

21st July 2015
IFIC Valencia

Neutrino propagation in core-collapse supernovae

A. Kartavtsev, G. Raffelt, and HV

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



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Outline

- Neutrino oscillation in matter
- Supernovae
- Helicity oscillations
- Pair correlations

Neutrinos

Interaction
eigenstates

ν_e

ν_μ

ν_τ



www.particlezoo.net

Neutrinos

Interaction
eigenstates

ν_e

ν_μ

ν_τ

Mass
eigenstates

ν_1

ν_2

ν_3



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Neutrinos

Interaction
eigenstates

ν_e

ν_μ

ν_τ



PMNS

Pontecorvo-Maki-Nakagawa-Sakata

Mass
eigenstates

ν_1

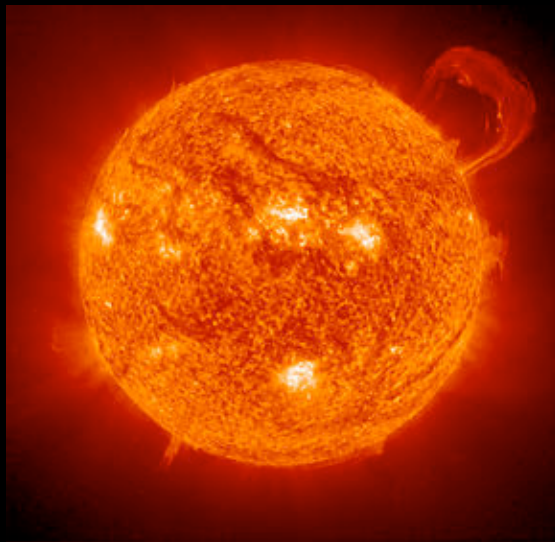
ν_2

ν_3



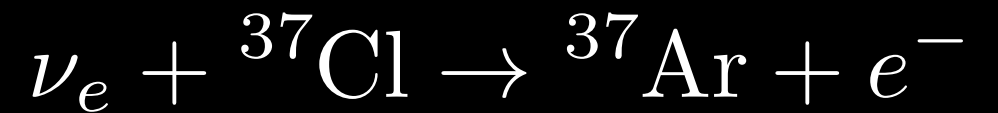
www.particlezoo.net

Homestake



solarsystem.nasa.gov

$1\nu_e$



nobelprize.org

$1/3\nu_e$

MSW effect

Wolfenstein (1978), Mikheyev & Smirnov (1986)

Vacuum:

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

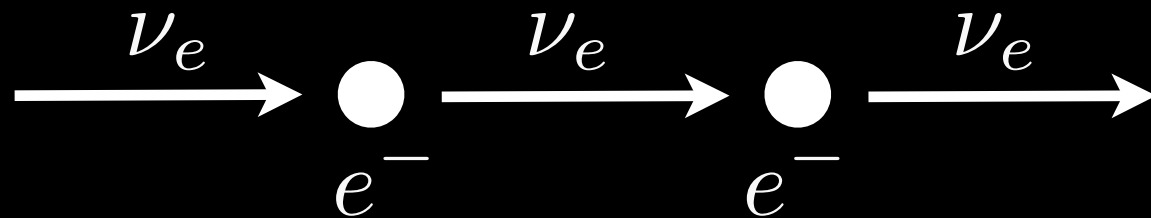
MSW effect

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Medium:



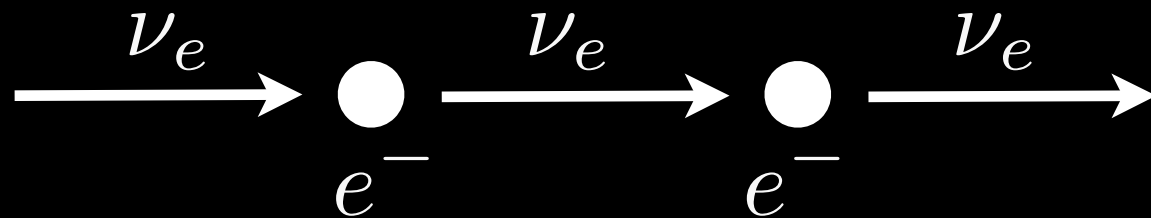
MSW effect

Wolfenstein (1978), Mikheyev & Smirnov (1986)

Vacuum:

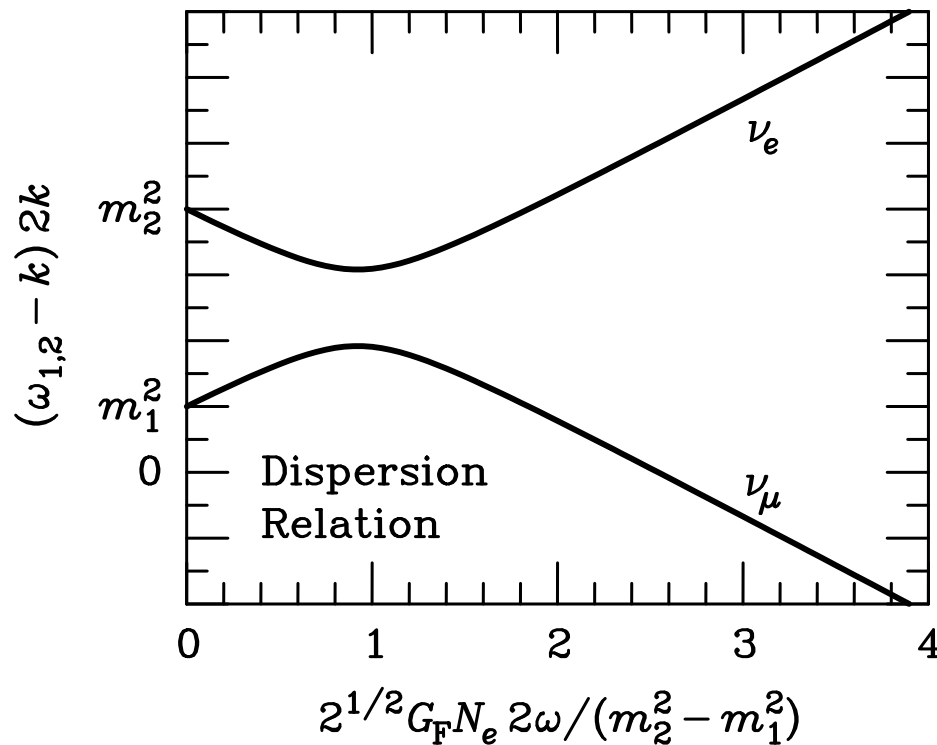
$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{2E} \rightarrow 1 - \frac{1}{2} \sin^2 2\theta > \frac{1}{2}$$

Medium:



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

Adiabatic conversion



Raffelt (1996)

Start

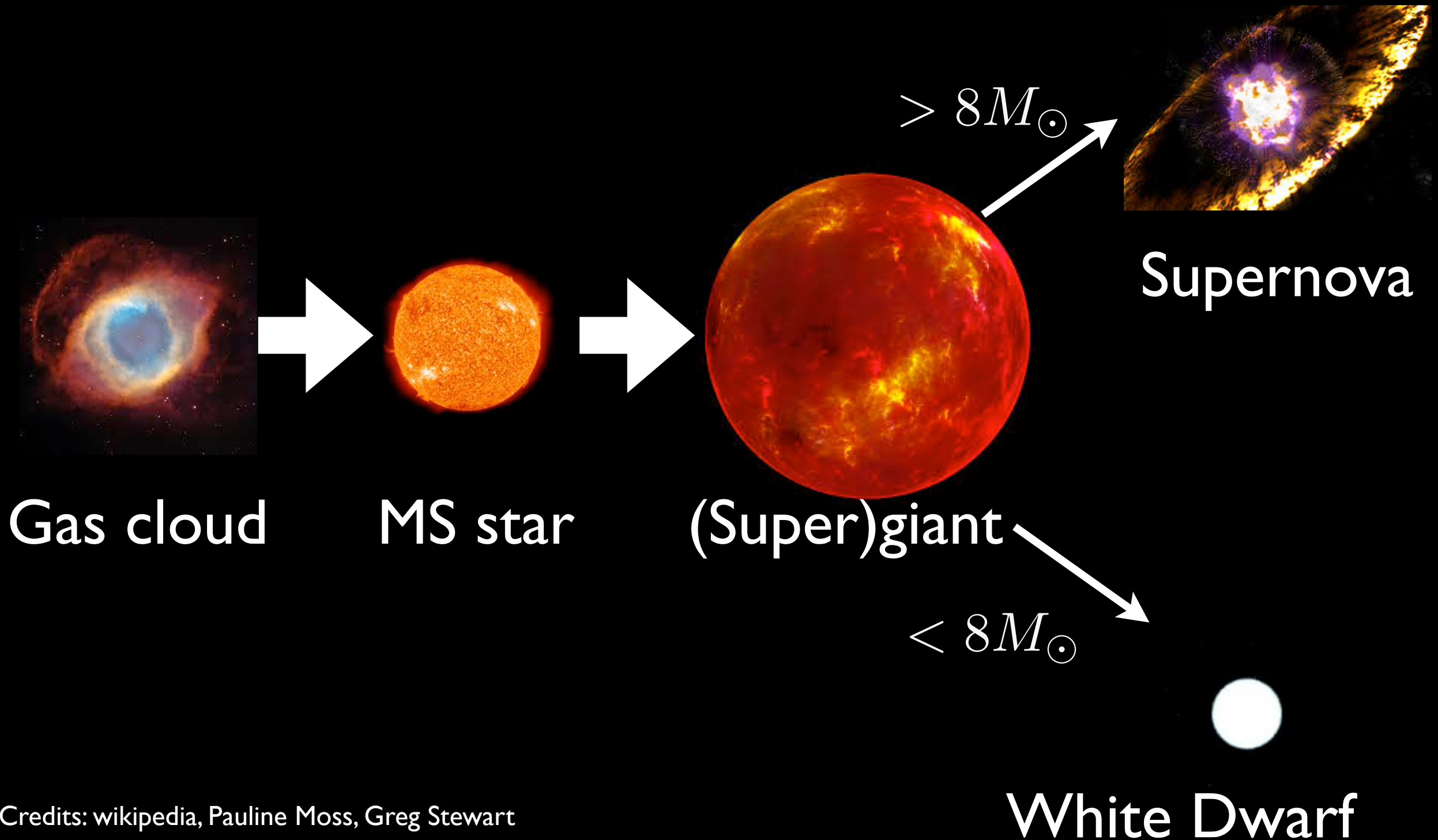
$$\nu_e = \cos\theta_m \nu_1 - \sin\theta_m \nu_2 \sim \nu_1$$

End

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

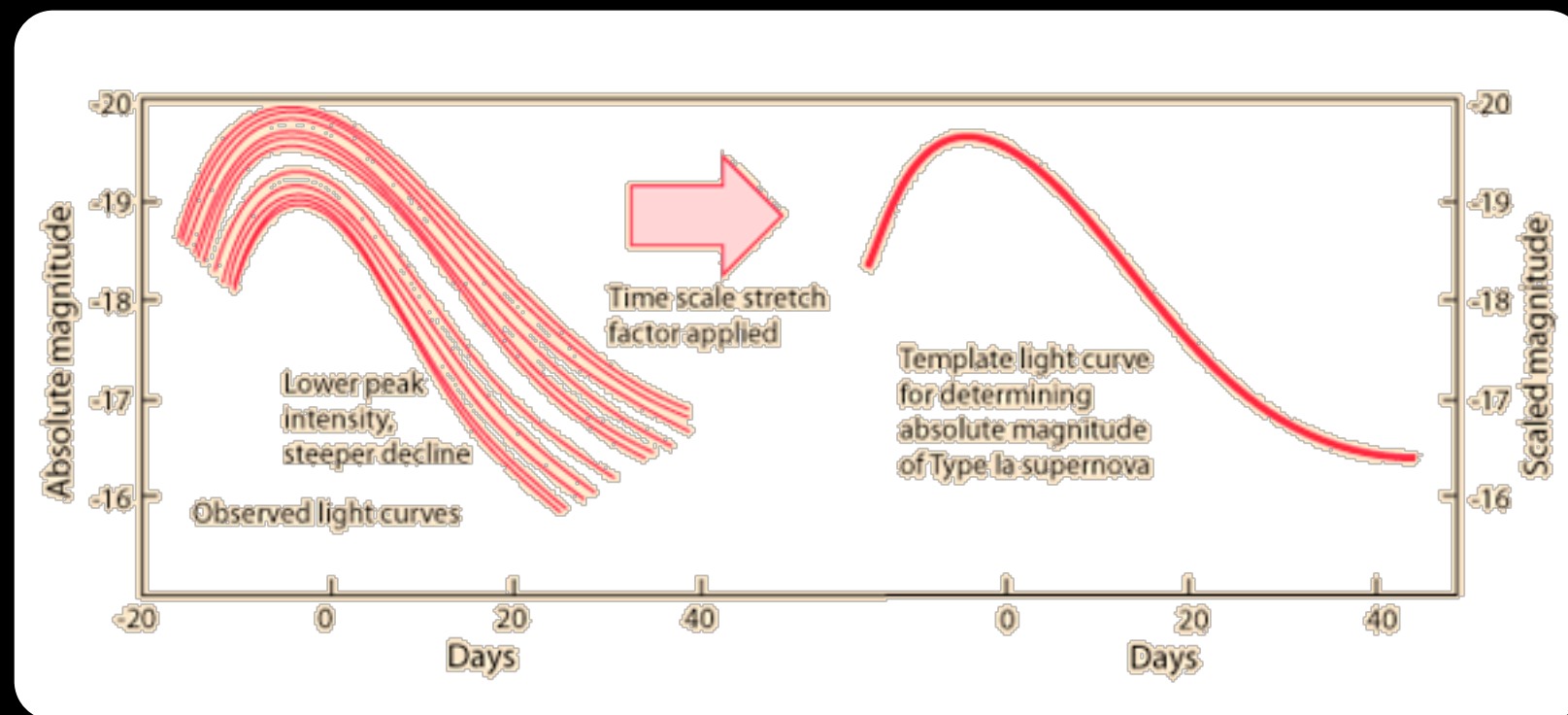
$$P(\nu_e \rightarrow \nu_e) = \sin^2\theta < \frac{1}{2}$$

The Life of a Star



Credits: wikipedia, Pauline Moss, Greg Stewart

Type Ia



SNIa

$$H_0 = 70.6 \pm 3.3 \text{ km/s/Mpc}$$

Efstathiou (2014)

Planck

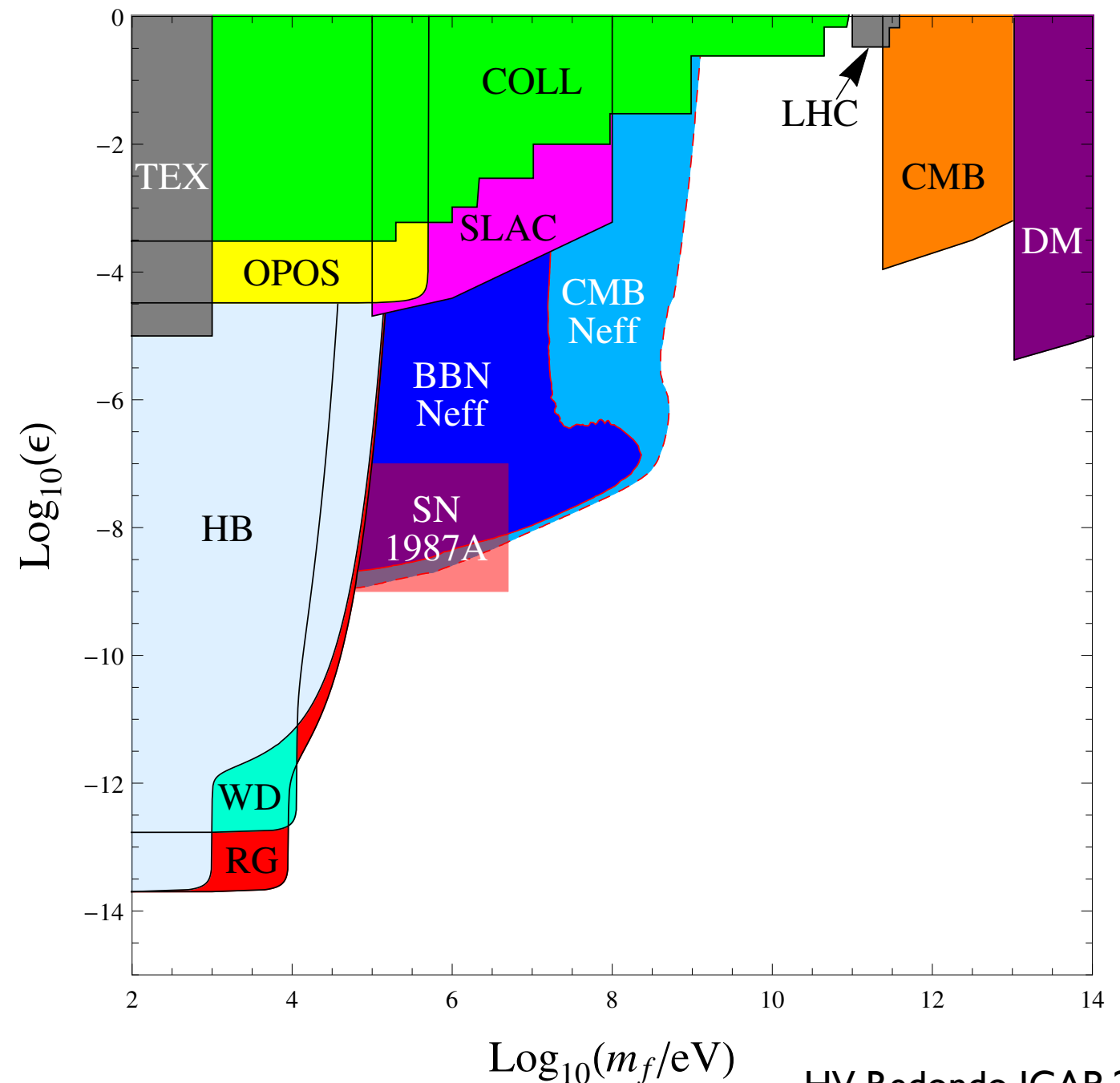
$$H_0 = 67.8 \pm 0.96 \text{ km/s/Mpc}$$

arXiv:1502.01589

Dark radiation

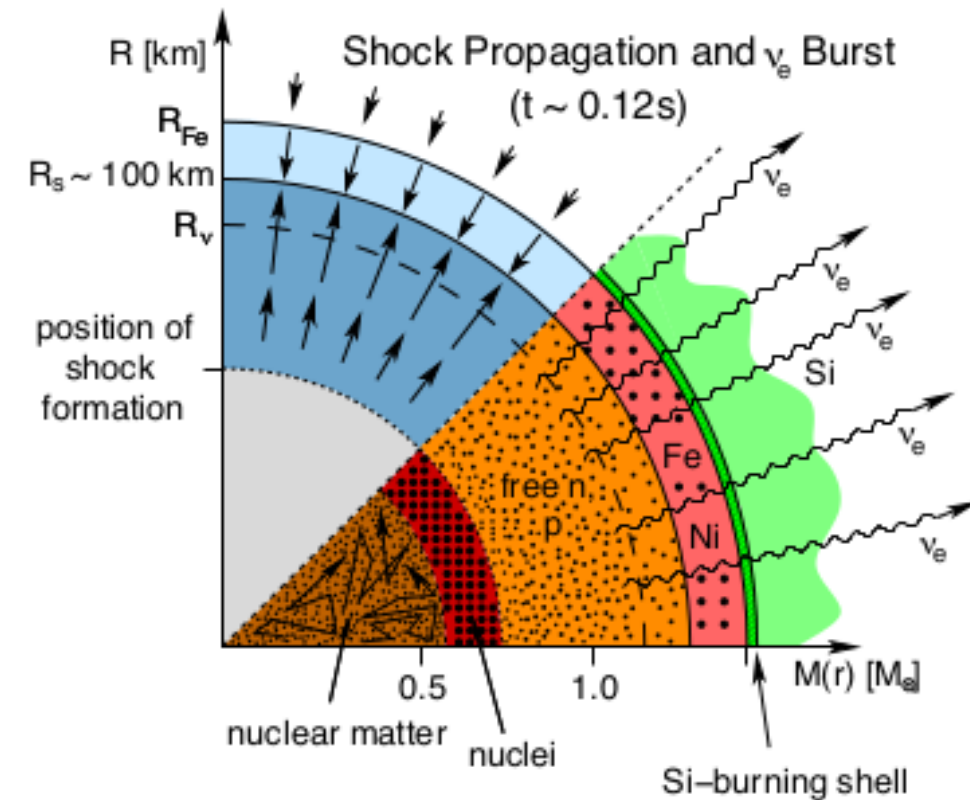
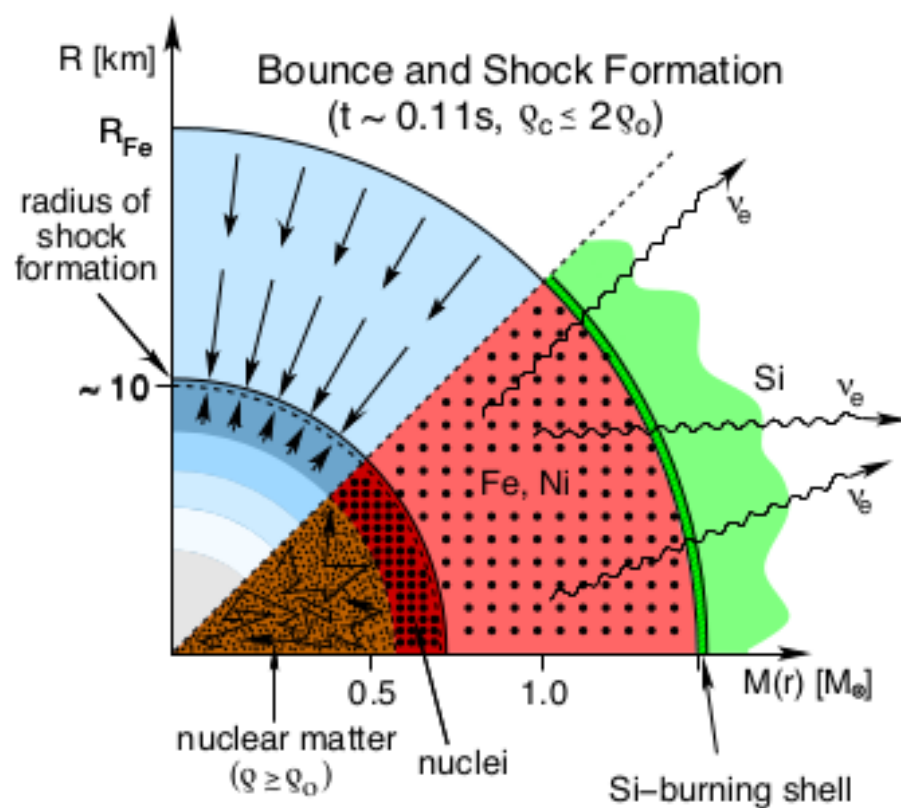
Number of light degrees
of freedom
 $H_0 \rightarrow \rho \rightarrow N_{\text{eff}}$

e.g. massless
hidden photon
+ minicharged
fermion



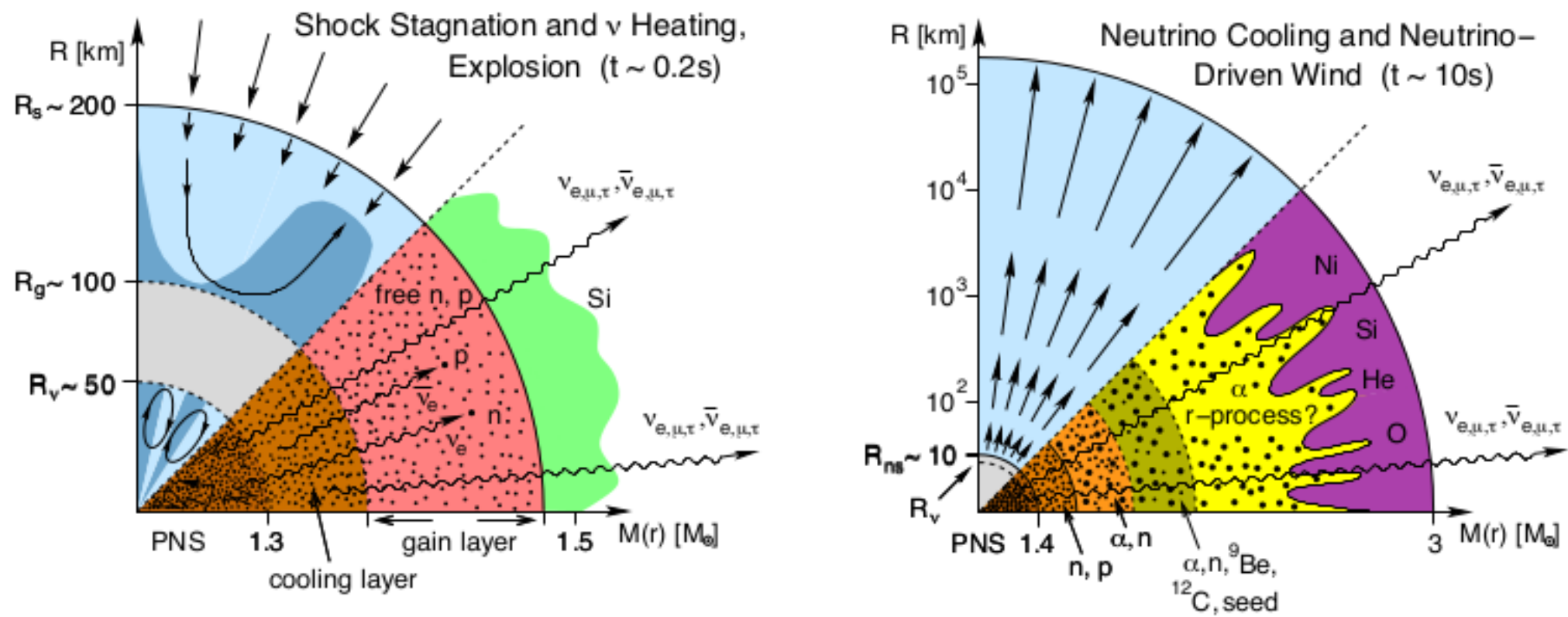
HV, Redondo JCAP 2014

Type II



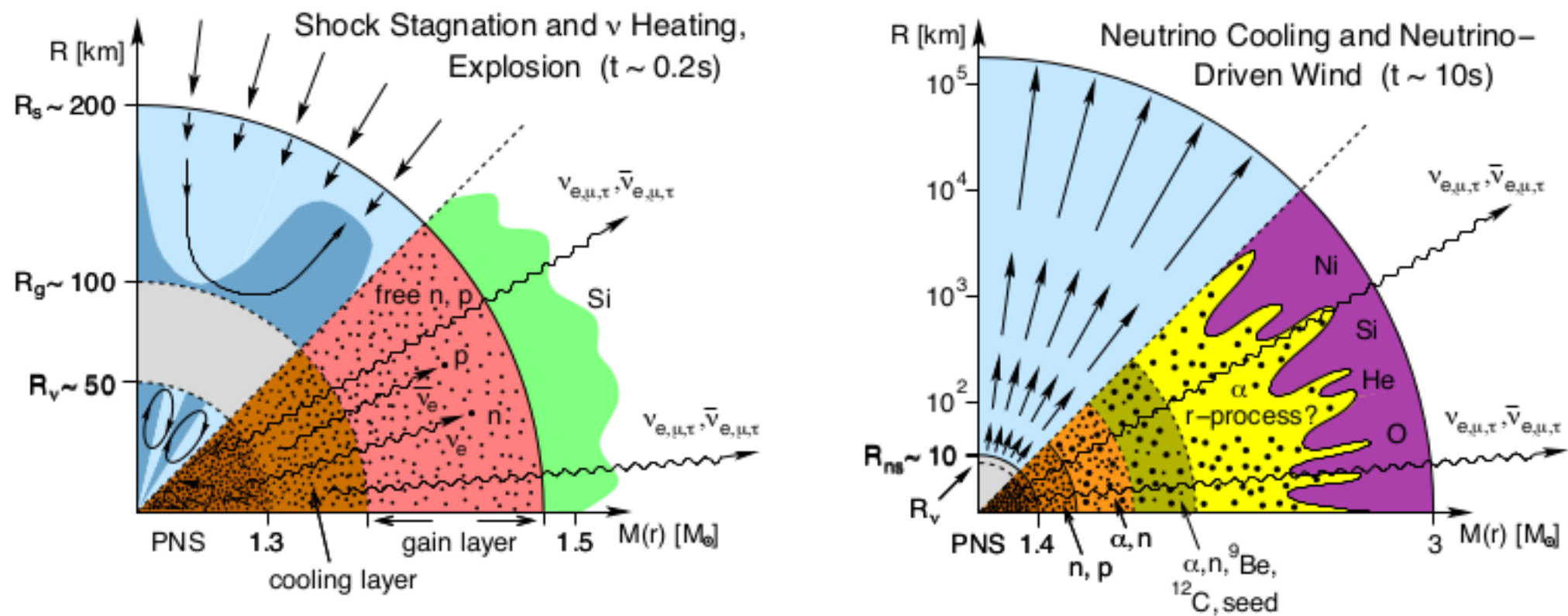
Janka *et al.* (2006)

Type II



Janka *et al.* (2006)

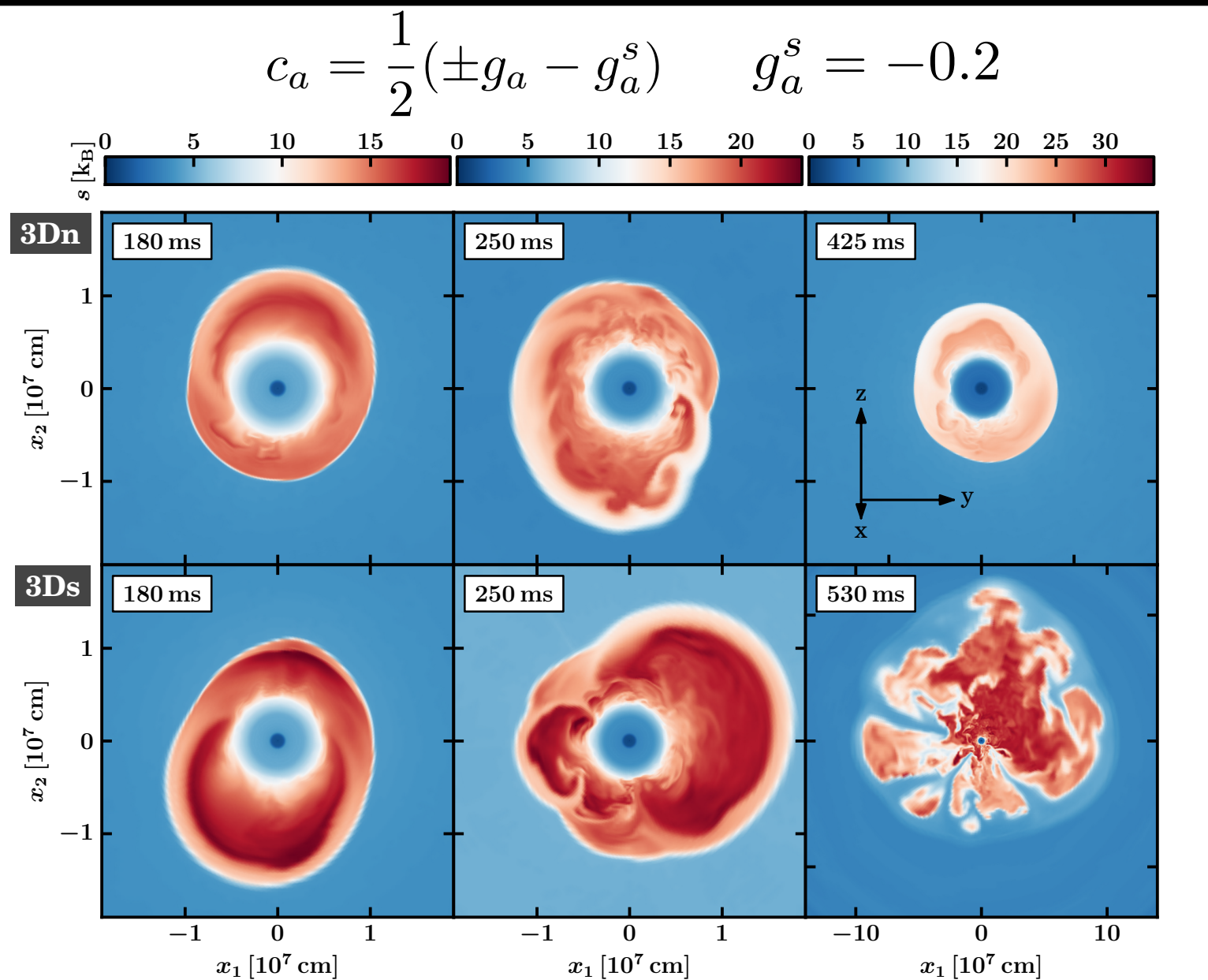
Type II



Janka et al. (2006)

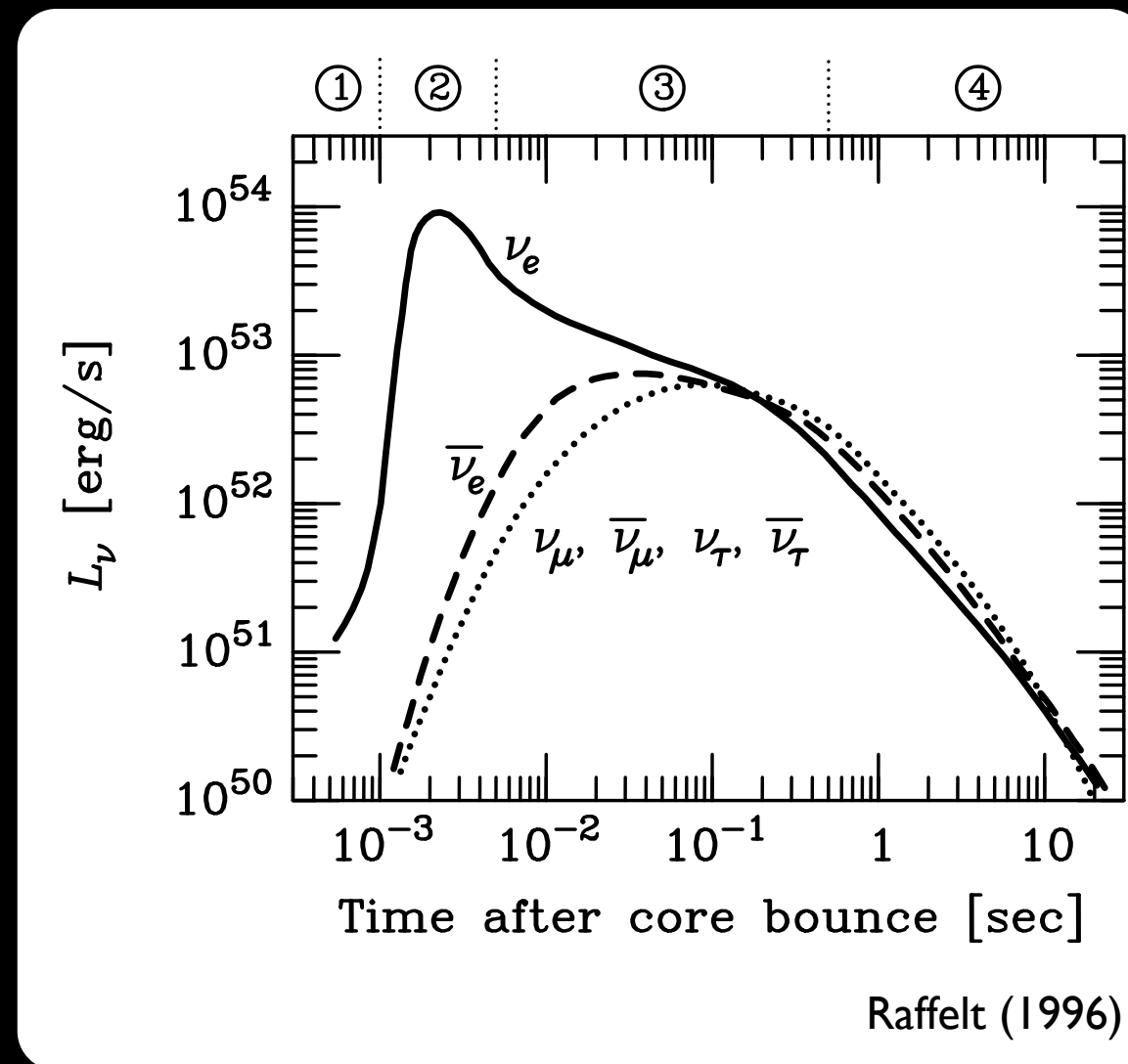
- Why does a supernova explode?
- How are the elements formed?

State of the Art



Melson et al. arXiv:1504.07631

Neutrino Signal



Formalism

Equation of motion (mean-field approximation)

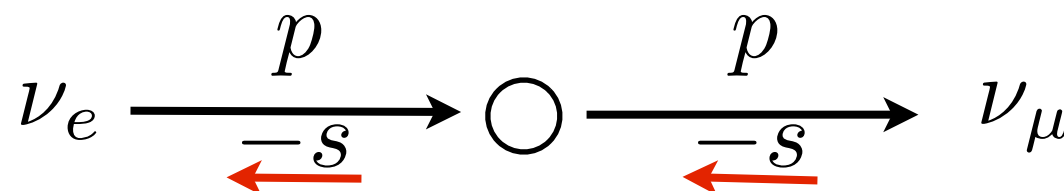
$$i\dot{\rho} = [H, \rho] + \text{coll.}$$

Sigl, Raffelt (1993)

Density matrices:

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

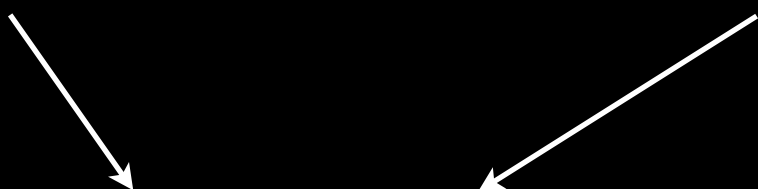
$$(2\pi)^3 \delta^3(p - k) \rho_{ij} = \langle a_j^\dagger(p) a_i(k) \rangle$$



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

$$\mathcal{L} = G_F [\bar{\psi} \gamma^\mu P_L \psi] [\bar{\psi} \gamma_\mu P_L \psi]$$

Helicity oscillations

Weak interaction is chiral

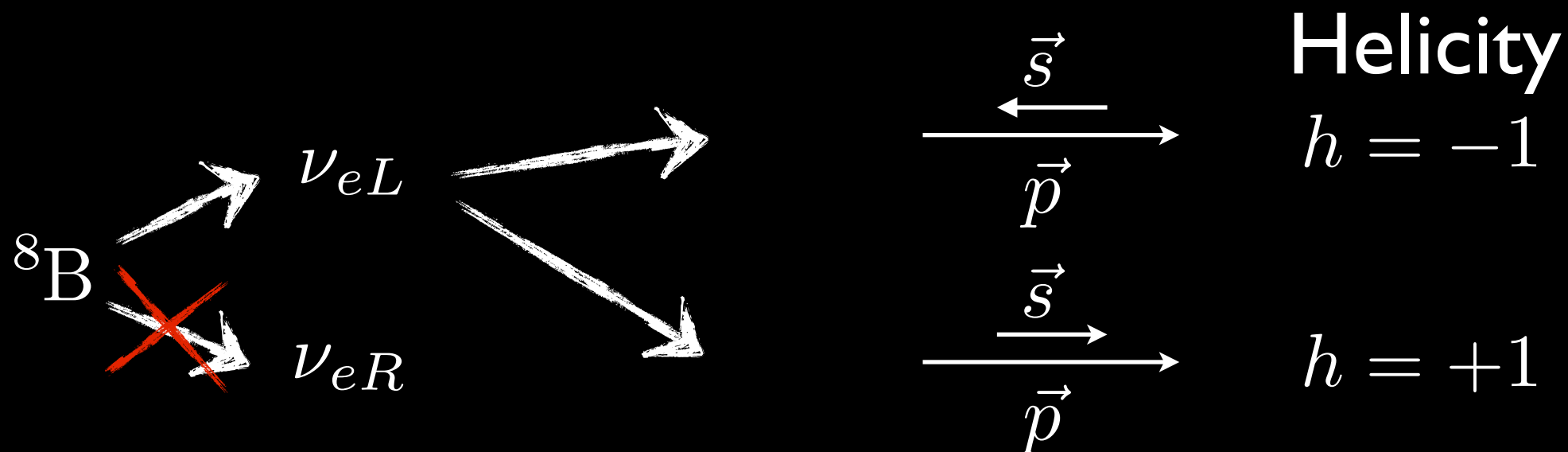
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Helicity oscillations

Weak interaction is chiral

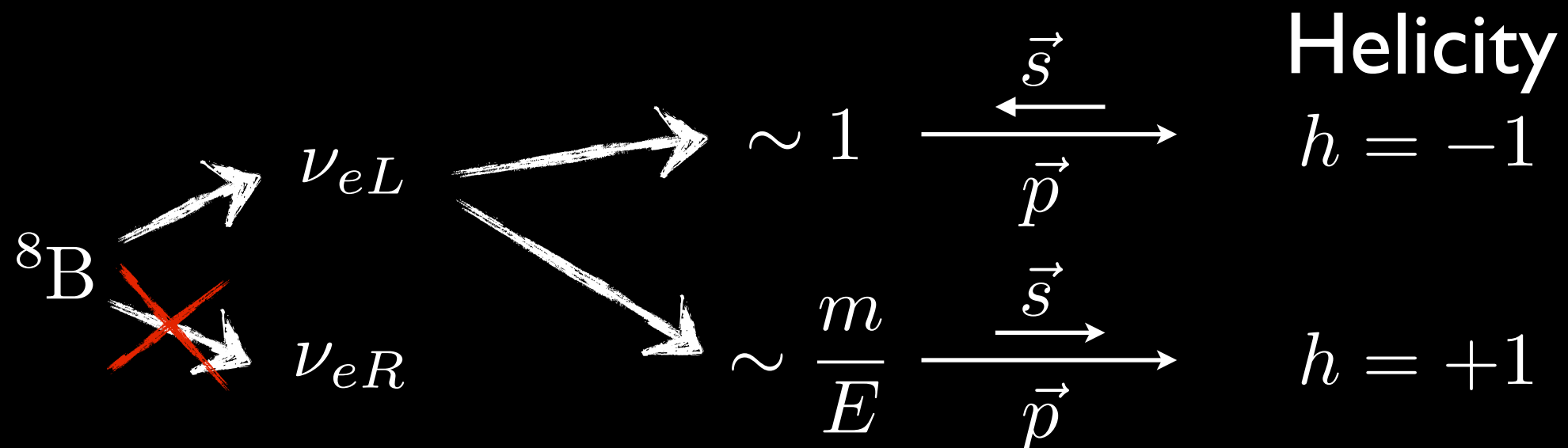
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Helicity oscillations

Weak interaction is chiral

$$\mathcal{L} = G_F [\bar{\psi} \gamma^\mu P_L \psi] [\bar{\psi} \gamma_\mu P_L \psi]$$



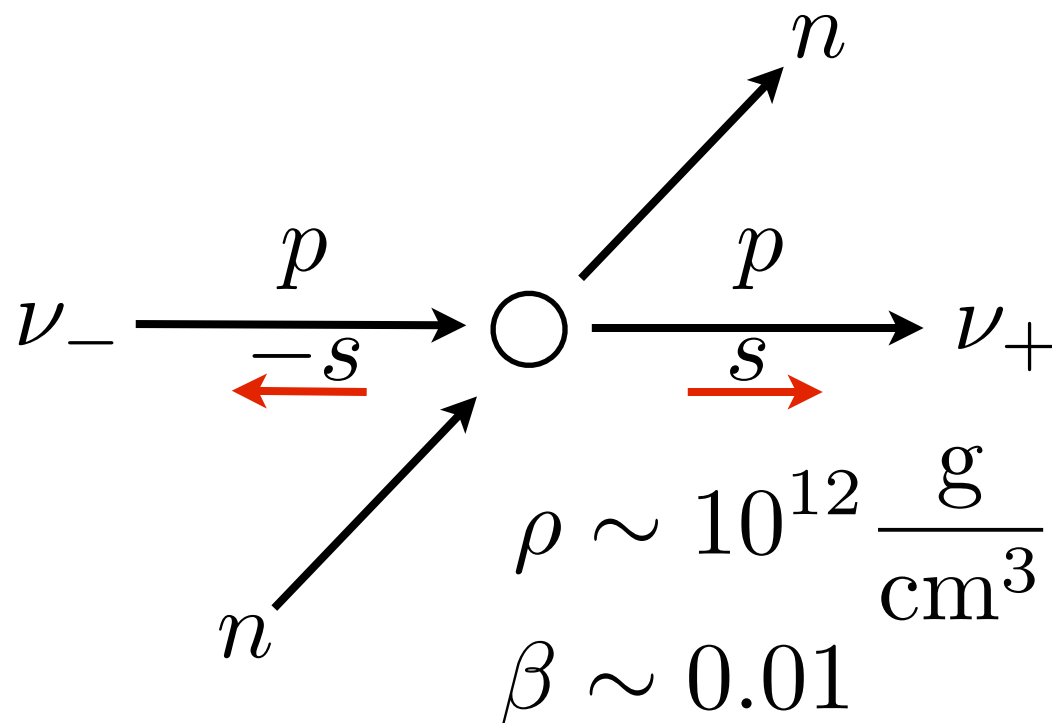
What does helicity do?

Dirac	Majorana
Flips the helicity of a particle/antiparticle	Converts particle into antiparticle
Changes opacity	Changes proton to neutron ratio

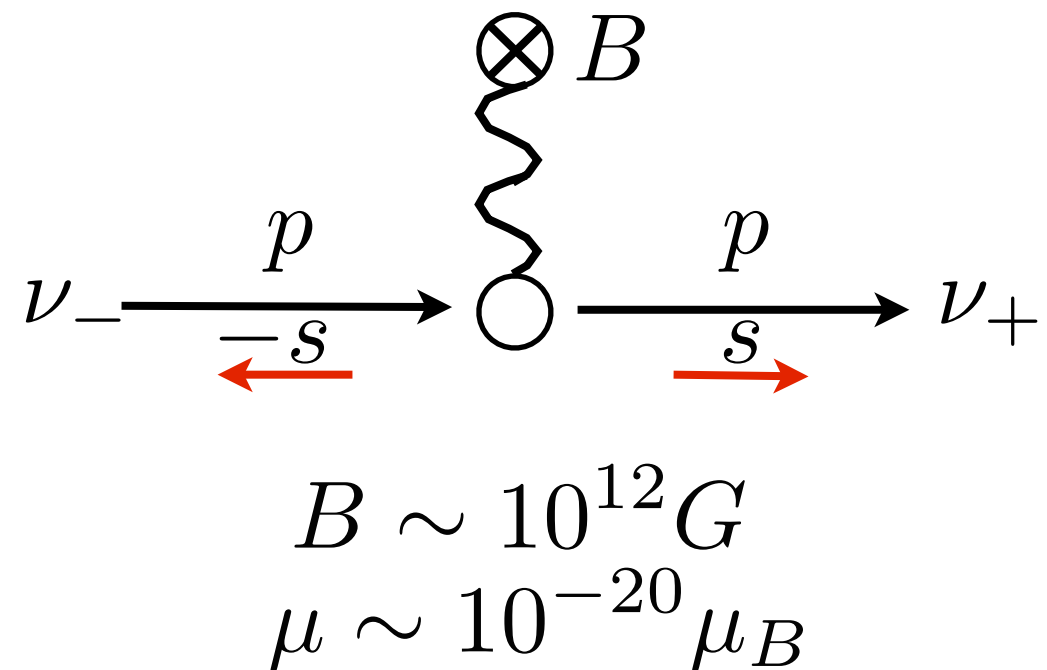
Helicity oscillations

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

Matter currents



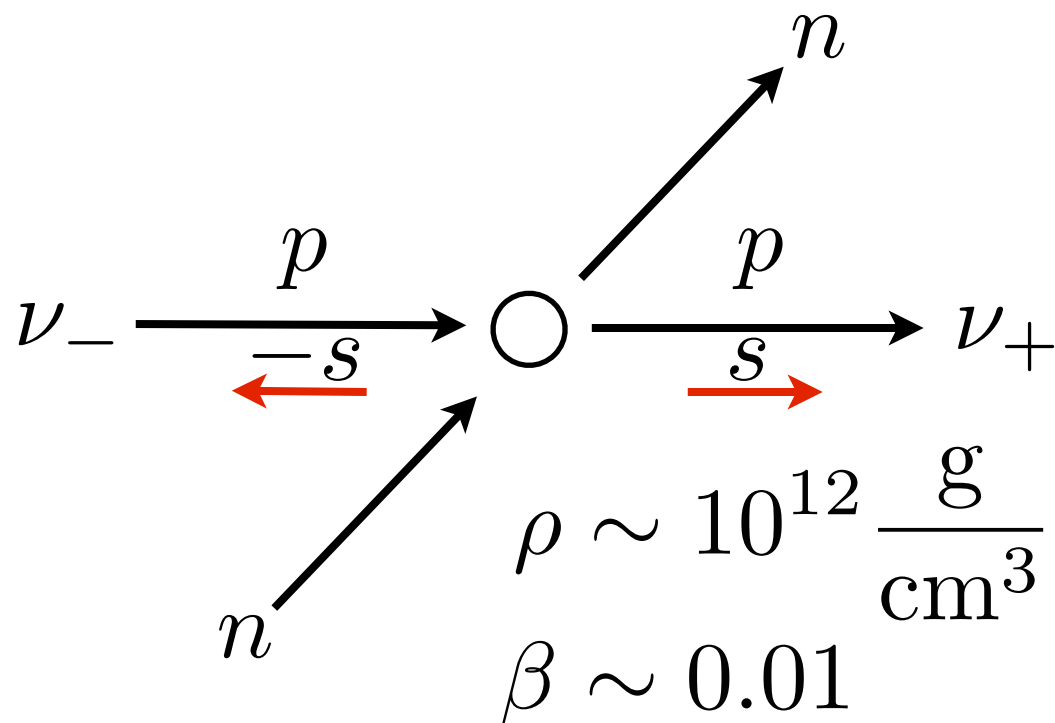
Magnetic fields



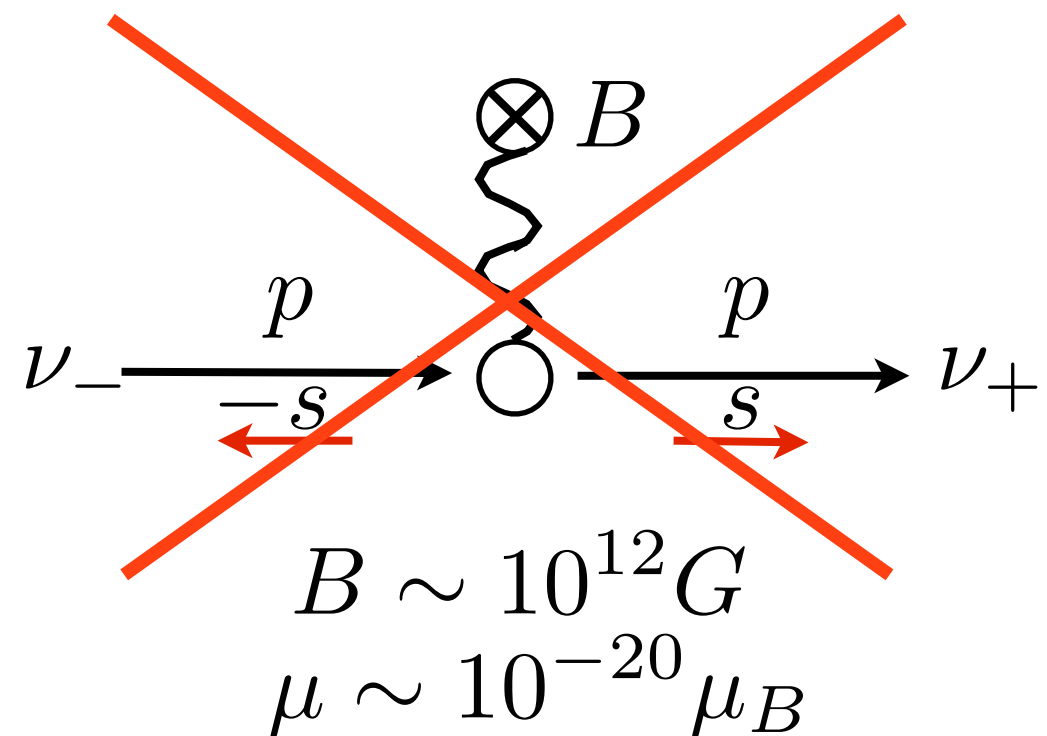
Helicity oscillations

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

Matter currents



Magnetic fields



Order of magnitude

Helicity part of Hamiltonian

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

Order of magnitude

Helicity part of Hamiltonian $V^0 \approx G_F n_n$

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

Order of magnitude

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In equilibrium:

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

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

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Helicity part of Hamiltonian $V^0 \approx G_F n_n$

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$$\rho_{-+} = \frac{H_{-+}^{\nu\nu}}{H_{--}^{\nu\nu} - H_{++}^{\nu\nu}}(\rho_{--} - \rho_{++}) \sim \frac{m}{2E}\beta$$

Order of magnitude

Helicity part of Hamiltonian $V^0 \approx G_F n_n$

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

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$$\rho_{-+} = \frac{H_{-+}^{\nu\nu}}{H_{--}^{\nu\nu} - H_{++}^{\nu\nu}}(\rho_{--} - \rho_{++}) \sim \frac{m}{2E}\beta$$

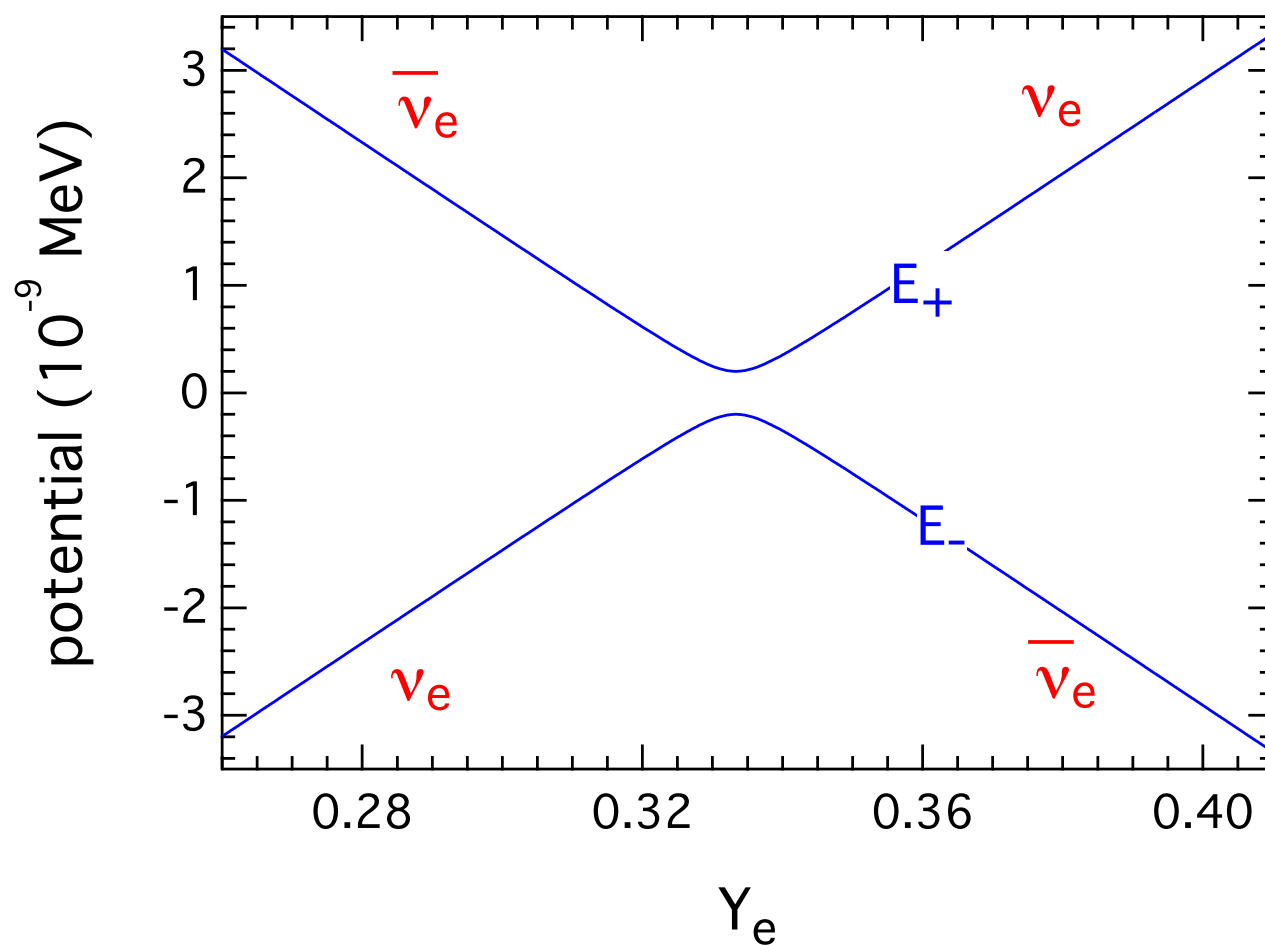
$$\rho_{-+} \sim 10^{-11}$$

Resonant enhancement

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

Resonant enhancement

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



$$\begin{aligned} \nu_- &\rightarrow \nu_e \\ \nu_+ &\rightarrow \bar{\nu}_e \end{aligned}$$

Vlasenko et al. arXiv:1406.6724

Pair correlations

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

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

Serreau, Volpe (2014)

Pair correlations

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Serreau, Volpe (2014)

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

Pair correlations

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Serreau, Volpe (2014)

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

$$H = \begin{pmatrix} H^{\nu\nu} & H^{\nu\bar{\nu}} \\ H^{\bar{\nu}\nu} & H^{\bar{\nu}\bar{\nu}} \end{pmatrix}$$

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

Goals

- What is the meaning of the pair correlations?
- What is the size of the effect?
- How to use the equations?

Weyl neutrino

Kartavtsev, Raffelt, HV (2015)

Densities:

$$\dot{\rho} = -2\text{Im}(\kappa H^{\bar{\nu}\nu}) \quad \dot{\bar{\rho}} = -2\text{Im}(\kappa H^{\bar{\nu}\nu})$$

Weyl neutrino

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$$\rho - \bar{\rho} = \text{const.} \quad \rho + \bar{\rho} \neq \text{const.}$$

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Kappa:

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

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$$\rho - \bar{\rho} = \text{const.} \quad \rho + \bar{\rho} \neq \text{const.}$$

Kappa:

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

Weyl neutrino

Kartavtsev, Raffelt, HV (2015)

Densities:

$$\dot{\rho} = -2\text{Im}(\kappa H^{\bar{\nu}\nu}) \quad \dot{\bar{\rho}} = -2\text{Im}(\kappa H^{\bar{\nu}\nu})$$

$$\rho - \bar{\rho} = \text{const.} \quad \rho + \bar{\rho} \neq \text{const.}$$

Kappa:

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

Weyl neutrino

Kartavtsev, Raffelt, HV (2015)

Densities:

$$\dot{\rho} = -2\text{Im}(\kappa H^{\bar{\nu}\nu}) \quad \dot{\bar{\rho}} = -2\text{Im}(\kappa H^{\bar{\nu}\nu})$$

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Kappa:

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

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

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

Schrödinger formalism

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

Schrödinger formalism

$$\begin{array}{c} \nu(p) \quad \bar{\nu}(-p) \\ \swarrow \quad \nwarrow \\ |\psi\rangle = A_{00}|00\rangle + A_{11}|11\rangle + A_{10}|10\rangle + A_{01}|01\rangle \end{array}$$

Schrödinger formalism

$$\begin{array}{c}
 \nu(p) \quad \bar{\nu}(-p) \\
 \swarrow \quad \nwarrow \\
 |\psi\rangle = A_{00}|00\rangle + A_{11}|11\rangle + A_{10}|10\rangle + A_{01}|01\rangle
 \end{array}$$

$$\begin{aligned}
 H = & a^\dagger(\vec{p}) H^{\nu\nu} a(\vec{p}) + a^\dagger(\vec{p}) H^{\nu\bar{\nu}} b^\dagger(-\vec{p}) \\
 & + b(-\vec{p}) H^{\bar{\nu}\nu} a(\vec{p}) - b^\dagger(-\vec{p}) H^{\bar{\nu}\bar{\nu}} b(-\vec{p})
 \end{aligned}$$

Schrödinger formalism

$$\begin{array}{c}
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 & + b(-\vec{p}) H^{\bar{\nu}\nu} a(\vec{p}) - b^\dagger(-\vec{p}) H^{\bar{\nu}\bar{\nu}} b(-\vec{p})
 \end{aligned}$$

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

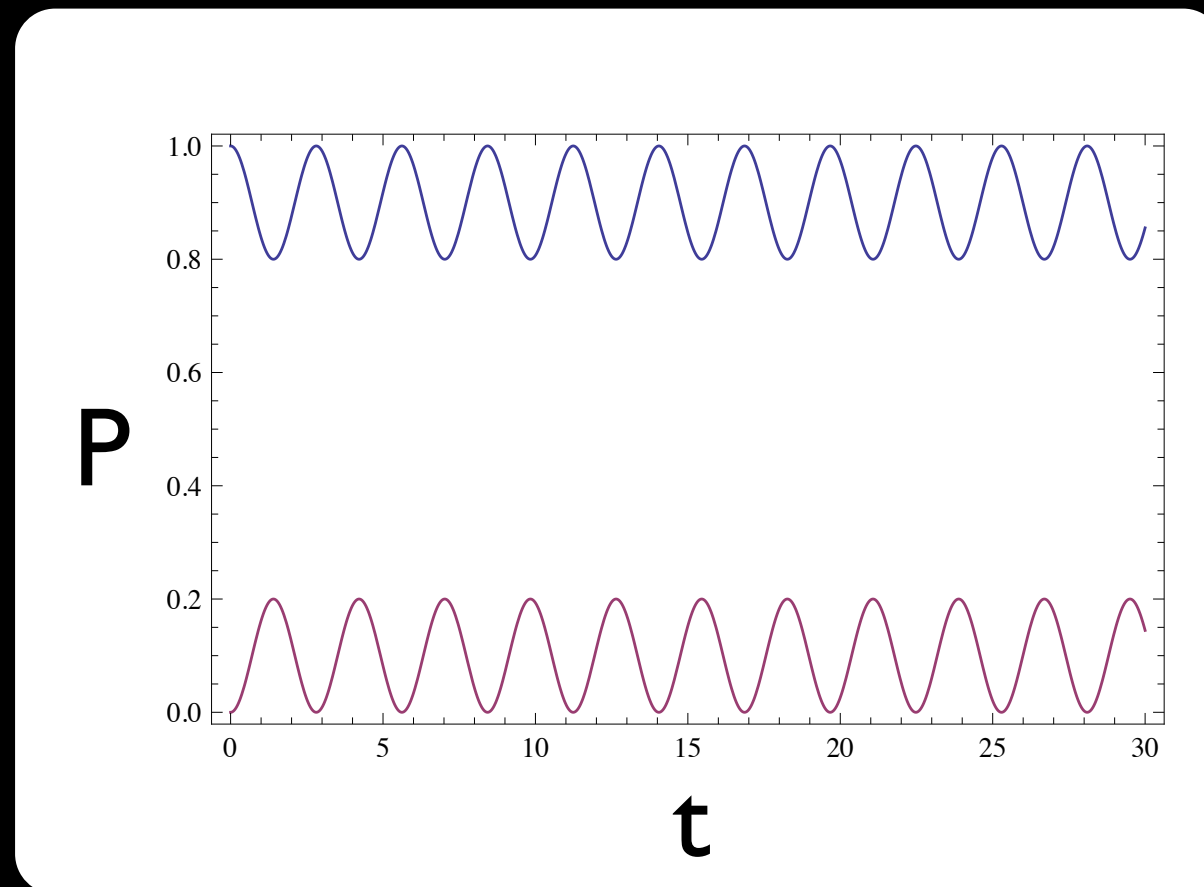
$$i\partial_t A_{10} = H^{\nu\nu} A_{10}$$

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

Pair creation

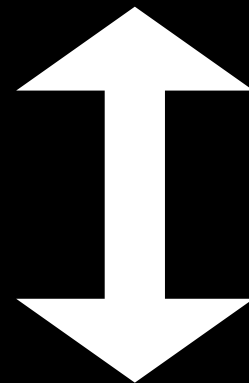
$$i\partial_t \begin{pmatrix} A_{00} \\ A_{11} \end{pmatrix} = \begin{pmatrix} 0 & H^{\bar{\nu}\nu} \\ H^{\nu\bar{\nu}} & H^{\nu\nu} - H^{\bar{\nu}\bar{\nu}} \end{pmatrix} \begin{pmatrix} A_{00} \\ A_{11} \end{pmatrix}$$

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



Equivalence

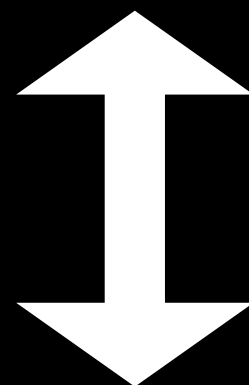
Schrödinger formalism



Density matrix formalism

Equivalence

Schrödinger formalism

$$\begin{aligned}\rho &= |A_{11}|^2 + |A_{10}|^2 \\ \bar{\rho} &= |A_{11}|^2 + |A_{01}|^2\end{aligned}$$


Density matrix formalism

Equivalence

Schrödinger formalism

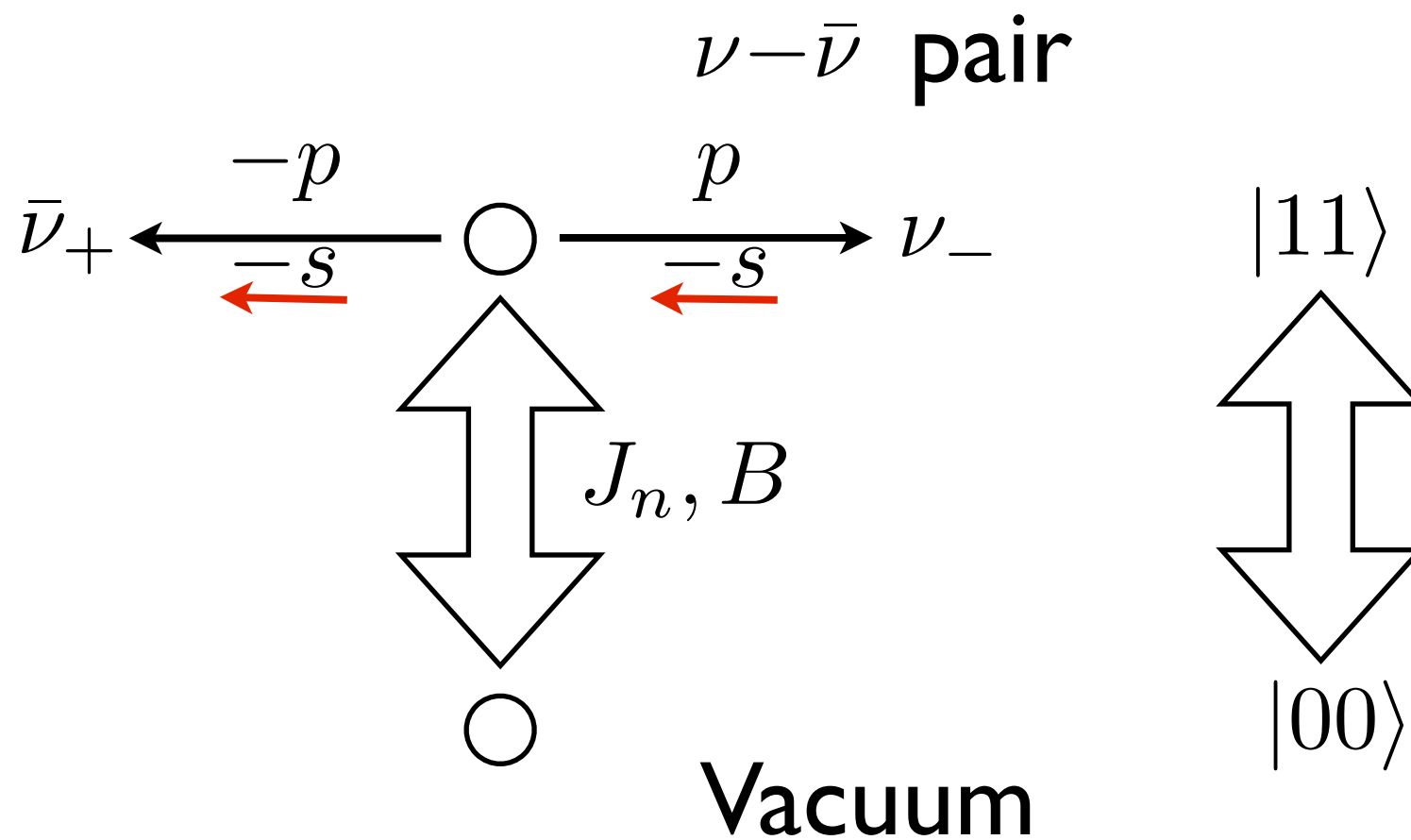
$$\begin{array}{l} \rho = |A_{11}|^2 + |A_{10}|^2 \\ \bar{\rho} = |A_{11}|^2 + |A_{01}|^2 \end{array} \begin{array}{c} \updownarrow \end{array} \begin{array}{l} \kappa = A_{00}^* A_{11} \end{array}$$

Density matrix formalism

Pair correlations

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

Serreau, Volpe (2014)



Order of magnitude

In equilibrium

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

$$H^{\nu\bar{\nu}} = -V\beta - 2\sqrt{2}G_F \hat{\vec{\epsilon}}^* \cdot \int_{\vec{q}} [\hat{\vec{q}} [\rho(q) - \bar{\rho}(-q)] + \hat{\vec{\epsilon}}\kappa + \hat{\vec{\epsilon}}^*\kappa^\dagger]$$

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without ν - ν -interaction:

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

Self-consistency

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

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


The integral diverges

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

Using a cut-off

Integration to infinity leads beyond our assumptions:

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

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with ν - ν -interaction:

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

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

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

Initial conditions

Reason for flavor oscillations:

$$\begin{array}{ll} \bullet \xrightarrow[\text{energy } E]{\nu} & \text{timescale} \\ \mathbf{B} & \tau \sim 1/E \\ \\ \nu_e \xrightarrow[\frac{\Delta m^2}{2E}]{} \nu_\mu & \tau_{\text{osc}} \gg \tau \end{array}$$

Initial conditions

Reason for flavor oscillations:

$$\bullet \xrightarrow[\text{energy } E]{\nu} \text{B}$$

timescale
 $\tau \sim 1/E$

$$\nu_e \xrightarrow[\frac{\Delta m^2}{2E}]{} \nu_\mu$$

$$\tau_{\text{osc}} \gg \tau$$

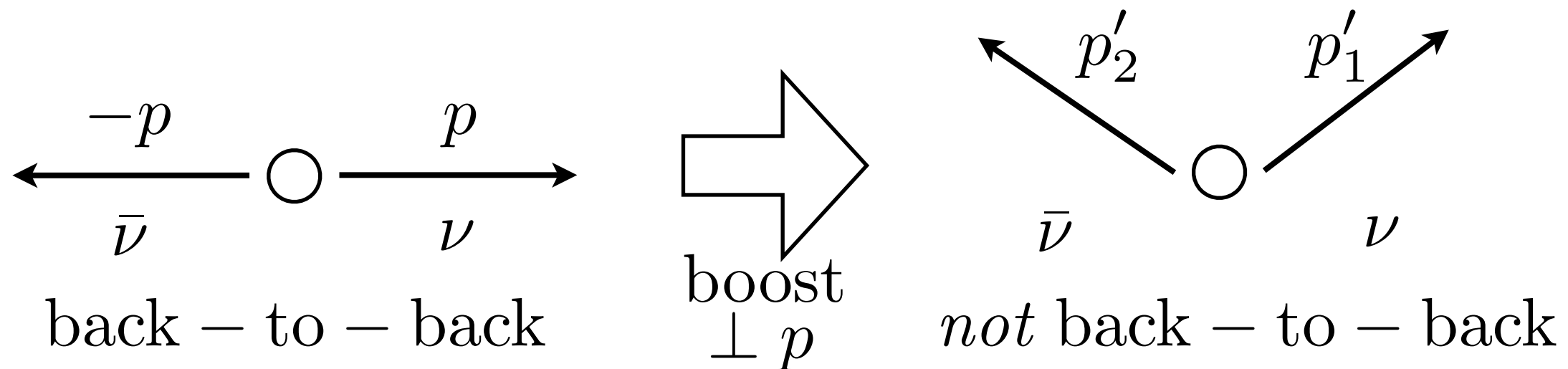
$$|00\rangle \xrightarrow[\text{energy } 2E]{} |11\rangle$$

$$\tau_{\text{pair}} \lesssim \tau$$

How to use the equations?

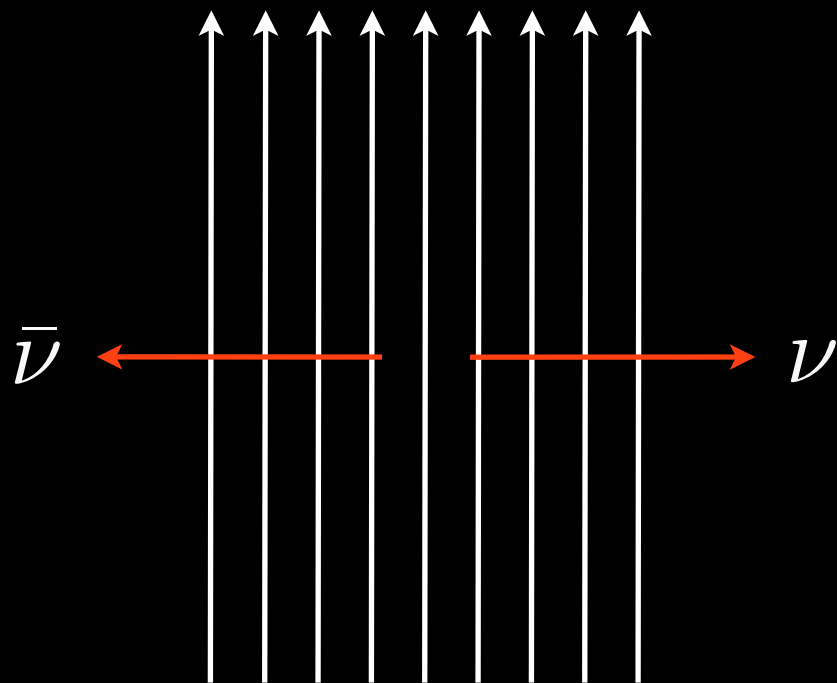
Lorentz invariance

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



Particle number?

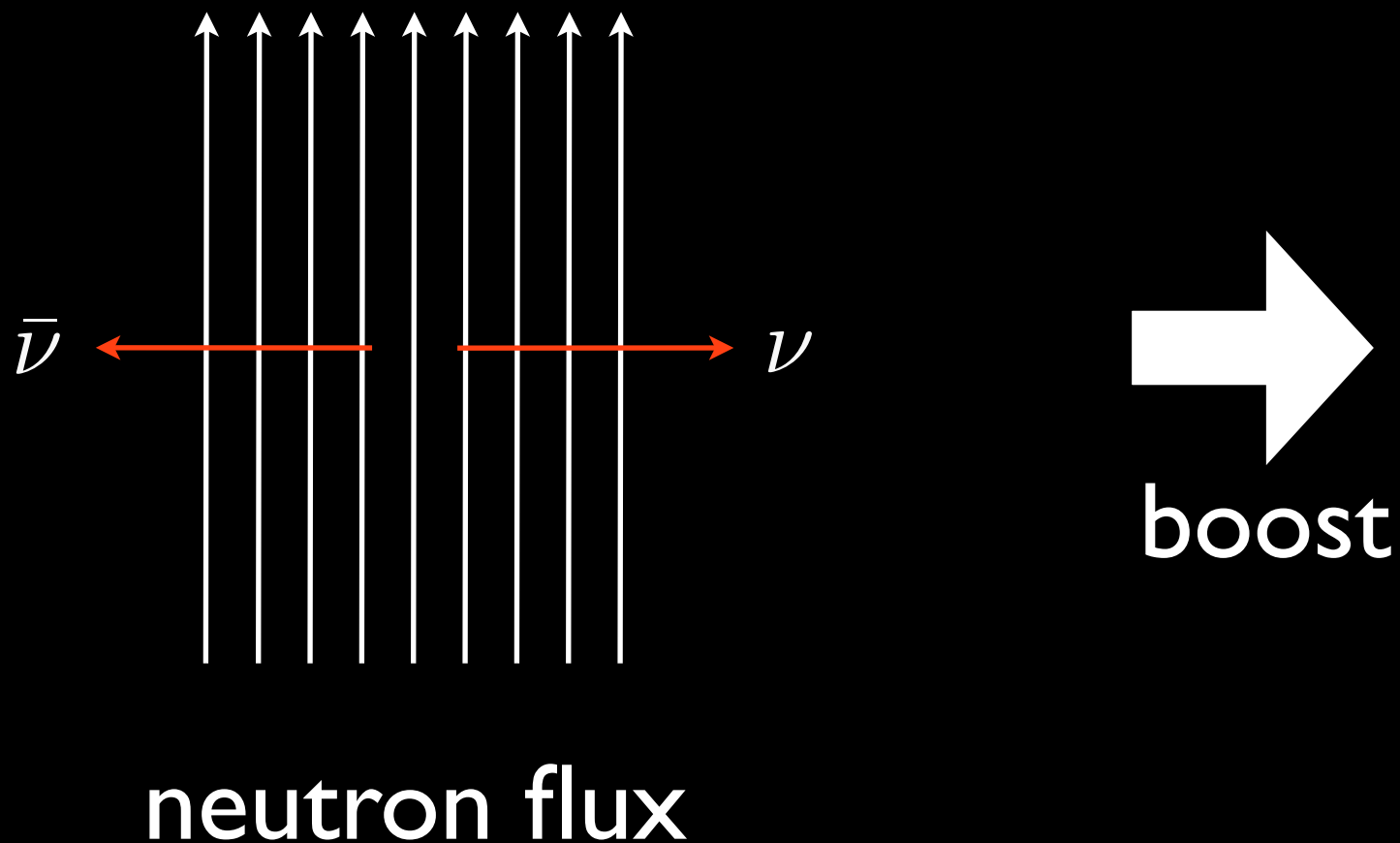
$$i\dot{\kappa} \approx 2E\kappa - G_F \vec{\epsilon}^* \cdot \vec{J}$$



neutron flux

Particle number?

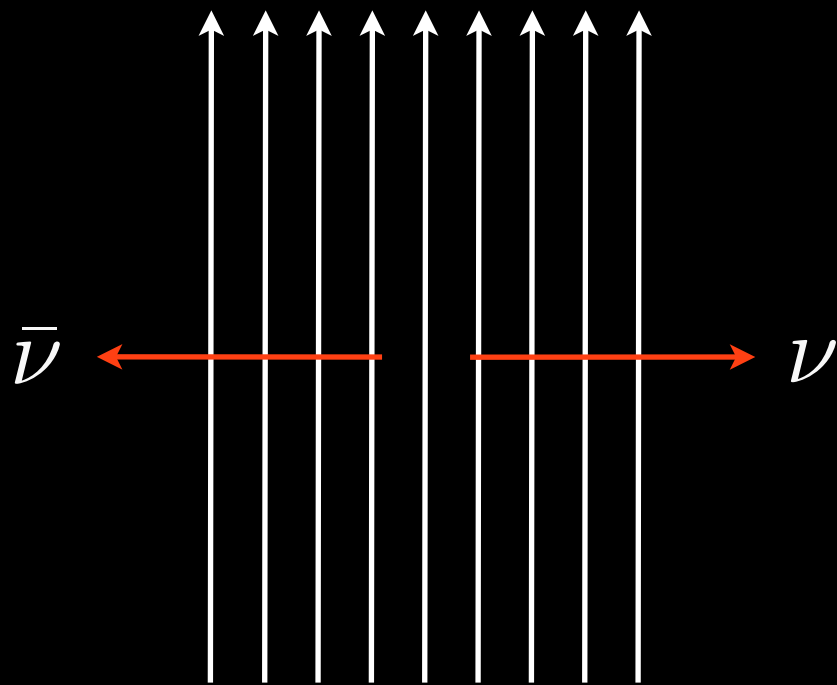
$$i\dot{\kappa} \approx 2E\kappa - G_F \vec{\epsilon}^* \cdot \vec{J}$$



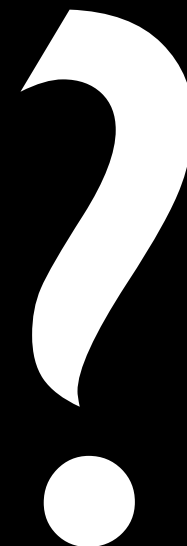
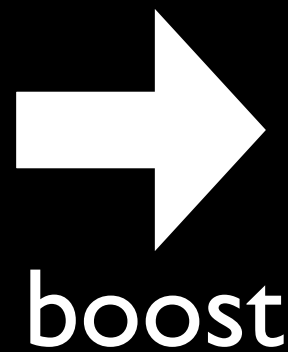
Particle number?

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

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



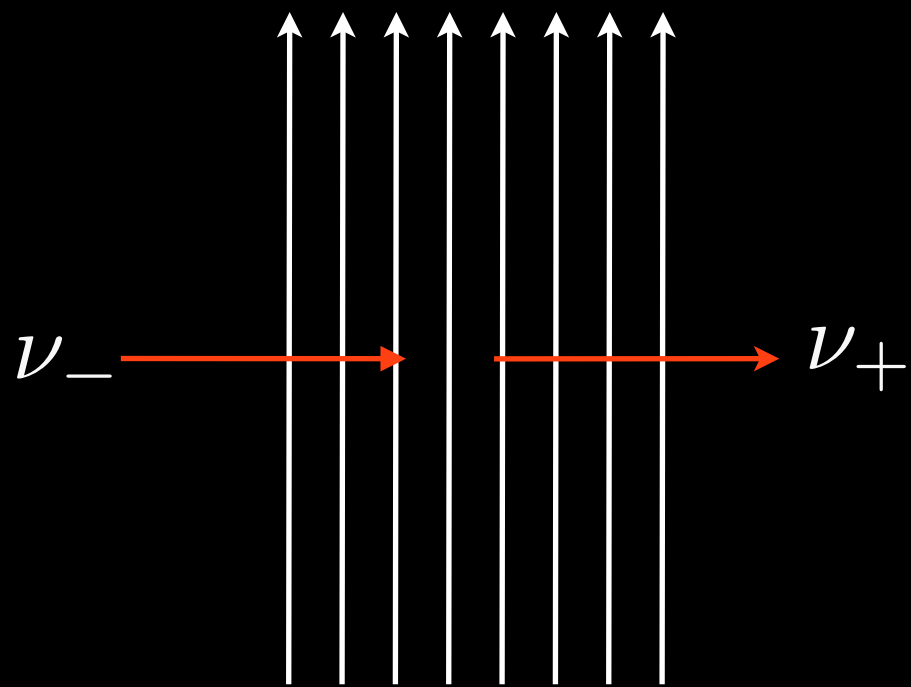
neutron flux



no neutron flux

Lorentz boosts and helicity

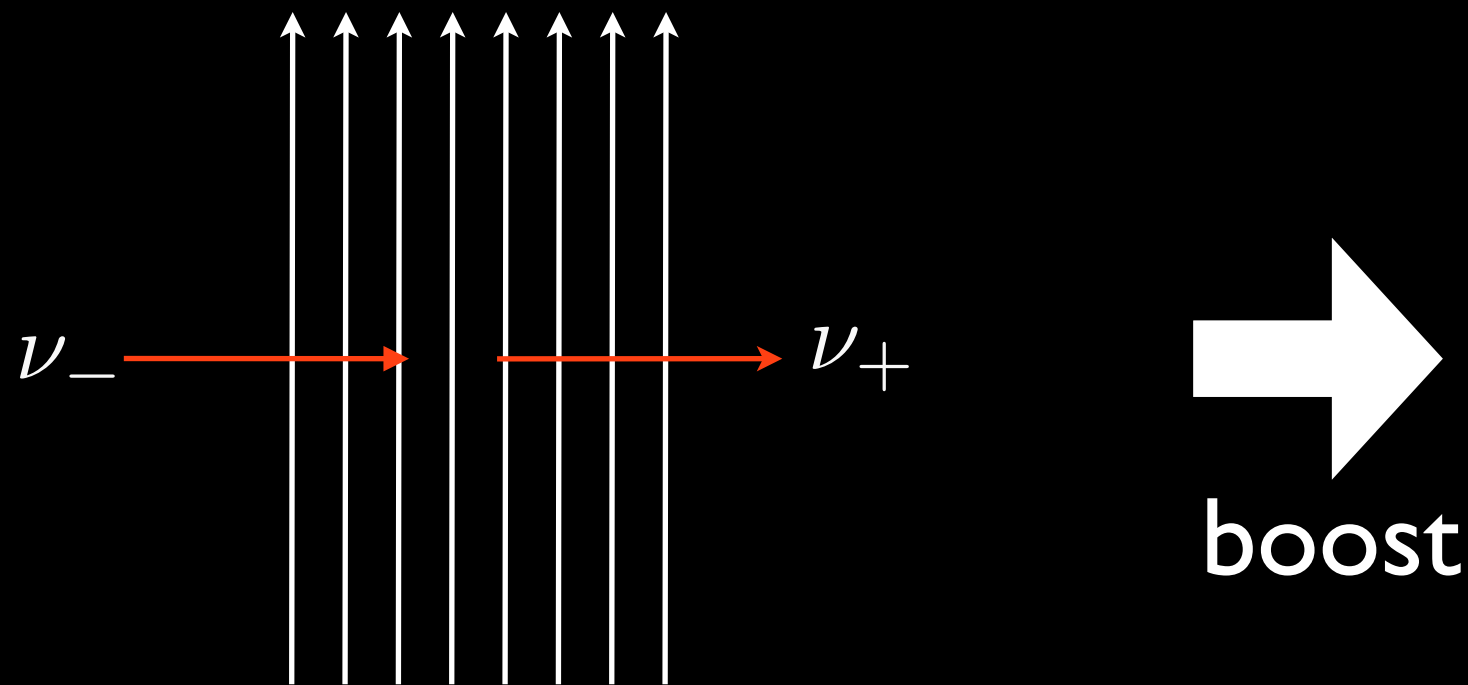
$$i\dot{\rho}_{-+} = 2V \cancel{\rho_{-+}} + G_F \frac{m}{2E} \vec{\epsilon} \cdot \vec{J} (\rho_{--} - \rho_{++})$$



neutron flux

Lorentz boosts and helicity

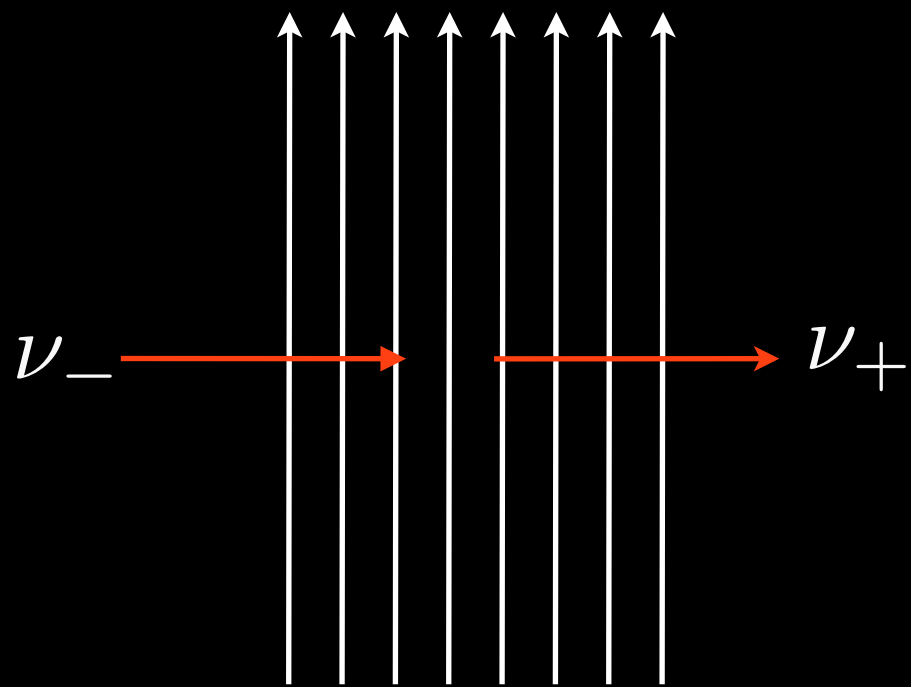
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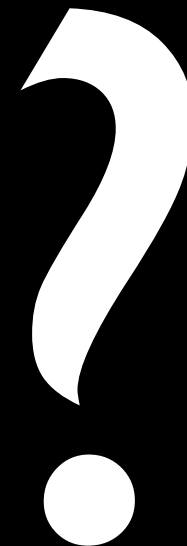
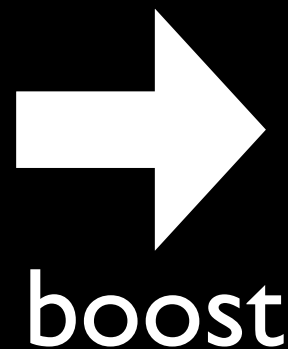
neutron flux

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



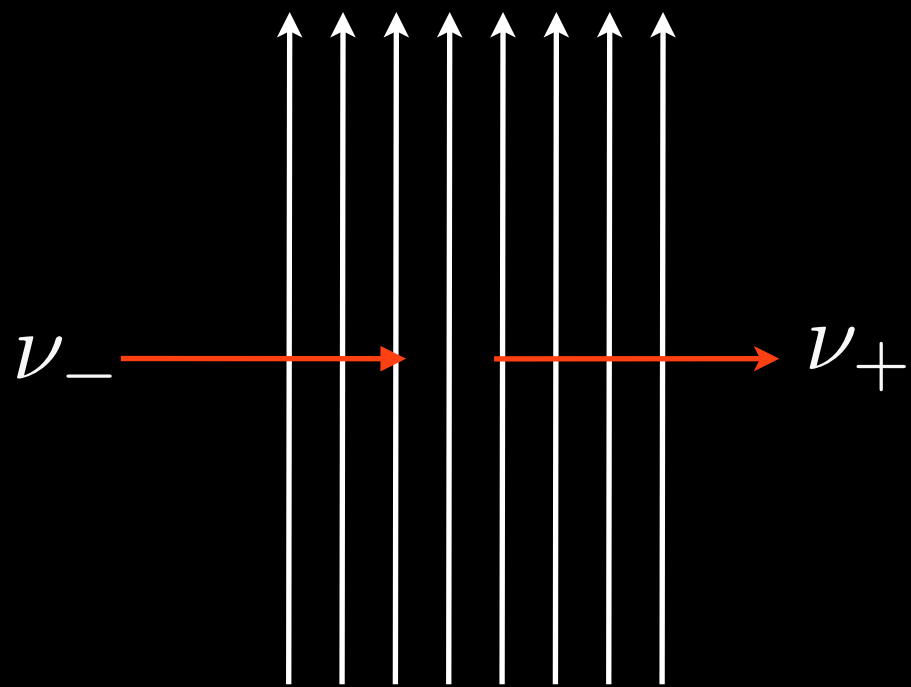
neutron flux



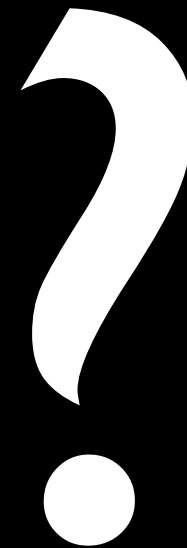
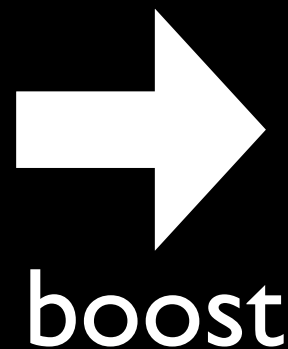
no neutron flux

Lorentz boosts and helicity

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



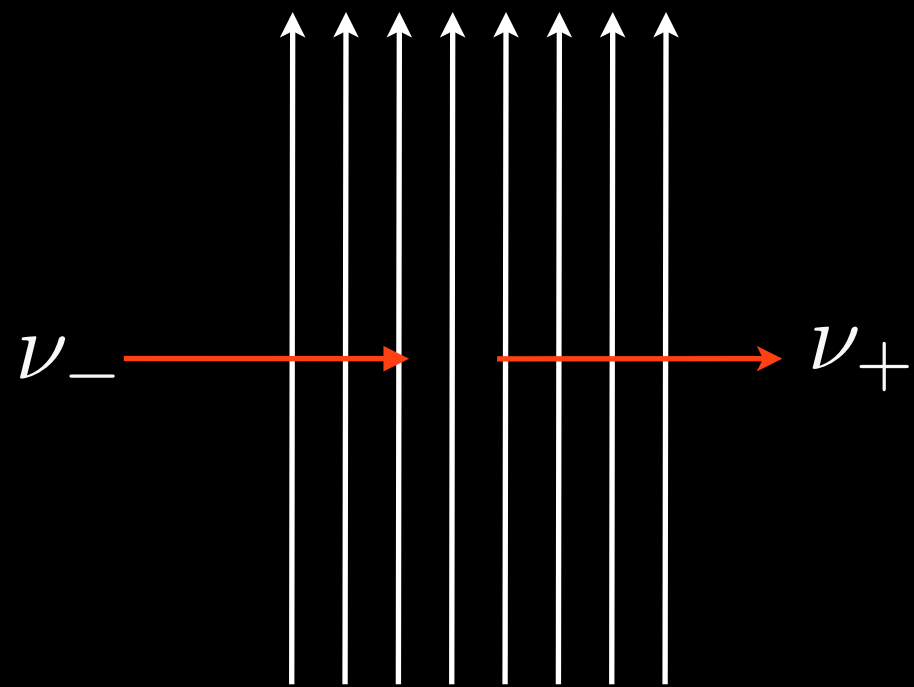
neutron flux



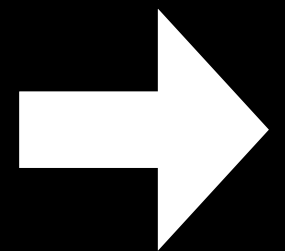
no neutron flux

Lorentz boosts and helicity

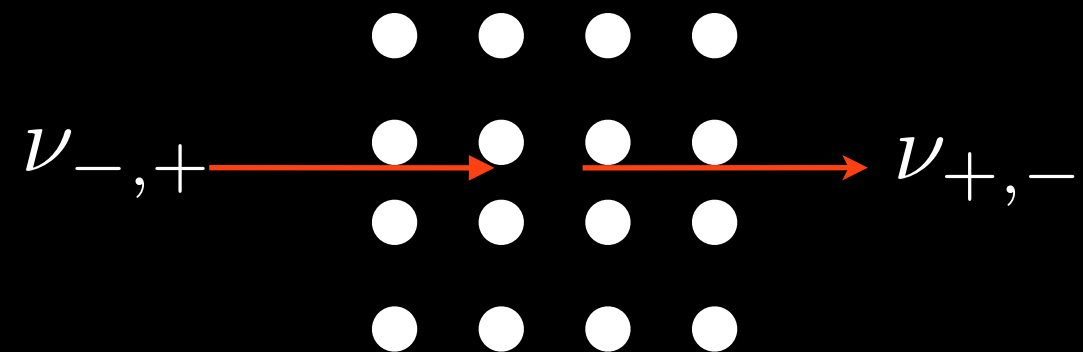
$$i\dot{\rho}_{-+} = 2V\rho_{-+} + G_F \frac{m}{2E} \vec{\epsilon} \cdot \cancel{\vec{J}} (\rho_{--} - \rho_{++})$$



neutron flux



boost

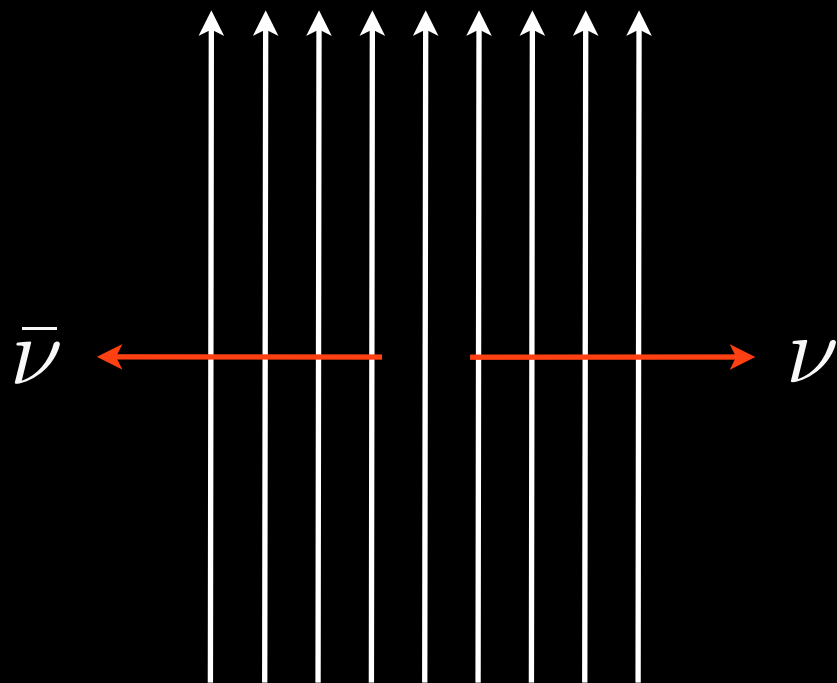


no neutron flux

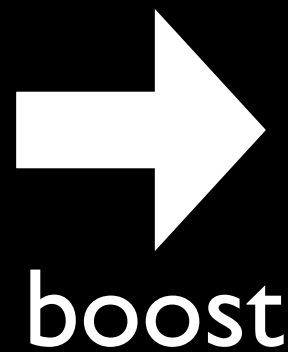
Particle number?

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

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



neutron flux



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

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

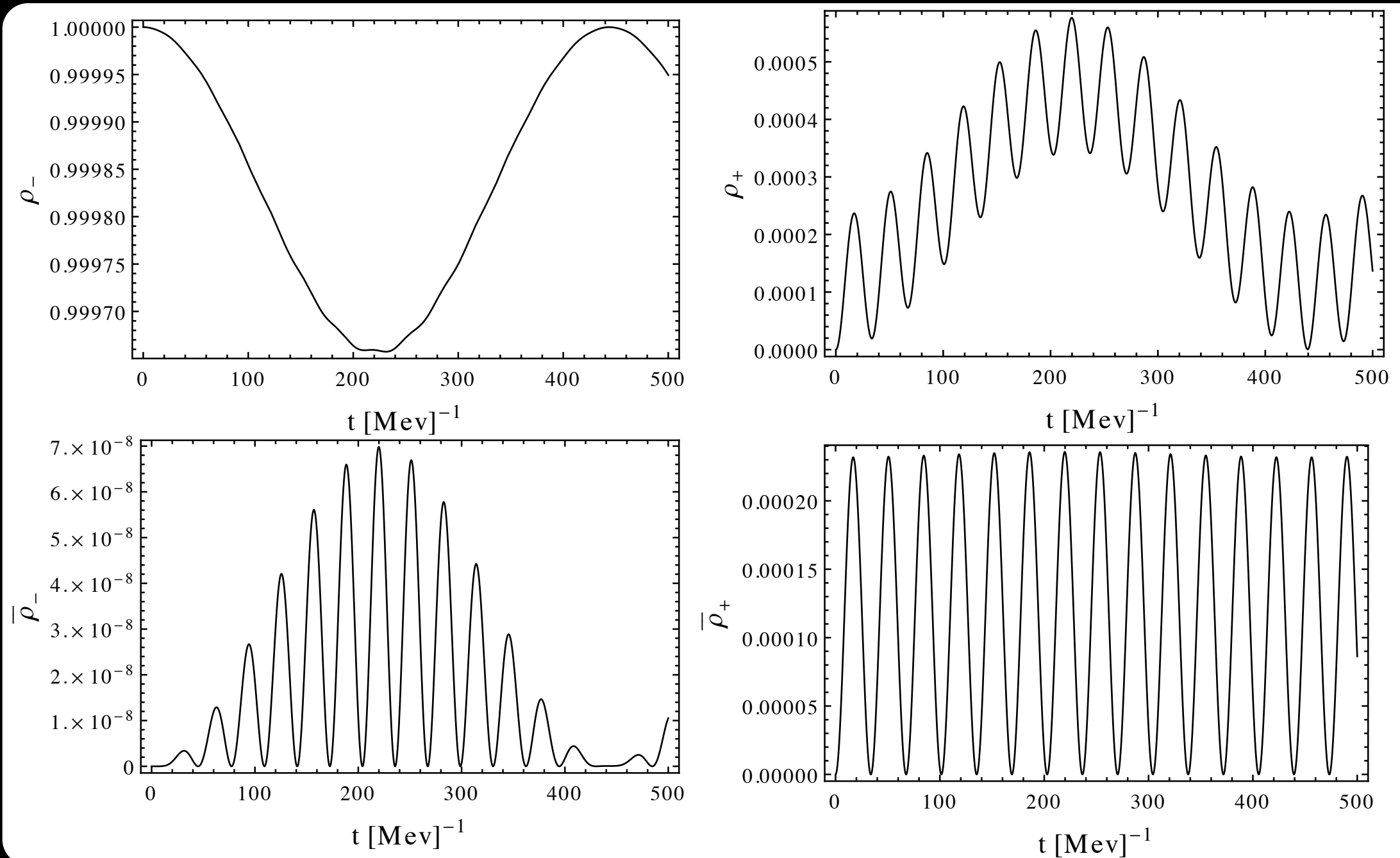
$$H^{\nu\bar{\nu}} \propto |J|$$

no neutron flux

Possible solutions

1. Use propagation eigenbasis
2. Equations only work in one frame
3. Go beyond forward-scattering formalism

Oscillations



Conclusion

We need to understand neutrinos transport
to understand supernovae

	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)

SN Explosion

