10th July 2015
Young Scientist Workshop, Ringberg

Pairing Correlations

A. Kartavtsev, G. Raffelt, and HV

Phys.Rev. D91 (2015), arXiv:1504.03230

Hendrik Vogel
Max Planck Institute for Physics

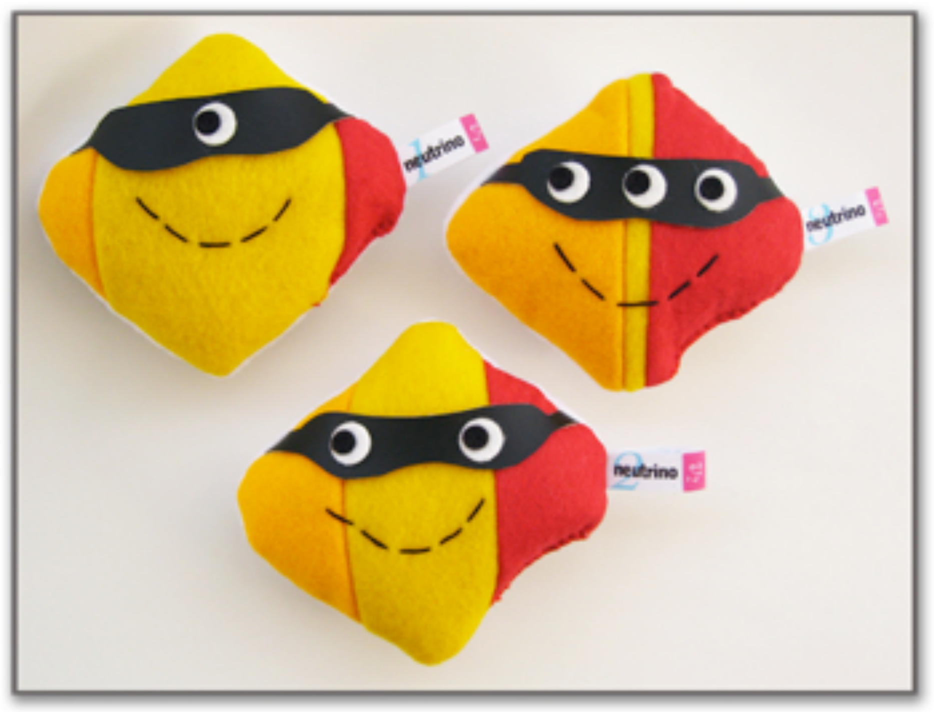
Neutrinos

Interaction eigenstates

ν_e

ν_μ

ν_τ



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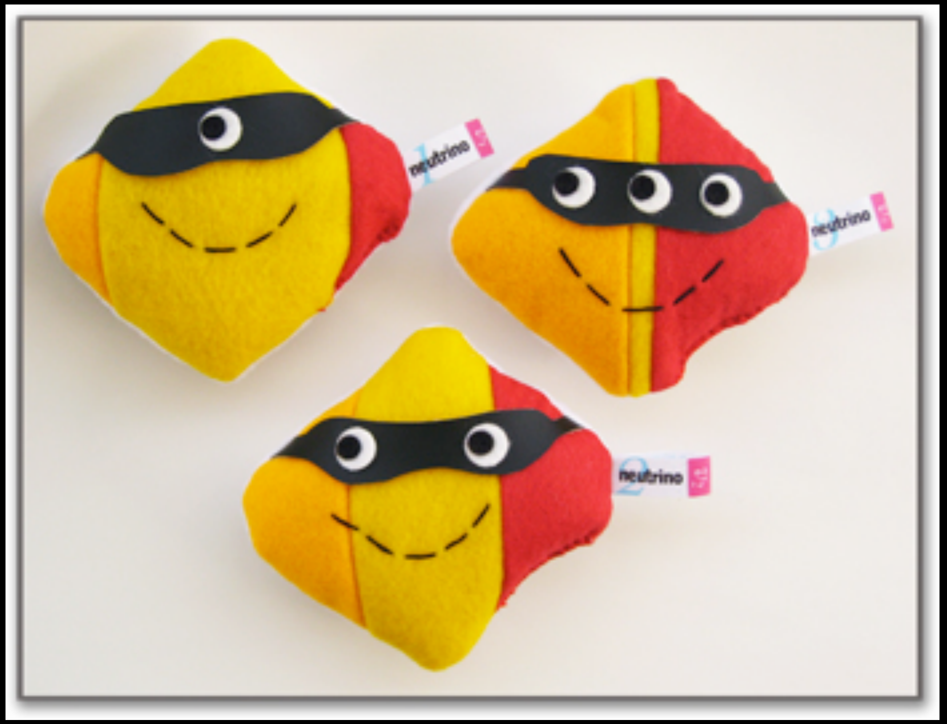
Neutrinos

Interaction eigenstates	Mass eigenstates
ν_e	ν_1
ν_μ	ν_2
ν_τ	ν_3



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Neutrinos

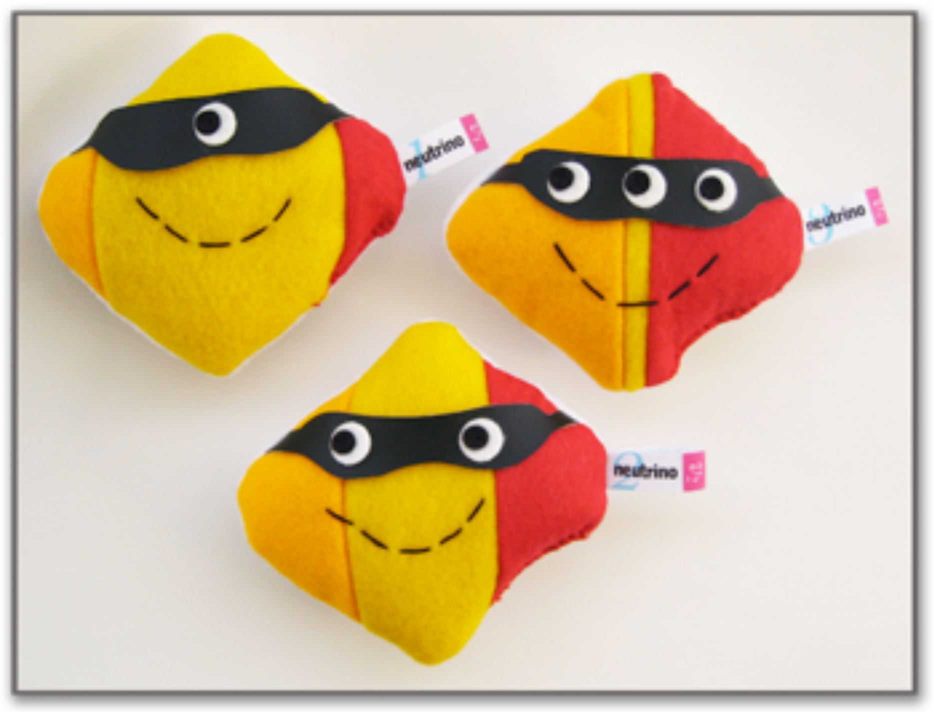
Interaction eigenstates

Mass eigenstates

ν_e ν_μ ν_τ $\longleftrightarrow$ ν_1 ν_2 ν_3

PMNS

Pontecorvo-Maki-Nakagawa-Sakata



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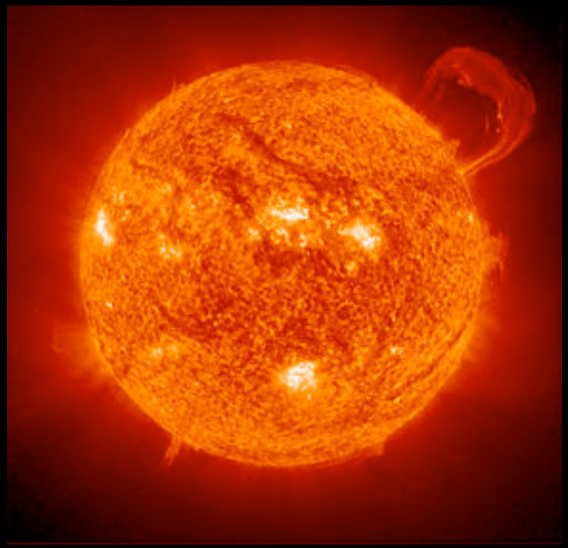
Homestake

$$^{8}\mathrm{B} \rightarrow {}^{8}\mathrm{Be} + e^{+} + \nu_e$$

$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^{-}$$



en.wikipedia.org

nobelprize.org

$$1\nu_e$$

$$1/3\nu_e$$

Survival Probability

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

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$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\theta \, \sin^2 \frac{\Delta m^2 L}{2E}$$

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mixing angle

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mass squared difference

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mass squared difference

distance

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mixing angle

energy

Survival Probability

Vacuum:

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$$P(\nu_e \to \nu_e) = 1 - \sin^2 2\theta \, \sin^2 \frac{\Delta m^2 L}{2E} \to 1 - \frac{1}{2}\sin^2 2\theta > \frac{1}{2}$$

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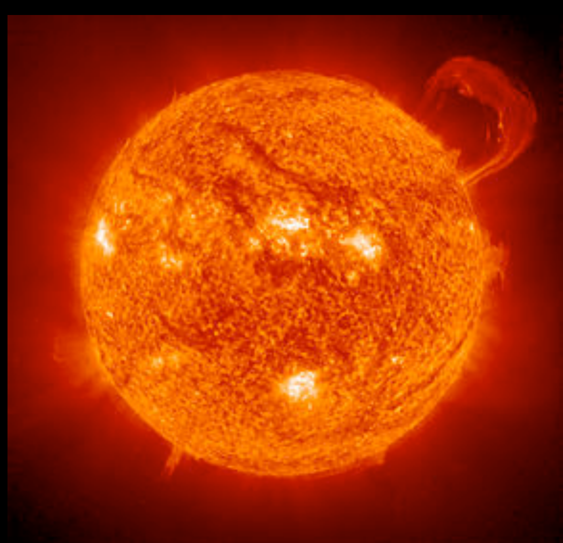

en.wikipedia.org

$$1\nu_e$$

$$e^{iE_1 t}\nu_1 + e^{iE_2 t}\nu_2 + e^{iE_3 t}\nu_3$$

www.particlezoo.net

$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^{-}$$

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MSW effect

Wolfenstein (1978), Mikheyev & Smirnov (1986)

Vacuum:

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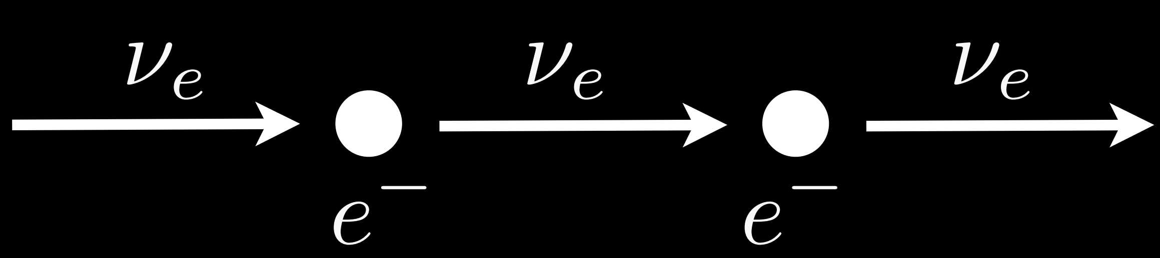
Medium:



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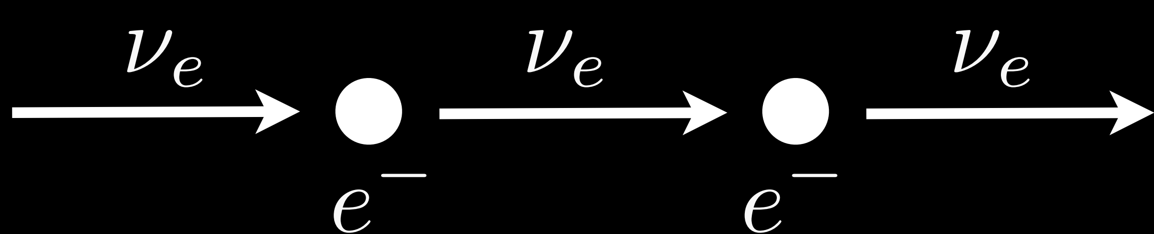
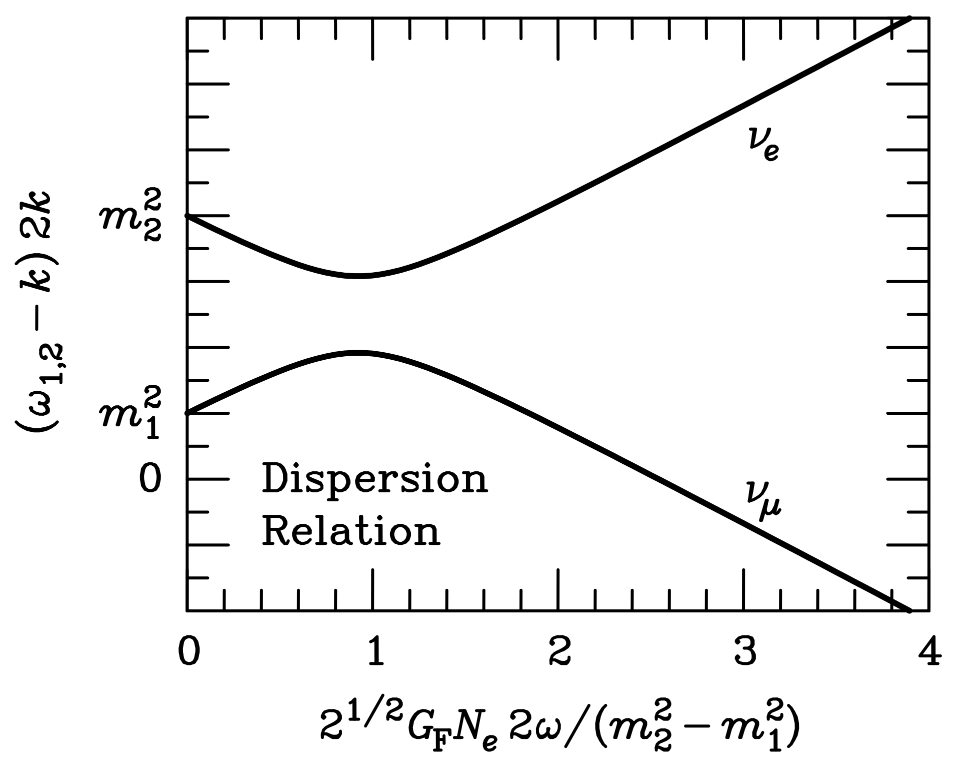


$$\sin 2\theta_m = \frac{\sin 2\theta}{\left[\sin^2 2\theta + (\cos 2\theta - \xi)^2\right]^{1/2}} \qquad \xi = \frac{\sqrt{2} G_F n_e}{m_2^2 - m_1^2} E$$

Adiabatic conversion



Raffelt (1996)

Start

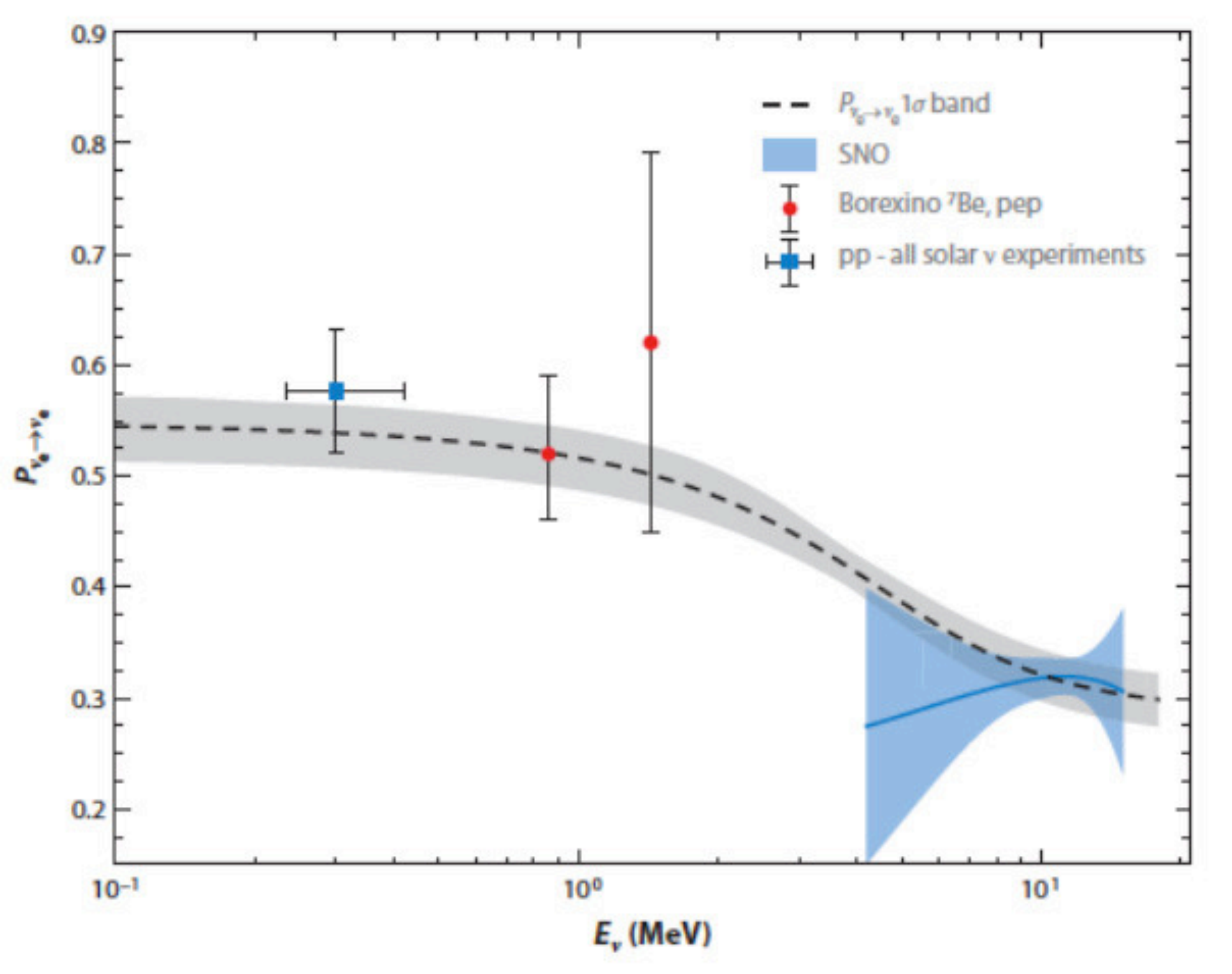
$$\nu_e = \cos\theta_m \nu_1 - \sin\theta_m \nu_2 \sim \nu_1$$

End

$$\nu_2 = \sin\theta \nu_e + \cos\theta \nu_\mu$$

$$P(\nu_e \to \nu_e) = \sin^2\theta < \frac{1}{2}$$

MSW effect



Formalism

Equation of motion

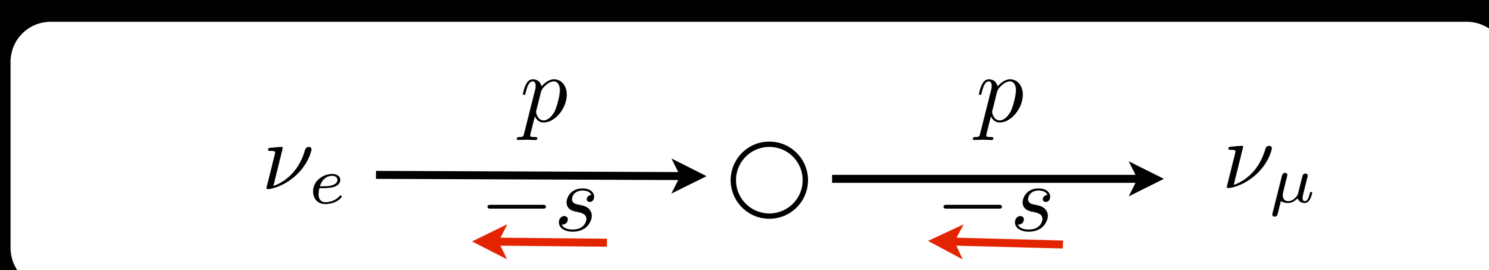
$$i\dot{\rho} = [H, \rho]$$

Sigl, Raffelt (1993)

Density matrices:

$$\rho = \begin{pmatrix} \rho_e & \rho_{e\mu} \\ \rho_{e\mu}^\dagger & \rho_\mu \end{pmatrix}$$

$$(2\pi)^3\delta^3(p-k)\rho_{ij} = \langle a_j^\dagger(p) a_i(k)\rangle$$



MSW Hamiltonian

Vacuum oscillations — Matter effect

$$H = \frac{1}{4E}\begin{pmatrix} -\Delta m^2 \cos 2\theta + 2EV & \Delta m^2 \sin 2\theta \\ \Delta m^2 \sin 2\theta & \Delta m^2 \cos 2\theta - 2EV \end{pmatrix}$$

Resonant enhancement when diagonals vanish.

Potential contains neutrinos!

Beyond Flavor

Helicity oscillations

Weak interaction is chiral

$$\mathcal{L} = G_{\mathrm{F}} \left[\bar{\psi}\gamma^{\mu} P_L \psi\right] \left[\bar{\psi}\gamma_{\mu} P_L \psi\right]$$

Helicity oscillations

Weak interaction is chiral

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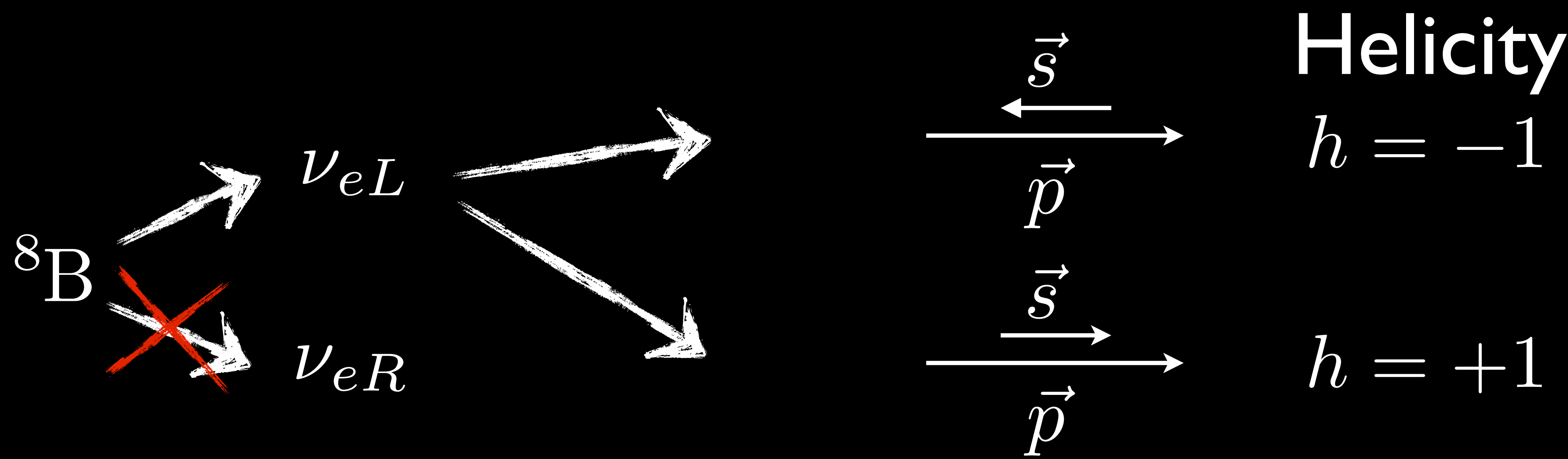

Helicity oscillations

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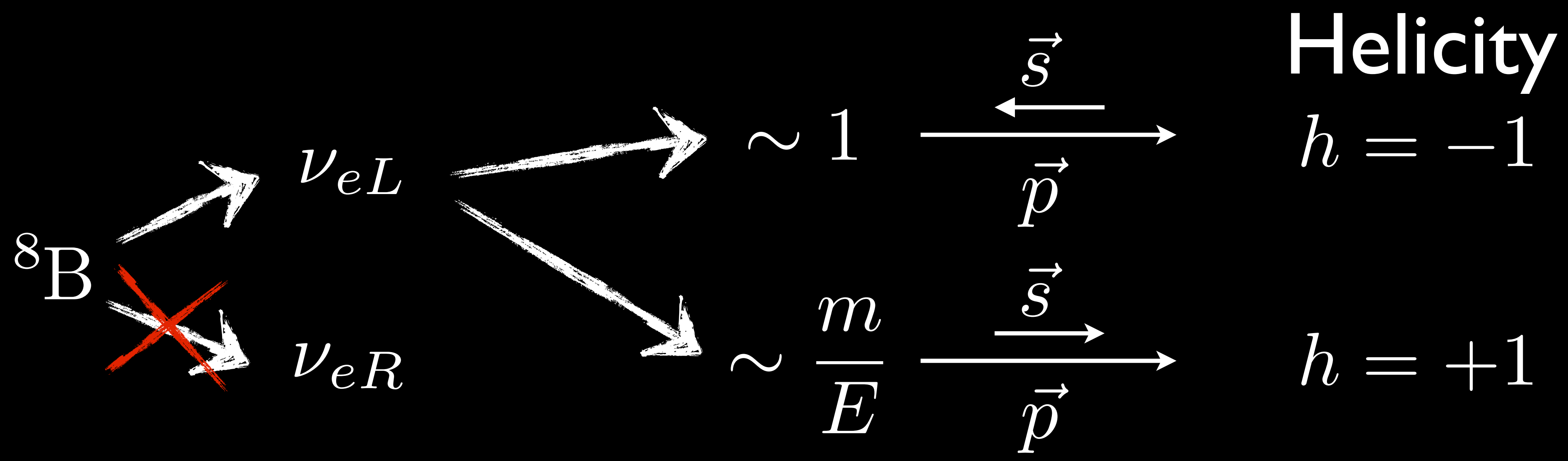
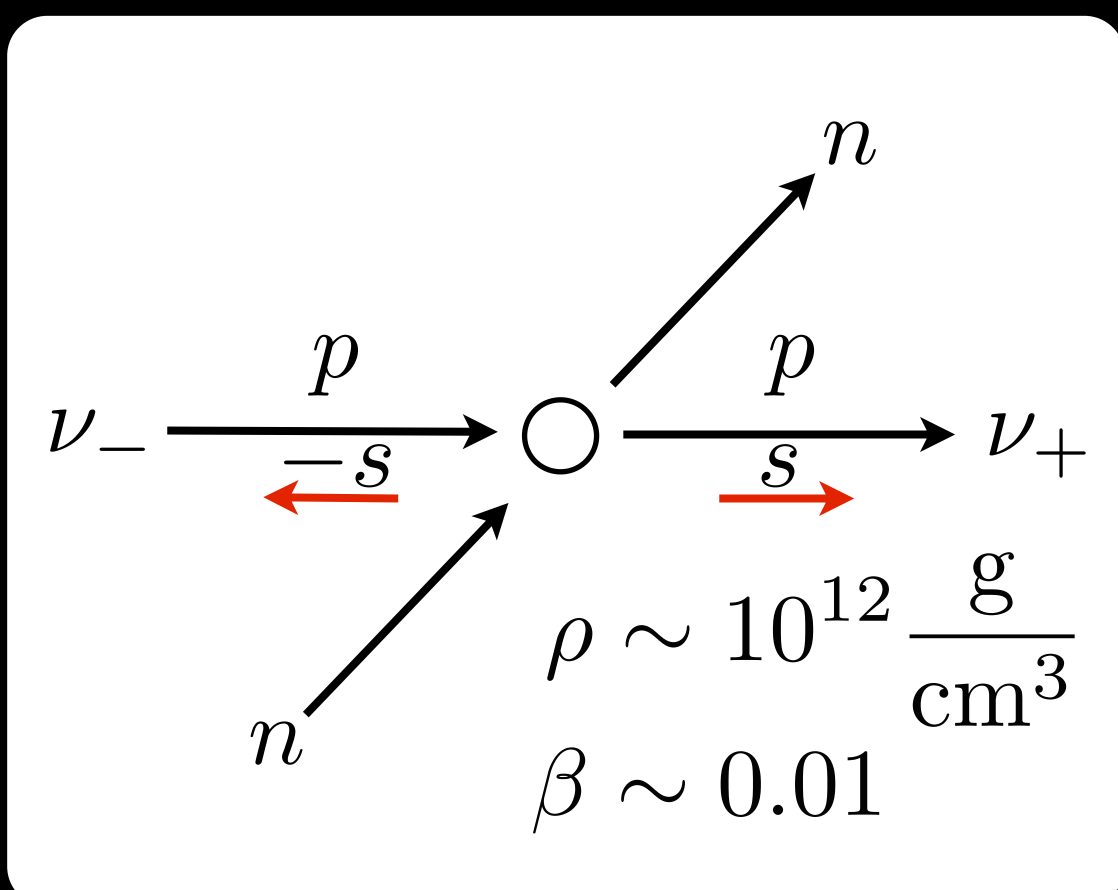


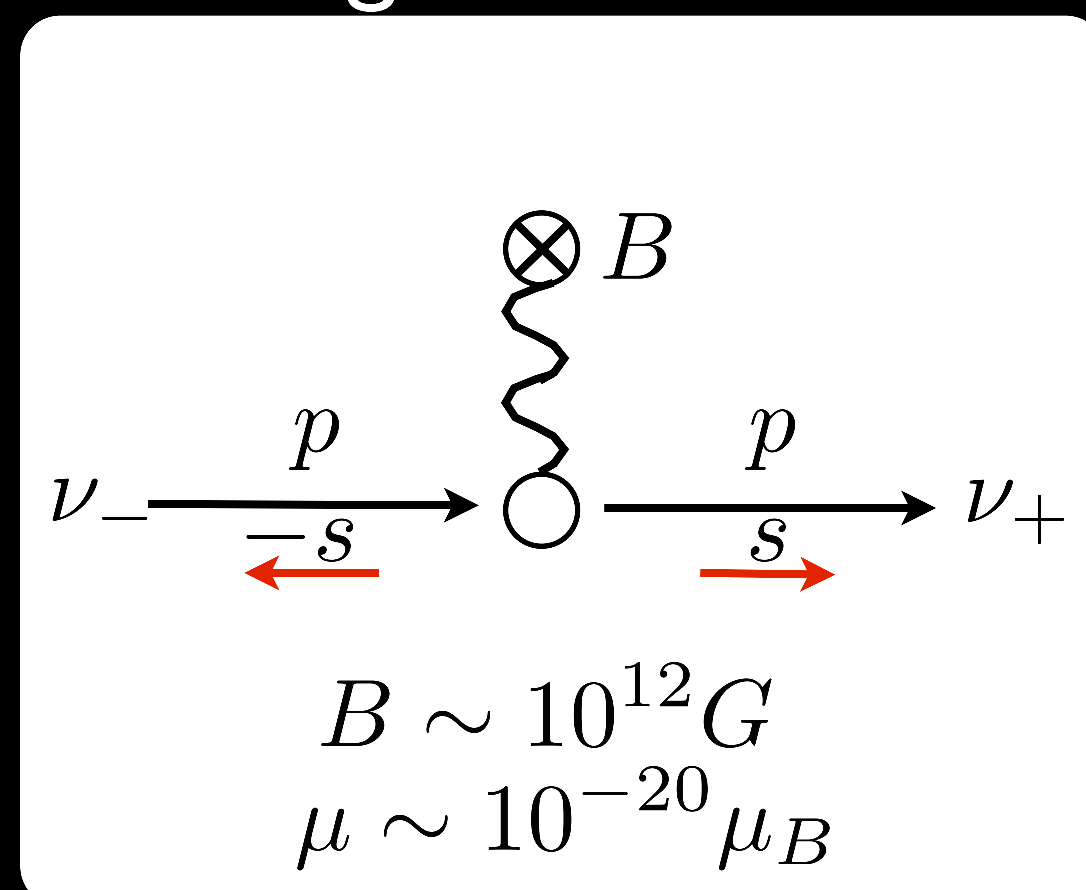
Helicity oscillations

$$(2\pi)^3\delta^3(p-k)\rho_{ij,sh} = \langle a^\dagger_{j,h}(p) a_{i,s}(k)\rangle$$

Matter currents



Magnetic fields



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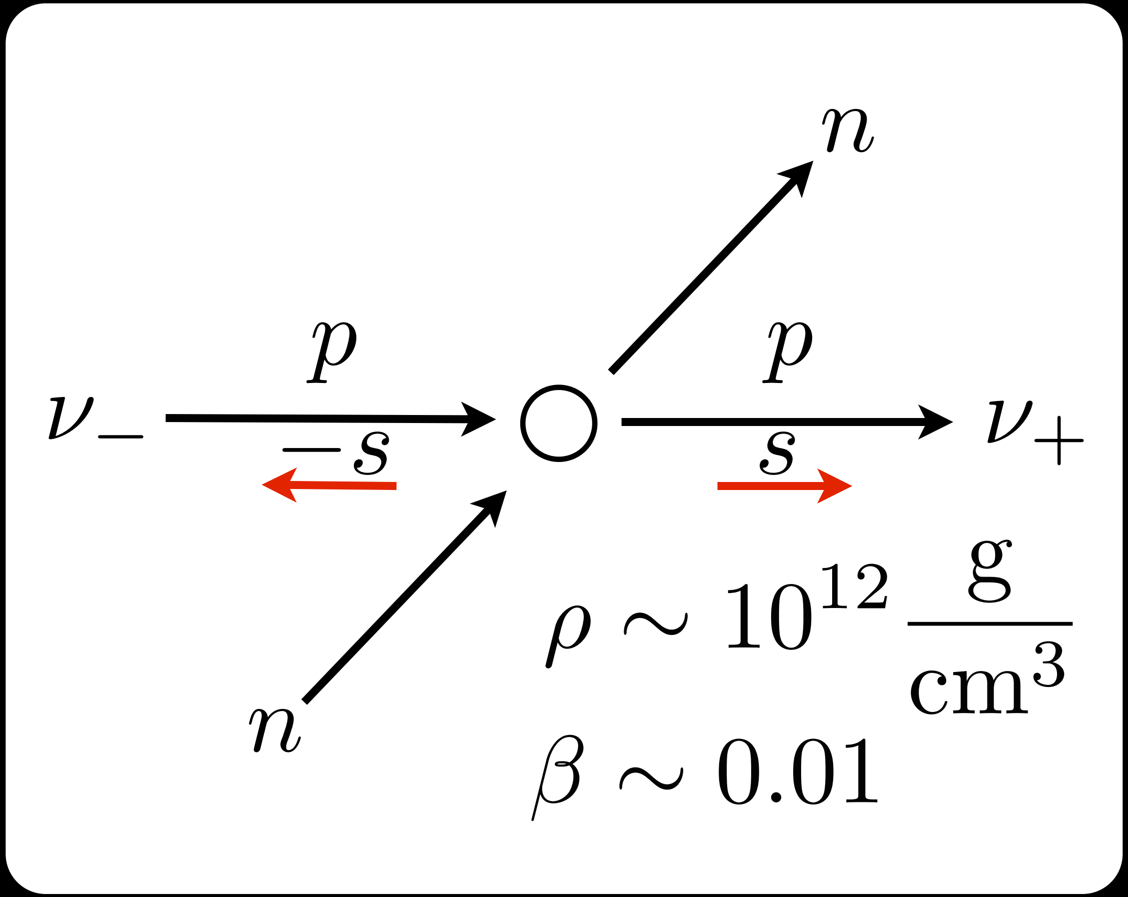

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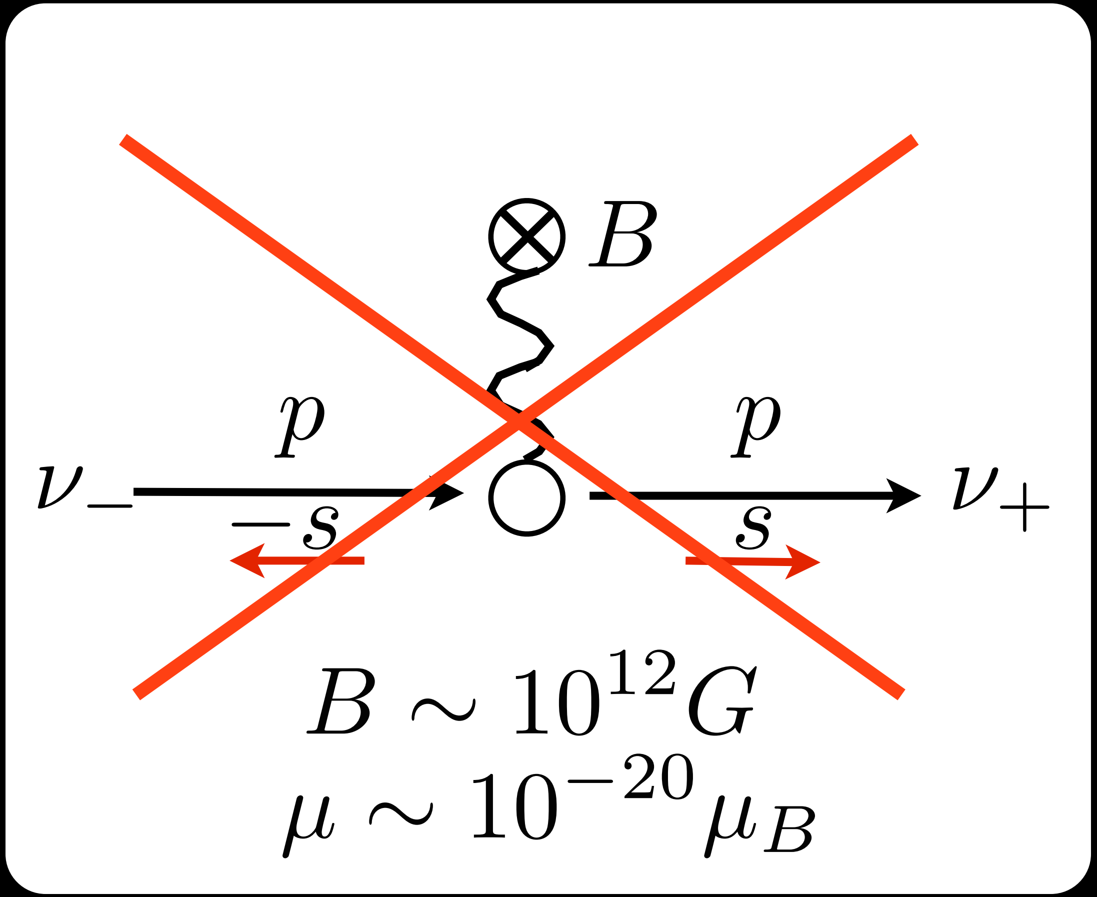
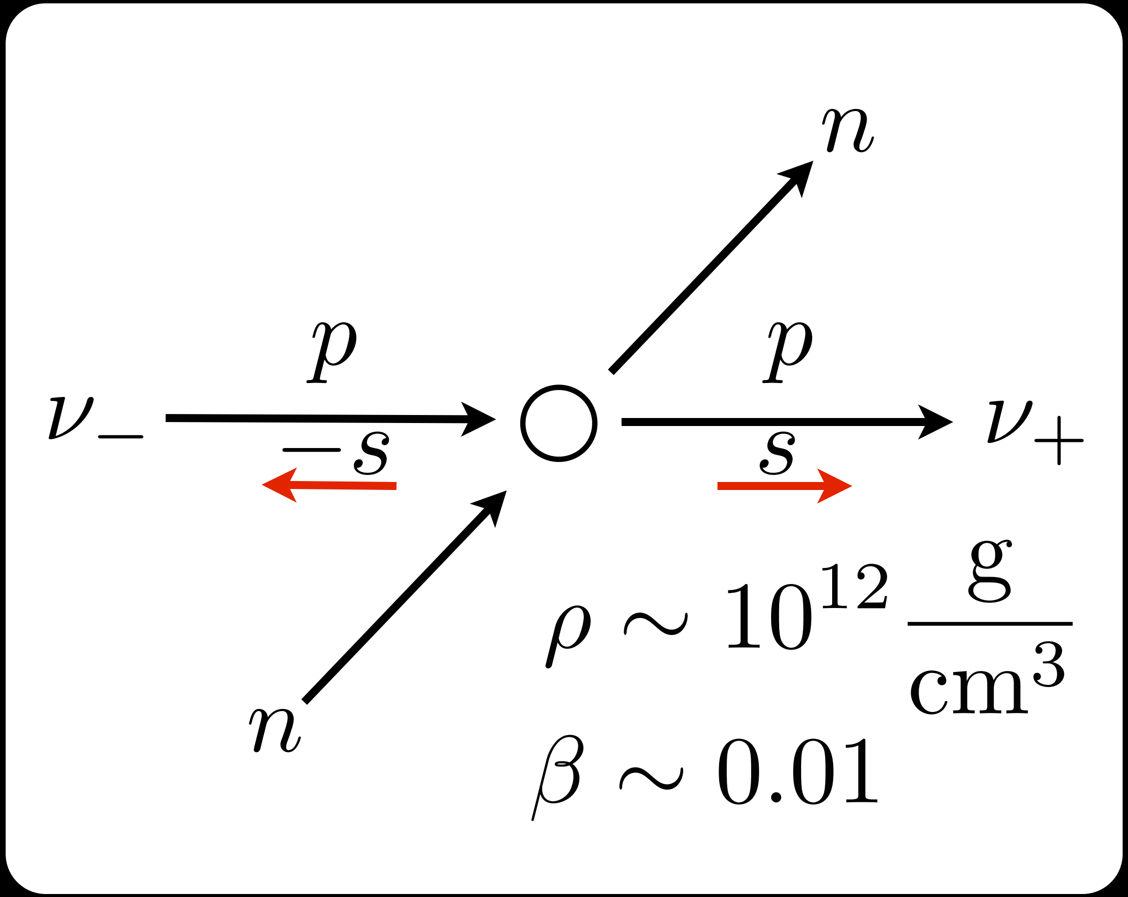


Helicity oscillations

$$(2\pi)^3\delta^3(p-k)\rho_{ij,sh} = \langle a^\dagger_{j,h}(p)a_{i,s}(k)\rangle$$

$$\rho_{-+} \sim 10^{-11}$$

Matter currents



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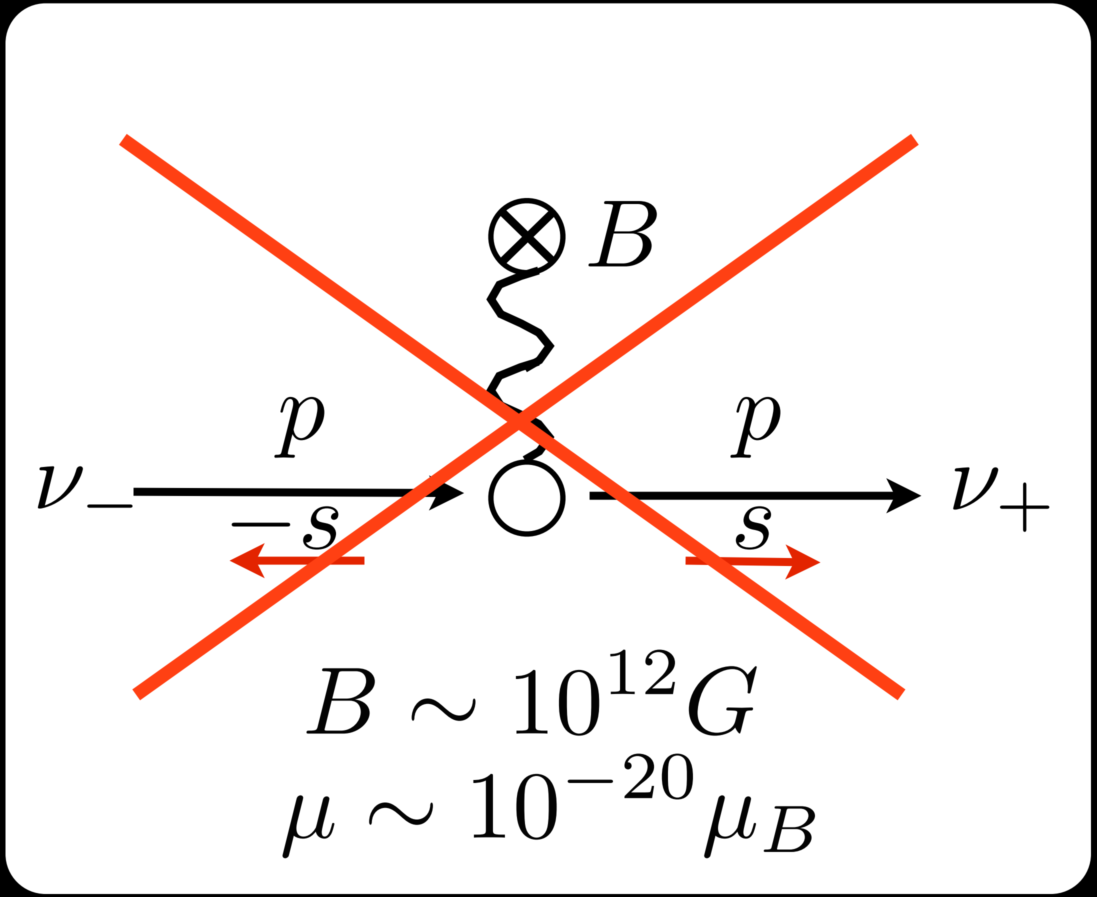

Resonant enhancement

$$H^{\nu\nu} = \begin{pmatrix} V^0 - V_\parallel & \frac{m}{2E} V_\perp \\ \frac{m}{2E} V_\perp & 0 \end{pmatrix} \qquad Y_e + \frac{4}{3}\left(Y_\nu - \frac{\beta J^r}{n_B}\right) = \frac{1}{3}$$

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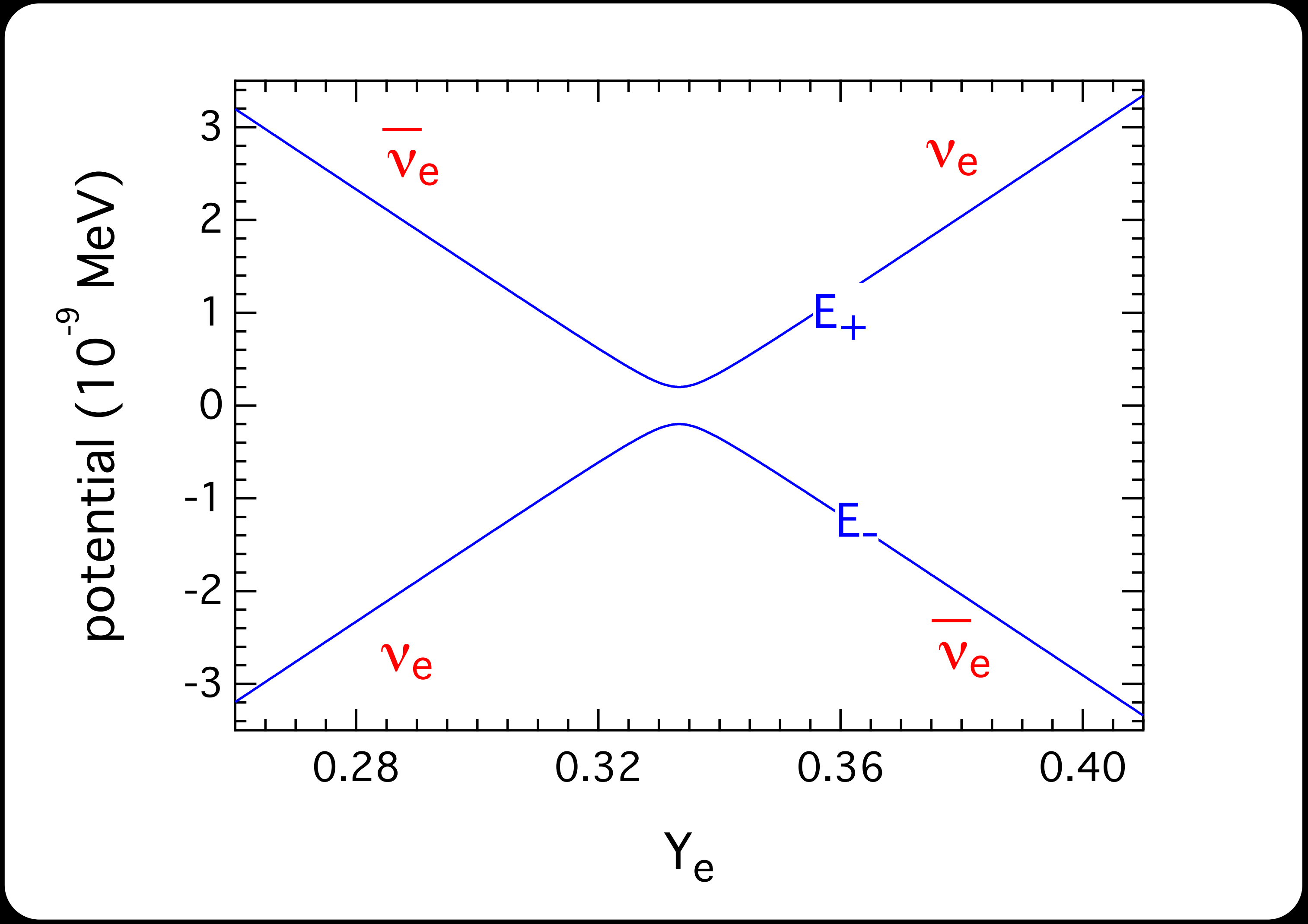

$$\nu_- \rightarrow \nu_e$$
$$\nu_+ \rightarrow \bar{\nu}_e$$

Vlasenko *et al.* arXiv:1406.6724

Pair correlations

$$(2\pi)^3\delta^3(p+k)\kappa = \langle b(p)a(k)\rangle$$

Serreau, Volpe (2014)

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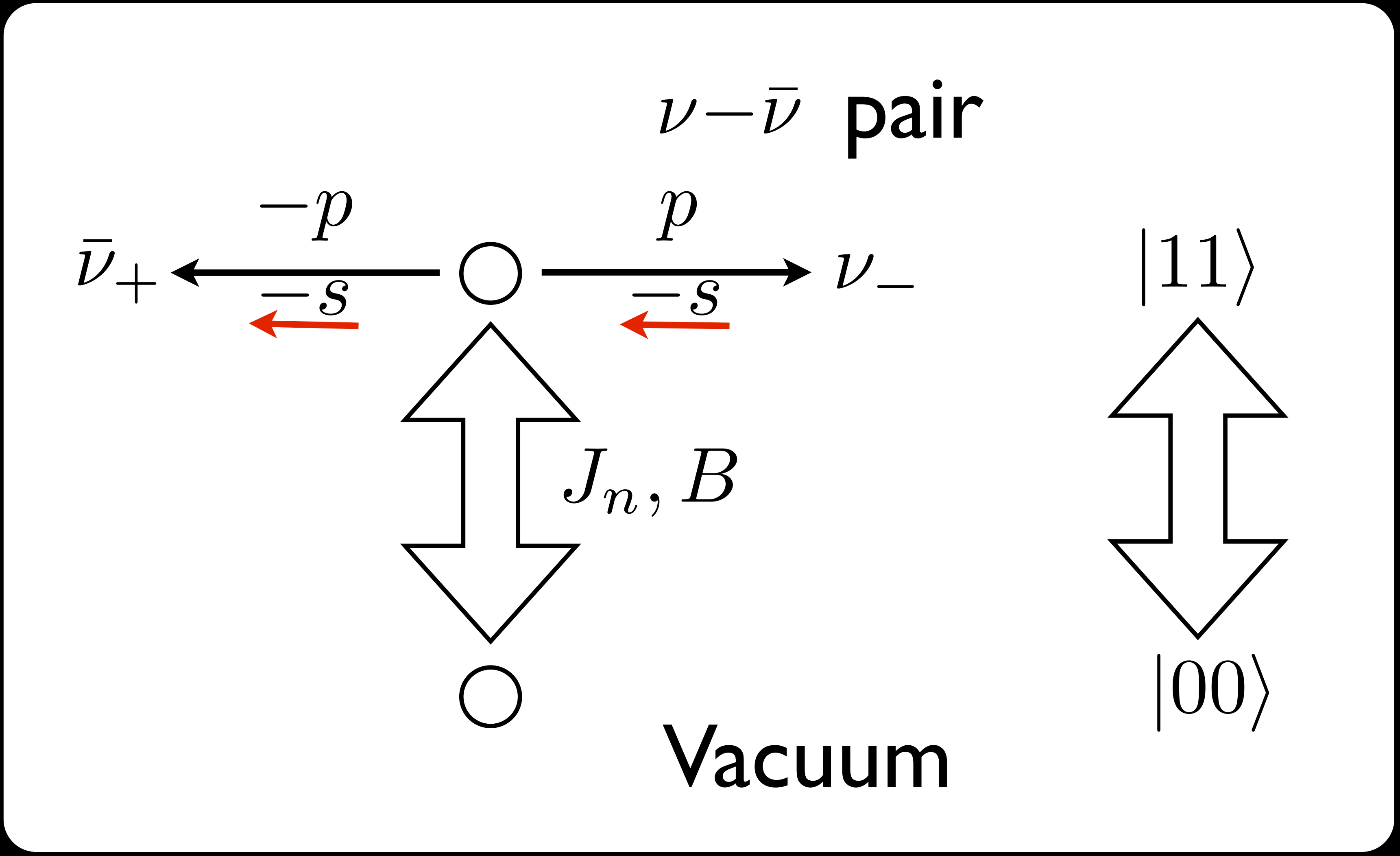

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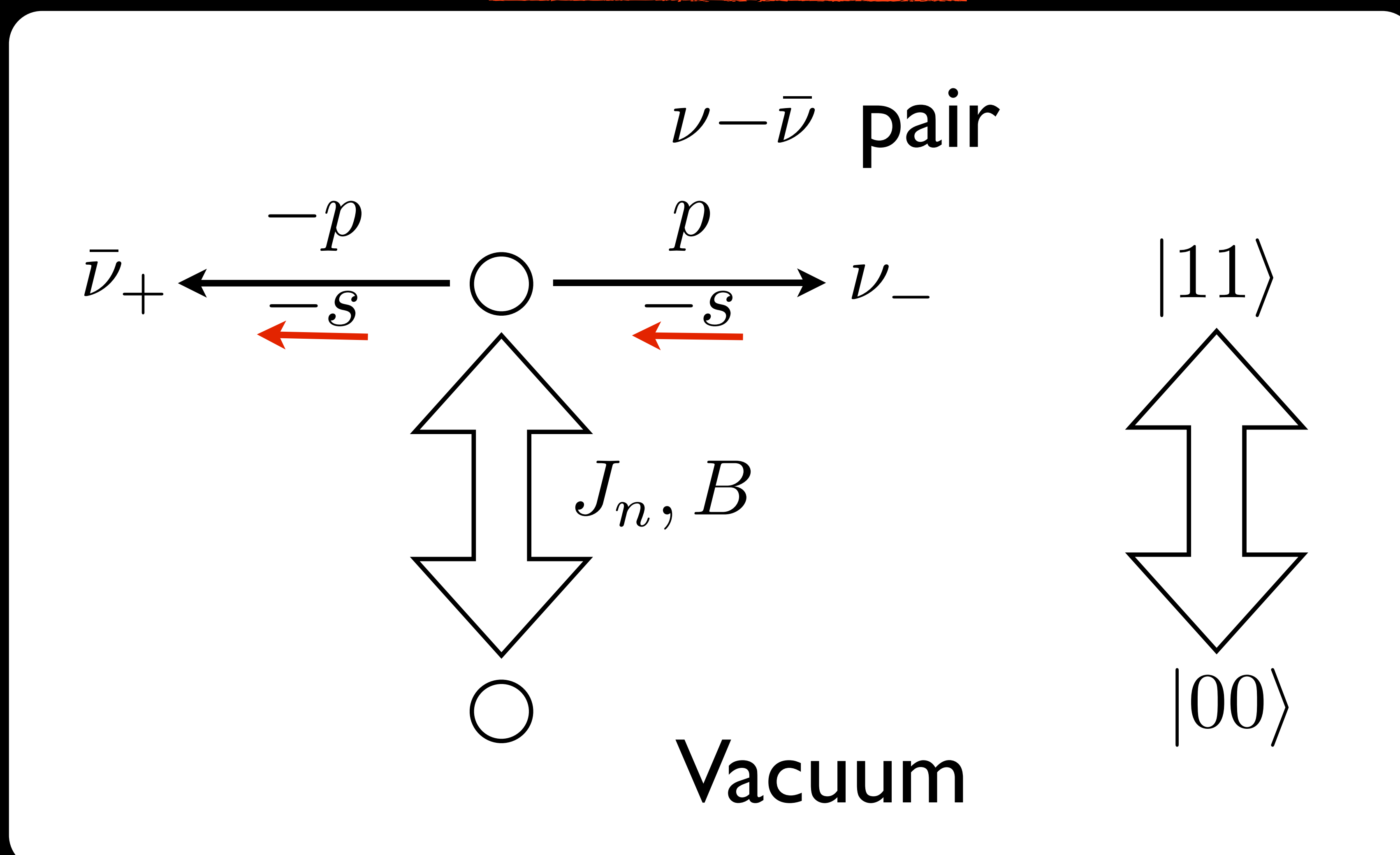

Resonant enhancement

$$H = \begin{pmatrix} E - V_{\parallel} & -V_{\perp} \\ -V_{\perp} & -E + V_{\parallel} \end{pmatrix}$$

Kartavtsev, Raffelt, HV (2015)

Resonance?

$$\frac{V_{\parallel}}{E} \sim 1$$

Typical supernova

$$\frac{V_{\parallel}}{E} \sim 10^{-9}$$

Conclusion

	Typical magnitude	Resonance?
Helicity oscillations	$\rho_{-+} \sim 10^{-11}$	Possible Vlasenko, Fuller, Cirigliano (2014)
Pair correlations	$\kappa \sim 10^{-11}$	No Kartavtsev, Raffelt, HV (2015)