

# Superradiant interactions of cosmic noise

**Marios Galanis**

Perimeter Institute

Based on [arXiv:2408.04021](https://arxiv.org/abs/2408.04021)

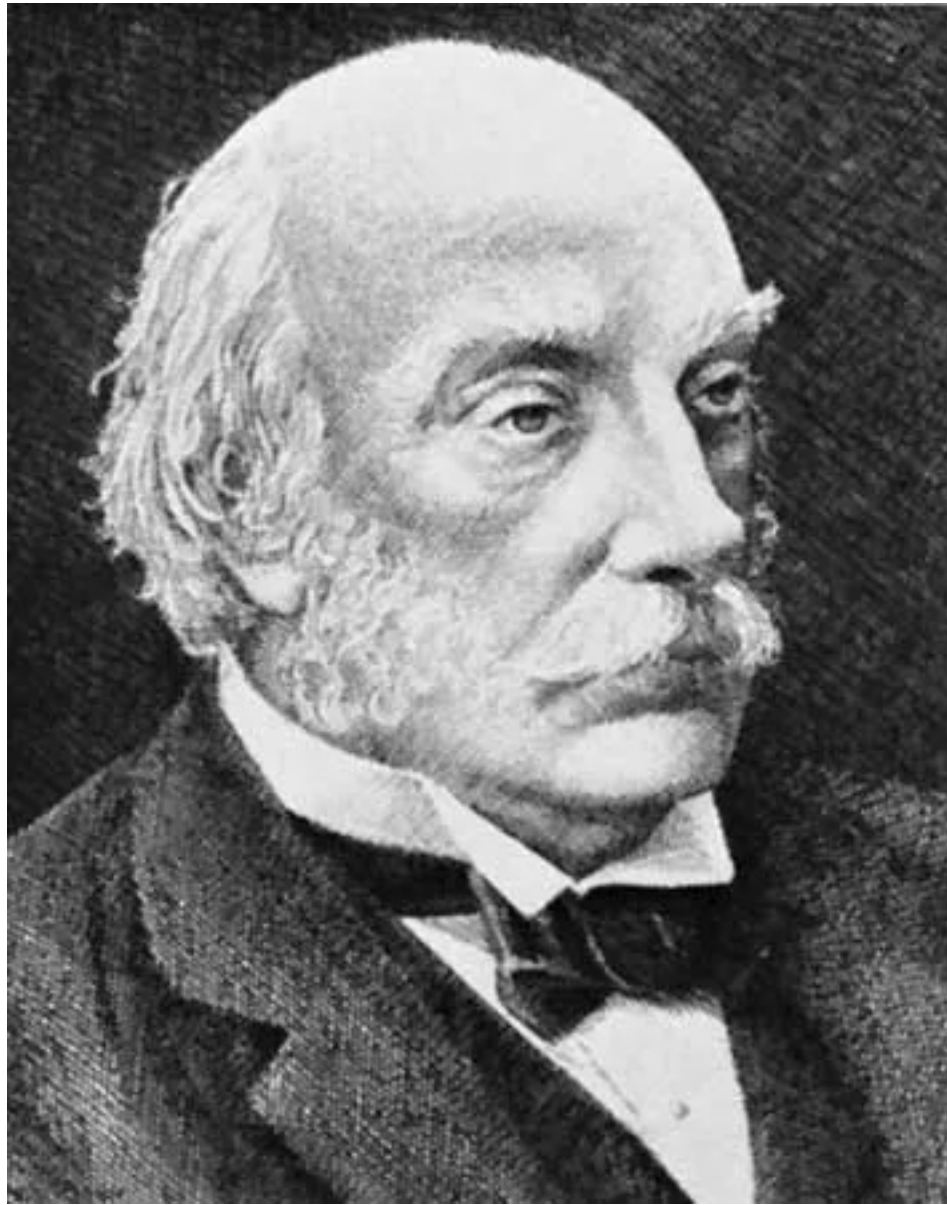
with Asimina Arvanitaki (PI) and Savas Dimopoulos (Stanford, PI)

# Outline

1. Coherence in elastic scattering
2. Superradiant interactions - Coherence in inelastic processes
3. Scattering: CνB, solar and reactor neutrinos, DM
4. Absorption/Emission: QCD axion, Dark Photons
5. Dark quantum optics

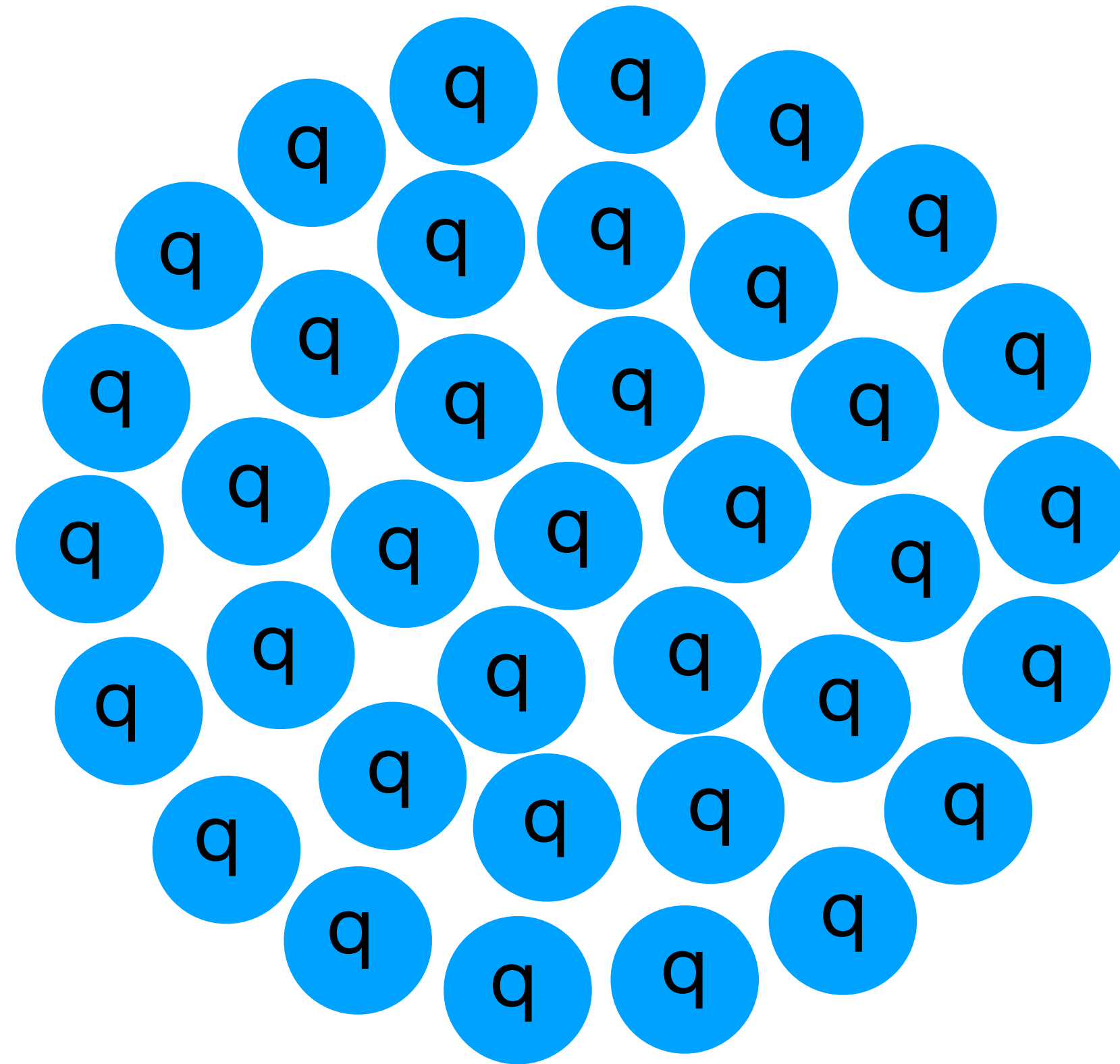
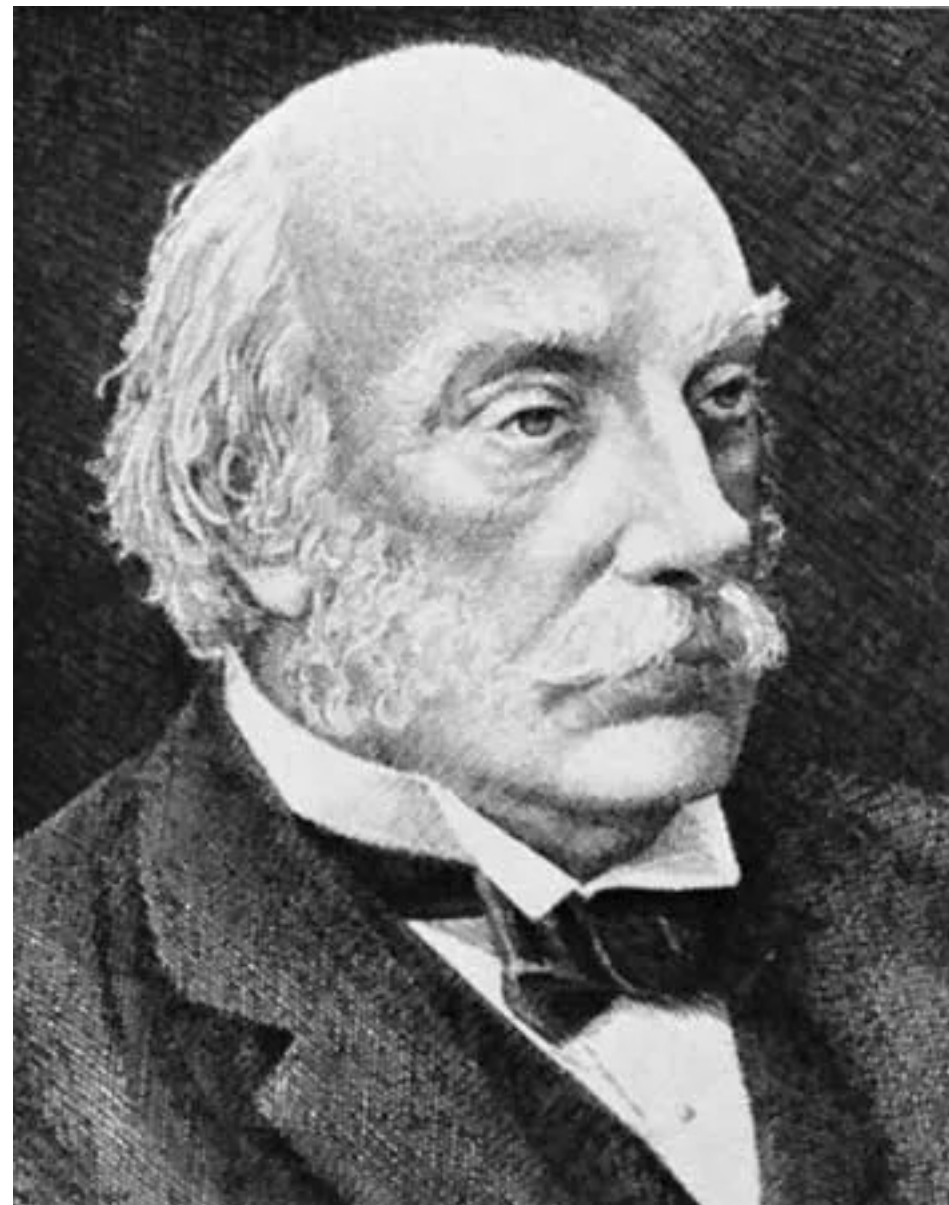
# Coherence in Elastic Scattering

Lord Rayleigh

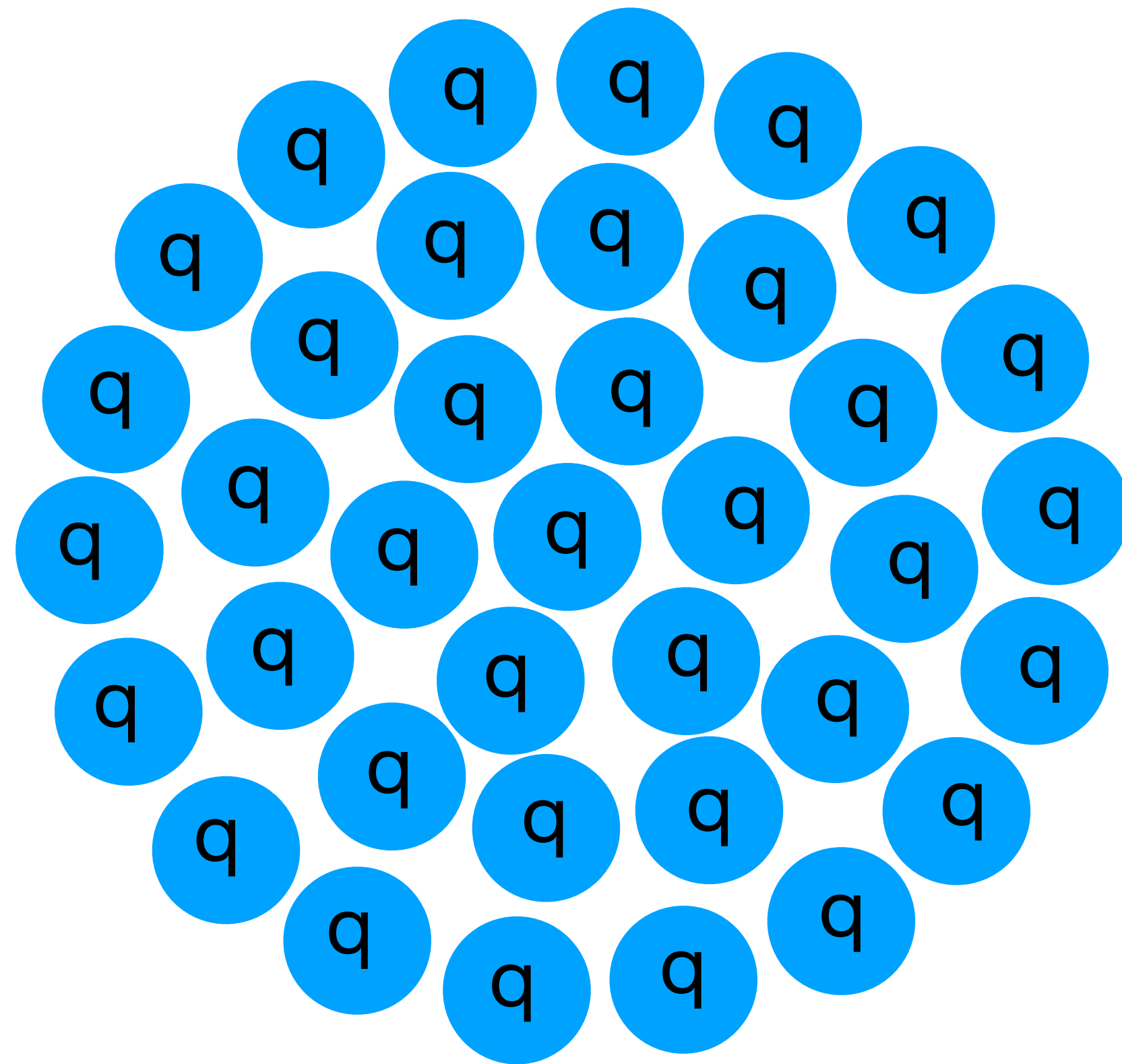
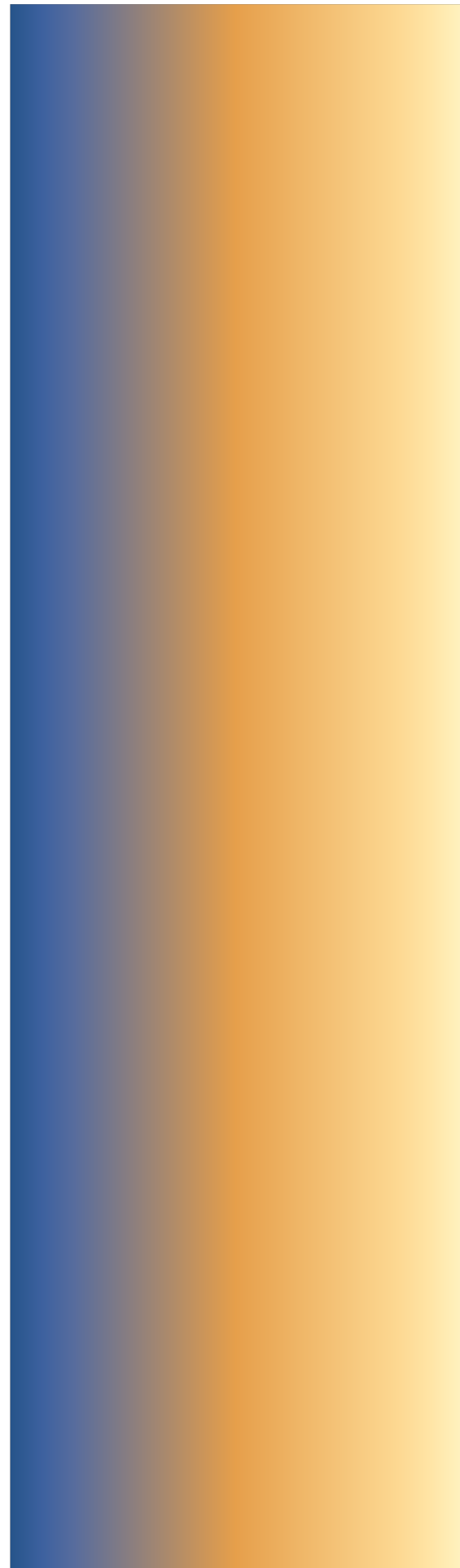


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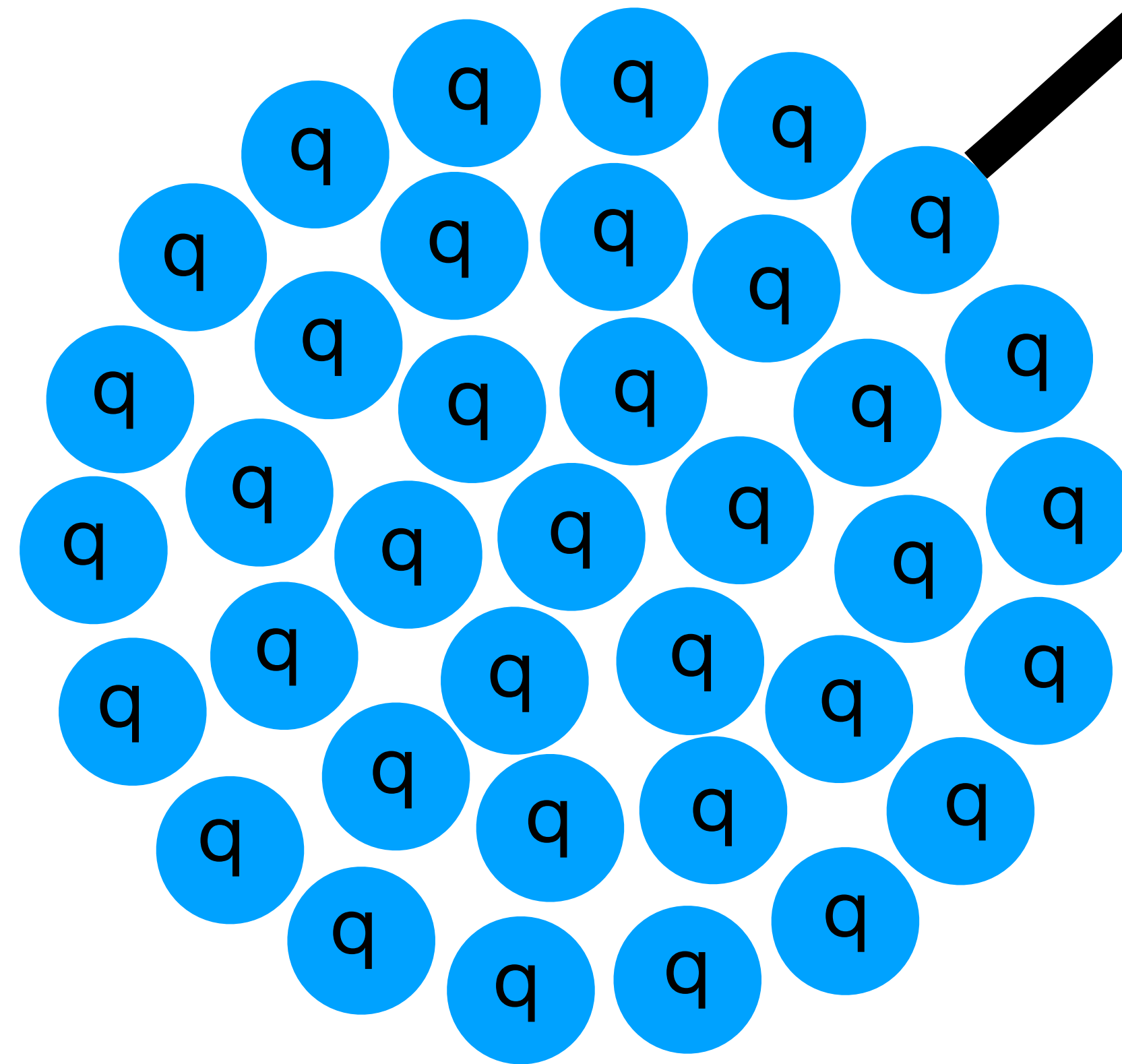
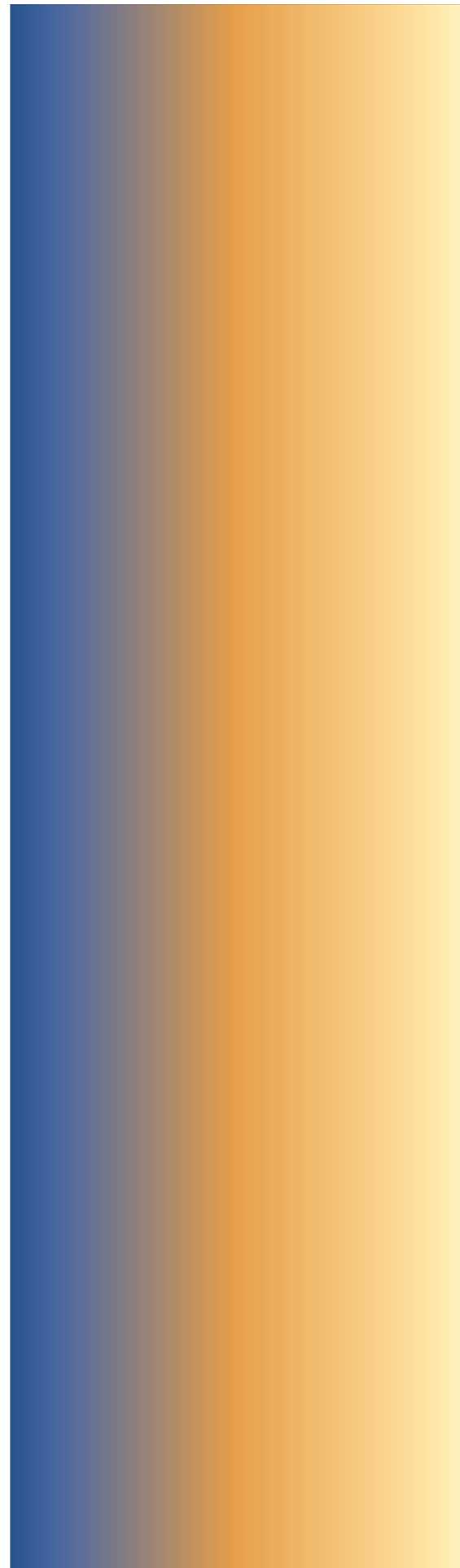
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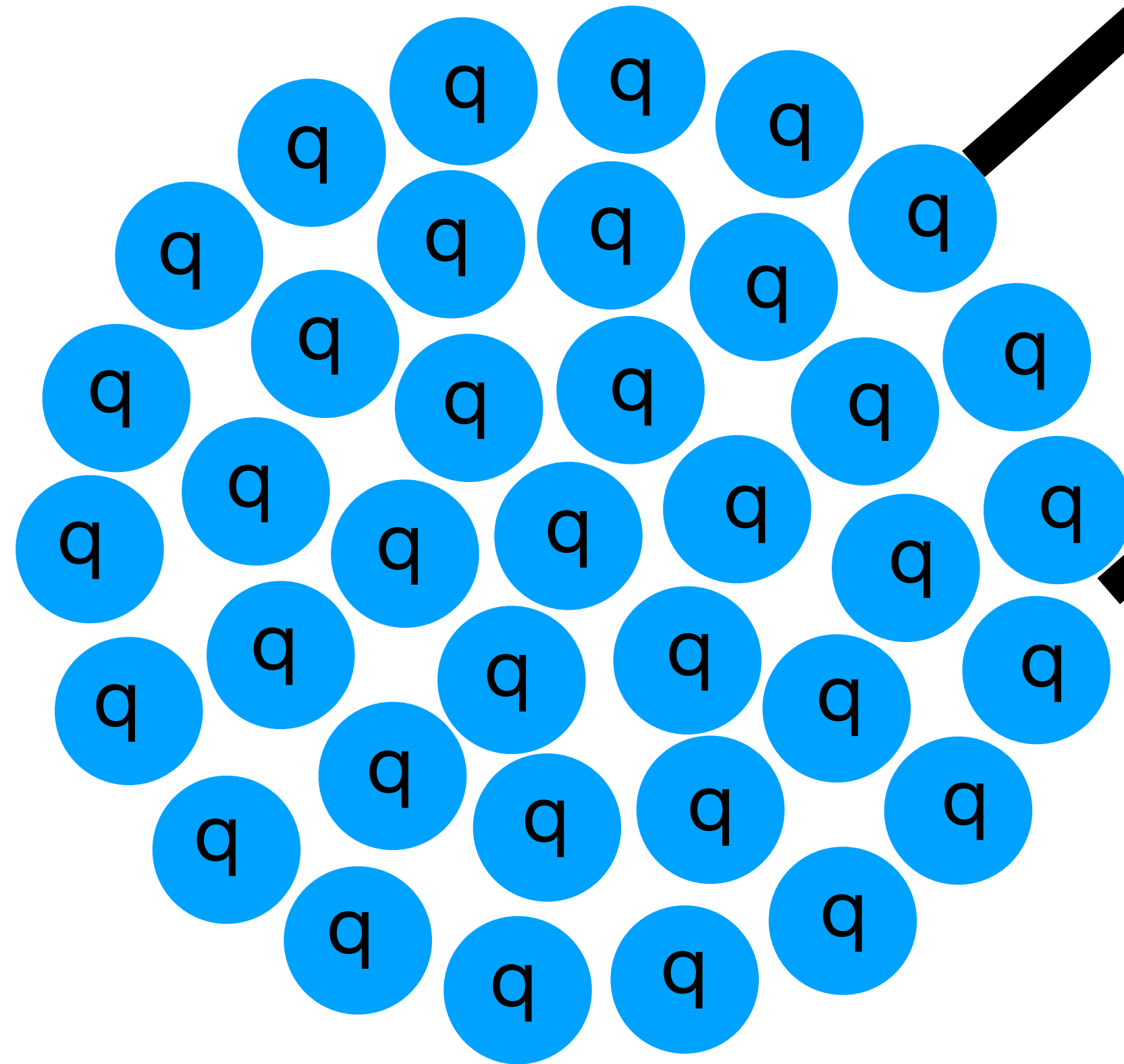
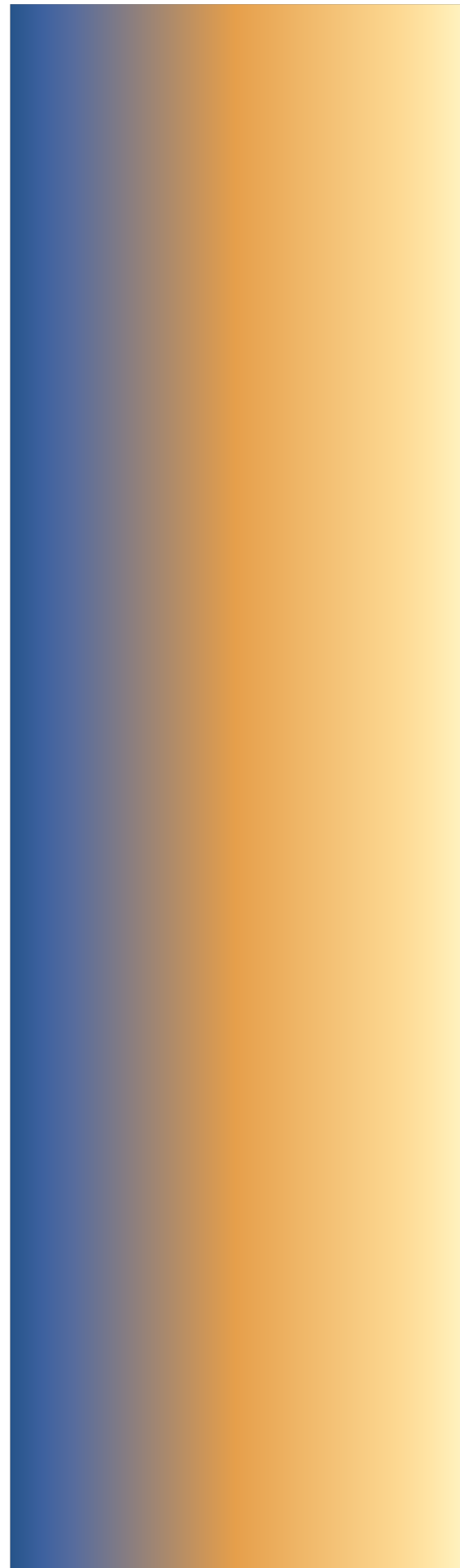
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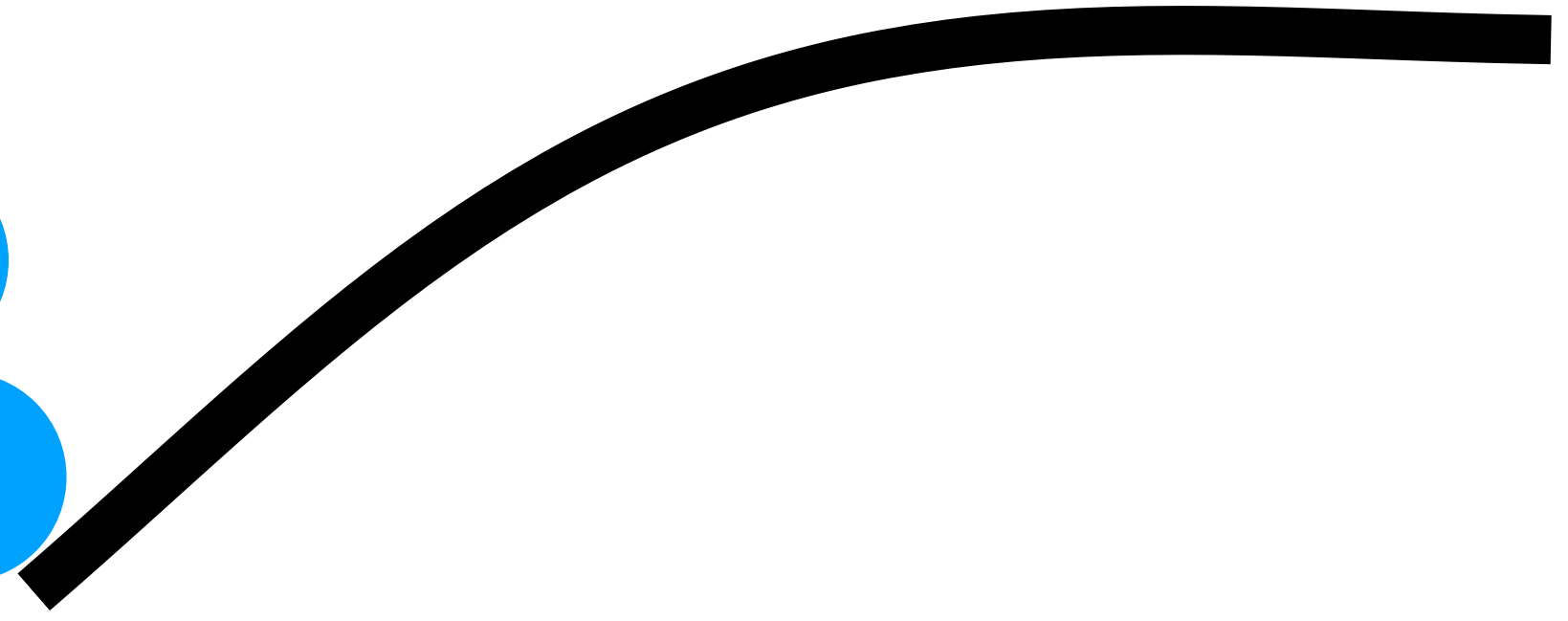
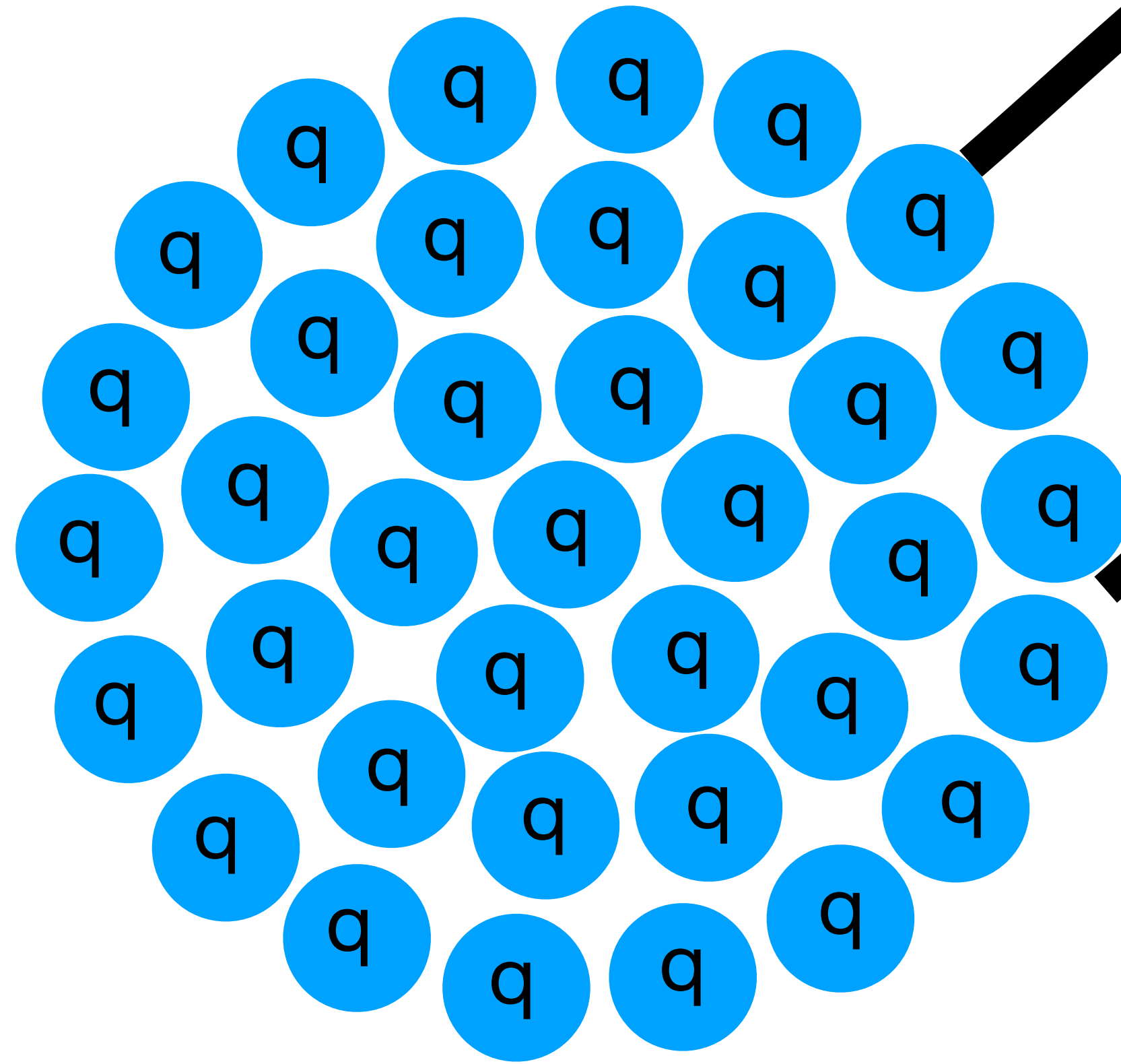
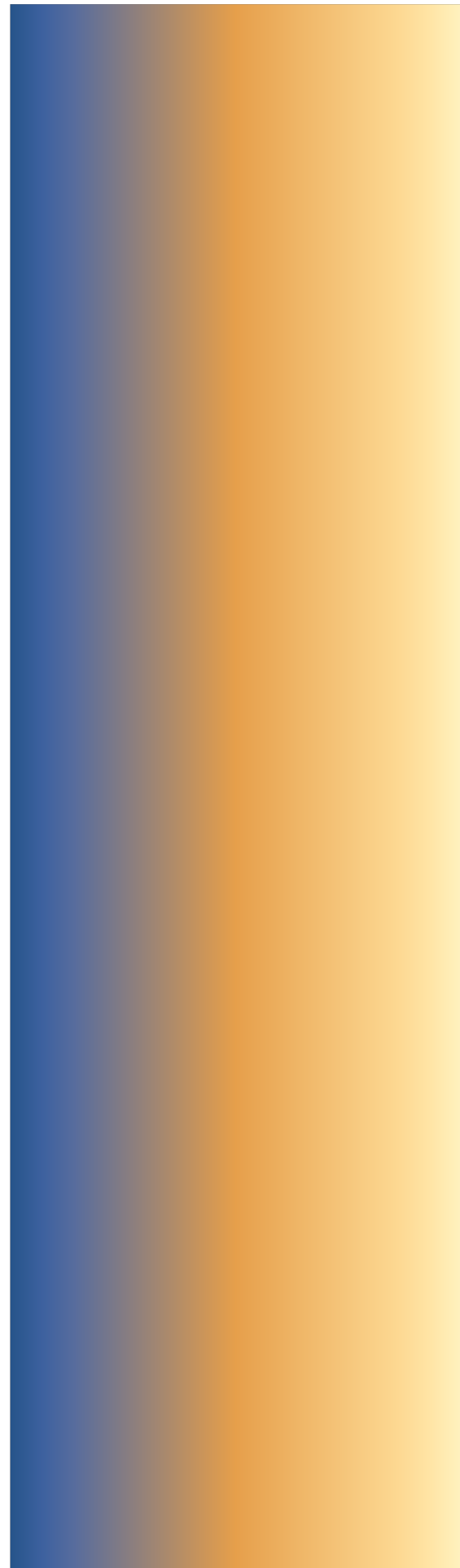
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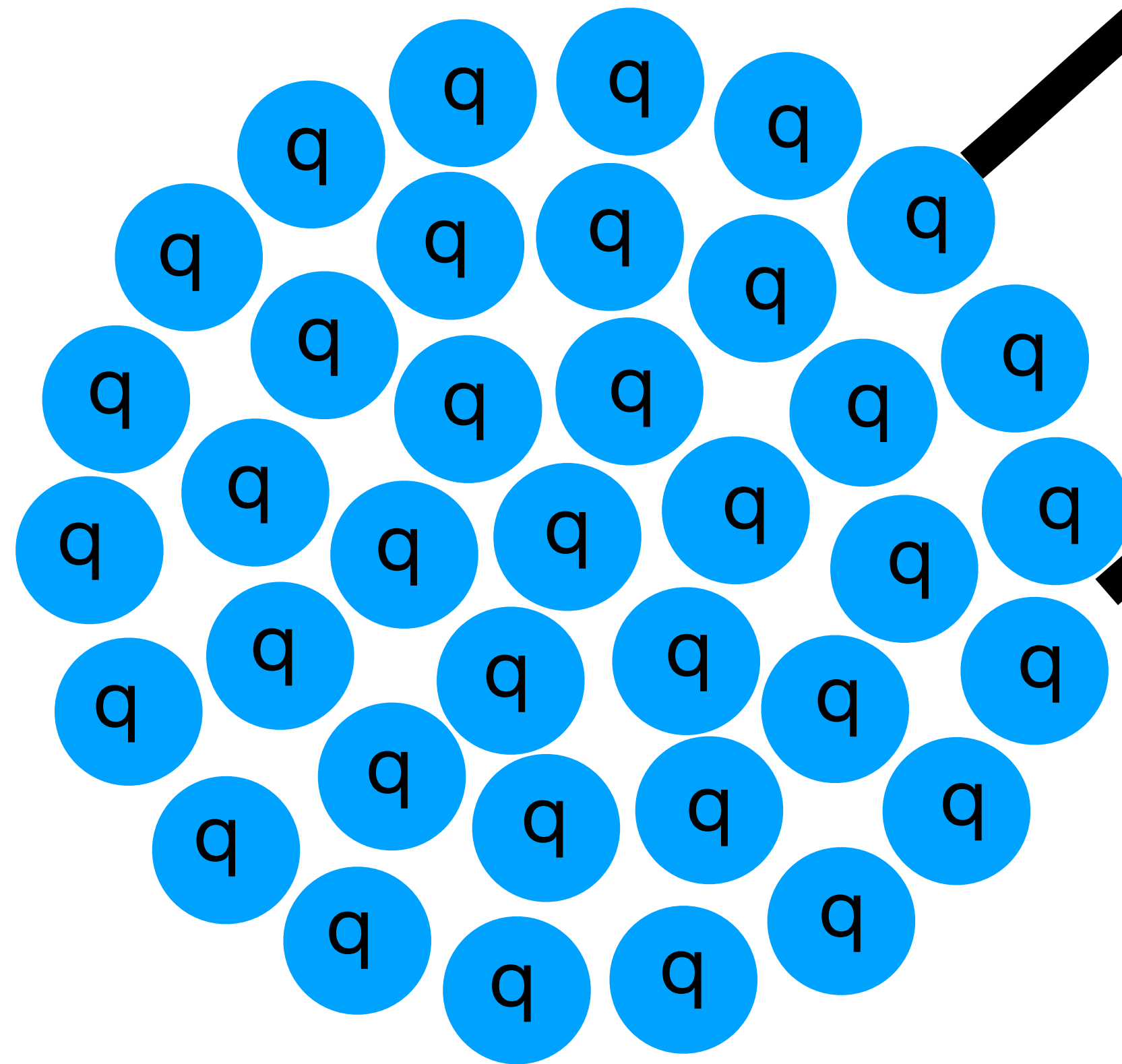
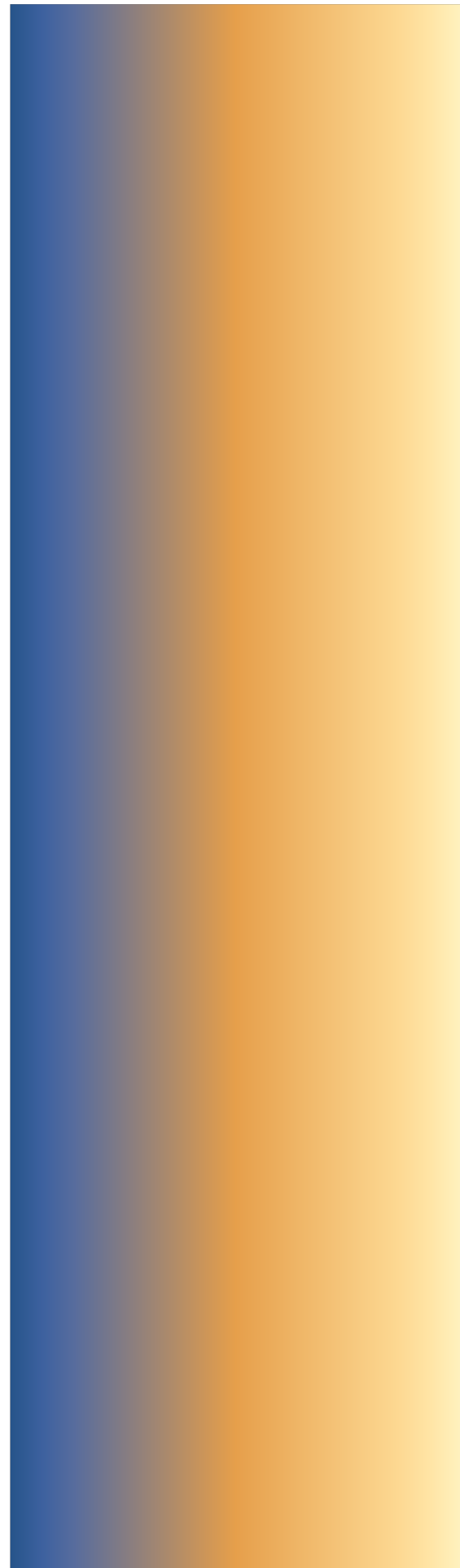
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Same phase  $\rightarrow$  Coherent



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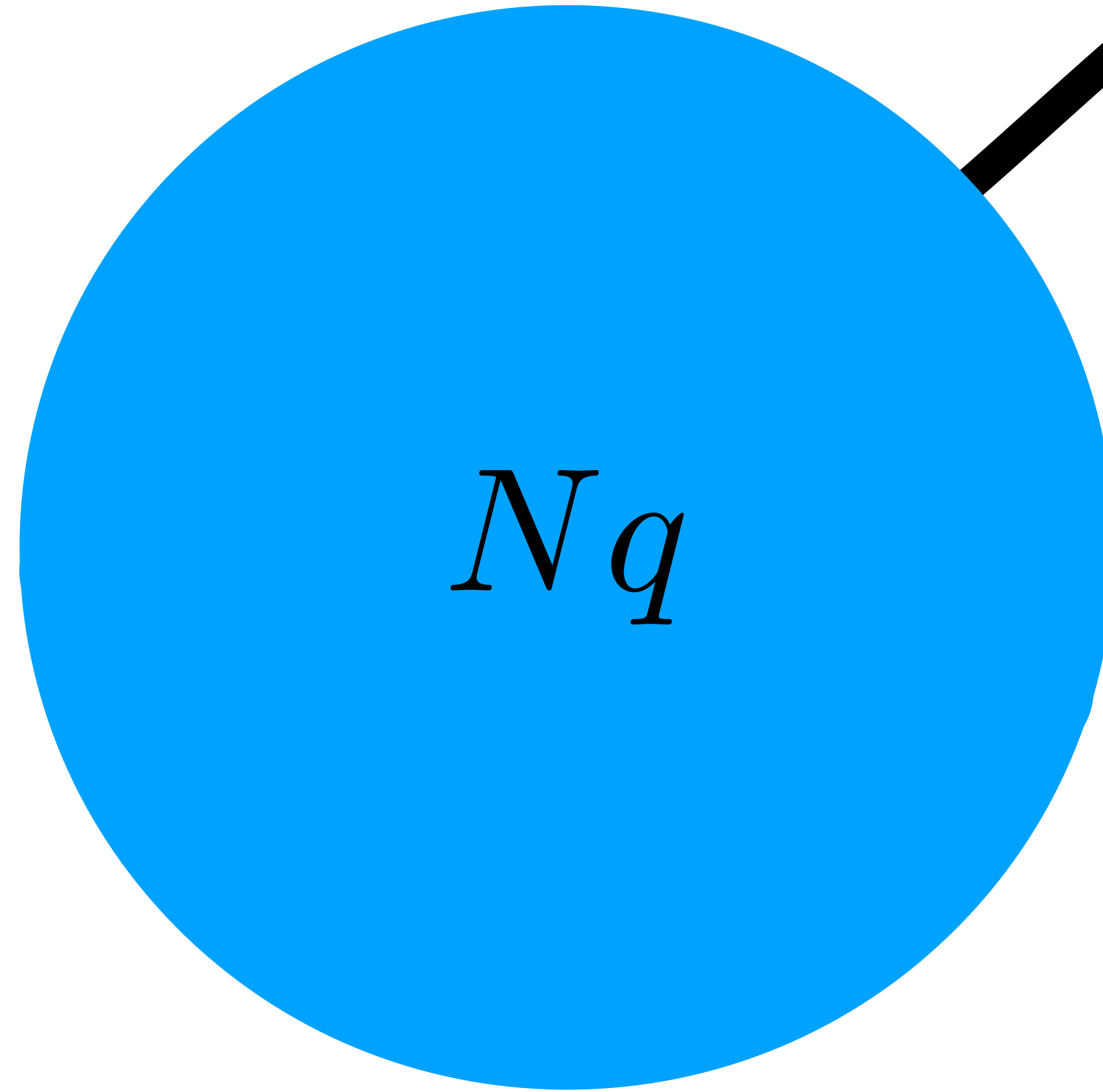
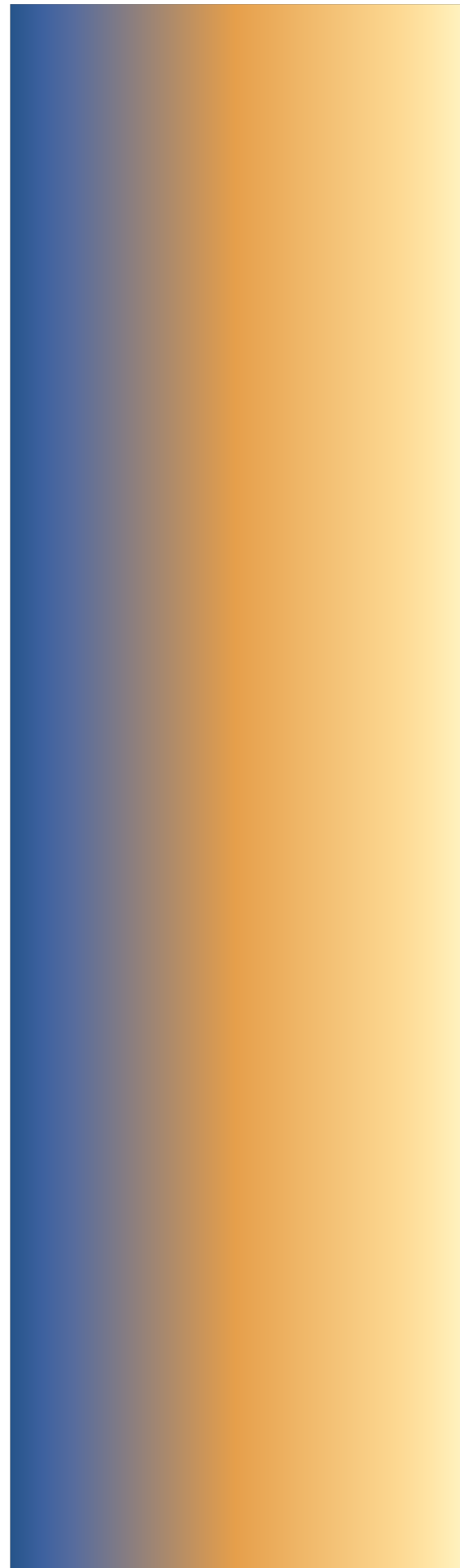


Same phase  $\rightarrow$  Coherent

$$\Gamma \sim q^2 \left| \sum_i e^{i\phi_i} \right|^2 \rightarrow N^2 q^2$$

$\phi_i = \mathbf{q} \cdot \mathbf{x}$

# Coherence in Elastic Scattering



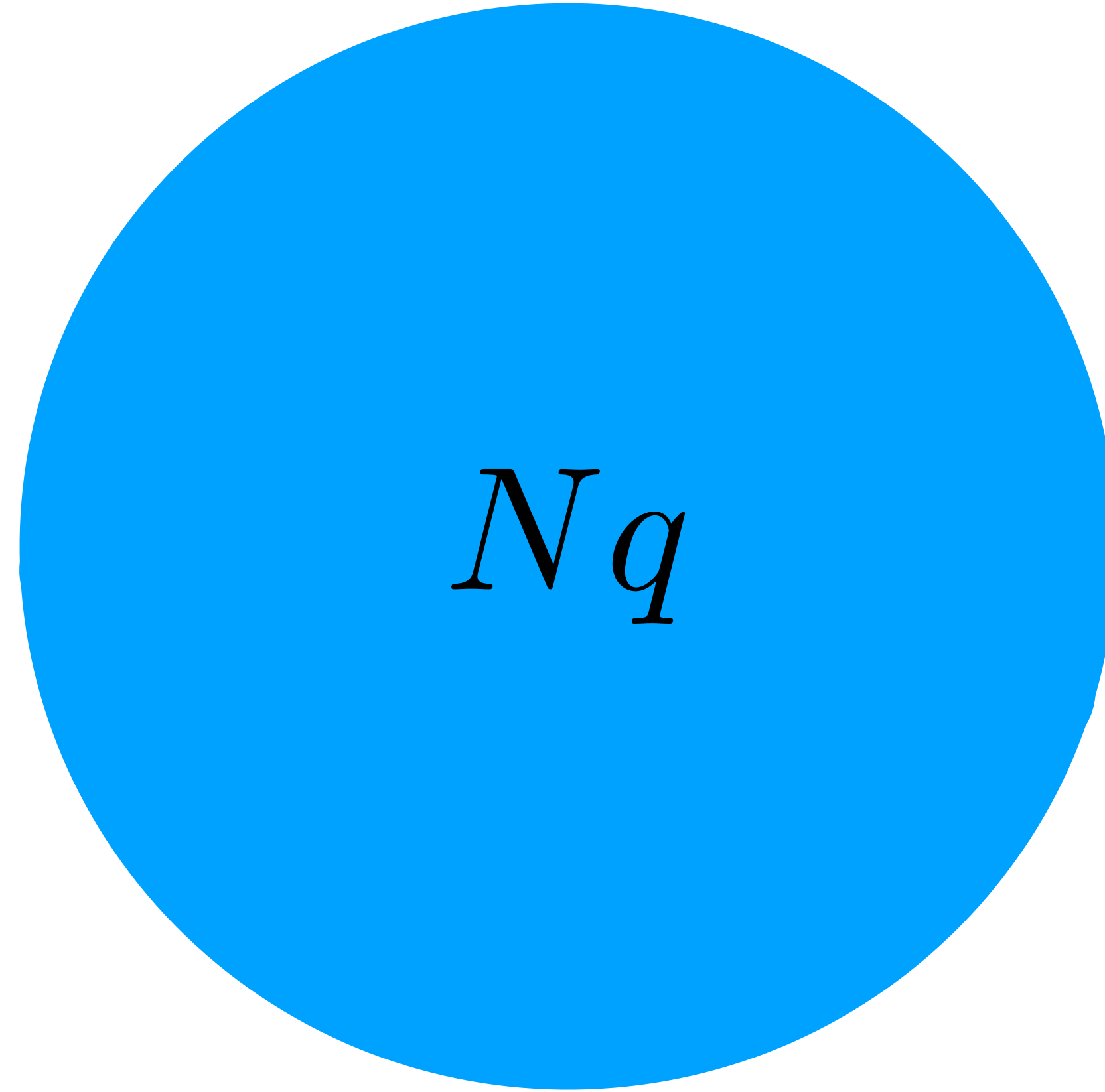
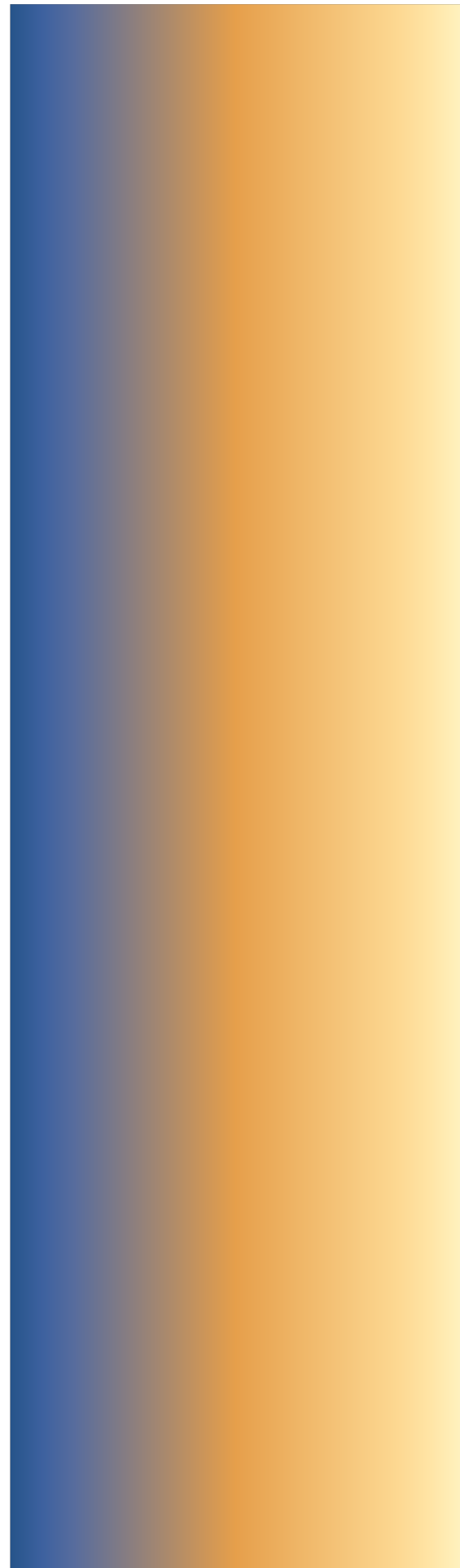
Macroscopic coherence

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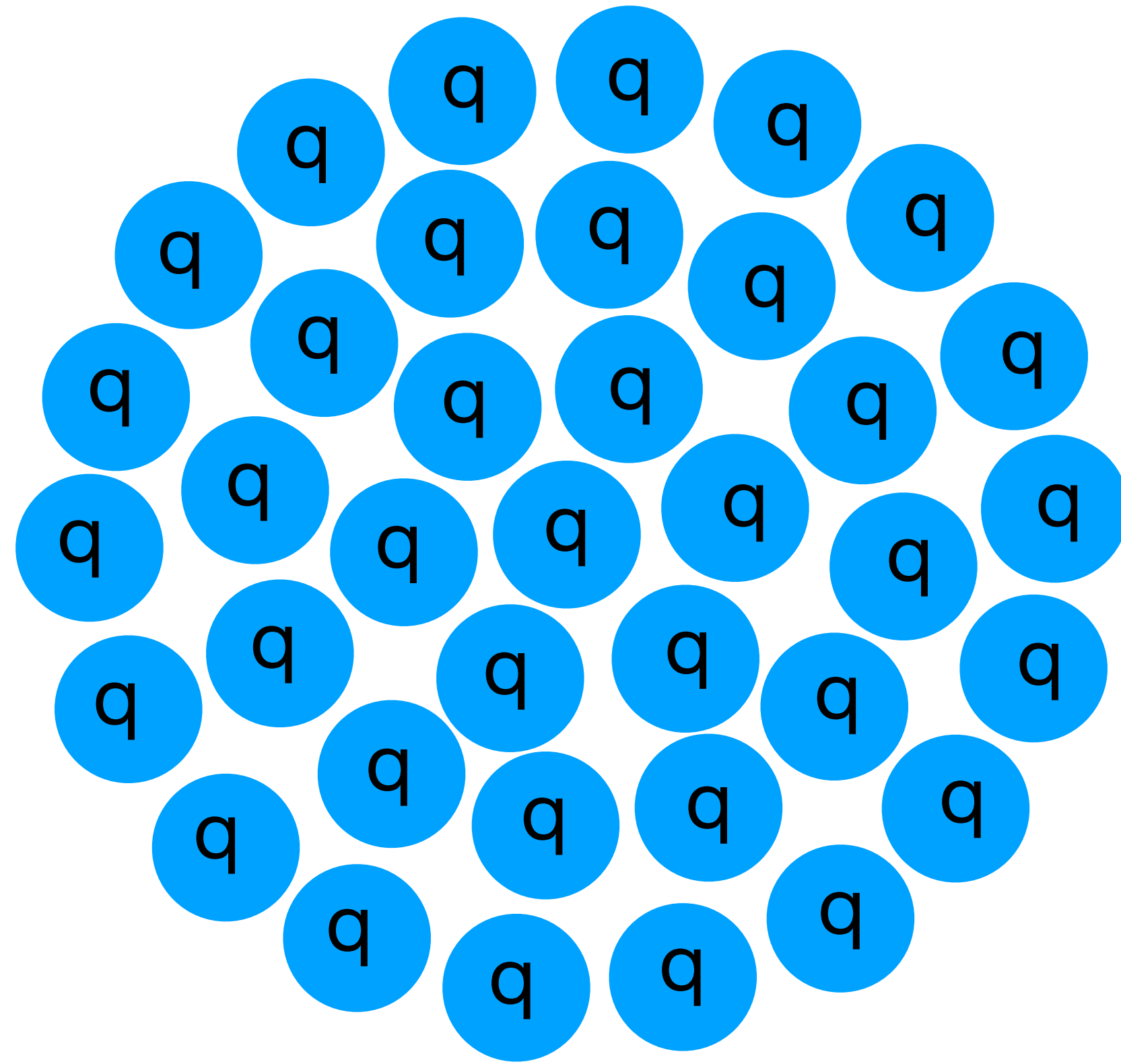
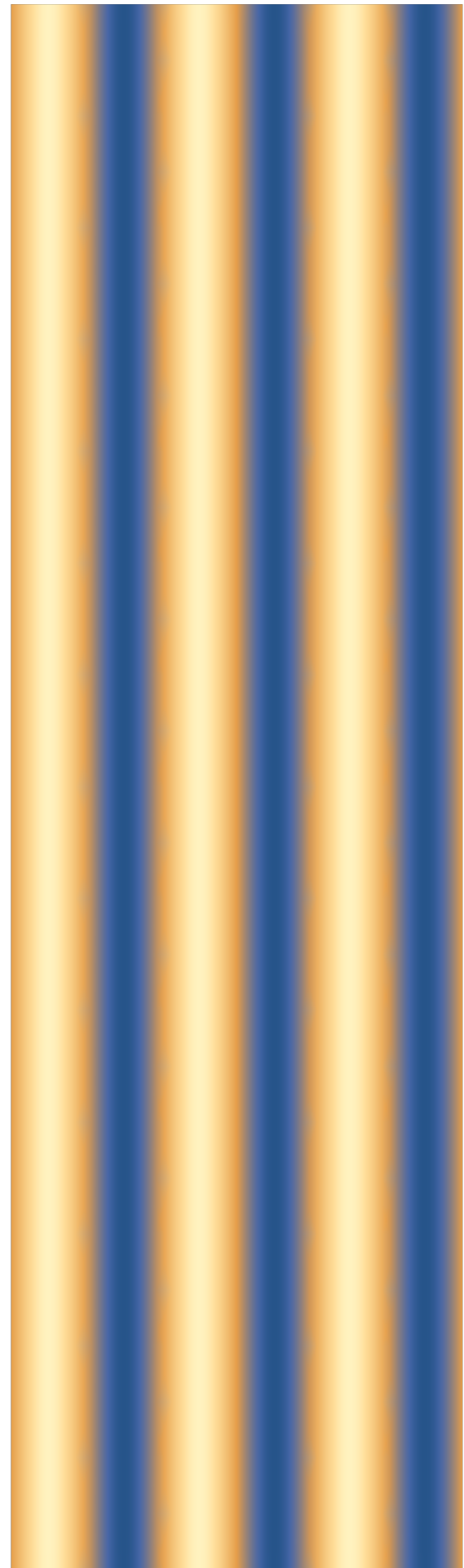
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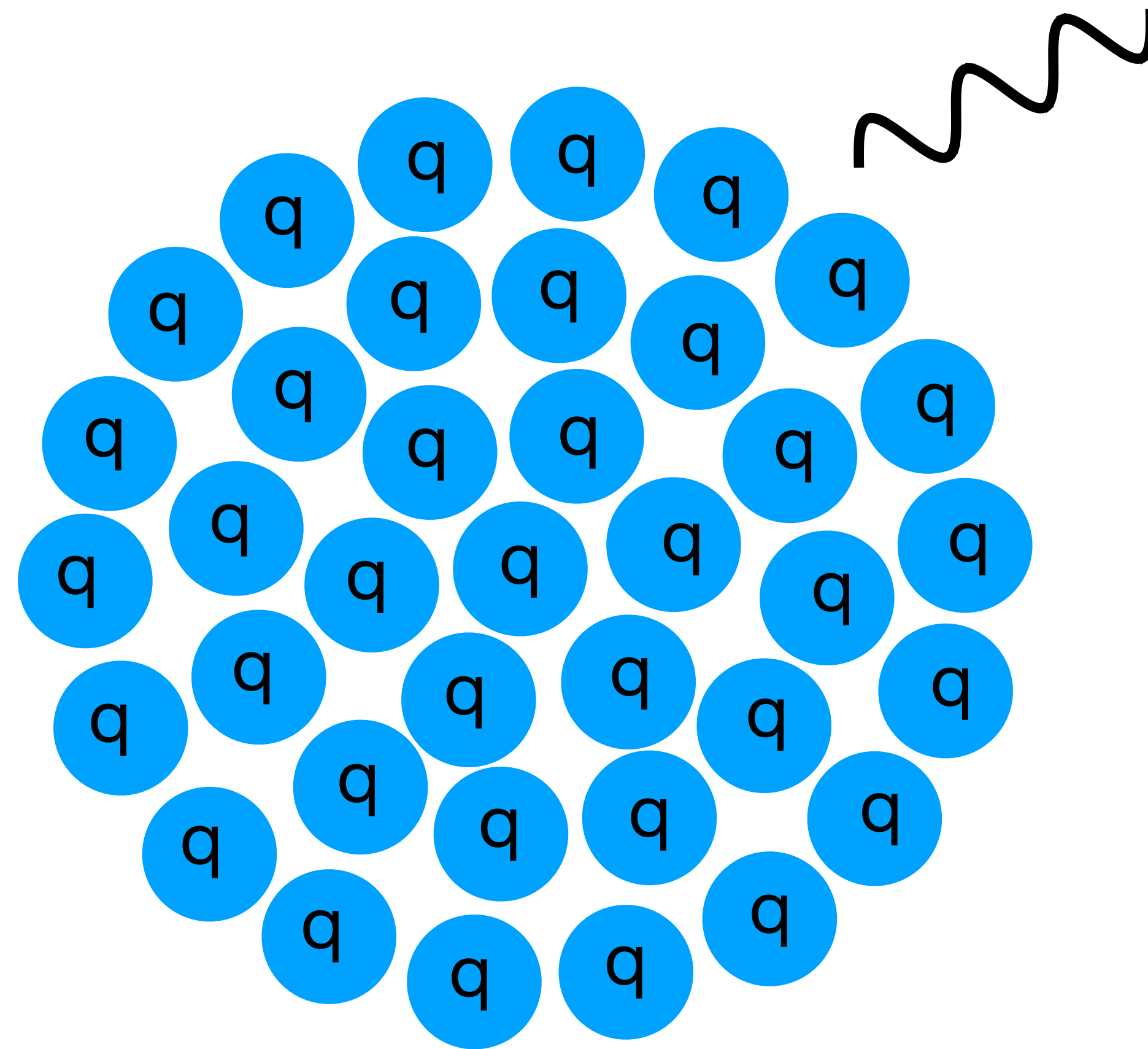
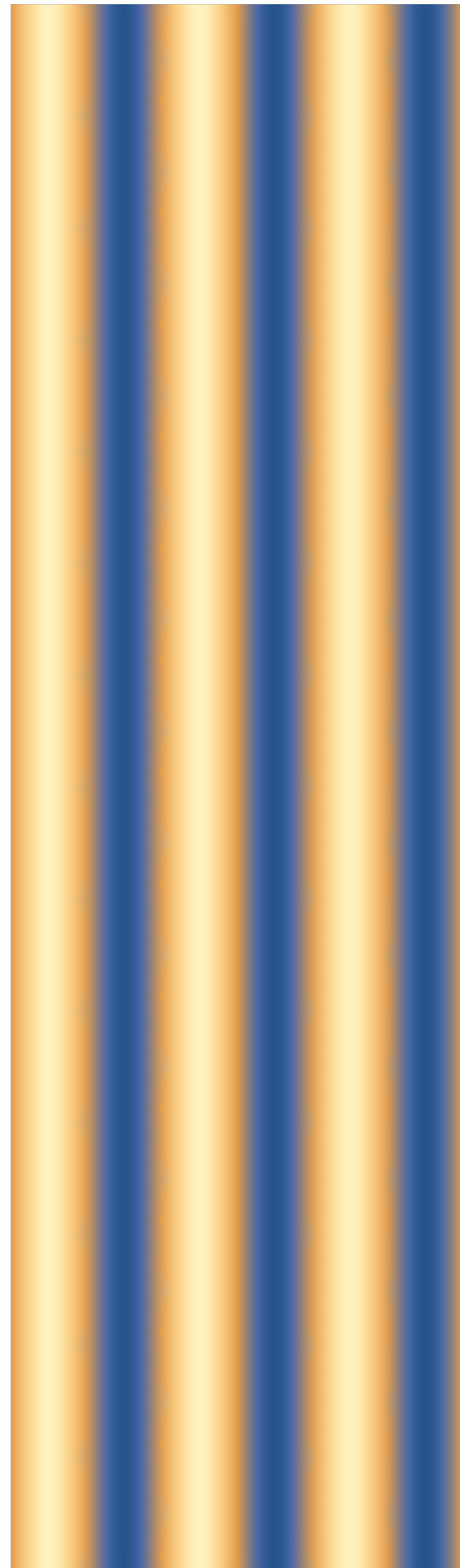


Macroscopic coherence

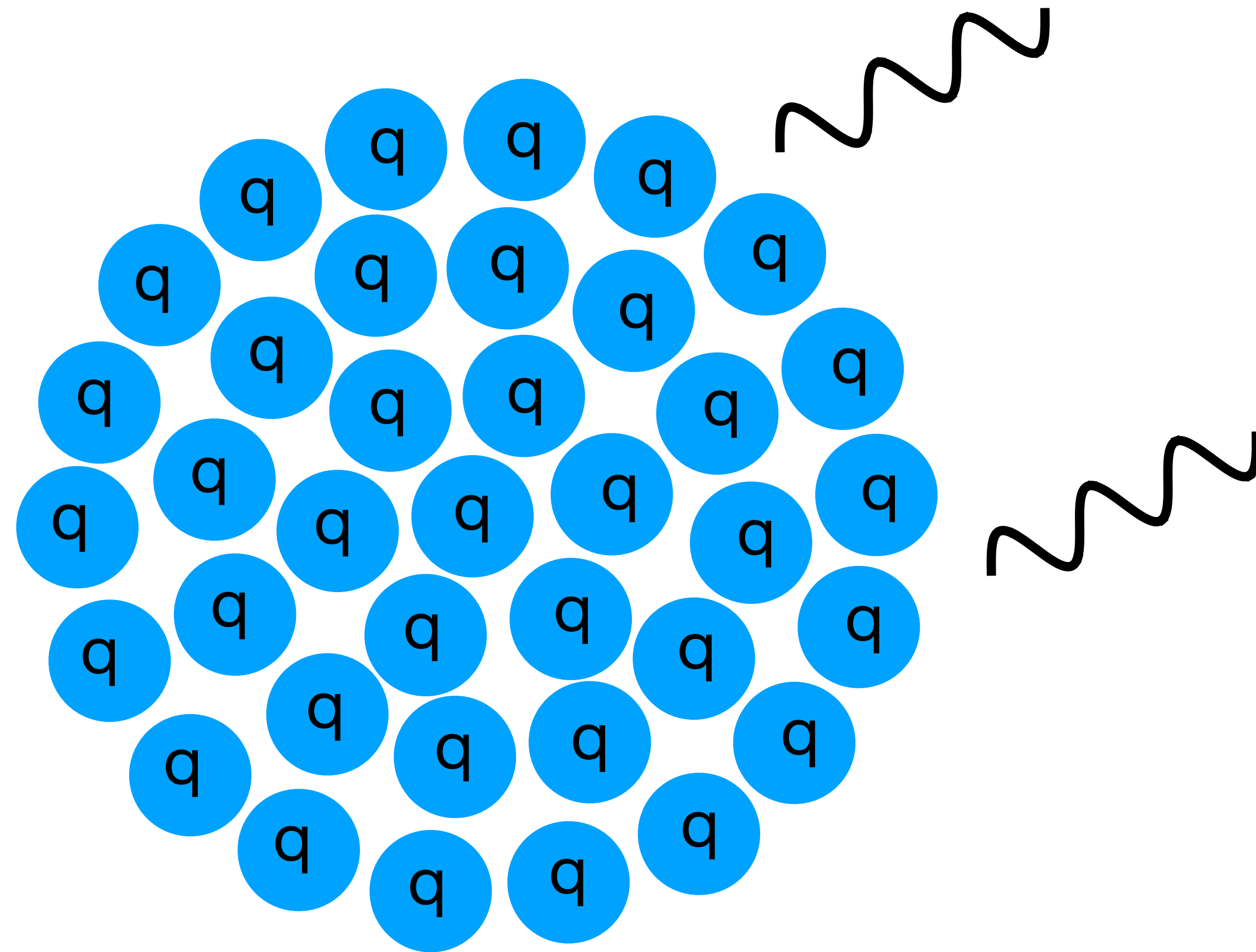
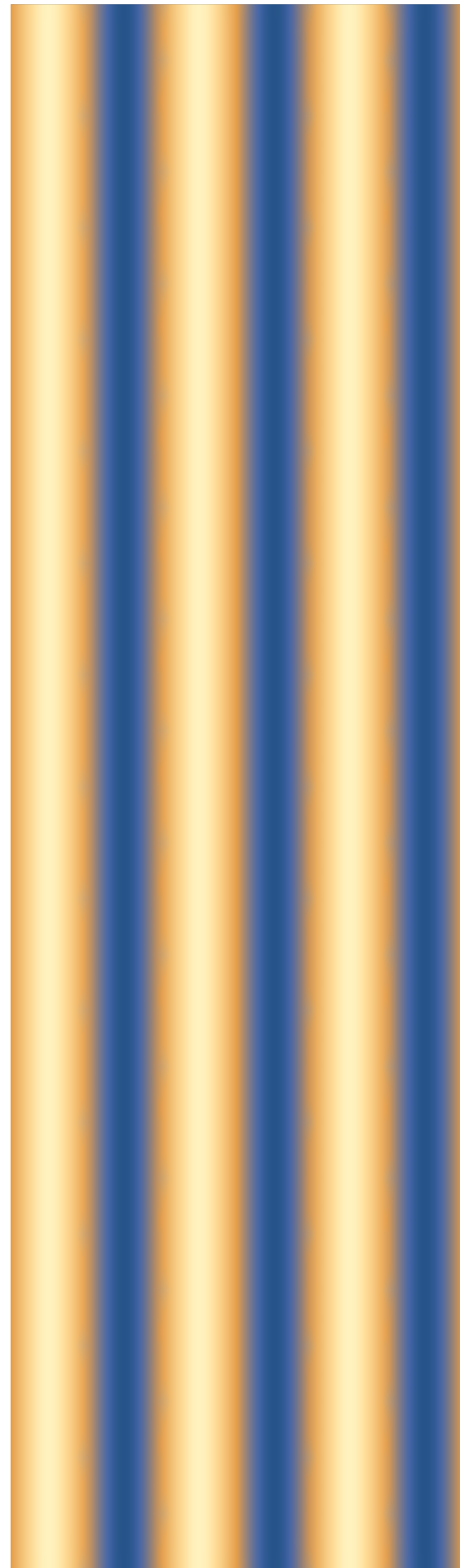
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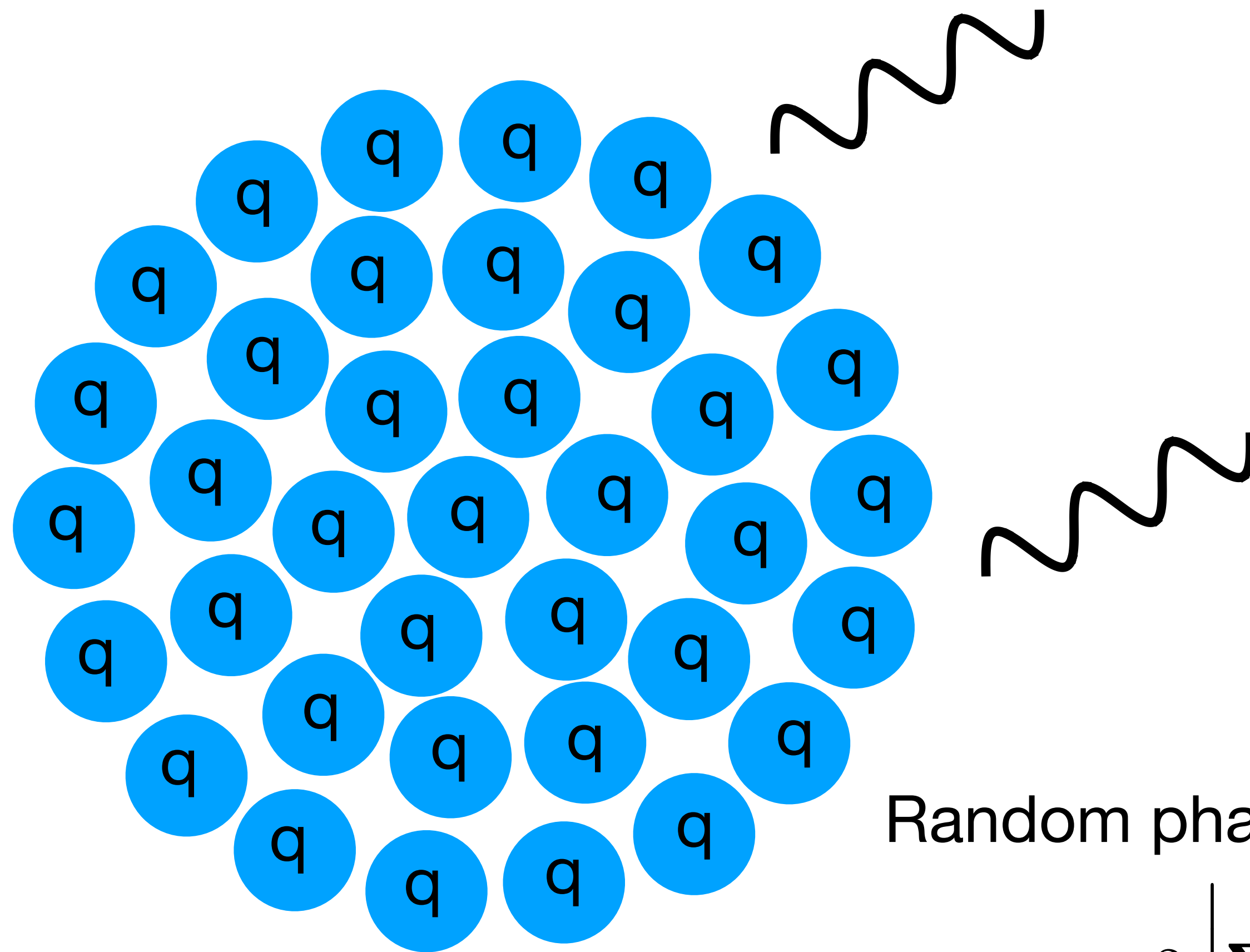
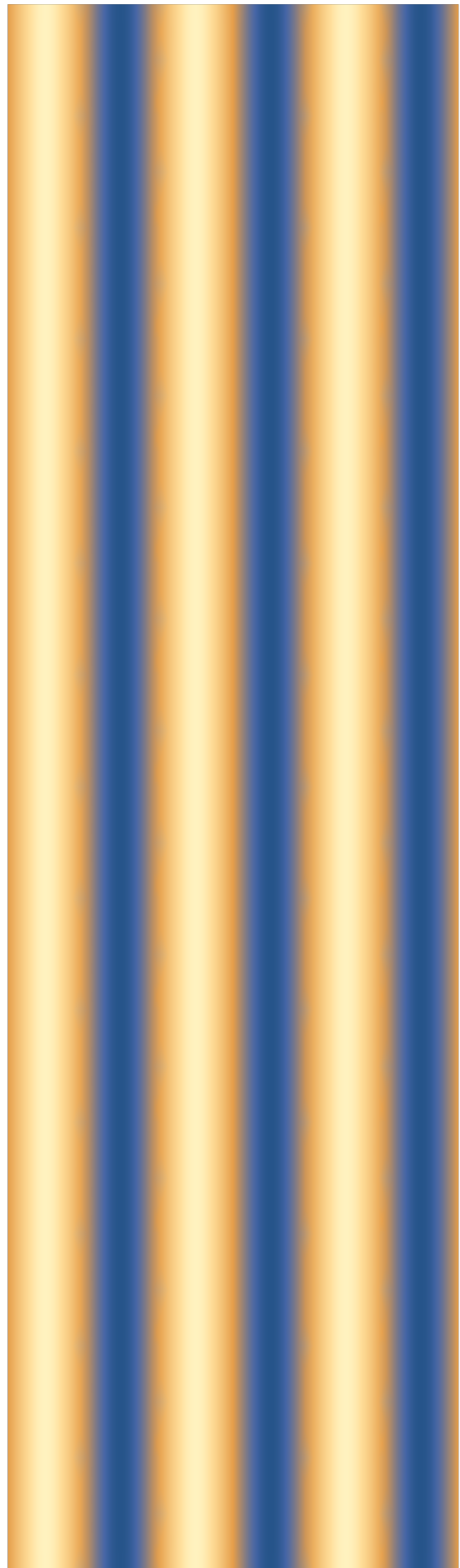
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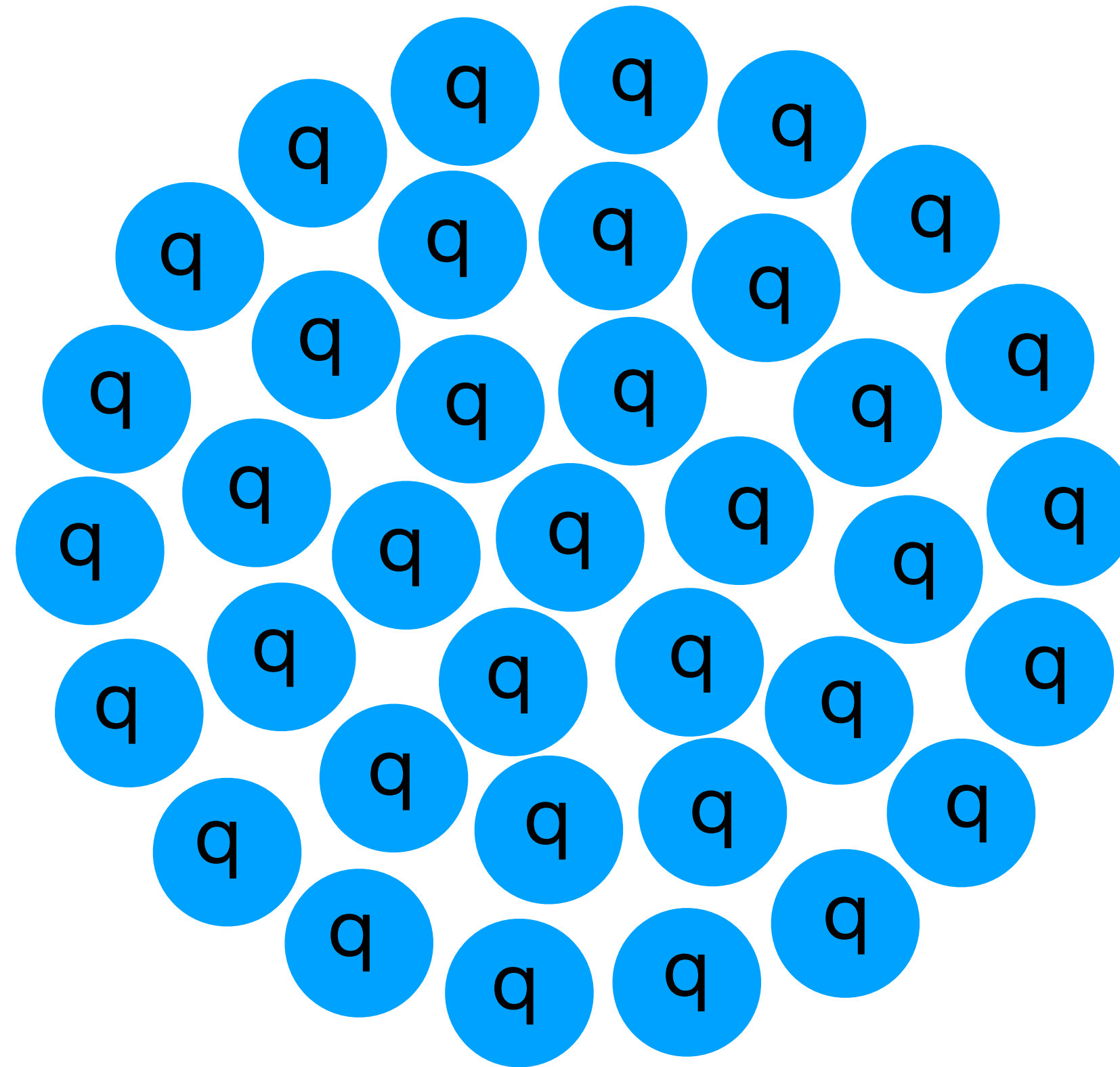


Random phases  $\rightarrow$  Incoherent

$$\Gamma \sim q^2 \left| \sum_i e^{i\phi_i} \right|^2 \rightarrow Nq^2$$

$\phi_i = \mathbf{q} \cdot \mathbf{x}$

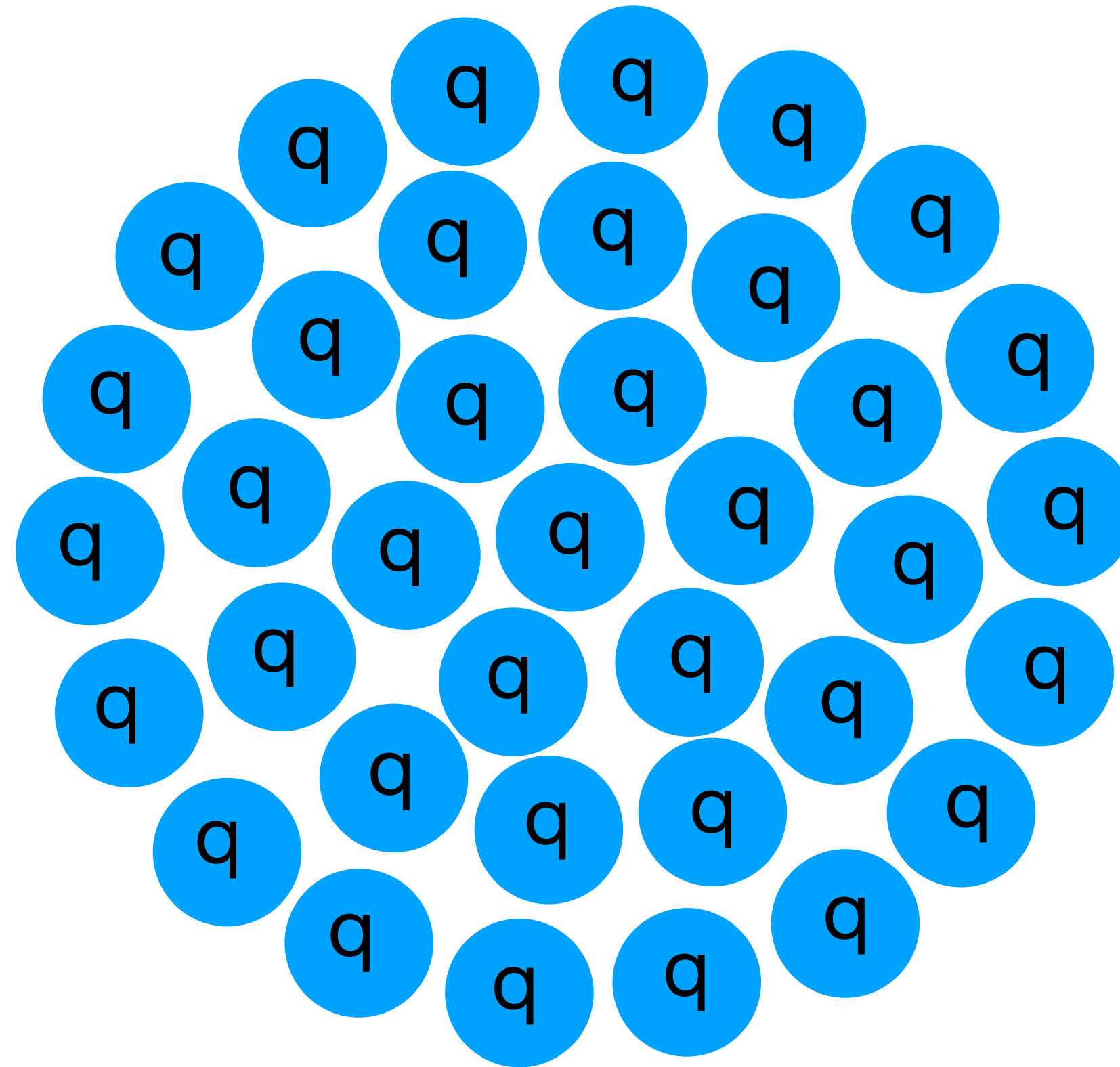
# Coherence in Elastic Scattering



Is this all?

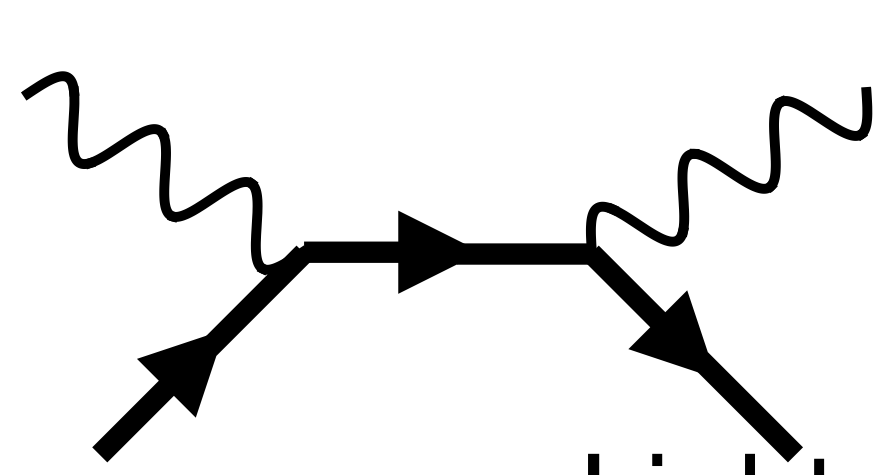


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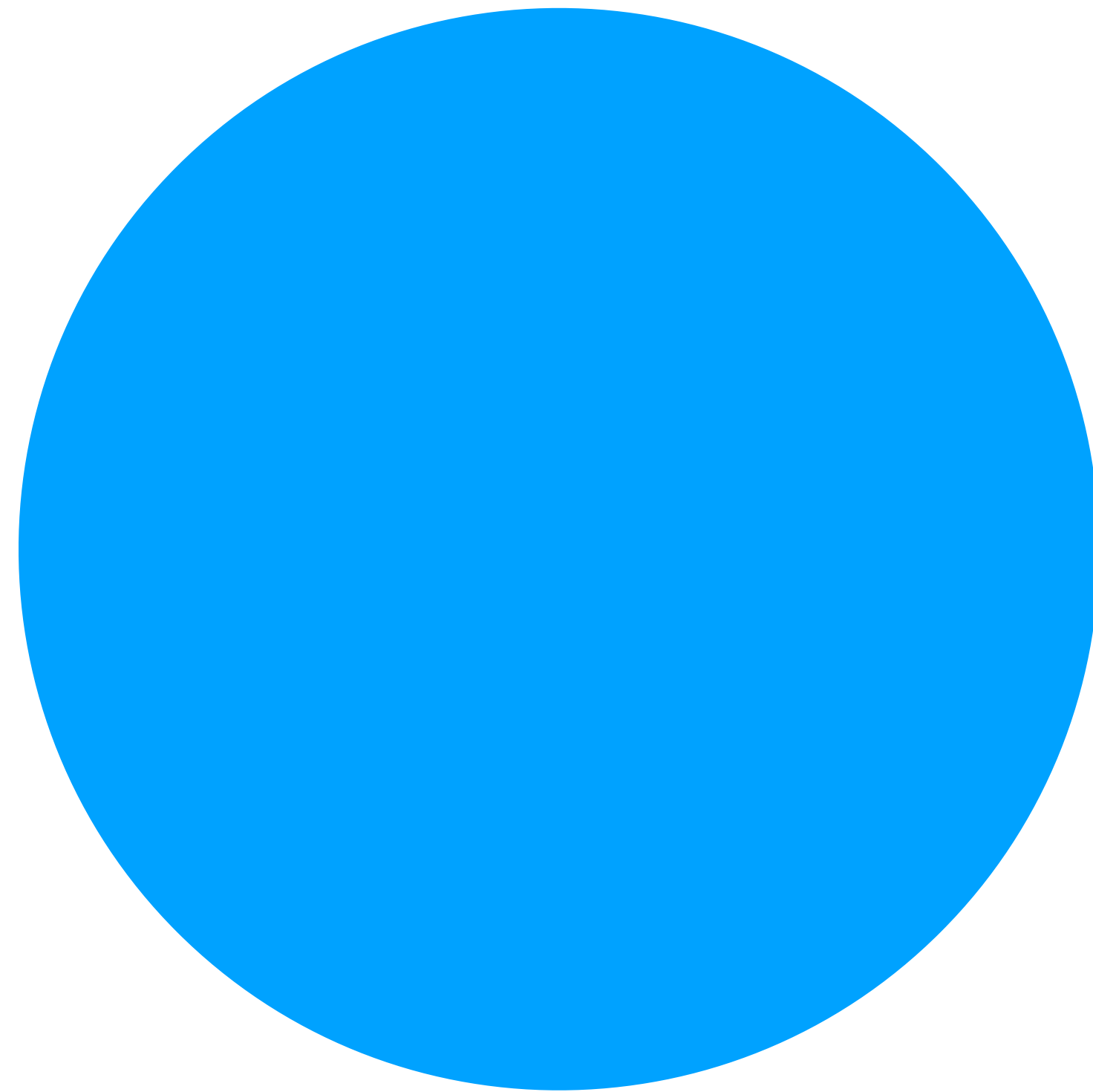
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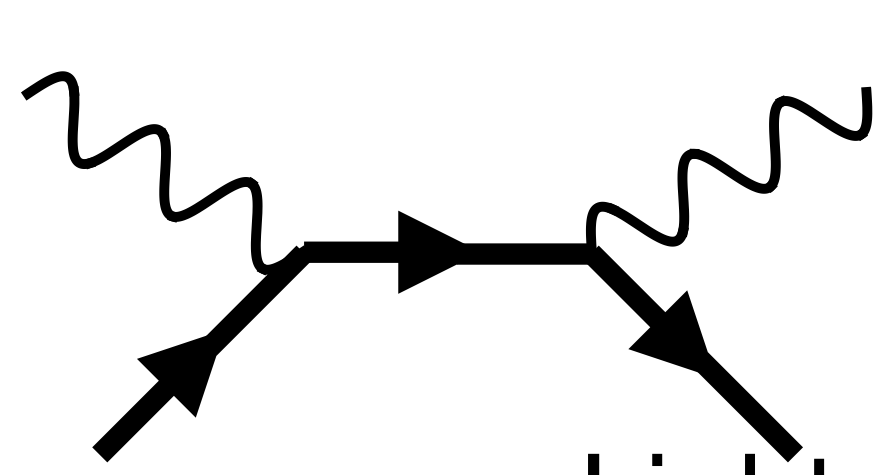
No.



# Wavelength smaller than object

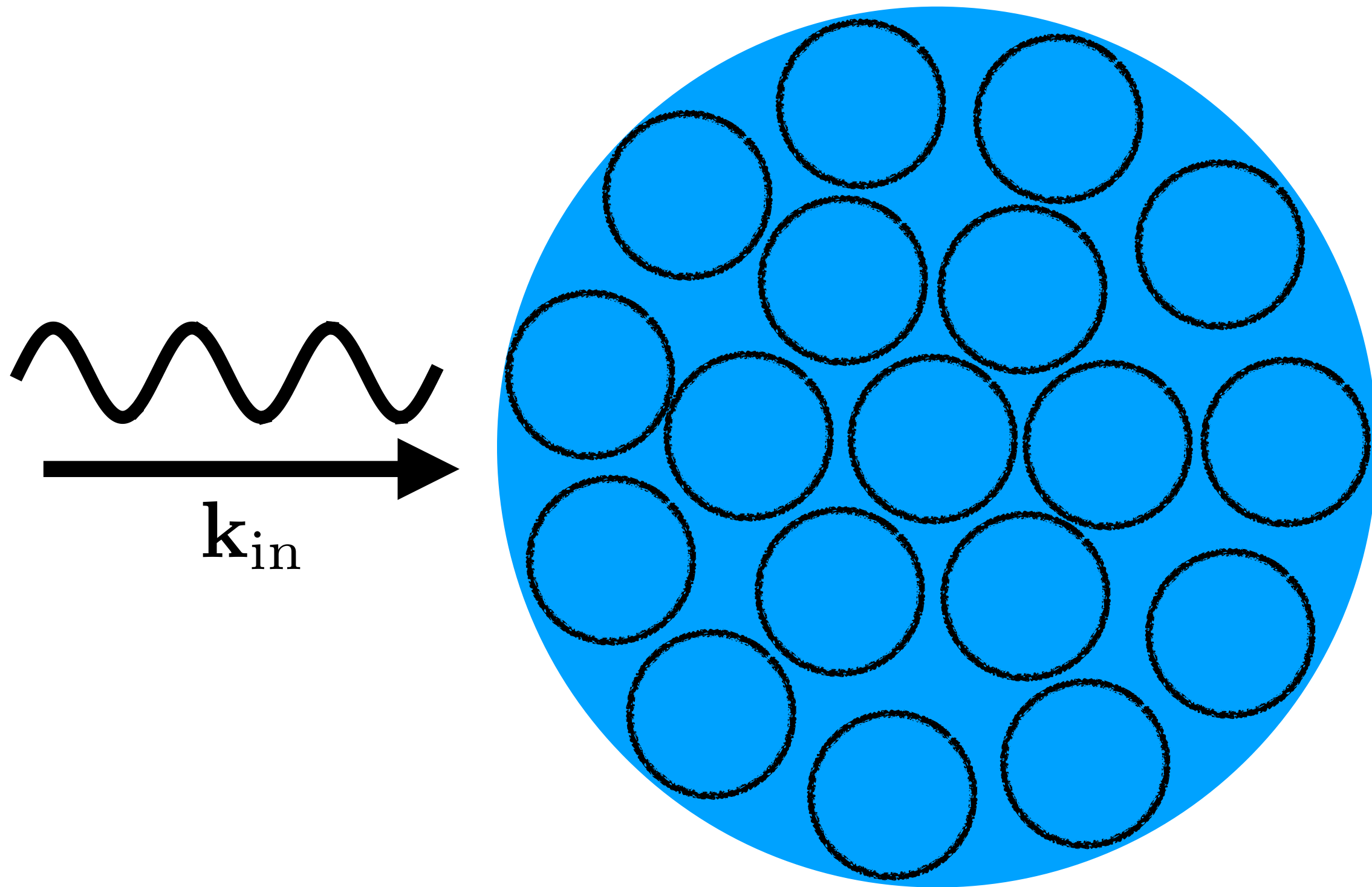
Light scattering or Four-Fermi vertex: Coherence set by *momentum transfer*



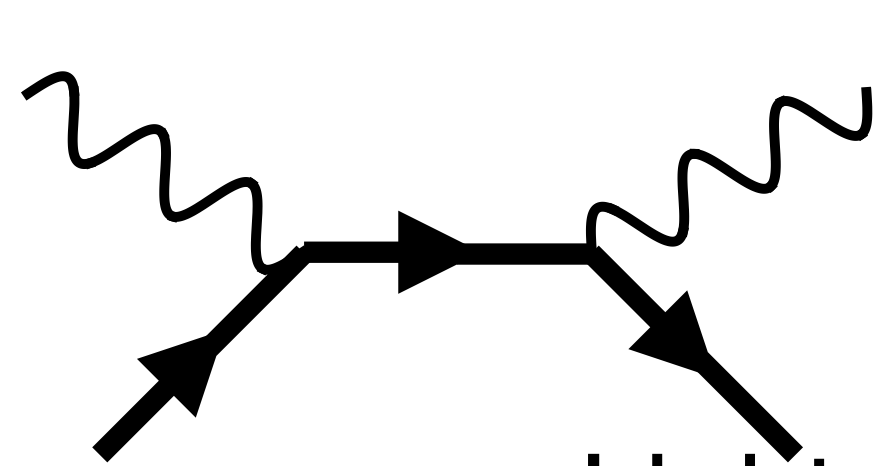


# Wavelength smaller than object

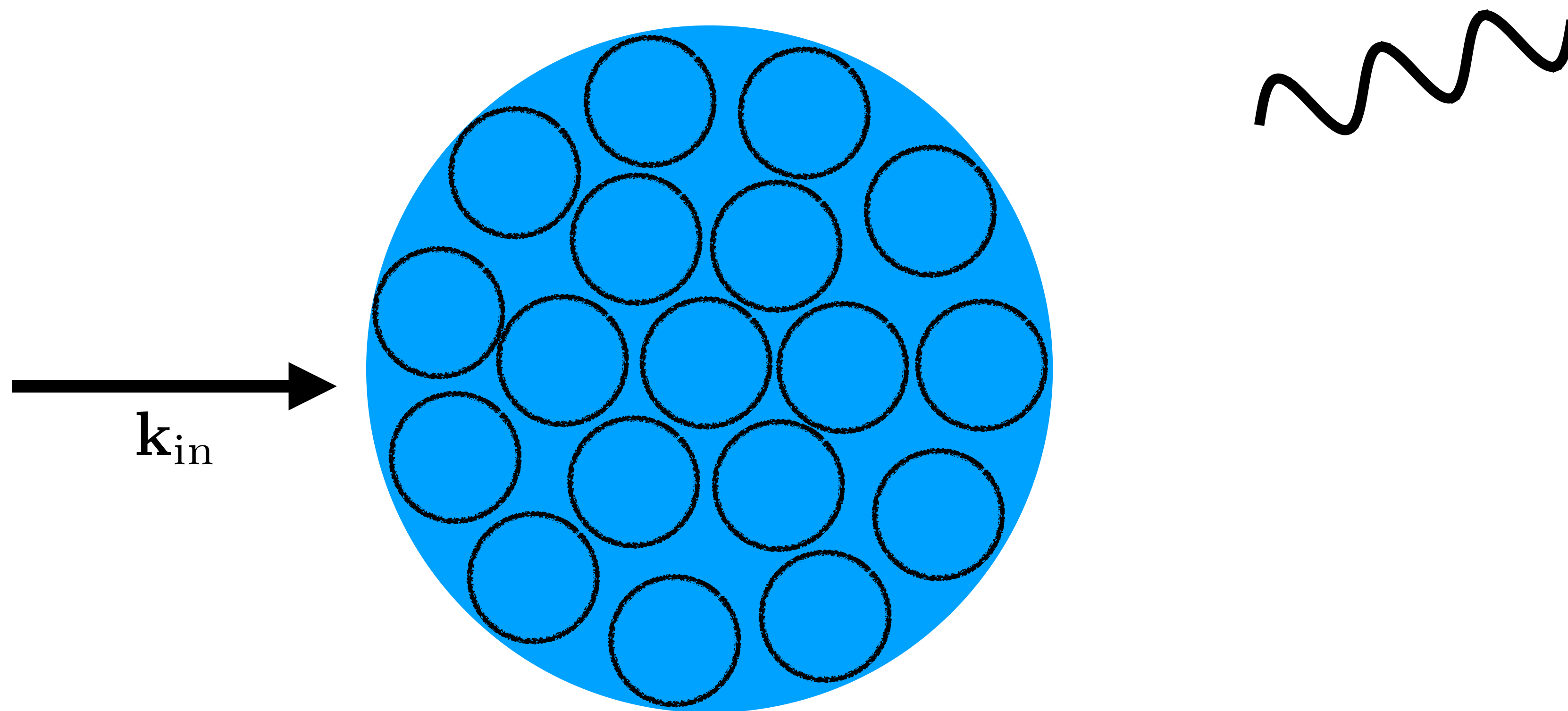
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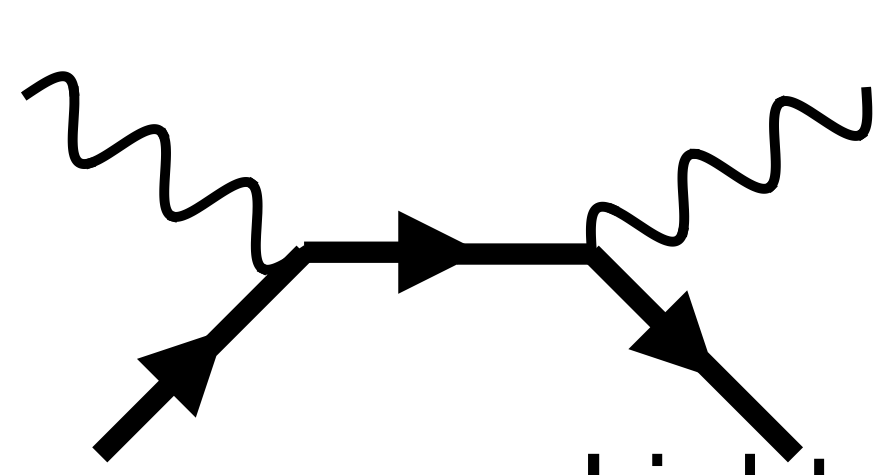


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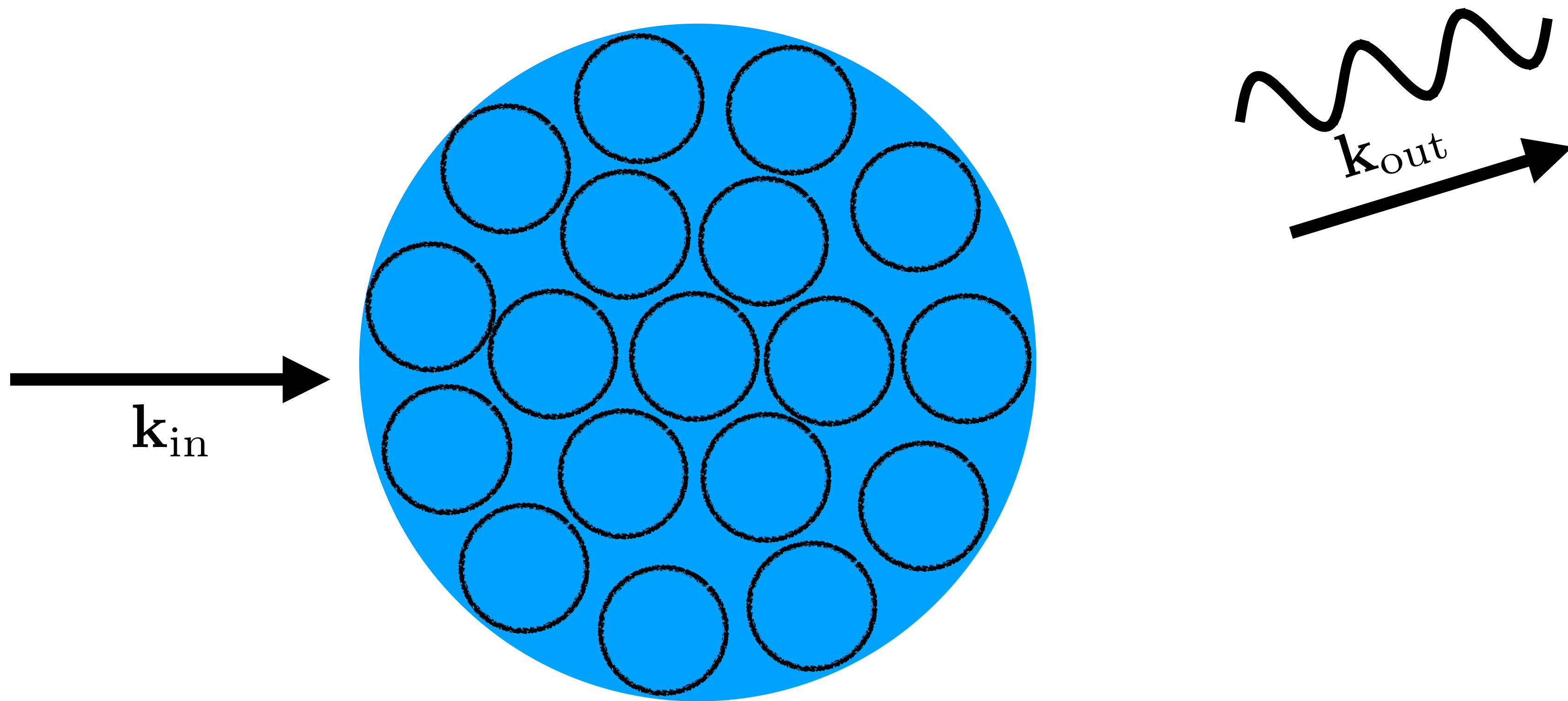
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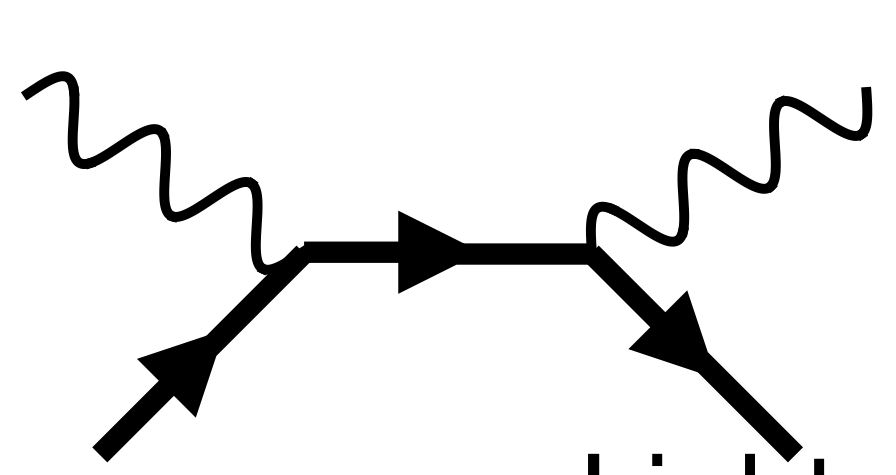




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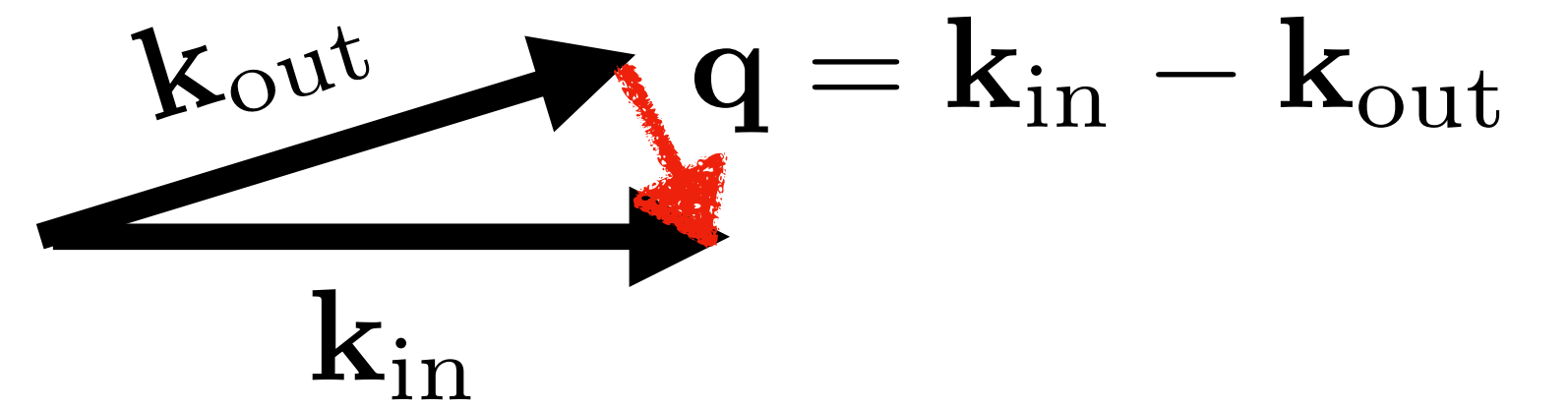
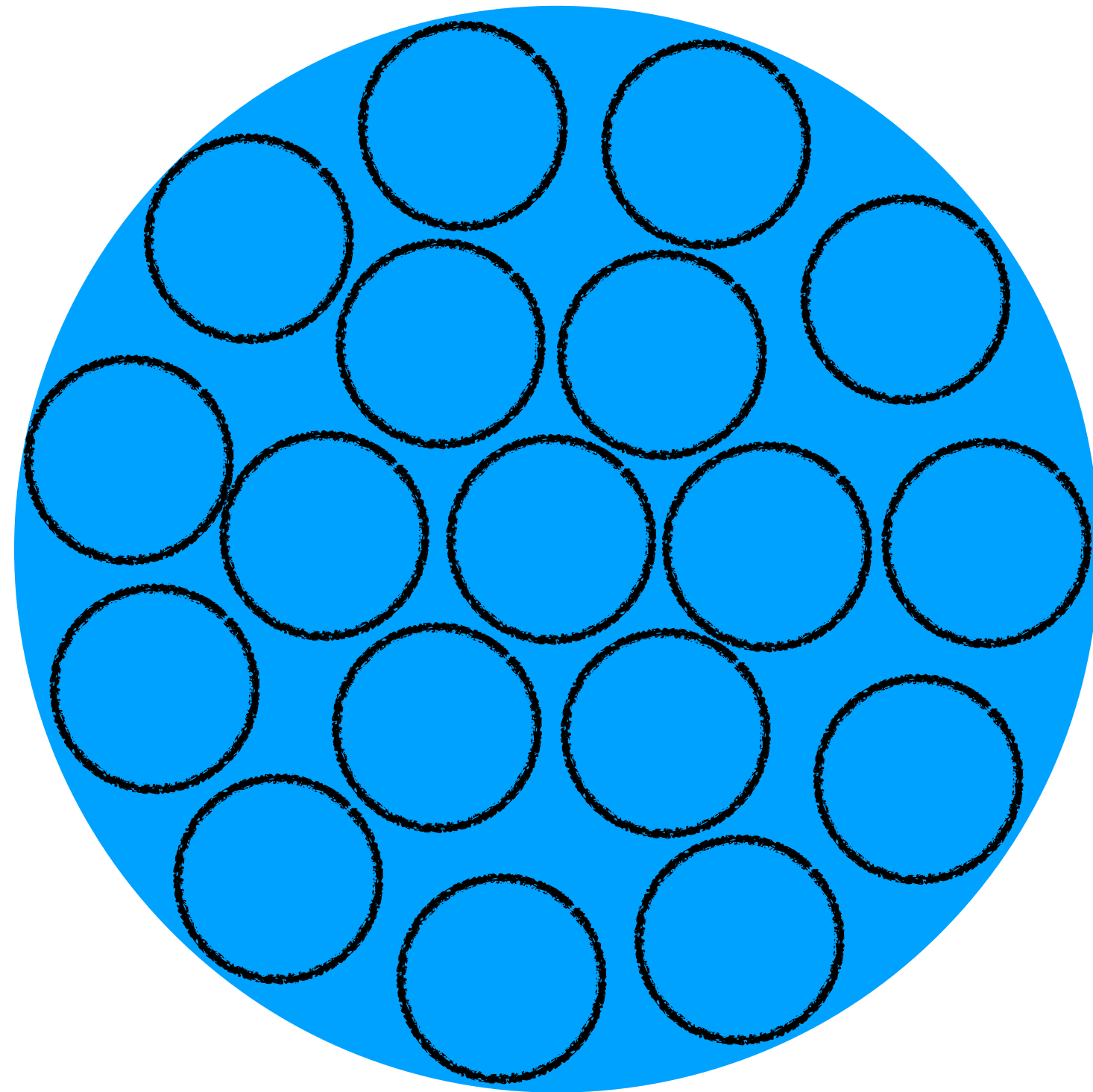
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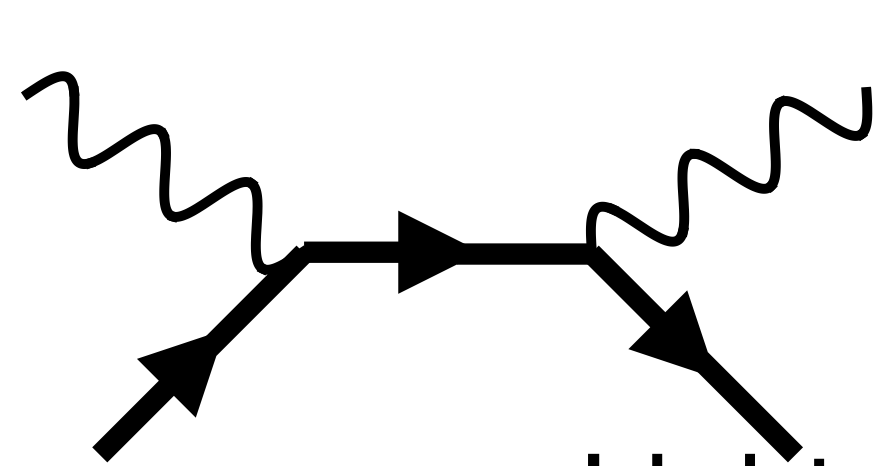




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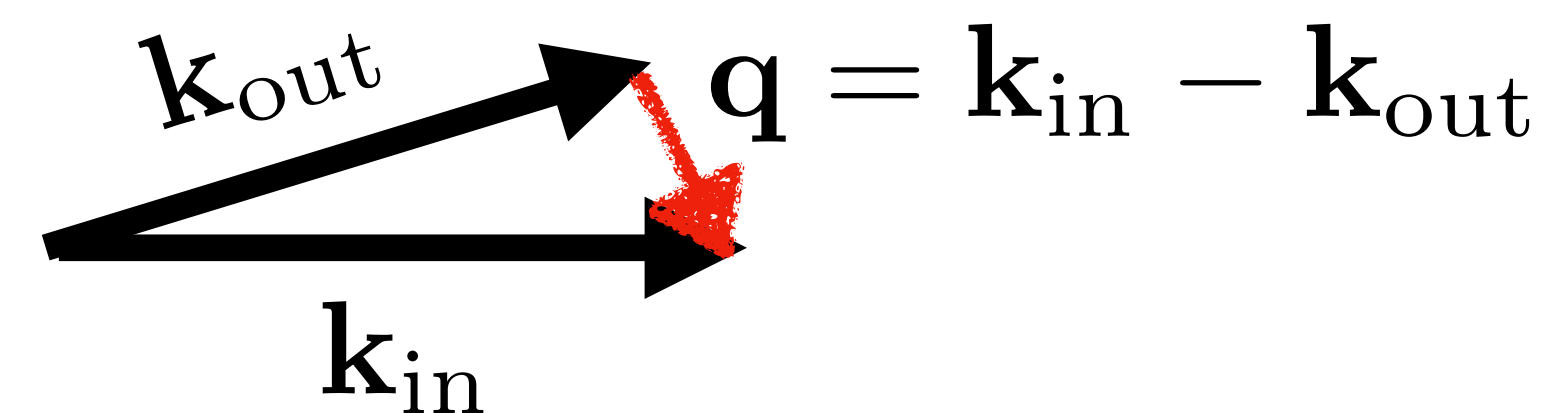
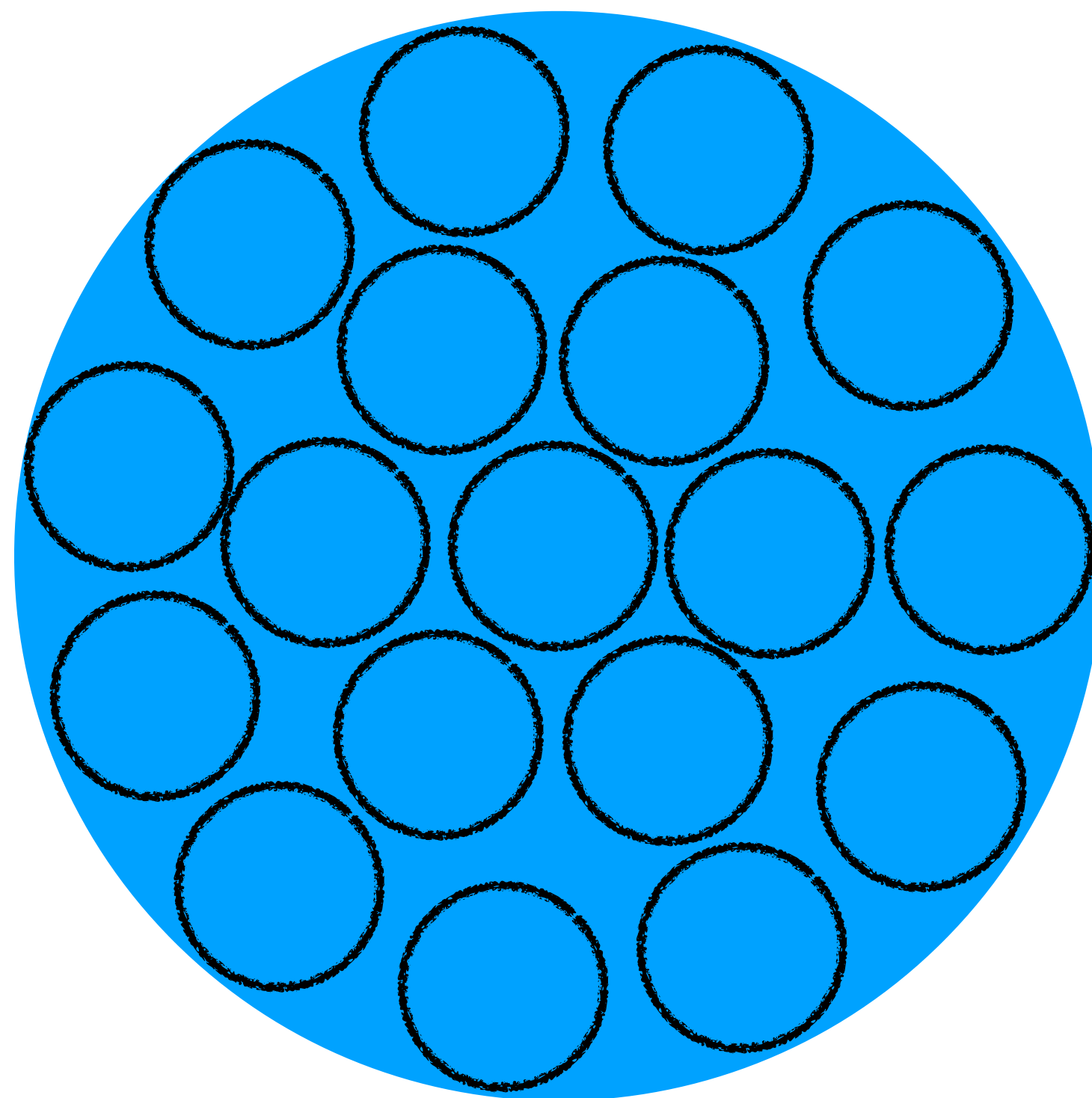
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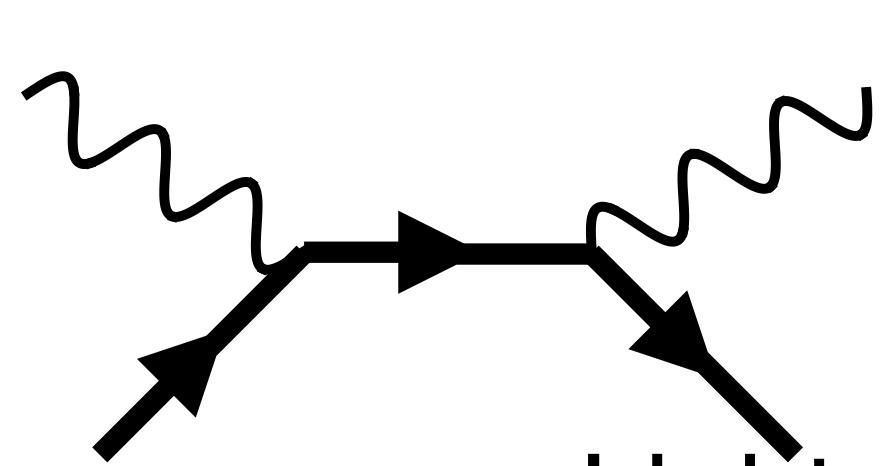
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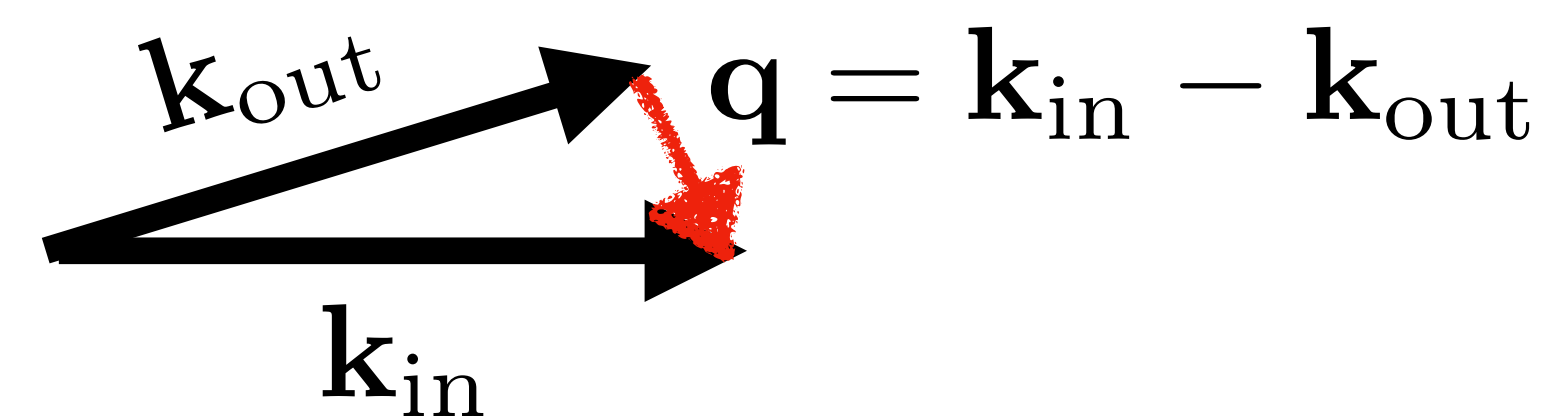
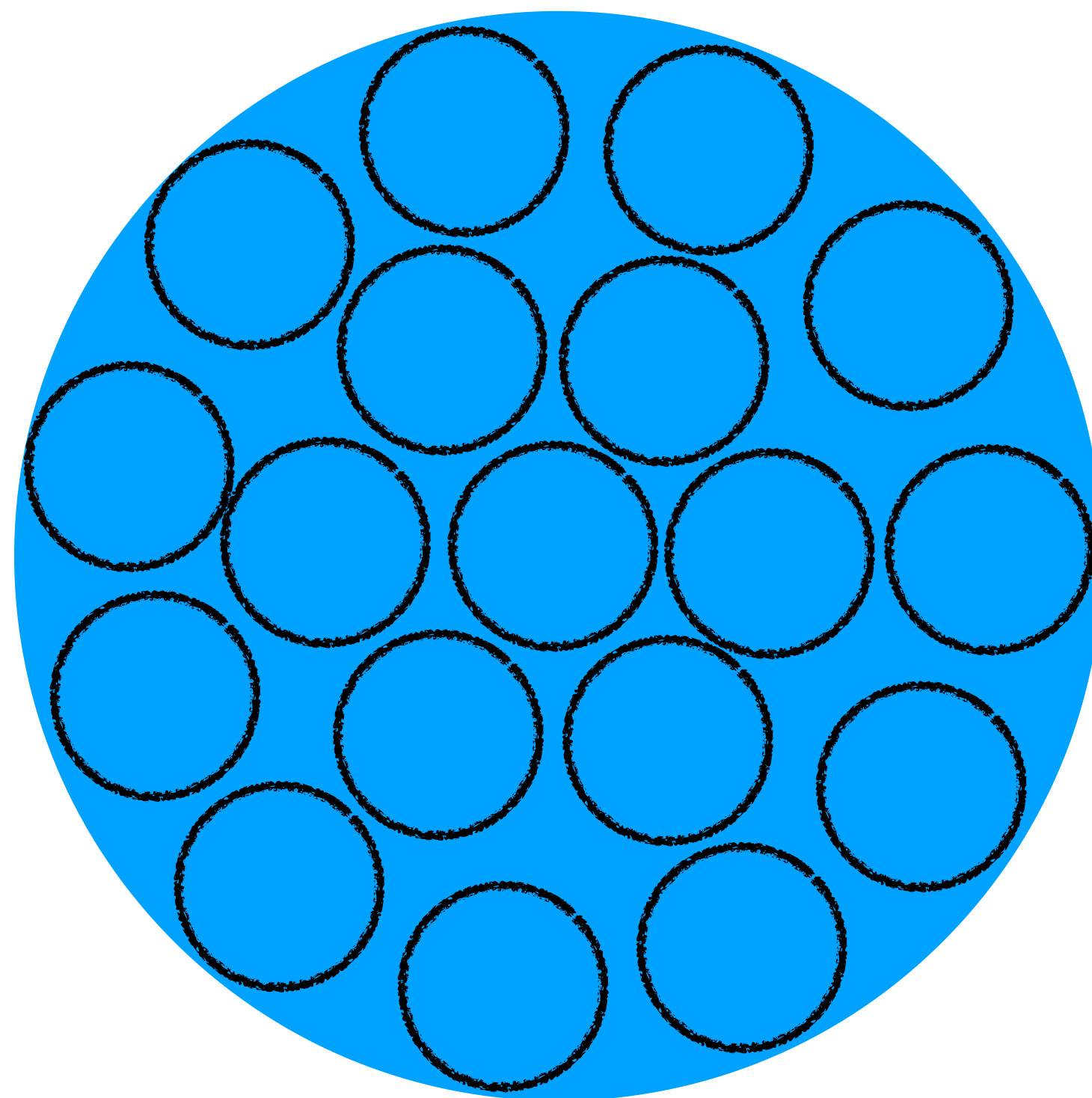
Coherence for a small  $d\Omega$  around  $k_{\text{in}}$   
for which  $q \ll R^{-1}$

$$\bar{\nu} \gamma^\mu \gamma_5 \nu \rightarrow \bar{u}(\mathbf{k}_{\text{out}}) \gamma^\mu \gamma_5 u(\mathbf{k}_{\text{in}}) e^{-i(\mathbf{k}_{\text{in}} - \mathbf{k}_{\text{out}}) \cdot \mathbf{x}_{\text{spin}}}$$



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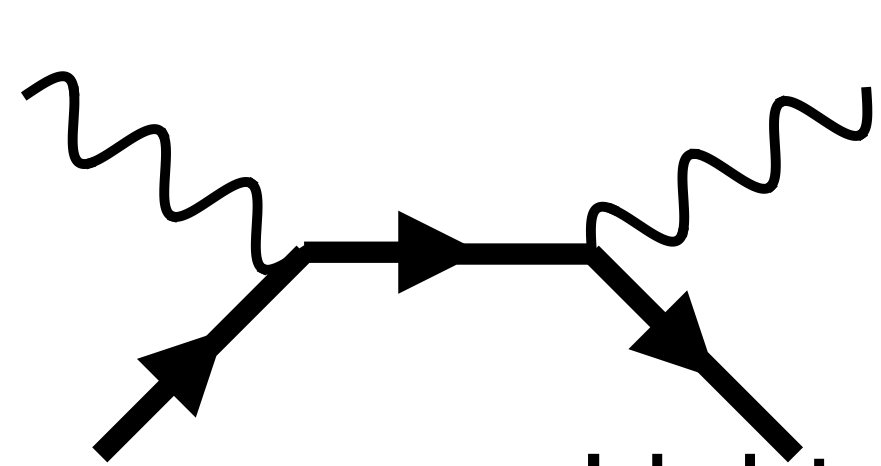
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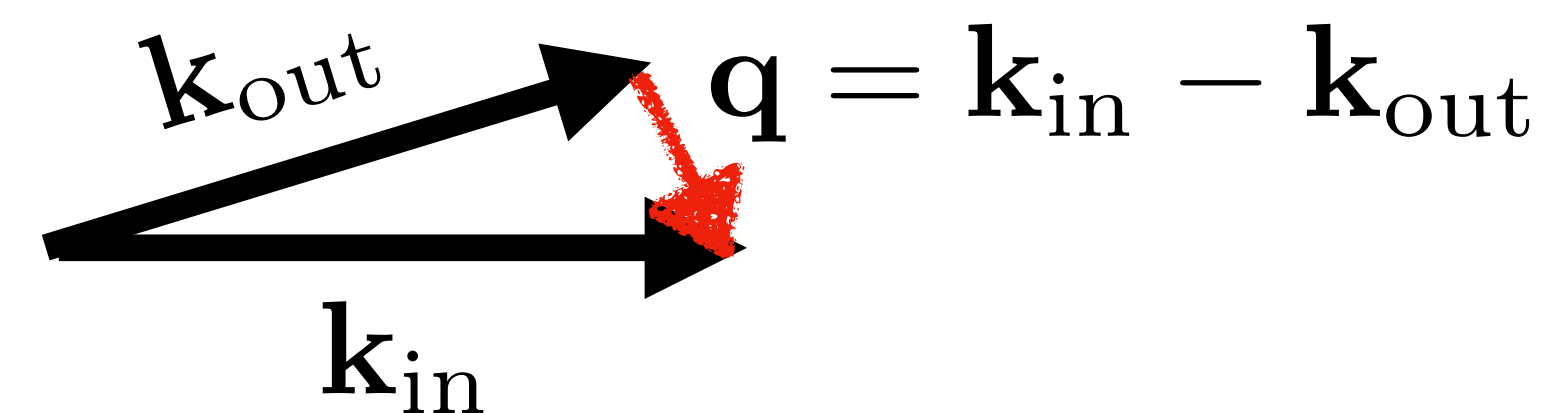
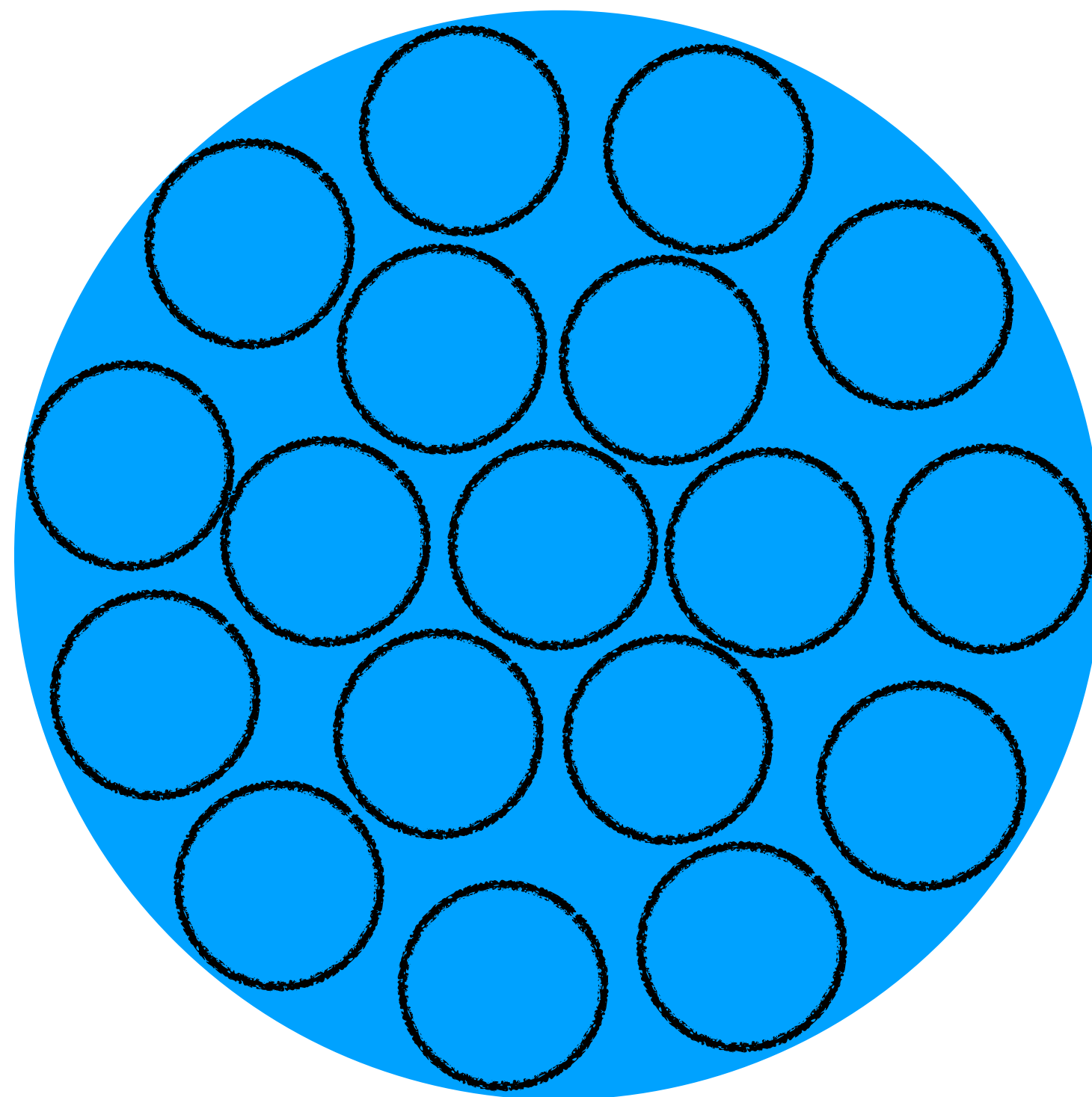
$$\bar{\nu} \gamma^\mu \gamma_5 \nu \rightarrow \bar{u}(\mathbf{k}_{\text{out}}) \gamma^\mu \gamma_5 u(\mathbf{k}_{\text{in}}) e^{-i(\mathbf{k}_{\text{in}} - \mathbf{k}_{\text{out}}) \cdot \mathbf{x}_{\text{spin}}} \xrightarrow{q \ll R^{-1}} \mathbf{x}_{\text{spin}} - \text{independent}$$





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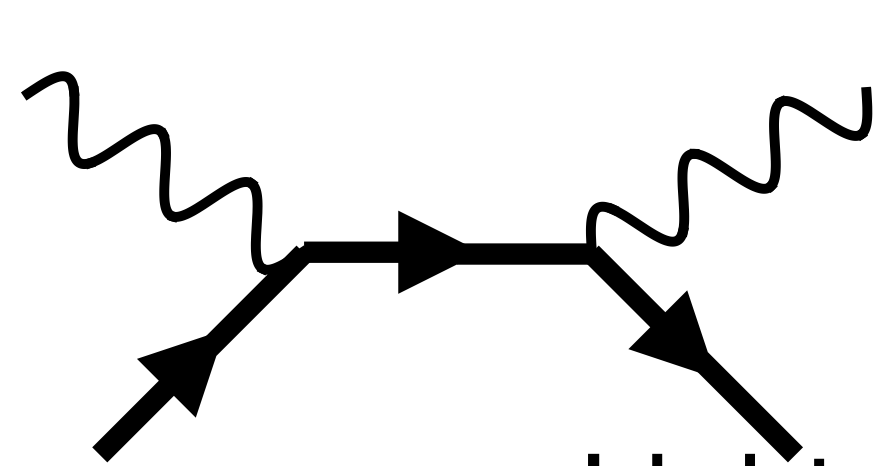
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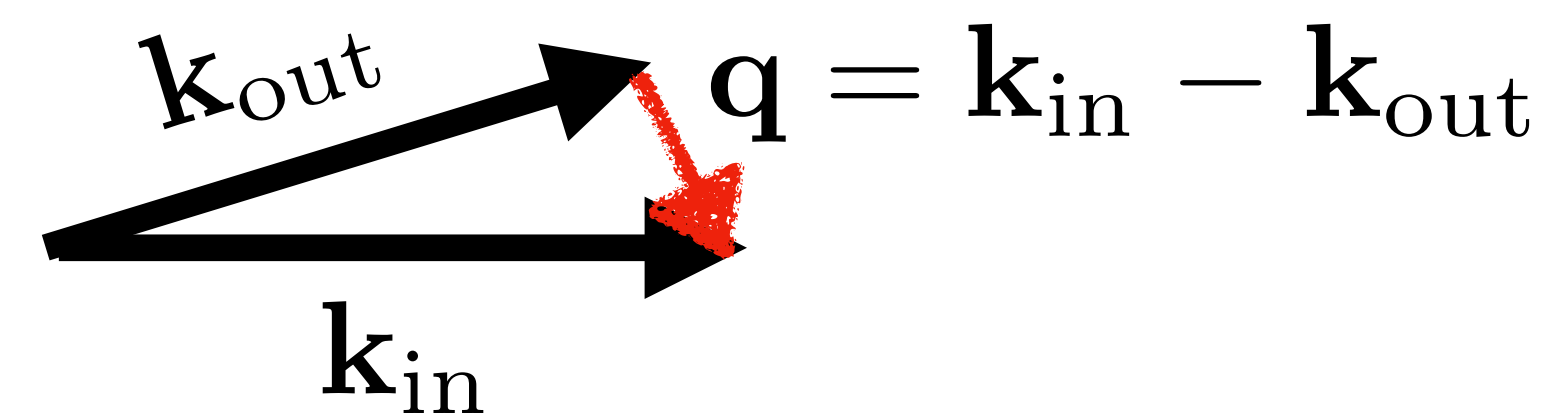
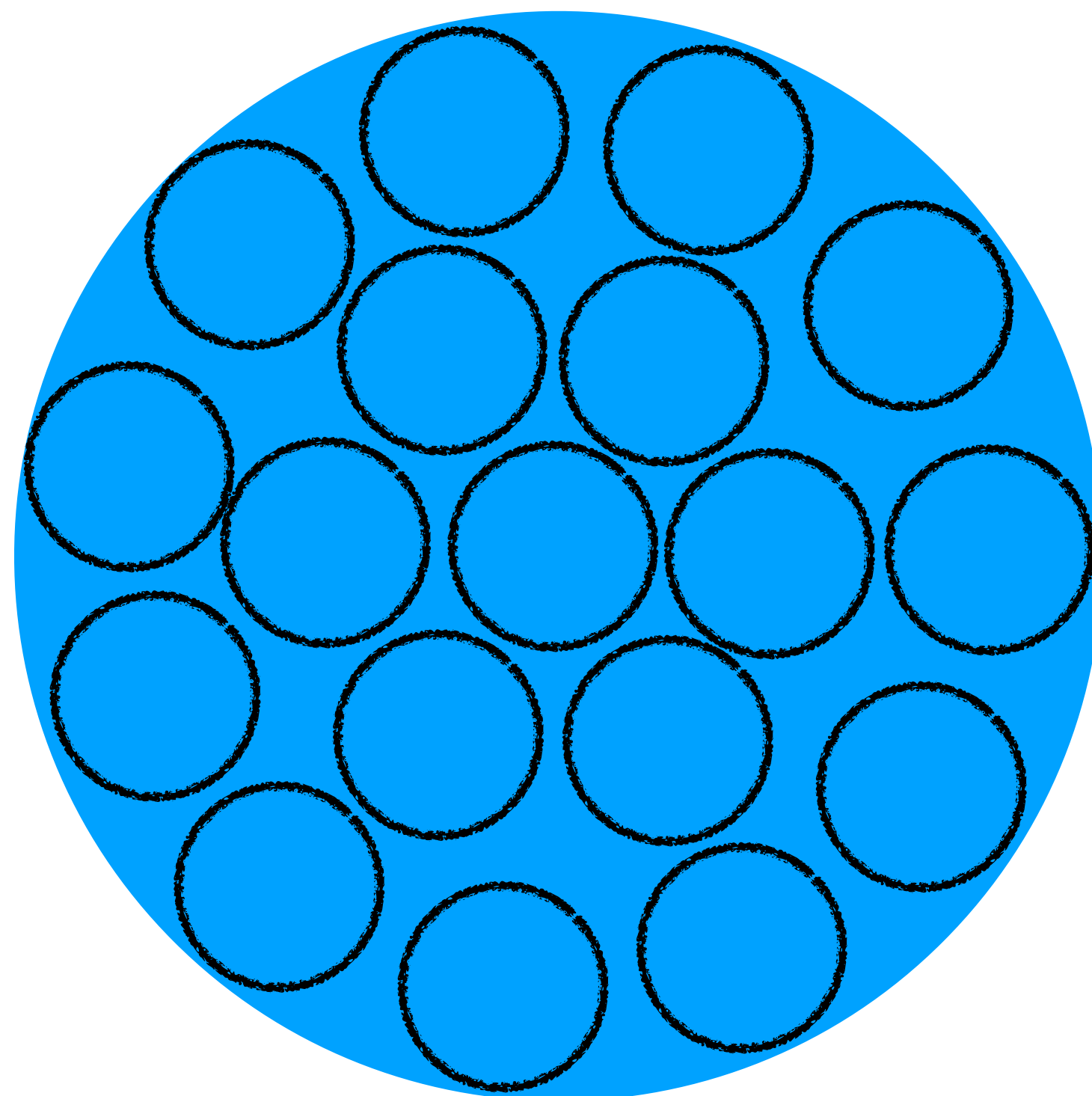
$$\Gamma \propto (nR^3)^2 \left( \frac{1}{kR} \right)^2 \sim n^2 \lambda^2 R^4$$

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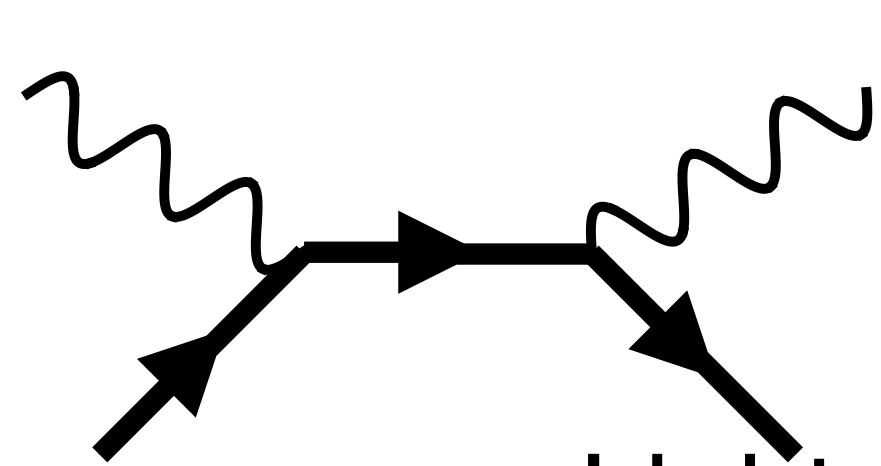


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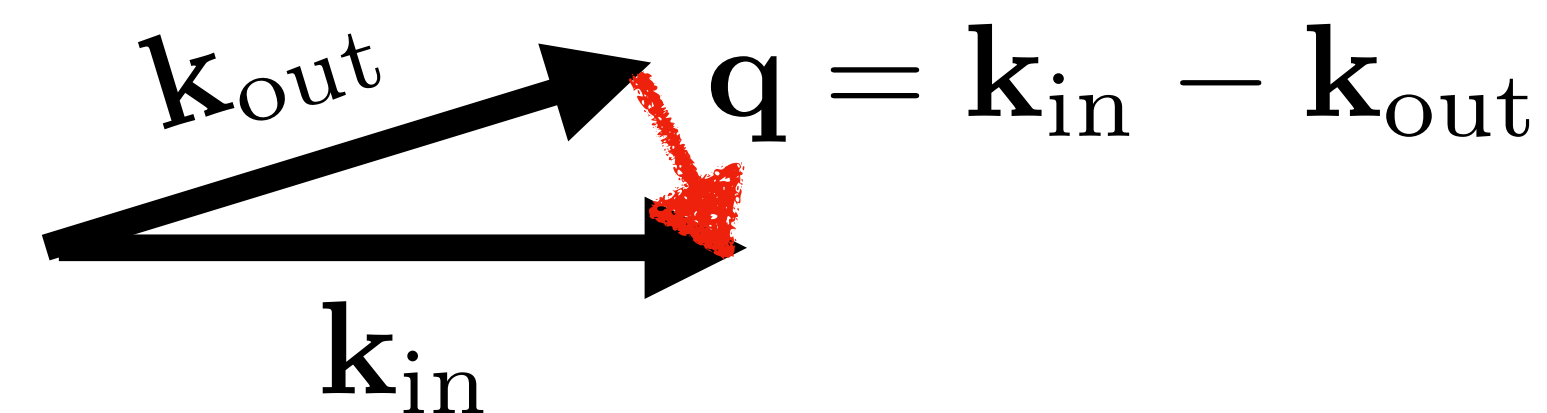
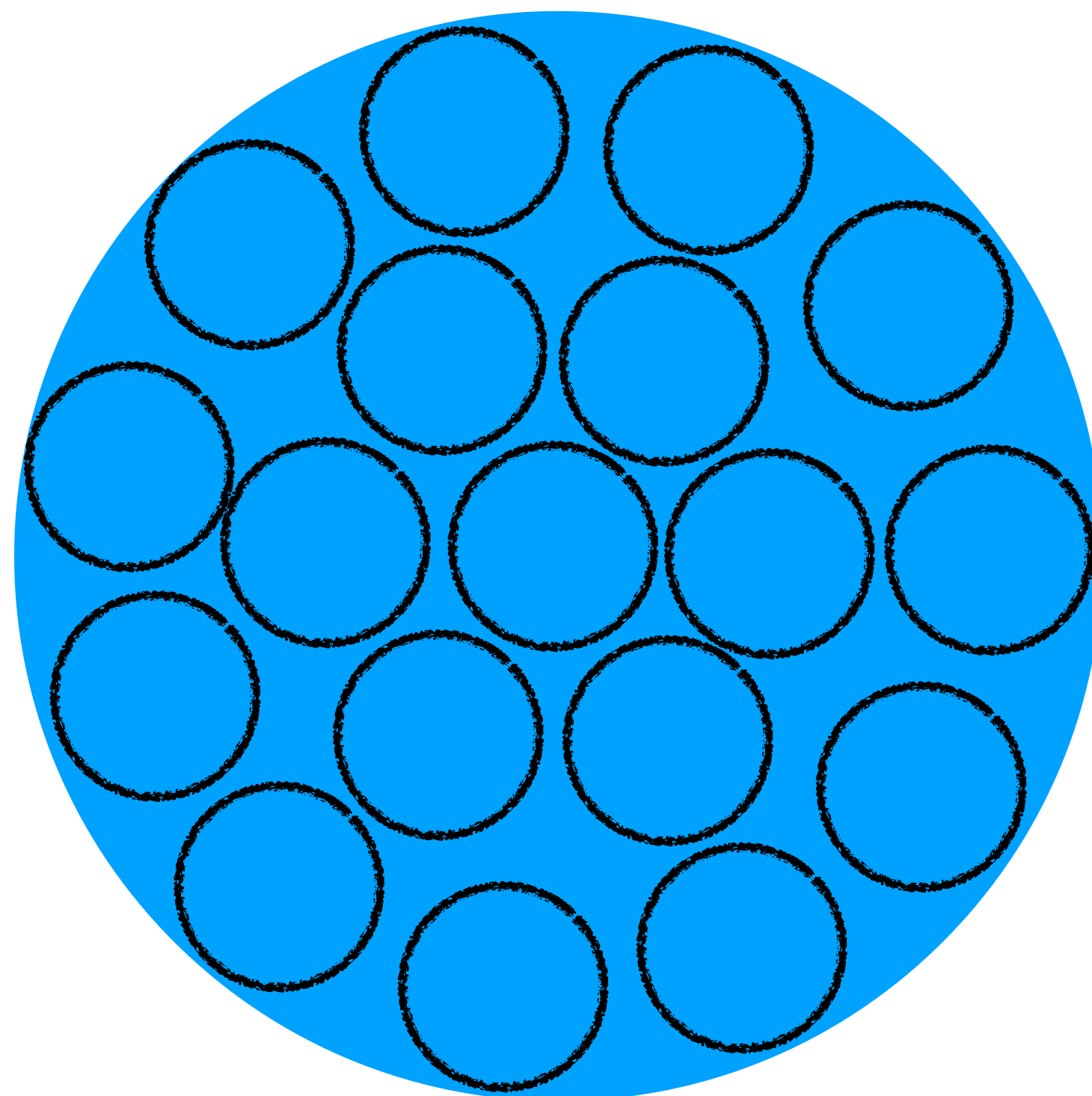
Solid angle

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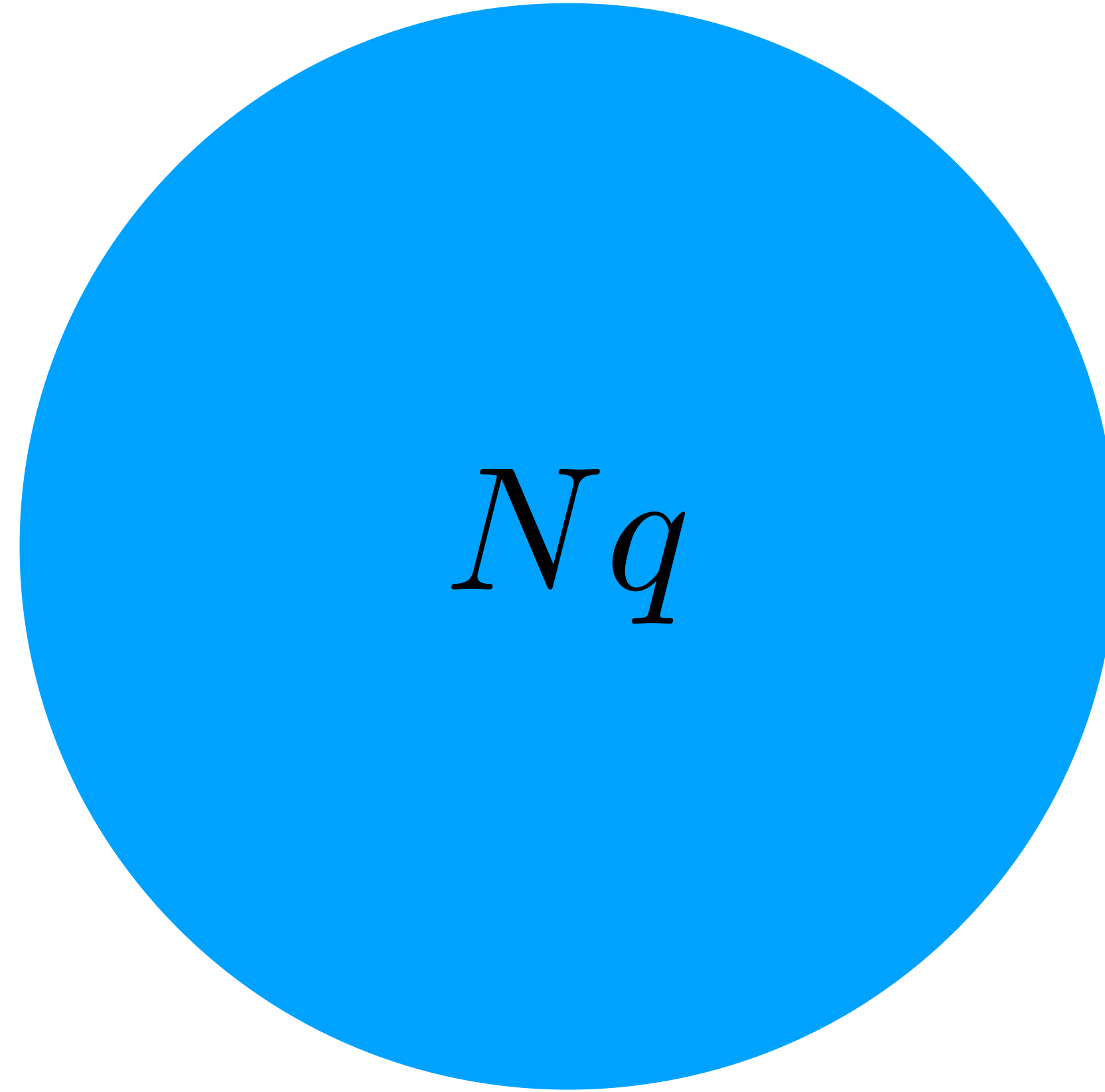
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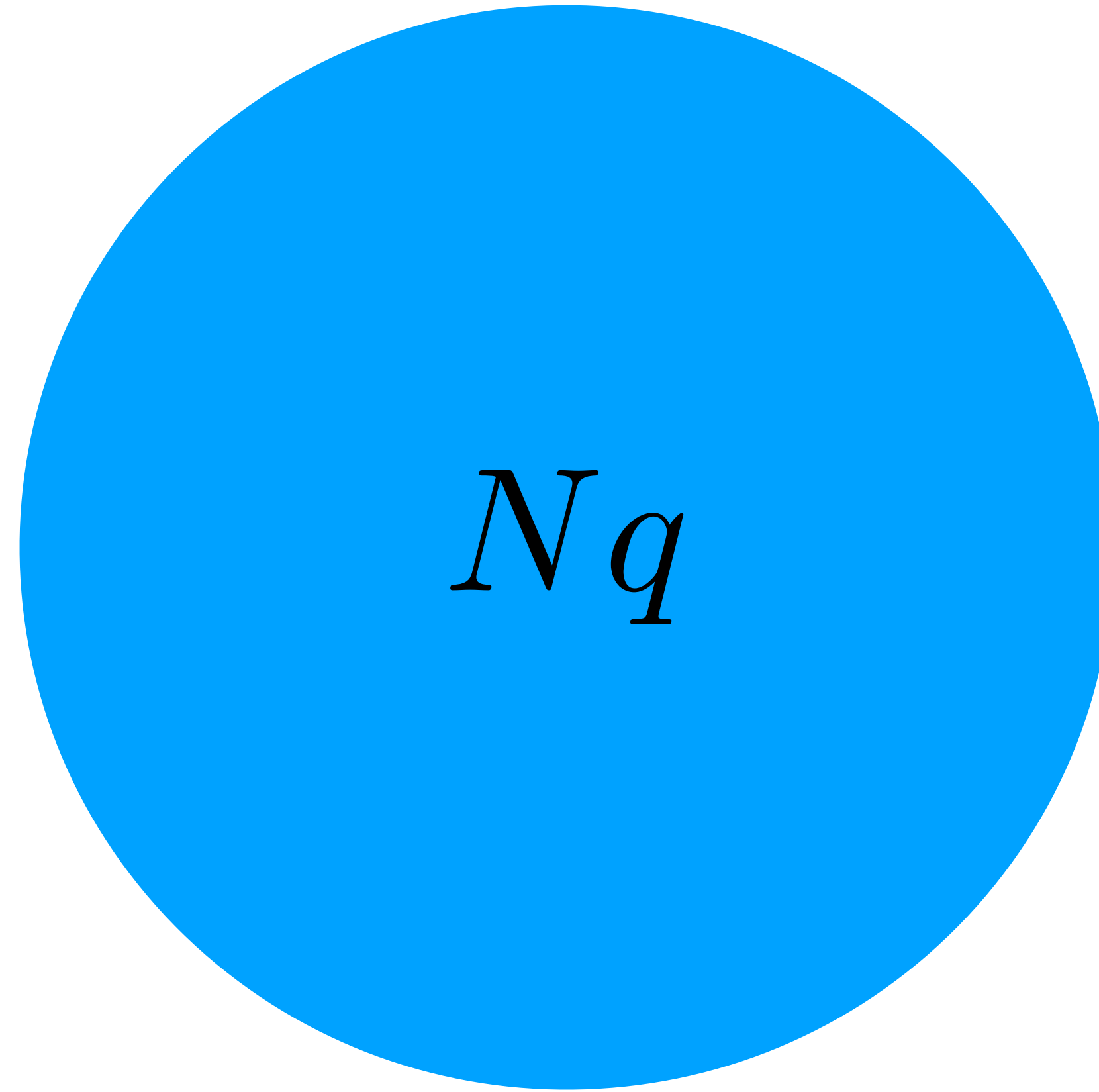
Rayleigh-Gans regime

# Observable in Elastic Scattering



Macroscopic coherence

# Observable in Elastic Scattering



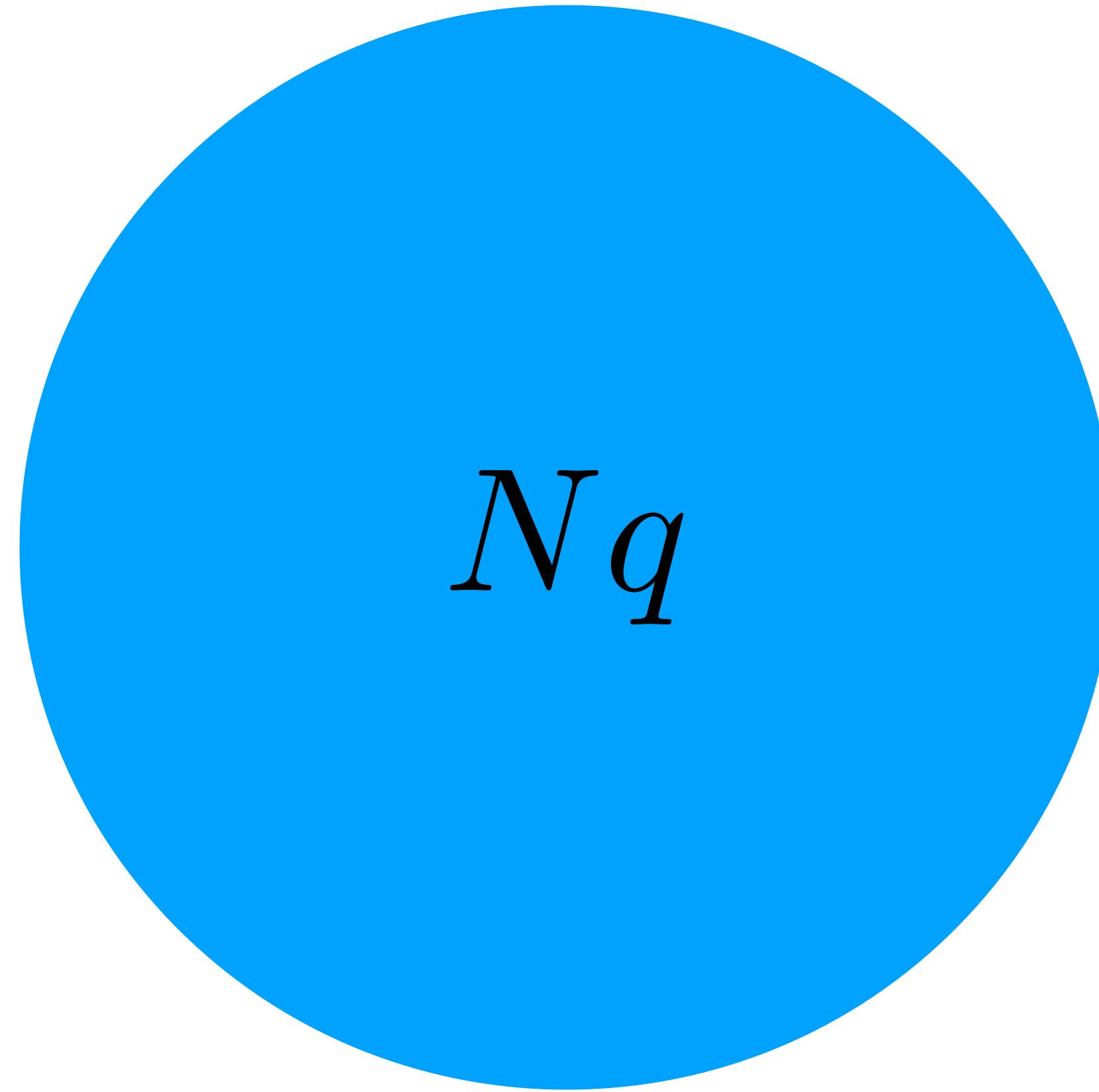
Macroscopic coherence

Momentum Transfer

$$q = |\mathbf{k}_{\text{in}} - \mathbf{k}_{\text{out}}| \sim R^{-1}$$
$$\sim 10^{-6} \text{eV}$$

For a 10cm sphere

# Observable in Elastic Scattering



Macroscopic coherence

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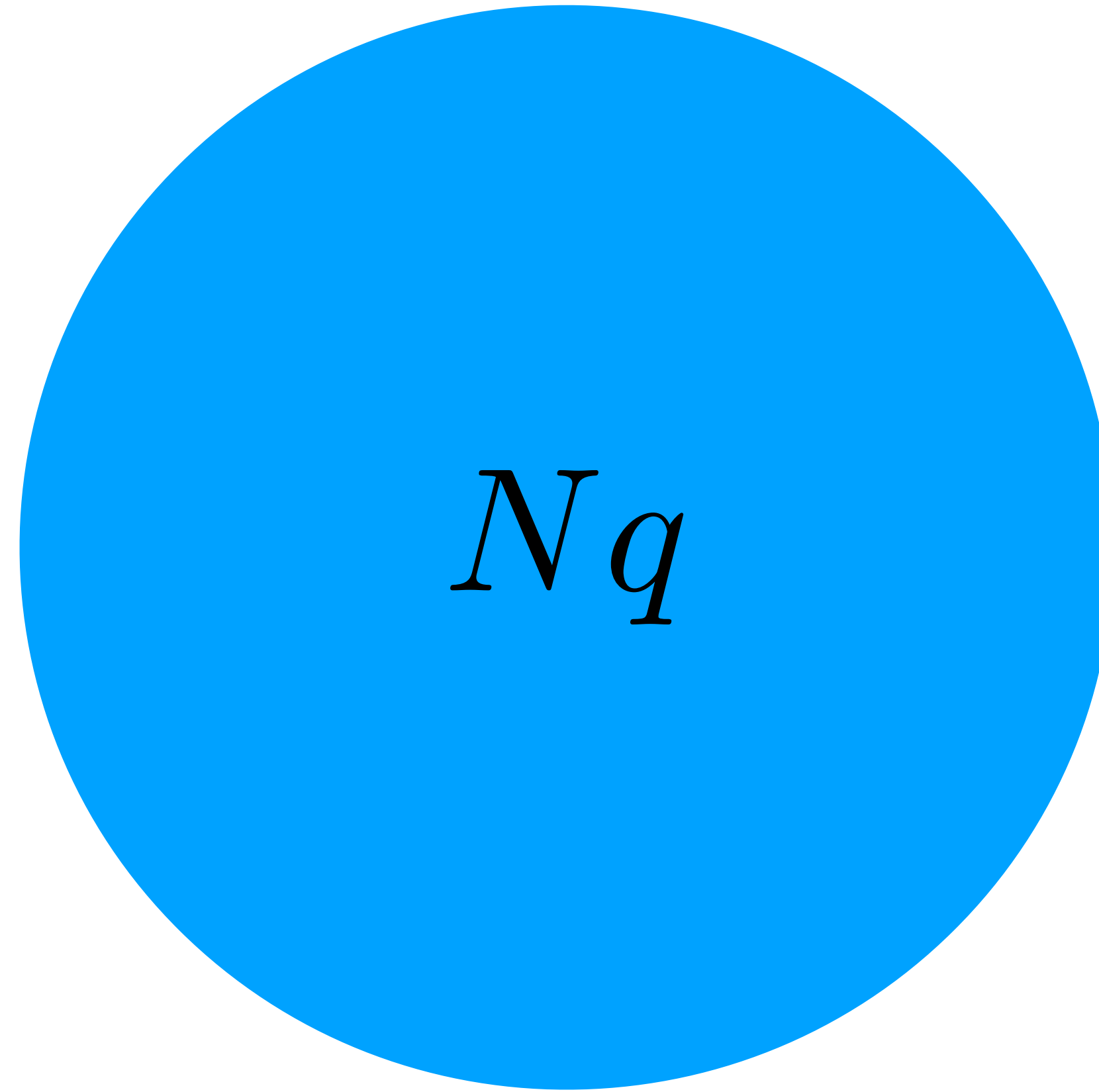
For a 10cm sphere

Energy Transfer

$$\frac{q^2}{2M} \sim 10^{-49} \text{eV}$$

For a 10cm sphere of tungsten

# Observable in Elastic Scattering



Macroscopic coherence

## Momentum Transfer

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For a 10cm sphere

## Energy Transfer

$$\frac{q^2}{2M} \sim 10^{-49} \text{ eV}$$

For a 10cm sphere of tungsten

Compare to 1 atom/cm<sup>3</sup> at 1K:

$$n(\pi R^2)v \sim 1 \text{ Hz}$$

$$q \sim 10^{-4} \text{ eV}$$

Need appropriate observables



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Idea: what if we changed the internal state?

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e.g: NMR splittings can be  $\sim 10^{-7}$  eV

ESR similarly  $\sim 10^{-4}$  eV

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Can we get macroscopic coherence *and* single spin flips?

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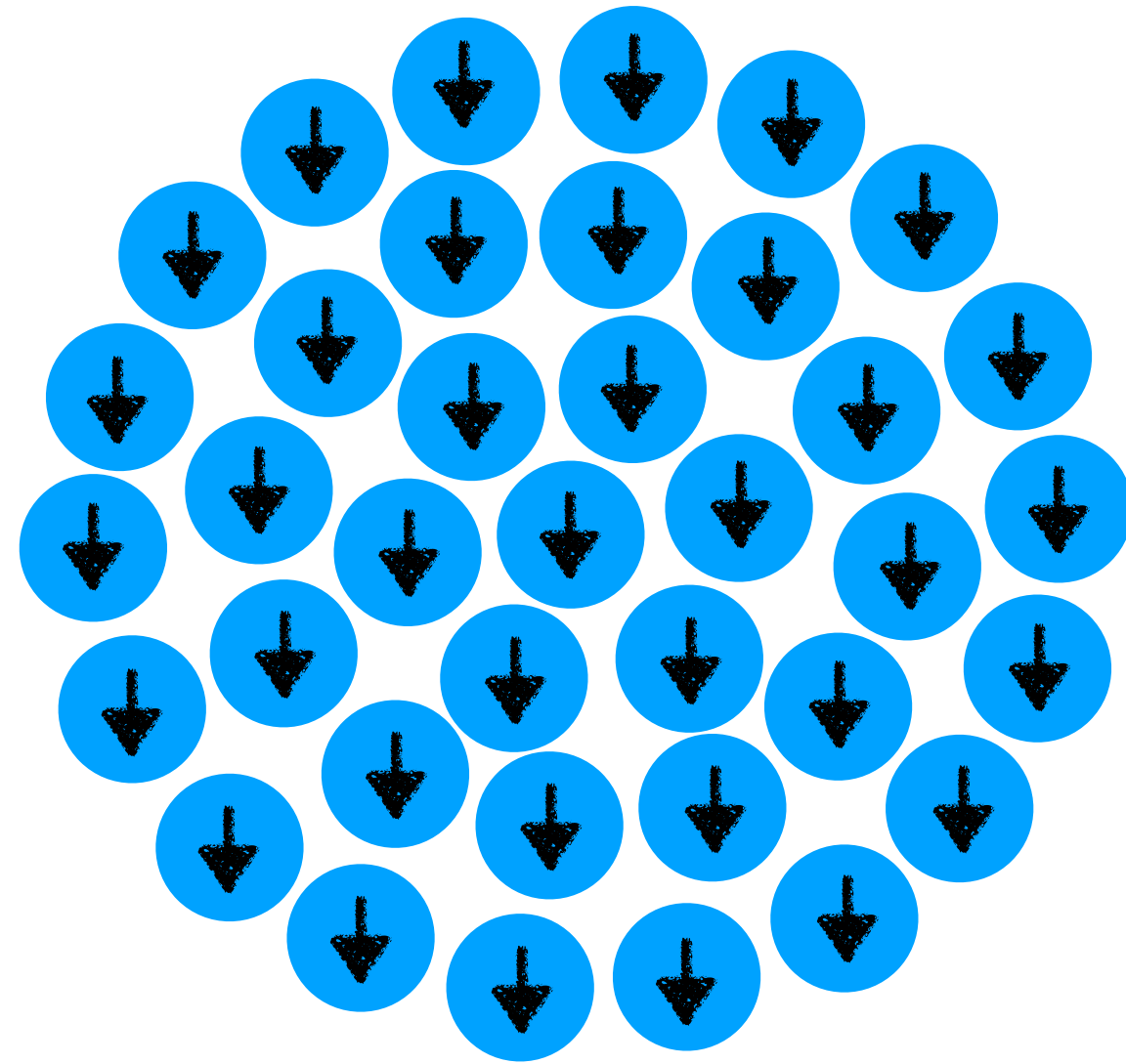
Can we get macroscopic coherence *and* single spin flips?

Then  $N^2$  *and* potential observable



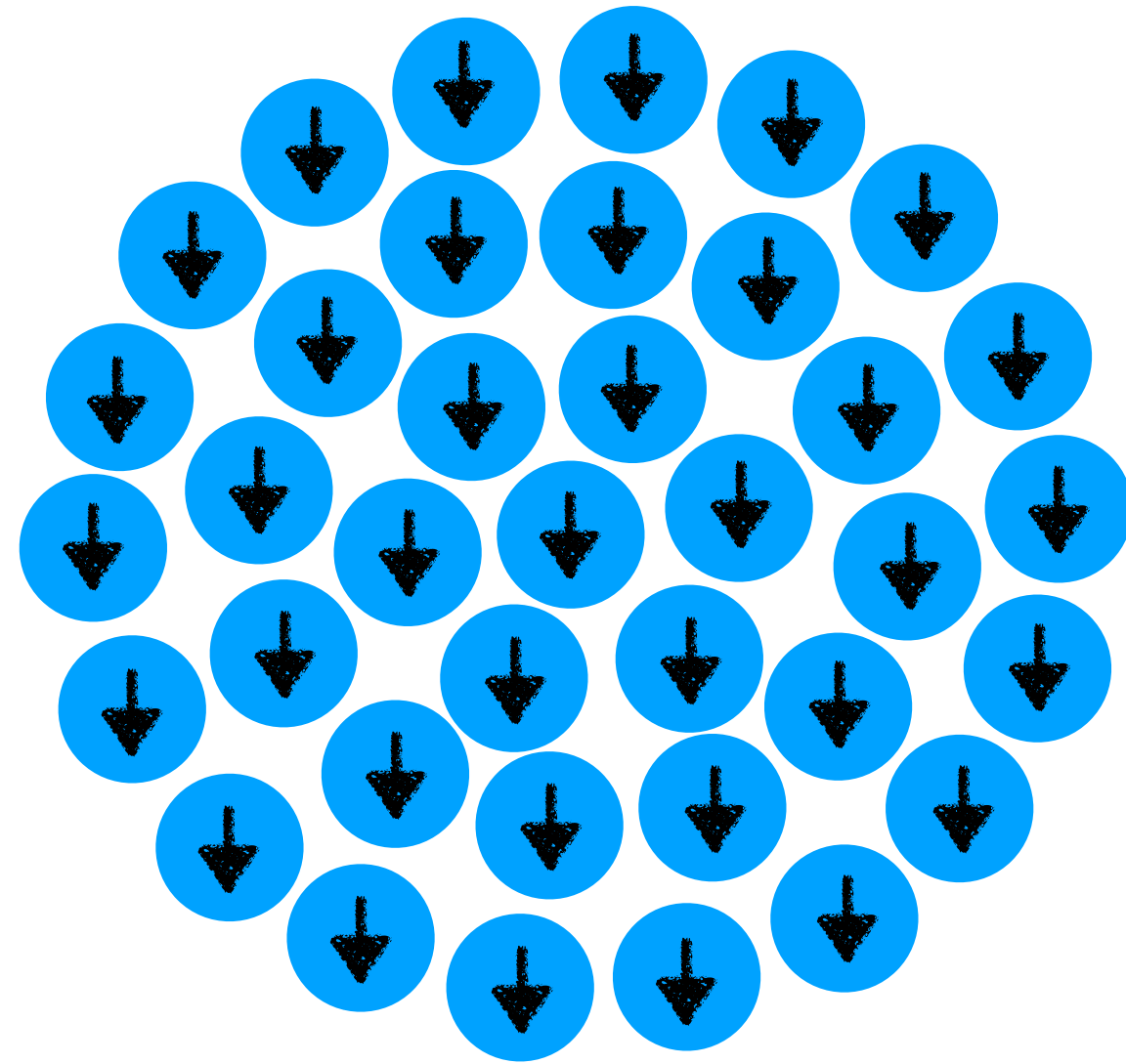
**Approves**

# Coherence in Inelastic Processes



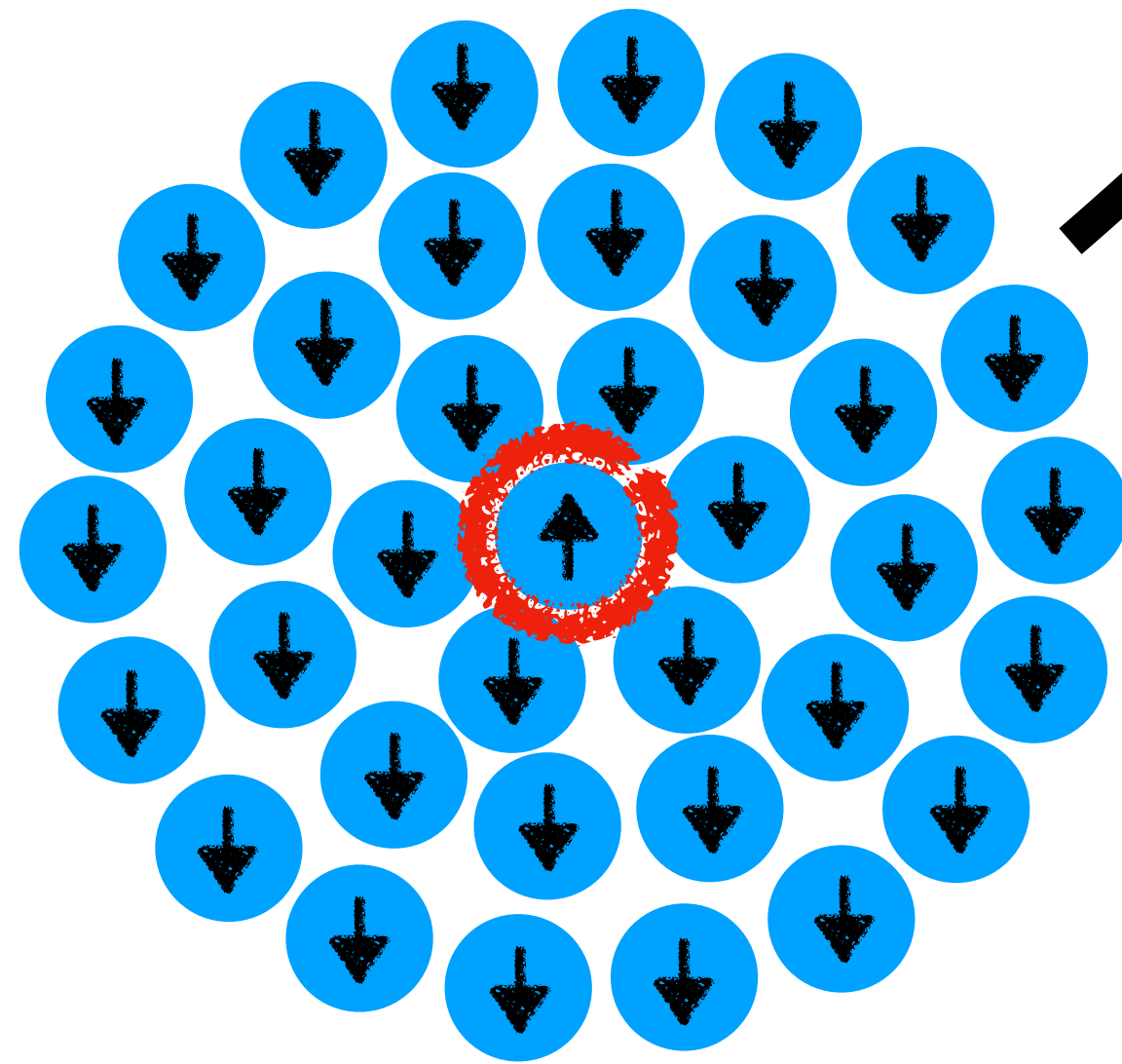
$$|\psi\rangle = \prod |g\rangle$$

# In Coherence in Inelastic Processes



$$|\psi\rangle = \prod |g\rangle$$

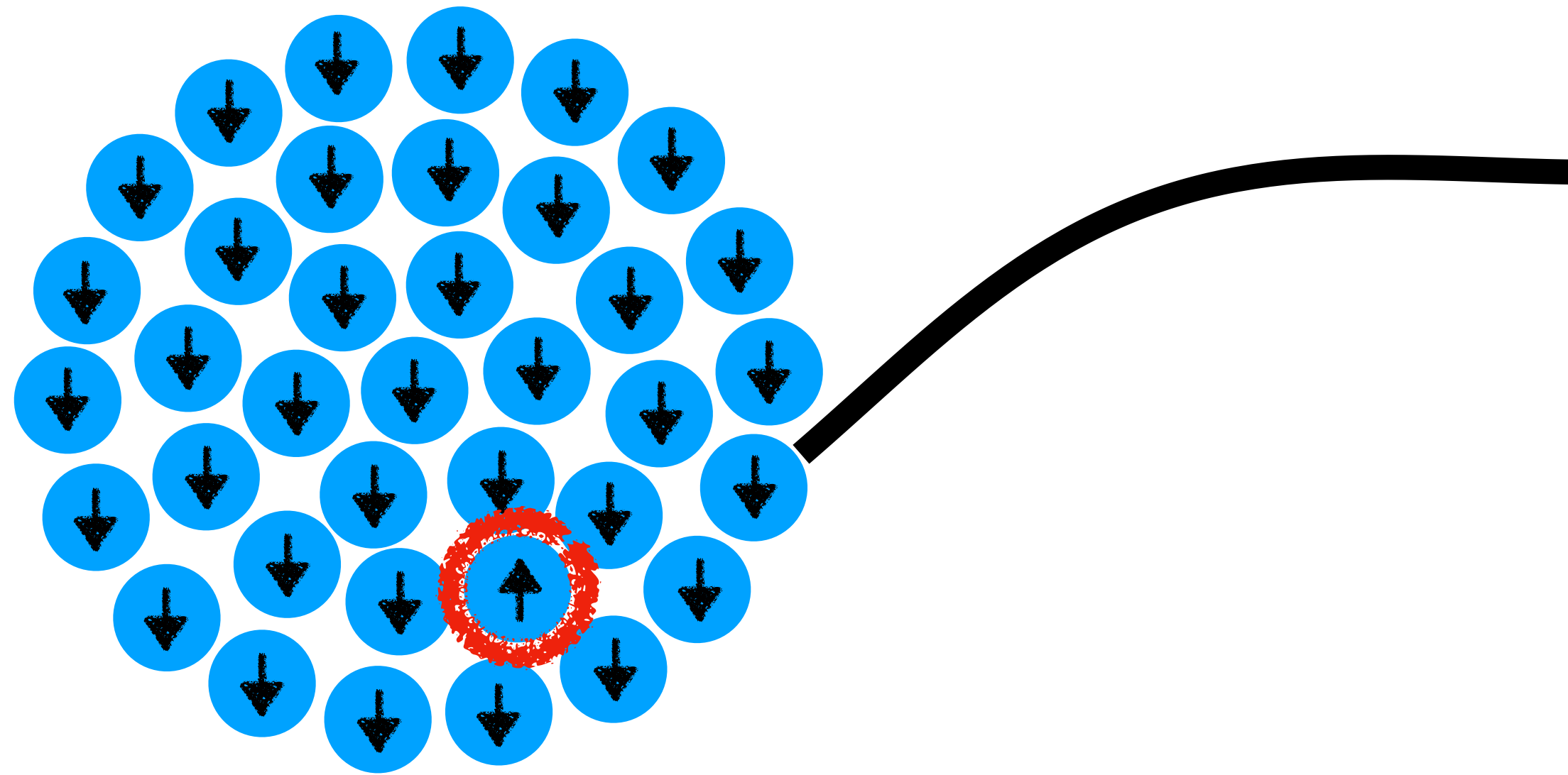
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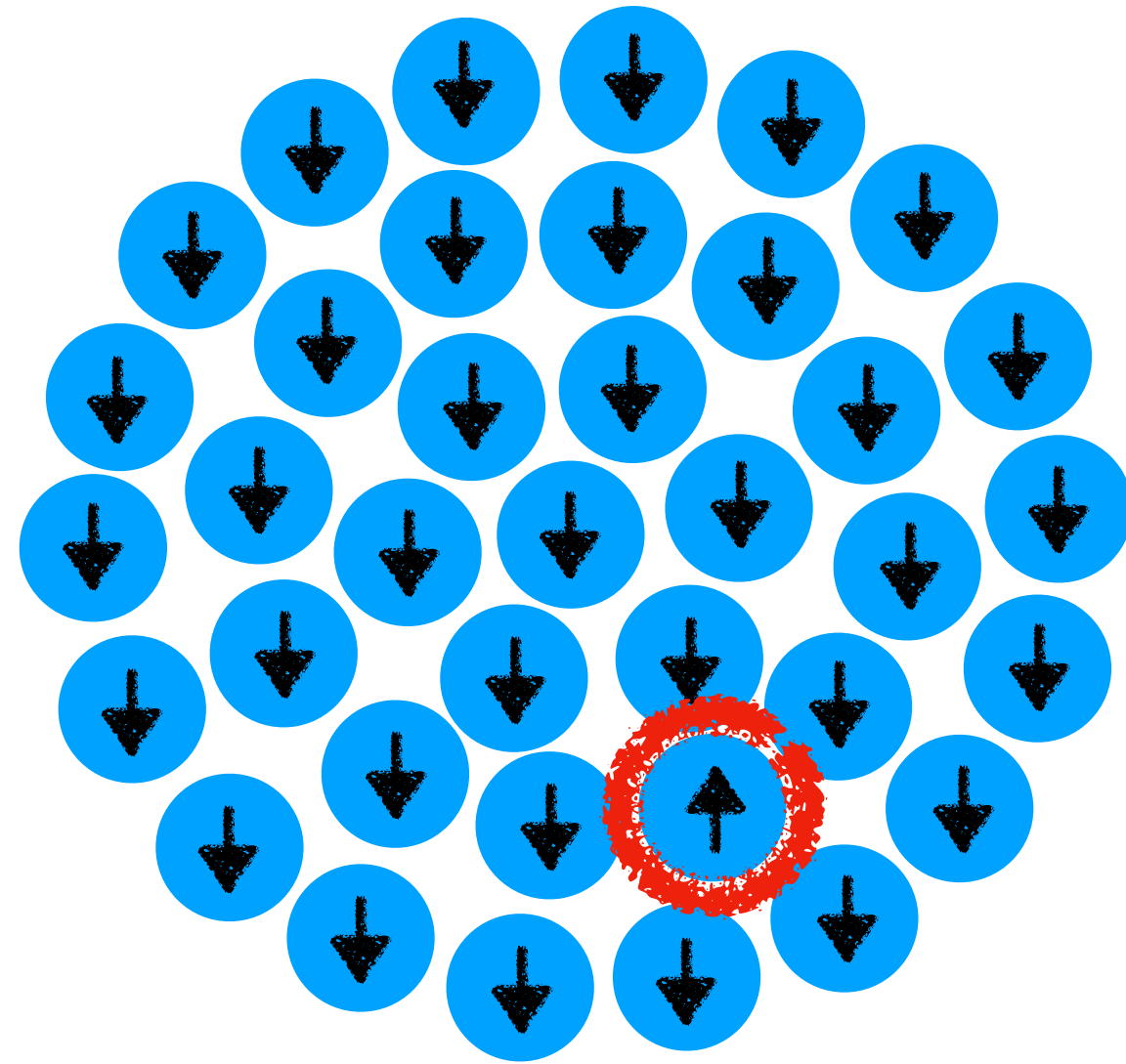


# In Coherence in Inelastic Processes



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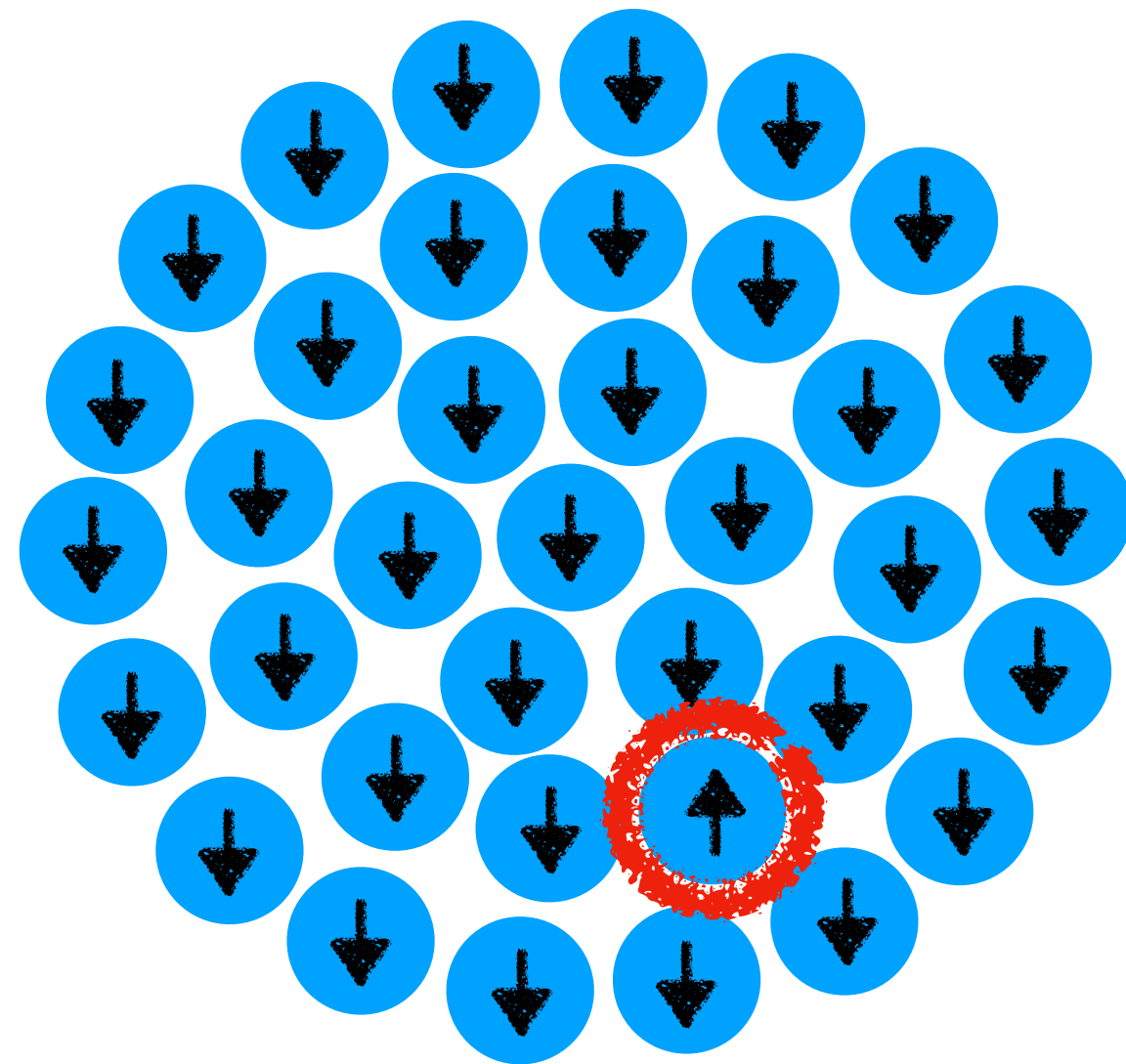


$$\Gamma \sim \left| \begin{array}{c} \text{[Diagram 1]} \\ + \\ \text{[Diagram 2]} \\ + \\ \text{[Diagram 3]} \\ + \dots \end{array} \right|^2$$

The equation shows the decay rate  $\Gamma$  as the squared magnitude of a sum of terms. Each term is a diagram of a 5-site cluster with one spin flipped (red upward arrow). The first diagram has the flipped spin in the center, the second has it at the top-right, and the third has it at the bottom-right. Ellipses indicate further terms in the sum.

$$|\psi\rangle = \prod |g\rangle$$

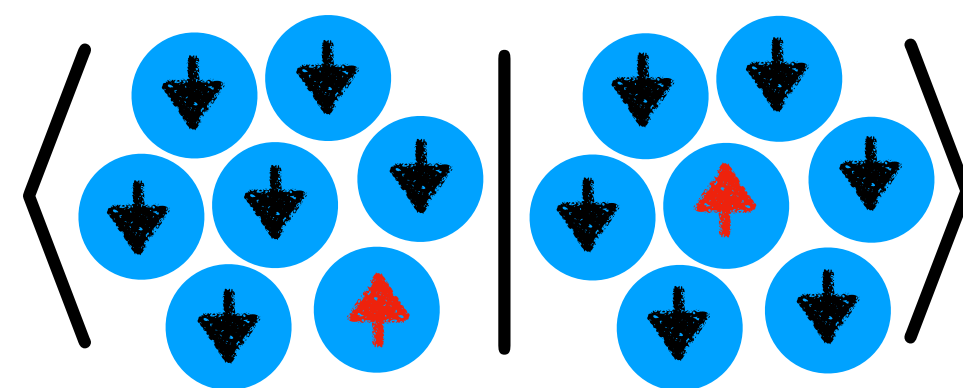
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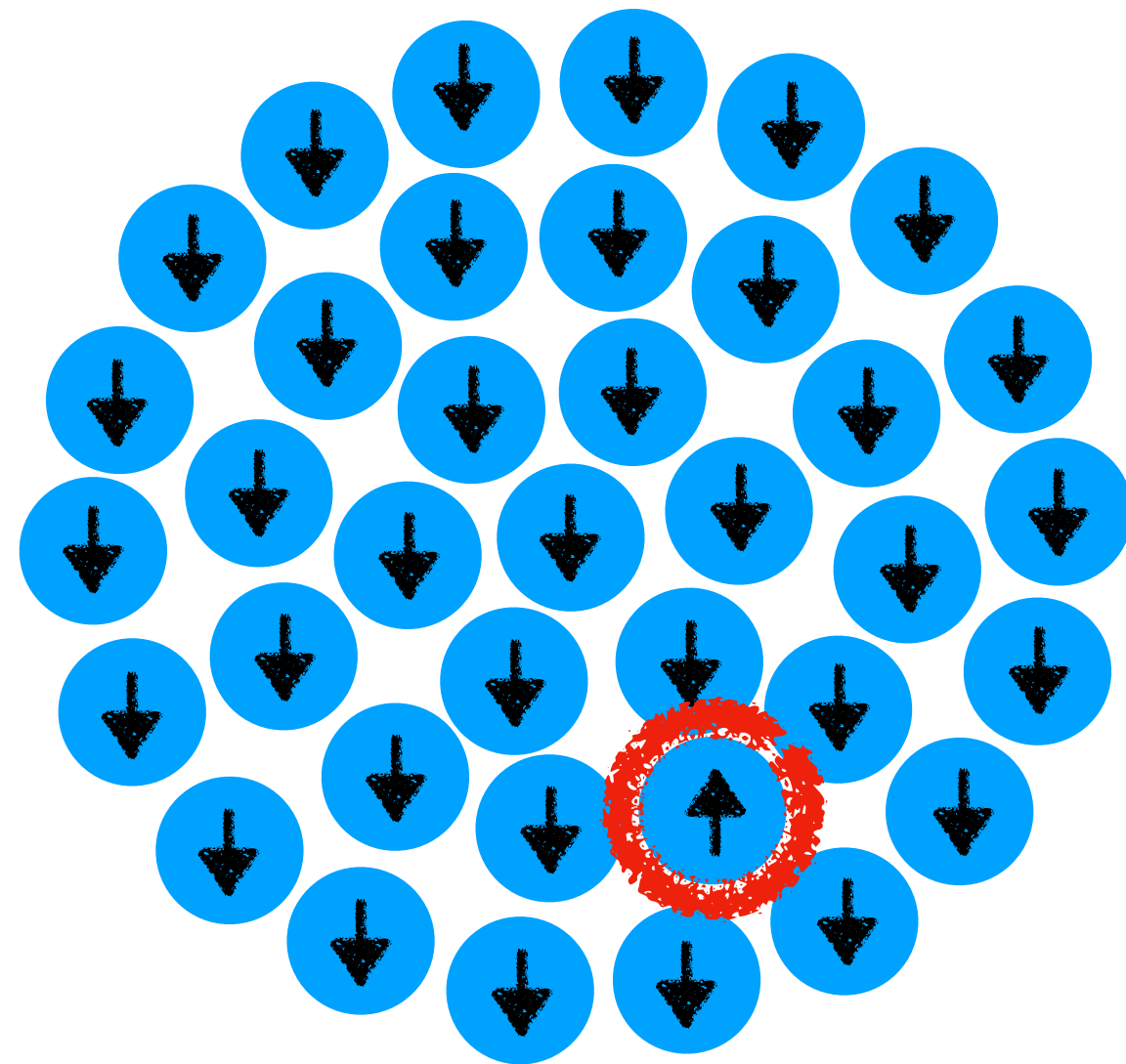
$$\Gamma \sim \left| \begin{array}{c} \text{[Diagram 1]} \\ \text{[Diagram 2]} \\ \text{[Diagram 3]} \\ \dots \end{array} \right|^2$$

The equation shows the decay rate  $\Gamma$  is proportional to the squared magnitude of a sum of states. The states are represented by diagrams of a 5-spin cluster. The first diagram has all spins down. The second diagram has the central spin up. The third diagram has the bottom-right spin up. Ellipses indicate further terms in the sum.

$$|\psi\rangle = \prod |g\rangle$$



# In Coherence in Inelastic Processes



$$\Gamma \sim \left| \begin{array}{c} \text{[Diagram 1]} \\ + \\ \text{[Diagram 2]} \\ + \\ \text{[Diagram 3]} \\ + \dots \end{array} \right|^2$$

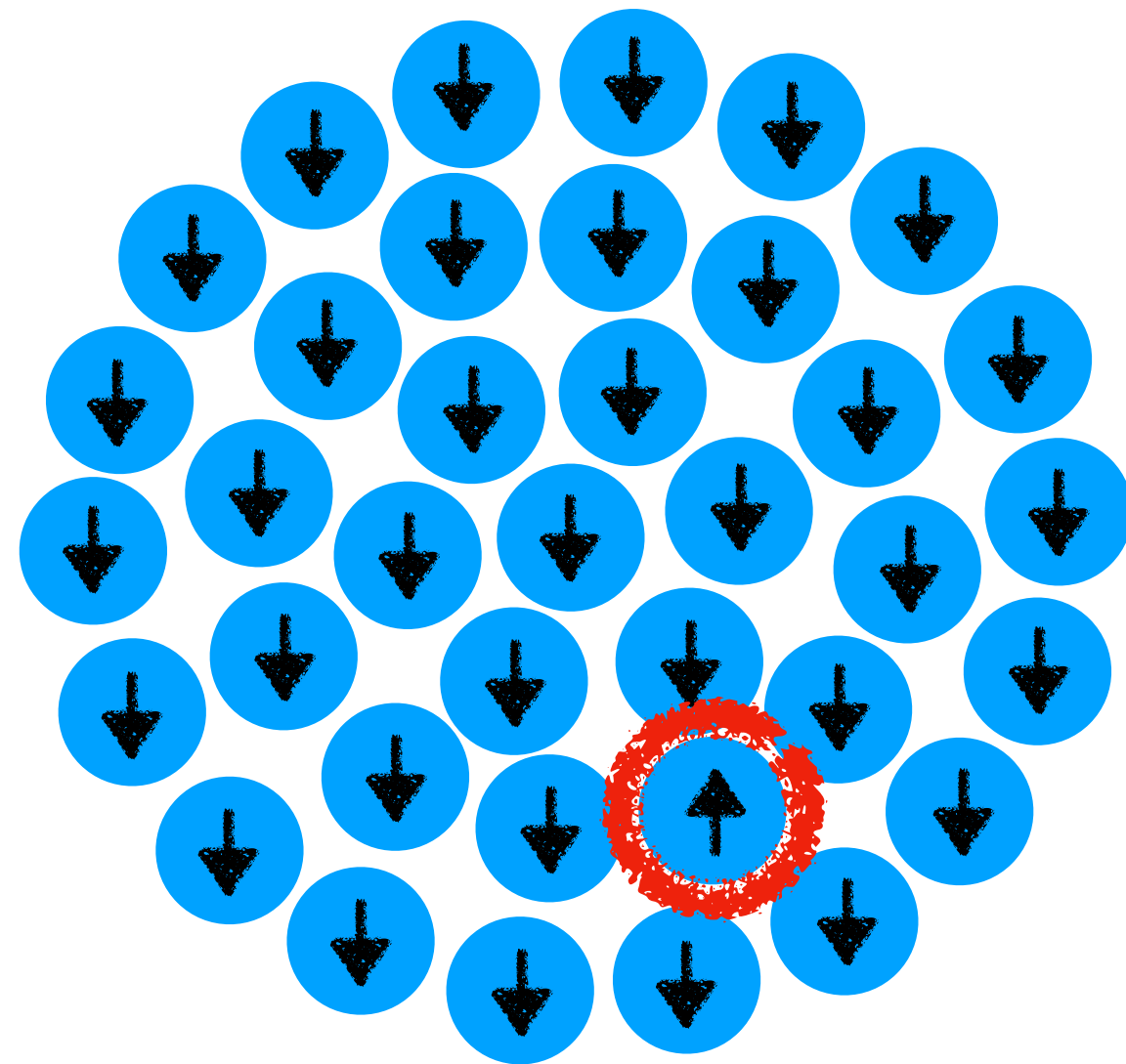
The diagram shows a sum of terms inside large vertical bars with a superscript 2. Each term is a small cluster of 6 blue particles with black arrows pointing down. In the first term, the central particle has a red arrow pointing up. In the second term, the particle to the right of the center has a red arrow pointing up. In the third term, the particle at the bottom right has a red arrow pointing up. Ellipses follow the third term.

$$|\psi\rangle = \prod |g\rangle$$

$$\langle \text{[Diagram 1]} | \text{[Diagram 2]} \rangle = \langle \text{[Diagram 3]} | \text{[Diagram 4]} \rangle$$

The diagram shows an inner product of two states. The left state is a cluster of 6 blue particles with black arrows pointing down, and the right state is a cluster of 6 blue particles with black arrows pointing down, where the central particle has a red arrow pointing up. This is equal to the product of two inner products: the first is a single blue particle with a black arrow pointing down and a single blue particle with a red arrow pointing up; the second is a single blue particle with a black arrow pointing up and a single blue particle with a red arrow pointing down.

# In Coherence in Inelastic Processes



$$\Gamma \sim \left| \begin{array}{c} \text{[Diagram 1]} \\ + \\ \text{[Diagram 2]} \\ + \\ \text{[Diagram 3]} \\ + \dots \end{array} \right|^2$$

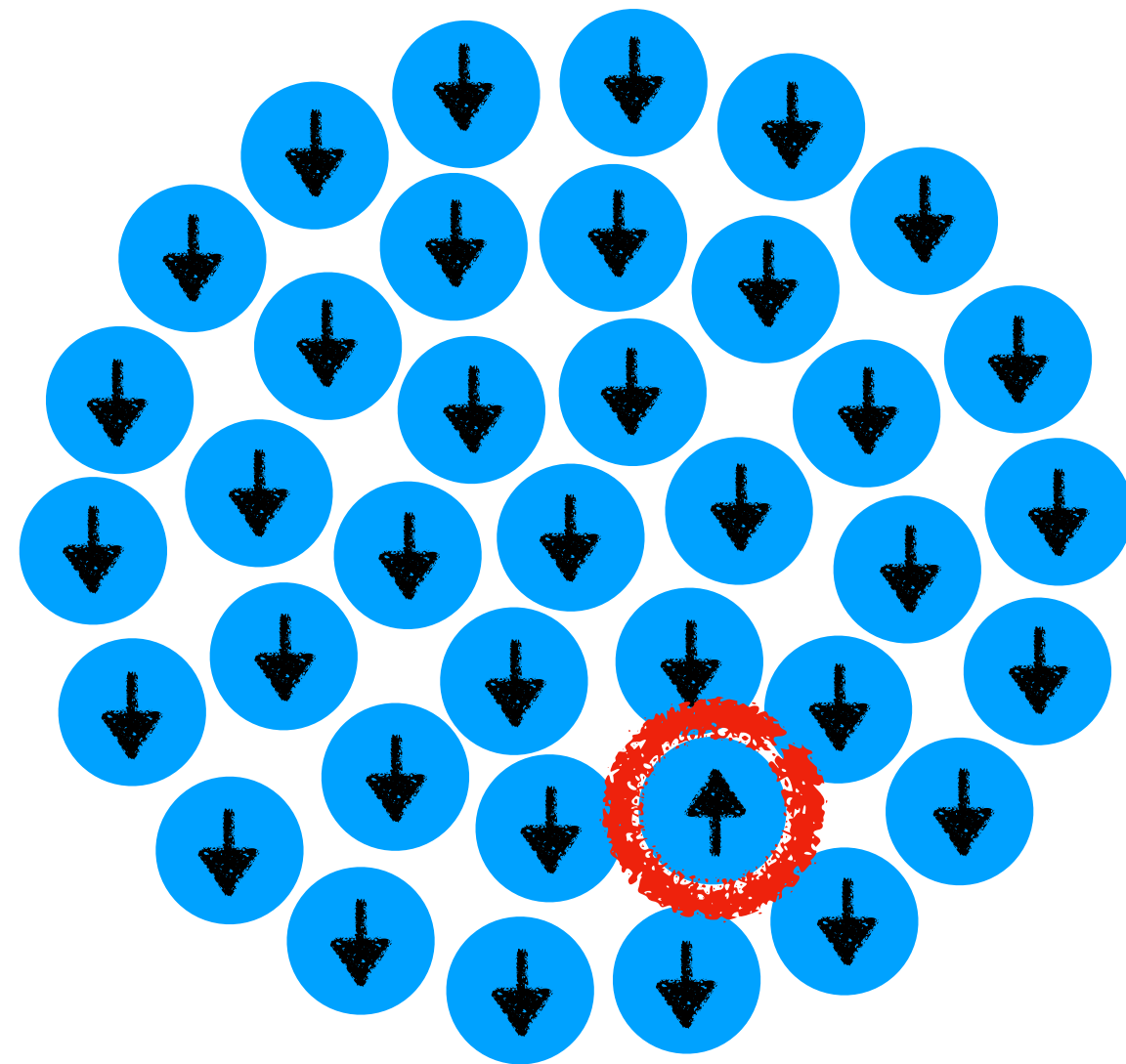
The diagram shows a sum of terms inside large vertical bars, with a superscript 2 to the right. Each term is a small cluster of blue atoms with black arrows pointing down. In each cluster, one atom has a red arrow pointing up. The position of the red arrow changes from one cluster to the next, illustrating a series of inelastic states.

$$|\psi\rangle = \prod |g\rangle$$

$$\langle \text{[Diagram 1]} | \text{[Diagram 2]} \rangle = \langle \text{[Red Up]} | \text{[Black Down]} \rangle \langle \text{[Black Down]} | \text{[Red Up]} \rangle = 0$$

The diagram shows the inner product of two states. The first state has a red arrow pointing up, and the second state has a black arrow pointing down. The inner product is shown to be zero, indicating that these states are orthogonal.

# In Coherence in Inelastic Processes



$$\Gamma \sim \left| \begin{array}{c} \text{[Diagram 1]} \\ \text{[Diagram 2]} \\ \text{[Diagram 3]} \\ \dots \end{array} \right|^2 = Nq^2$$

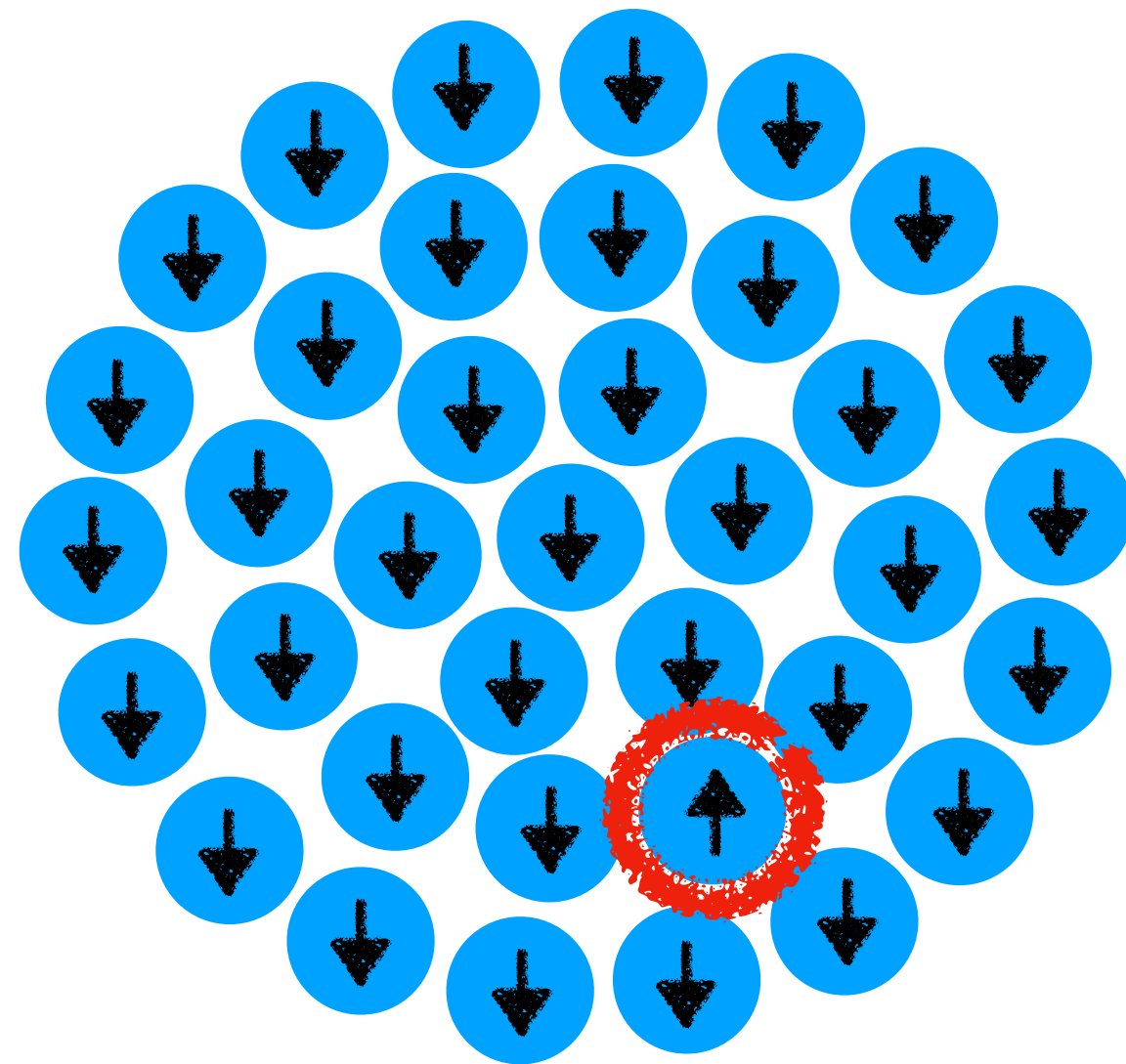
The diagram shows a sum of terms inside large vertical bars, squared. Each term is a small cluster of 6 blue circles with arrows. The first term has 5 downward arrows and 1 upward arrow in the center. The second term has 4 downward arrows and 1 upward arrow at the top. The third term has 4 downward arrows and 1 upward arrow at the bottom. Ellipses follow, indicating more terms.

$$|\psi\rangle = \prod |g\rangle$$

$$\langle \text{[Diagram 1]} | \text{[Diagram 2]} \rangle = \langle \uparrow | \downarrow \rangle \langle \downarrow | \uparrow \rangle = 0$$

The diagram shows two small clusters of 6 blue circles with arrows. The left cluster has 5 downward arrows and 1 upward arrow in the center. The right cluster has 4 downward arrows and 1 upward arrow at the top. The inner products are shown as  $\langle \uparrow | \downarrow \rangle$  and  $\langle \downarrow | \uparrow \rangle$ .

# In Coherence in Inelastic Processes



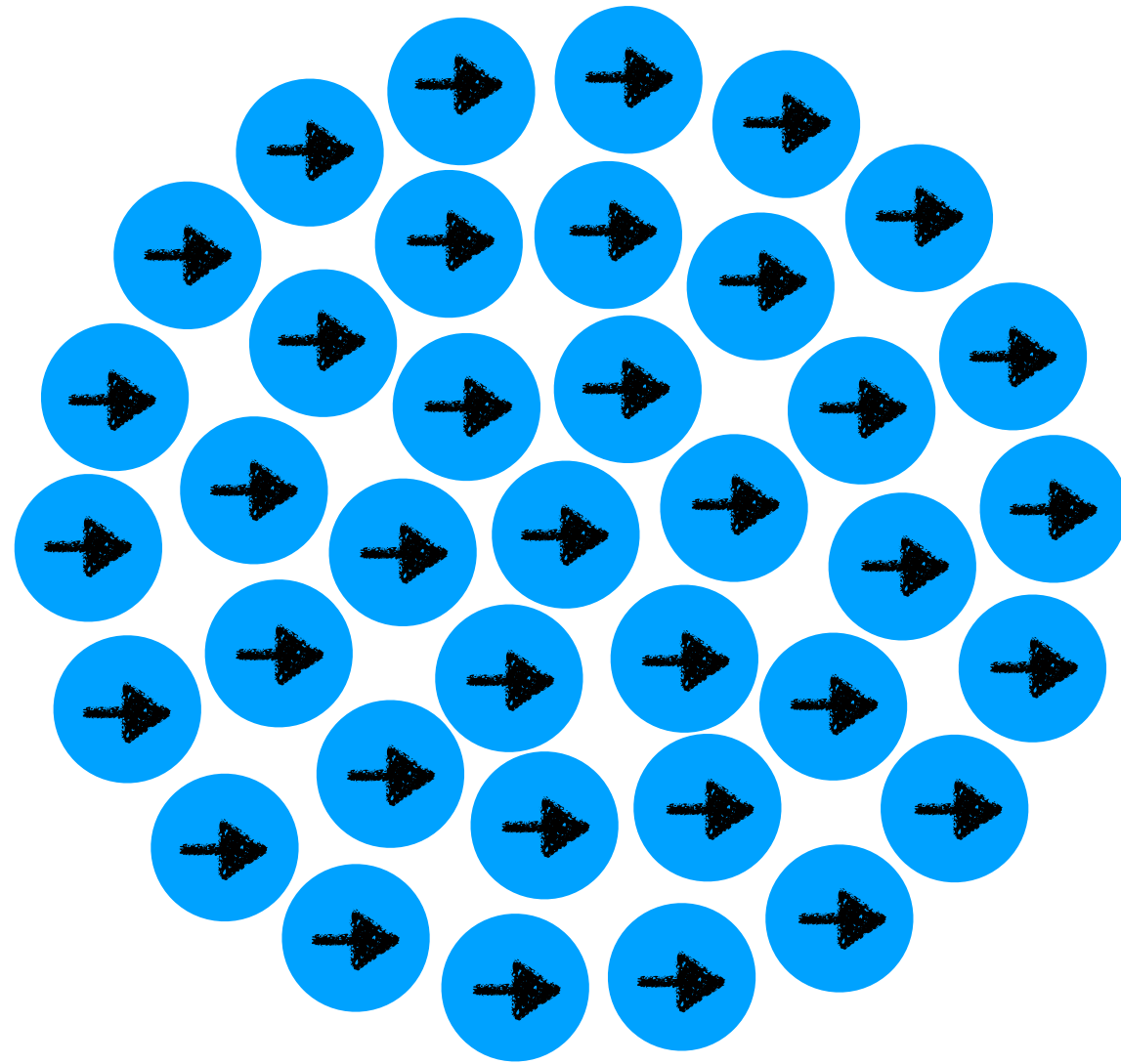
$$\Gamma \sim \left| \begin{array}{c} \text{[Diagram: 6 blue circles, 1 red up arrow]} \\ \text{[Diagram: 6 blue circles, 1 red up arrow]} \\ \text{[Diagram: 6 blue circles, 1 red up arrow]} \\ \dots \end{array} \right|^2$$

$= Nq^2$  Incoherent

$$|\psi\rangle = \prod |g\rangle$$

$$\langle \text{[Diagram: 6 blue circles, 1 red up arrow]} | \text{[Diagram: 6 blue circles, 1 red up arrow]} \rangle = \langle \text{[Diagram: 1 red up arrow]} | \text{[Diagram: 1 blue down arrow]} \rangle \langle \text{[Diagram: 1 blue down arrow]} | \text{[Diagram: 1 red up arrow]} \rangle = 0$$

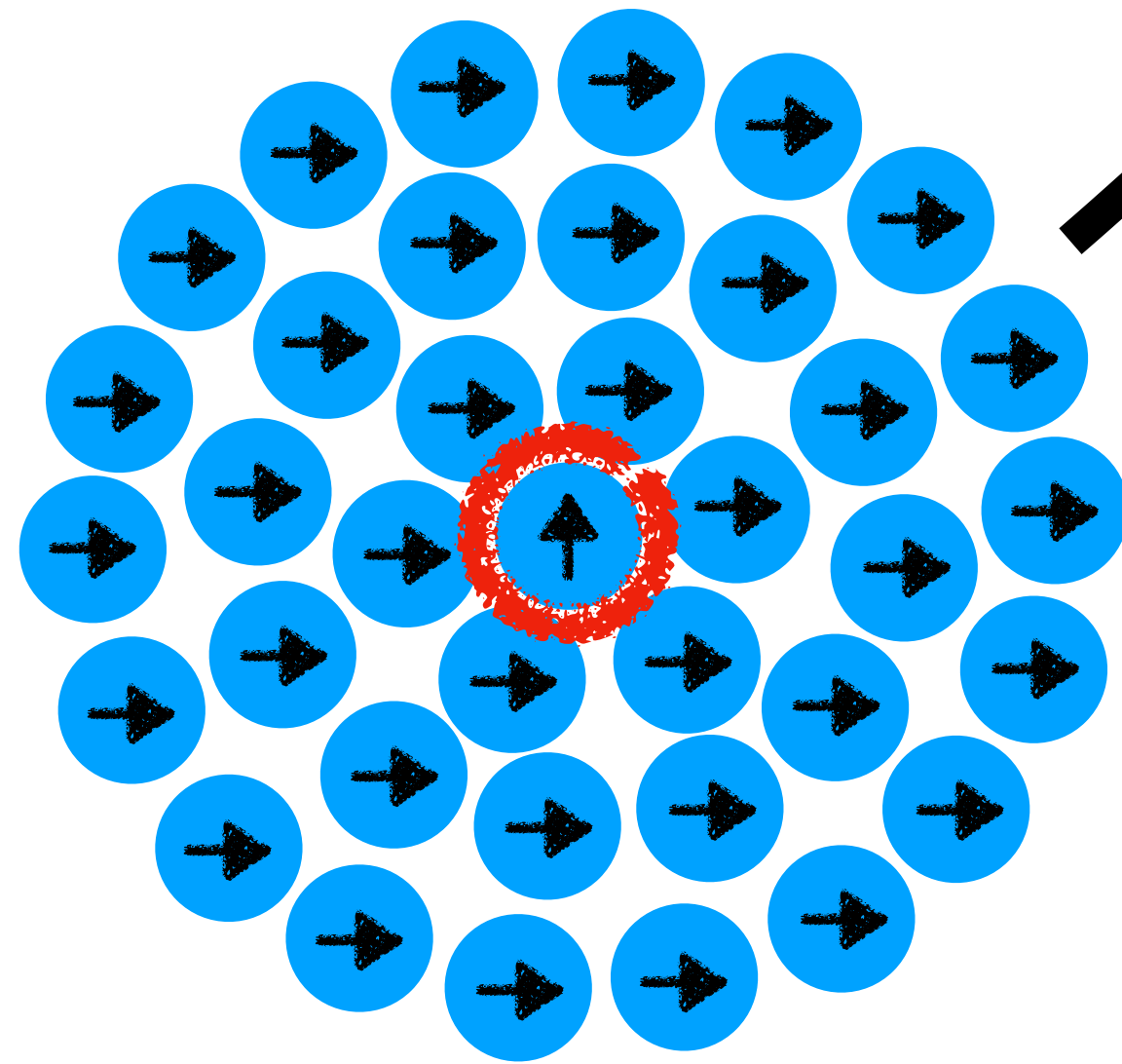
# Coherence in Inelastic Processes



$$|\psi\rangle = \prod \frac{1}{\sqrt{2}} (|g\rangle + |e\rangle)$$

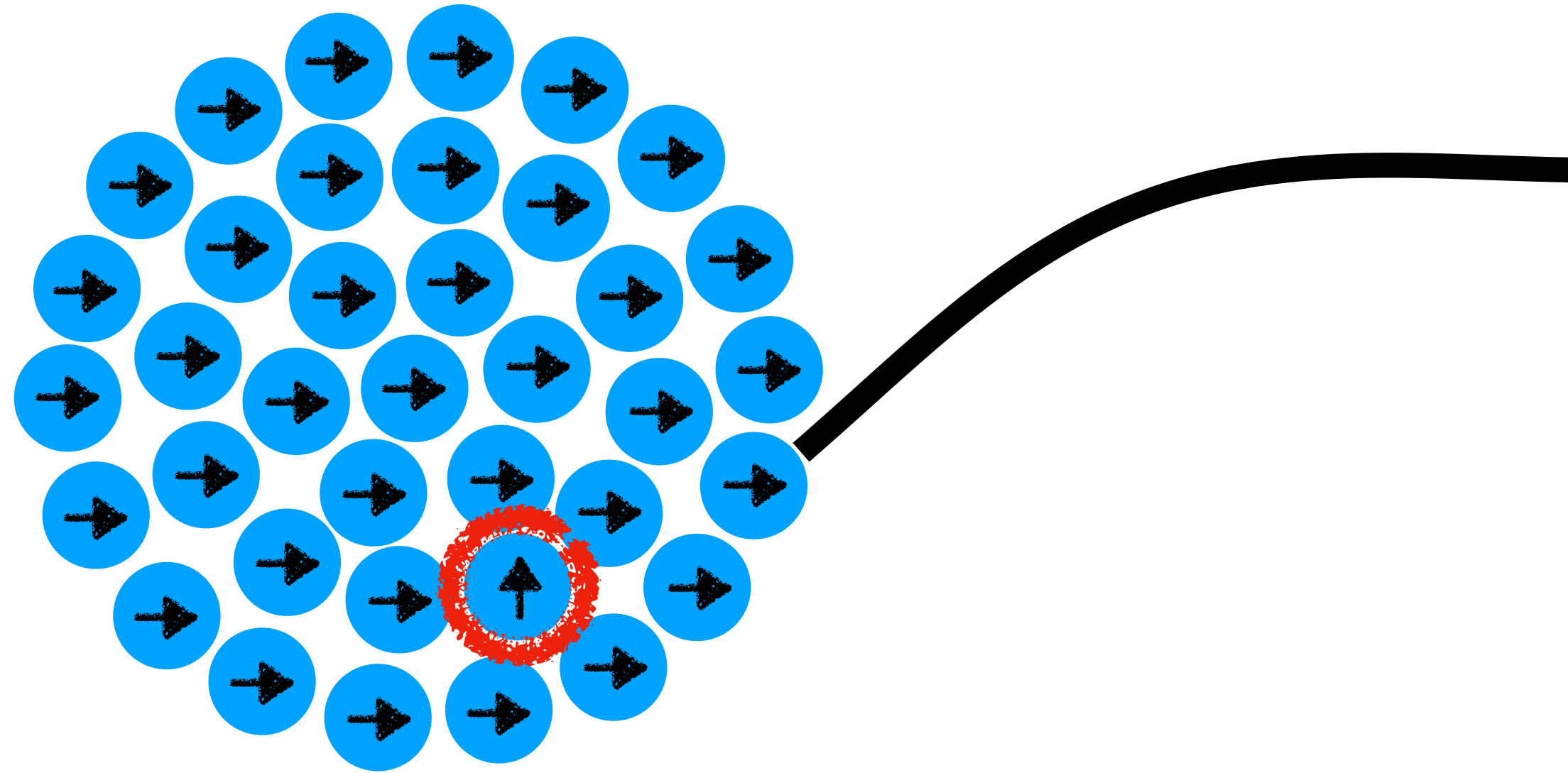


# Coherence in Inelastic Processes



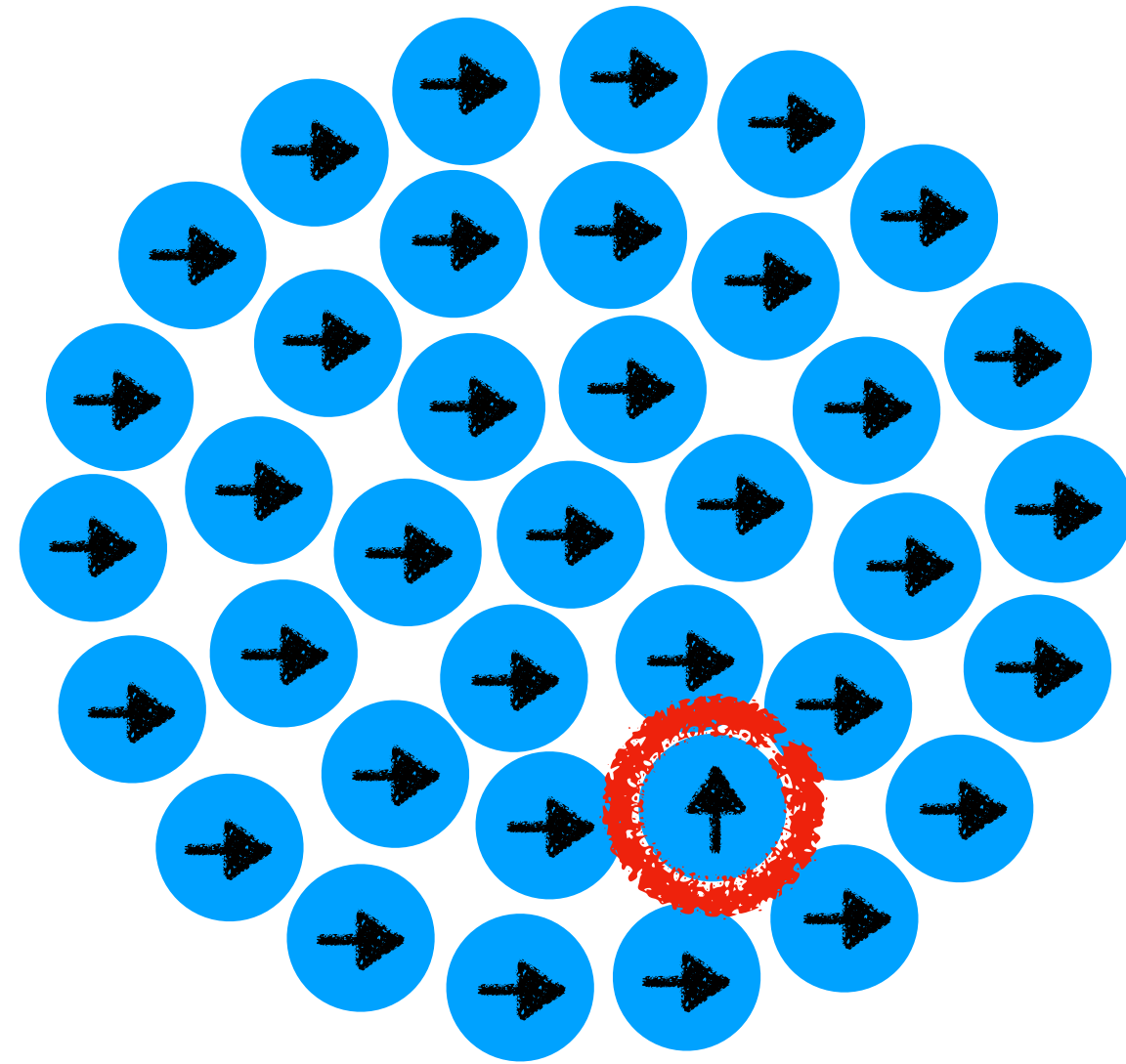
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# Coherence in Inelastic Processes



$$|\psi\rangle = \prod \frac{1}{\sqrt{2}} (|g\rangle + |e\rangle)$$

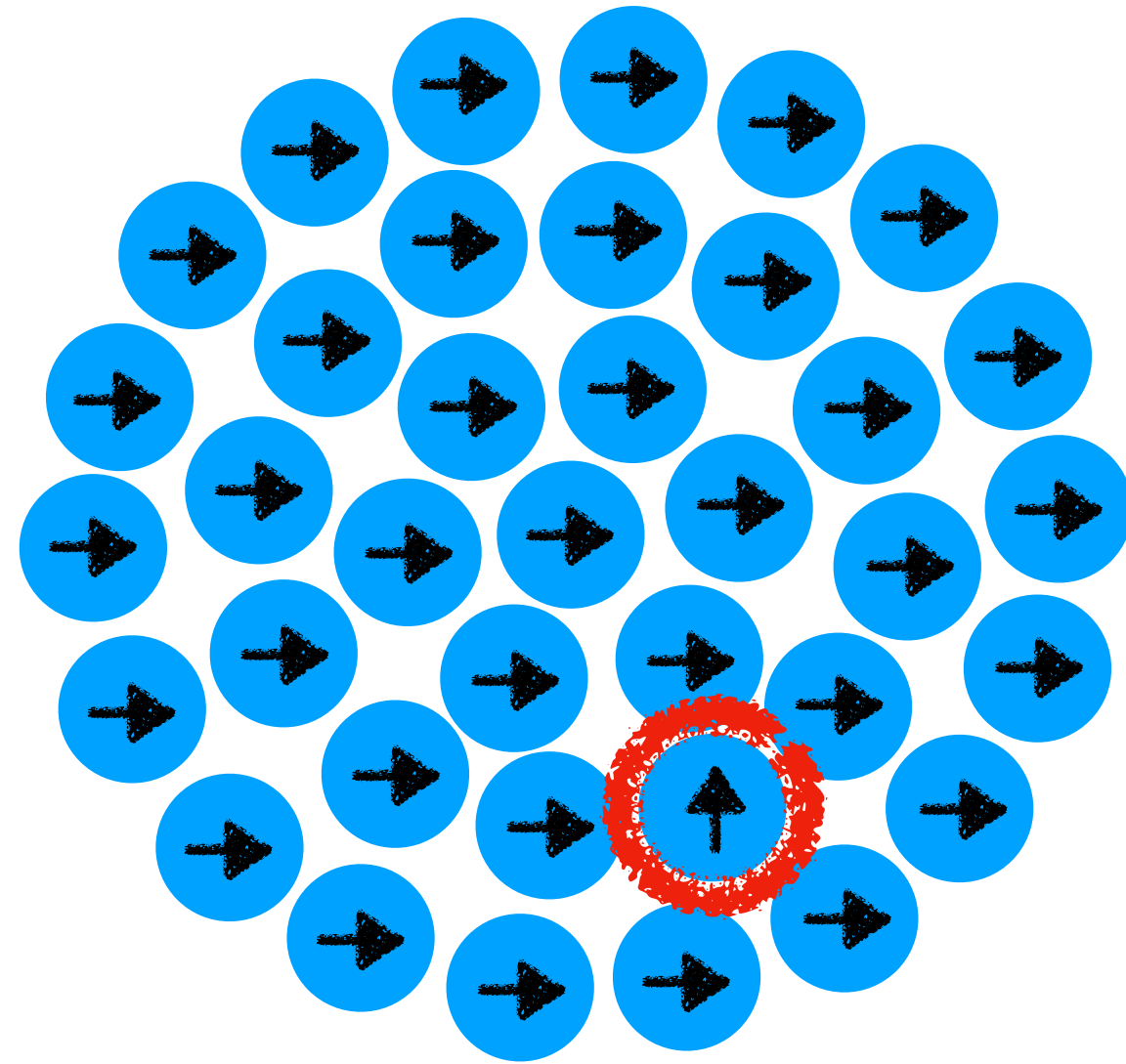
# Coherence in Inelastic Processes



$$\Gamma \sim \left| \frac{1}{\sqrt{2}} \begin{array}{c} \rightarrow \rightarrow \\ \rightarrow \uparrow \rightarrow \\ \rightarrow \rightarrow \end{array} + \frac{1}{\sqrt{2}} \begin{array}{c} \rightarrow \rightarrow \\ \rightarrow \rightarrow \rightarrow \\ \rightarrow \rightarrow \end{array} + \frac{1}{\sqrt{2}} \begin{array}{c} \rightarrow \rightarrow \\ \rightarrow \rightarrow \rightarrow \\ \rightarrow \uparrow \end{array} + \dots \right|^2$$

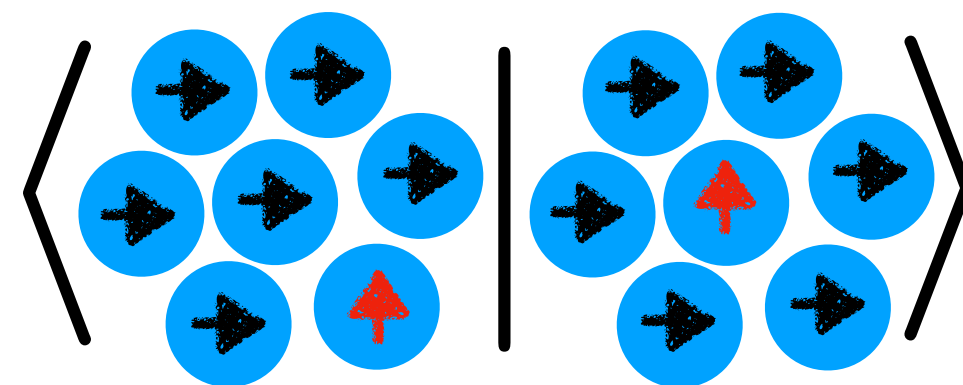
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# Coherence in Inelastic Processes

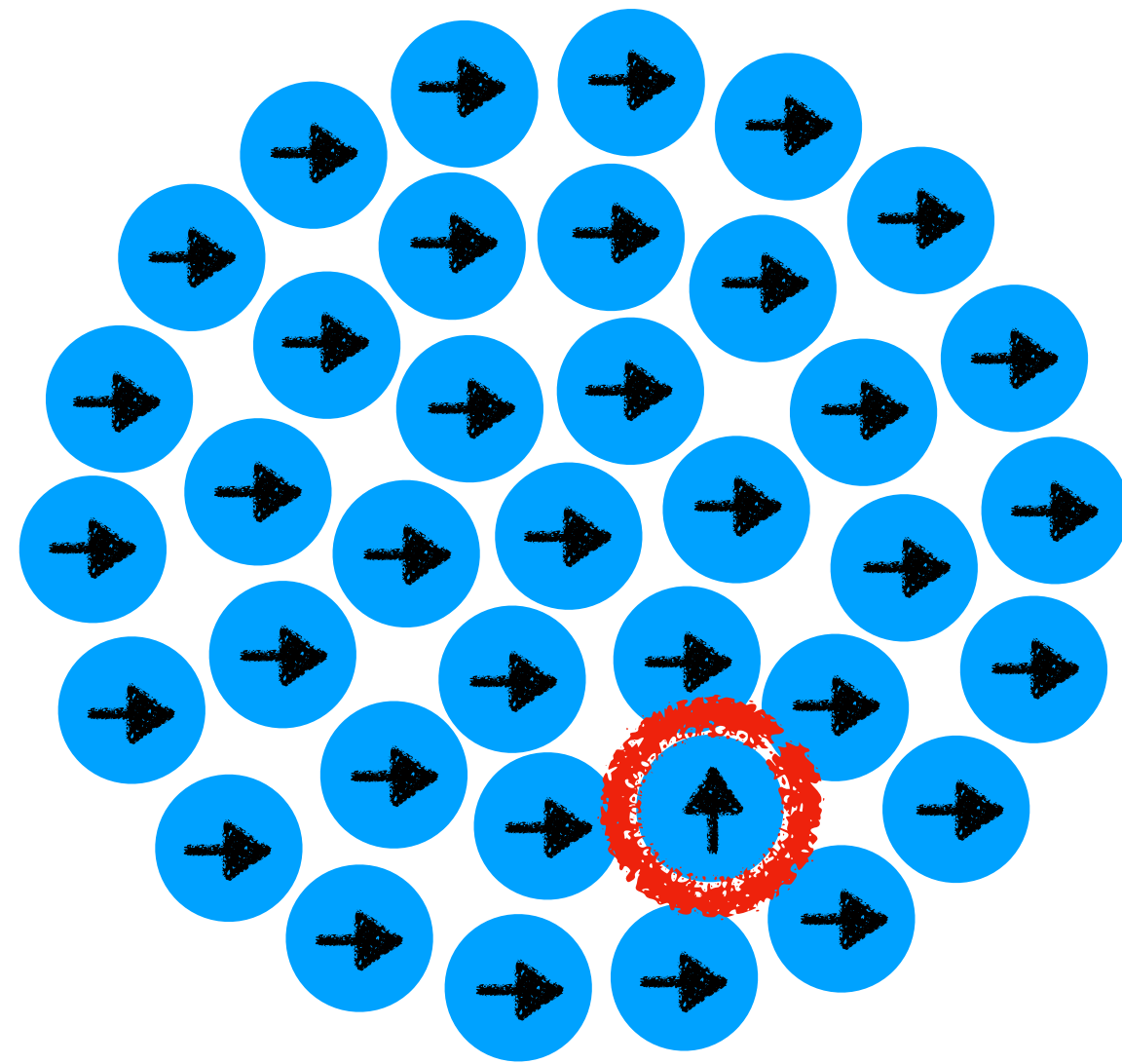


$$\Gamma \sim \left| \frac{1}{\sqrt{2}} \begin{array}{c} \rightarrow \rightarrow \\ \rightarrow \uparrow \rightarrow \\ \rightarrow \rightarrow \end{array} + \frac{1}{\sqrt{2}} \begin{array}{c} \rightarrow \rightarrow \\ \rightarrow \rightarrow \uparrow \\ \rightarrow \rightarrow \end{array} + \frac{1}{\sqrt{2}} \begin{array}{c} \rightarrow \rightarrow \\ \rightarrow \rightarrow \\ \rightarrow \uparrow \end{array} + \dots \right|^2$$

$$|\psi\rangle = \frac{1}{\sqrt{2}} (|g\rangle + |e\rangle)$$



# Coherence in Inelastic Processes

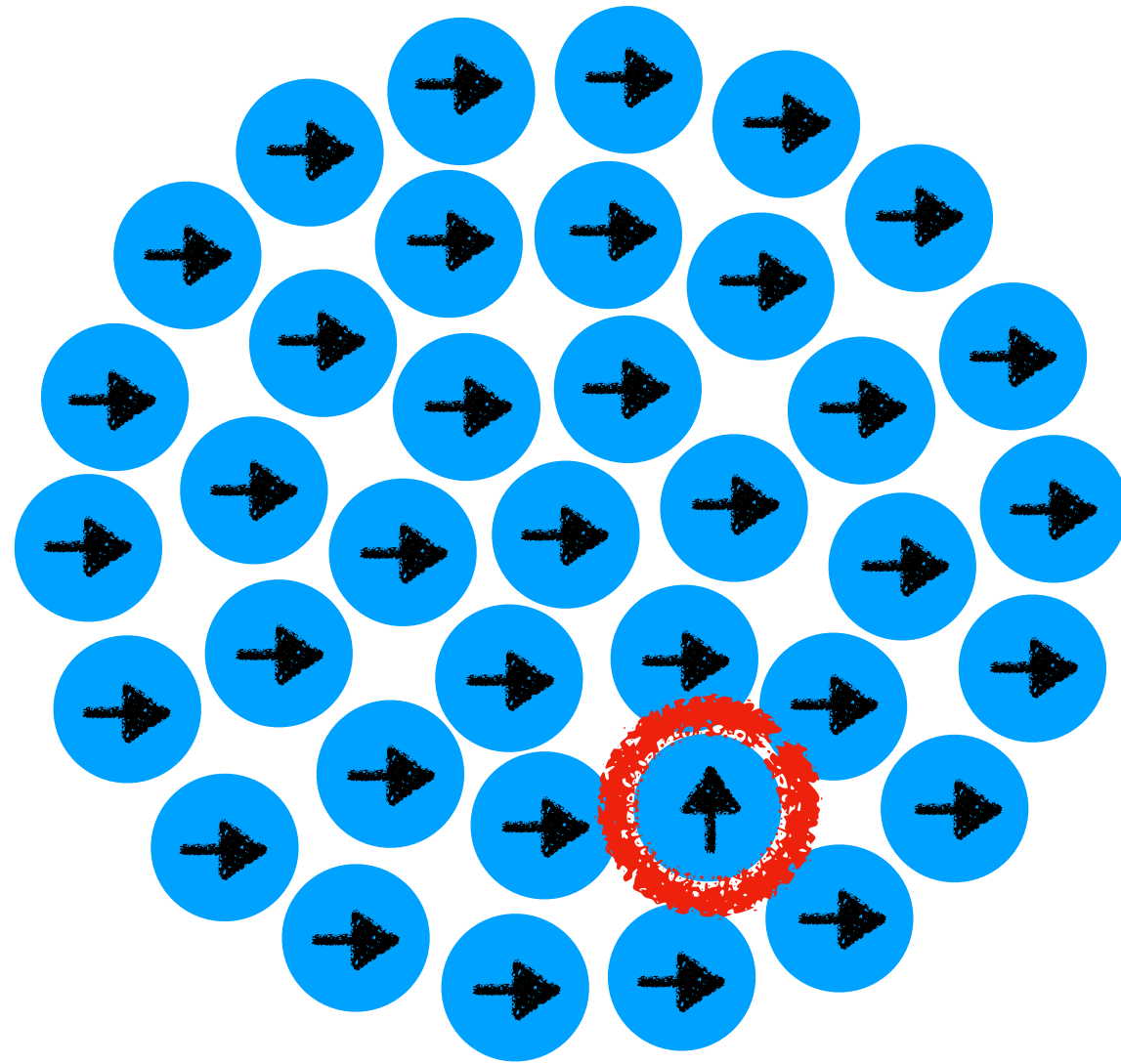


$$\Gamma \sim \left| \frac{1}{\sqrt{2}} \begin{array}{c} \blackrightarrow \blackrightarrow \\ \blackrightarrow \color{red}\blackrightarrow \blackrightarrow \\ \blackrightarrow \blackrightarrow \end{array} + \frac{1}{\sqrt{2}} \begin{array}{c} \blackrightarrow \blackrightarrow \\ \blackrightarrow \blackrightarrow \color{red}\blackrightarrow \\ \blackrightarrow \blackrightarrow \end{array} + \frac{1}{\sqrt{2}} \begin{array}{c} \blackrightarrow \blackrightarrow \\ \blackrightarrow \blackrightarrow \blackrightarrow \\ \blackrightarrow \color{red}\blackrightarrow \end{array} + \dots \right|^2$$

$$|\psi\rangle = \frac{1}{\sqrt{2}} (|g\rangle + |e\rangle)$$

$$\left\langle \begin{array}{c} \blackrightarrow \blackrightarrow \\ \blackrightarrow \color{red}\blackrightarrow \blackrightarrow \\ \blackrightarrow \blackrightarrow \end{array} \middle| \begin{array}{c} \blackrightarrow \blackrightarrow \\ \blackrightarrow \blackrightarrow \color{red}\blackrightarrow \\ \blackrightarrow \blackrightarrow \end{array} \right\rangle = \langle \color{red}\blackrightarrow | \blackrightarrow \rangle \langle \blackrightarrow | \color{red}\blackrightarrow \rangle$$

# Coherence in Inelastic Processes

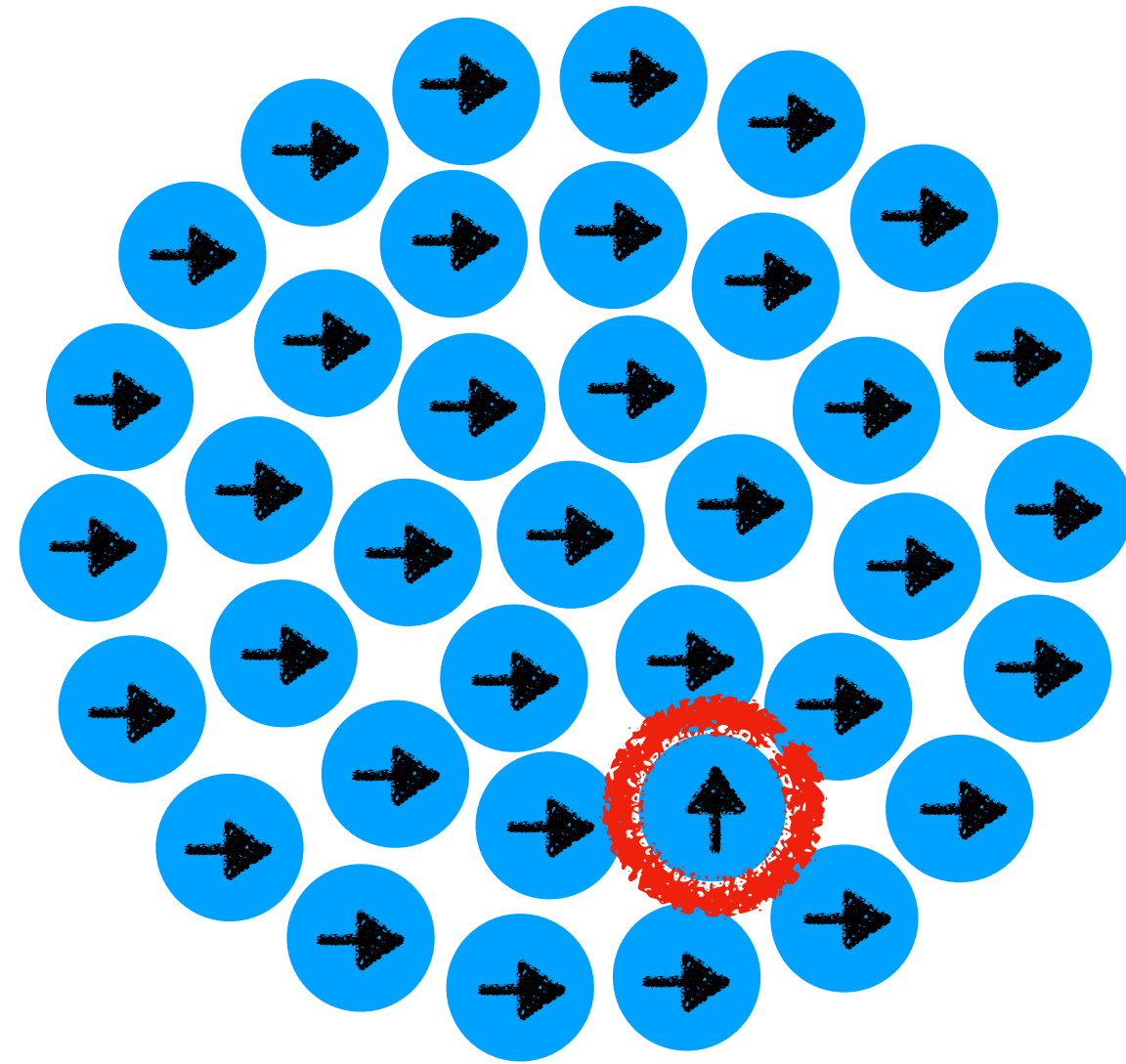


$$\Gamma \sim \left| \frac{1}{\sqrt{2}} \begin{array}{c} \rightarrow \rightarrow \\ \rightarrow \color{red}{\rightarrow} \\ \rightarrow \rightarrow \end{array} + \frac{1}{\sqrt{2}} \begin{array}{c} \rightarrow \rightarrow \\ \rightarrow \rightarrow \\ \rightarrow \color{red}{\rightarrow} \end{array} + \frac{1}{\sqrt{2}} \begin{array}{c} \rightarrow \rightarrow \\ \rightarrow \rightarrow \\ \color{red}{\rightarrow} \end{array} + \dots \right|^2$$

$$|\psi\rangle = \frac{1}{\sqrt{2}} (|g\rangle + |e\rangle)$$

$$\left\langle \begin{array}{c} \rightarrow \rightarrow \\ \rightarrow \color{red}{\rightarrow} \\ \rightarrow \rightarrow \end{array} \middle| \begin{array}{c} \rightarrow \rightarrow \\ \rightarrow \rightarrow \\ \rightarrow \color{red}{\rightarrow} \end{array} \right\rangle = \langle \color{red}{\rightarrow} | \rightarrow \rangle \langle \rightarrow | \color{red}{\rightarrow} \rangle = \frac{1}{2}$$

# Coherence in Inelastic Processes



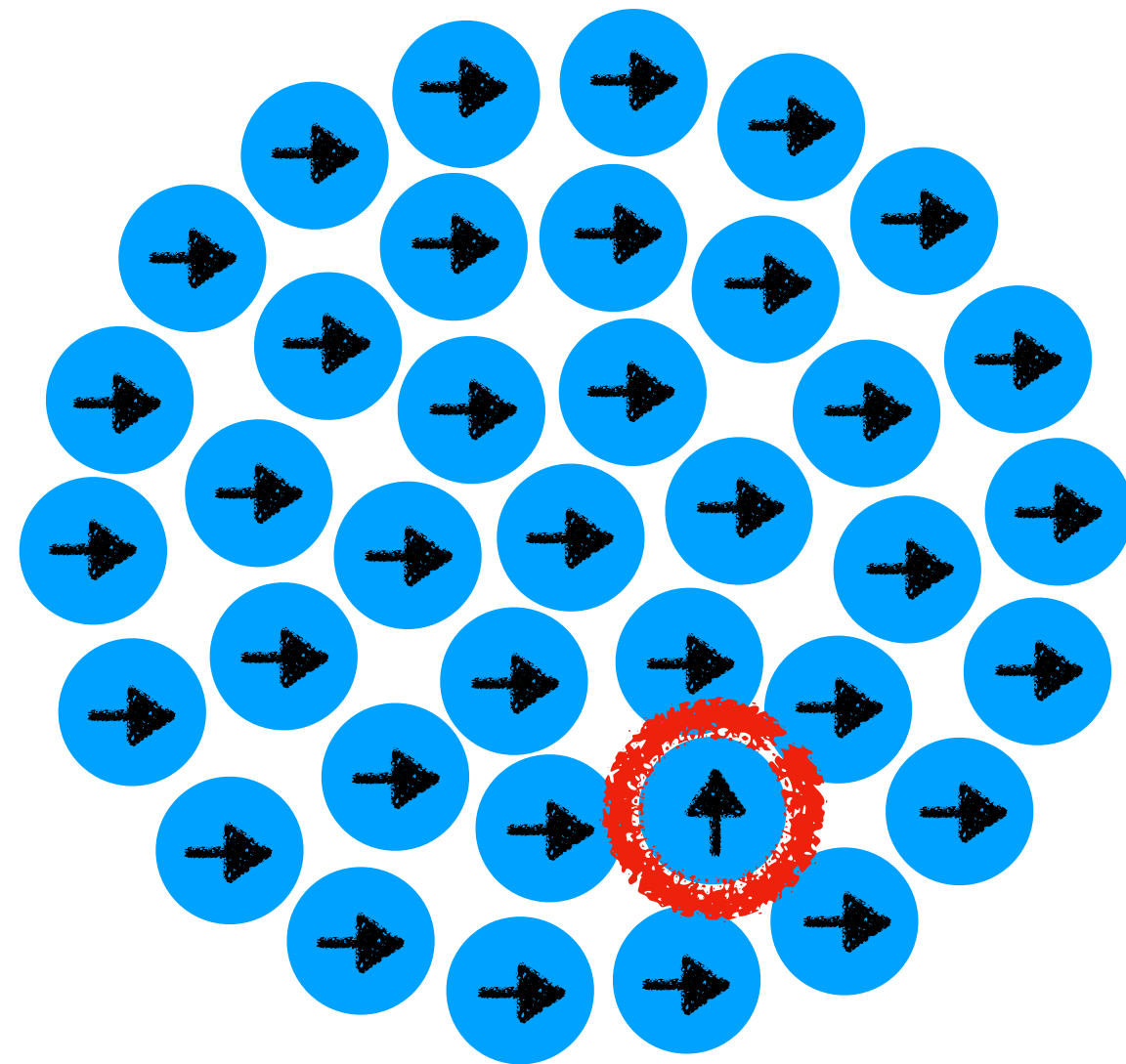
$$\Gamma \sim \left| \frac{1}{\sqrt{2}} \begin{array}{c} \rightarrow \rightarrow \\ \rightarrow \color{red}{\uparrow} \rightarrow \\ \rightarrow \rightarrow \end{array} + \frac{1}{\sqrt{2}} \begin{array}{c} \rightarrow \rightarrow \\ \rightarrow \rightarrow \color{red}{\uparrow} \\ \rightarrow \rightarrow \end{array} + \frac{1}{\sqrt{2}} \begin{array}{c} \rightarrow \rightarrow \\ \rightarrow \rightarrow \\ \rightarrow \color{red}{\uparrow} \end{array} + \dots \right|^2$$

$$= \frac{N^2}{4}$$

$$|\psi\rangle = \frac{1}{\sqrt{2}} (|g\rangle + |e\rangle)$$

$$\left\langle \begin{array}{c} \rightarrow \rightarrow \\ \rightarrow \color{red}{\uparrow} \rightarrow \\ \rightarrow \rightarrow \end{array} \middle| \begin{array}{c} \rightarrow \rightarrow \\ \rightarrow \rightarrow \color{red}{\uparrow} \\ \rightarrow \rightarrow \end{array} \right\rangle = \langle \color{red}{\uparrow} | \rightarrow \rangle \langle \rightarrow | \color{red}{\uparrow} \rangle = \frac{1}{2}$$

# Coherence in Inelastic Processes



$$\Gamma \sim \left| \frac{1}{\sqrt{2}} \begin{array}{c} \rightarrow \rightarrow \\ \rightarrow \uparrow \rightarrow \\ \rightarrow \rightarrow \end{array} + \frac{1}{\sqrt{2}} \begin{array}{c} \rightarrow \rightarrow \\ \rightarrow \rightarrow \uparrow \\ \rightarrow \rightarrow \end{array} + \frac{1}{\sqrt{2}} \begin{array}{c} \rightarrow \rightarrow \\ \rightarrow \rightarrow \\ \rightarrow \uparrow \end{array} + \dots \right|^2$$

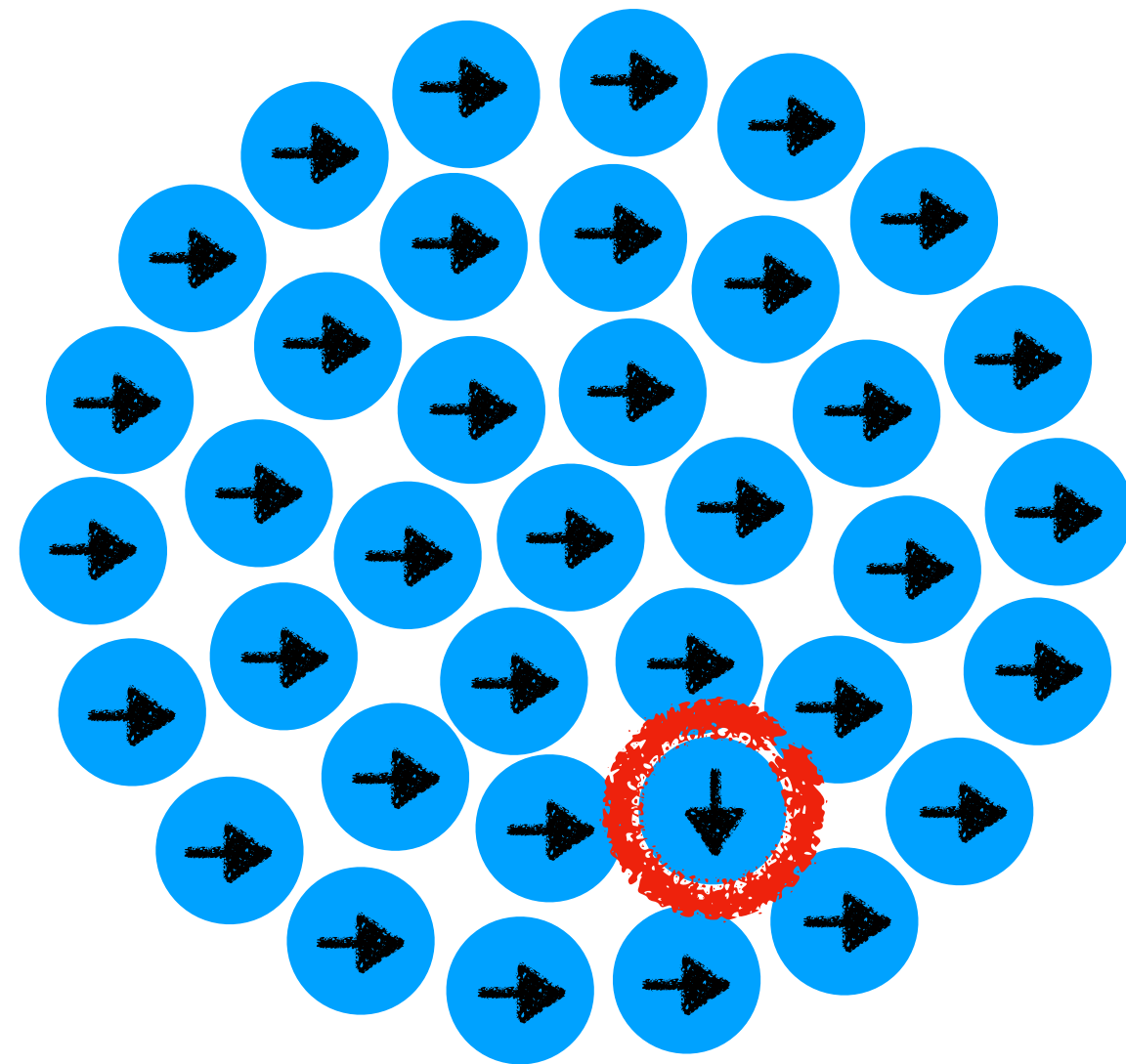
$= \frac{N^2}{4}$ 
Coherent Excitation

$$|\psi\rangle = \frac{1}{\sqrt{2}} (|g\rangle + |e\rangle)$$

$$\left\langle \begin{array}{c} \rightarrow \rightarrow \\ \rightarrow \rightarrow \uparrow \\ \rightarrow \rightarrow \end{array} \middle| \begin{array}{c} \rightarrow \rightarrow \\ \rightarrow \rightarrow \\ \rightarrow \uparrow \end{array} \right\rangle = \langle \uparrow | \rightarrow \rangle \langle \rightarrow | \uparrow \rangle = \frac{1}{2}$$



# Coherence in Inelastic Processes



$$\Gamma \sim \left| \frac{1}{\sqrt{2}} \begin{array}{c} \rightarrow \rightarrow \\ \rightarrow \downarrow \rightarrow \\ \rightarrow \rightarrow \end{array} + \frac{1}{\sqrt{2}} \begin{array}{c} \rightarrow \rightarrow \\ \rightarrow \rightarrow \downarrow \\ \rightarrow \end{array} + \frac{1}{\sqrt{2}} \begin{array}{c} \rightarrow \rightarrow \\ \rightarrow \rightarrow \\ \rightarrow \rightarrow \downarrow \end{array} + \dots \right|^2$$

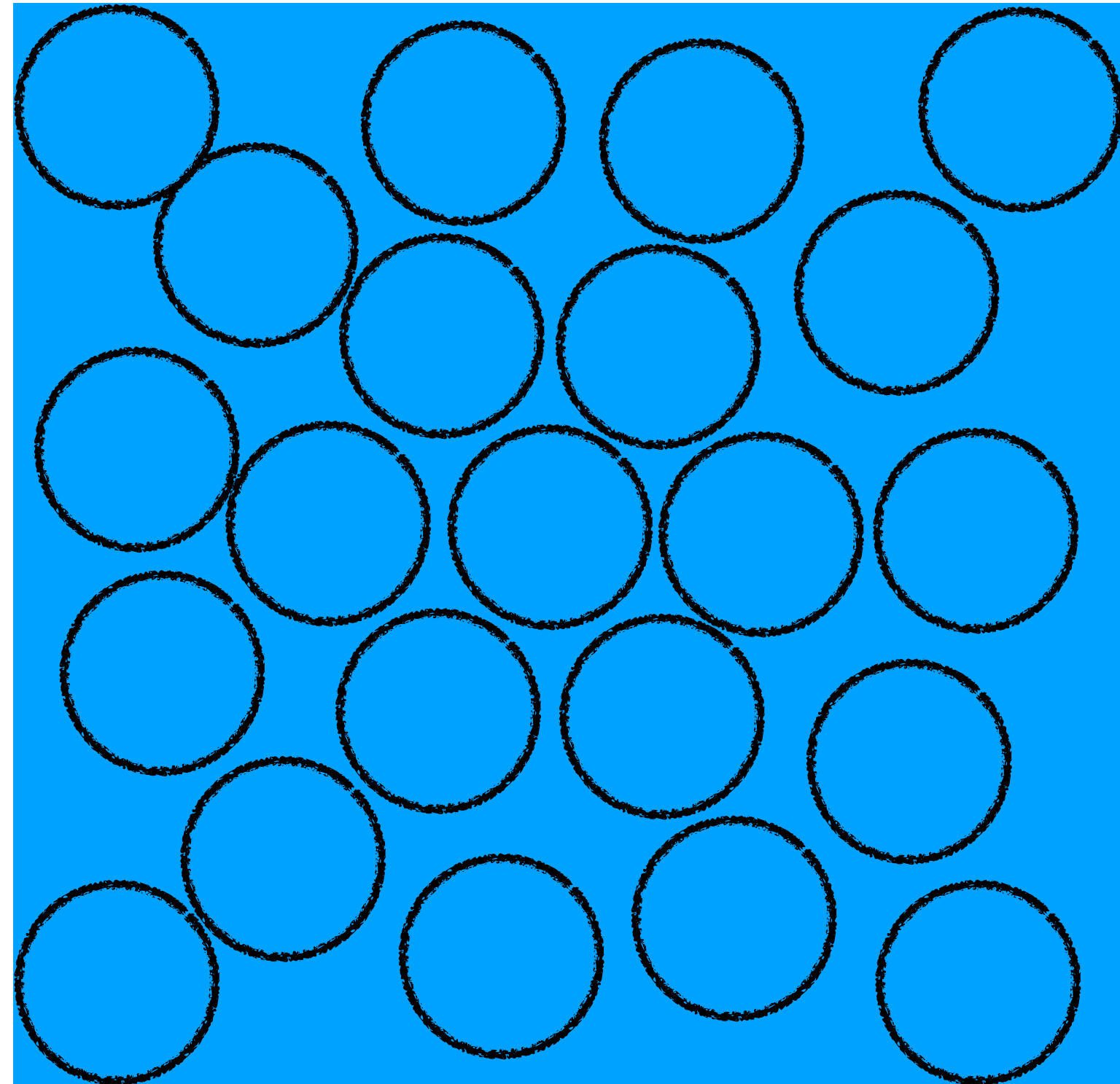
$$= \frac{N^2}{4}$$

Coherent De-excitation

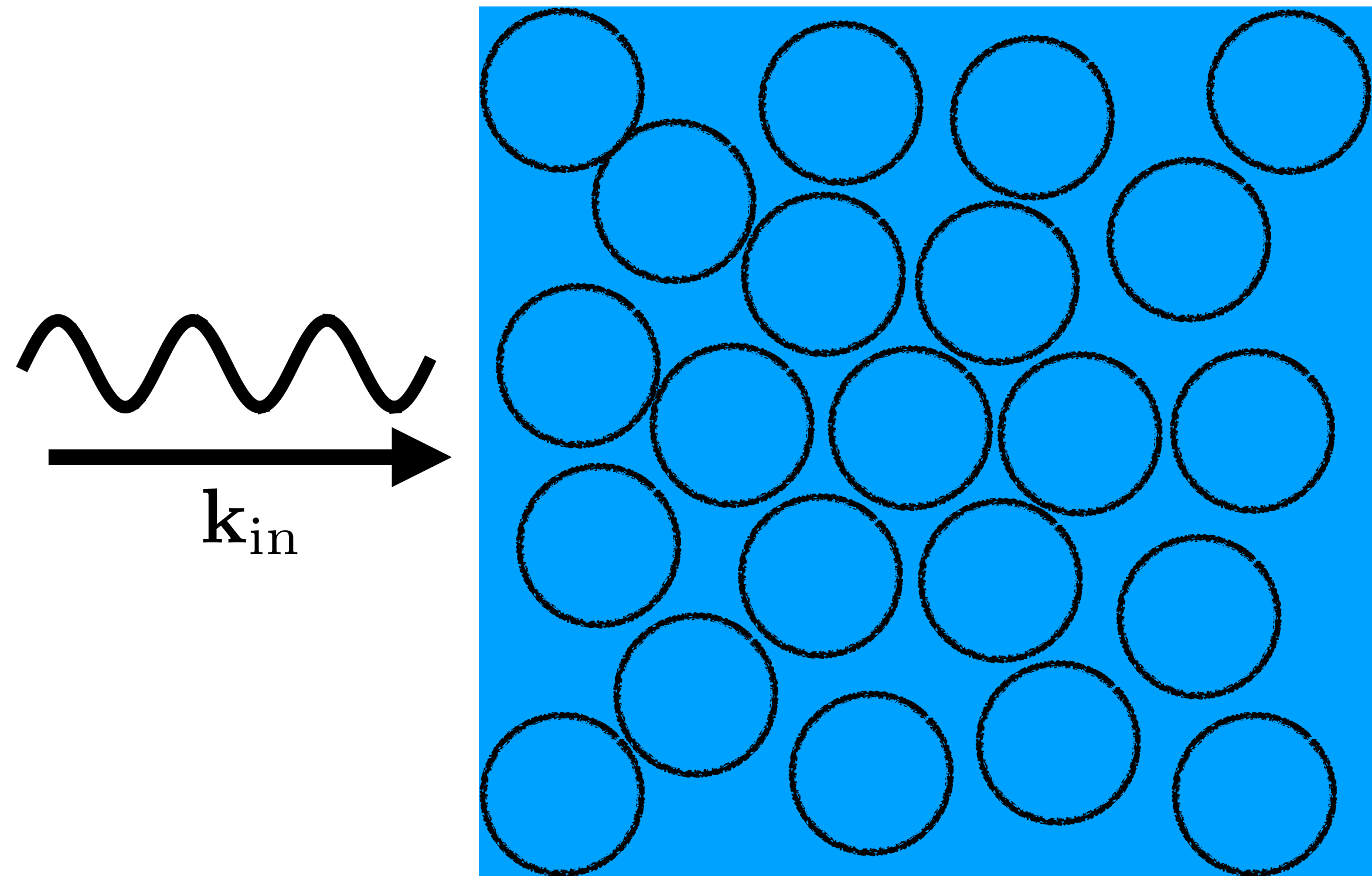
$$|\psi\rangle = \frac{1}{\sqrt{2}} (|g\rangle + |e\rangle)$$

$$\left\langle \begin{array}{c} \rightarrow \rightarrow \\ \rightarrow \rightarrow \downarrow \\ \rightarrow \end{array} \middle| \begin{array}{c} \rightarrow \rightarrow \\ \rightarrow \rightarrow \\ \rightarrow \rightarrow \downarrow \end{array} \right\rangle = \langle \downarrow | \rightarrow \rangle \langle \rightarrow | \downarrow \rangle = \frac{1}{2}$$

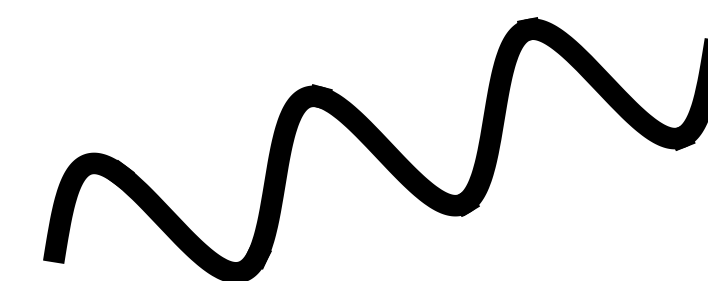
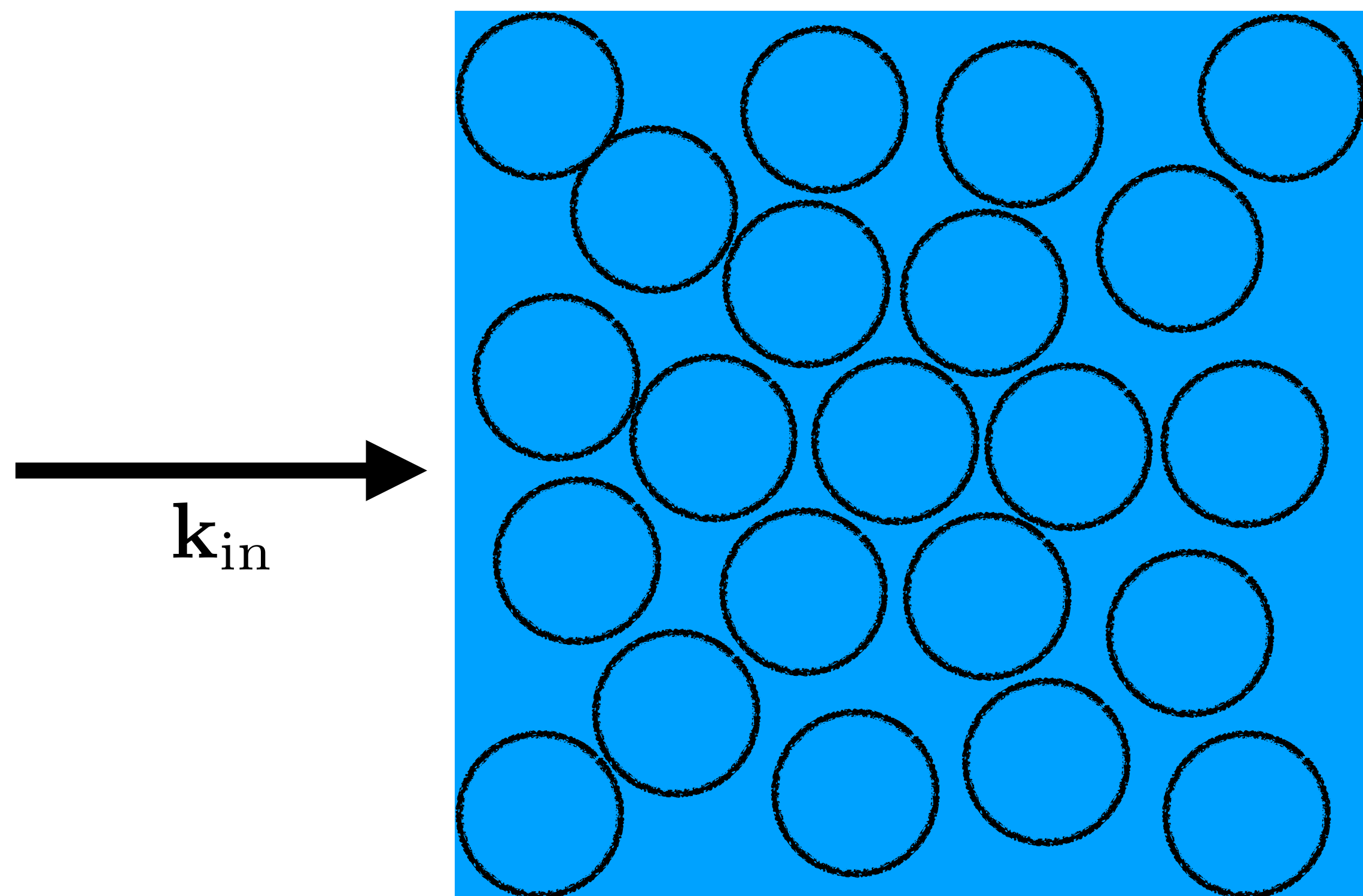
# Another regime



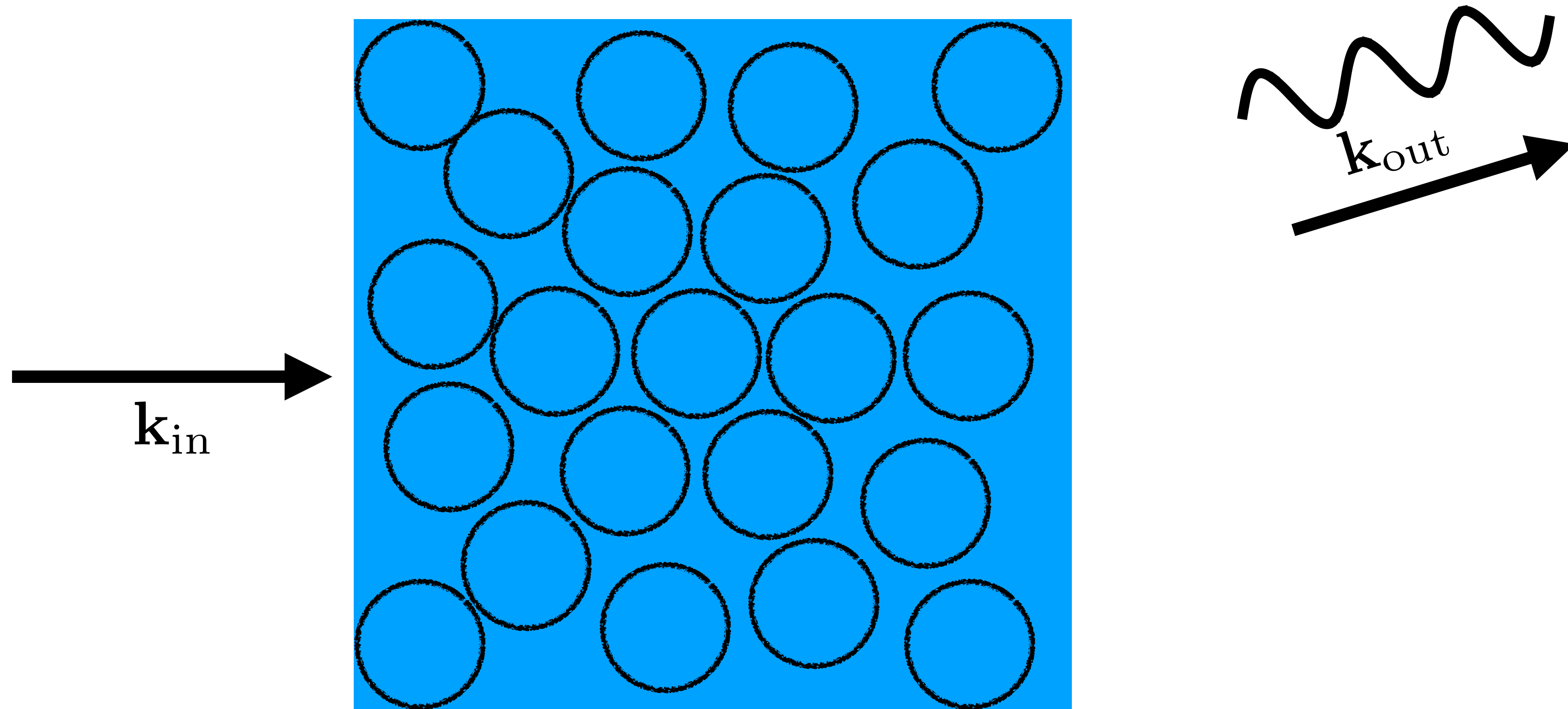
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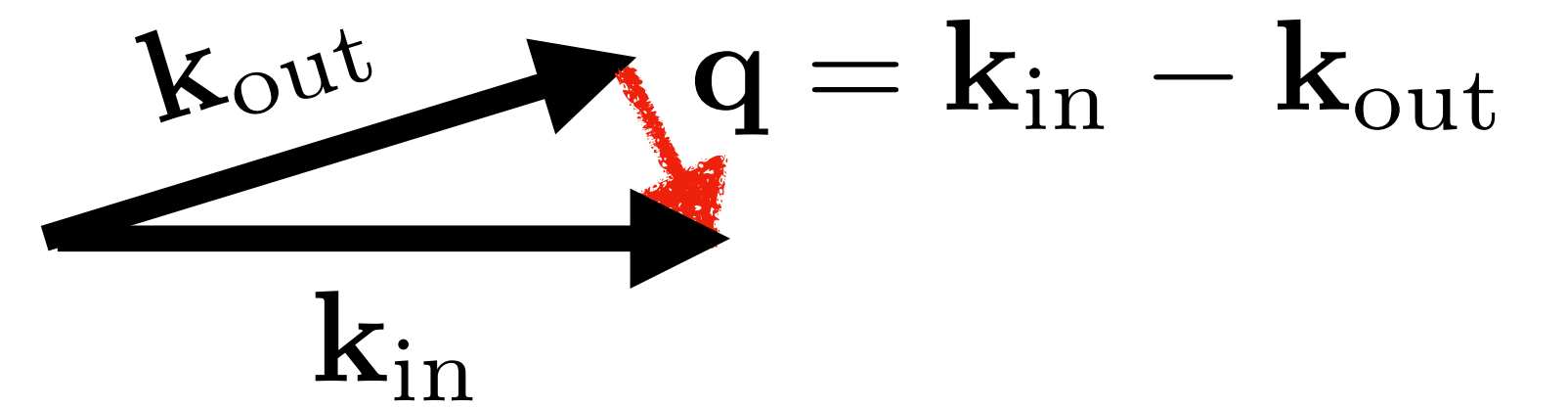
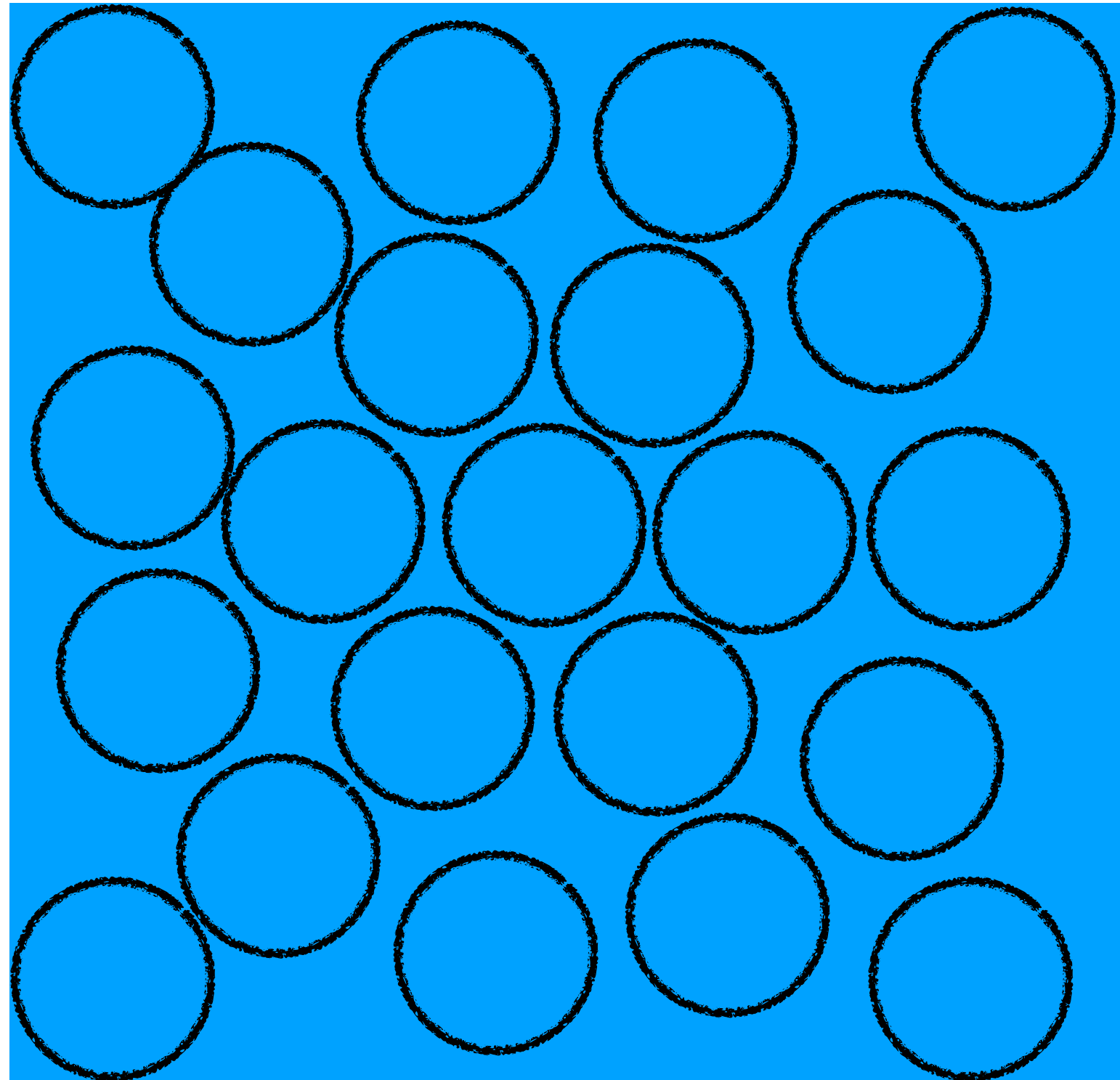
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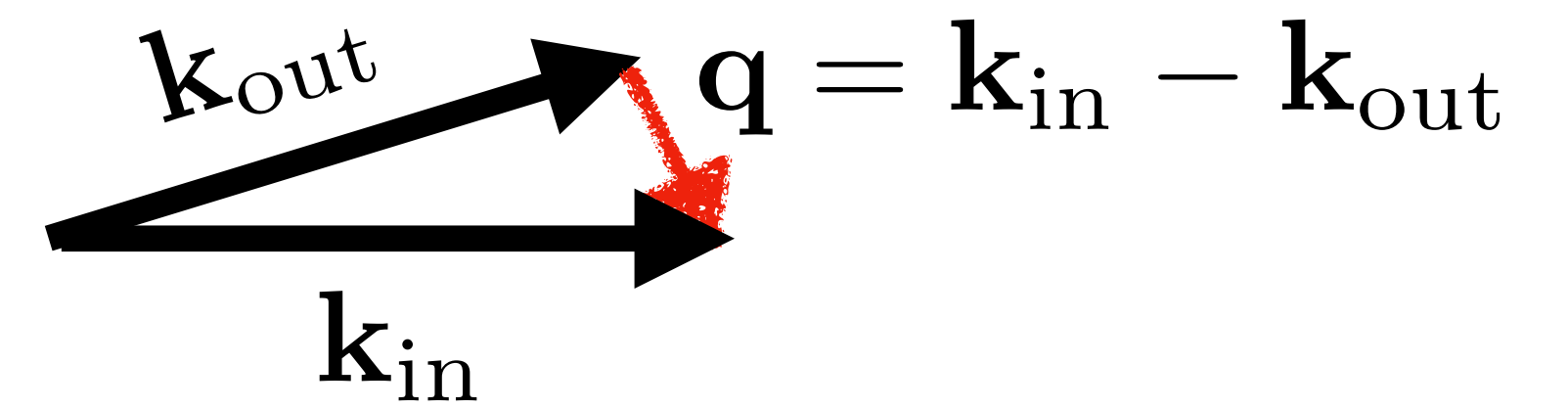
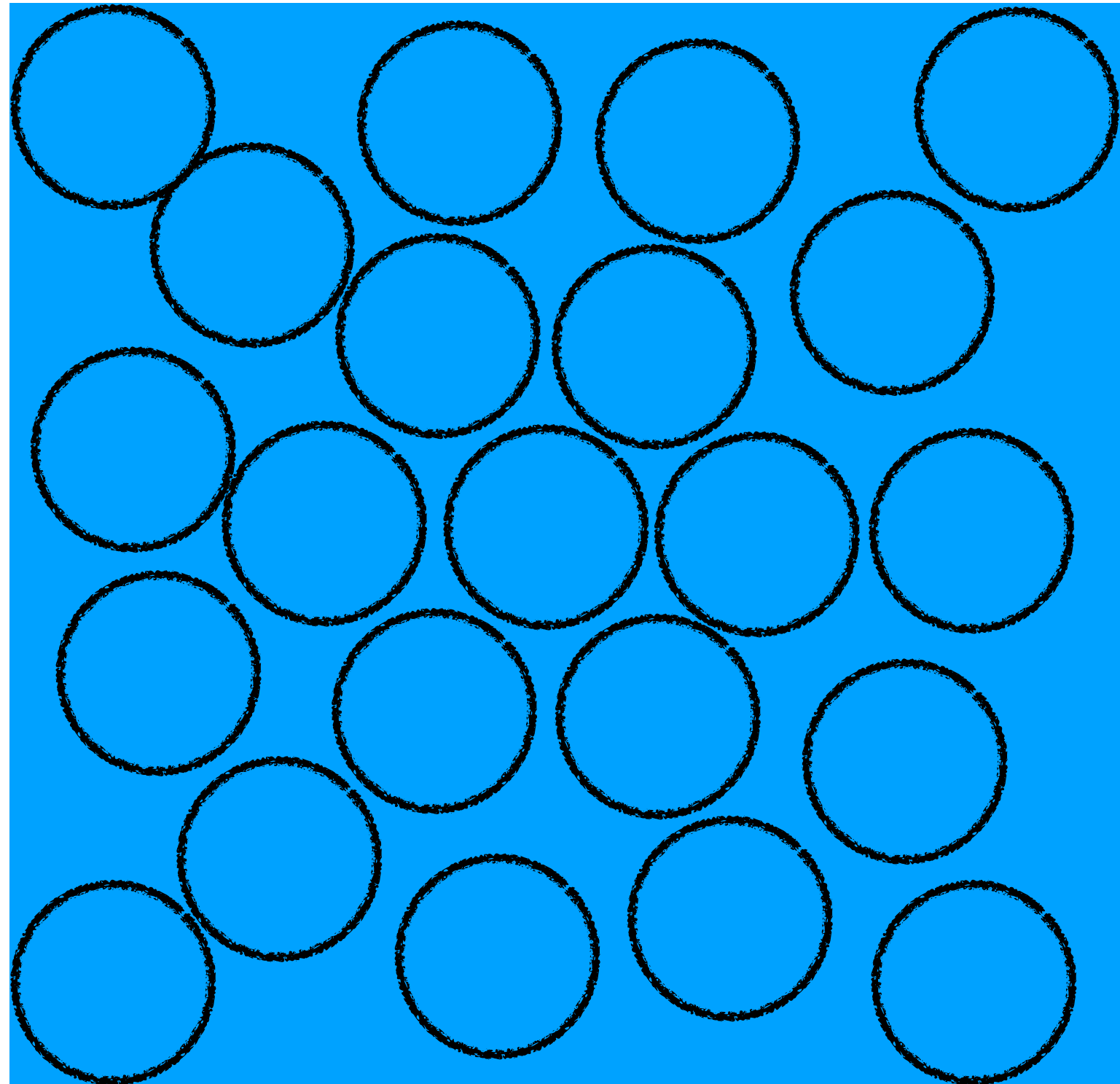
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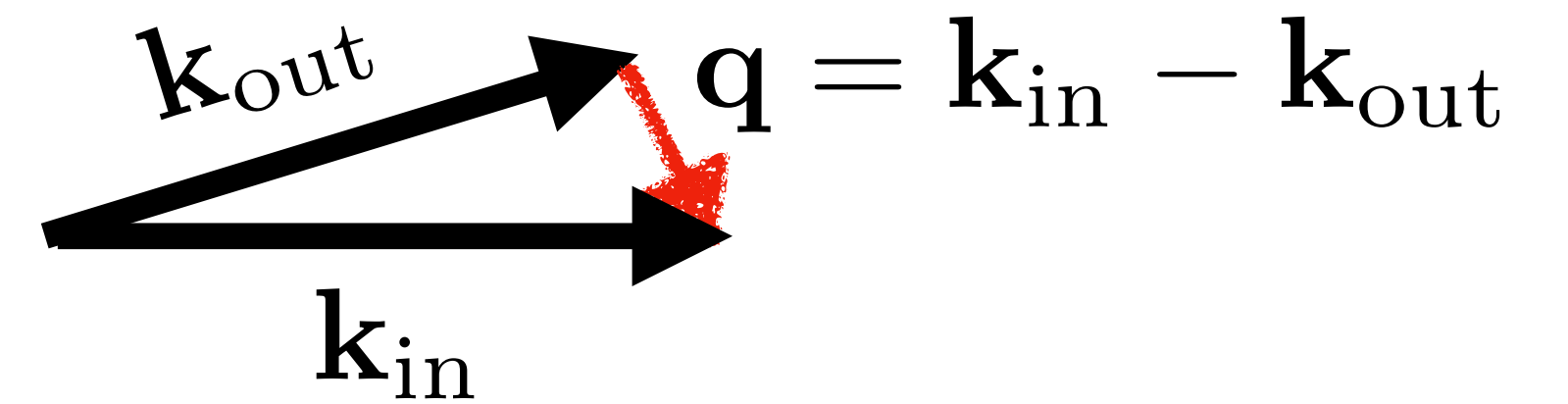
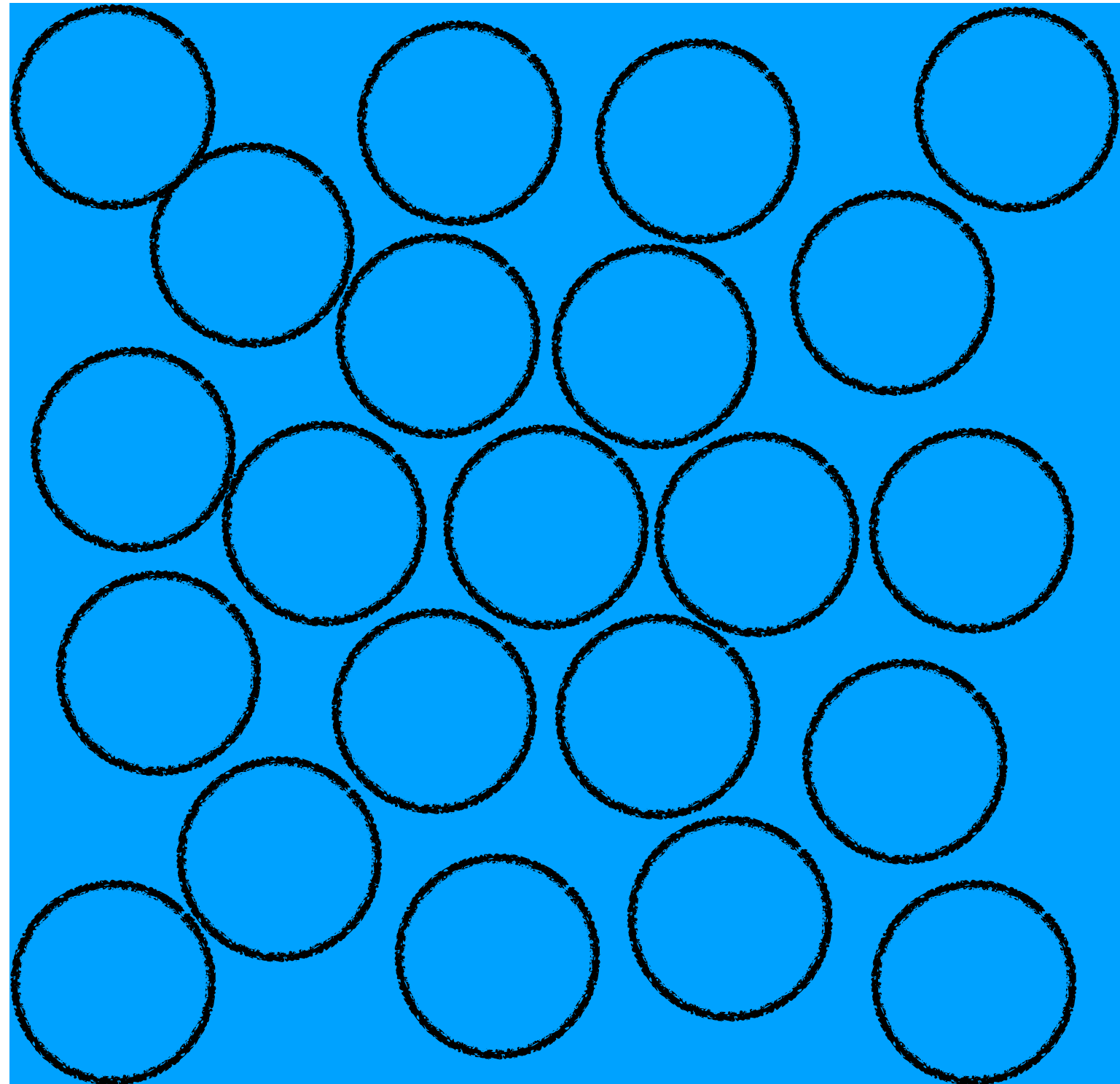


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Coherence for a small  $d\Omega$  around  $k_{in}$   
for which  $q \ll R^{-1}$

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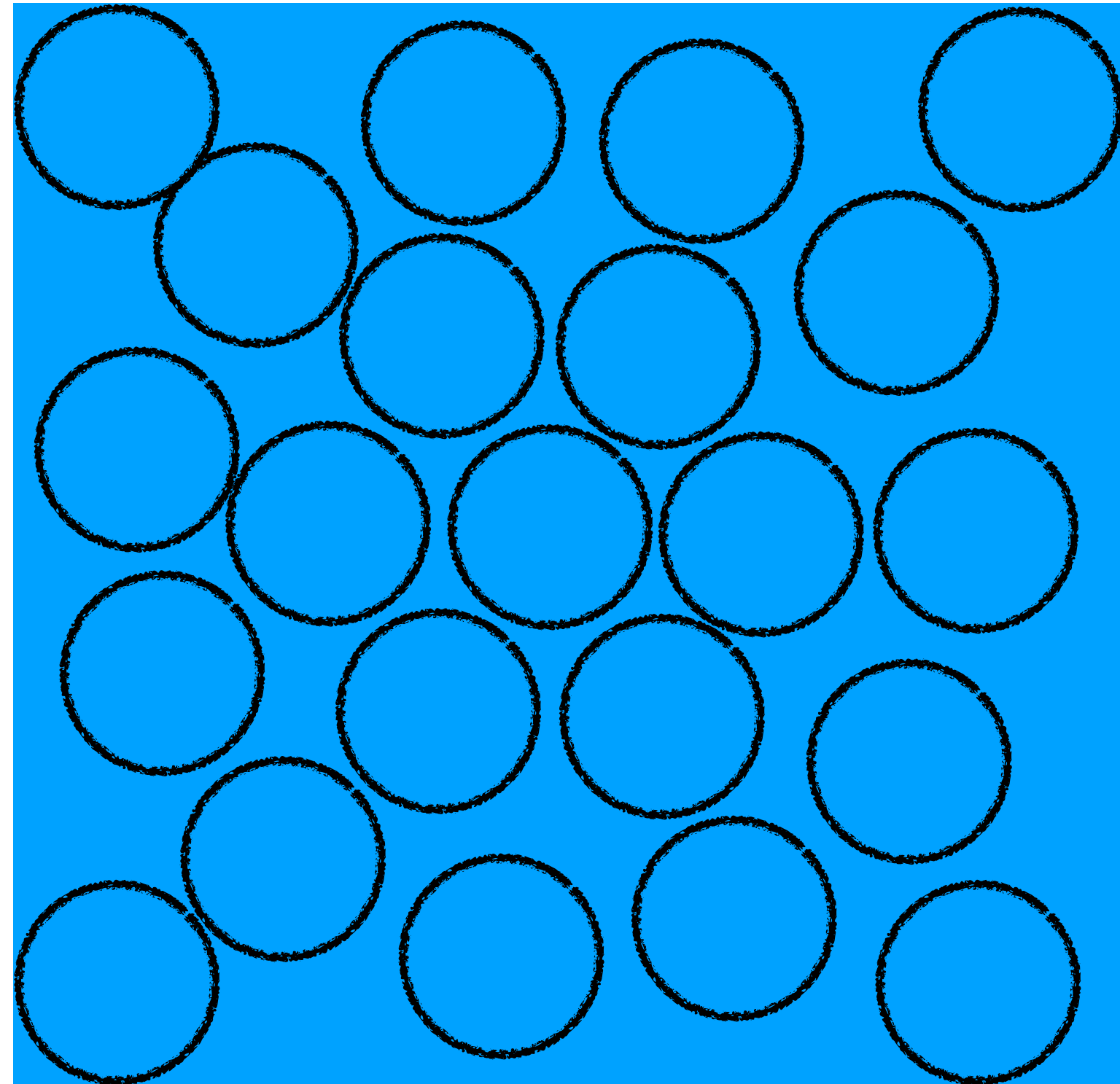


Coherence for a small  $d\Omega$  around  $k_{\text{in}}$   
for which  $q \ll R^{-1}$

$$\Gamma \propto (nR^3)^2 \left( \frac{1}{kR} \right)^2 \sim n^2 \lambda^2 R^4$$

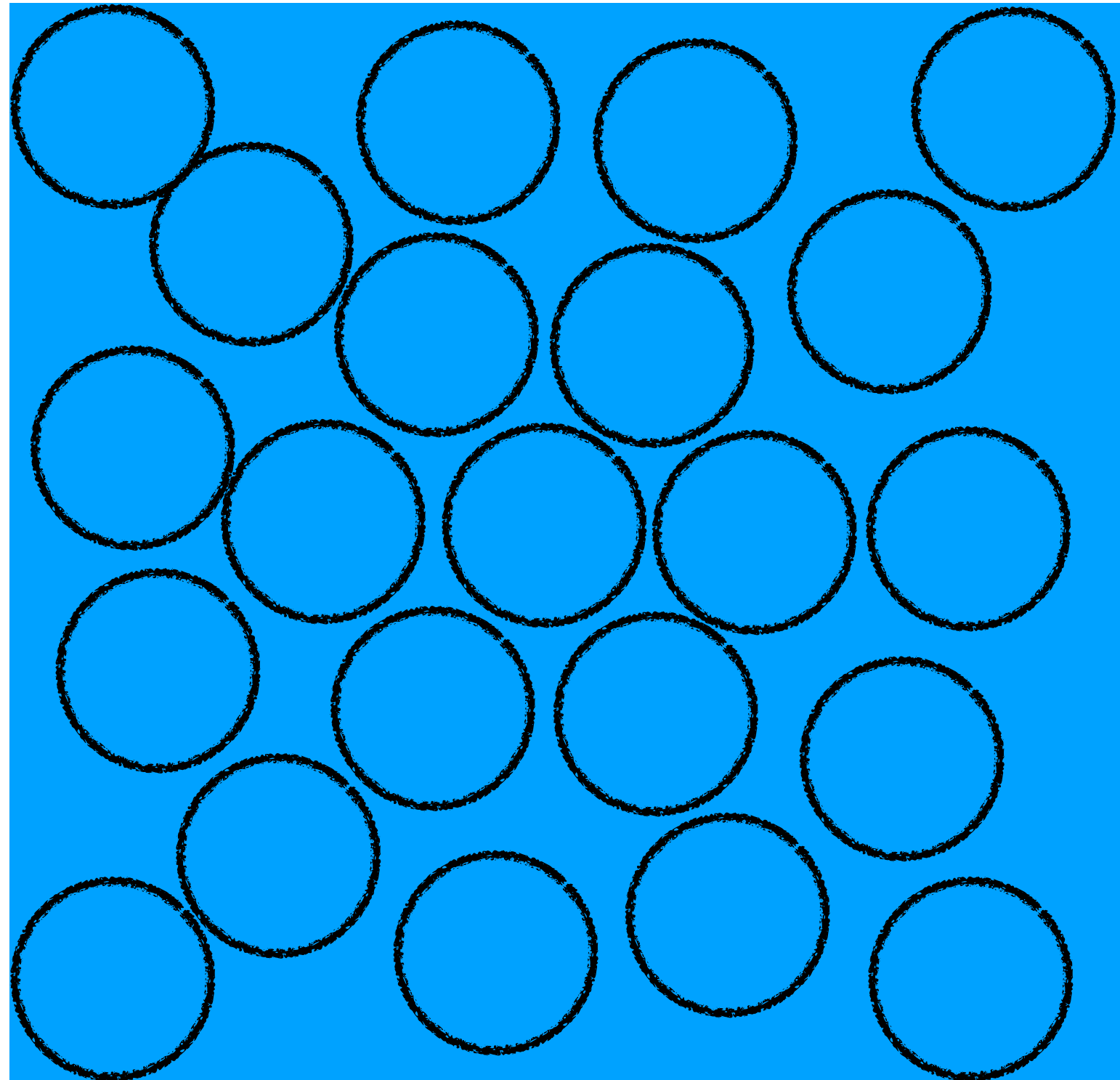


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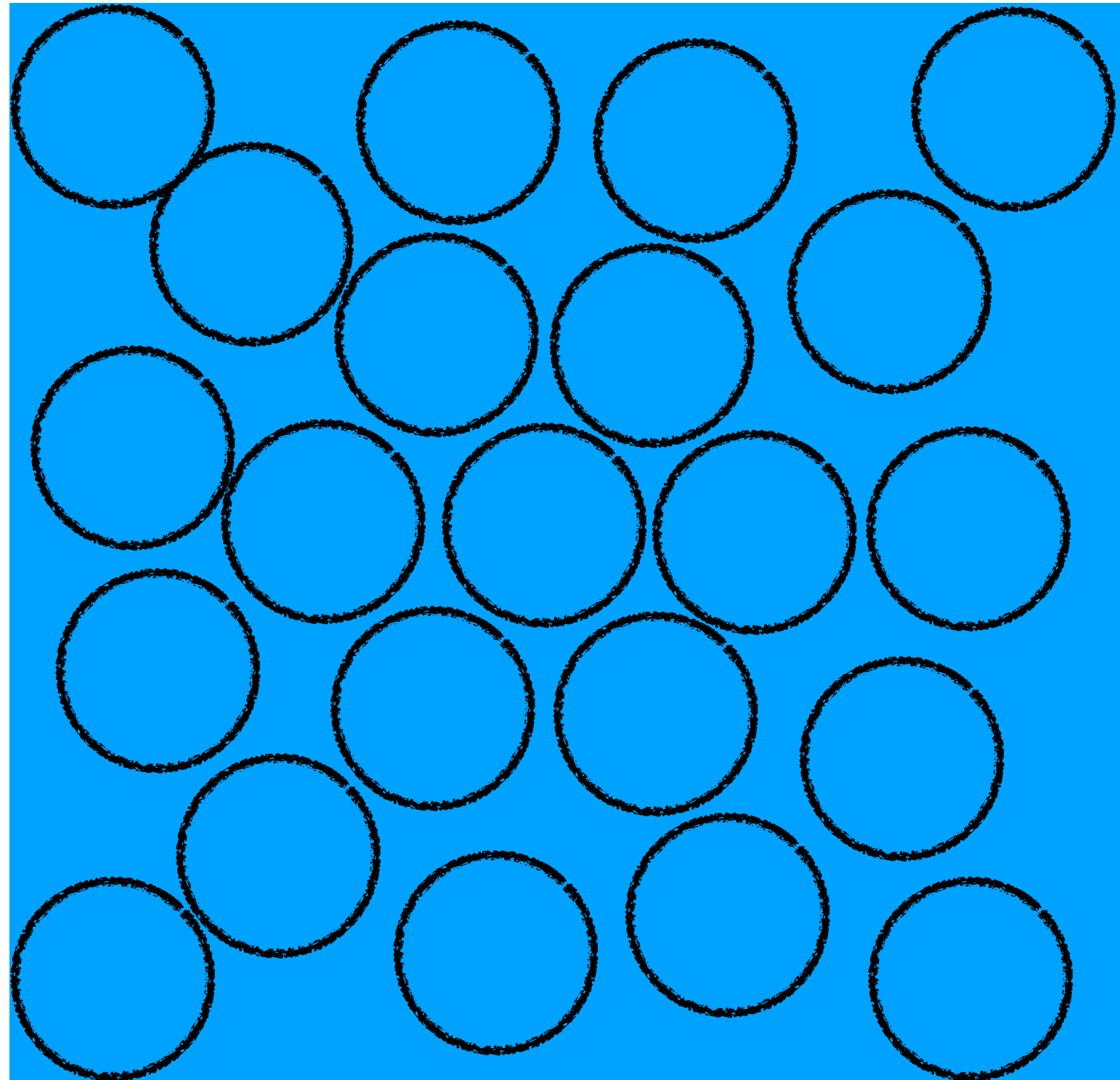
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# Another regime



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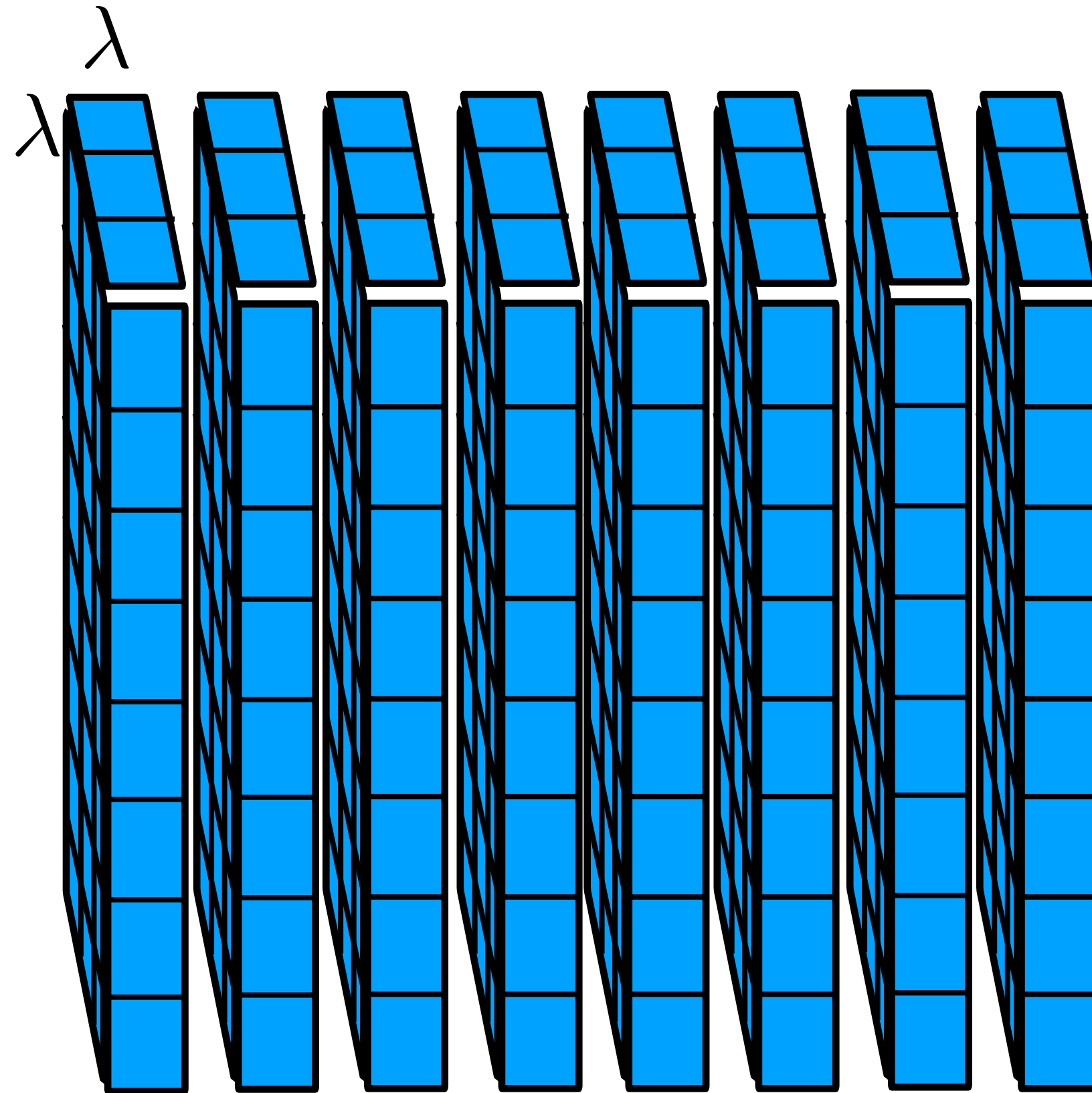


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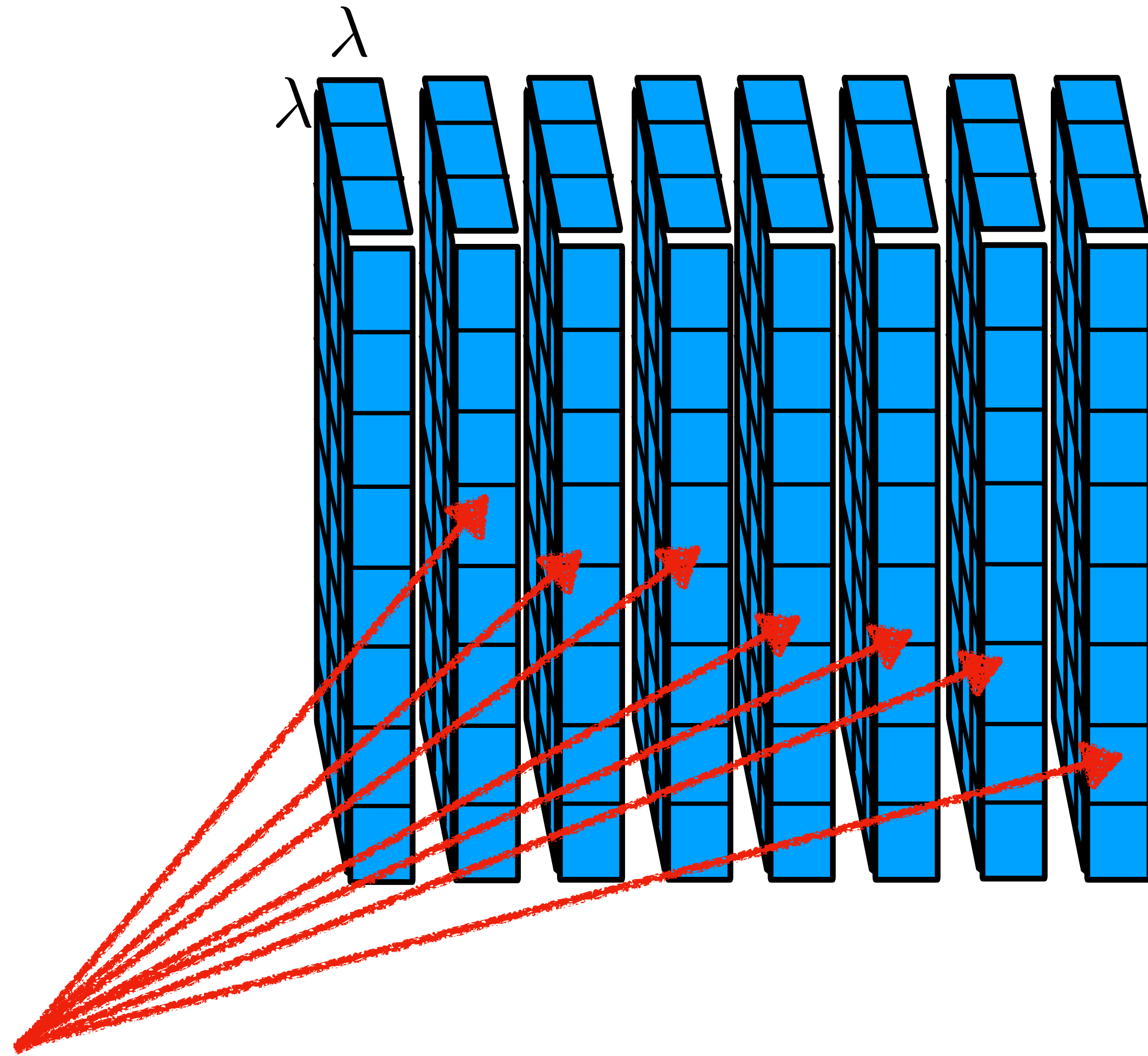


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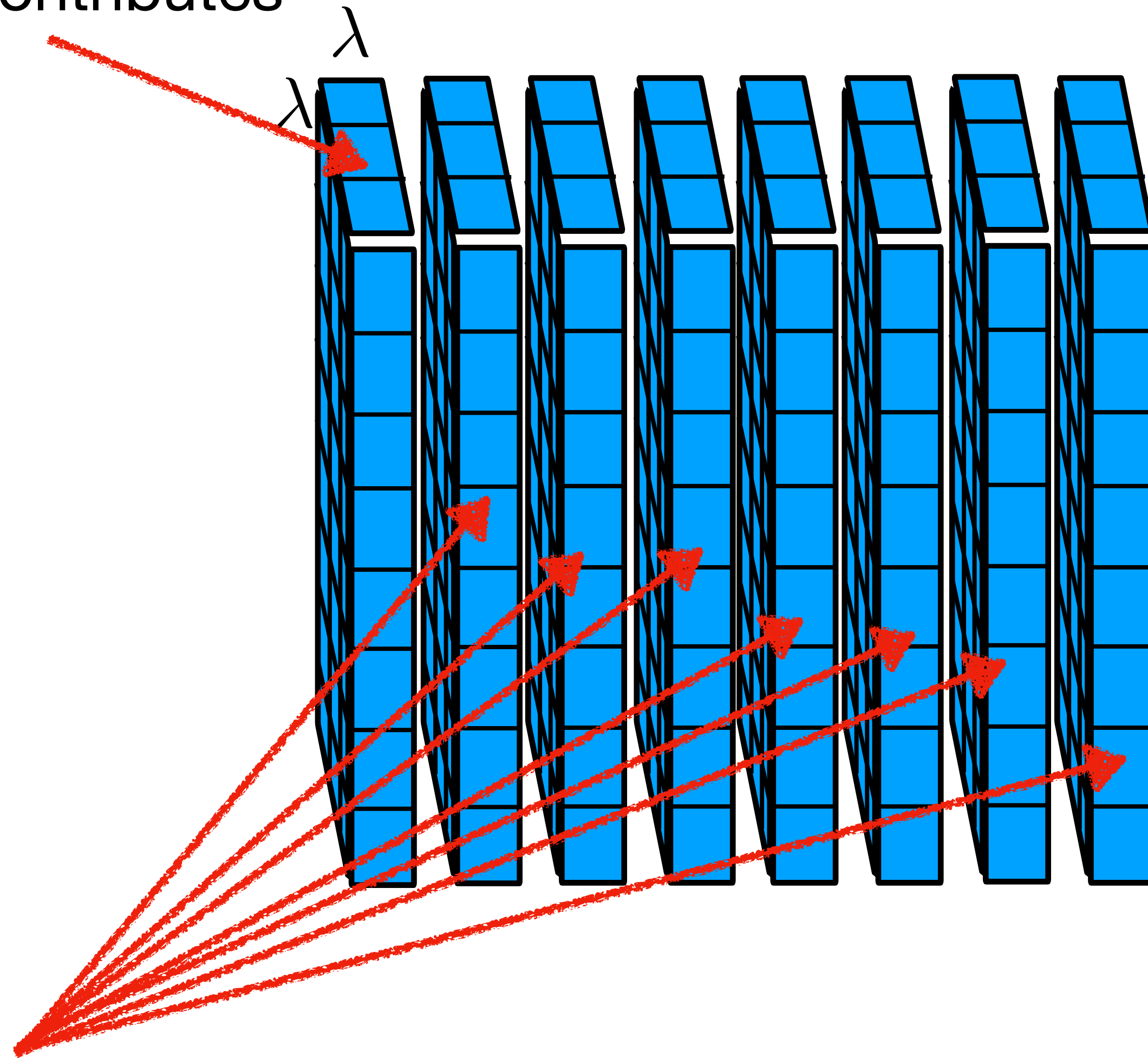
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These interfere destructively

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Only this contributes



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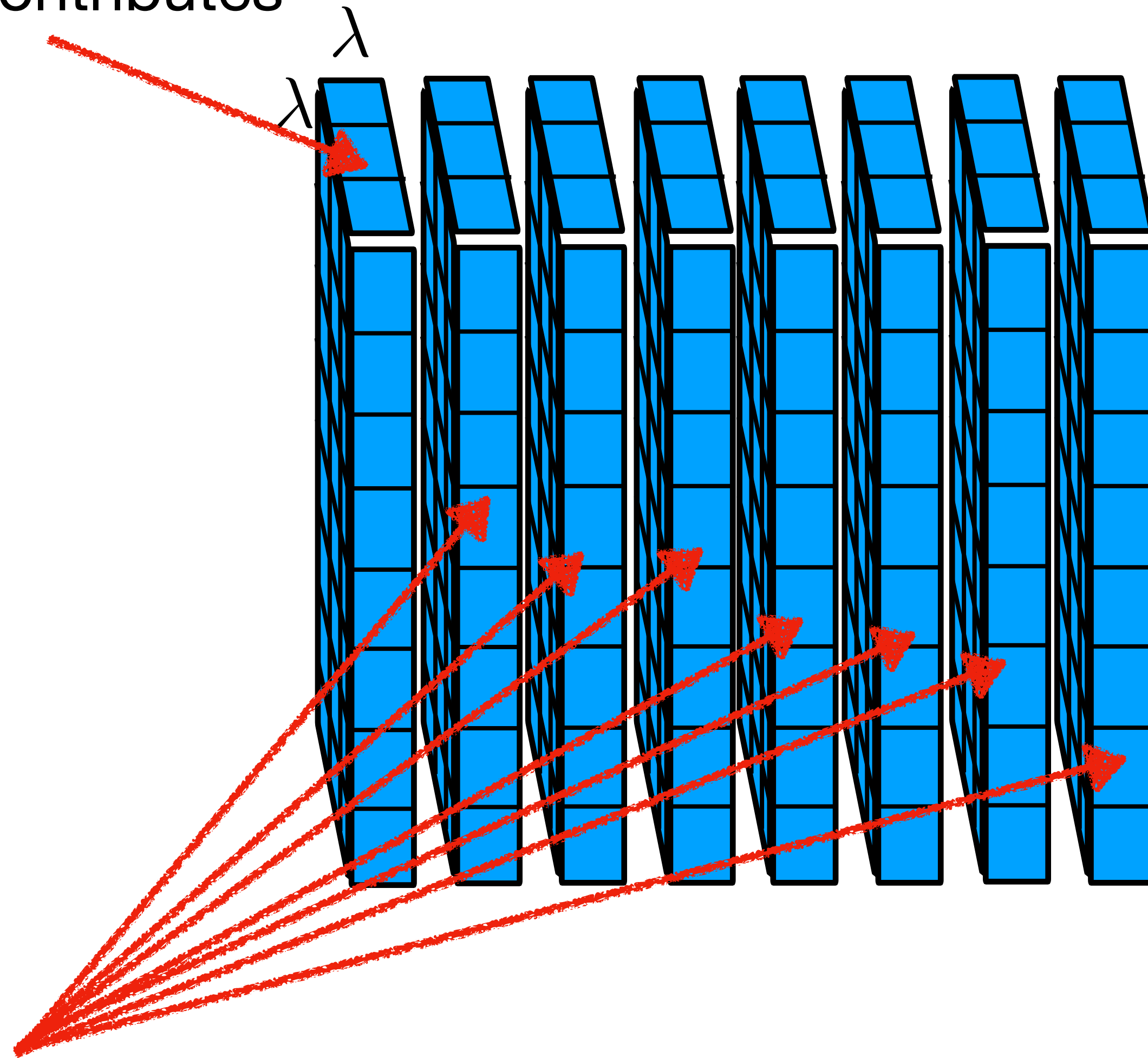
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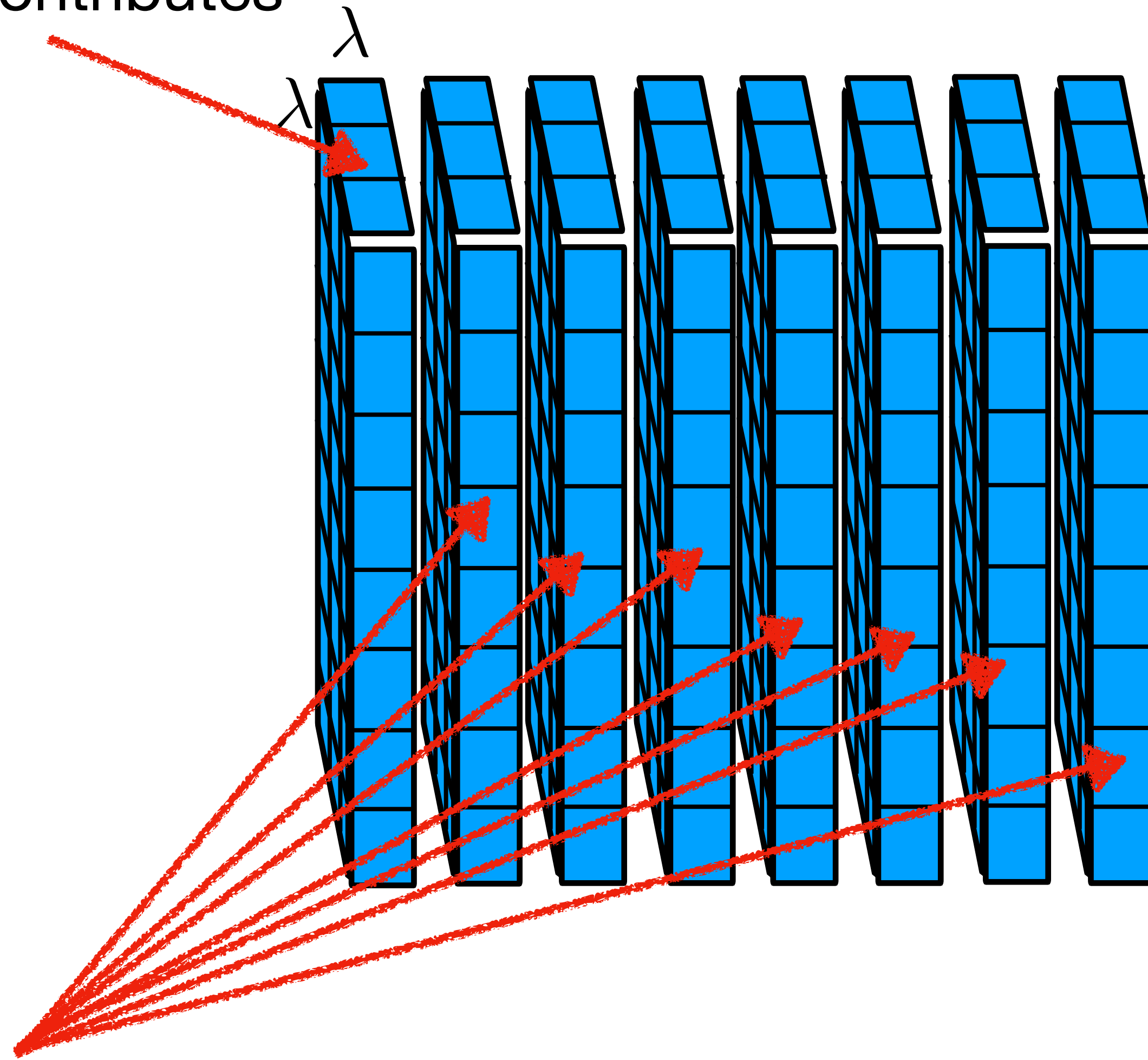
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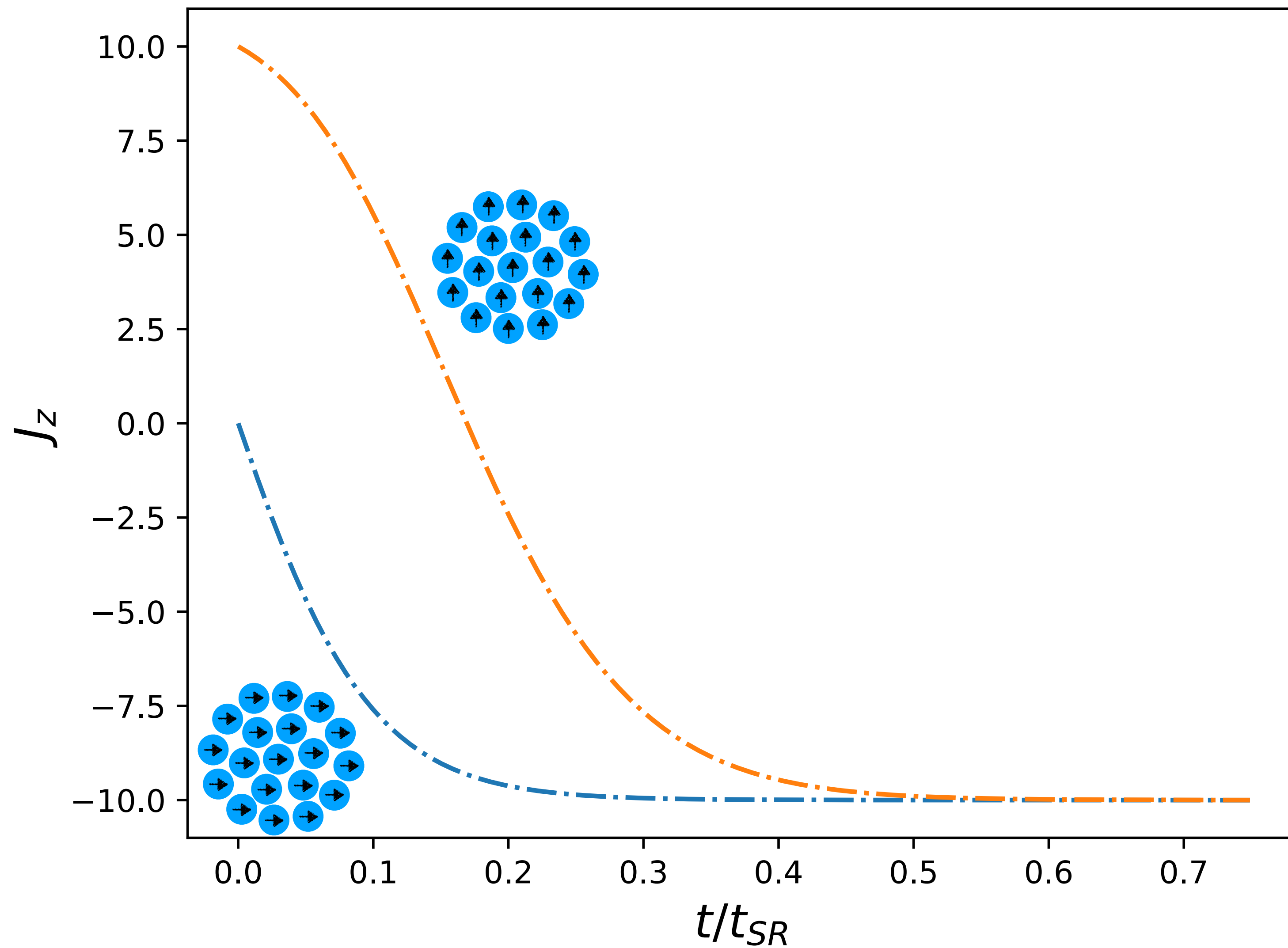
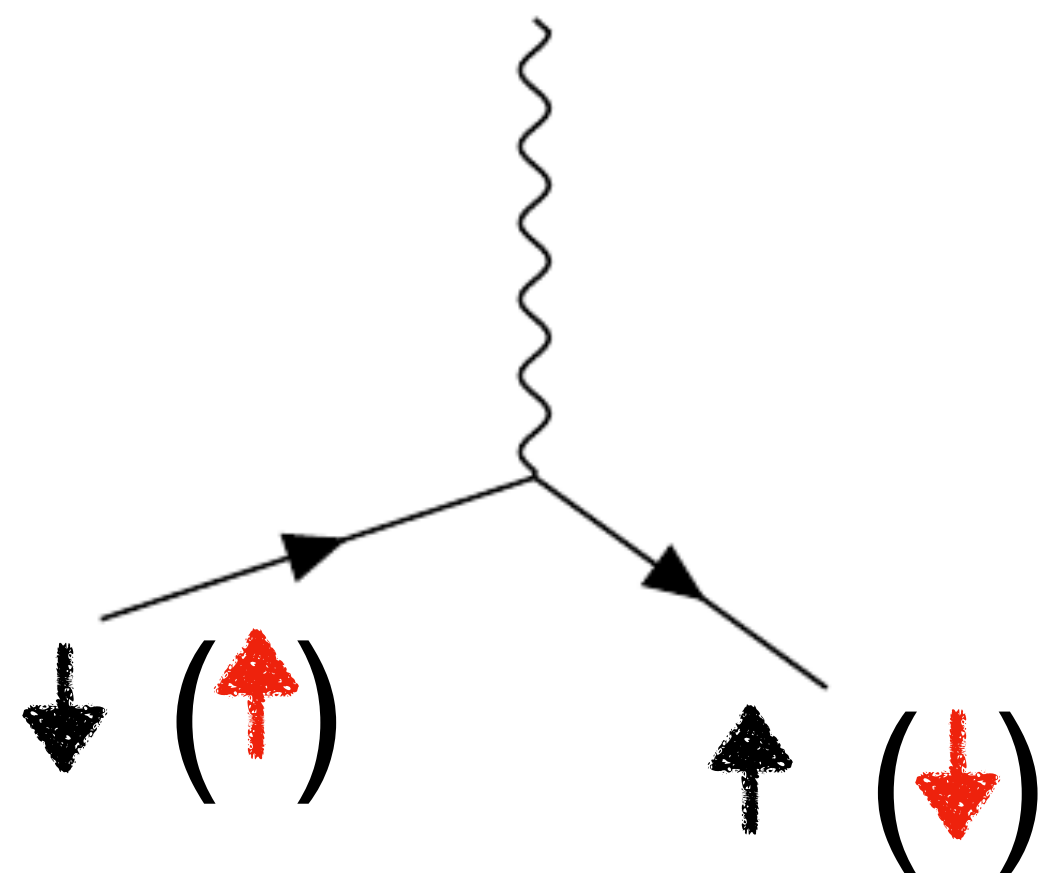
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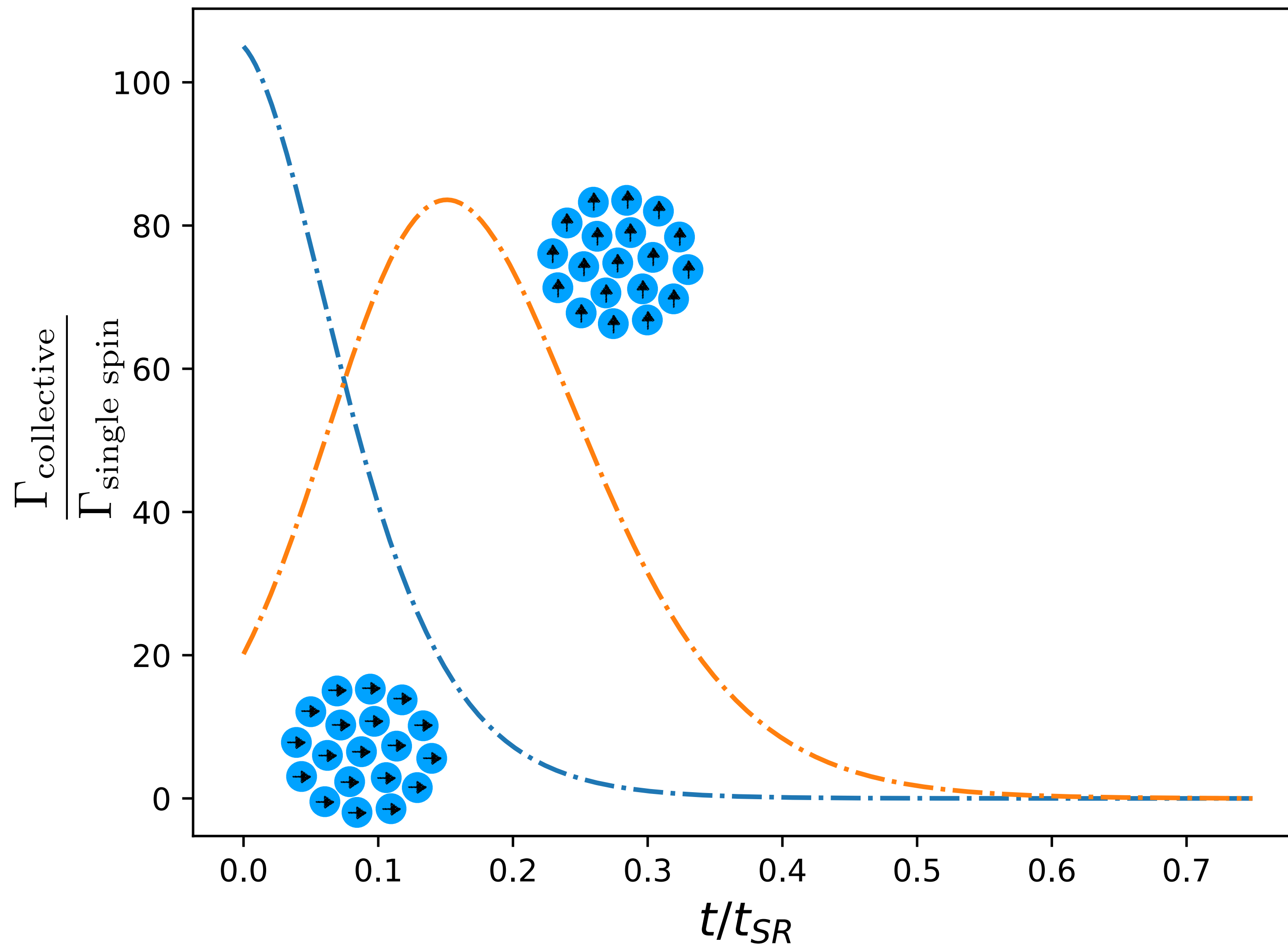
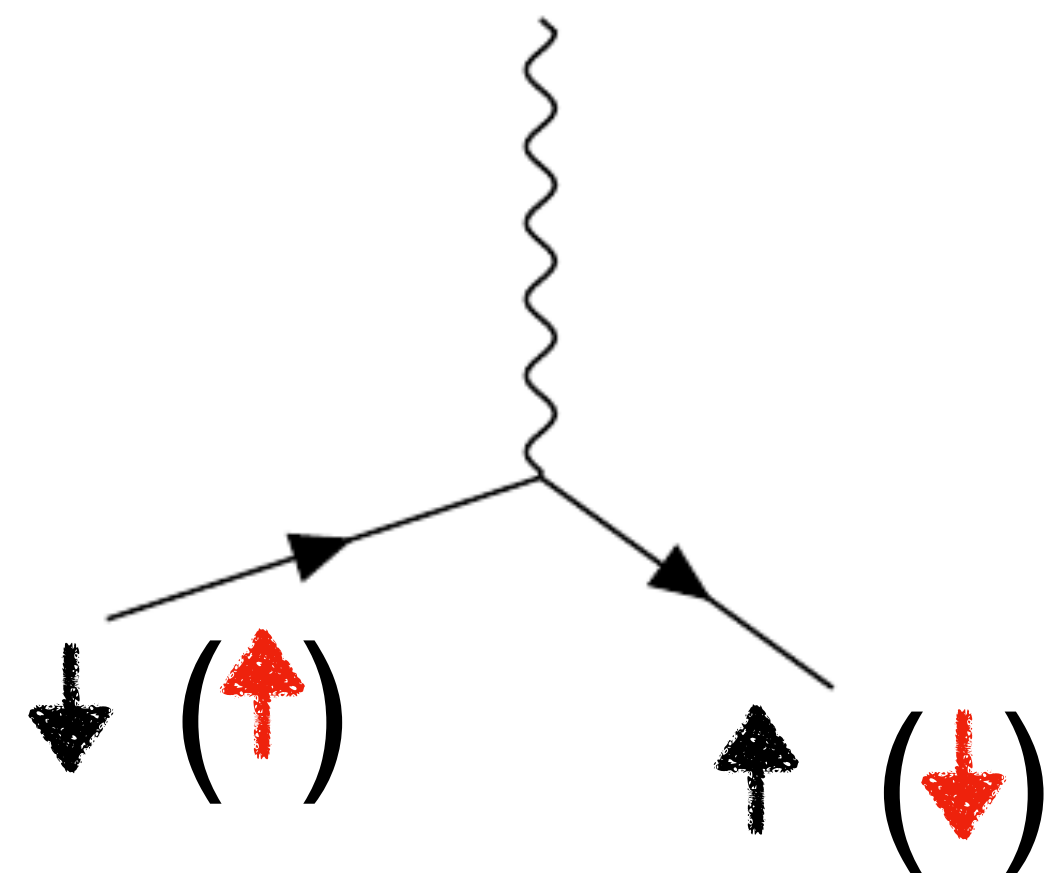
$$\text{Incoherent contribution: } \Gamma \propto nR^3$$



# Dicke superradiance

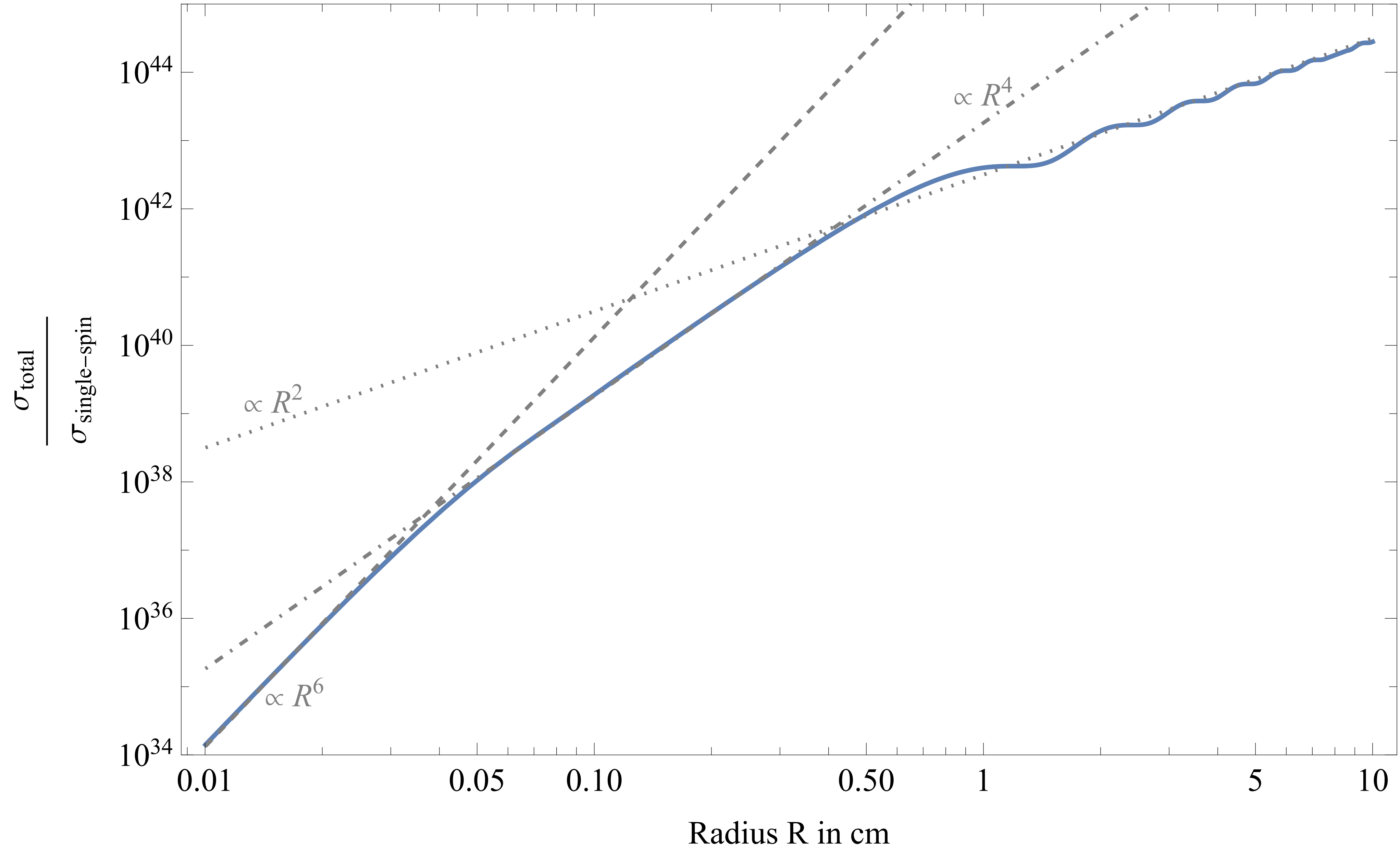


# Dicke superradiance



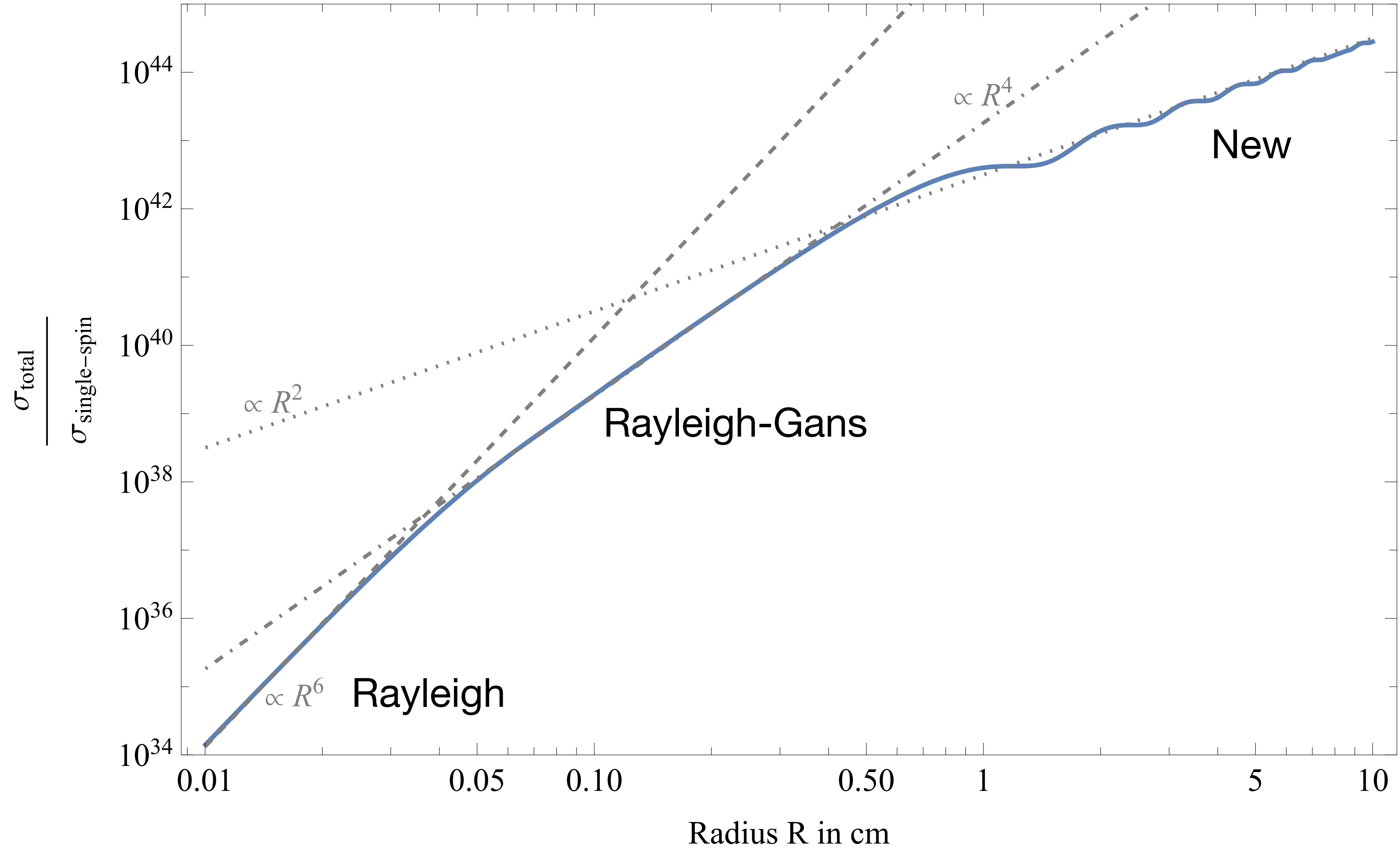
# CvB

$$n_s = 3 \times 10^{22} \text{ cm}^{-3}, k_{\text{in}} = \frac{2\pi}{2.1 \text{ mm}}, \text{ and } \omega_o = 3 \times 10^{-7} \text{ eV}$$



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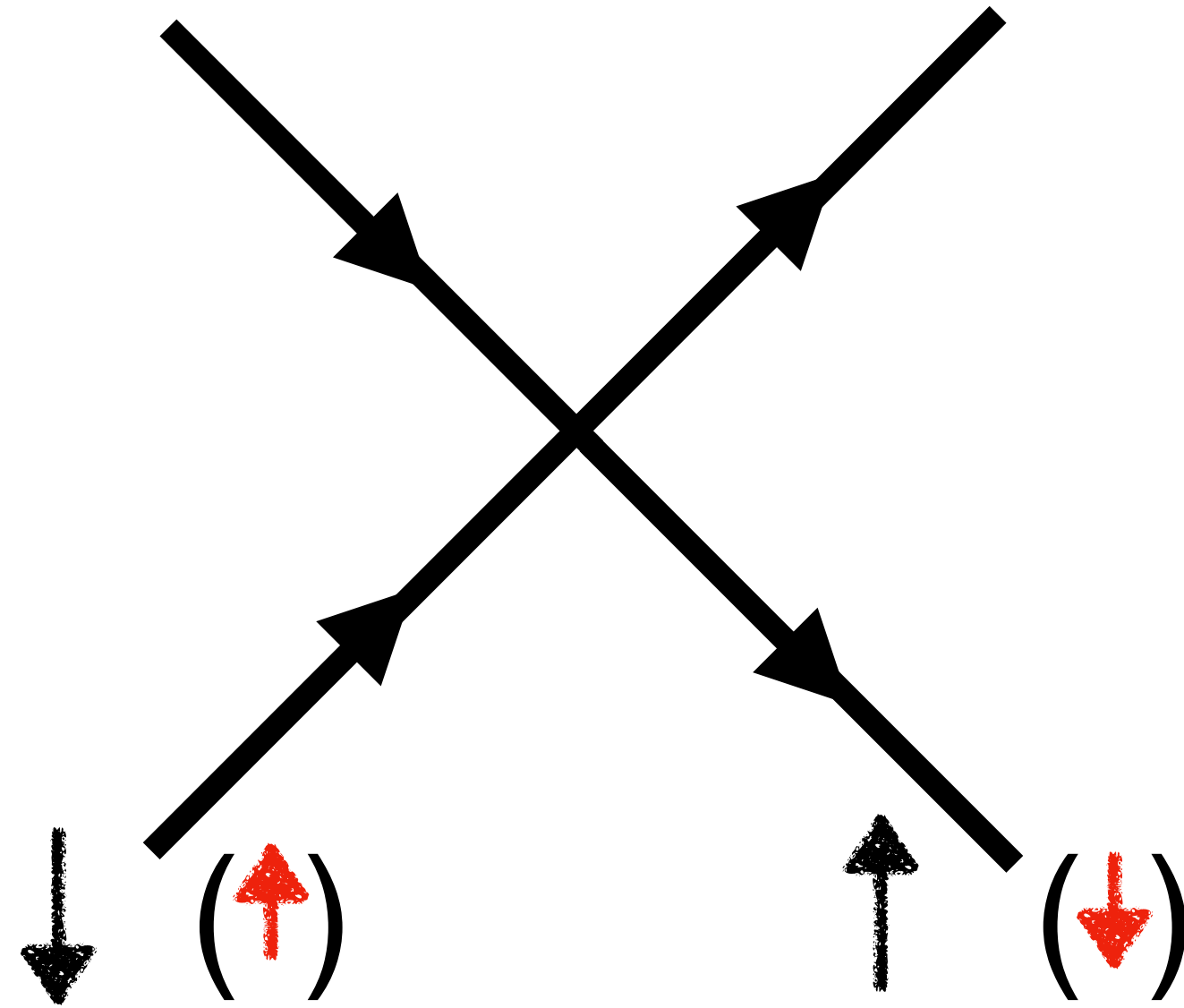
Inelastic processes need **product states** for coherence

**Large energy exchange** per interaction

Macroscopic coherence is set by the **momentum transfer**

Splitting of two-level system serves as **control parameter**

# Scattering



# The Cosmic Neutrino Background

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Produced when  $\tau_{\text{Universe}} \sim 1$  second

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Consists of three mass eigenstates, evolving independently



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Produced when  $\tau_{\text{Universe}} \sim 1$  second

Follows a relativistic Fermi-Dirac with temperature  $1.95 \text{ K} \sim 1.7 \times 10^{-4} \text{ eV}$

$$f(p) = \left( e^{p/T} + 1 \right)^{-1}$$

Number density  $n_\nu = 55.6/\text{cm}^3$  per neutrino

Wavelength  $\langle \lambda_\nu \rangle \approx 2.1 \text{ mm}$

Consists of three mass eigenstates, evolving independently

Only source of non-relativistic neutrinos

# CvB and spin systems

Interaction with any fermionic spin  $\psi$

$$\mathcal{H} = \frac{G_F}{\sqrt{2}} (g_L - g_R) \bar{\psi} \gamma^\mu \gamma_5 \psi \bar{\nu}_f \gamma_\mu \gamma_5 \nu_f$$

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PMNS matrix mixes mass eigenstates

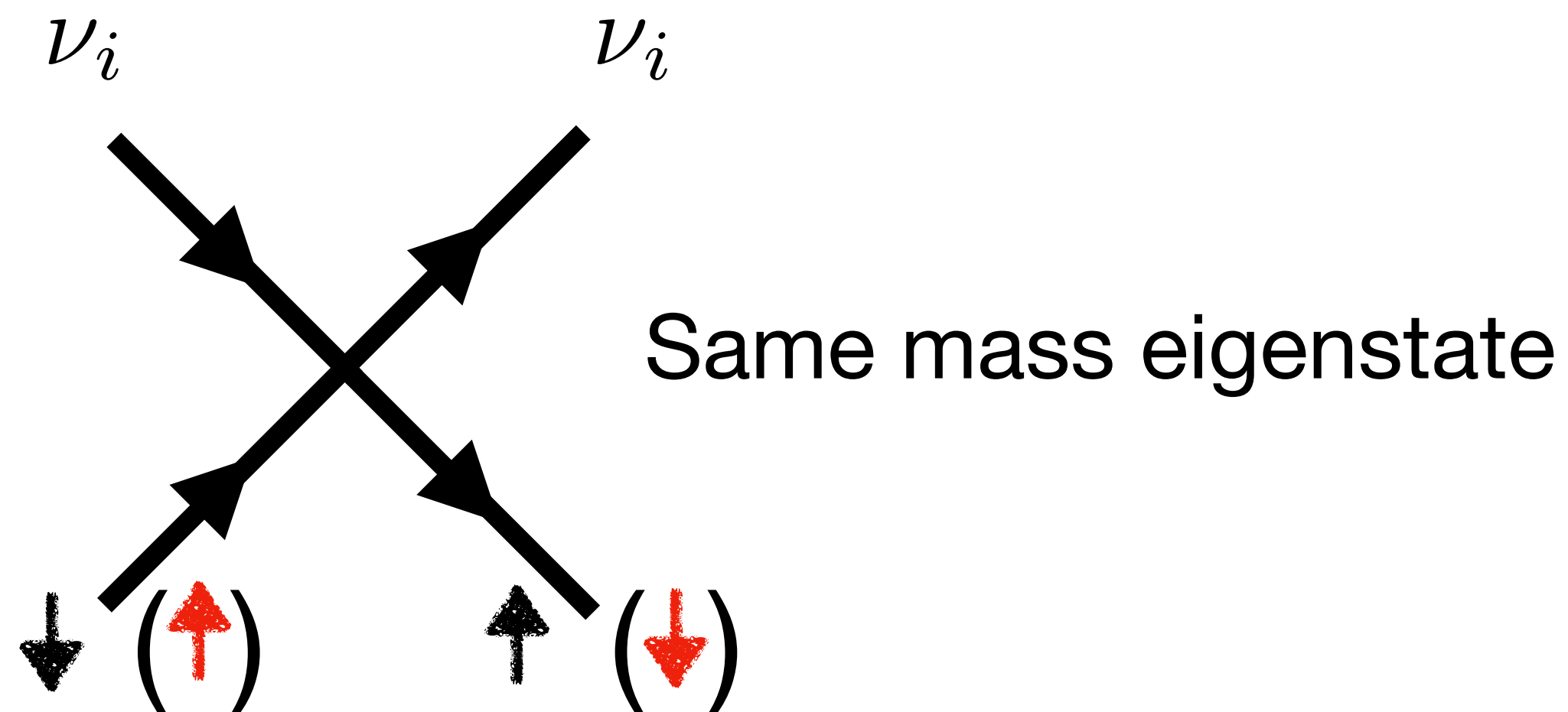
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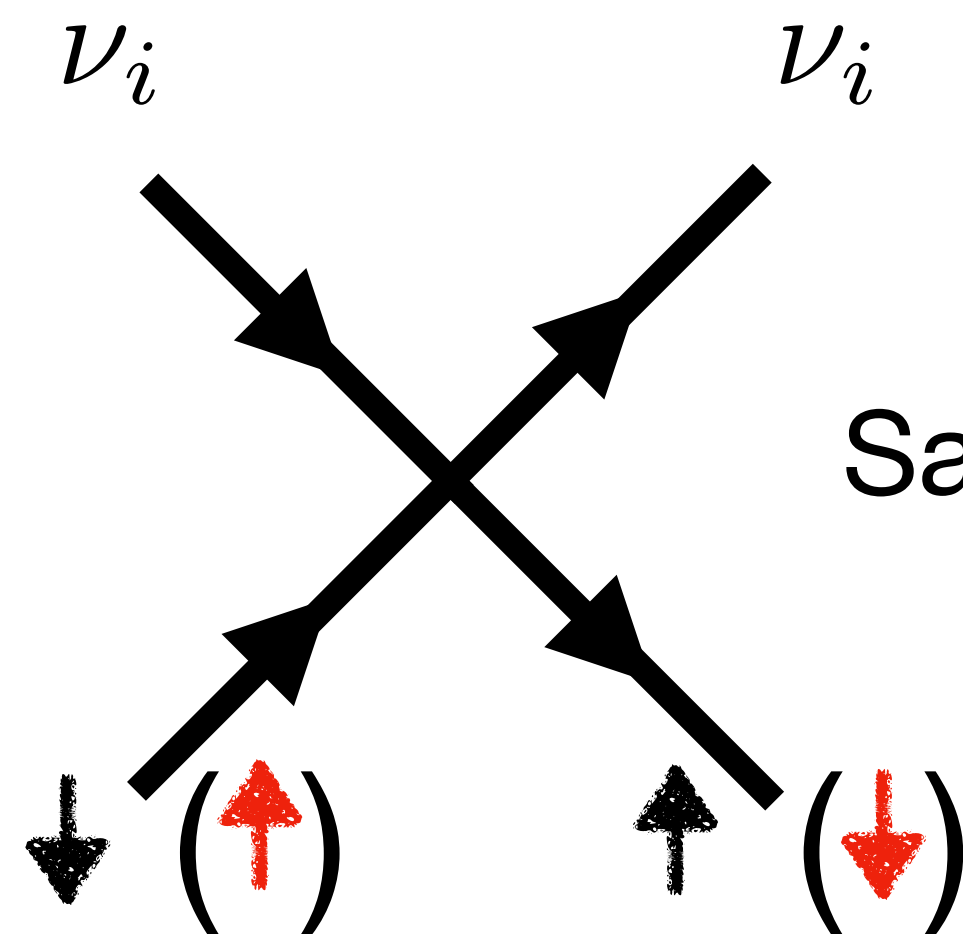
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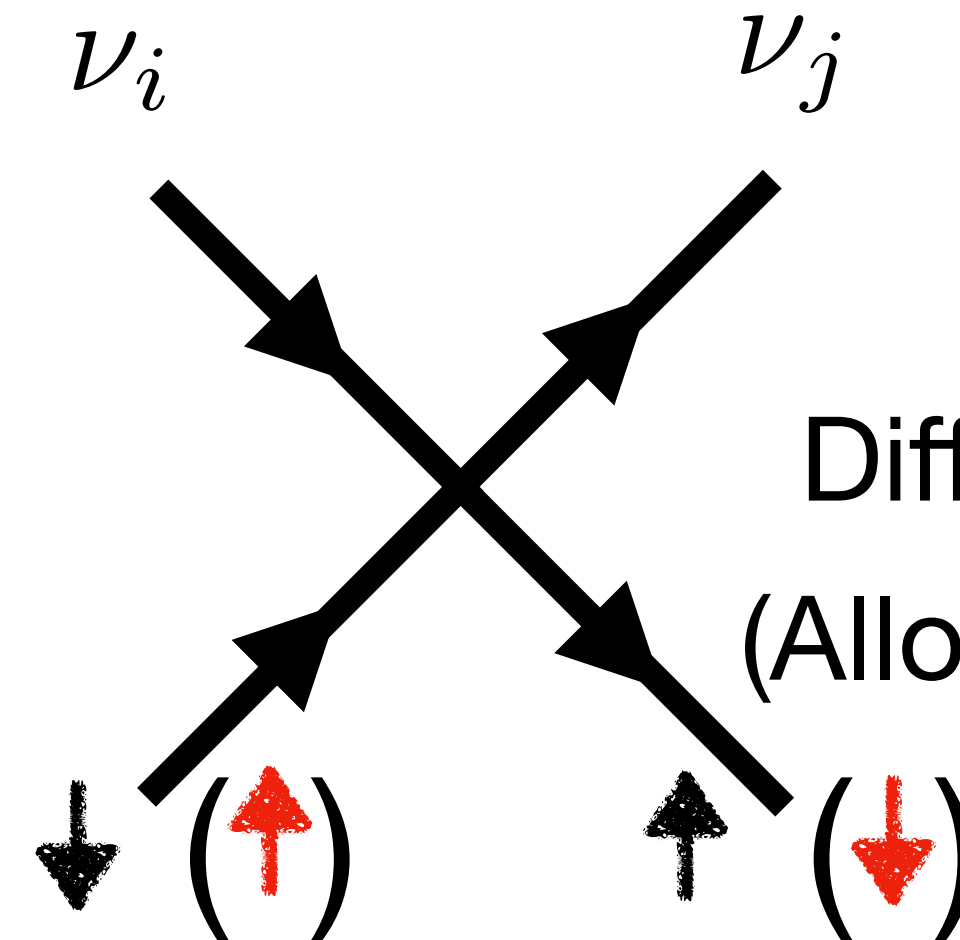
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Same mass eigenstate



Different mass eigenstate  
(Allowed only on e, due to W)

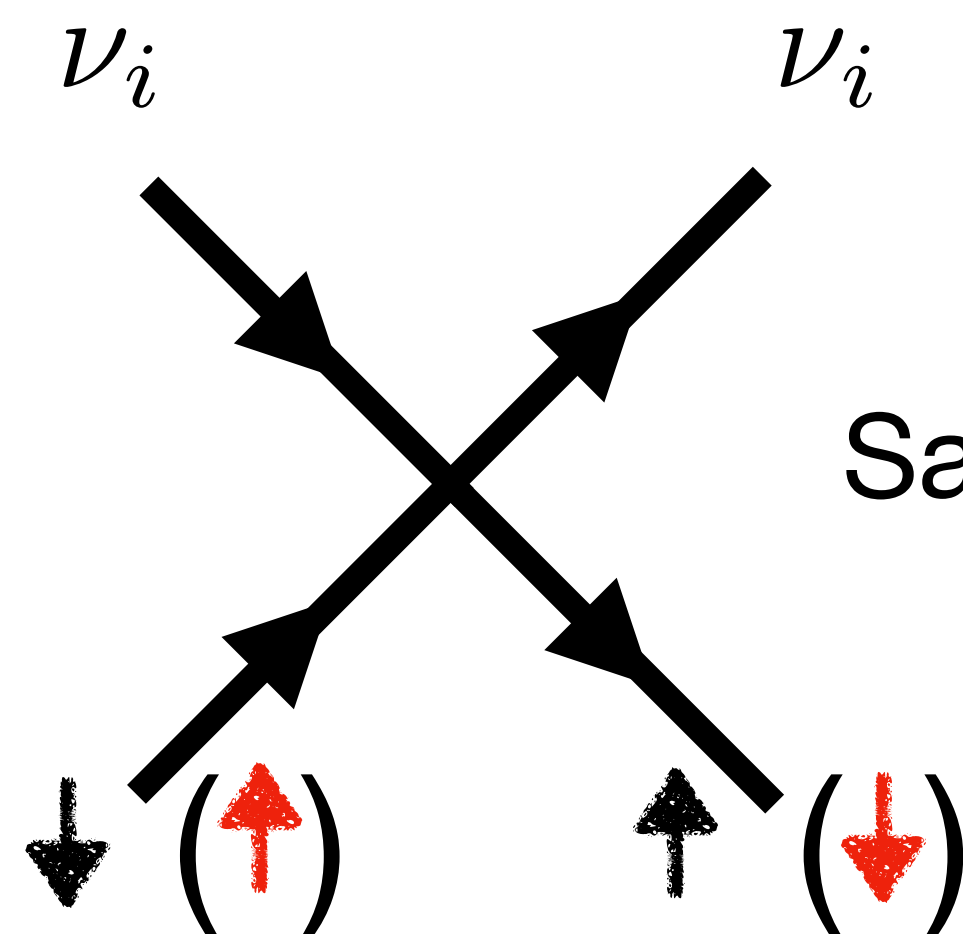
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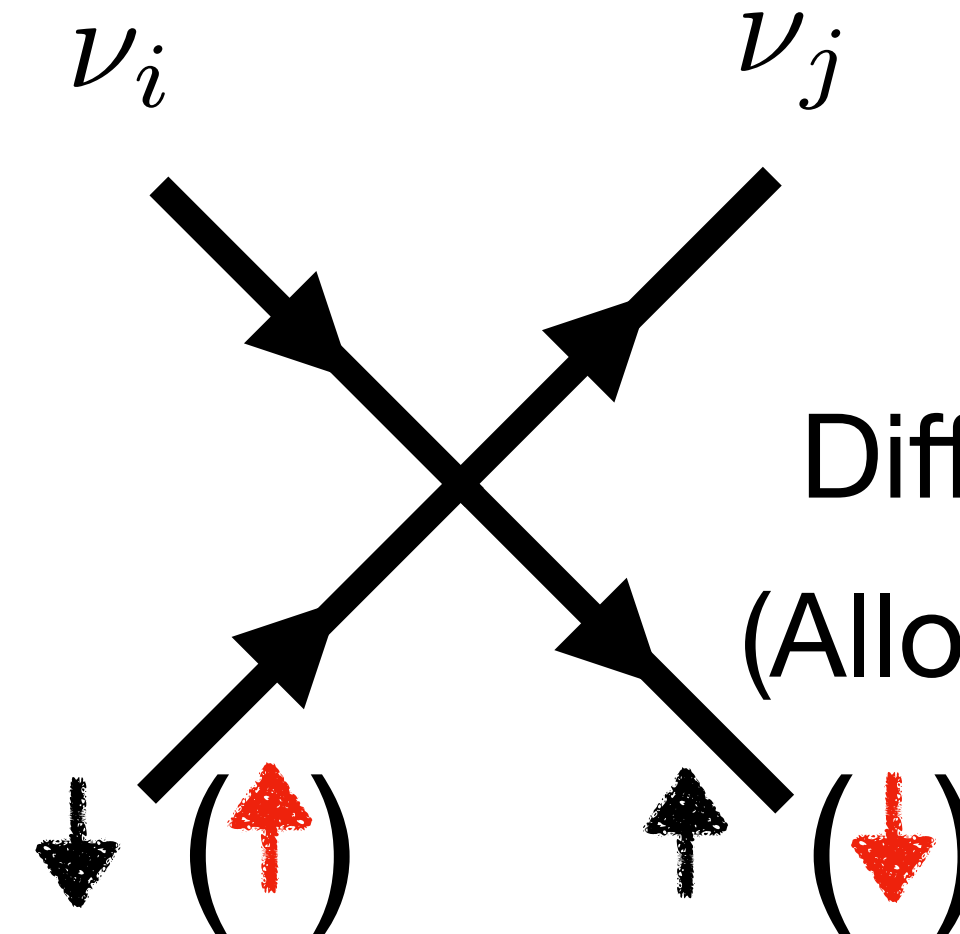
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Same mass eigenstate  
NMR



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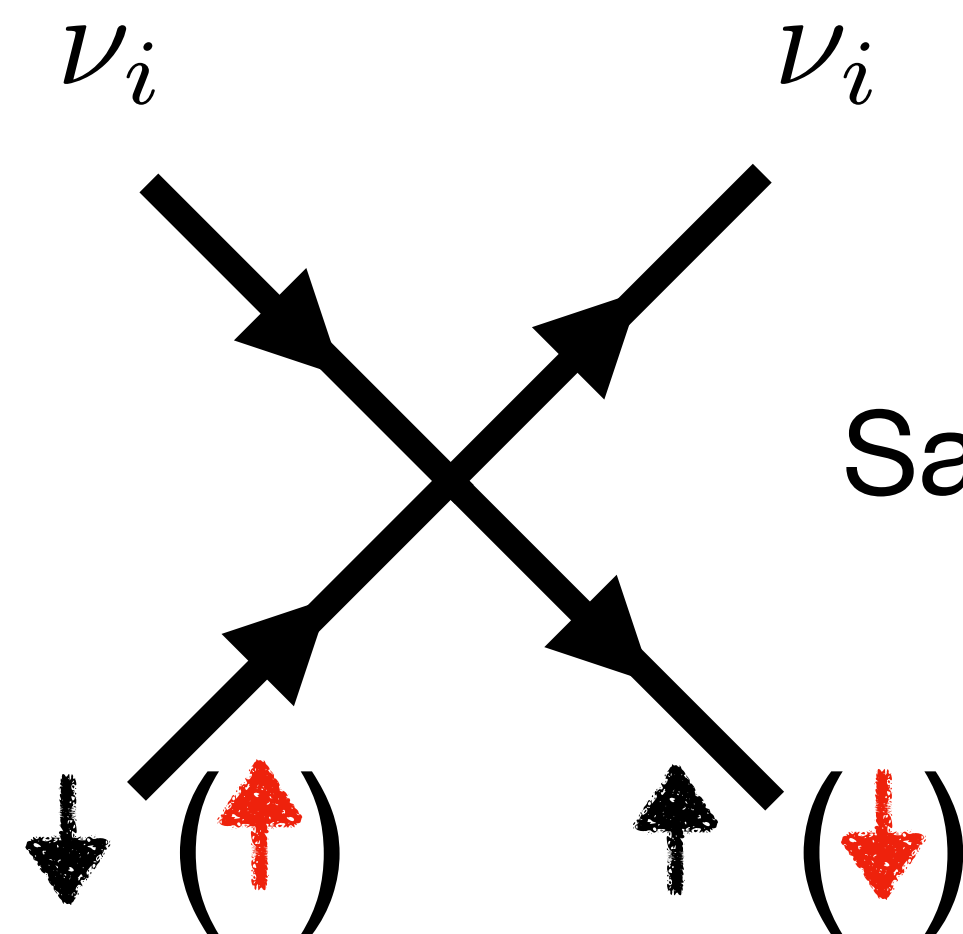
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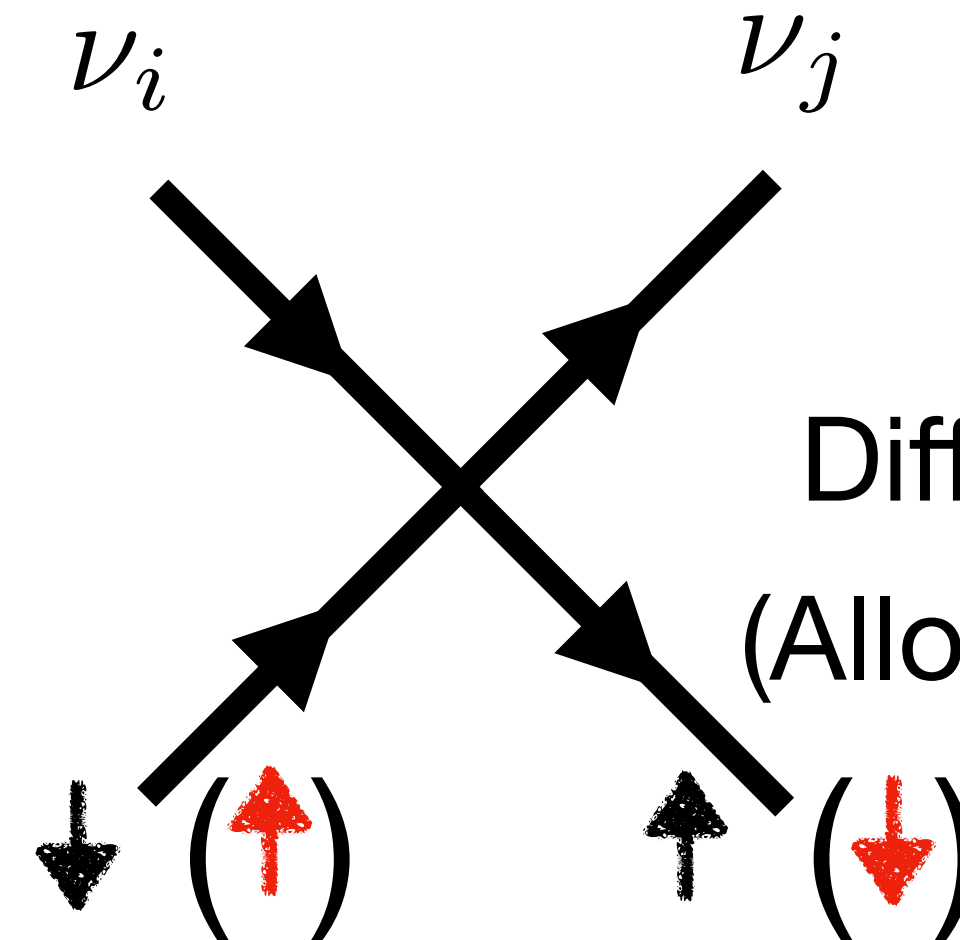
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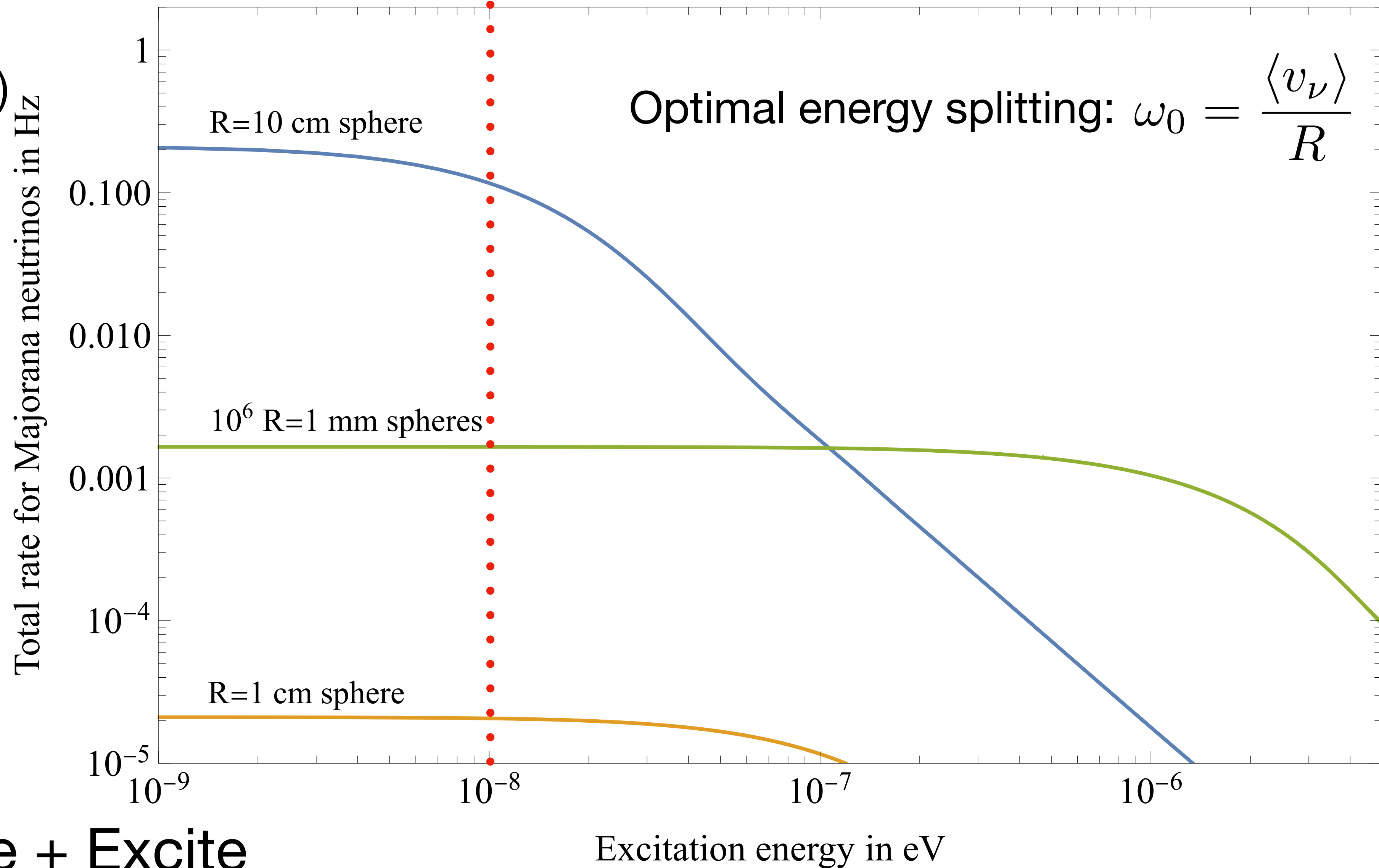
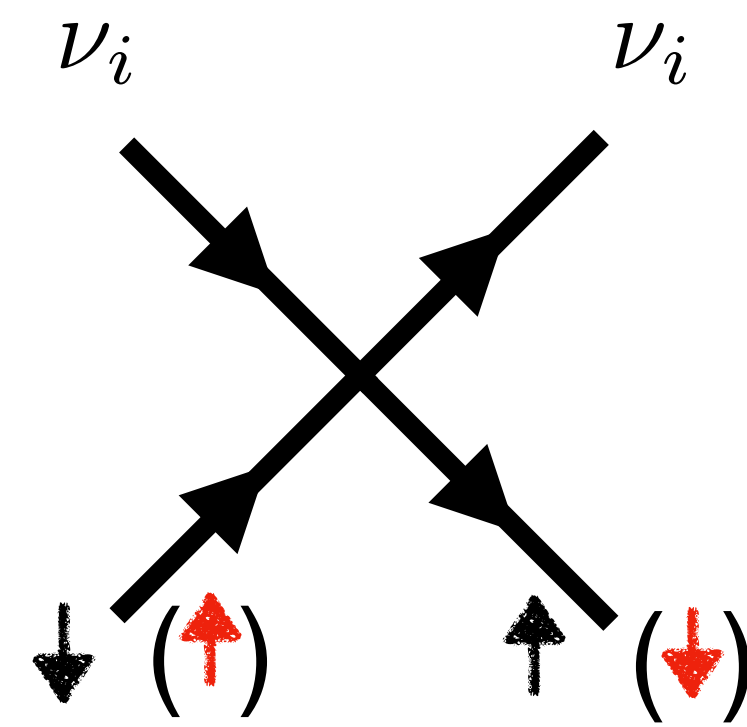


Different mass eigenstate  
(Allowed only on e, due to W)  
ESR



# Same mass eigenstate: NMR

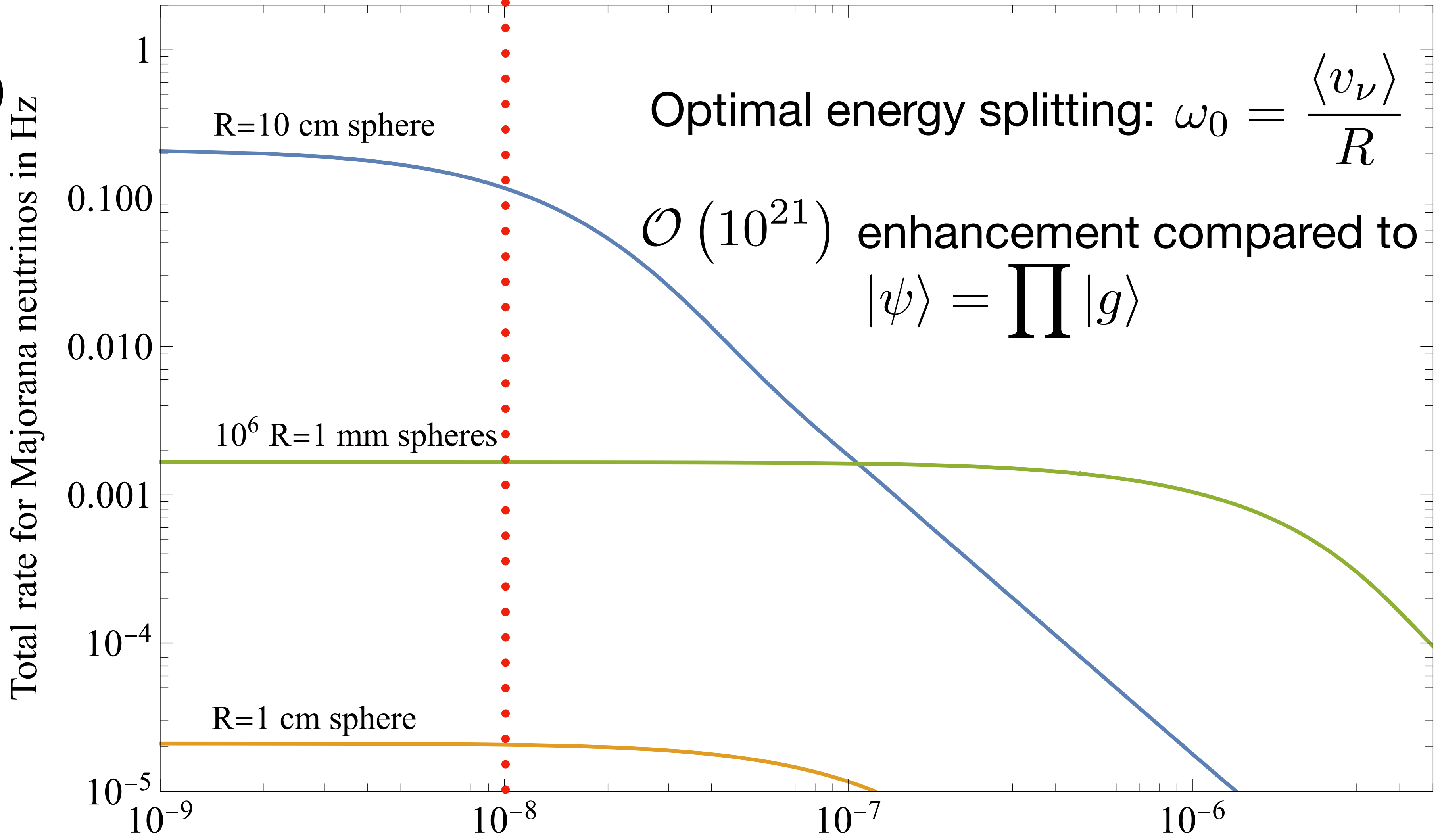
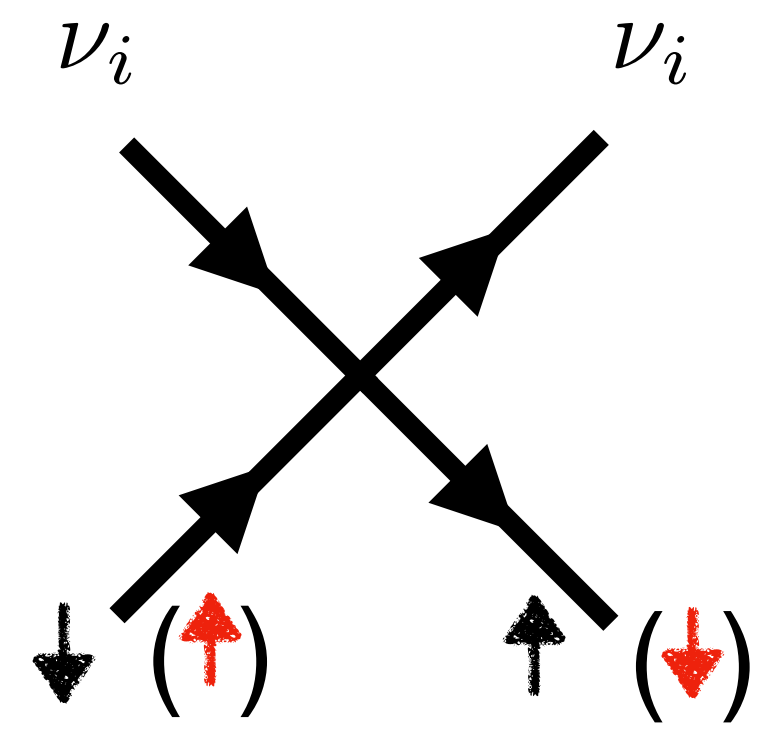
$$n_s = 3 \times 10^{22} \text{ cm}^{-3}$$



De-excite + Excite

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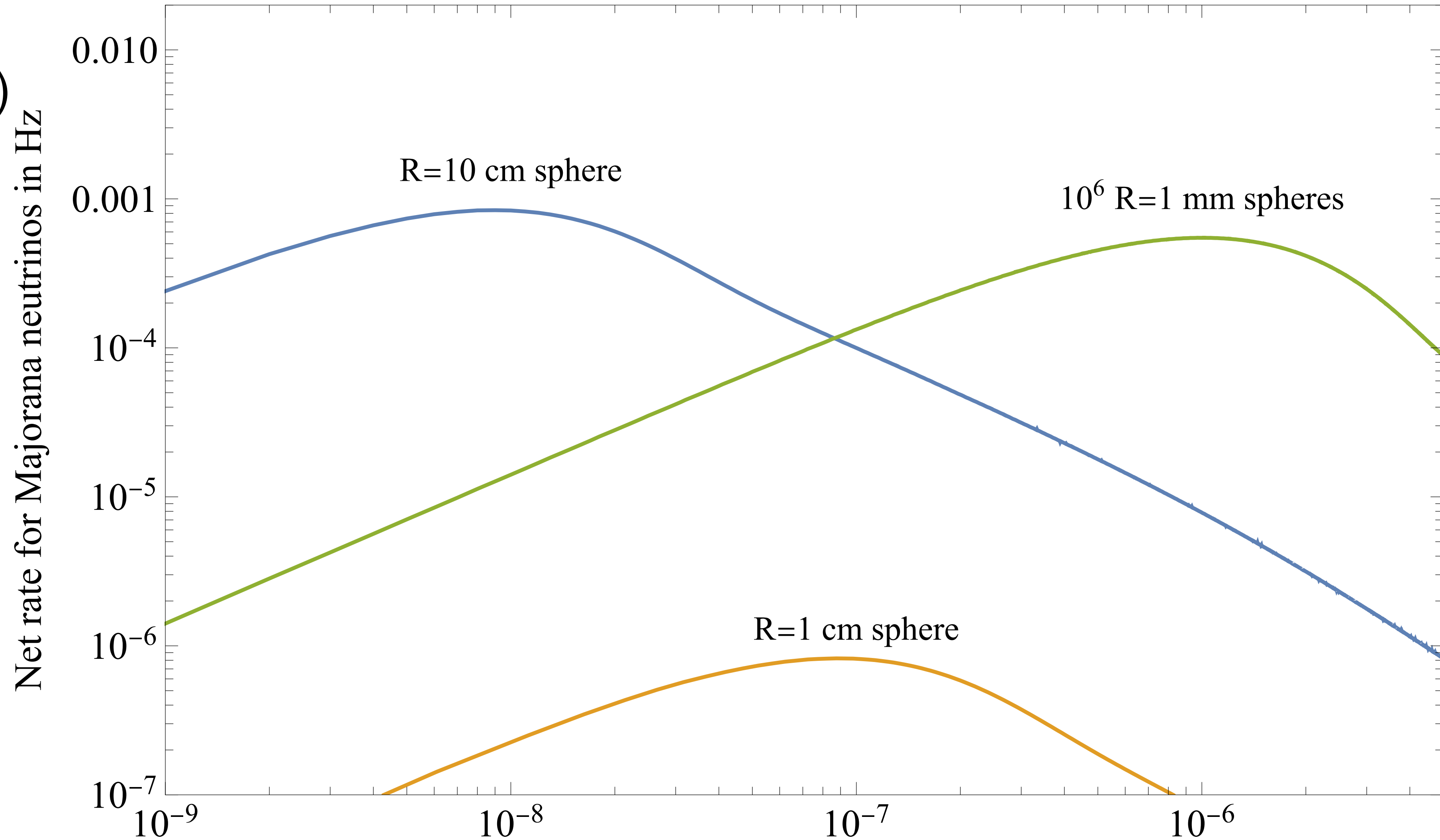
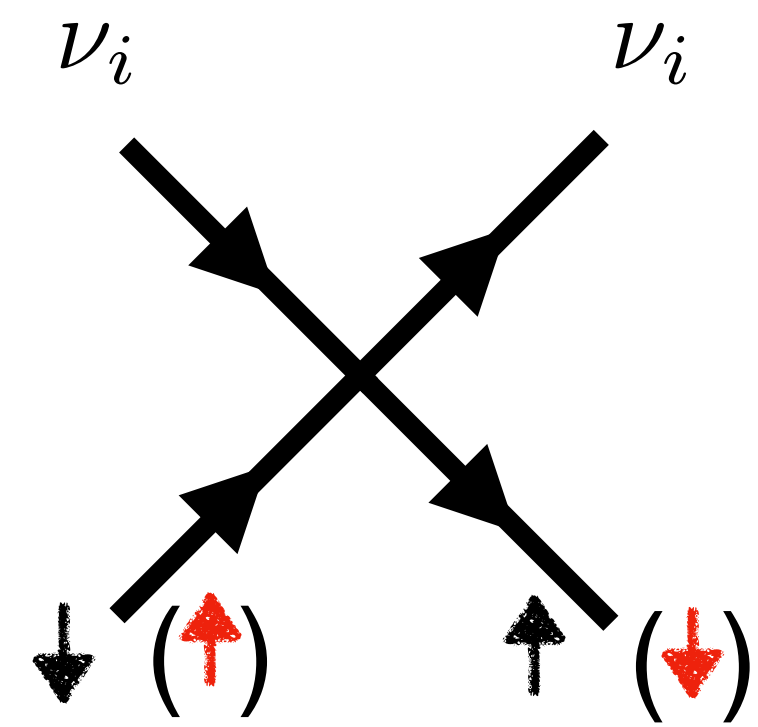


De-excite + Excite

Excitation energy in eV

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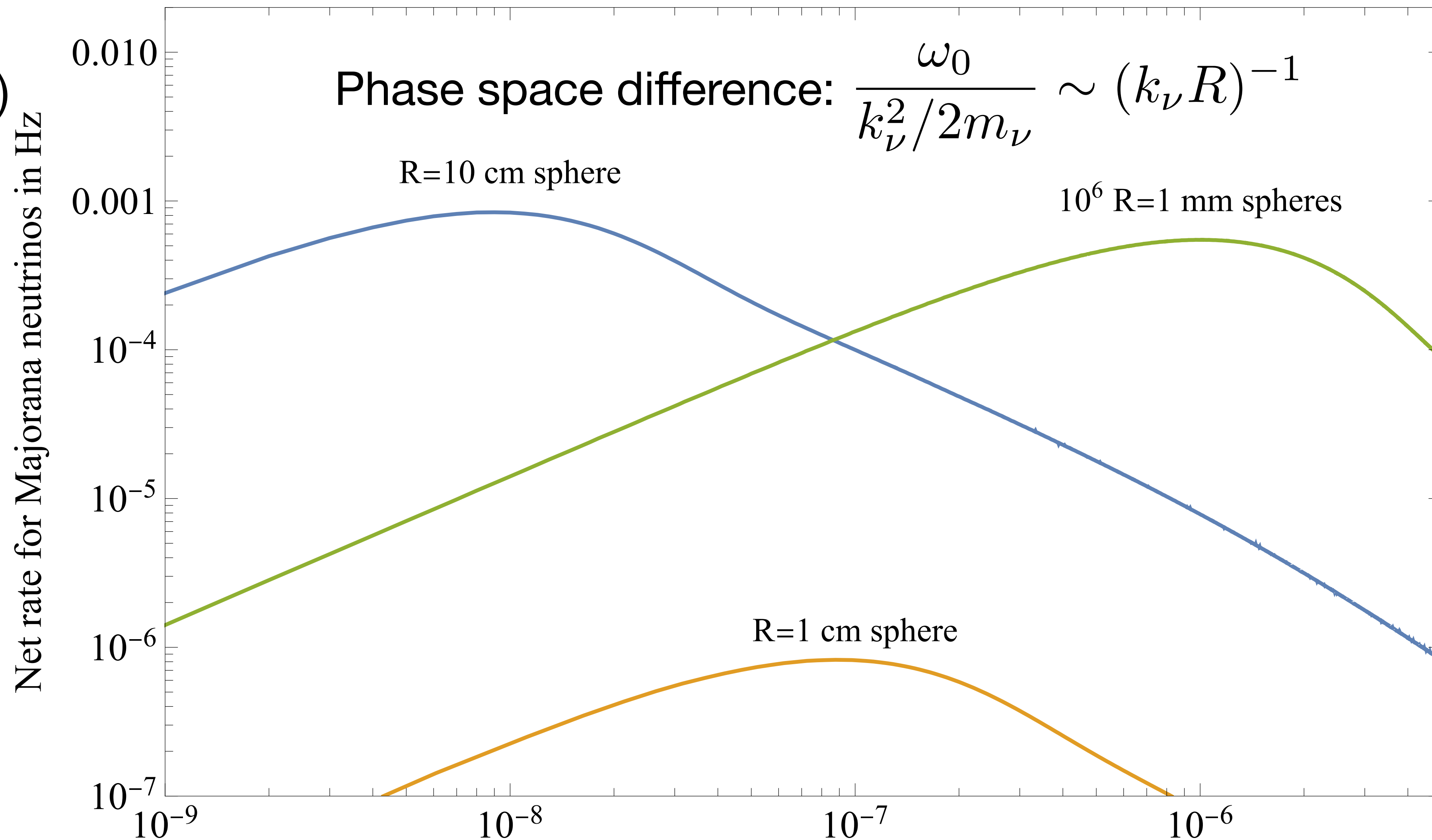
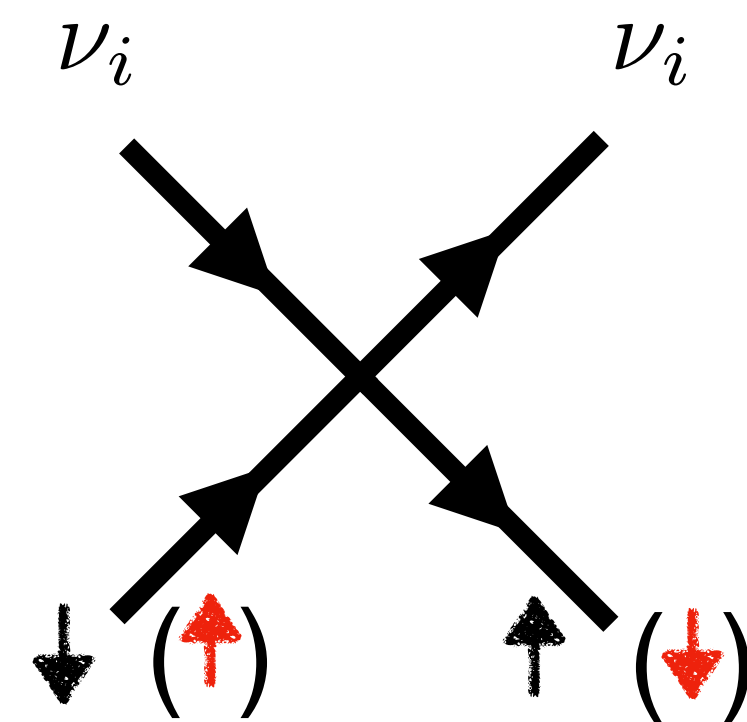


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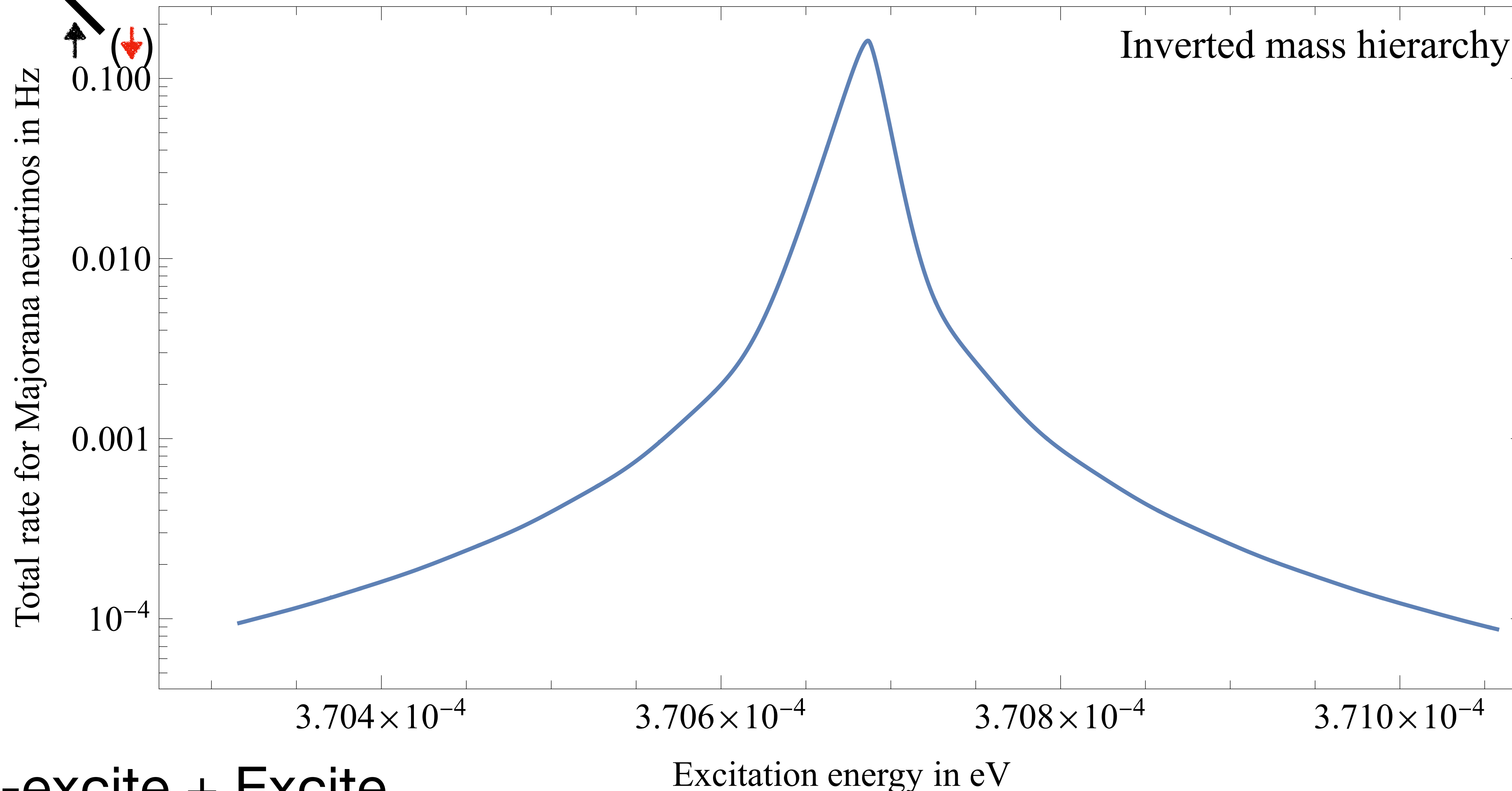
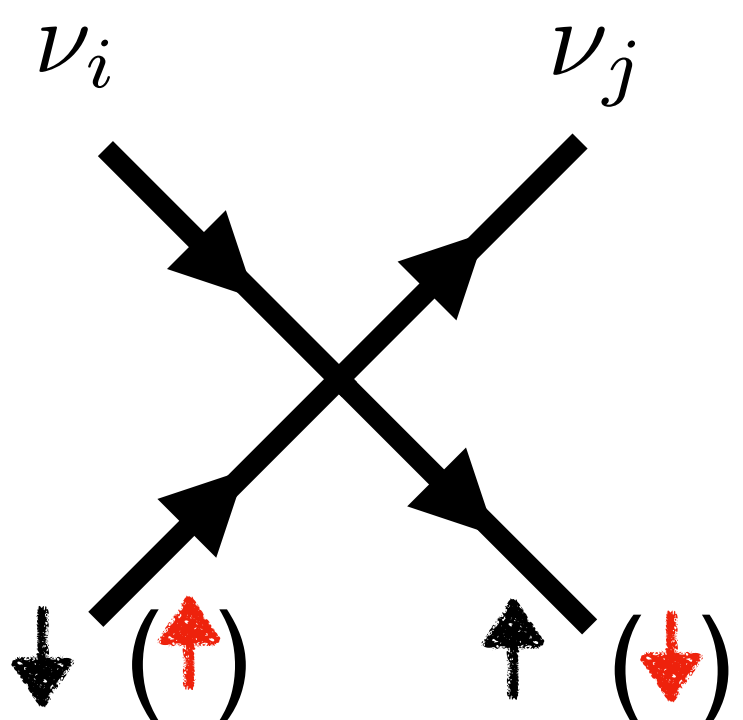


De-excite - Excite

Excitation energy in eV

# Different mass eigenstate: ESR

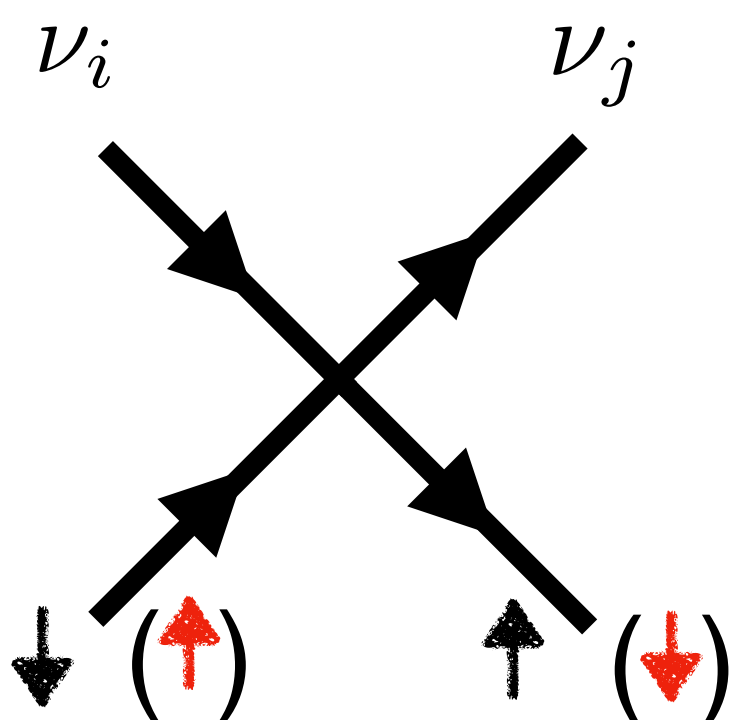
$n_s = 3 \times 10^{22} \text{ cm}^{-3}$ ,  $m_\nu = 0.1 \text{ eV}$  and  $R = 10 \text{ cm}$



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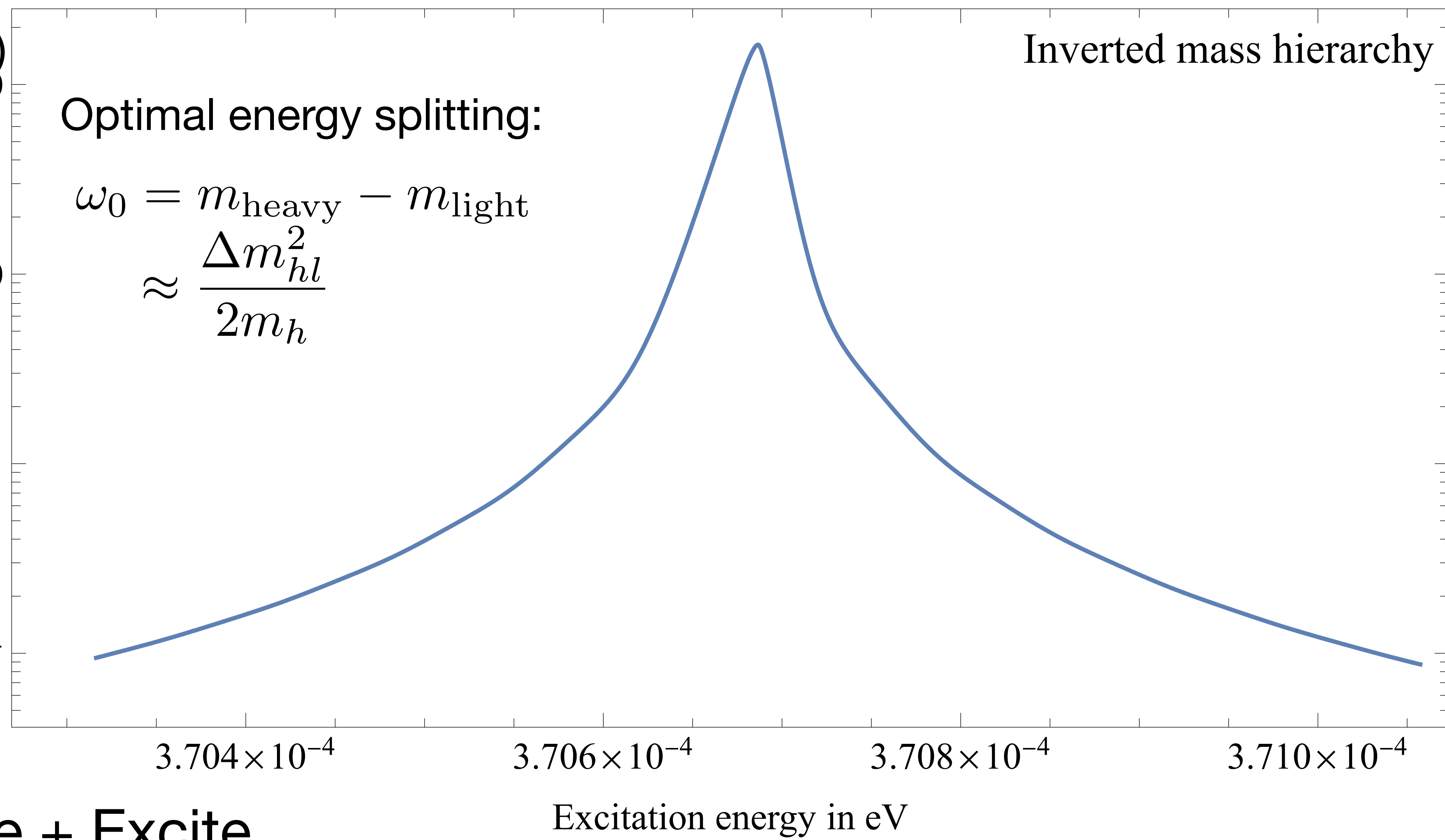


Total rate for Majorana neutrinos in Hz

Optimal energy splitting:

$$\omega_0 = m_{\text{heavy}} - m_{\text{light}} \approx \frac{\Delta m_{hl}^2}{2m_h}$$

Inverted mass hierarchy

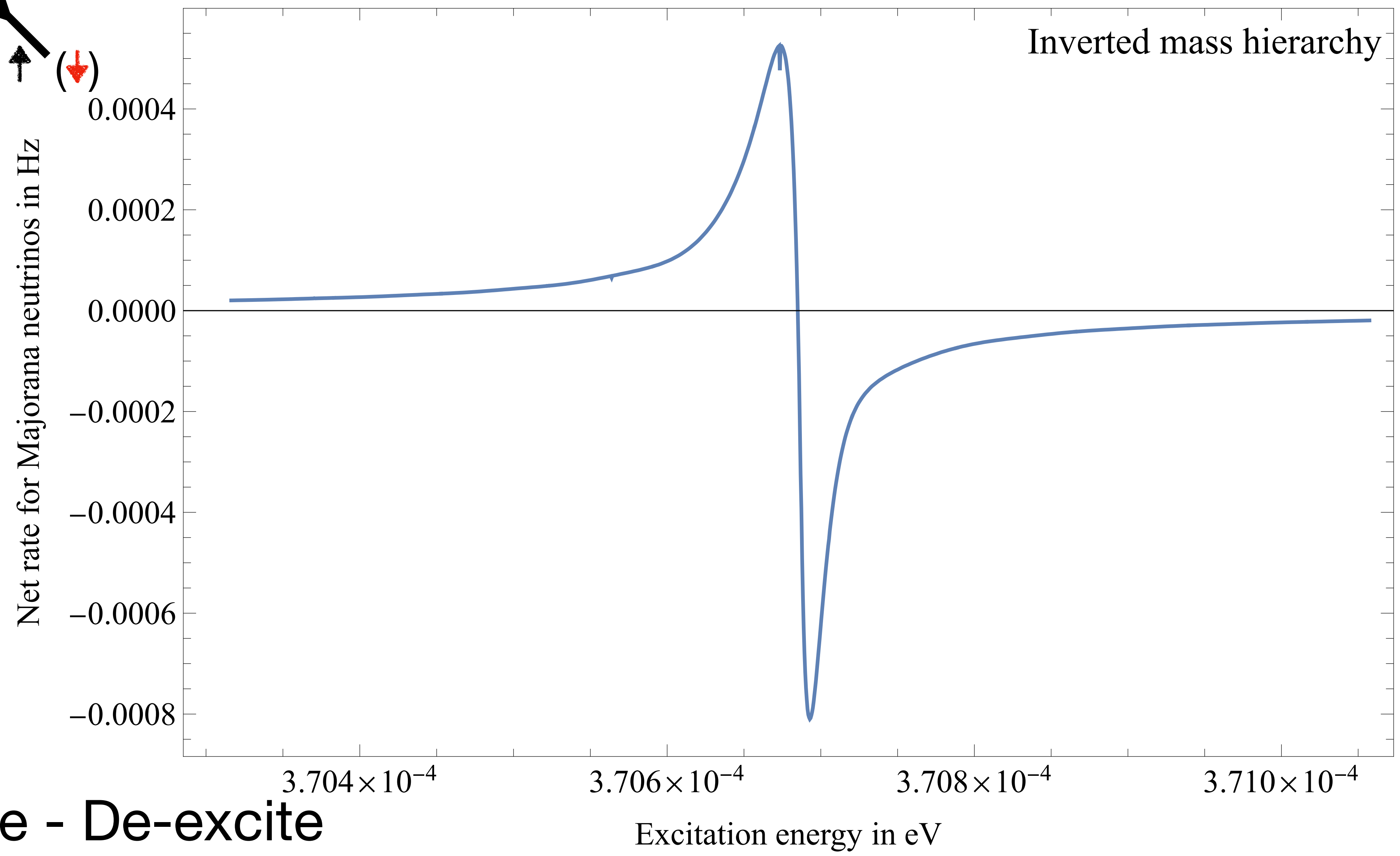
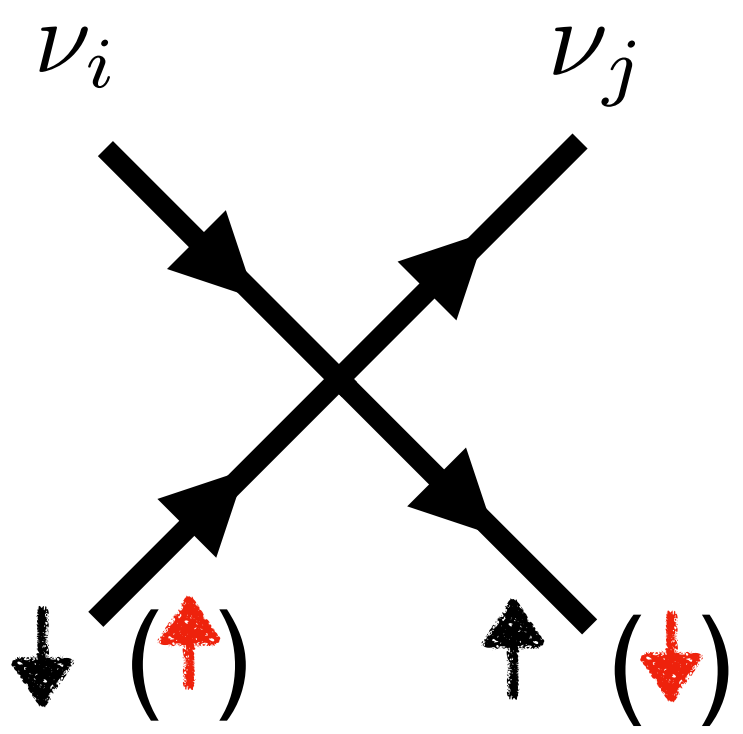


De-excite + Excite

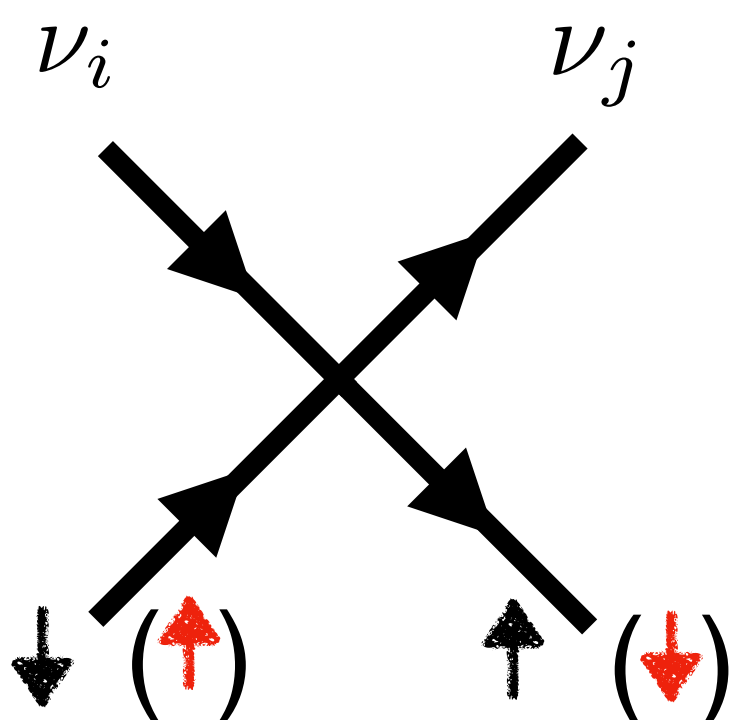
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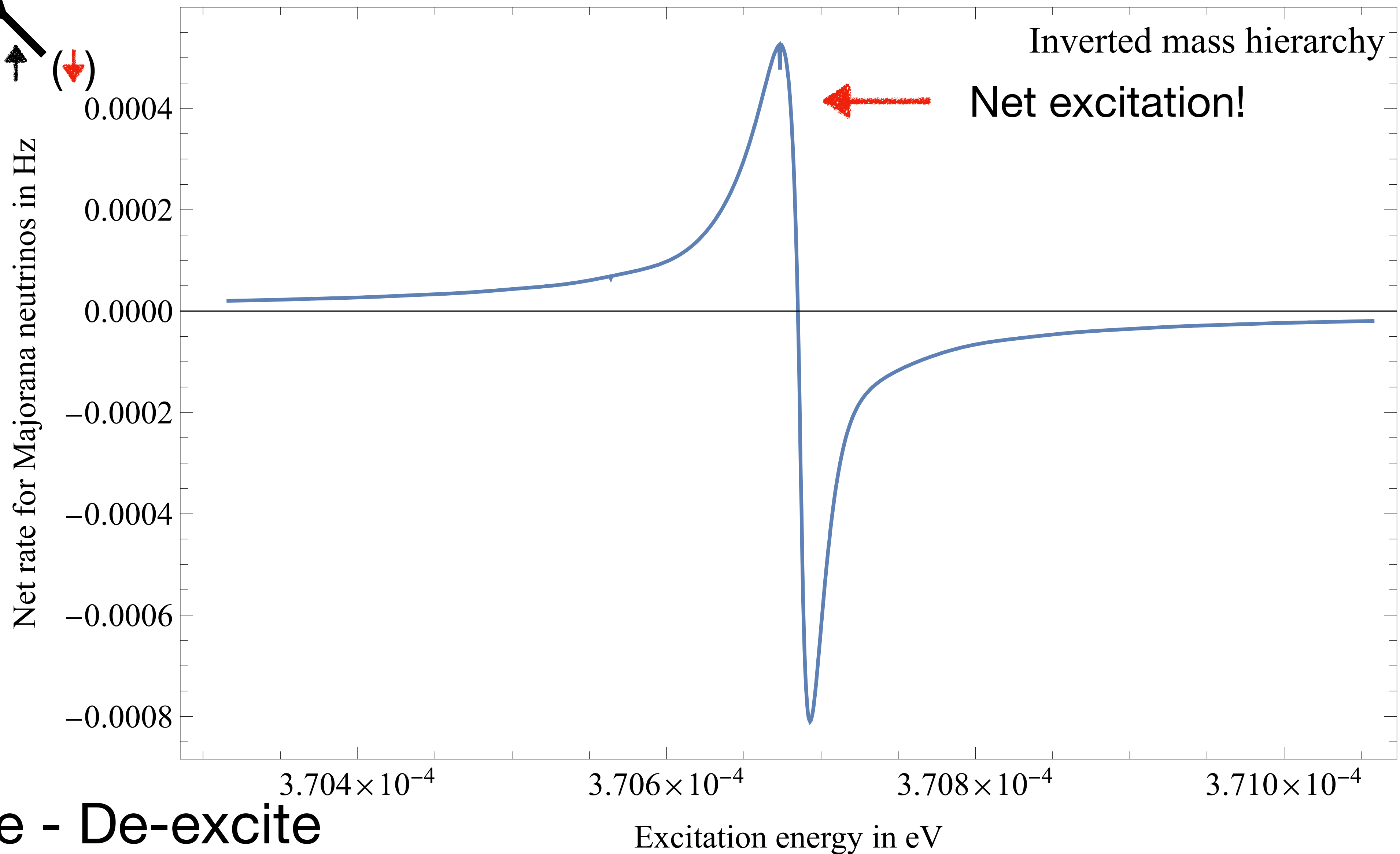


Excite - De-excite



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Excite - De-excite



# Other neutrinos

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Very suppressed net rates, but total rates:

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Rayleigh-Gans regime for relativistic particles

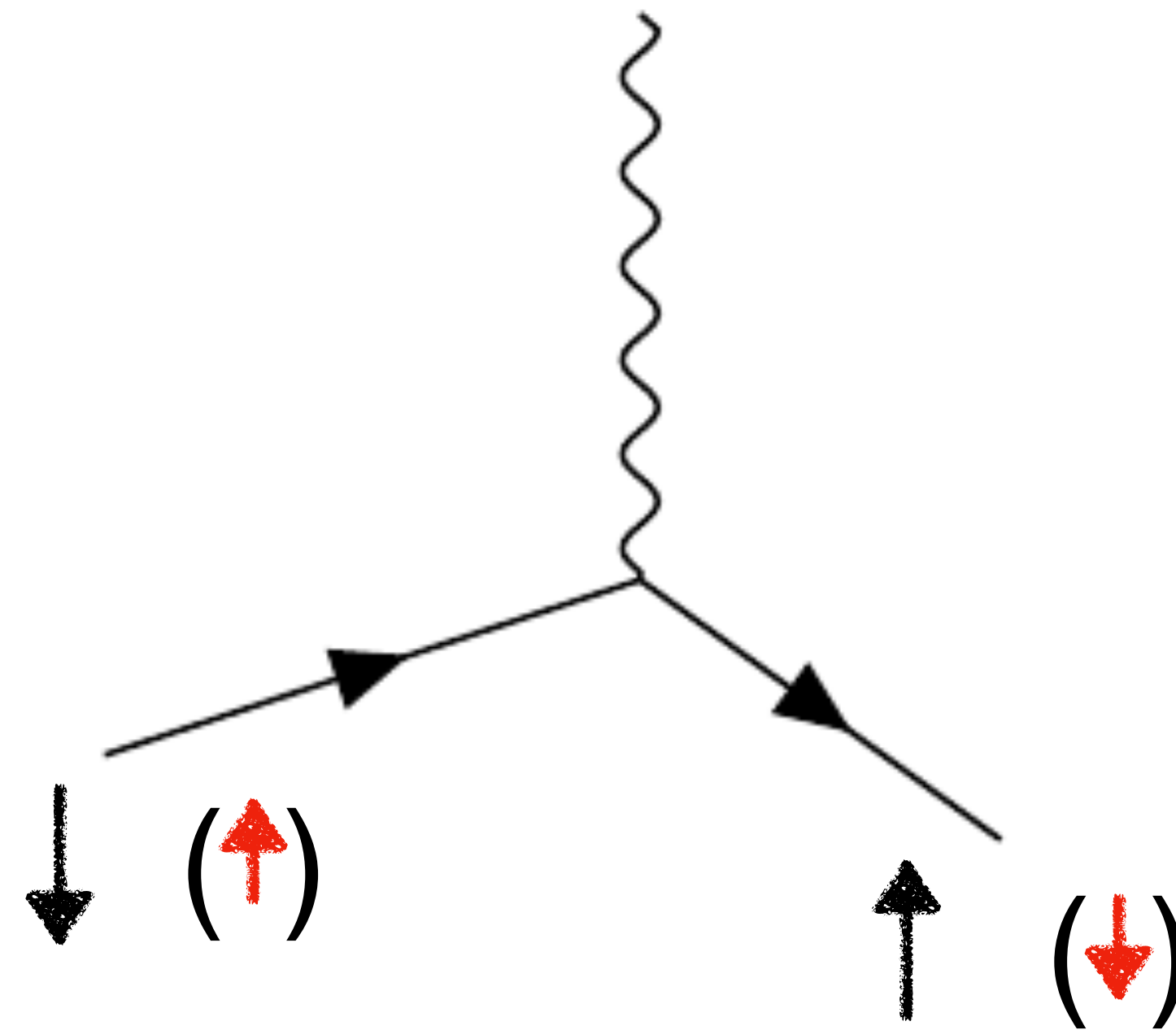
Very suppressed net rates, but total rates:

$$\Gamma_{\text{solar}} \sim \frac{1}{2.5 \text{ hours}} \left( \frac{n_s}{3 \cdot 10^{22} \text{ cm}^{-3}} \right)^2 \left( \frac{R}{10 \text{ cm}} \right)^4$$

$$\Gamma_{\text{reac}} \sim \frac{1}{3 \text{ hrs}} \left( \frac{n_s}{3 \cdot 10^{22} \text{ cm}^{-3}} \right)^2 \left( \frac{R}{10 \text{ cm}} \right)^4 \left( \frac{100 \text{ m}}{d} \right)^2$$

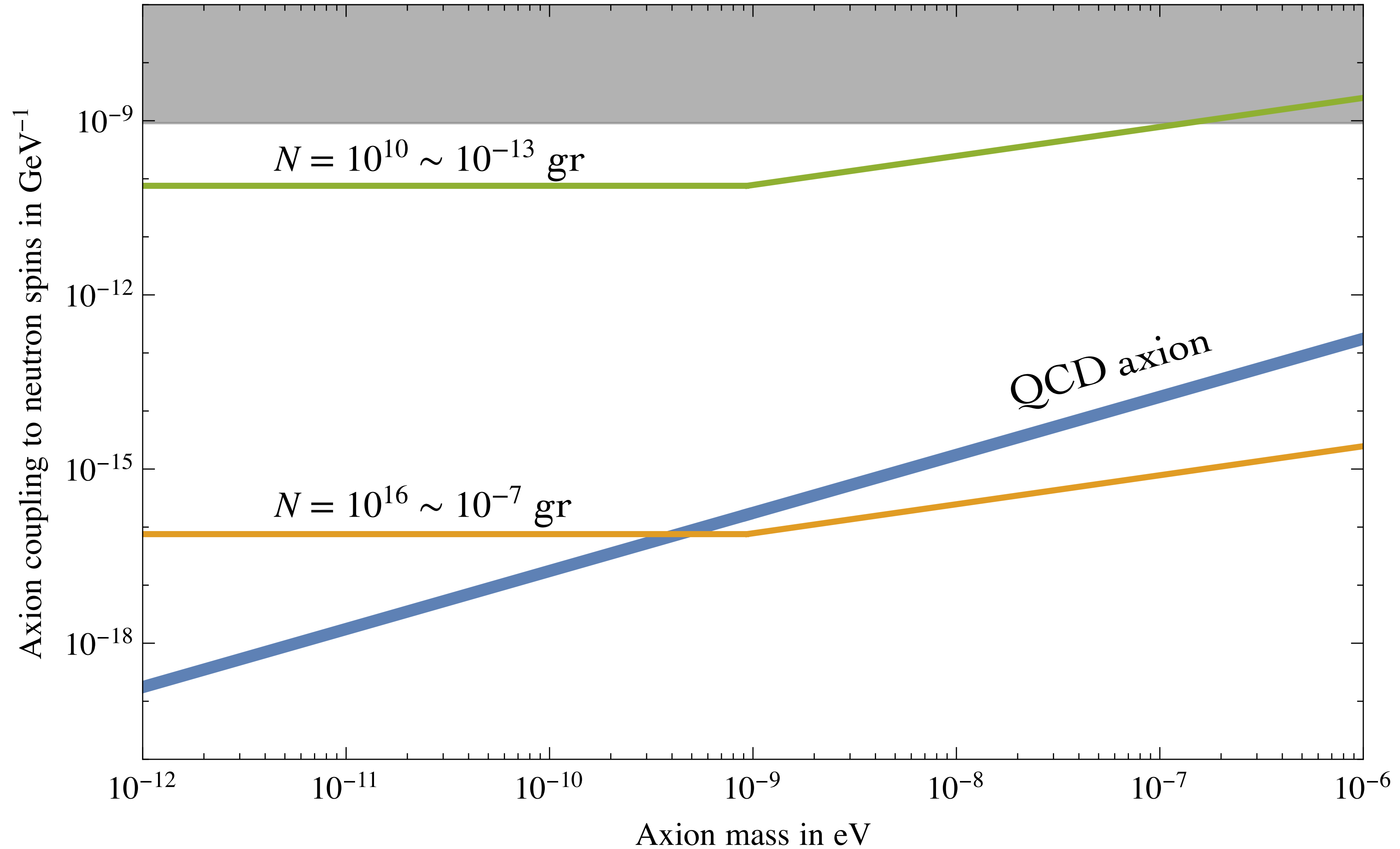
$$N_{\text{bomb}} \sim \mathcal{O}(1) \left( \frac{n_s}{3 \cdot 10^{22} \text{ cm}^{-3}} \right)^2 \left( \frac{R}{10 \text{ cm}} \right)^4 \left( \frac{10 \text{ km}}{d} \right)^2$$

# Absorption or Emission



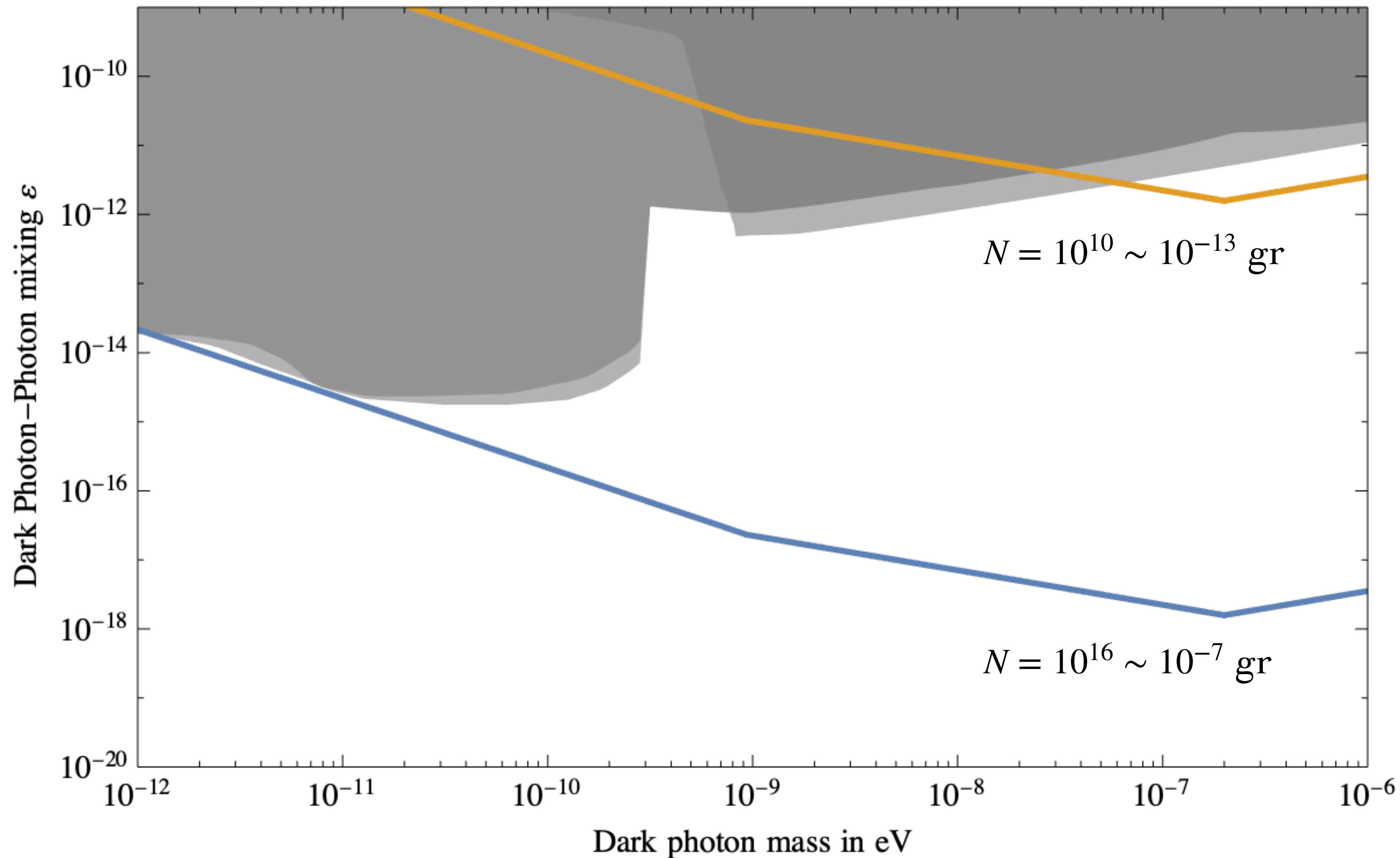
# QCD Axion

1 Hz rate contours for  $10^{10}$  and  $10^{16}$  atoms



# Dark Photons

1 Hz rate contours for  $10^{10}$  and  $10^{16}$  atoms



# Dark Quantum Optics



# Observables

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Lindblad equation for CvB

$$\dot{\rho}_S \simeq -i\delta\omega_S [J_z, \rho_S] + \frac{\gamma_-}{2} \mathcal{L}_{J_-} [\rho_S(t)] + \frac{\gamma_+}{2} \mathcal{L}_{J_+} [\rho_S(t)] + \frac{\gamma_z}{2} \mathcal{L}_{J_z} [\rho_S(t)].$$

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Compare to Lindblad equation for thermal photons

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Spontaneous emission  $\rightarrow$  Dicke superradiance

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Net rate zero!

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For example:

$$\langle \dot{J}_z(t) \rangle \approx \gamma_+ \frac{\langle J_- J_+ \rangle}{N^2/4} - \gamma_- \frac{\langle J_+ J_- \rangle}{N^2/4} \quad \text{Net suppressed}$$

# Observables

Lindblad equation for CvB

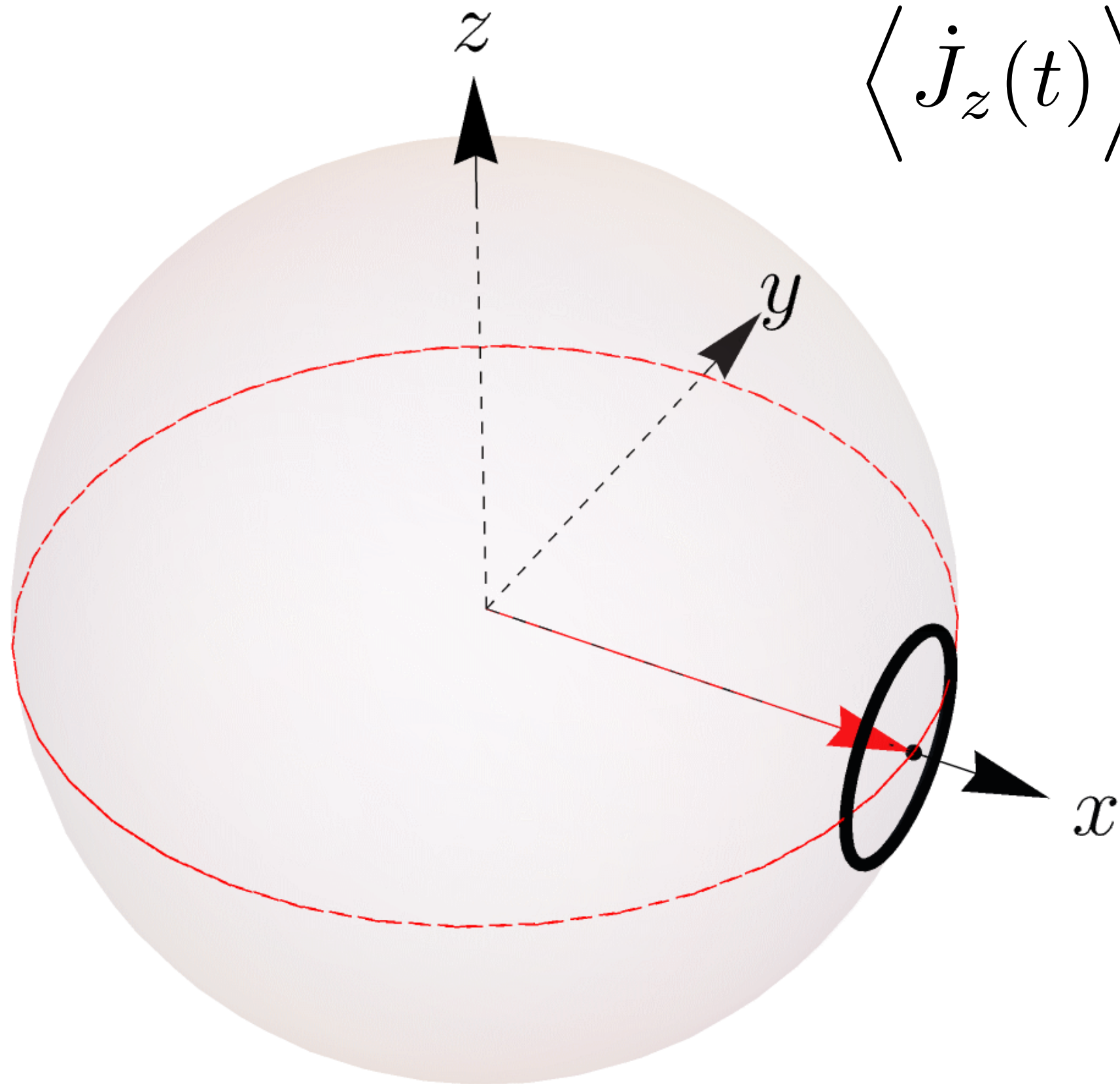
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$N^2/4$                        $N^2/4$

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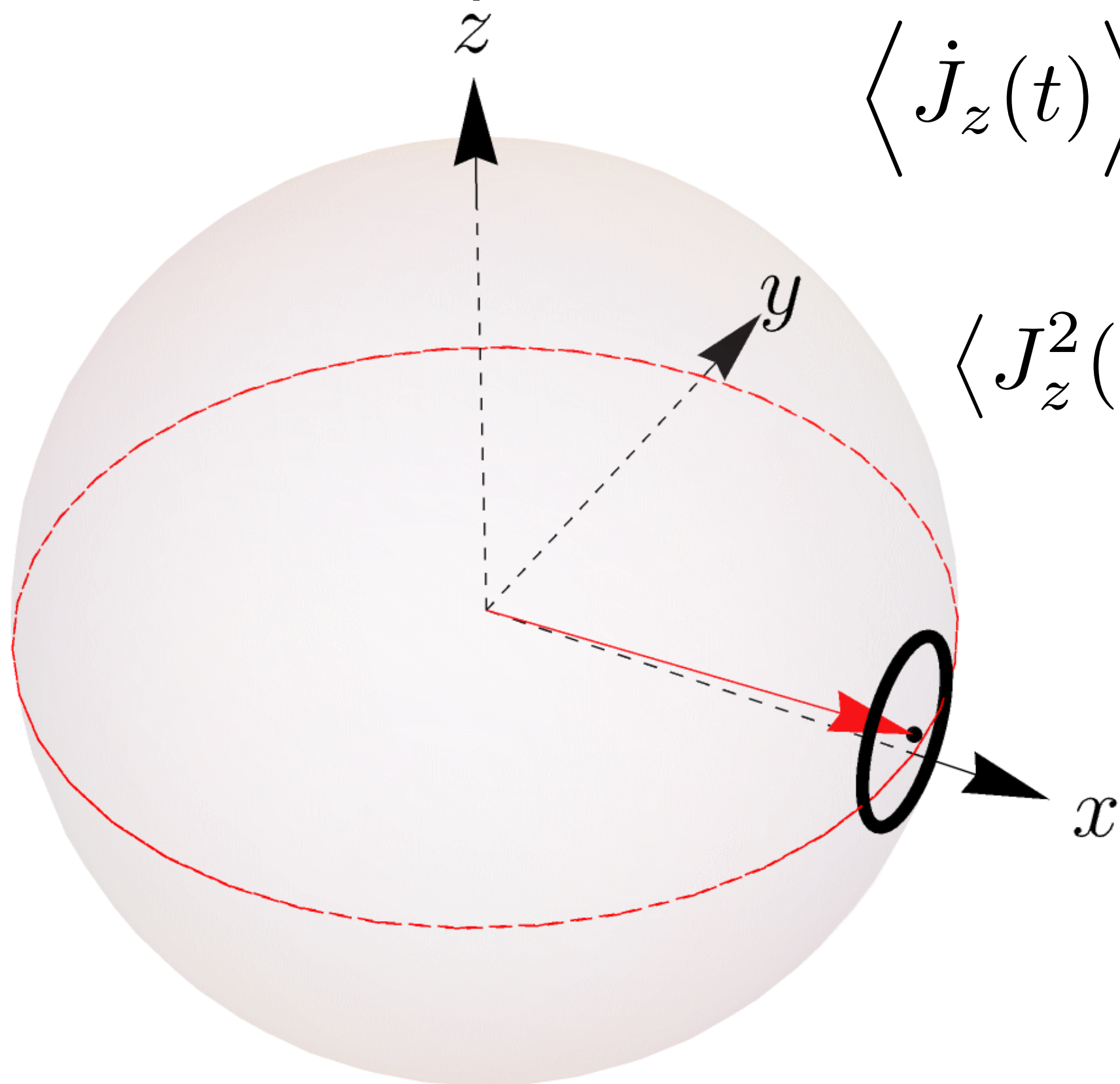
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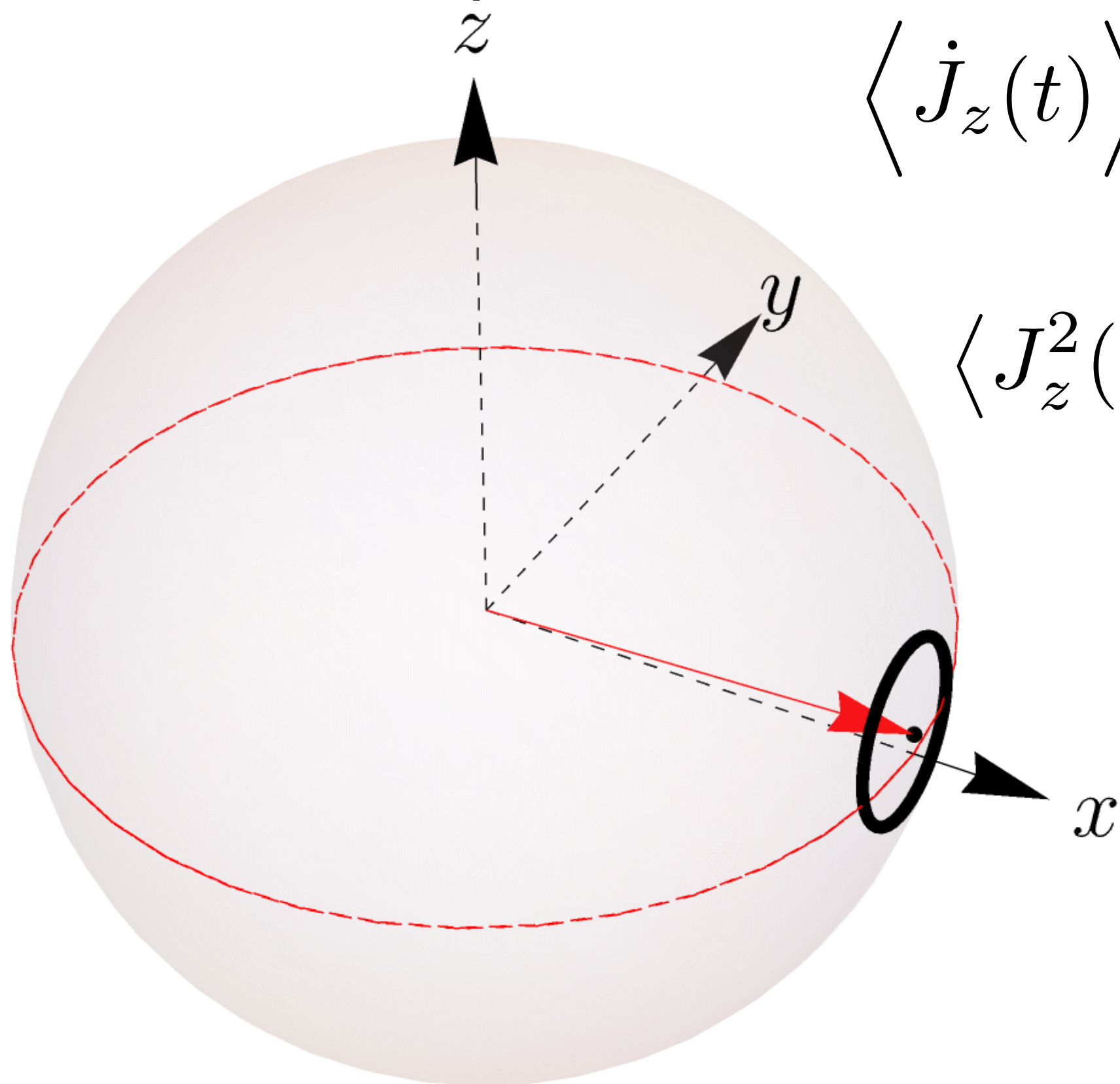
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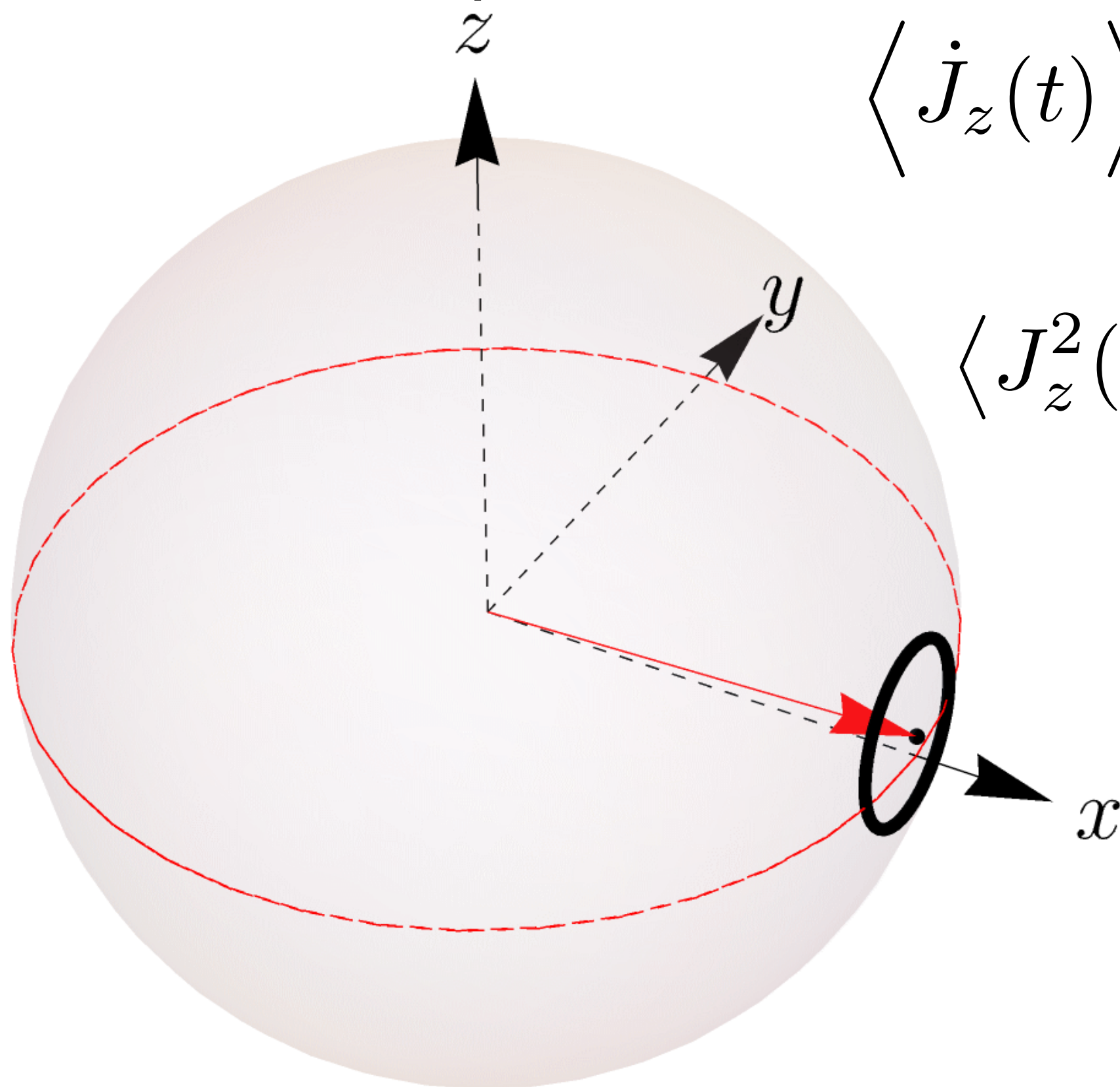
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Can look for variance change

Need to overcome  $N$



# Net energy CvB bound

$$\text{SNR} = \frac{n^2 \lambda^2 R^4 |\gamma_+ - \gamma_-| t}{\sqrt{N}}$$

$$C_{\text{boost}} \sim 2 \cdot 10^{11} \left( \frac{10 \text{ cm}}{R} \right)^{3/2} \left( \frac{3 \cdot 10^{22} \text{ cm}^3}{n_s} \right)^{3/2} \left( \frac{1000 \text{ sec}}{t} \right) \left( \frac{10^3}{N_{\text{shots}}} \right)^{1/2}$$



# Net energy CvB bound

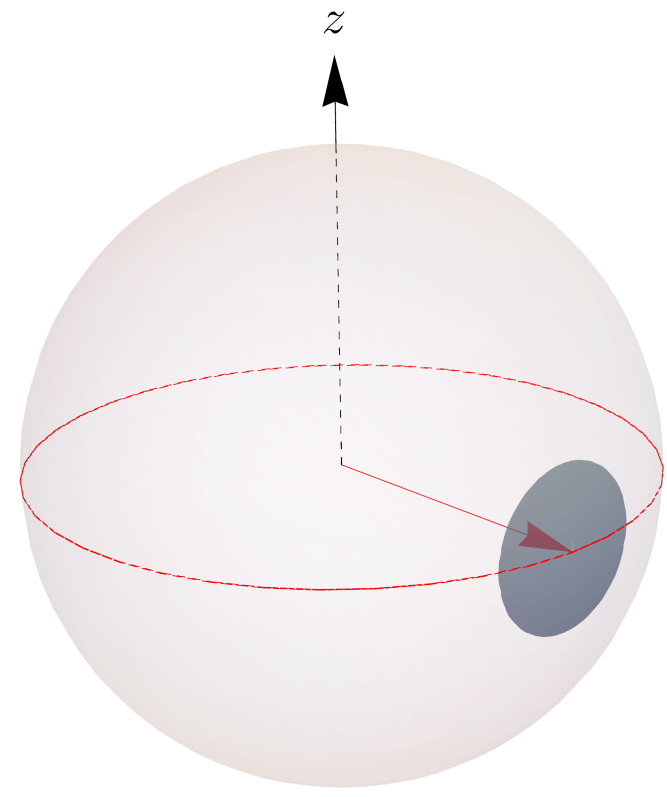
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Comparable to KATRIN (200 ton spectrometer)

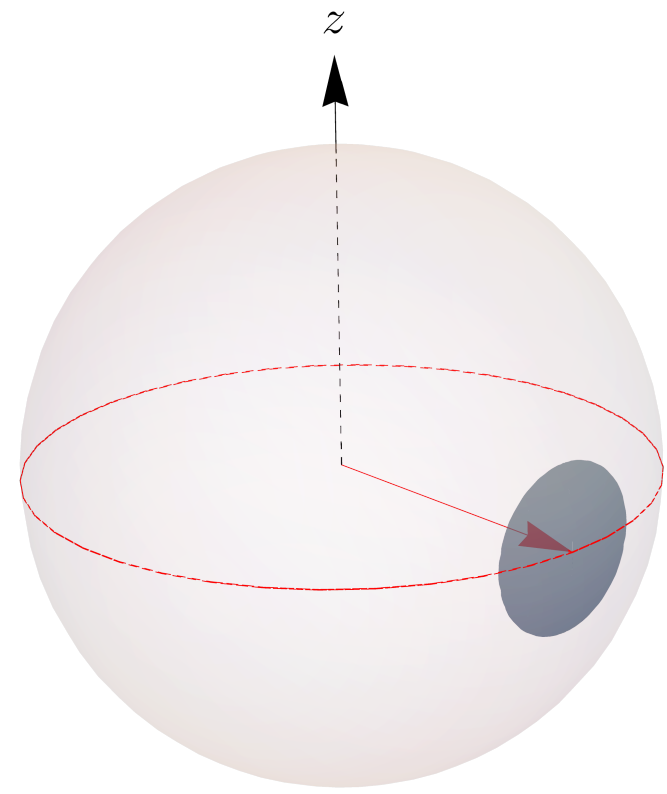
# States

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Product state:  $\Delta J_z = \sqrt{N}$

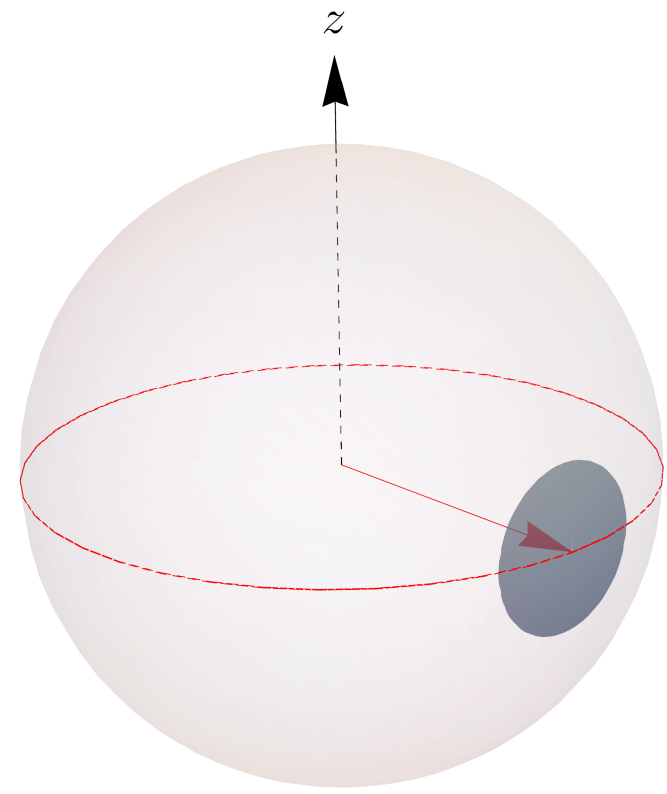
# States



Product state:  $\Delta J_z = \sqrt{N}$

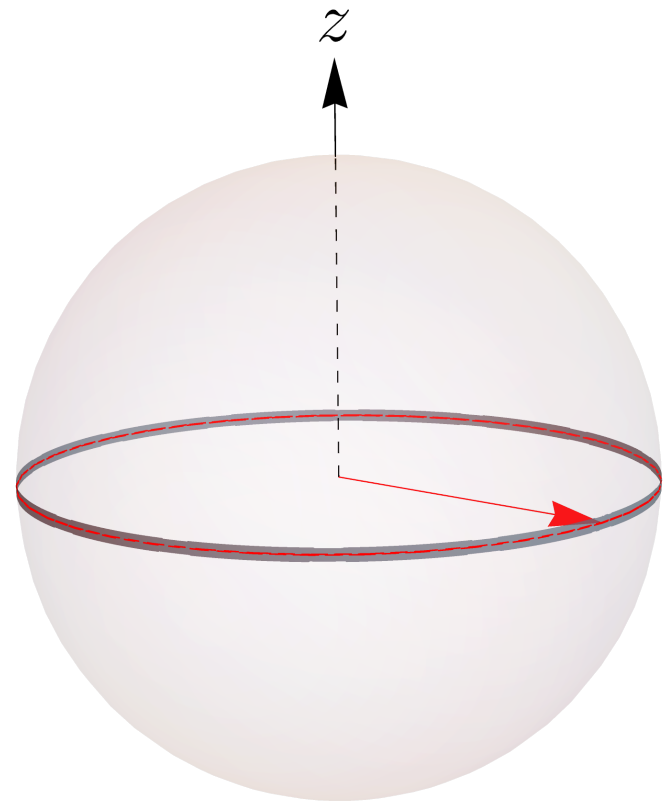
Easy to produce, noisy

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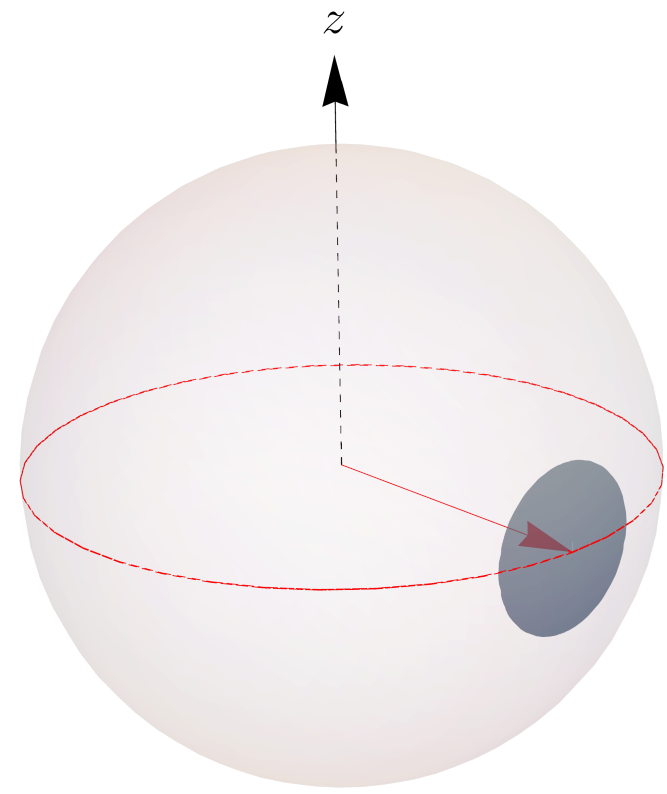
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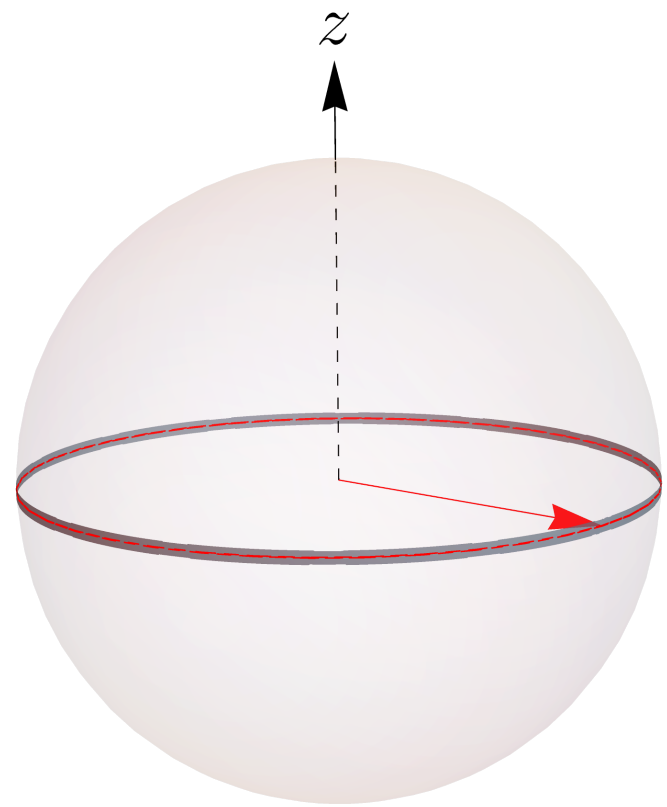
Equatorial Dicke state:  $\Delta J_z = 0$

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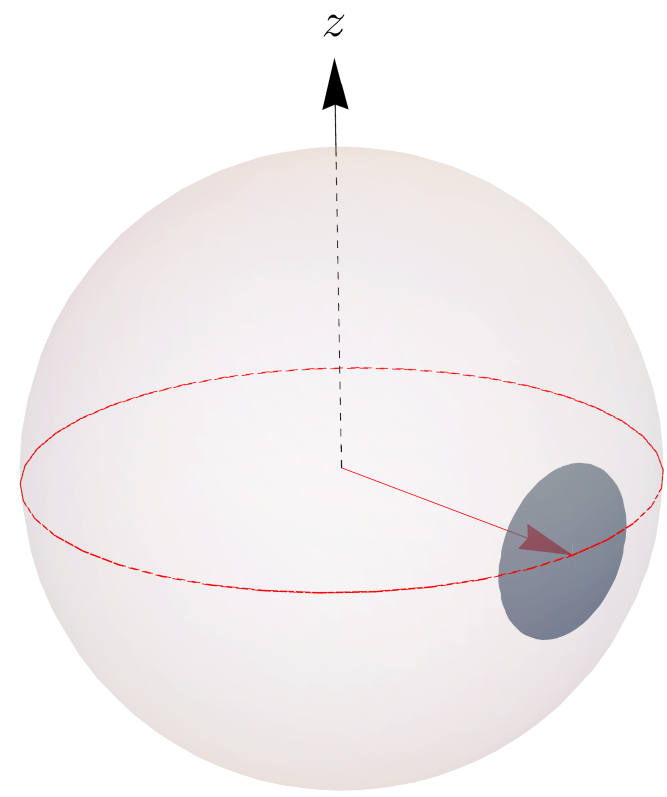
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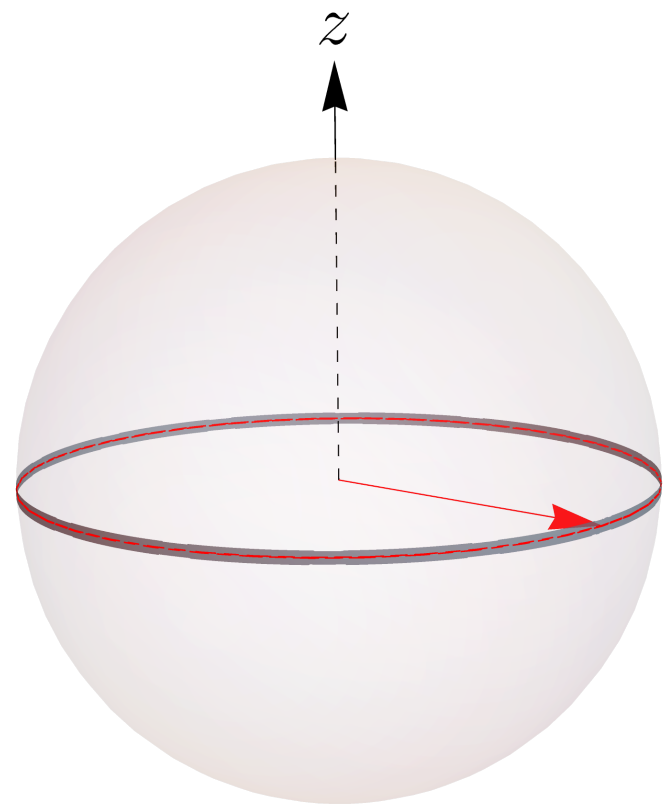
Hard to produce

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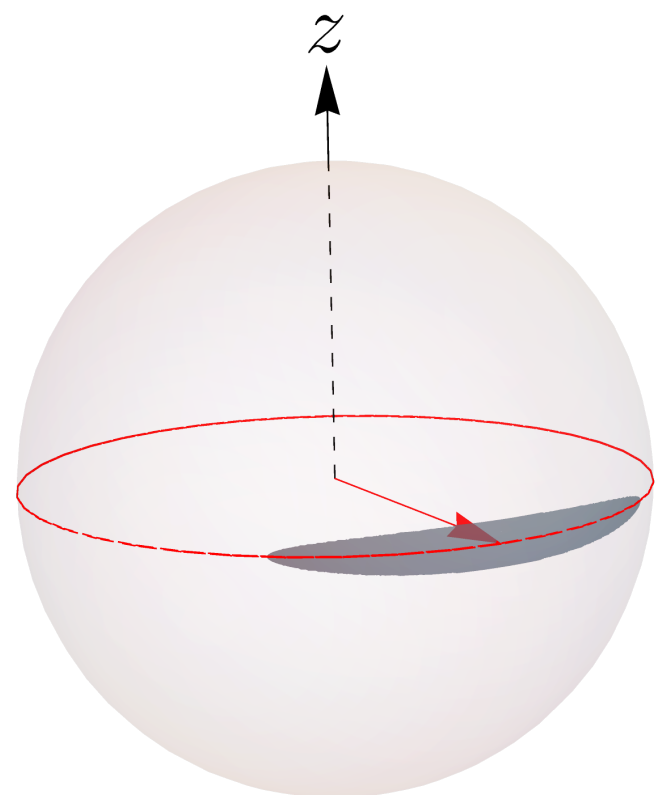
Product state:  $\Delta J_z = \sqrt{N}$

Easy to produce, noisy



Equatorial Dicke state:  $\Delta J_z = 0$

Hard to produce



Squeezed state:  $\Delta J_z = \sqrt{\xi N}$ ,  $\xi \ll 1$  Best bet

# Conclusions



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May point to a new type of **table-top** and **ultra-low threshold** particle detectors

**Backup**

# Dark Matter

$$\mathcal{L} \supset \frac{1}{\Lambda^2} \frac{i}{2} (\phi^\dagger \partial_\mu \phi - \phi \partial_\mu \phi^\dagger) \bar{N} \gamma^\mu \gamma^5 N$$

$$\mathcal{L} \supset \frac{1}{\Lambda^2} \bar{\psi} \gamma_\mu \gamma^5 \psi \bar{N} \gamma^\mu \gamma^5 N$$

Inelastic DM scattering from R=10 cm sphere with  $n_s=3 \times 10^{22} \text{ cm}^{-3}$

