Supernovae as laboratories for non-standard ν properties

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in collaboration with Andreu Esteban Pretel and J.W.F. Valle

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Outline

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Why non-standard neutrino properties?

- ν experiments: perfectly described within the *new* standard model (SM)

  $\longrightarrow$ non-zero masses and mixing angles

- mass hierarchy, θ_{13}, θ_{23} octant, CP δ not yet known

$\Rightarrow$ why to worry about non-standard ν properties?

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- SM: not complete $\rightarrow$ more fundamental theory required
- non-standard ν properties $\rightarrow$ hint for physics beyond SM

subleading effects in ν experiments $\Rightarrow$ is it possible to observe them?

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- ν physics $\rightarrow$ precision era: osc. param. at % level (M. Tórtola, A. Marrone)

$\Downarrow$

not so crazy

Why in core-collapse supernovae?

subleading effects$\Rightarrow$ precision required $\rightarrow$ but in SNe

- uncertainties: initial fluxes, explosion mechanism, etc.
- many effects already in SM: bipolar conv., spectral splits, etc (A. Mirizzi)

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what are the advantages of SNe?

- extreme conditions (ρ, B): drastically enhance the effects of non-standard ν properties
  ⇒ sensitive to a range of parameters not reachable in terrestrial exp.
- future galactic SN → $10^4 - 10^5$ events

Ok, let's wait for the next SN ...

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Ok, let's wait for the next SN ...

well, ..., in the meantime we can see what would happen

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Non-standard neutrino interactions

Non-standard ν properties include:

- magnetic moment μ_ν, additional (sterile) ν's, decay
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NSI arise naturally in many extensions of the SM

- types: flavor changing (FC), non-universality (NU)
- parametrization at low energies

$$\mathcal{L}_{\rm NSI} = -\varepsilon^{fP}_{\alpha\beta} 2\sqrt{2} G_F (\bar{\nu}_\alpha \gamma_\mu L \nu_\beta)(\bar{f} \gamma^\mu P f)$$

where $\varepsilon^{fP}_{\alpha\beta}$: strength of NSI between ν_α, ν_β and fermion f

- limits from ν scattering exp, solar, reactor, atmospheric, accelerator, etc
  - $|\varepsilon^f_{e\mu}| \lesssim 10^{-4}$
  - $|\varepsilon^f_{\tau\tau} - \varepsilon^f_{\mu\mu}| \lesssim 10^{-1}$, $|\varepsilon^f_{e\tau}| \lesssim 10^{-1}$

Outline

NSI in Supernovae: before collective revolution

How can it affect?

- production mechanism in the core (νN)
  - may affect the SN dynamics $\Rightarrow |\varepsilon_{e\alpha}| \lesssim 10^{-3}$ [Amanik *et al.*, 2005 and 2007]
  - modify ν spectra
- propagation through SN envelope and Earth
- detection

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Propagation: Evolution equation

$$i\frac{d\nu_\alpha}{dr} = \left(H_{\rm kin} + H_{int}^{\rm nsi}\right)_{\alpha\beta}\nu_\beta \longrightarrow \text{if } f = d\text{, and only } \varepsilon_{e\tau}, \varepsilon_{\tau\tau} \neq 0$$

$$H_{\rm int}^{\rm nsi} = H_{\rm std} + H_{\rm nsi} = \lambda \begin{pmatrix} Y_e & 0 & (2-Y_e)\varepsilon_{e\tau} \\ 0 & 0 & 0 \\ (2-Y_e)\varepsilon_{e\tau} & 0 & Y_\tau^{\rm eff} + (2-Y_e)\varepsilon_{\tau\tau} \end{pmatrix}$$

where $\lambda = \sqrt{2}G_F n_B$ and $Y_\tau^{\rm eff} \approx 10^{-5}$ [F.J. Botella *et al.*, 1987]

NSI in Supernovae: before collective revolution

Consequences (flavor dynamics at the resonances)

- modify existing MSW resonances: position and adiabaticity γ

- L: unchanged
- H: more adiabatic $\rightarrow \gamma_H \propto \sin^2(2\theta_{13}^{\rm eff})$, $\theta_{13}^{\rm eff} = \theta_{13} + \varepsilon_{e\tau}(2 - Y_e)/Y_e$

  $\Rightarrow$ degeneracy $\theta_{13} \leftrightarrow \varepsilon_{e\tau}$ [A. Mirizzi *et al.*, 2002, A. Esteban-Pretel, R.T., J.W.F. Valle, 2007]
- $\mu\tau$: pushed outwards $\lambda(Y_\tau^{\rm eff} + (2 - Y_e)\varepsilon_{\tau\tau}) \approx \Delta m^2_{\rm atm}/2E$

NSI in Supernovae: before collective revolution

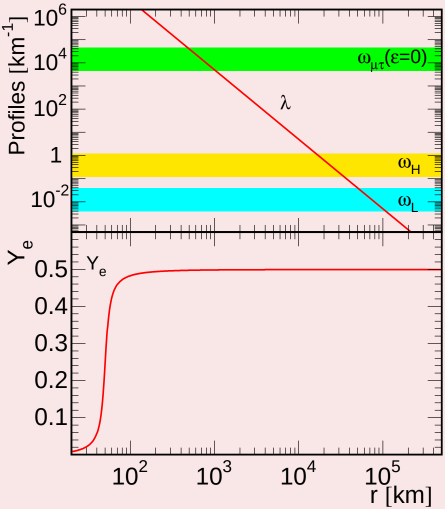
Consequences (flavor dynamics at the resonances)

- modify existing MSW resonances: position and adiabaticity γ
- generate new resonances

- L: unchanged
- H: more adiabatic $\rightarrow \gamma_H \propto \sin^2(2\theta_{13}^{\text{eff}})$, $\theta_{13}^{\text{eff}} = \theta_{13} + \varepsilon_{e\tau}(2 - Y_e)/Y_e$
  $\Rightarrow$ degeneracy $\theta_{13} \leftrightarrow \varepsilon_{e\tau}$ [A. Mirizzi *et al.*, 2002, A. Esteban-Pretel, R.T., J.W.F. Valle, 2007]
- $\mu\tau$: pushed outwards $\lambda(Y_\tau^{\text{eff}} + (2 - Y_e)\varepsilon_{\tau\tau}) \approx \Delta m^2_{\text{atm}}/2E$
- new internal non-MSW $I-$ resonance [J.W.F. Valle, 1987, Nunokawa *et al.*, 1996]
  - inner layers $H \approx H_{\text{int}} \longrightarrow$ resonance at $Y_e^I = 2\varepsilon_{\tau\tau}/(1 + \varepsilon_{\tau\tau})$
  - adiabatic for $|\varepsilon_{e\tau}| \gtrsim 10^{-5}$
  - simultaneously for ν_e and $\bar{\nu}_e$

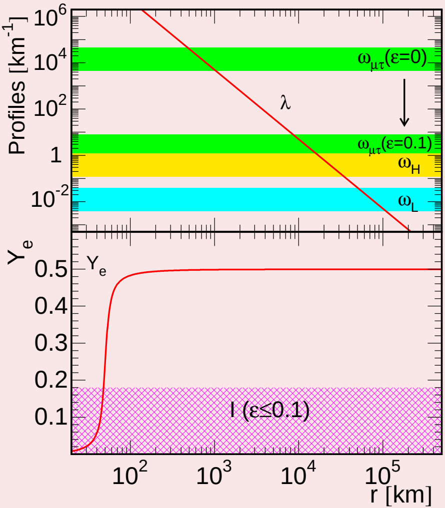
NSI in Supernovae: before collective revolution

Resonances for $\varepsilon_{\tau\tau} = 0$ (matter potential $\lambda = \lambda_0(R/r)^3$)



NSI in Supernovae: before collective revolution

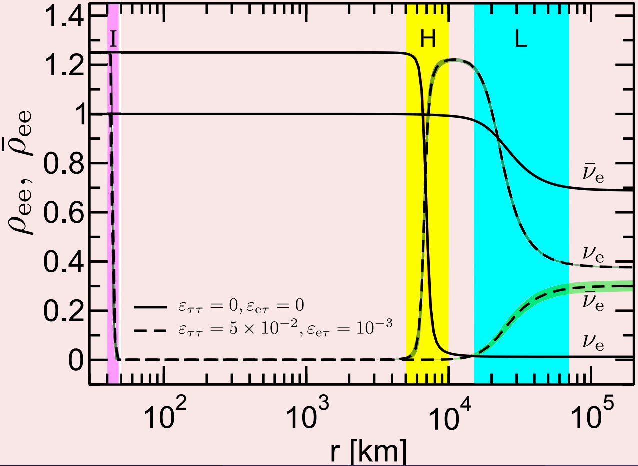
Resonances for $\varepsilon_{\tau\tau} = 0.1$ (matter potential $\lambda = \lambda_0 (R/r)^3$)



NSI in Supernovae: before collective revolution

Radial evolution (NH, $\sin^2\theta_{13} = 10^{-3}$)

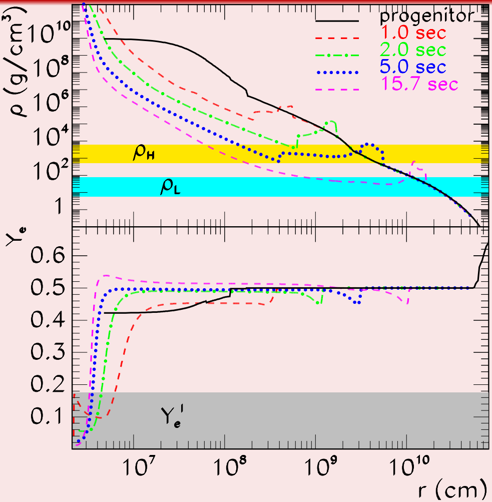
[A. Esteban-Pretel, R. T., J.W.F Valle, 2009]



NSI in Supernovae: before collective revolution

Observables: shock wave tracking

[A. Esteban-Pretel, R.T., J.W.F. Valle, 2007]



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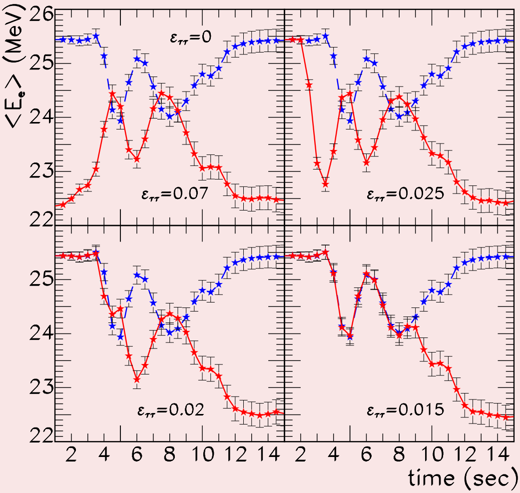


Outline

NSI in Supernovae: after collective revolution

Including $\nu - \nu$ interactions

$$H = H_{\rm kin} + H_{\rm int} + H_{\nu\nu}$$

$$\Downarrow$$

Plenty of new effects:

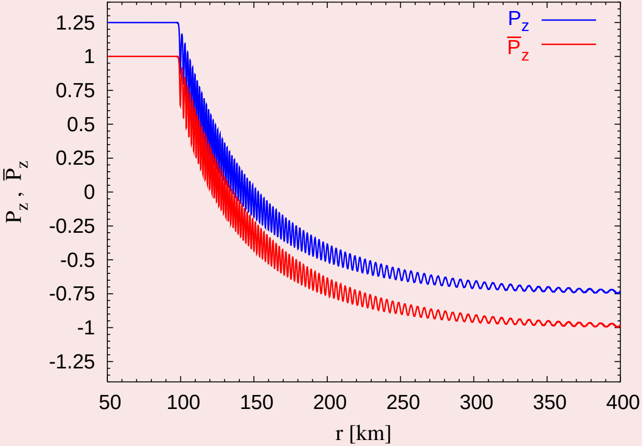
- synchronization
- bipolar conversion
- spectral swaps
- multiangle kinematical decoherence
- multiangle matter-induced decoherence
- $\mu\tau$ effect: ν_e depends on θ_{23}

A. Mirizzi, B. Dasgupta, S. Pastor, A. Marrone, I. Tamborra, P. Serpico, S. Charkaborty

NSI in Supernovae: before collective revolution

Single energy, single angle

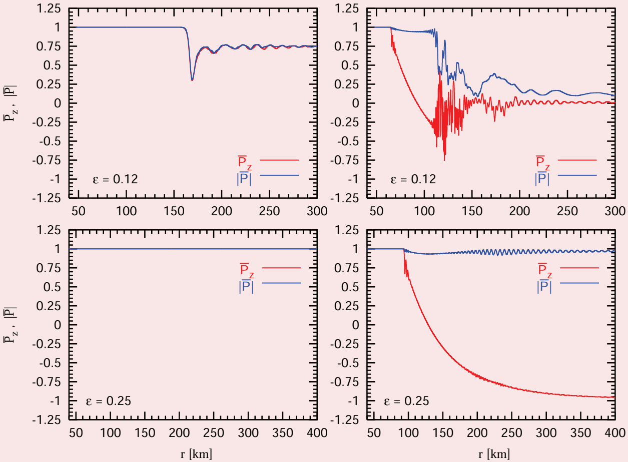
[A. Esteban-Pretel, S. Pastor, G. Raffelt, G. Sigl, R.T., 2007]



$R_\nu = 10$ km, $\mu_0 = 7 \times 10^{-5}$ km^{-1}

NSI in Supernovae: before collective revolution

Single energy, multiangle, $\epsilon \equiv (F_e - F_{\bar{e}})/(F_{\bar{e}} - F_{\bar{x}})$



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Now, on top of that, we add NSI

Where? in $H_{\rm int}$ or $H_{\nu\nu}$

NSI in the $\nu - \nu$ term

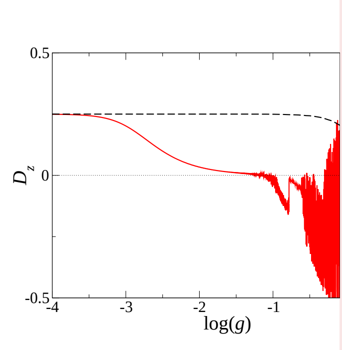
$$H^{\rm nsi}_{\nu\nu} = \sqrt{2} G_F \int d\mathbf{q} (1 - \mathbf{v_q} \cdot \mathbf{v_p}) \{ G(\rho_\mathbf{q} - \bar{\rho}_\mathbf{q}) G + G \mathrm{Tr}[(\rho_\mathbf{q} - \bar{\rho}_\mathbf{q}) G] \}$$

where $G = (g_0 + \mathbf{g} \cdot \sigma)/2$

Consequences

- even small NSI (g) trigger flavor conversion for $\theta = 0$
- in vacuum $g \gtrsim 10^{-4} \Rightarrow$ flavor equilibration: $D_z = P_z - \bar{P}_z \to 0$

  $\to$ but matter washes out the effect [M. Blennow, A. Mirizzi, P. Serpico, 2008]



NSI in the matter potential

- $H_{\nu\nu} = \sqrt{2}G_F \int d\mathbf{q}(\rho_{\mathbf{q}} - \bar{\rho}_{\mathbf{q}})(1 - \mathbf{v_q} \cdot \mathbf{v_p})$
- $H_{\rm int}^{\rm nsi} = H_{\rm std} + H_{\rm nsi} = \lambda \begin{pmatrix} Y_e & 0 & (2-Y_e)\varepsilon_{e\tau} \\ 0 & 0 & 0 \\ (2-Y_e)\varepsilon_{e\tau} & 0 & Y_\tau^{\rm eff} + (2-Y_e)\varepsilon_{\tau\tau} \end{pmatrix}$

Consequences

$(\epsilon = 0.25)$

- A) if $|\varepsilon_{\tau\tau}| \gtrsim 10^{-3} \Rightarrow \mu\tau$ effect resurrection
- B) if $\varepsilon_{\tau\tau} \gtrsim 10^{-2} \Rightarrow I-$resonance
  - inversion of fluxes $(\nu_e(\bar{\nu}_e) \leftrightarrow \nu_x(\bar{\nu}_x))$ entering bipolar region

NSI in the matter potential

A) $\mu\tau$ effect: birth, death

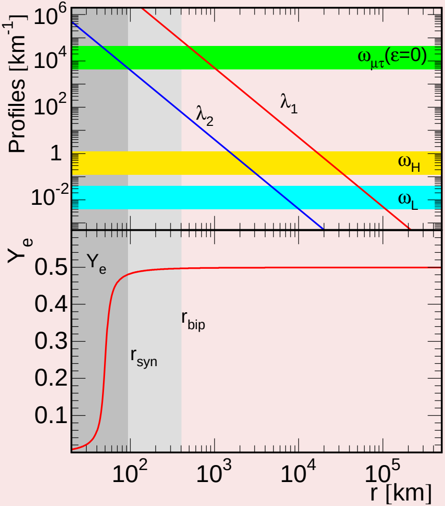
- birth: if $r_{\mu\tau} \gtrsim r_{\rm bip} \Rightarrow \nu_e$ evolution strongly depends on θ_{23} octant

  [A. Esteban-Pretel, S. Pastor, G. Raffelt, G. Sigl, R.T., 2008, Duan *et al.*, 2008]

- death
  - only at early times

NSI in the matter potential

$\mu\tau$ effect: early times (λ_1) $\surd \longrightarrow$ late times (λ_2) $\times$



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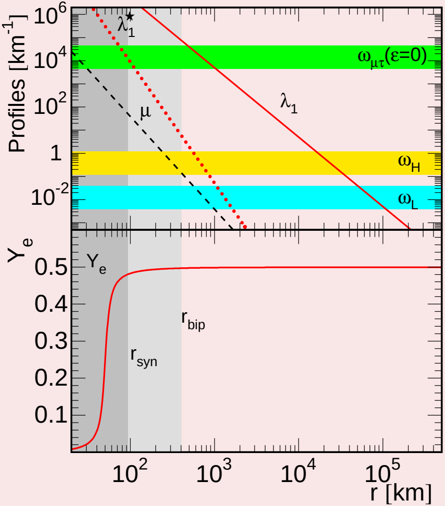
- death
  - only at early times
  - but large densities: $\lambda^\star \sim \lambda \frac{R^2}{2r^2} \gtrsim \mu \rightarrow$ multiangle matter effects suppress collective behavior [A. Esteban-Pretel, A. Mirizzi, S. Pastor, P. Serpico, G. Raffelt, G. Sigl, R. T., 2008]

NSI in the matter potential

$\mu\tau$ effect suppressed by matter at early times



NSI in the matter potential

$\mu\tau$ effect: birth, death and resurrection

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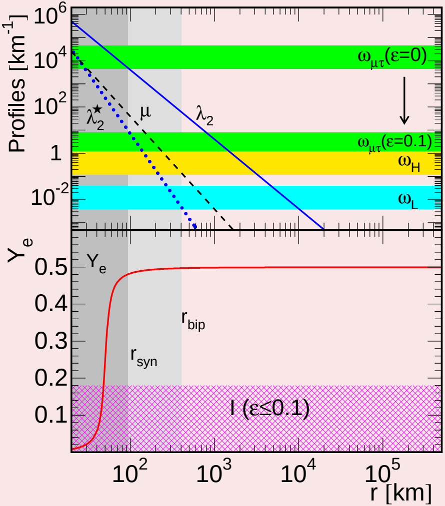
- resurrection: NSI ($\varepsilon_{\tau\tau}$) pushes $\mu\tau-$resonance outwards $\Rightarrow r^{\rm nsi}_{\mu\tau} \gtrsim r_{\rm bip}$
  - only at late times!! [A. Esteban-Pretel, R. T., J.W.F Valle, 2009, J. Gava and C.C. Jean-Louis, 2009]

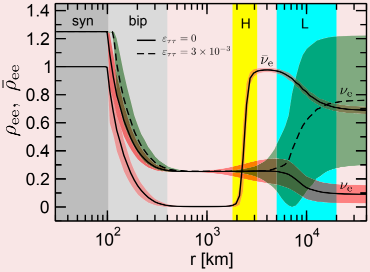
NSI in the matter potential

NSI $\Rightarrow$ $\mu\tau$ effect resurrection at late times

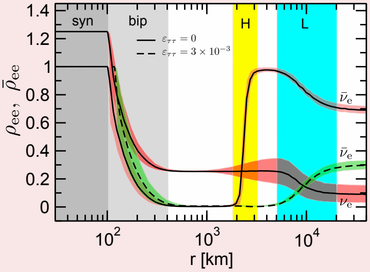


NSI in the matter potential

$\sin^2\theta_{23} = 0.4$



$\sin^2\theta_{23} = 0.6$



NSI in the matter potential

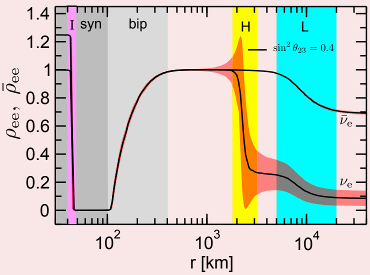
B) $I-$resonance and collective effects

inversion of fluxes $(\nu_e(\bar{\nu}_e) \leftrightarrow \nu_x(\bar{\nu}_x))$ entering bipolar region

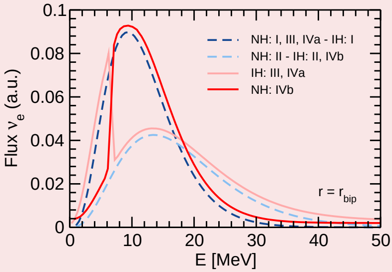
- NH $\rightarrow$ collective effects
  - single energy: almost cancellation $I-$res. $\leftrightarrow$ bipolar conversion
  - spectra: swap at low energies

NSI in the matter potential

NH, single energy



NH, spectra



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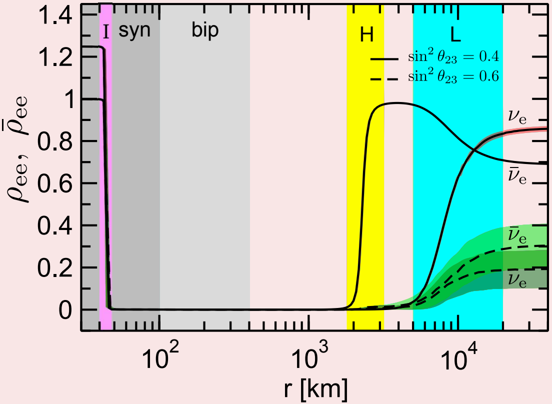
- IH
  - θ_{23} in 1st octant $\rightarrow$ no collective
  - θ_{23} in 2nd octant $\rightarrow$ *invisible* collective

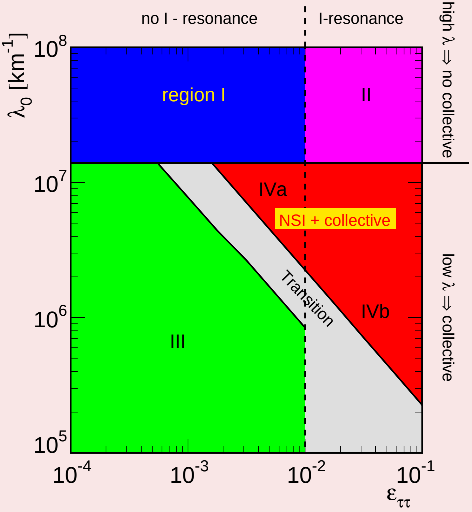
NSI in the matter potential

IH



NSI in the matter potential

Summary



Outline

Conclusions

- non-standard ν properties: hint of physics beyond SM
- SN extreme conditions enhance drastically the effect of non-standard ν properties
- $\nu - \nu$ interactions $\rightarrow$ many effects $\Rightarrow$ disentangle standard from non-standard effects $\rightarrow$ challenging
- basic ingredients:
  - better understanding of the collective phenomena
  - better knowledge of initial spectra (and SN dynamics)
  - time dependent signal