9th September 2015
TAUP 2015

Helicity and Pair Correlations

A. Kartavtsev, G. Raffelt and HV,
Phys.Rev. D91 (2015), arXiv:1504.03230

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Max Planck Institute for Physics

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Flavor Oscillations

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Equation of motion:

$$i\dot{\rho} = [H, \rho] + \text{coll.}$$

Density matrices:

$$\rho = \begin{pmatrix} \rho_{\nu_e \nu_e} & \rho_{\nu_e \nu_\mu} \\ \rho^\dagger_{\nu_e \nu_\mu} & \rho_{\nu_\mu \nu_\mu} \end{pmatrix}$$

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

Sigl, Raffelt (1993)

Helicity Oscillations

Effect of Helicity Flips

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Dirac	Majorana
Flips the helicity of a particle/antiparticle e.g. changes opacity	Converts particle into antiparticle e.g. changes proton-to-neutron ratio

Helicity Oscillations

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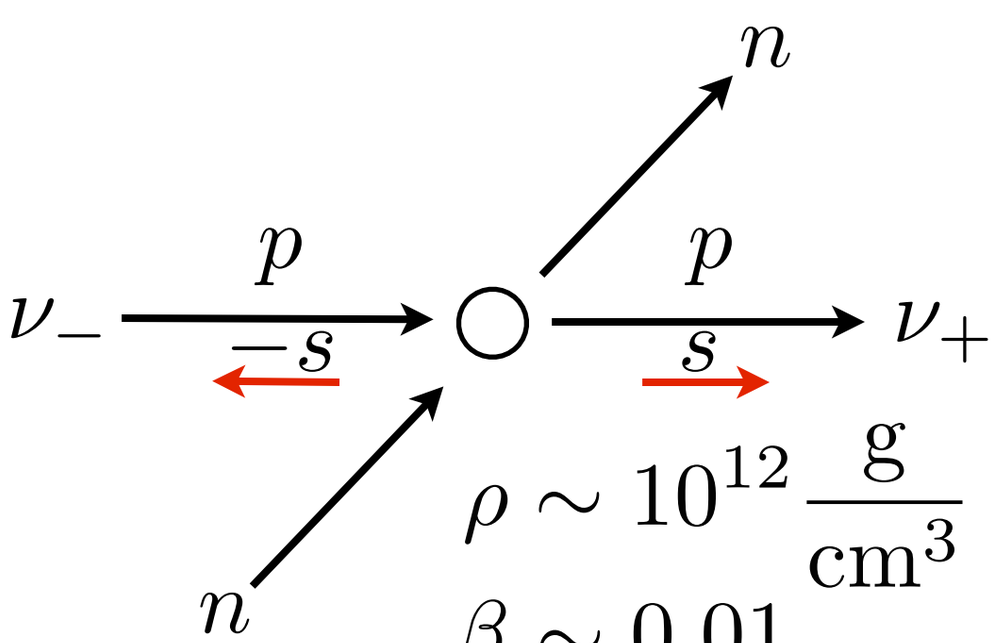
Helicity density matrix:

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

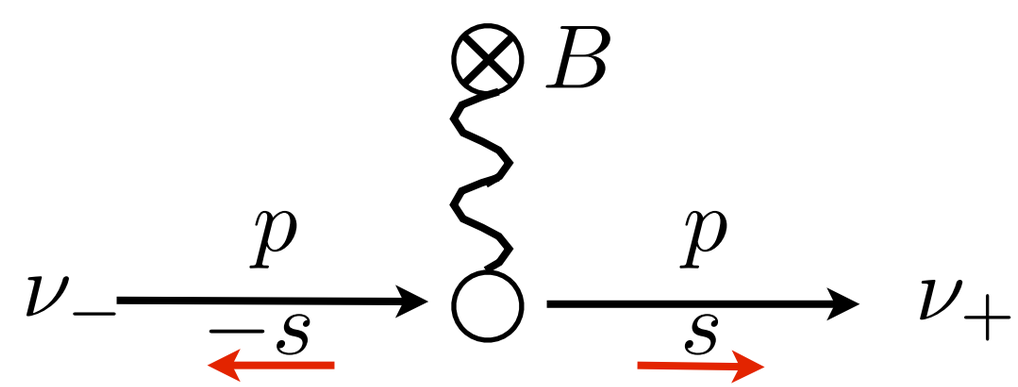
Matter currents



$$\rho \sim 10^{12}\,\frac{\mathrm{g}}{\mathrm{cm}^3}$$

$$\beta \sim 0.01$$

Magnetic fields



$$B \sim 10^{12} G$$

$$\mu \sim 10^{-20}\mu_B$$

Helicity Oscillations

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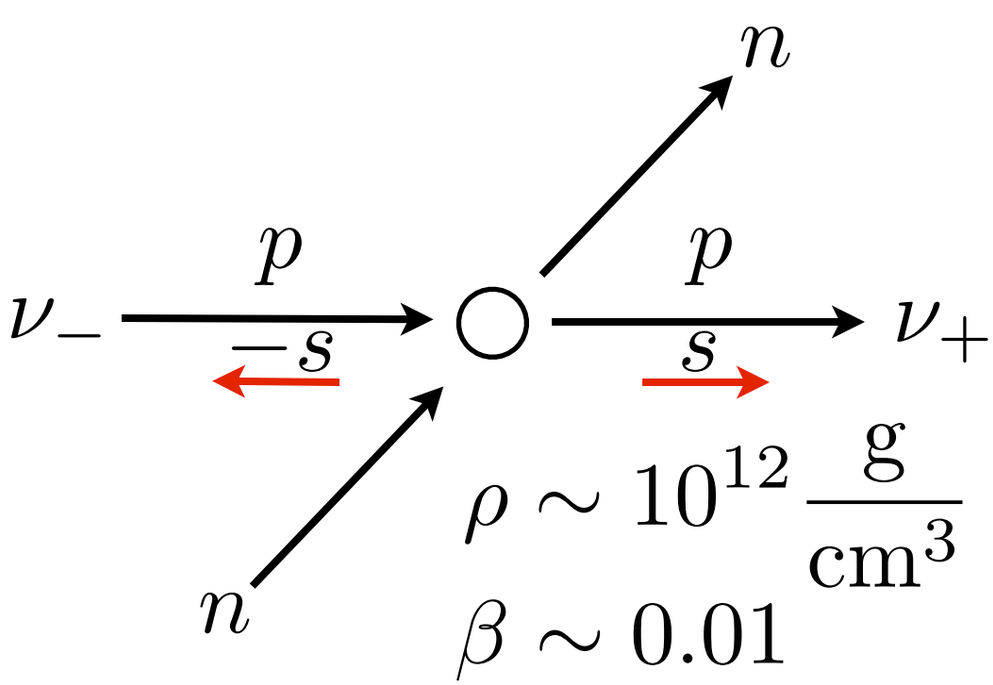
Matter currents



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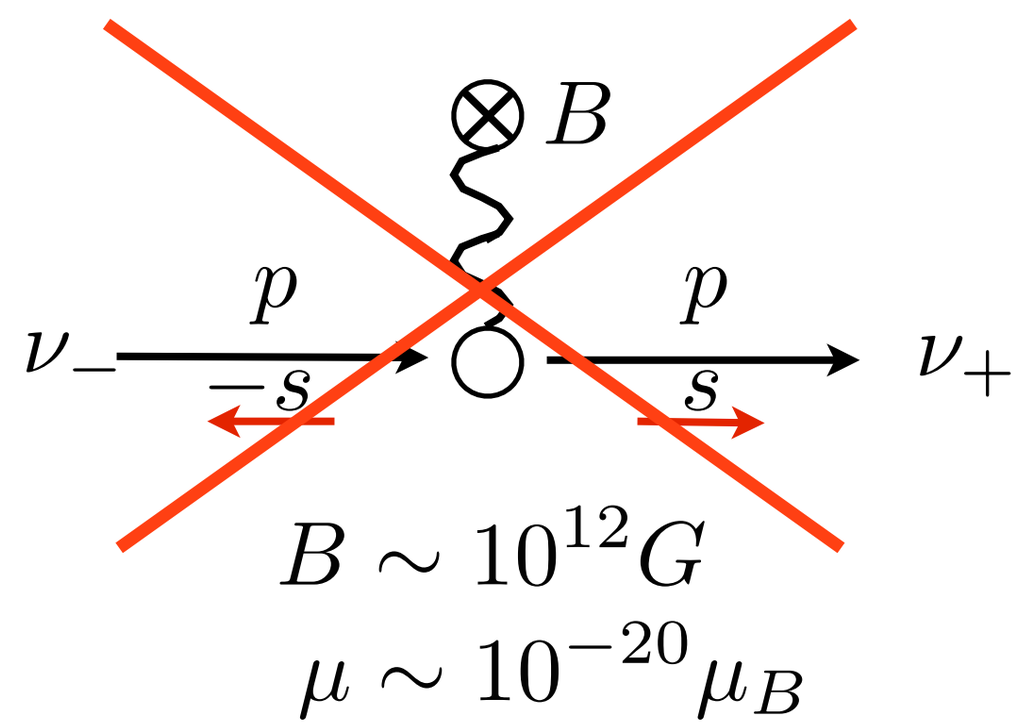

Order of Magnitude

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Helicity part of Hamiltonian

$$\mathsf{H}^{\nu\nu} = \begin{pmatrix} \mathsf{H}^{\nu\nu}_{--} & \mathsf{H}^{\nu\nu}_{-+} \\ \mathsf{H}^{\nu\nu}_{+-} & \mathsf{H}^{\nu\nu}_{++} \end{pmatrix} = \begin{pmatrix} V^0 - V_{\parallel} & \frac{m}{2E} V_{\perp} \\ \frac{m}{2E} V_{\perp} & 0 \end{pmatrix}$$

Order of Magnitude

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Helicity part of Hamiltonian

$$V^0 \approx G_F n_n$$

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$$V_{\perp} \approx G_F n_n \beta_{\perp}$$

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In equilibrium:

$$i\dot{\rho}_{-+} = (\mathsf{H}^{\nu\nu}_{--} - \mathsf{H}^{\nu\nu}_{++})\rho_{-+} - \mathsf{H}^{\nu\nu}_{-+}(\rho_{--} - \rho_{++}) = 0$$

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

Adiabatic Conversion

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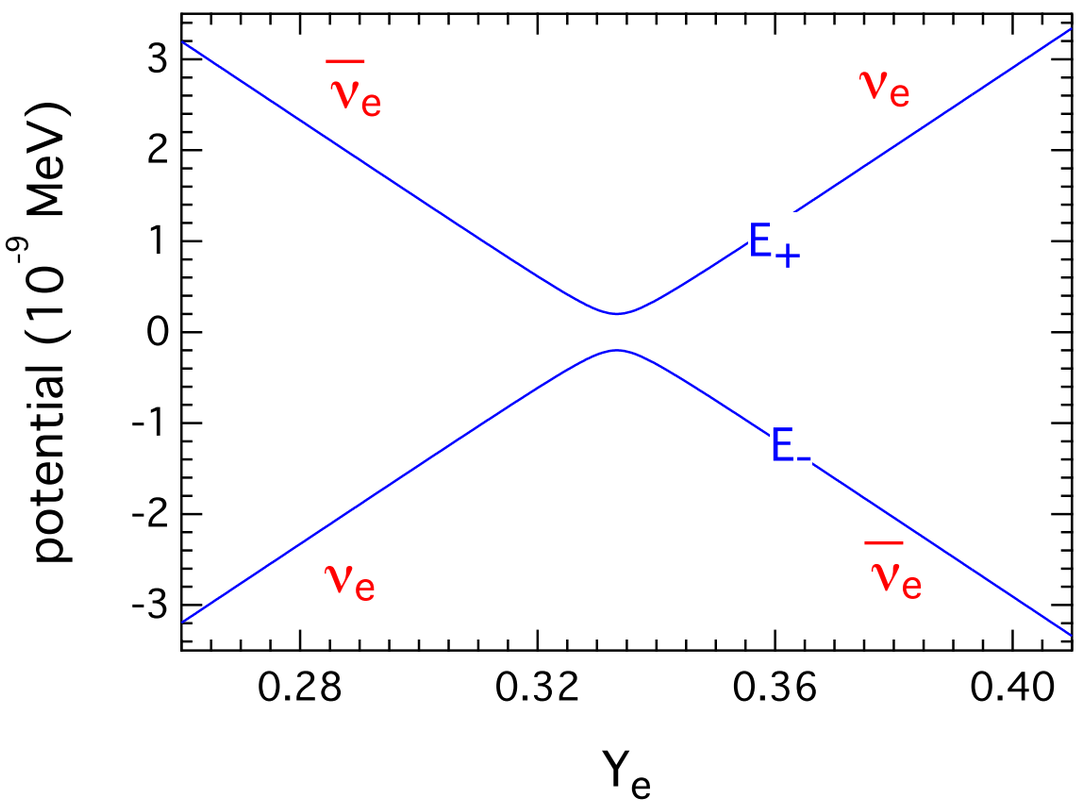

Vlasenko *et al.* (2014)

Hamiltonian (Majorana):

$$H = \begin{pmatrix} V^0 - V_\parallel & \frac{m}{2E} V_\perp \\ \frac{m}{2E} V_\perp & -V^0 + V_\parallel \end{pmatrix}$$

Resonance condition

$$Y_e + \frac{4}{3}\left(Y_\nu - \frac{V_\parallel}{2n_B}\right) = \frac{1}{3}$$

Pair Correlations

Pair Correlations

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

Volpe, Väänänen, Espinoza (2013)
Serreau, Volpe (2014)

Extended equation of motion:

$$i\dot{\mathsf{R}} = [\mathsf{H}, \mathsf{R}]$$

$$\mathsf{H} = \begin{pmatrix} \mathsf{H}^{\nu\nu} & \mathsf{H}^{\nu\bar{\nu}} \\ \mathsf{H}^{\bar{\nu}\nu} & \mathsf{H}^{\bar{\nu}\bar{\nu}} \end{pmatrix} \qquad \mathsf{R} = \begin{pmatrix} \rho & \kappa \\ \kappa^\dagger & 1-\bar{\rho} \end{pmatrix}$$

Goals

- What is the physical interpretation?
- What is the size of the effect?

What is the physical interpretation?

Pair Correlations

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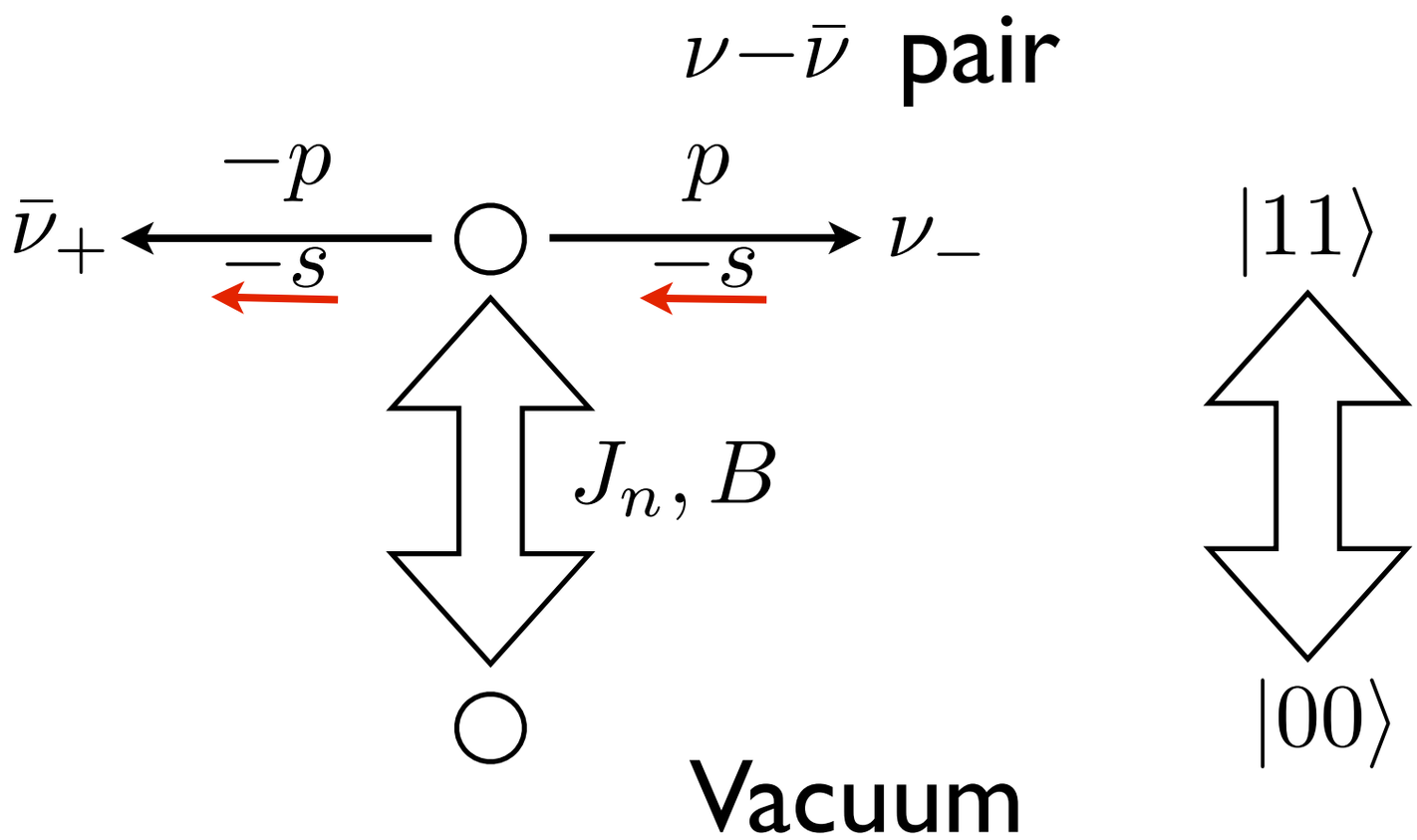
$$\delta^3(p+k)\kappa \propto \langle b(p)a(k)\rangle$$

Volpe, Väänänen, Espinoza (2013)
Serreau, Volpe (2014)



Weyl Neutrino

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Serreau, Volpe (2014), Kartavtsev, Raffelt, HV (2015)

Rate equations of densities:

$$\dot{\rho} = -2\mathrm{Im}\left(\kappa \mathsf{H}^{\bar{\nu}\nu}\right) \qquad \dot{\bar{\rho}} = -2\mathrm{Im}\left(\kappa \mathsf{H}^{\bar{\nu}\nu}\right)$$

$$\rho - \bar{\rho} = \mathrm{const.} \qquad \rho + \bar{\rho} \neq \mathrm{const.}$$

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For pair correlations:

$$i\dot{\kappa} = \left(\mathsf{H}^{\nu\nu} - \mathsf{H}^{\bar{\nu}\bar{\nu}}\right)\kappa + \mathsf{H}^{\nu\bar{\nu}}\left(1 - \rho - \bar{\rho}\right)$$

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For pair correlations:

$$i\dot{\kappa} = \underbrace{\left(\mathsf{H}^{\nu\nu} - \mathsf{H}^{\bar{\nu}\bar{\nu}}\right)}_{\approx 2E}\kappa + \mathsf{H}^{\nu\bar{\nu}}\left(1 - \rho - \bar{\rho}\right)$$

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$$i\dot{\kappa} = \underbrace{\left(\mathsf{H}^{\nu\nu} - \mathsf{H}^{\bar{\nu}\bar{\nu}}\right)}_{\approx 2E}\kappa + \underbrace{\mathsf{H}^{\nu\bar{\nu}}}_{\sim G_F \vec{\epsilon}^{\,*} \cdot \vec{J}}(1 - \rho - \bar{\rho})$$

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$$\epsilon^{\mu} = 1/2\ \bar{v}(-\vec{p})\gamma^{\mu}(1 - \gamma_5)u(\vec{p})$$

$$\sim \begin{pmatrix} 0 & 1 & i & 0 \end{pmatrix}$$

Schrödinger Formalism

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Decomposition of state:

$$|\psi\rangle = A_{00}|00\rangle + A_{11}|11\rangle + A_{10}|10\rangle + A_{01}|01\rangle$$

$\nu(p)$ $\bar{\nu}(-p)$

Hamiltonian:

$$H = \mathsf{H}^{\nu\nu} a^\dagger a + \mathsf{H}^{\nu\bar{\nu}} a^\dagger b^\dagger + \mathsf{H}^{\bar{\nu}\nu} ba - \mathsf{H}^{\bar{\nu}\bar{\nu}} b^\dagger b$$

Schrödinger Formalism

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Decomposition of state:

$$|\psi\rangle = A_{00}|00\rangle + A_{11}|11\rangle + A_{10}|10\rangle + A_{01}|01\rangle$$

$$\nu(p) \quad \bar{\nu}(-p)$$

Schrödinger equation:

$$i\partial_t \begin{pmatrix} A_{00} \\ A_{11} \end{pmatrix} = \begin{pmatrix} 0 & \mathsf{H}^{\bar{\nu}\nu} \\ \mathsf{H}^{\nu\bar{\nu}} & \mathsf{H}^{\nu\nu} - \mathsf{H}^{\bar{\nu}\bar{\nu}} \end{pmatrix} \begin{pmatrix} A_{00} \\ A_{11} \end{pmatrix}$$

$$i\partial_t A_{10} = \mathsf{H}^{\nu\nu} A_{10}$$

$$i\partial_t A_{01} = -\mathsf{H}^{\bar{\nu}\bar{\nu}} A_{01}$$

Pair Creation

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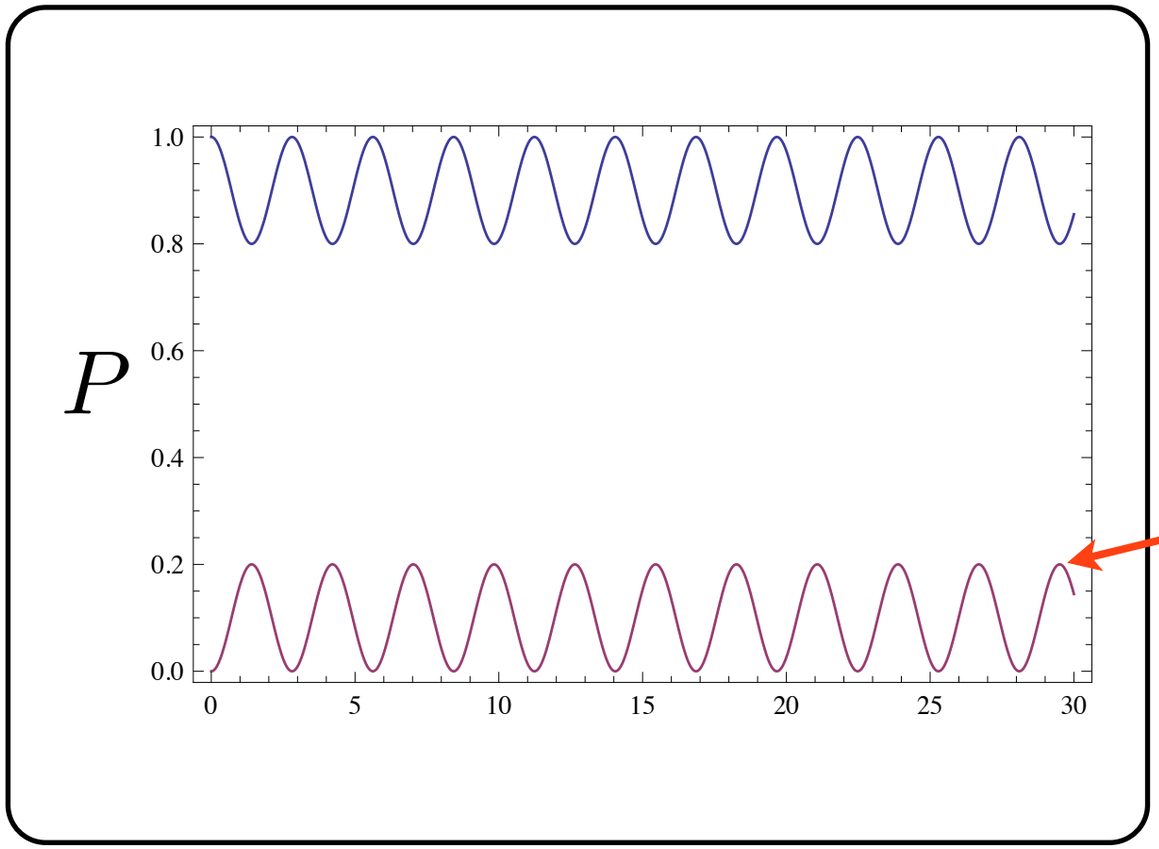
$$i\partial_t \begin{pmatrix} A_{00} \\ A_{11} \end{pmatrix} = \begin{pmatrix} 0 & \mathsf{H}^{\bar{\nu}\nu} \\ \mathsf{H}^{\nu\bar{\nu}} & \mathsf{H}^{\nu\nu} - \mathsf{H}^{\bar{\nu}\bar{\nu}} \end{pmatrix} \begin{pmatrix} A_{00} \\ A_{11} \end{pmatrix}$$

Initial condition: $|\psi\rangle_0 = |00\rangle$



Creation of pairs

Equivalence

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Schrödinger formalism

$$\rho = |A_{11}|^2 + |A_{10}|^2$$

$$\bar{\rho} = |A_{11}|^2 + |A_{01}|^2$$

$$\kappa = A_{00}^* A_{11}$$

Density matrix formalism

What is the size of the effect?

Order of Magnitude

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In equilibrium

$$\kappa = -\frac{\mathsf{H}^{\nu\bar{\nu}}}{\mathsf{H}^{\nu\nu} - \mathsf{H}^{\bar{\nu}\bar{\nu}}}(1 - \rho - \bar{\rho})$$

$$\mathsf{H}^{\nu\bar{\nu}}(\hat{\vec{p}}) = -\underbrace{\mathcal{A}\beta}_{\text{anisotropy}} - 4\sqrt{2}G_F\,\hat{\vec{\epsilon}}^{*}(\vec{p}) \cdot \underbrace{\int_{\vec{q}} \mathrm{Re}[\hat{\vec{\epsilon}}\kappa]}_{\text{kappa}}$$

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anisotropy

kappa

Order of Magnitude

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anisotropy

kappa

without ν-ν-interaction:

$$\kappa \sim G_F n_n \beta / 2E \approx 10^{-11}$$

Self-Consistency

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$$\kappa = -\frac{\mathsf{H}^{\nu\bar{\nu}}}{\mathsf{H}^{\nu\nu} - \mathsf{H}^{\bar{\nu}\bar{\nu}}}(1 - \rho - \bar{\rho}) \sim -\frac{\mathsf{H}^{\nu\bar{\nu}}}{2E}$$

Including neutrinos:

$$\mathsf{H}^{\nu\bar{\nu}}(\hat{\vec{p}}) = -\mathcal{A}\beta - 4\sqrt{2}G_F\,\hat{\vec{\epsilon}}^*(\vec{p}) \cdot \int_{\vec{q}} \mathrm{Re}[\hat{\vec{\epsilon}}\kappa]$$

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The integral diverges

$$\int_0^\infty dq q^2 \frac{1}{q} \to \infty$$

Using a cut-off

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Integration to infinity leads beyond our assumptions:

$$\mathrm{H}^{\nu\bar{\nu}} \approx -\mathcal{A}\beta\left(1-\sqrt{2}\frac{G_F M_W^2}{3\pi^2}\right)^{-1} \approx -\mathcal{A}\beta$$

with ν-ν-interaction:

$$\boxed{\kappa \sim G_F n_n \beta / 2E \approx 10^{-11}}$$

Resonant Enhancement

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Kartavtsev, Raffelt, HV (2015)

Hamiltonian for Weyl neutrinos:

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

Resonance?

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

Typical supernova

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

Conclusion

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

Backup

How to use the equations?

Lorentz Invariance

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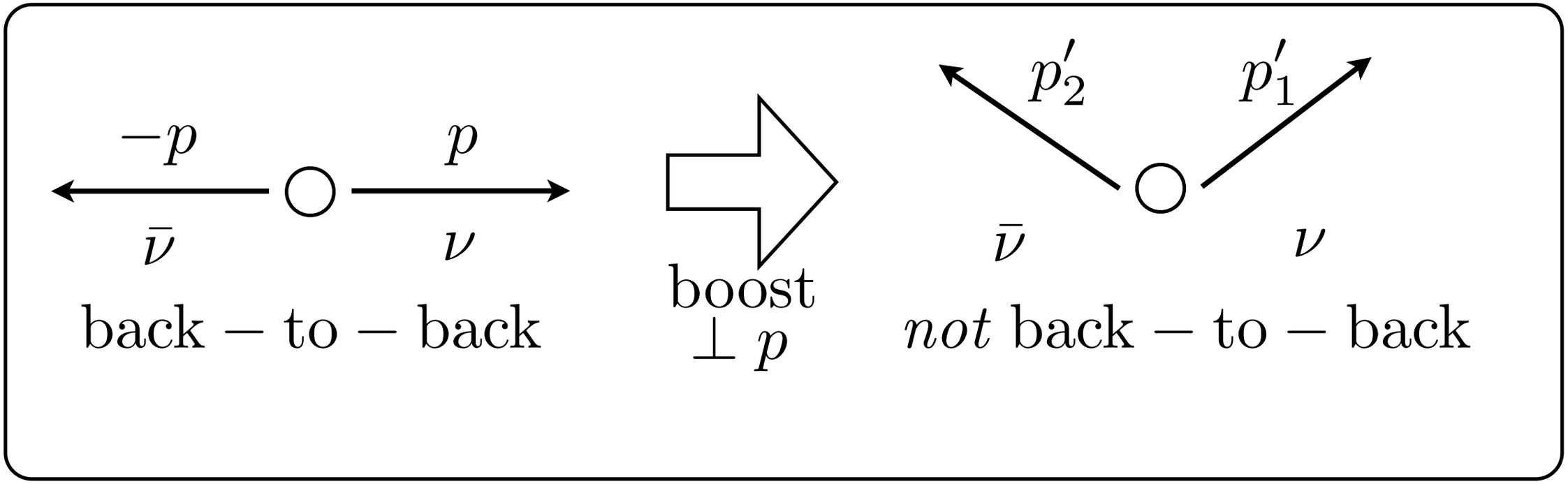
$$(2\pi)^3\delta^3(p+k)\kappa = \langle b(p)a(k)\rangle$$



Particle Number?

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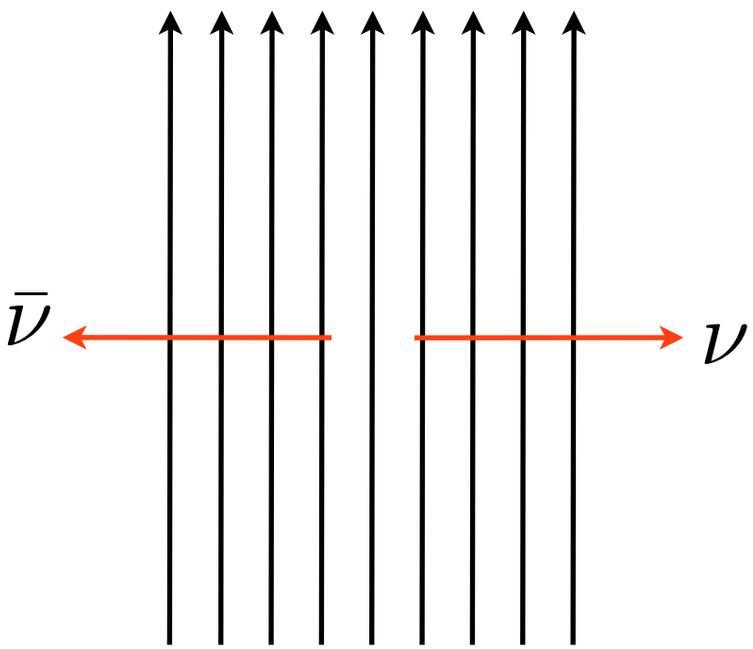
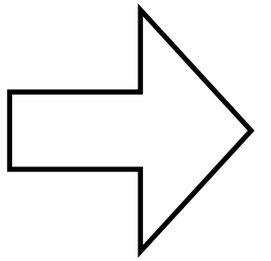
$$i\dot{\kappa} \approx 2E\kappa - G_F \vec{\epsilon}^{\,*} \cdot \vec{J}$$

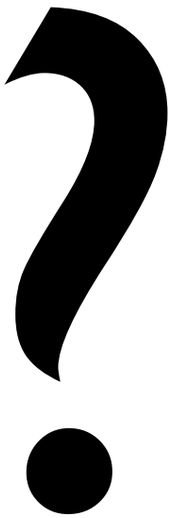
$$i\dot{\kappa}' \approx 2E'\kappa'$$



neutron flux



boost



no neutron flux

Helicity?

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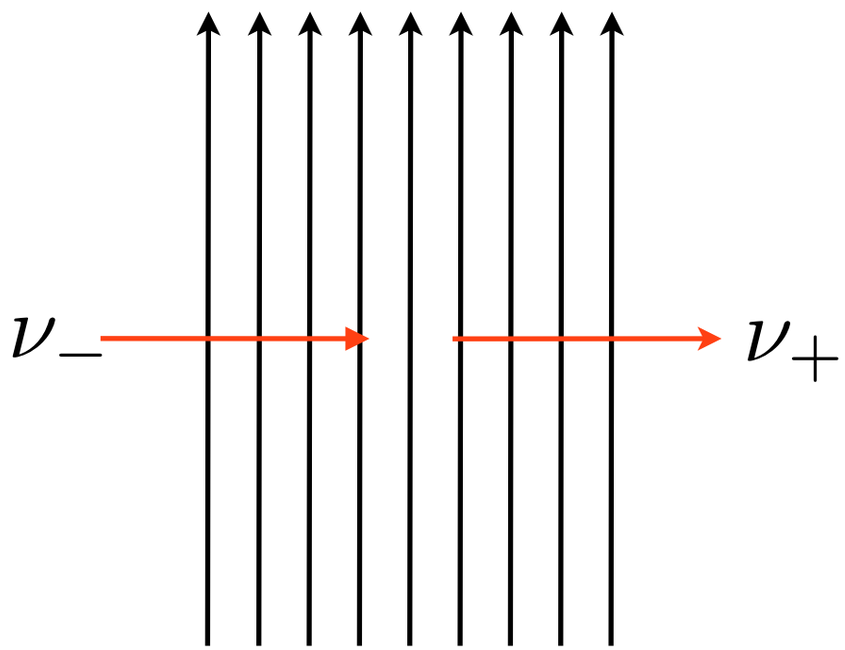
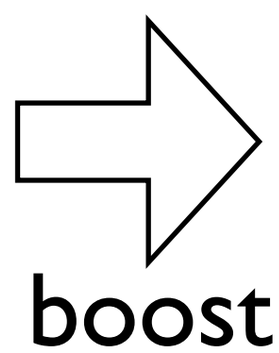
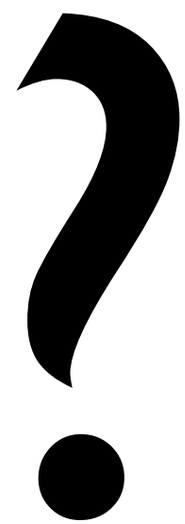
$$i\dot{\rho}_{-+} = 2V\cancel{\rho_{-+}} + G_F \frac{m}{2E}\vec{\epsilon}\cdot\vec{J}(\rho_{--} - \rho_{++})$$



neutron flux



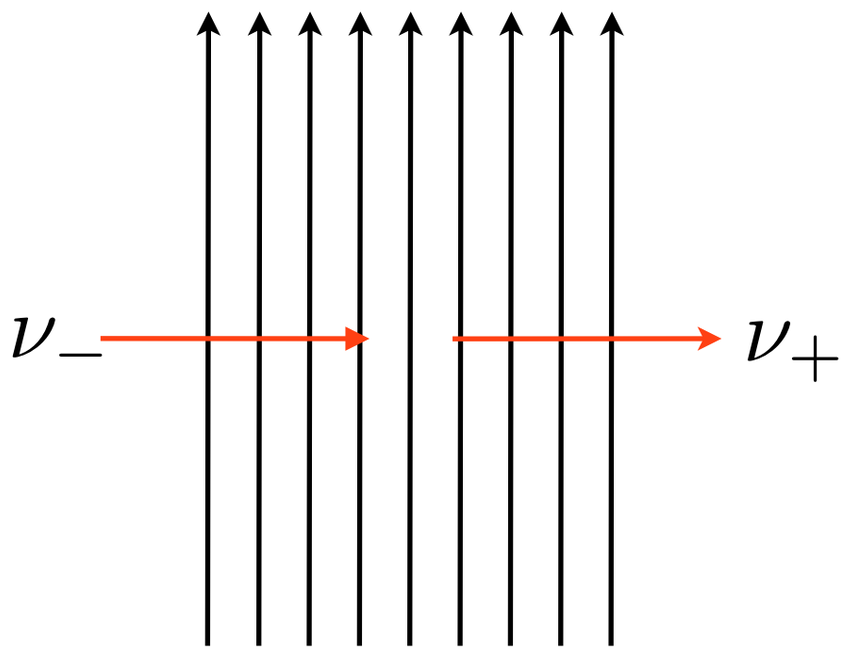


no neutron flux

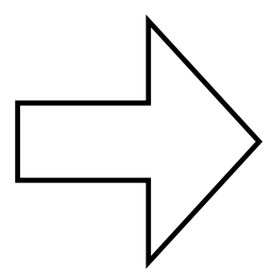
Helicity?

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

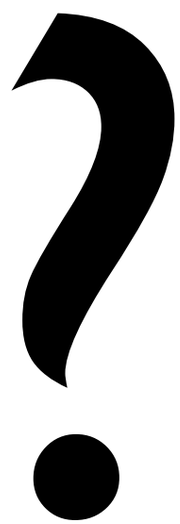
$$i\dot{\rho}_{-+} = 2V\rho_{-+} + G_F \frac{m}{2E}\vec{\epsilon}\cdot\cancel{\vec{J}}(\rho_{--} - \rho_{++})$$



neutron flux



boost



no neutron flux

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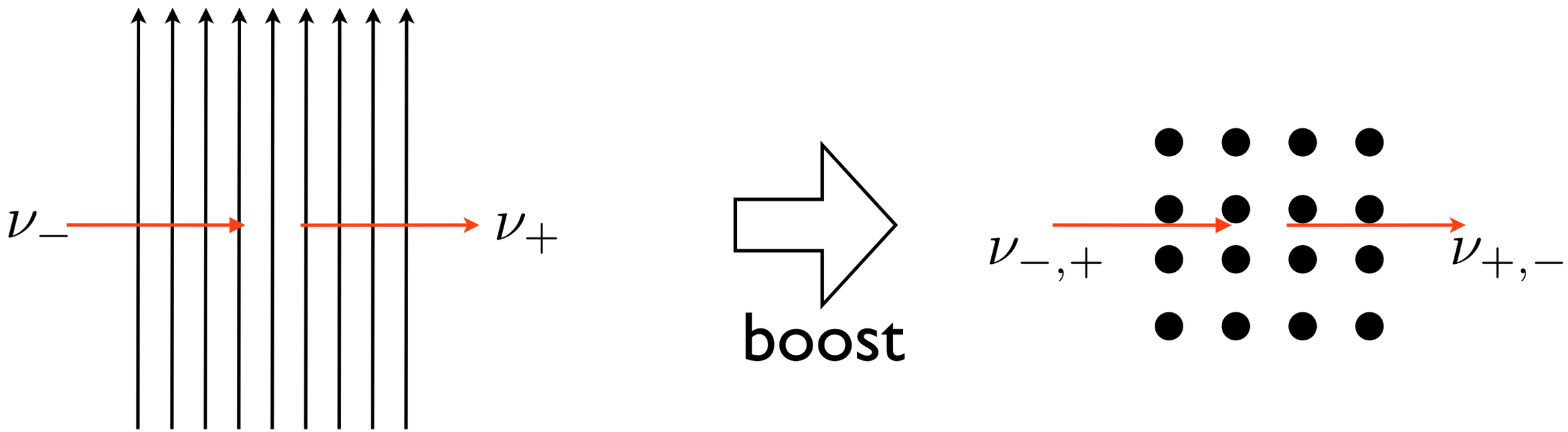

neutron flux

no neutron flux

Helicity?

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(Werner-Heisenberg-Institut)

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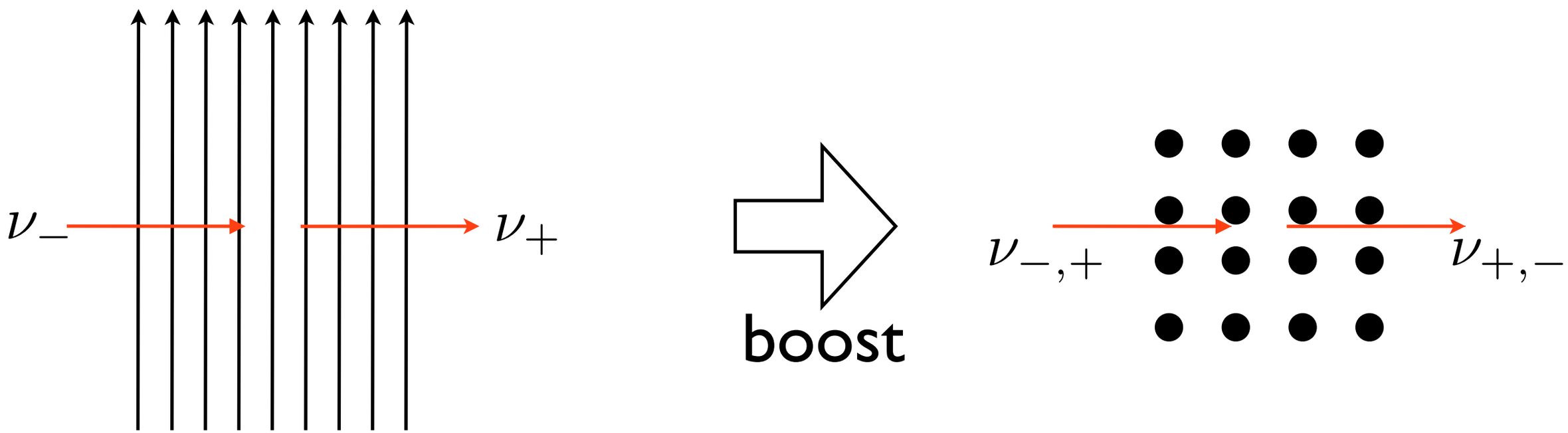

neutron flux

no neutron flux

Particle Number?

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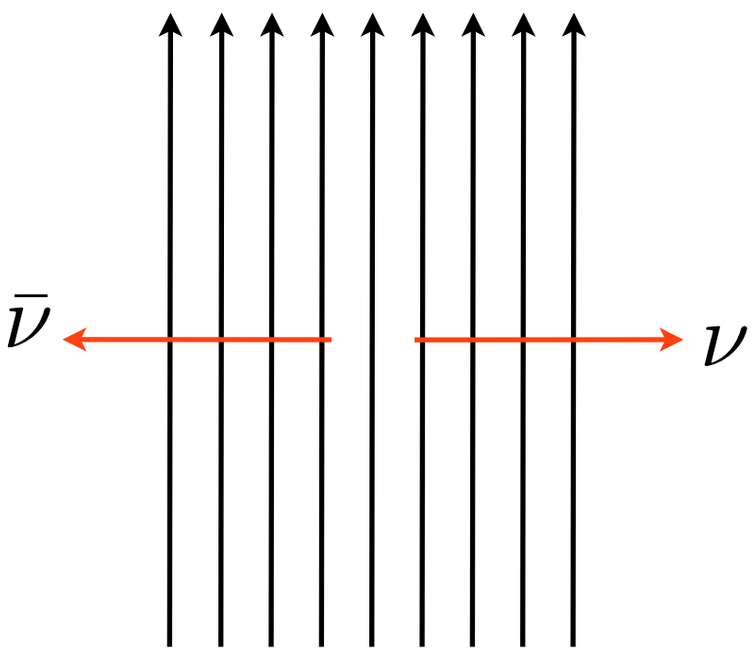
$$i\dot{\kappa} \approx 2E\kappa - G_F \vec{\epsilon}^{\,*} \cdot \vec{J}$$

$$i\dot{\kappa}' \approx 2E'\kappa'$$



neutron flux

boost

$$\kappa \xrightarrow{?} \kappa'$$

$$\kappa \not\rightarrow \rho$$

$$H^{\nu\bar{\nu}} \propto |J|$$

no neutron flux

Solutions?

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1. Use propagation eigenbasis

2. Equations only work in one frame

3. Go beyond forward-scattering formalism

Initial Conditions

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Reason for flavor oscillations:

neutron $\xrightarrow[\text{energy } E]{\bar{\nu}}$ timescale $\tau \sim 1/E$

$$\nu_e \xrightarrow[\frac{\Delta m^2}{2E}]{} \nu_\mu \qquad \tau_{\text{osc}} \gg \tau$$

$$|00\rangle \xrightarrow[\text{energy } 2E]{} |11\rangle \qquad \tau_{\text{pair}} \lesssim \tau$$