Constraining neutrino self-interactions from resonant light gauge boson production in proto-neutron stars

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arXiv: 2301.00661, in collaboration with D. G. Cerdeño and Y. Farzan

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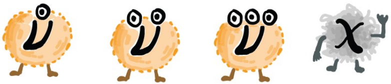
New light mediators in the neutrino (ν) sector



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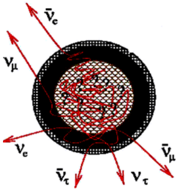
- Two of the most important challenges in cosmology and particle physics: understanding the dark matter nature and the lepton flavour violation in ν propagation
- Beyond the Standard Model realisations that feature **new low-mass mediators**
  - Well-motivated low-mass mediator models postulate the existence of new heavy gauge-singlet fermions that mix with the SM ν's and can explain their lightness
  - Some models can explain the discrepancy in the muon anomalous magnetic moment, $(g-2)_\mu$, and connect to a secluded sector that could account for the dark matter content in the Universe $\Rightarrow U(1)_{L_\mu - L_\tau}$ the simplest extension
  - Low-mass mediator scenarios provide new interactions in the neutrino sector

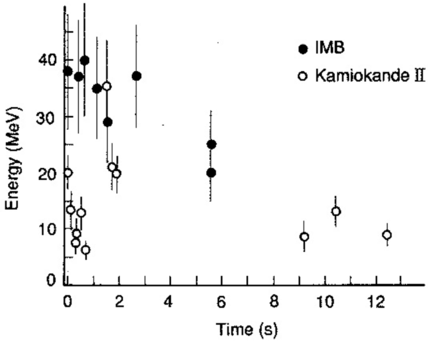
Supernova neutrinos

ν's are crucial in proto-NS evolution $\Rightarrow$ good sites to test new ν interactions

During the final phases of core collapse SN, and after the initial burst, ν's are still trapped due to their scattering with Ns within the nascent proto-NS and are emitted as it cools down (Kelvin-Helmholtz cooling)



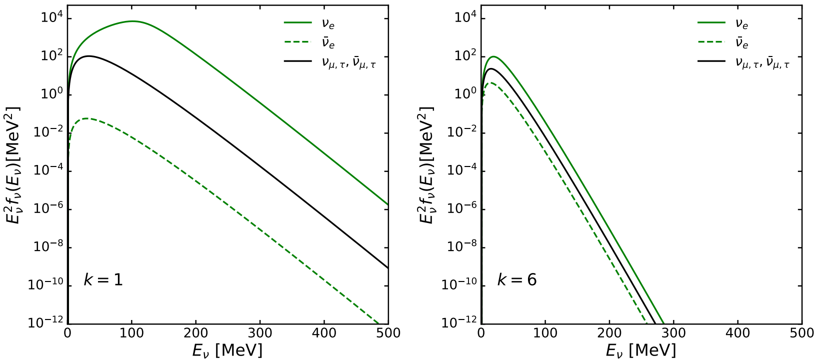
- Emitted ν's observed during $t_{\text{signal}} \sim 10$ s from the SN 1987A
- t_{signal} proportional to the ν diffusion time in the stellar material $t_{\text{signal}} \sim 10\, t_{\text{diff}}$
- The observed emision time is compatible with the one predicted by the SM



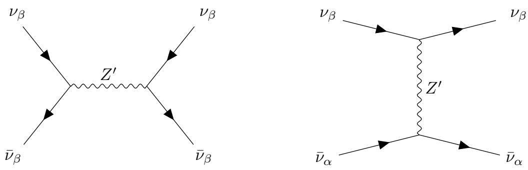
Neutrino energy distribution inside the proto-NS

T, n_B and Y_e from *Fischer et al., PRD 85 (2012) 083003*,
$\mu_n^*, \mu_p^*, \mu_{\nu_e}^*$ and $m_N^\star$ from *Cerdeño, **Cermeño**, Pérez-García and Reid, PRD 104 (2021) 063013*
Neutrino's chemical potentials for the different flavour $\mu^*_{\bar{\nu}_e} = -\mu^*_{\nu_e}, \mu_{\nu_{\mu,\tau}} = \mu_{\bar{\nu}_{\mu,\tau}} = 0$

	R (km)	T (MeV)	$n_B(\text{fm}^{-3})$	Y_e	μ_n^* (MeV)	μ_p^* (MeV)	$\mu_{\nu_e}^*$ (MeV)	$m_N^\star$ (MeV)
$k=1$	5.0	15	0.5	0.3	496.6	405.4	114.6	249.6
$k=2$	7.5	20	0.3	0.28	530.0	458.3	102.7	384.9
$k=3$	10.0	28	0.15	0.25	656.5	601.9	79.9	599.4
$k=4$	15.0	33	0.06	0.2	779.8	723.0	29.0	786.0
$k=5$	17.5	18	0.03	0.1	858.7	813.1	14.4	857.0
$k=6$	20.0	7	0.008	0.05	917.2	893.9	12.5	915.9

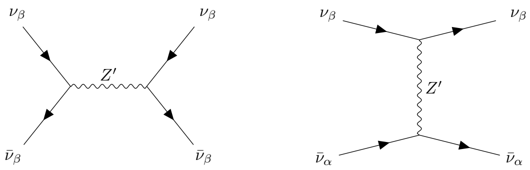


Resonant production of light mediators in the SN interior



- The process $\nu\bar{\nu} \to Z'^* \to \nu\bar{\nu}$ can be resonant if $m_{Z'} \sim T \sim 10$ MeV
- We study the effect on the SN neutrino flux duration in two regimes
  - Large coupling regime: $\sigma_{\nu,\bar{\nu}} \gtrsim \sigma_{\nu,N}$
  - Small coupling regime: Z' decay length $\ell_{Z'} > 3\,\mathrm{m} \sim$ standard ν mean free path
- If $\sigma_{\nu,\bar{\nu}} \gtrsim \sigma_{\nu,N}$, ν's will behave like tightly coupled perfect fluid and $t_{\rm diff}$ will not be affected
  Dicus et al., PLB 218 (1989) 84
- For $\ell_{Z'} > R_{ns} \sim 20$ km, $t_{\rm signal}$ can be shortened by half if the energy taken away by the Z' is comparable to 3×10^{53} erg (energy taken by neutrinos in the first 10 s)
  Burrows, Turner, Brinkmann, PRD 39 (1989) 1020, Choi, Santamaria, PRD 42 (1990) 293, Raffelt, Phys. Rept. 198 (1990) 1

Neutrino-antineutrino coalescence in the $U(1)_{L_\mu - L_\tau}$ model



- The $U(1)_{L_\mu - L_\tau}$ model is a simple anomaly-free extensions of the SM which feature a Z' vector boson that mediates new interactions in the neutrino sector

$$\mathcal{L}_{L_\mu - L_\tau} = -\frac{1}{4} Z'^{\alpha\beta} Z'_{\alpha\beta} + \frac{m_{Z'}^2}{2} Z'_\alpha Z'^\alpha + Z'_\alpha g_{\mu-\tau} \left(\bar{\mu}\gamma^\alpha \mu + \bar{\nu}_\mu \gamma^\alpha P_L \nu_\mu - \bar{\tau}\gamma^\alpha \tau - \bar{\nu}_\tau \gamma^\alpha P_L \nu_\tau \right)$$

$Z'_{\alpha\beta} \equiv \partial_\alpha Z'_\beta - \partial_\beta Z'_\alpha$ the field strength tensor, $P_L = \frac{1}{2}(1 - \gamma_5)$ the left chirality projector

$\beta = \mu, \tau$: tree level coupling only to μ, τ, ν_μ, ν_τ and their antiparticles

$m_{Z'}$ the mass of the gauge boson, $g_{\mu-\tau}$ the gauge coupling

Large coupling regime: Neutrino energy redistribution

- Linear momentum conservation $\Rightarrow$ short-ranged $\nu - \bar{\nu}$ interactions inside the proto-NS cannot change the energy flux of $\nu - \bar{\nu}$ gas $\Rightarrow$ $t_{\rm signal}$ not affected
- **$\nu - \bar{\nu}$ coalescence can redistribute ν and $\bar{\nu}$ energies** with a rate larger than that of scattering off the background matter

ν with energy $E_1 = \pi T - \Delta$ interacting with $\bar{\nu}$ with energy $E_2 = \frac{m_{Z'}^2}{2E_1(1-\cos\theta)} > E_1$ produce the Z' on-shell (Δ positive constant and θ the angle between ν and $\bar{\nu}$)

The final ν and $\bar{\nu}$ from the Z' decay will have a flat energy distribution in the range

$$[(E_1 + E_2)(1 - v_{Z'})/2, (E_1 + E_2)(1 + v_{Z'})/2],$$

with $v_{Z'} = (1 - m_{Z'}^2/(E_1 + E_2)^2)^{1/2}$

The less energetic ν with initial energy E_1 **will gain energy and will become more bounded to stellar matter** ($\sigma_{\nu,N} \propto E_\nu^2$)

- The fraction of ν_μ and ν_τ with $E_\nu < T$ ($E_\nu < T/3$) is only 8% (0.48%) of the whole number density, impact on $t_{\rm diff}$ not observable in the SN 1987A data
- Future SN detection?

Large coupling regime: Neutrino energy redistribution

Values of $(g_{\mu-\tau},\, m_{Z'})$ for which the average of the ν-$\bar{\nu}$ scattering rate via Z' equals the SM value in each of the proto-NS shells $\Rightarrow$ neutrino energy redistribution for $\sim 10\%$ of the total neutrinos emitted

*Cerdeño, **Cermeño**, Farzan, arXiv: 2301.00661*

The average of the ν-$\bar{\nu}$ scattering rate via Z'

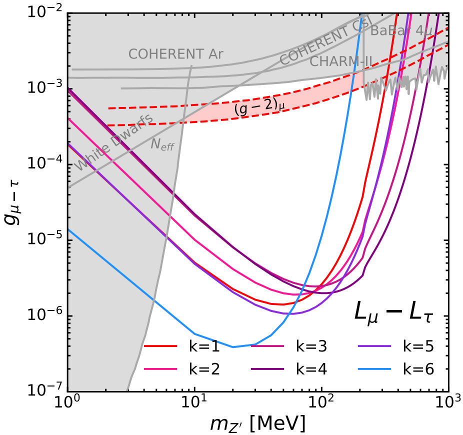
$$\langle \mathcal{R}_{\nu_\beta\bar{\nu}_\beta\to Z'\to\nu_\alpha\bar{\nu}_\alpha}\rangle = \frac{\int dE_{\nu_\beta} f(E_{\nu_\beta},\mu^*_{\nu_\beta},T)E^2_{\nu_\beta}\mathcal{R}_{\nu_\beta\bar{\nu}_\beta\to Z'\to\nu_\alpha\bar{\nu}_\alpha}}{\int dE_{\nu_\beta} f(E_{\nu_\beta},\mu^*_{\nu_\beta},T)E^2_{\nu_\beta}},$$

$$\mathcal{R}_{\nu_\beta\bar{\nu}_\beta\to Z'\to\nu_\alpha\bar{\nu}_\alpha} = \int \frac{d^3\vec{p}_{\bar{\nu}_\beta}}{(2\pi)^3} f(E_{\bar{\nu}_\beta},\mu^*_{\bar{\nu}_\beta},T)|\vec{v}_{\nu_\beta} - \vec{v}_{\bar{\nu}_\beta}|\sigma_{\nu_\beta,\bar{\nu}_\beta}$$

$\mathcal{R}_{\nu_\beta\bar{\nu}_\beta\to Z'\to\nu_\alpha\bar{\nu}_\alpha}$ depends on E_{ν_β}

$|\vec{v}_{\nu_\beta} - \vec{v}_{\bar{\nu}_\beta}|$ the ν-$\bar{\nu}$ relative velocity

$\sigma_{\nu_\beta,\bar{\nu}_\beta}$ the ν-$\bar{\nu}$ scattering cross section



Small coupling regime: Shortening of the ν flux duration

- We study cases when the Z' decay length, $\ell_{Z'}$, is $\mathbf{3\,m} < \boldsymbol{\ell_{Z'}} < \mathbf{20\ km}$

  $\ell_{Z'}$ calculated multiplying the Z' lifetime by $\gamma_{Z'} = E_{Z'}/m_{Z'}$ and v'_Z, averaged over $E_{Z'}$

  $\langle \mathcal{R}_{\nu\bar{\nu}\to Z'} \rangle$ is the average in E_ν of the $\nu\bar{\nu} \to Z'$ interaction rate

$$\mathcal{R}_{\nu\bar{\nu}\to Z'}(E_\nu) = \int \frac{d^3\vec{p}_{\bar{\nu}}}{(2\pi)^3} f(E_{\bar{\nu}}, \mu^*_{\bar{\nu}}, T) |\vec{v}_\nu - \vec{v}_{\bar{\nu}}| \sigma_{\nu\bar{\nu}\to Z'}$$

- In a time $\tau_{\nu\bar{\nu}\to Z'} = c/\langle \mathcal{R}_{\nu\bar{\nu}\to Z'} \rangle$, $\nu\bar{\nu} \to Z'$ and Z' decay into $\nu\bar{\nu}$ at a distance $\ell_{Z'}$
- After time t, ν-$\bar{\nu}$ pairs take $N = t/\tau_{\nu\bar{\nu}\to Z'}$ random steps, which takes them on average a distance $\sqrt{N}\ell_{Z'}$ far away from where they started

  For $\sqrt{N}\ell_{Z'} = R_{ns} \Rightarrow$ **the ν diffusion time** $\boldsymbol{t^{\rm new}_{\rm diff} = (R_{ns}/\ell_{Z'})^2 \tau_{\nu\bar{\nu}\to Z'}}$

  Describing the proto-NS interior with 6 different shells of radius R_k (different T)

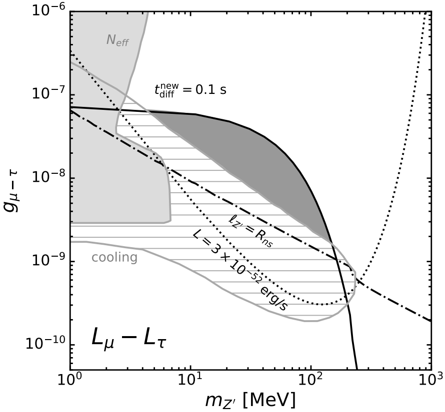
$$t^{\rm new}_{\rm diff} = \sum_{k=1}^{n} \frac{\left(R_k^2 - R_{k-1}^2\right)}{(\ell^k_{Z'})^2} \tau^k_{\nu\bar{\nu}\to Z'}$$

Small coupling regime: Bounds $U(1)_{L_\mu - L_\tau}$

The total energy in form of $\nu_{\mu,\tau}$, $\bar{\nu}_{\mu,\tau}$ at the on-set of the cooling phase is $\sim 3 \times 10^{51}$ erg

- If $\boldsymbol{t_{\rm diff}^{\rm new} \leq 0.1}$ **s**, the energy transfer via the Z' production will be comparable to the luminosity within the SM, $\boldsymbol{t_{\rm signal}}$ **shortened by half** $\Rightarrow$ lower limit as long as $l_{Z'} < R_{ns}$
  *Cerdeño, **Cermeño**, Farzan, arXiv: 2301.00661*

For $\ell_{Z'} > R_{ns}$, if the energy taken by the Z' is $\sim 3 \times 10^{53}$ erg in the first 10 s $\Rightarrow t_{\rm signal}$ shortened by a half (cooling bounds, for $U(1)_{L_\mu - L_\tau}$ *Croon et al., JHEP 01 (2021) 107*)



Conclusions

- We have investigated the effect of the resonant production of low-mass vector mediators from ν-$\bar{\nu}$ interactions in the core of proto-NS on the ν signal duration in SN
- We argue that, if ν-$\bar{\nu}$ interaction rate via Z' can exceed that of the SM scattering off nucleon, ν and $\bar{\nu}$ energies can be redistributed, leading to an enhancement in the burst duration. Too small effect to lead to a discernible impact in the SN 1987A data
- For the first time, we have focused on the region of the parameter space for which the decay length of Z' is larger than the standard neutrino mean free path, $\sim$ 3 m, but smaller than the proto-NS radius
- We have showed that, in this range, the ν burst duration can be significantly reduced, allowing us to rule out new areas of the parameter space for the $U(1)_{L_\mu - L_\tau}$ model with couplings of $\sim 6 \times 10^{-8}$ (extending the excluded regions from cooling)

Backup slides

Relation between ν emission time and diffusion time

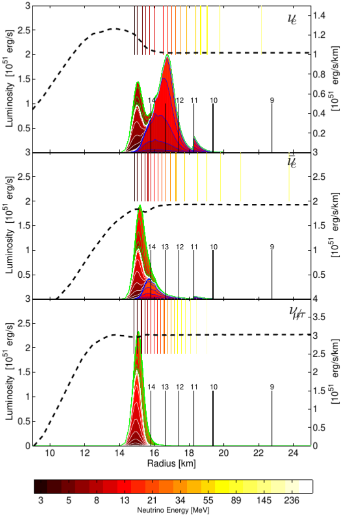
- At the onset of the cooling phase (~ 1 s after the bounce), the luminosity is of the order of 10^{52} erg s^{-1} for each ν and $\bar{\nu}$ species
- The outer layers cool down fast, the neutrinosphere recedes to smaller radii and the luminosity quickly drops
- The neutrino emission is backed up with the diffusion of ν's from the inner layers. Due to multiple scattering, ν's take a sizable time to reach the outer layers of the proto-NS, from where they are radiated out with a time scale of
  Janka arXiv: 1702.08713. In 'Handbook of Supernovae,' Springer

$$t_{\text{signal}} \sim \frac{3}{\pi^2} \frac{E_{th}^{tot}}{2E_{th}^{\nu}} R_{ns}^2 \left\langle \frac{1}{\lambda} \right\rangle \sim 10\, s,$$

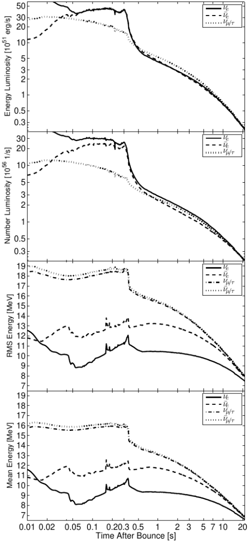
- E_{th}^{tot} and E_{th}^{ν} are the total baryon and neutrino thermal energies, $E_{th}^{tot}/(2E_{th}^{\nu}) \sim 10$
- $\langle 1/\lambda \rangle$ the average of the inverse of the neutrino mean free path
- $R_{ns}^2 \langle 1/\lambda \rangle$ (where R_{ns} is the radius of the neutrinosphere) gives the time scale of the diffusion of a single particle with a velocity of light and with random walk steps of λ
- In order to fullfil $t_{\text{signal}} \sim 10$ s, $R_{ns}^2 \langle 1/\lambda \rangle \sim 3\,\mathrm{s}/c$. From our calculation we get $R_{ns}^2 \langle 1/\lambda \rangle \sim 2.9\,\mathrm{s}/c$ for electron neutrinos and $1.3\,\mathrm{s}/c$ for muon and tau neutrinos

Neutrino luminosity

Fischer et al., PRD 85 (2012) 083003 $M_{\text{proj}} = 18\,M_\odot$



(a) 5 seconds post bounce



Calculation of the mean free path

The average of the inverse of the mean free path for neutrino scattering on a target particle, j, can be calculated by integrating the invariant cross section, $\sigma_{\nu_\beta,j}$, as follows

$$\langle 1/\lambda_{\nu_\beta}\rangle = \frac{\int dE_{\nu_\beta} f(E_{\nu_\beta},\mu^*_{\nu_\beta},T)E^2_{\nu_\beta}\lambda^{-1}_{\nu_\beta}(E_{\nu_\beta})}{\int dE_{\nu_\beta} f(E_{\nu_\beta},\mu^*_{\nu_\beta},T)E^2_{\nu_\beta}},$$

where $\beta = e,\mu,\tau$ indicates the neutrino flavour and

$$\lambda^{-1}_{\nu_\beta}(E_{\nu_\beta}) = \sum_j \int g_j \frac{d^3\vec{p}_j}{(2\pi)^3} f(E_j,\mu^*_j,T)|\vec{v_{\nu_\beta}} - \vec{v_j}|\sigma_{\nu_\beta,j}$$

is the inverse of the neutrino mean free path including neutrino scattering with all possible targets. g_j denotes the relativistic degrees of freedom of the corresponding target and $|\vec{v_{\nu_\beta}} - \vec{v_j}|$ is the relative velocity between the neutrino and the target, and $f(E,\mu^*,T)$ are the Fermi-Dirac distribution functions. For a general 2 by 2 process,

$$|\vec{v_{\nu_\beta}}-\vec{v_j}|\sigma_{\nu_\beta,j} = \int \frac{d^3\vec{p'}_{\nu_\beta}}{(2\pi)^3 2E'_{\nu_\beta}} \int \frac{d^3\vec{p'}_j}{(2\pi)^3 2E'_j}(2\pi)^4\delta^{(4)}(p_{\nu_\beta}+p_j-p'_{\nu_\beta}+p'_j)\frac{|\overline{\mathcal{M}}|^2_{\nu_\beta,j}}{4E_{\nu_\beta}E_j}(1-f(E'_{\nu_\beta},\mu^*_{\nu_\beta},T))(1-f(E'_j,\mu^*_j,T)),$$

where E_{ν_β}, E_j, $\vec{p}_{\nu_\beta}$, $\vec{p}_j$ are the energies and momenta of the incoming particles, E'_{ν_β}, E'_j, $\vec{p'}_{\nu_\beta}$, $\vec{p'}_j$ are those of the outgoing states, and p_{ν_β}, p_j, p'_{ν_β}, p'_j are the corresponding four-momenta.

Calculation of the $\nu - \bar{\nu}$ scattering rate via Z'

The average of the neutrino-antineutrino scattering rate

$$\langle \mathcal{R}_{\nu_\beta \bar{\nu}_\beta \to Z' \to \nu_\alpha \bar{\nu}_\alpha} \rangle = \frac{\int dE_{\nu_\beta} f(E_{\nu_\beta}, \mu^*_{\nu_\beta}, T) E^2_{\nu_\beta} \mathcal{R}_{\nu_\beta \bar{\nu}_\beta \to Z' \to \nu_\alpha \bar{\nu}_\alpha}(E_{\nu_\beta})}{\int dE_{\nu_\beta} f(E_{\nu_\beta}, \mu^*_{\nu_\beta}, T) E^2_{\nu_\beta}}$$

where $\beta = e, \mu, \tau$ indicates the neutrino flavour and

$$\mathcal{R}_{\nu_\beta \bar{\nu}_\beta \to Z' \to \nu_\alpha \bar{\nu}_\alpha}(E_{\nu_\beta}) = \int \frac{d^3 \vec{p}_{\bar{\nu}_\beta}}{(2\pi)^3} f(E_{\bar{\nu}_\beta}, \mu^*_{\bar{\nu}_\beta}, T) |\vec{v}_{\nu_\beta} - \vec{v}_{\bar{\nu}_\beta}| \sigma_{\nu_\beta, \bar{\nu}_\beta}$$

is the neutrino-antineutrino scattering rate via Z', $|\vec{v}_{\nu_\beta} - \vec{v}_{\bar{\nu}_\beta}|$ is the relative velocity between neutrinos and antineutrinos and $\sigma_{\nu_\beta, \bar{\nu}_\beta}$ is the neutrino-antineutrino scattering cross section, its product

$$|\vec{v}_{\nu_\beta} - \vec{v}_{\bar{\nu}_\beta}| \sigma_{\nu_\beta, \bar{\nu}_\beta} = \int \frac{d^3 \vec{p'}_{\nu_\alpha}}{(2\pi)^3 2E'_{\nu_\alpha}} \int \frac{d^3 \vec{p'}_{\bar{\nu}_\alpha}}{(2\pi)^3 2E'_{\bar{\nu}_\alpha}} (2\pi)^4 \delta^{(4)}(p_{\nu_\beta} + p_{\bar{\nu}_\beta} - p'_{\nu_\alpha} + p'_{\bar{\nu}_\alpha}) \frac{|\overline{\mathcal{M}}|^2_{\nu_\beta, \bar{\nu}_\beta}}{4 E_{\nu_\beta} E_{\bar{\nu}_\beta}} \mathcal{F}(E'_{\nu_\alpha}, E'_{\bar{\nu}_\alpha})$$

with $E_{\nu_\beta}, E_{\bar{\nu}_\beta}, \vec{p}_{\nu_\beta}, \vec{p}_{\bar{\nu}_\beta}$ the energies and momenta of the incoming particles, $E'_{\nu_\alpha}, E'_{\bar{\nu}_\alpha}, \vec{p'}_{\nu_\alpha}, \vec{p'}_{\bar{\nu}_\alpha}$ those of the outgoing states, and $p_{\nu_\beta}, p_{\bar{\nu}_\beta}, p'_{\nu_\alpha}, p'_{\bar{\nu}_\alpha}$ the corresponding four-momenta
$\mathcal{F}(E'_{\nu_\alpha}, E'_{\bar{\nu}_\alpha}) = (1 - f(E'_{\nu_\alpha}, \mu^*_{\nu_\alpha}, T))(1 - f(E'_{\bar{\nu}_\alpha}, \mu^*_{\bar{\nu}_\alpha}, T))$ accounts for Pauli blocking in the outgoing states

Narrow Width Approximation

In the parameter space under analysis

- The resonant production of the Z' boson is the leading new physics process
- $\Gamma_{Z'\to\bar{\nu}_\beta\nu_\beta}/m_{Z'} \ll 1$ is fulfilled, with $\Gamma_{Z'\to\bar{\nu}_\beta\nu_\beta}$ the decay width of the Z' into neutrinos
- The narrow width approximation can be used to obtain the neutrino-antineutrino scattering rate

$$\mathcal{R}_{\nu_\beta\bar{\nu}_\beta\to Z'\to\nu_\alpha\bar{\nu}_\alpha}(E_{\nu_\beta}) = \frac{1}{32\pi}\int_{E^{min}_{\bar{\nu}_\beta}}^{\infty} dE_{\bar{\nu}_\beta}\frac{f(E_{\bar{\nu}_\beta},\mu^*_{\bar{\nu}_\beta},T)E_{\bar{\nu}_\beta}}{E_{\bar{\nu}_\beta}+E_{\nu_\beta}}\left(\frac{m_{Z'}}{E_{\bar{\nu}_\beta}E_{\nu_\beta}}\right)^2 |\overline{\mathcal{M}}|^2_{\nu_\beta\bar{\nu}_\beta\to Z'}\frac{\Gamma_{Z'\to\nu_\alpha\bar{\nu}_\alpha}}{\Gamma^{tot}_{Z'}},$$

- $E^{min}_{\bar{\nu}_\beta} = m^2_{Z'}/(4E_{\nu_\beta})$
- The total Z' decay width $\Gamma^{tot}_{Z'} = \sum_\beta \Gamma_{Z'\to\bar{\nu}_\beta\nu_\beta} + \Gamma_{Z'\to\beta^+\beta^-}$, where $\beta = \mu, \tau$
- The average of the $\nu - \bar{\nu}$ scattering rate

$$\langle\mathcal{R}_{\nu_\beta\bar{\nu}_\beta\to Z'\to\nu_\alpha\bar{\nu}_\alpha}\rangle = \frac{\int dE_{\nu_\beta} f(E_{\nu_\beta},\mu^*_{\nu_\beta},T)E^2_{\nu_\beta}\mathcal{R}_{\nu_\beta\bar{\nu}_\beta\to Z'\to\nu_\alpha\bar{\nu}_\alpha}(E_{\nu_\beta})}{\int dE_{\nu_\beta} f(E_{\nu_\beta},\mu^*_{\nu_\beta},T)E^2_{\nu_\beta}}$$

$\nu - \bar{\nu}$ coalescence rate and Z' decay length

The rate of the scattering of a single ν off any $\bar{\nu}$ in the medium producing the Z' on-shell can be computed via the following relation,

$$\mathcal{R}_{\nu_\beta\bar{\nu}_\beta\to Z'}(E_{\nu_\beta}) = \frac{1}{32\pi}\int_{E^{min}_{\bar{\nu}_\beta}}^{\infty} dE_{\bar{\nu}_\beta}\frac{f(E_{\bar{\nu}_\beta},\mu^*_{\bar{\nu}_\beta},T)E_{\bar{\nu}_\beta}}{E_{\bar{\nu}_\beta}+E_{\nu_\beta}}\left(\frac{m_{Z'}}{E_{\bar{\nu}_\beta}E_{\nu_\beta}}\right)^2 |\overline{\mathcal{M}}|^2_{\nu_\beta\bar{\nu}_\beta\to Z'}.$$

The time scale of the interaction can be defined as $\tau_{\nu_\beta\bar{\nu}_\beta\to Z'} = c/\langle\mathcal{R}_{\nu_\beta\bar{\nu}_\beta\to Z'}\rangle$, with

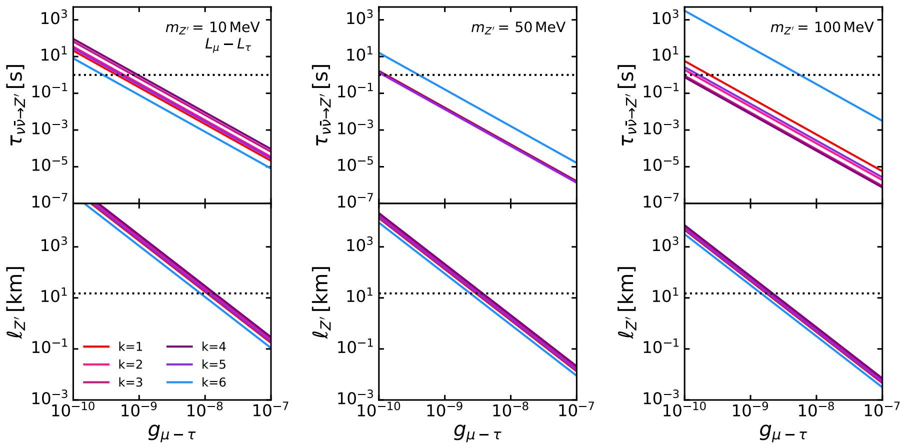
$$\langle\mathcal{R}_{\nu_\beta\bar{\nu}_\beta\to Z'}\rangle = \frac{\int dE_{\nu_\beta} f(E_{\nu_\beta},\mu^*_{\nu_\beta},T)E^2_{\nu_\beta}\mathcal{R}_{\nu_\beta\bar{\nu}_\beta\to Z'}(E_{\nu_\beta})}{\int dE_{\nu_\beta} f(E_{\nu_\beta},\mu^*_{\nu_\beta},T)E^2_{\nu_\beta}}.$$

The Z' decay length

$$\ell_{Z'} = \frac{\int\frac{d^3\vec{p}_{\nu_\beta}}{(2\pi)^3}f(E_{\nu_\beta},\mu^*_{\nu_\beta},T)\int\frac{d^3\vec{p}_{\bar{\nu}_\beta}}{(2\pi)^3}f(E_{\bar{\nu}_\beta},\mu^*_{\bar{\nu}_\beta},T)\sigma_{\nu_\beta\bar{\nu}_\beta\to Z'}|\vec{v_{\nu_\beta}}-\vec{v}_{\bar{\nu}_\beta}|\gamma_{Z'}v_{Z'}\frac{\hbar}{\Gamma^{tot}_{Z'}}}{\int\frac{d^3\vec{p}_{\nu_\beta}}{(2\pi)^3}f(E_{\nu_\beta},\mu^*_{\nu_\beta},T)\int\frac{d^3\vec{p}_{\bar{\nu}_\beta}}{(2\pi)^3}f(E_{\bar{\nu}_\beta},\mu^*_{\bar{\nu}_\beta},T)\sigma_{\nu_\beta\bar{\nu}_\beta\to Z'}|\vec{v_{\nu_\beta}}-\vec{v}_{\bar{\nu}_\beta}|},$$

where $v_{Z'}$ is the Z' velocity, $\gamma_{Z'} = E_{Z'}/m_{Z'}$ and $\sigma_{\nu_\beta\bar{\nu}_\beta\to Z'}$ is the cross section for ν-$\bar{\nu}$ coalescence

$\nu - \bar{\nu}$ coalescence rate and Z' decay length



Total luminosity carried by Z' outside the star

In the the regime where $\ell_{Z'} > R_{ns}$, each $\nu\bar{\nu}$ pair producing the Z' on-shell will be transferred outside the neutrinosphere. The energy transfer rate per unit volume and time taken by the Z' can be written as

$$\mathcal{L} = \frac{1}{2\pi^2} \int dE_{\nu_\beta} f(E_{\nu_\beta}, \mu^*_{\nu_\beta}, T) E^2_{\nu_\beta} \int_{E^{min}_{\bar{\nu}_\beta}}^{\infty} 2 \frac{dE_{\bar{\nu}_\beta}}{32\pi} f(E_{\bar{\nu}_\beta}, \mu^*_{\bar{\nu}_\beta}, T) E_{\bar{\nu}_\beta} \left(\frac{m_{Z'}}{E_{\bar{\nu}_\beta} E_{\nu_\beta}} \right)^2 |\overline{\mathcal{M}}|^2_{\nu_\beta \bar{\nu}_\beta \to Z'}$$

where the factor 2 at the beginning of the inner integral comes from considering both muon and tau neutrino flavours.
The total energy carried by the Z' per unit time is

$$L = \sum_{k=1}^{n} \frac{4\pi}{3} (R_k^3 - R_{k-1}^3) \mathcal{L}_k.$$

Imposing $L \leq 3 \times 10^{-52}\,\mathrm{erg/s}$ is equivalent to the upper bound obtained in *Croon et al., JHEP 01 (2021) 107* for the $U(1)_{L_\mu - L_\tau}$ model. $\mathcal{L}_k$ corresponds to the Z' energy transfer rate per unit volume and time in each shell, which depends on T.

Effective nucleon masses and chemical potentials

Considering the TM1 model for a $18\,M_\odot$ progenitor in a relativistic mean field approach:

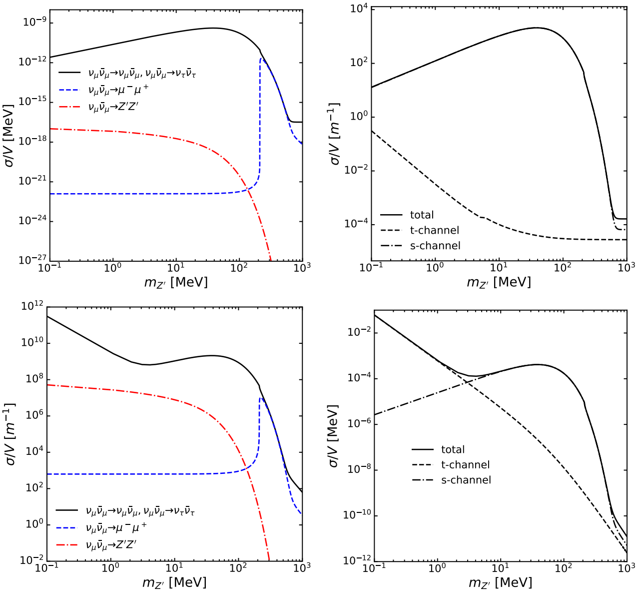
- The baryonic density, n_B, temperature, T, and electron fraction, Y_e, derived by *Fischer et al., PRD 85 (2012) 083003*
- The effective nucleon masses, $m_N^\star$, and the neutrino and nucleon effective chemical potentials, $\mu^*_{\nu_e}$, μ^*_n, μ^*_p obtained by *Cerdeño, **Cermeño**, Pérez-García and Reid, PRD 104 (2021) 063013*
- $\mu^*_{\nu_e}$ is obtained solving the equilibrium equation that involves effective meson fields: $\mu^*_n + \mu^*_{\nu_e} = \mu^*_p + \mu^*_e + 2g_\rho\langle\rho\rangle$, where ρ is an effective field responsible of the strong interaction

	R (km)	T (MeV)	$n_B(\mathrm{fm}^{-3})$	Y_e	μ^*_n (MeV)	μ^*_p (MeV)	$\mu^*_{\nu_e}$ (MeV)	$m^\star_N$ (MeV)
$k=1$	5.0	15	0.5	0.3	496.6	405.4	114.6	249.6
$k=2$	7.5	20	0.3	0.28	530.0	458.3	102.7	384.9
$k=3$	10.0	28	0.15	0.25	656.5	601.9	79.9	599.4
$k=4$	15.0	33	0.06	0.2	779.8	723.0	29.0	786.0
$k=5$	17.5	18	0.03	0.1	858.7	813.1	14.4	857.0
$k=6$	20.0	7	0.008	0.05	917.2	893.9	12.5	915.9

TABLE I. Values of neutron effective chemical potential, μ^*_n, proton effective chemical potential, μ^*_p, electron neutrino effective chemical potential, μ^*_ν, and nucleon effective mass, $m^\star_N$, for the spherical shells (labeled by the index k and defined by an outer radius R) that we consider at 1 s after bounce, with a baryonic density, n_B, temperature, T and electron fraction, Y_e. Temperatures, densities and electron fraction are taken from Ref. [45].

Other interactions and channels

$k = 1$, upper pannel $g_{\mu-\tau} = 10^{-4}$, lower pannel $g_{\mu-\tau} = 0.1$



Relevant interactions inside SN

Janka arXiv: 1702.08713. In 'Handbook of Supernovae,' Springer

Table 1 Most important neutrino processes in supernova and proto-neutron star matter.

Process	Reaction[a]
Beta-processes (direct URCA processes)	
electron and ν_e absorption by nuclei	$e^- + (A,Z) \longleftrightarrow (A,Z-1) + \nu_e$
electron and ν_e captures by nucleons	$e^- + p \longleftrightarrow n + \nu_e$
positron and $\bar{\nu}_e$ captures by nucleons	$e^+ + n \longleftrightarrow p + \bar{\nu}_e$
"Thermal" pair production and annihilation processes	
Nucleon-nucleon bremsstrahlung	$N + N \longleftrightarrow N + N + \nu + \bar{\nu}$
Electron-position pair process	$e^- + e^+ \longleftrightarrow \nu + \bar{\nu}$
Plasmon pair-neutrino process	$\widetilde{\gamma} \longleftrightarrow \nu + \bar{\nu}$
Reactions between neutrinos	
Neutrino-pair annihilation	$\nu_e + \bar{\nu}_e \longleftrightarrow \nu_x + \bar{\nu}_x$
Neutrino scattering	$\nu_x + \{\nu_e, \bar{\nu}_e\} \longleftrightarrow \nu_x + \{\nu_e, \bar{\nu}_e\}$
Scattering processes with medium particles	
Neutrino scattering with nuclei	$\nu + (A,Z) \longleftrightarrow \nu + (A,Z)$
Neutrino scattering with nucleons	$\nu + N \longleftrightarrow \nu + N$
Neutrino scattering with electrons and positrons	$\nu + e^{\pm} \longleftrightarrow \nu + e^{\pm}$

[a] N means nucleons, i.e., either n or p, $\nu \in \{\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau\}$, $\nu_x \in \{\nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau\}$

Neutrino decoupling SM

Janka arXiv: 1702.08713. In 'Handbook of Supernovae,' Springer

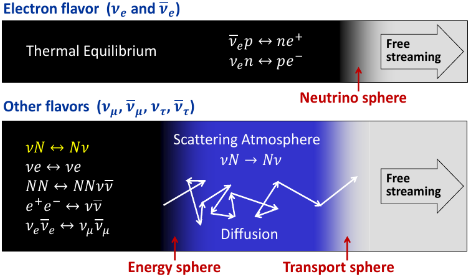
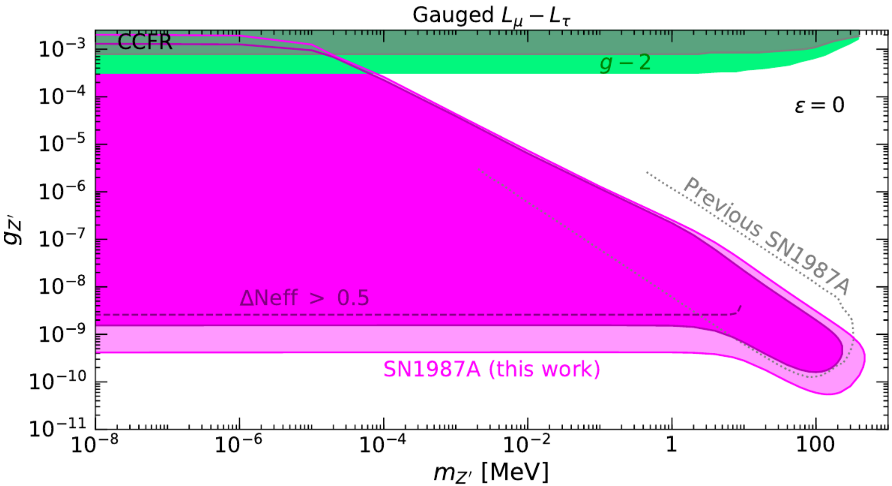


Fig. 4 Sketch of the transport properties of electron-flavor neutrinos and antineutrinos (*upper part*) compared to heavy-lepton neutrinos (*lower part*). In the supernova core ν_e and $\bar{\nu}_e$ interact with the stellar medium by charged-current absorption and emission reactions, which provide a major contribution to their opacities and lead to a strong energetic coupling up to the location of their neutrinospheres, outside of which both chemical equilibrium between neutrinos and stellar matter (indicated by the black region) and diffusion cannot be maintained. In contrast, heavy-lepton neutrinos are energetically less tightly coupled to the stellar plasma, mainly by pair creation reactions like nucleon bremsstrahlung, electron-position annihilation and $\nu_e\bar{\nu}_e$ annihilation. The total opacity, however, is determined mostly by neutrino-nucleon scatterings, whose small energy exchange per scattering does not allow for an efficient energetic coupling. Therefore heavy-lepton neutrinos fall out of thermal equilibrium at an energy sphere that is considerably deeper inside the nascent neutron star than the transport sphere, where the transition from diffusion to free streaming sets in. The blue band indicates the scattering atmosphere where the heavy-lepton neutrinos still collide frequently with neutron and protons and lose some of their energy, but cannot reach equilibrium with the background medium any longer. (Figure adapted from Raffelt 2012, courtesy of Georg Raffelt)

Cooling and net muon number effect in the $U(1)_{L_\mu - L_\tau}$

Within the SM, a suppressed population of muons is expected to exist inside a proto-NS. *Croon et al., JHEP 01 (2021) 107* has studied the Z' production by this background muon population through semi-Compton and Bremsstrahlung processes.

The effect can be significant only for the Z' masses below ~ 5 MeV.



Effect of the production of muons

- Will ν-$\bar{\nu}$ annihilation into muons via s-channel Z' diagram have an impact on the physics of the proto-NS?
- These processes generate the same amount of muons and antimuons $\Rightarrow$ $\mu_{\mu^-} = \mu_{\mu^+} = 0$ (as we assume in the SM) and therefore we do not expect the equation of state of the nuclear matter to change
- ν_μ ($\bar{\nu}_\mu$) can scatter on μ^+ (μ^-), but $n_\mu \ll n_n$ and $\sigma_{\nu_\mu,\mu} \ll \sigma_{\nu_\mu,n}$, the mean free path of scattering on μ^- (μ^+) is negligible compared to the scattering on n
- The decay of muons into muon neutrinos close to the neutrinosphere can change equality between the muon neutrino and tau neutrino fluxes that come out of the neutrinosphere, having consequences for collective neutrino oscillation

Bounds on ν self-interactions outside the proto-NS from the enhancement of the ν diffusion time

Chang et al., arXiv:2206.12426 for the burst-outflow scenario

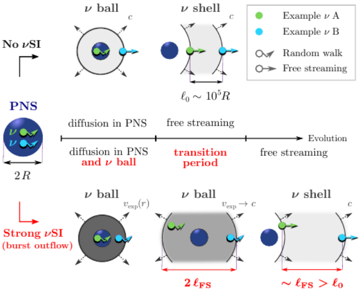


FIG. 2. Macroscopic evolution of a neutrino outflow from a supernova (lengths not to scale). **Without νSI**, the final width of the neutrino shell is $\ell_0 \sim c \cdot 10\,\mathrm{s}$, much larger than the PNS and set by neutrino diffusion therein. **With strong νSI**, neutrinos diffuse in the expanding neutrino ball. In the burst-outflow case, the size of the ball when neutrinos start decoupling from each other, $\ell_{\rm FS}$, sets the final width of the neutrino shell. *The duration of the observed neutrino signal will thus be significantly extended when* $\ell_{\rm FS} > \ell_0$.

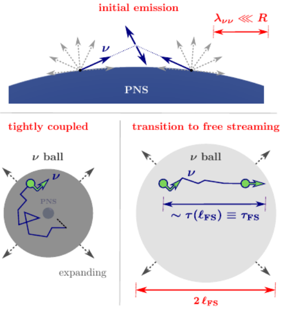


FIG. 3. Microscopic evolution of neutrino scattering due to νSI at different times for the burst-outflow case (lengths not to scale). *Neutrinos move in all directions until the νSI optical depth becomes small. After then, neutrinos are no longer significantly deflected and the ball becomes a shell.*

Bounds on ν self-interactions outside the proto-NS from the enhancement of the ν diffusion time

Chang et al., arXiv:2206.12426 for the burst-outflow scenario, Majorana νs and a mediator ϕ

$$\mathcal{L}_{\nu\,\mathrm{SI}} = -1/2 g \nu \bar{\nu}$$

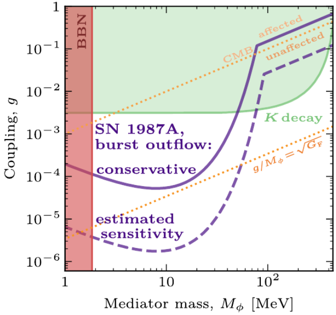


FIG. 1. Potential constraints on νSI from SN 1987A (assuming the burst-outflow case), previous limits, and relevant scales [12, 35]. K-decay bounds apply only to ν_e and ν_μ. *Strong νSI would change the time profile of the SN 1987A neutrino signal*; we show a **conservative analysis** (30-s duration), and an **estimated sensitivity** (3-s smearing).

Supernova bounds on new neutrino physics

Farzan et al., JHEP 05 (2018) 066, Suliga, Tamborra, PRD 103 (2021) 083002 derived bounds on ν-N interactions in models with light scalar and vector mediators imposing $t_E \lesssim 10$ s

*Cerdeño, **Cermeño**, Pérez-García and Reid, PRD 104 (2021) 063013* improved these bounds taking into account the temperature, T, and density, n_B, effects on the ν mean free path, λ_ν

$m_N^\star$ effective nucleon mass,

$\mu^*_{\nu_e}, \mu^*_n, \mu^*_p$,
ν_e, neutron (n), proton (p) effective chemical potentials,

$\mu_{\nu_\mu} = \mu_{\nu_\tau} = 0$

$f(E_j, \mu_j^*, T) = \frac{1}{1+e^{(E_j-\mu_j^*)/T}}$,

distribution function of the target, $j \equiv N = n,\ p$

T, n_B and Y_e from *Fischer et al., PRD 85 (2012) 083003*

	R (km)	T (MeV)	n_B(fm^{-3})	Y_e	μ_n^* (MeV)	μ_p^* (MeV)	$\mu_{\nu_e}^*$ (MeV)	$m_N^\star$ (MeV)
$k=1$	5.0	15	0.5	0.3	496.6	405.4	114.6	249.6
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$$c\ \Delta t \equiv c\ t_{\rm diff} = \sum_{k=1}^n \left(R_k^2 - R_{k-1}^2\right)\langle 1/\lambda_\nu\rangle_k\,, \quad \langle 1/\lambda_\nu\rangle = \frac{\int dE_\nu f(E_\nu,\mu_\nu^*,T)E_\nu^2\lambda_\nu^{-1}(E_\nu)}{\int dE_\nu f(E_\nu,\mu_\nu^*,T)E_\nu^2}$$

$$\lambda_\nu^{-1}(E_\nu) = \sum_j \int g_j \frac{d^3\vec{p}_j}{(2\pi)^3} f(E_j,\mu_j^*,T) \int \frac{d^3\vec{p'}_\nu}{(2\pi)^3 2E'_\nu} \int \frac{d^3\vec{p'}_j}{(2\pi)^3 2E'_j} (2\pi)^4\delta^{(4)}(p_\nu + p_j - p'_\nu + p'_j) \frac{\overline{|\mathcal{M}|}^2_{\nu,j}}{4E_\nu E_j}(1-f(E'_\nu,\mu_\nu^*,T))(1-f(E'_j,\mu_j^*,T))$$

Bounds on new ν-N interactions from the ν diffusion time in the SN interior

*Cerdeño, **Cermeño**, Pérez-García and Reid, PRD 104 (2021) 063013*

$$\Delta t \lesssim 2\,\Delta t^{\mathrm{SM}}, \quad \Delta t^{\mathrm{SM}} \sim 1\,s$$

Δt includes both new physics and SM interactions, i.e., the $2\,\Delta t^{\mathrm{SM}}$ line indicates where new physics interactions starts contributing equally to the diffusion time than SM interactions

$$\mathcal{L}_{\mathrm{LNC}} \supset -C_\nu \bar{\nu}_R \phi \nu_L - \bar{\psi}_N C_N \psi_N \phi - \textstyle\sum_l C_l \bar{l}\phi l, \qquad Y = \sqrt{C_\nu C_N}$$

$$\mathcal{L}_{\mathrm{B-L}} = -\textstyle\sum_q C_q \bar{q}\gamma^\mu q Z'_\mu - \sum_l C_l \bar{l}\gamma^\mu l Z'_\mu - \sum_\nu C_\nu \bar{\nu}\gamma^\mu \nu Z'_\mu, \qquad C_q = g_{B-L}/3,\ C_{l,\nu} = -g_{B-L}$$