Neutrino and Photon Opacity in SN explosion, CMB and RHIC

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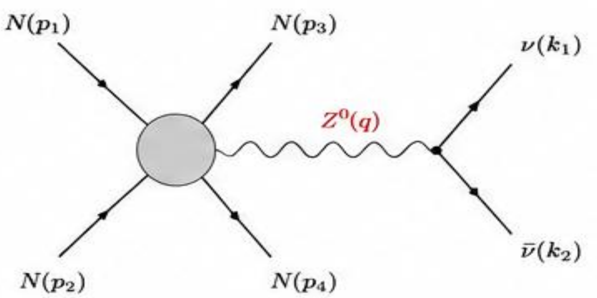
Neutrino Pair Production in Nucleon–Nucleon Scattering

$(NN \to NN + \nu + \bar{\nu})$

1. Overall process

$$N(p_1) + N(p_2) \to N(p_3) + N(p_4) + \nu(k_1) + \bar{\nu}(k_2)$$



Neutral current weak interaction

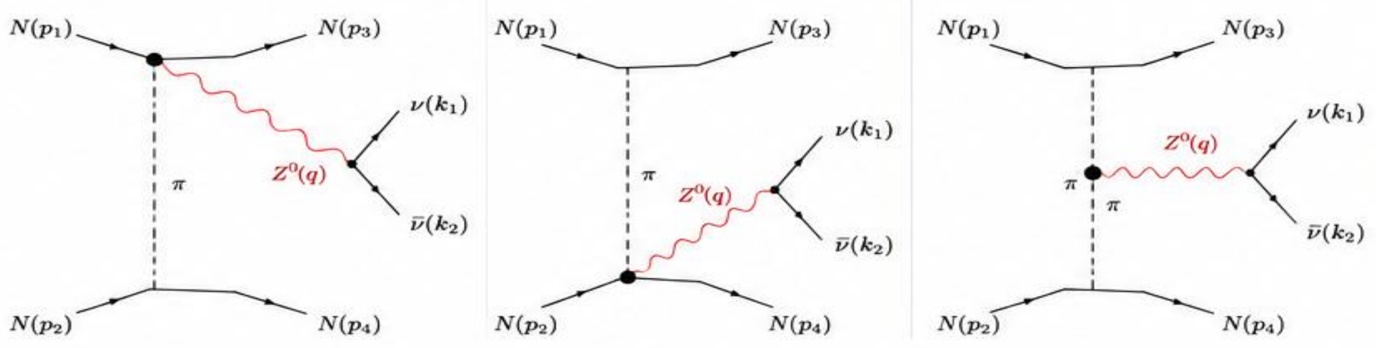
A virtual Z^0 boson is emitted from the nucleon system and decays into a neutrino pair.

2. Leading Feynman diagrams (one-pion-exchange mechanism)

(a) Z^0 emission from nucleon 1

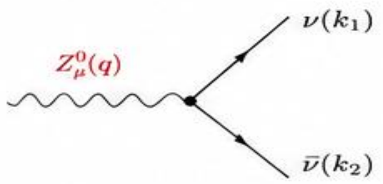
(b) Z^0 emission from nucleon 2

(c) Z^0 emission from exchanged pion



The total amplitude is the sum of all diagrams plus the ones with nucleons exchanged $(p_3 \leftrightarrow p_4)$ due to antisymmetrization of identical nucleons.

3. $Z^0 \to \nu\bar{\nu}$ decay vertex



$$-i\frac{G_F}{\sqrt{2}}\gamma^\mu\,(1-\gamma^5)$$

(for each neutrino flavor)

Leptonic tensor

$$L^{\mu\nu} = \sum_{\text{spins}} [\bar{u}(k_1)\,\gamma^\mu\,(1-\gamma^5)\,\nu(k_2)]\,[\bar{u}(k_1)\,\gamma^\nu\,(1-\gamma^5)\,\nu(k_2)]^* = 8\left(k_1^\mu k_2^\nu + k_1^\nu k_2^\mu - g^{\mu\nu}(k_1\cdot k_2) + i\epsilon^{\mu\nu\alpha\beta}k_{1\alpha}k_{2\beta}\right)$$

(massless neutrinos)

4. Hadronic neutral current vertices

Vector current (isovector part)

$$\Gamma_V^\mu = F_1^V(q^2)\,\gamma^\mu + F_2^V(q^2)\,\frac{i\sigma^{\mu\nu}q_\nu}{2M}$$

Axial current

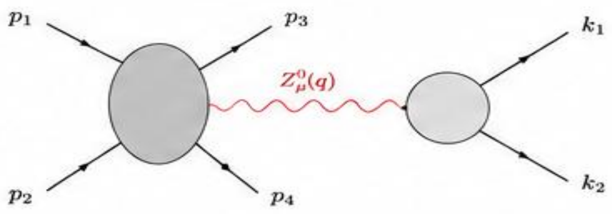
$$\Gamma_A^\mu = G_A(q^2)\,\gamma^\mu\gamma^5 + G_P(q^2)\,q^\mu\gamma^5$$

$$\Gamma_{NC}^\mu = \Gamma_V^\mu - \Gamma_A^\mu$$

(neutral current of nucleon)

5. Schematic amplitude

$$i\mathcal{M} =$$



$J^\mu_{NC}(q)$ (hadronic current)

$L_\mu(k_1, k_2)$ (leptonic current)

6. Differential cross section

$$d\sigma = \frac{1}{2s}\,\frac{1}{(2\pi)^8}\,\frac{|\mathcal{M}|^2}{4E_1E_2E_3E_4} \times d^3p_3\;d^3p_4\;d^3k_1\;d^3k_2\;\delta^{(4)}(p_1+p_2-p_3-p_4-k_1-k_2)$$

$$|\mathcal{M}|^2 = \frac{G_F^2}{2}\,L_{\mu\nu}\,H^{\mu\nu}_{NC}(q)$$

$$H^{\mu\nu}_{NC}(q) = J^\mu_{NC}(q)\,J^{\nu\dagger}_{NC}(q)$$

7. Other possible mechanisms (diagrams not shown)

- Heavy meson exchange (ρ, ω)
- Nucleon–Δ excitation $(N\Delta, \Delta N)$
- Two-pion exchange currents
- Short-range correlations (contact terms)
- Diagrams with nucleon exchange $(p_3 \leftrightarrow p_4)$

8. Typical kinematics

- Incident nucleon energy: $E \sim 10 - 1000$ MeV
- Neutrino pair invariant mass: $M^2_{\nu\nu} = q^2 \ll s$
- Neutrinos are typically back-to-back in the pair CM
- Soft radiation (small q) dominates the rate

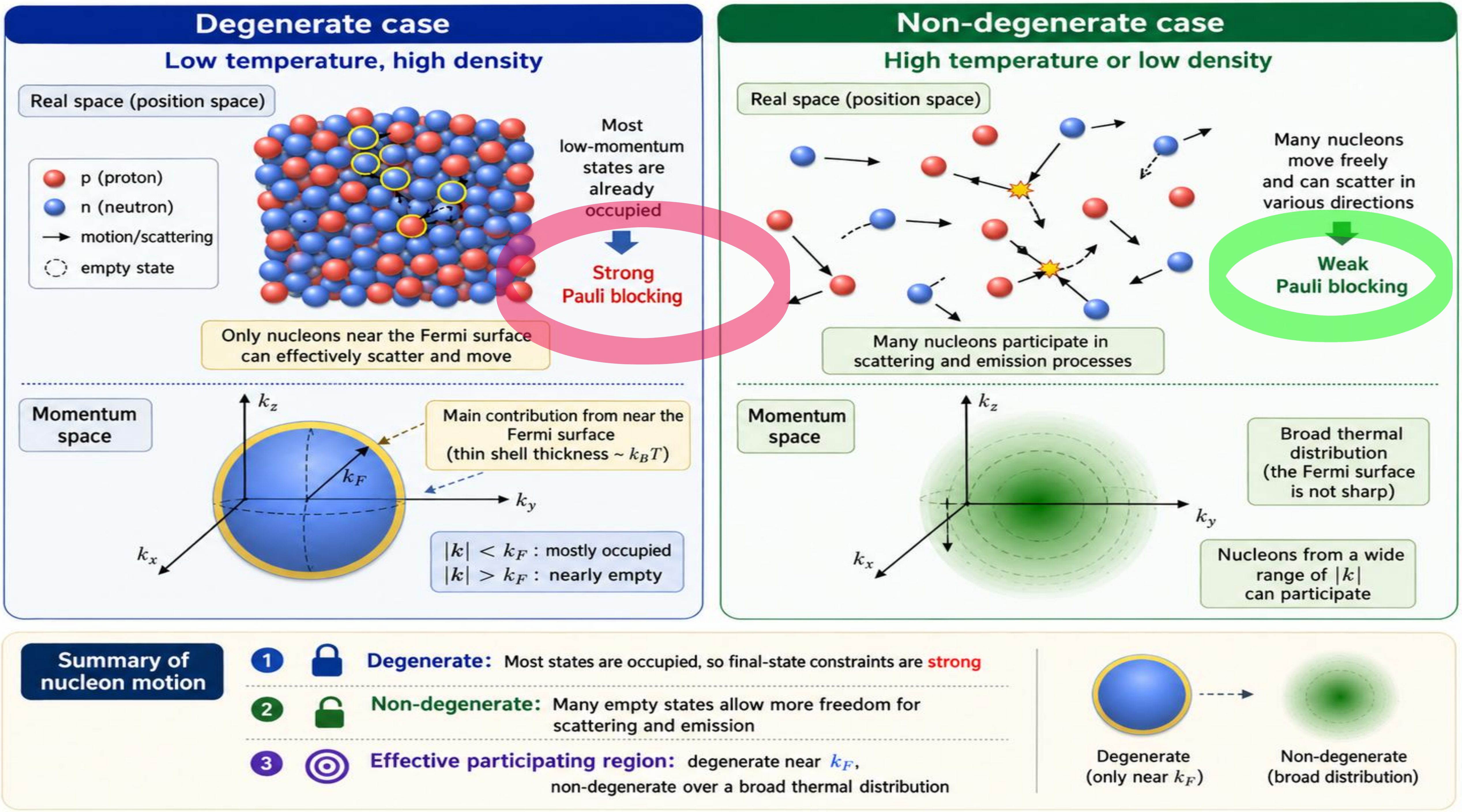
9. Key features

- Two-body (pair) emission via neutral weak current
- Dominated by spin–isospin fluctuations in the medium
- Important process for supernova neutrino emission and neutron star cooling

10. Summary

NN bremsstrahlung: $NN \to NN + \nu + \bar{\nu}$ mediated by spin neutral weak current.

Main contribution: one-pion exchange diagrams with Z^0 emission from nucleons or the pion.



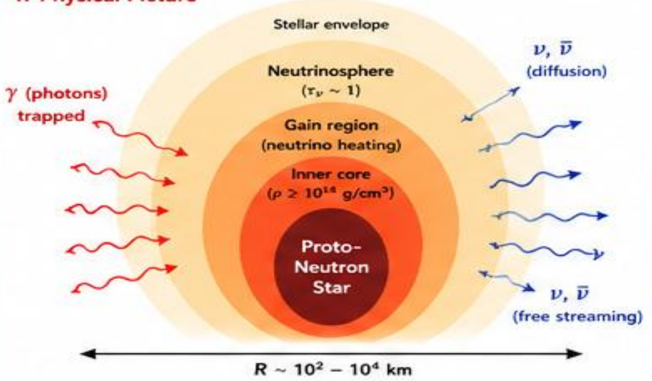
Degenerate case
Low temperature, high density
Real space (position space)
p (proton)
n (neutron)
motion/scattering
empty state
Most low-momentum states are already occupied
Strong Pauli blocking
Only nucleons near the Fermi surface can effectively scatter and move
Momentum space
k_z
k_F
k_y
k_x
Main contribution from near the Fermi surface (thin shell thickness ~ $k_B T$)
$|k| < k_F$: mostly occupied
$|k| > k_F$: nearly empty
Non-degenerate case
High temperature or low density
Real space (position space)
Many nucleons move freely and can scatter in various directions
Weak Pauli blocking
Many nucleons participate in scattering and emission processes
Momentum space
k_z
k_y
k_x
Broad thermal distribution (the Fermi surface is not sharp)
Nucleons from a wide range of $|k|$ can participate
Summary of nucleon motion
1 Degenerate: Most states are occupied, so final-state constraints are strong
2 Non-degenerate: Many empty states allow more freedom for scattering and emission
3 Effective participating region: degenerate near k_F, non-degenerate over a broad thermal distribution
Degenerate (only near k_F)
Non-degenerate (broad distribution)

Core–Collapse Supernovae (CCSN) vs. Relativistic Heavy-Ion Collisions (RHIC/LHC)

Photon and Neutrino Opacity, Transport, and Their Roles

CORE–COLLAPSE SUPERNOVA (CCSN)

1. Physical Picture



2. Conditions (Typical)

- Density: $10^{10} - 10^{15}$ g/cm^3
- Temperature: $1 - 30$ MeV
- Size: $\sim 10 - 100$ km
- Time scale: ms – sec

3. Opacity (Typical)

Photons (QED)

- κ_γ very large
- Mean free path $\lambda_\gamma \ll 1$ cm
- Completely trapped (diffusion only)

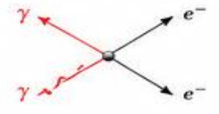
Neutrinos (Weak)

- κ_ν moderate
- Mean free path $\lambda_\nu \sim 10 - 100$ cm
- Partially trapped (diffusion) + free streaming outside (neutrinosphere at $\tau_\nu \sim 1$)

4. Dominant Interactions

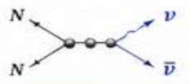
Photon (Electromagnetic)

- Thomson scattering ($\gamma + e^- \to \gamma + e^-$)
- Compton scattering
- e^+e^- pair processes



Neutrino (Weak)

- Scattering: $\nu + N \to \nu + N$
- Absorption: $\nu_e + n \to p + e^-$ (and CC for $\bar{\nu}_e$)
- Bremsstrahlung: $N + N \to N + N + \nu + \bar{\nu}$
- Pair annihilation: $e^+ + e^- \to \nu + \bar{\nu}$



5. Transport & Role

Photons

- Completely trapped
- Transport: diffusion
- Do NOT escape
- No role in energy transport or explosion

6. Characteristic Numbers

Quantity	Photons (CCSN Core)	Neutrinos (CCSN Core)
Cross section (typical)	$\sigma_\gamma \sim 10^{-25}$ cm^2 (Thomson)	$\sigma_\nu \sim 10^{-41}$ cm^2 $(E_\nu/10\text{ MeV})^2$
Mean free path λ	$\ll 1$ cm	$10 - 100$ cm
Optical depth τ (center)	$\gg 10^{10}$	$\sim 10^2 - 10^4$
Transport	Diffusion only	Diffusion + Free streaming
Energy luminosity	Negligible	$L_\nu \sim 10^{52} - 10^{53}$ erg/s

7. Key Takeaway (CCSN)

Photons are trapped by extremely high density. Neutrinos are the only particles that can escape and carry energy, controlling the explosion mechanism.

DIRECT COMPARISON

Environment

	CCSN	RHIC/LHC
System size	$\sim 10 - 100$ km	$\sim 5 - 10$ fm
Density	$10^{10} - 10^{15}$ g/cm^3	$\lesssim 10-20$ GeV/fm^3 ($\sim$ few 10^{14} g/cm^3)
Temperature	$1 - 30$ MeV	$150 - 600$ MeV
Time scale	ms – sec	$1 - 20$ fm/c ($10^{-24} - 10^{-23}$ s)
Medium	Nuclear matter + degenerate leptons	Quark–Gluon Plasma (QGP)

Opacity & Mean Free Path

	CCSN	RHIC/LHC
Photons	κ_γ very large, $\lambda_\gamma \ll$ cm (trapped)	κ_γ small, $\lambda_\gamma \gg$ system size (free streaming)
Neutrinos	κ_ν moderate, $\lambda_\nu \sim 10 - 100$ cm (partially trapped)	κ_ν extremely small, $\lambda_\nu \gg 10^{10}$ cm (essentially free streaming)

Role in the System

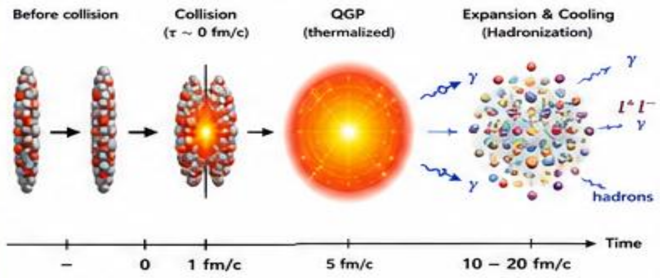
	CCSN	RHIC/LHC
Photons	Do NOT escape, No role in energy transport	Escape freely, Important probe of the hot medium
Neutrinos	Escape and transport energy, Essential for cooling and explosion	Escape freely, Almost no role in the system

Legend

κ : opacity (cm^2/g) λ : mean free path
τ : optical depth σ : cross section
fm $= 10^{-13}$ cm

RELATIVISTIC HEAVY-ION COLLISIONS (RHIC/LHC)

1. Physical Picture



2. Conditions (Typical)

- Energy: $\sqrt{s_{NN}} = 7$ GeV – 5.02 TeV
- Temperature: $150 - 600$ MeV
- Energy density: $\lesssim 10-20$ GeV/fm^3
- Size: $\sim 5 - 10$ fm
- Time scale: $1 - 20$ fm/c

3. Opacity (Typical)

Photons (QED)

- κ_γ small
- Mean free path $\lambda_\gamma \gg$ system size
- Free streaming (escape easily)

Neutrinos (Weak)

- κ_ν extremely tiny
- Mean free path $\lambda_\nu \gg 10^{10}$ cm
- Completely free streaming (transparent medium)

4. Dominant Interactions

Photon (Electromagnetic)

- QGP: $q(\bar{q}) + g \to q(\bar{q}) + \gamma$ (Compton)
- $q + \bar{q} \to g + \gamma$ (Annihilation)
- Hadronic gas: $\pi + \rho \to \pi + \gamma$, etc.

Neutrino (Weak)

- $q + \bar{q} \to Z^0 \to \nu + \bar{\nu}$ (very rare)
- Hadronic decays (very small)

Photons

- Escape freely
- Penetrate the whole system
- Direct probe of the earliest
- hot and dense stage (QGP)
- Thermal photons, prompt photons

Neutrinos

- Escape freely
- Produced in negligible amounts
- Do not affect the dynamics or energy transport

6. Characteristic Numbers

Quantity	Photons (RHIC/LHC)	Neutrinos (RHIC/LHC)
Cross section (typical)	$\sigma_\gamma \sim 10^{-2} - 10^{-1}$ mb ($= 10^{-27} - 10^{-26}$ cm^2)	$\sigma_\nu \sim 10^{-43} - 10^{-42}$ cm^2 ($E \sim 100$ MeV)
Mean free path λ	$1 - 100$ fm $\gg$ system size	$\gg 10^{10}$ cm
Optical depth τ	$\ll 1$	$\ll 1$
Transport	Free streaming	Free streaming
Energy luminosity	$L_\gamma \sim 10^{49} - 10^{50}$ erg/s	$L_\nu \ll 10^{45}$ erg/s (negligible)

7. Key Takeaway (RHIC/LHC)

Photons escape freely and carry undistorted information from the hot medium. Neutrinos are essentially transparent and play no important role.

Physical Origin of the Difference

CCSN

Huge size and density $\Rightarrow$ large optical depth (photons and neutrinos interact many times)

RHIC/LHC

Tiny size and short time $\Rightarrow$ small optical depth (particles escape easily)

SUMMARY TABLE

Aspect	CCSN	RHIC/LHC
Dominant degree of freedom	Nucleons, nuclei, leptons	Quarks, gluons (QGP), hadrons
Photon opacity	Very high (trapped)	Low (free streaming)
Neutrino opacity	Moderate (partially trapped)	Extremely low (transparent)
Energy transport	By neutrinos	By expansion (hydrodynamics)
Photons role	Negligible	Essential probe
Neutrinos role	Essential (cooling, heating, explosion)	Negligible

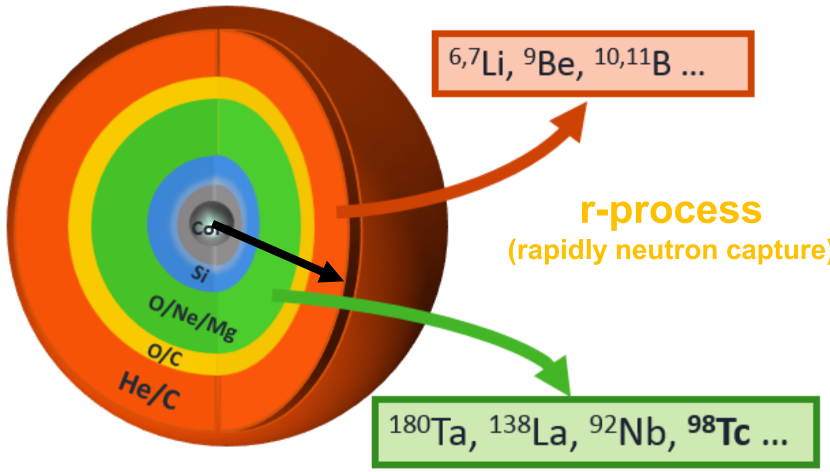
One-Line Message

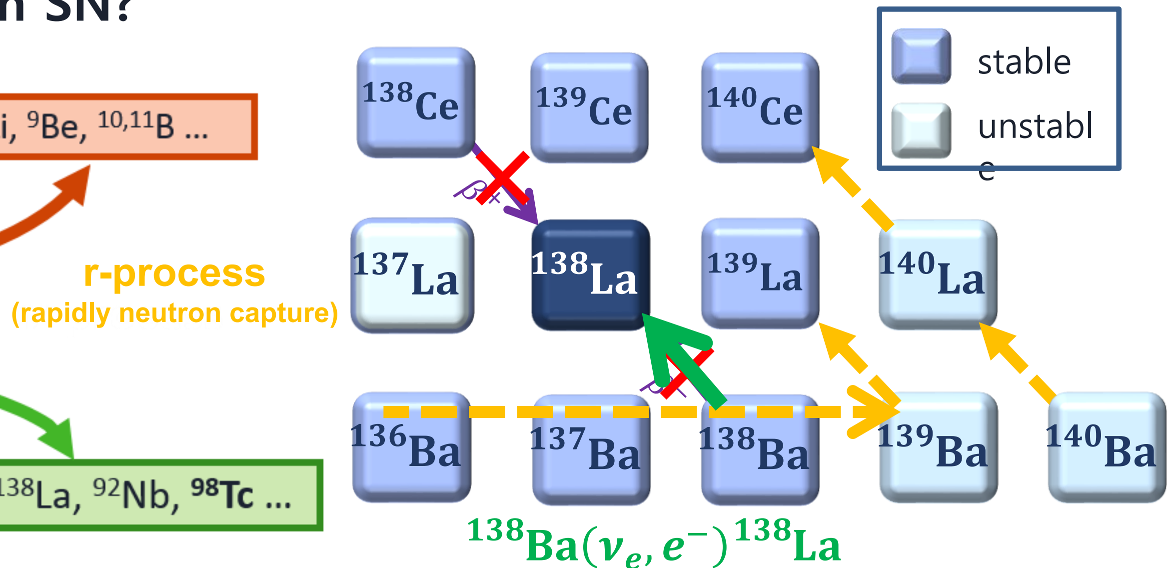
In CCSNē, only neutrinos can escape the opaque core and drive the explosion.
In relativistic heavy-ion collisions, photons escape freely and serve as clean messengers of the QGP, while neutrinos are irrelevant.

Contents

1. Introduction and Motivation from CCSNe Neutrino and Neutrino Process
2. **Neutrino Luminosity** from CCSNe by Neutrino Transport Equation by GR1D code
3. Effects of **axial vector quenching and nucleon effective mass** in nuclear dense matter

Why neutrino process in SN?





Introduction

Non-equal (NEQ) **Neutrino Luminosity in CCSN Explosion**

J. Phys. G: Nucl. Part. Phys. **45** (20 ... 4001 E O'Connor *et al*

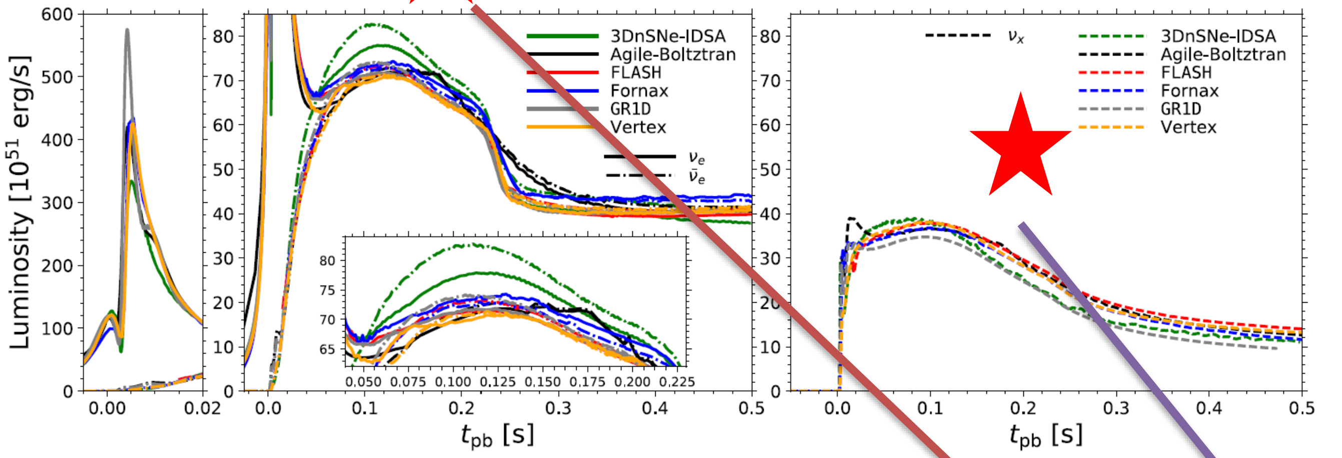


Figure 3. Neutrino luminosities as a function of postbounce time. In the left panels we show electron-type neutrino luminosities (solid lines show electron neutrinos while dashed–dotted lines show electron antineutrinos) and in the right panel we show the characteristic heavy-lepton neutrino luminosity (dashed line) inset to highlight the early accretion epoch for the electron-t to show the neutronization burst. Some curves have been sr zones to remove noise and improve clarity.

NEQ Luminosity is higher than EQ luminosity scenario !!

3.1. 3DnSNe-IDSA

Contributors: *Tomoya Takiwaki, Kei Kotake*

3.2. AGILE-BOLTZTRAN

Contributors: *Tobias Fischer, Eric Lentz, Matthias Liebendörfer, Bronson Messer, Anthony Mezzacappa*The radiation-hydrodynamics module AGILE is based on the spherically-sym-

3.3. FLASH-M1

Contributors: *Evan O'Connor, Sean Couch*

3.4. FORNAX

Contributors: *Adam Burrows, David Vartanyan*

3.5. GR1D

Contributors: *Evan O'Connor*

3.6. PROMETHEUS-VERTEX

Contributors: *Robert Bollig, Hans-Thomas Janka*

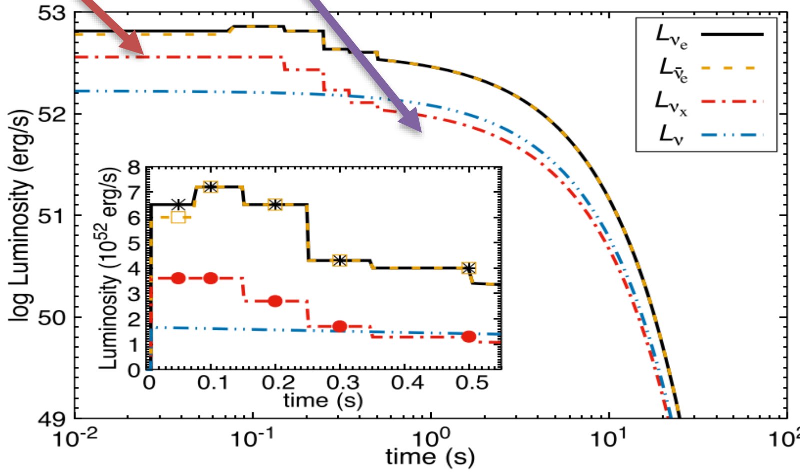


Figure 10. The neutrino luminosities for each flavor: ν_e, $\bar{\nu}_e$, and $\nu_x(= \nu_\mu, \nu_\tau, \bar{\nu}_\mu$ and $\bar{\nu}_\tau)$ in the region of $M_r \sim 1.6 M_\odot$(corresponding to $r \approx 2300$ km). The inset shows an enlarged figure of the x- and y-axes. The yellow line denotes the luminosity calculated by Equation (14) and the others are adopted from Table 2.

Contents

Neutrino transport : GR Boltzmann equation

Boltzmann equation –

Equation describing non-equilibrium system

General Relativistic form of Boltzmann equation

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

$$\frac{\partial f}{\partial t} + c\mathbf{n}\cdot\nabla f - \epsilon(\mathbf{n}\cdot\nabla\Phi)\frac{\partial f}{\partial \epsilon} - (\nabla_{\perp}\Phi)\cdot\frac{\partial f}{\partial \mathbf{n}} = C[f]$$

Neutrino + Matter interaction

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

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

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

η : emissivity

κ_{α} : absorption opacity

κ_s : scattering opacity

$S^{\alpha}_{e/a}$: emission/absorption

$S^{\alpha}_{\mathrm{iso}}$: isoenergetic elastic scattering

$S^{\alpha}_{\mathrm{scatter}}$: inelastic scattering

$S^{\alpha}_{\mathrm{thermal}}$: pair creation/annihilation 같은 thermal process

$$\mathcal{J}_{\nu}(\vec{x},\epsilon_{\nu}\ t) = \frac{\epsilon_{\nu}^{3}}{4\pi(hc)^{3}}\int_{\Omega} f_{\nu}(\vec{x},\vec{p},t)d\Omega$$

$$\mathcal{H}^{i}_{\nu}(\vec{x},\epsilon_{\nu}\ t) = \frac{\epsilon_{\nu}^{3}}{4\pi(hc)^{3}}\int_{\Omega} l^{i} f_{\nu}(\vec{x},\vec{p},t)d\Omega$$

$$\mathcal{K}^{ij}_{\nu}(\vec{x},\epsilon_{\nu}\ t) = \frac{\epsilon_{\nu}^{3}}{4\pi(hc)^{3}}\int_{\Omega} l^{i} l^{j} f_{\nu}(\vec{x},\vec{p},t)d\Omega$$

Luminsotiy $L(r)$

$$= (4\pi r)^2\int_{\epsilon} \mathcal{H}^{r} d\epsilon = (4\pi)^2\frac{W}{\alpha}\frac{1-\nu}{1+\nu}\frac{\alpha r^2\int_{\epsilon} F_r d\epsilon}{X^2}$$

$$\frac{dm}{dr} = 4\pi(\rho h W^2 - P + \tau^{\nu}_{m})$$

ρ = density, h =enthalpy, W =Lorentz factor, P = pressure

$$X = \frac{1}{\sqrt{2m(r)/r}}$$

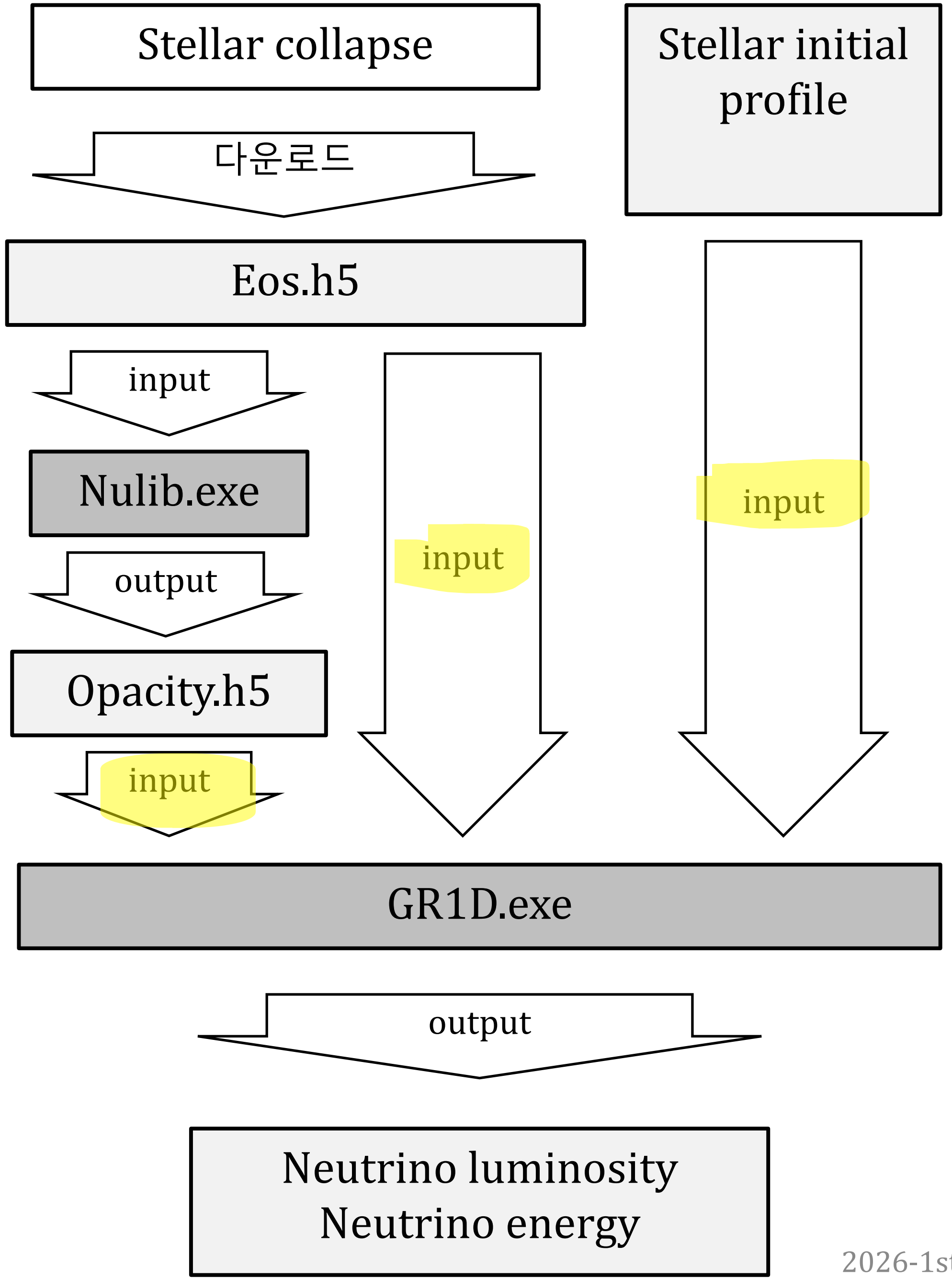
$$\frac{d\phi}{dr} = X^2\left[\frac{m}{r^2} + 4\pi r\left(\rho h W^2 v^2 + P + \tau^{\nu}_{\phi}\right)\right]$$

$\alpha = \exp(\phi)$, ν = fluid velocity

Root mean square Energy $\langle\epsilon\rangle(r)$

$$= \frac{\alpha(r_{surface})}{\alpha(r)}\frac{\langle\epsilon_{surface}\rangle}{W(1+\nu)}$$

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



Eos.h5

- Electron fraction
- Temperature
- density

- Pressure($dynes/cm^2$)
- Energy (erg/g)
- Mass number
- Mass fraction of all
- Number fraction of all
- Entropy ($k_B/baryon$)
- Adiabatic index
- Velocity of sound (cm^2/s^2)
- Chemical potential ($MeV/baryon$
- dpde, dpdrho, de/dt

Opacity.h5

- Neutrino energy
- Neutrino species
- Electron fraction
- Temperature
- density

- Absorption opacity (cm -1)
- Emissivity ($erg/cm^3/s/MeV/sra$
- Scattering opacity (cm-1)

Stellar initial profile

- Mass (g)
- Radial coordinate (cm)
- Temperature (K)
- Density (g/cm3)
- Radial velocity (cm/s)
- Fraction
- Angular velocity (rad/s)

Equation of States in Default

TABLE II: Properties of nuclear matter calculated for the considered Skyrme interactions. n_0 (in fm^{-3}) is the saturation density of symmetric nuclear matter (SNM) and ϵ_0 (in MeV baryon^{-1}) is the binding energy of SNM at n_0. Given in MeV K_0, the skewness K', the symmetry energy parameters J, L, K_{sym}, and Q_{sym}, and the volume part M_n^*/m_n is the dimensionless ratio of the neutron effective mass to the neutron rest mass in SNM at neutron effective mass difference in SNM at n_0. Also given in MeV is the critical temperature T_c for tw between the LS220 results listed here and the original results of L&S are due to differences in the emp the neutron proton mass difference (see the discussion in Section IV A) and from calculating the syr explicitly from the derivatives of ϵ_B and not from the difference in ϵ_B between SNM and pure neutro

Parametrization	n_0	ϵ_0	K_0	K'	J	L	K_{sym}	Q_{sym}	
LS220 [8]	0.1549	−16.64	219.85	410.80	28.61	73.81	−24.04	96.17	−3
KDE0v1 [68]	0.1646	−16.88	227.53	384.83	34.58	54.70	−127.12	484.44	−3
LNS [69]	0.1746	−15.96	210.76	382.50	33.43	61.45	−127.35	302.52	−3
NRAPR [59]	0.1606	−16.50	225.64	362.51	32.78	59.64	−123.32	311.60	−3
SKRA [70]	0.1594	−16.43	216.97	378.73	31.32	53.04	−139.28	310.83	−3
SkT1 [71]	0.1610	−16.63	236.14	383.49	32.02	56.18	−134.83	318.99	−3
Skxs20 [72]	0.1617	−16.46	201.94	425.53	35.50	67.06	−122.31	328.52	−3
SLy4 [73]	0.1595	−16.62	229.90	363.07	32.00	45.96	−119.70	521.48	−3
SQMC700 [74]	0.1704	−16.14	219.59	367.98	33.40	59.14	−140.23	312.66	−3

PHYSICAL REVIEW C **96**, 065802 (2017)

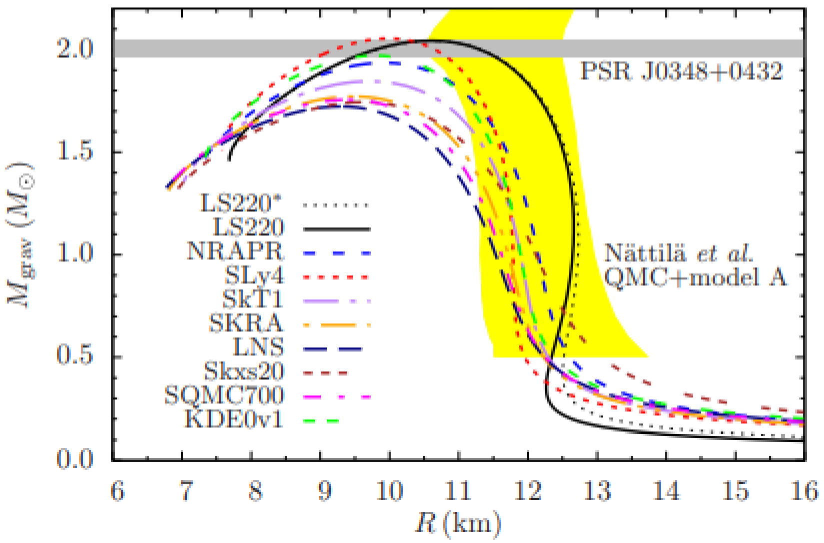


FIG. 9. Mass-radius curves for cold, beta-equilibrated neutron stars (NSs) obtained by solving the Tolman-Oppenheimer-Volkoff equations for the considered Skyrme parametrizations. We summarize NS properties in Table IV. The gray strip represents the mass of the NS PSR J0348 + 0432, $M_{\mathrm{J0348+0432}} = 2.01 \pm 0.04 M_\odot$ [79]. The yellow region indicates the NS mass-radius constraints from model A of Nättilä *et al.* [12]. Besides the LS220 parametrization, only SLy4 and (barely) KDE0v1 and NRAPR satisfy the $M_{\mathrm{max}} \gtrsim 2\,M_\odot$ constraint. Differences between our implementation of LS220 and the original L&S implementation (LS220*) are due to the lower limit of $y \geqslant 0.035$ in the latter (cf. Fig. 8).

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Open-source nuclear equation of state framework based on the liquid-drop model with Skyrme interaction

A. S. Schneider,[1,*] L. F. Roberts,[2,†] and C. D. Ott[1,3,‡]

Neutrino Emission by Bremsstrahlung by A. Burrow

Burrows, Adam, Sanjay Reddy, and Todd A. Thompson. "Neutrino opacities in nuclear matter." *Nuclear Physics A* 777 (2006): 356-394.

Emissivity $Q_{nb} = (2\pi)^4 \int \left[\prod_{i=1}^{4} \frac{d^3\vec{p}_i}{(2\pi)^3}\right] \frac{d^3 q_\nu}{(2\pi)^3 2\omega_\nu} \frac{d^3\vec{q}_{\bar{\nu}_i}}{(2\pi)^3 2\omega_{\bar{\nu}}} \omega \sum_s |\mathcal{M}|^2 \delta^4(P) \Xi_{brems}$

$$\sum_s |\mathcal{M}|^2 = \frac{64}{4} G_F^2 \left(\frac{f}{m_\pi}\right)^4 g_A^2 \left[\left(\frac{k^2}{k^2+m_\pi^2}\right)^2 + \cdots\right] \frac{\omega_\nu \omega_{\bar{\nu}}}{\omega^2}$$

$$dQ_{nn} = C'_{\rm Bur}\, m^{*9/2}\, T^{17/2}\, e^{2y}\, e^{-\Omega/T} \left(\frac{\Omega}{T}\right)^4 \left[\int_0^\infty e^{-z}\left(z^2 + z\frac{\Omega}{T}\right)^{1/2} dz\right] d\Omega$$

m=> m*= m (m*/m)

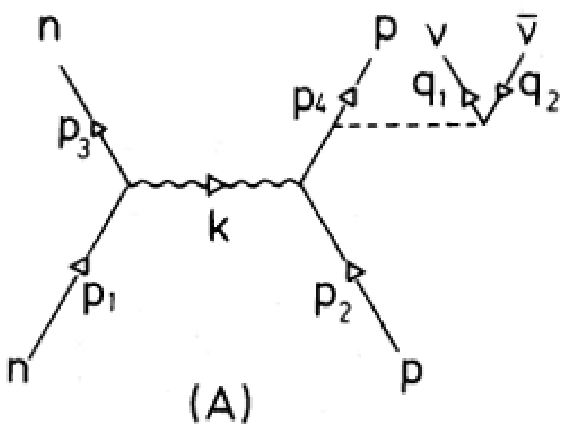
$$\frac{dQ_{nn}}{d\Omega} \propto m^{*9/2}\, T^{7/2}\, e^{2y}\, e^{-\Omega/2T}\, \Omega^5 K_1\left(\frac{\Omega}{2T}\right),$$

If in Eq. (136) we do not integrate over ω_ν, but at the end of the calculation we integrate over ω from ω_ν to ∞, after some manipulation we obtain the single neutrino emissivity spectrum:

$$\frac{dQ'_{nb}}{d\omega_\nu} = 2C\left(\frac{Q_{nb}}{T^4}\right)\omega_\nu^3 \int_{\eta_\nu}^{\infty} \frac{e^{-\eta}}{\eta} K_1(\eta)(\eta-\eta_\nu)^2\, d\eta \qquad (143)$$

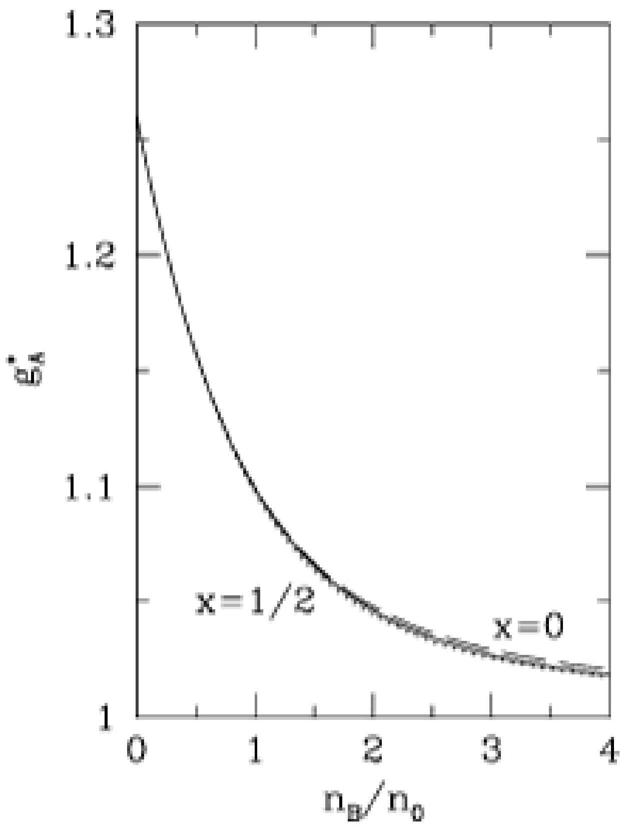
$$= 2C\left(\frac{Q_{nb}}{T^4}\right)\omega_\nu^3 \int_1^{\infty} \frac{e^{-2\eta_\nu \xi}}{\xi^3}(\xi^2-\xi)^{1/2}\, d\xi, \qquad (144)$$

where $\eta_\nu = \omega_\nu/2T$, C is the normalization constant equal to $(3\times5\times7\times11)/2^{11}$ ($\cong 0.564$), and for the second expression we have used the integral representation of $K_1(\eta)$ and reversed the order of integration. In Eq. (144), Q_{nb} is the emissivity for the pair.



$$Q_{nn}^{\rm nondeg}(m^*_{\rm kin}) \simeq Q_{nn}^{\rm nondeg}(m)\left(\frac{m^*_{\rm kin}}{m}\right)^\delta$$

delta = 1.5= 3/2 for Non-deg.case

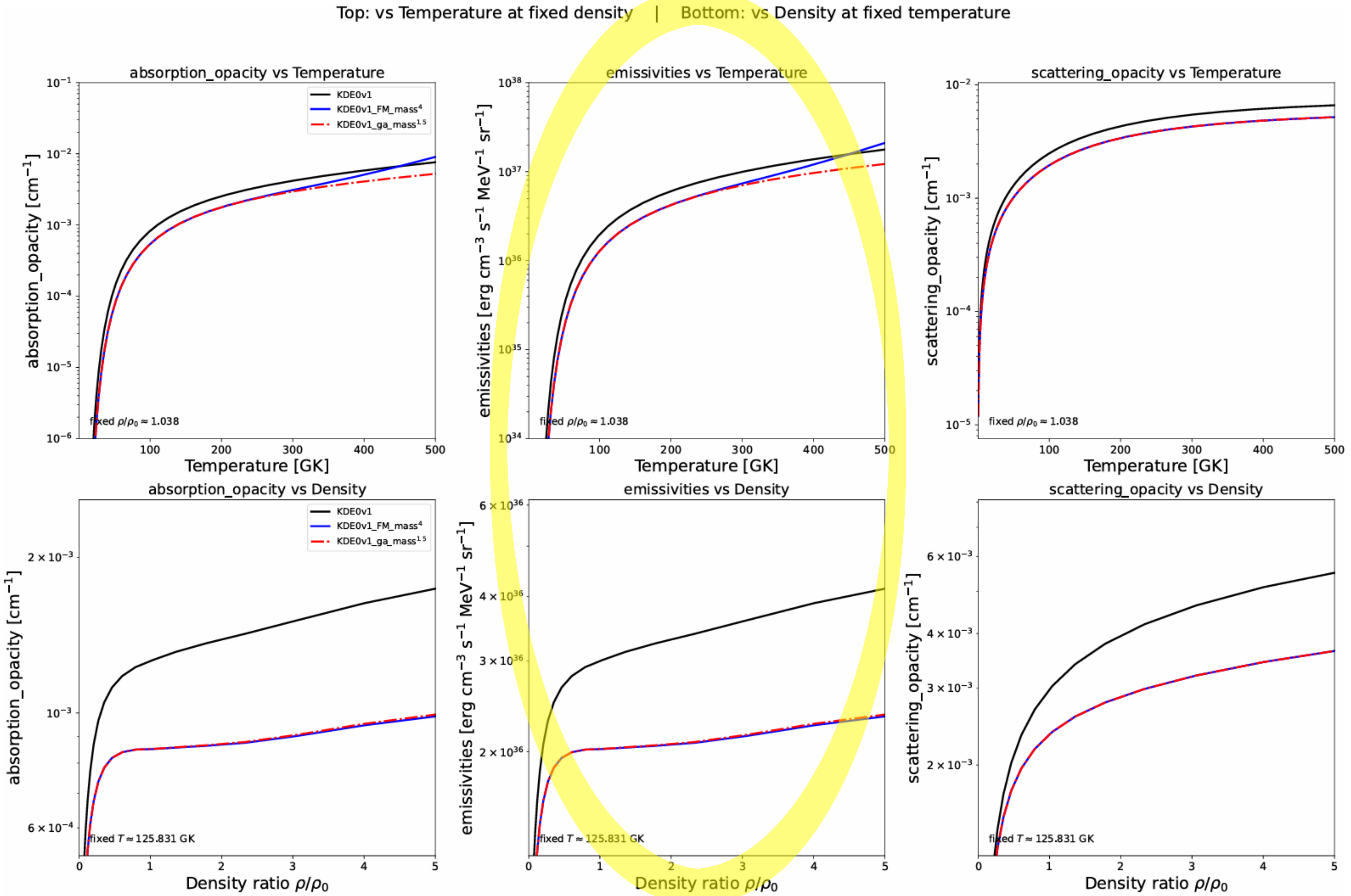


$g_{A,eff} \cong g_A\left(1 - \frac{n_{Baryon}}{4.15(n_0+n_{Baryon})}\right)$

Within 1% accuracy for all $n_{Baryon} < 4.5 n_0$

Contents

Neutrino Opacity vs. Density & Temperature(KDE)



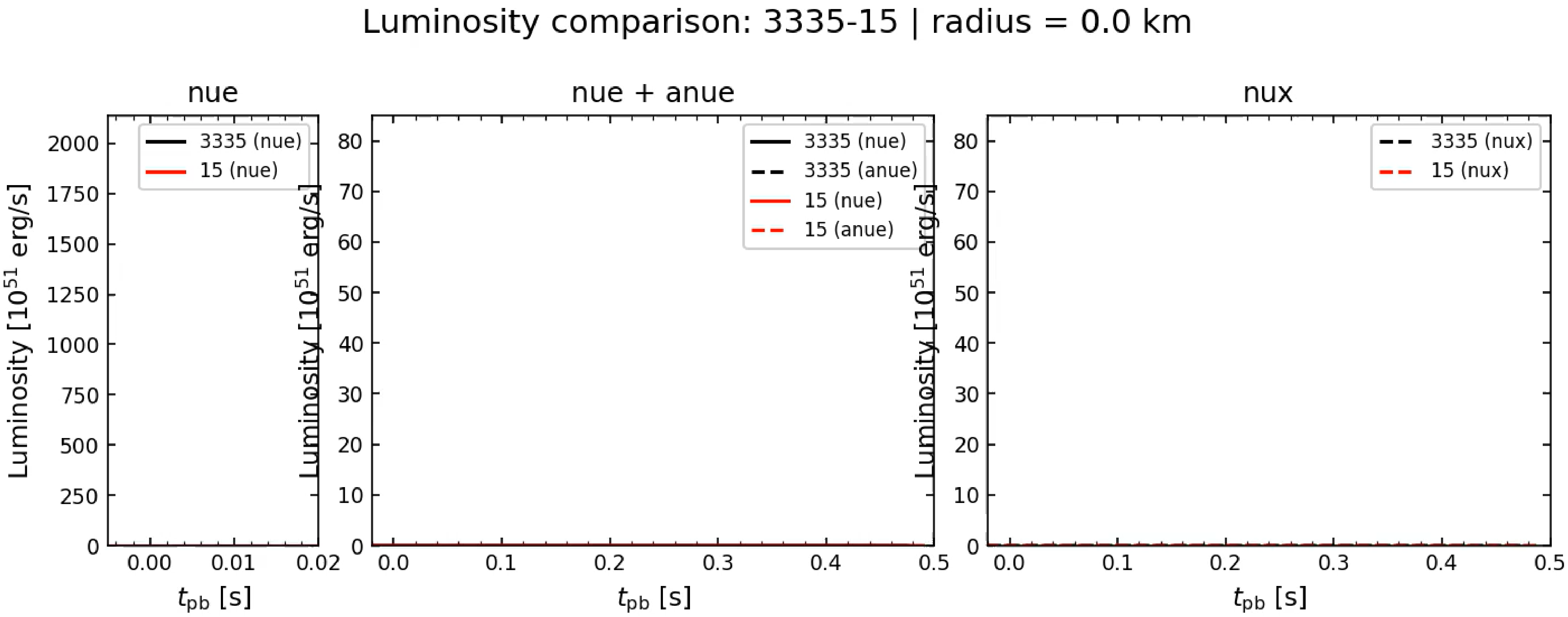
Black : KDE0v1

Red : + g_a quenching

Blue: + Effective mass depending on **temperature**

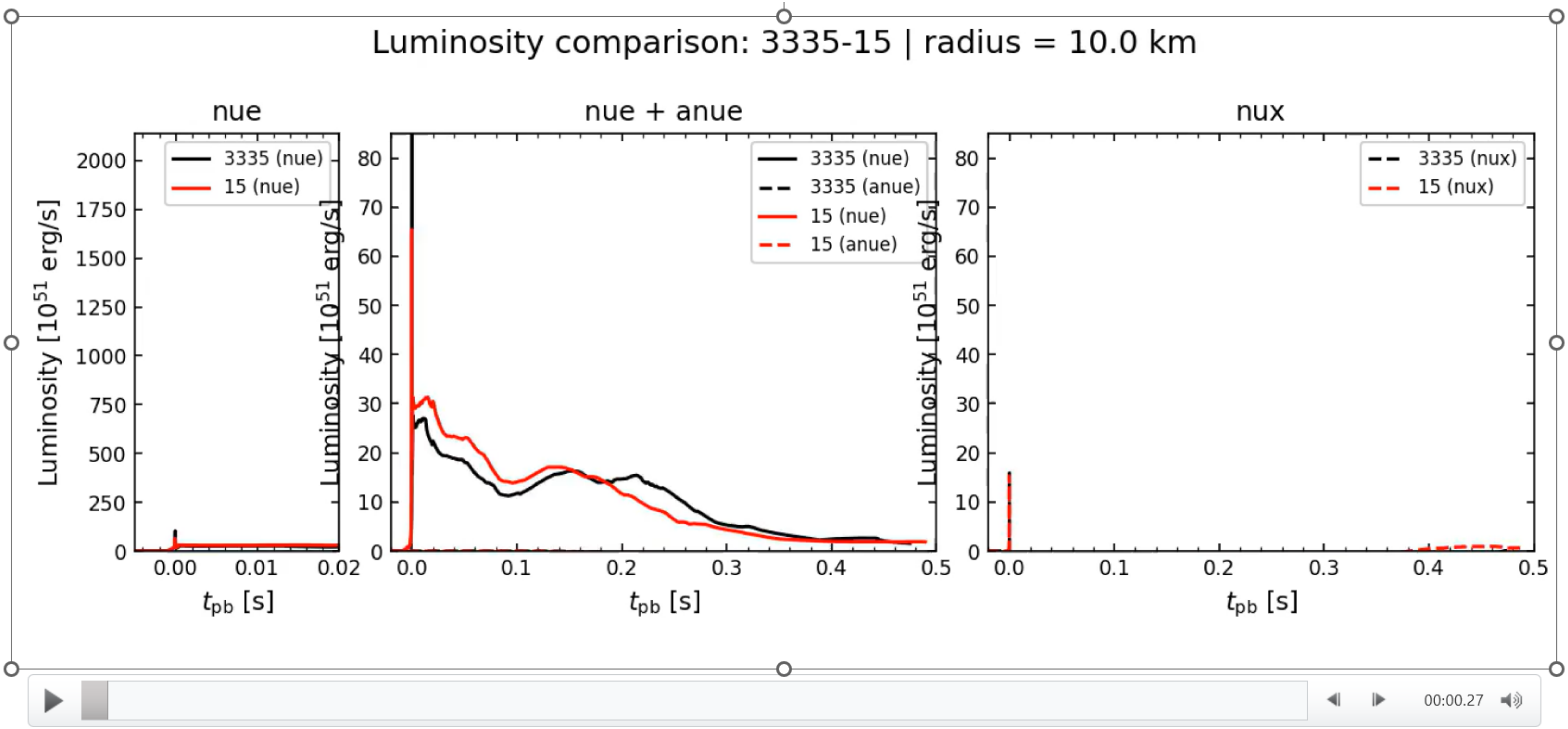
$\eta - \kappa_a \mathcal{J} = 0, \mathcal{J}$: blackbody spectra $[ergs/cm^2/s/MeV/srad]$

Effects of quenching and effective mass in Luminosity
for non-degenerate case



Effective mass effects **decrease the luminosity during the post bounce** and **increases it at the accretion phase** !!

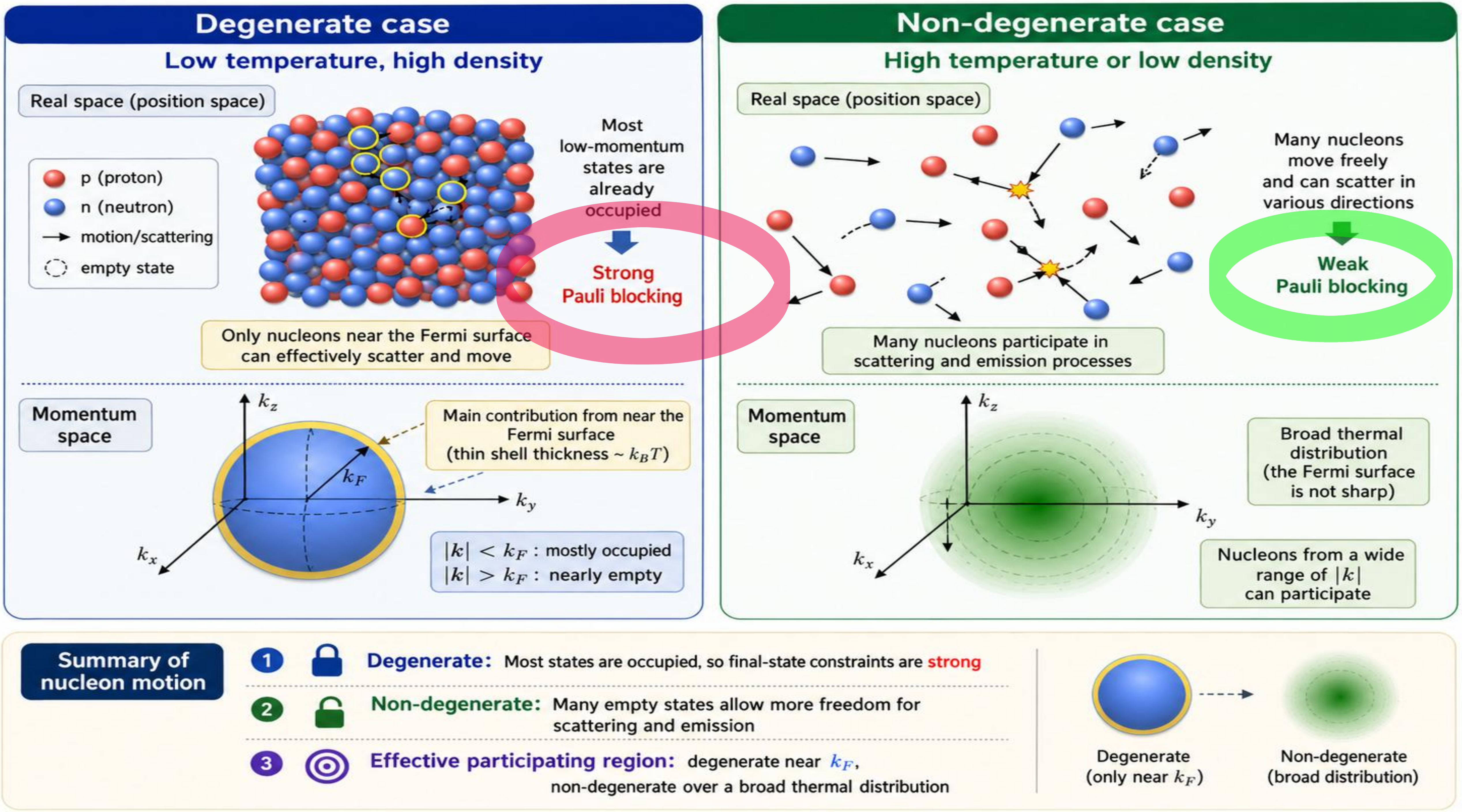
Effects of quenching and effective mass in Luminosity
for non-degenerate case



Effective mass effects **decrease the luminosity during the post bounce** and **increases it at the accretion phase** !!

However,
this is far from the whole story.

So—what are we really missing?


Degenerate case
Low temperature, high density
Real space (position space)
p (proton)
n (neutron)
motion/scattering
empty state
Most low-momentum states are already occupied
Strong Pauli blocking
Only nucleons near the Fermi surface can effectively scatter and move
Momentum space
k_z
k_F
k_y
k_x
Main contribution from near the Fermi surface (thin shell thickness ~ k_BT)
$|k| < k_F$: mostly occupied
$|k| > k_F$: nearly empty
Non-degenerate case
High temperature or low density
Real space (position space)
Many nucleons move freely and can scatter in various directions
Weak Pauli blocking
Many nucleons participate in scattering and emission processes
Momentum space
k_z
k_y
k_x
Broad thermal distribution (the Fermi surface is not sharp)
Nucleons from a wide range of $|k|$ can participate
Summary of nucleon motion
1 Degenerate: Most states are occupied, so final-state constraints are strong
2 Non-degenerate: Many empty states allow more freedom for scattering and emission
3 Effective participating region: degenerate near k_F, non-degenerate over a broad thermal distribution
Degenerate (only near k_F)
Non-degenerate (broad distribution)

Contents

Degeneracy by chemical potential & Thermal de Broglie wave length: Degenerate and Non-degenerate vs time and radius

$$\boxed{\eta \equiv \frac{\mu - m}{T} \ll -1 \quad \Longleftrightarrow \quad n\lambda_T^3 \ll 1}$$

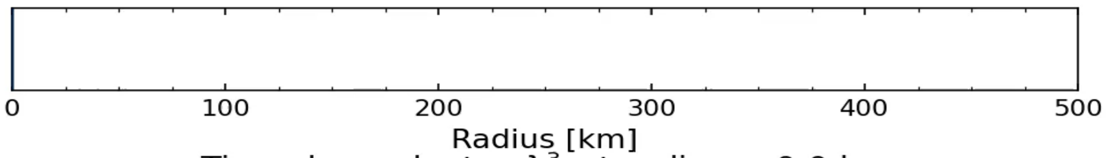
$$\boxed{\lambda_T \equiv \sqrt{\frac{2\pi\hbar^2}{mT}}}$$

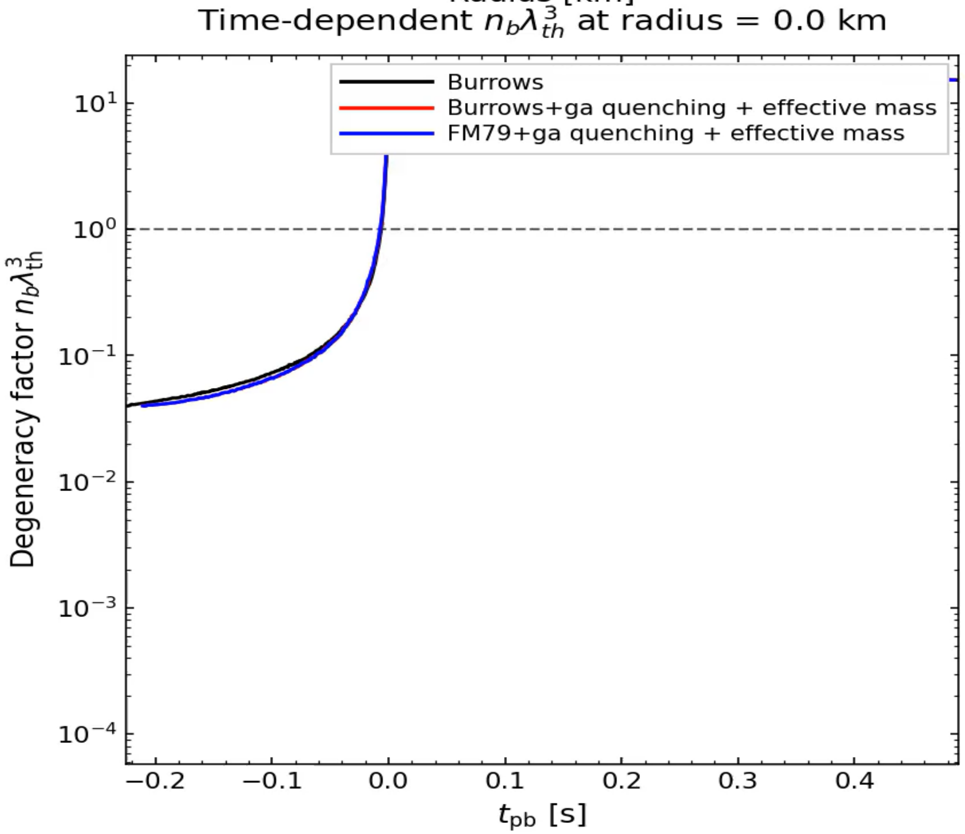
따라서

- $n\lambda_T^3 \ll 1$ No overlap => Classical gas
- $n\lambda_T^3 \gtrsim 1$: Overlap => Quantum Degenerate gas

입니다.

Deg. and Non-deg. Cases show significant difference near neutrino sphere !!





B-2. NON-DEGENERATE LIMIT OF THE OCCUPATION FACTORS

In the non-degenerate regime, the nucleon degeneracy parameter, $y \equiv \frac{\mu - m}{T}$, satisfies $y \ll -1$. The occupation factors reduce to Maxwell–Boltzmann form,

$$F_i \simeq e^{-(E_i-\mu)/T} = e^y\, e^{-p_i^2/2mT}, \qquad (1 - F_i) \simeq 1. \tag{69}$$

Hence

$$F_1F_2(1-F_3)(1-F_4) \;\to\; e^{2y} \exp\left[-\frac{p_1^2+p_2^2}{2mT}\right]. \tag{70}$$

A-2. DEGENERATE NUCLEON PHASE SPACE AND FERMI-SURFACE RESTRICTION

For strongly degenerate neutrons, the phase space is restricted to a thin shell near the Fermi surface:

$$d^3p_i = d^3p_i \int dE_i\, \delta(E_i - E_{p_i}) \;\to\; d^3p_i\, \delta(E_i - E_F)\, dE_i. \tag{8}$$

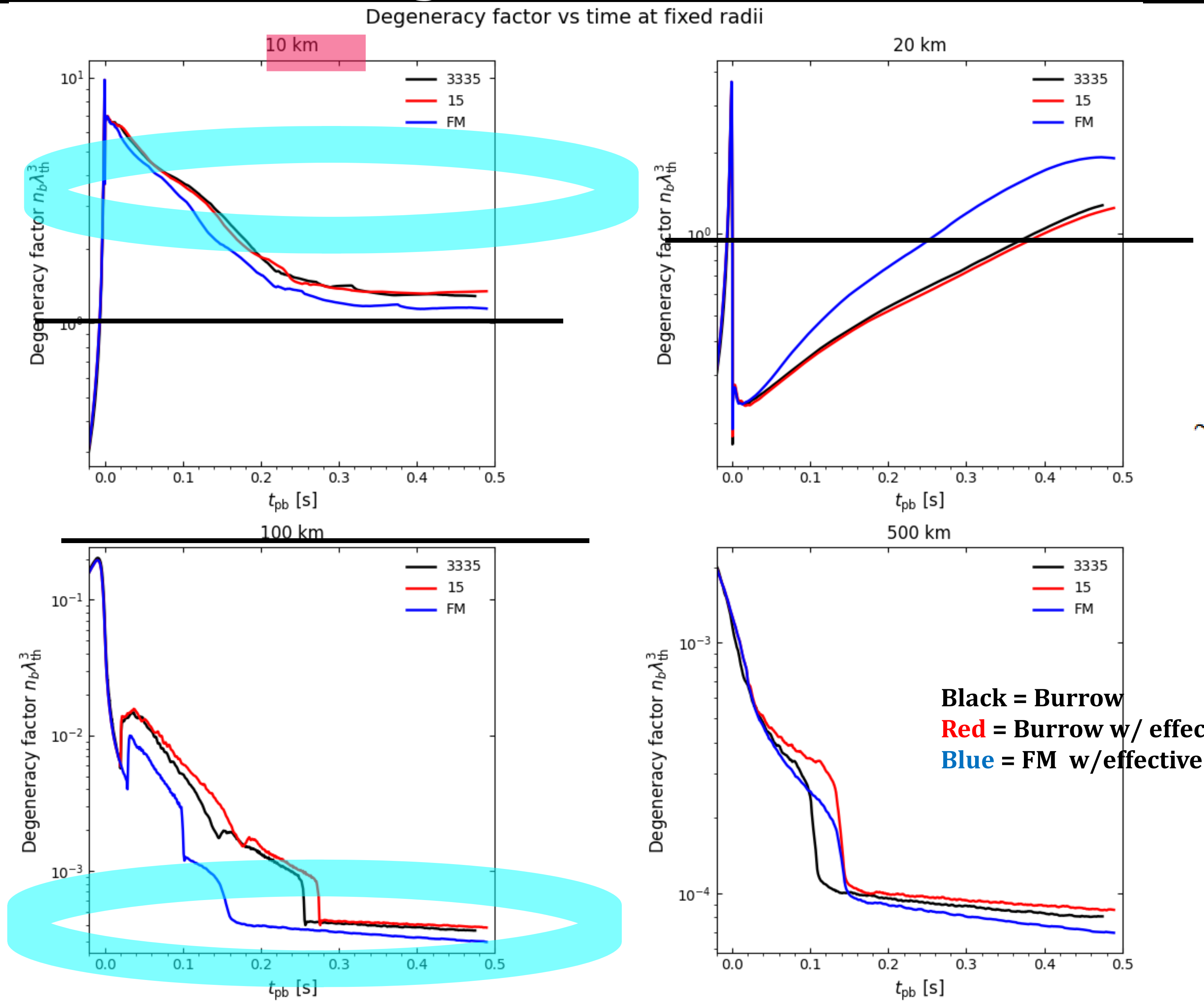
Using the nonrelativistic relation, $\delta(E_i - E_F) = \frac{m^*}{p_F}\delta(p_i - p_F)$, each nucleon measure becomes $d^3p_i \to \frac{m^*}{p_F} dE_i\, d^3p_i\, \delta(p_i - p_F)$. Therefore,

$$\prod_{i=1}^{4} d^3p_i \;\longrightarrow\; \left(\frac{m^*}{p_F}\right)^4 \left[\prod_{i=1}^{4} dE_i\right]\left[\prod_{i=1}^{4} d^3p_i\, \delta(p_i - p_F)\right]. \tag{9}$$

Degeneracy by Chemical Potential & Thermal de Broglie wave length: Degenerate and Non-degenerate vs time for fixed radius

$$\eta \equiv \frac{\mu - m}{T} \ll -1 \quad \Longleftrightarrow \quad n\lambda_T^3 \ll 1$$

$$\lambda_T \equiv \sqrt{\frac{2\pi\hbar^2}{mT}}$$



Normal density

$\sim 2.3 \times 10^{14}$ g/cm^3

Black = Burrow
Red = Burrow w/ effective mass and quenching
Blue = FM w/effective mass and quenching

Deg. and Non-deg. Cases show significant difference around neutrino sphere just after post-bounce & in the cooling phase !!

Neutrino Emission by Bremsstrahlung (Non-deg. & Deg. Cases)

Burrows, Adam, Sanjay Reddy, and Todd A. Thompson. "Neutrino opacities in nuclear matter." *Nuclear Physics A* 777 (2006): 356-394.

$$\text{Emissivity } Q_{nb} = (2\pi)^4 \int \left[\prod_{i=1}^{4} \frac{d^3\vec{p}_i}{(2\pi)^3}\right] \frac{d^3 q_\nu}{(2\pi)^3 2\omega_\nu} \frac{d^3 \vec{q}_{\bar{\nu}_i}}{(2\pi)^3 2\omega_{\bar{\nu}}}\, \omega \sum_s |\mathcal{M}|^2 \delta^4(P)\, \Xi_{brems}$$

$$\sum_s |\mathcal{M}|^2 = \frac{64}{4} G_F^2 \left(\frac{f}{m_\pi}\right)^4 g_A^2 \left[\left(\frac{k^2}{k^2+m_\pi^2}\right)^2 + \cdots\right] \frac{\omega_\nu \omega_{\bar{\nu}}}{\omega^2}$$

$$dQ_{nn} = C'_{\mathrm{Bur}}\, m^{*9/2}\, T^{17/2}\, e^{2y}\, e^{-\Omega/T} \left(\frac{\Omega}{T}\right)^4 \left[\int_0^\infty e^{-z}\left(z^2 + z\frac{\Omega}{T}\right)^{1/2} dz\right] d\Omega$$

$$\frac{dQ_{nn}}{d\Omega} \propto m^{*9/2}\, T^{7/2}\, e^{2y}\, e^{-\Omega/2T}\, \Omega^5 K_1\left(\frac{\Omega}{2T}\right),$$

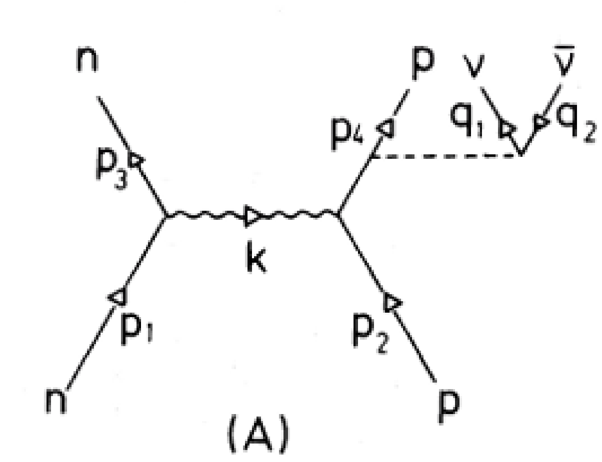
Substituting Eq. (56) into Eq. (45), the final emissivity is

$$\epsilon_{nn} = \frac{41}{14175} \frac{G^2 g_A^2 m^{*4}}{2\pi\hbar} \left(\frac{f}{m_\pi}\right)^4 p_F F\left(\frac{m_\pi}{2p_F}\right) (kT)^8. \qquad (39)$$

It is useful to summarize the scaling structure as 1) m^{*4} $\leftarrow$ four degenerate nucleon legs restricted to the Fermi surface,, 2) $p_F\, F\left(\frac{m_\pi}{2p_F}\right)$ $\leftarrow$ angle-averaged OPE kernel,, and 3) T^8 $\leftarrow$ Ω^4 from the neutrino pair phase space $\times$ T^4 from the four-fermion energy convolution,, so that

$$\epsilon_{nn} \propto m^{*4} p_F\, F\left(\frac{m_\pi}{2p_F}\right) T^8. \qquad (40)$$

$$\frac{d\epsilon_\nu}{d\omega_\nu} = 1.99 \times 10^{23} \left(\frac{m_n^*}{m_n}\right)^4 \left(\frac{p_{Fn}}{\mathrm{MeV}}\right) F\left(\frac{m_\pi}{2p_{Fn}}\right) \left(\frac{T}{\mathrm{MeV}}\right)^7 x_\nu^3 \mathcal{I}(x_\nu) \quad \mathrm{erg\,cm^{-3}\,s^{-1}\,MeV^{-1}}.$$



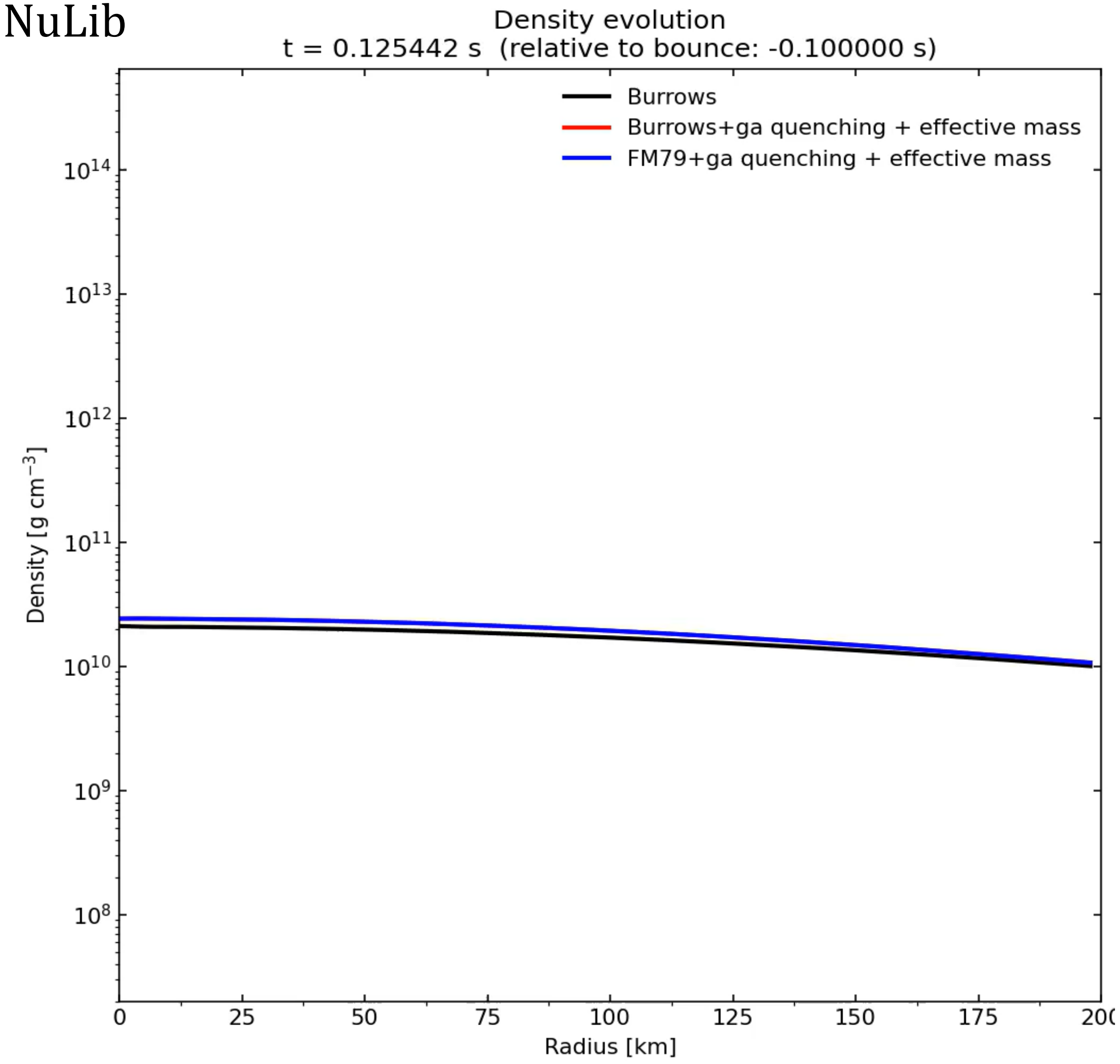
$$Q_{nn}^{\mathrm{nondeg}}(m_{\mathrm{kin}}^*) \simeq Q_{nn}^{\mathrm{nondeg}}(m) \left(\frac{m_{\mathrm{kin}}^*}{m}\right)^\delta$$

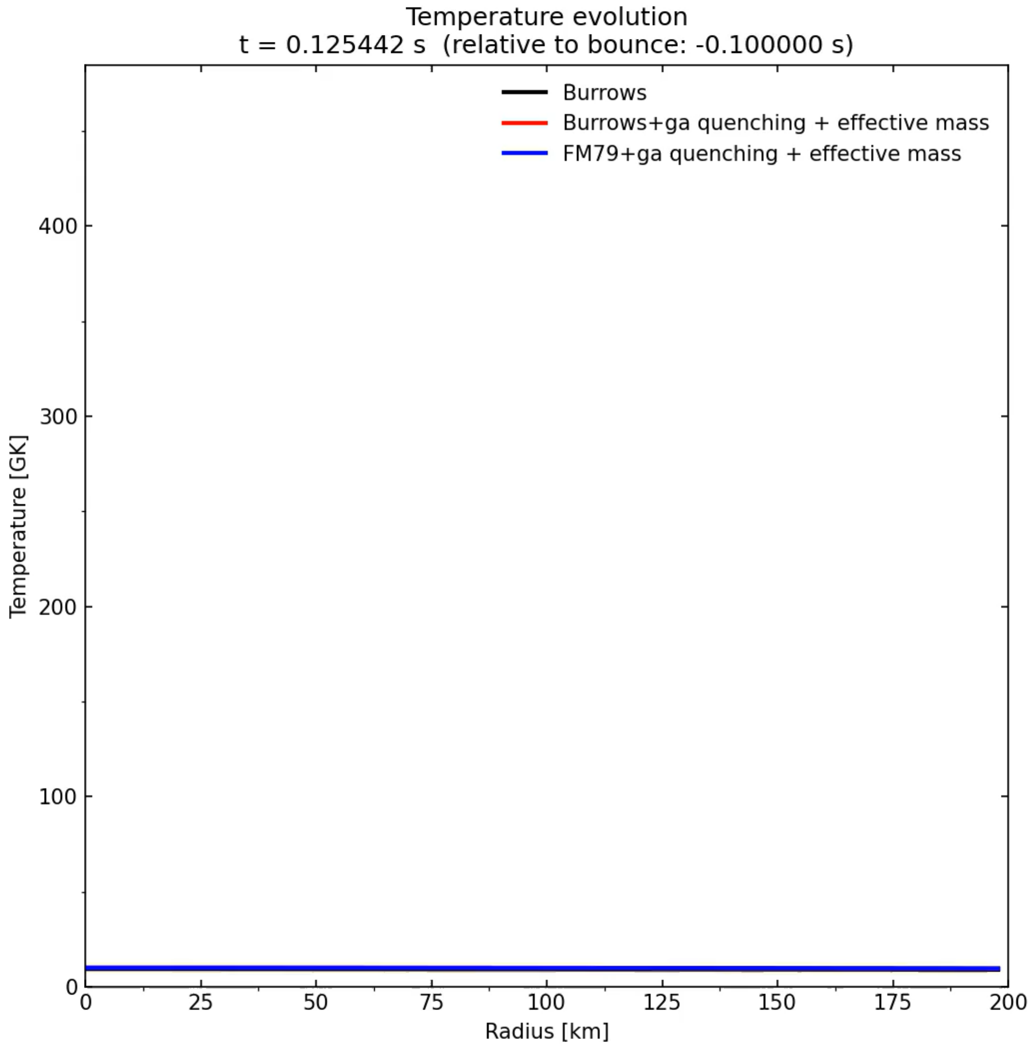
delta = 1.5 for Non-deg. Case

= **4.0 for Deg. case**

Density and Temperature Profiles vs radius

EoS = LS220
for GR1D and NuLib

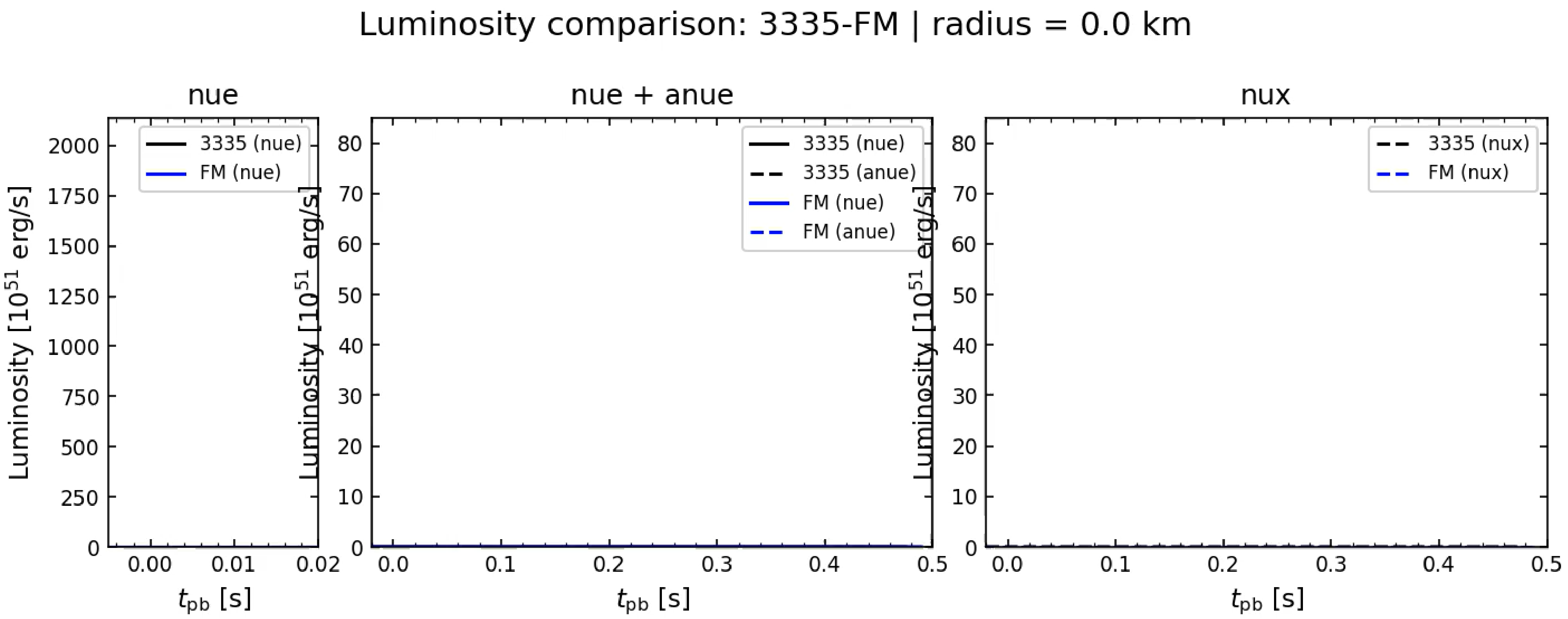




Black = Burrow
Red = Burrow w
Blue = FM

Comparison of Luminosity vs Time (LS220)

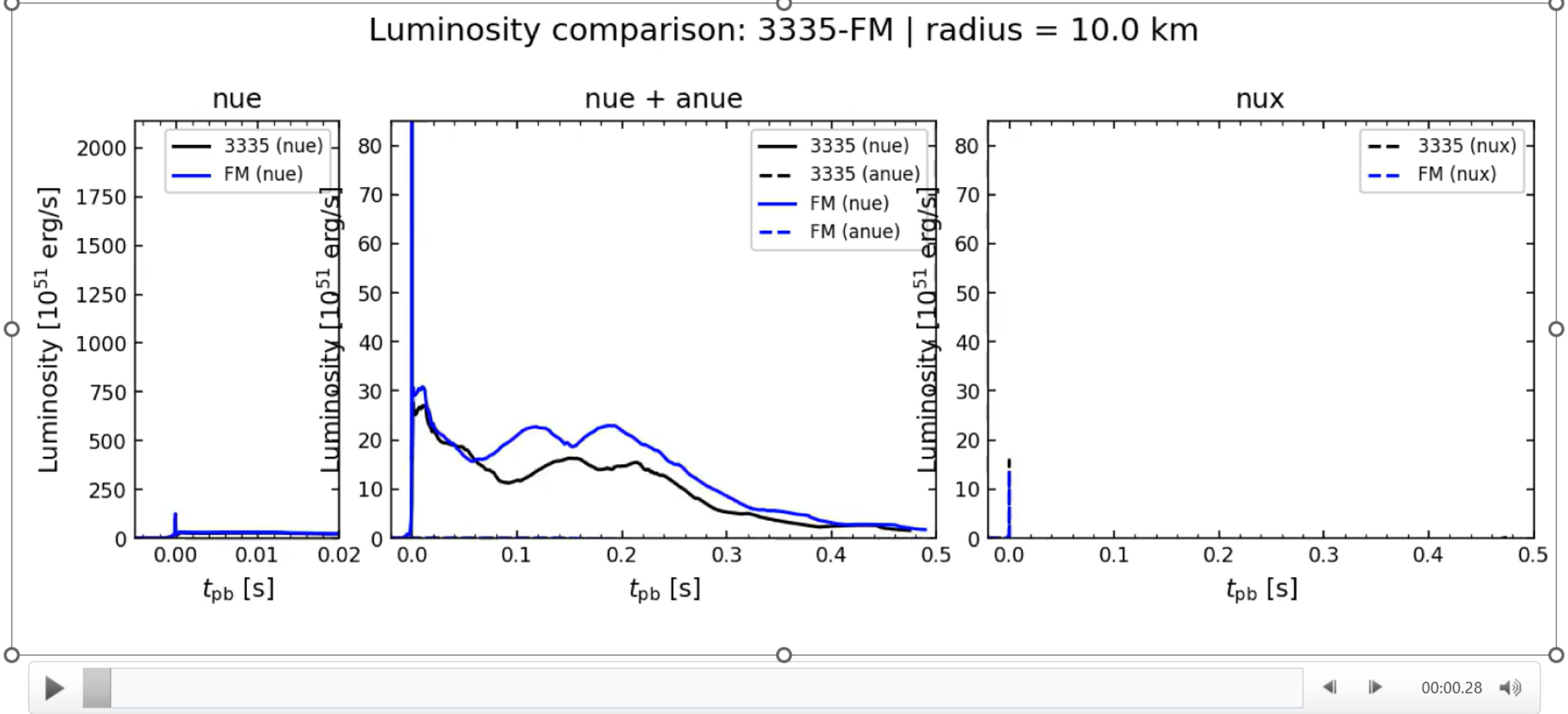
by Non-deg. and Deg. cases



Degenerate case **delays** a bit the neutrino burst during the post-bounce and **increases the luminosity** at the accretion phase **near neutrino sphere** !!

Comparison of Luminosity vs Time (LS220)

by Non-deg. and Deg. cases



Degenerate case **delays** a bit the neutrino burst during the post-bounce and **increases the luminosity** at the accretion phase **near neutrino sphere** !!

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NEUTRINO EMISSIVITIES OF NEUTRON STARS[1]

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Received 1978 May 31; accepted 1979 March 14

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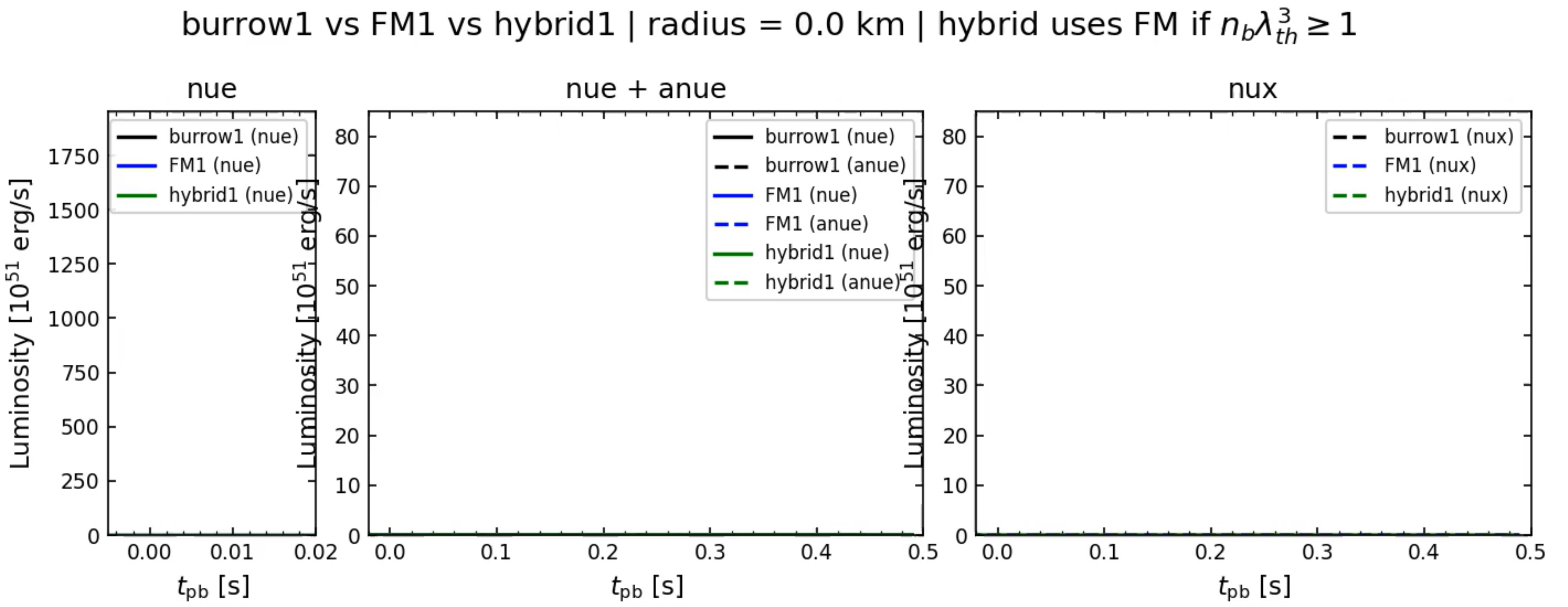
NUCLEAR PHYSICS A

Neutrino opacities in nuclear matter

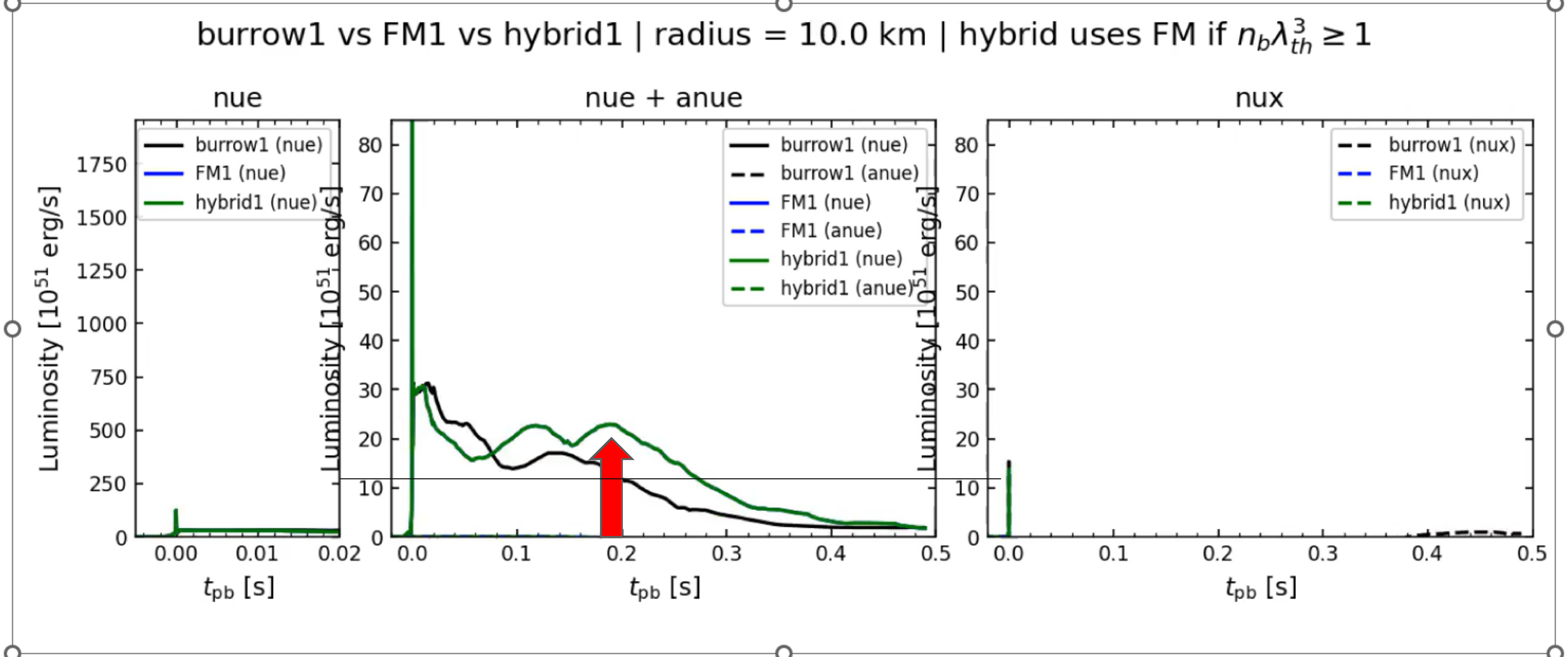
Adam Burrows[a,*], Sanjay Reddy[b], Todd A. Thompson[c]

Comparison of Effective Mass Effects by Hybrid model



Effective mass and quenching effects **decreases luminosity near post-bounce and cooling phase,**
but increases it at accretion phase near post-bounce near neutrino sphere.
Perhaps, in the degenerate case, luminosity is proportional to effective mass ratio ~1.5

Comparison of Effective Mass Effects by Hybrid Model



Effective mass and quenching effects **decreases luminosity near post-bounce and cooling phase,**
but increases it at accretion phase near post-bounce near neutrino sphere.
Perhaps, in the degenerate case, luminosity is proportional to effective mass ratio ~1.5.

Effective mass and quenching show larger luminosity rather than the original Hybrid model.

Summary

1. Neutrino already came to your Nuclear Physics.
2. Scattering data, Neutron Skin Thickness are available now.
3. In CCSN, most of gravitational energy is transferred to neutrino energy.
4. Now there are many proposals to detect the SN neutrino as well as other neutrinos on Earth.
5. Most of SN simulation by the neutrino transport equation needs more elaborate treatments of the nuclear physics input.
6. We tried to examine the density dependence of the weak interaction and the effects of the effective nucleon mass in dense mater in the GR1D simulation.

Summary

7. The weak interaction quenching reduces the neutrino absorption, scattering and emission rate, which gives rise to the increase of the mean free path in the neutrino streaming, i.e., makes the SN matter transparent to the neutrino.

8. That is, the neutrino opacity becomes smaller, and consequently provides much larger neutrino luminosity, about 10 % maximally in the neutrino burst and the accretion epoch.

9. But almost no effects are found in the cooling phase.

10. The change of nucleon effective masses is found to be more serious.

11. For the non-degenerate case, the effective mass and quenching effects **decreases luminosity near post-bounce and cooling phase**, **but increases it at accretion phase near post-bounce near neutrino sphere.**

12. But, for the degenerate case, the feature is reversed. Perhaps, in the degenerate case, luminosity is proportional to effective mass ratio ~1.5.

13. We need to consider a hybrid model depending the degeneracy factor depending on temperature and density. More deliberate analysis is being done now.

崇實大學校

Thanks for your attention !!