

Title: Superradiant interactions of cosmic noise

Speakers: Marios Galanis

Collection/Series: Particle Physics

Subject: Particle Physics

Date: September 24, 2024 - 1:00 PM

URL: <https://pirsa.org/24090187>

Abstract:

In this talk I will do three things. First, I will outline the conditions under which the interaction rate of inelastic processes with a system consisting of N targets scales as N^2 . Second, I will present computations of interaction rates for several weakly interacting particles, including the Cosmic Neutrino Background and QCD axion dark matter, and will explain the underlying physics. Third, I will introduce new quantum observables that do not rely on net energy transfer, but can still extract these N^2 effects. This talk will not address a concrete experimental proposal, but the effects presented may point to a new class of table-top and ultra-low threshold particle detectors.

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)

PI Particle Seminar - September 24, 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

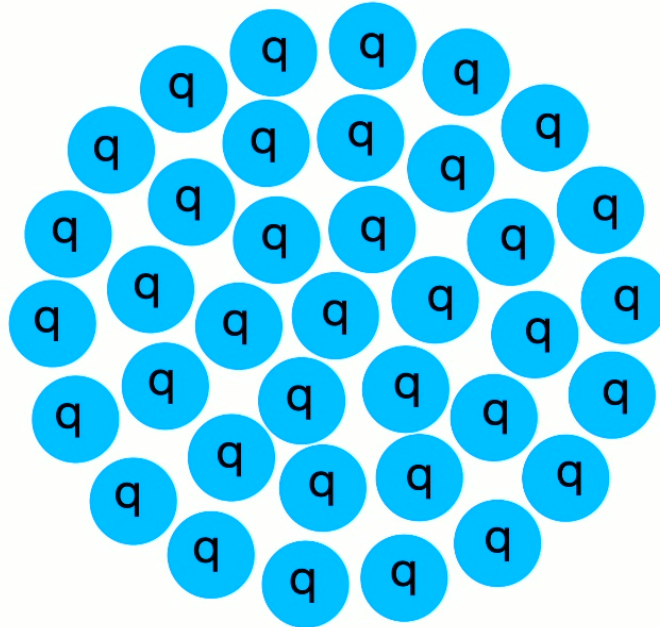
Coherence in Elastic Scattering

Lord Rayleigh

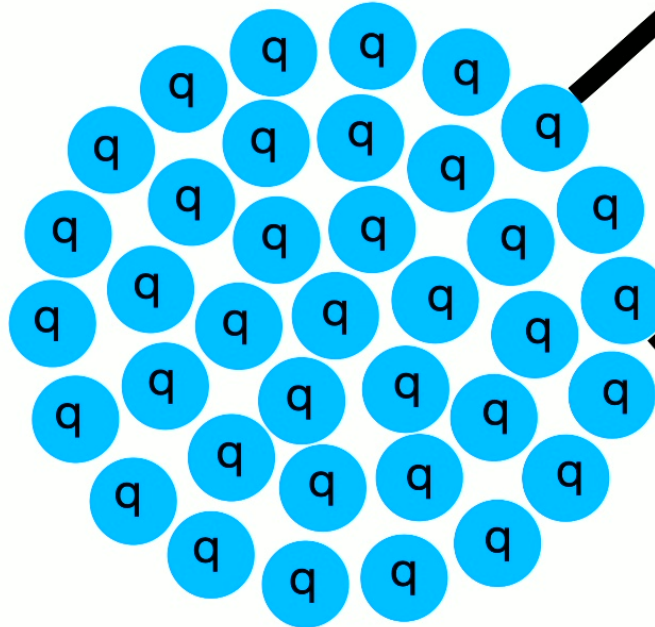
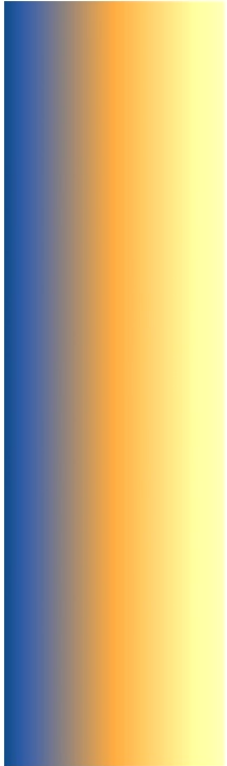


Coherence in Elastic Scattering

Lord Rayleigh



Coherence in Elastic Scattering

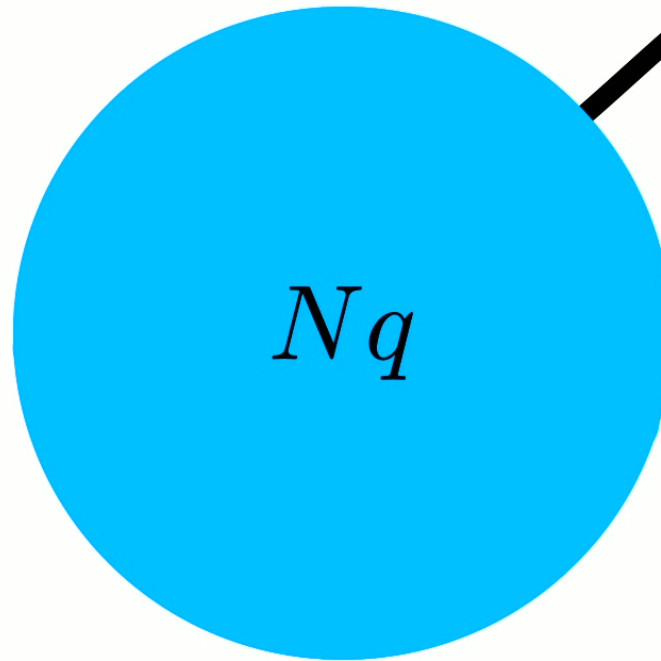
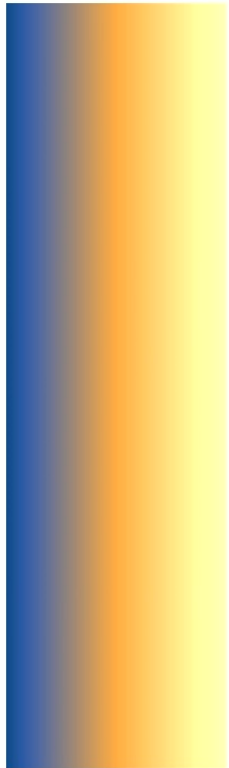


Same phase $\rightarrow$ Coherent

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

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

Coherence in Elastic Scattering

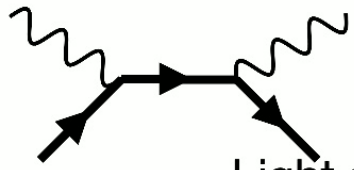


Macroscopic coherence

Same phase $\rightarrow$ Coherent

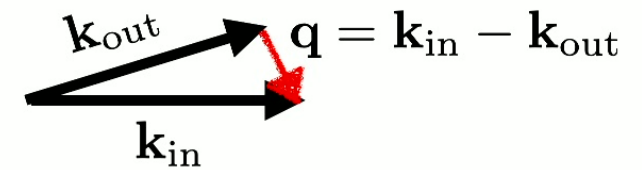
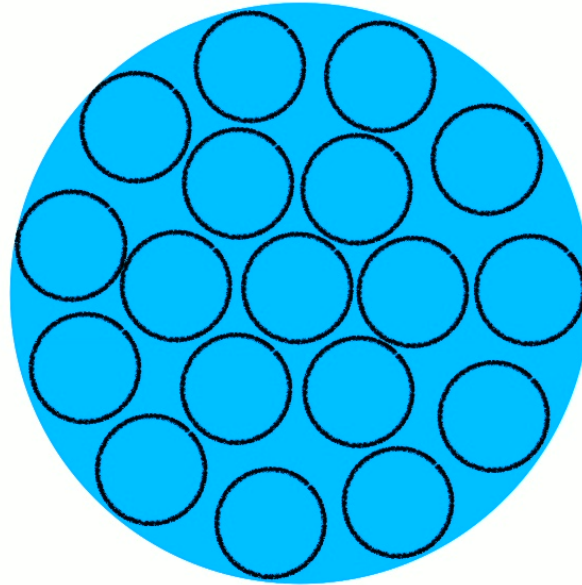
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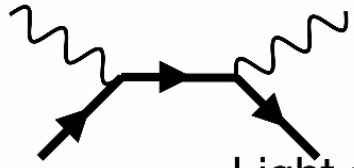
Wavelength smaller than object

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



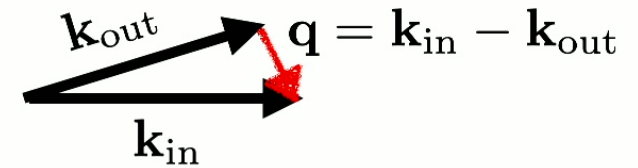
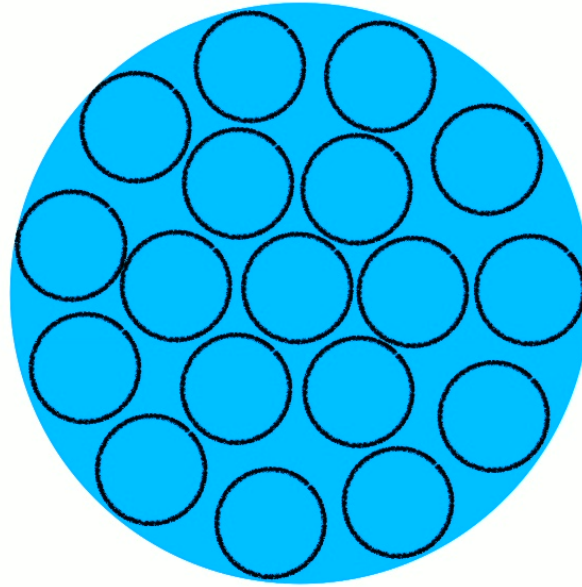
Coherence for a small $d\Omega$ around k_{in}
for which $q \ll R^{-1}$

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



Wavelength smaller than object

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

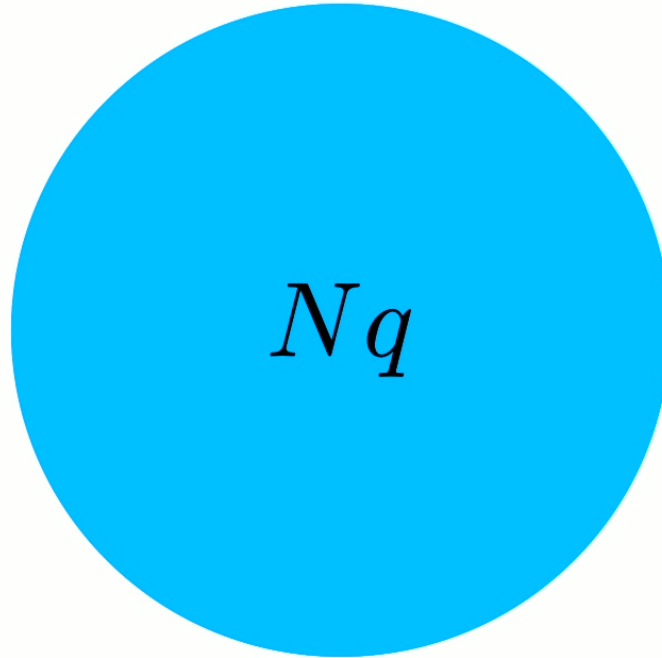


Coherence for a small $d\Omega$ around k_{in}
for which $q \ll R^{-1}$

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

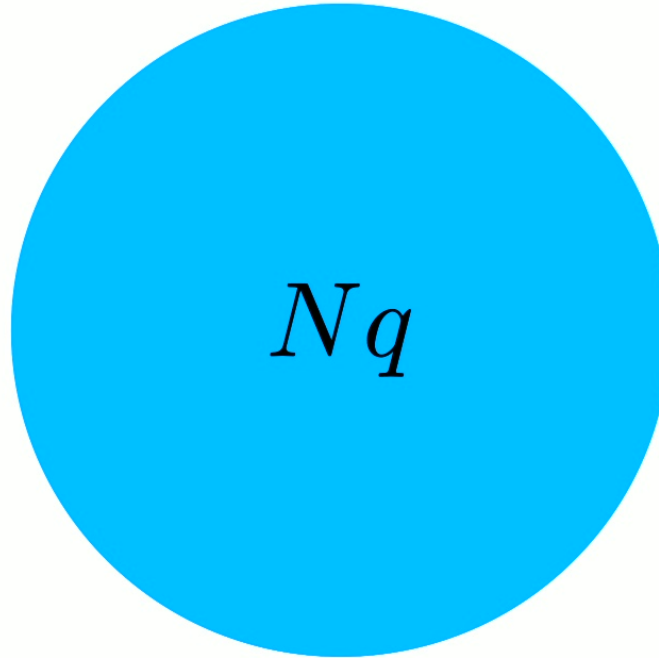
$$\bar{\nu} \gamma^\mu \gamma_5 \nu \rightarrow \bar{u}(\mathbf{k}_{\text{out}}) \gamma^\mu \gamma_5 u(\mathbf{k}_{\text{in}}) e^{-i(\mathbf{k}_{\text{in}} - \mathbf{k}_{\text{out}}) \cdot \mathbf{x}_{\text{spin}}} \xrightarrow{q \ll R} \mathbf{x}_{\text{spin}} - \text{independent}$$

Observable in Elastic Scattering



Macroscopic coherence

Observable in Elastic Scattering



Macroscopic coherence

Momentum Transfer

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

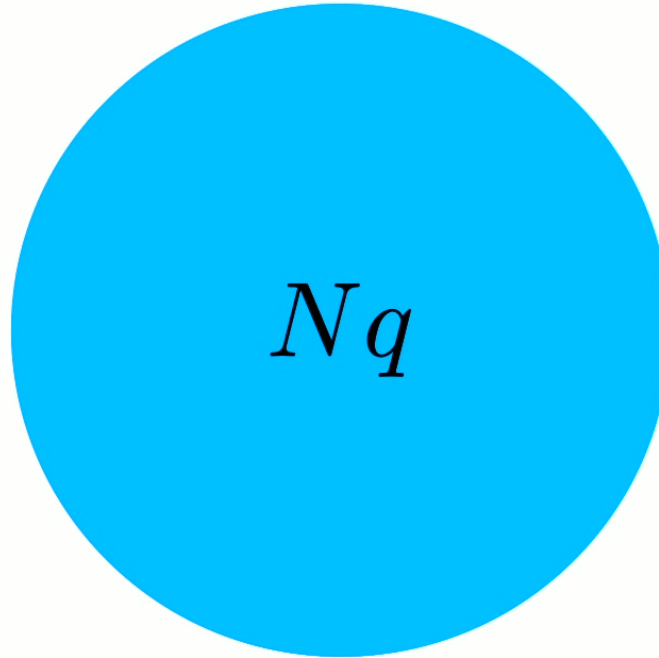
For a 10cm sphere

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/cm³ at 1K:

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

Need appropriate observables

Idea: what if we changed the internal state?

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

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

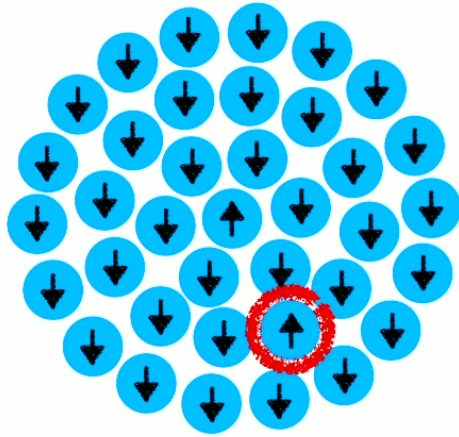
Can we get macroscopic coherence *and* single spin flips?

Then N^2 *and* potential observable



Approves

InCoherence in Inelastic Processes



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

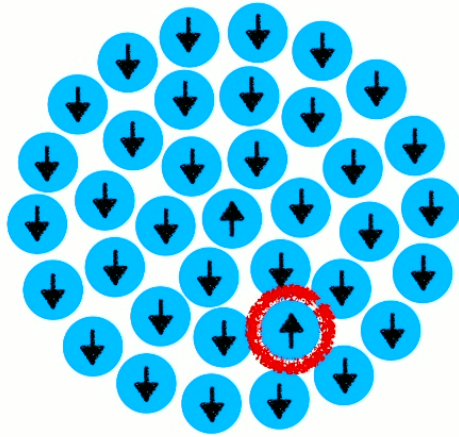
$$\Gamma \sim \left| \begin{array}{c} \text{Diagram 1} + \text{Diagram 2} + \text{Diagram 3} + \dots \end{array} \right|^2 = Nq^2$$

The diagrams in the sum represent different configurations of the cluster where one site is flipped (red upward arrow) and the others are down (black downward arrows). Diagram 1 has the flip at the center, Diagram 2 at a top neighbor, and Diagram 3 at a bottom neighbor.

$$\left\langle \begin{array}{c} \text{Diagram 1} \middle| \begin{array}{c} \text{Diagram 2} \end{array} \right\rangle = \langle \uparrow | \downarrow \rangle \langle \downarrow | \uparrow \rangle = 0$$

The diagrams in the bra and ket represent the same configurations as in the previous equation: Diagram 1 has the flip at the center, and Diagram 2 has the flip at a top neighbor.

InCoherence in Inelastic Processes



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

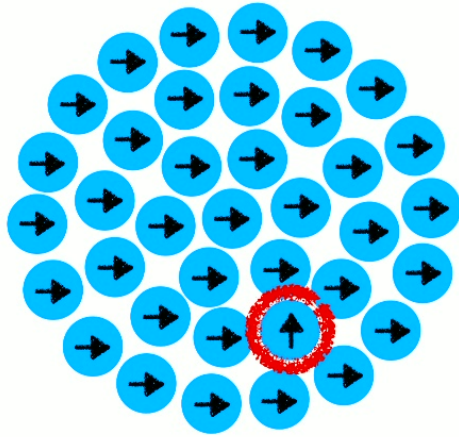
The equation shows the decay rate Γ as the squared magnitude of a sum of diagrams. Each diagram is a cluster of blue circles with mostly downward arrows and one upward arrow in a different position. The first diagram has the upward arrow in the center, the second has it to the right, and the third has it at the bottom right. The sum is squared, and the result is given as Nq^2 .

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

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

The equation shows the inner product of two diagrams. The first diagram has an upward arrow in the center, and the second has an upward arrow to the right. The inner product is calculated as the product of single-site overlaps: $\langle \uparrow | \downarrow \rangle \langle \downarrow | \uparrow \rangle$, which equals zero.

Coherence in Inelastic Processes

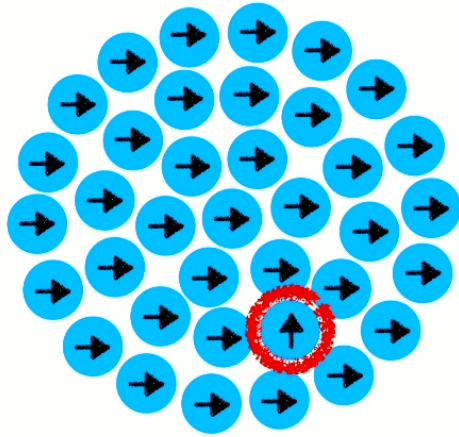


$$\Gamma \sim \left| \frac{1}{\sqrt{2}} \begin{array}{c} \rightarrow \rightarrow \\ \rightarrow \rightarrow \rightarrow \\ \rightarrow \rightarrow \rightarrow \end{array} + \frac{1}{\sqrt{2}} \begin{array}{c} \rightarrow \rightarrow \\ \rightarrow \rightarrow \rightarrow \\ \rightarrow \rightarrow \end{array}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

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

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

Coherence in Inelastic Processes



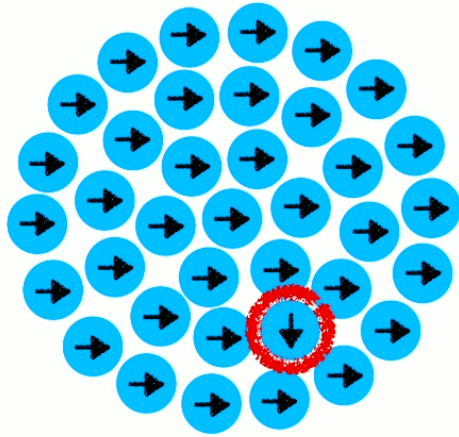
$$\Gamma \sim \left| \frac{1}{\sqrt{2}} \begin{array}{c} \rightarrow \rightarrow \rightarrow \\ \rightarrow \rightarrow \rightarrow \\ \rightarrow \rightarrow \rightarrow \end{array} + \frac{1}{\sqrt{2}} \begin{array}{c} \rightarrow \rightarrow \rightarrow \\ \rightarrow \rightarrow \rightarrow \\ \rightarrow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

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

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

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

Coherence in Inelastic Processes



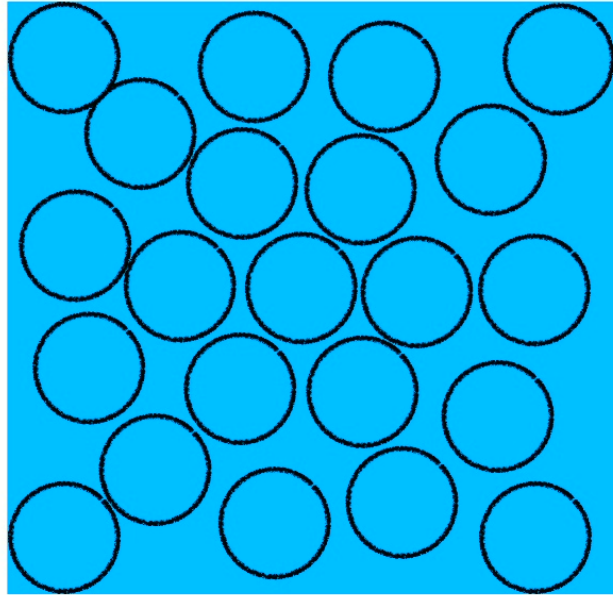
$$\Gamma \sim \left| \frac{1}{\sqrt{2}} \begin{array}{c} \rightarrow \rightarrow \rightarrow \\ \rightarrow \downarrow \rightarrow \\ \rightarrow \rightarrow \rightarrow \end{array} + \frac{1}{\sqrt{2}} \begin{array}{c} \rightarrow \rightarrow \\ \rightarrow \rightarrow \rightarrow \downarrow \\ \rightarrow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

$= \frac{N^2}{4}$
Coherent De-excitation

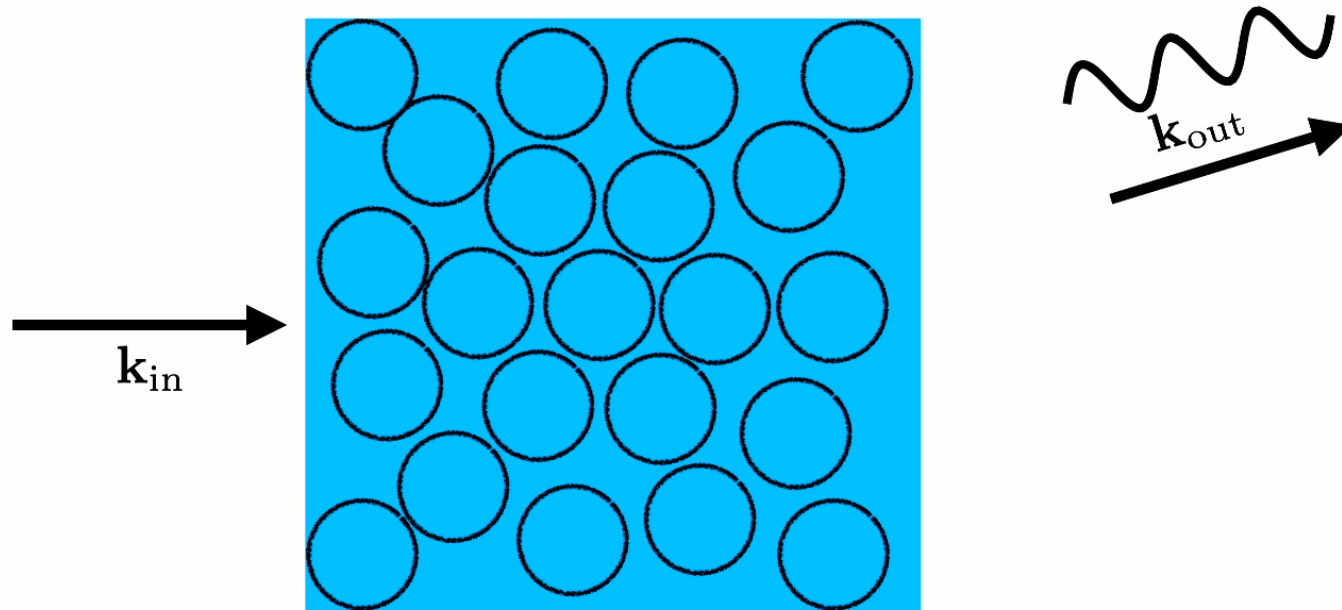
$$|\psi\rangle = \prod \frac{1}{\sqrt{2}} (|g\rangle + |e\rangle)$$

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

Another regime

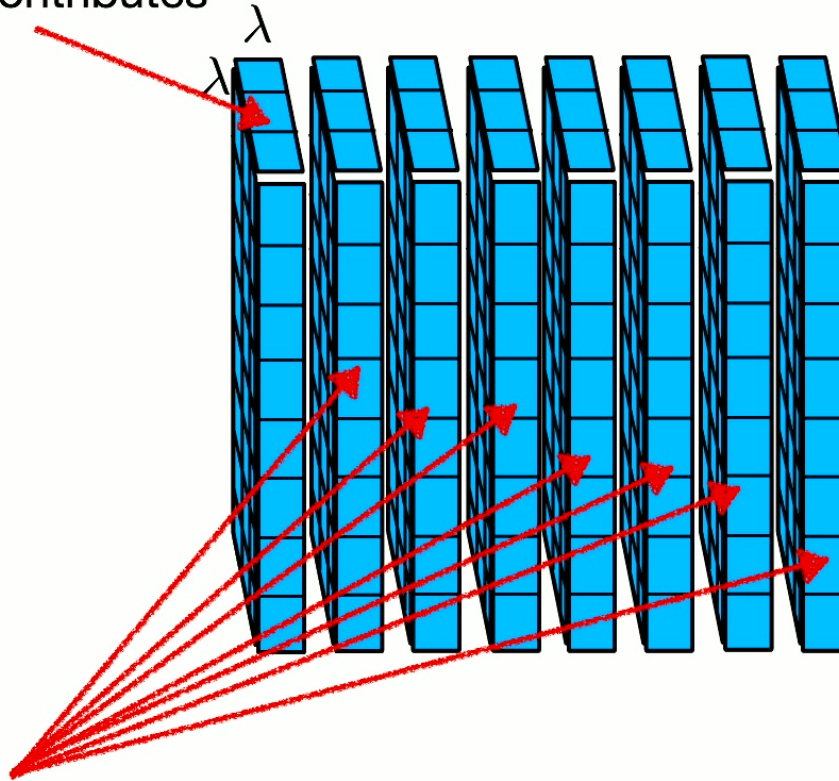


Another regime



Another regime

Only this contributes



These interfere destructively

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

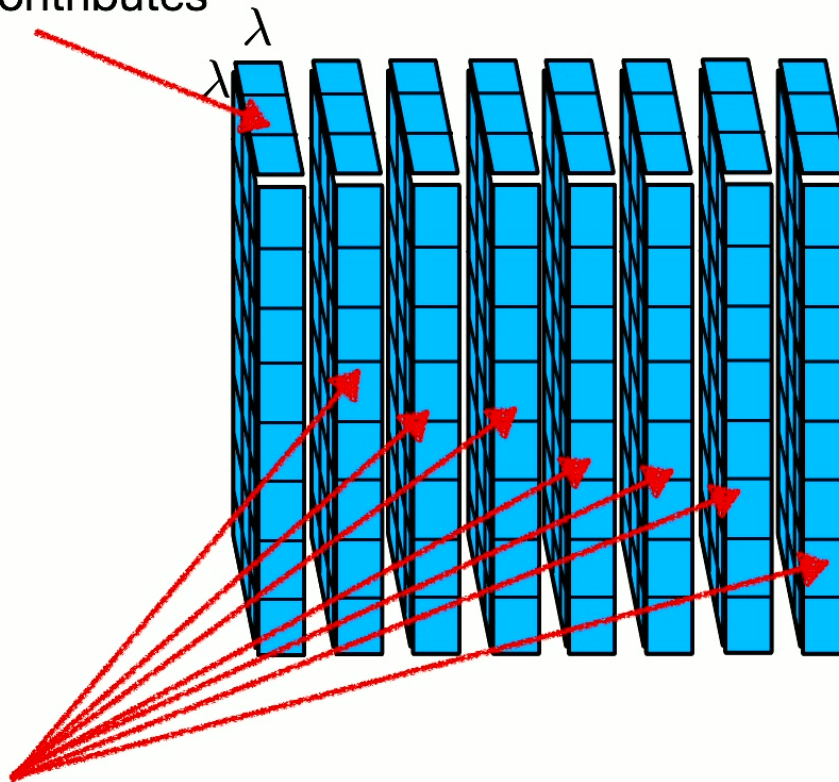
$$q \gtrsim \omega_0/v_{\text{in}}$$

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

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

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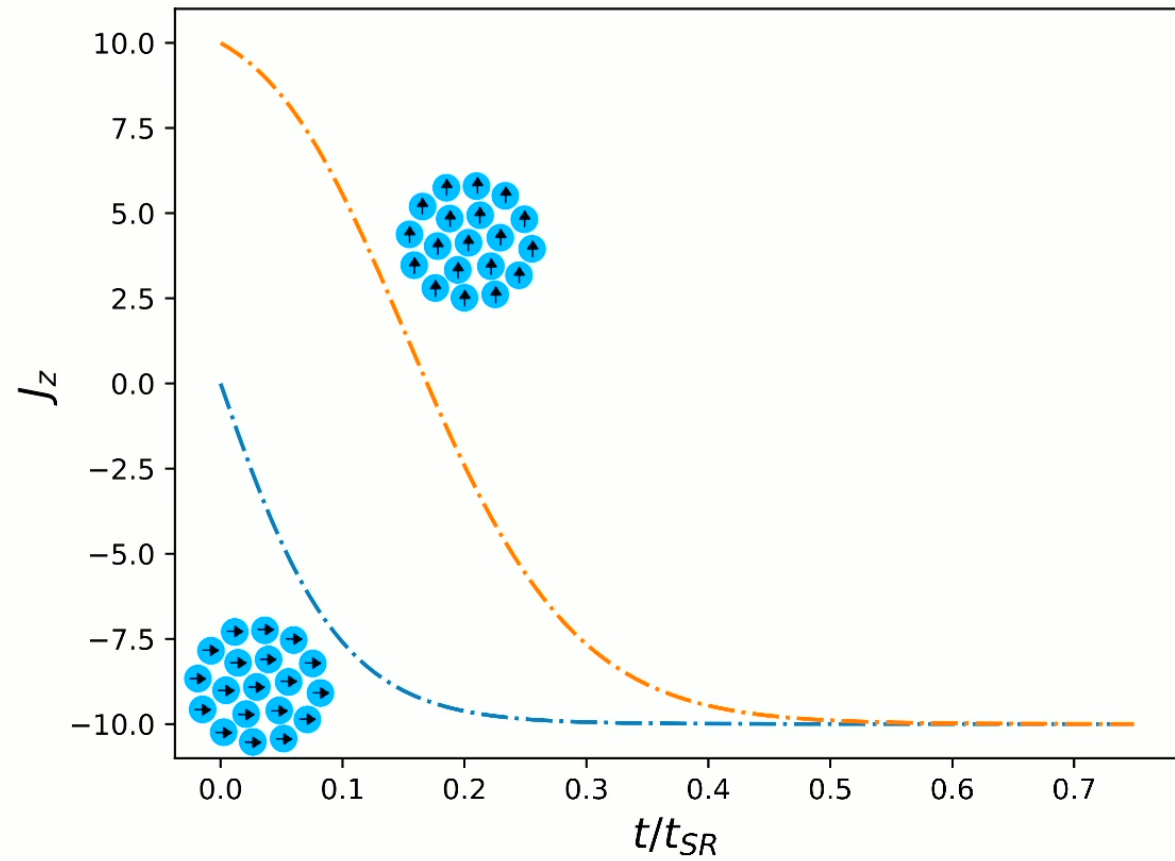
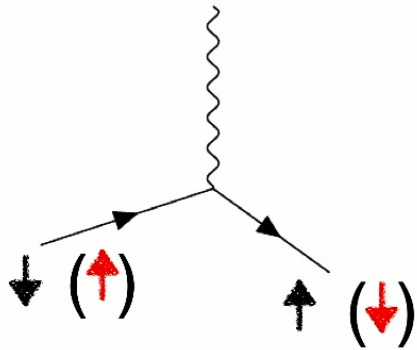
$$q \gtrsim \omega_0/v_{\text{in}}$$

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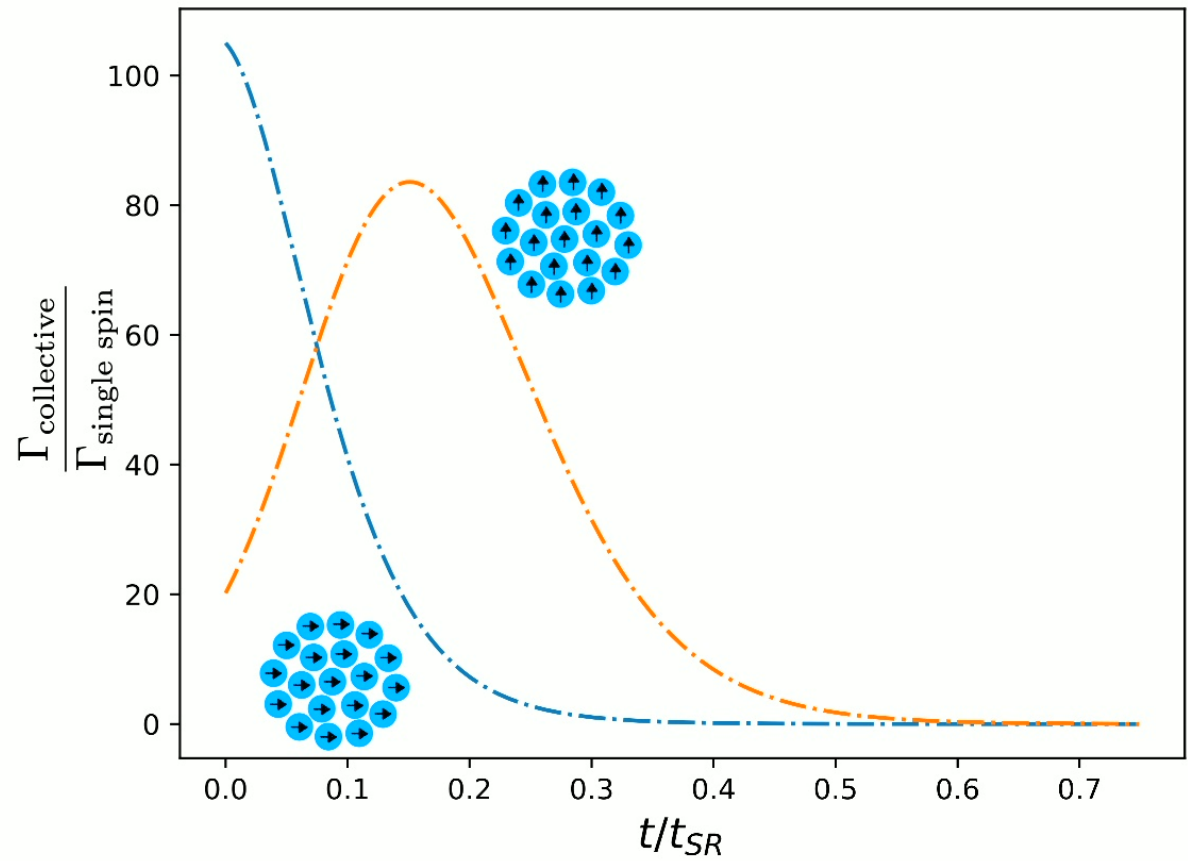
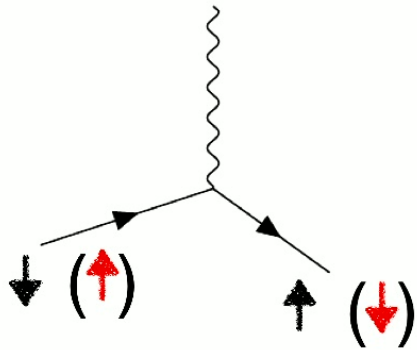
$$\lambda \ll R : \quad \Gamma \propto n^2 \lambda^6 \frac{R^2}{\lambda^2} \sim n^2 \lambda^4 R^2$$

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

Dicke superradiance

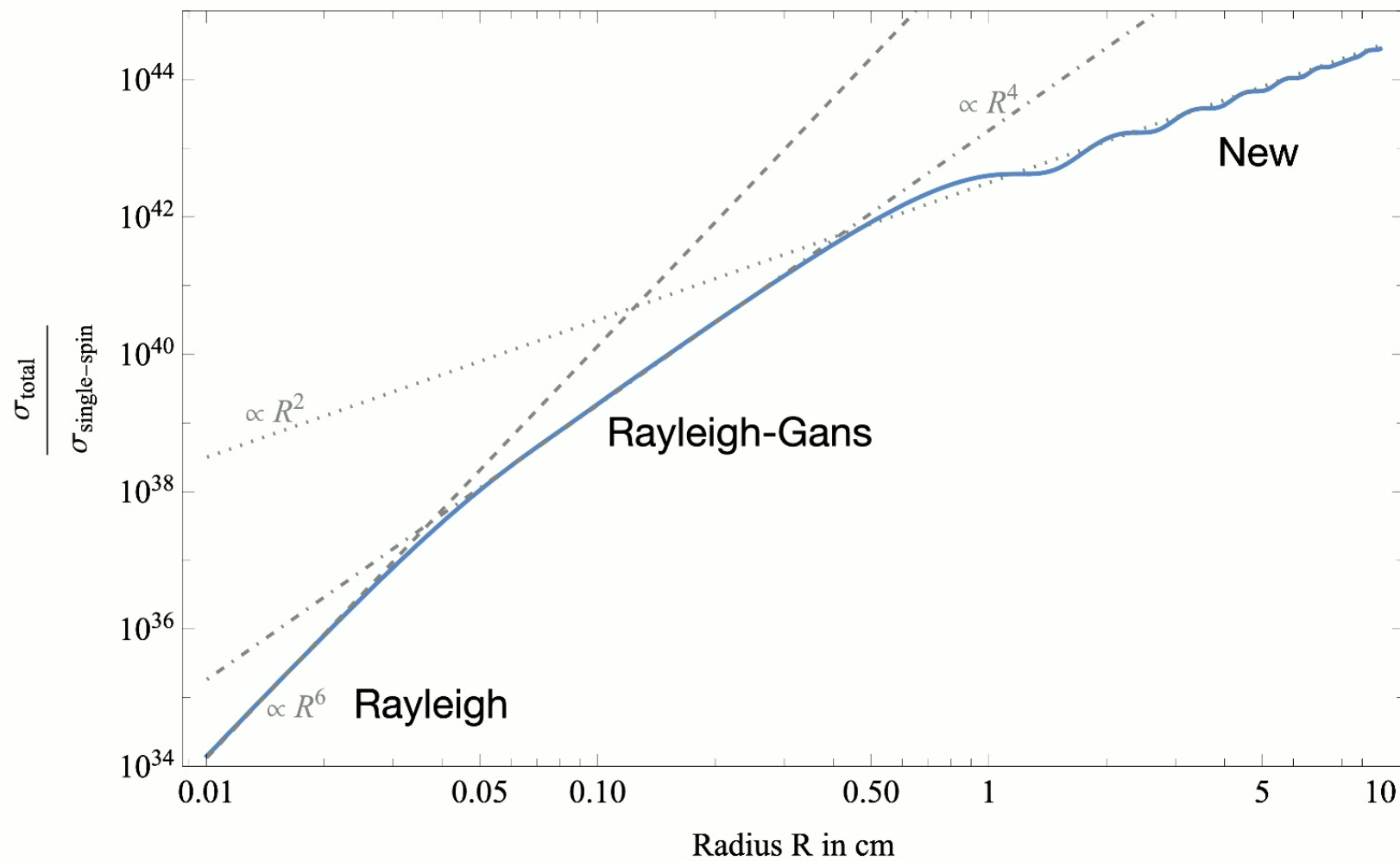


Dicke superradiance



CvB

$$n_s = 3 \times 10^{22} \text{ cm}^{-3}, k_{\text{in}} = \frac{2\pi}{2.1 \text{ mm}}, \text{ and } \omega_0 = 3 \times 10^{-7} \text{ eV}$$



Summary

Inelastic processes need **product states** for coherence

Large energy exchange per interaction

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

Summary

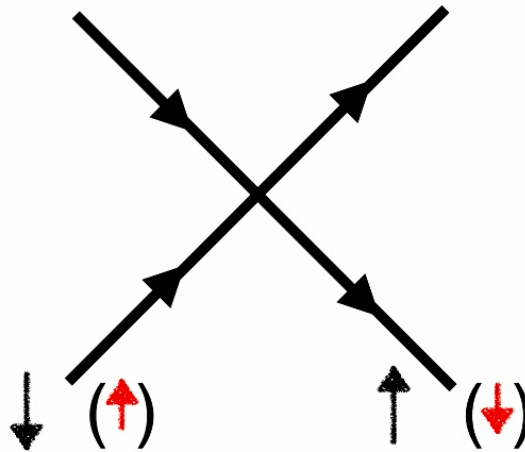
Inelastic processes need **product states** for coherence

Large energy exchange per interaction

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

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

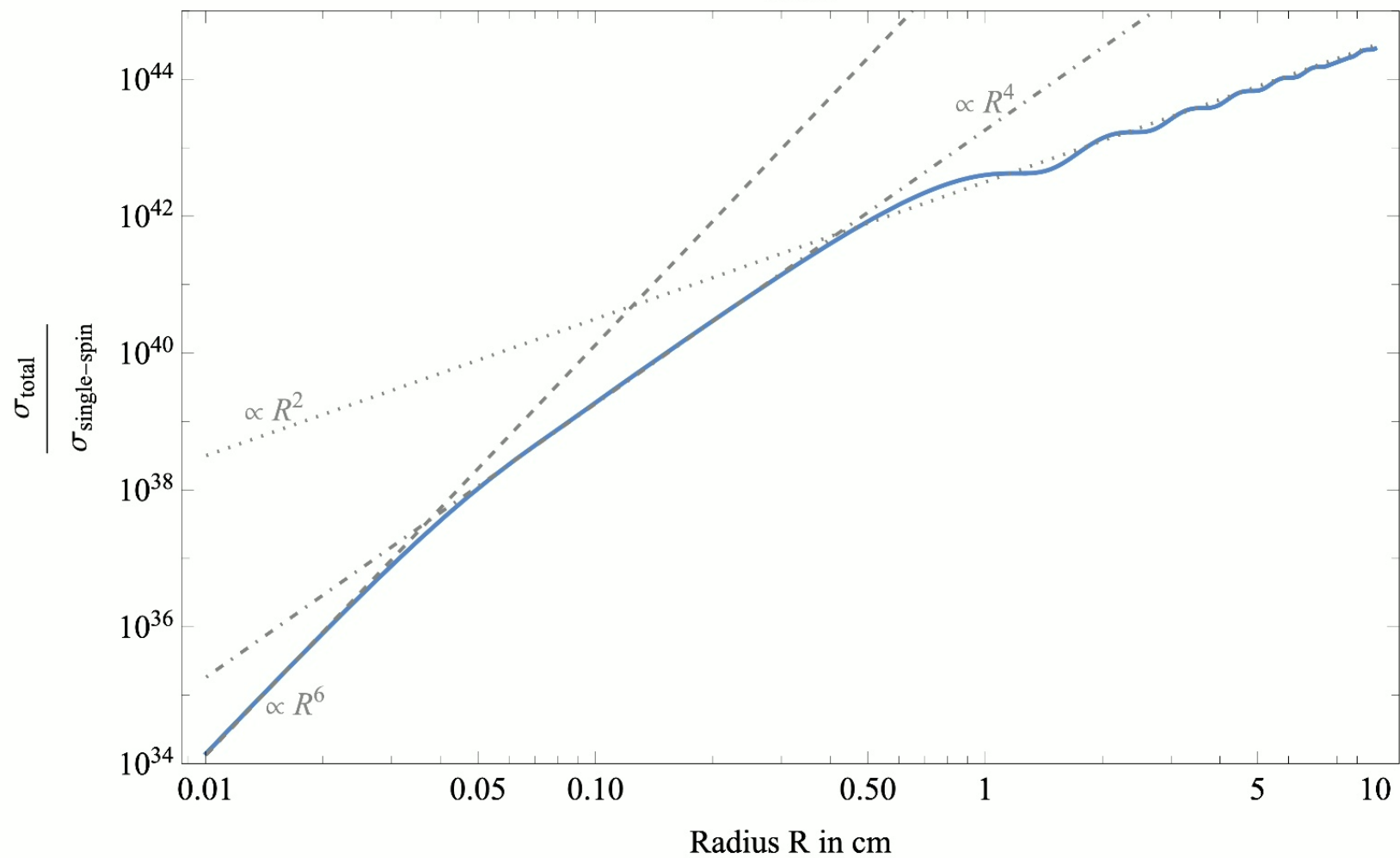
Scattering



The Cosmic Neutrino Background

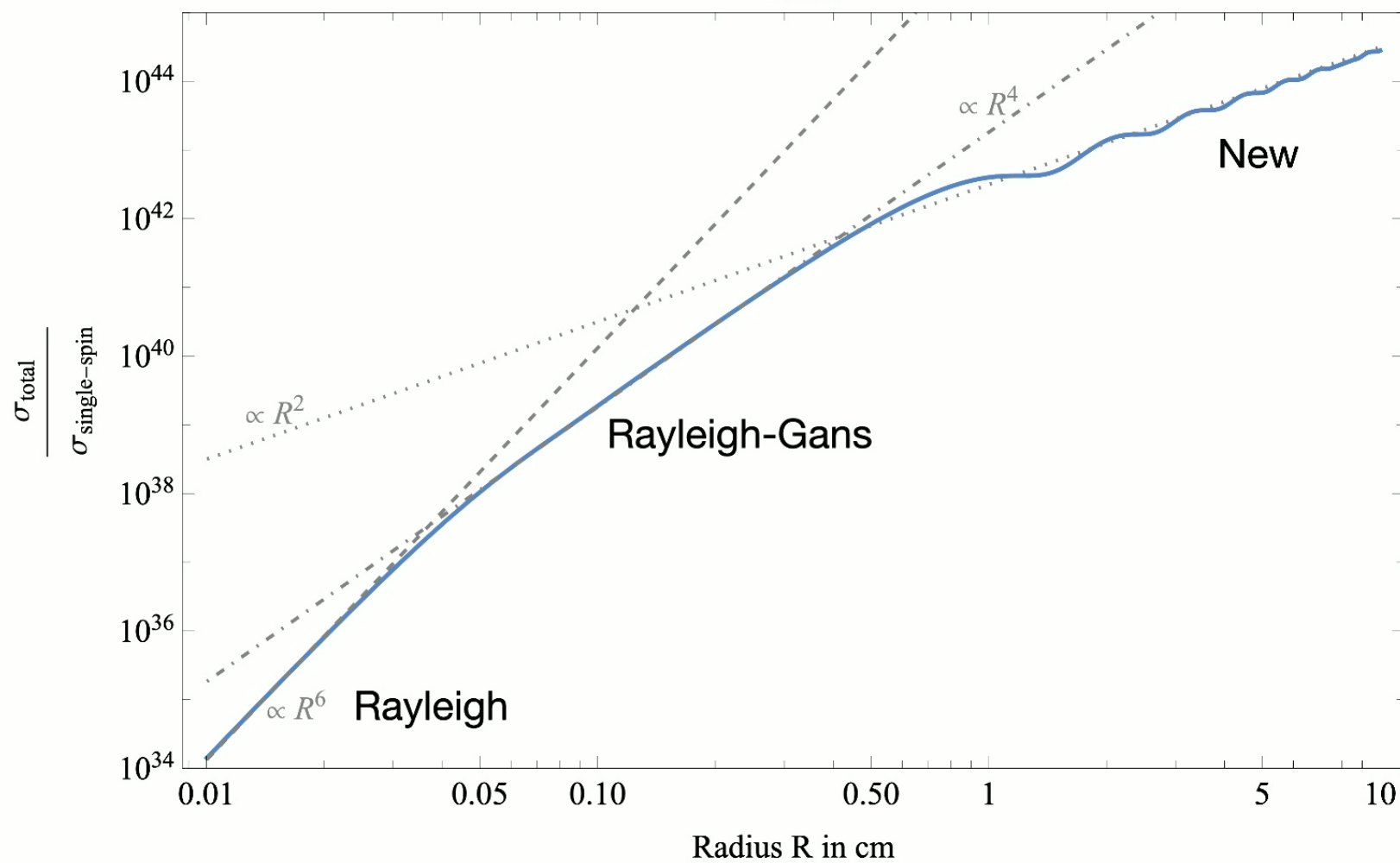
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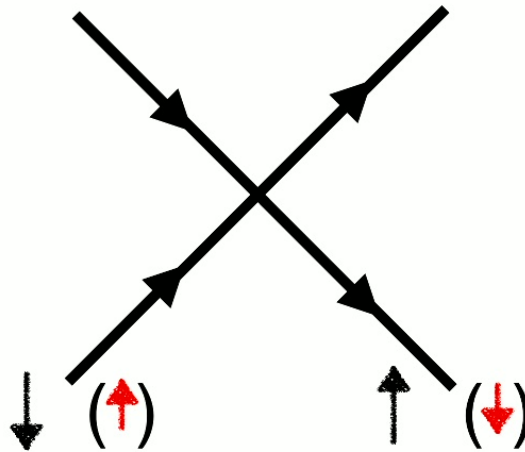


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Scattering



The Cosmic Neutrino Background

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

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

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

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

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

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Consists of three mass eigenstates, evolving independently

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Only source of non-relativistic neutrinos

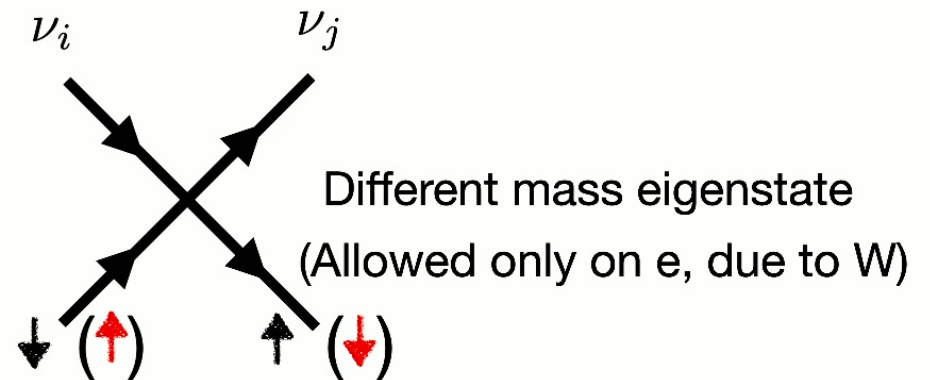
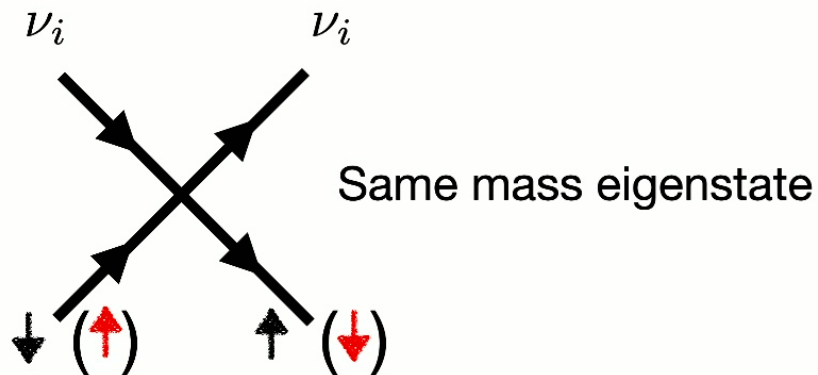
CvB and spin systems

Interaction with any fermionic spin ψ

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

$$H \approx \frac{G_F}{\sqrt{2}}(g_L - g_R)\delta^{(3)}(\mathbf{x}_\nu - \mathbf{x}_\psi)\boldsymbol{\sigma}_\nu \cdot \boldsymbol{\sigma}_\psi$$

PMNS matrix mixes mass eigenstates



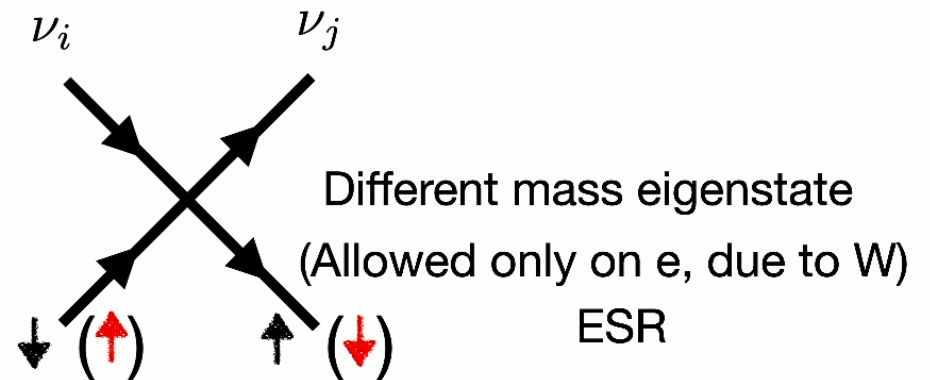
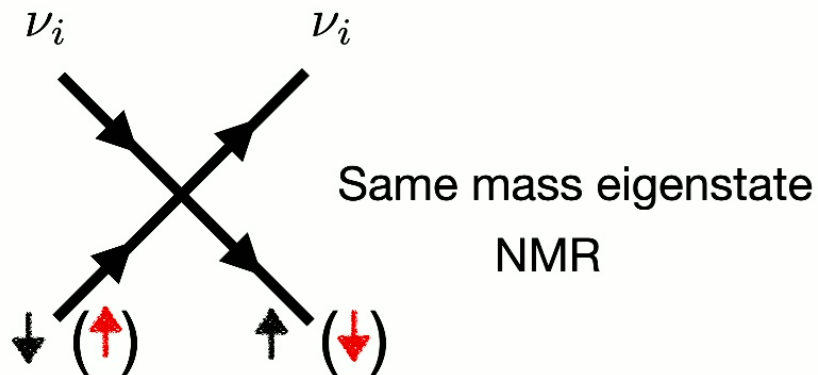
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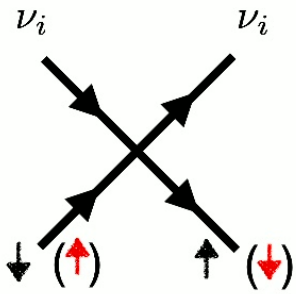
Interaction with any fermionic spin ψ

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

$$H \approx \frac{G_F}{\sqrt{2}} (g_L - g_R) \delta^{(3)}(\mathbf{x}_\nu - \mathbf{x}_\psi) \boldsymbol{\sigma}_\nu \cdot \boldsymbol{\sigma}_\psi$$

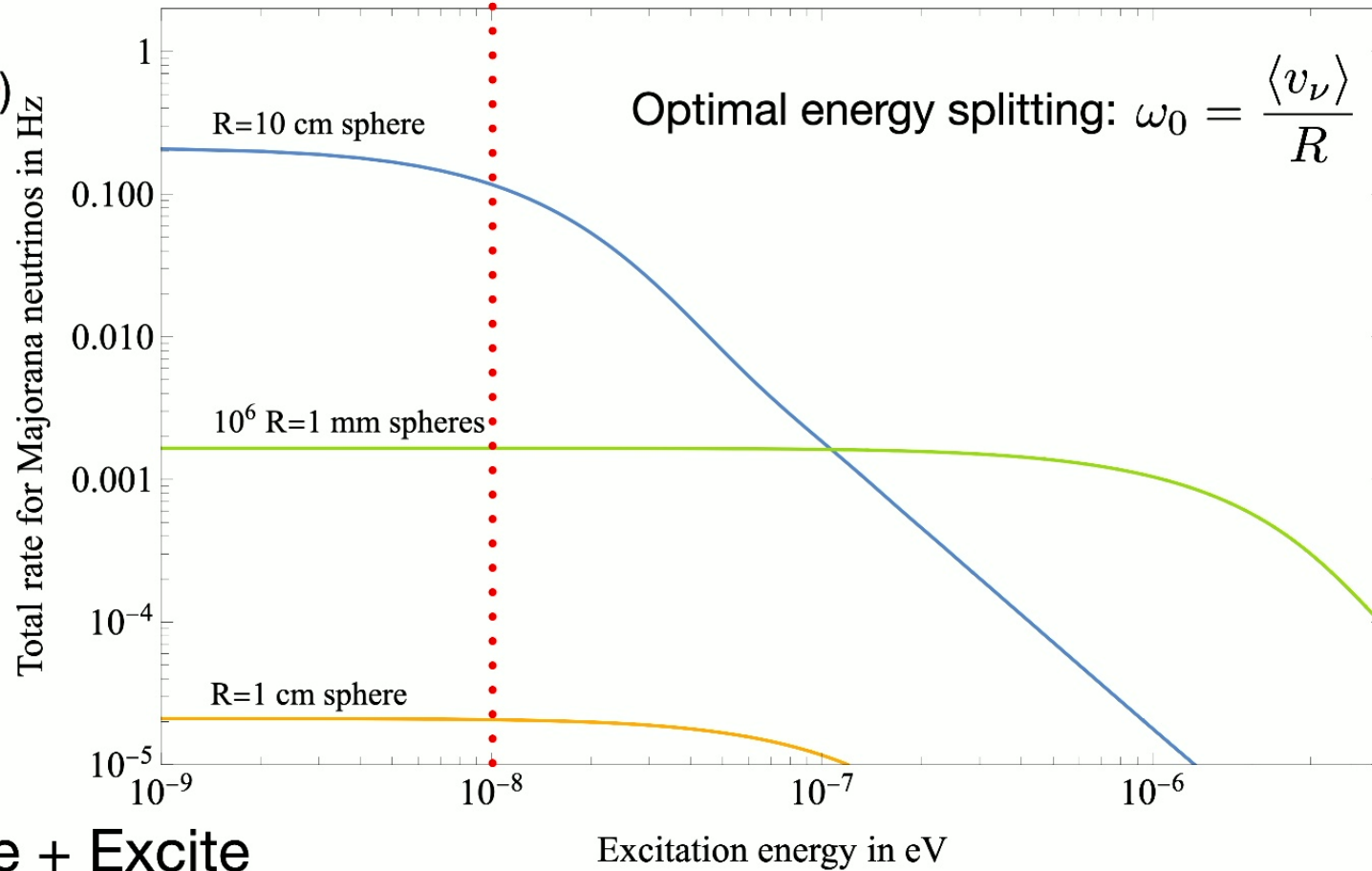
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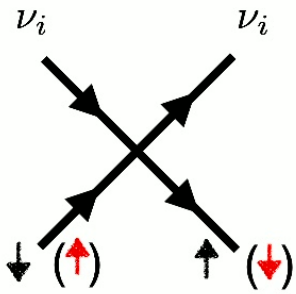


Same mass eigenstate: NMR

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

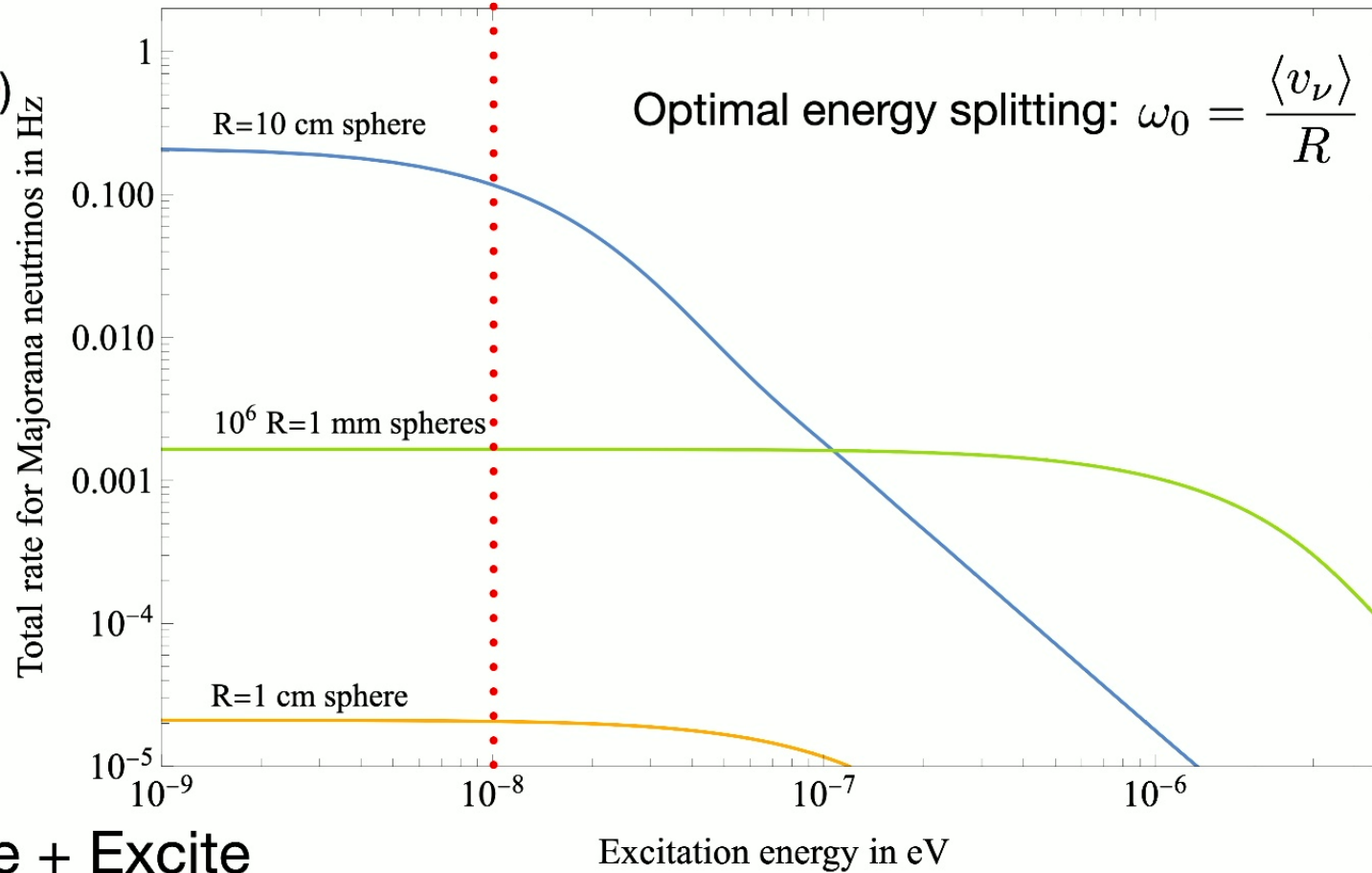


De-excite + Excite

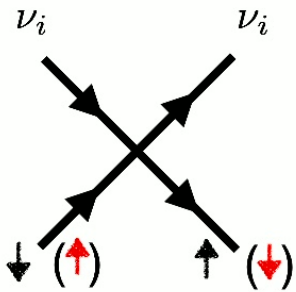


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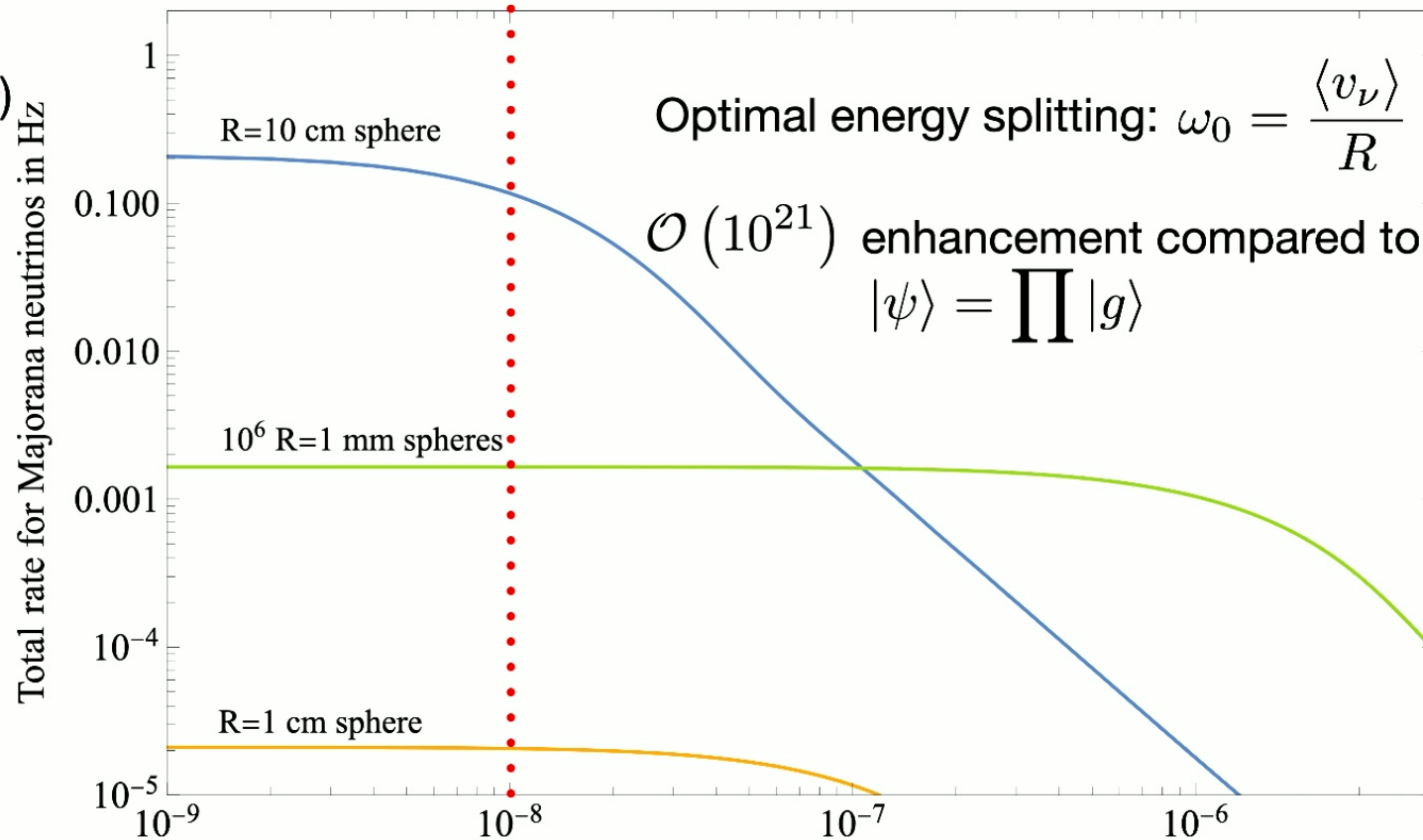


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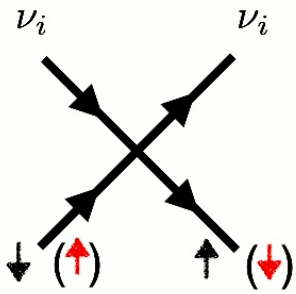


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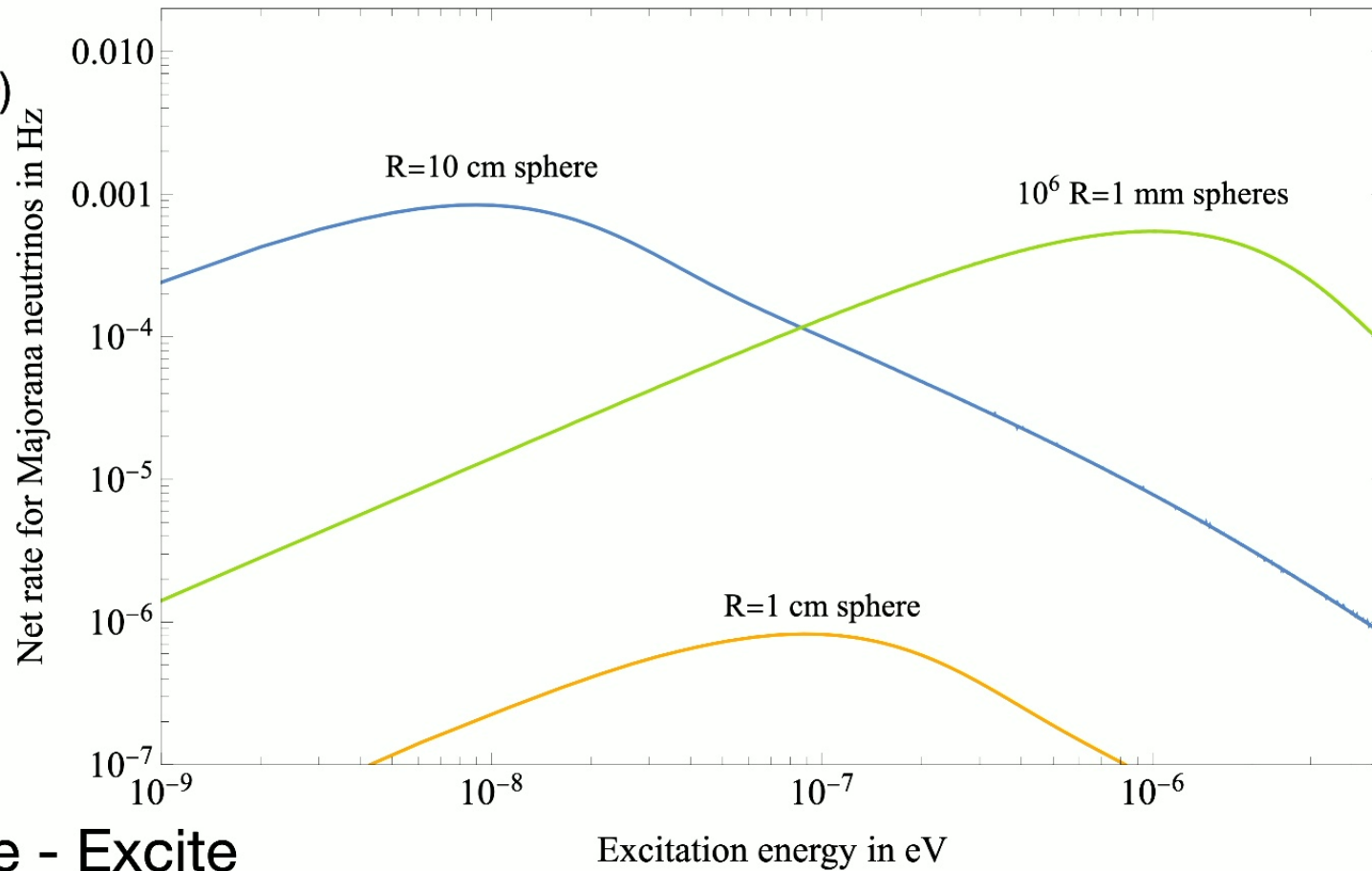


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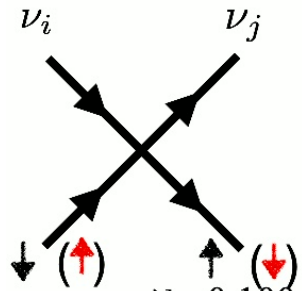
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De-excite - Excite

Different mass eigenstate: ESR

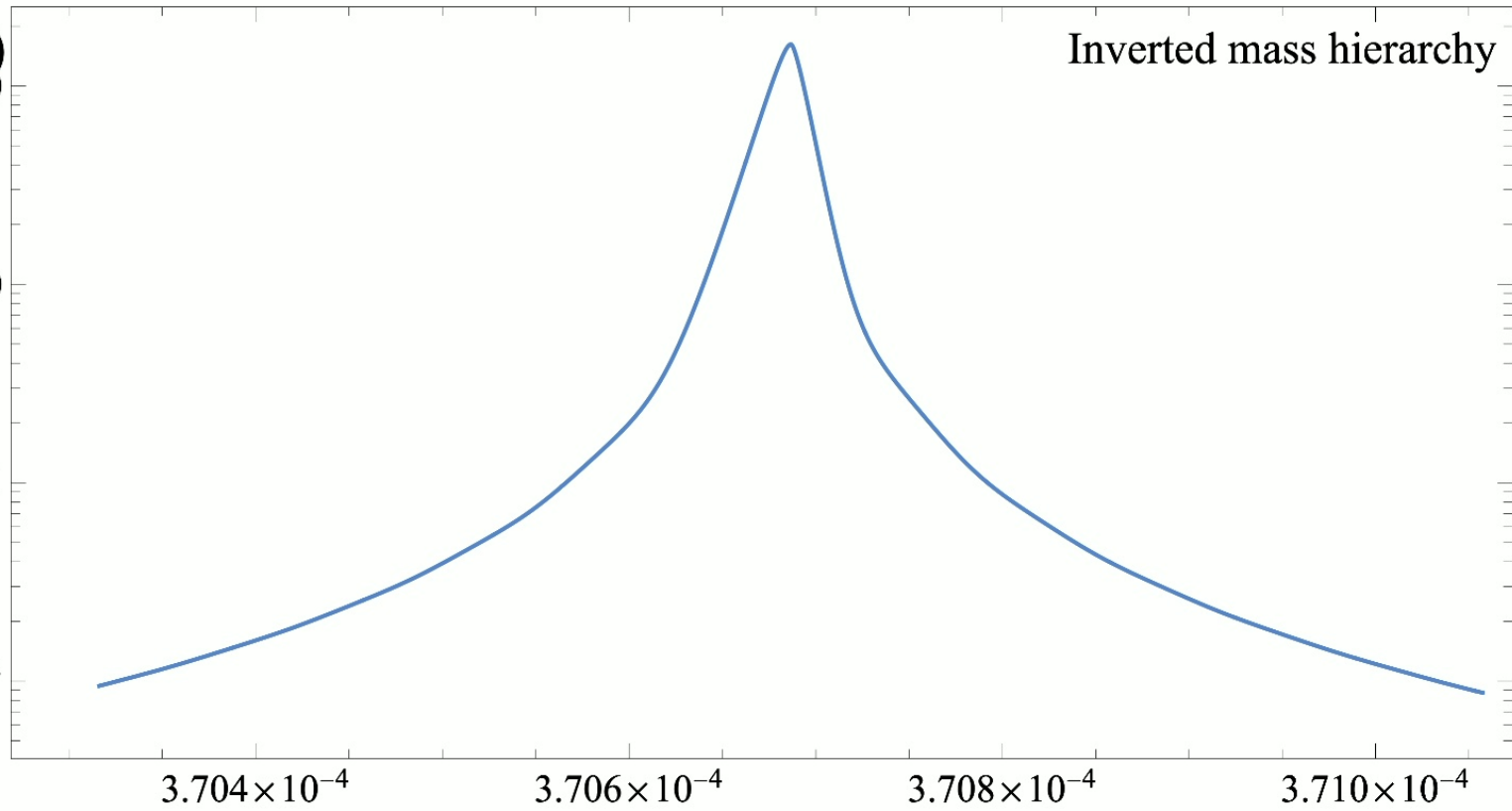
$n_s = 3 \times 10^{22} \text{ cm}^{-3}$, $m_\nu = 0.1 \text{ eV}$ and $R = 10 \text{ cm}$



Total rate for Majorana neutrinos in Hz

0.100
0.010
0.001
 10^{-4}

Inverted mass hierarchy

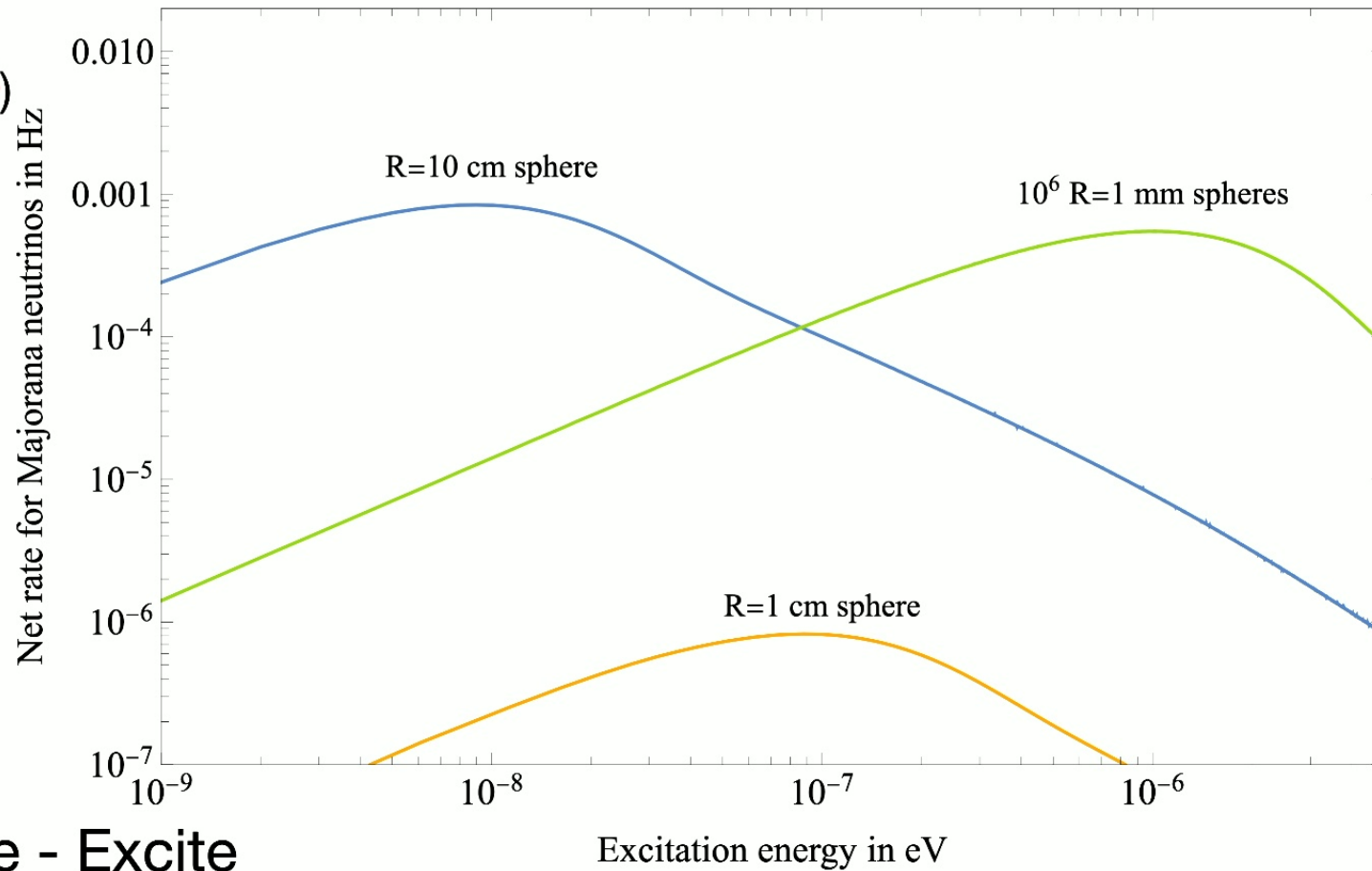
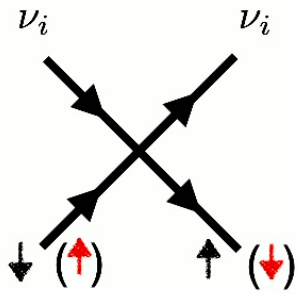


De-excite + Excite

Excitation energy in eV

Same mass eigenstate: NMR

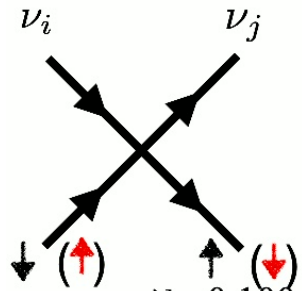
$$n_s = 3 \times 10^{22} \text{ cm}^{-3}$$



De-excite - Excite

Different mass eigenstate: ESR

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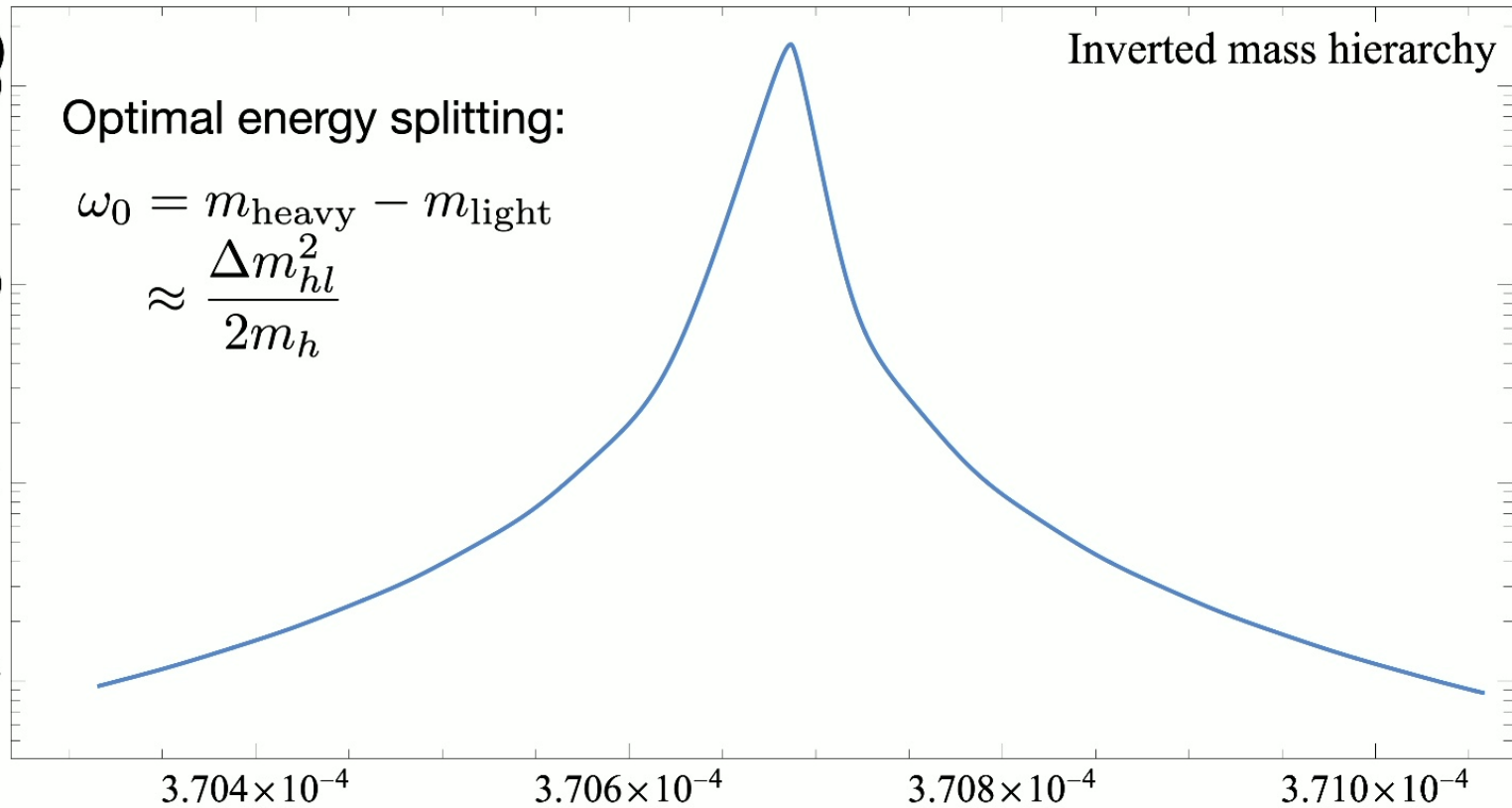


Total rate for Majorana neutrinos in Hz

Optimal energy splitting:

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

Inverted mass hierarchy

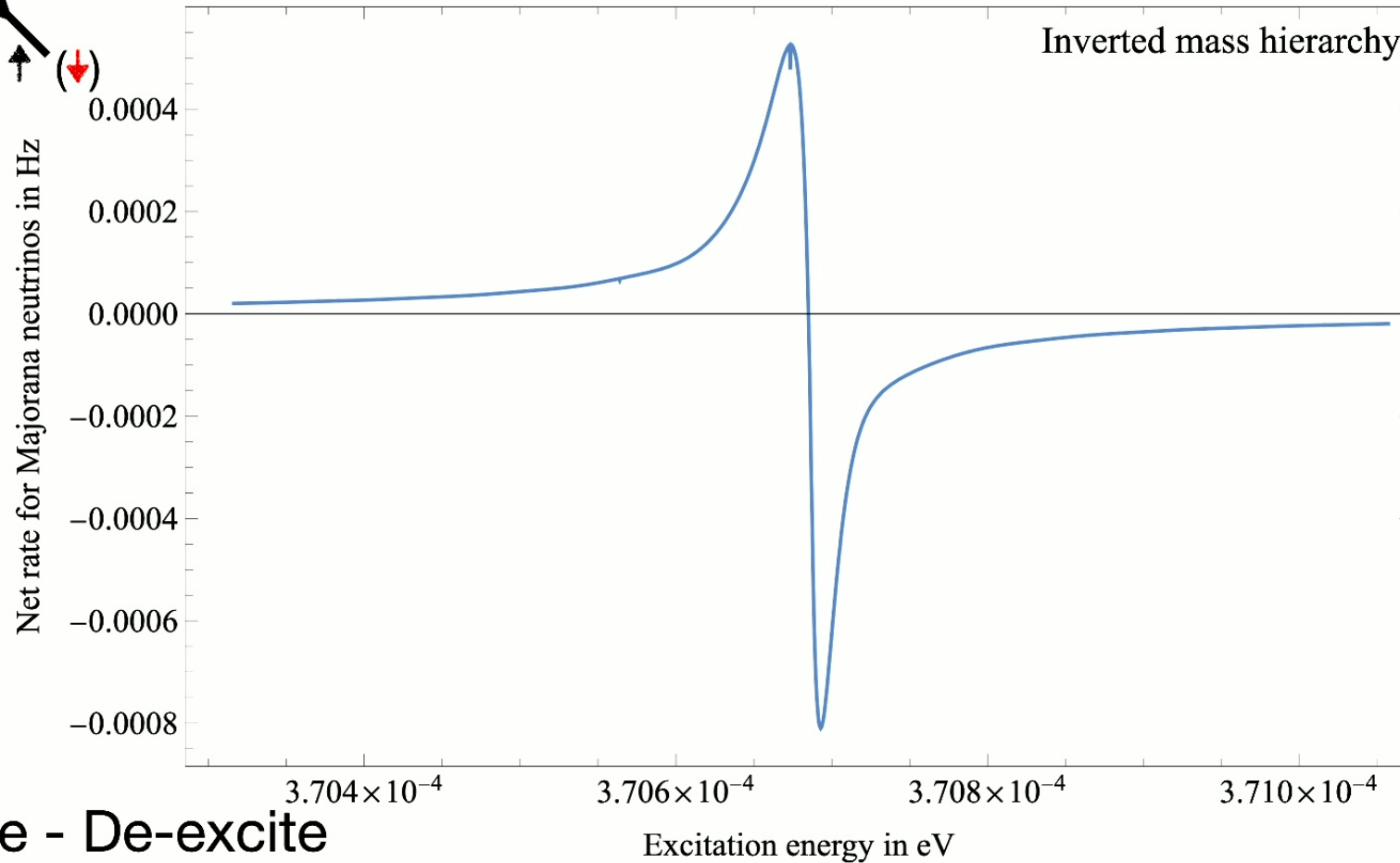


De-excite + Excite

Excitation energy in eV

Different mass eigenstate: ESR

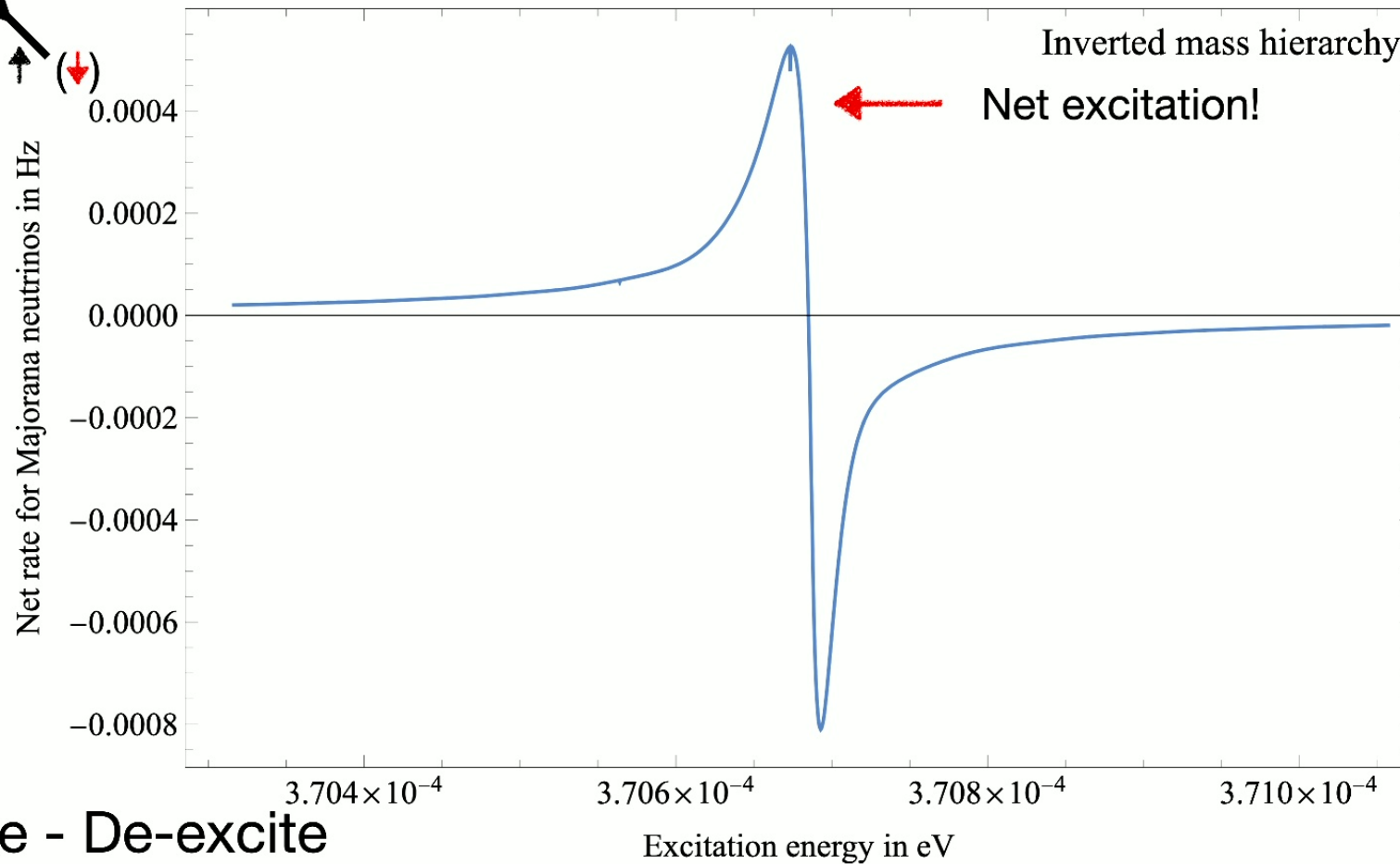
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Excite - De-excite

Different mass eigenstate: ESR

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



Excite - De-excite

Other neutrinos

Rayleigh-Gans regime for relativistic particles

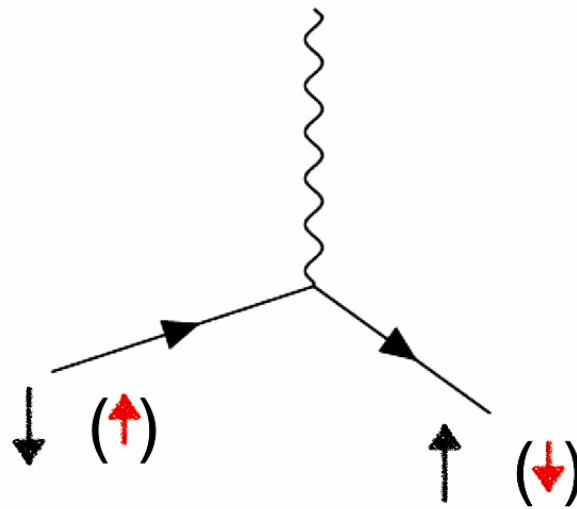
Very suppressed net rates, but total rates:

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

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

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

Absorption or Emission



Other neutrinos

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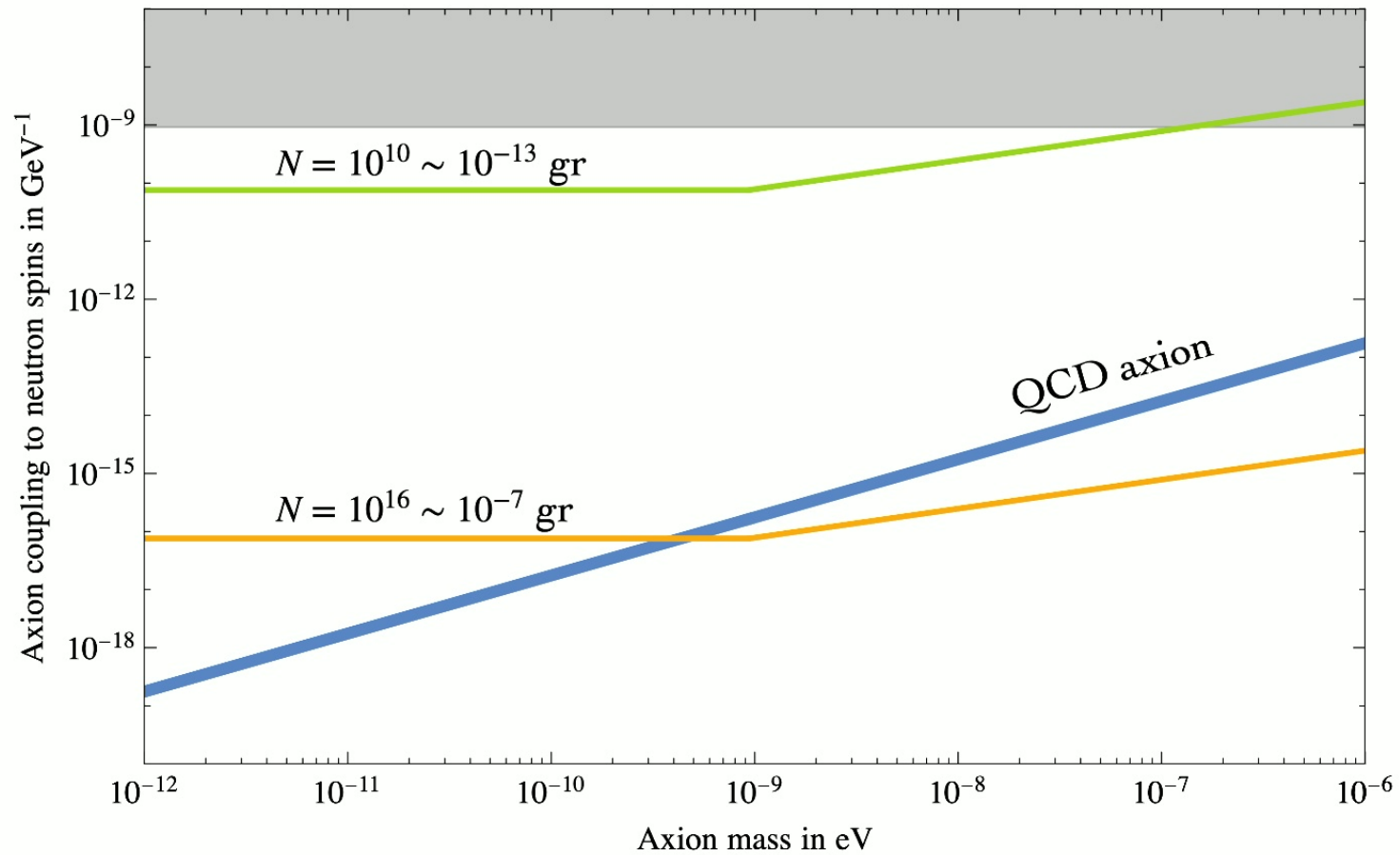
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QCD Axion

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



Dark Quantum Optics

Observables

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

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

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

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

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Spontaneous emission $\rightarrow$ Dicke superradiance

Observables

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

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Net rate zero!

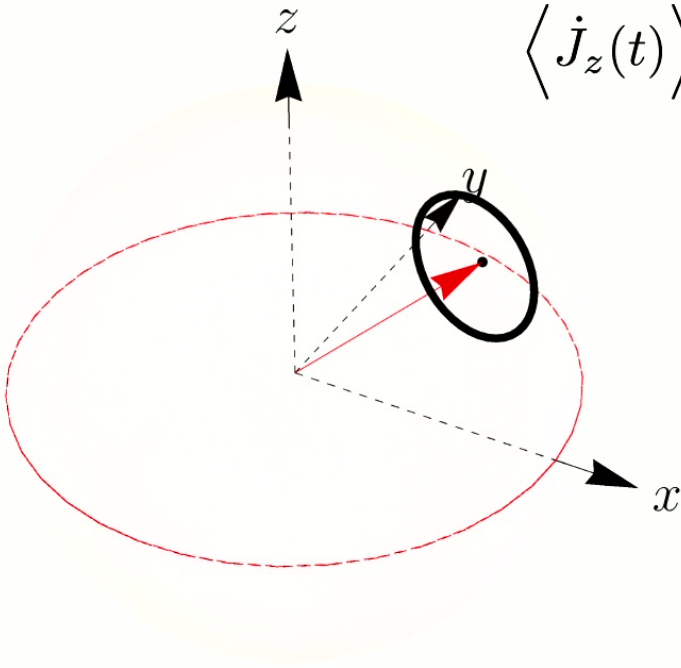
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For example:

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



Observables

Lindblad equation for CvB

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

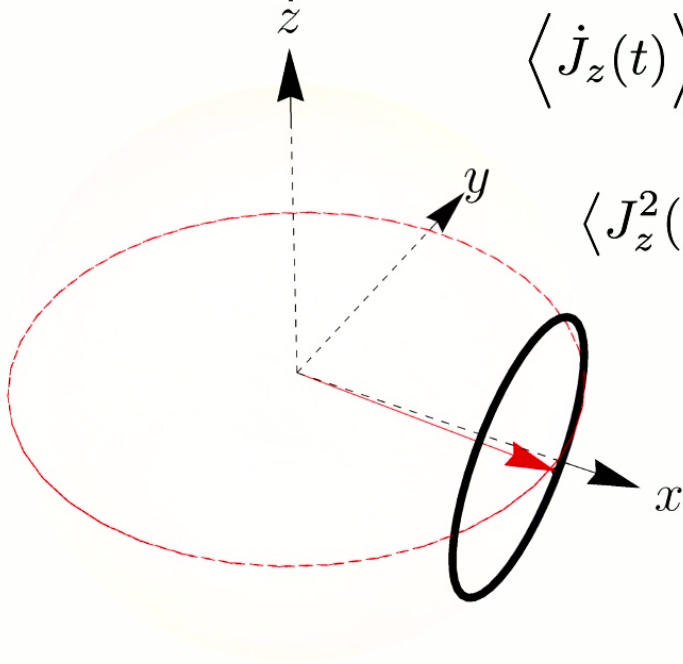
For example:

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Net suppressed

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

Sum of rates



Observables

Lindblad equation for CvB

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

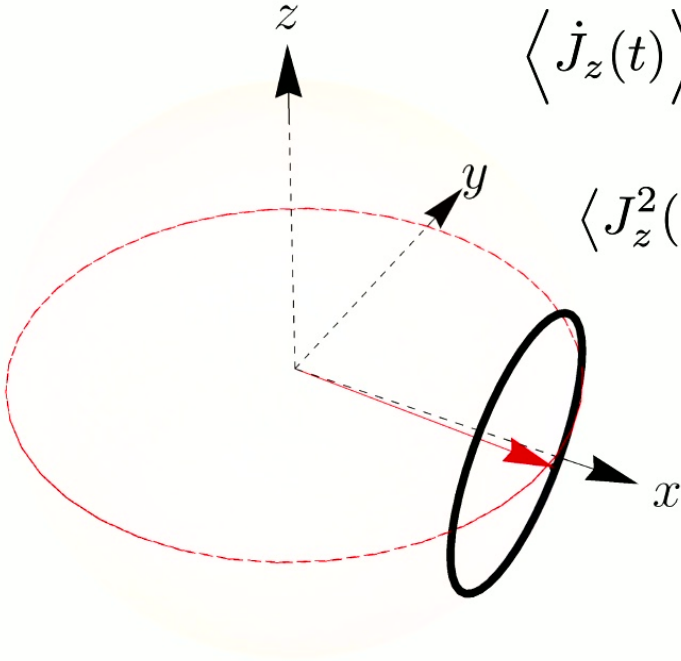
For example:

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Can look for variance change

Need to overcome N



Net energy CvB bound

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

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