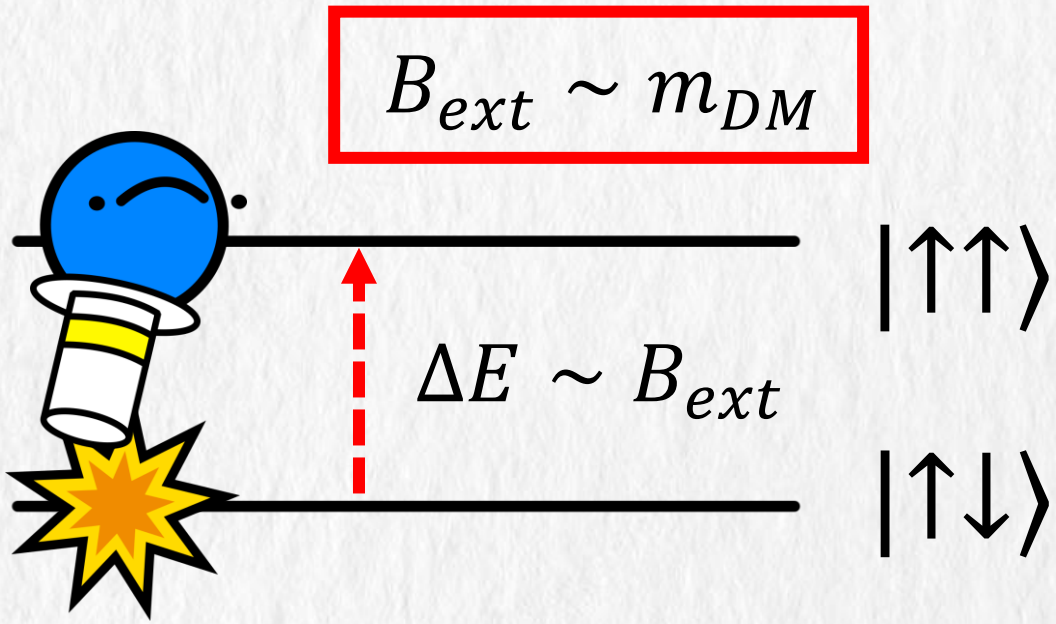
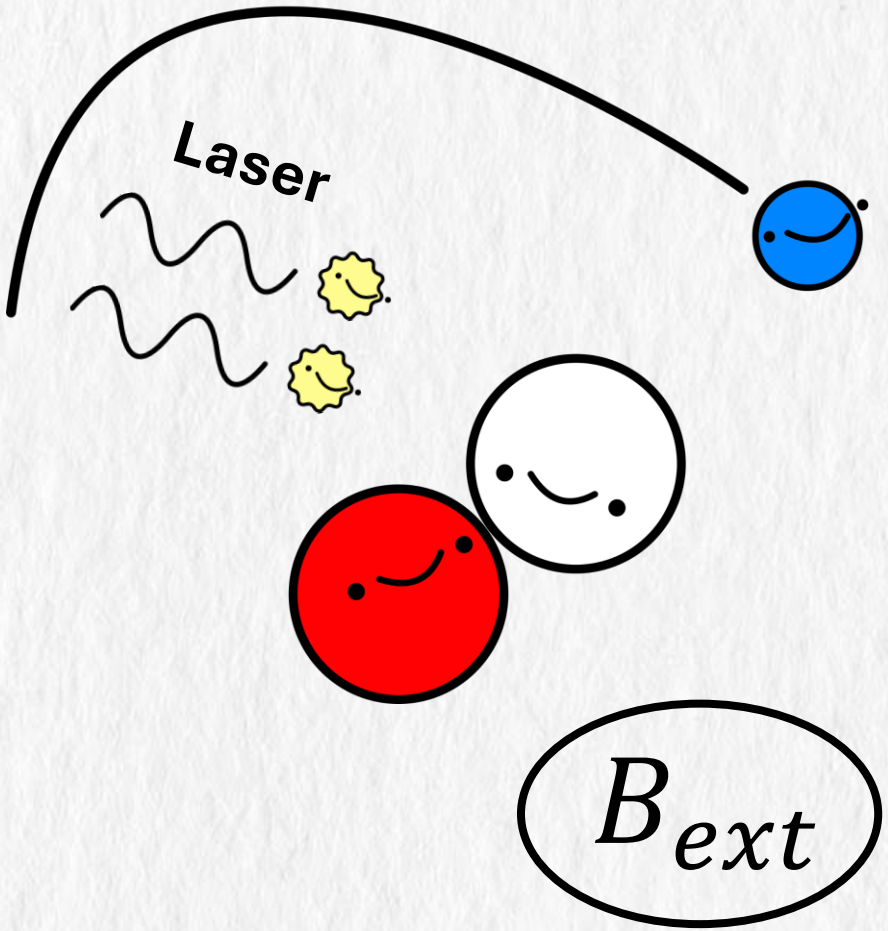
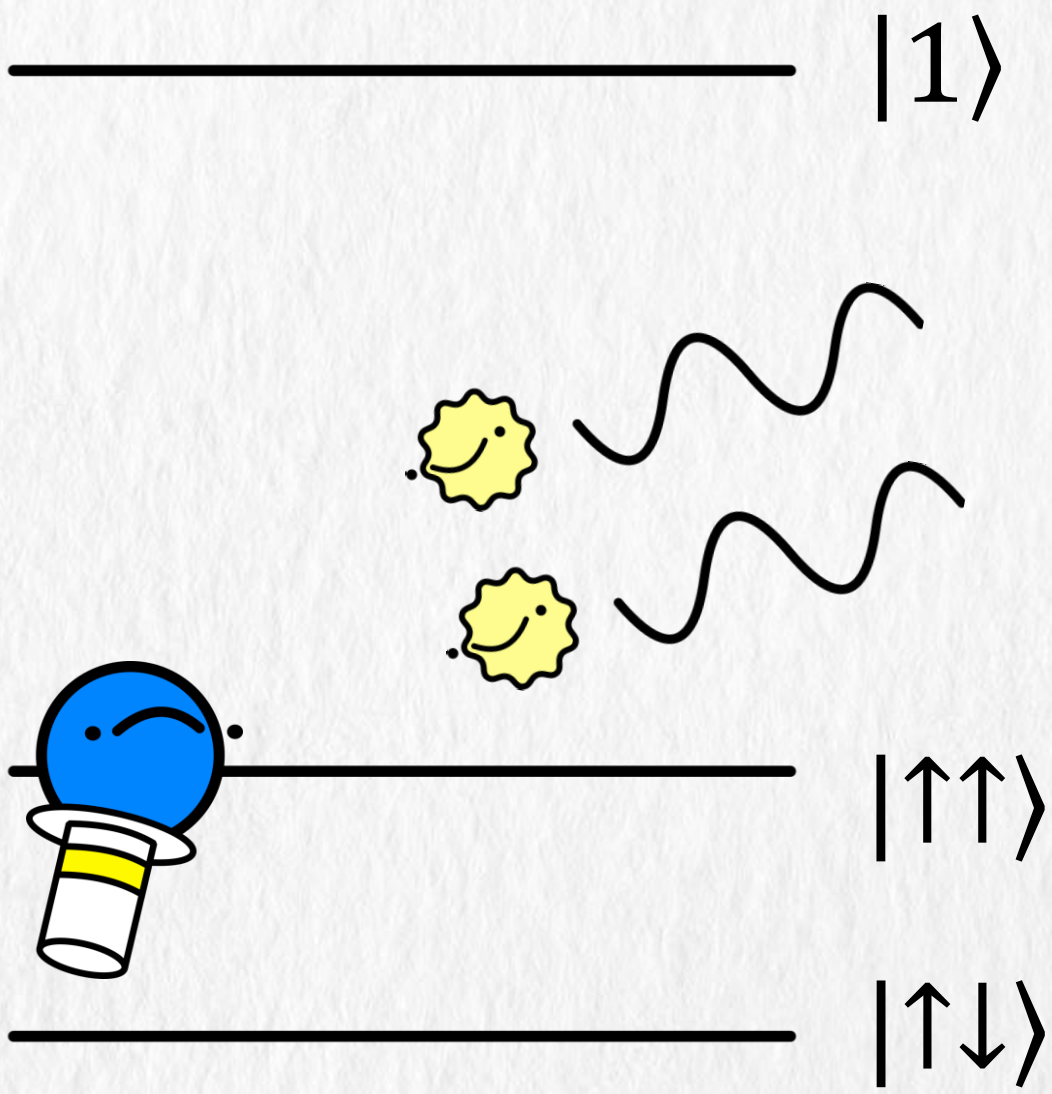


The **laser is tuned to the gap** between $|\uparrow\uparrow\rangle$ and $|1\rangle$...





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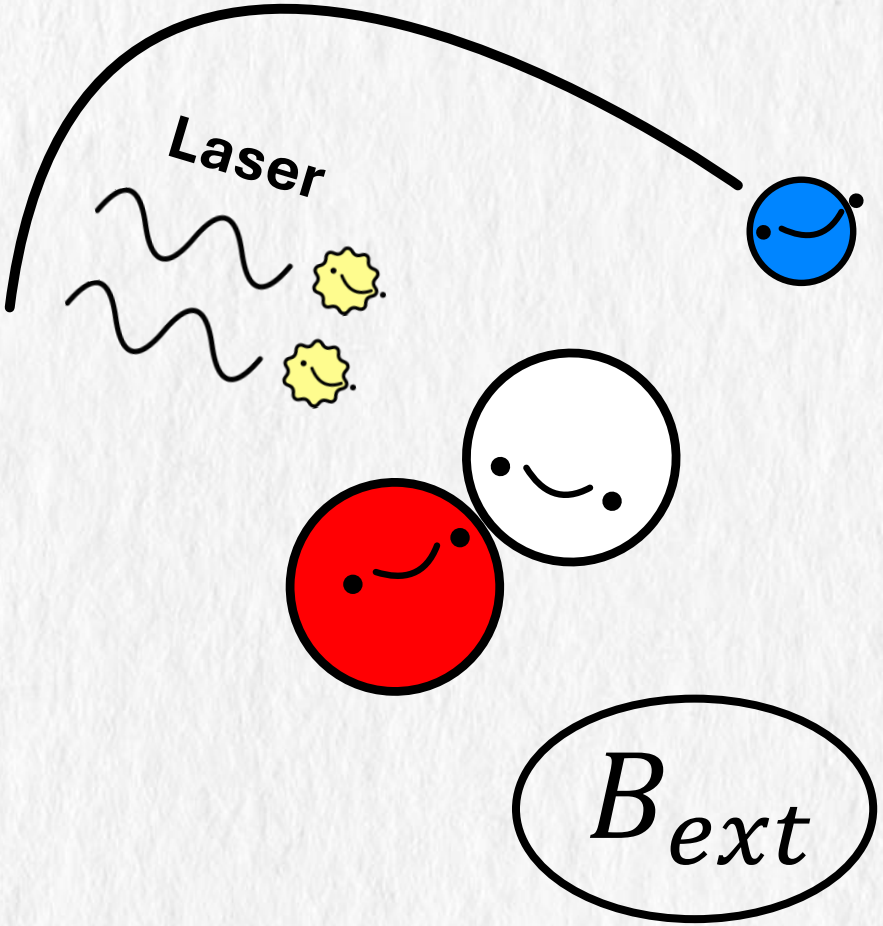

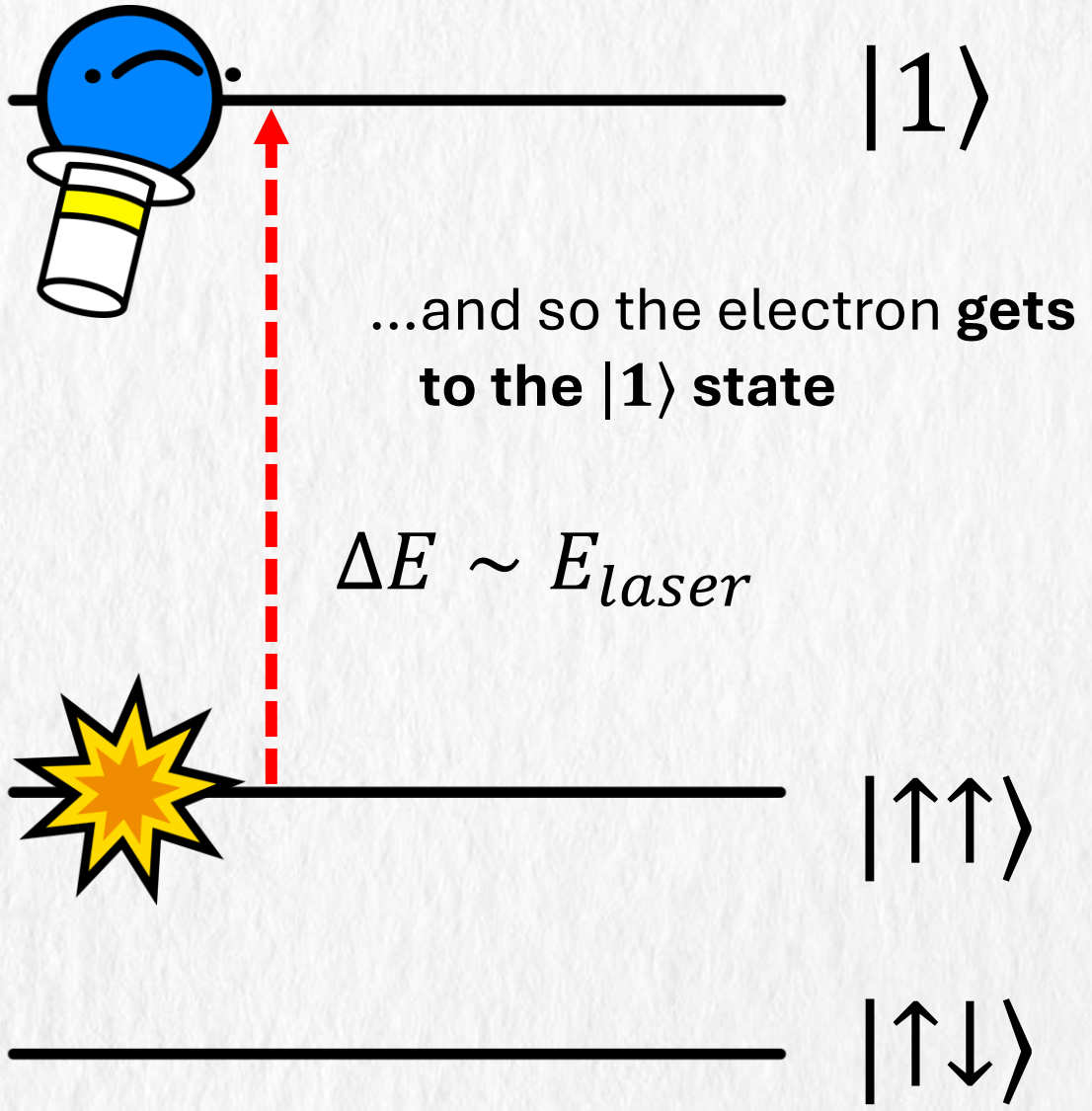

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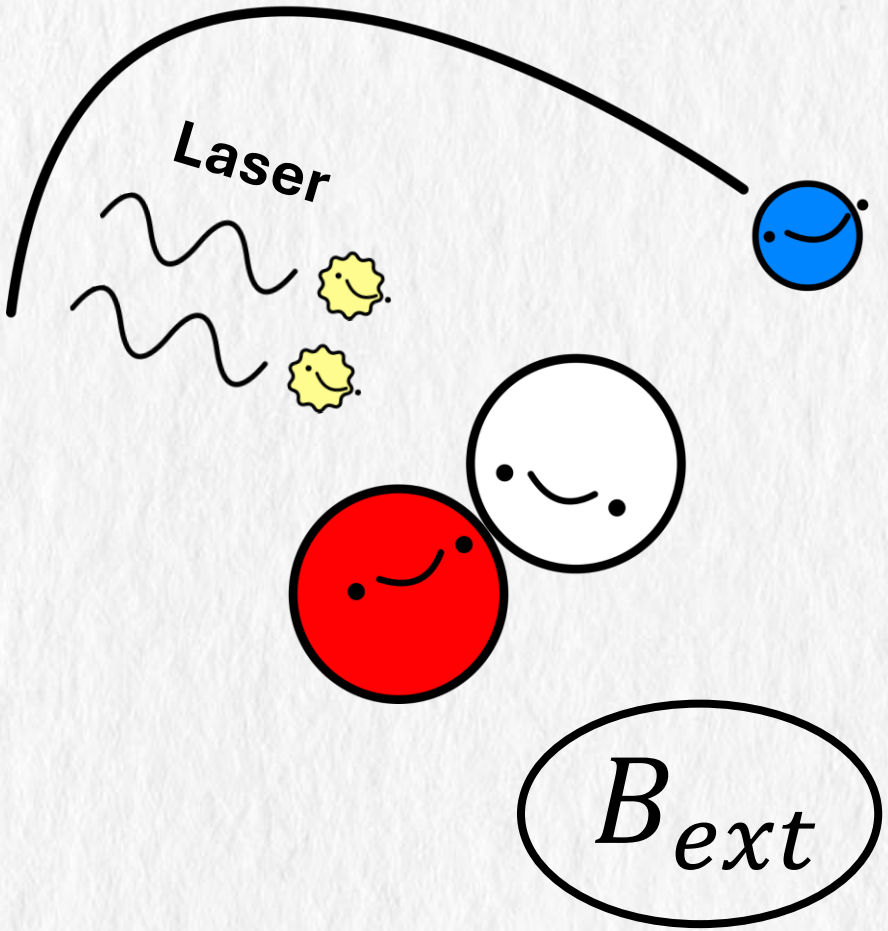

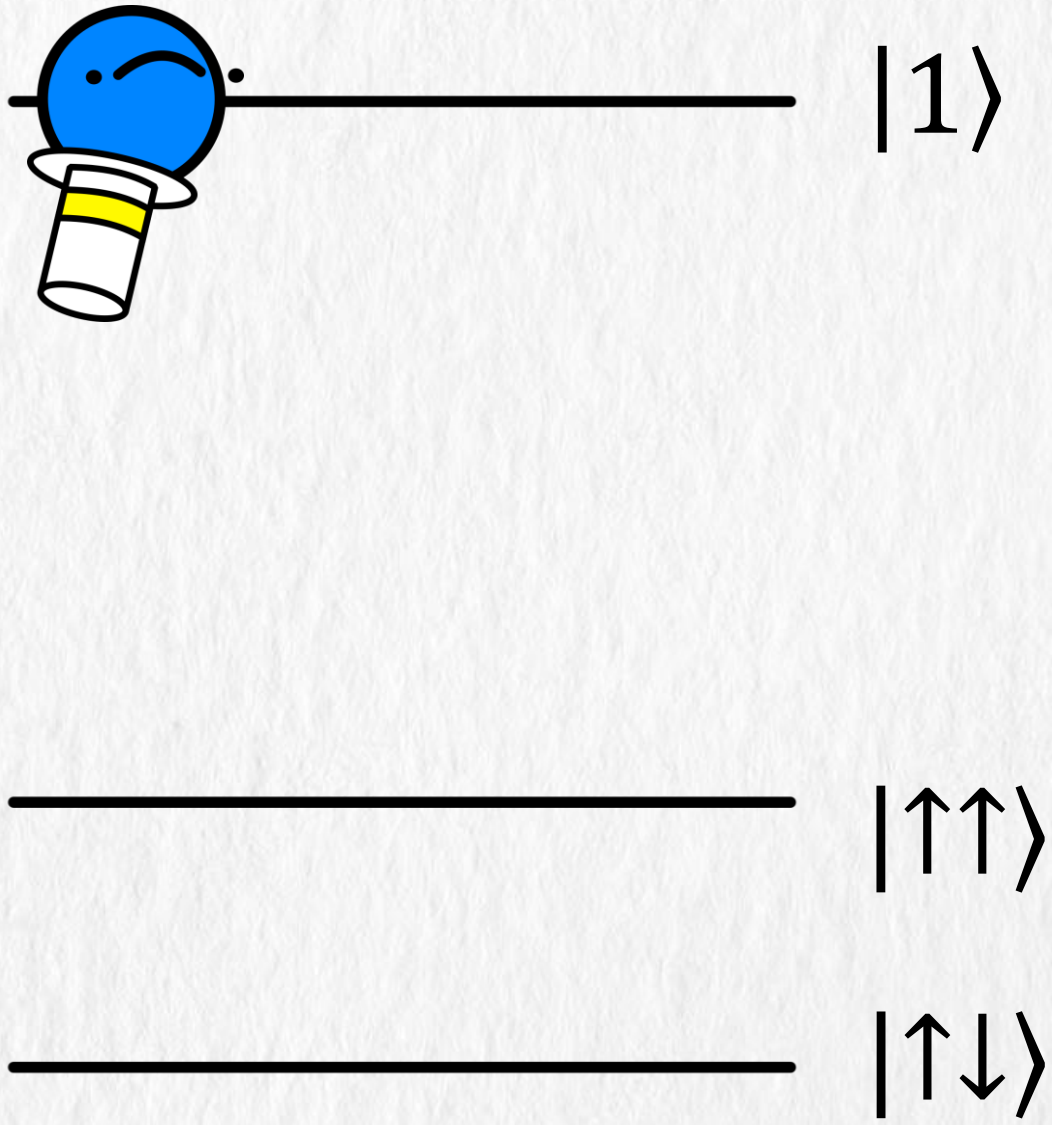

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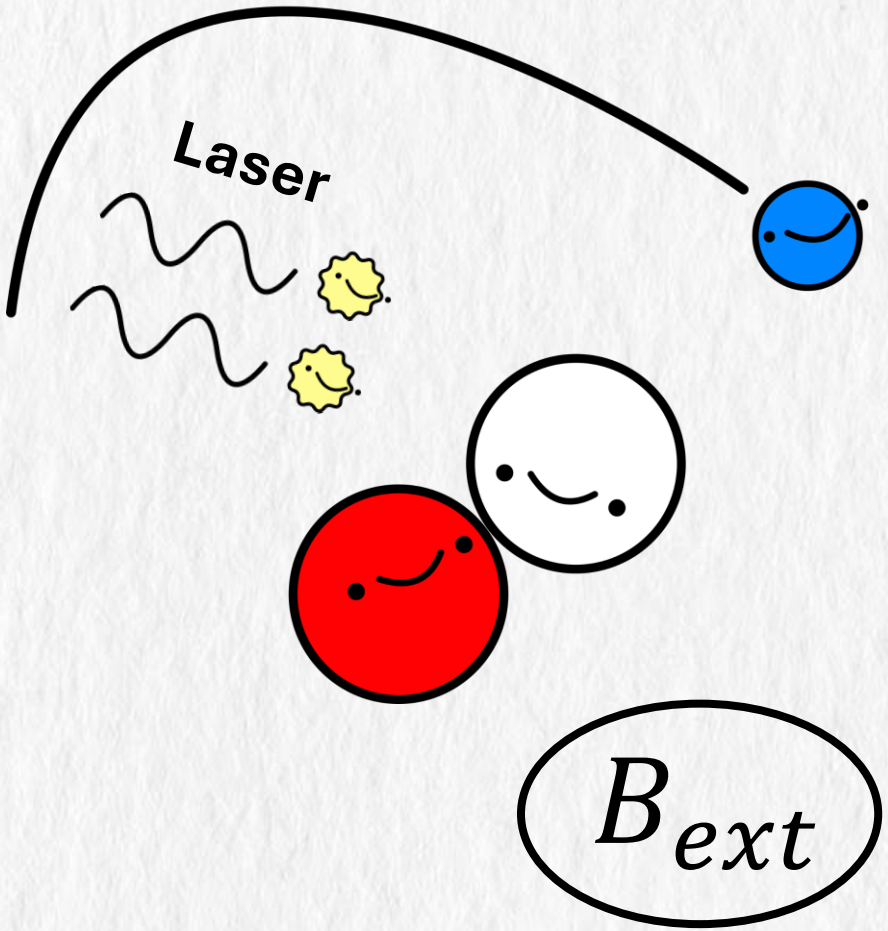

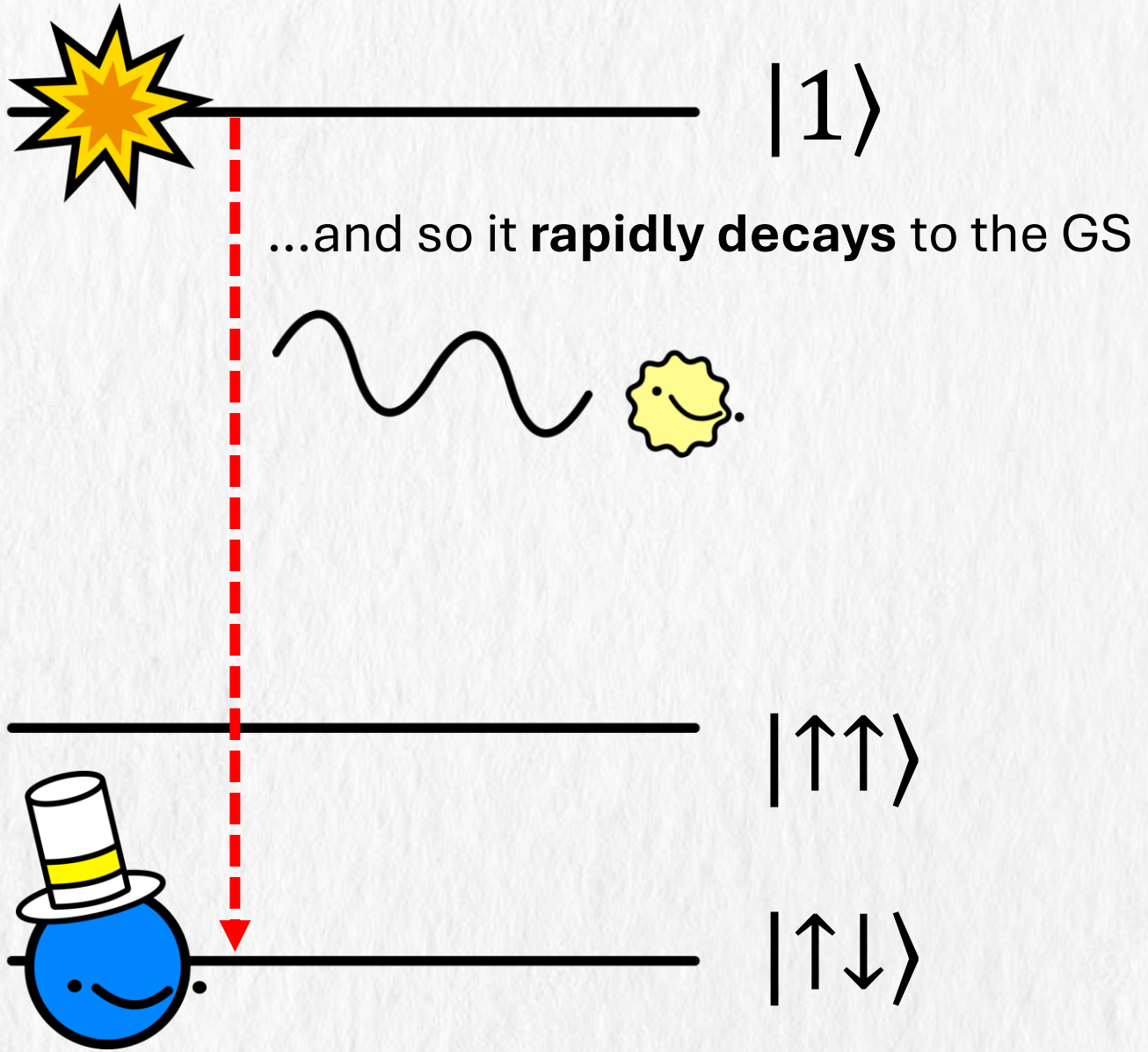

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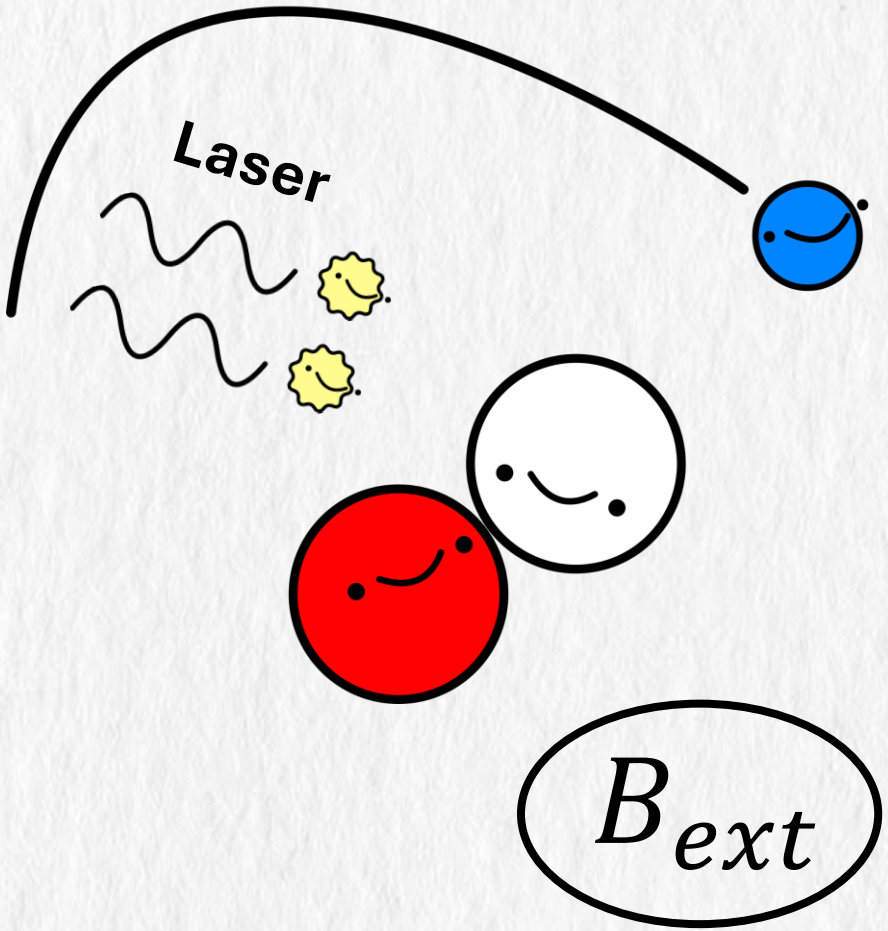
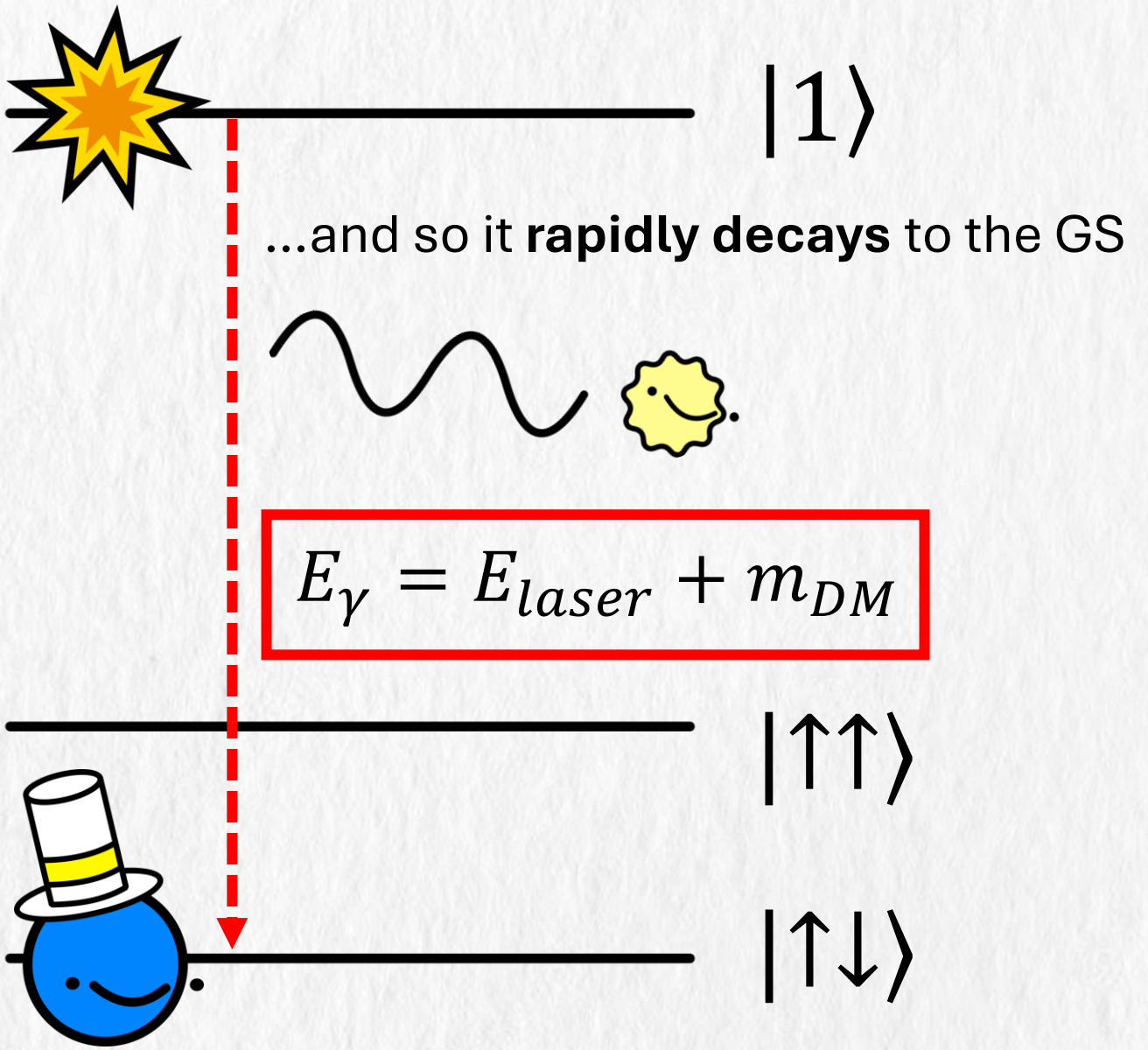
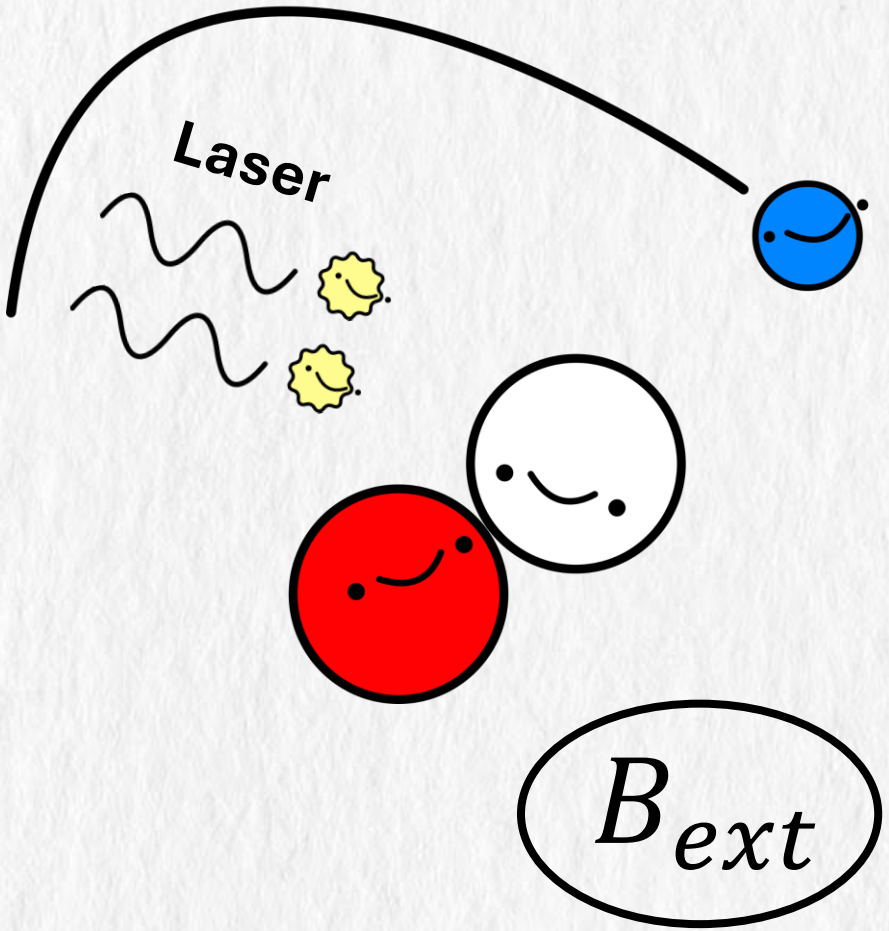
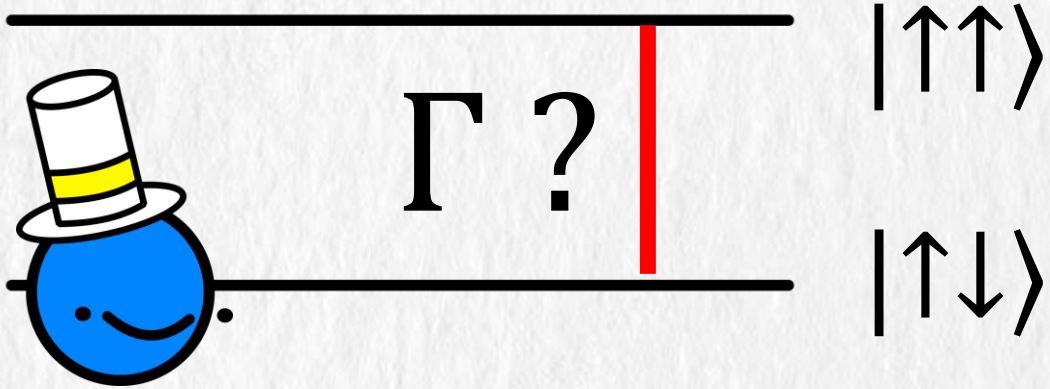




All this rests on us having a
sizeable rate for the DM transition





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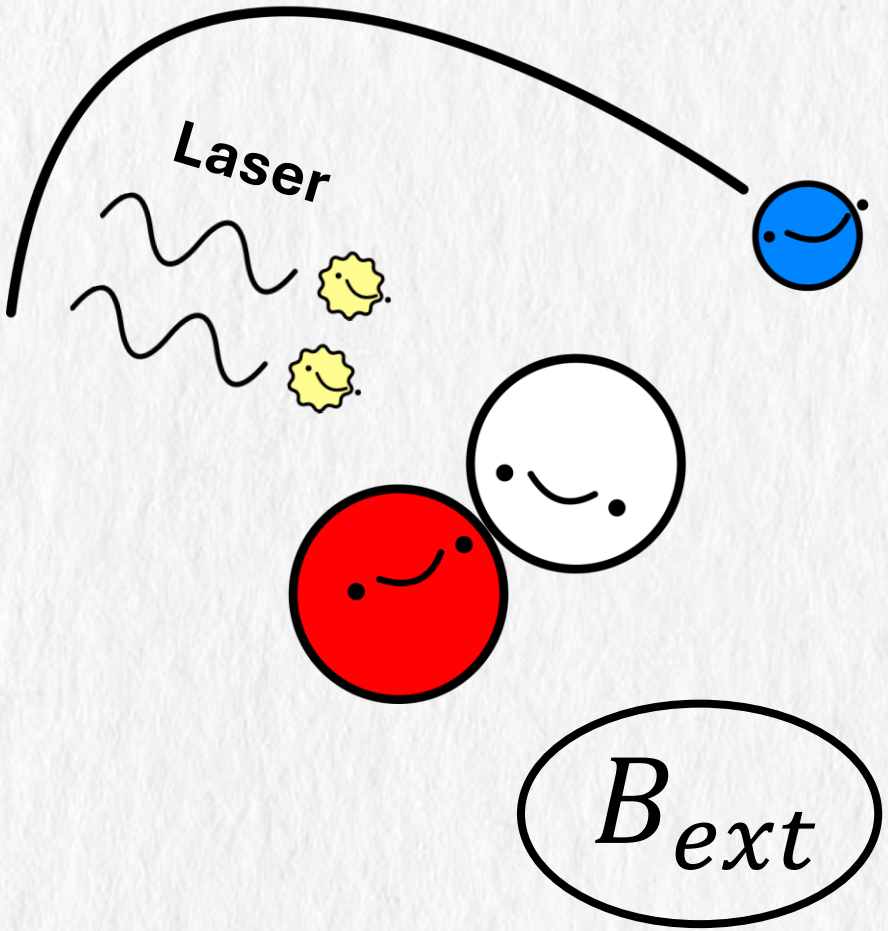
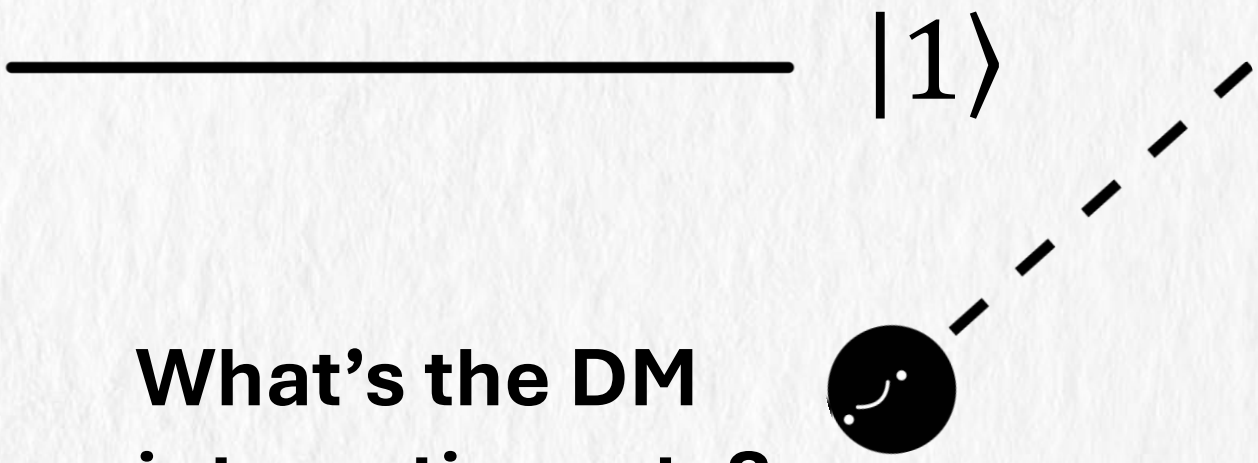
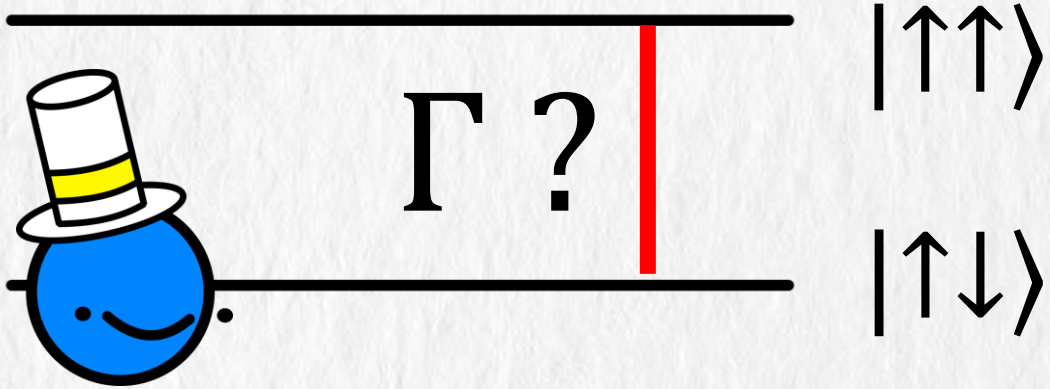




What's the DM interaction rate?



Transition rates 101

- Fermi's golden rule

$$d\Gamma = 2\pi \left|\mathcal{M}_{fi}\right|^2 \delta\left(\sum_i E_i - \sum_f E_f\right) d\rho$$

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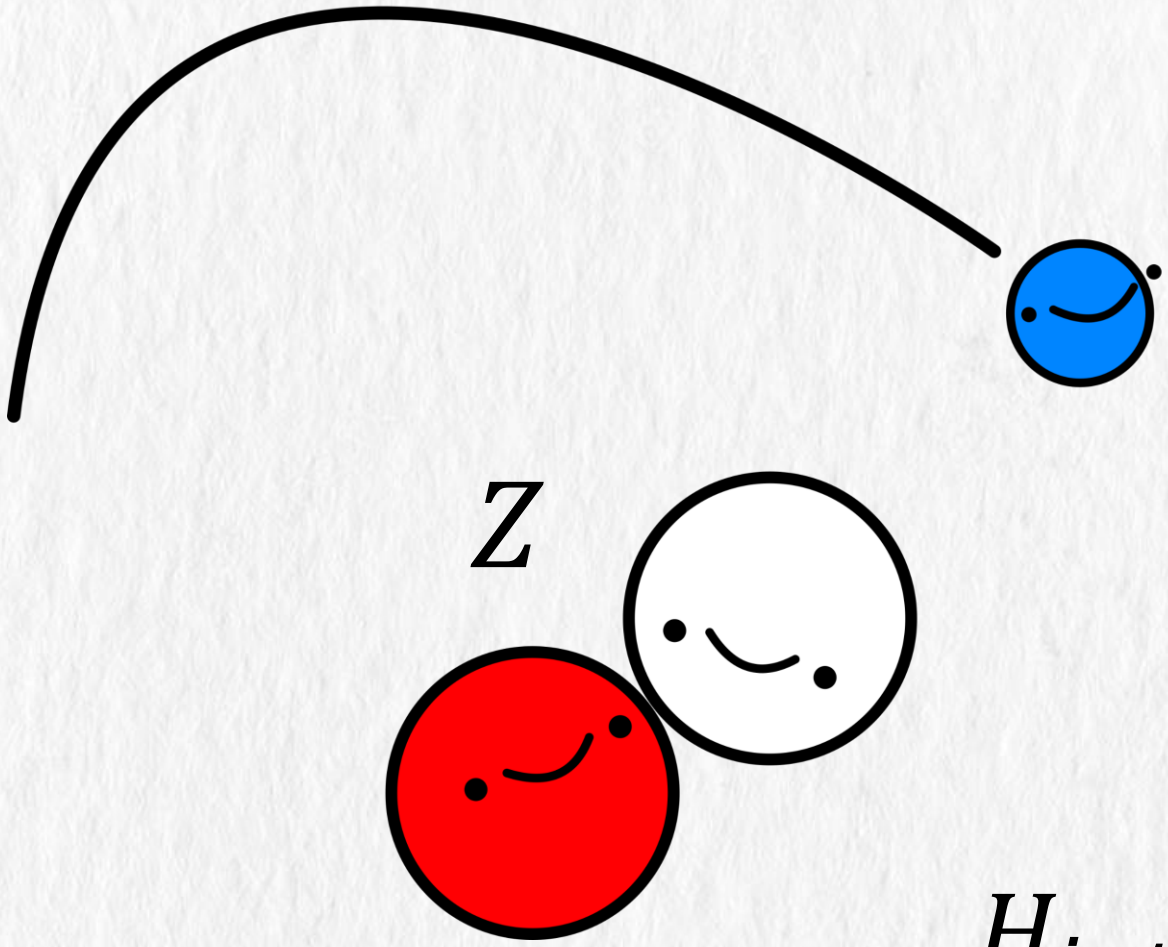
Initial state (n, j, m)



$$H_{int} = \overline{\psi_e}\,\Gamma_{\{\mu\}}\psi_e \times \mathcal{O}_{\{\mu\}}(\phi_i)$$

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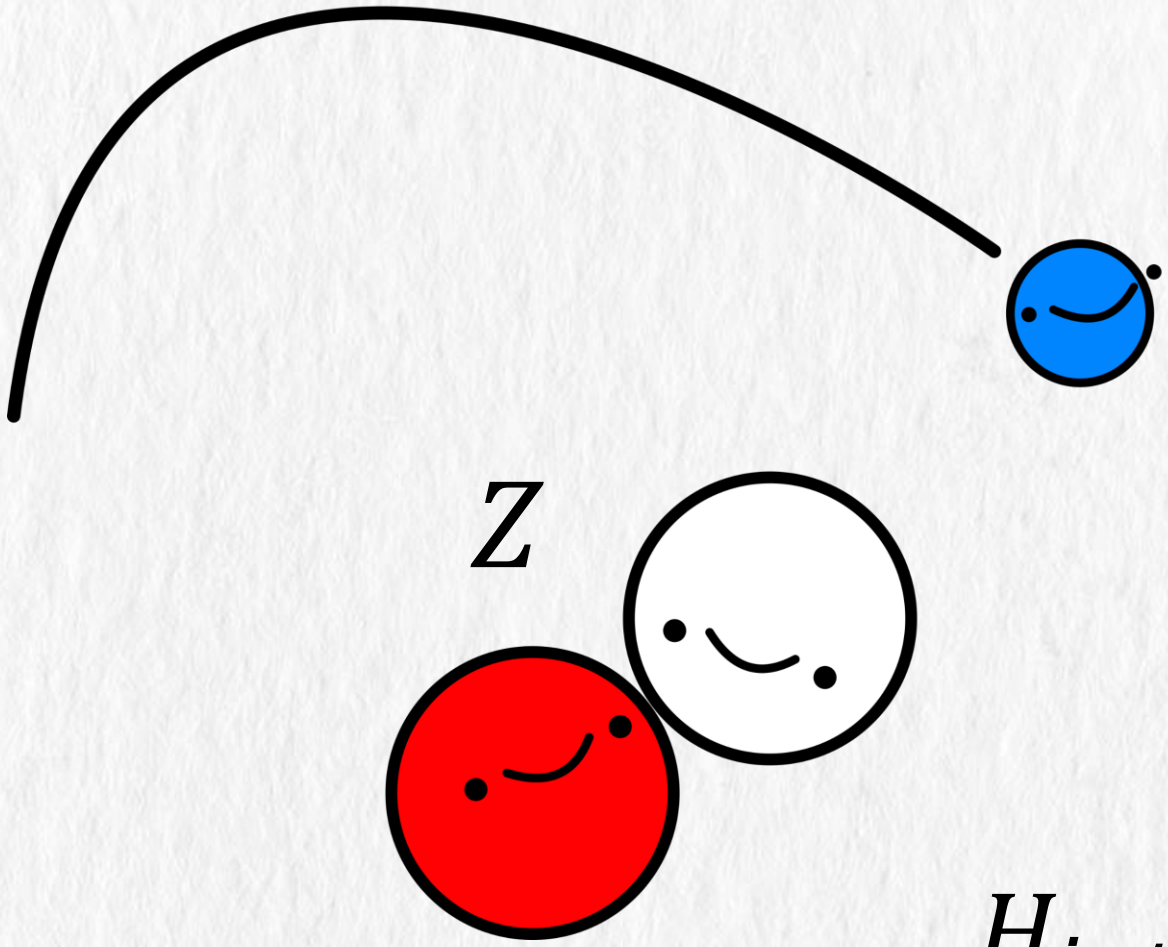

$$\psi_e(x) = \sum_{\substack{Quantum \\ numbers}} a\, U(x) + b^{\dagger}\, V^{\dagger}(x)$$

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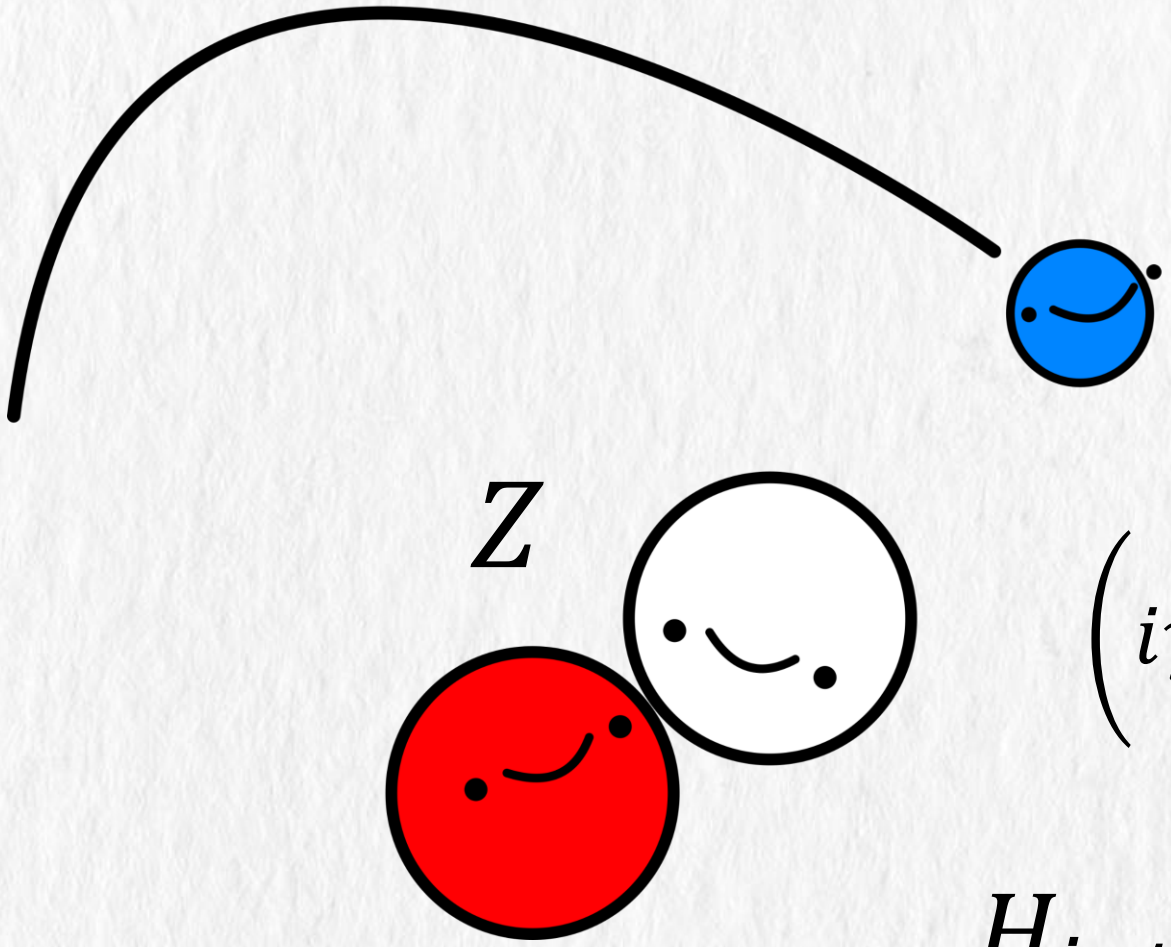

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Dirac equation with Coulomb potential

$$\left(i\gamma^\mu \partial_\mu - \gamma^0 \frac{Z\alpha_{\mathrm{em}}}{r} - \mu\right) U(x) = 0$$

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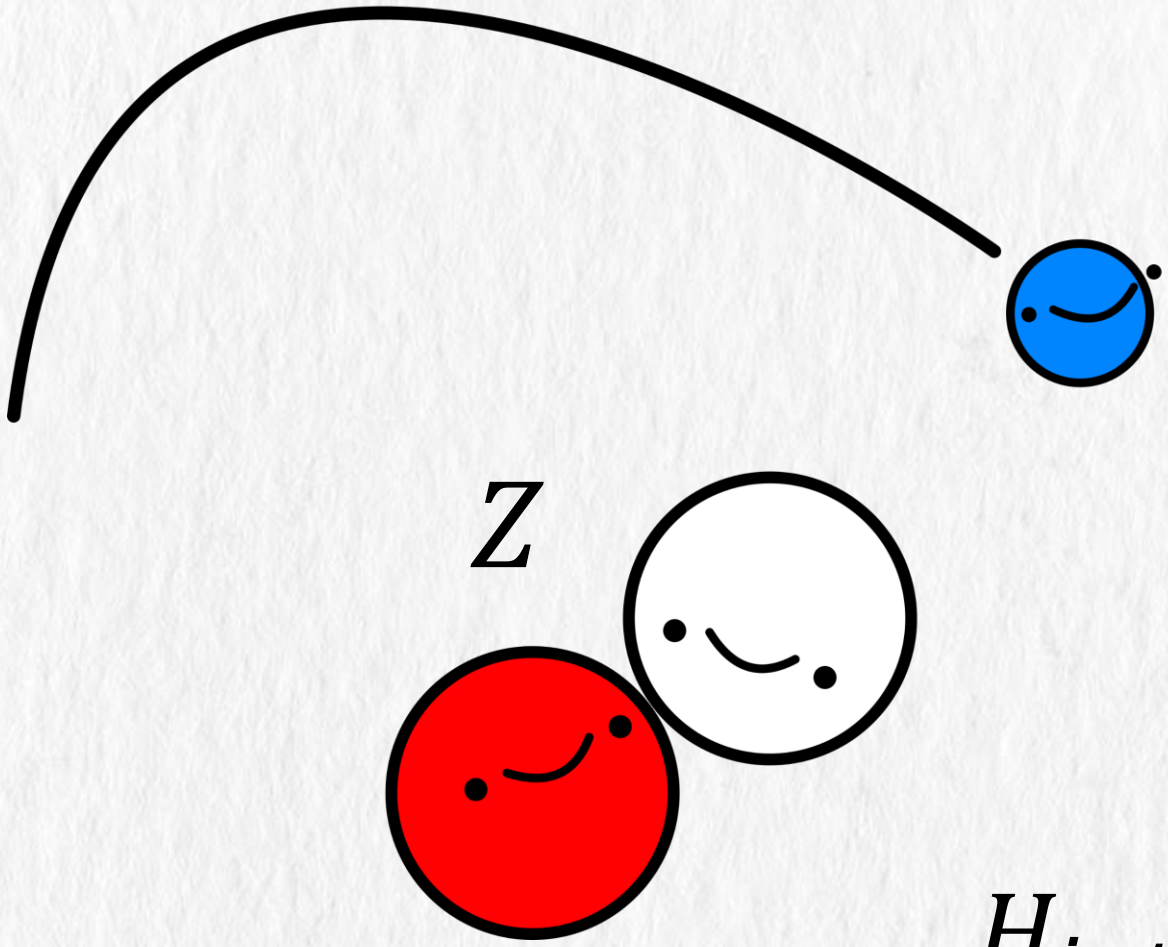

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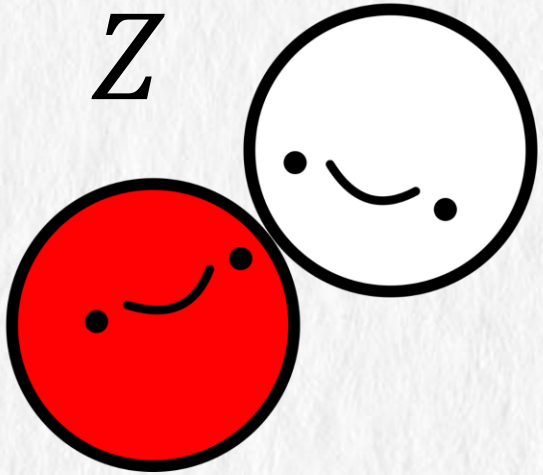
Initial state (n, j, m)

Incident particle/s

Z



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Initial state (n, j, m)

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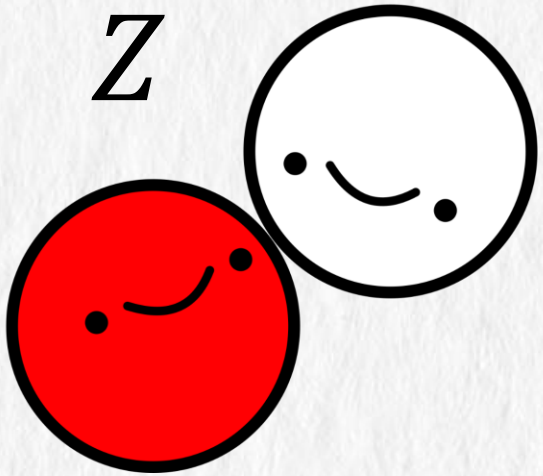
Whatever interacts with the electron

Z



$$\text{Axion} \rightarrow \frac{g_f}{2f_a}\partial_\mu a \qquad \text{Photon} \rightarrow eA_\mu$$

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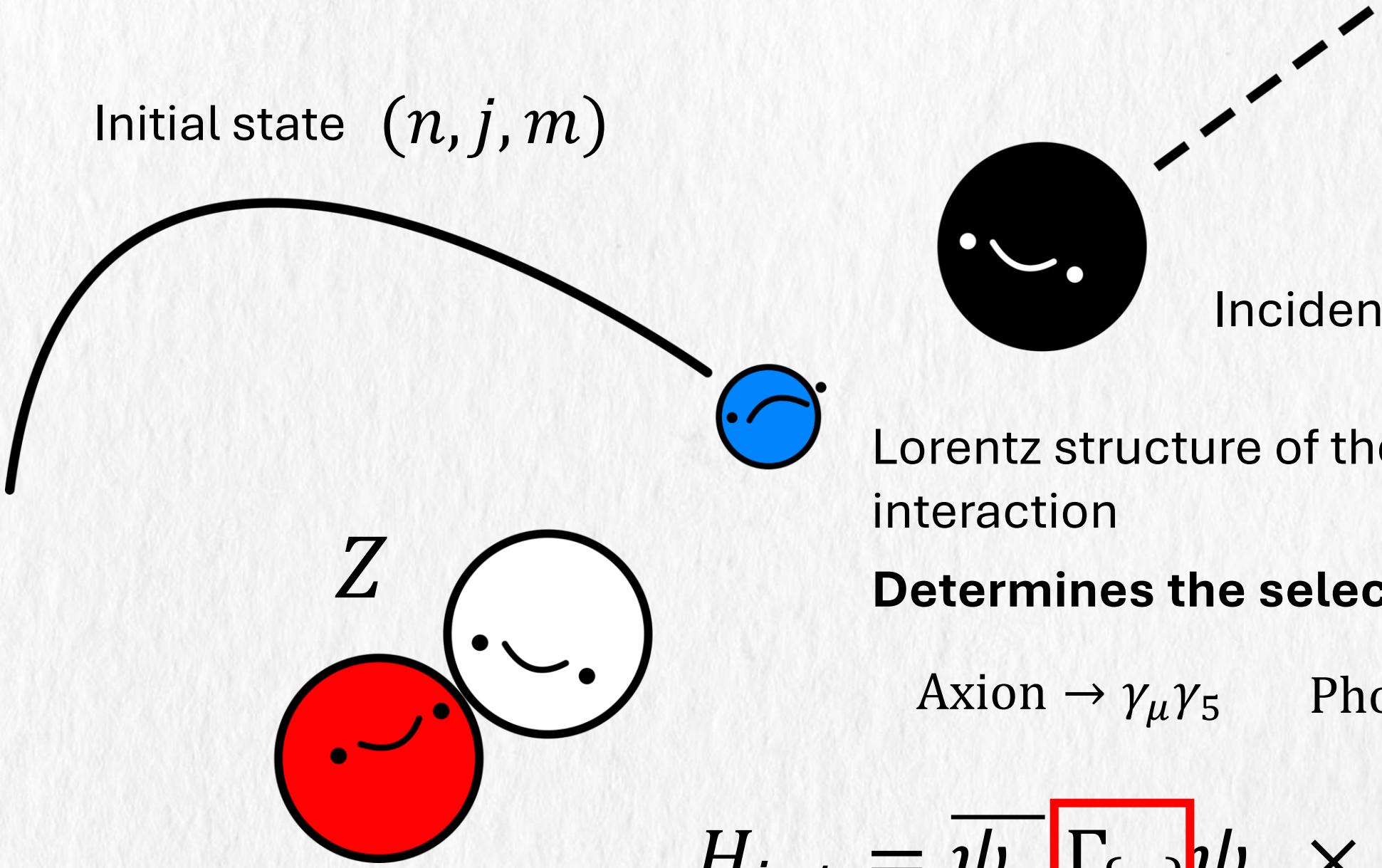


Incident particle/s

Lorentz structure of the interaction

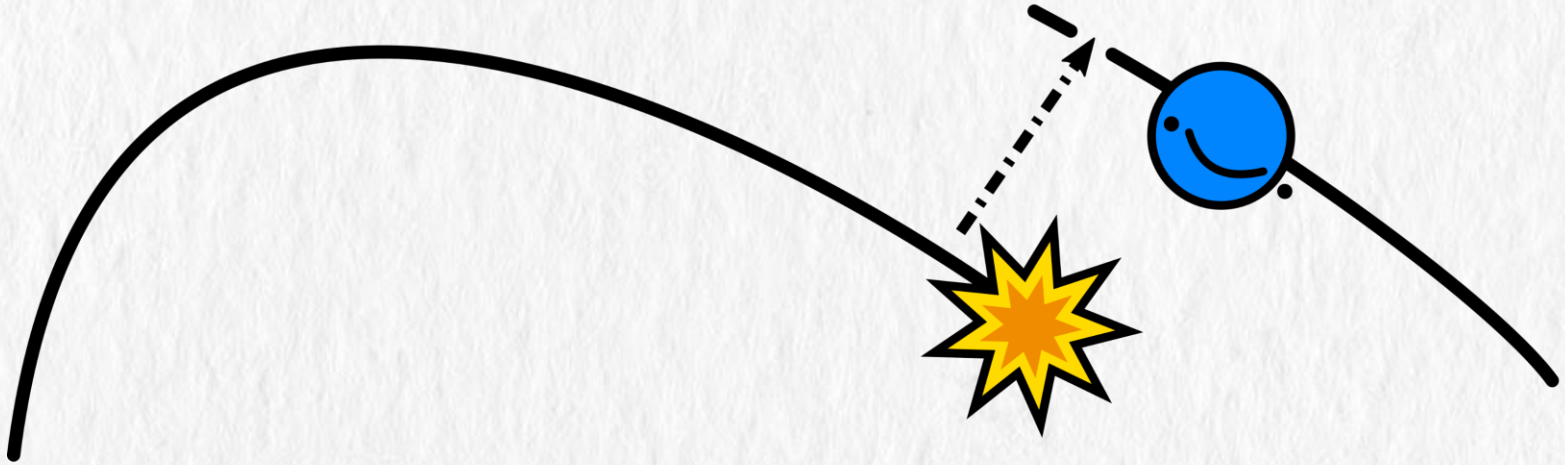
Determines the selection rules

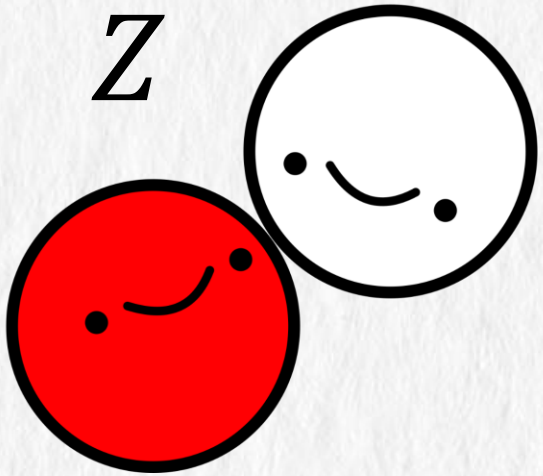
$$\text{Axion} \rightarrow \gamma_\mu\gamma_5 \qquad \text{Photon} \rightarrow \gamma_\mu$$

$$H_{int} = \overline{\psi_e}\,\Gamma_{\{\mu\}}\psi_e \times \mathcal{O}_{\{\mu\}}(\phi_i)$$

Initial state (n, j, m)

Final state (n', j', m')





$$\mathcal{M}_{fi} = \langle f | \int d^3x \, \mathcal{H}_{int} \, | i \rangle$$

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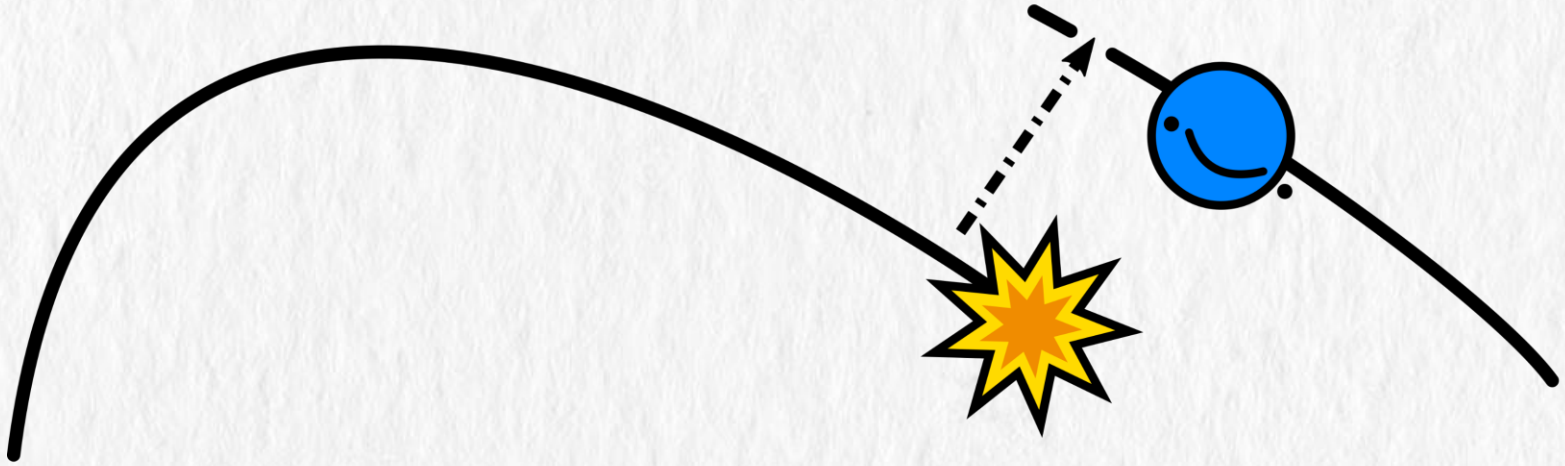

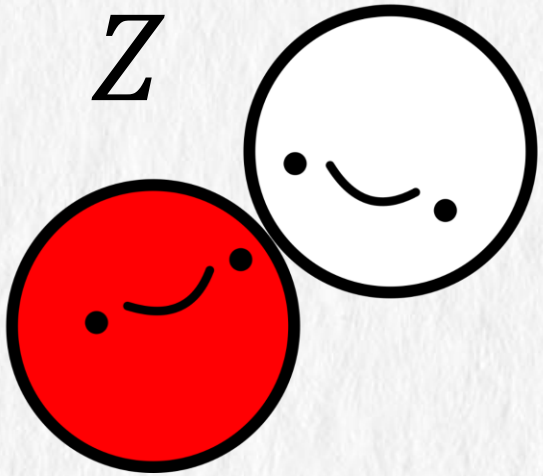

We can compute the **amplitude with semi-analytical methods** [2407.12913]

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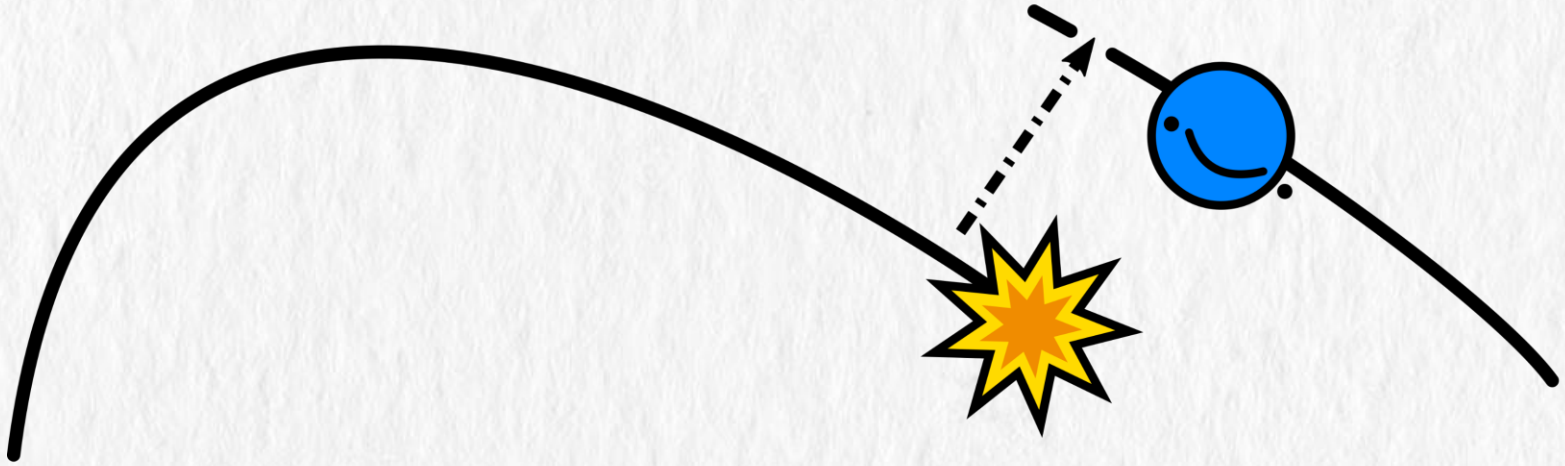
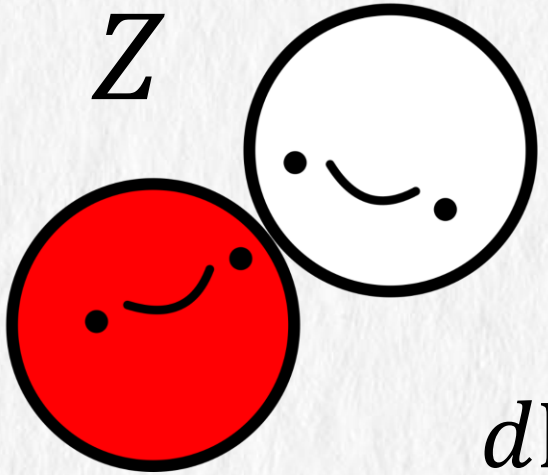


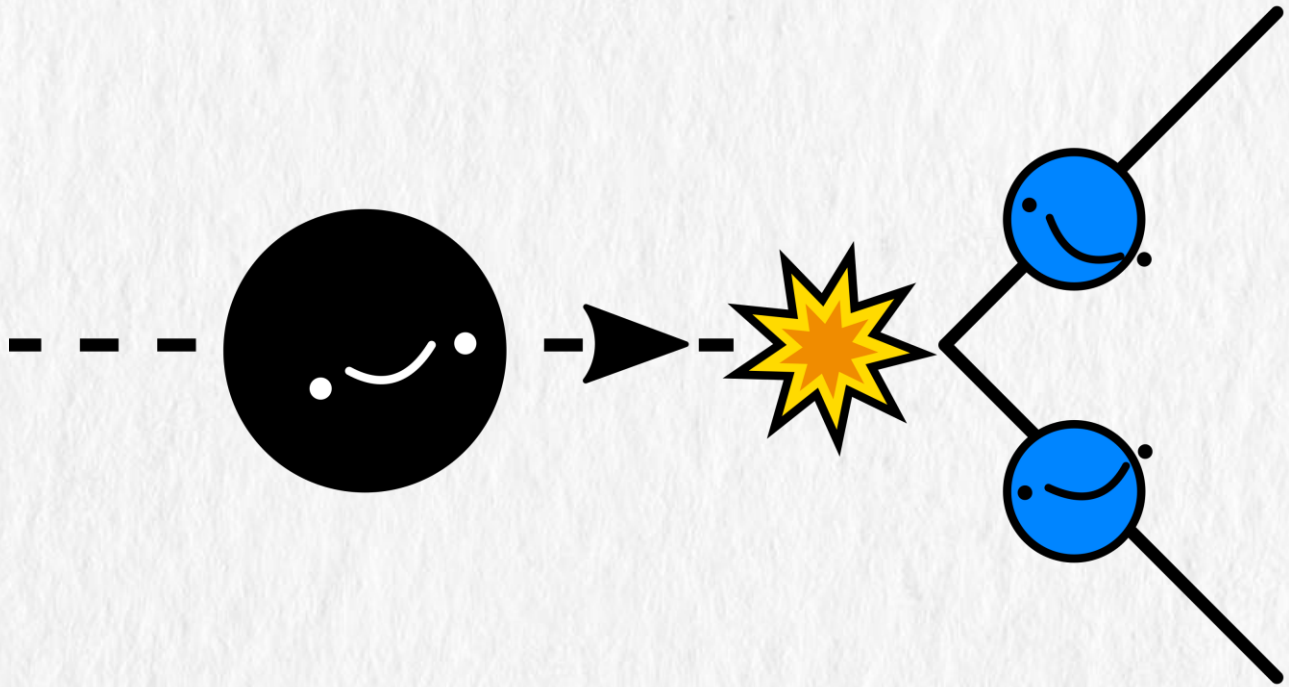
Integrate over the phase space and,

Done!



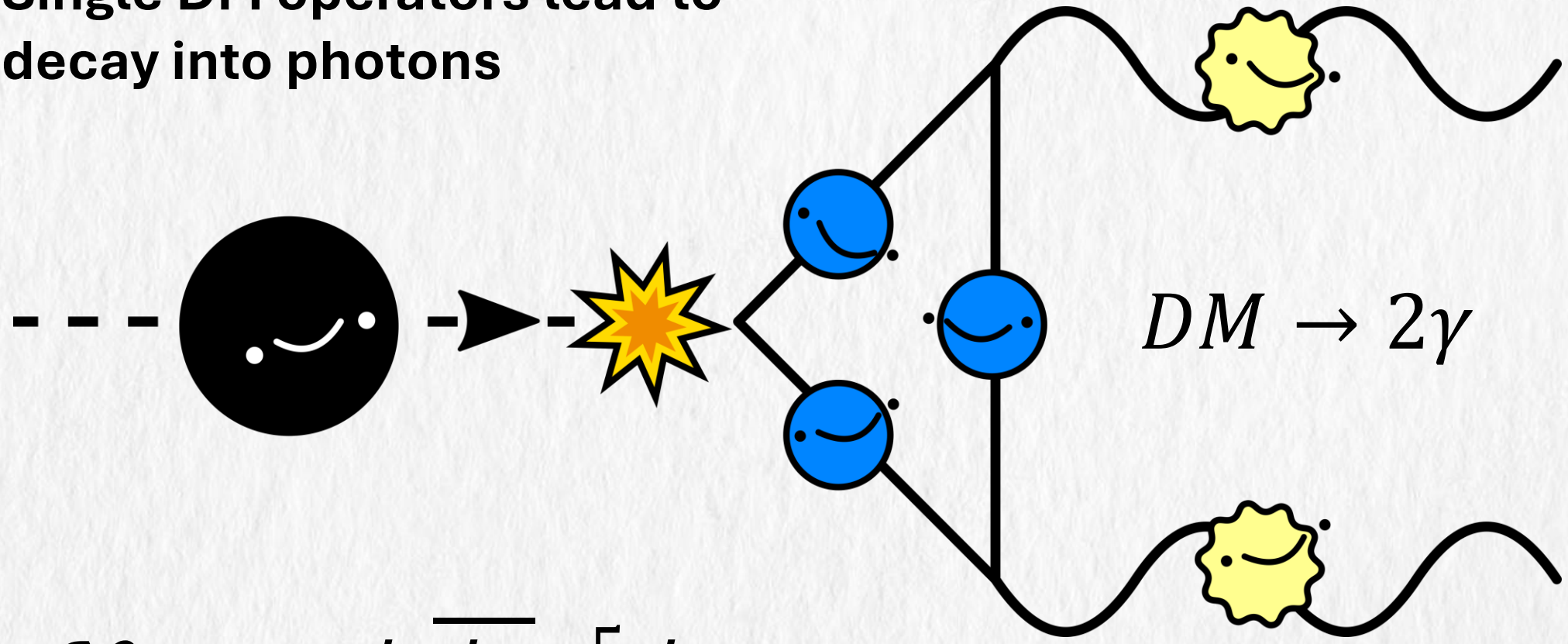
We can compute **the amplitude with semi-analytical methods** [2407.12913]

$$d\Gamma = 2\pi \left|\mathcal{M}_{fi}\right|^2 \delta\left(\sum_i E_i - \sum_f E_f\right) d\rho$$



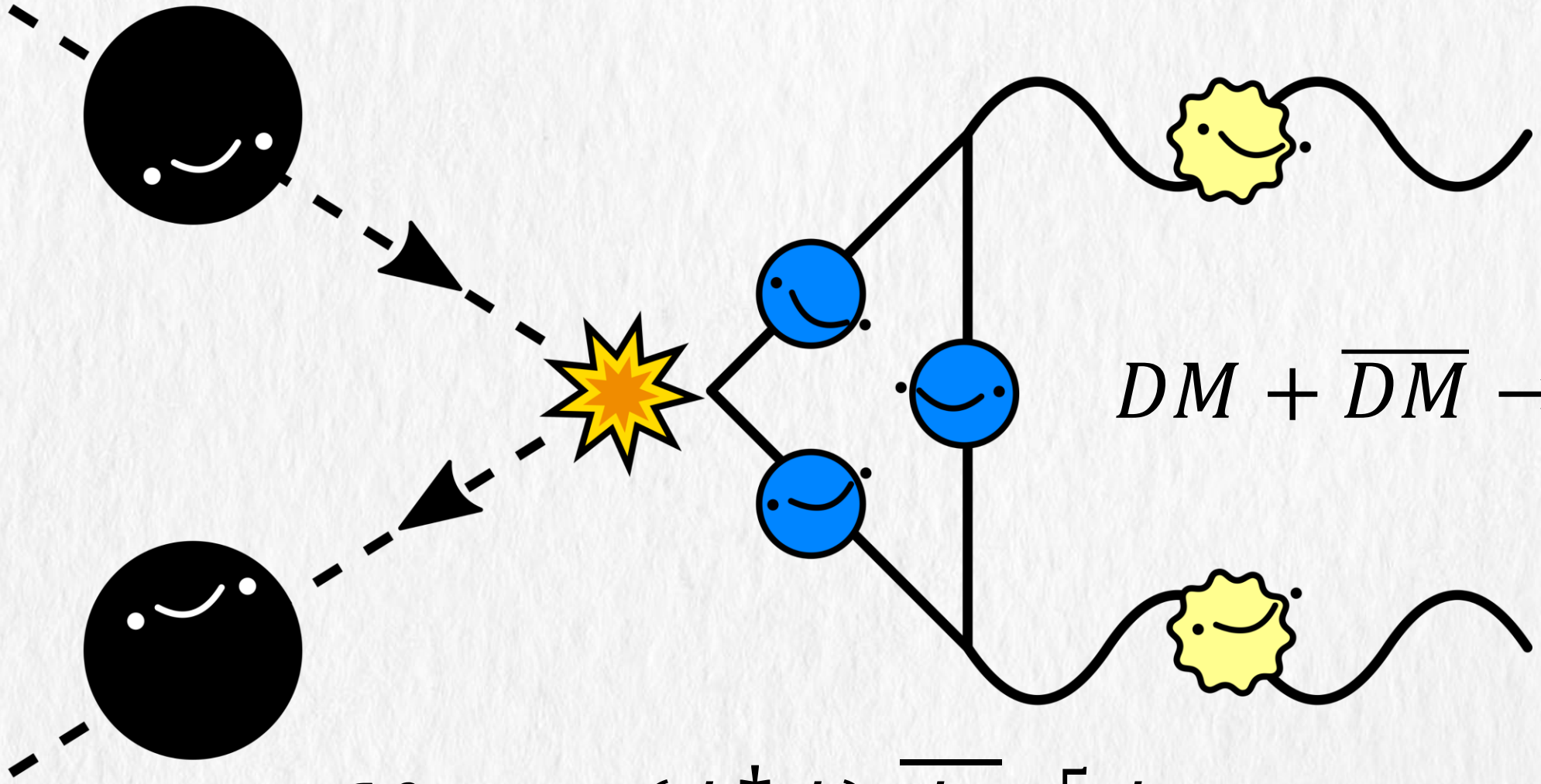
$$\mathcal{H}_{int} = \phi\, \overline{\overline{\psi_e} \gamma^5 \psi_e}$$

Single DM operators lead to decay into photons



$$\mathcal{H}_{int} = \phi\, \overline{\psi_e} \gamma^5 \psi_e$$

Quadratic operators don't have this issue...

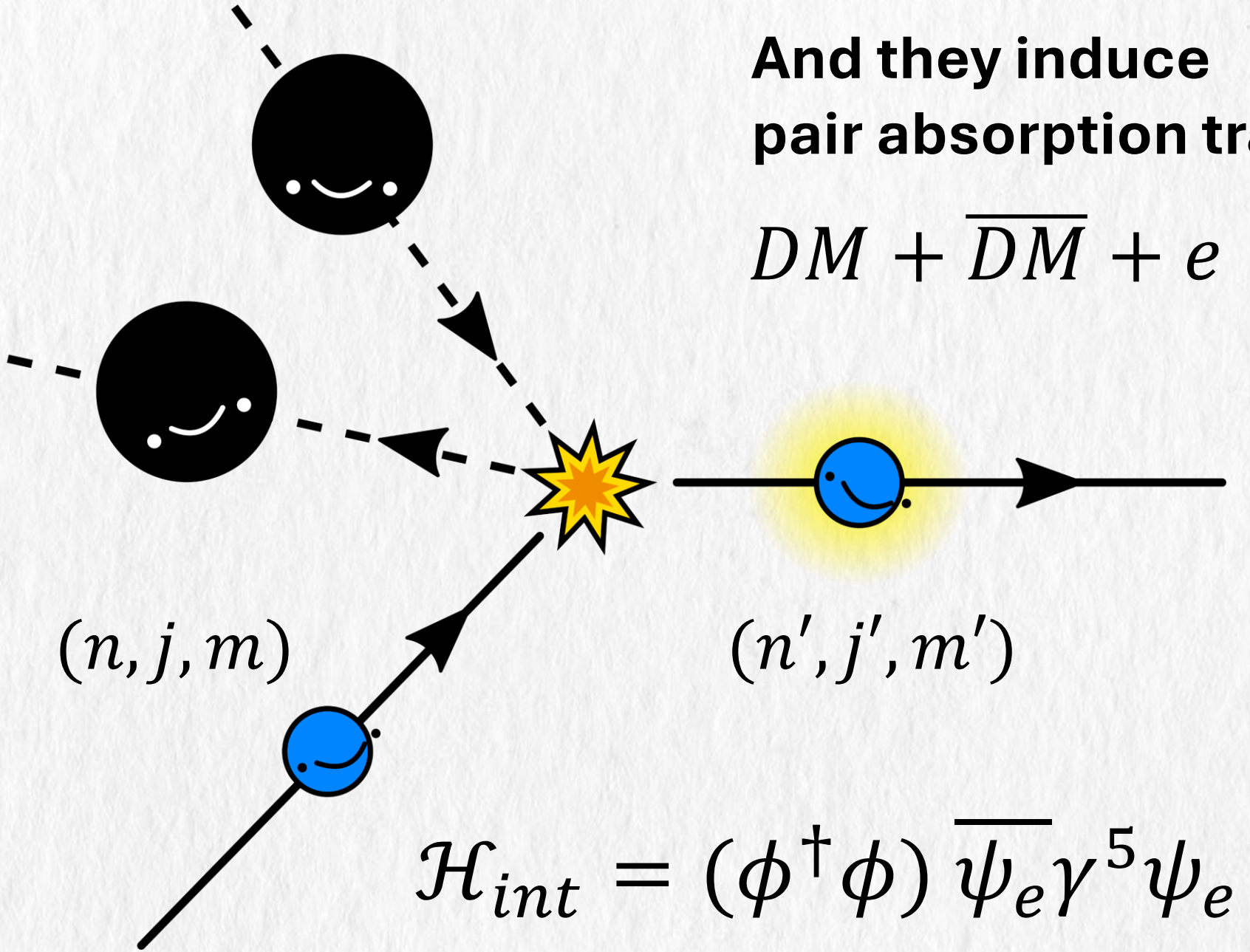


$$DM + \overline{DM} \rightarrow 2\gamma$$

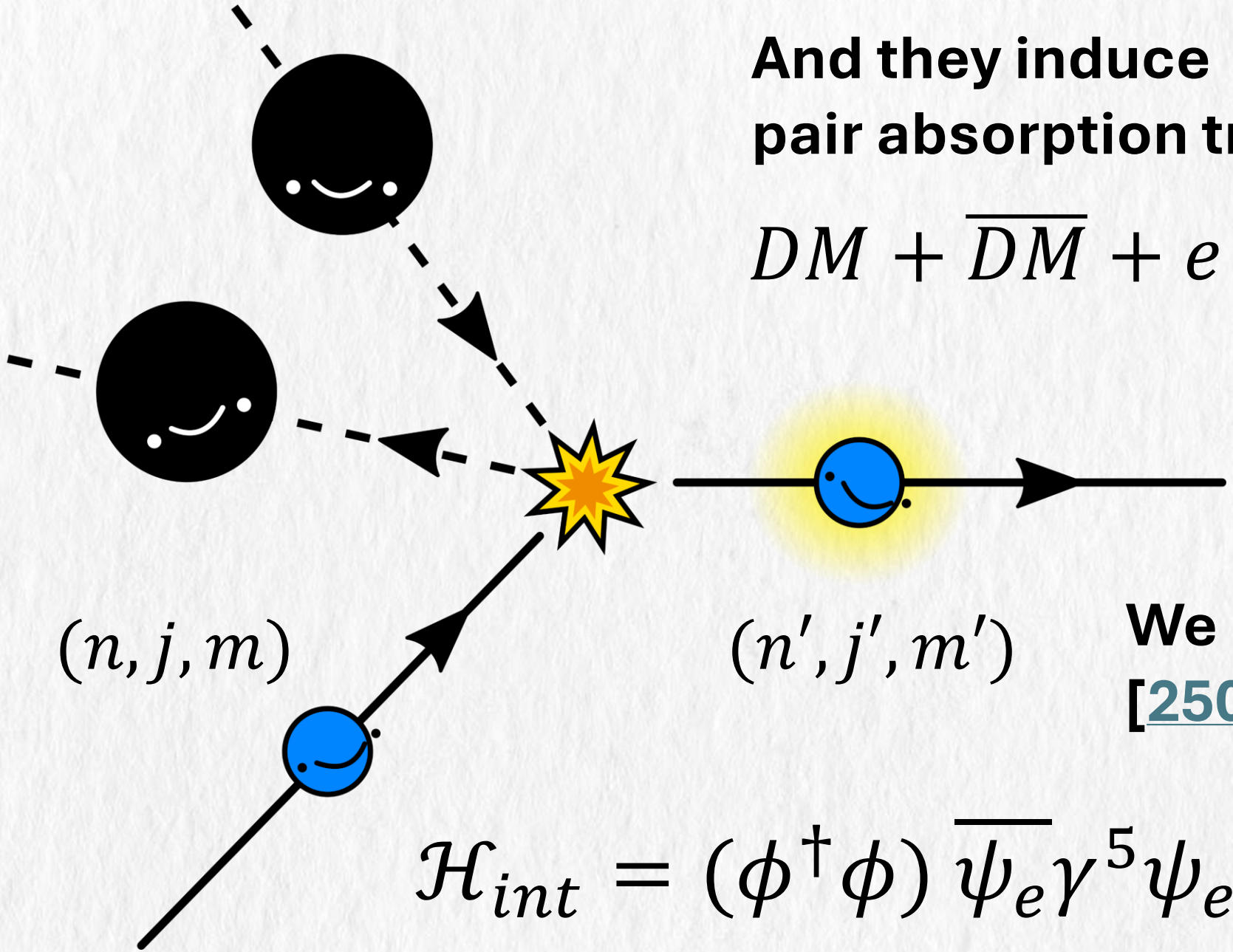
$$\mathcal{H}_{int} = (\phi^{\dagger}\phi)\,\overline{\psi_e}\gamma^5\psi_e$$

And they induce pair absorption transitions!

$$DM + \overline{DM} + e \rightarrow e^*$$



$$\mathcal{H}_{int} = (\phi^\dagger \phi)\, \overline{\psi_e} \gamma^5 \psi_e$$



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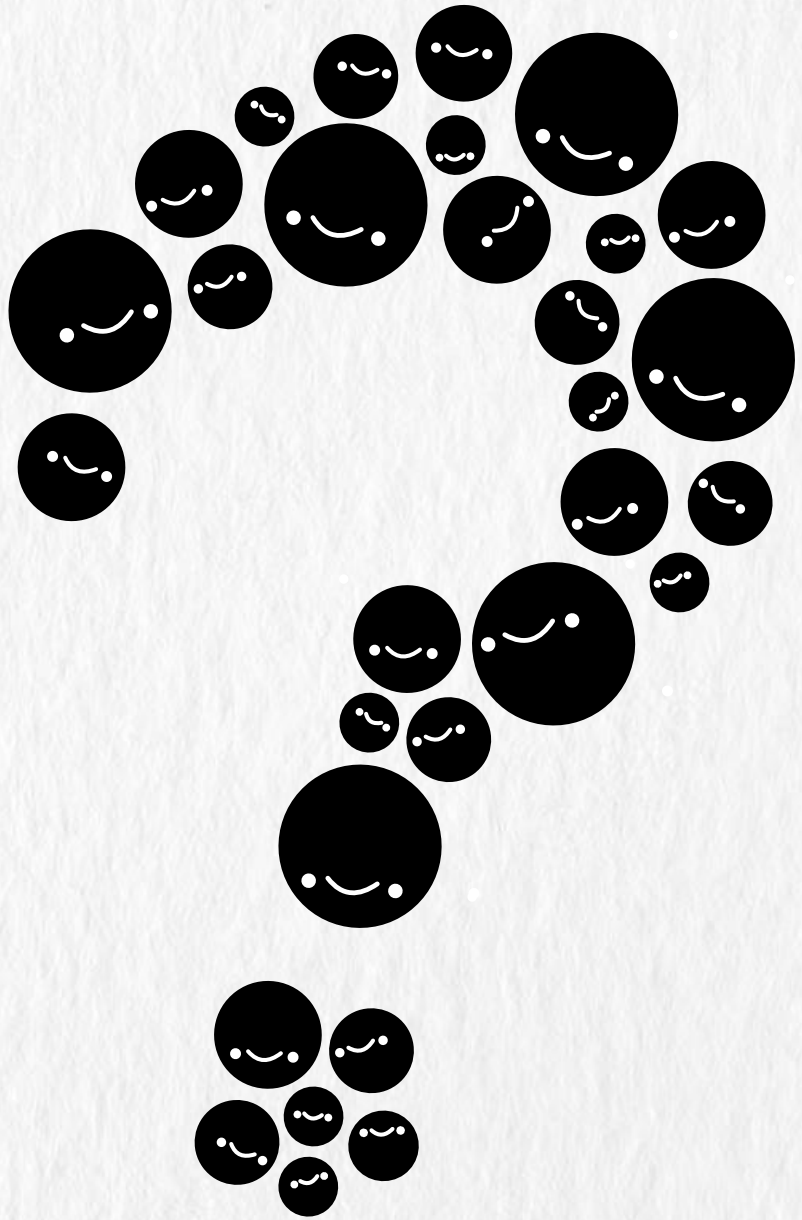
We studied these in [2507.14287]

$$\mathcal{H}_{int} = (\phi^\dagger \phi)\, \overline{\psi_e} \gamma^5 \psi_e$$

Why pair absorption?

- Working in pairs means the **DM can be charged** under whatever quantum numbers



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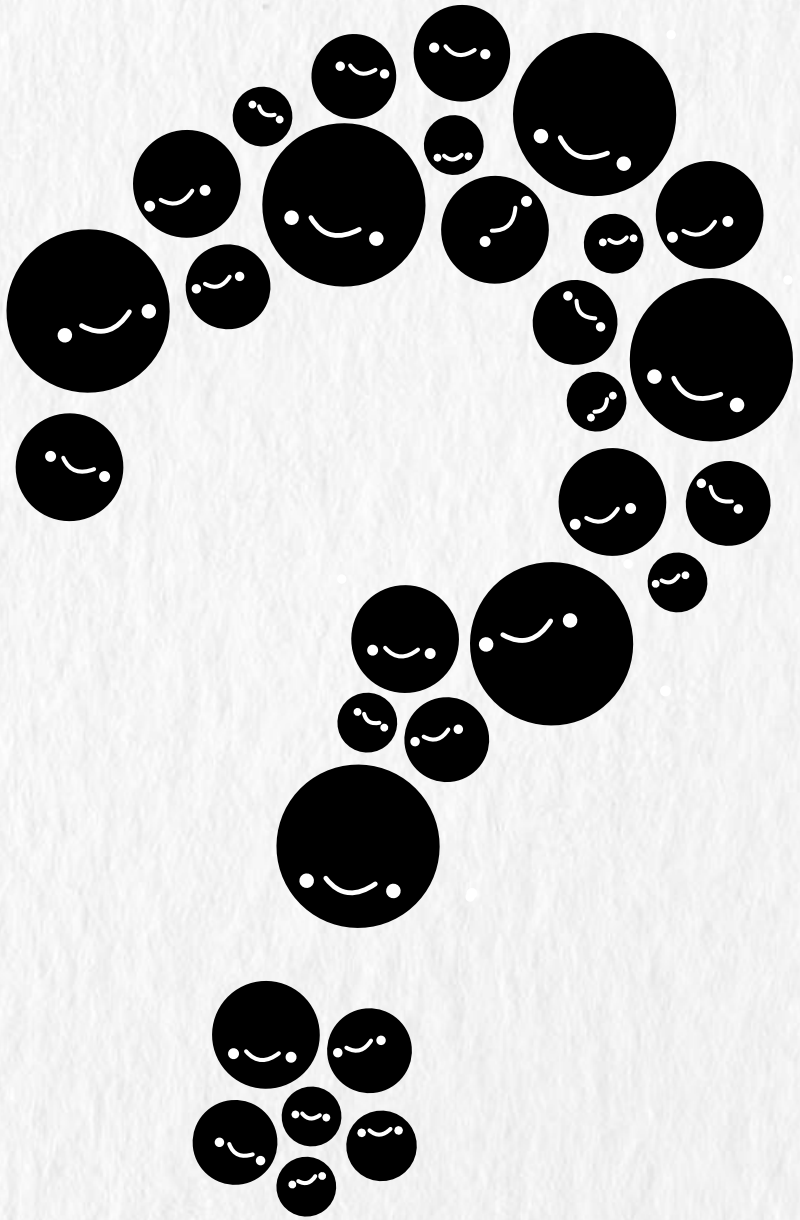
- Transition rates are proportional to $n^2 \sim (\rho_{DM}/m_{DM})^2$ so it gets **big for low DM masses**



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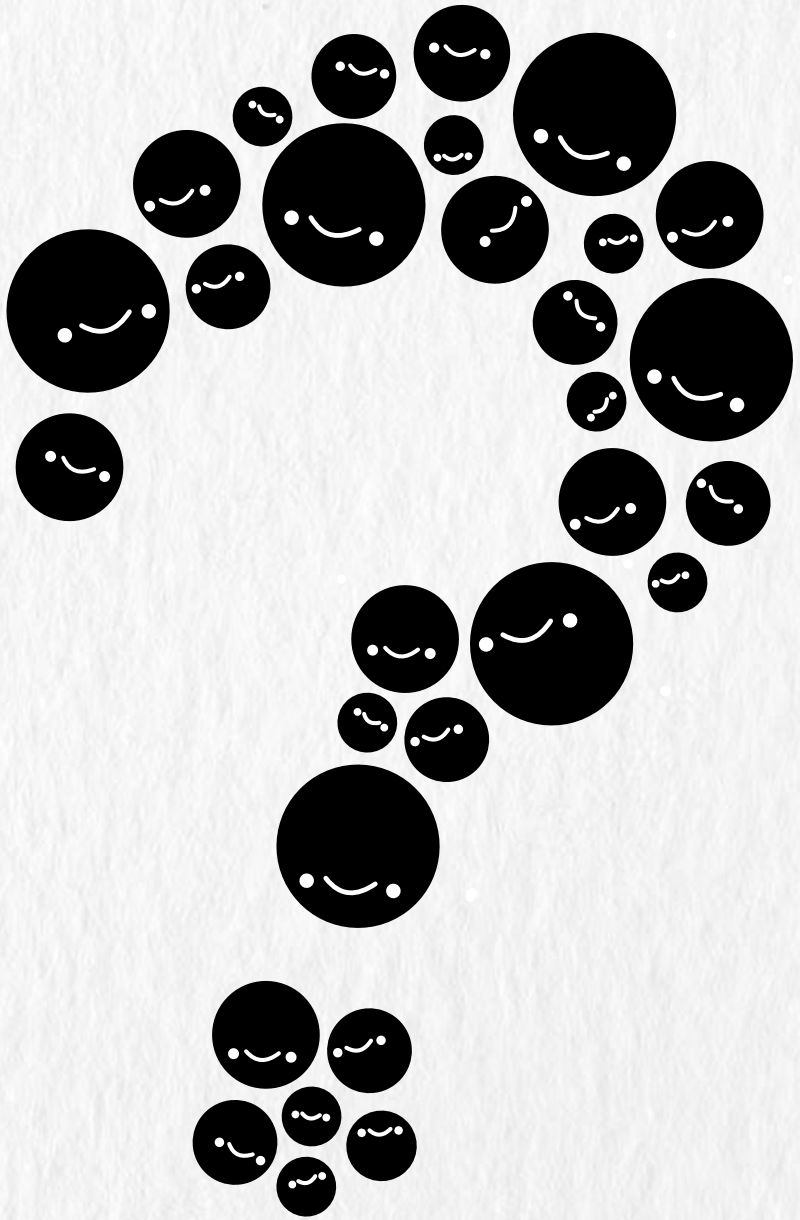
- Final comment: **molecular systems** may be more interesting for detection (more variety) but hard to study (WIP)



Thank you!