Non-standard self-interactions of neutrinos

Impact on supernova neutrino oscillations

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Supernova neutrinos at the crossroads
ECT* workshop, Trento, May 14th, 2019

Why NSSI...

... when the SM collective effects are already so complicated ?

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... when the SM collective effects are already so complicated ?

- May affect neutrino signal from a SN
- May affect neutrino oscillations $\rightarrow$ SN explosion
- Insights into symmetries / mathematical structures

NSI effects on SN neutrino oscillations

Non-standard self-interactions (NSSI)

The new effective 6-dim operator

$$G_F \left(G^{\alpha\beta} \, \bar{\nu}_{\mathrm{L}\alpha} \, \gamma^{\mu} \, \nu_{\mathrm{L}\beta} \right) \left(G^{\zeta\eta} \, \bar{\nu}_{\mathrm{L}\zeta} \, \gamma_{\mu} \, \nu_{\mathrm{L}\eta} \right)$$

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Effective coupling matrix $G^{\alpha\beta}$ (two-flavor, e and x):

$$G = \begin{bmatrix} 1 + \gamma_{ee} & \gamma_{ex} \\ \gamma_{ex}^* & 1 + \gamma_{xx} \end{bmatrix}$$

Standard Model: $\gamma_{\alpha\beta} = 0$

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Effective $\nu - \nu$ Hamiltonian

$$\mathcal{H}_{\mathbf{p}}^{\nu\nu} = \sqrt{2} G_F \int \frac{d^3\mathbf{q}}{(2\pi)^3} (1 - \mathbf{v_p} \cdot \mathbf{v_q}) \Big\{ G(\varrho_{\mathbf{q}} - \bar{\varrho}_{\mathbf{q}}) G + G \, \mathrm{Tr} \left[(\varrho_{\mathbf{q}} - \bar{\varrho}_{\mathbf{q}}) G \right] \Big\}$$

Blennow, Mirizzi, Serpico 2008

Bounds on NSSI from experiments

Direct constraints: $|\gamma_{\alpha\beta}| \lesssim \mathcal{O}(0.1 - 1)$

- Flavor physics
  Bardeen, Bilenky, Pontecorvo 1970; Bakhti, Farzan, 2017
- Supernova 1987A bounds — Kolb, Turner 1987
- Invisible Z width — Bilenky, Bilenky, Santamaria 1993
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Constraints through gauge invariance

- Bounds on NSI with charged fermions: $|\gamma_{\alpha\beta}| \lesssim \mathcal{O}(0.02 - 1)$
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Constraints through gauge invariance

- Bounds on NSI with charged fermions: $|\gamma_{\alpha\beta}| \lesssim \mathcal{O}(0.02-1)$

  Gonzalez-Garcia, Maltoni, Schwetz 2016
- From electron-electron scattering: $|\gamma_{\alpha\beta}| \lesssim \mathcal{O}(0.01)$
- Can be evaded by constructing models with higher-dim operators

  Farzan, Heeck 2016

Notations and normalizations

Pauli vectors

$$\mathcal{H}^{\rm vac}_{\mathbf{p}} = \frac{1}{2}\left(\omega_0 \mathbb{I} + \omega_{\mathbf{p}} \mathbf{B}\cdot\sigma\right), \qquad \mathcal{H}^{\rm MSW} = \frac{1}{2}\left(\lambda \mathbb{I} + \lambda \mathbf{L}\cdot\sigma\right),$$

$$\varrho_{\mathbf{p}} = \frac{1}{2}\left(f_{\mathbf{p}} \mathbb{I} + n_{\bar\nu} \mathbf{P}_{\mathbf{p}}\cdot\sigma\right), \qquad \bar\varrho_{\mathbf{p}} = \frac{1}{2}\left(\bar f_{\mathbf{p}} \mathbb{I} + n_{\bar\nu} \overline{\mathbf{P}}_{\mathbf{p}}\cdot\sigma\right)$$

Normalizations

$$n_\nu \equiv \int d^3\mathbf{p}\, f_{\mathbf{p}}\,, \qquad n_{\bar\nu} \equiv \int d^3\mathbf{p}\, \bar f_{\mathbf{p}} \qquad |\overline{\mathbf{P}}_{\mathbf{p}}| = 1$$

- $\mathbf{B} = (\sin 2\vartheta_0, 0, -\cos 2\vartheta_0)$
- $\mathbf{L} = (0, 0, 1)$
- Collective potential μ: $\mu \equiv \sqrt{2} G_F\, n_{\bar\nu}$
- Neutrino-antineutrino asymmetry ξ : $n_\nu = (1+\xi)\, n_{\bar\nu}$

Effect of the new coupling matrix G

Pauli vector for G

$$G = \frac{1}{2}\left(g_0 \mathbb{I} + \boldsymbol{g} \cdot \sigma\right)$$

SM: $G = I$, i.e. $g_0 = 2, \boldsymbol{g} = 0$

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Equations of motion:

$$\begin{aligned}
\dot{\mathbf{P}}_{\mathbf{p}} &= \left(\omega_{\mathbf{p}} \mathbf{B} + \lambda \mathbf{L} + \Omega^{\nu\nu}_{\mathbf{p}}\right) \times \mathbf{P}_{\mathbf{p}}, \\
\dot{\overline{\mathbf{P}}}_{\mathbf{p}} &= \left(-\omega_{\mathbf{p}} \mathbf{B} + \lambda \mathbf{L} + \Omega^{\nu\nu}_{\mathbf{p}}\right) \times \overline{\mathbf{P}}_{\mathbf{p}}
\end{aligned}$$

$$\begin{aligned}
\mathcal{H}^{\nu\nu}_{\mathbf{p}} &= \mu \int \frac{d^3\mathbf{q}}{(2\pi)^3}(1 - \mathbf{v_p} \cdot \mathbf{v_q})\left\{\frac{1}{4}\left(g_0^2 - |\boldsymbol{g}|^2\right)\left(\mathbf{P_q} - \overline{\mathbf{P}}_{\mathbf{q}}\right) + \right. \\
&\qquad \left. \left[g_o \xi + \boldsymbol{g} \cdot \left(\mathbf{P_q} - \overline{\mathbf{P}}_{\mathbf{q}}\right)\right] \boldsymbol{g}\right\}
\end{aligned}$$

Rescaling to focus on two parameters

Rescaling

$$\mu \to \mu\,(g_0/2)^2\,, \qquad \boldsymbol{g} \to \frac{\boldsymbol{g}}{(g_0/2)}\,, \qquad g_0 \to \frac{g_0}{(g_0/2)} = 2$$

- g_0 normalized to 2
- g_2 rotated away by redefinition of ν_x phase
- g_1: flavor-conserving (FP) NSSI
- g_3: flavor-violating (FV) NSSI

$$\mathcal{H}_{\mathbf{p}}^{\nu\nu} = \mu \int \frac{d^3\mathbf{q}}{(2\pi)^3}(1 - \mathbf{v_p}\cdot\mathbf{v_q})\left\{ \left(1 - \frac{|\boldsymbol{g}|^2}{4}\right)(\mathbf{P_q} - \overline{\mathbf{P}}_\mathbf{q}) + \left[2\xi + \boldsymbol{g}\cdot(\mathbf{P_q} - \overline{\mathbf{P}}_\mathbf{q})\right]\boldsymbol{g}\right\}.$$

$$G = \begin{bmatrix} 1+g_3 & g_1 \\ g_1 & 1-g_3 \end{bmatrix}. \qquad \mathbf{g} = (g_1, 0, g_3)$$

The flavor pendulum anology (a diversion)

EoMs maintain their form under:

$$\mu \to \widetilde{\mu} \equiv \mu \left(1 - |\boldsymbol{g}|^2/4\right) \,, \qquad \lambda \mathbf{L} \to \widetilde{\lambda}\widetilde{\mathbf{L}} \equiv \lambda \mathbf{L} + \mu\,(2\xi + \mathbf{D}\cdot\boldsymbol{g})\,\boldsymbol{g}$$

$\widetilde{\mathbf{L}}$ normalized to unity

Spherical pendulum in Q (when $\widetilde{\lambda} = 0$)

$$\mathbf{Q} \equiv \mathbf{S} - (\omega/\widetilde{\mu})\mathbf{B} \,, \qquad \mathbf{S} \equiv \mathbf{P} + \overline{\mathbf{P}} \,, \quad \mathbf{D} \equiv \mathbf{P} - \overline{\mathbf{P}}$$

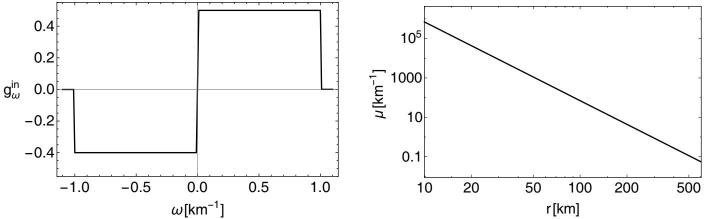
EoMs for Q:

$$\begin{aligned} \dot{\mathbf{Q}} &= \widetilde{\mu}\,\mathbf{D} \times \mathbf{Q} + \widetilde{\lambda}\,\widetilde{\mathbf{L}} \times \mathbf{S} \\ \dot{\mathbf{D}} &= \omega\,\mathbf{B} \times \mathbf{Q} + \widetilde{\lambda}\,\widetilde{\mathbf{L}} \times \mathbf{D} \end{aligned}$$

- When $\widetilde{\lambda} = 0$, $|\mathbf{Q}|$ is conserved
- $\mathbf{Q}$ a spherical pendulum in the flavor space, with length $|\mathbf{Q}|$.

NSI effects on SN neutrino oscillations

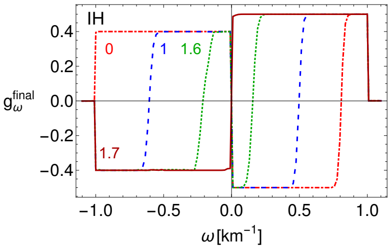
Box spectrum: Initial conditions and evolution

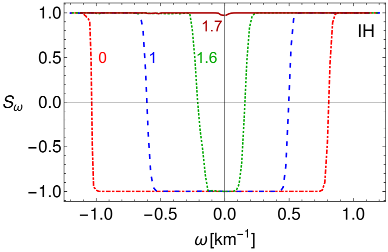


$$\mu = 7.5 \times 10^5 \,\mathrm{km}^{-1} \left(\frac{r_0}{r}\right)^4 , \qquad r > r_0 , \tag{1}$$

$r_0 = 10$ km, $\omega = 0.3\,\mathrm{km}^{-1}$, $E \simeq 20$ MeV, Flux asymmetry $\xi = 20\%$

FP-NSSI (g_3): pinching of spectral swaps





g_3 values shown in the figures

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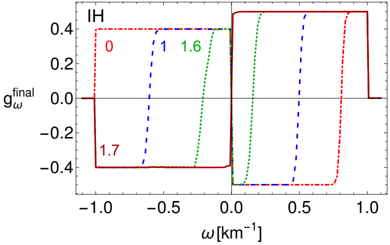

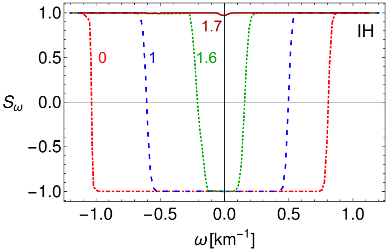

g_3 values shown in the figures

- NSSI terms act like a matter potential:

$$\overline{\lambda} = \lambda + u[\lambda + \mu\xi(1 - g_1^2 + 3g_3^2 + 4g_3)]$$

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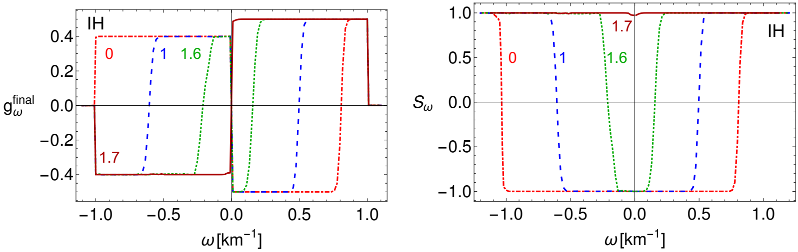

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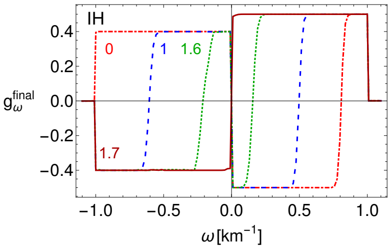

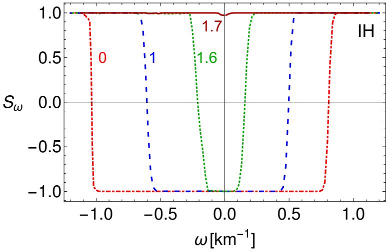

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- $\frac{d}{dt}\mathbf{B} \cdot \mathbf{D} = \widetilde{\lambda}\,[\mathbf{B}\,\boldsymbol{g}\,\mathbf{D}]$

$\mathbf{B} \cdot \mathbf{D}$ approximately conserved since $\vartheta \approx 0$

Raffelt, Smirnov 2007; Dasgupta, AD, Raffelt, Smirnov 2009

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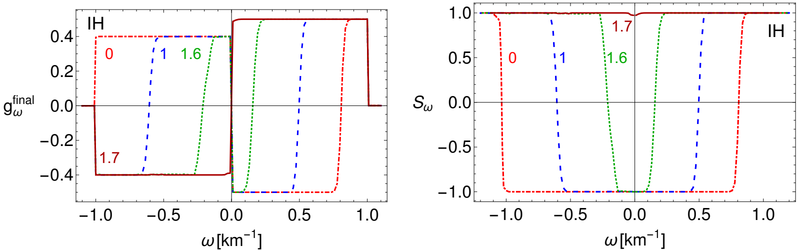

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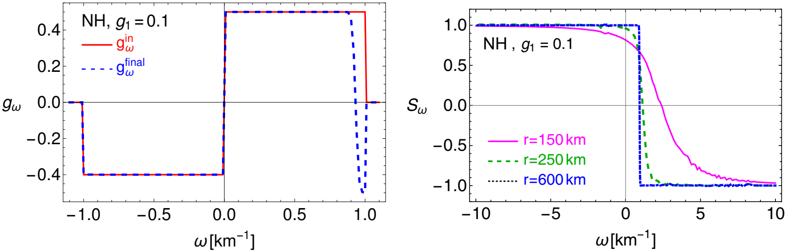
- No swap for $g_3 > 2$ (flavor pendulum)

FV-NSSI (g_1): swaps develop where they should not !

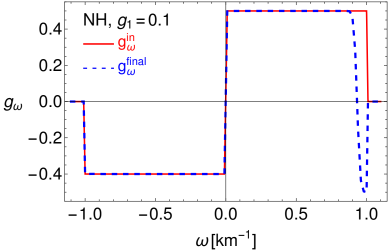


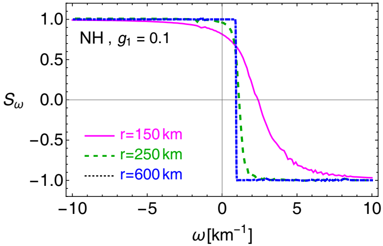
- $\mathbf{B} \cdot \mathbf{D}$ not conserved even when $\vartheta = 0$:

$$\frac{d}{dt}\mathbf{B} \cdot \mathbf{D} = -\widetilde{\lambda} g_1 D_y \cos 2\vartheta_0$$

- Swaps do not have to develop about spectral crossing !
  (That wisdom was due to $\mathbf{B} \cdot \mathbf{D}$ conservation)

FV-NSSI (g_1): swaps develop where they should not !





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- Swaps do not have to develop about spectral crossing ! (That wisdom was due to $\mathbf{B} \cdot \mathbf{D}$ conservation)
- Swaps can start developing way beyond the spectrum !

Das, AD, Sen, 2017

Neutronization burst: common wisdom

Neutronization burst: a clean signal ?

- Only ν_e so no collective effects
- Clean way of determining mass ordering:
  $P_{ee} \approx 0.03 \Rightarrow$ Normal, $P_{ee} \approx 0.3 \Rightarrow$ Inverted
- Energy-dependence of $P_{ee} \Rightarrow$ MSW-prepared spectral splits (O-Ne-Mg supernovae)

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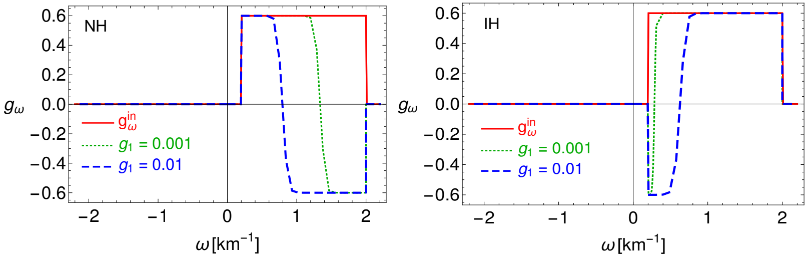
Flavor lepton number non-conservation $\Rightarrow$
New collective effects and signals !

FV-NSSI effects on only-ν_e spectra



Spectral split possible, in both orderings !

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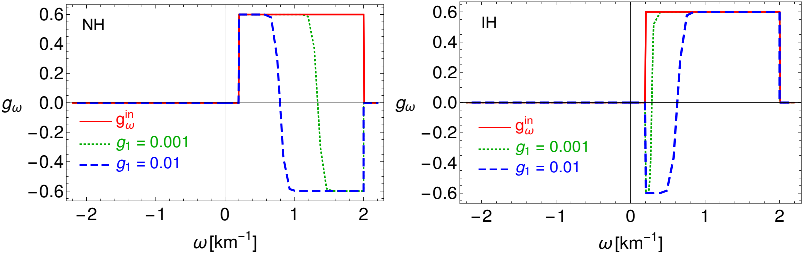

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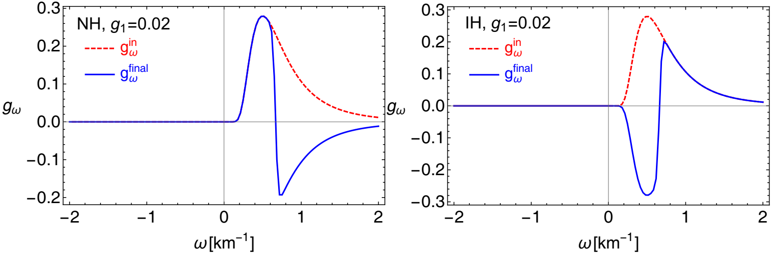
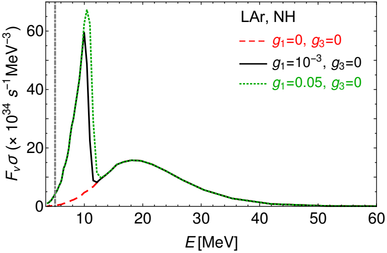
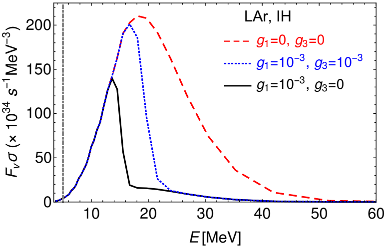


Observation of the neutronization burst at LAr detector





- Possible to get similar-looking signals in both orderings
- Split may mimic lower-energy ν_e flux
- Data analysis needs to be done with caution.

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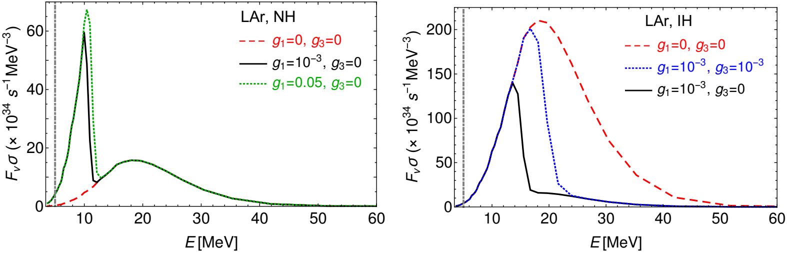

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Das, AD, Sen 2017

Re-emphasizes the importance of neutronization burst

NSI effects on SN neutrino oscillations

Linear stability analysis

Flux and its normalization

$$F_{\omega,u} d\omega\, du = 2\pi r^2\, v_{r,u}\, \varrho_{\mathbf{p}} \frac{d^3\mathbf{p}}{(2\pi)^3}$$

- Rescaling $F \to f$: $\int d\Gamma \left[f^{\bar{e}}_{\omega,u}(R) - f^{\bar{x}}_{\omega,u}(R) \right] = 1$

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$$g_{\omega,u} = \begin{cases} f^{e}_{\omega,u} - f^{x}_{\omega,u} & \text{for } \omega > 0 \quad , \\ f^{\bar{x}}_{\omega,u} - f^{\bar{e}}_{\omega,u} & \text{for } \omega < 0 \quad . \end{cases}$$

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Linear stability analysis in SM

- Find linearized EoMs for $S_{\omega,u}$ $\Rightarrow$ eigenvalue equations
- Look for solutions that are unstable (grow as $e^{\alpha t}$)

Banerjee, AD, Raffelt 2011

- Types of instabilities, dispersion relations, ...

Iziguirre, Raffelt, Tamborra 2017; Capozzi, Dasgupta, Lisi, Marrone, Mirizzi 2017; Yi, Ma, Martin, Duan 2019

No more an eigenvalue problem !

Linearized EOMs for $S_{\omega,u}$

$$
\begin{aligned}
i\partial_r S_{\omega,u} &= (\omega + \lambda_r)\, v_{u,r}^{-1} S_{\omega,u} \\
&\quad + (1 - g_1^2 + 3g_3^2 + 4g_3) \int d\Gamma'\, X_{\omega,u,r,u',r'}\ S_{\omega,u} \\
&\quad - \int d\Gamma'\, X_{\omega,u,r,u',r'} \left[(1 + g_1^2 - g_3^2) S_{\omega',u'} + 2g_1^2 S^*_{\omega',u'} + 4\, g_1 g_3 \right]
\end{aligned}
$$

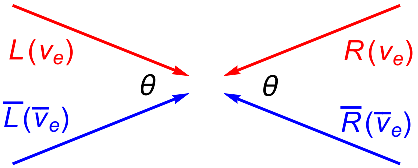
$$
\lambda_r \equiv \sqrt{2} G_F\, n_e(r), \qquad v_{u,r} \equiv \sqrt{1 - uR^2/r^2}
$$

$$
X_{\omega,u,r,u',r'} \equiv \frac{\sqrt{2} G_F\, \left[F^{\bar{e}}_{\omega,u}(R) - F^{\bar{x}}_{\omega,u}(R) \right]}{4\pi r^2} \frac{(1 - v_{u,r} v_{u',r'})}{v_{u,r} v_{u',r'}} g_{\omega',u'}
$$

- Not an eigenvalue equation if g_1 nonzero (FV- NSSI)
- If both g_1 and g_3 nonzero, even linear growth possible !

The intersecting four-beam model (constant μ)

SHO of fast oscillations:



- Fluxes for $Q_L, Q_{\bar{L}}, Q_R, Q_{\bar{R}}$:

$$g_{\mathrm{R}} = g_{\mathrm{L}} = \frac{1}{2}(1+a)\ , \qquad g_{\bar{\mathrm{R}}} = g_{\bar{\mathrm{L}}} = -\frac{1}{2}(1-a)$$

- Two parameters describing fluxes (if homogeneous): Asymmetry a , Angle θ
- If non-homogeneous fluxes, more parameters: moments...

  Chakraborty, Hansen, Izaguerre, Raffelt 2016; Dasgupta, Sen 2018

Discretized linearized EoM

$$
\begin{aligned}
i(\partial_t + \mathbf{v_p}\cdot\nabla)S_\mathbf{p} &= (w+\lambda)S_\mathbf{p} \\
&+\mu\left(1-g_1^2+3g_3^2+4g_3\right)\sum_\mathbf{q}(1-\mathbf{v_p}\cdot\mathbf{v_q})g_\mathbf{q}\Big] S_\mathbf{p} \\
&-\mu\sum_\mathbf{q}(1-\mathbf{v_p}\cdot\mathbf{v_q})g_\mathbf{q}\left[S_\mathbf{q}+(g_1^2-g_3^2)S_\mathbf{q}+2g_1^2S_\mathbf{q}^*+4\,g_1g_3\right]
\end{aligned}
$$

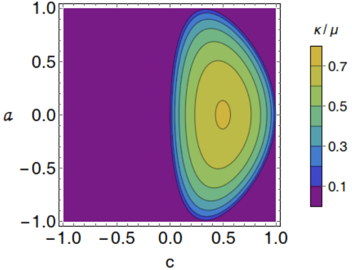
$\mathbf{q}$: the other three modes

"Eigenmodes" when only g_1 or g_3 present:

- $Q_\pm \equiv (Q_L \pm Q_R)/2$
- $\bar{Q}_\pm \equiv (Q_{\bar{L}} \pm Q_{\bar{R}})/2$
- Q_+: L-R symmetric, Q_-: L-R symmetry breaking

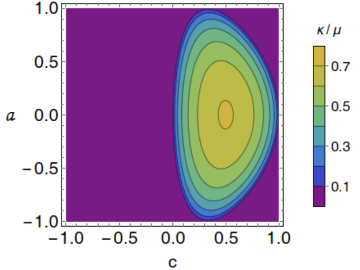
Chakraborty, Hansen, Izaguerre, Raffelt 2016; Dasgupta, Sen 2018

Instabilities in $(Q_-, \bar{Q}_-)$ solution



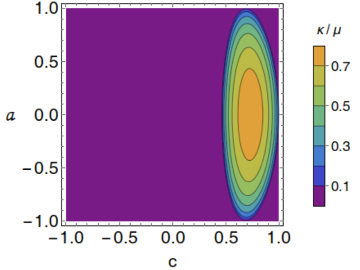
SM:
instability only for
$c \equiv \cos\theta > 0$

Instabilities in $(Q_-, \bar{Q}_-)$ solution

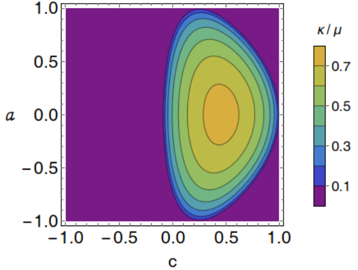


SM:
instability only for
$c \equiv \cos\theta > 0$

$g_3 = 0.3$

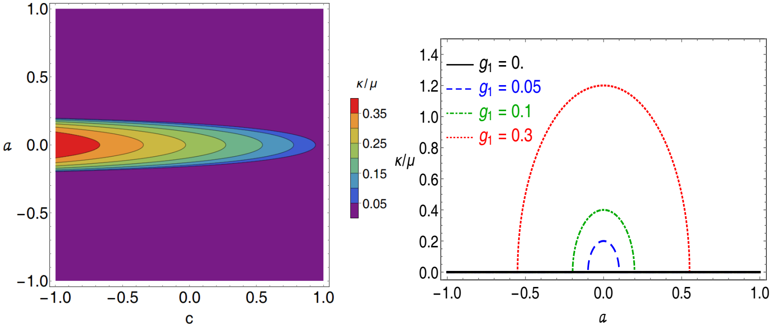


$g_1 = 0.3$



- Fast oscillations possible for θ obtuse angle (with FV-NSSI)

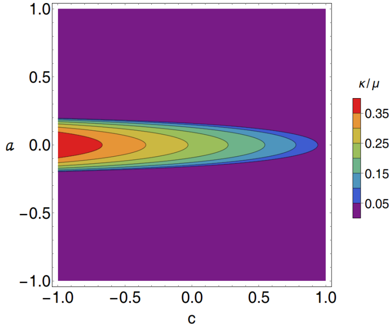
Instabilities in $(Q_+, \bar{Q}_+)$ solution

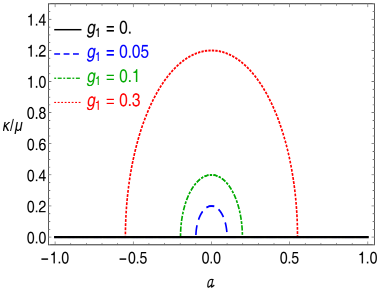


- Instability possible with / without ν–$\bar{\nu}$ asymmetry
- Instability possible with $\cos\theta = -1$,
  i.e. with two opposing ν and $\bar{\nu}$ beams !

AD, Sen 2018

Instabilities in $(Q_+, \bar{Q}_+)$ solution





- Instability possible with / without ν–$\bar{\nu}$ asymmetry
- Instability possible with $\cos\theta = -1$,
  i.e. with two opposing ν and $\bar{\nu}$ beams !

AD, Sen 2018

- SM: Instability with two beams needs inhomogeneities

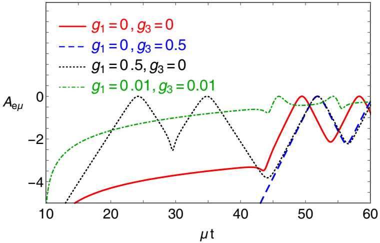
Chakraborty, Hansen, Izaguerre, Raffelt 2016

- FV-NSSI performs the job of symmetry-breaking ??

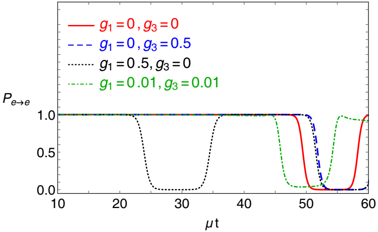
NSI effects on SN neutrino oscillations

Effect of NSSI on onset time (four-beam model)

$A_{e\mu} = \log_{10}|S|$



$P_{e\to e}$

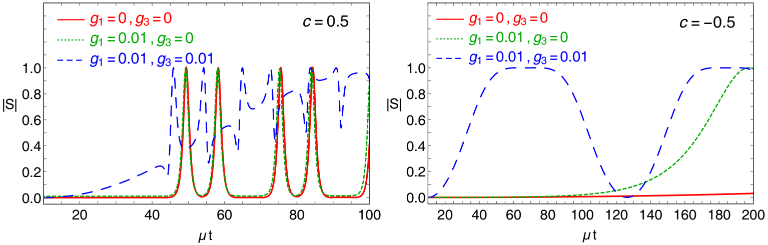


$a = 0,\ c = 0.5,\ \omega/\mu_R = 10^{-5},\ \vartheta_0 = 10^{-2}$

- FV-NSSI (g_1): extremely early onset
- FP-NSSI (g_3): slighly delayed onset
- Both g_1 and g_3: early linear increase in S, sunstantial even for very low g_1, g_3 values

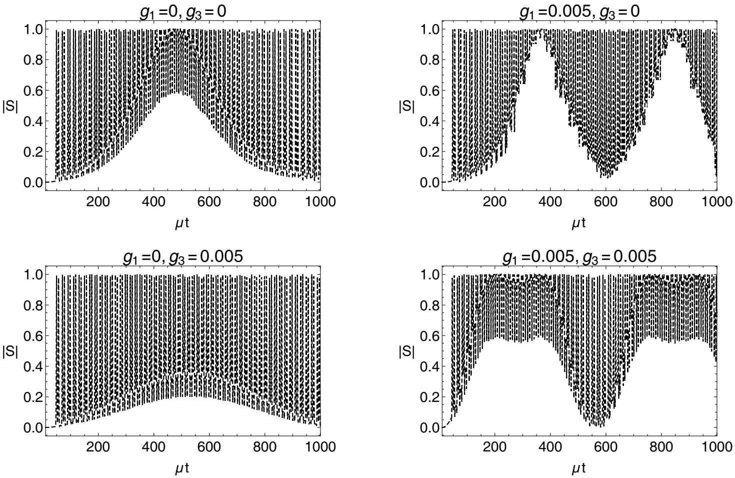
AD, Sen 2018

Fast vs slow oscillations



- Linear increase in $|S|$ when both g_1 and g_3 present
- When fast oscillations not expected, slow oscillations are still seeded much earlier

Long-time behaviour (four-beam model, constant μ)



- Slow oscillations modulate fast oscillations

Concluding remarks

Non-standard self-interactions (NSSI) of neutrinos can:

- Pinch / suppress spectral swaps (FP-NSSI)
- Violate flavor-lepton number even for $\vartheta_0 = 0$ (FV-NSSI)
- Make spectral swaps possible without spectral crossing / with only ν_e
- Significantly alter neutronization burst signatures
- Prevent linear stability analysis from leading to an eigenvalue problem
- Allow instabilities to grow in previously disallowed regions
- Allows instability for two intersecting homogeneous ν and $\bar{\nu}$ beams
- Advance/delay the onset of oscillations