Supernova neutrino oscillations: new physics!

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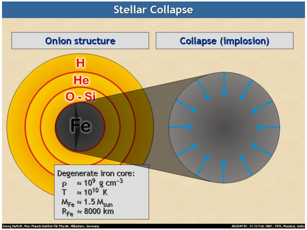
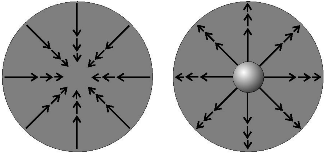
Workshop in High Energy Physics Phenomenology XV

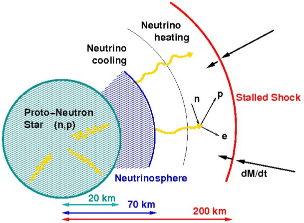
Supernova explosion



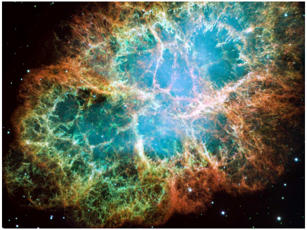
Explosion of a massive $6-8\ M_\odot$ star



Collapse of degenerate core.
Bounce and Shock.



Stalled shock and accretion.
99% energy emitted as νs.

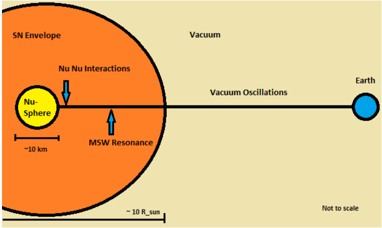


Explosion!

Amol's talk

A quick recap: major fronts!

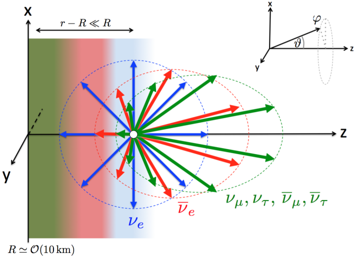
- Pre-2006 : Flavor conversions mainly in MSW regions $r \sim O(10^3)$ km. MSW conversions $\propto \omega = \frac{\Delta m^2}{2\,E}$
- Post-2006 : Collective effects. Significant flavor conversions at $r \sim O(10^2)$ km from neutrinosphere. Rates $\propto \sqrt{\omega\mu}$, where $\mu = \sqrt{2}\,G_F n_\nu \gg \omega$.
- More recently: Faster conversions: $\propto \mathcal{O}(\mu) \gg \omega$, very near the core of the SN $r \sim O(10\,\mathrm{m})$! Can occur for massless neutrinos.



Illustrative of different length scales involved.

Fast flavor oscillations near SN core!

- Close to ν-sphere, ν angular emissions are different due to different radii of decoupling: $R_{\nu_x} < R_{\bar{\nu}_e} < R_{\nu_e}$.



- Leads to new instability, absent for isotropic angular distributions.
- Fast oscillations: $\propto \mu$.
- Outcome would be a *possible* complete flavor mixing of the outgoing stream just above the ν-sphere.

Fast Oscillations: 4-beam model

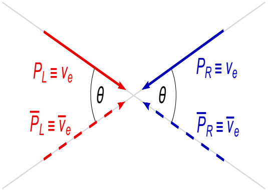
- Simplest system which shows fast conversions. $\nu - \bar{\nu}$ asymmetry $\equiv a$.
- Use LSA $\rightarrow \rho_{ex} \equiv S \sim e^{-i\gamma t + \kappa t}$. Growth rate

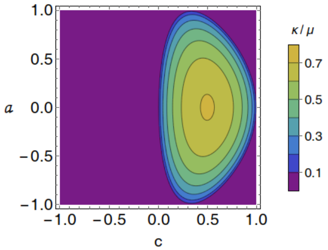
$$\frac{\kappa}{\mu} = \frac{1}{2}\sqrt{(1+c)^2\, a^2 - 8c\,(1-c)}\,.$$

- Conversions obtained for $c \equiv \cos\theta > 0$.
- No dependence on ω.

  G. Raffelt et. al. (2016)

- Why such a dependence on c?





4-beam: Quartic oscillator

- Define
  $$\mathbf{Q} \equiv \mathbf{P}_L + \mathbf{P}_R + \overline{\mathbf{P}}_L + \overline{\mathbf{P}}_R - \frac{2\omega}{\mu(3-c)}\mathbf{B}\,,$$
- Classical analogy: particle in a quartic potential!

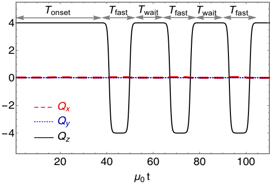
$$V(Q_z) \approx \mu^2\, c\,(1-c)\left[|\mathbf{Q}_0|^2 - \frac{Q_z^2}{2}\right]\frac{Q_z^2}{2}\,.$$

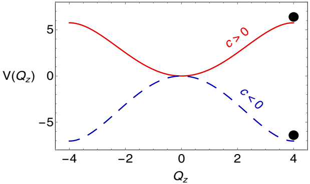
- Compute time period using adiabatic invariance.

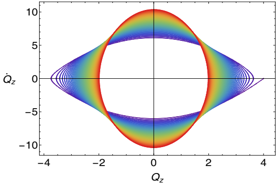
$$T_{\rm onset} \propto \frac{1}{\mu\sqrt{2c(1-c)}}\ln\left[\frac{(3-c)}{\cos 2\vartheta_0}\,\frac{\mu_0}{\omega}\right], \quad (1)$$

- Predict motion for a varying μ.

  B. Dasgupta and MS (2017)

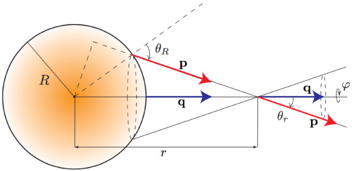


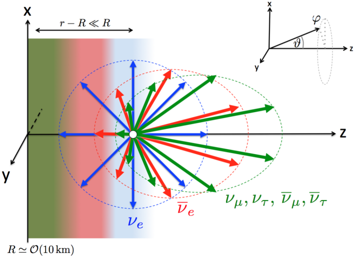




Modelling a realistic SN

- Different flavors of neutrinos have different rates of interactions. Decouple at different times.
- Discard the "bulb model", and because of the near field effect, model the source as an infinitely long plane.



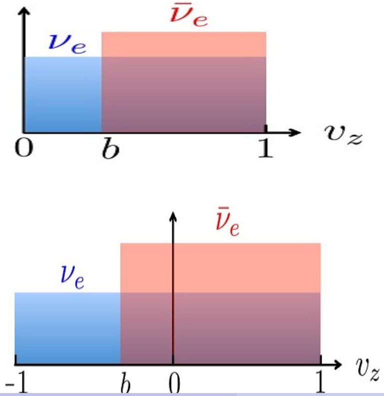


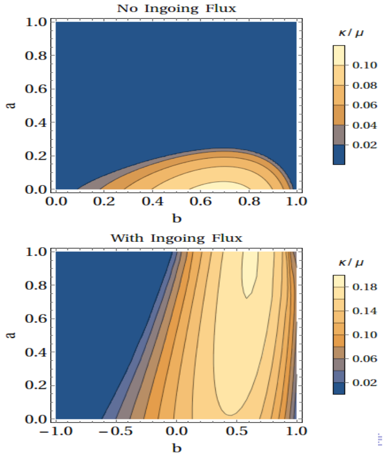
- Use flavor dependent angular spectrum. Realistic approximation.
- Consider different cones of emission for ν and $\bar{\nu}$. Can consider inward going rays also.

Halo effect → Amol's talk!

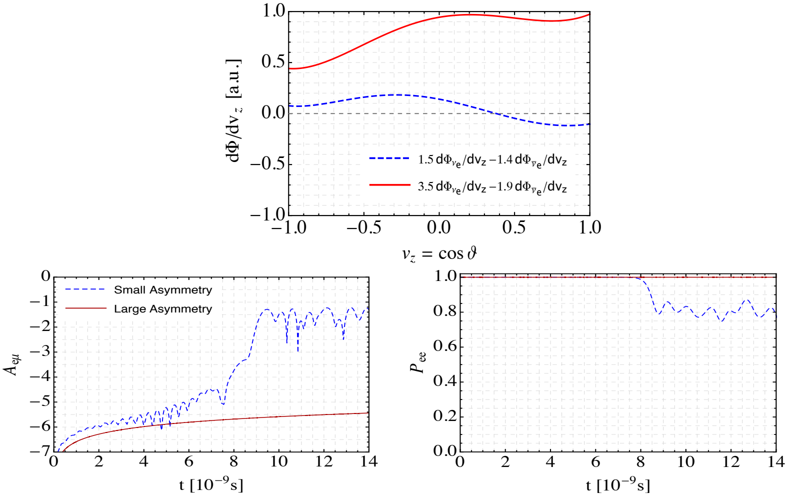
Fast growths ubiquitous

$$
\begin{aligned}
g_{\omega,v} &\propto F_{\nu_e}(\omega,v) - F_{\nu_\alpha}(\omega,v) \text{ for } \nu, \\
&\propto F_{\bar{\nu}_\alpha}(\omega,v) - F_{\bar{\nu}_e}(\omega,v) \text{ for } \bar{\nu}\,.
\end{aligned}
$$





Crossing in Angular spectrum!

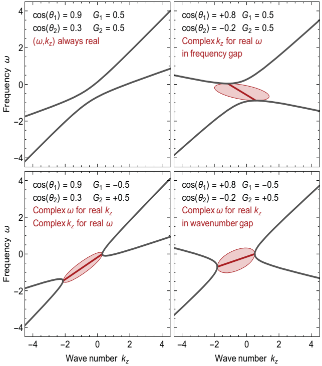


Dispersion Gaps as instabilities

- Instability $\equiv$ blowing up of flavor waves. Gaps in dispersion relation.
- $\rho_{ex} \sim e^{i(k\,z - \omega t)}$.
- $i(\partial_t + v\partial_z)\rho_{ex} = (\omega - vk)\rho_{ex} = \mathcal{H}(\rho'_{ex})$.
- Dispersion relation : $D(\omega,\, k) = 0$.
- Task: Derive soln as

$$\begin{aligned} \omega &= \Omega(k)\,\epsilon\,\mathbb{C} \rightarrow \text{temporal instability} \\ k &= K(\omega)\,\epsilon\,\mathbb{C} \rightarrow \text{spatial instability} \end{aligned}$$

- Different types of instability: absolute, convective, and damped.



Landau-Lifshitz “Physical Kinetics”,

B. Dasgupta et. al. (2017)

Why should we worry about these effects?

- If flavor changes occur in the deepest SN regions, they would modify the neutrino heating behind the stalled shock wave, possibly helping a SN to explode.
- This would modify the n/p ratio deep inside the star, thereby affecting the formation of heavy elements through r-process nucleosynthesis.
- If flavor equilibrium would occur close to the ν-sphere, all further flavor information *could* be washed-out. Crucial to predict observable SN ν signal.

The path less travelled

- Fast flavor conversions: relatively new topic. Hardly 10 papers till now.
- Many unanswered questions.
- Collisions?

  We are currently working on it!
- Complete flavor averaging? Spectra formation?
- What is the effect of "new" physics? $\Rightarrow$ Last few minutes of this talk!

Secret ν interactions: NSI

- Effective operator of the form $\varepsilon_{\alpha\beta} 2\sqrt{2}(\bar{\nu}_\alpha \gamma^\mu \nu_\beta)(\bar{f}\gamma_\mu f)$. Bounds on $\varepsilon_{\alpha\beta}$.
- Can lead to new resonances: "I" resonances, deeper inside the star. Can convert less energetic ν_e spectra to more energetic ν_τ. Useful for shock revival.
- Can have clear signatures in neutronization burst.

  Esteban-Pretel et. al. (2007)
- Flavor changing couplings $\varepsilon_{e\mu,\tau} > 10^{-4}$ causes a reduction in electron fraction. Affects stellar collapse.

  Fuller et. al. (2007)
- Many other references in cosmology, solar and SN neutrinos.

  Friedland, Lunardini and Pena-Garay, Bergmann et. al., Farzan et. al.

ν non-standard self-interactions (NSSI)

- Effective operator of the form $G_F \left(G^{\alpha\beta}\, \bar{\nu}_{\mathrm{L}\alpha}\gamma^\mu\nu_{\mathrm{L}\beta}\right) \left(G^{\zeta\eta}\, \bar{\nu}_{\mathrm{L}\zeta}\gamma_\mu\nu_{\mathrm{L}\eta}\right)$.

  Cosmology: Dasgupta and Kopp; Hannestad, Hansen, and Tram; Mirizzi, Mangano, Pianti, and Saviano; Archidiacono, Hannestad, Hansen, and Tram; Chu, Dasgupta, Kopp; Cherry, Friedland, Shoemaker;

  SN: Mirizzi, Blennow and Serpico;

- $\alpha = \beta \to G^{\alpha\beta}$ is flavor-preserving $\to$ flavor-preserving NSSI (FP-NSSI).
- $\alpha \neq \beta \to G^{\alpha\beta}$ is flavor-violating $\to$ flavor-violating NSSI (FV-NSSI).
- Modulo some rescaling and rephasing, one can write

$$G = \begin{bmatrix} 1+\gamma_{ee} & \gamma_{ex} \\ \gamma_{ex}^* & 1+\gamma_{xx} \end{bmatrix} = g_0 + i\sigma \cdot \boldsymbol{g} = \begin{bmatrix} 1+g_3 & g_1 \\ g_1 & 1-g_3 \end{bmatrix} .$$

- $g_3 \equiv$ FP-NSSI and $g_1 \equiv$ FV-NSSI.
- Bounds give $|\gamma_{ee}|$, $|\gamma_{xx}|$ and $|\gamma_{ex}| \sim \mathcal{O}(1)$.

A. Das, A. Dighe, and MS (2017)

Implications of NSSI

- Essentially new neutrino self-interactions. Much of the results in previous talk a special case of zero NSSI !

- Interesting new effects:
  $\langle$i$\rangle$ FP-NSSI acts like a matter term, suppressing collective oscillations.

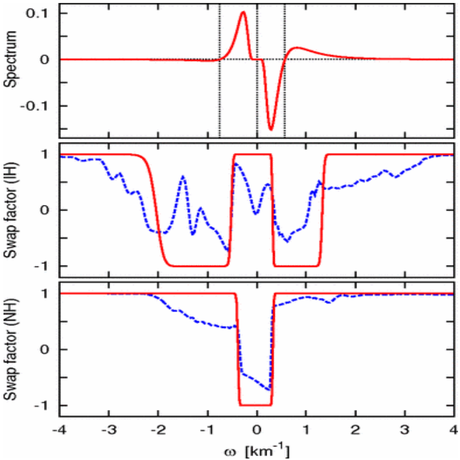
  $\langle$ii$\rangle$ FV-NSSI can cause flavor conversion even without any initial mixing angle, i.e., $\vartheta = 0$. Not possible in SM. Need a non-zero ϑ as a seed.

  $\langle$iii$\rangle$ FV-NSSI *does not* conserve flavor lepton number $\nu_e\bar{\nu}_e \nrightarrow \nu_\alpha\bar{\nu}_\alpha$.

- This will have direct observable consequences on "bipolar" as well as "fast" oscillations.

Bipolar Oscillations in the SM: Spectral splits

- Collective effects → exchange of $\nu_e(\bar{\nu}_e)$ spectrum with $\nu_\alpha(\bar{\nu}_\alpha)$ spectrum in certain energy intervals.
- "Swap"≡flavor exchange. " Splits" ≡ sharp boundary features at the swap edges.
- Swaps occur around every " + " crossing for IH and " - " crossing for NH.



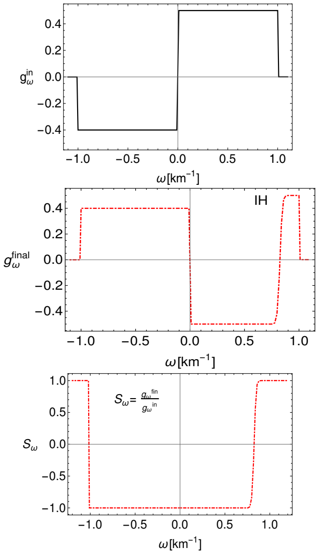
B. Dasgupta et. al (2009, 2010)

Simple case: what to expect in the SM?

- Define a spectral function :

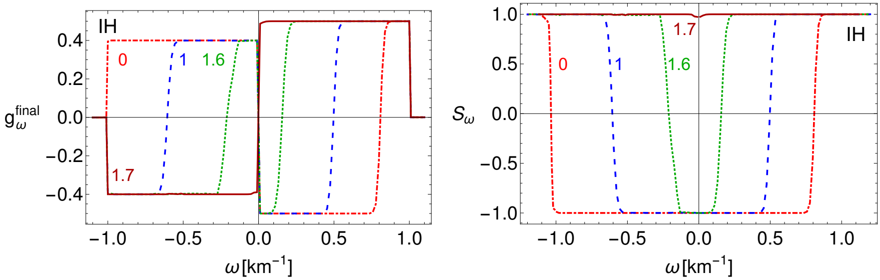
$$g_\omega \propto F_{\nu_e}(\omega) - F_{\nu_\alpha}(\omega) \text{ for } \nu; ,$$
$$\propto F_{\bar{\nu}_\alpha}(\omega) - F_{\bar{\nu}_e}(\omega) \text{ for } \bar{\nu} .$$

- Define a swap factor $S_\omega = \frac{g_\omega^{\rm fin}}{g_\omega^{\rm in}}$.
- Hence a crossing in the spectra is necessary for swaps.



Dasgupta, Dighe, Raffelt and Smirnov (2009)

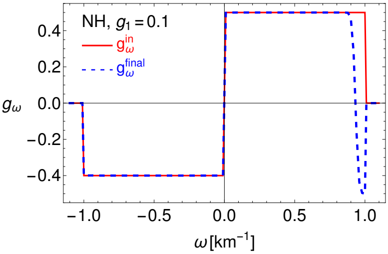
FP-NSSI scenario: pinching of spectral swaps

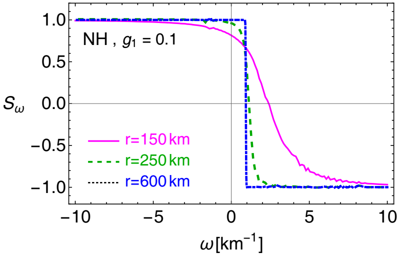


- Pinching of swaps.
- Flavor lepton number conserved. So swaps develop around the crossing.

A. Das, A. Dighe, and MS (2017)

FV-NSSI : development of swaps away from crossing !





- Flavor lepton number not conserved. No need to develop around a spectral crossing.
- Standard scenario → NH and "+" crossing is stable. Becomes unstable in presence of FV-NSSI.
- Can have observable consequences in neutronization burst.

A. Das, A. Dighe, and MS (2017)

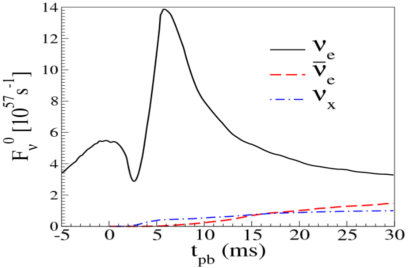
Neutronization burst

- Prompt emission of ν_e during the first 25 ms after bounce.
- ν_αs are absent during neutronisation. Hence no crossing in spectra, therefore no collective effects. Only MSW effects are considered.
- ν_e flux received at Earth

$$F_{\nu_e} = pF^0_{\nu_e} + (1-p)F_{\nu_\alpha} \; .$$

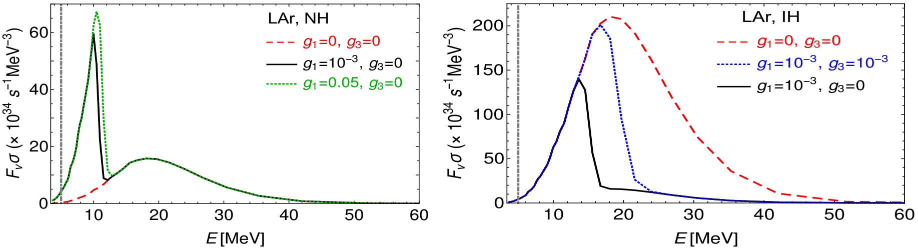
where p is the ν_e survival probability.

- Hierarchy determination.



Garching simulations

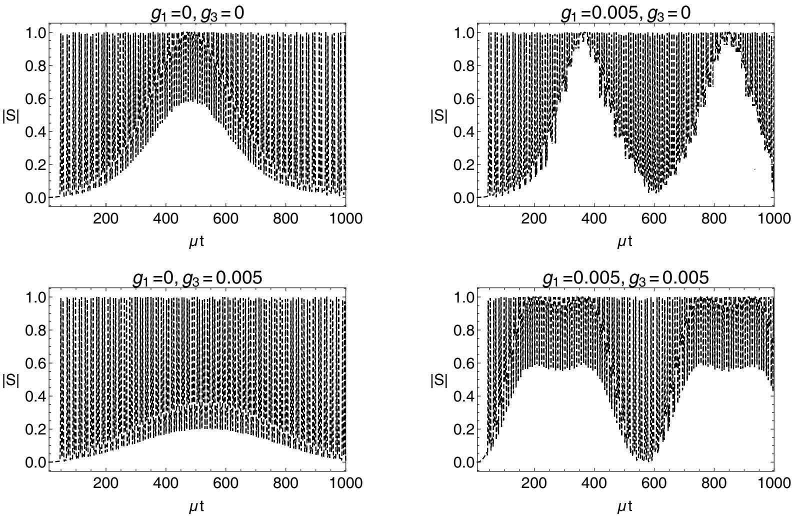
Neutronization burst: signals



- Signals in a liquid Argon detector using $(\nu_e +^{40} Ar \rightarrow^{40} K^* + e^-)$ channel.
- Can make hierarchy determination ambiguous.
- Put flux dependent constraints on NSSI.

A. Das, A. Dighe, and MS (2017)

Finally, NSSI and Fast Oscillations: interplay!



A. Dighe, and MS (2017)

What should we do now?

- Self-induced collective flavor conversions in SN are undergoing a paradigm shift.
- Self-interacting neutrinos can spontaneously break space-time symmetries. This could lead to instabilities at all length scales.
- Fast conversions could be possible near the SN core, leading to a quick flavor equilibration. Much more conclusive work is needed, both from theory and numerics.
- Effect of new physics presents a plethora of new phenomenology.
- Finally,

THANK YOU

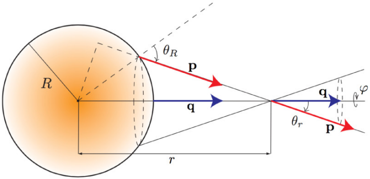
BACKUP

Non-linearity from neutrino-neutrino interactions

- Effective Hamiltonian $H = H_{vac} + H_{MSW} + H_{\nu\nu}$ where

$$
\begin{aligned}
H_{\text{vac}} &= \omega = \frac{M^2}{2E_p} \\
H_{\text{MSW}} &= \lambda = \sqrt{2}G_F N_e \;\; \text{diag}\{1,0,0\} \\
H_{\nu\nu} &= \sqrt{2}G_F \int \frac{d^3q}{(2\pi)^3} \, (1 - \vec{v_p}.\vec{v_q})(\rho_q - \bar{\rho_q})
\end{aligned}
$$

Define $\mu = \sqrt{2}G_F N_\nu$.

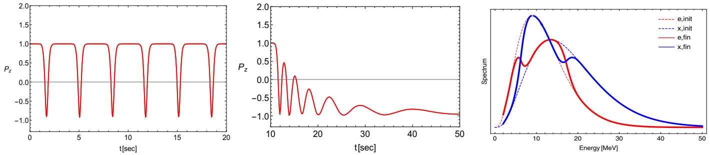


H. Duan *et al.*(2006)

- Hierarchy of scales $\mu > \lambda > \omega$.

Collective effects : new phenomena

- Synchronized oscillations: ν and $\bar{\nu}$ of all energies oscillate with the same frequency.



- Coherent $\nu_e\bar{\nu}_e \leftrightarrow \nu_x\bar{\nu}_x$ oscillations. Intermediate μ.
- Realistic declining μ can cause complete conversion.
- ν_e and ν_x spectra swap completely, but only within certain energy ranges. Occurs in both hierarchies.

G. Raffelt *et al.*(2007), B. Dasgupta *et al.*(2009)

Bipolar Oscillations : Linear stability analysis

- Deep inside $\rightarrow$ high density $\rightarrow$ flavor and mass states almost equal. ρ is almost identity.
- Expand the matrices

$$\rho = \frac{\mathrm{Tr}\rho}{2} + \frac{g_{\omega v \phi}}{2}\begin{bmatrix} s & S \\ S^* & -s \end{bmatrix}$$

  Drop trace since net flavor conserved.
- Linearize in off-diagonal element to get eigenvalue equation.

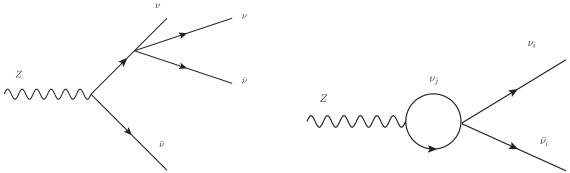
$$\begin{aligned} i(\partial_t + \vec{v}\cdot\vec{\nabla}_r)S_{\omega v z} \quad &= \quad \left(\omega + \lambda + \mu\int \frac{d\Gamma'}{(2\pi)}\left(1 - v_z v'_z - \vec{v_T}.\vec{v_T}'\right) g_{\omega' v' \phi'}\right) S_{\omega v z} \\ &\quad -\mu\int \frac{d\Gamma'}{(2\pi)}\left(1 - v_z v'_z - \vec{v_T}.\vec{v_T}'\right) g_{\omega' v' \phi'} S_{\omega' v' z'} \end{aligned}$$

A. Dighe *et al.*(2011)

- Check for exponentially growing $S \rightarrow$ instability.

Bounds on NSSI

- $\nu - \nu$ interactions not observed yet, loose bounds.
- Primary bounds come from invisible width of Z boson. Four neutrino decays $\rightarrow G \lesssim 100$.



- $\nu - \nu$ interactions contribute to $Z \rightarrow \nu\nu$ at one loop. Stronger constraints $G \lesssim 5$.
- Roughly translates to $\gamma_{\alpha\beta} \sim \mathcal{O}(1)$.

Bilenky and Santamaria(1999)