Sensitivity Study of the Axial-Vector Coupling Constant in Neutrino Transport for Core-Collapse Supernovae

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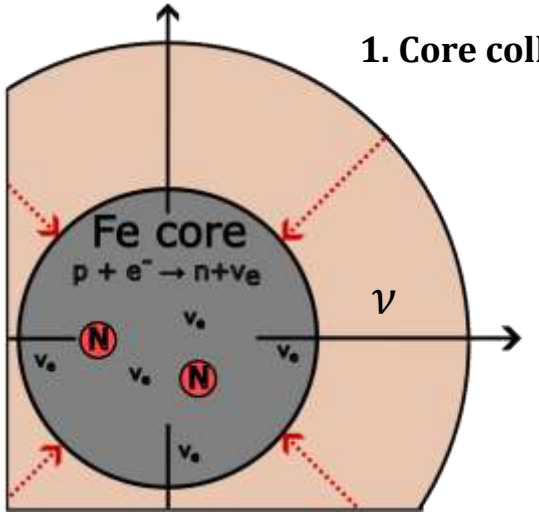
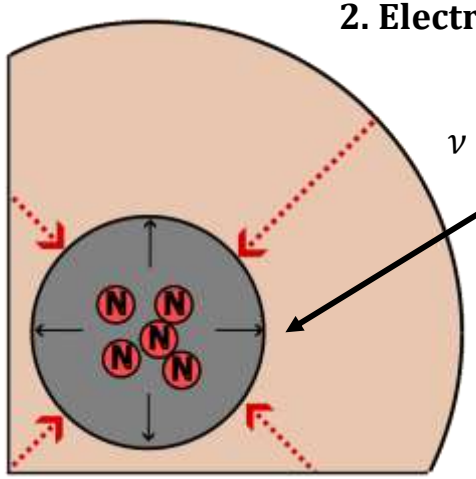
2025 K-Neutrino Symposium 6/25(Wed), 2025 Chung-Ang University

OMEG Origin of Matter and Evolution of Galaxies Key Research Institutes in Universities

Supernovae type II

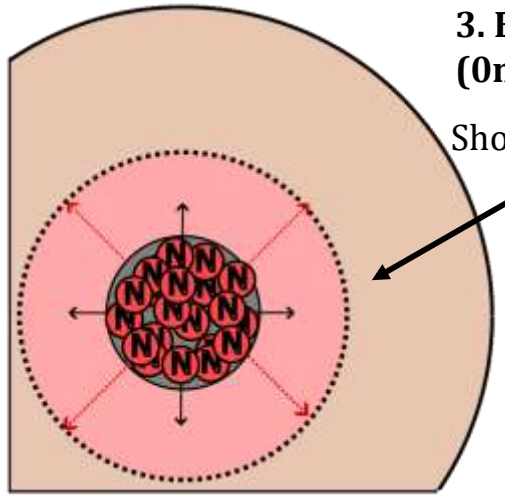


1. Core collapse



2. Electron capture

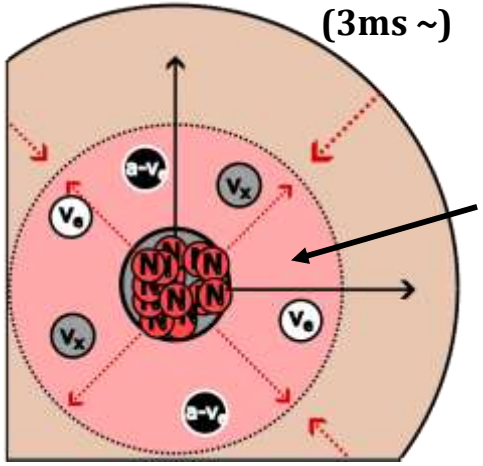
ν can't escape



3. Bounce (0ms~)

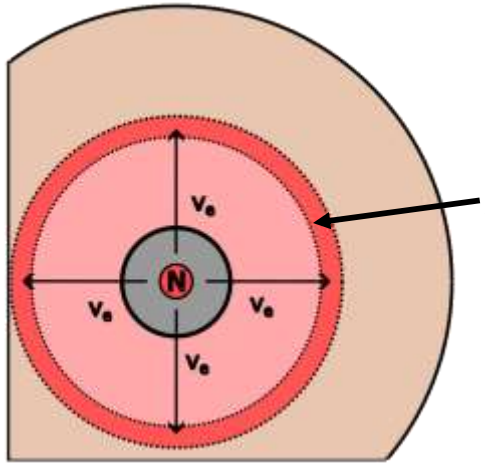
Shockwave front

4-1. Thermal neutrino process (3ms ~)



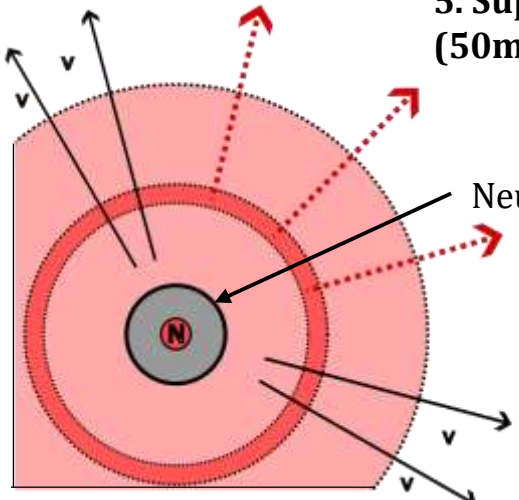
High energy

4-2. Neutrino heating



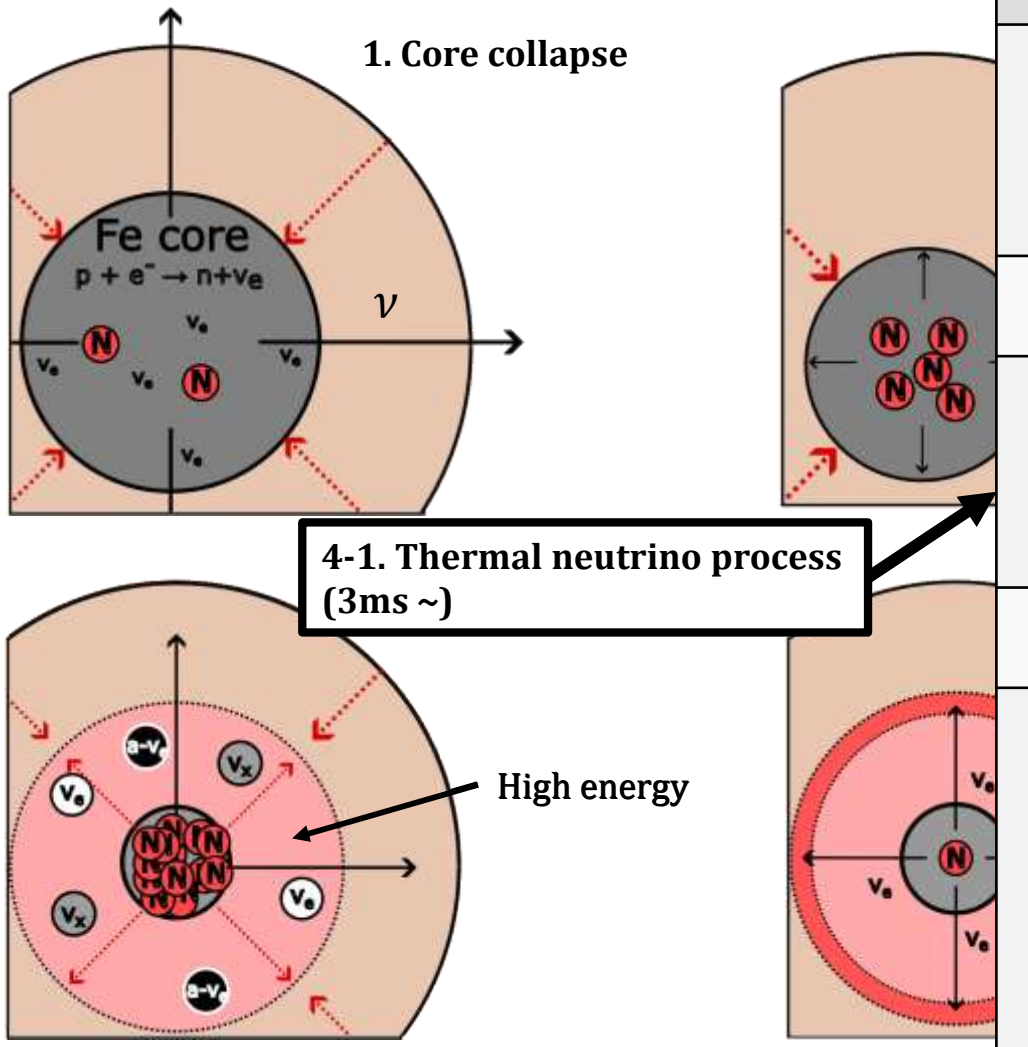
Accretion front

5. Supernovae (50ms ~)



Neutron star

Supernovae type II



Absorption process
$\nu_e + n \rightarrow p + e^-$ $\overline{\nu_e} + p \rightarrow n + e^+$ $\nu_e + (A, Z) \rightarrow (A, Z+1) + e^-$
Thermal process
$e^- + e^+ \rightarrow \nu_i + \overline{\nu_i}$ $N + N \rightarrow N + N + \nu_i + \overline{\nu_i}$ $\gamma^* \rightarrow \nu_i + \overline{\nu_i}$
Scattering process
$\nu_i + \alpha \rightarrow \nu_i + \alpha$ $\nu_i + p \rightarrow \nu_i + p$ $\nu_i + n \rightarrow \nu_i + n$ $\nu_i + e \rightarrow \nu_i + e$ $\nu_i + (A, Z) \rightarrow \nu_i' + (\mathrm{A}, \mathrm{Z})'$

Neutrino transport : Boltzmann equation

Boltzmann equation –

Equation describing non-equilibrium system

General Relativistic form of Boltzmann equation

$$\rightarrow \quad p^{\alpha}\left[\frac{\partial f_{\mu_i}}{\partial x^{\alpha}} - \Gamma^{\beta}_{\alpha\gamma} p^{\gamma} \frac{\partial f_{\nu}}{\partial p^{\beta}}\right] = \left[\frac{df_{\nu}}{d\tau}\right]_{coll}$$

Neutrino + Matter interaction

$$S^{\alpha}_{e/a} + S^{\alpha}_{iso} + S^{\alpha}_{scatter} + S^{\alpha}_{thermal}$$

$$S^{\alpha}_{e/a} = [\eta - \kappa_{\alpha}\mathcal{J}]u^{\alpha} - \kappa_a \mathcal{H}^{\alpha}$$

$$S^{\alpha}_{iso} = -\kappa_s \mathcal{H}^{\alpha}$$

η : emissivity
κ_{α} : absorption opacity
κ_s : scattering opacity

$e^+e^- \rightarrow \nu_i \bar{\nu}_i$ Emissivity

$$\eta \cong 4.1724 \times 10^{24}\left[\frac{kT}{MeV}\right]^9 f\left(\frac{\mu_e}{kT}\right) ergs\ cm^{-3}s^{-1}$$

$$\left(f(x) = \frac{F_4(x)F_3(-x)+F_4(x)F_3(x)}{2F_4(0)F_3(0)}\right)$$

Neutron-neutrino Absorption cross section

$$\sigma_{\alpha} = \sigma_0\left(\frac{1+3g_A^2}{4}\right)\left(\frac{\epsilon_{\nu_e}+\Delta_{np}}{m_e c^2}\right)^2\left[1-\left(\frac{m_e c^2}{\epsilon_{\nu_e}+\Delta_{np}}\right)^2\right]^{\frac{1}{2}}$$

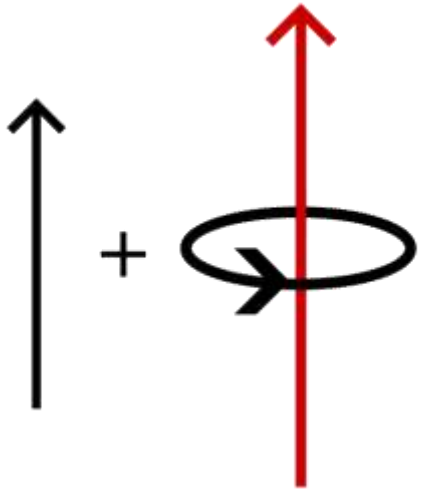
Neutron-neutrino Scattering cross section

$$\sigma_s = \frac{\sigma_0}{4}\left(\frac{\epsilon_{\nu}}{m_e c^2}\right)^2\left[\frac{1+3g_A^2}{4}\right]$$

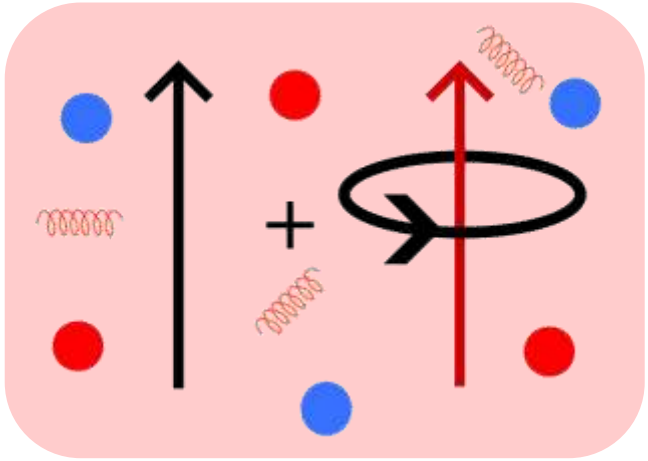
[1] Burrows, Reddy & Thompson, Nuclear Physics A 777, 356 (2006)

Neutrino interaction

Axial coupling constant = g_A in Weak interaction,



Free space



High baryon density

$$g_{A,eff} \cong g_A \left(1 - \frac{n_{Baryon}}{4.15(n_0 + n_{Baryon})}\right) * \left(1 - \frac{1}{12}\frac{T^2}{F_\pi^2}\right) / \left(1 + \frac{Q^2}{M_A^2}\right)^2$$

For

- $n_{Baryon} < 4.5 n_0$
- $Q^2 < 1\ \mathrm{GeV}^2$

↑ vector, ↑ axial vector

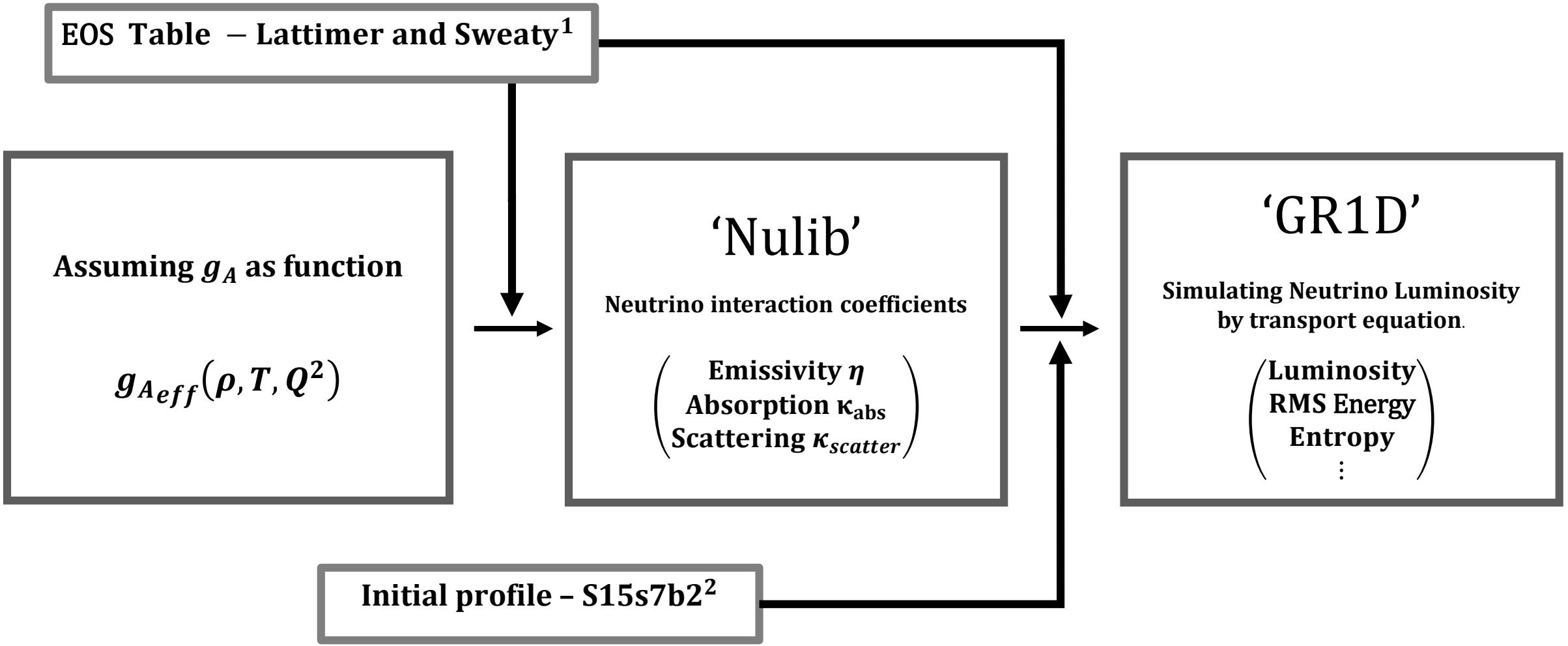
g_A quenching from matter effect

[1] Carter, & Prakash, *Physics Letters B* 525, 249 (2002)

[1] Eletsky, & Kogan *Phys.Rev.D* 49 R3083 (1994)

[1] Ramalho, Tsushima, M. K. Cheoun *Phys.Rev.D* 111 (2025)

Sensitivity study of g_A on Neutrino Transport

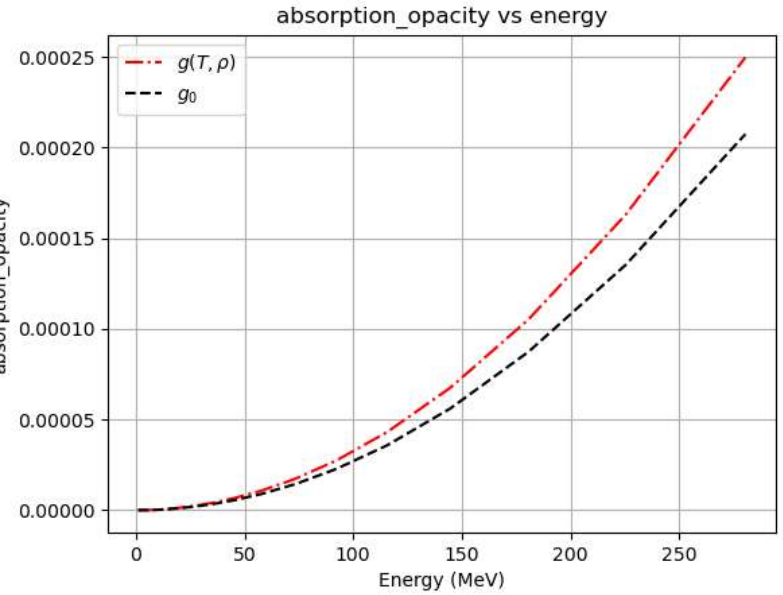


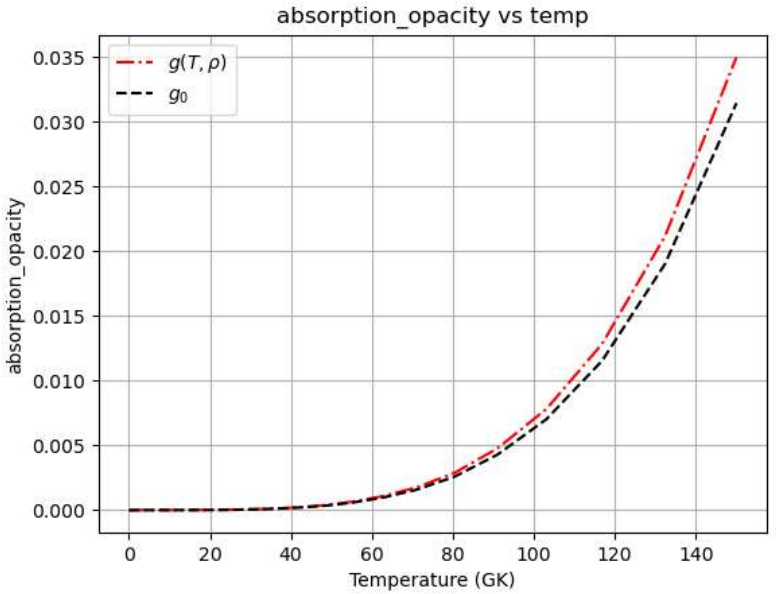
[1] O'Connor, E. 2015, ApJS 219, 24.

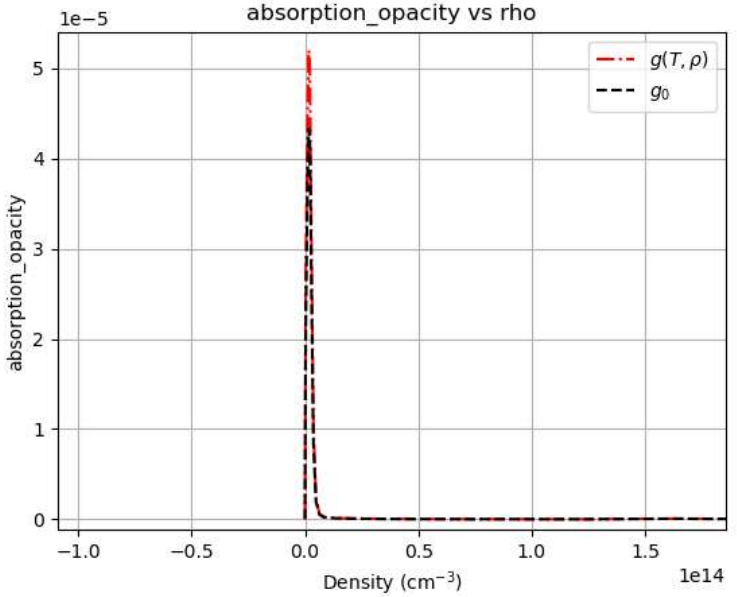
[2] Woosley, S.E. & Weaver, T.A. 1995, LLNL Rep. UCRL-ID-122106.

Change in Neutrino interaction (Nulib data)

(g_A =1.254) vs ($g_A(q^2, \rho, T)$)







X axis : Energy [MeV]

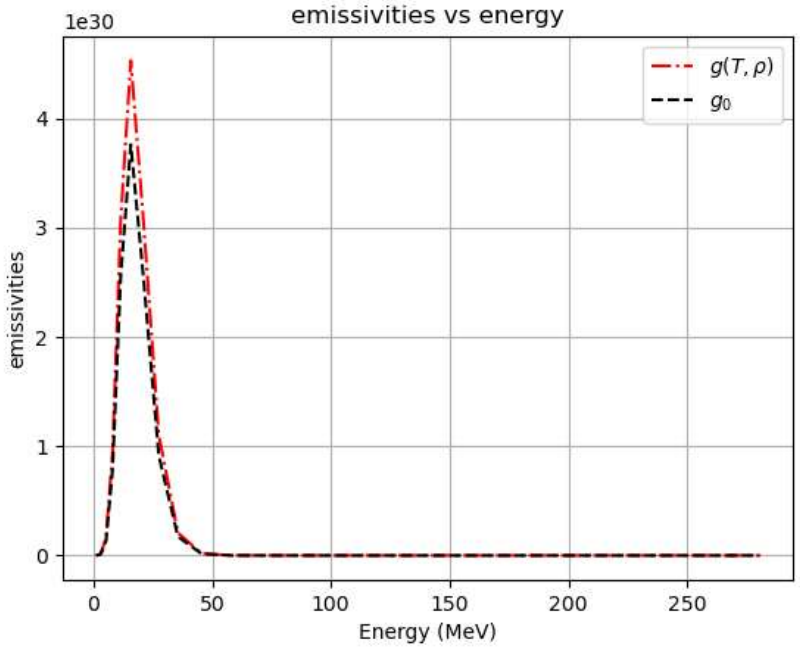
Y axis : absorption opacity ($\boldsymbol{\kappa_a}$) [cm^{-1}]

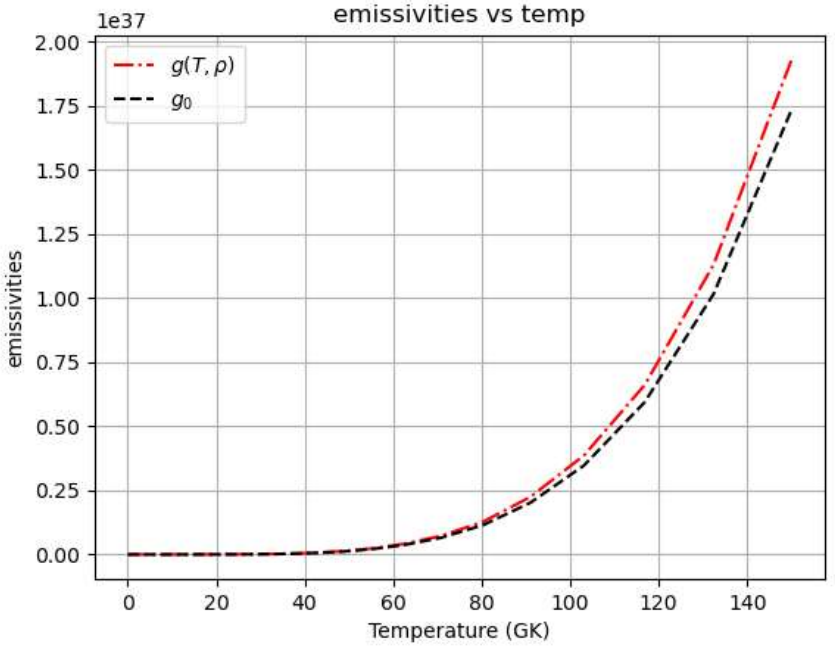
Red line : $g_A(\rho, T, Q^2)$

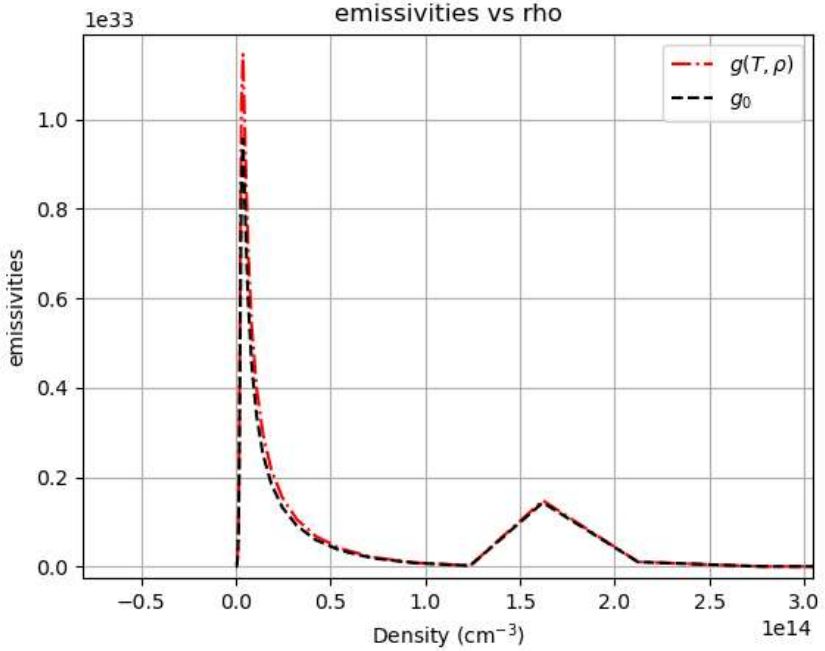
Black line : $g_A = 1.254$

Change in Neutrino interaction (Nulib data)

(g_A =1.254) vs ($g_A(q^2, \rho, T)$)







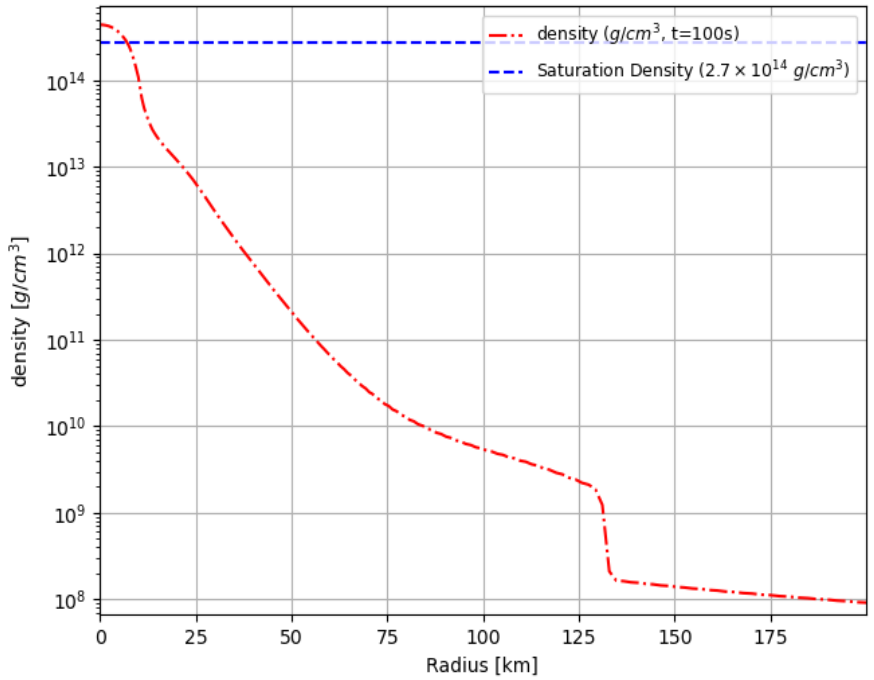
X axis : Energy [MeV]

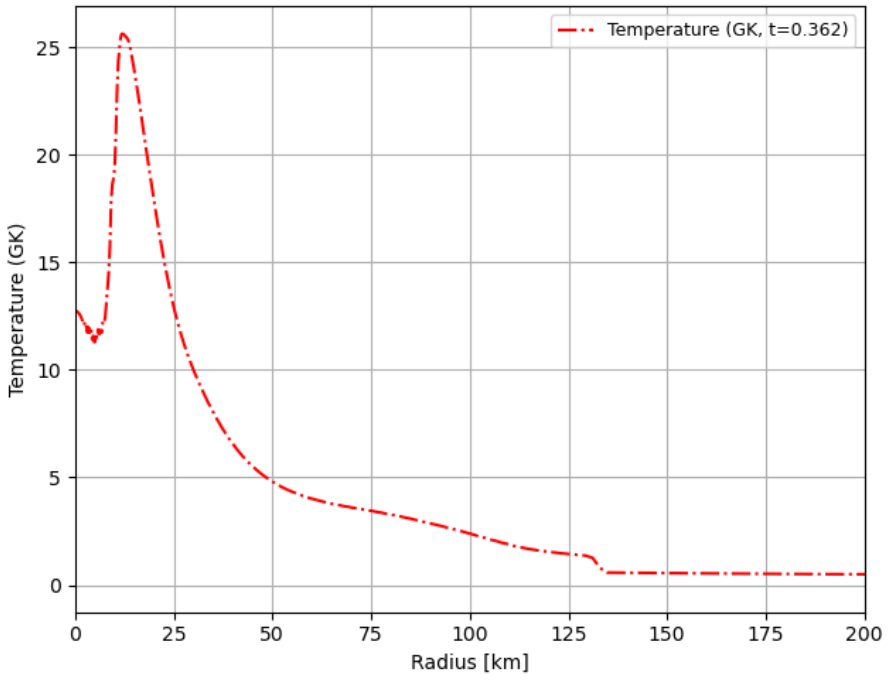
Y axis : emissivity ($\boldsymbol{\eta}$). [cm^{-1}]

Red line : $g_A(\rho, T, Q^2)$

Black line : $g_A = 1.254$

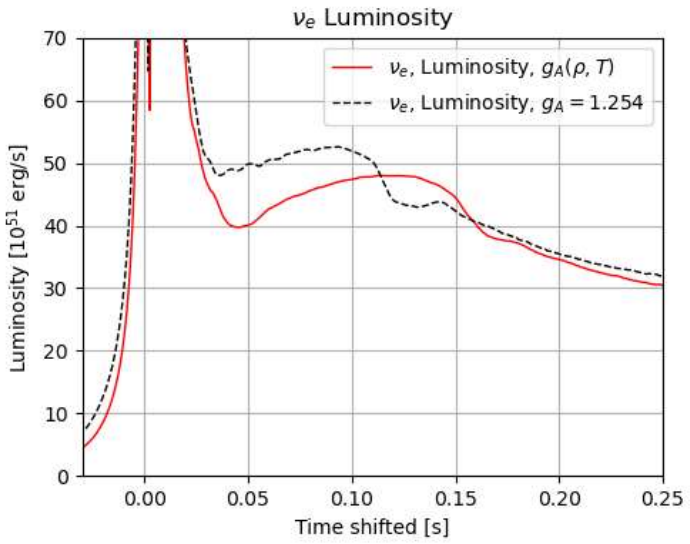
S15s7b2 Density, Temperature profile

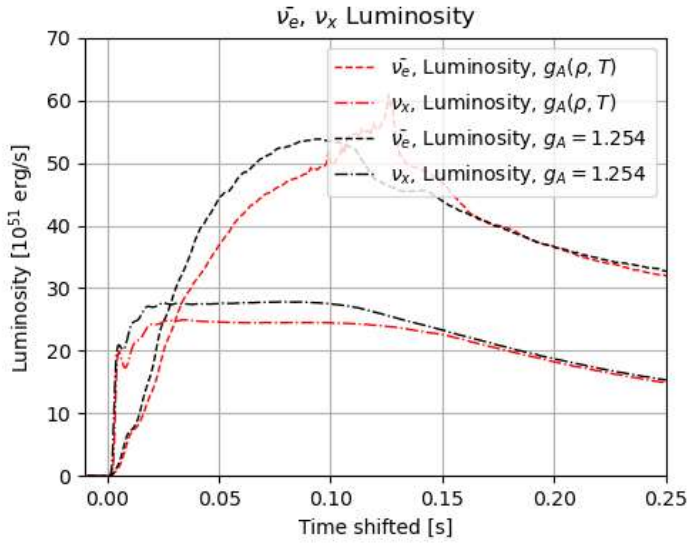


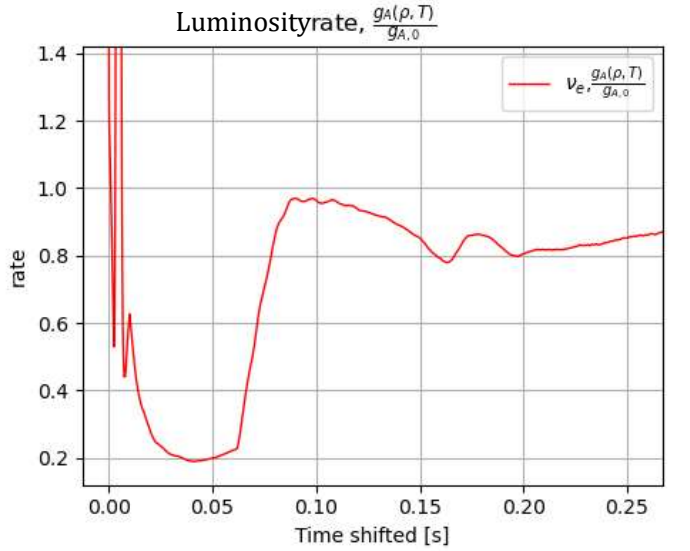


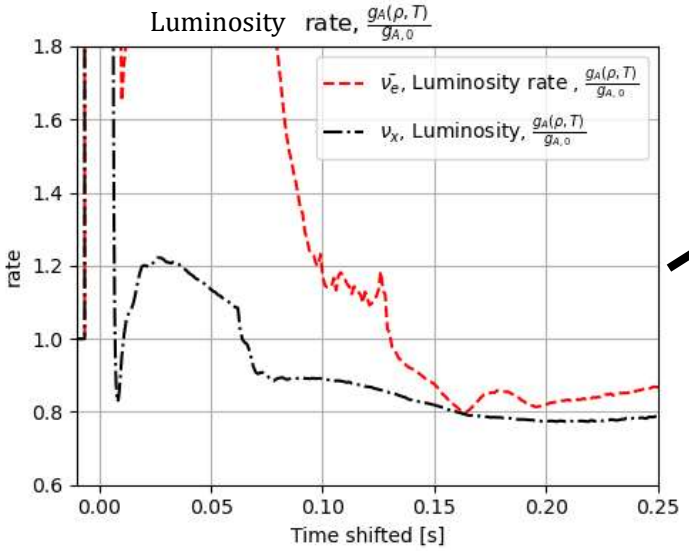
left : Radial profile of the density. Blue line is the nuclear saturation density, $2.7 \times 10^{14} g/cm$^3
Right : Radial profile of the temperature

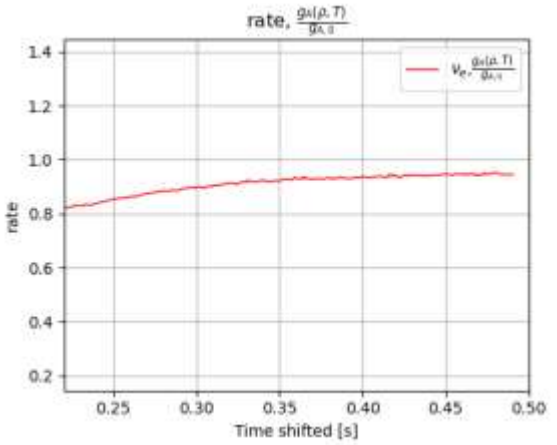
$g_A(q^2, \rho, T)$ vs $g_A = 1.254$ preliminary data for Luminosity

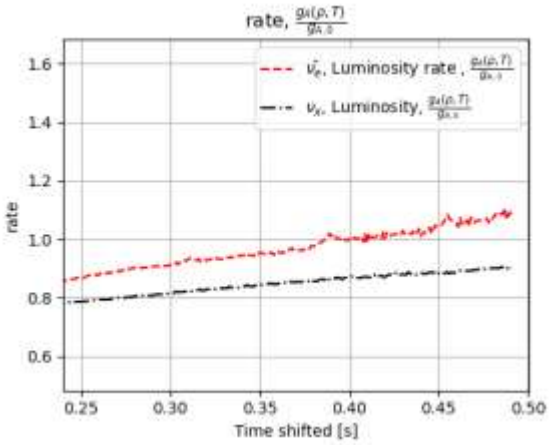












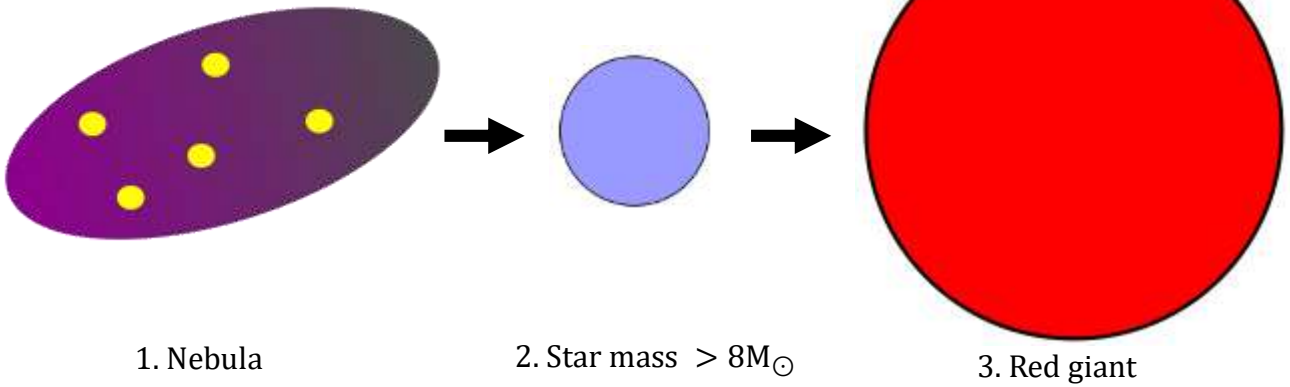
X axis : Time after bounce $[s]$
Y axis : Luminosity$[10^{51}\mathrm{erg/s}]$
Red line : $g_A(\rho, T, Q^2)$
Black line : $g_A = 1.254$

Conclusion

- At high temperature and density, the axial vector coupling constant g_A decreases, leading to reduced weak interaction process.
- We tested a new g_A model dependent with momentum transfer, density and temperature, and observed that the lumonisty shows a sharp initial deviation, but returns to the value obtained when g_A was constant.

Thank you

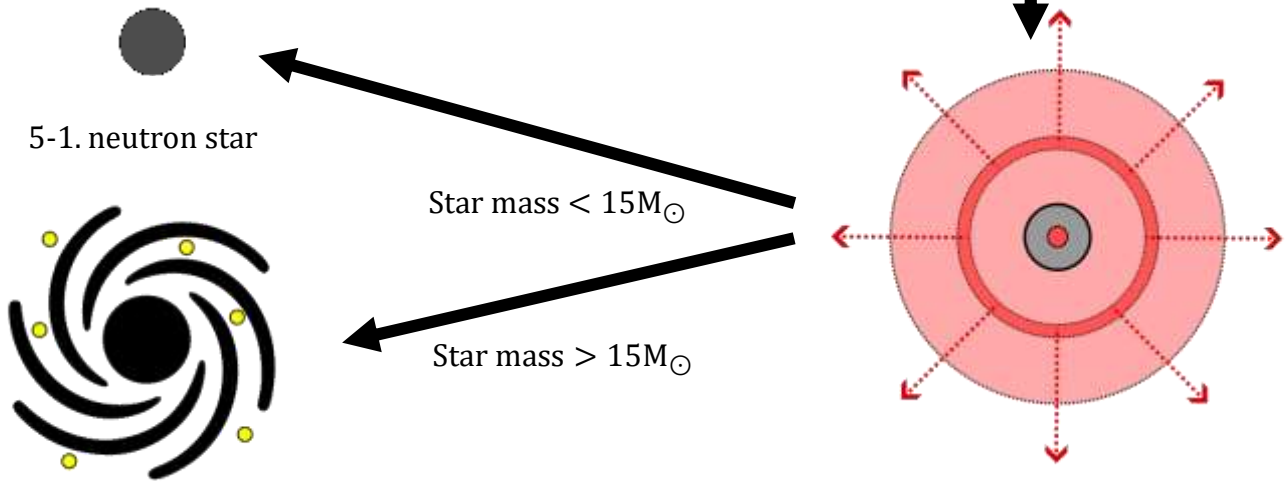
Supernovae and neutrino



1. Nebula

2. Star mass $> 8M_{\odot}$

3. Red giant



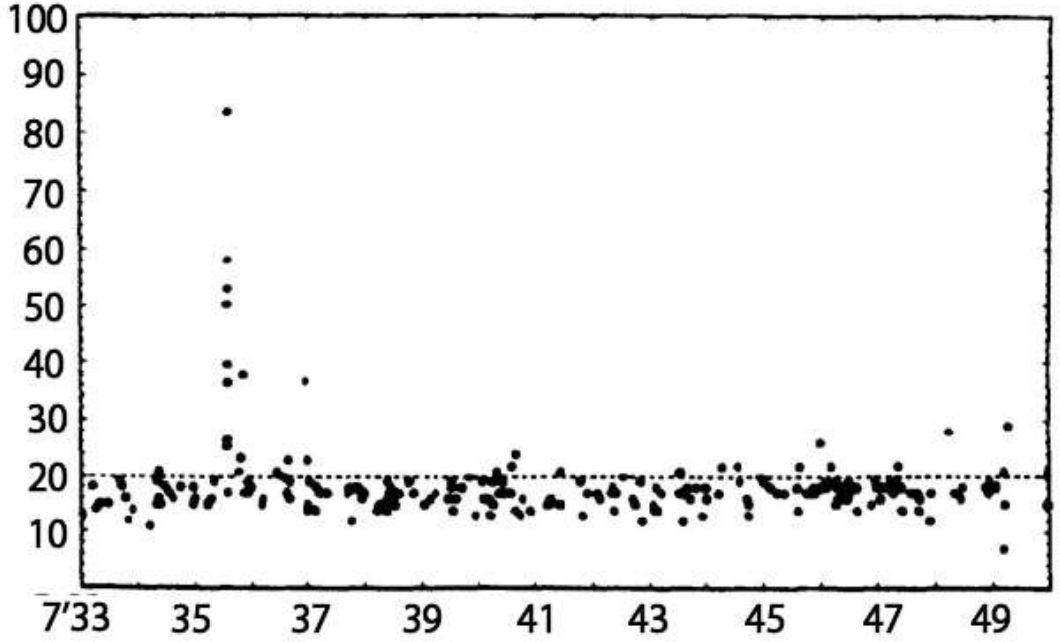
4. Supernovae

Star mass $< 15M_{\odot}$

5-1. neutron star

Star mass $> 15M_{\odot}$

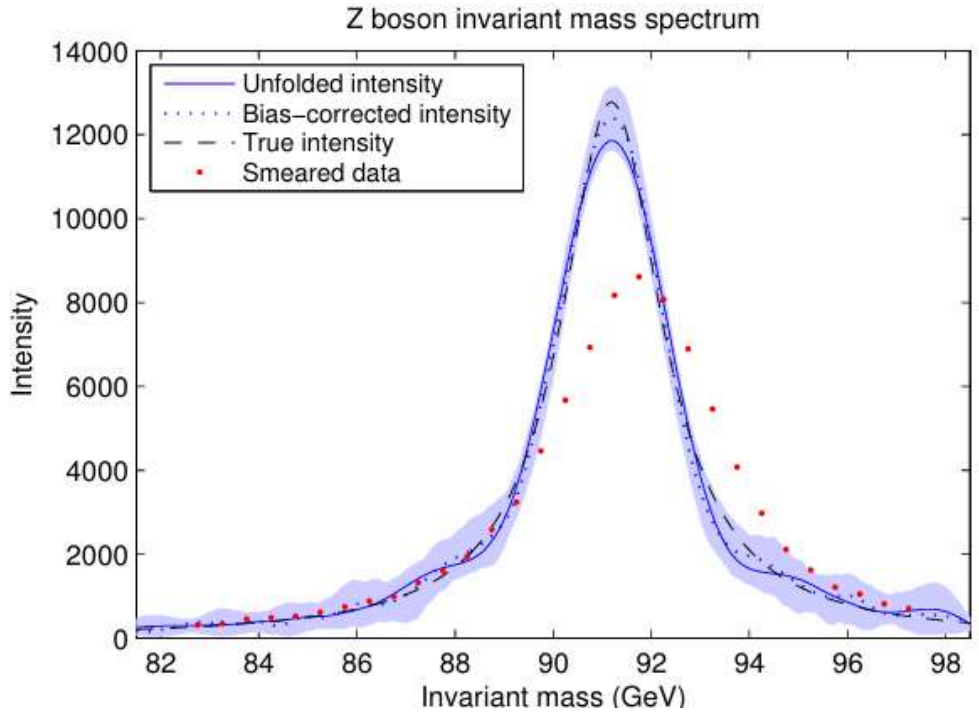
5-2. black hole



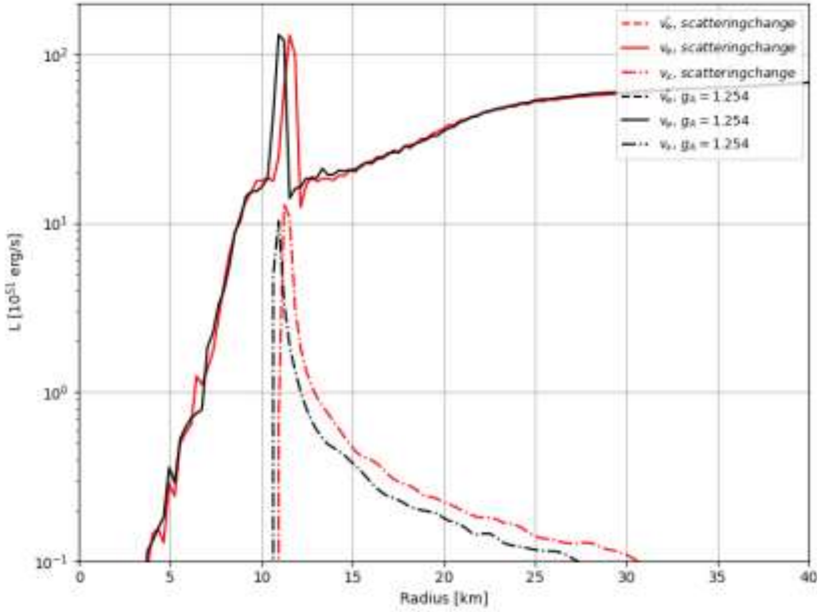
Neutrino events observed in
Kamiokande detectors from SN1987A

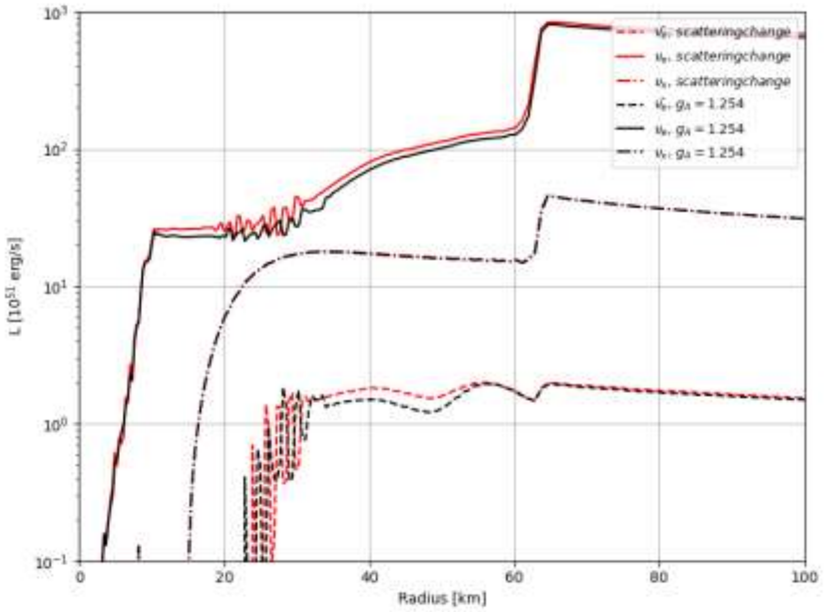
Mz

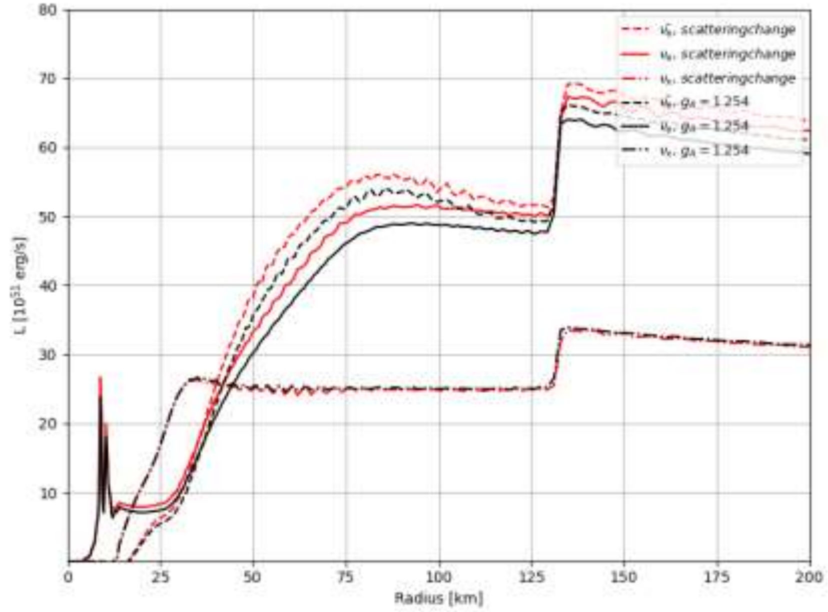
- Z Boson decay into a Fermion-Antifermion pair



gA_1.254 vs g_A_1.07(scattering = gA1.254)







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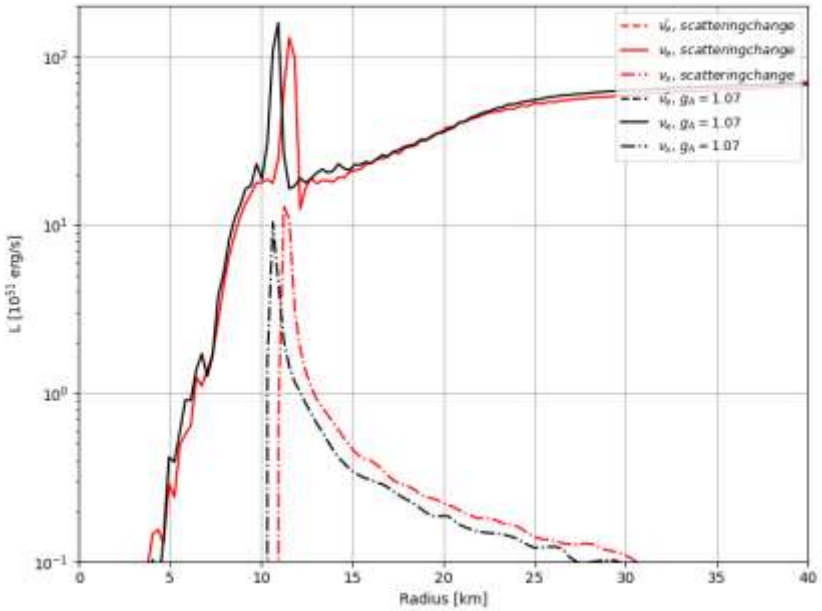
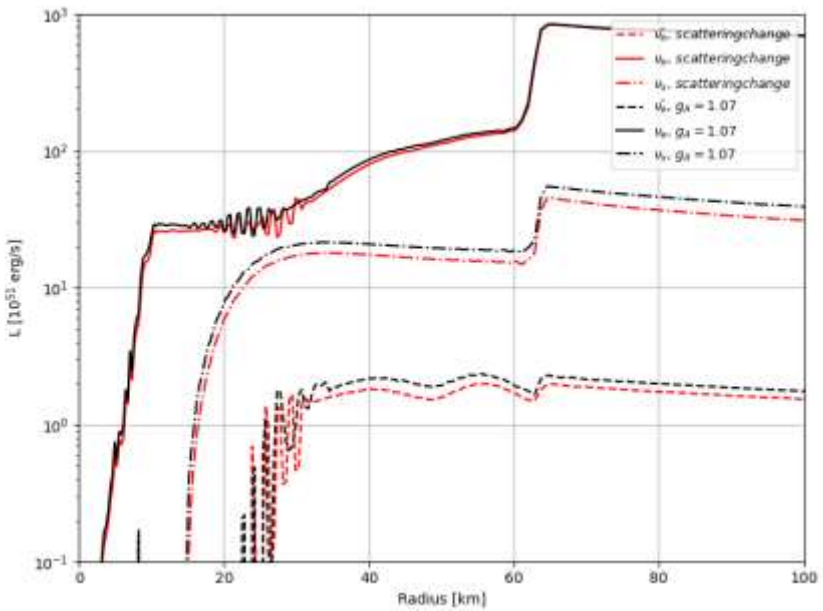
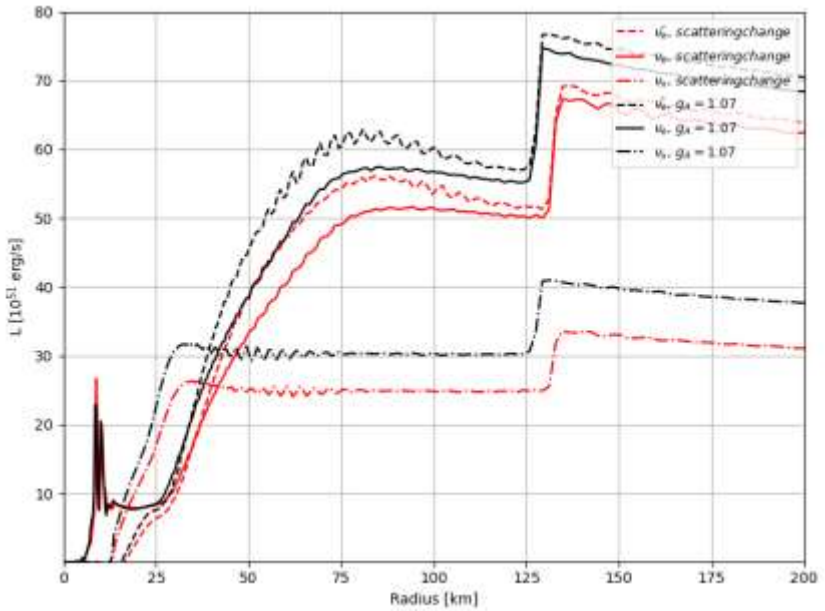
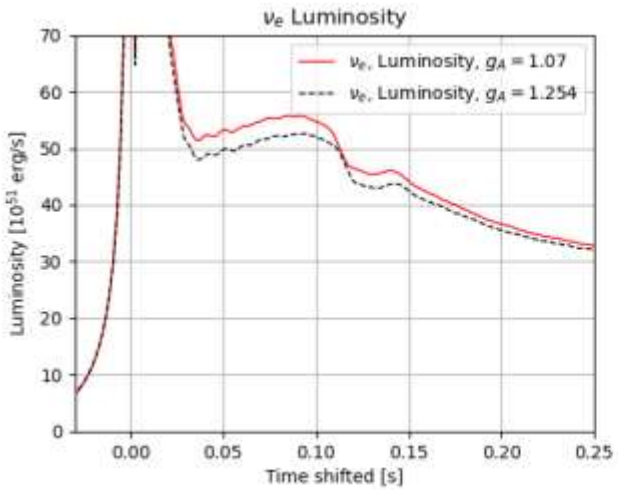
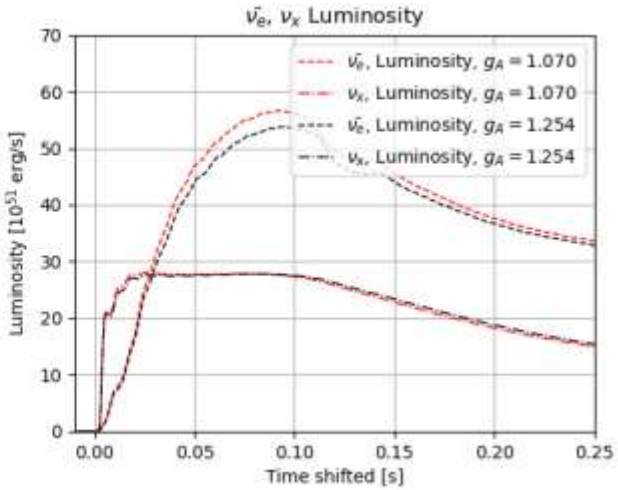


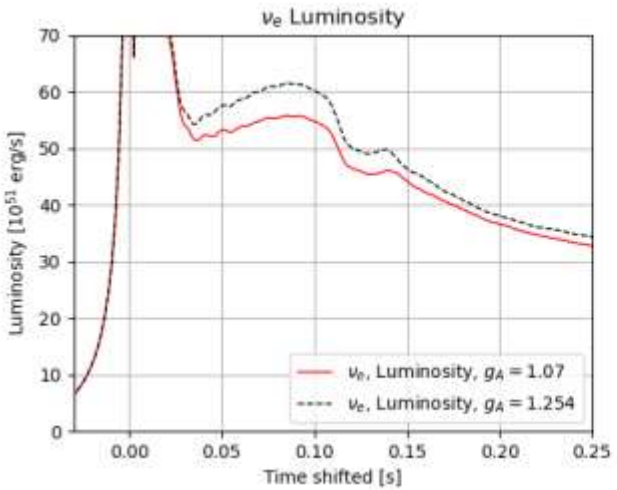


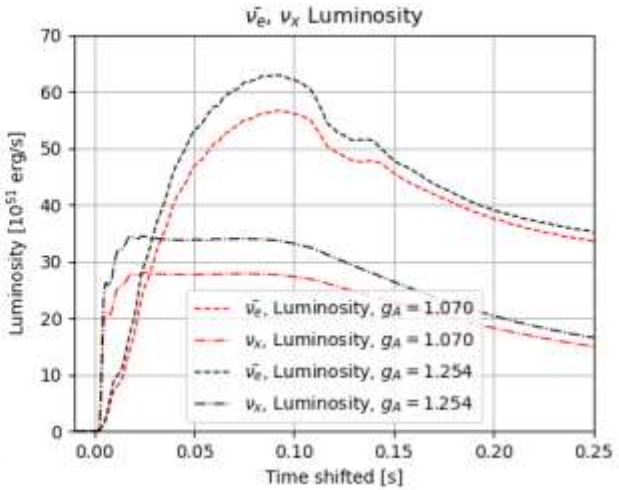


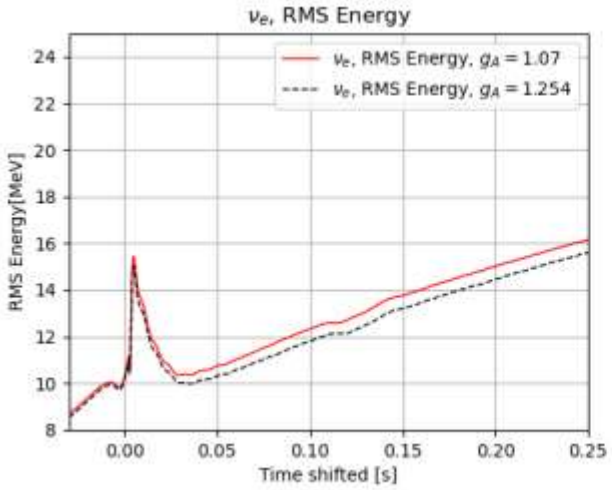
g_A_1.07(scattering = gA1.254)
1.254 vs 1.07

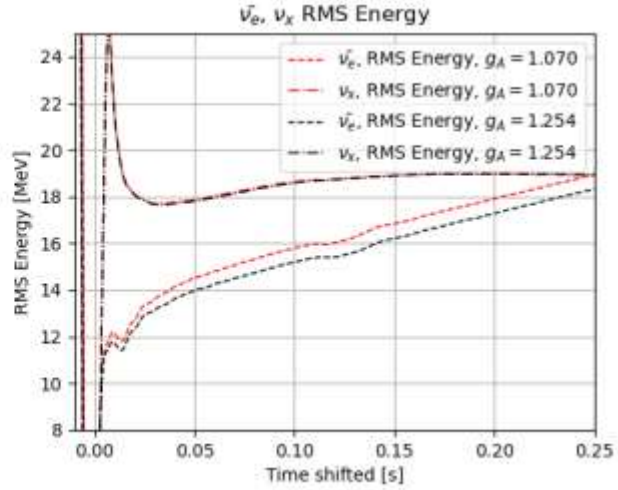


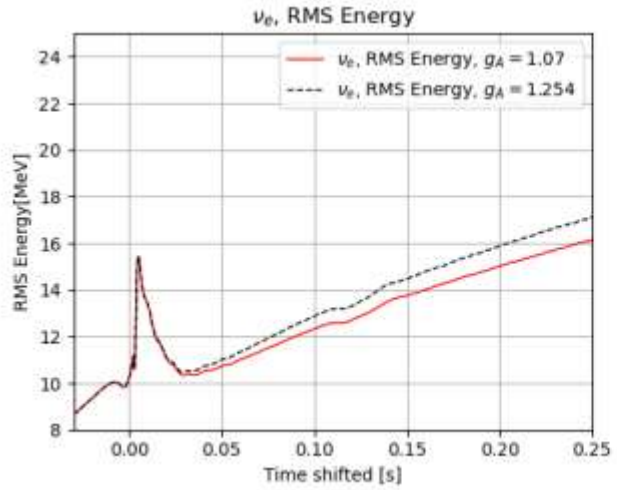


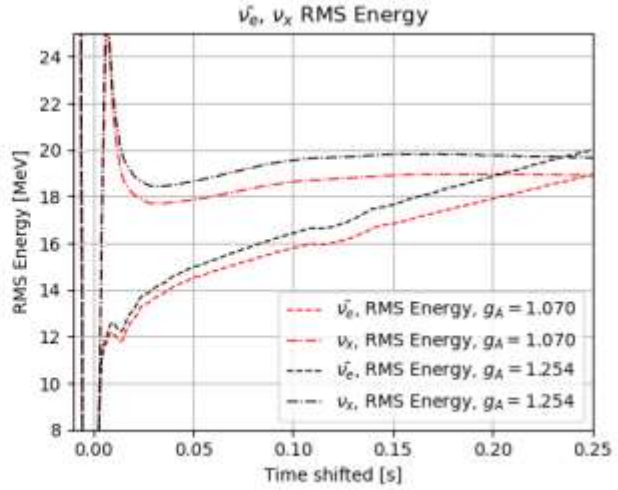




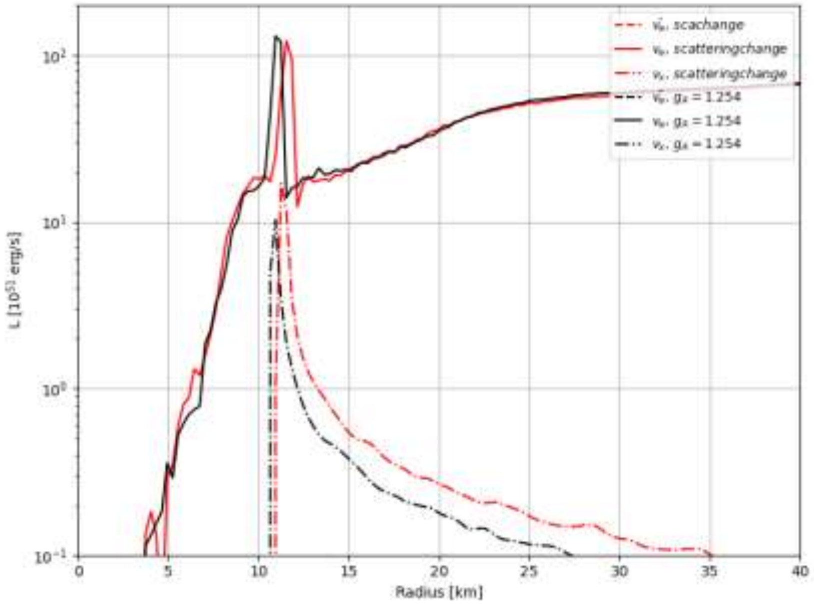


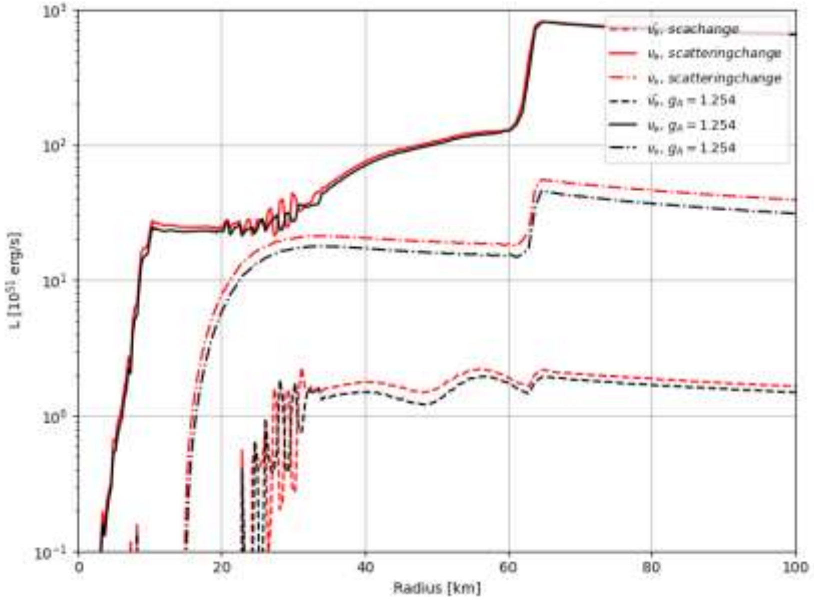


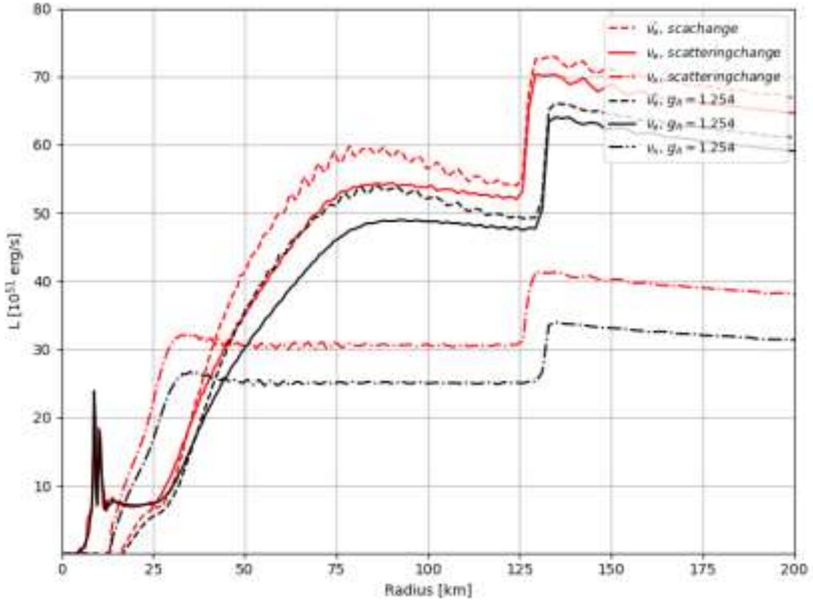




gA_1.254 vs g_A_1.254(scattering = gA1.07)







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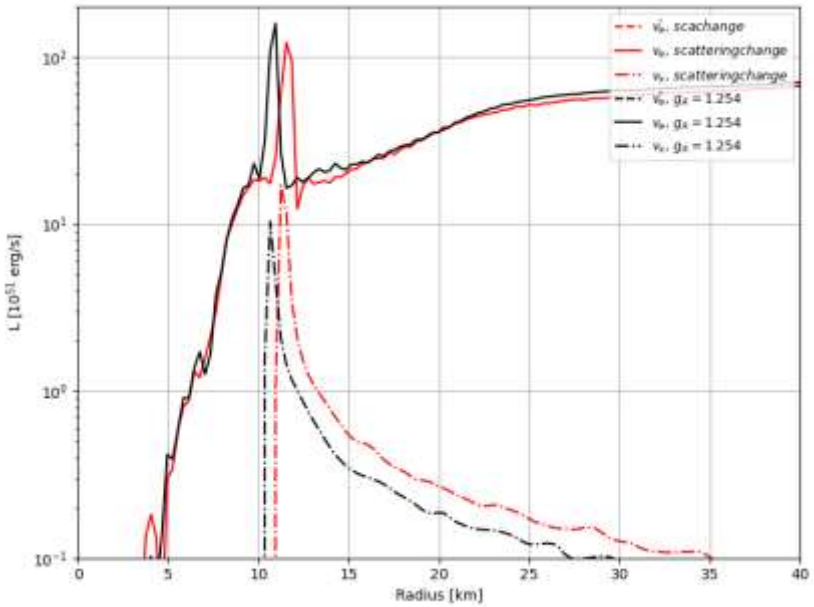
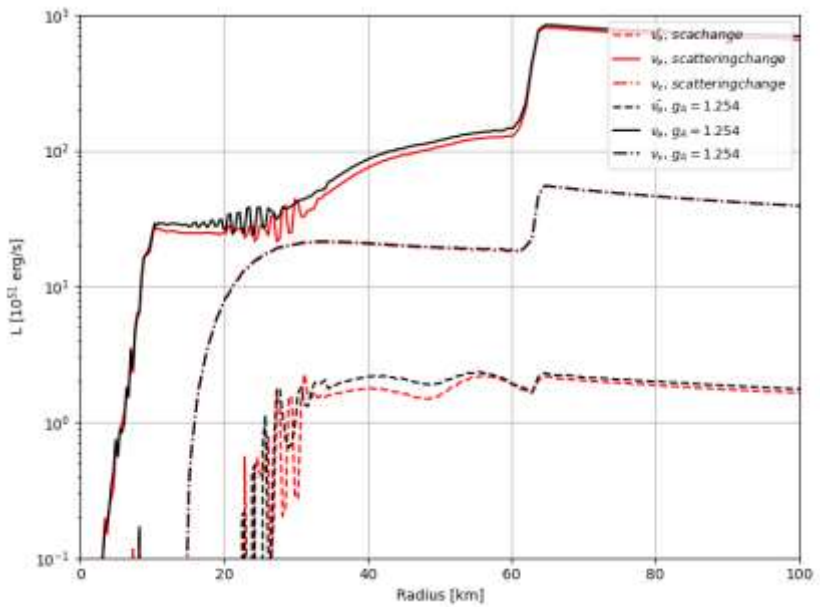
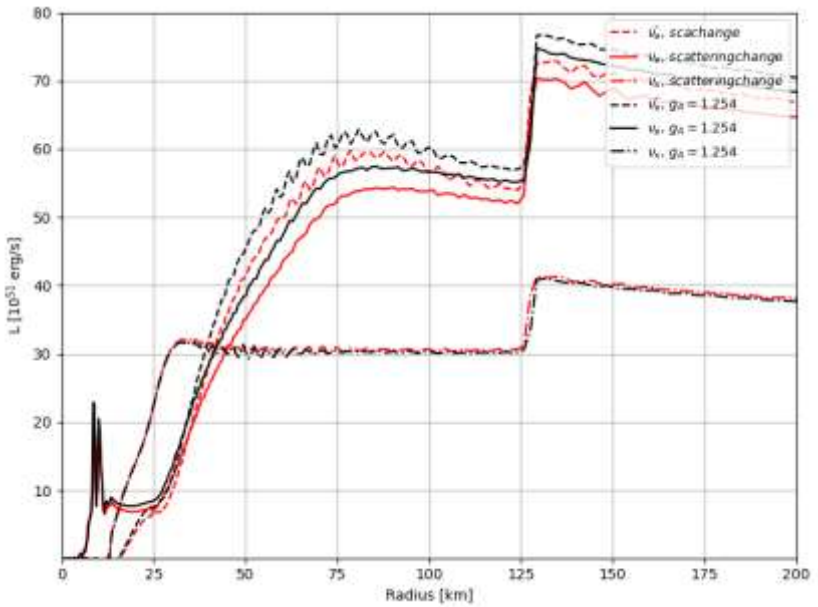
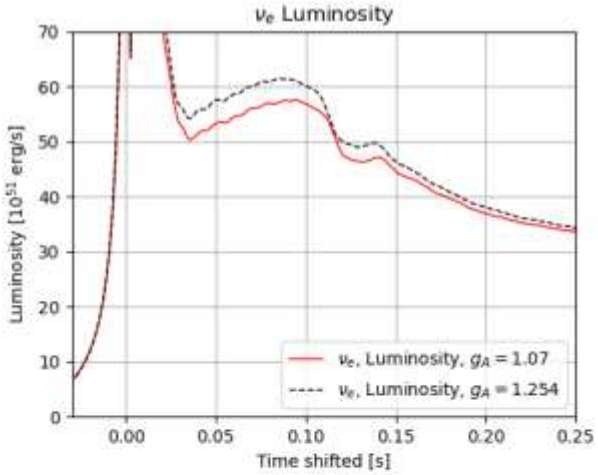
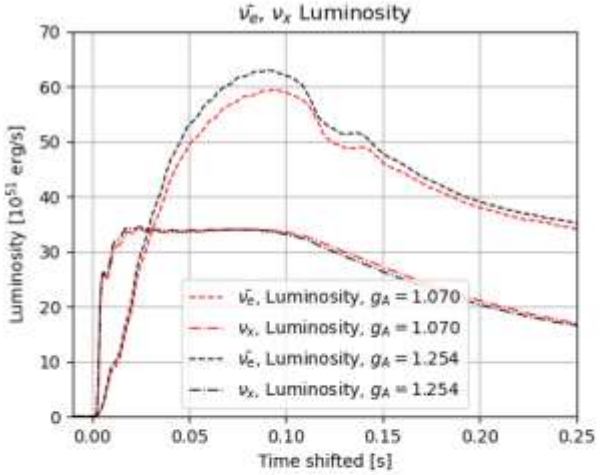


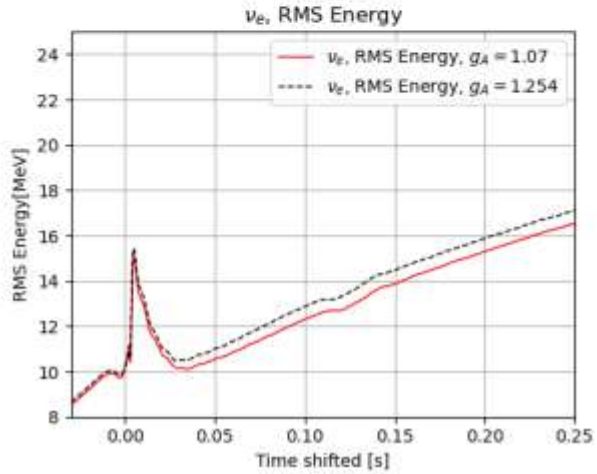


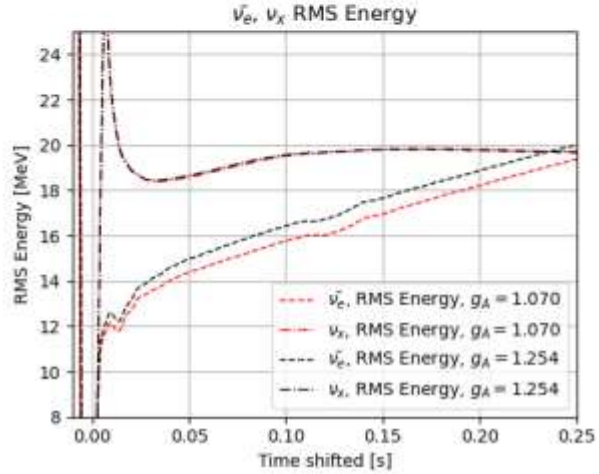


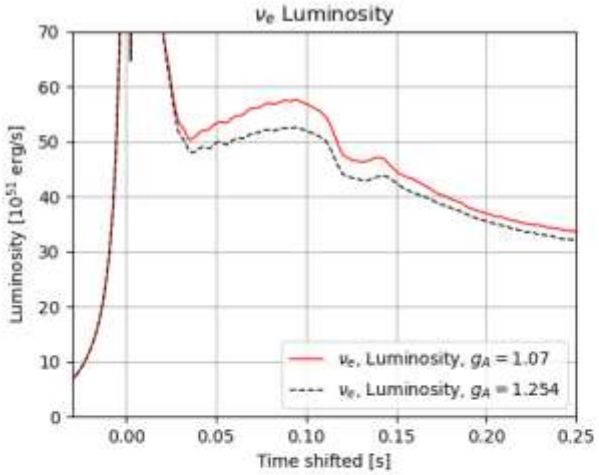
g_A_1.07(scattering = gA1.254)
1.254 vs 1.07

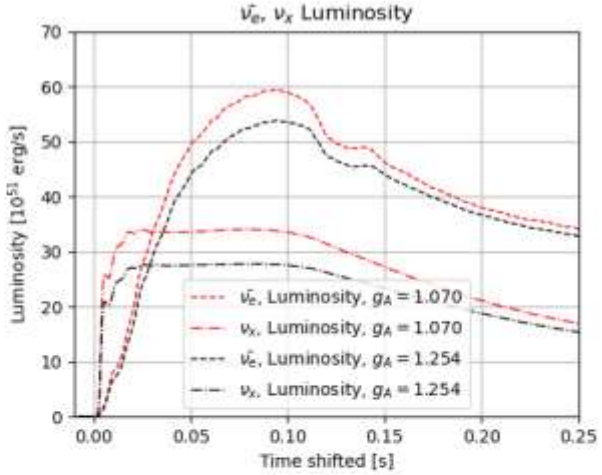


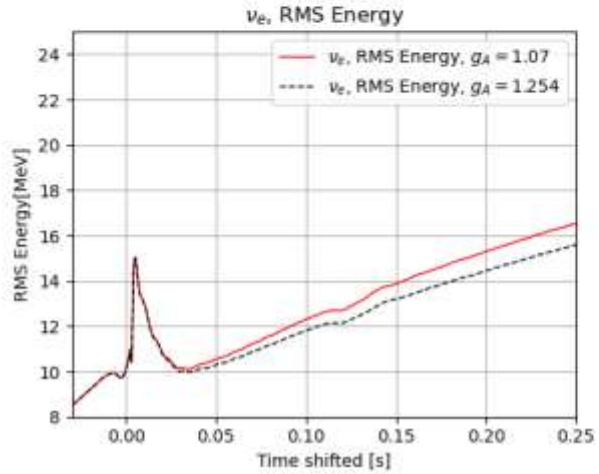


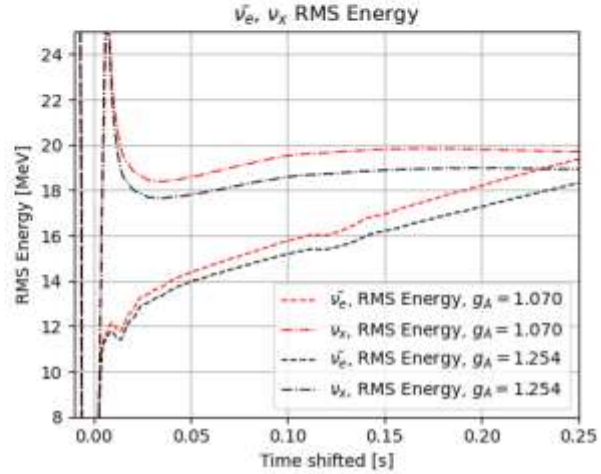




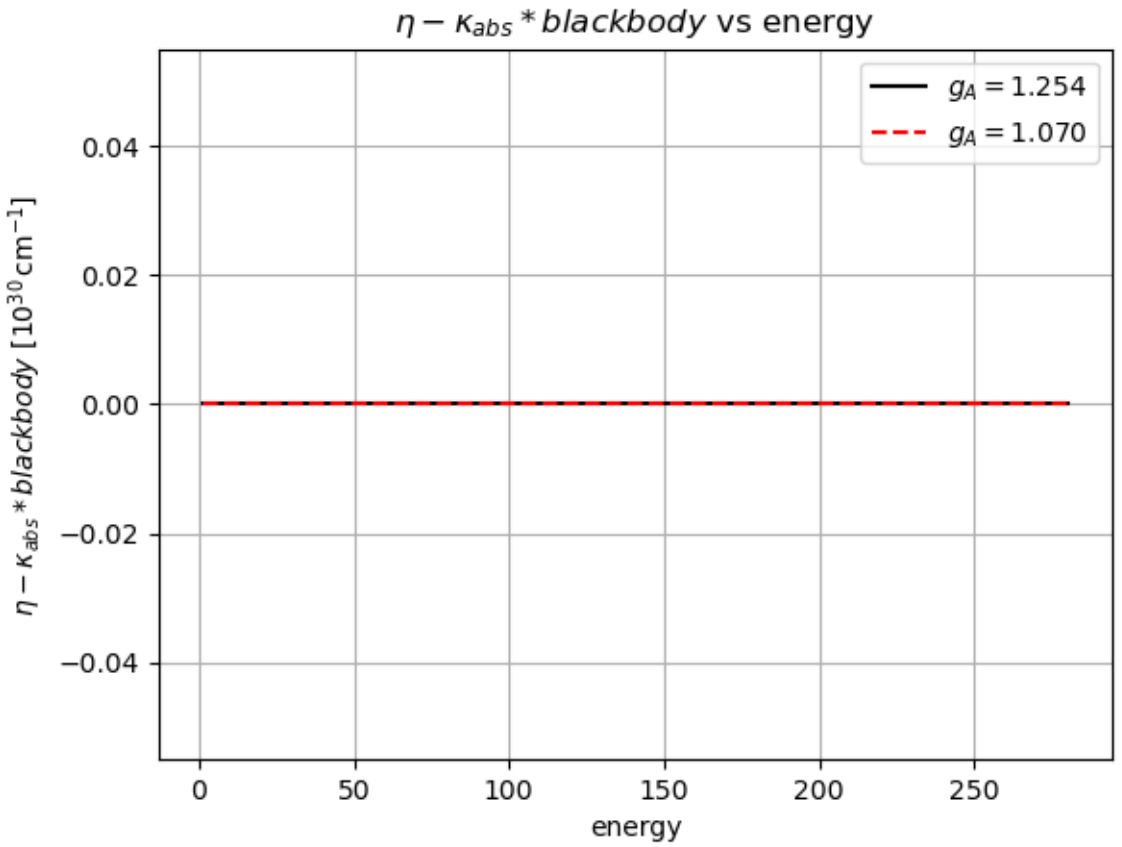








Kirchhoff' law of thermal radiation



Sensitivity study of g_A on Neutrino Transport

Assuming g_A is constant →

$$g_A = 1.254 \text{ in vacuum}$$

$$g_A = 1.070 \text{ in saturation density}$$

Calculating Neutrino interactions Using **Nulib** →

$$\sigma^{\alpha}_{\nu_e n} = \sigma_0 \left(\frac{1+3g_A^2}{4}\right)\left(\frac{\epsilon_{\nu_e}+\Delta_{np}}{m_e c^2}\right)^2 \left[1-\left(\frac{m_e c^2}{\epsilon_{\nu_e}+\Delta_{np}}\right)^2\right]^{1/2} W_M$$

$$\kappa_\alpha = \sigma^{\alpha}_{\nu_e n} * (\text{effective target density})$$

Getting data via transport equation using **GR1D** →

$$S^{\alpha}_{e/a} = [\eta - \kappa_\alpha \mathcal{J}]u^\alpha - \kappa \mathcal{H}^\alpha$$

$$S^{\alpha}_{iso} = -\kappa_s \mathcal{H}^\alpha$$

$$p^\alpha \left[\frac{\partial f_{\mu_i}}{\partial x^\alpha} - \Gamma^\beta_{\alpha\gamma} p^\gamma \frac{\partial f_\nu}{\partial p^\beta}\right] = \left[\frac{df_\nu}{d\tau}\right]_{coll}$$

Initial profile – S15s7b2

O'Connor, Evan. "An open-source neutrino radiation hydrodynamics code for core-collapse supernovae." *The Astrophysical Journal Supplement Series* 219.2 (2015): 24.

Woosley, S. E., and Thomas A. Weaver. *The evolution and explosion of massive Stars II: Explosive hydrodynamics and nucleosynthesis*. No. UCRL-ID-122106. Lawrence Livermore National Lab.(LLNL), Livermore, CA (United States), 1995.

Neutrino interaction

Emissions / Absorptionc

(in)Elastic scattering

Thermal production

Neutrino process

Absorption process
$\nu_e + n \rightarrow p + e^-$
$\bar{\nu}_e + p \rightarrow n + e^+$
$\nu_e + (A,Z) \rightarrow (A,Z+1) + e^-$

Thermal process
$e^- + e^+ \rightarrow \nu_i + \bar{\nu}_i$
$N + N \rightarrow N + N + \nu_i + \bar{\nu}_i$
$\gamma^* \rightarrow \nu_i + \bar{\nu}_i$

Scattering process	
$\nu_i + \alpha \rightarrow \nu_i + \alpha$	$\nu_i + p \rightarrow \nu_i + p$
$\nu_i + n \rightarrow \nu_i + n$	$\nu_i + (A,Z) \rightarrow \nu_i + (A,Z)$
$\nu_i + e^- \rightarrow \nu_i' + e^{-\prime}$	

Weak interaction -> coupling constant: g_A

G_A
Free sapce

같지 않음

G_A
Matter
(Free space 값보다 작음)

Ramalho, G., K. Tsushima, and Myung-Ki Cheoun. "Weak interaction axial form factors of the octet baryons in nuclear medium." *Physical Review D* 111.1 (2025): 013002.

$(g_A = 1.070)$ vs $(g_A = 1.254)$ Luminosity + rms energy data