Superradiant interactions of cosmic noise

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Perimeter Institute

Based on arXiv:2408.04021
with Asimina Arvanitaki (PI) and Savas Dimopoulos (Stanford, PI)

Fermilab Theory Seminar - October 10, 2024

Outline

1. Coherence in elastic scattering

2. Superradiant interactions - Coherence in inelastic processes

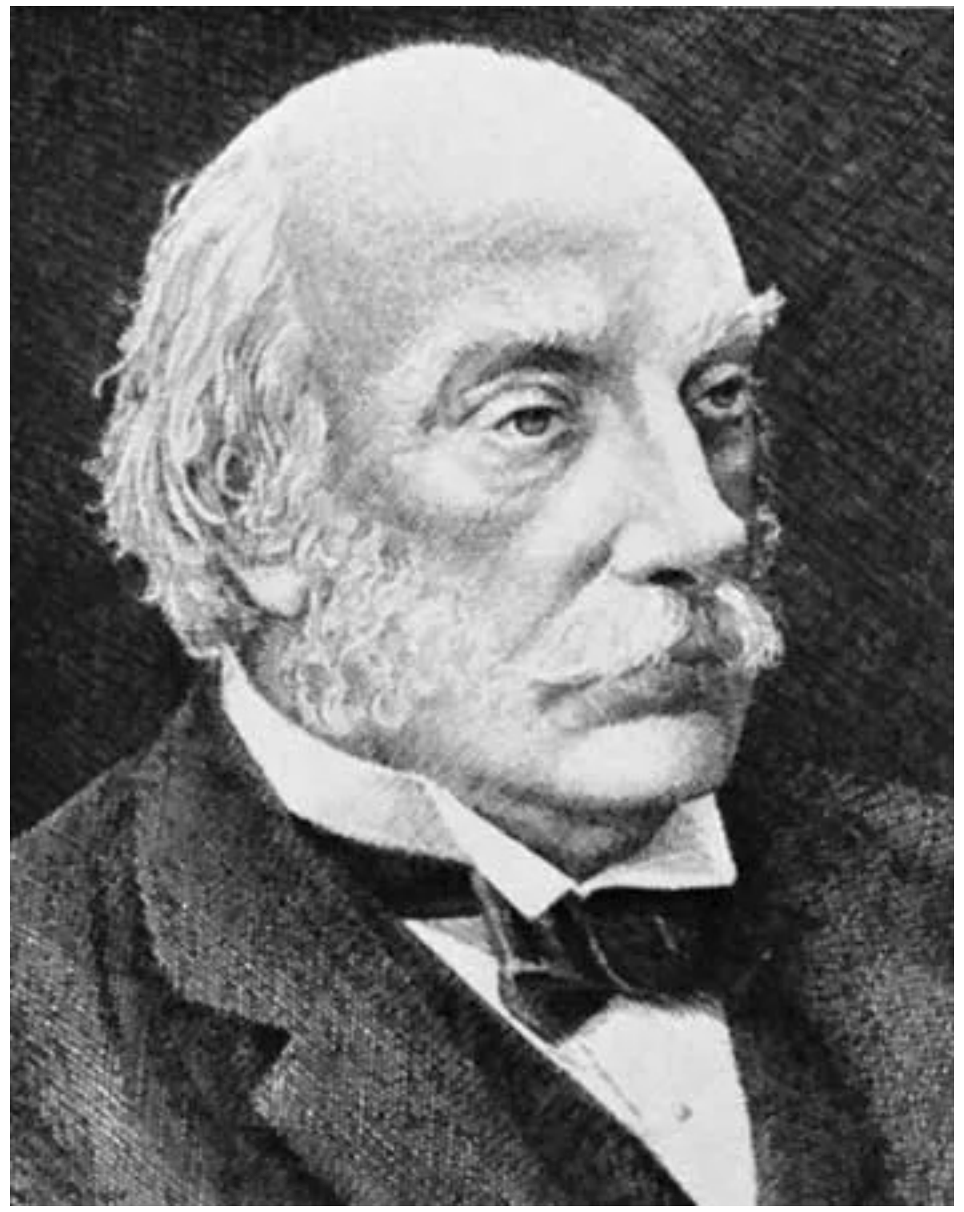
3. Scattering: CvB, solar and reactor neutrinos, DM

4. Absorption/Emission: QCD axion, Dark Photons

5. Dark quantum optics

Coherence in Elastic Scattering

Lord Rayleigh



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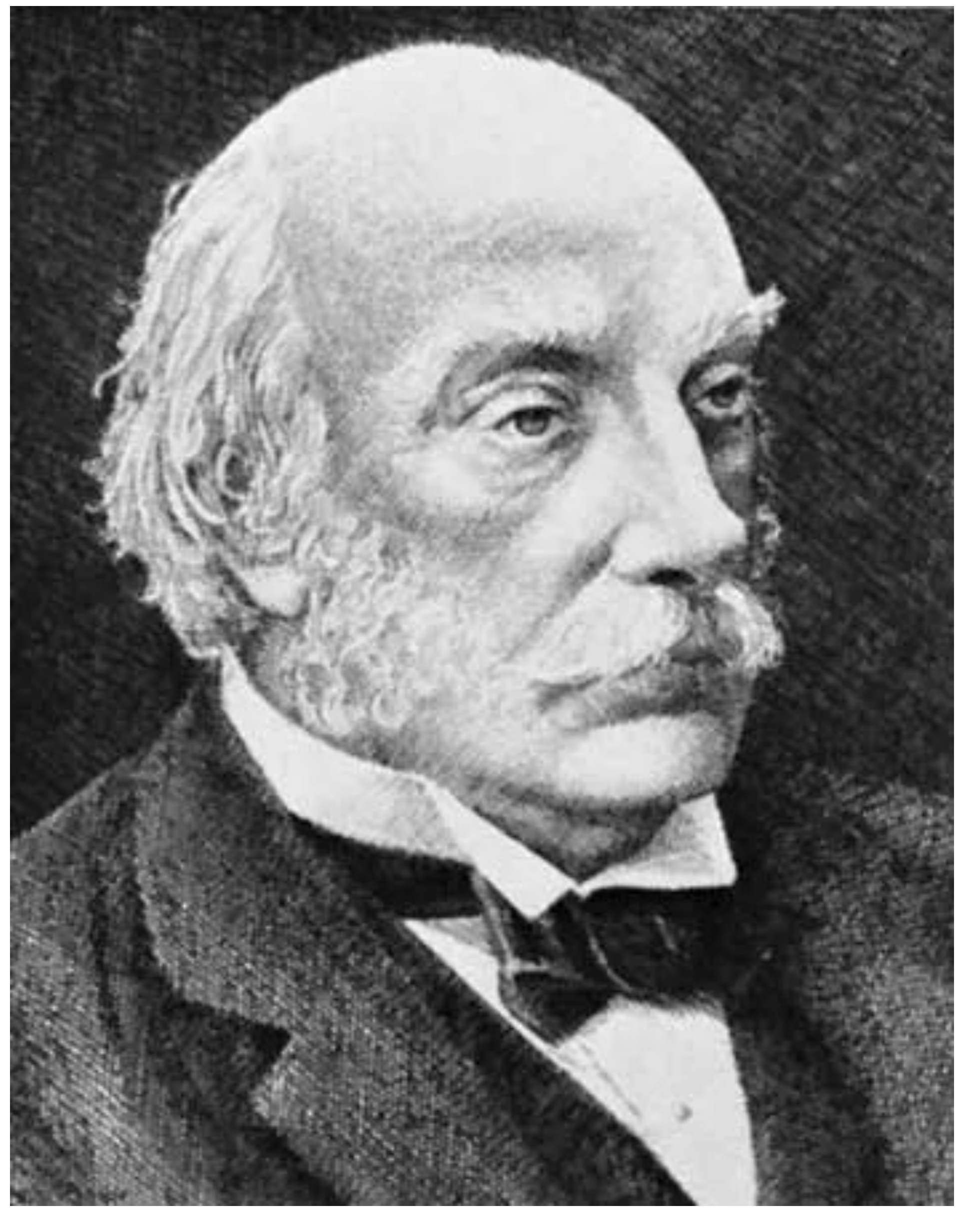

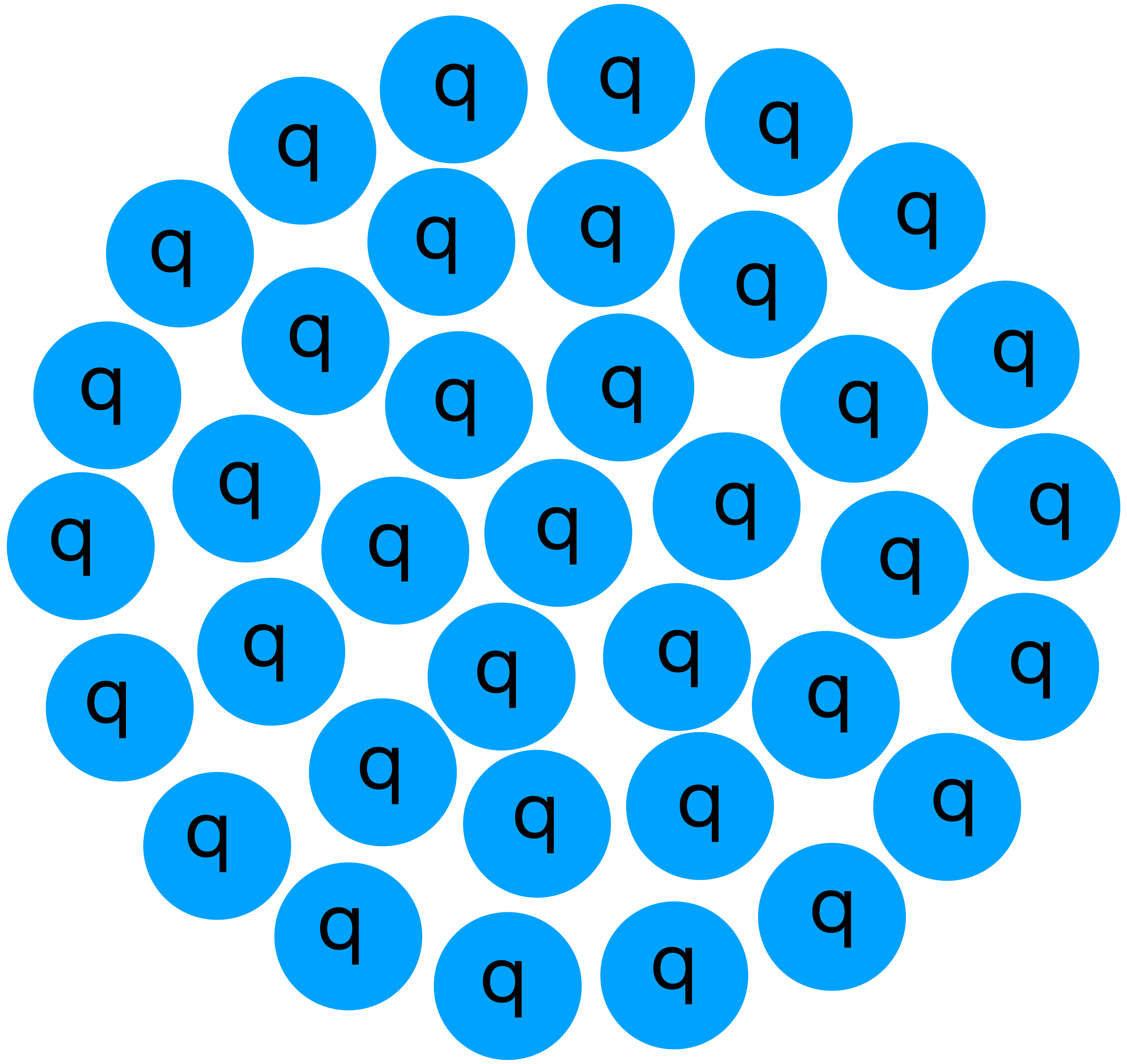

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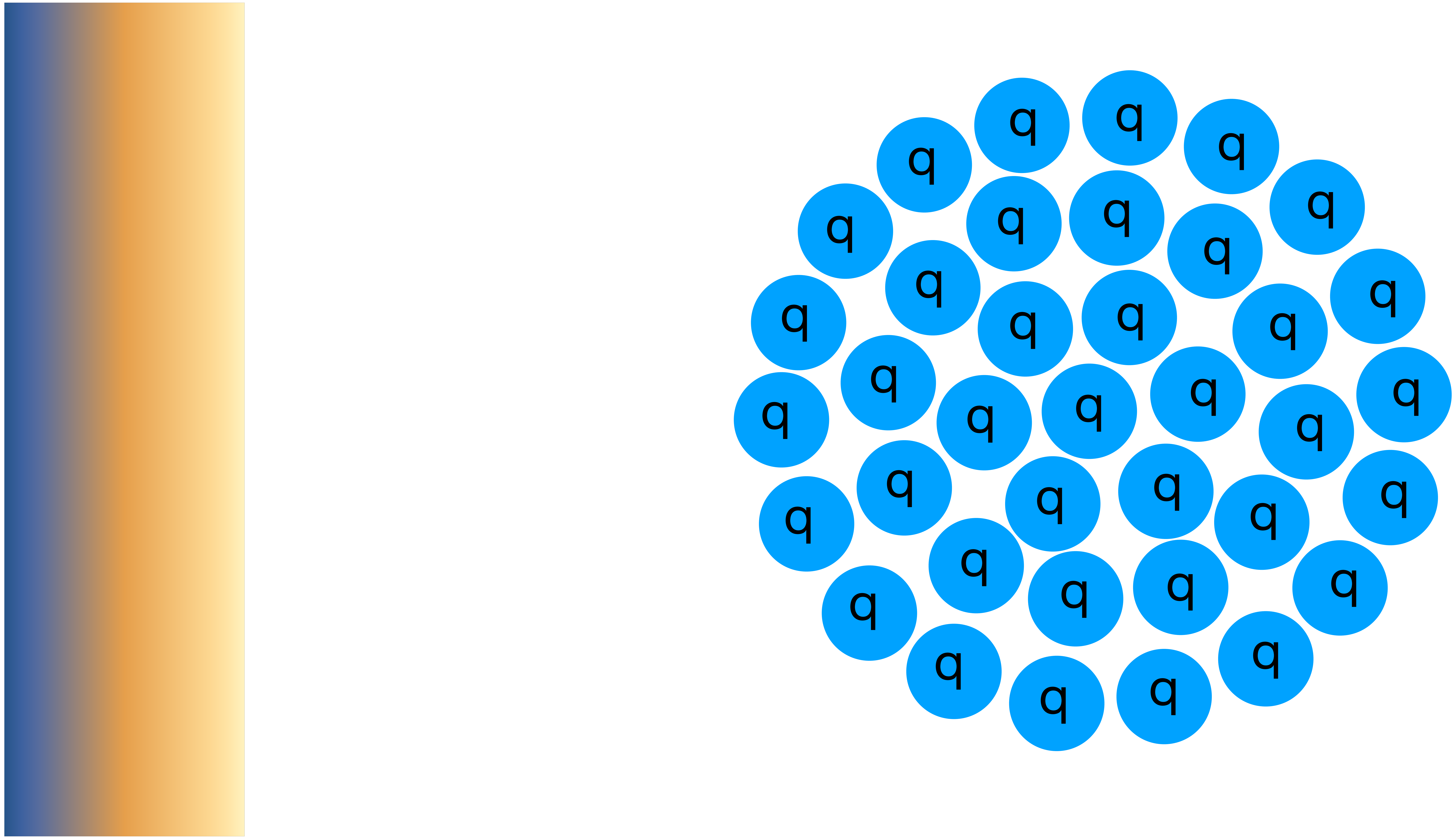

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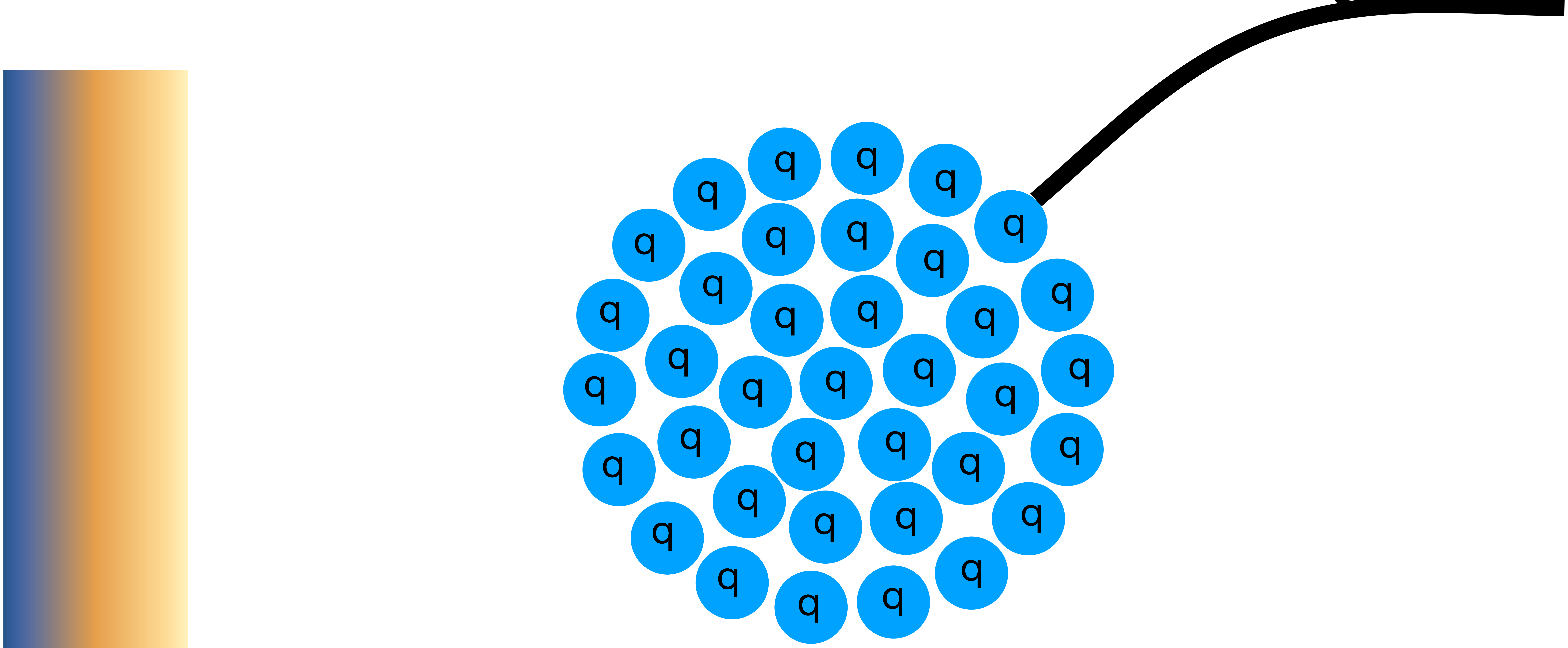

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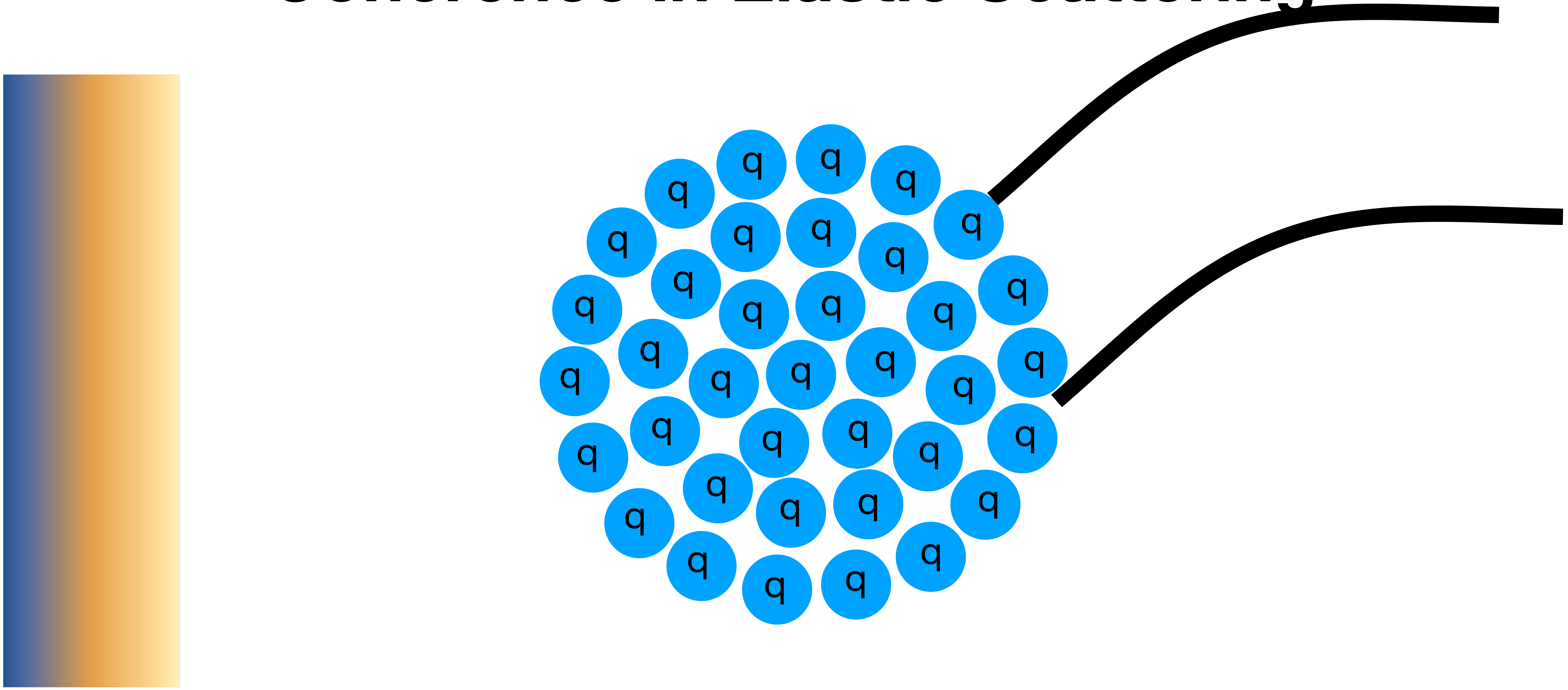

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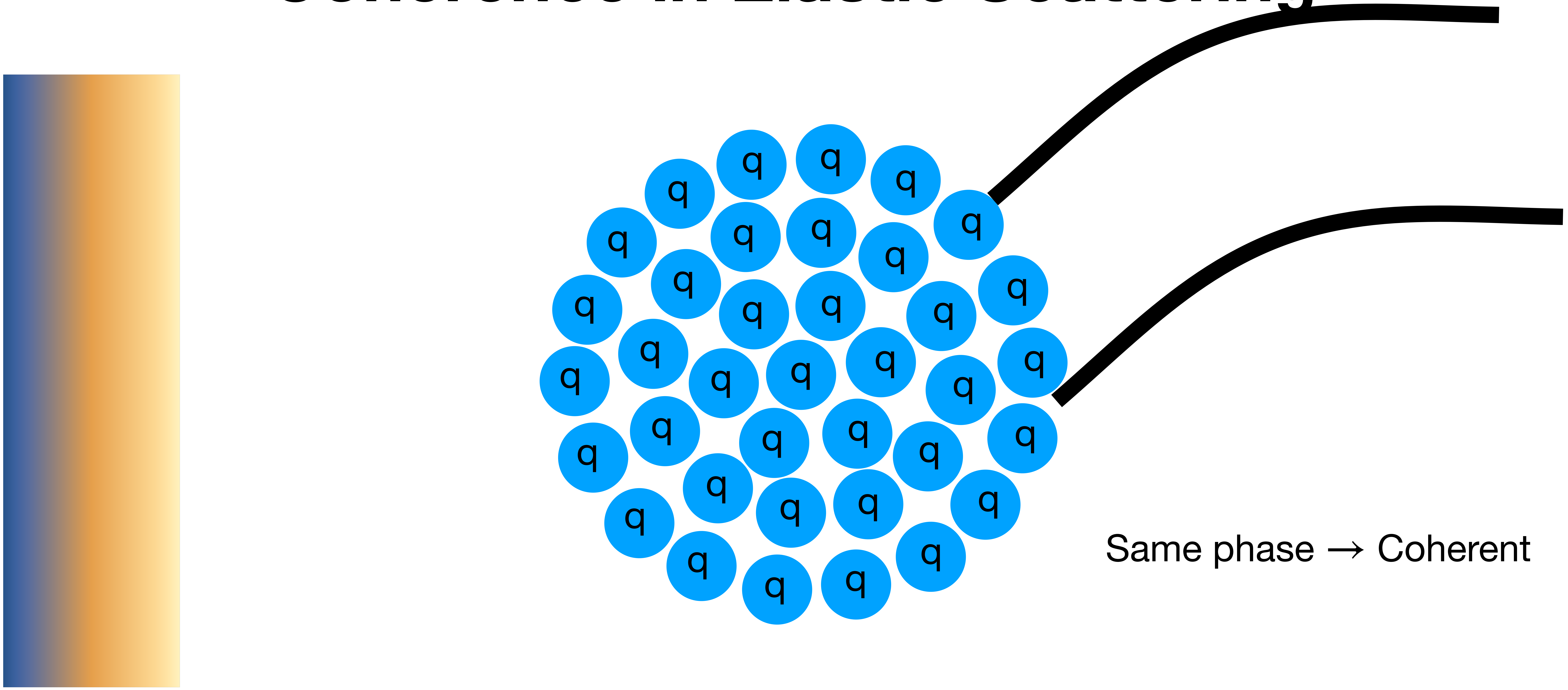

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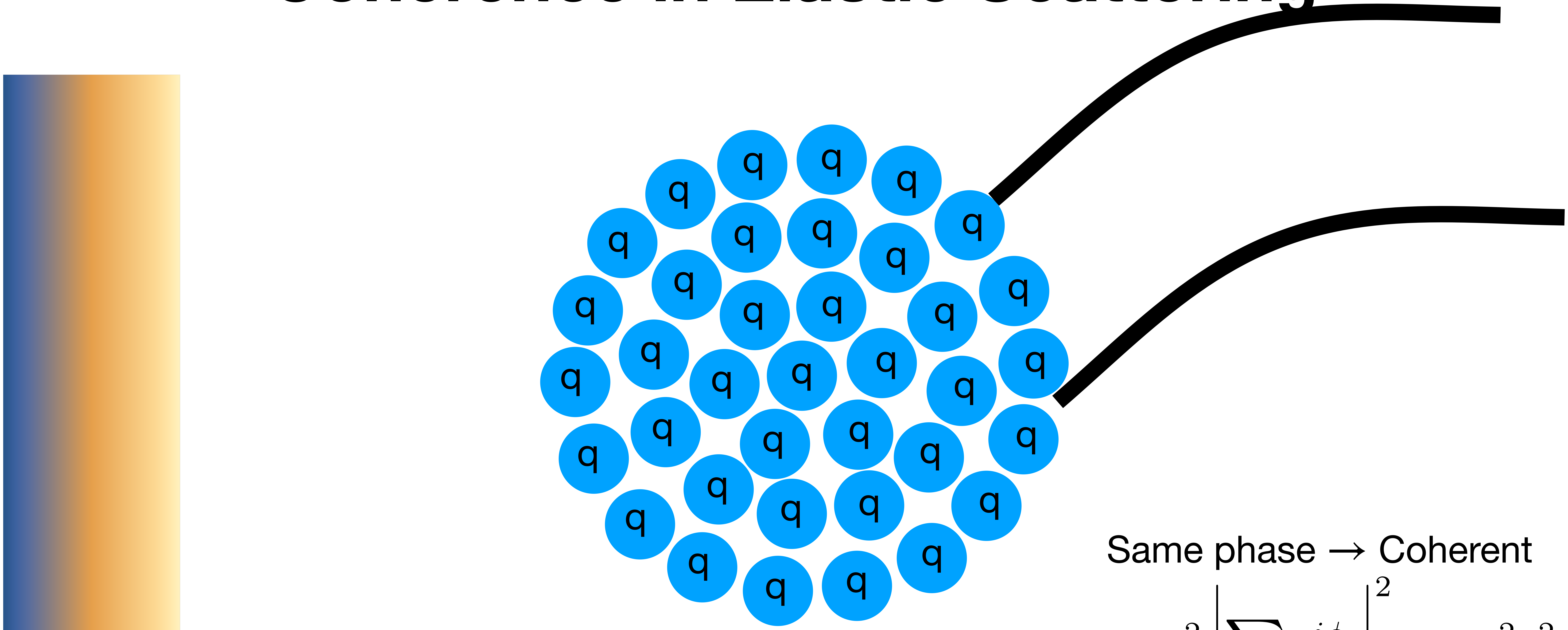
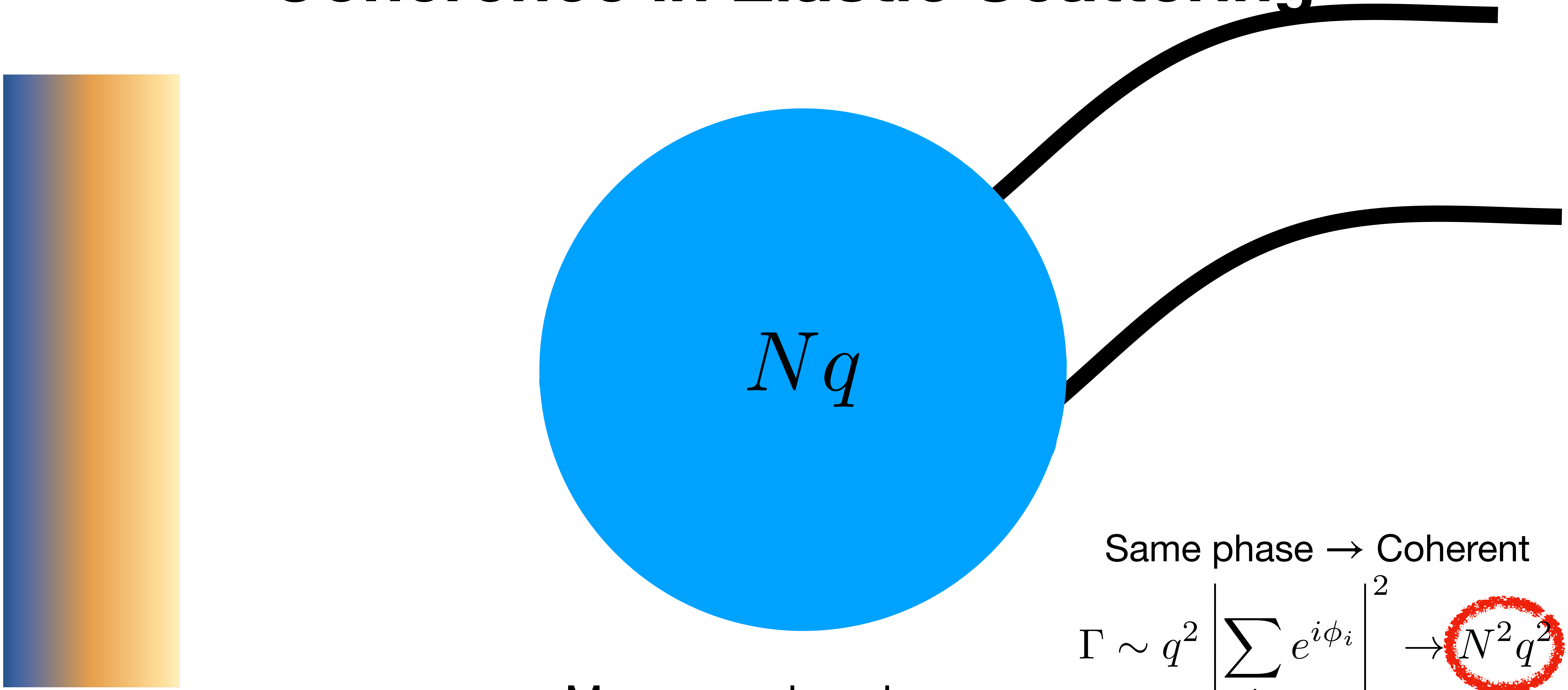


Same phase → Coherent

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

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

Coherence in Elastic Scattering



Macroscopic coherence

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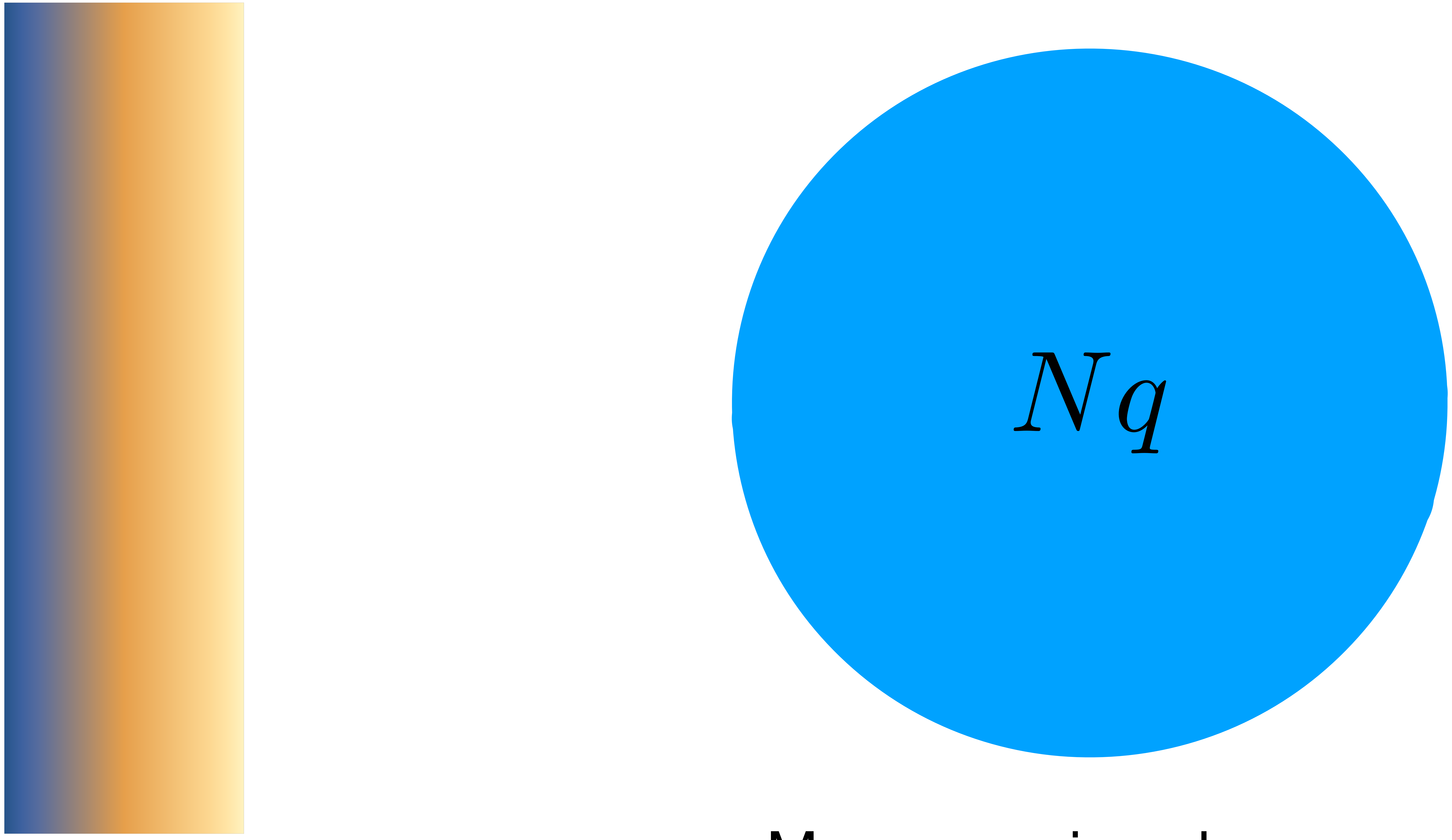

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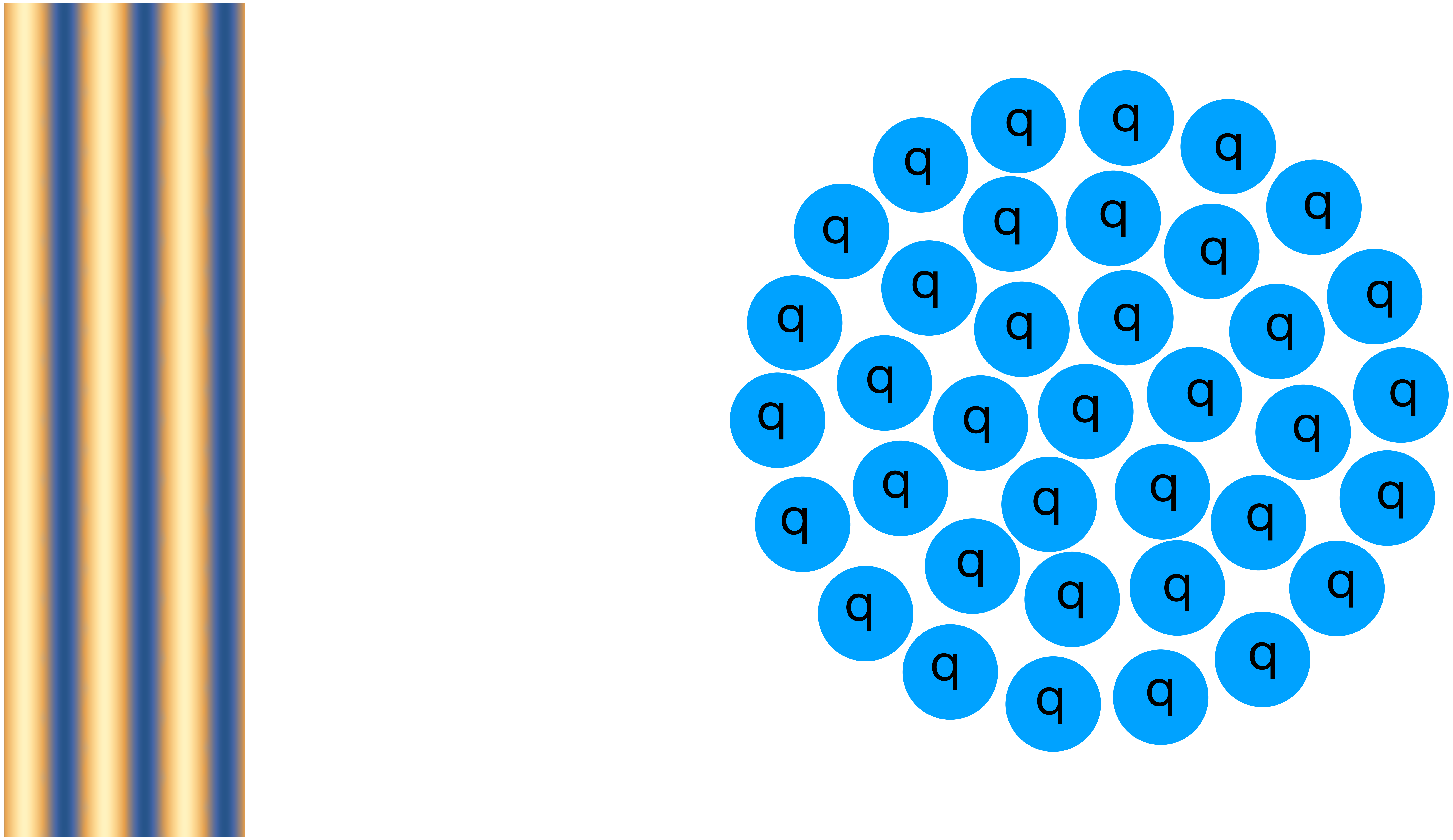

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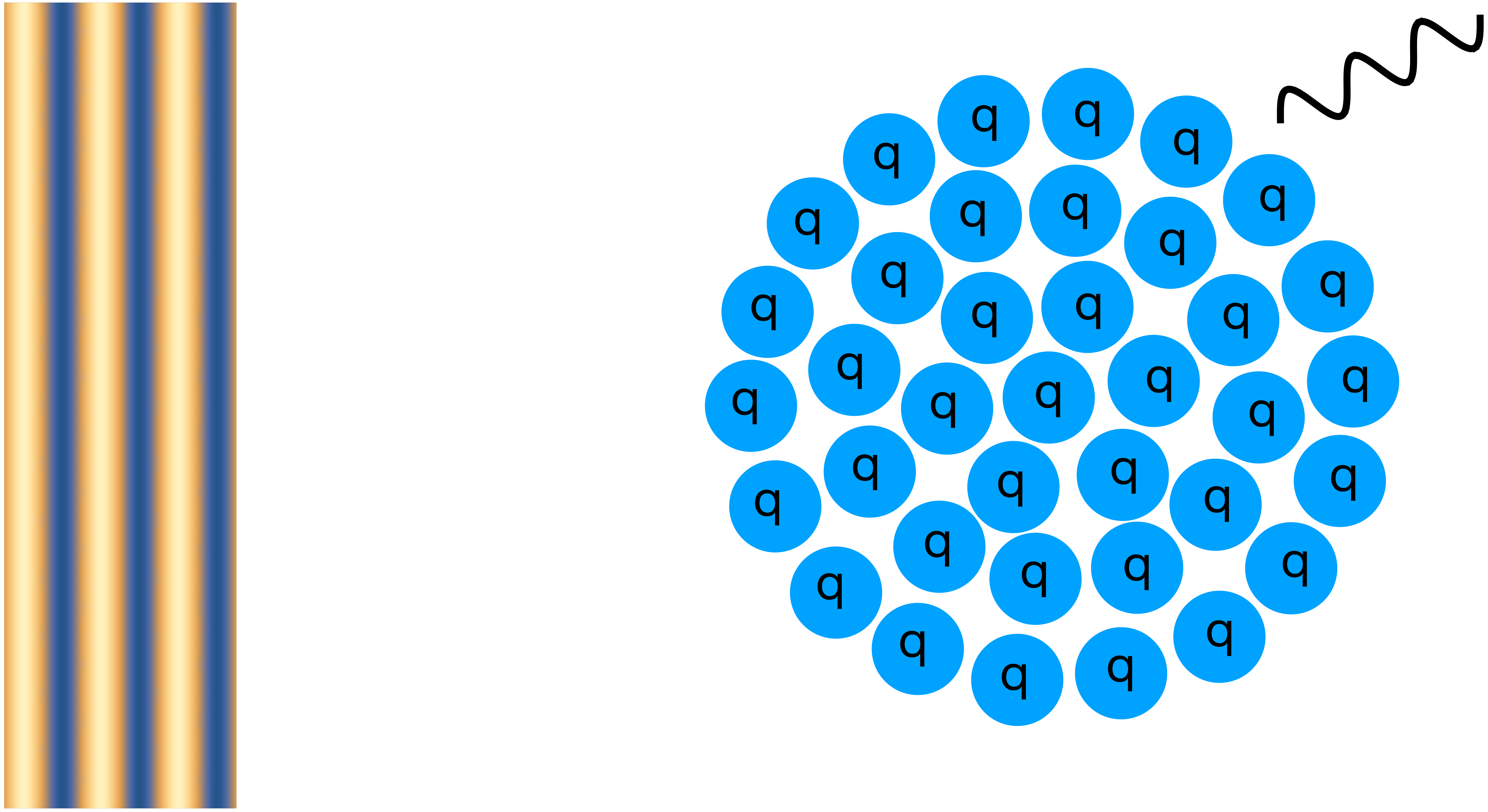

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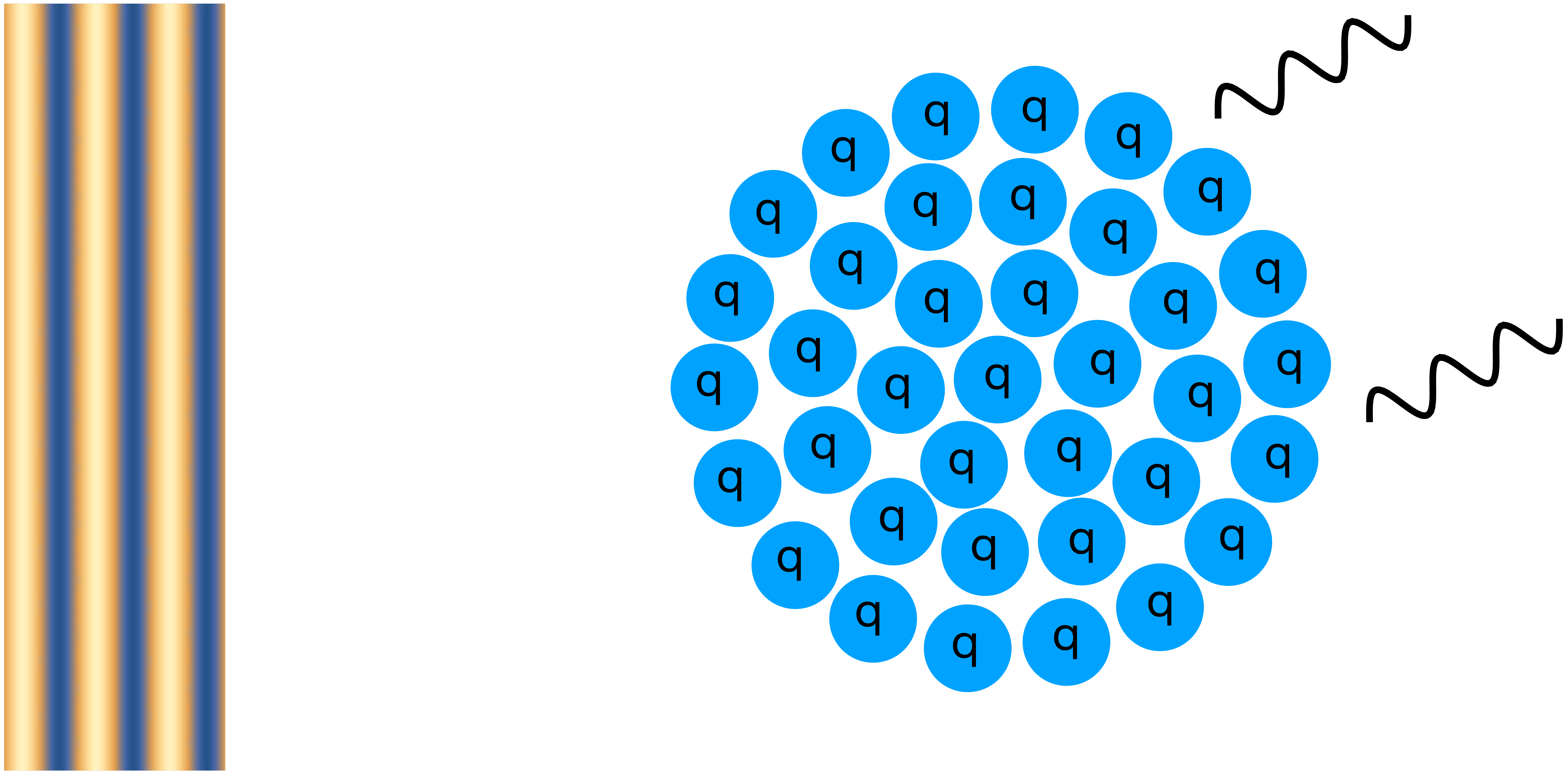

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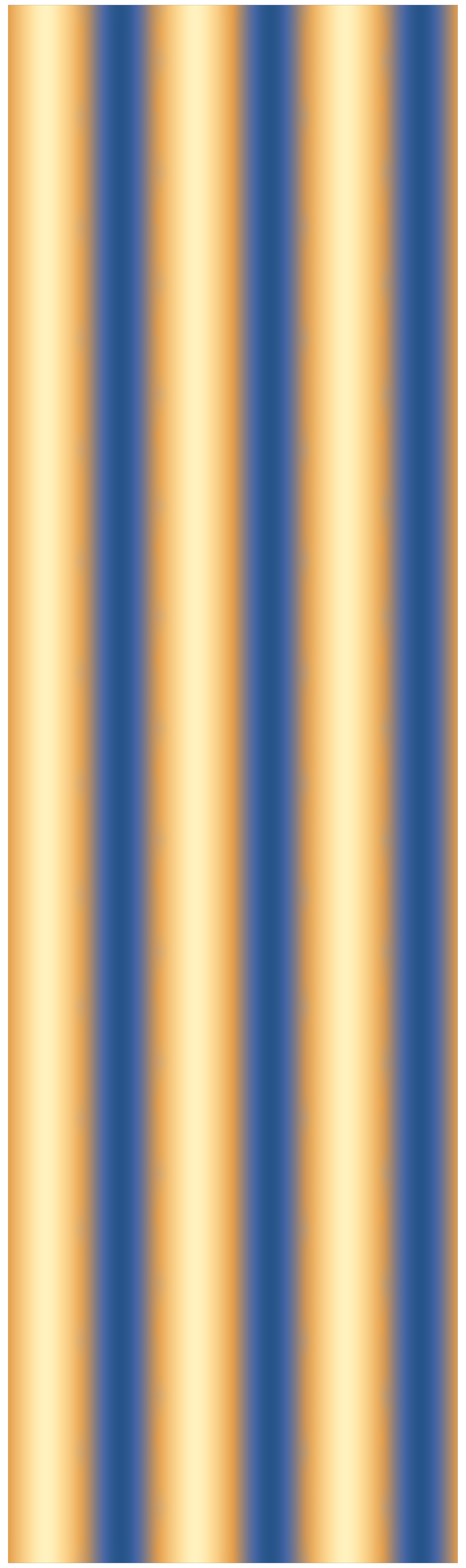

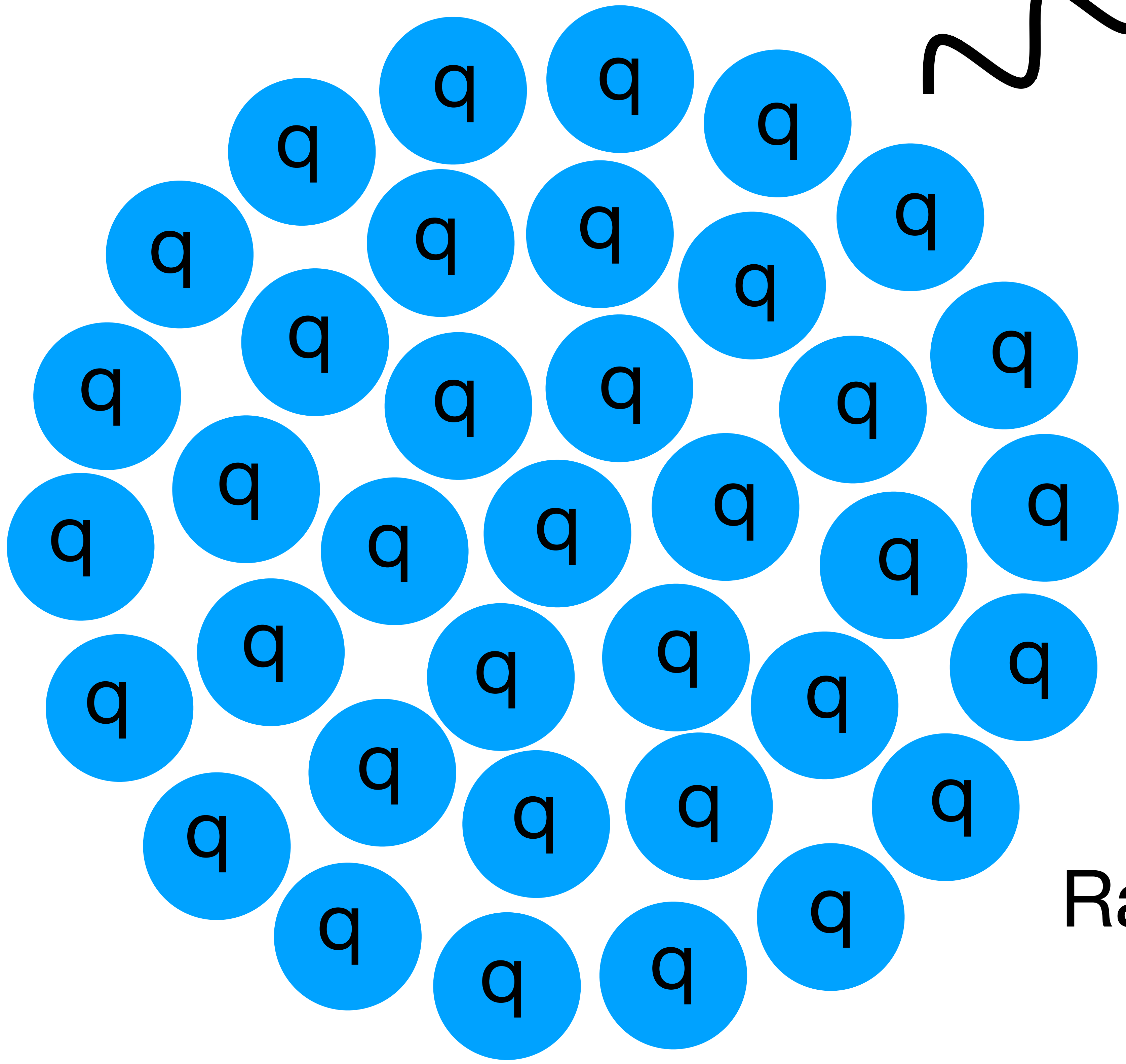

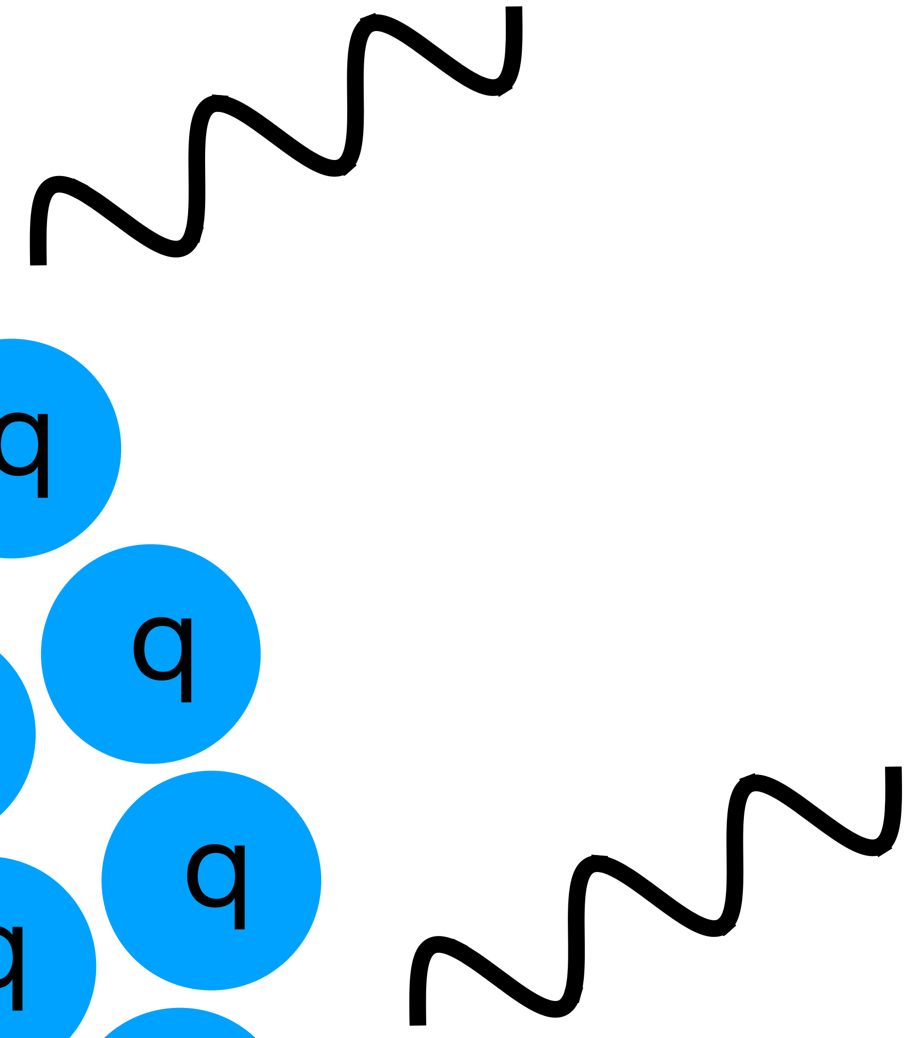

Random phases → Incoherent

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

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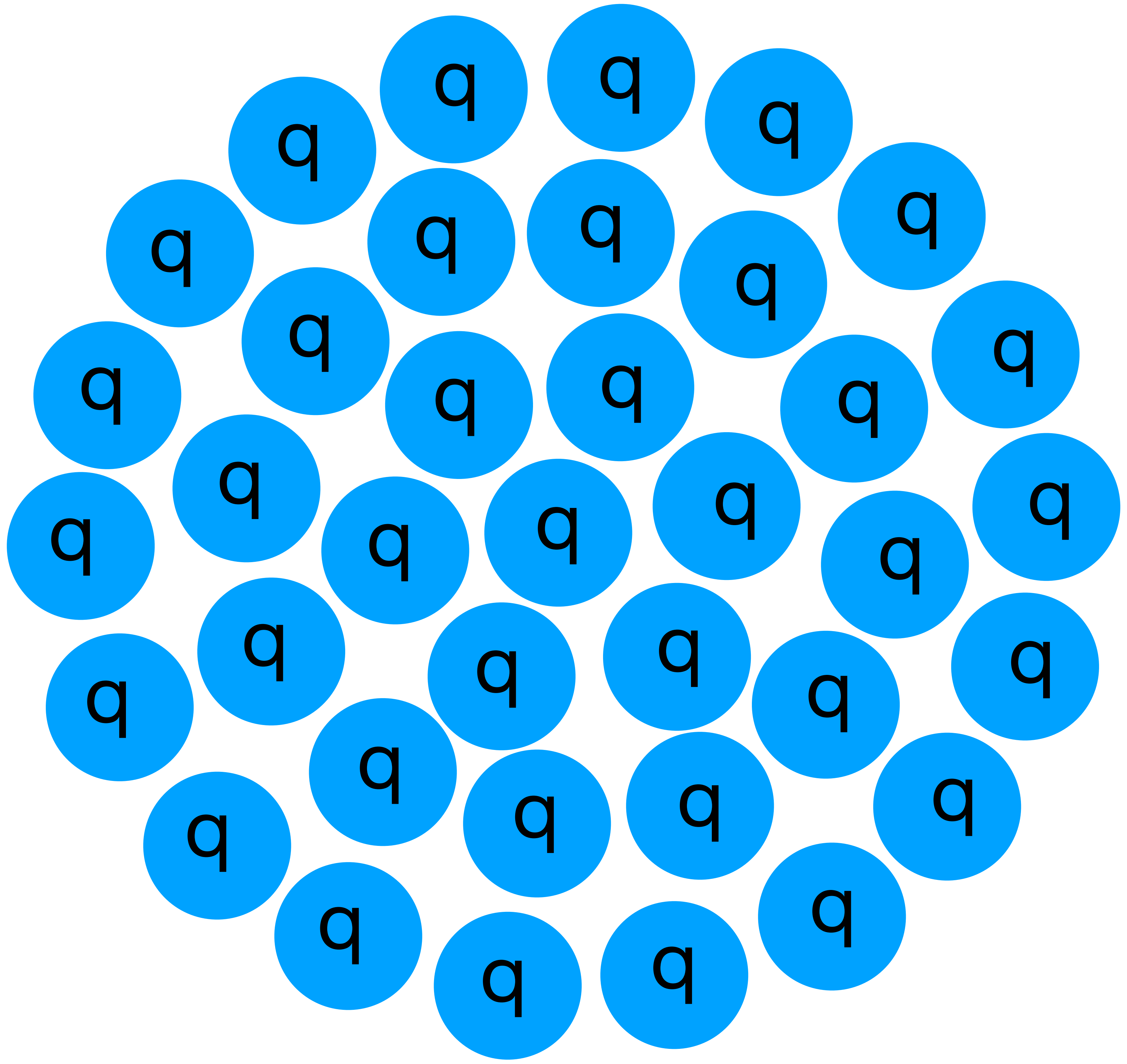
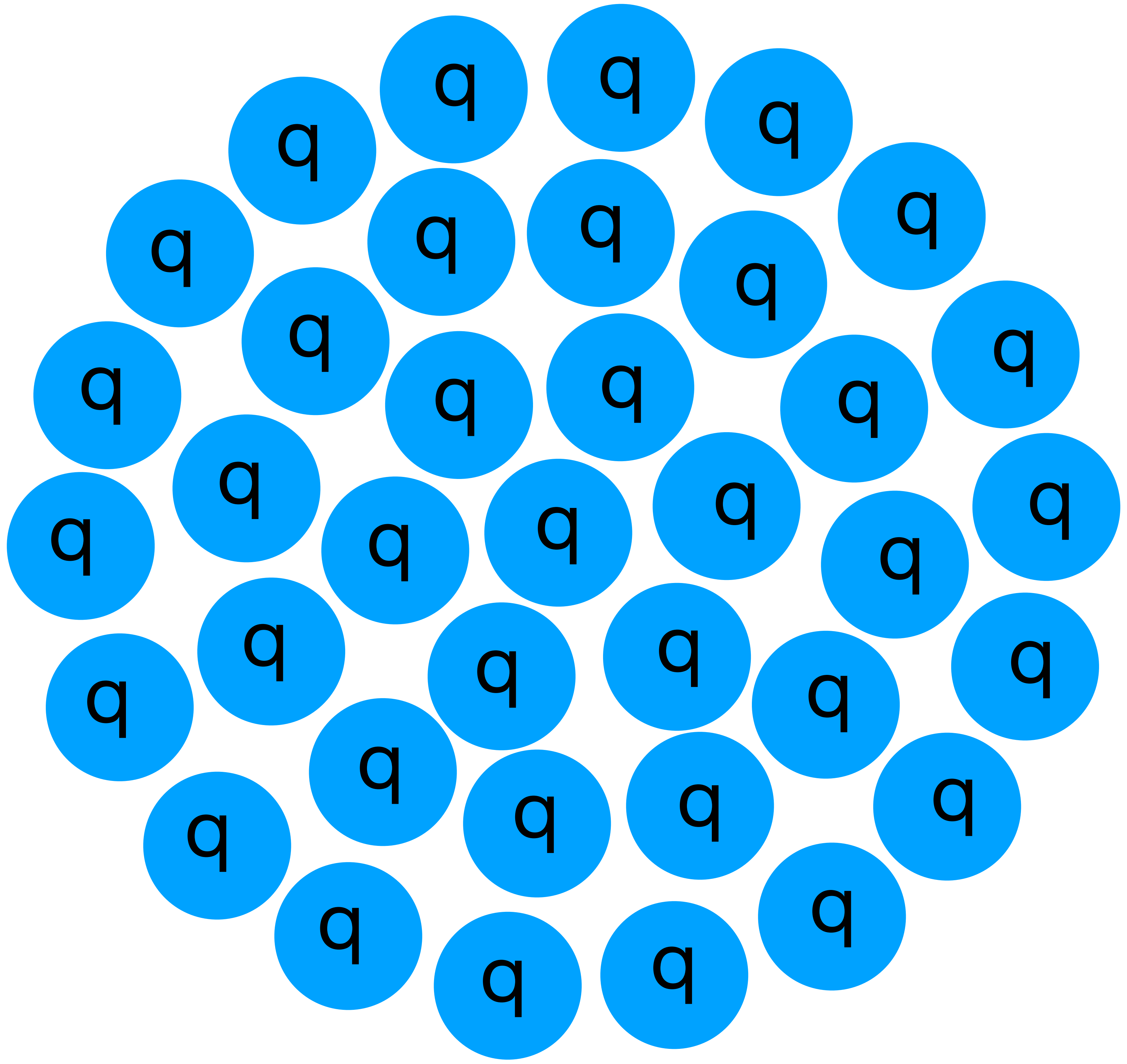
Coherence in Elastic Scattering



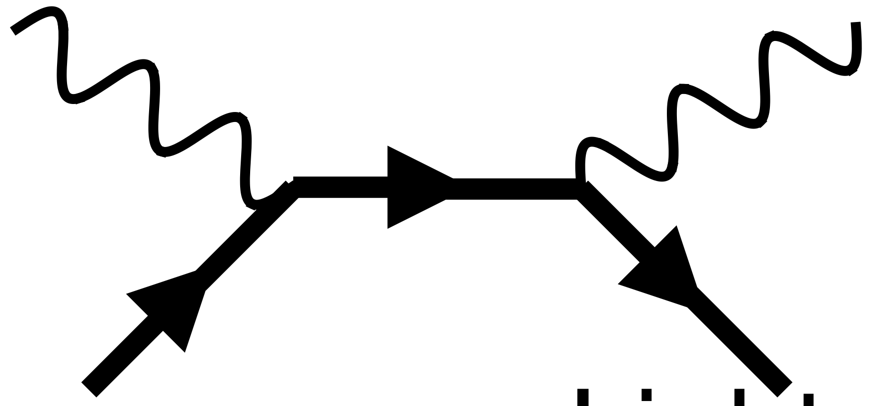
Is this all?

Coherence in Elastic Scattering



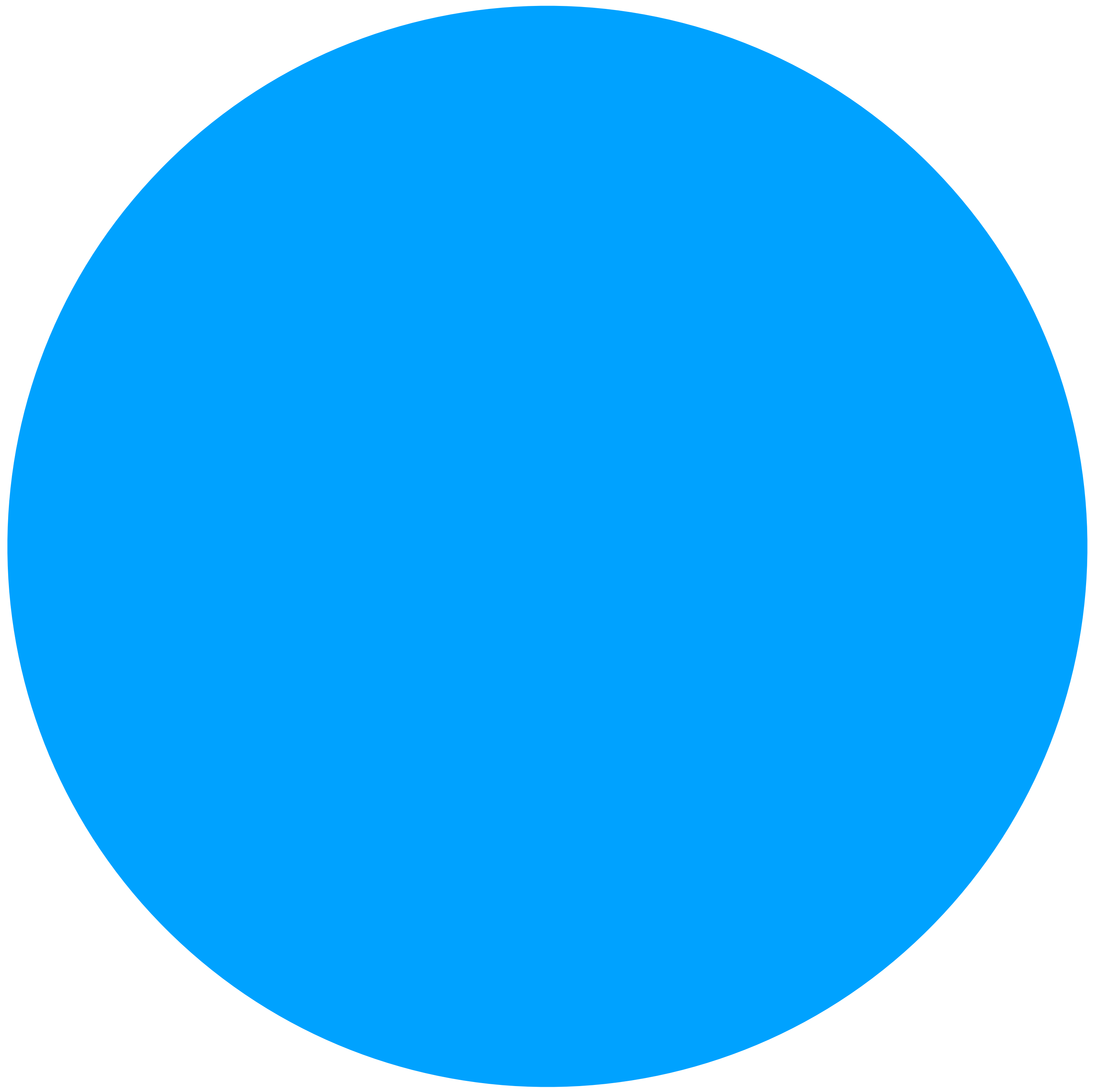
Is this all?

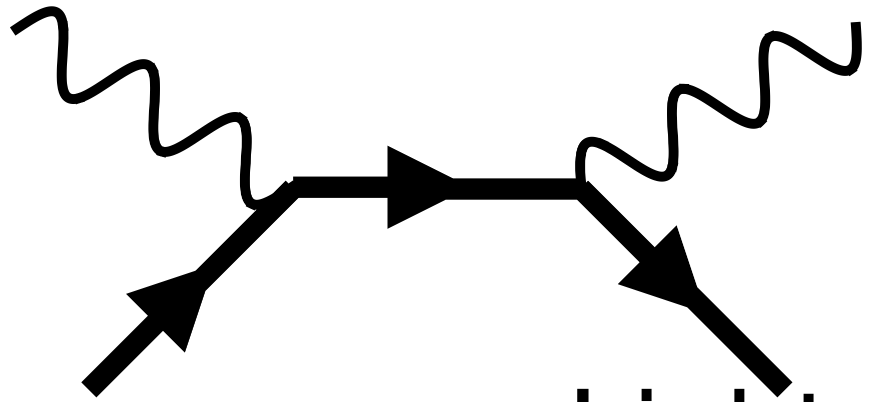
No.



Wavelength smaller than object

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





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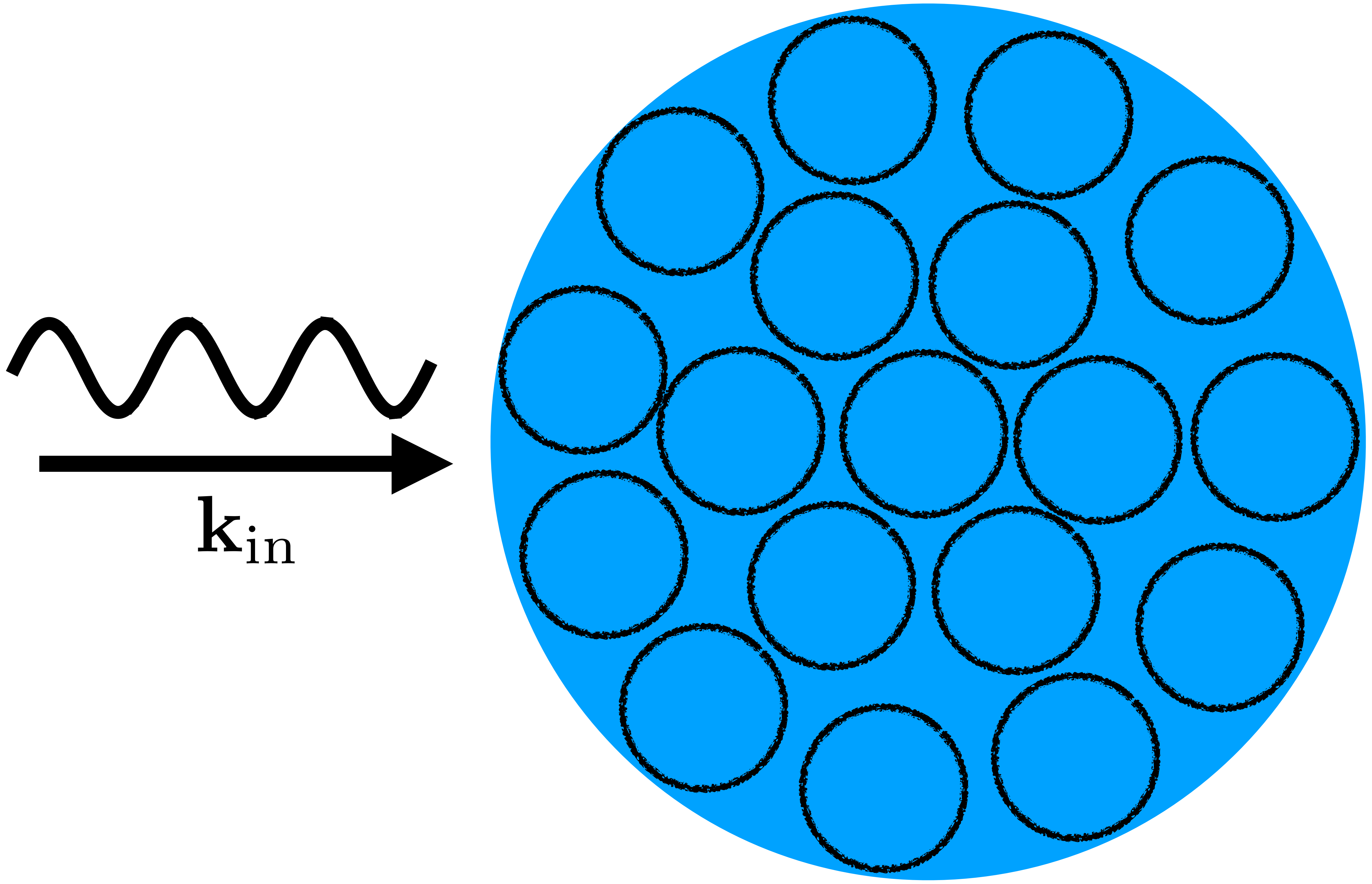

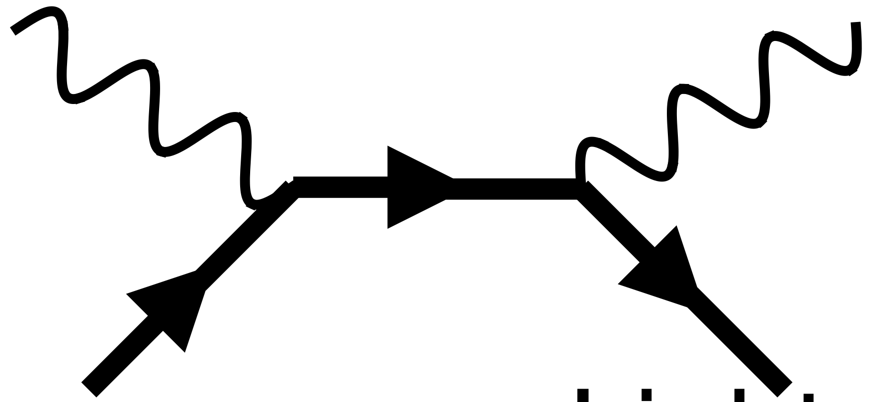

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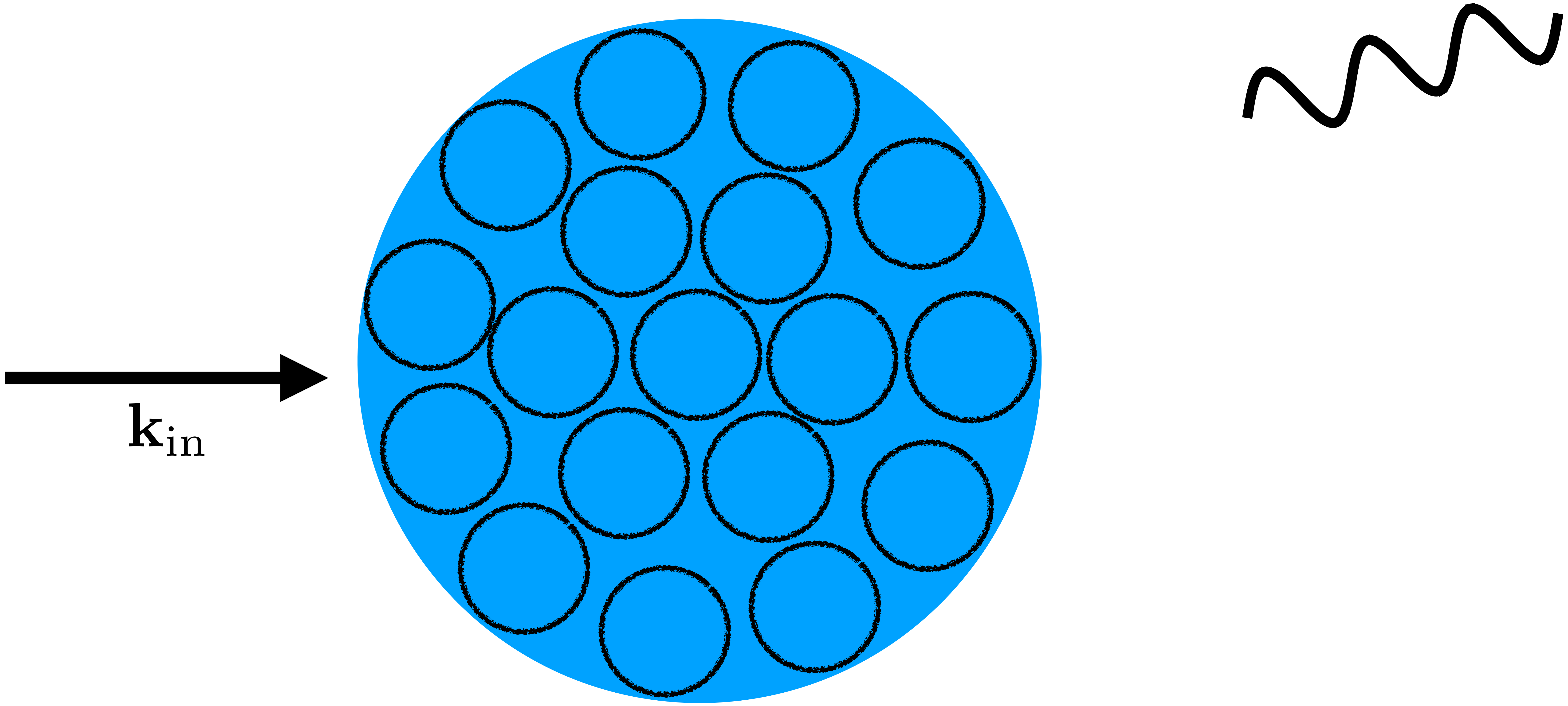

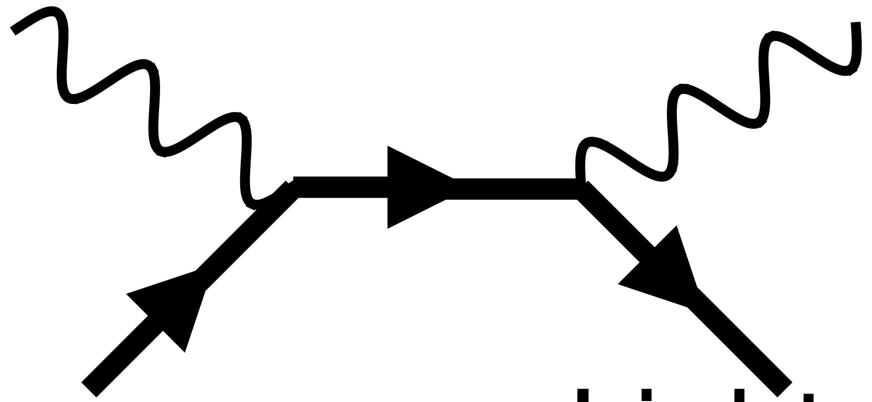

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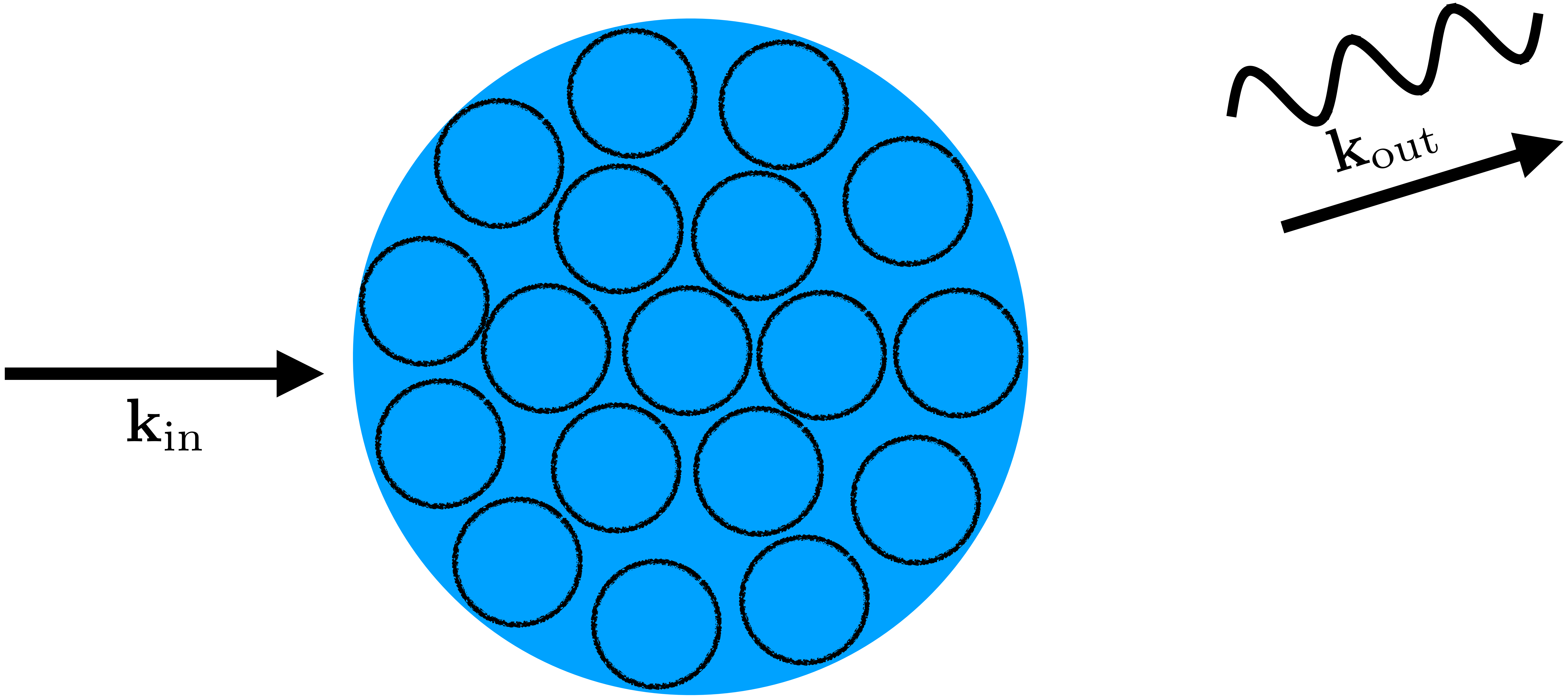

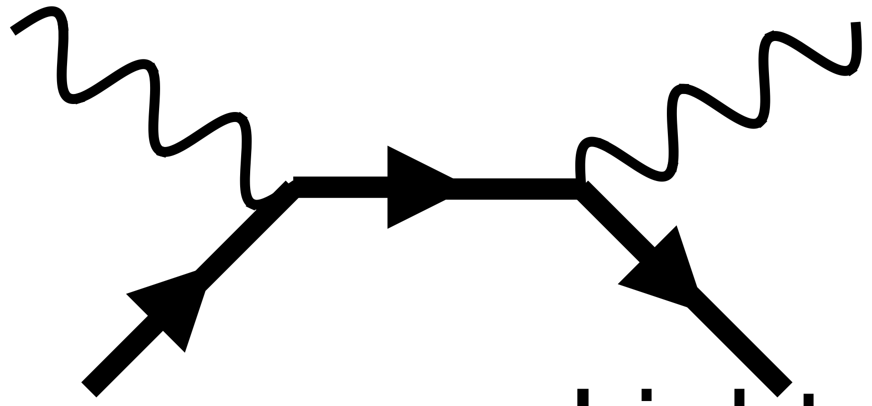

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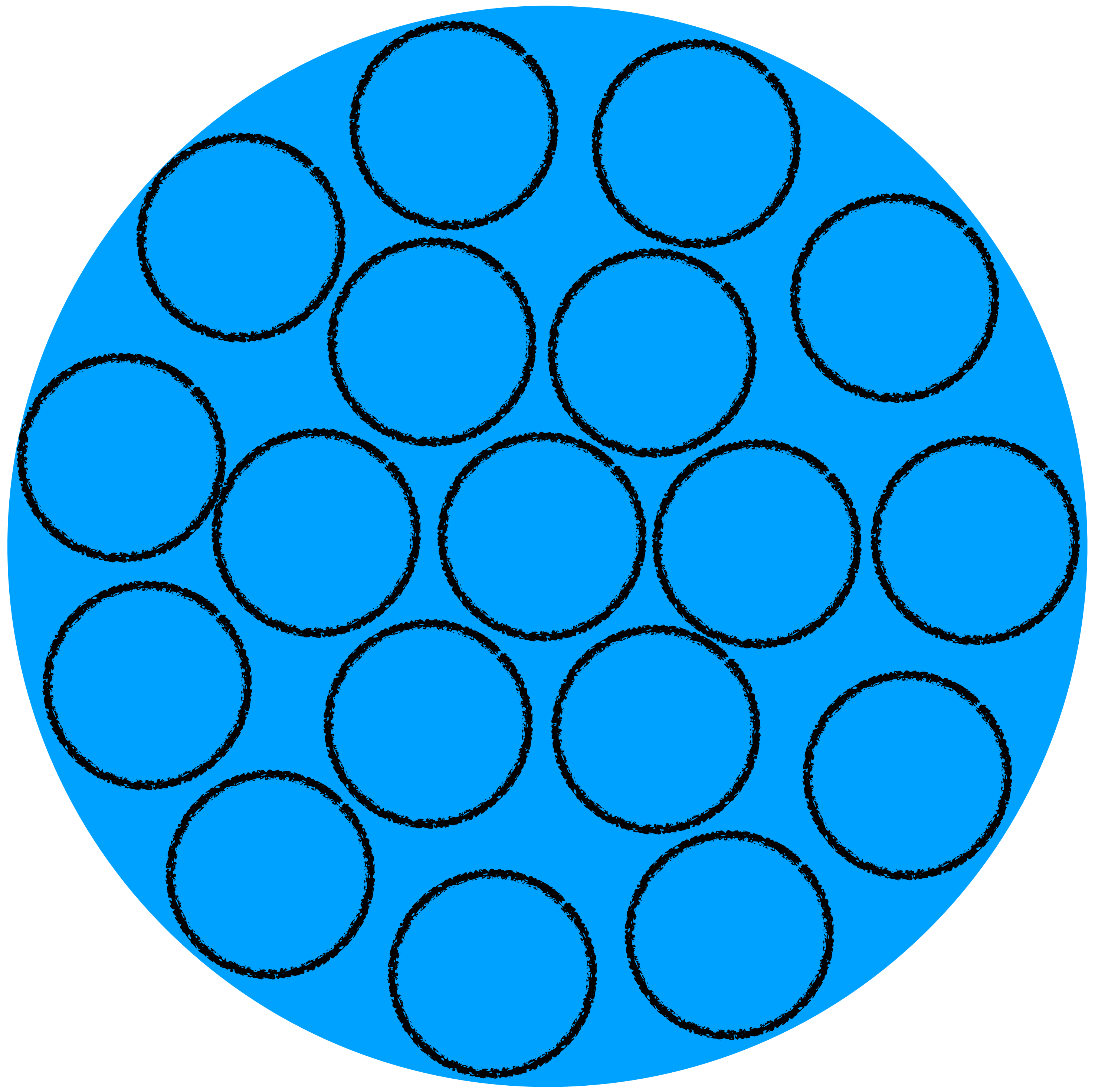

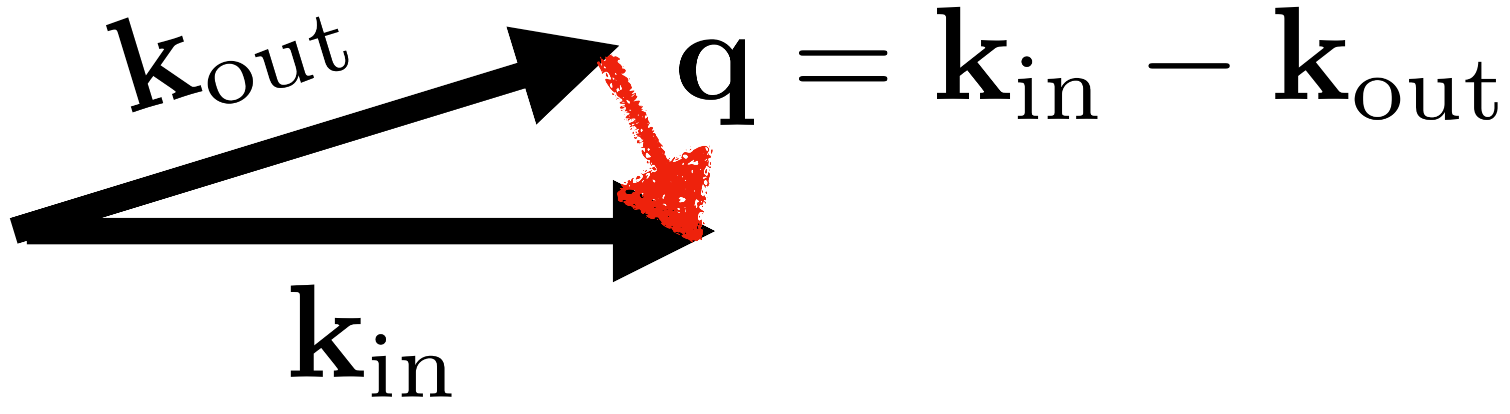

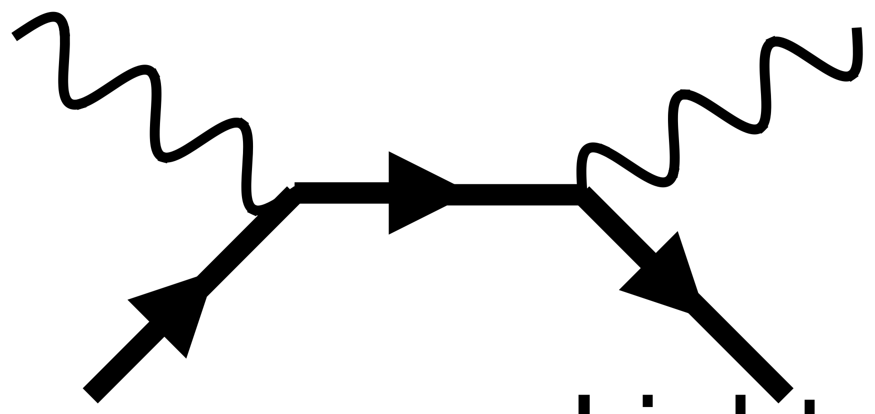

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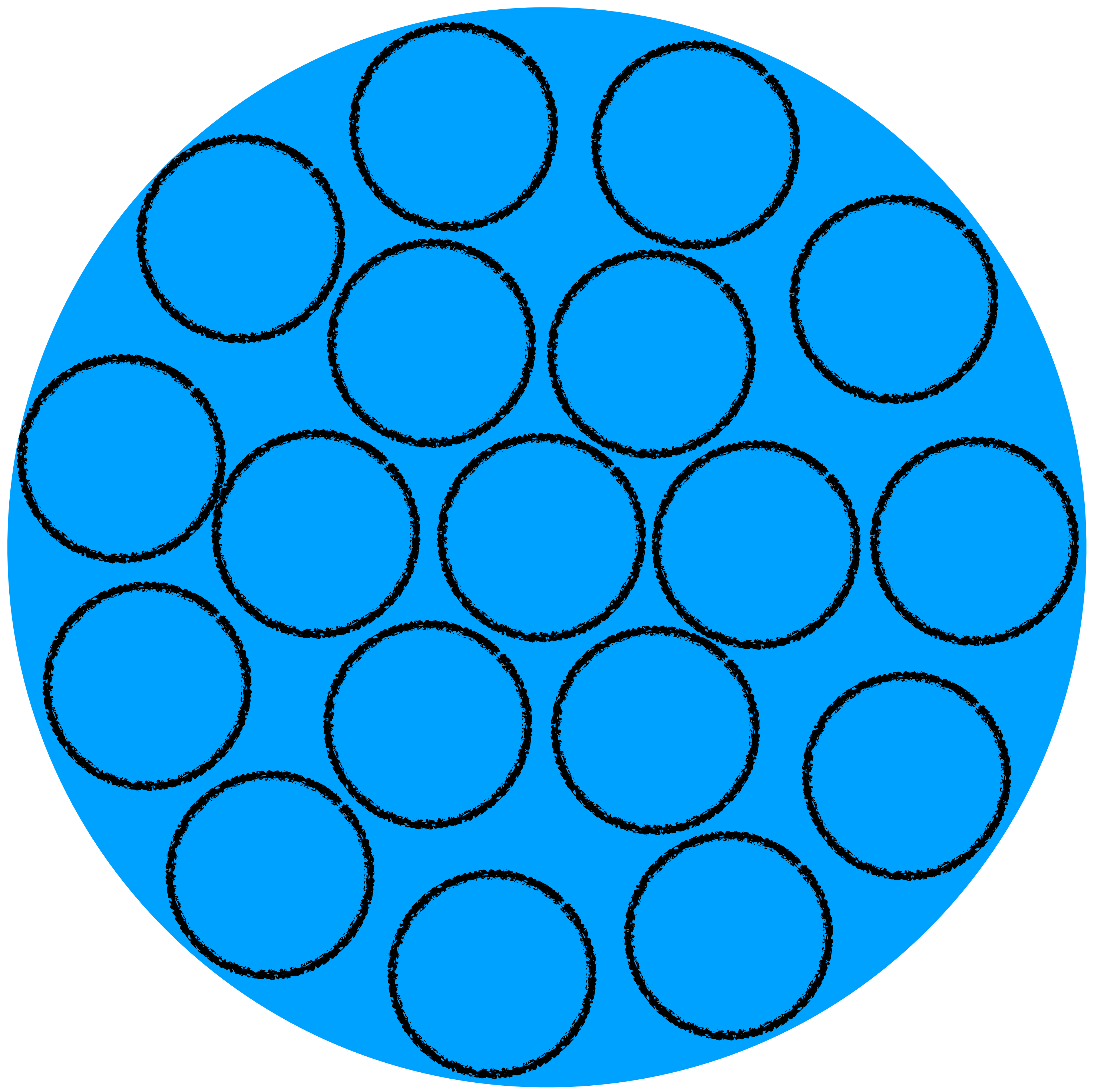
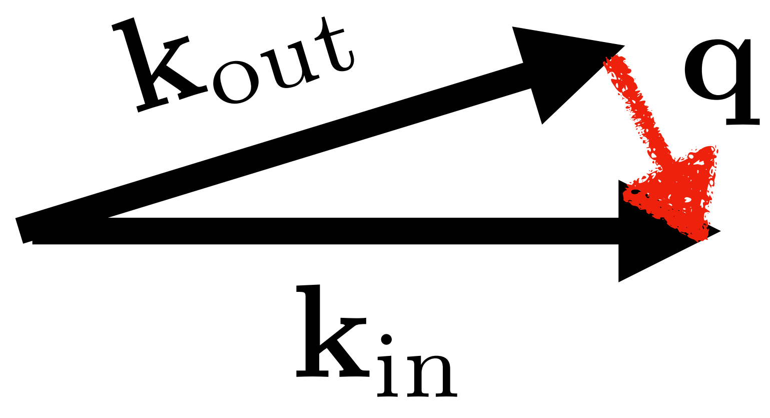
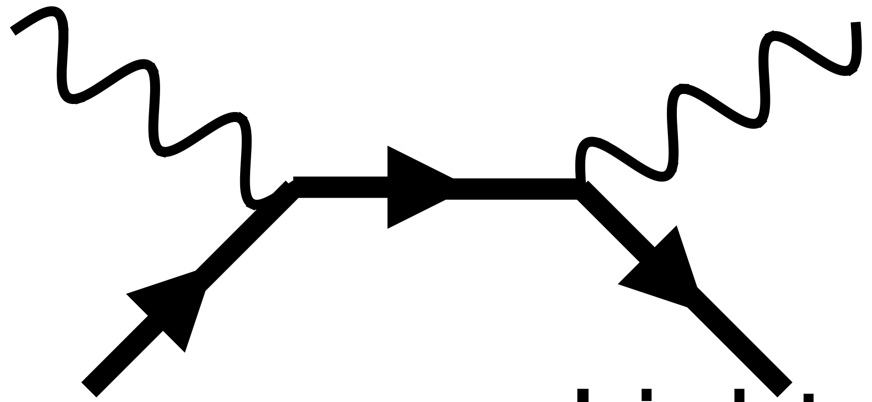




$$\mathbf{q} = \mathbf{k}_{\rm in} - \mathbf{k}_{\rm out}$$

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

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



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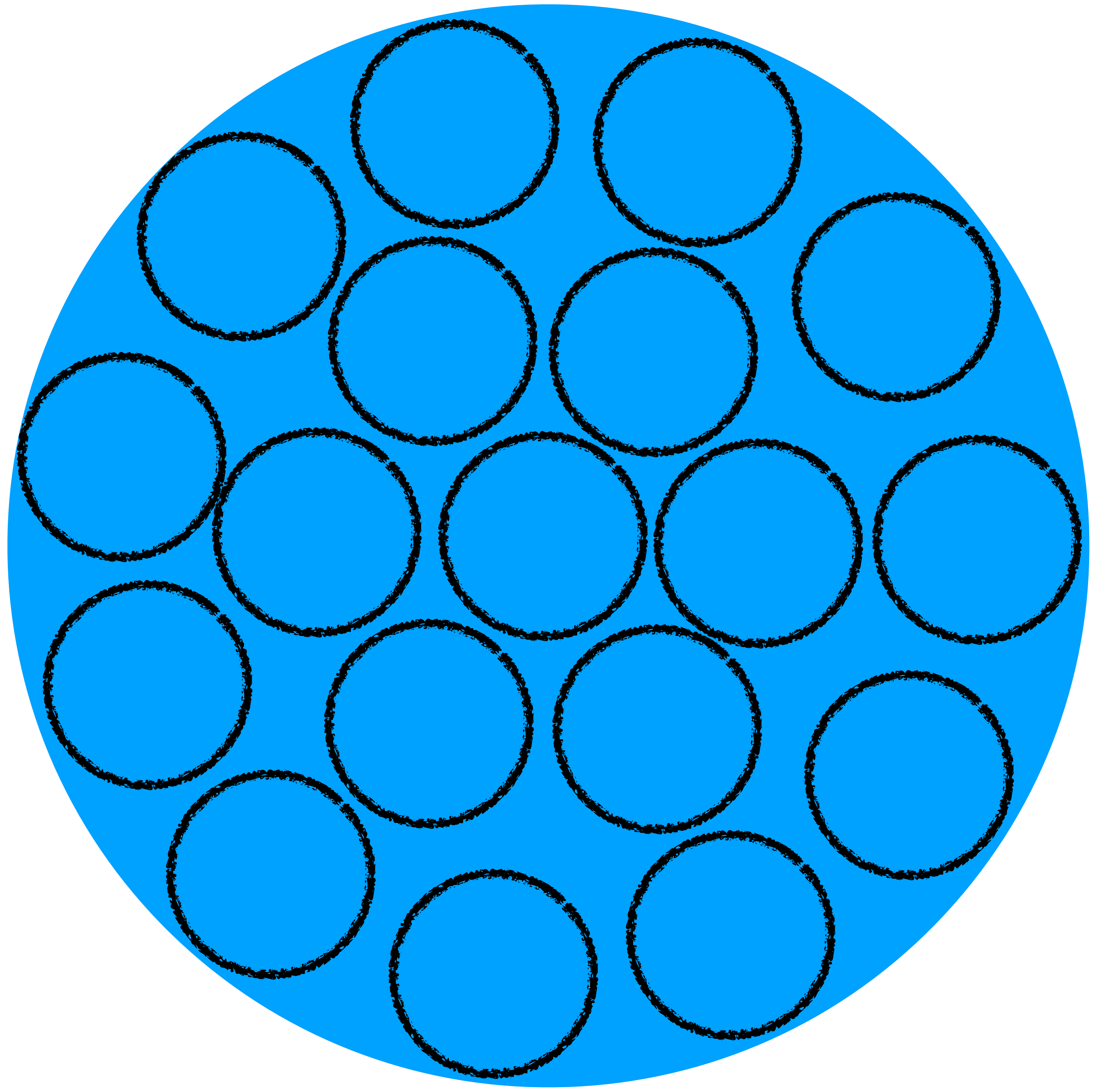

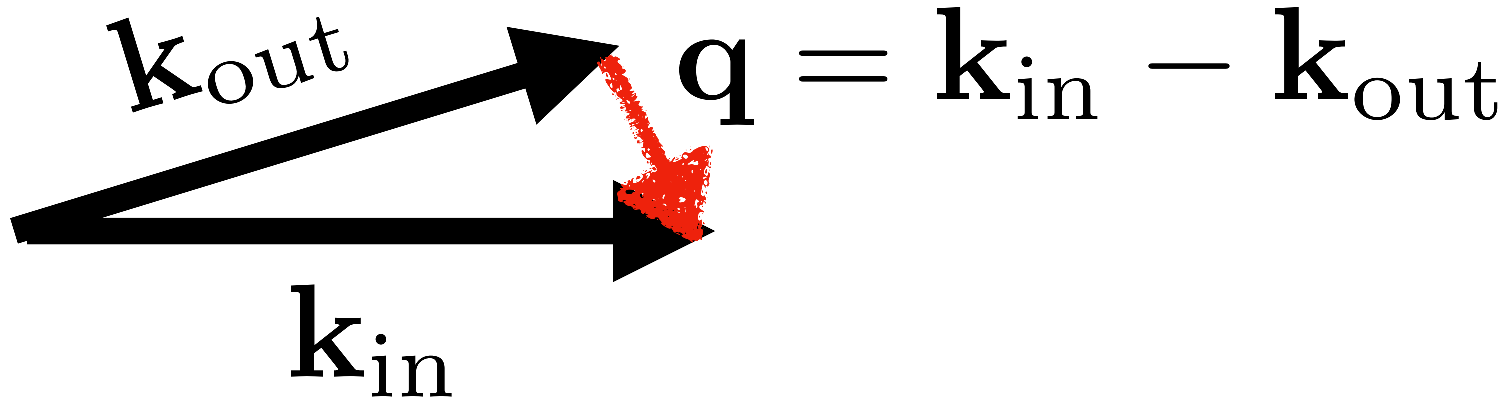

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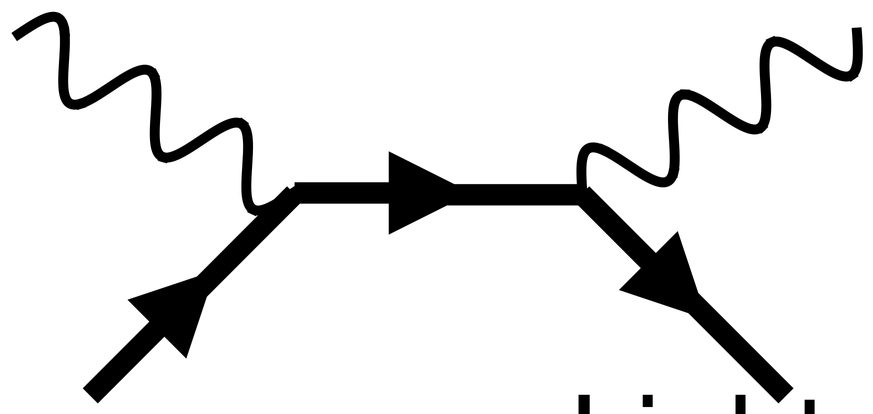

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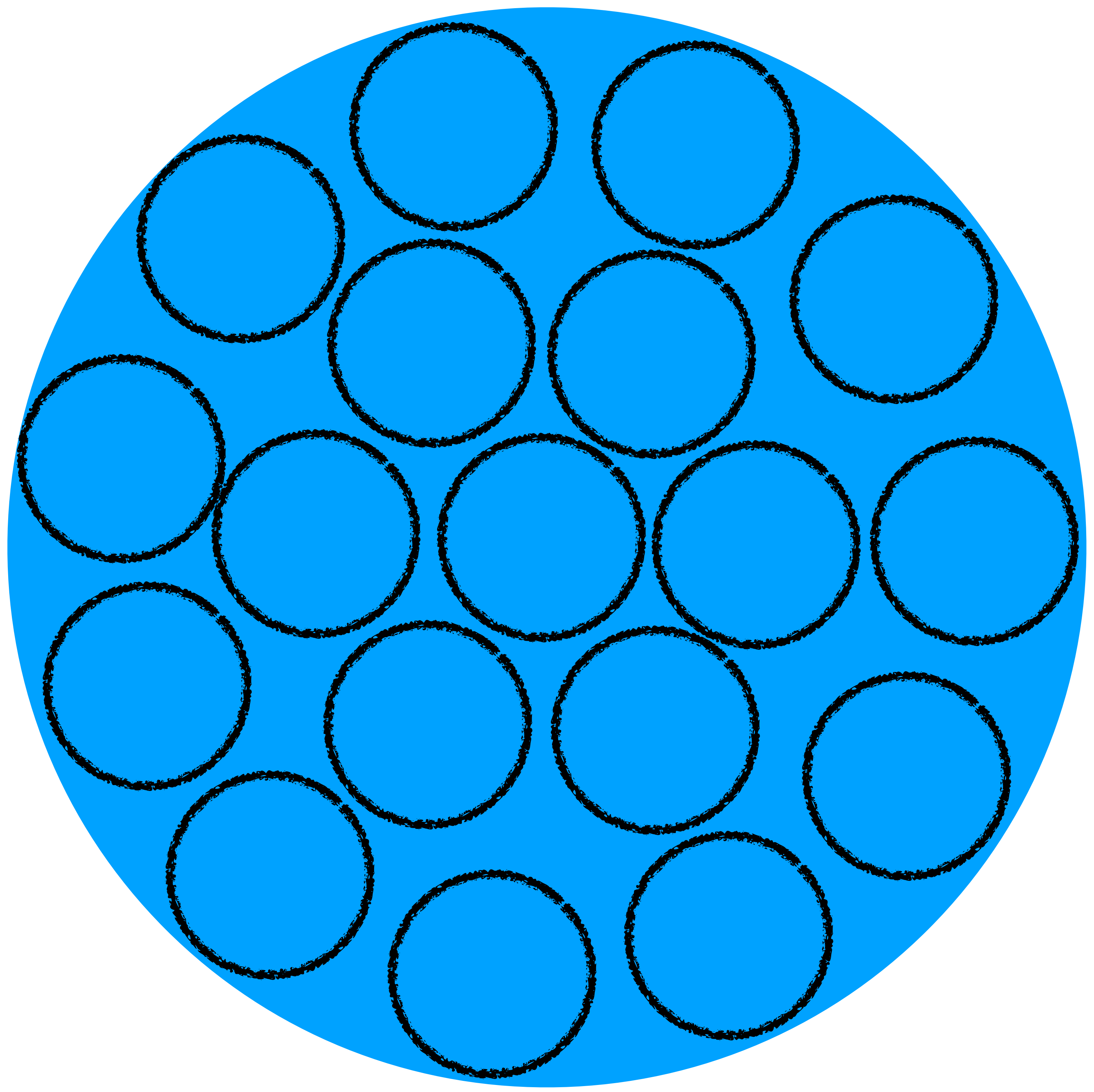

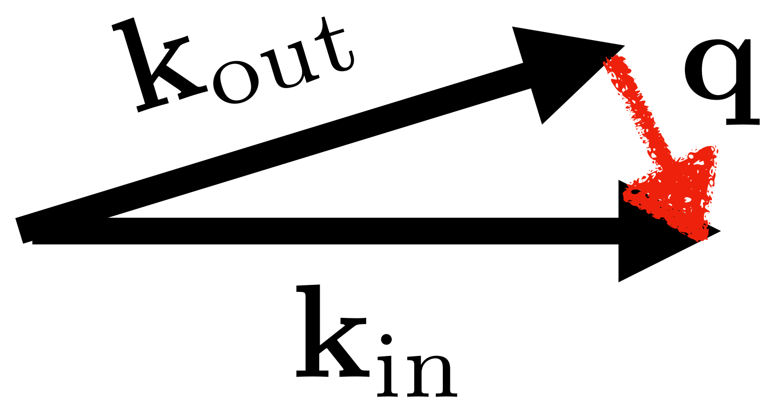

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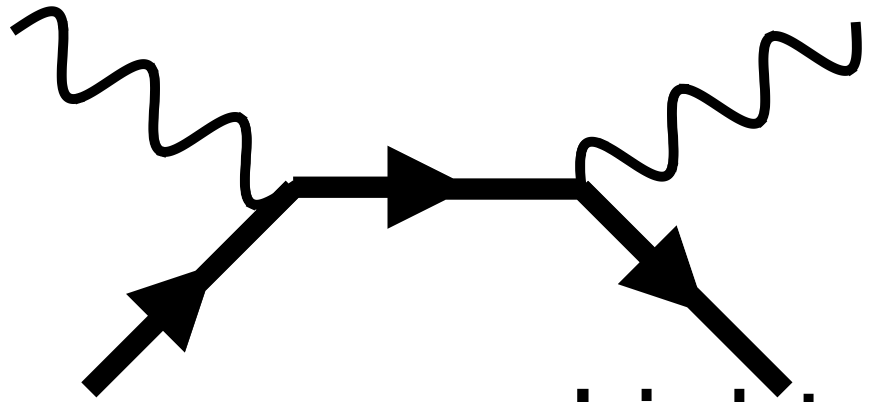

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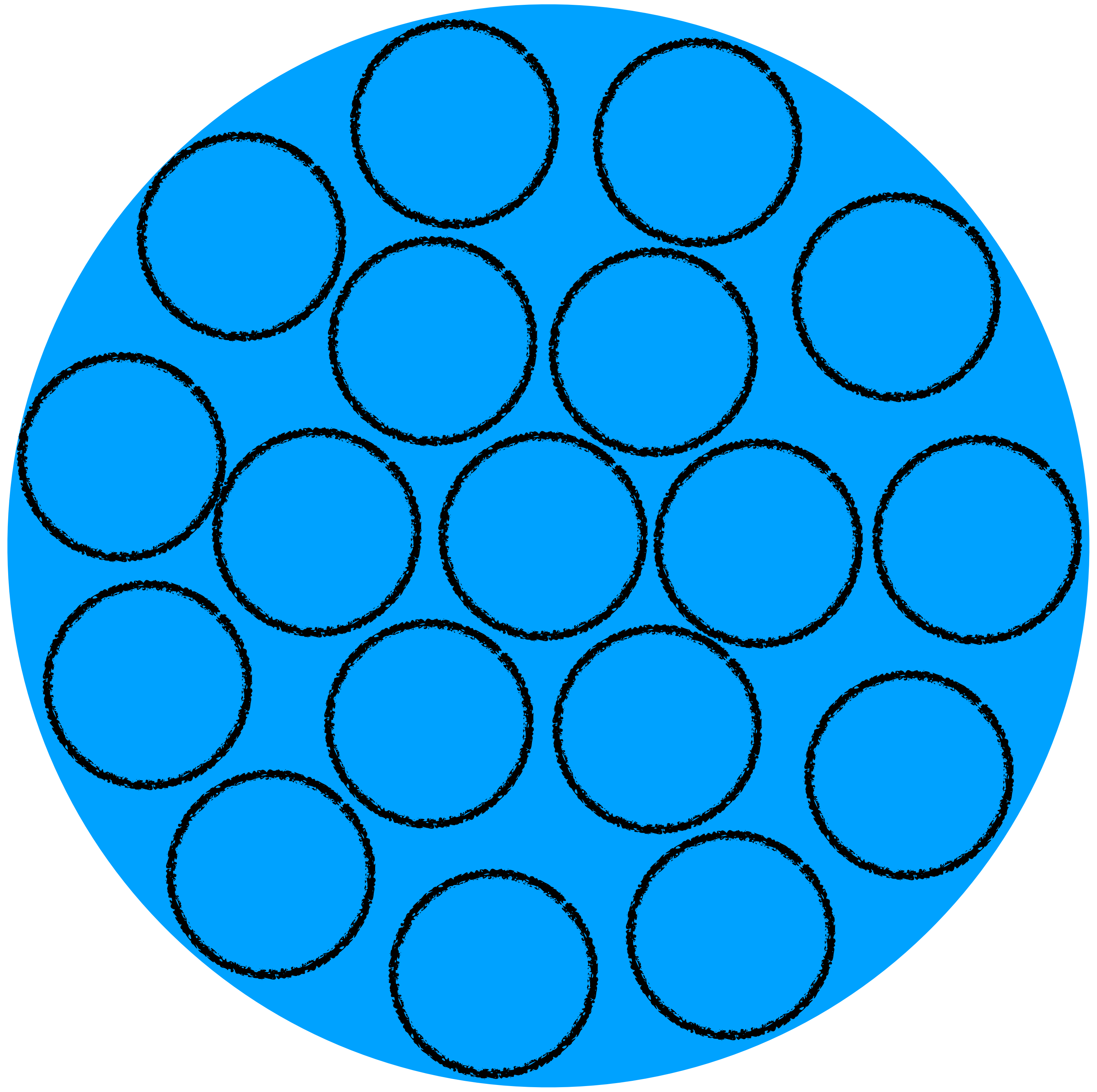

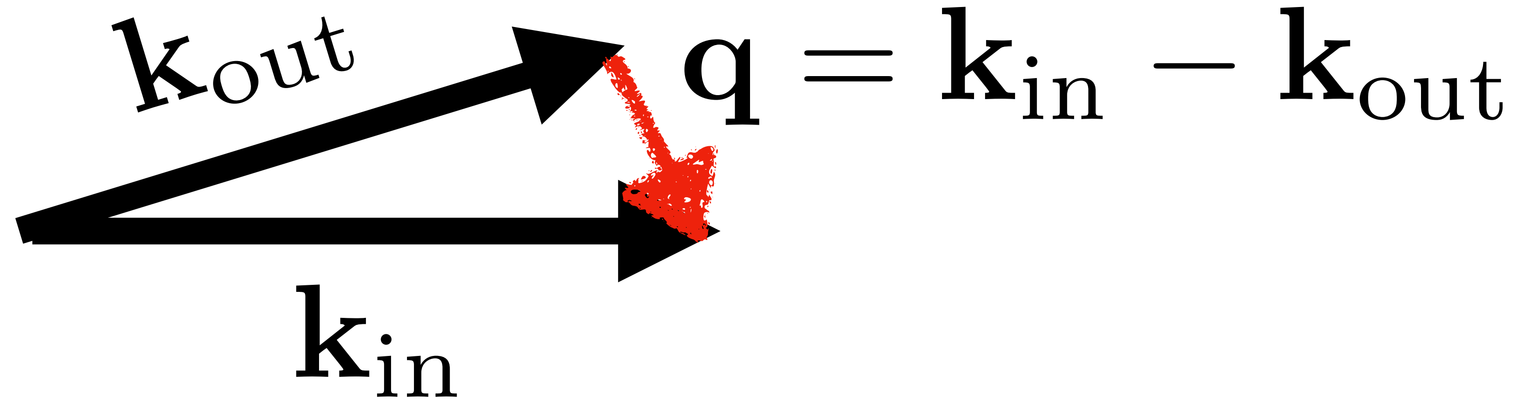

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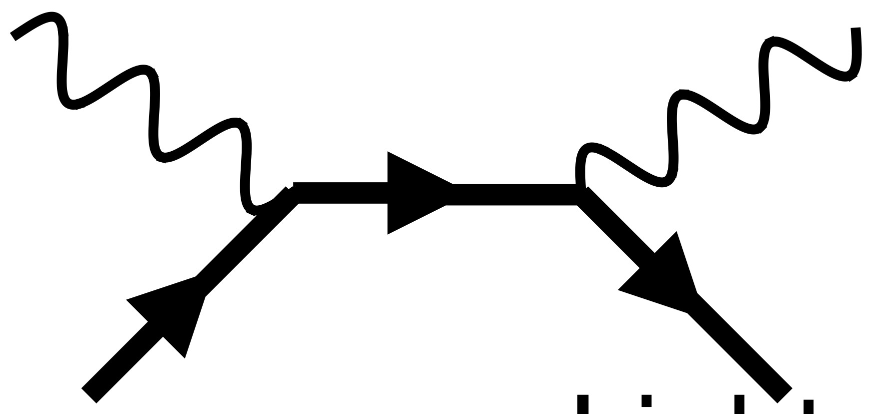

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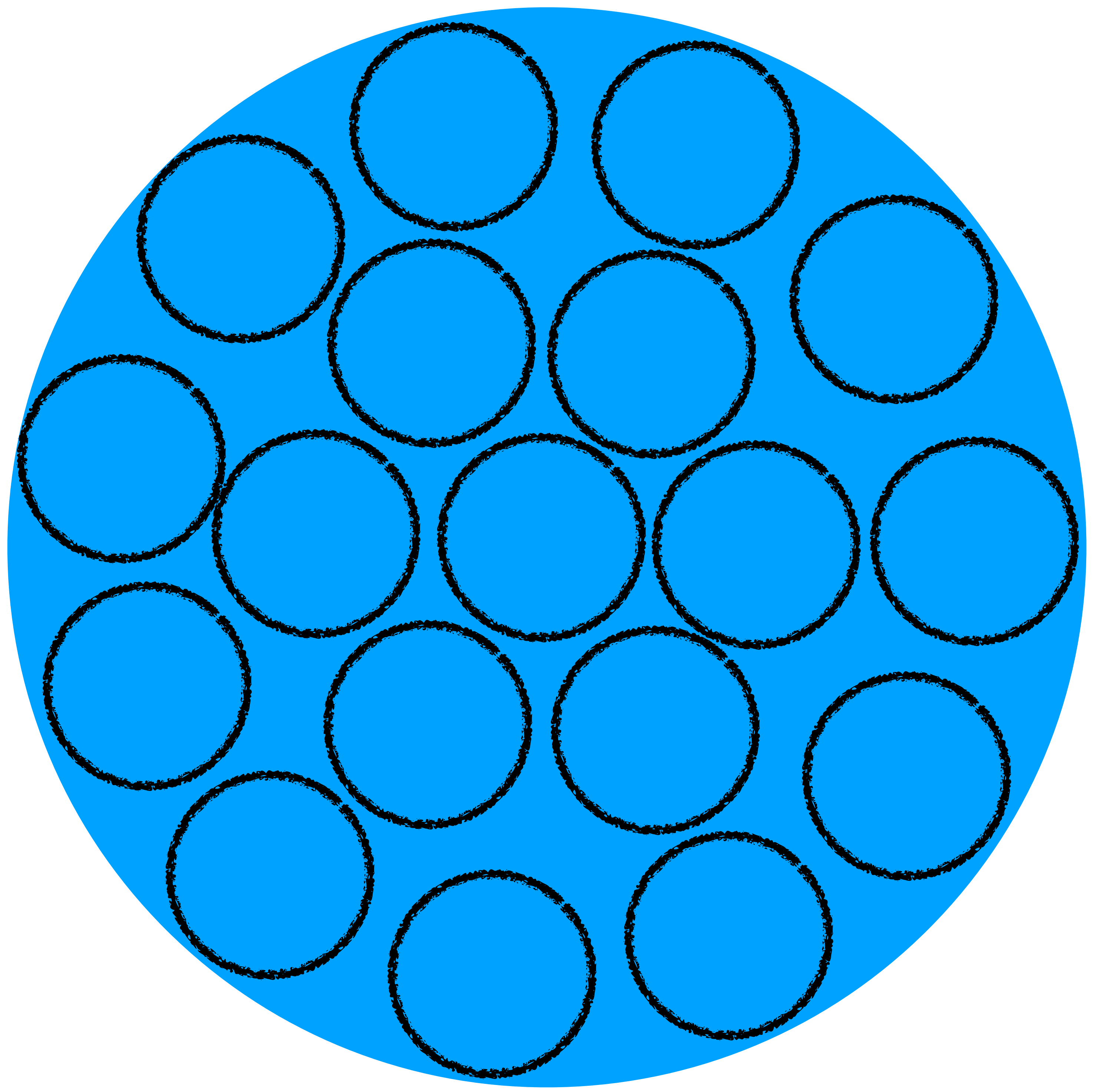

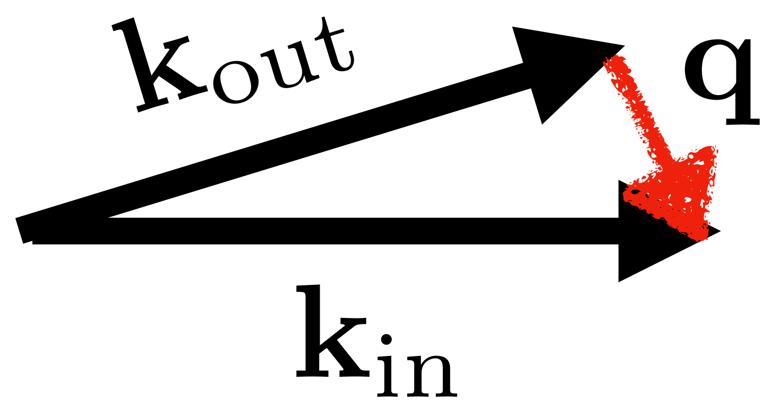

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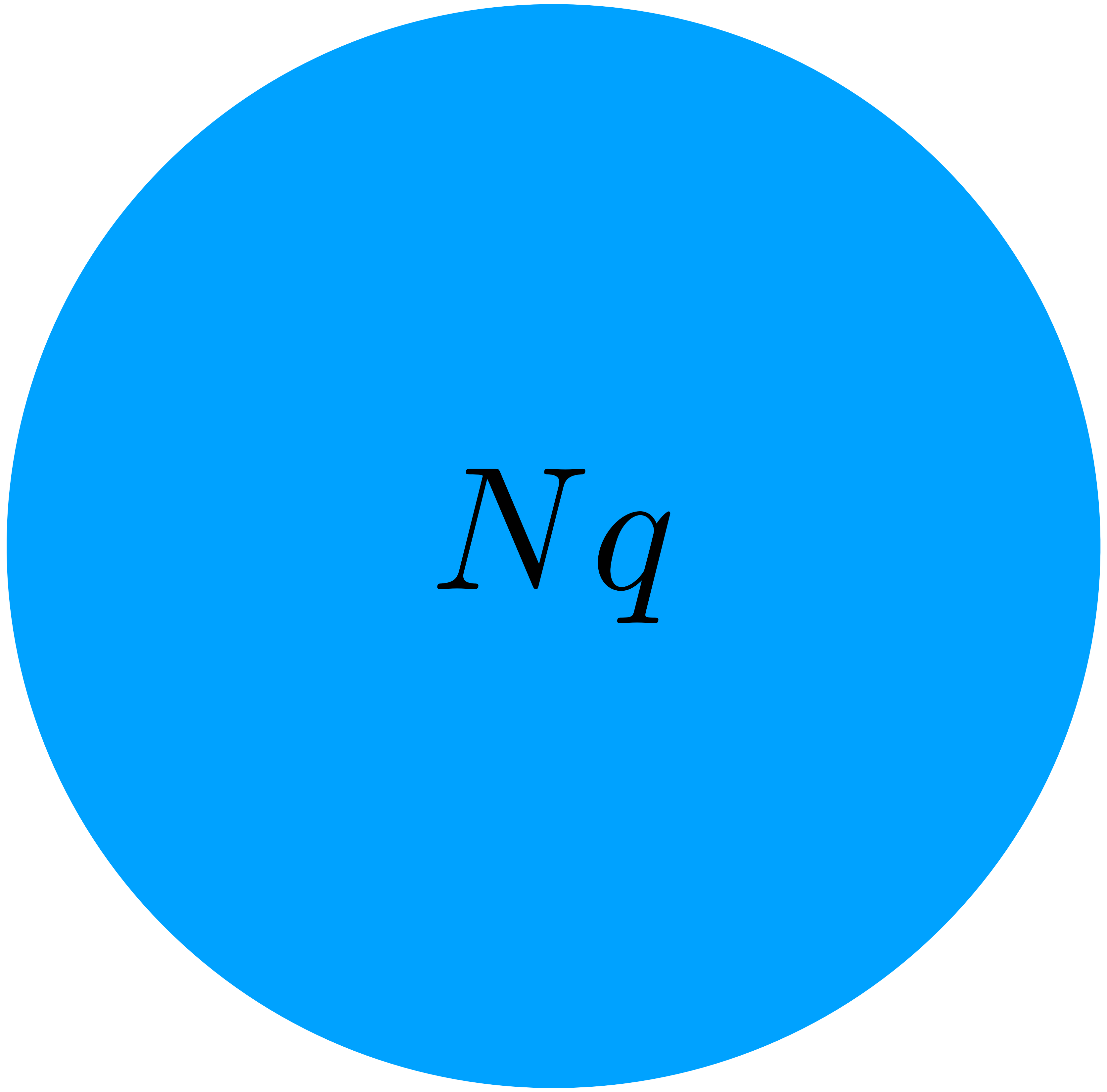
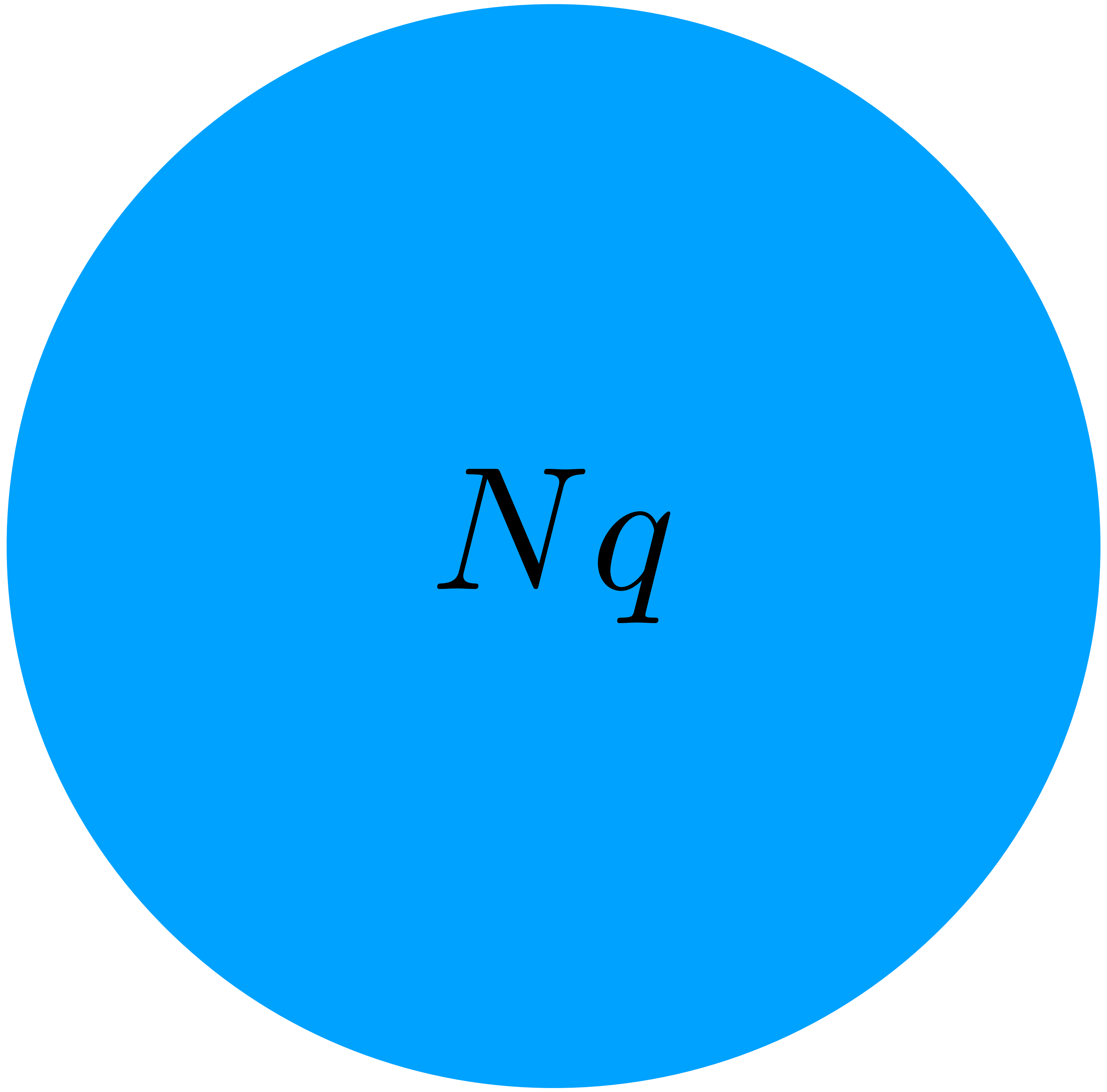
Rayleigh-Gans regime

Observable in Elastic Scattering



Macroscopic coherence

Observable in Elastic Scattering



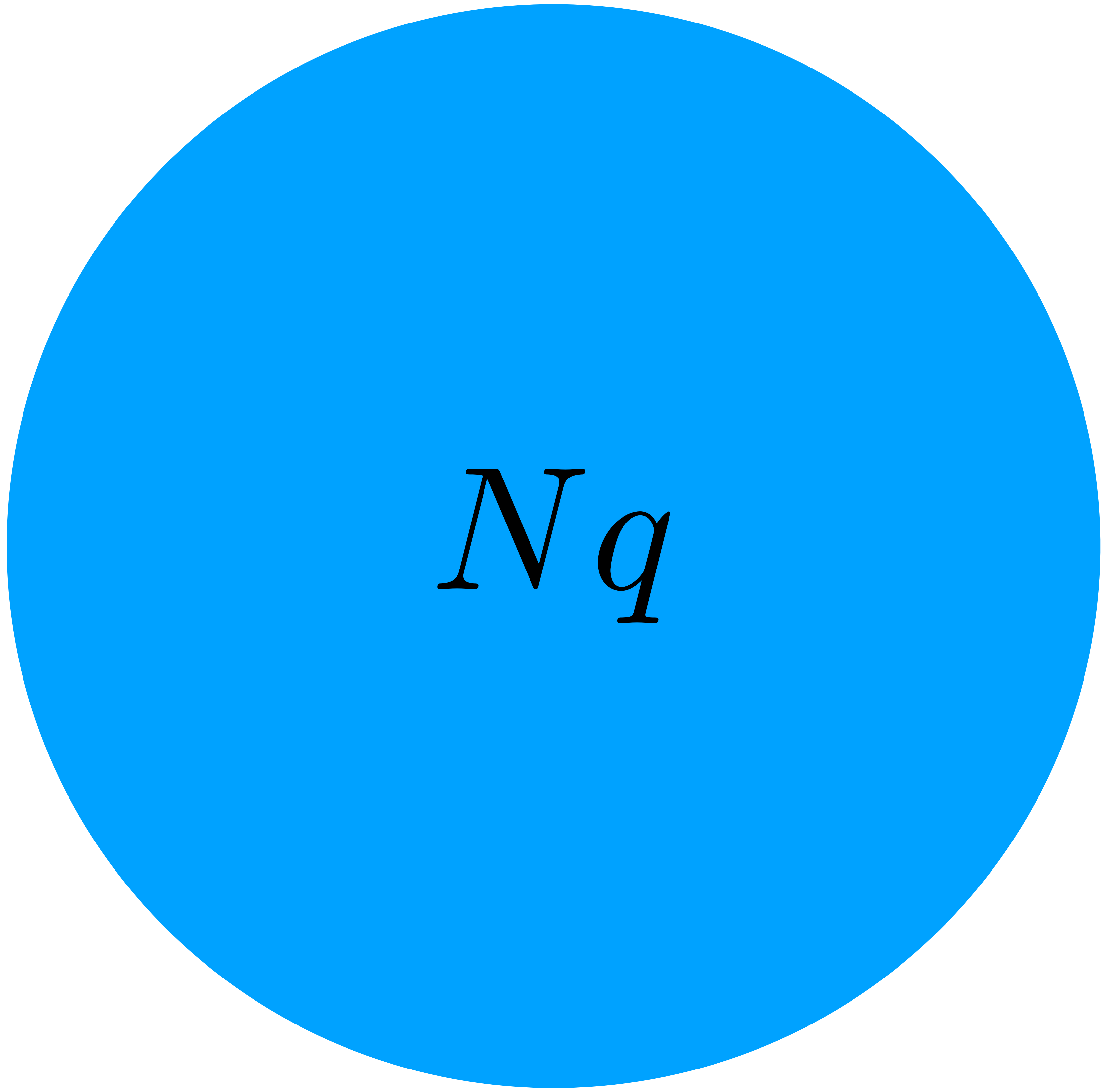
Macroscopic coherence

<u>Momentum Transfer</u>

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

For a 10cm sphere

Observable in Elastic Scattering



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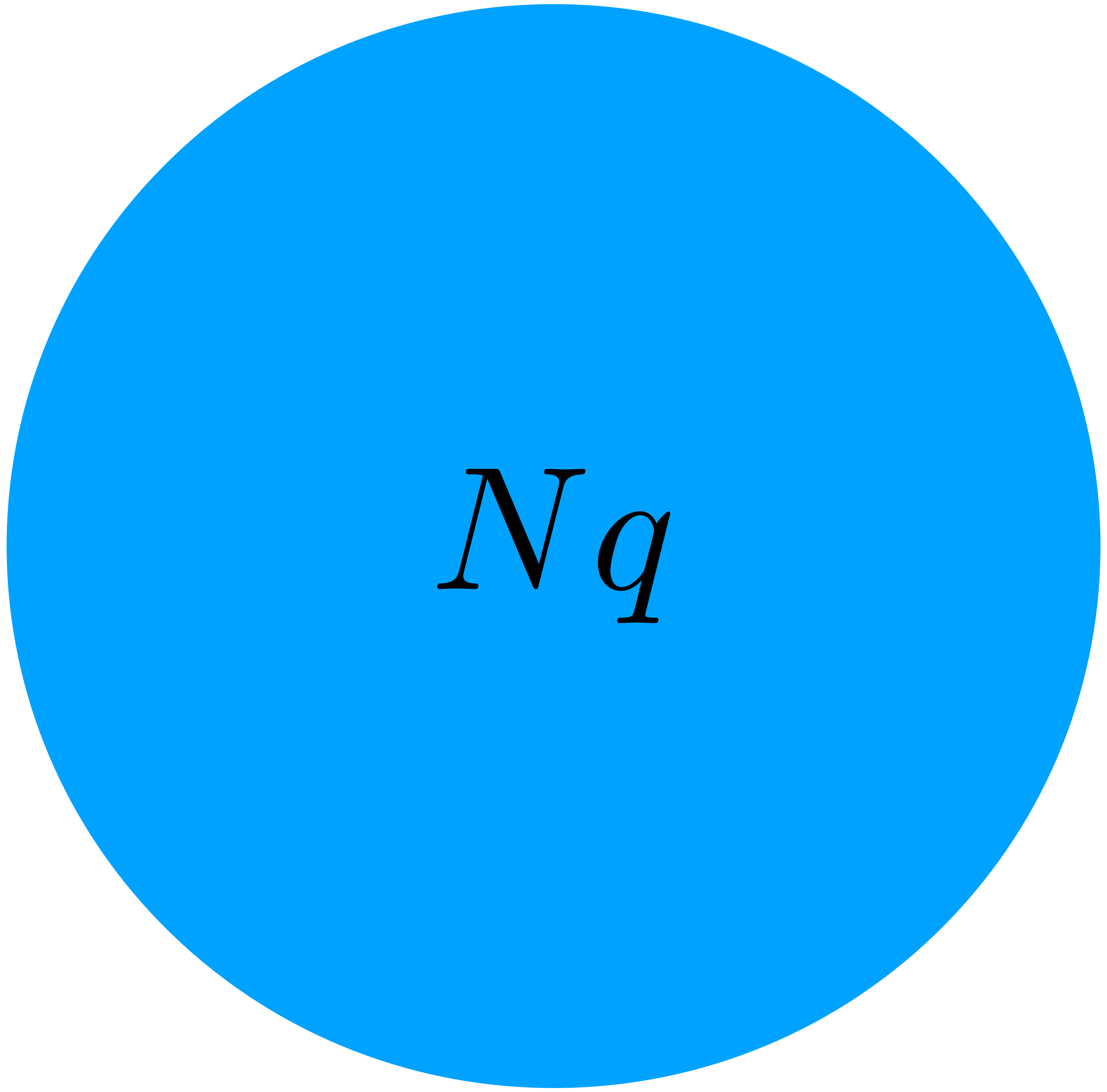
For a 10cm sphere

Energy Transfer

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

For a 10cm sphere of tungsten

Observable in Elastic Scattering



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<u>Energy Transfer</u>

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

For a 10cm sphere of tungsten

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

$$n(\pi R^2)v \sim 1 \text{ Hz}$$
$$q \sim 10^{-4} \text{ eV}$$

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

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

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Idea: what if we changed the internal state?

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

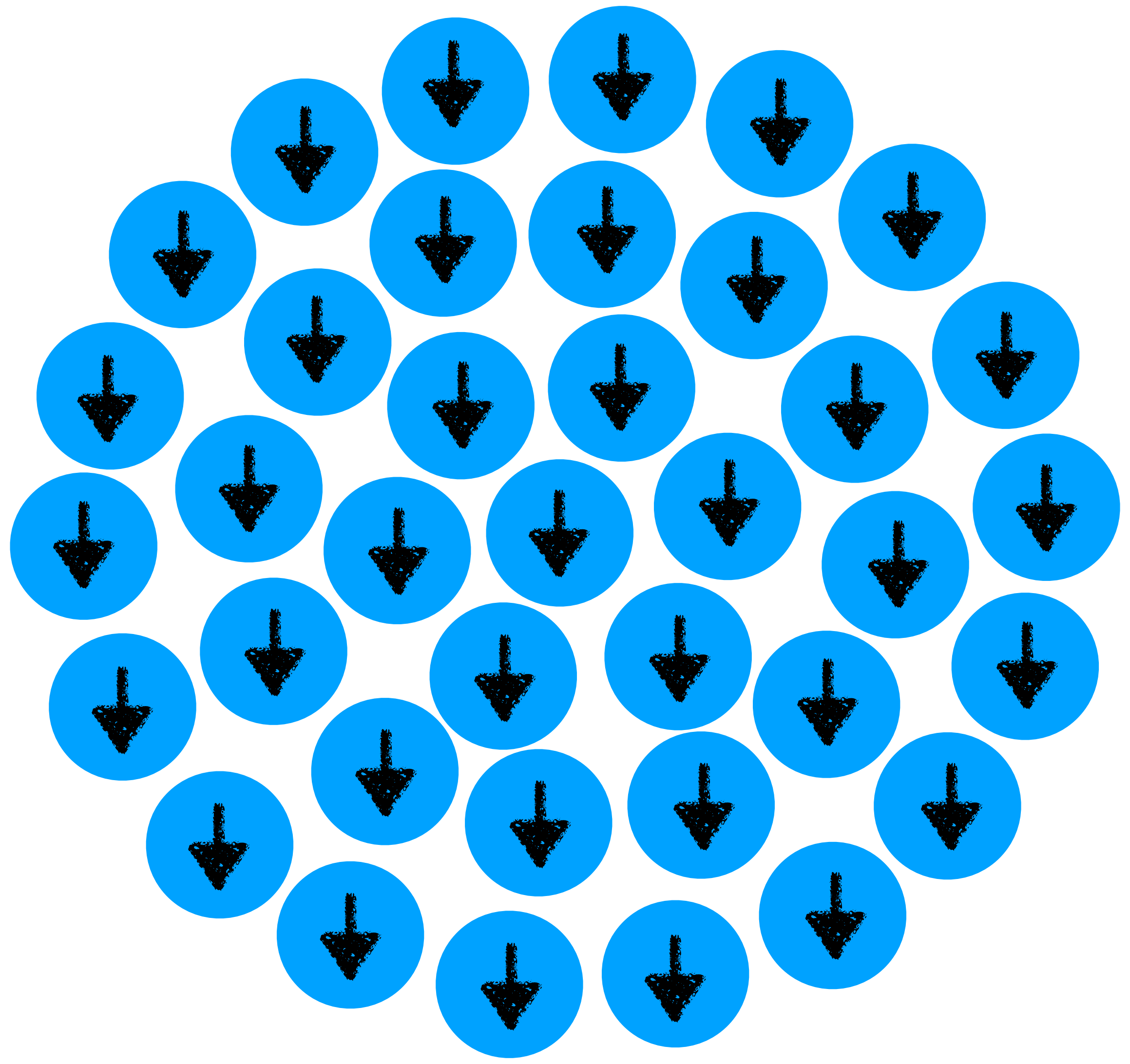
ESR similarly $\sim 10^{-4}$ eV

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

Then N^2 *and* potential observable

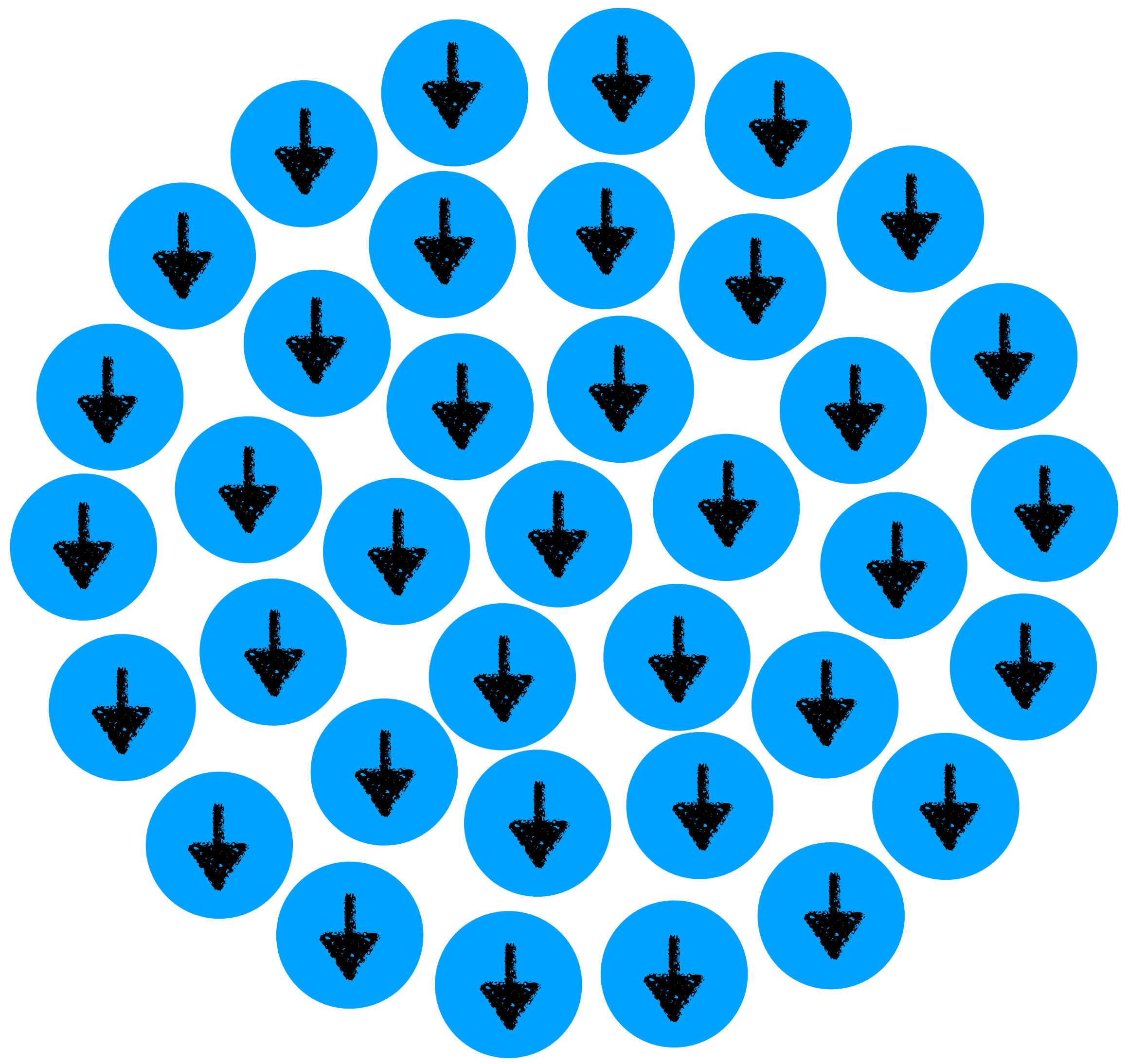
Approves

Coherence in Inelastic Processes



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

InCoherence in Inelastic Processes



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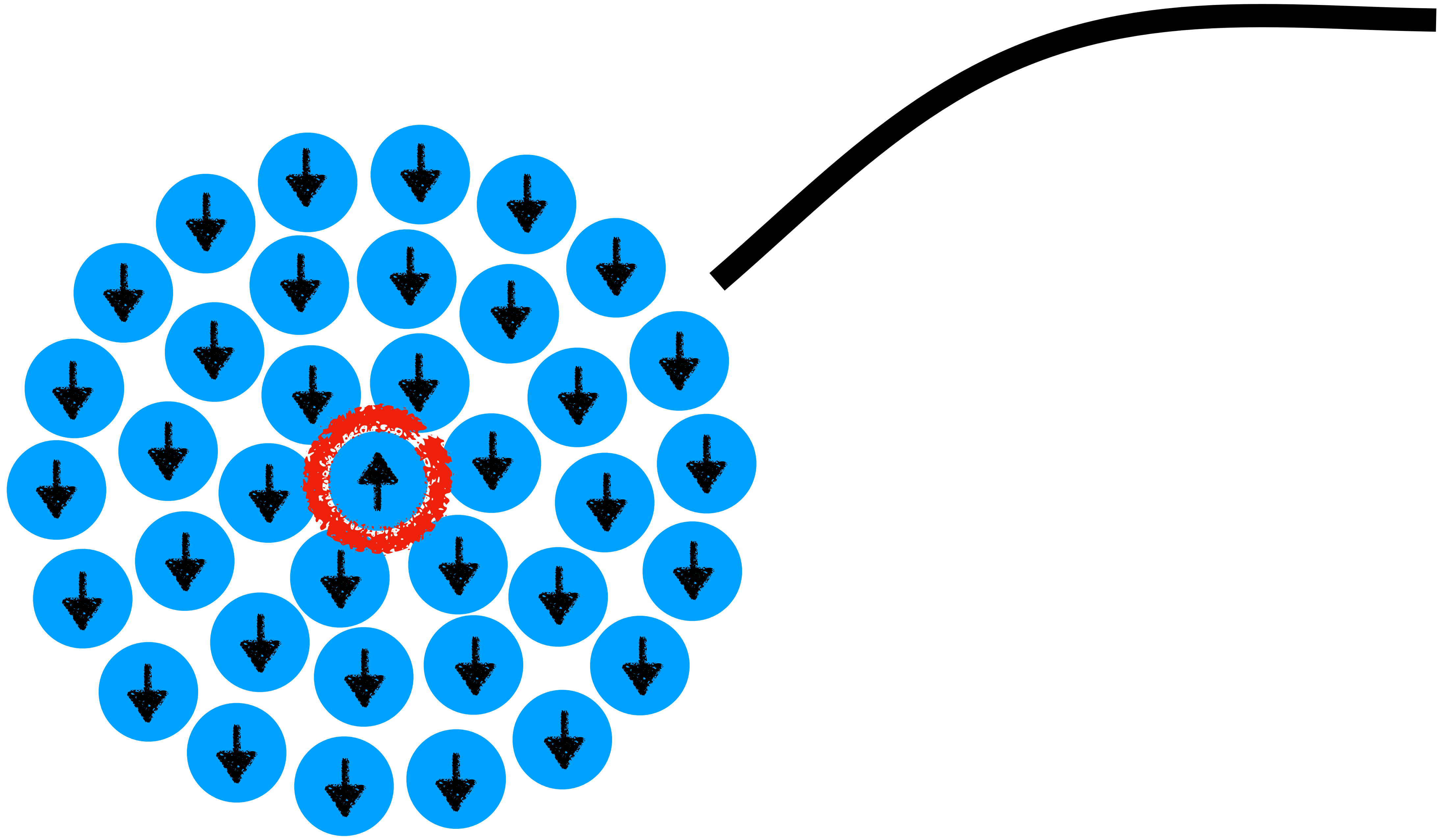

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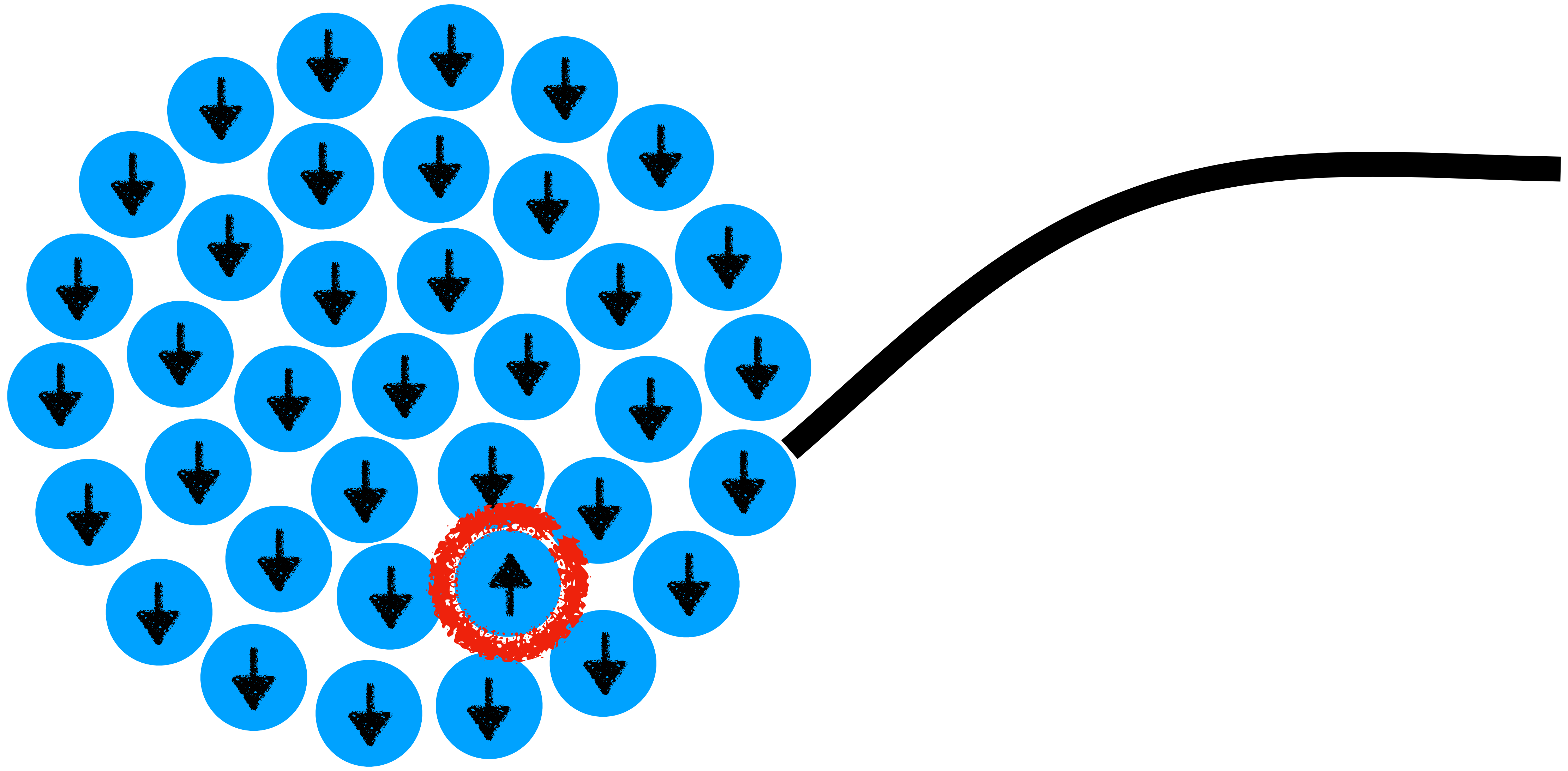

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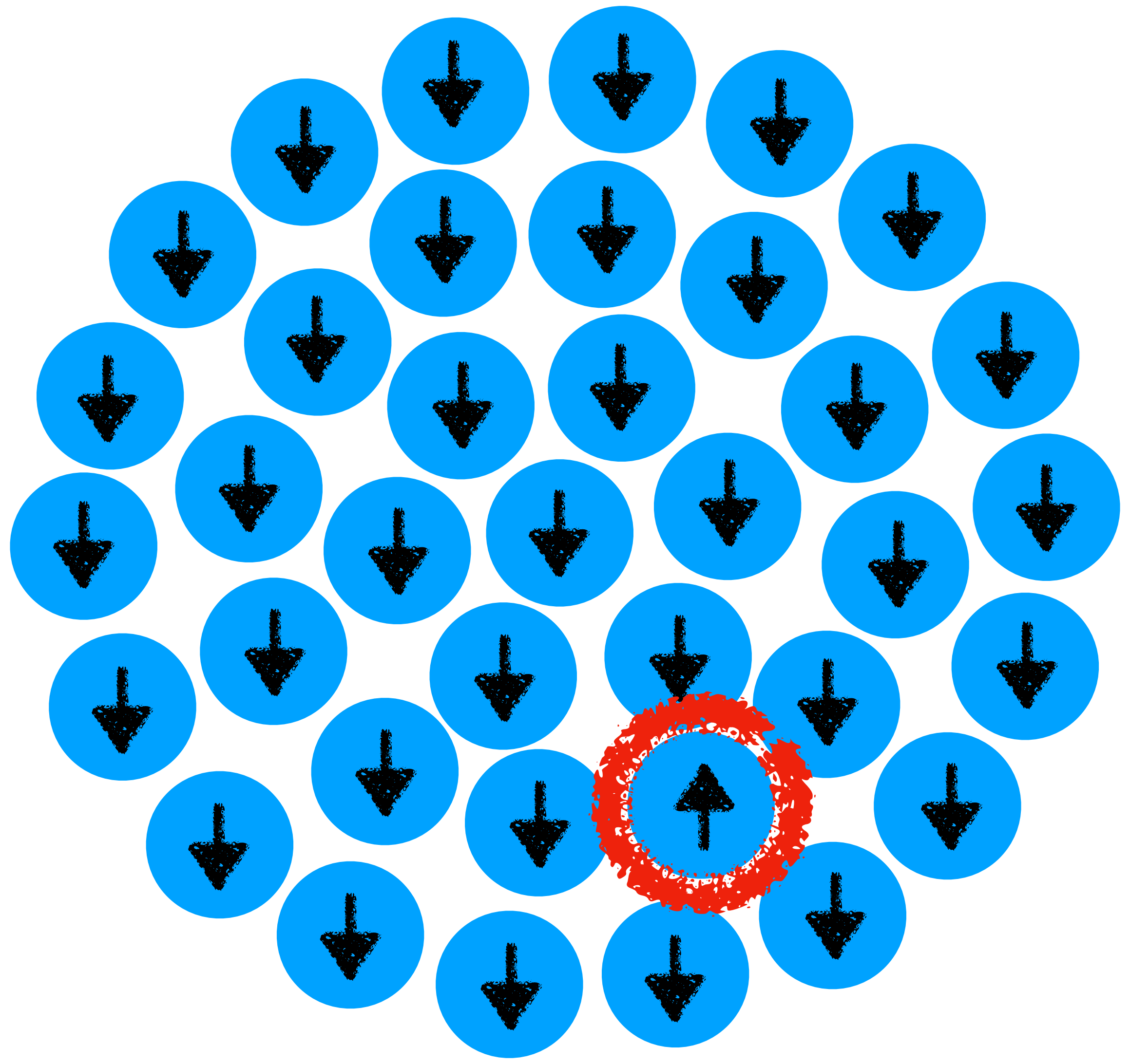
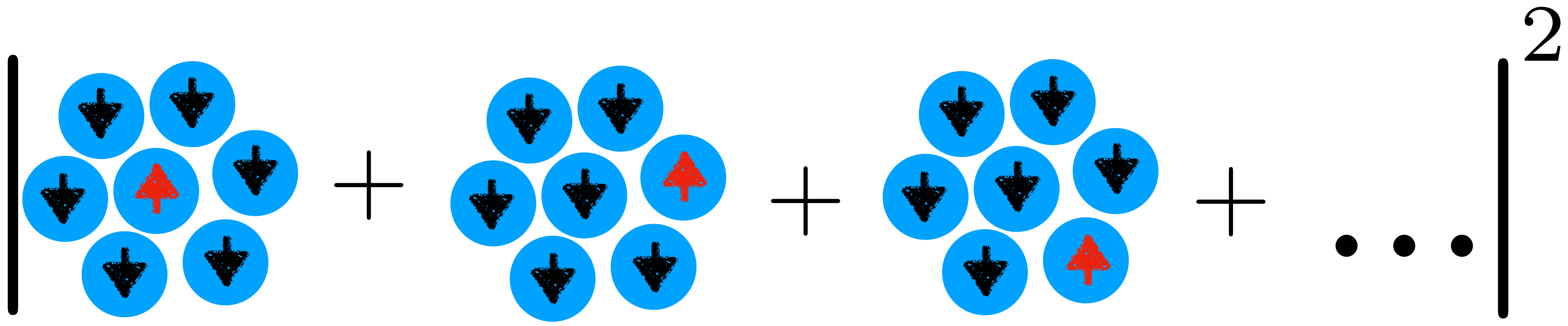


$\Gamma \sim$



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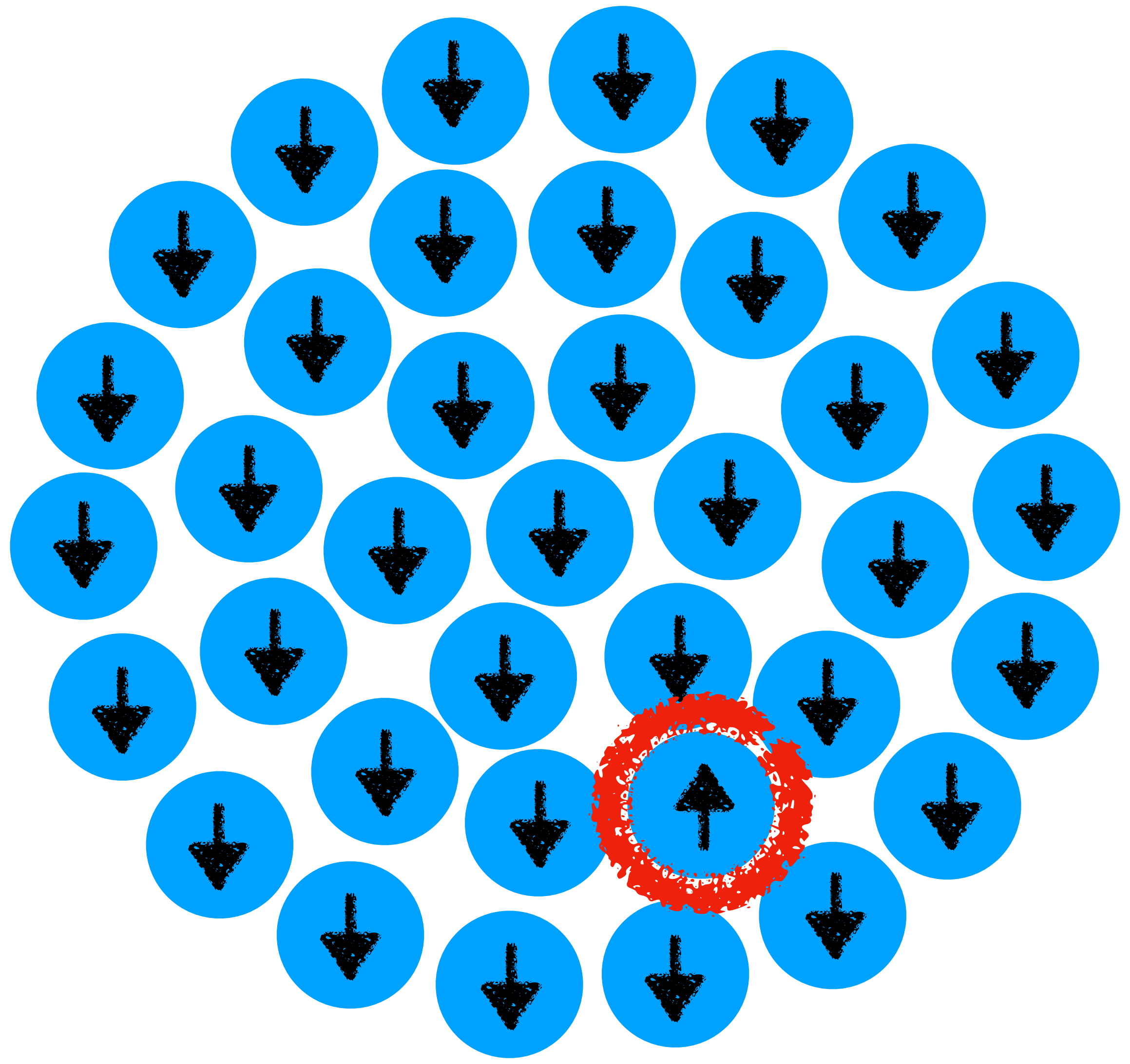
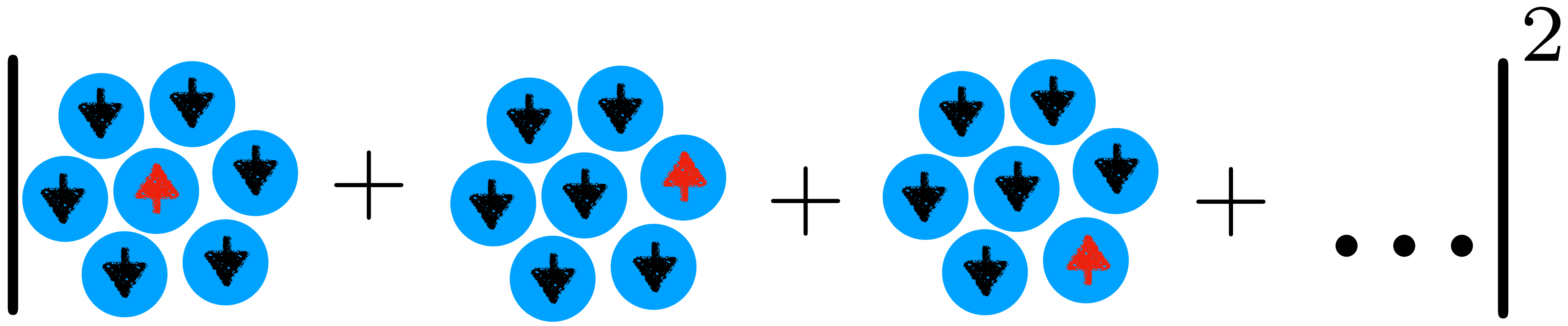


$\Gamma \sim$ 

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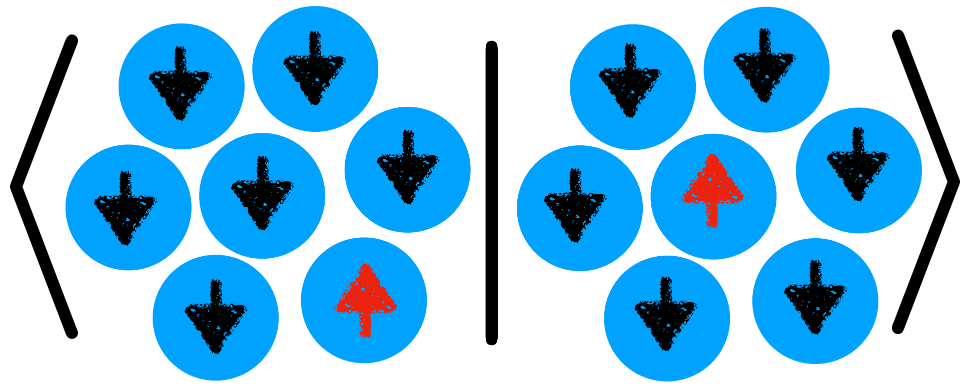
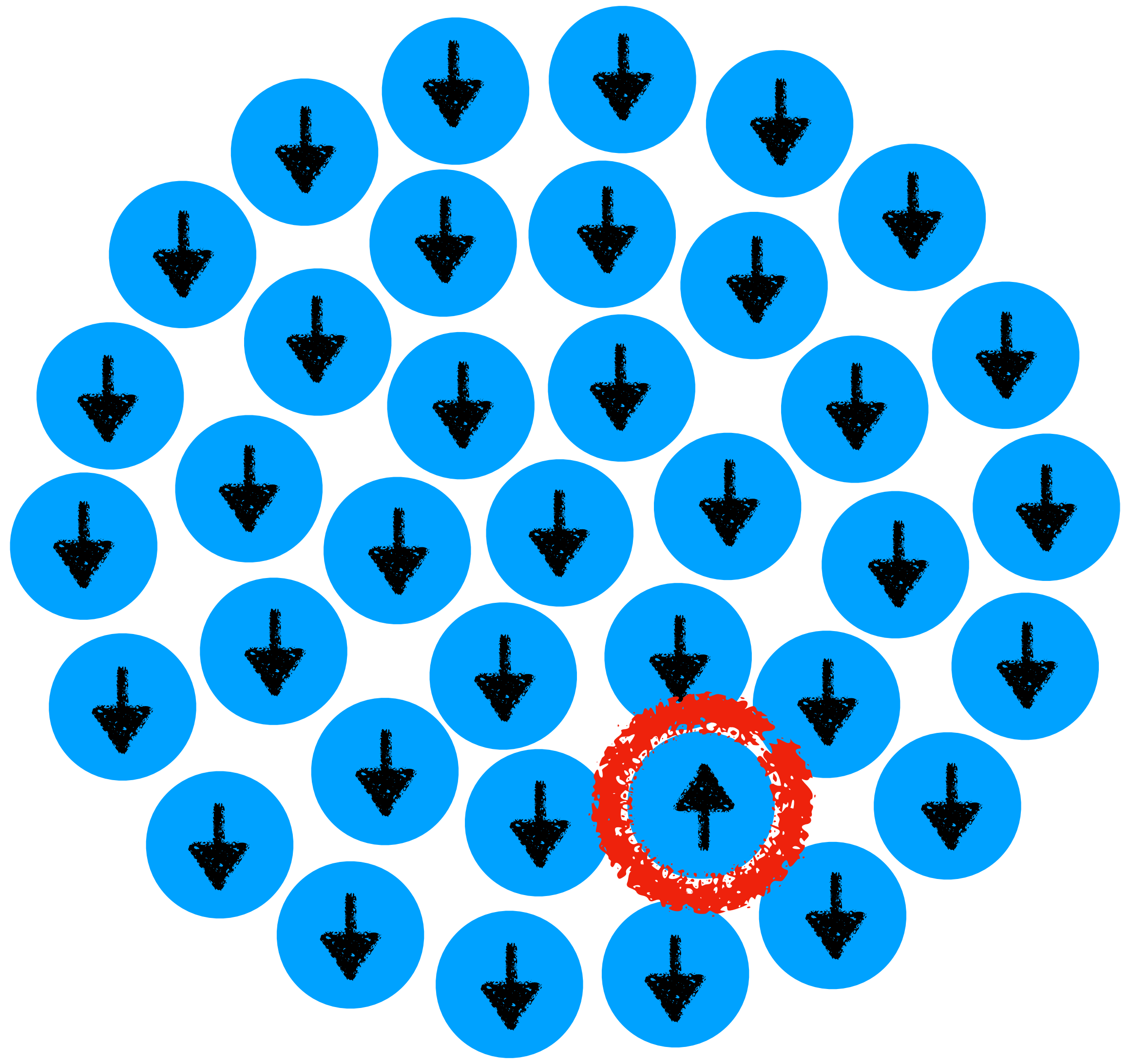
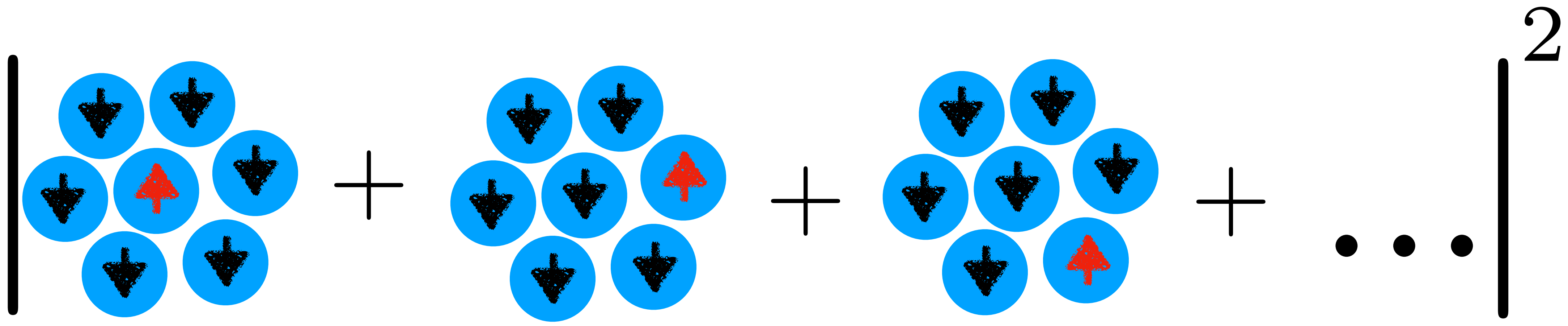
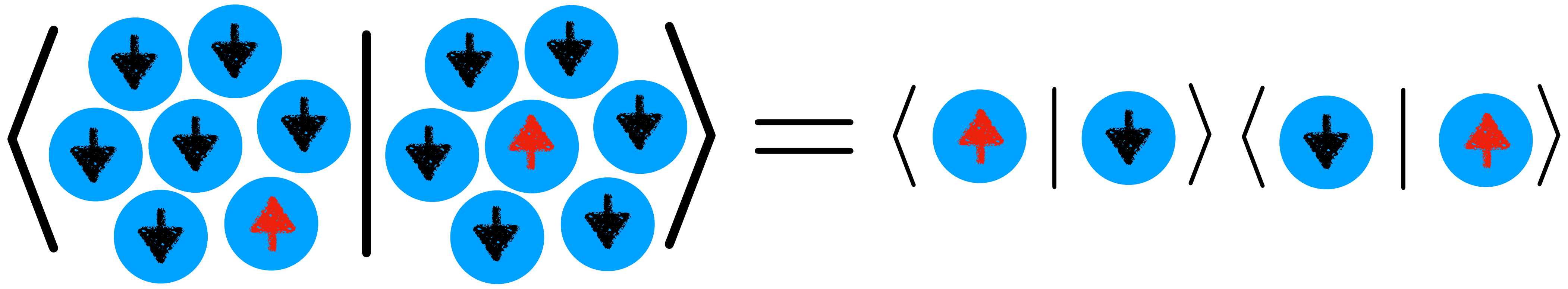


InCoherence in Inelastic Processes

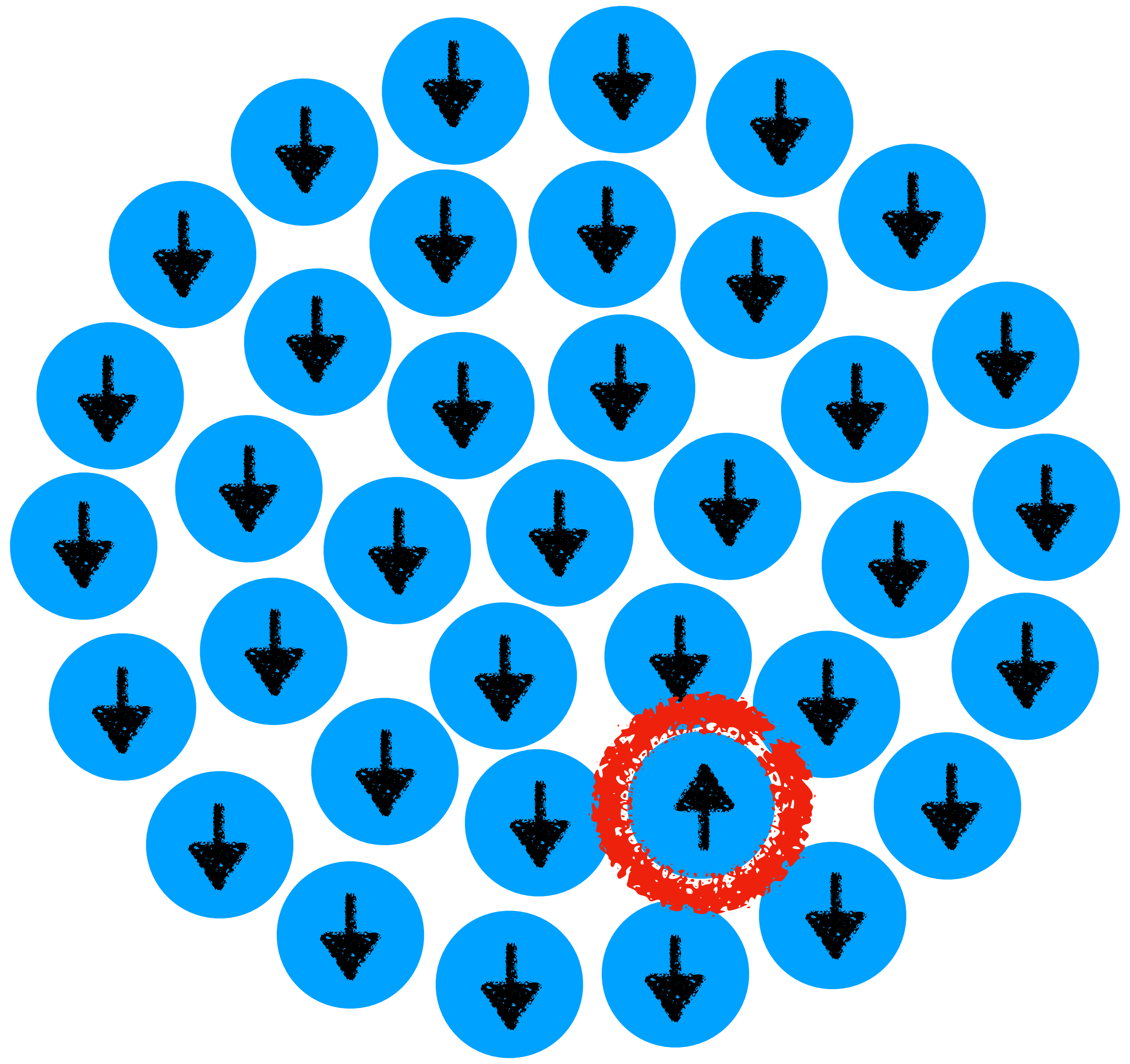


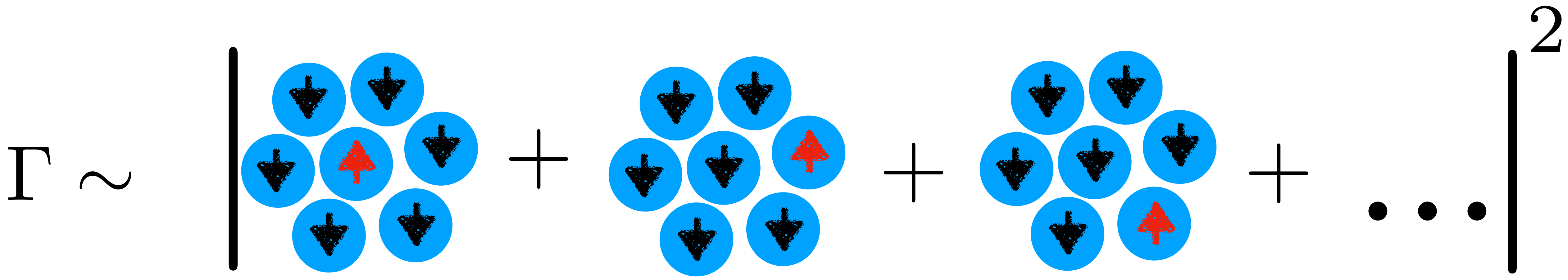
$\Gamma \sim$ 

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

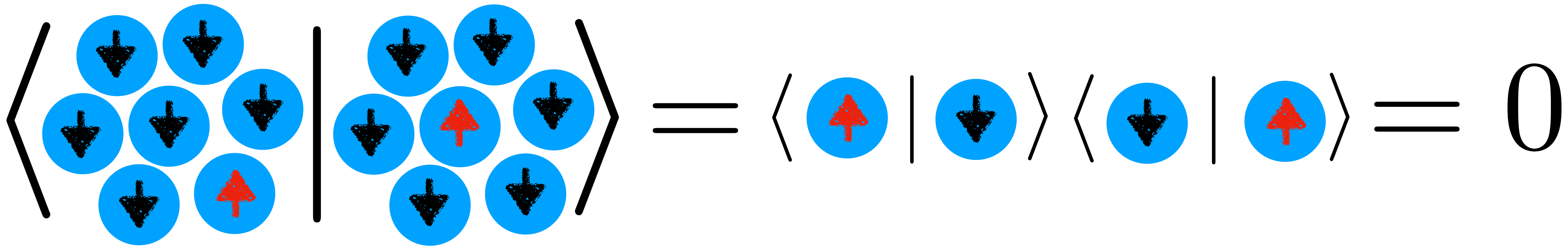


InCoherence in Inelastic Processes

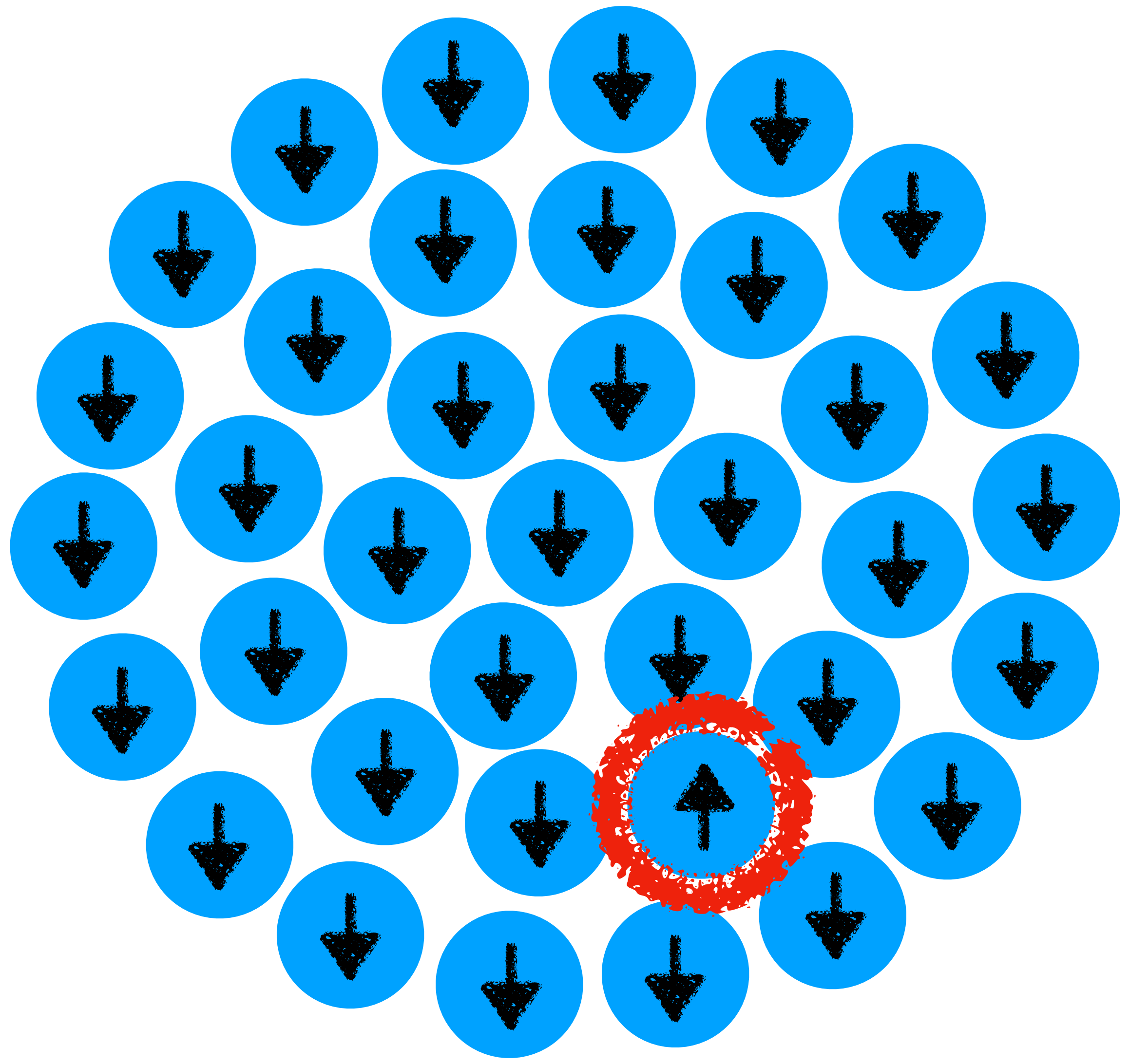


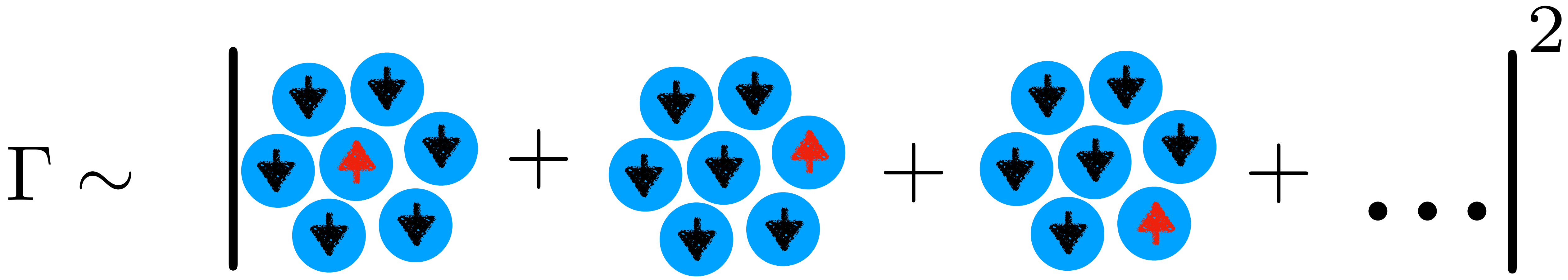


$$|\psi\rangle = \prod |g\rangle$$



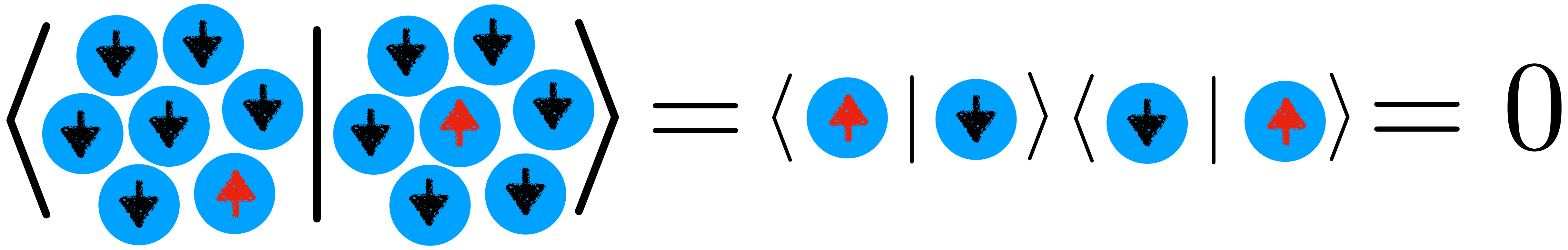
InCoherence in Inelastic Processes



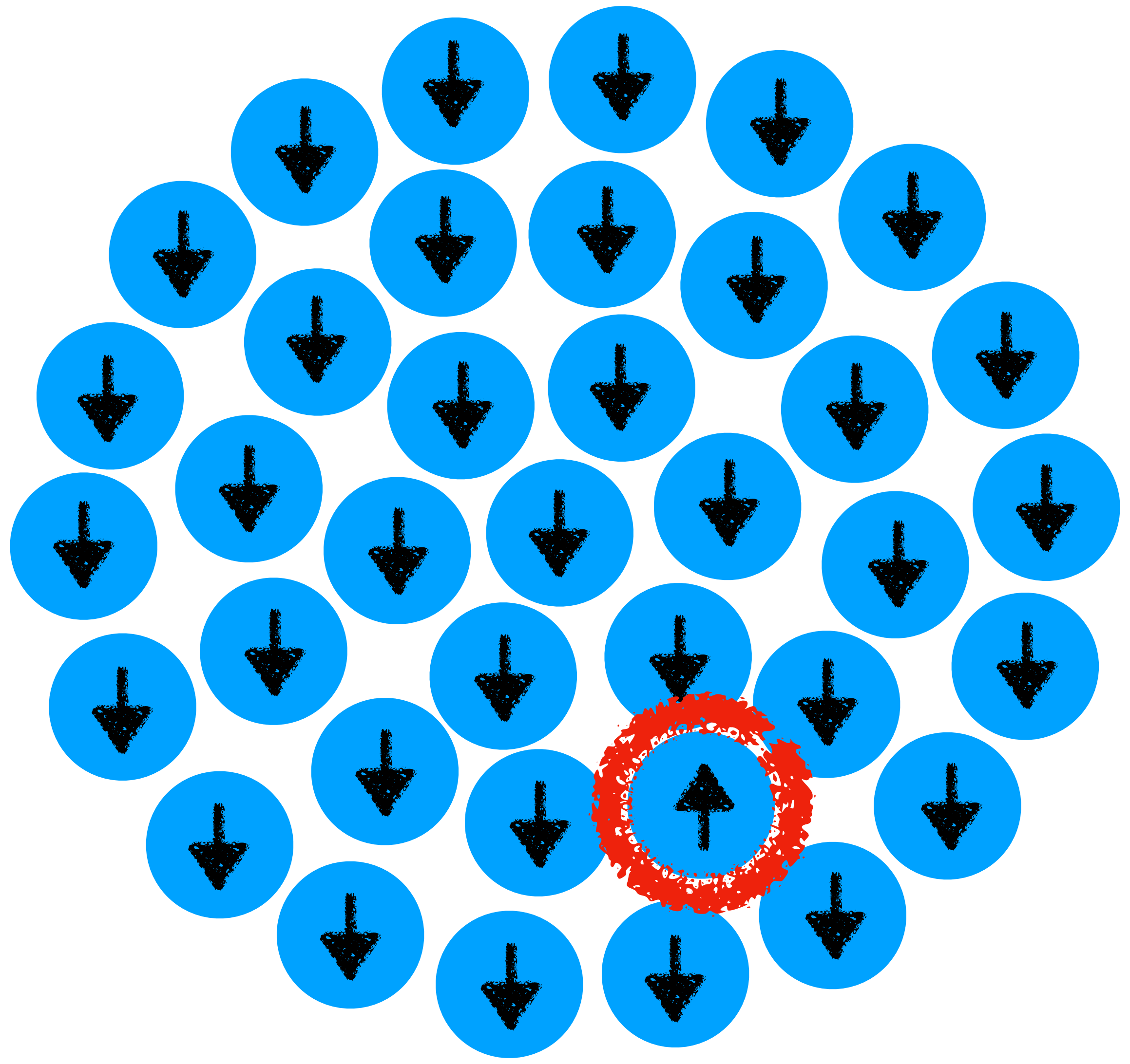


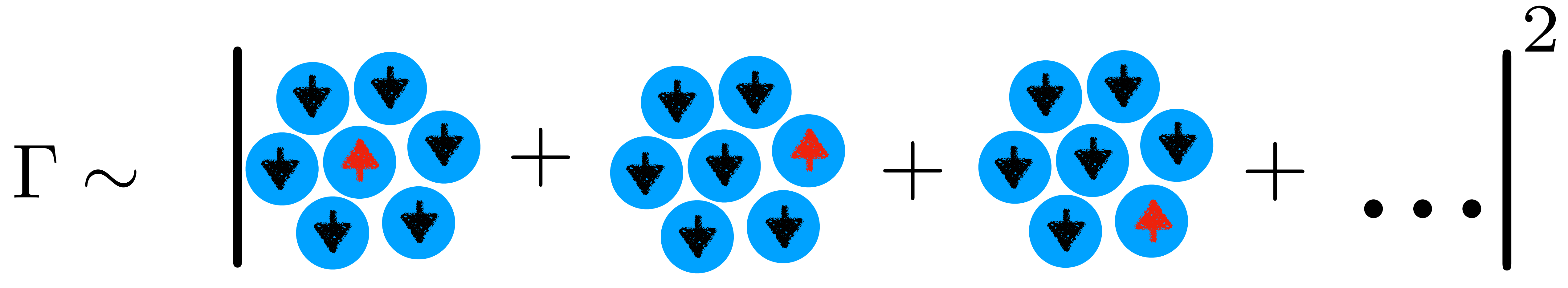
$$= Nq^2$$

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



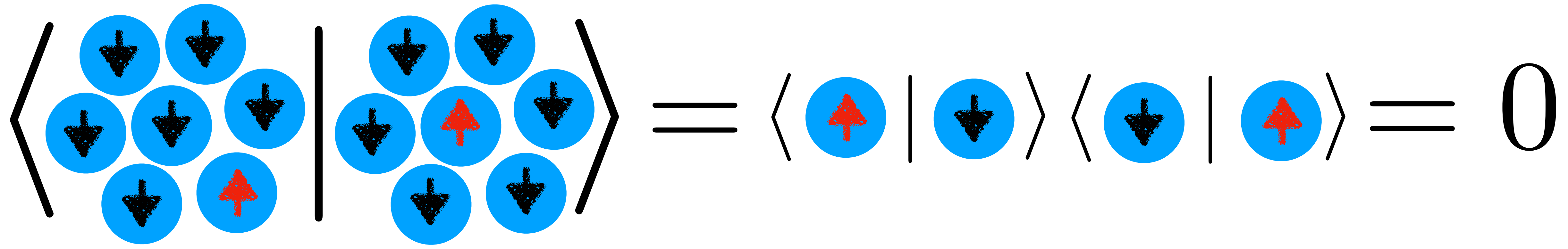
InCoherence in Inelastic Processes



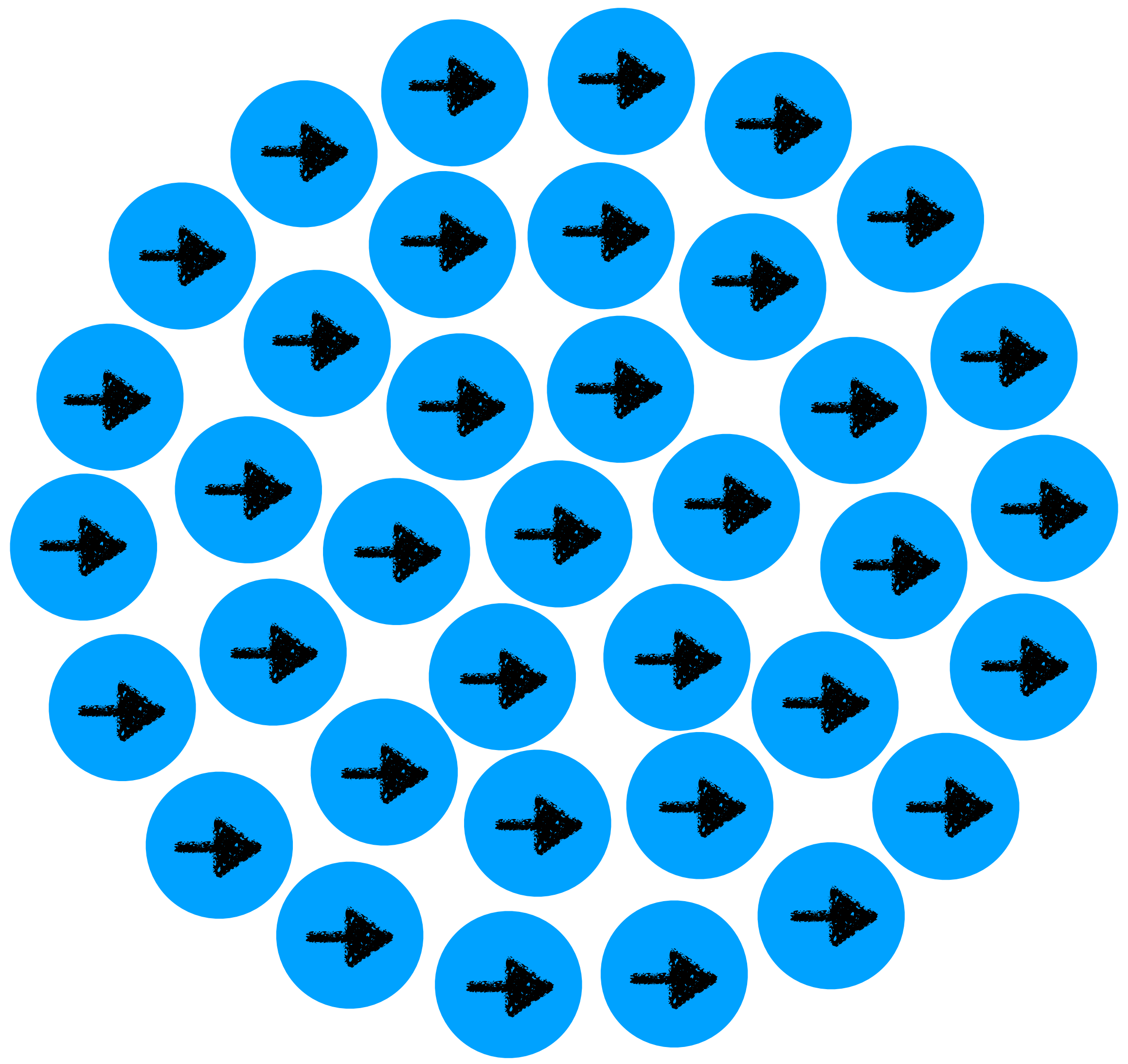


$= Nq^2$ Incoherent

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

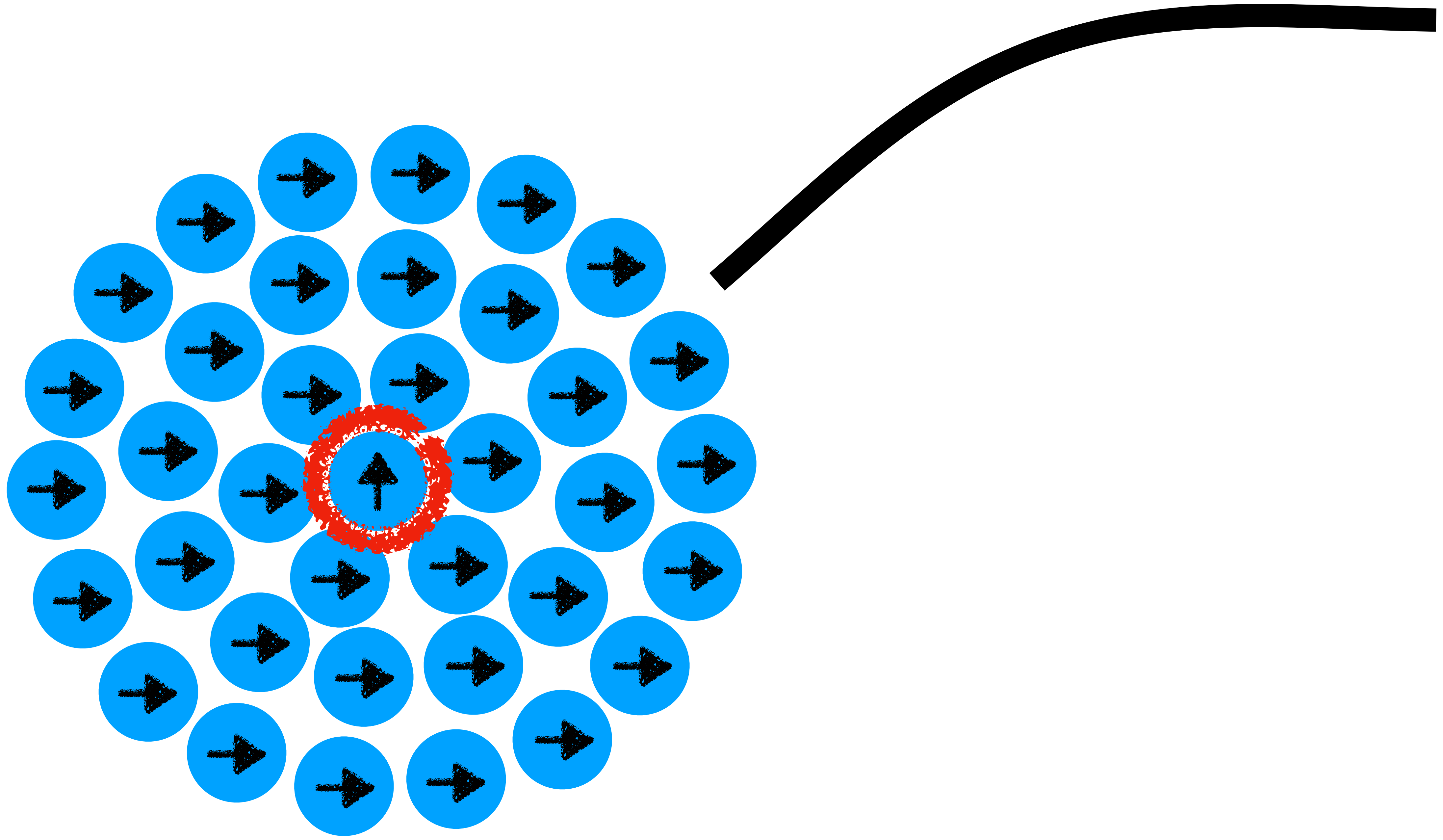


Coherence in Inelastic Processes



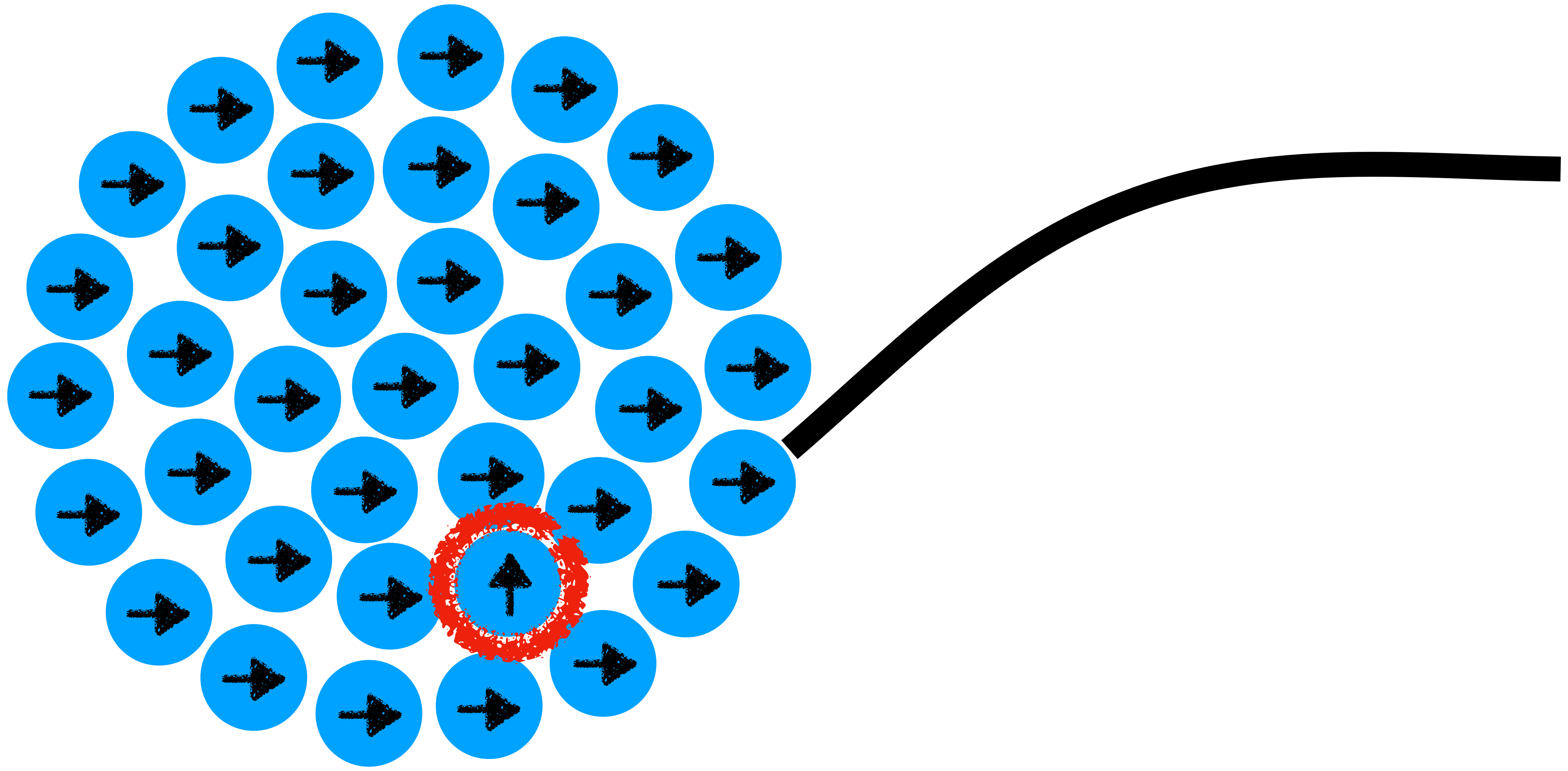
$$|\psi\rangle = \prod \frac{1}{\sqrt{2}} \left(|g\rangle + |e\rangle\right)$$

Coherence in Inelastic Processes



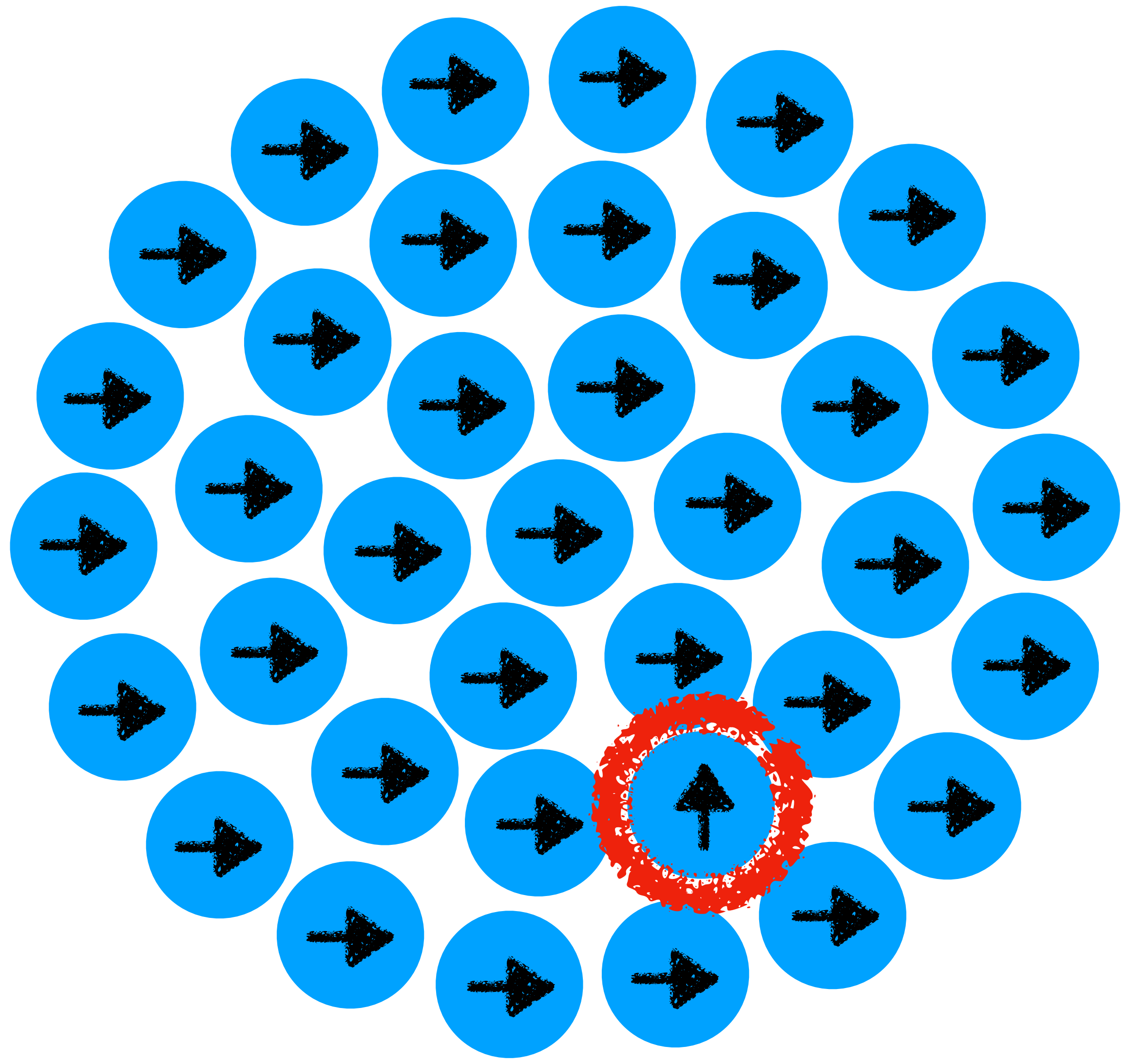
$$|\psi\rangle = \prod \frac{1}{\sqrt{2}} \left(|g\rangle + |e\rangle \right)$$

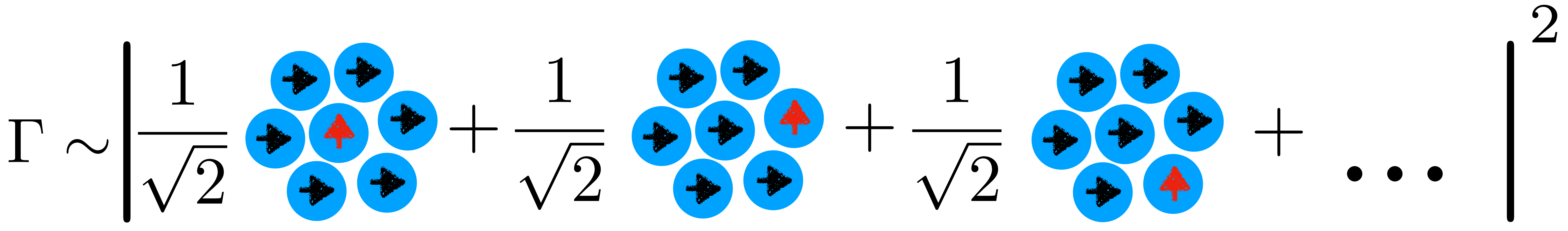
Coherence in Inelastic Processes



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

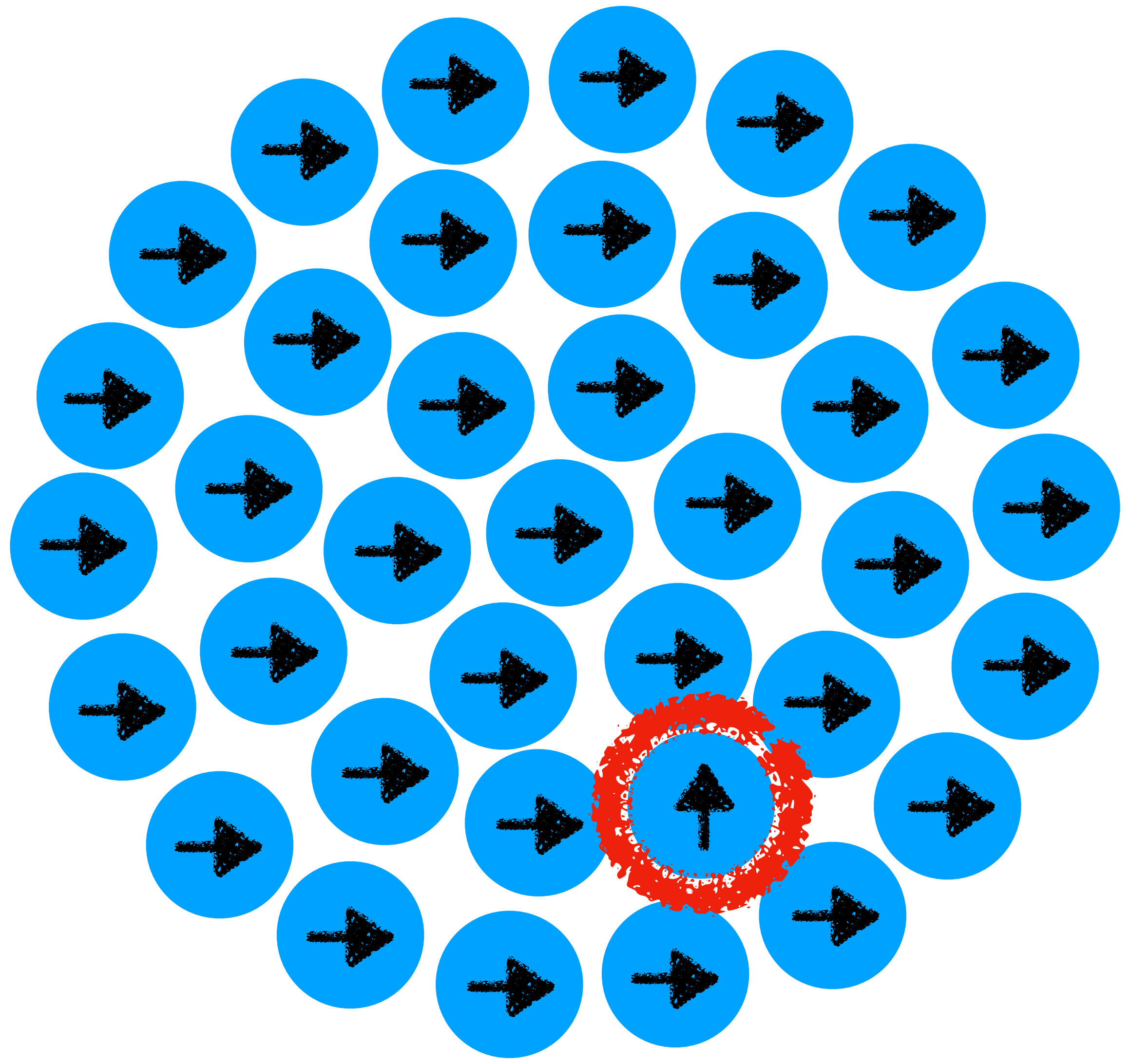
Coherence in Inelastic Processes

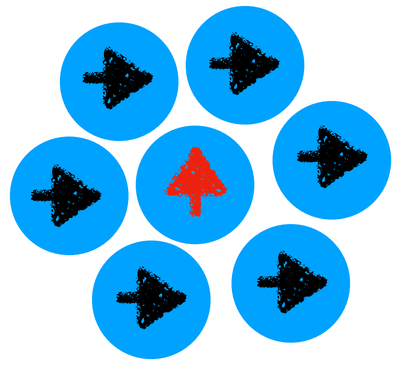
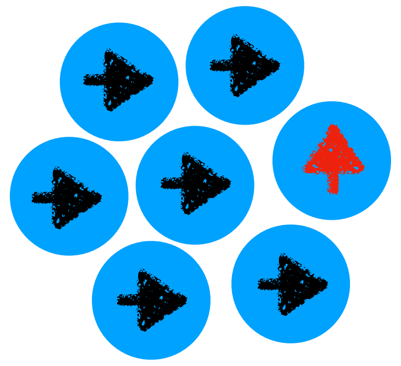
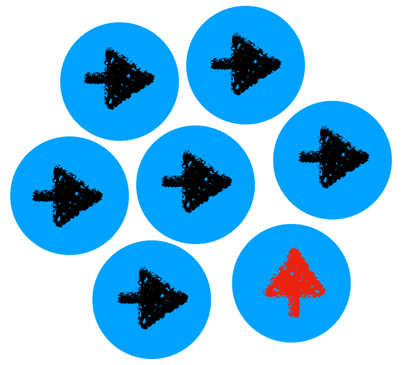




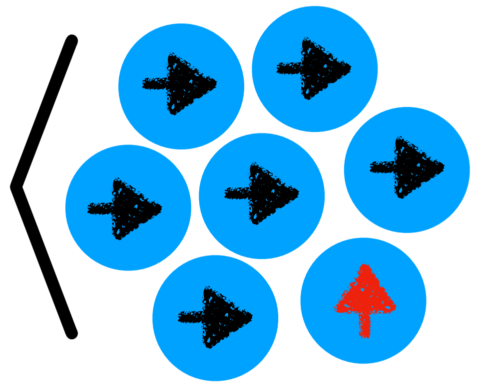
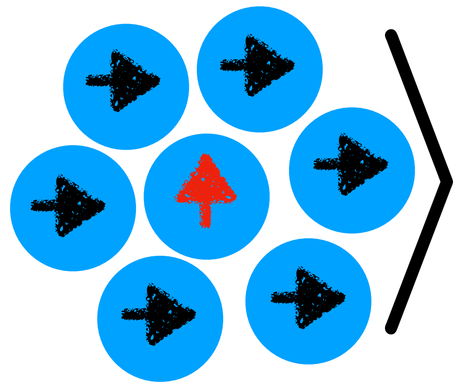
$$|\psi\rangle = \prod \frac{1}{\sqrt{2}} \left(|g\rangle + |e\rangle\right)$$

Coherence in Inelastic Processes

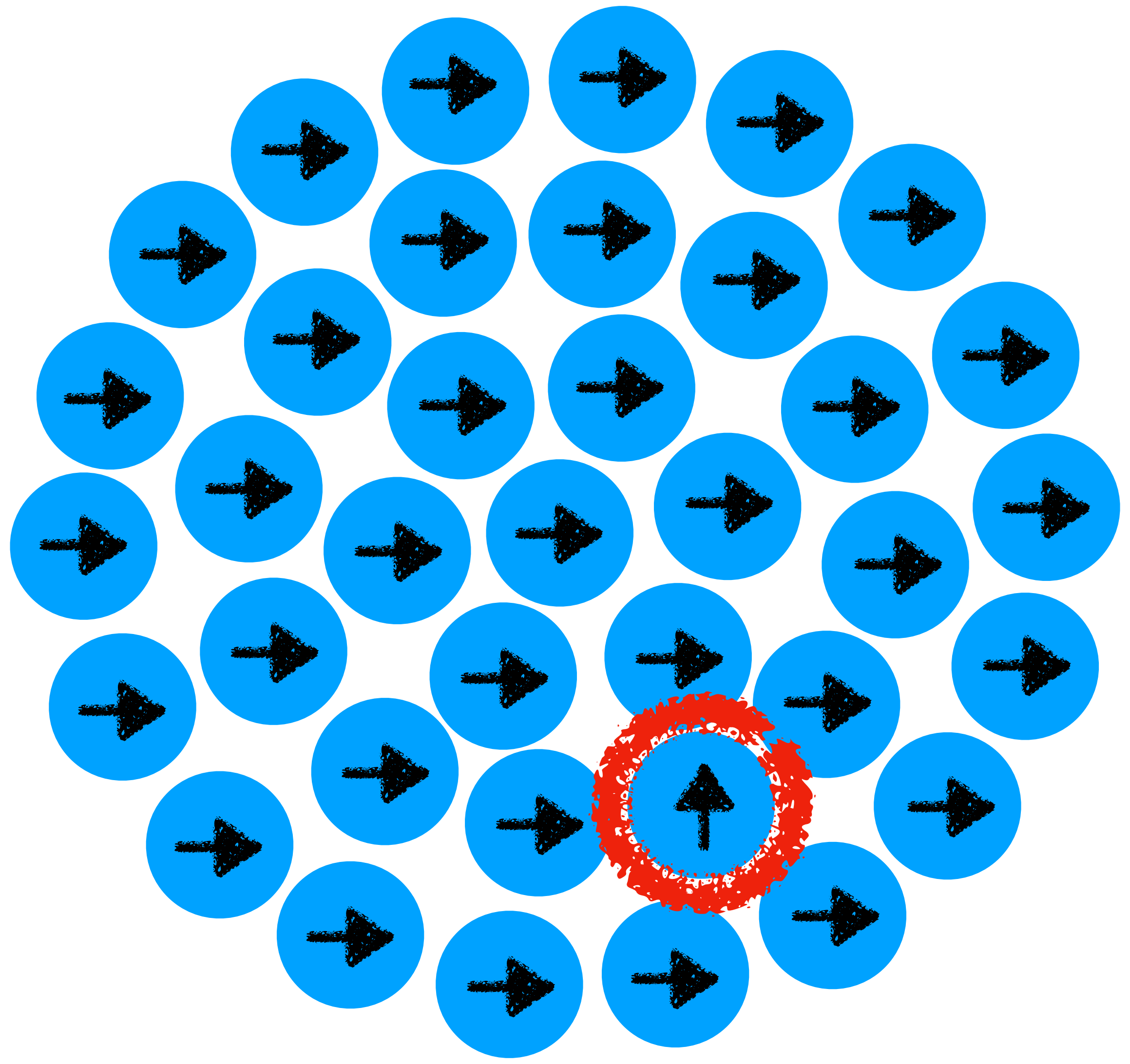


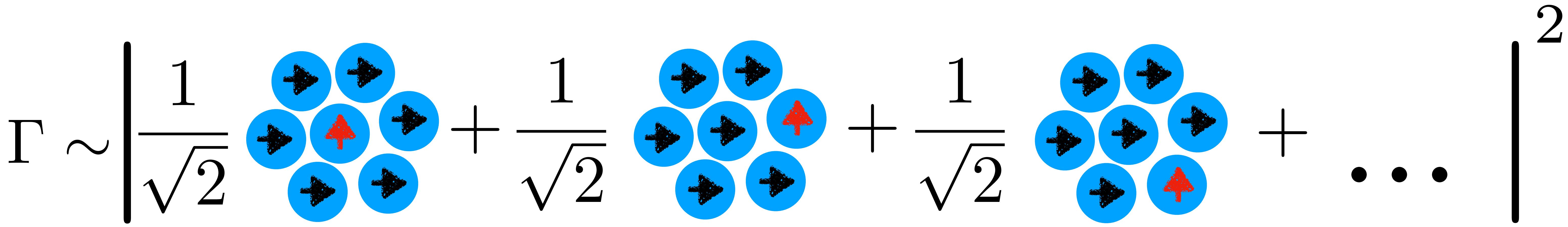
$\Gamma \sim \Bigg| \frac{1}{\sqrt{2}}$  $+ \frac{1}{\sqrt{2}}$  $+ \frac{1}{\sqrt{2}}$  $+ \ \ldots \ \Bigg|^2$

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

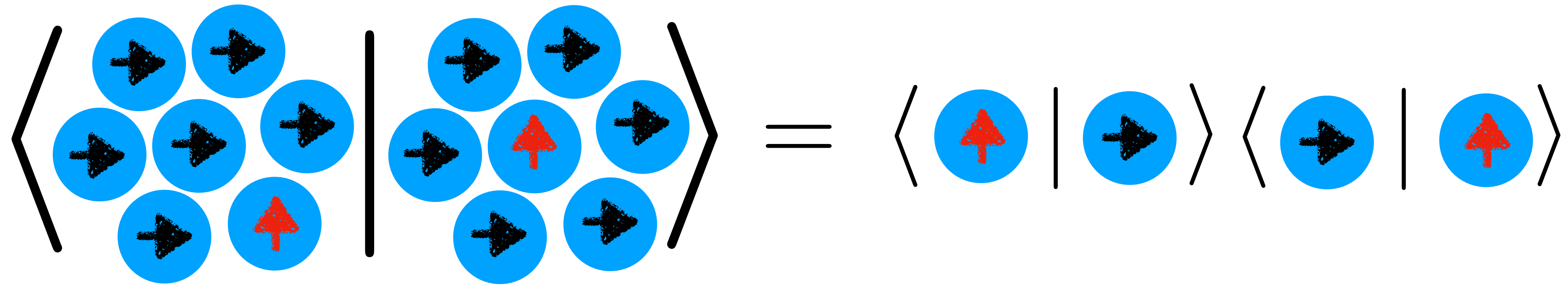
$\Big\langle$  $\Big|$  $\Big\rangle$

Coherence in Inelastic Processes

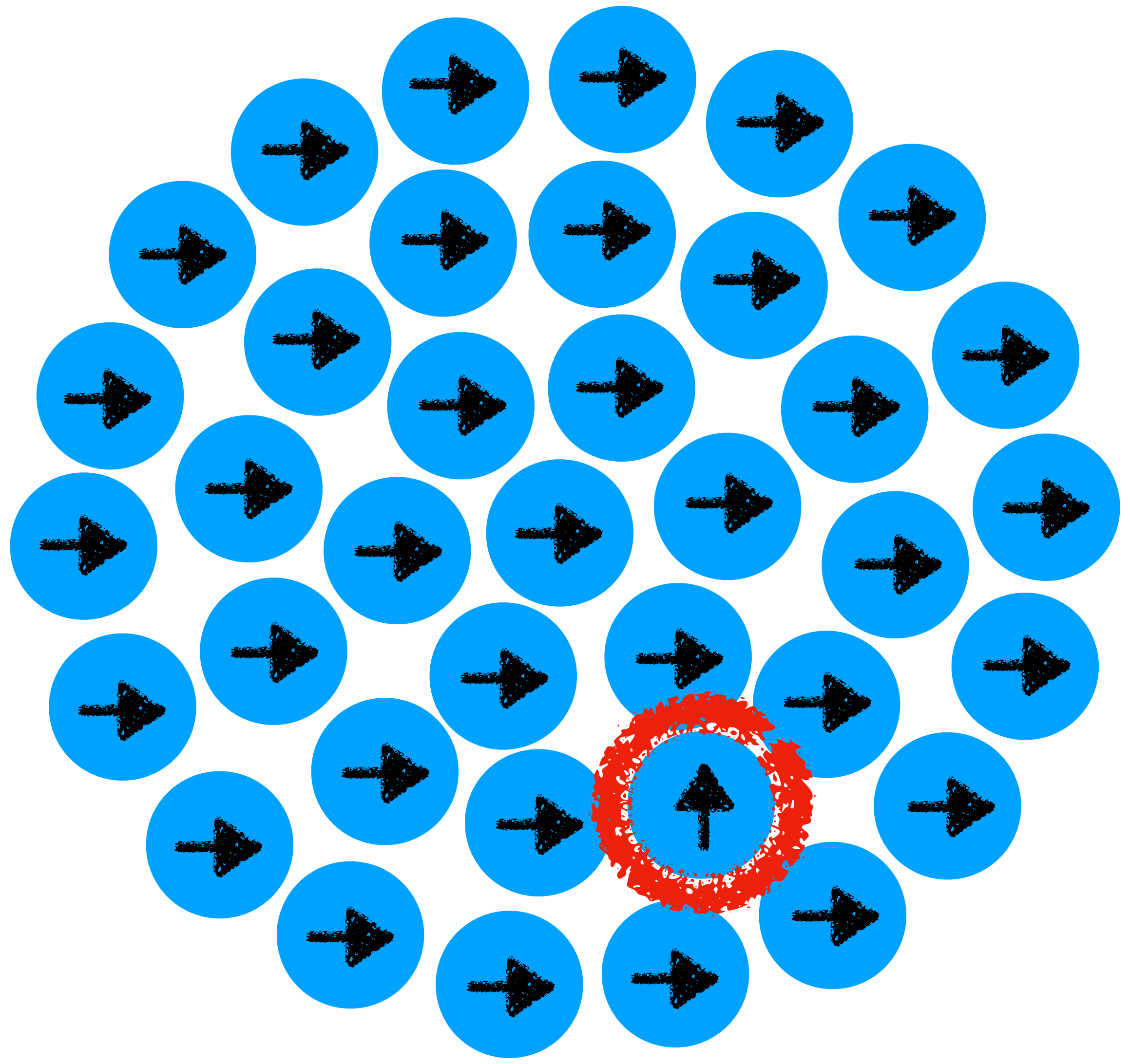


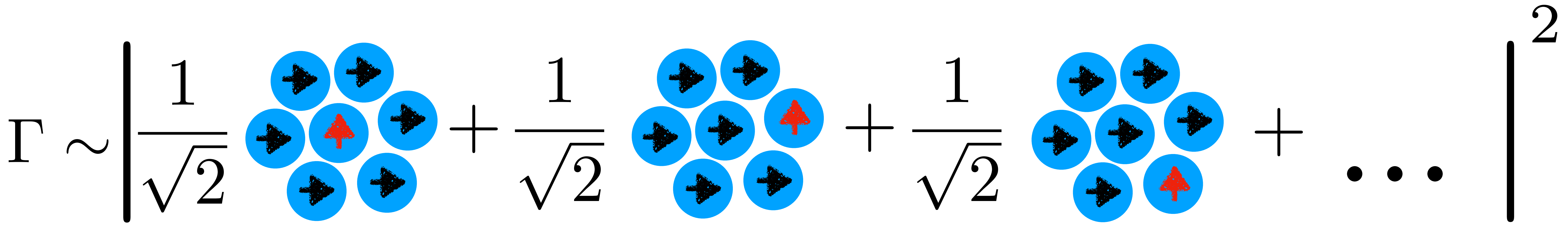


$$|\psi\rangle = \prod \frac{1}{\sqrt{2}} \left(|g\rangle + |e\rangle\right)$$

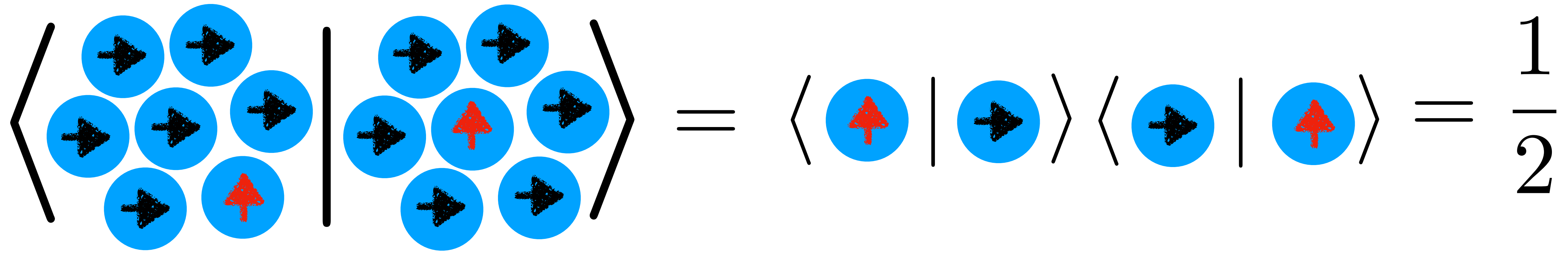


Coherence in Inelastic Processes

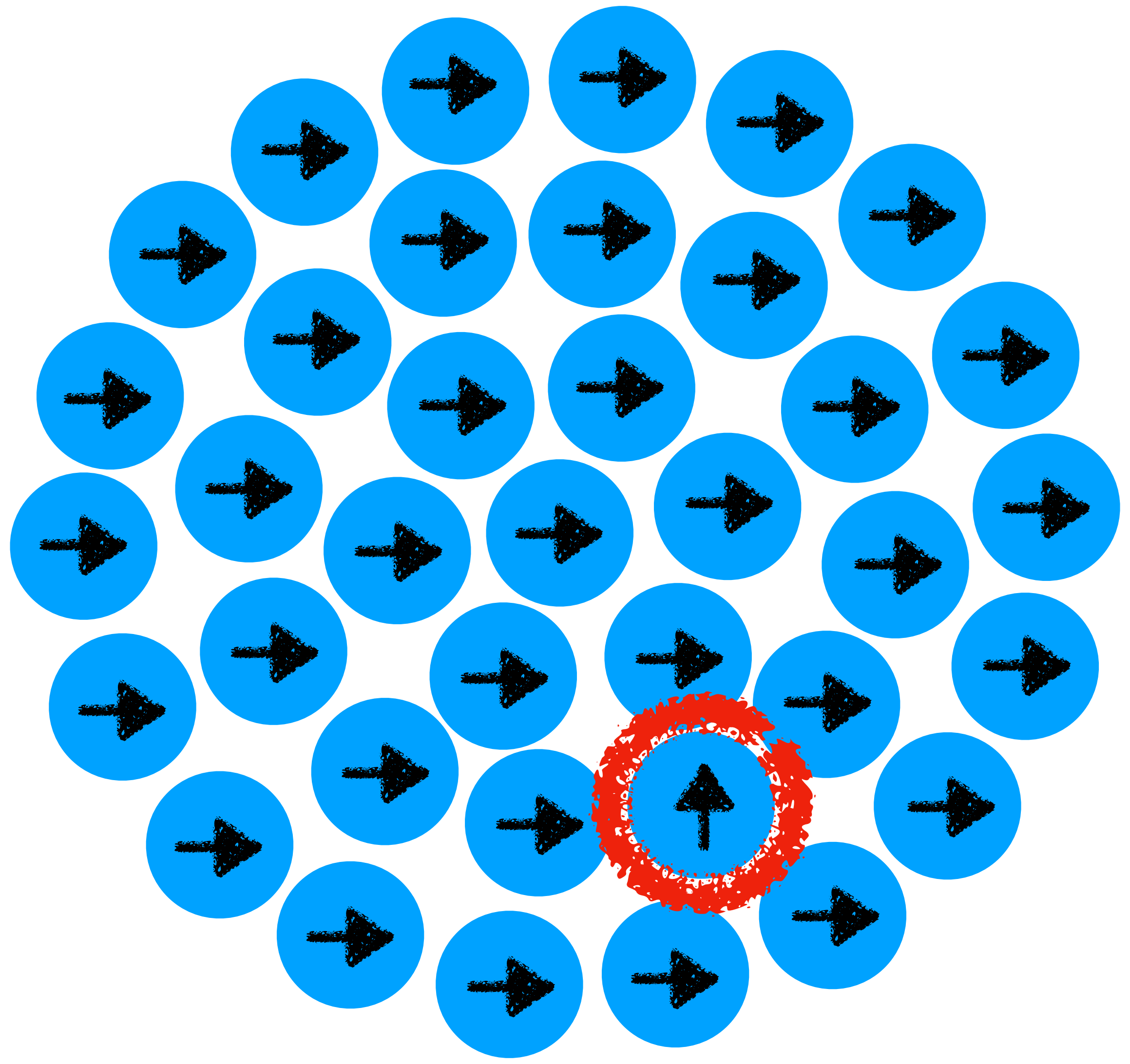


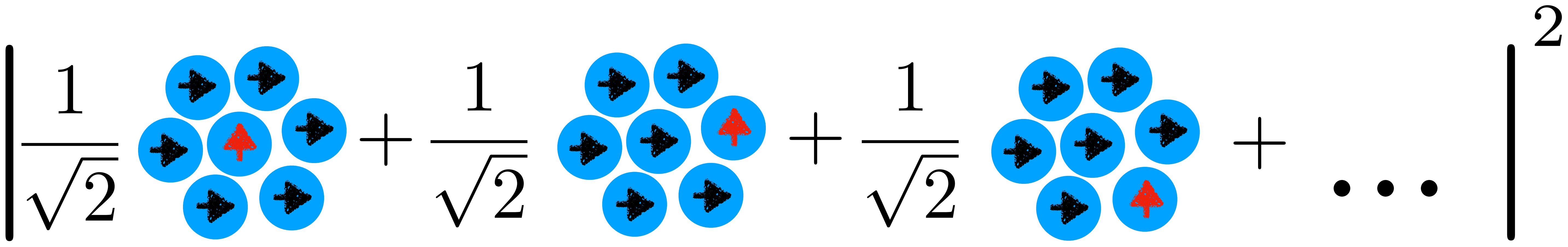


$$|\psi\rangle = \prod \frac{1}{\sqrt{2}} \left(|g\rangle + |e\rangle\right)$$



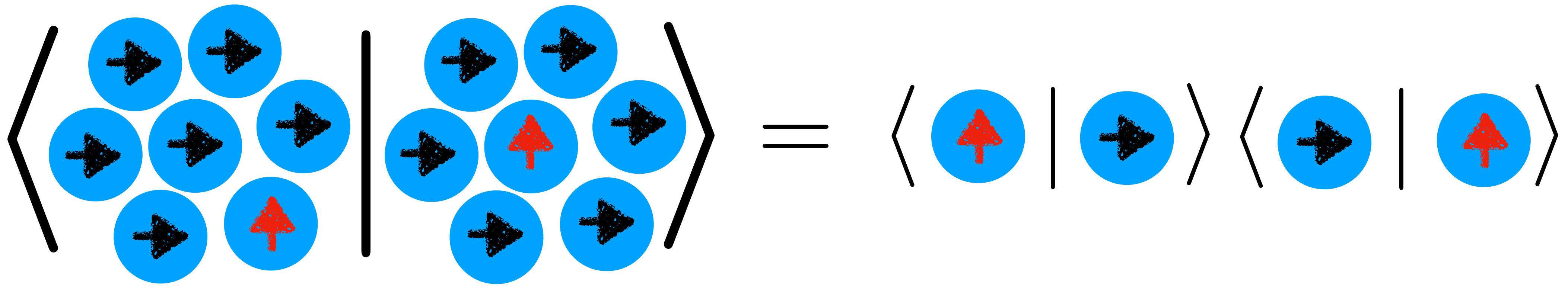
Coherence in Inelastic Processes



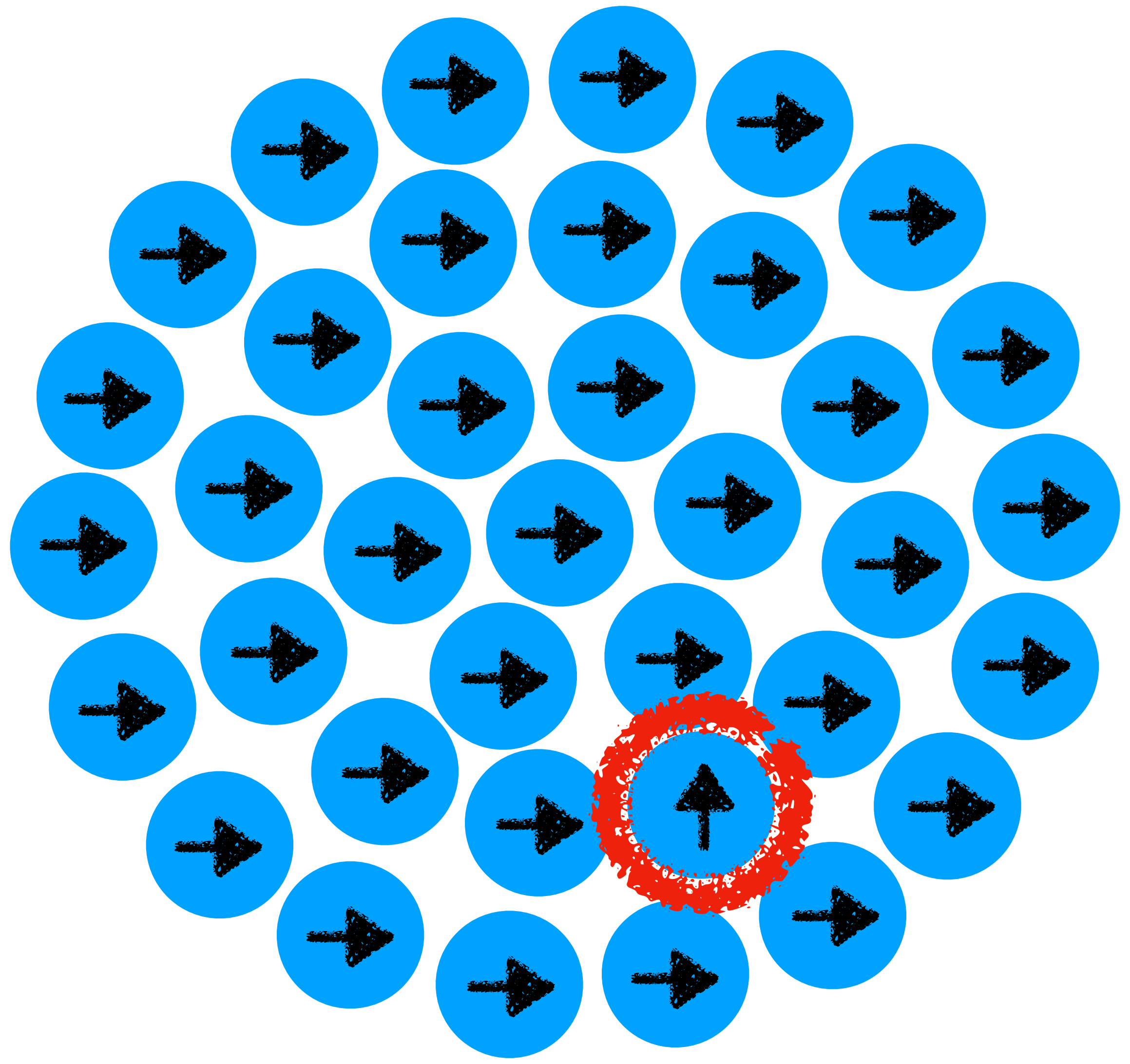
$\Gamma \sim$ 

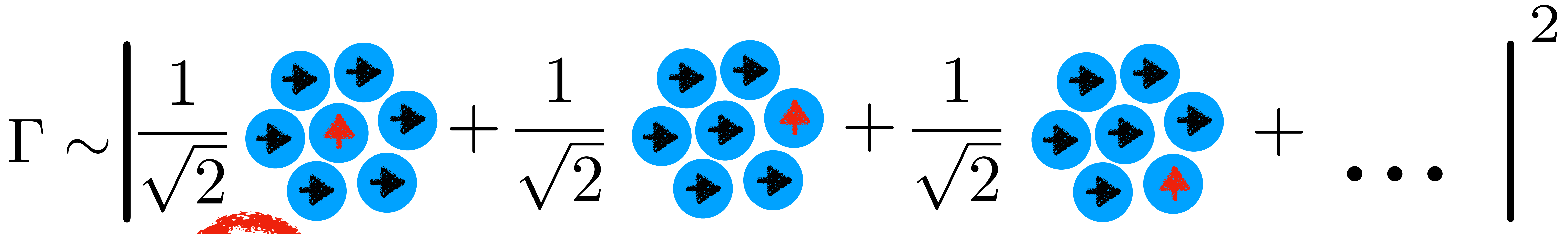
$$= \frac{N^2}{4}$$

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

 $= \frac{1}{2}$

Coherence in Inelastic Processes

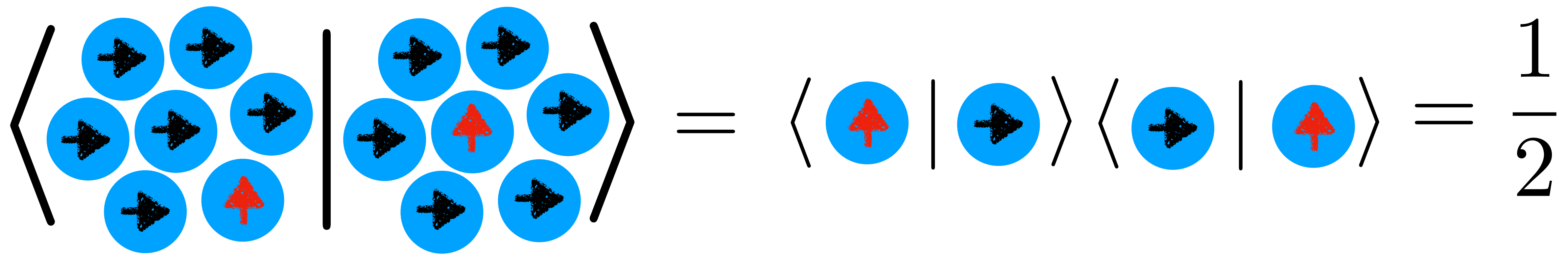




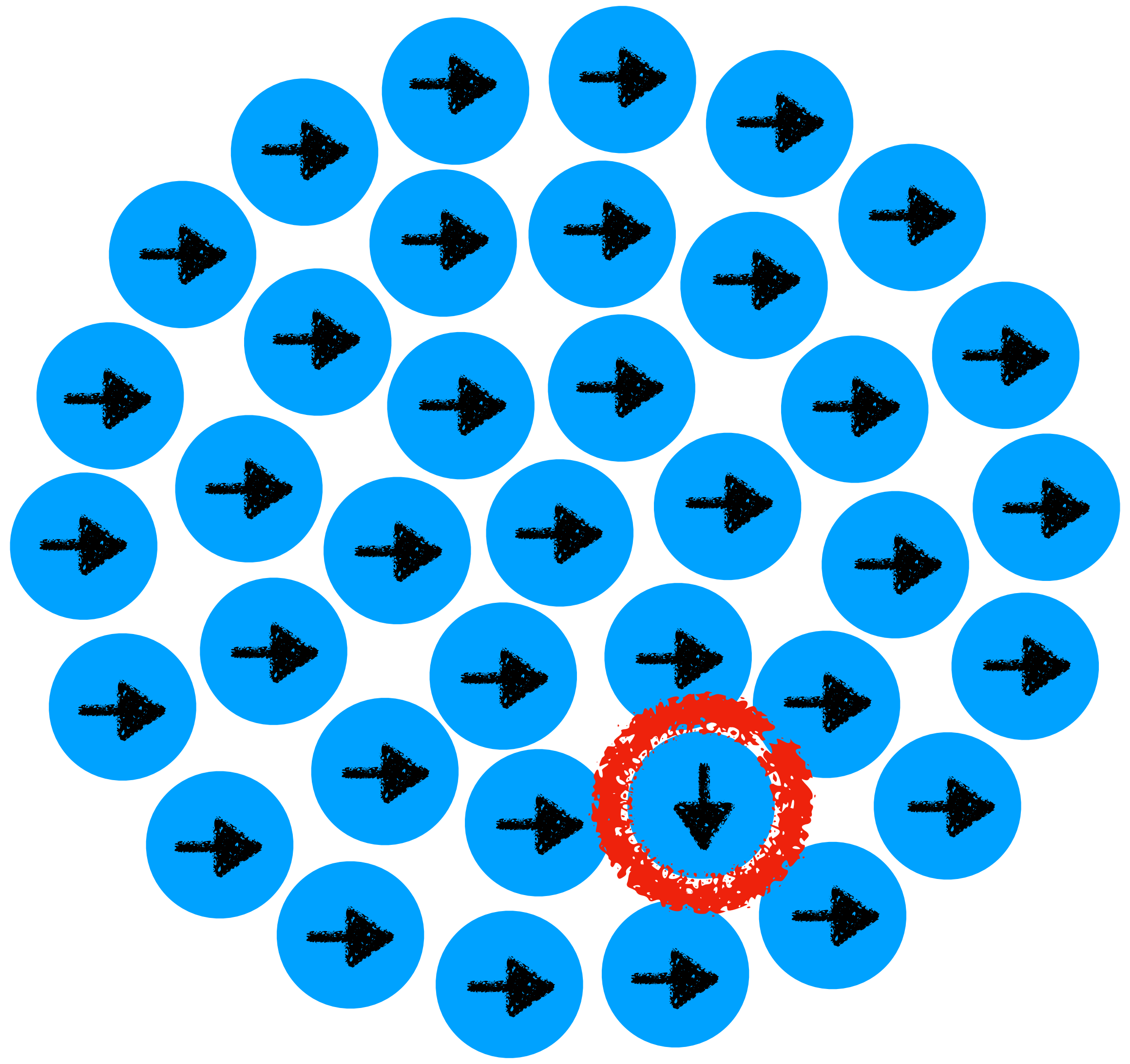
$$= \frac{N^2}{4}$$

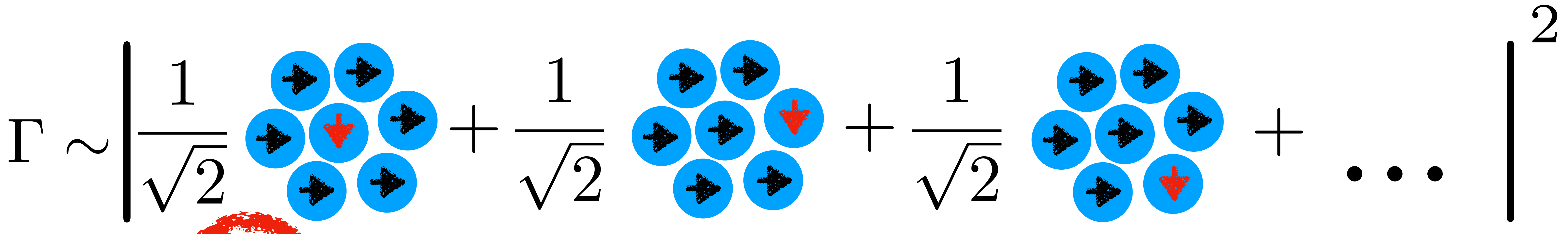
Coherent Excitation

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



Coherence in Inelastic Processes

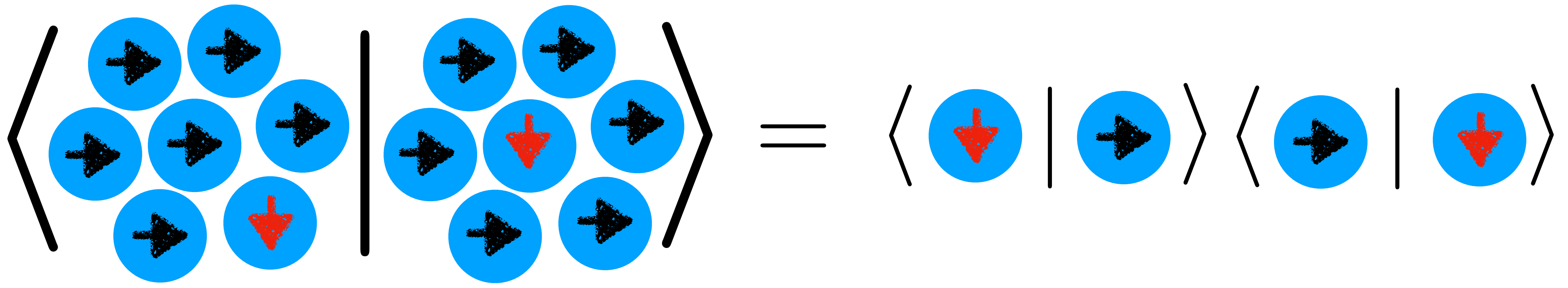




$$= \frac{N^2}{4}$$

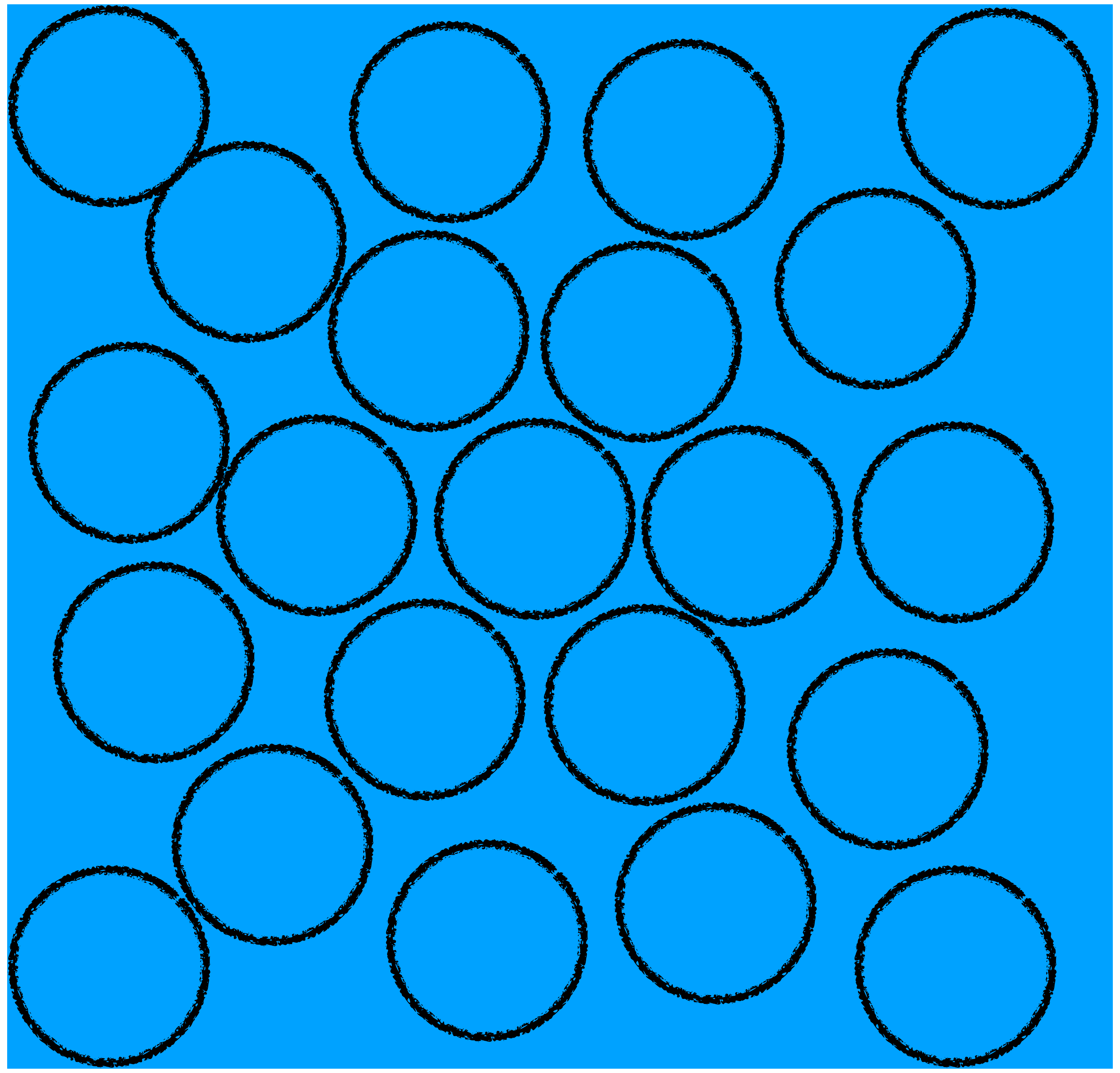
Coherent De-excitation

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

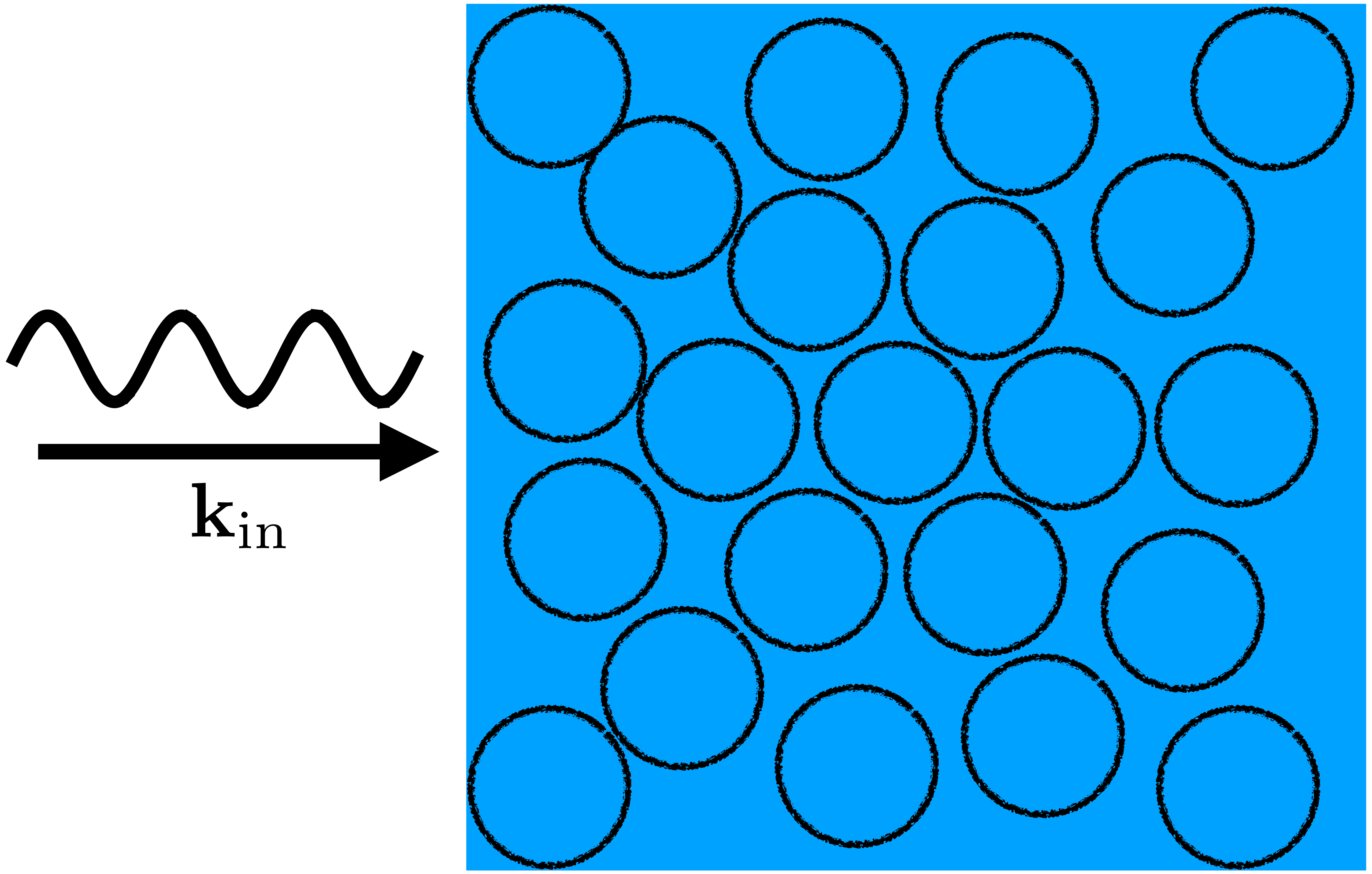


$$= \frac{1}{2}$$

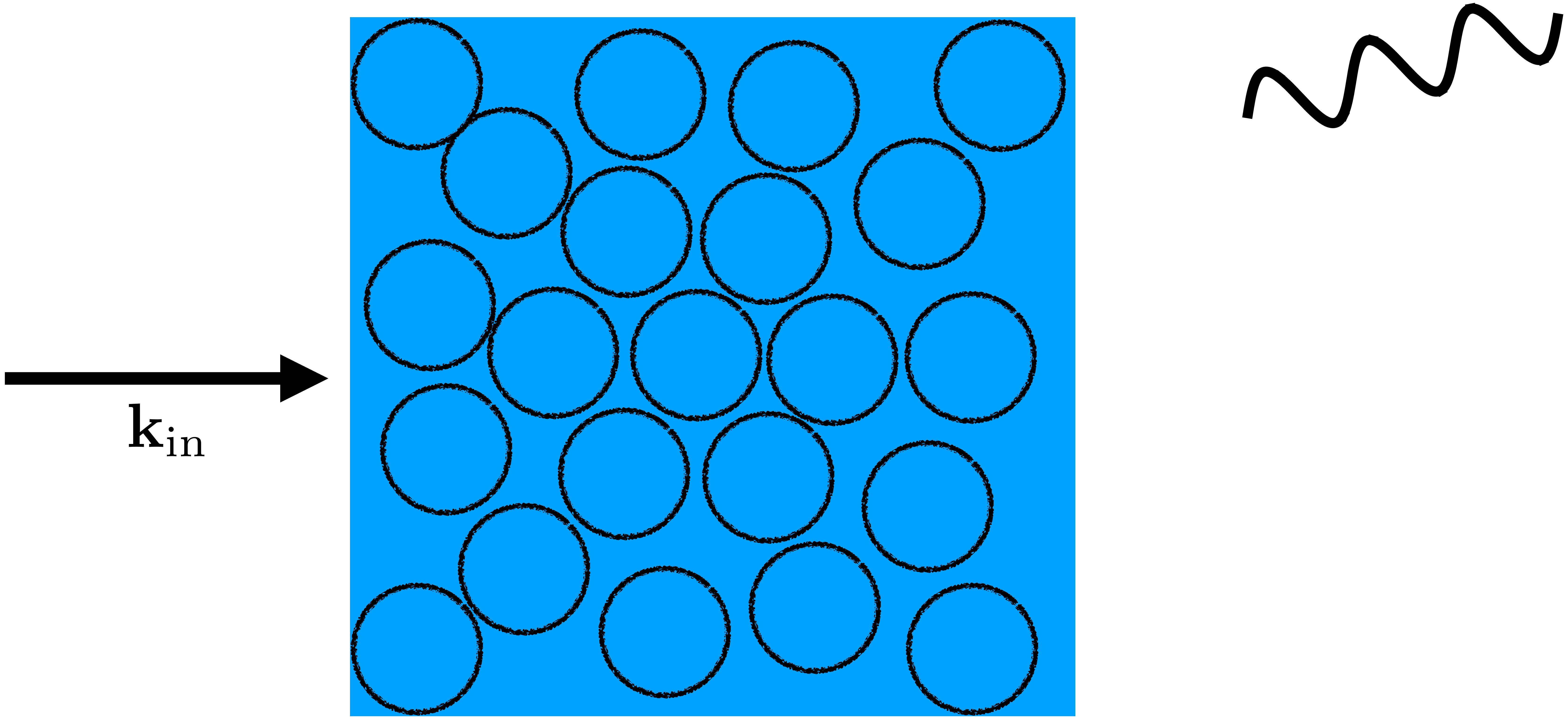
Another regime



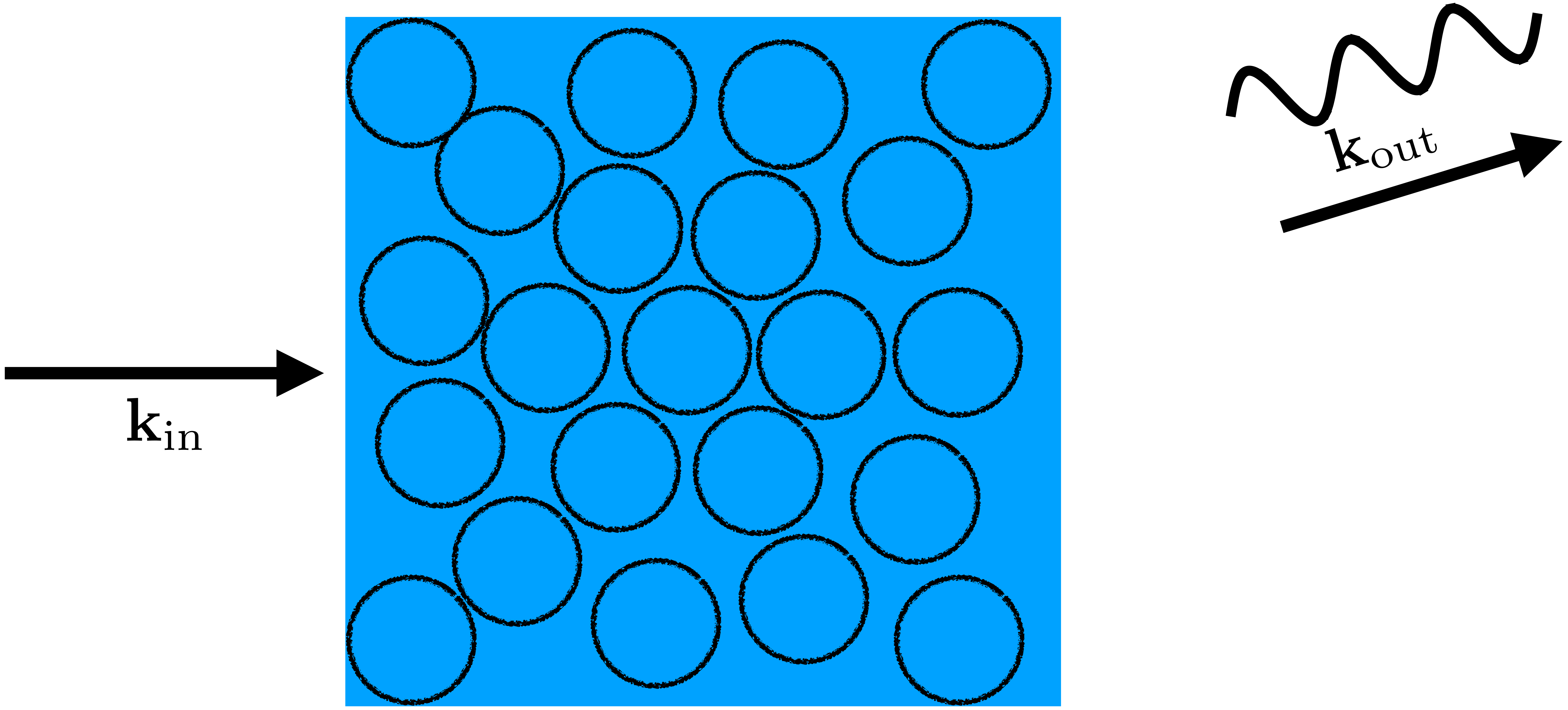
Another regime



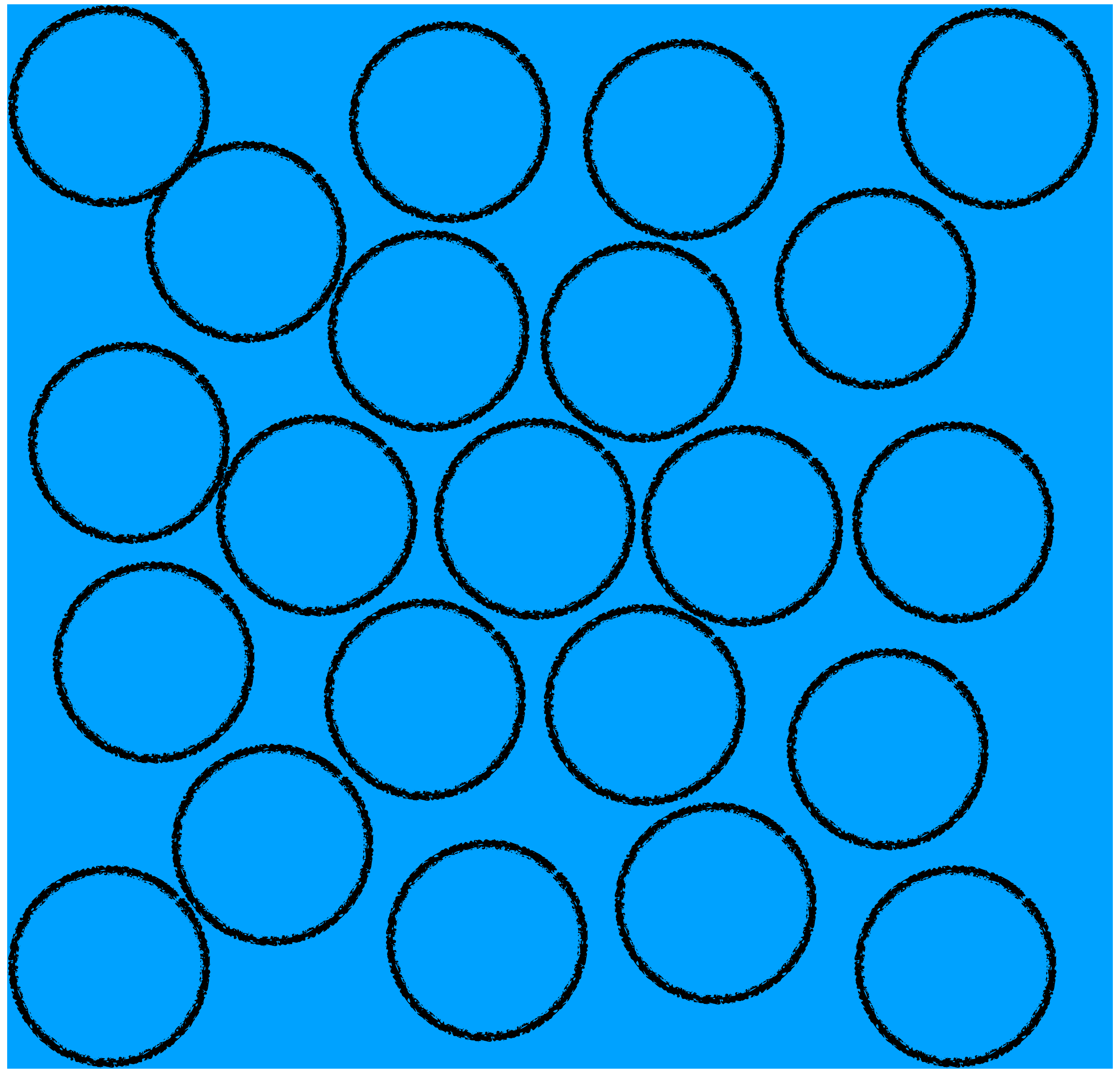
Another regime

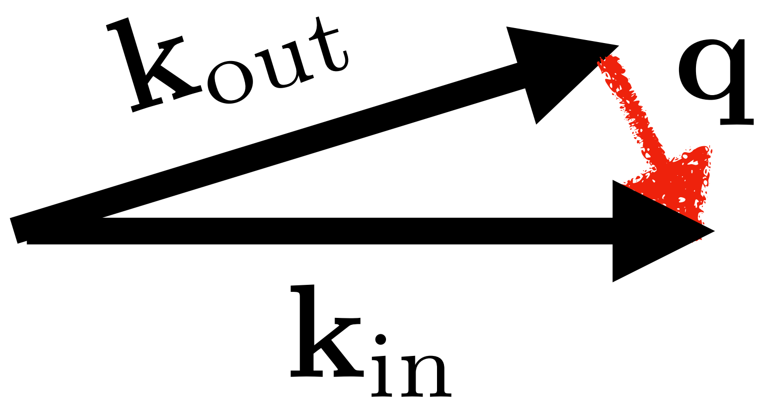


Another regime



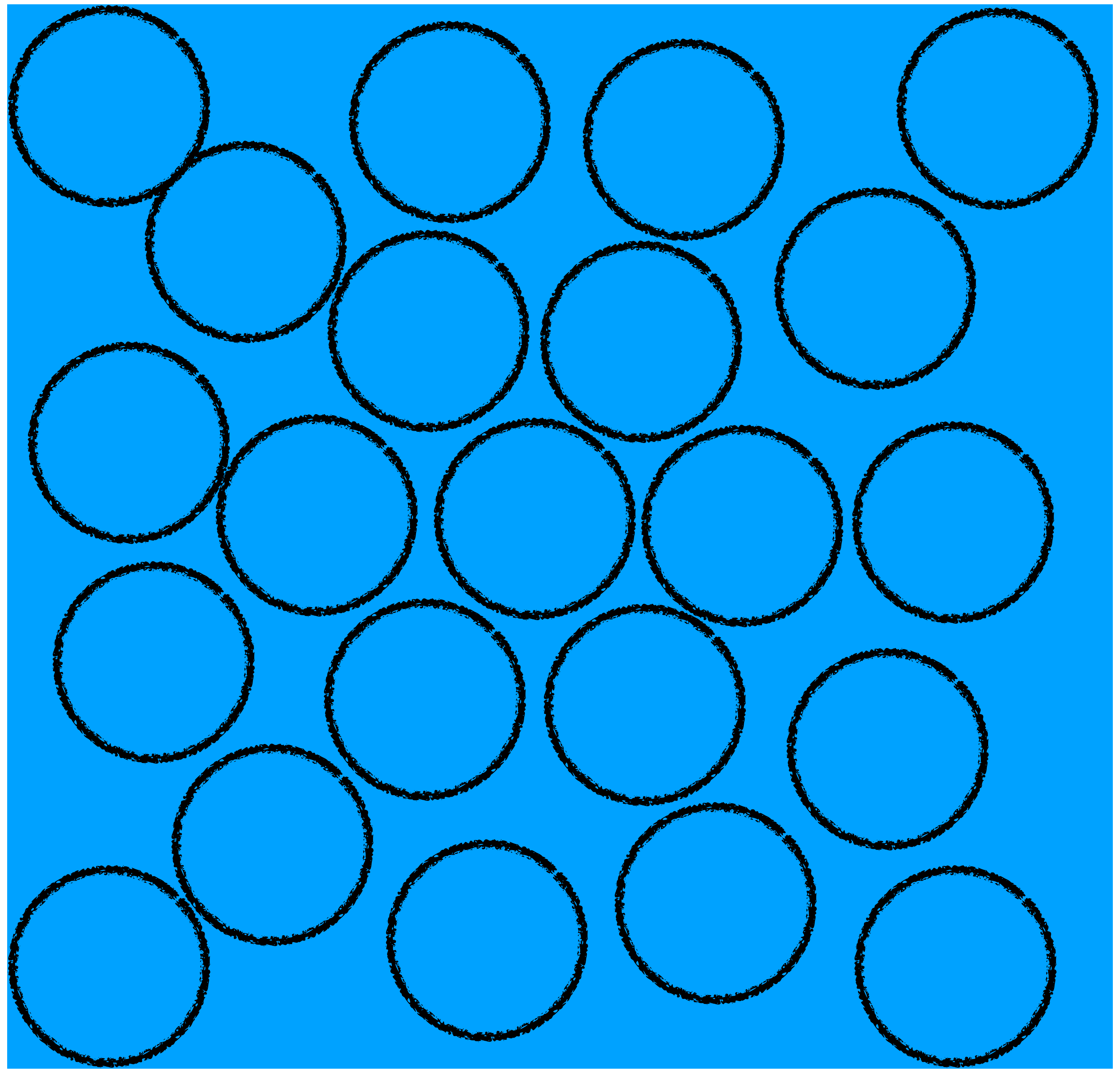
Another regime

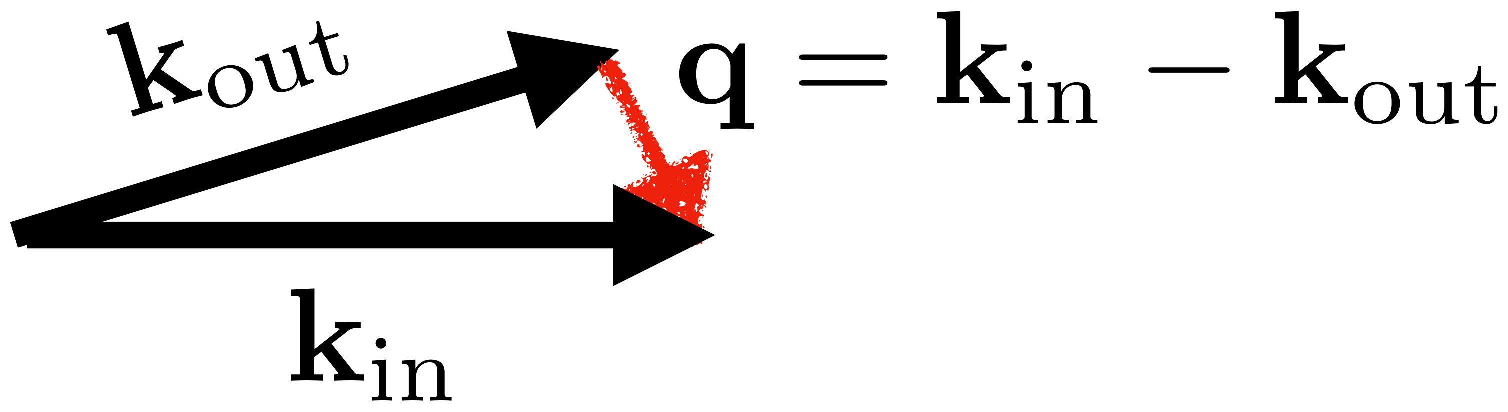




$$\mathbf{q} = \mathbf{k}_{\mathrm{in}} - \mathbf{k}_{\mathrm{out}}$$

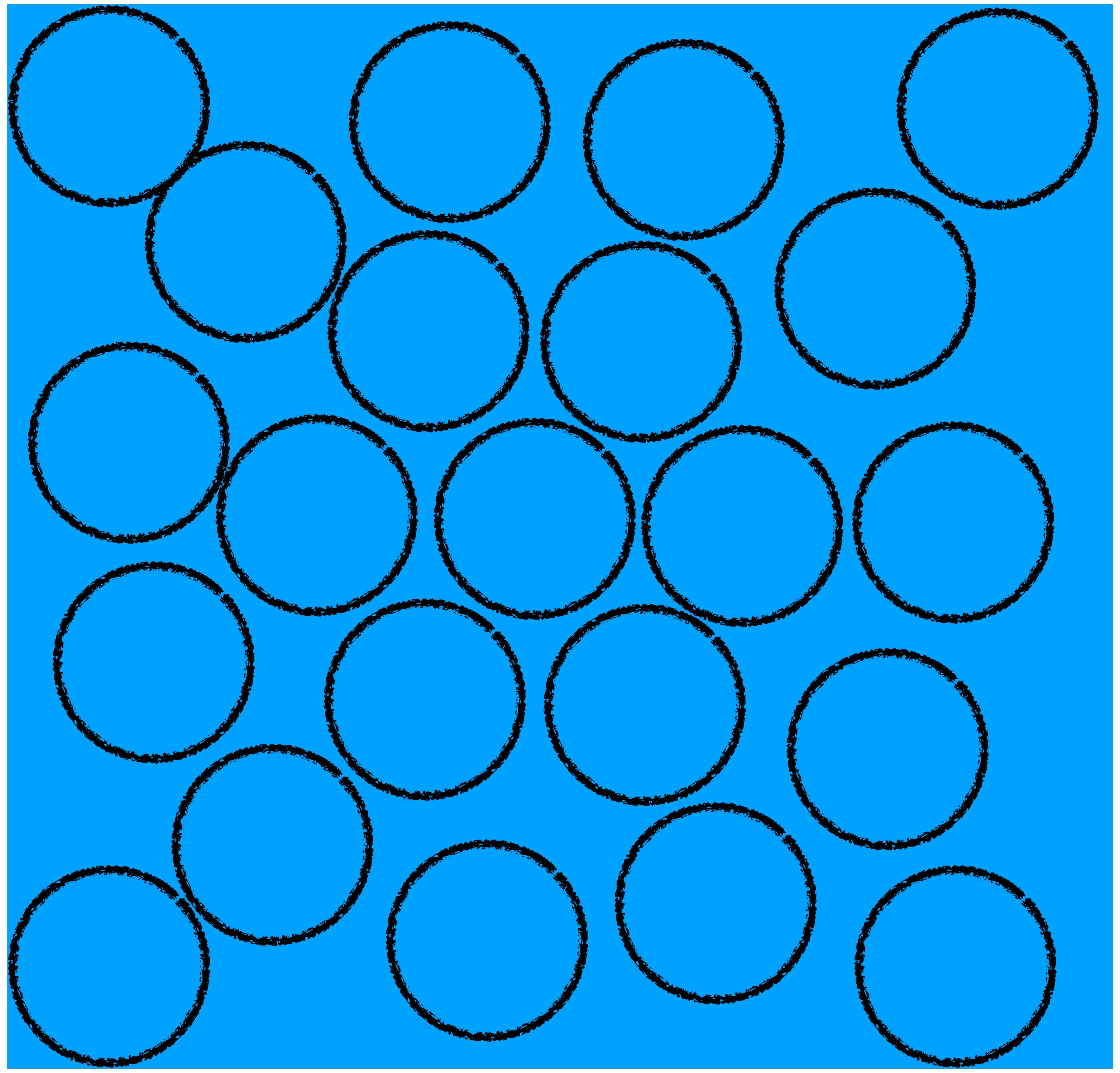
Another regime

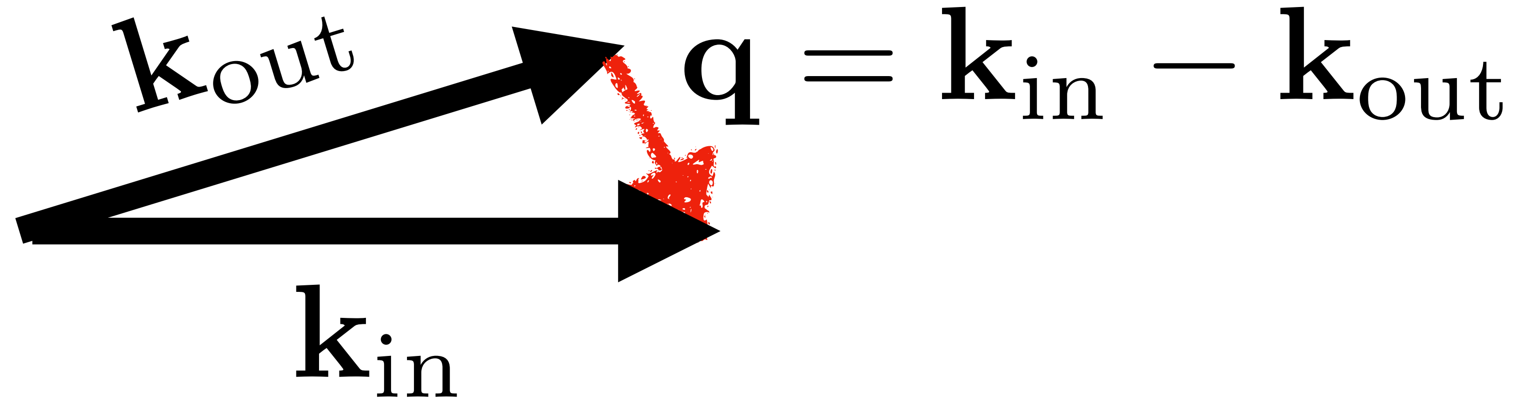




Coherence for a small dΩ around k_{in} for which $q \ll R^{-1}$

Another regime

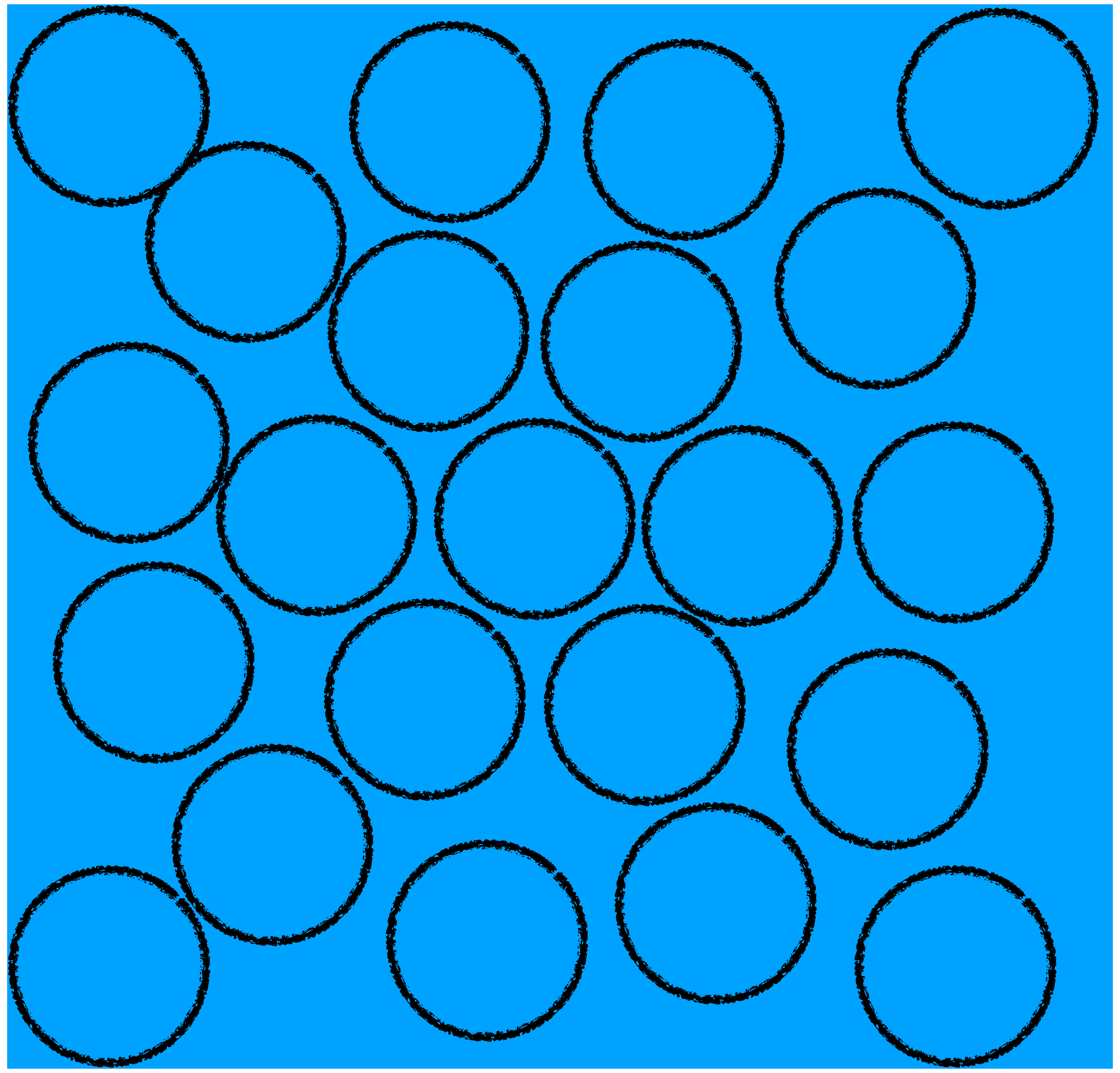




Coherence for a small dΩ around k_{in} for which $q \ll R^{-1}$

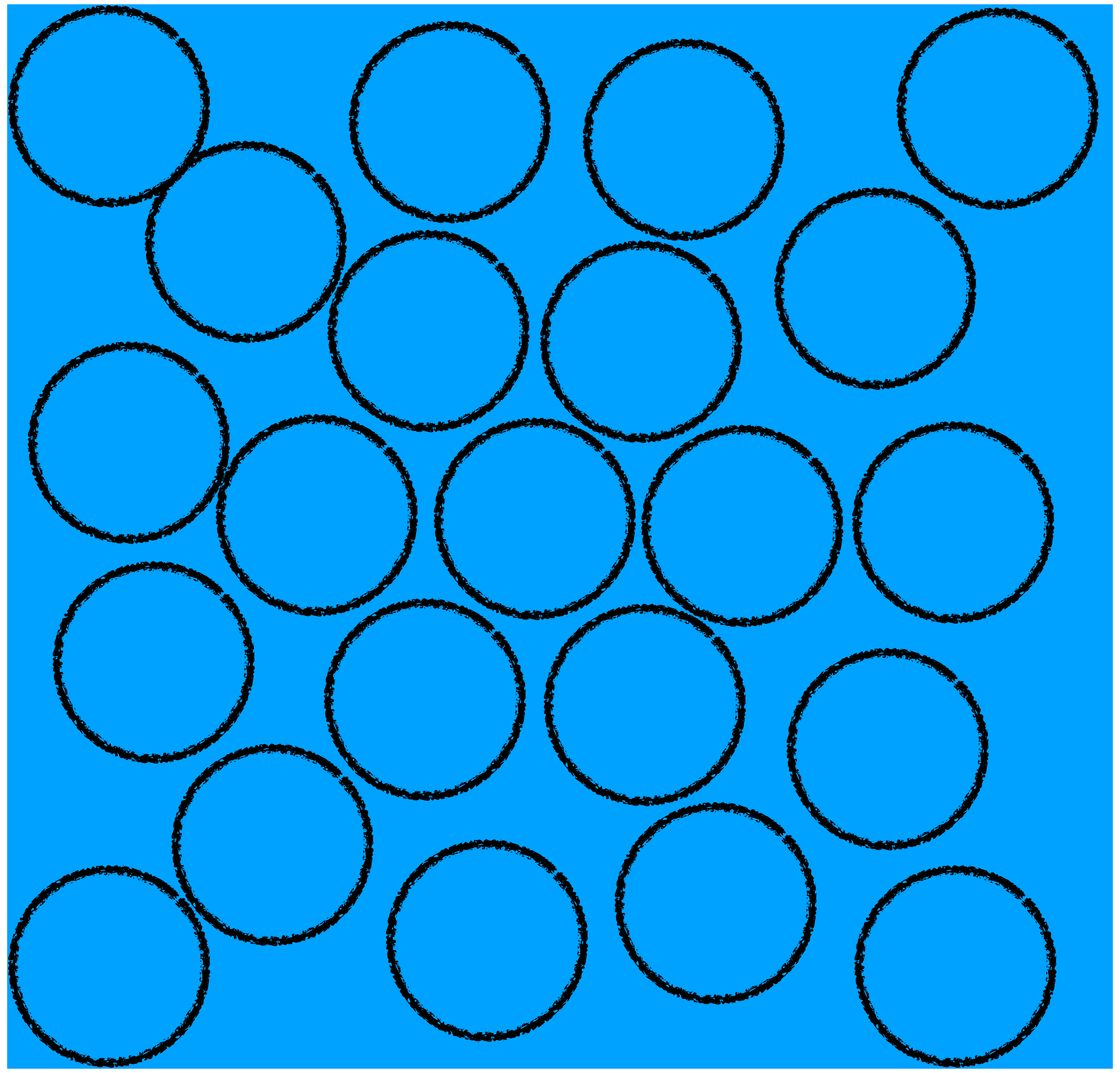
$$\Gamma \propto (nR^3)^2 \left(\frac{1}{kR}\right)^2 \sim n^2 \lambda^2 R^4$$

Another regime



$$k_{\rm out} = \left(k_{\rm in}^2 \pm 2m\omega_0\right)^{1/2}$$

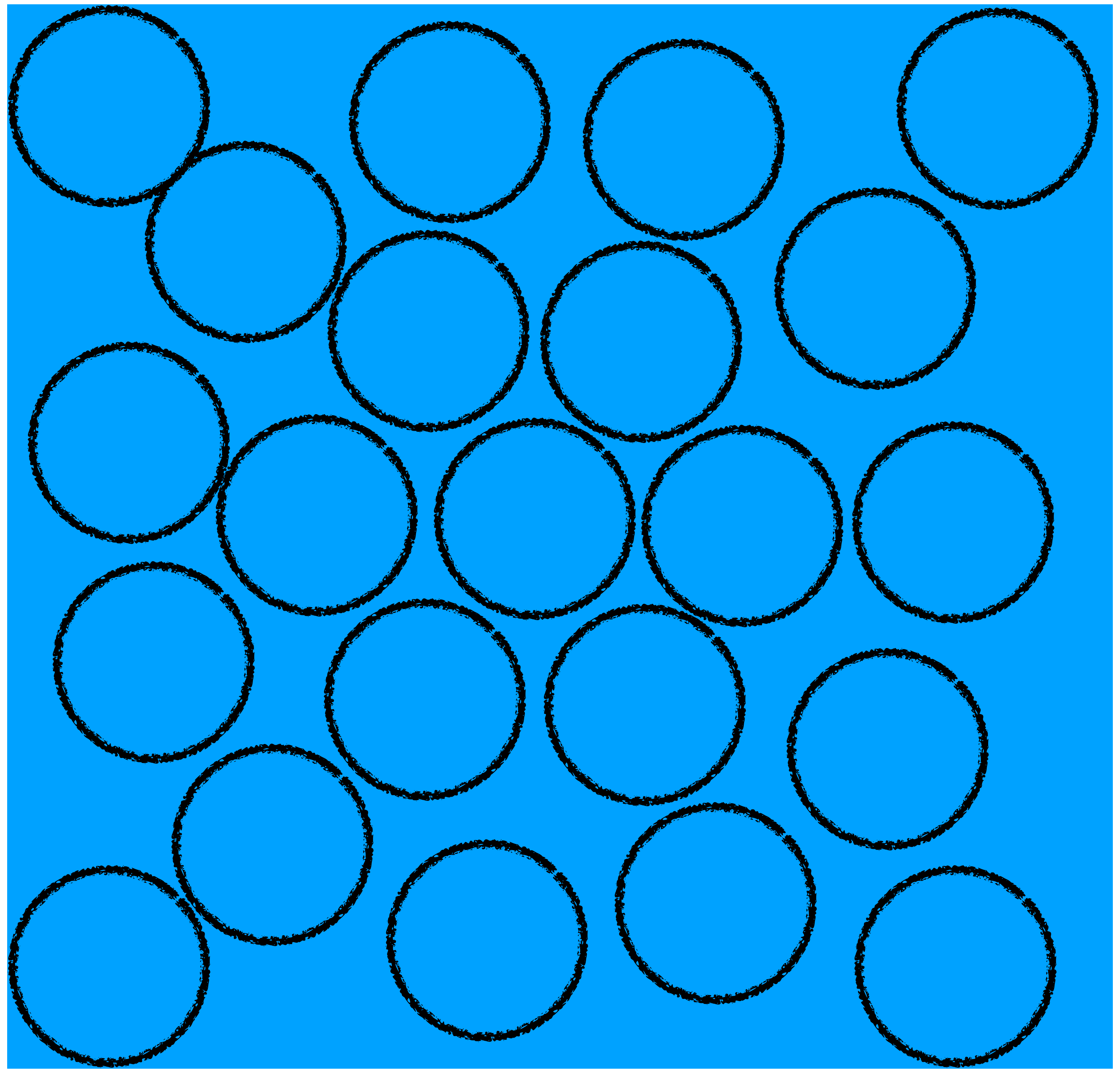
Another regime



$$k_{\text{out}} = \left(k_{\text{in}}^2 \pm 2m\omega_0\right)^{1/2}$$

$$q \gtrsim \omega_0 / v_{\text{in}}$$

Another regime

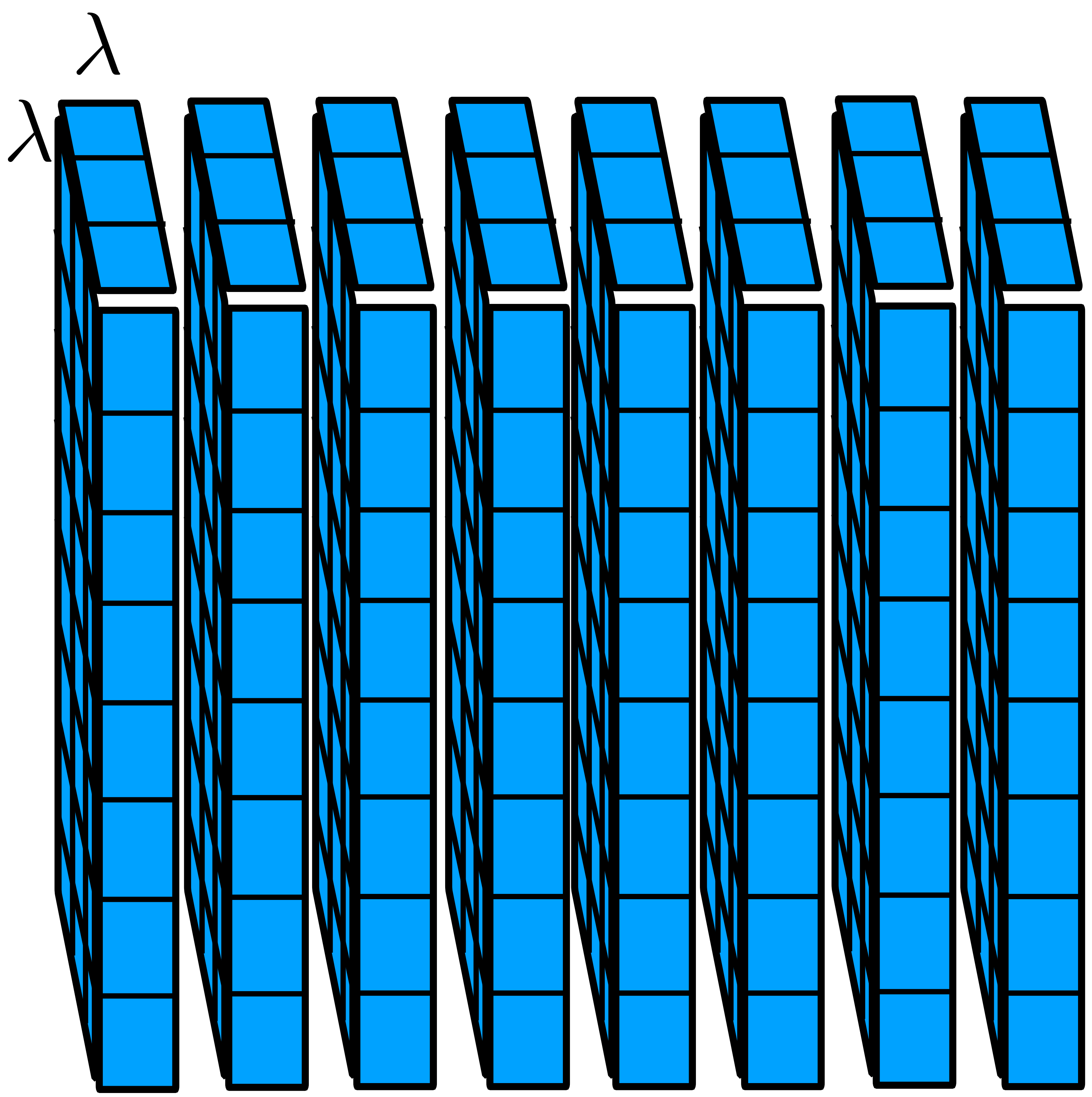


$$k_{\rm out} = \left(k_{\rm in}^2 \pm 2m\omega_0\right)^{1/2}$$

$$q \gtrsim \omega_0 / v_{\rm in}$$

$$\omega_0 \lesssim \frac{v_{\rm in}}{R}$$

Another regime

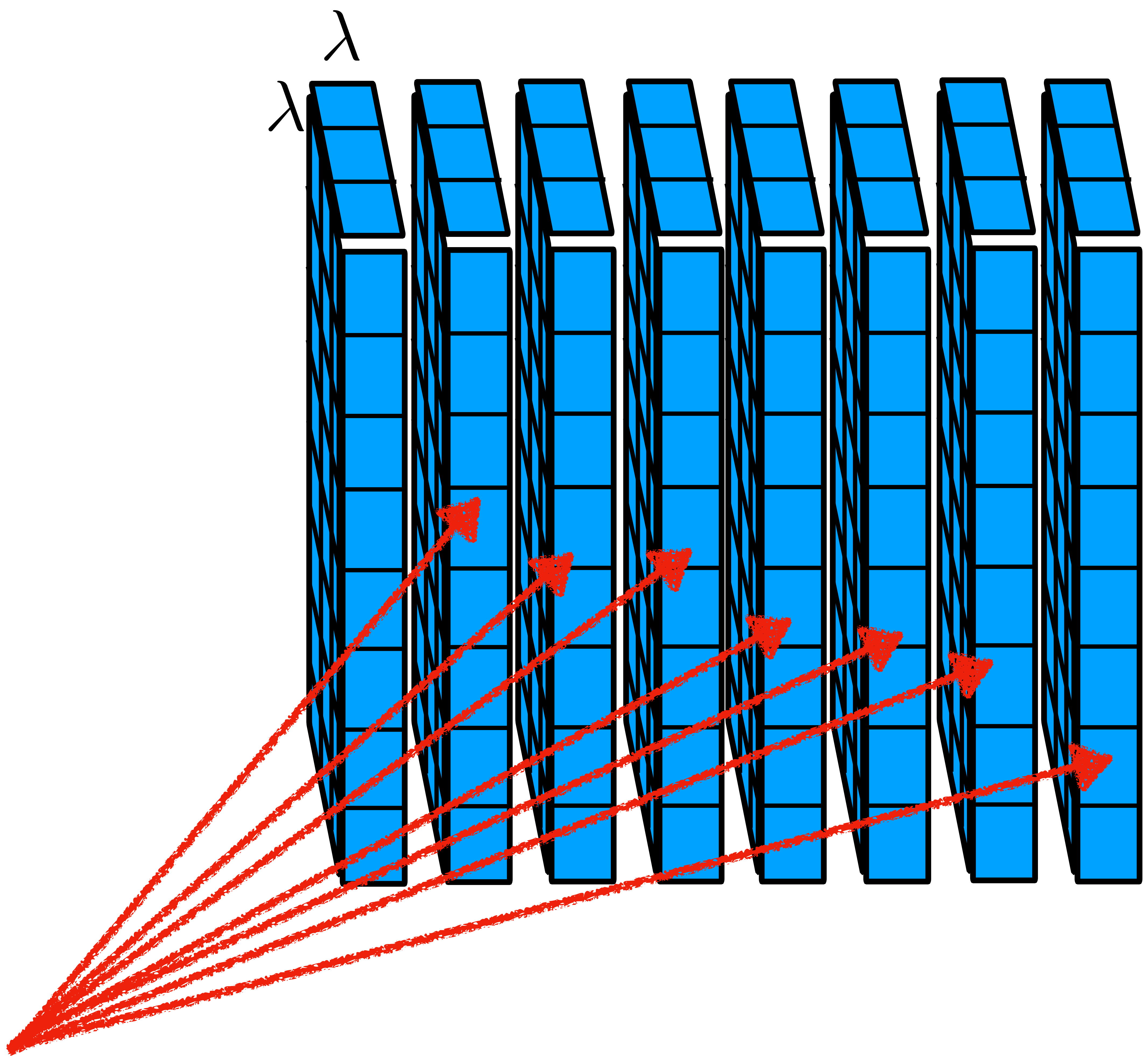


$$k_{\text{out}} = \left(k_{\text{in}}^2 \pm 2m\omega_0\right)^{1/2}$$

$$q \gtrsim \omega_0 / v_{\text{in}}$$

$$\omega_0 \lesssim \frac{v_{\text{in}}}{R}$$

Another regime



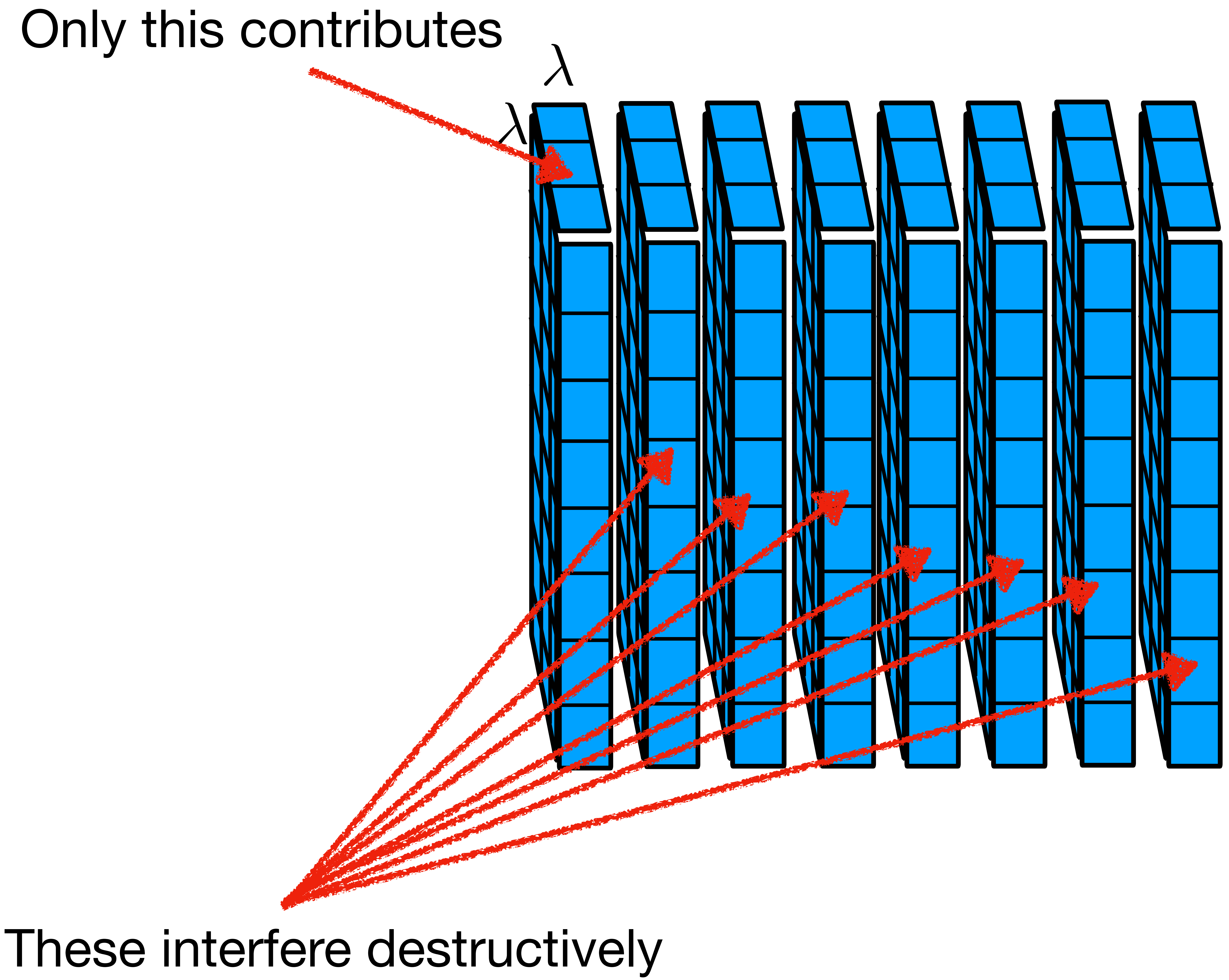
$$k_{\rm out} = \left(k_{\rm in}^2 \pm 2m\omega_0\right)^{1/2}$$

$$q \gtrsim \omega_0 / v_{\rm in}$$

$$\omega_0 \lesssim \frac{v_{\rm in}}{R}$$

These interfere destructively

Another regime

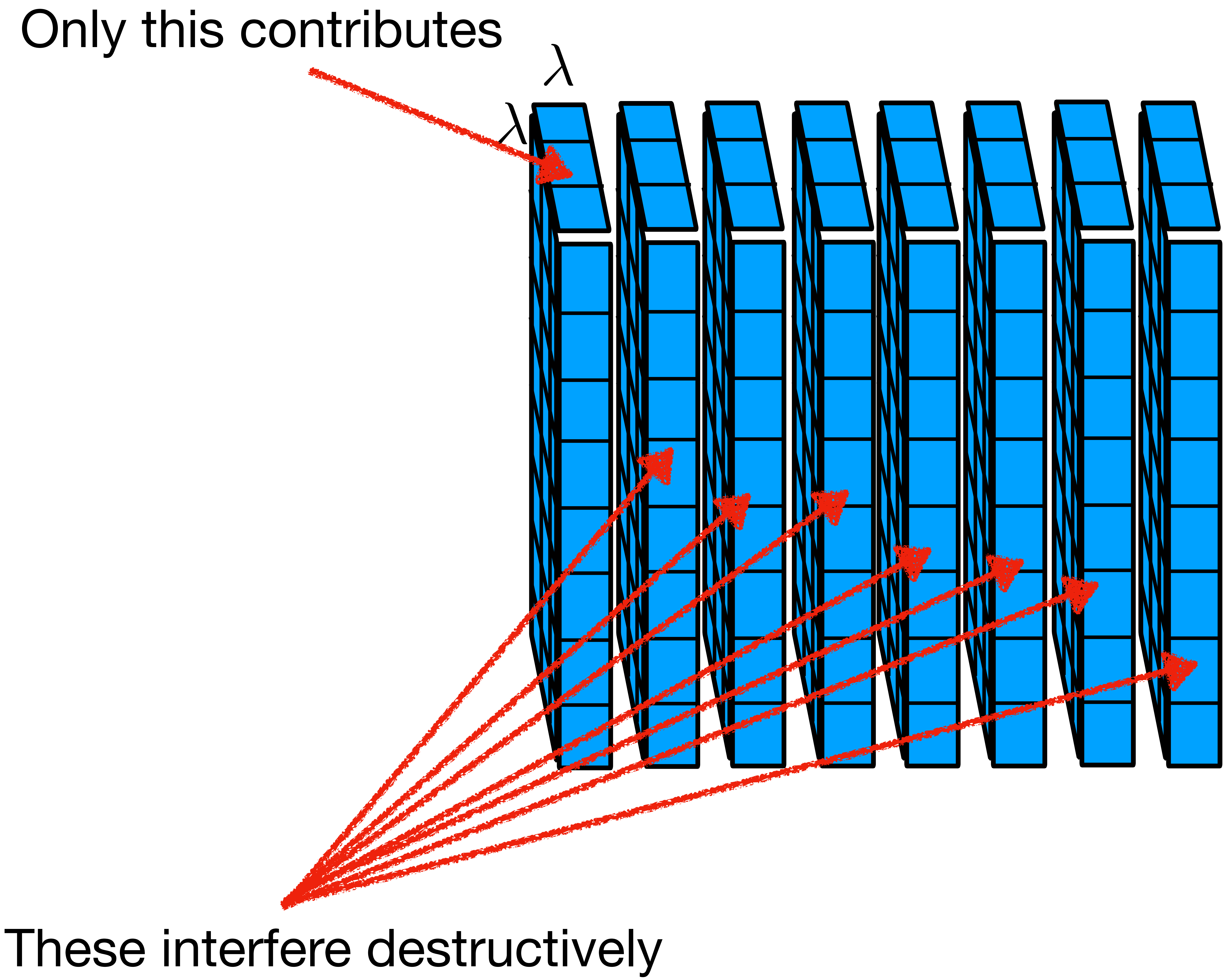


$$k_{\text{out}} = \left(k_{\text{in}}^2 \pm 2m\omega_0\right)^{1/2}$$

$$q \gtrsim \omega_0 / v_{\text{in}}$$

$$\omega_0 \lesssim \frac{v_{\text{in}}}{R}$$

Another regime



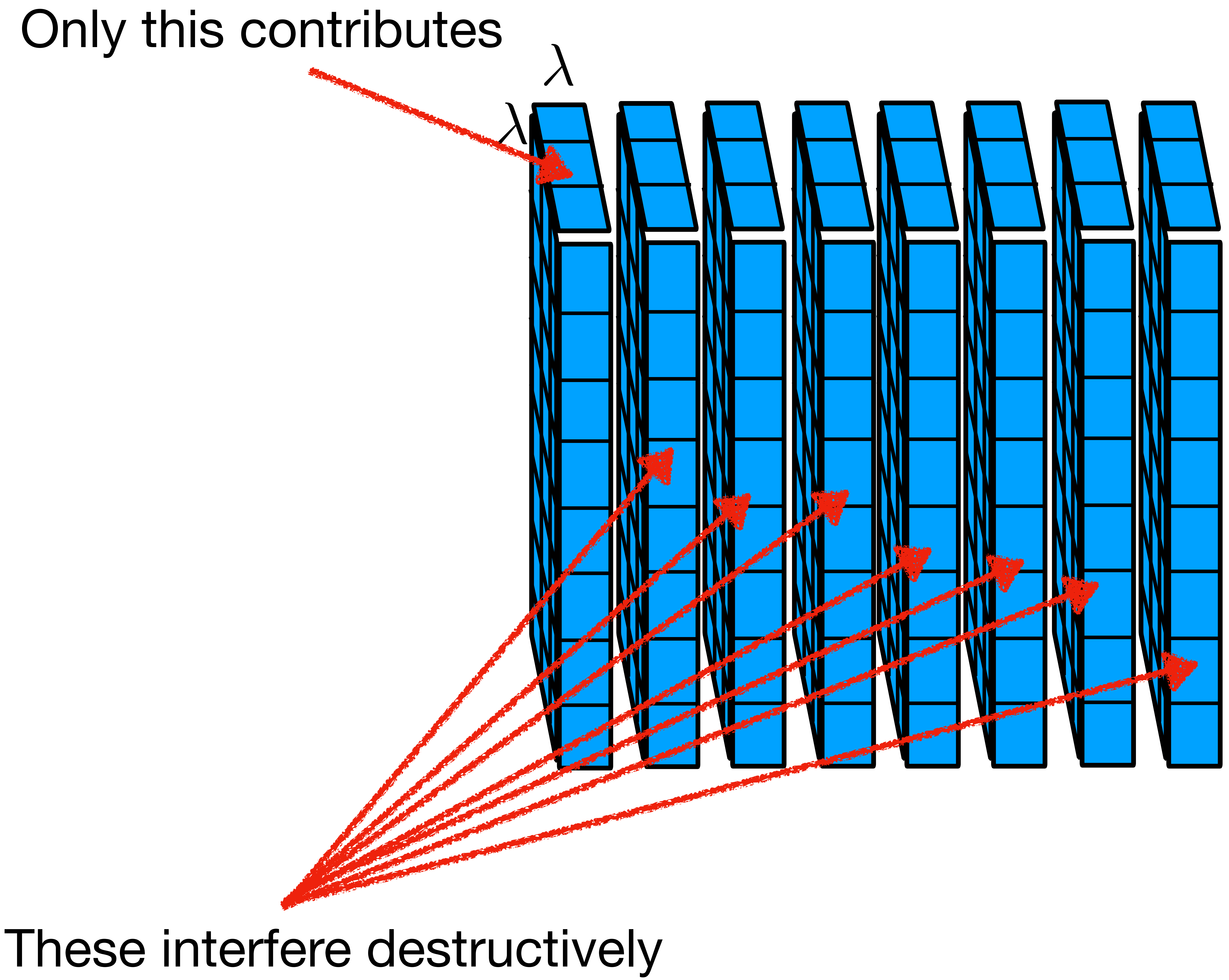
$$k_{\text{out}} = \left(k_{\text{in}}^2 \pm 2m\omega_0\right)^{1/2}$$

$$q \gtrsim \omega_0 / v_{\text{in}}$$

$$\omega_0 \lesssim \frac{v_{\text{in}}}{R}$$

$$\lambda \ll R: \quad \Gamma \propto n^2 \lambda^6 \frac{R^2}{\lambda^2} \sim n^2 \lambda^4 R^2$$

Another regime



$$k_{\rm out} = \left(k_{\rm in}^2 \pm 2m\omega_0\right)^{1/2}$$

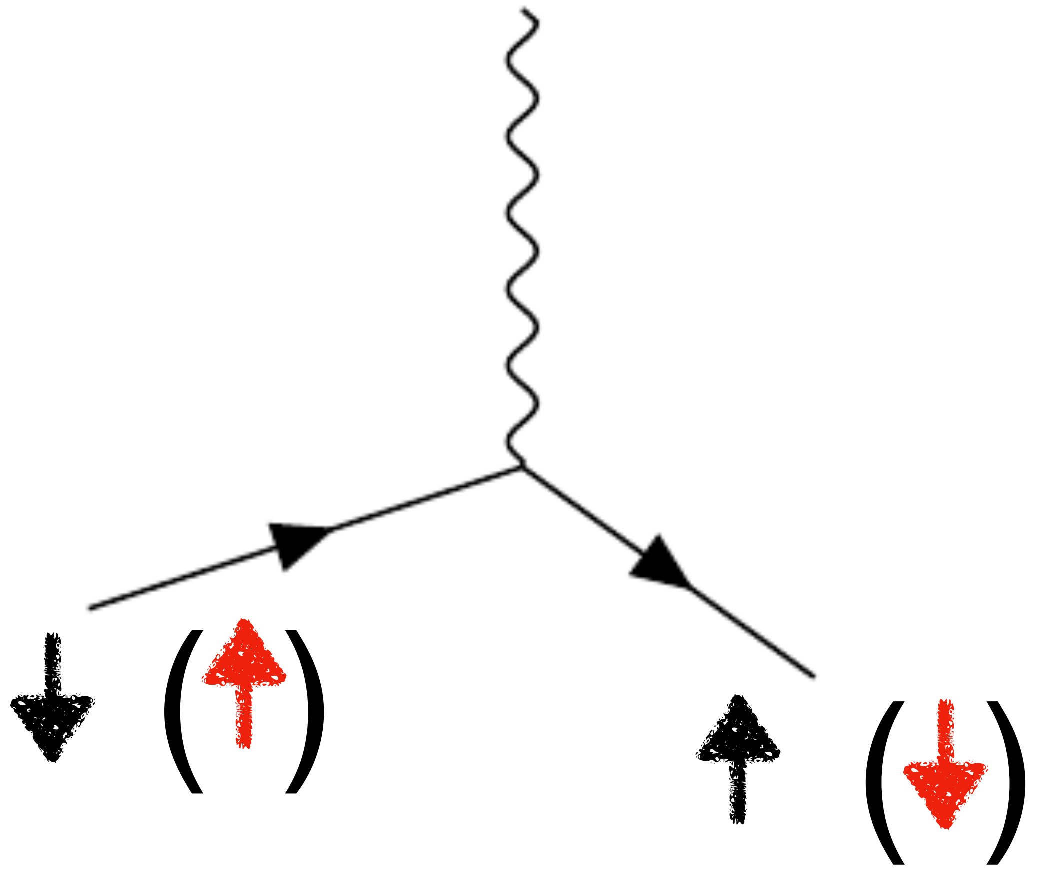
$$q \gtrsim \omega_0/v_{\rm in}$$

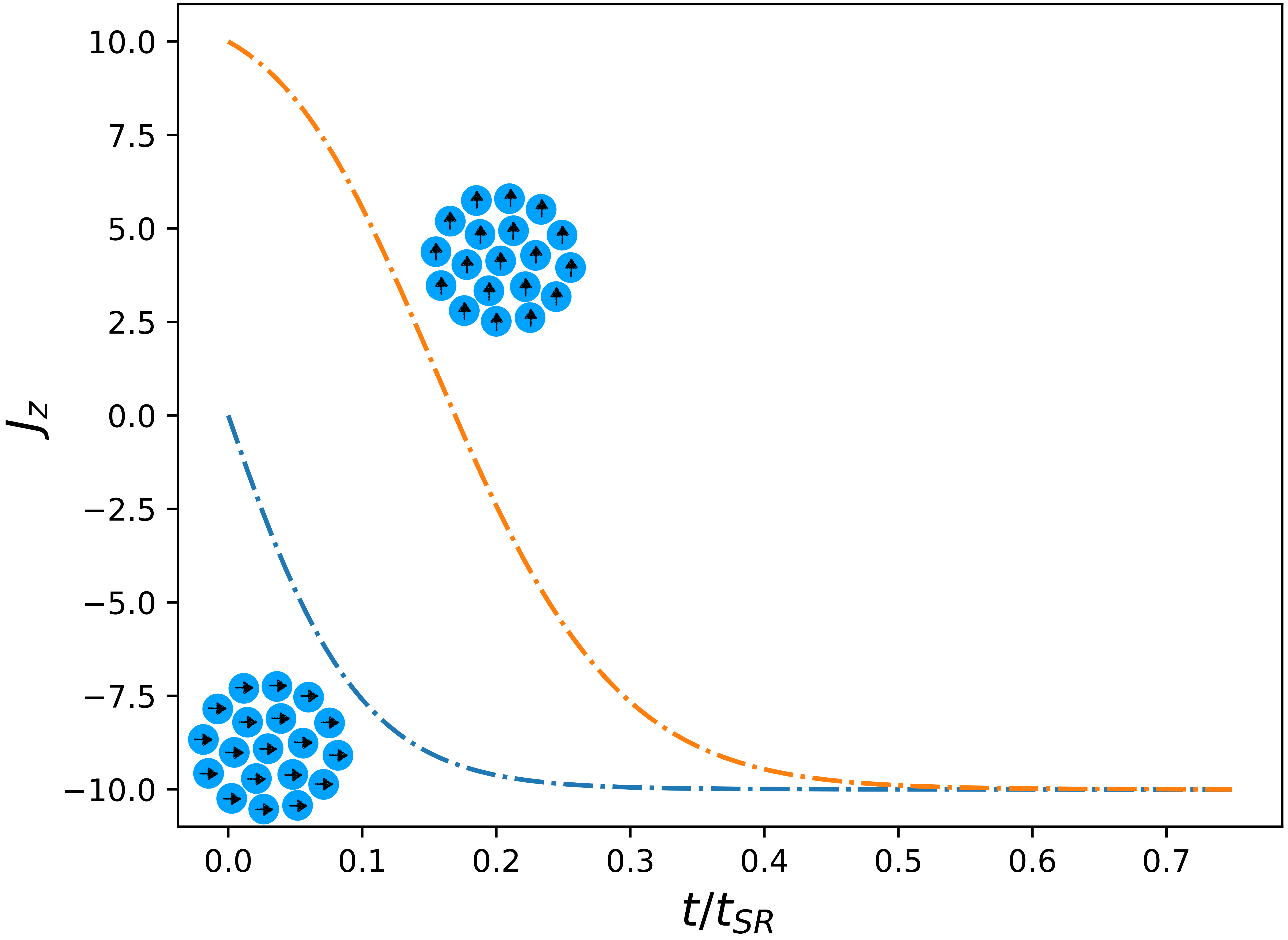
$$\omega_0 \lesssim \frac{v_{\rm in}}{R}$$

$$\lambda \ll R: \quad \Gamma \propto n^2\lambda^6\frac{R^2}{\lambda^2} \sim n^2\lambda^4R^2$$

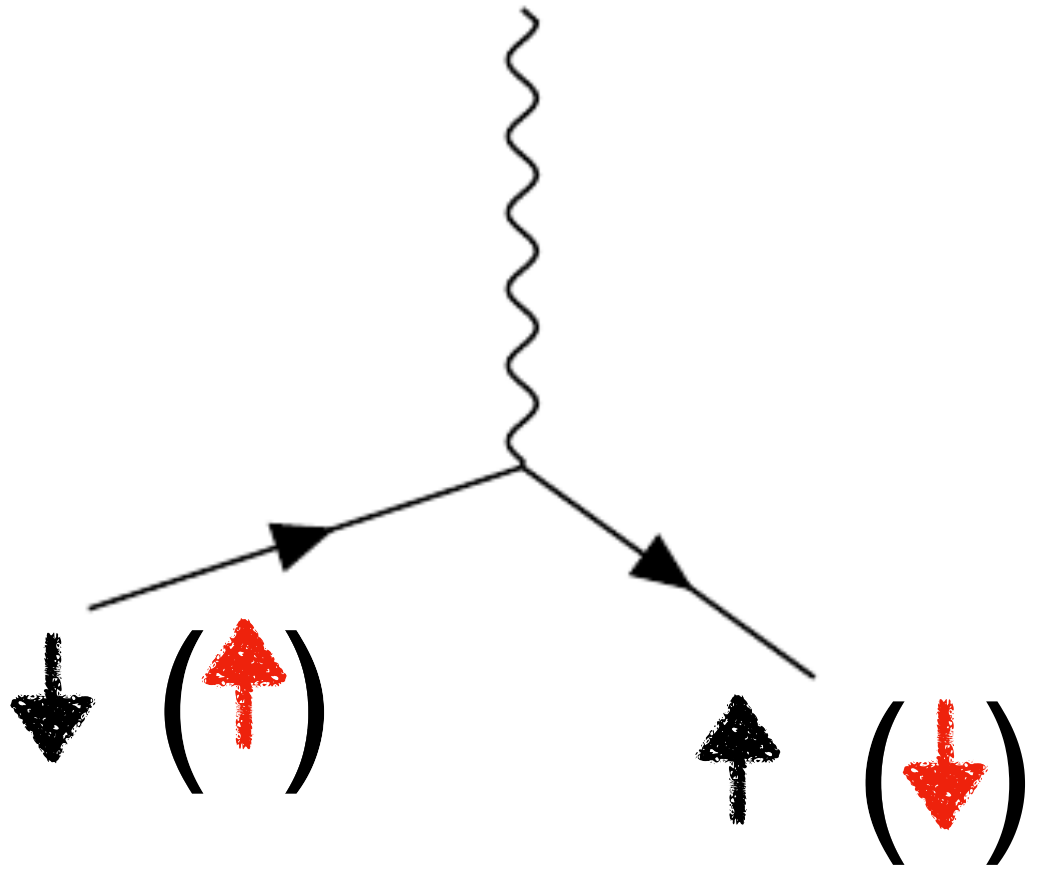
Incoherent contribution: $\Gamma \propto nR^3$

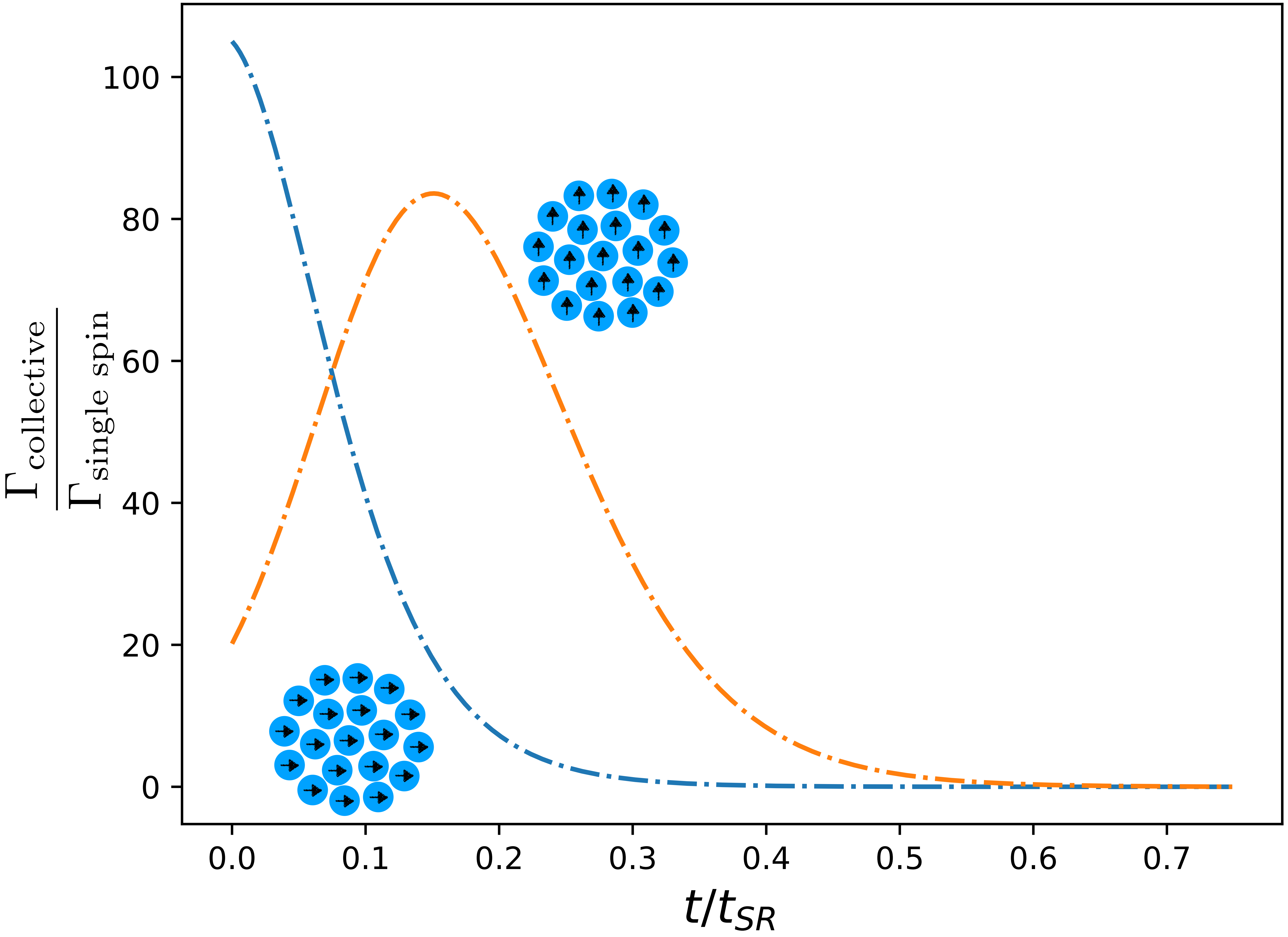
Dicke superradiance



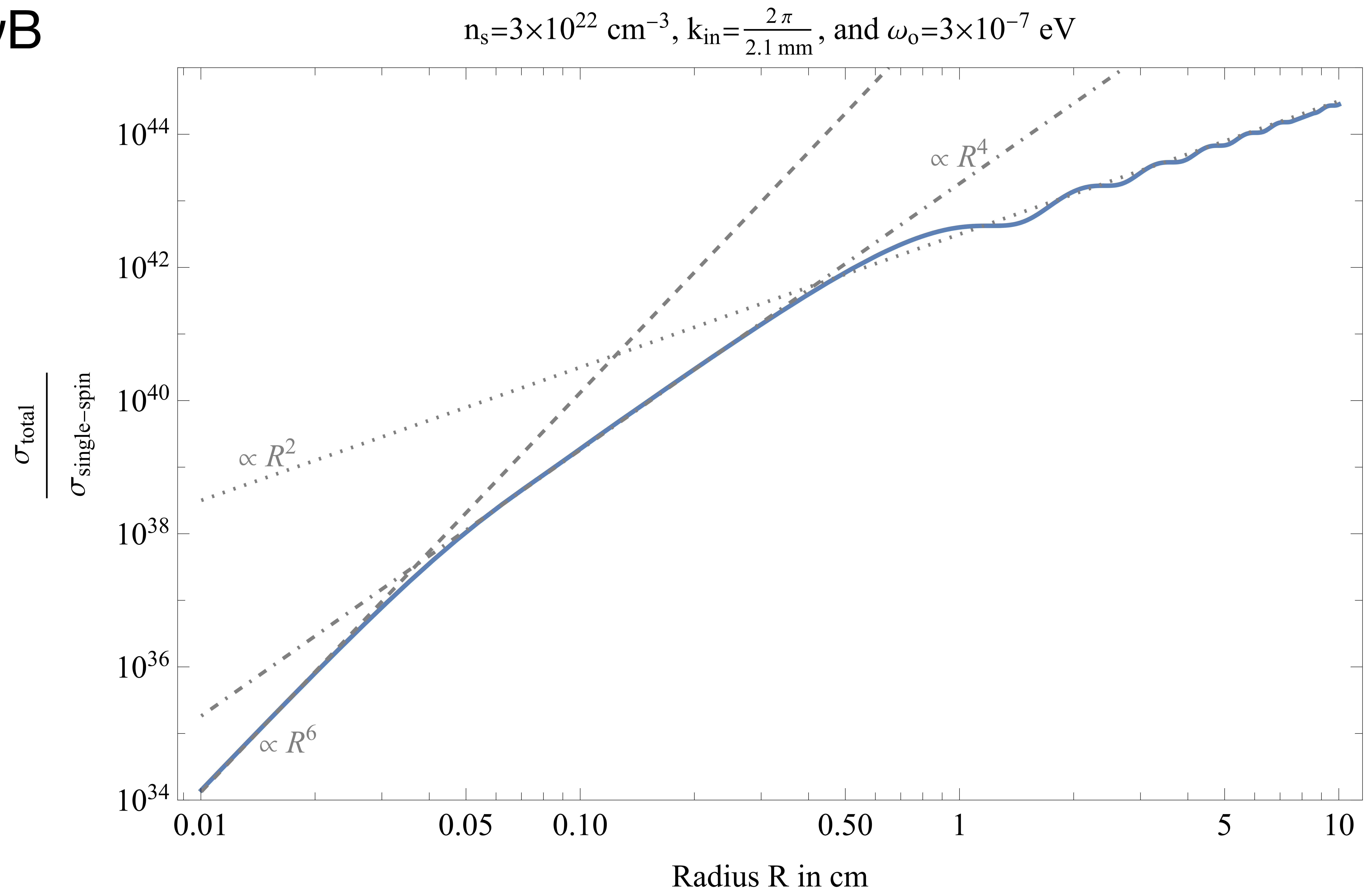


Dicke superradiance



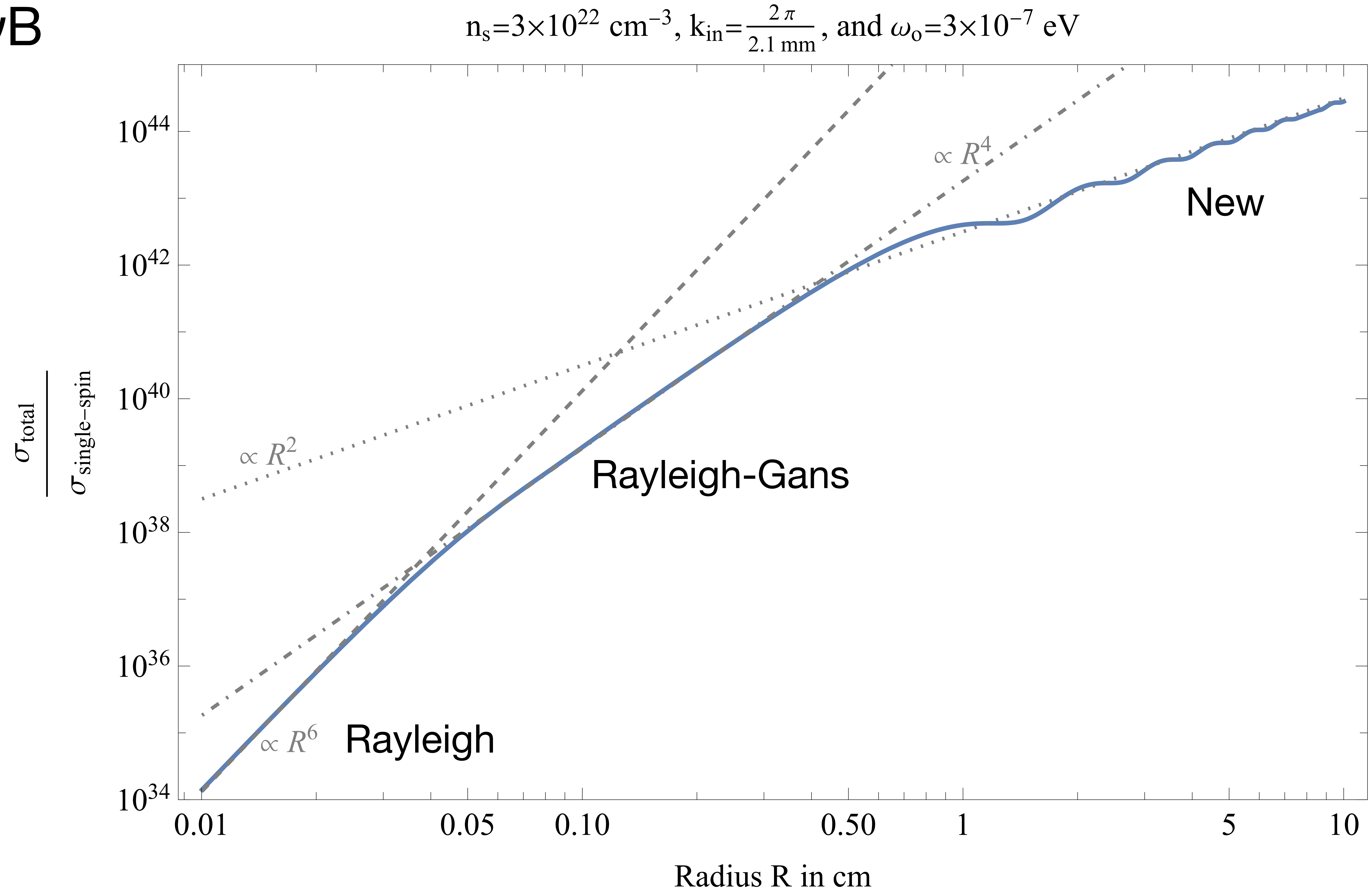


CvB



$n_s = 3\times10^{22}$ cm^{-3}, $k_{in} = \frac{2\pi}{2.1\text{ mm}}$, and $\omega_o = 3\times10^{-7}$ eV
$\frac{\sigma_{total}}{\sigma_{single-spin}}$
$\propto R^2$
$\propto R^4$
$\propto R^6$
10^{34}
10^{36}
10^{38}
10^{40}
10^{42}
10^{44}
0.01
0.05
0.10
0.50
1
5
10
Radius R in cm

CvB



n_s=3×10^{22} cm^{-3}, $k_{in}=\frac{2\pi}{2.1\text{ mm}}$, and ω_o=3×10^{-7} eV
$\frac{\sigma_{total}}{\sigma_{single-spin}}$
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10^{42}
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10^{34}
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New
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Summary

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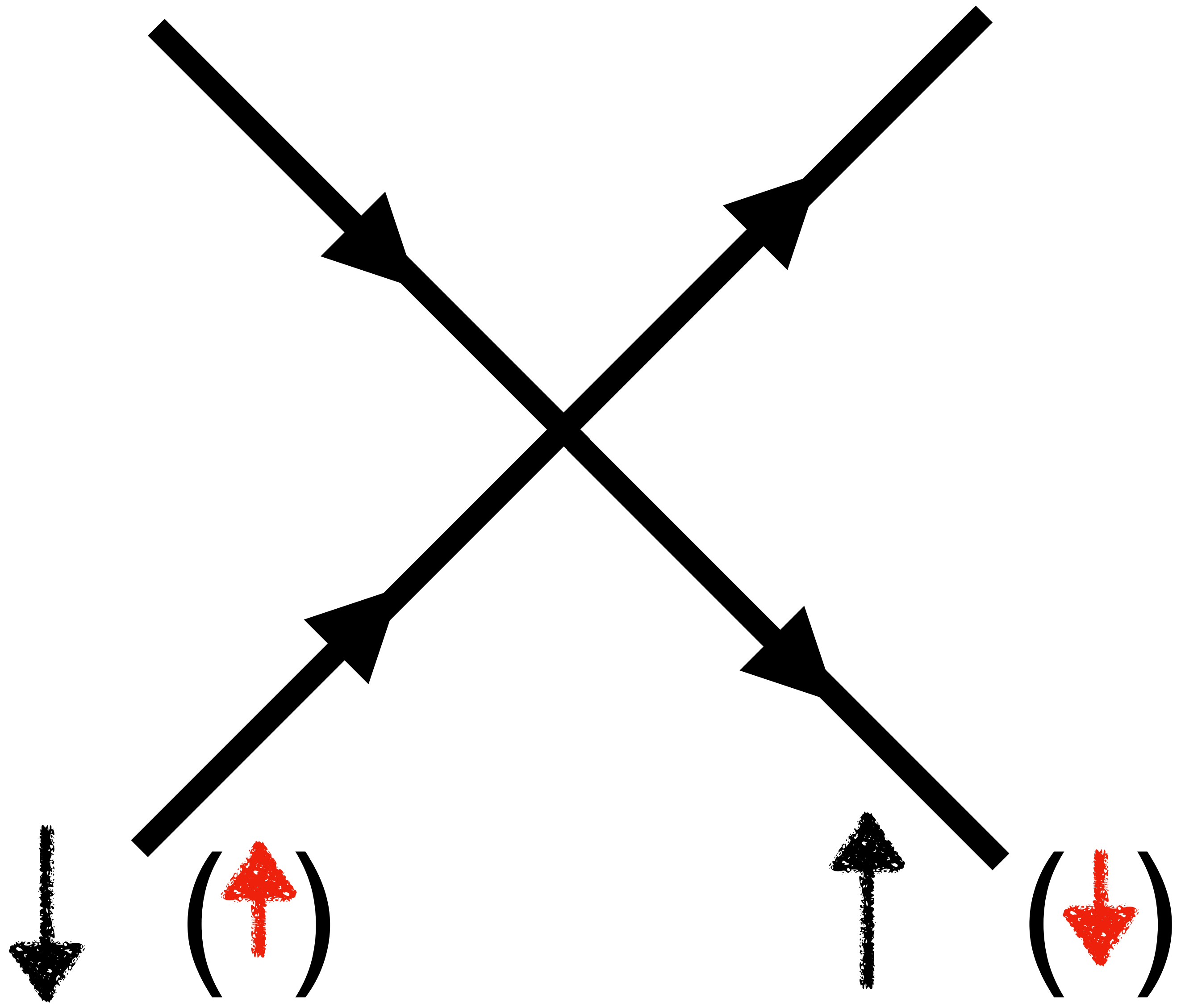
Macroscopic coherence is set by the **momentum transfer**

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

Scattering



The Cosmic Neutrino Background

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

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CνB and spin systems

Interaction with any fermionic spin ψ

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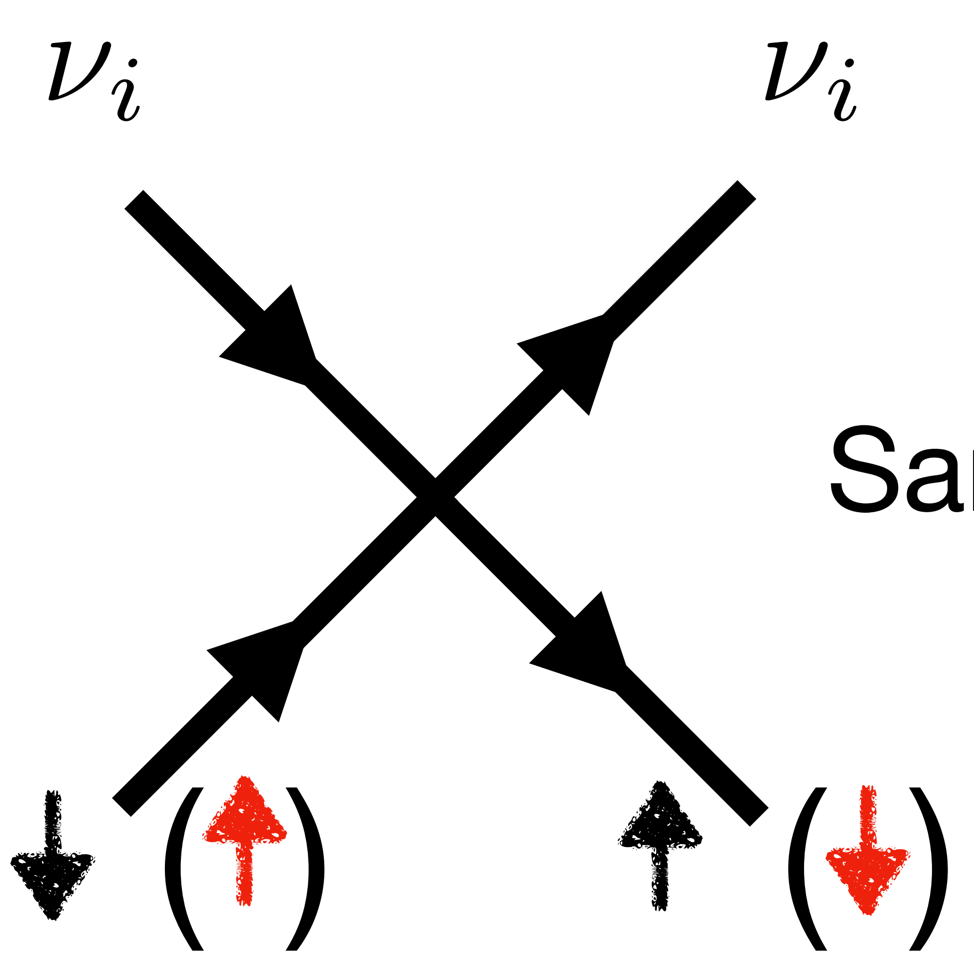

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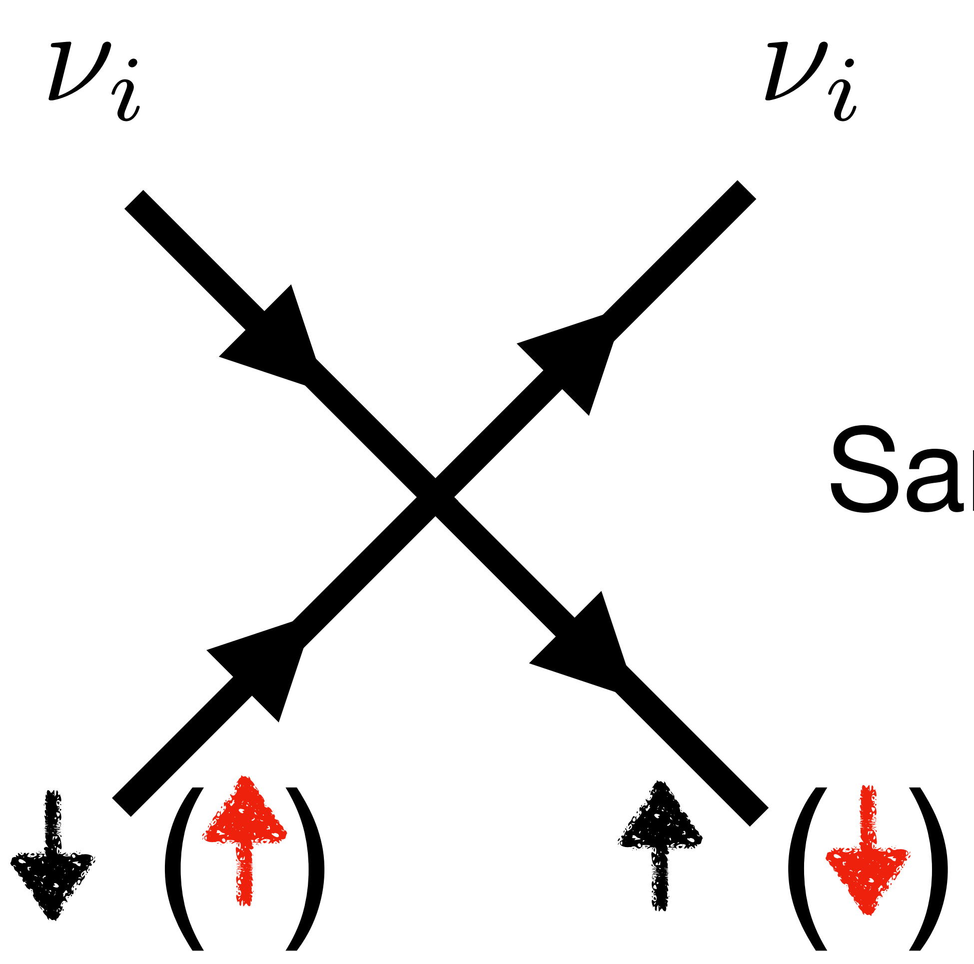

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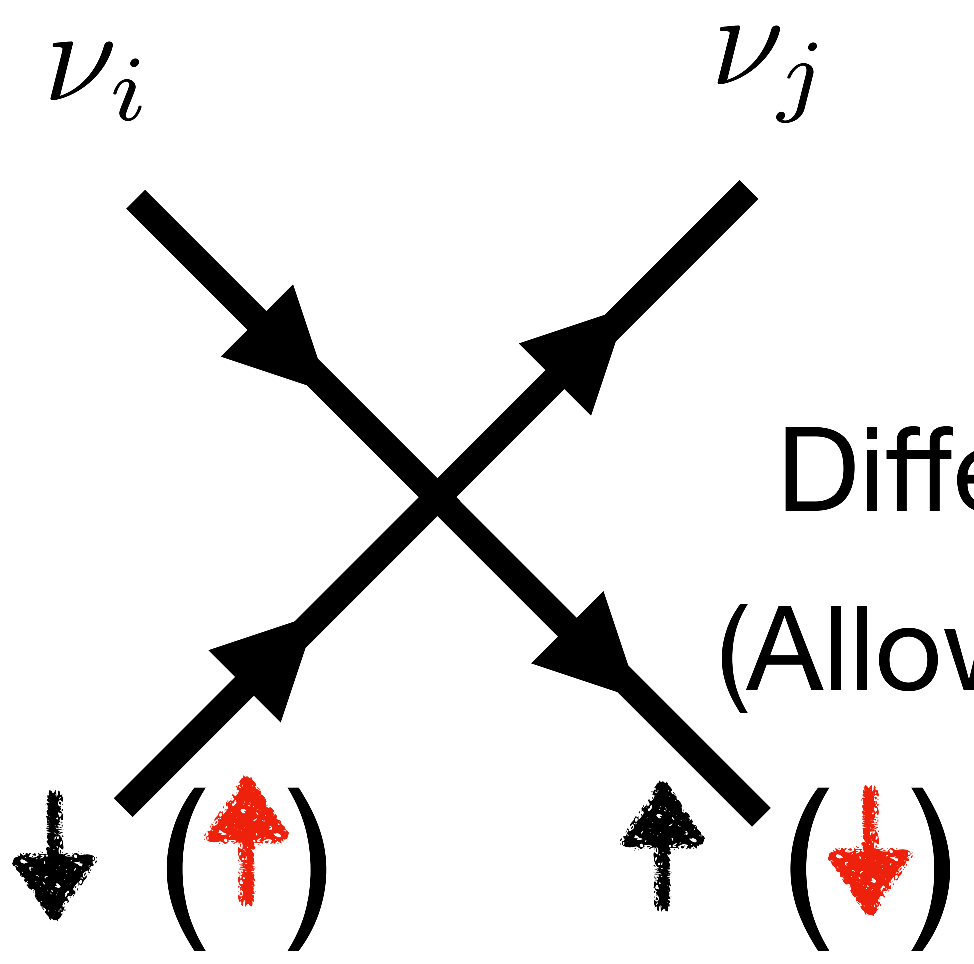

Different mass eigenstate

(Allowed only on e, due to W)

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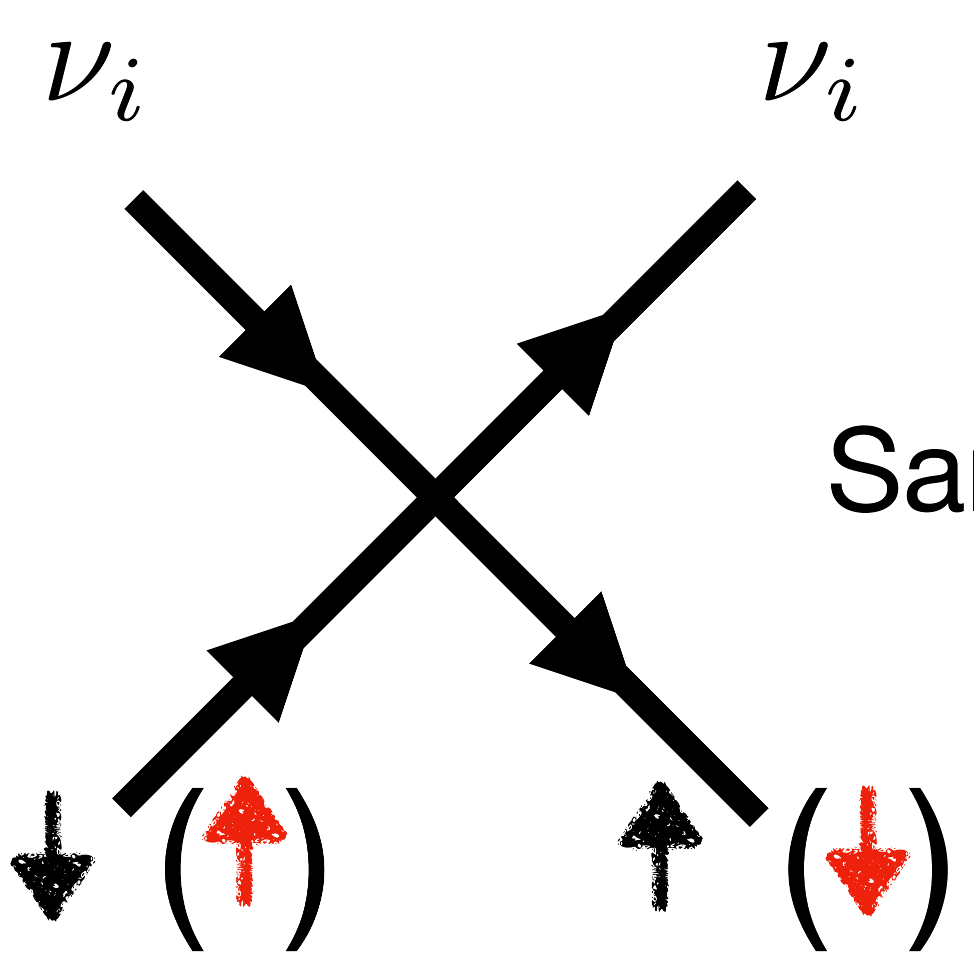
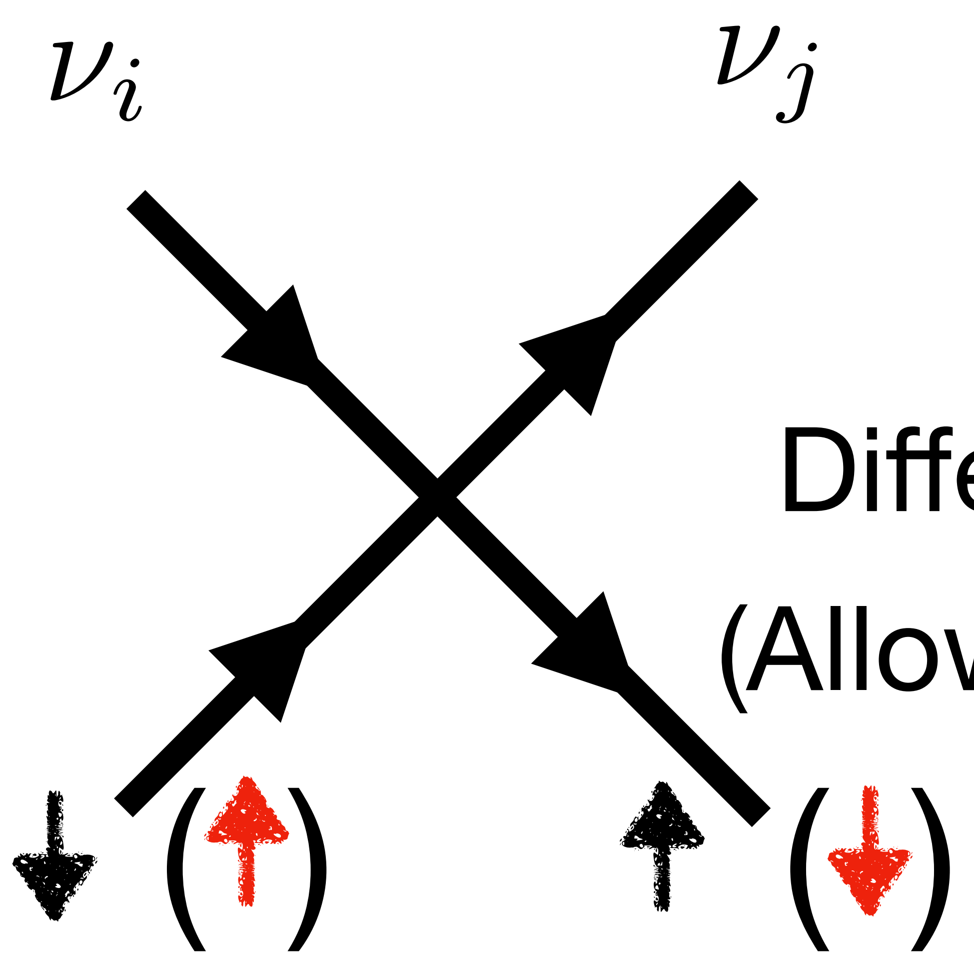


Same mass eigenstate

NMR



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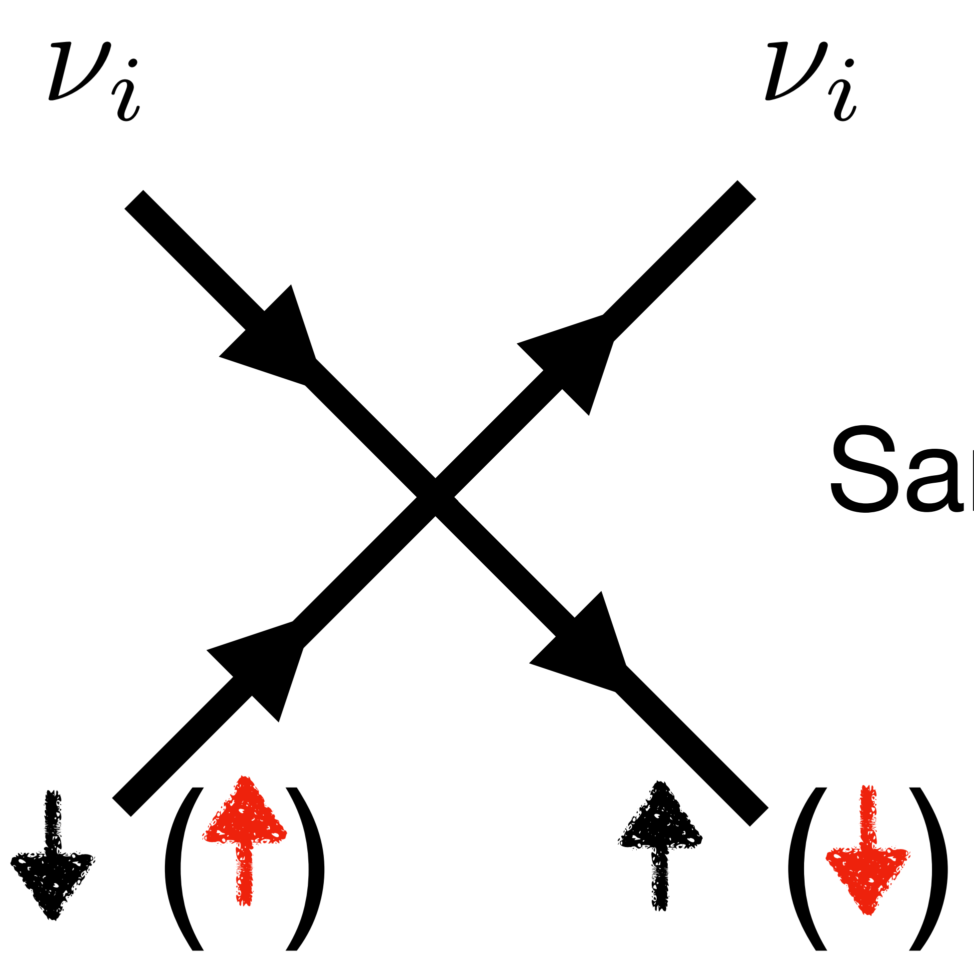

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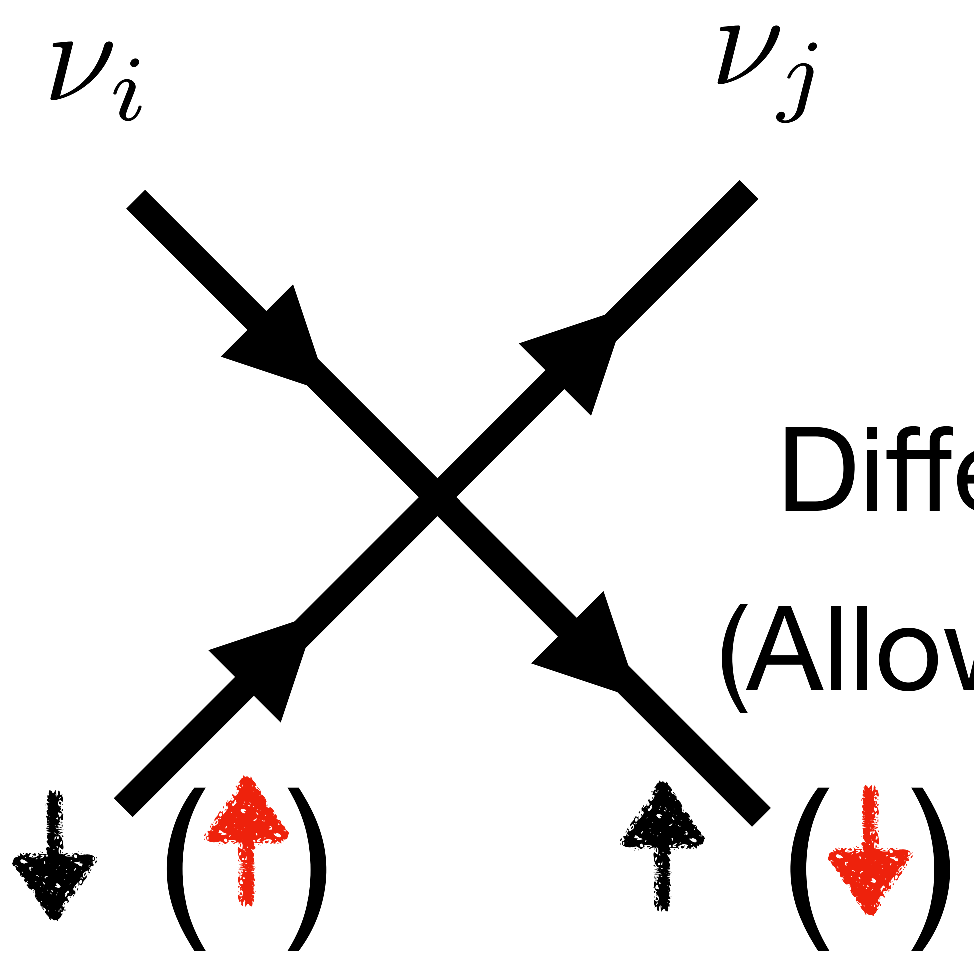
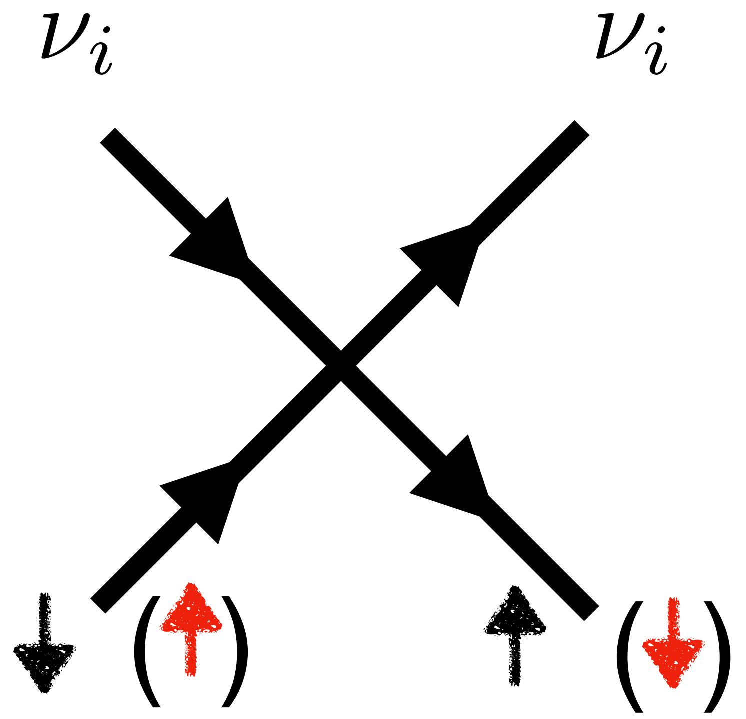


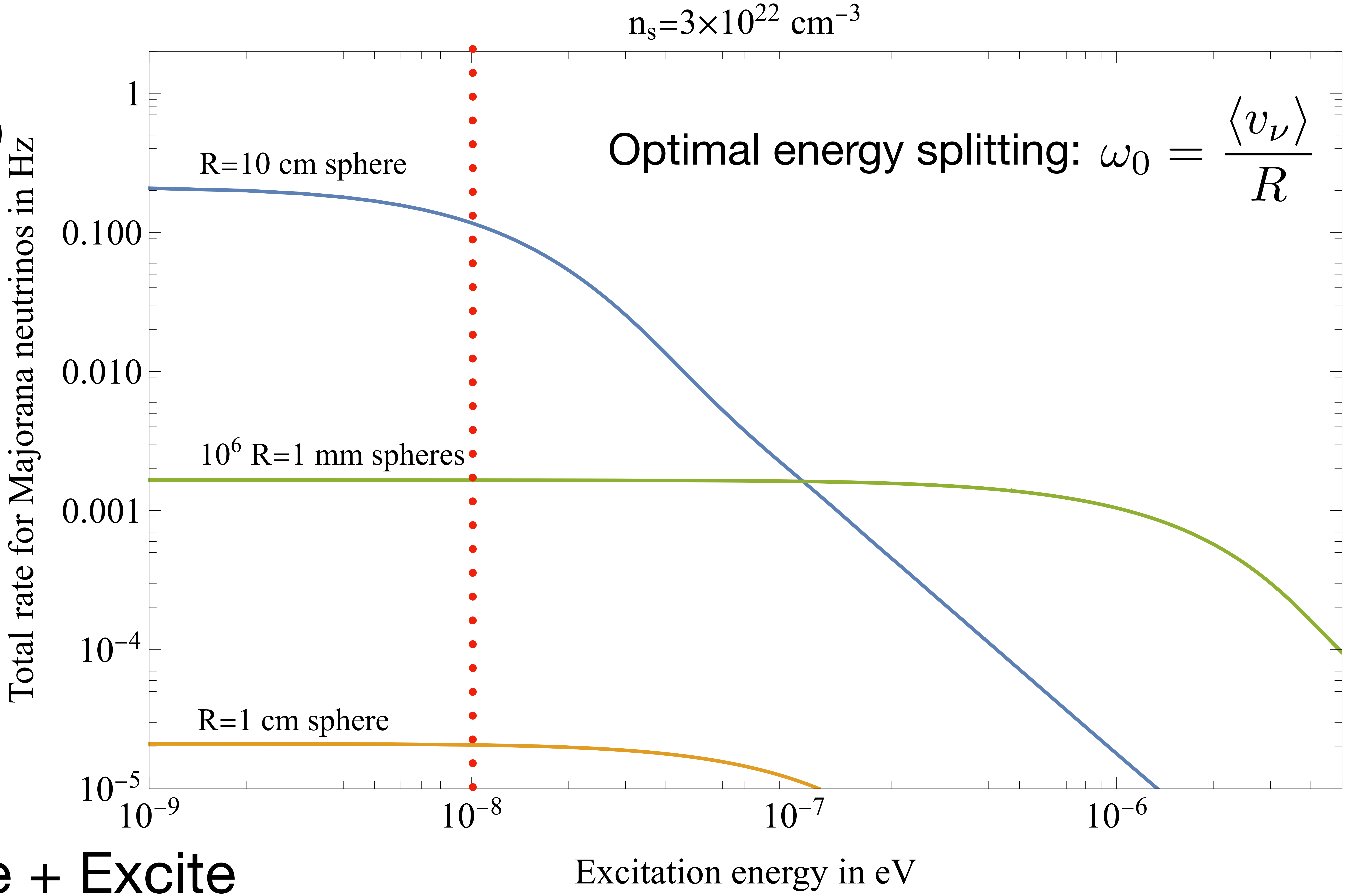
Different mass eigenstate

(Allowed only on e, due to W)

ESR

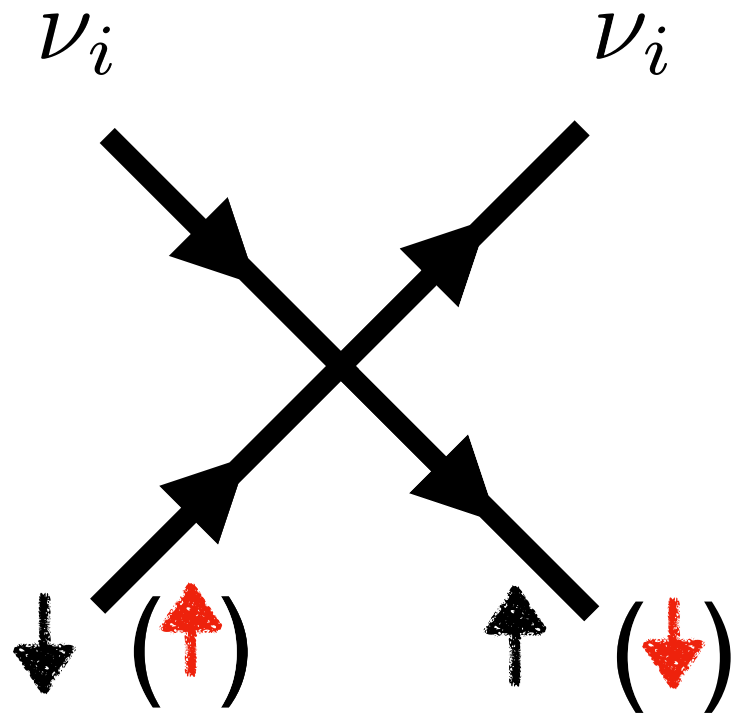
Same mass eigenstate: NMR

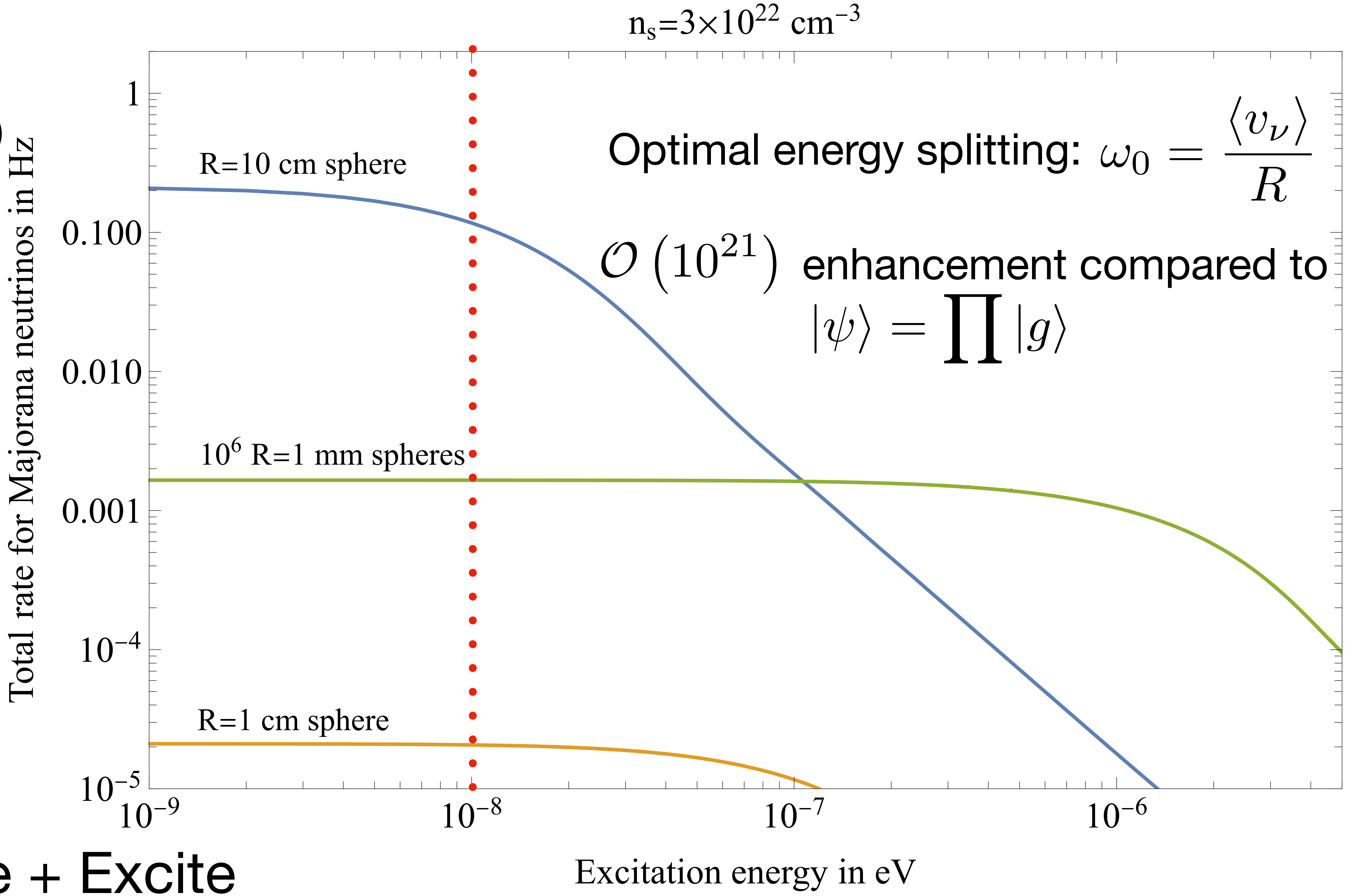




De-excite + Excite

Same mass eigenstate: NMR



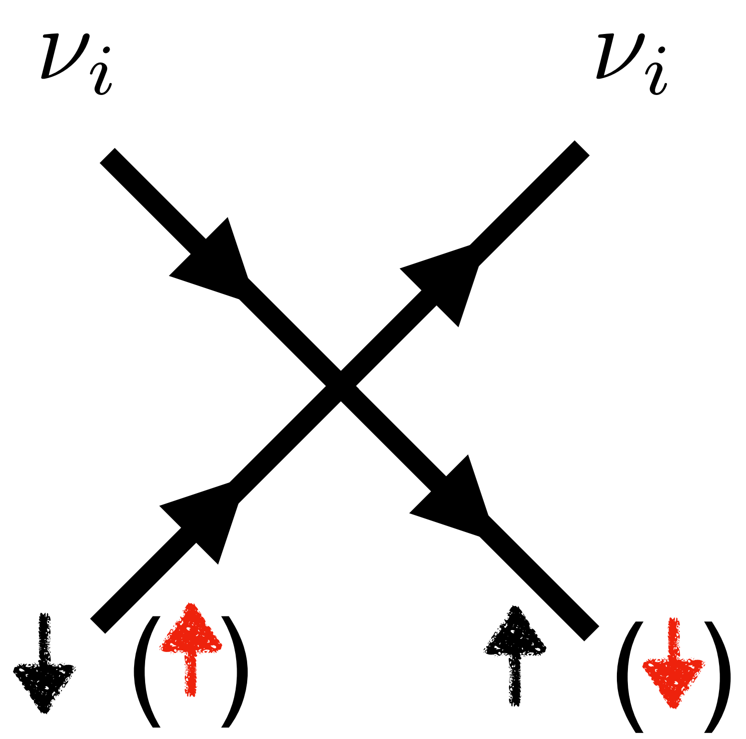


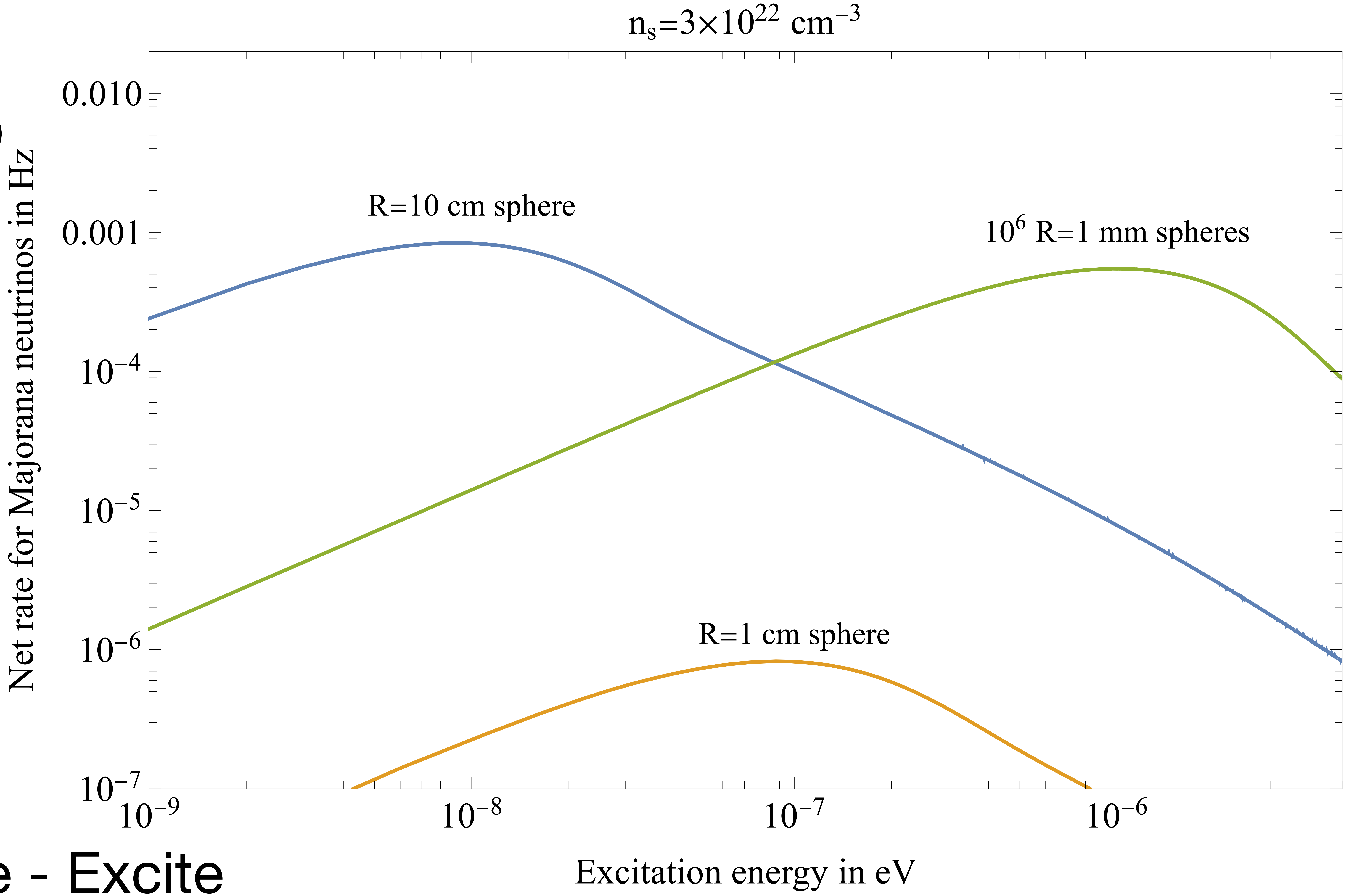
Optimal energy splitting: $\omega_0 = \frac{\langle v_\nu \rangle}{R}$

$\mathcal{O}\left(10^{21}\right)$ enhancement compared to $|\psi\rangle = \prod |g\rangle$

De-excite + Excite

Same mass eigenstate: NMR





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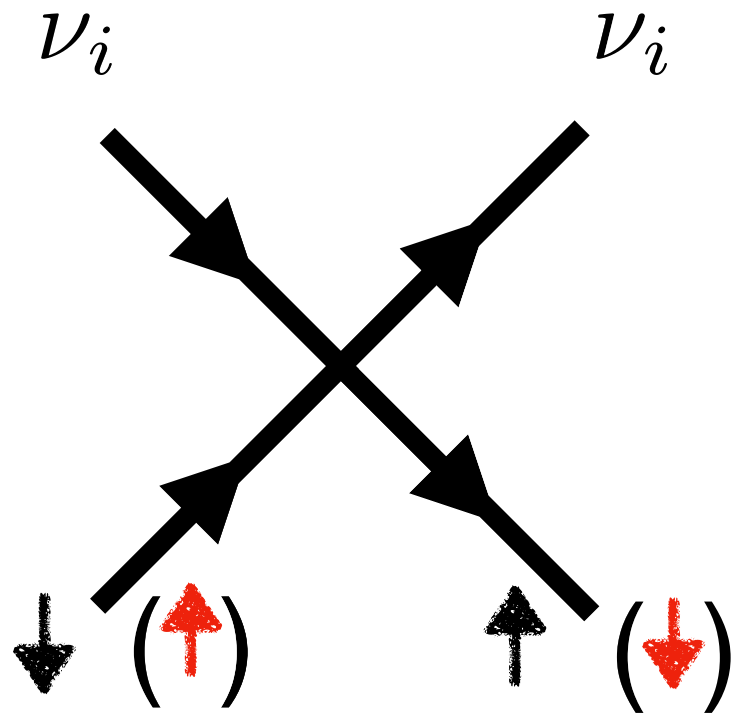

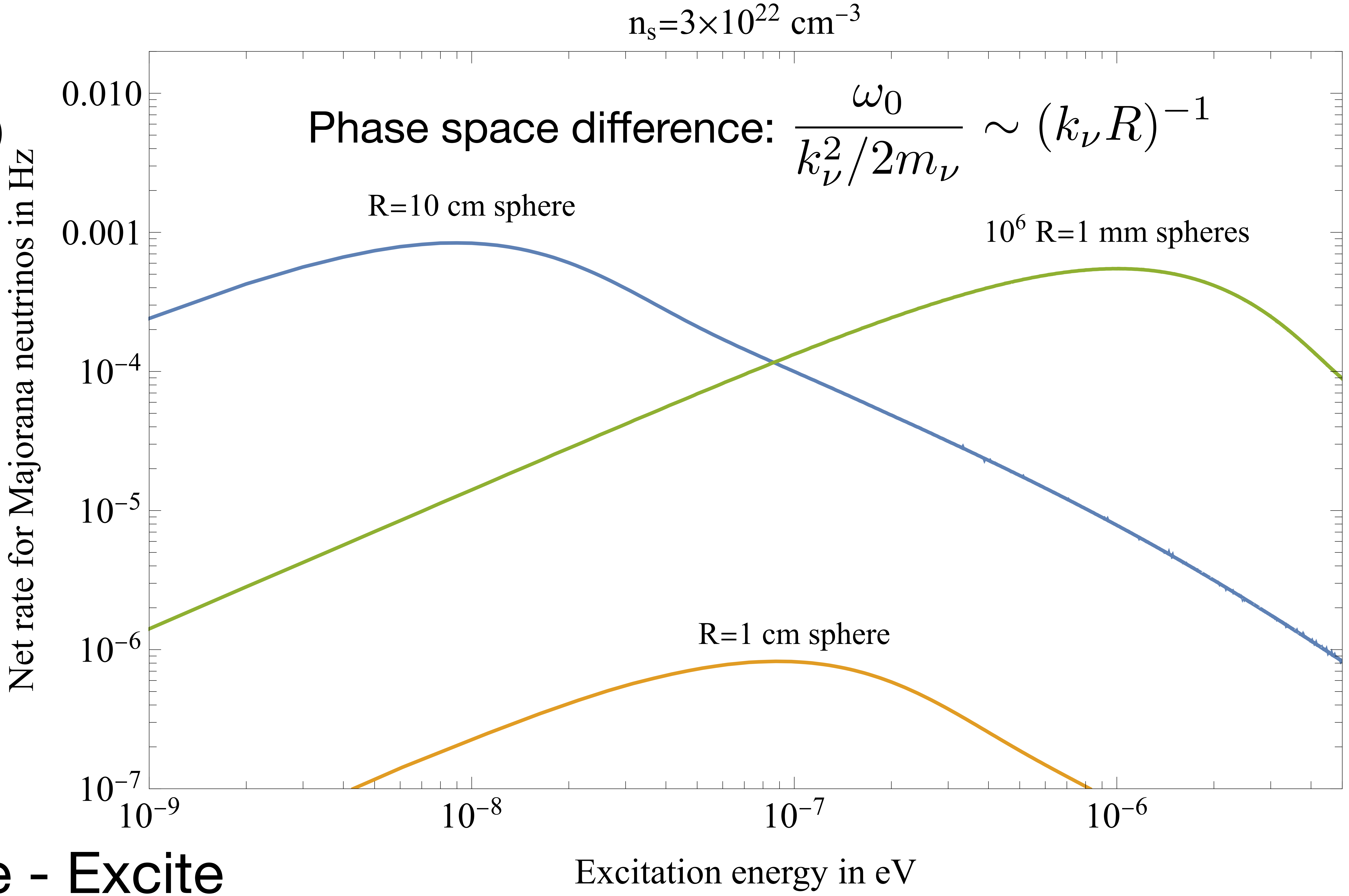

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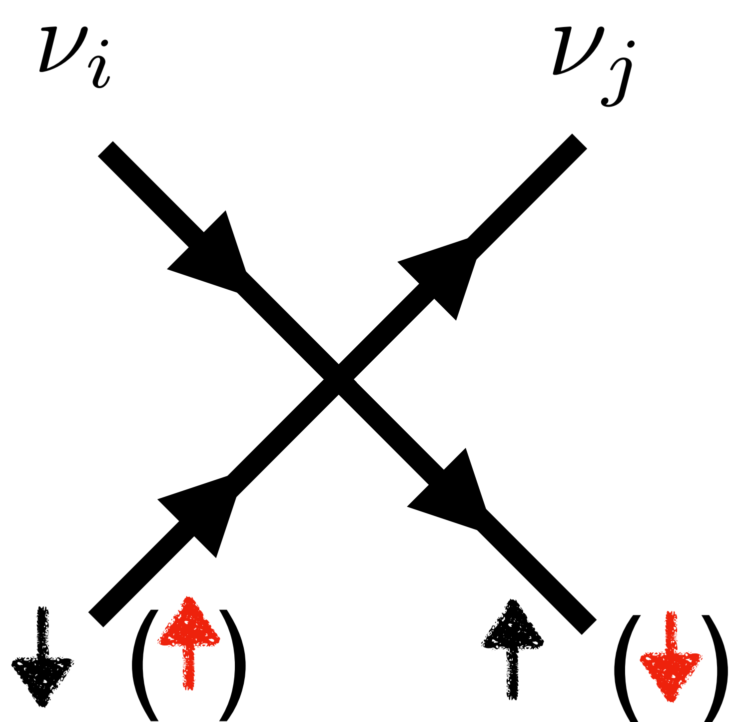
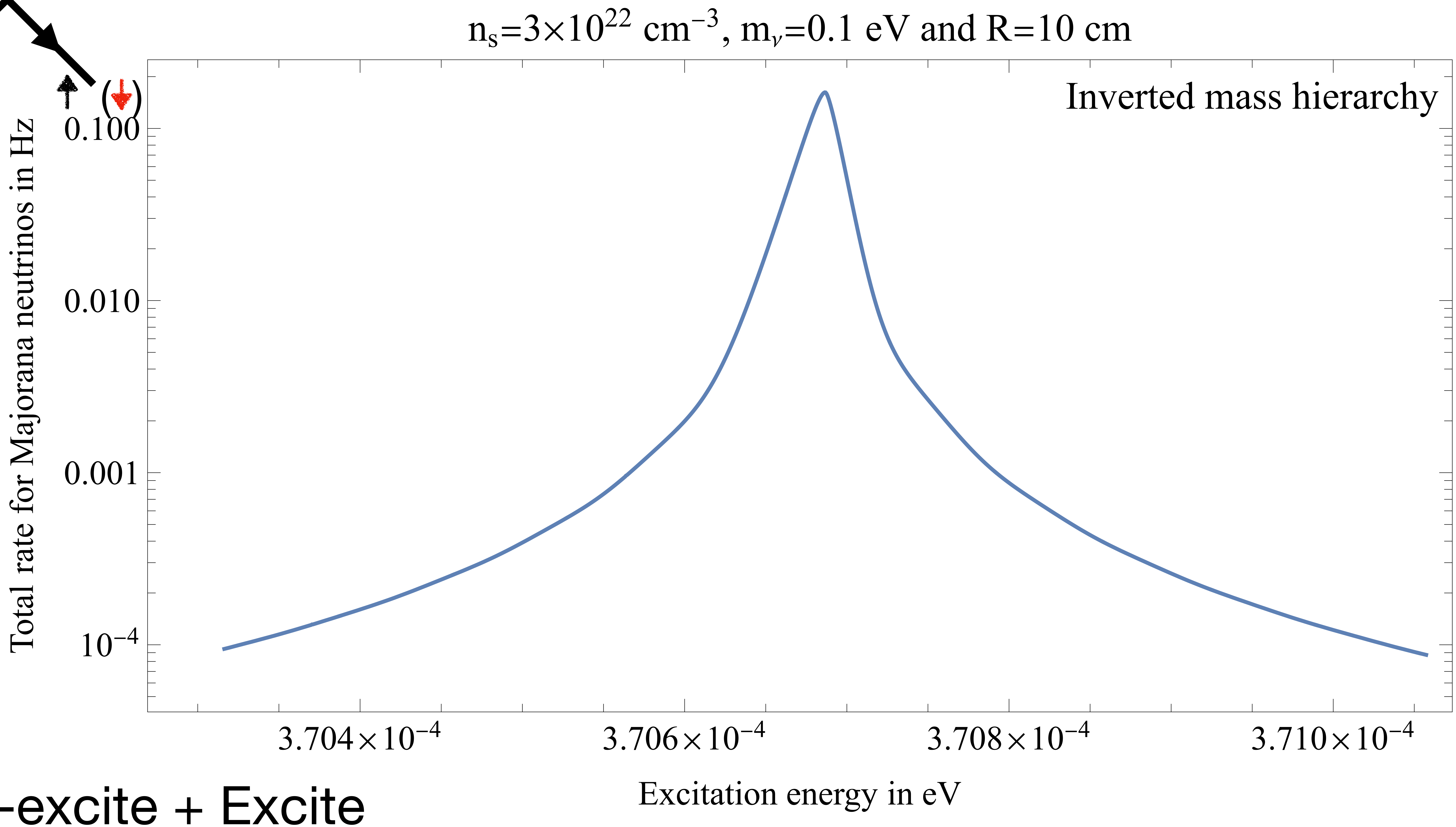
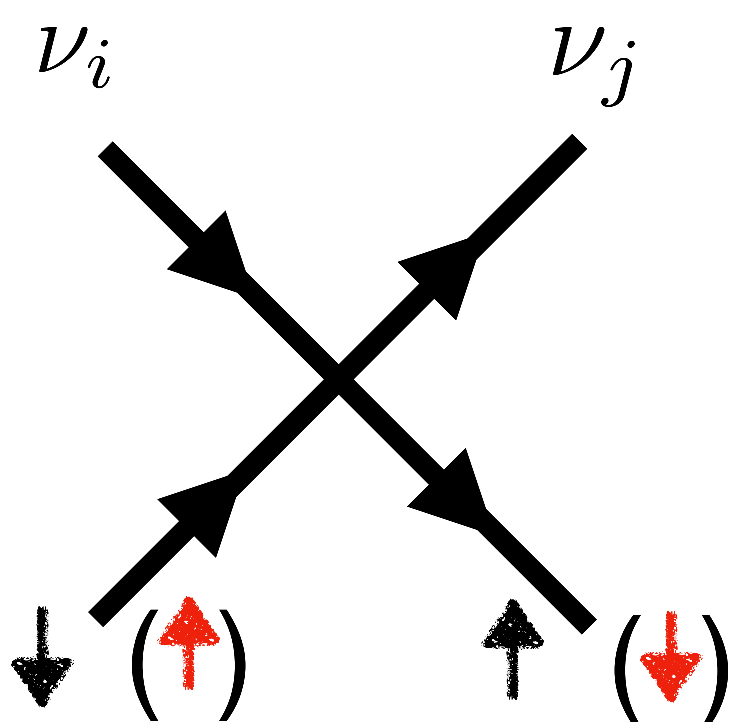


Different mass eigenstate: ESR

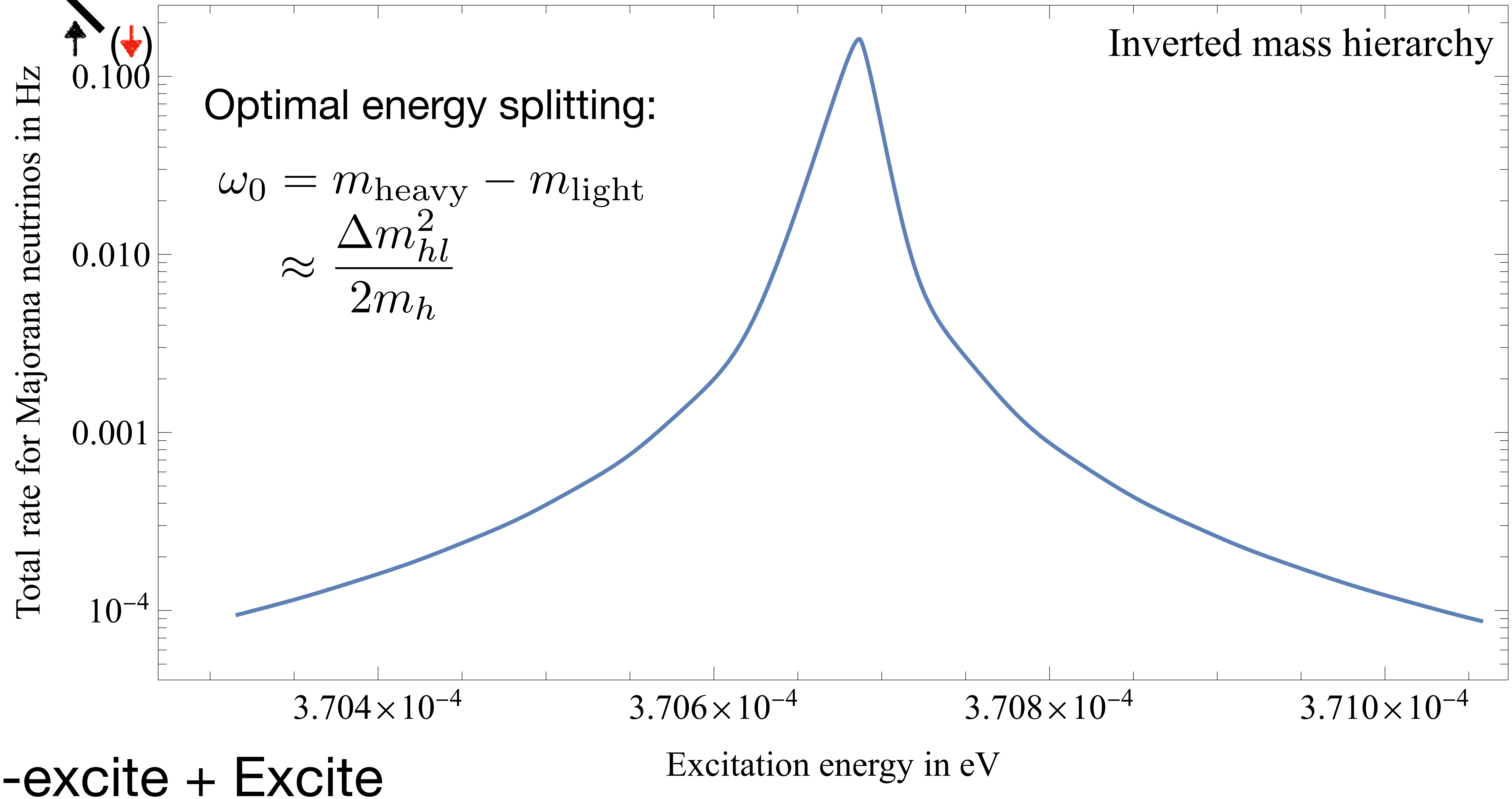


De-excite + Excite



Different mass eigenstate: ESR

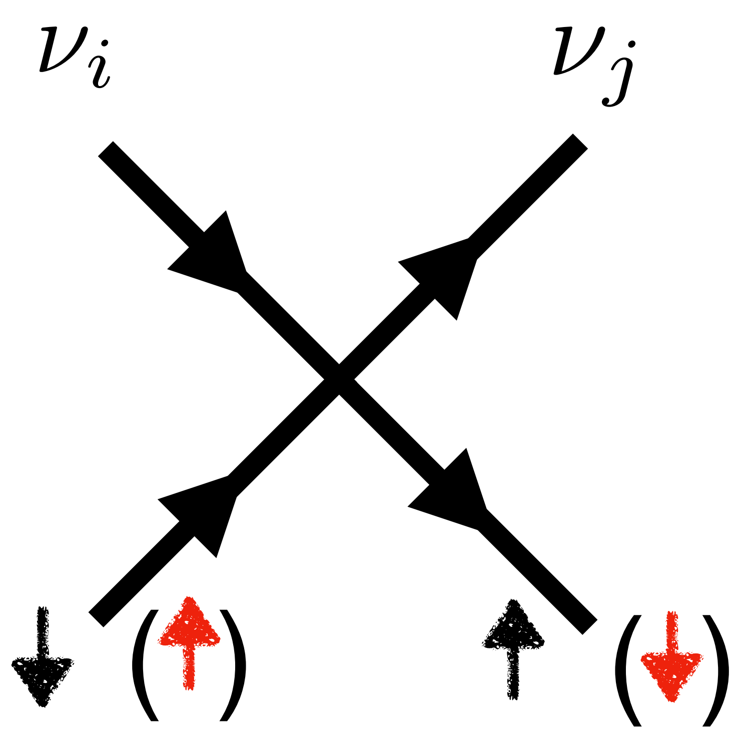
$n_s=3\times10^{22}$ cm^{-3}, $m_\nu=0.1$ eV and R=10 cm



Optimal energy splitting:

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

De-excite + Excite



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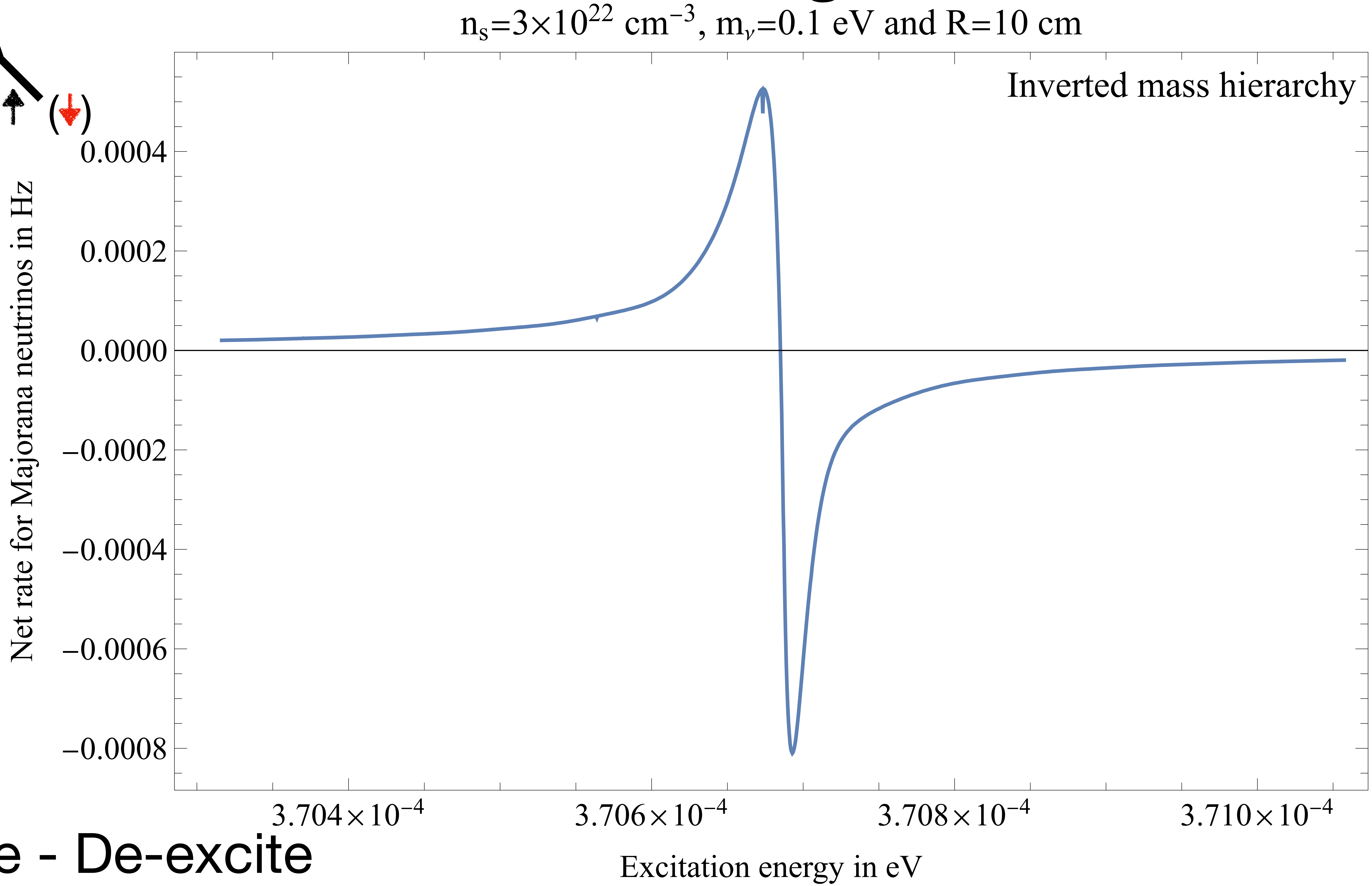
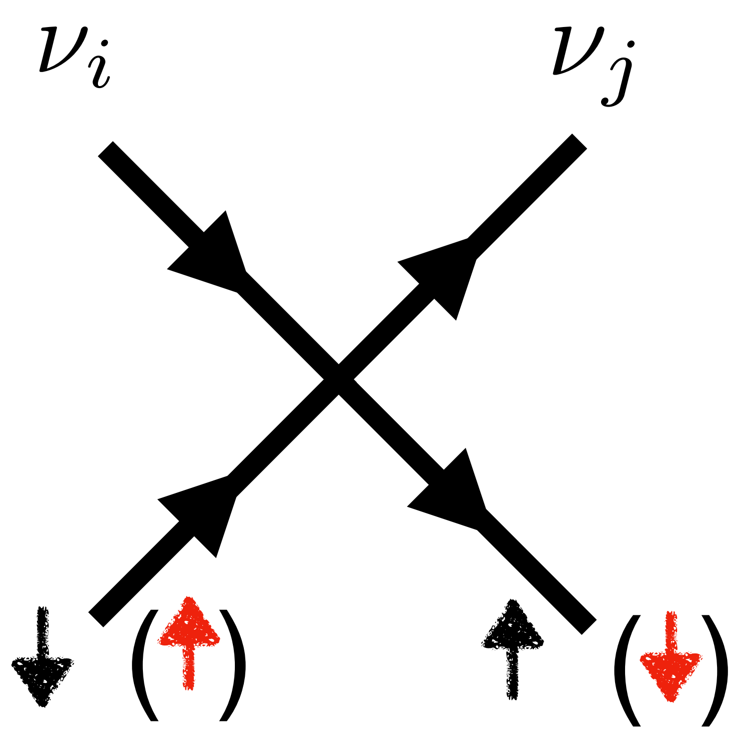
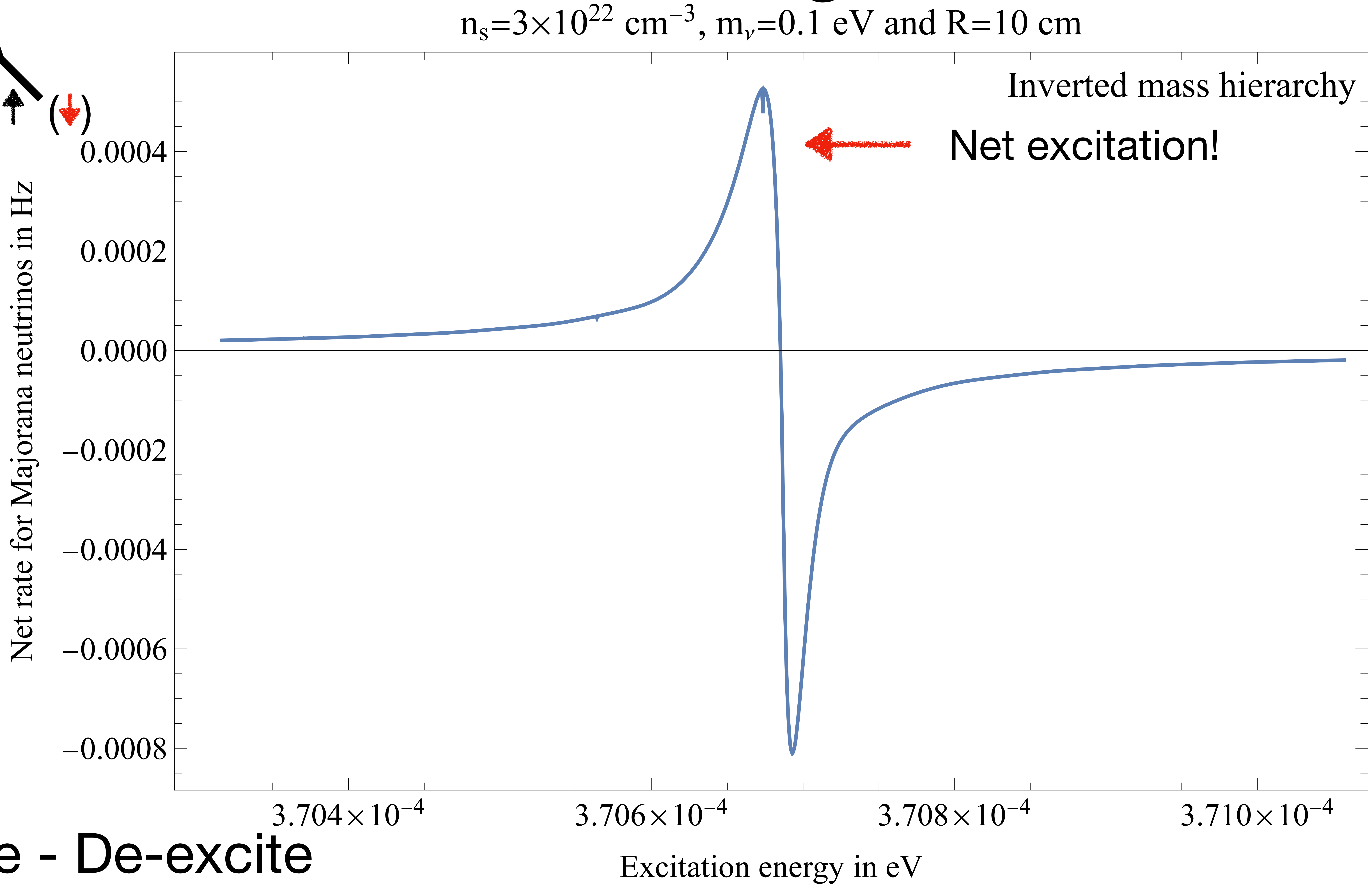


Excite - De-excite



Different mass eigenstate: ESR



Excite - De-excite

Other neutrinos

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Rayleigh-Gans regime for relativistic particles

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Very suppressed net rates, but total rates:

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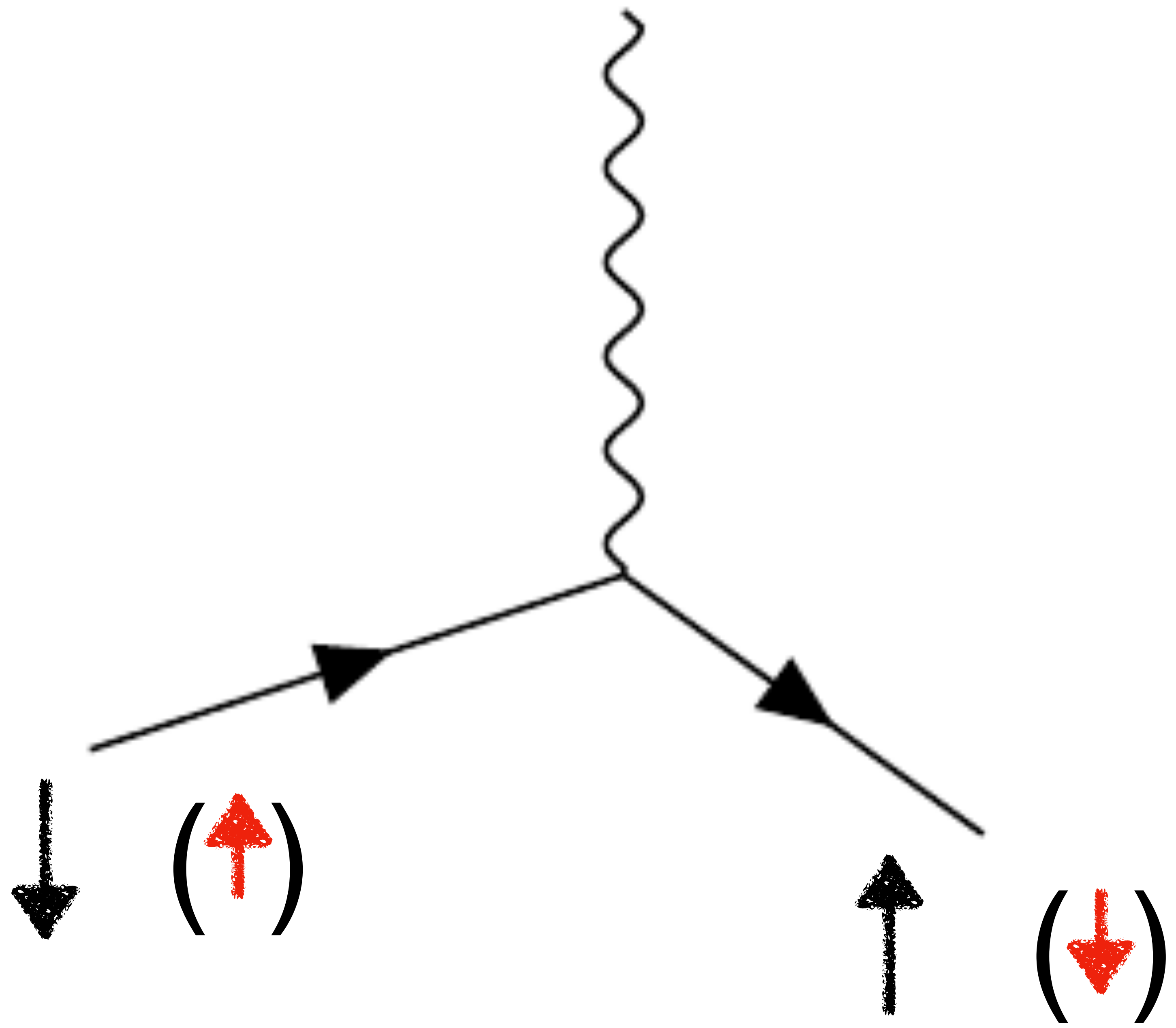
$$\Gamma_{\rm solar} \sim \frac{1}{2.5\ \rm hours} \left(\frac{n_s}{3\cdot 10^{22}\ \rm cm^{-3}}\right)^2 \left(\frac{R}{10\ \rm cm}\right)^4$$

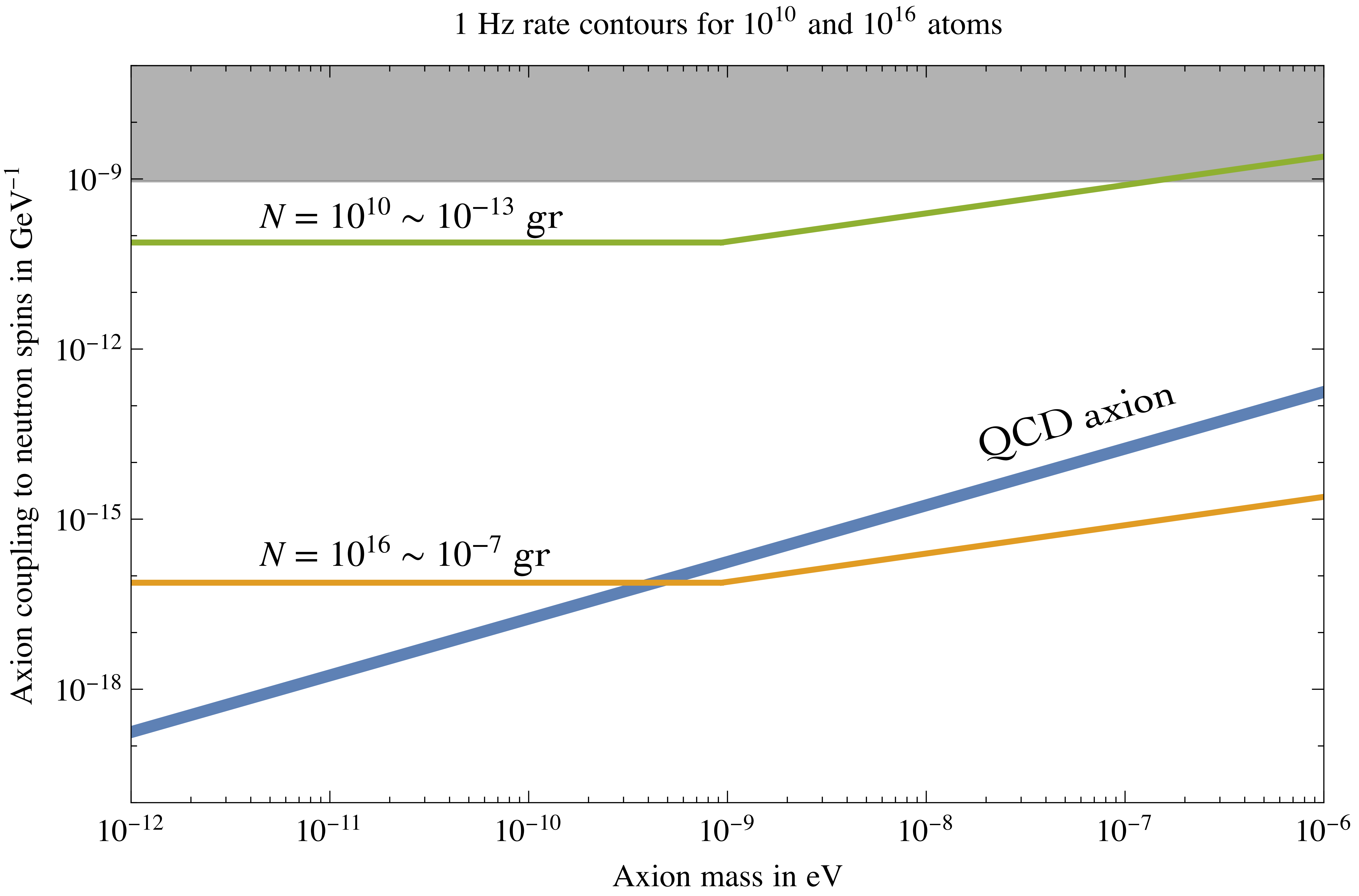
$$\Gamma_{\rm reac} \sim \frac{1}{3\ \rm hrs} \left(\frac{n_s}{3\cdot 10^{22}\ \rm cm^{-3}}\right)^2 \left(\frac{R}{10\ \rm cm}\right)^4 \left(\frac{100\ \rm m}{d}\right)^2$$

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

Absorption or Emission

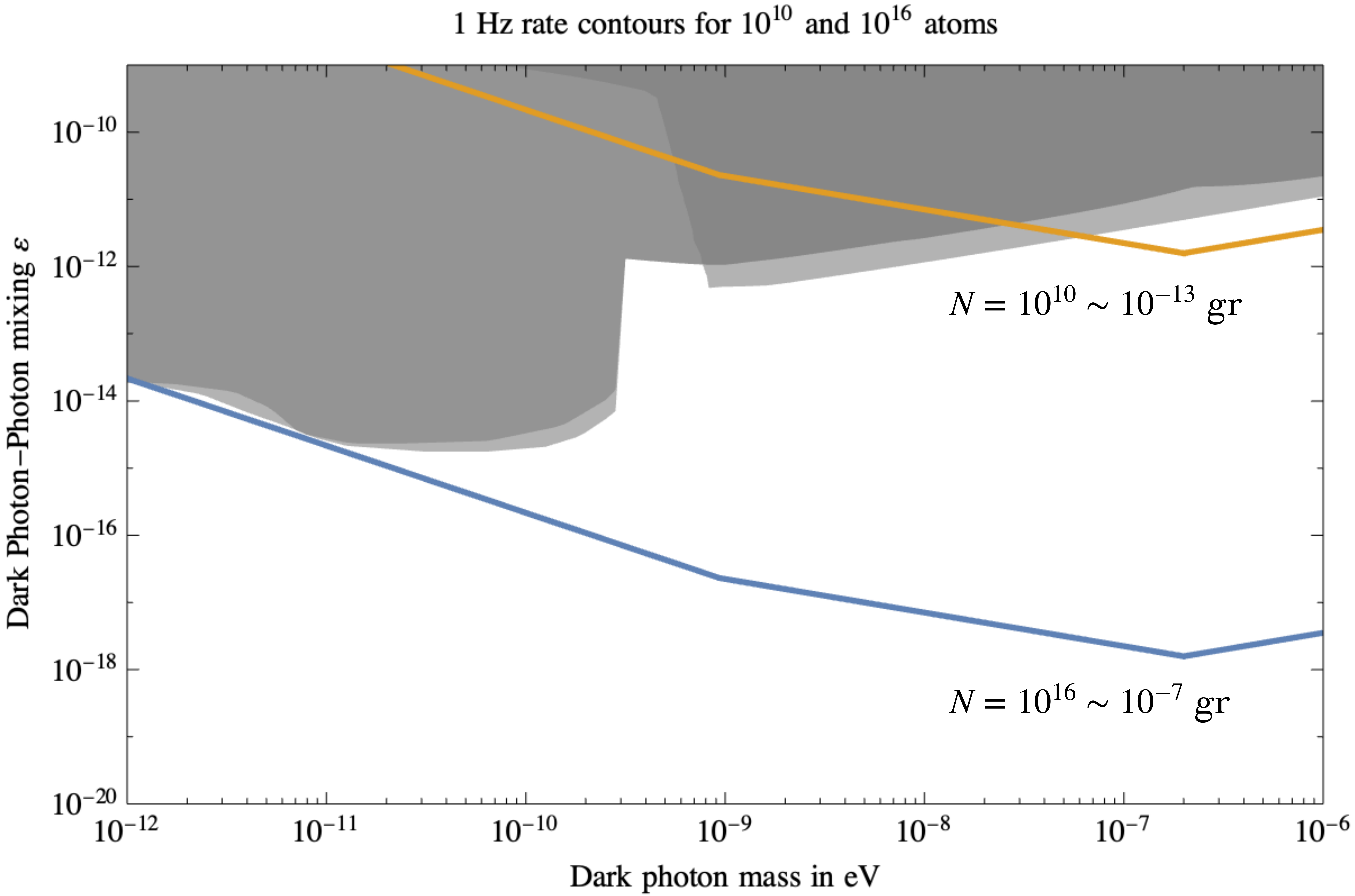


QCD Axion



1 Hz rate contours for 10^{10} and 10^{16} atoms
$N = 10^{10} \sim 10^{-13}$ gr
$N = 10^{16} \sim 10^{-7}$ gr
QCD axion
Axion coupling to neutron spins in GeV^{-1}
10^{-9}
10^{-12}
10^{-15}
10^{-18}
10^{-12}
10^{-11}
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
Axion mass in eV

Dark Photons



Dark Quantum Optics

Observables

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Interested in system dynamics $\rightarrow$ integrate out cosmic noise

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$$\rho_\nu = \prod_{\{\mathbf{k},s\}} \left[\left(1 - \langle n \rangle_{\mathbf{k},s}\right) |0\rangle_{\mathbf{k},s} \langle 0|_{\mathbf{k},s} + \langle n \rangle_{\mathbf{k},s} |1\rangle_{\mathbf{k},s} \langle 1|_{\mathbf{k},s} \right]$$

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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

$$\dot{\rho}_S \simeq \frac{\gamma_a}{2} (\bar{n}_{\rm th} + 1) \mathcal{L}_{J_-}[\rho_S(t)] + \frac{\gamma_a}{2} \bar{n}_{\rm th} \mathcal{L}_{J_+}[\rho_S(t)].$$

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Spontaneous emission $\to$ Dicke superradiance

Observables

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Net rate zero!

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$$\left\langle \dot{J}_z(t) \right\rangle \approx \gamma_+ \langle J_- J_+ \rangle - \gamma_- \langle J_+ J_- \rangle$$

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Net suppressed

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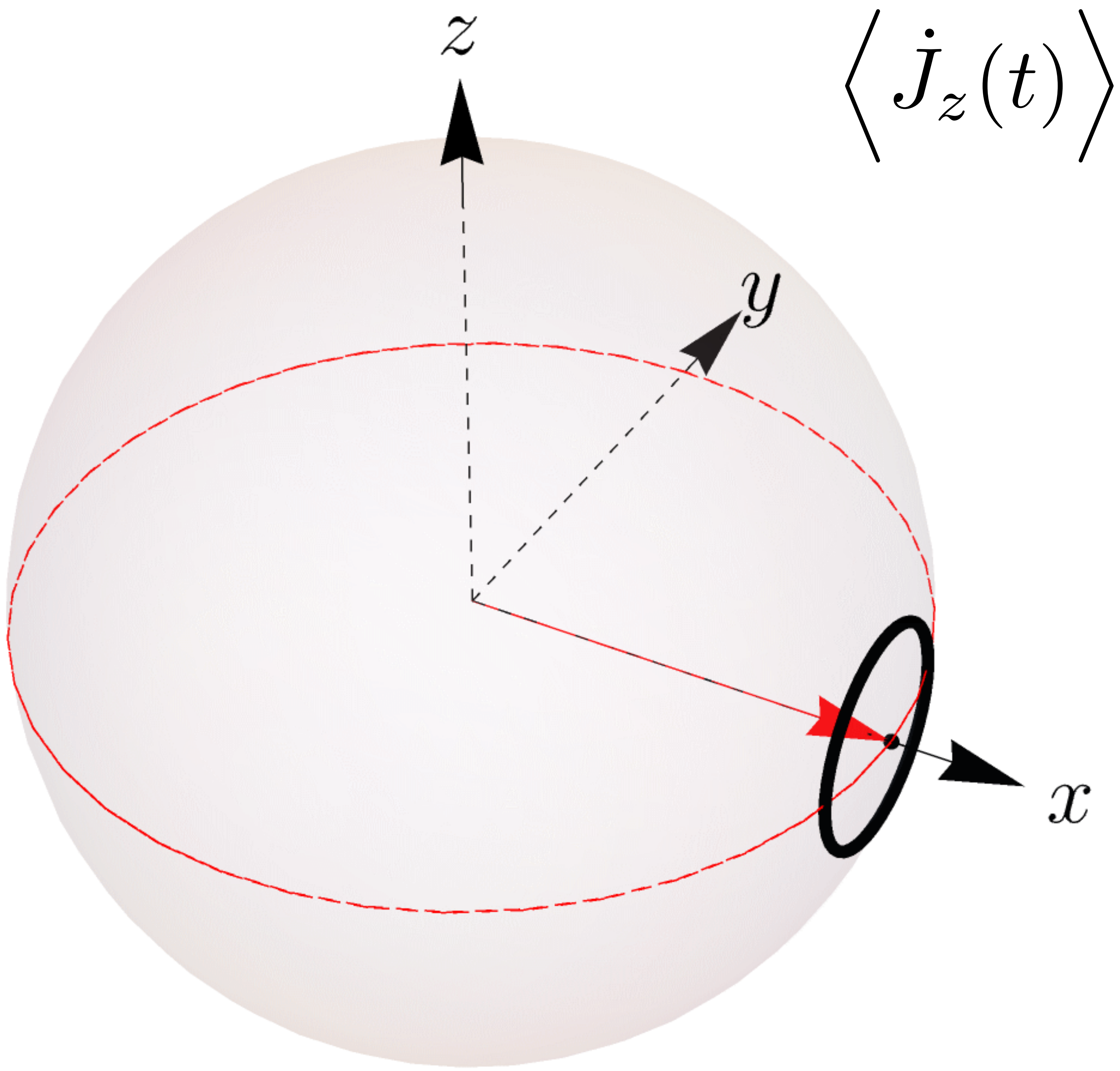

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Net suppressed

$$\left\langle J_z^2(t) \right\rangle = \frac{N}{4} + \frac{N^2}{4}(\gamma_+ + \gamma_-)t$$

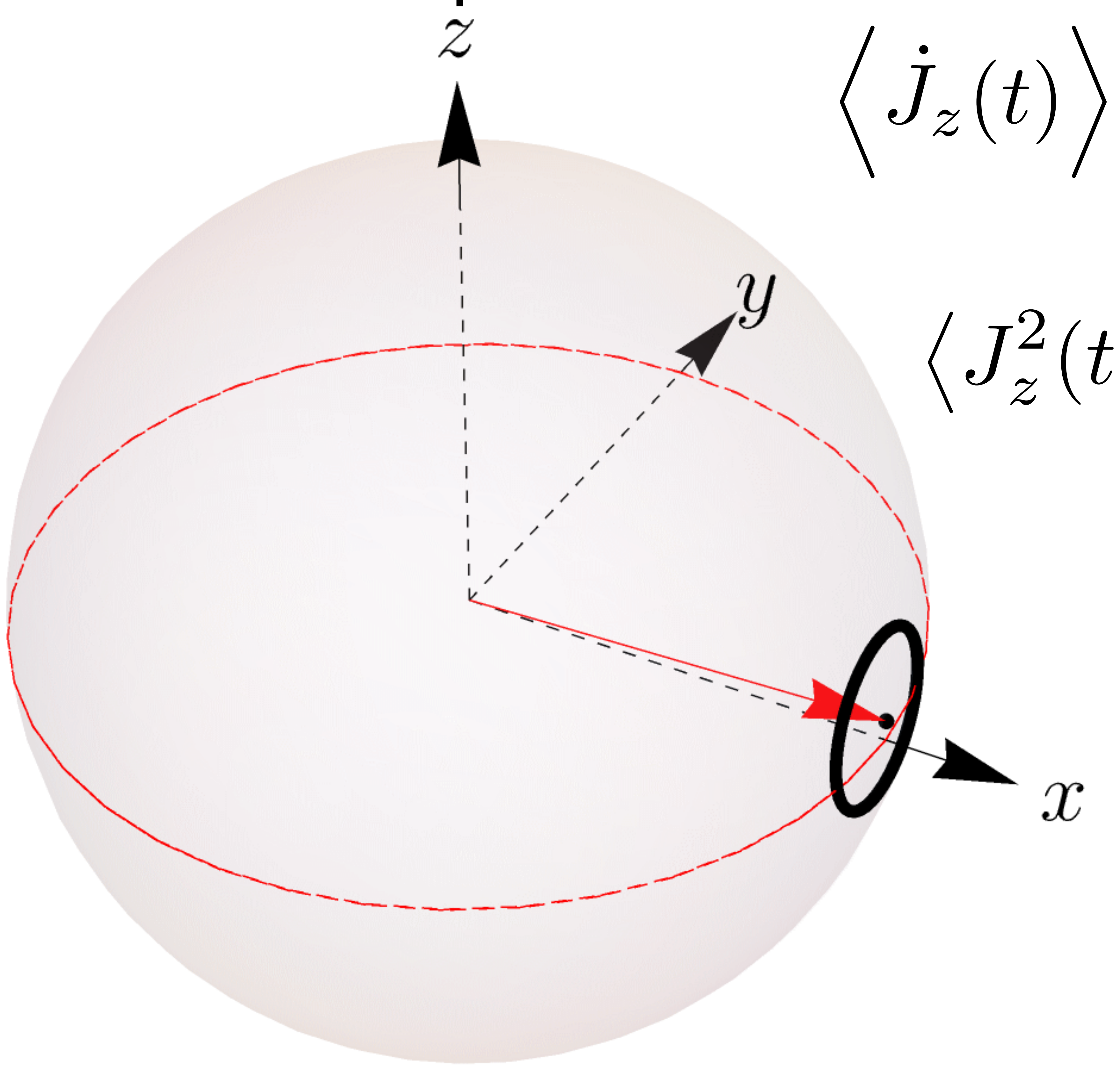
Sum of rates

Observables

Lindblad equation for CvB

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

For example:



$$\left\langle \dot{J}_z(t) \right\rangle \approx \gamma_+ \langle J_- J_+ \rangle - \gamma_- \langle J_+ J_- \rangle$$

Net suppressed

$$\left\langle J_z^2(t) \right\rangle = \frac{N}{4} + \frac{N^2}{4}(\gamma_+ + \gamma_-)t$$

Sum of rates

Observables

Lindblad equation for CvB

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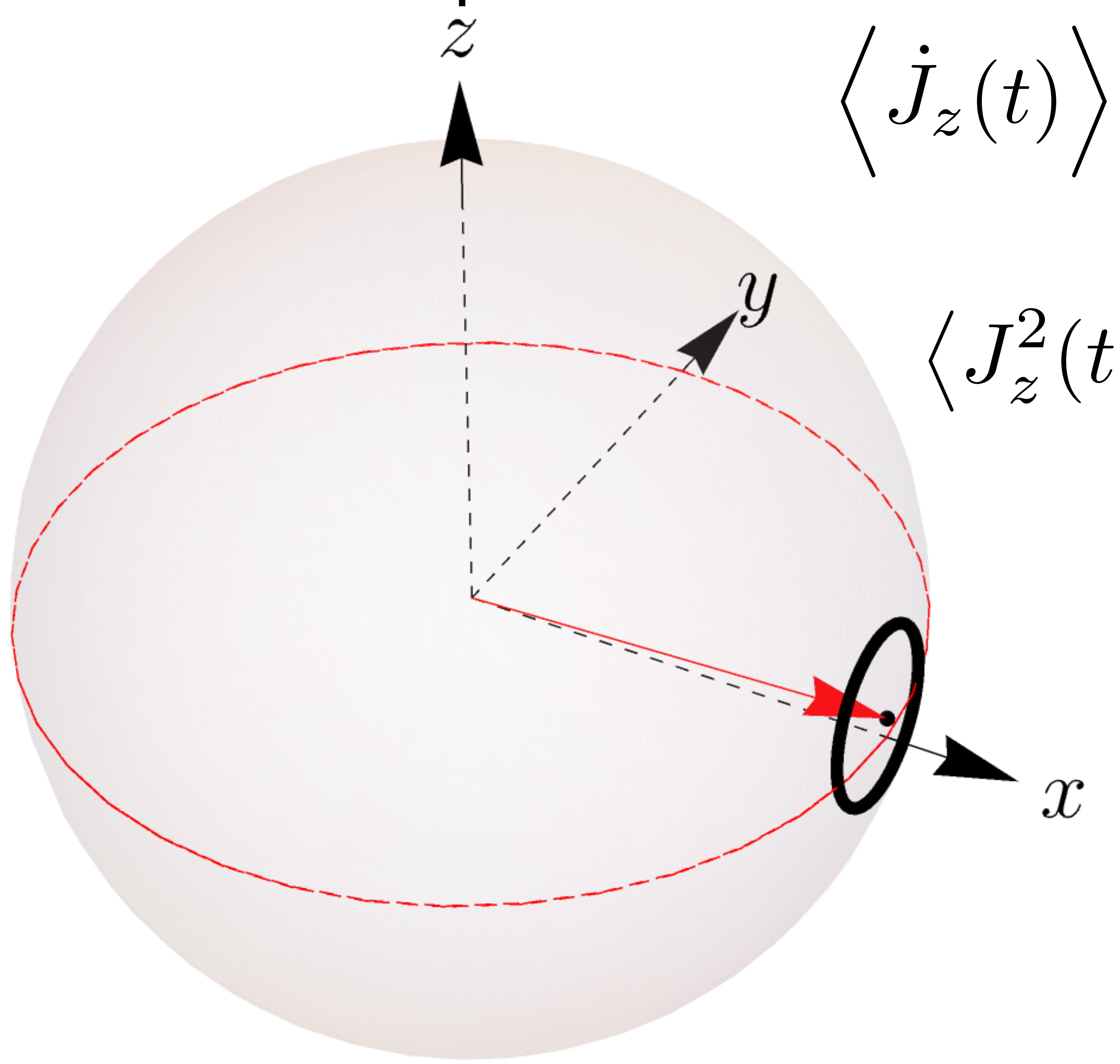

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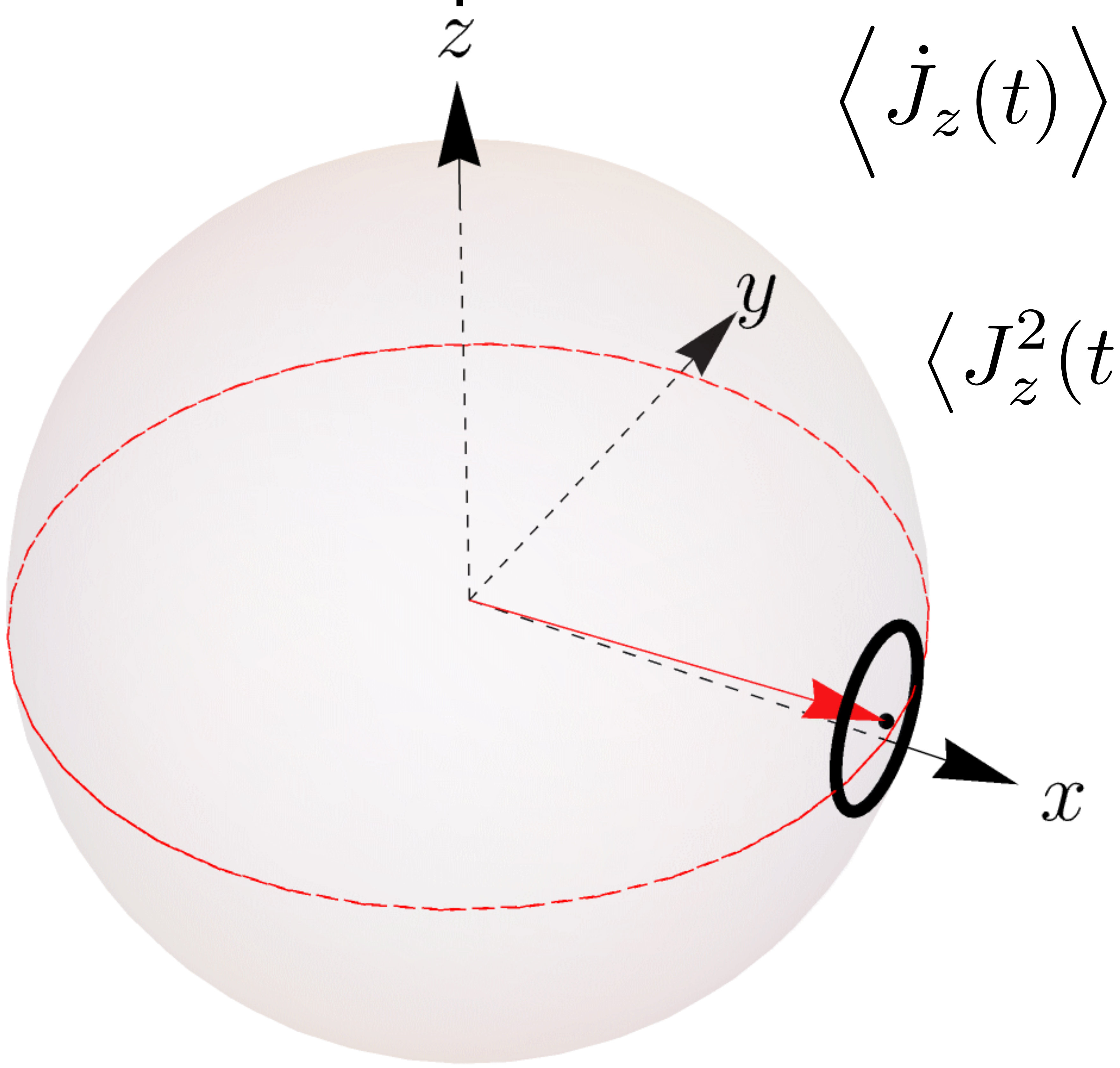

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Need to overcome N

Net energy CvB bound

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

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

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Comparable to KATRIN (200 ton spectrometer)

States

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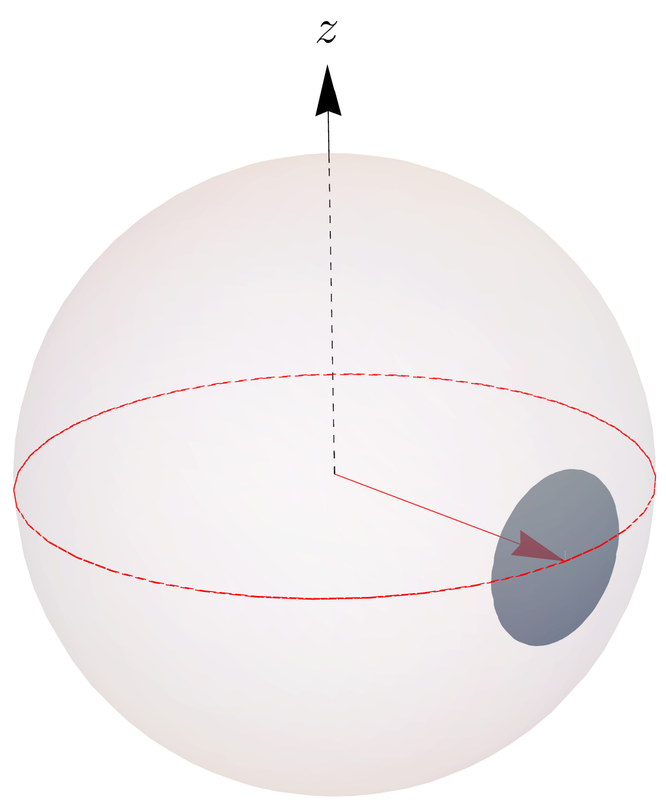

Product state: $\Delta J_z = \sqrt{N}$

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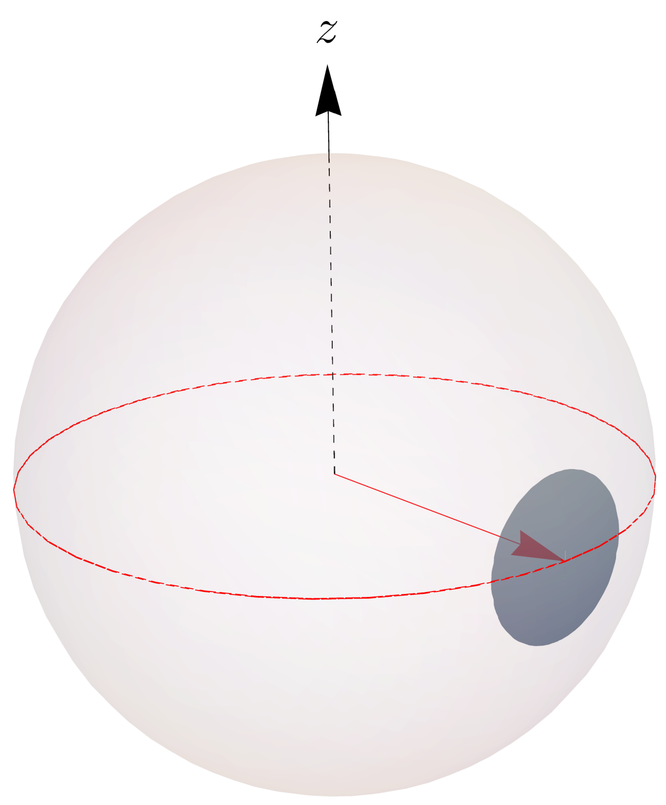

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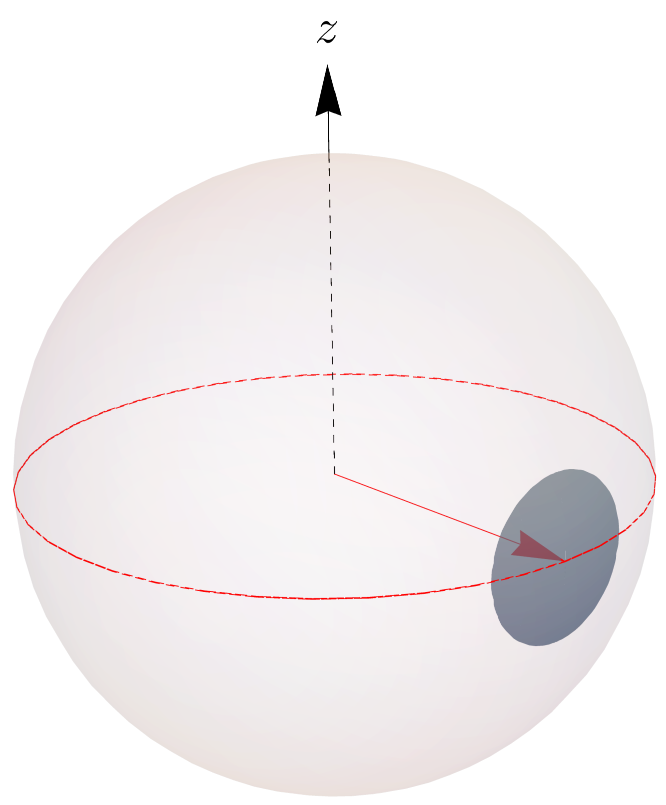

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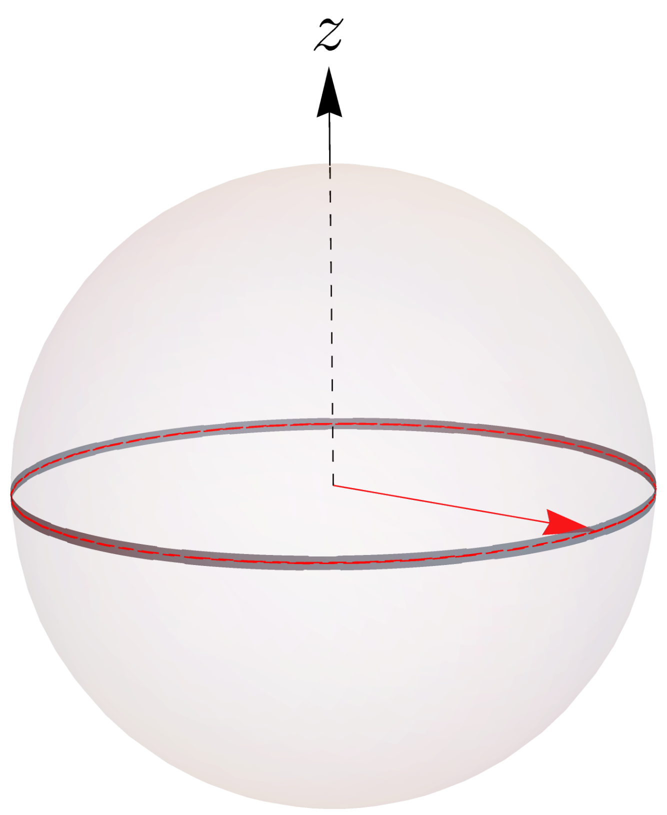

Equatorial Dicke state: $\Delta J_z = 0$

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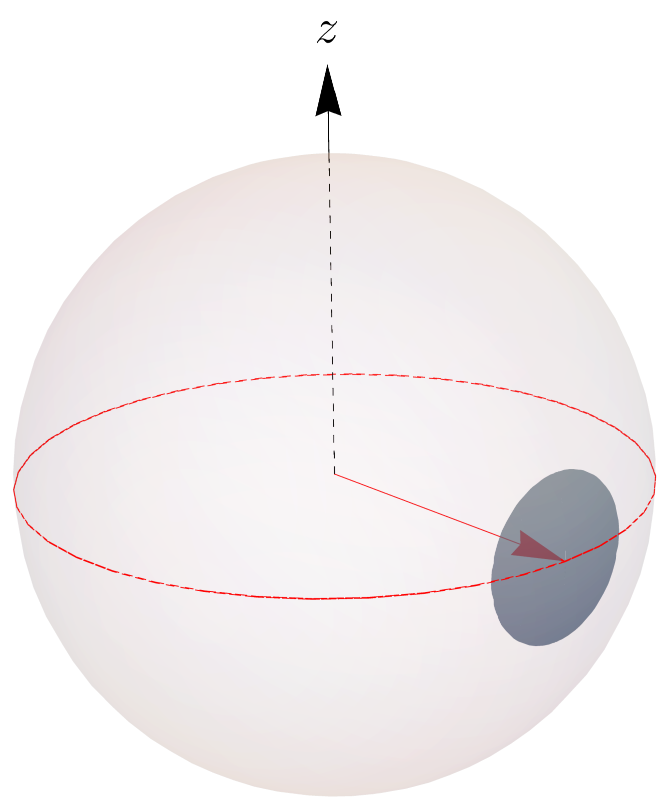

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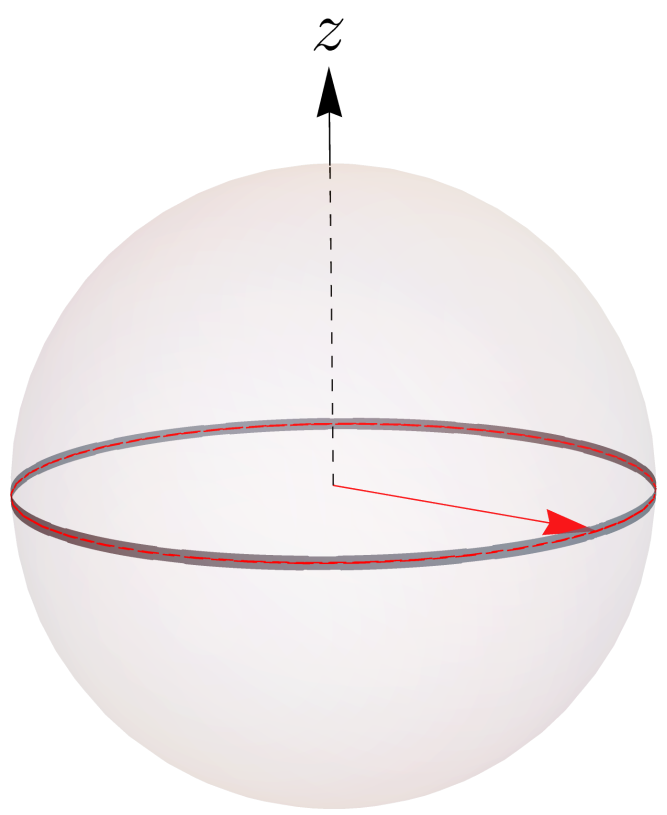

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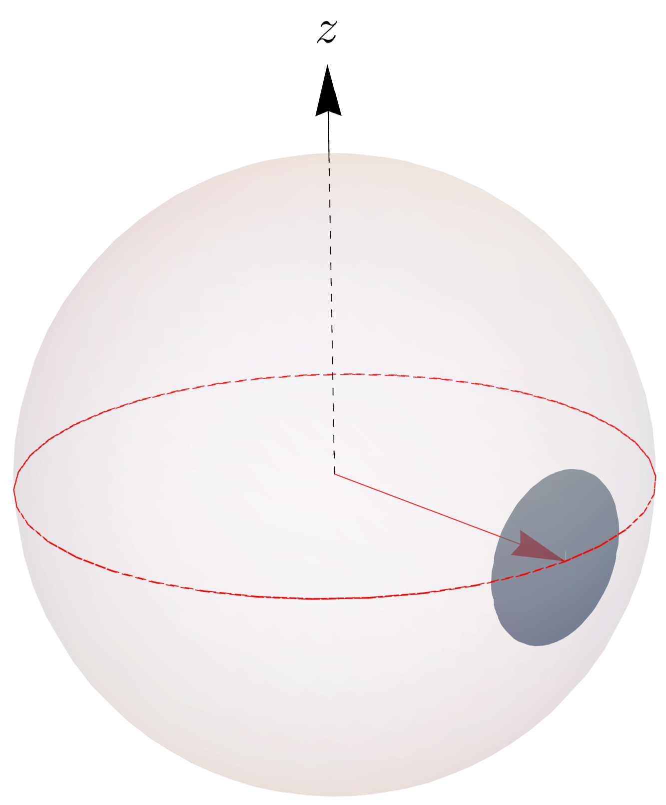

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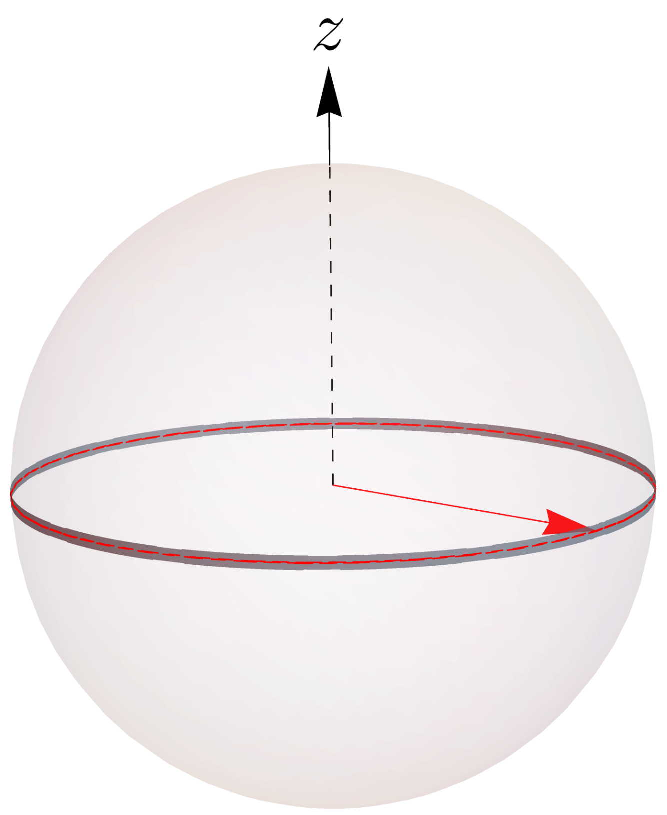

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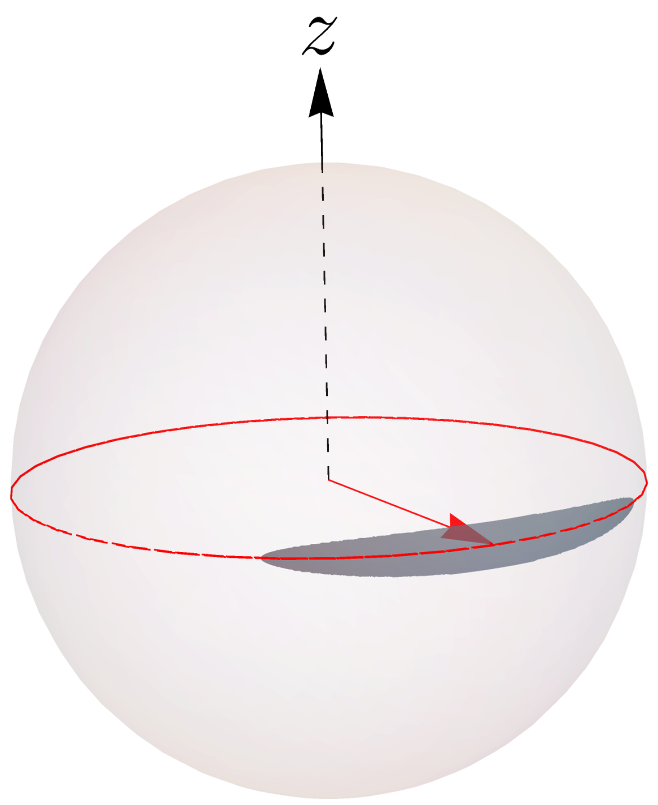

Squeezed state: $\Delta J_z = \sqrt{\xi N}, \quad \xi \ll 1$ Best bet

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Superradiant interactions: **macroscopic** coherence and **change the internal state** of the system

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

Backup

Dark Matter

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

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

Inelastic DM scattering from R=10 cm sphere with $n_s=3\times10^{22}\ \text{cm}^{-3}$