Energizing gamma ray bursts (GRBs) via Z' mediated neutrino heating

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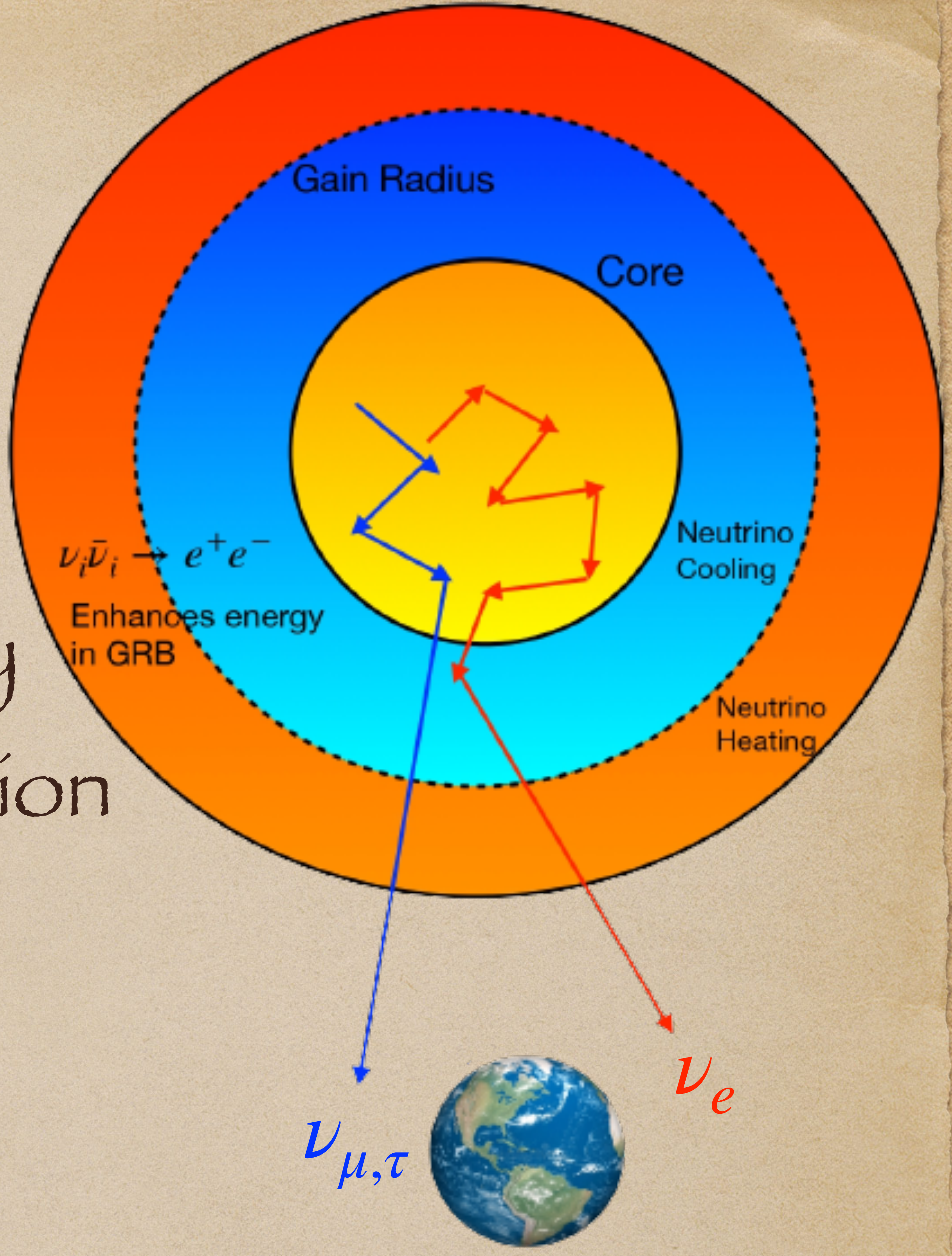
Outline

- Motivations
- Neutrino heating through Z'
- Neutrino heating in different spacetimes
- Combined effects (Z'+background spacetimes)
- Constraints on Z': Results and Analysis
- Conclusions

Motivations

- Neutrino Cooling: Emission of huge number of neutrinos makes the stellar objects cool, $L_\nu \sim 10^{52}$erg/s



- Neutrino Heating: Neutrino flux can also deposit energy into the stellar envelope through neutrino pair annihilation

$$\nu_i\bar{\nu}_i \rightarrow e^+e^-, i = e, \mu, \tau$$ Energizes GRB

$E_{\rm GRB} \sim 10^{52}$erg (Observation)

$E_{GRB}^{\rm Theory} \sim 8.48 \times 10^{47}$erg (Newtonian)

Could not match with the observations!!

$E_{GRB}^{\rm Theory} \sim 2.5 \times 10^{49}$erg (Schwarzschild)

Contd…

Extension in the gravity sector

- Several modified gravity models
- Quintessence model
- Temperature gradient model etc…

Still could not match the energy deposition rate with the observations!!

Extension in the particle physics sector?? (This work)

Extending Standard Model (SM) gauge group with an $U(1)_X$ gauge symmetry

What is the energy deposition rate in different background spacetimes? Let's see!

Neutrino heating through Z′

The energy deposition rate per unit volume

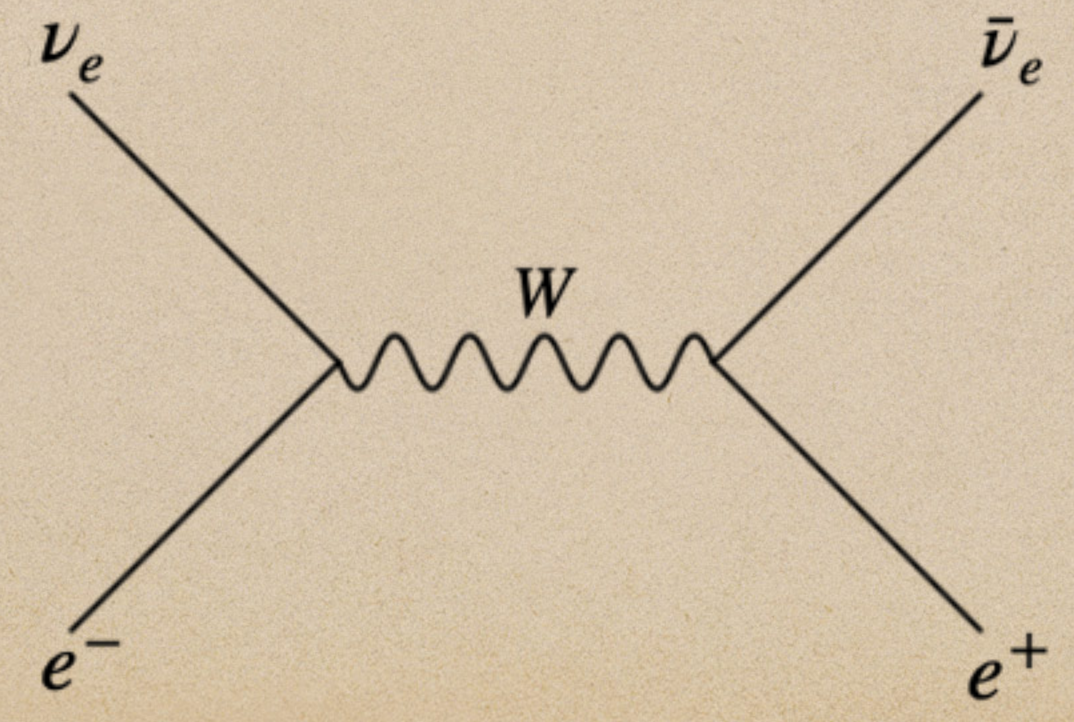
$$\dot{q}(r) = \int\int f_\nu(\mathbf{p}_\nu, r) f_{\bar{\nu}}(\mathbf{p}_{\bar{\nu}}, r)(\sigma|\mathbf{v}_\nu - \mathbf{v}_{\bar{\nu}}|E_\nu E_{\bar{\nu}}) \times \frac{E_\nu + E_{\bar{\nu}}}{E_\nu E_{\bar{\nu}}} d^3\mathbf{p}_\nu d^3\mathbf{p}_{\bar{\nu}},$$

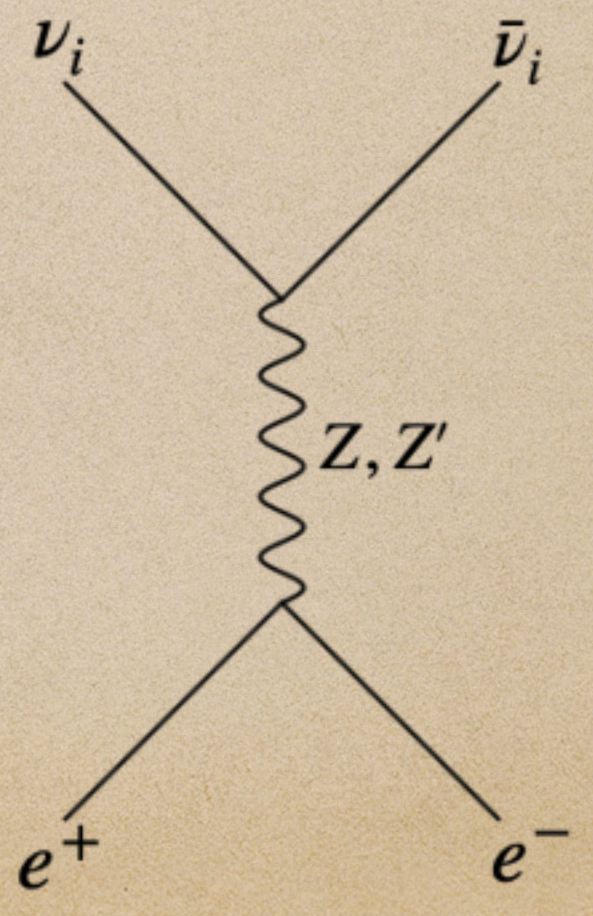
Also,

$$\int\int f_\nu f_{\bar{\nu}} (E_\nu + E_{\bar{\nu}}) E_\nu^3 E_{\bar{\nu}}^3 dE_\nu dE_{\bar{\nu}} = \frac{21}{2(2\pi)^6} \pi^4 (kT)^9 \zeta(5)$$

$\nu_e \bar{\nu}_e \to e^+ e^- \quad (W, Z, Z')$

$\nu_{\mu,\tau} \bar{\nu}_{\mu,\tau} \to e^+ e^- \quad (Z, Z')$





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$U(1)_X$:

$$(\sigma|\mathbf{v}_{\nu_e}-\mathbf{v}_{\overline{\nu}_e}|E_{\nu_e}E_{\overline{\nu}_e})_{U(1)_X}=\Big[\frac{G_F^2}{3\pi}(1+4\sin^2\theta_W+8\sin^4\theta_W)+\frac{4g'^4}{6\pi M_{Z'}^4}\Big\{\Big(\frac{3}{4}x_H+x_\Phi\Big)^2+\Big(\frac{x_H}{4}\Big)^2\Big\}\times \Big\{\Big(x_\Phi+\frac{x_H}{4}\Big)^2+\Big(\frac{x_H}{4}\Big)^2\Big\}+\frac{4G_F g'^2}{3\sqrt{2}\pi M_{Z'}^2}\Big(x_\Phi+\frac{x_H}{2}\Big)\Big[\Big(\frac{3}{4}x_H+x_\Phi\Big)\Big(-\frac{1}{2}+2\sin^2\theta_W\Big)+\frac{x_H}{8}\Big]+ \frac{4G_F g'^2}{3\sqrt{2}\pi M_{Z'}^2}\Big(x_\Phi+\frac{x_H}{2}\Big)^2\Big](E_{\nu_e}E_{\overline{\nu}_e}-\mathbf{p}_{\nu_e}.\mathbf{p}_{\overline{\nu}_e})^2,$$

$$(\sigma|\mathbf{v}_{\nu_{\mu,\tau}}-\mathbf{v}_{\overline{\nu}_{\mu,\tau}}|E_{\nu_{\mu,\tau}}E_{\overline{\nu}_{\mu,\tau}})_{U(1)_X}=\Big[\frac{G_F^2}{3\pi}(1-4\sin^2\theta_W+8\sin^4\theta_W)+\frac{4g'^4}{6\pi M_{Z'}^4}\Big\{\Big(\frac{3}{4}x_H+x_\Phi\Big)^2+\Big(\frac{x_H}{4}\Big)^2\Big\}\times \Big\{\Big(x_\Phi+\frac{x_H}{4}\Big)^2+\Big(\frac{x_H}{4}\Big)^2\Big\}+\frac{4G_F g'^2}{3\sqrt{2}\pi M_{Z'}^2}\Big(x_\Phi+\frac{x_H}{2}\Big)\Big[\Big(\frac{3}{4}x_H+x_\Phi\Big)\Big(-\frac{1}{2}+2\sin^2\theta_W\Big)+\frac{x_H}{8}\Big]\Big]\times (E_{\nu_{\mu,\tau}}E_{\overline{\nu}_{\mu,\tau}}-\mathbf{p}_{\nu_{\mu,\tau}}.\mathbf{p}_{\overline{\nu}_{\mu,\tau}})^2.$$

$x_H=0, x_\Phi=1\rightarrow U(1)_{B-L}$

Contd...

The energy deposition rate

$$\dot{q}_{\nu_e}(r) = \frac{21}{2(2\pi)^6}\pi^4(kT_{\nu_e}(r))^9\zeta(5)\times\Big[\frac{G_F^2}{3\pi}(1+4\sin^2\theta_W+8\sin^4\theta_W)+\frac{4g'^4}{6\pi M_{Z'}^4}+ \frac{4G_F g'^2}{3\sqrt{2}\pi M_{Z'}^2}\Big(-\frac{1}{2}+2\sin^2\theta_W\Big)+\frac{4G_F g'^2}{3\sqrt{2}\pi M_{Z'}^2}\Big]\Theta_{\nu_e}(r),$$

$$\dot{q}_{\nu_{\mu,\tau}}(r) = \frac{21}{2(2\pi)^6}\pi^4(kT_{\nu_{\mu,\tau}}(r))^9\zeta(5)\times\Big[\frac{G_F^2}{3\pi}(1-4\sin^2\theta_W+8\sin^4\theta_W)+\frac{4g'^4}{6\pi M_{Z'}^4}+ \frac{4G_F g'^2}{3\sqrt{2}\pi M_{Z'}^2}\Big(-\frac{1}{2}+2\sin^2\theta_W\Big)\Big]\Theta_{\nu_{\mu,\tau}}(r).$$

in $\frac{g'}{M_{Z'}} \to 0$ limit,

$$\dot{q}(r) = \frac{7G_F^2\pi^3\zeta(5)}{2(2\pi)^6}(kT)^9\Theta(r)(1\pm 4\sin^2\theta_W+8\sin^4\theta_W)$$ → SM

where,

$$\Theta(r) = \int\int(1-\Omega_\nu.\Omega_{\overline{\nu}})^2 d\Omega_\nu d\Omega_{\overline{\nu}}$$ depends on background geometry

Neutrino heating in different spacetimes

The Hartle-Thorne (HT) metric

$$ds^2 = -\left(1 - \frac{2M}{r} + \frac{2J^2}{r^4}\right)dt^2 + \left(1 - \frac{2M}{r} + \frac{2J^2}{r^4}\right)^{-1} dr^2 + r^2 d\theta^2 + \left(d\phi - \frac{2J}{r^3}dt\right)^2$$

$J \to 0$ Schwarzschild metric

$J \to 0, M \to 0$ Newtonian metric

We calculate the angular integration factor $\Theta(r)$ in Hartle-Thorne, Schwarzschild, and Newtonian background

Contd…

$$\Theta(r) = \frac{2\pi^2}{3}(1-x)^4(x^2+4x+5)$$

where,

$$x = (\sin\theta_r^{\nu_i})_{\rm HT} = \left[1 - \frac{R_{\nu_i}^6 r^4\left(1-\frac{2M}{r}+\frac{2J^2}{r^4}\right)}{\left(2J(r^3-R_{\nu_i}^3)+R_{\nu_i}^2 r^3\left(1-\frac{2M}{R_{\nu_i}}+\frac{2J^2}{R_{\nu_i}^4}\right)^{\frac{1}{2}}\right)^2}\right]^{\frac{1}{2}}$$

proportional to $\dot{q}$

$$T_{\nu_i}^9(r)\Theta_{\nu_i}(r) = \frac{\left(1-\frac{2M}{R_{\nu_i}}-\frac{2J^2}{R_{\nu_i}^4}\right)^{\frac{9}{4}}}{\left(1-\frac{2M}{r}-\frac{2J^2}{r^4}\right)^{\frac{9}{2}}}\left(\frac{7}{4}\pi a\right)^{-\frac{9}{4}} R_{\nu_i}^{-\frac{9}{2}} L_{\rm obs}^{\frac{9}{4}} \times \frac{2\pi^2}{3}(1-x_{\nu_i})^4(x_{\nu_i}^2+4x_{\nu_i}+5)$$

$$T_{\nu_i}(r) = \sqrt{\frac{1-\frac{2M}{R_{\nu_i}}-\frac{2J^2}{R_{\nu_i}^4}}{1-\frac{2M}{r}-\frac{2J^2}{r^4}}}\, T_{\nu_i}(R_{\nu_i})$$

$$L_{\rm obs} = \left(1-\frac{2M}{R_{\nu_i}}-\frac{2J^2}{R_{\nu_i}^4}\right)L_{\nu_i}(R_{\nu_i})$$

$$L_{\nu_i}(R_{\nu_i}) = 4\pi R_{\nu_i}^2 \frac{7}{16} a T_{\nu_i}^4(R_{\nu_i})$$

Combined effects (Z′+background spacetimes)

Extending gravity sector+ extending particle sector

The total energy deposition rate

$$\dot{Q}_{\nu_i} = \int_{R_{\nu_i}}^{\infty} \dot{q_{\nu_i}} \frac{4\pi r^2 dr}{\sqrt{1 - \frac{2M}{r} - \frac{2J^2}{r^4}}}$$

$$\dot{Q}^{\rm HT}_{\nu_e} = \frac{28\pi^7}{(2\pi)^6} k^9 \zeta(5) \times \Big[\frac{G_F^2}{3\pi}(1 + 4\sin^2\theta_W + 8\sin^4\theta_W) + \frac{4g'^4}{6\pi M_{Z'}^4} + \frac{4G_F g'^2}{3\sqrt{2}\pi M_{Z'}^2}\Big(-\frac{1}{2} + 2\sin^2\theta_W\Big) + \frac{4G_F g'^2}{3\sqrt{2}\pi M_{Z'}^2}\Big]\Big(1 - \frac{2M}{R_{\nu_e}} - \frac{2J^2}{R_{\nu_e}^4}\Big)^{\frac{9}{4}}\Big(\frac{7\pi a}{4}\Big)^{-\frac{9}{4}} R_{\nu_e}^{-\frac{3}{2}} L_{\rm obs}^{\frac{9}{4}} \int_1^{\infty} \frac{y_{\nu_e}^2 dy_{\nu_e}}{\Big(1 - \frac{2M}{y_{\nu_e}R_{\nu_e}} - \frac{2J^2}{(y_{\nu_e}R_{\nu_e})^4}\Big)^5}(1 - x_{\nu_e}^{\rm HT})^4 (x_{\nu_e}^{2\ \rm HT} + 4x_{\nu_e}^{\rm HT} + 5),$$

Contd…

$$\dot{Q}^{\mathrm{HT}}_{\nu_{\mu,\tau}} = \frac{28\pi^7}{(2\pi)^6} k^9 \zeta(5) \times \Big[\frac{G_F^2}{3\pi}(1 - 4\sin^2\theta_W + 8\sin^4\theta_W) + \frac{4g'^4}{6\pi M_{Z'}^4} + \frac{4G_F g'^2}{3\sqrt{2}\pi M_{Z'}^2}\Big(-\frac{1}{2} + 2\sin^2\theta_W\Big)\Big]\Big(1 - \frac{2M}{R_{\nu_{\mu,\tau}}} - \frac{2J^2}{R^4_{\nu_{\mu,\tau}}}\Big)^{\frac{9}{4}}\Big(\frac{7\pi a}{4}\Big)^{-\frac{9}{4}} R_{\nu_{\mu,\tau}}^{-\frac{3}{2}} L_{\mathrm{obs}}^{\frac{9}{4}} \int_1^\infty \frac{y^2_{\nu_{\mu,\tau}} dy_{\nu_{\mu,\tau}}}{\Big(1 - \frac{2M}{y_{\nu_{\mu,\tau}} R_{\nu_{\mu,\tau}}} - \frac{2J^2}{(y_{\nu_{\mu,\tau}} R_{\nu_{\mu,\tau}})^4}\Big)^5}(1 - x^{\mathrm{HT}}_{\nu_{\mu,\tau}})^4 (x^{2\ \mathrm{HT}}_{\nu_{\mu,\tau}} + 4x^{\mathrm{HT}}_{\nu_{\mu,\tau}} + 5),$$

Total energy $\longrightarrow \dot{Q}_{\nu_e} + \dot{Q}_{\nu_\mu,\nu_\tau}$

Contd…

In SM,

$$\dot{Q}_{51} = 1.09 \times 10^{-5} F\left(\frac{M}{R}, \frac{J}{R^2}\right) D L_{51}^{9/4} R_6^{-3/2}$$

$$\dot{Q}_{51}^{HT} = \frac{\dot{Q}}{10^{51}\ \mathrm{erg/sec}},\ L_{51} = \frac{L_{\mathrm{obs}}}{10^{51}\ \mathrm{erg/sec}},\ R_6 = \frac{R}{10\ \mathrm{km}}$$

$$D = 1 \pm 4\sin^2\theta_w + 8\sin^4\theta_w$$

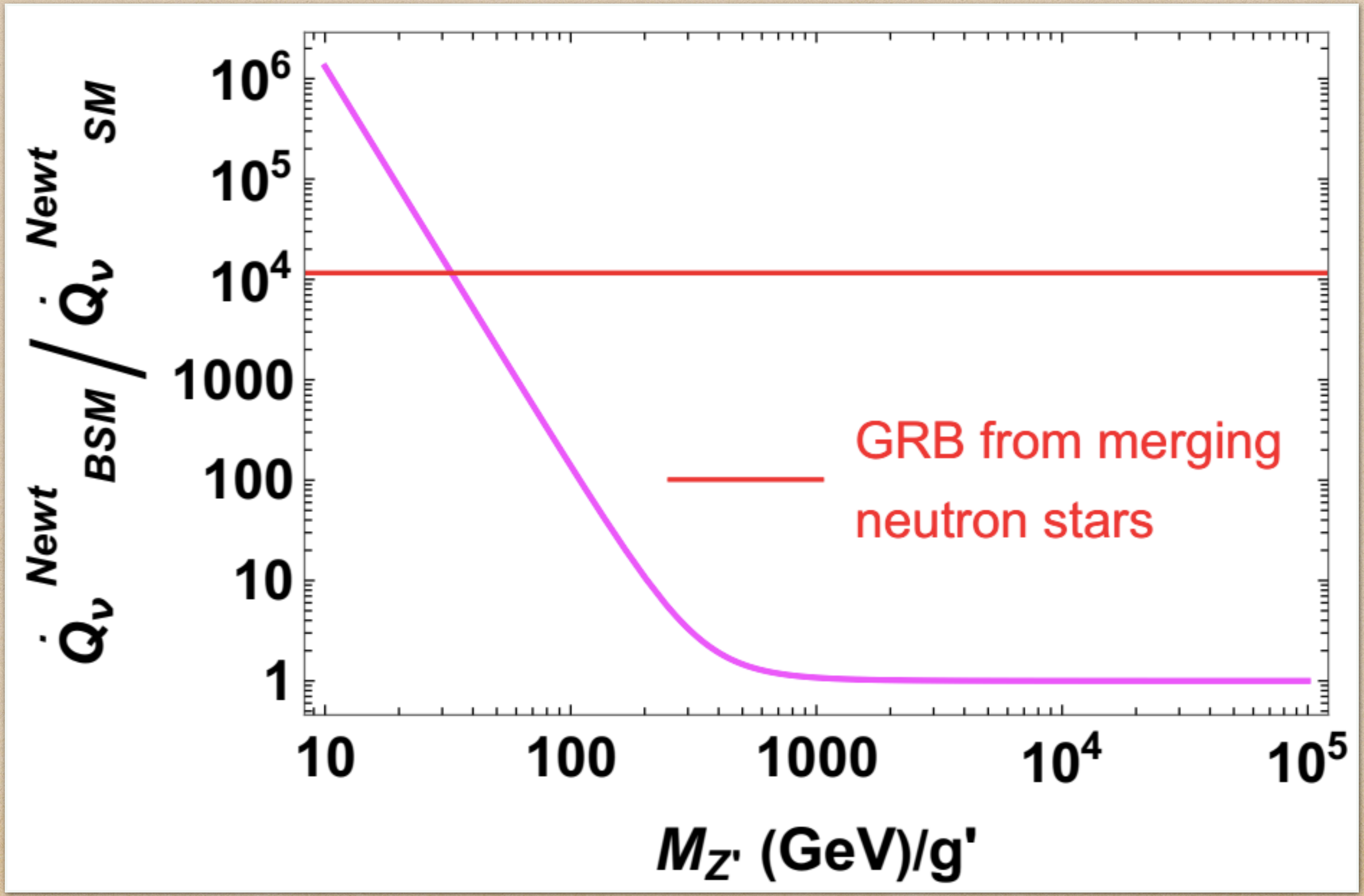
The enhancement factor

$$F\left(\frac{M}{R}, \frac{J}{R^2}\right) = 3\left(1 - \frac{2M}{R} - \frac{2J^2}{R^4}\right)^{9/4} \int_1^\infty \frac{y^2 dy}{\left(1 - \frac{2M}{yR} - \frac{2J^2}{(yR)^4}\right)^5} (1 - x^{\mathrm{HT}})^4 (x^{2\,\mathrm{HT}} + 4x^{\mathrm{HT}} + 5)$$

$$Q_{\mathrm{SM}}^{\mathrm{Sch}} = 2.4 \times 10^{48} F\left(\frac{M}{R}\right) R_6^{-3/2}\ \mathrm{erg} \quad \sim 2.5 \times 10^{49}\mathrm{erg}\ ,\frac{R}{M} = 3$$

Constraints on Z′: Results and Analysis

Newtonian background



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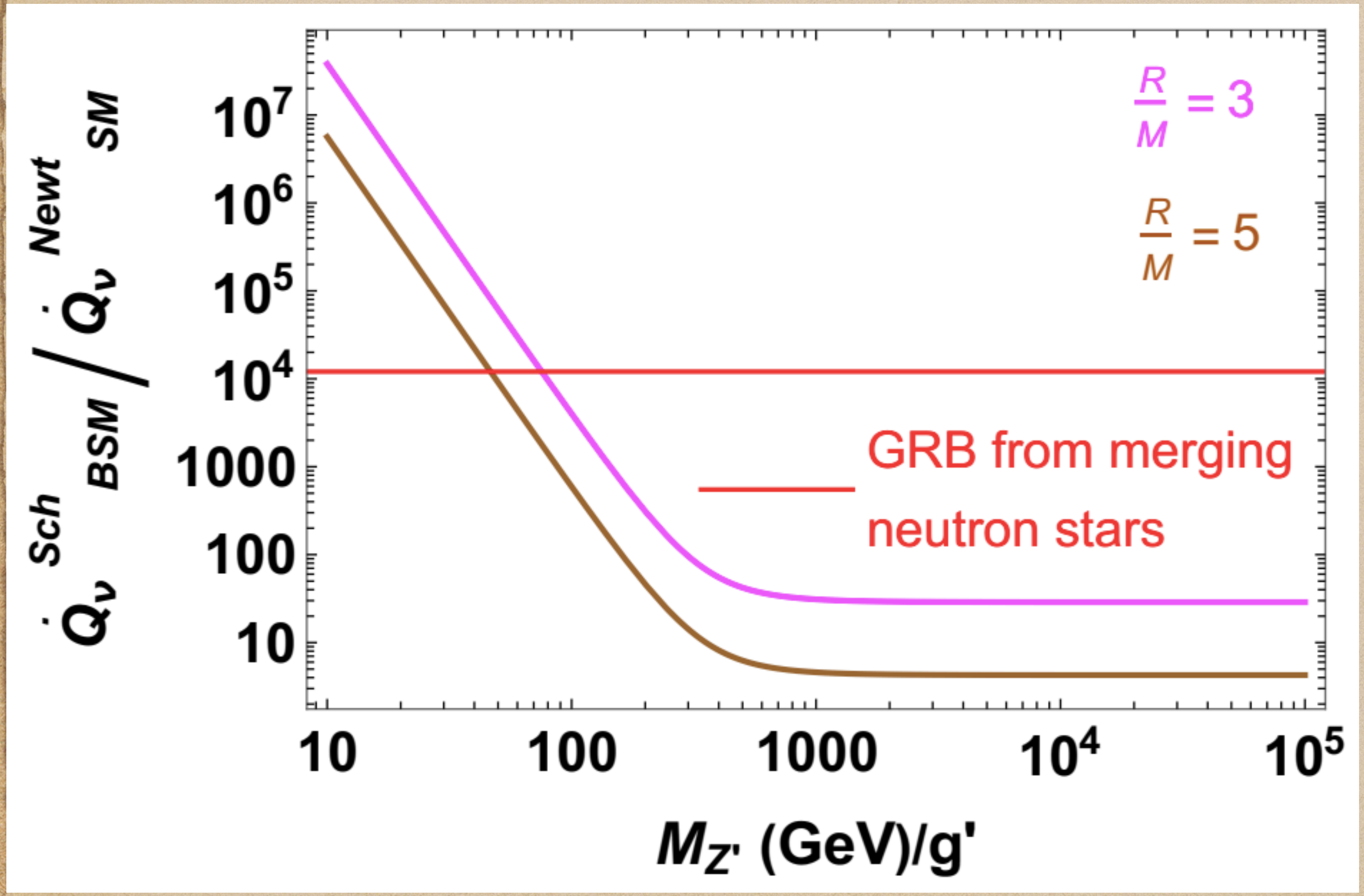
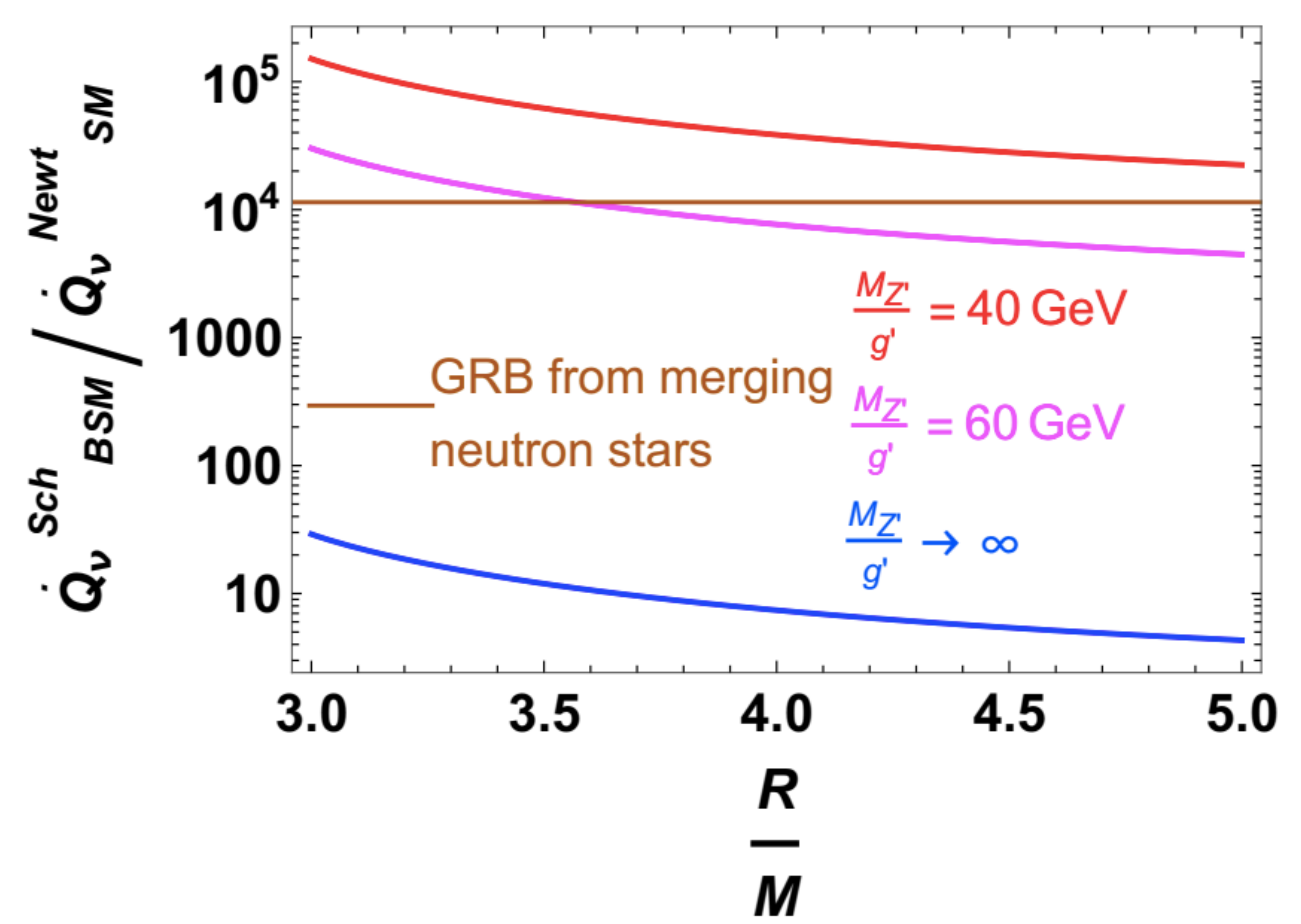
Schwarzschild background





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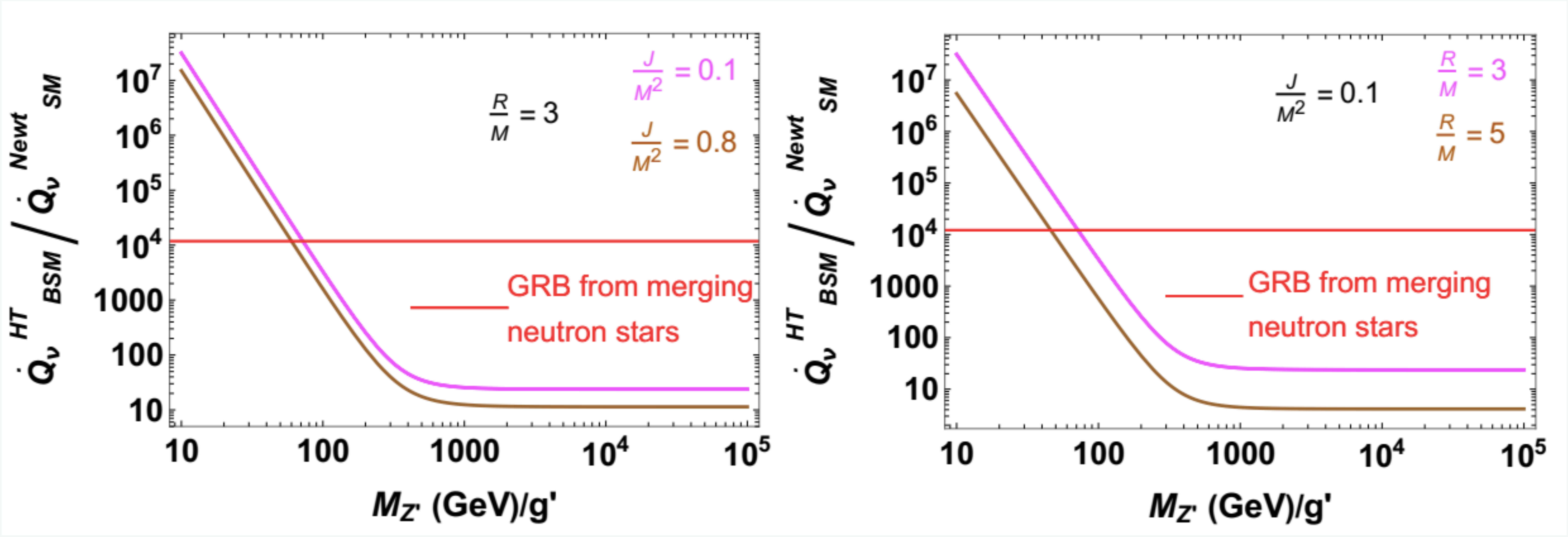
Hartle-Thorne background



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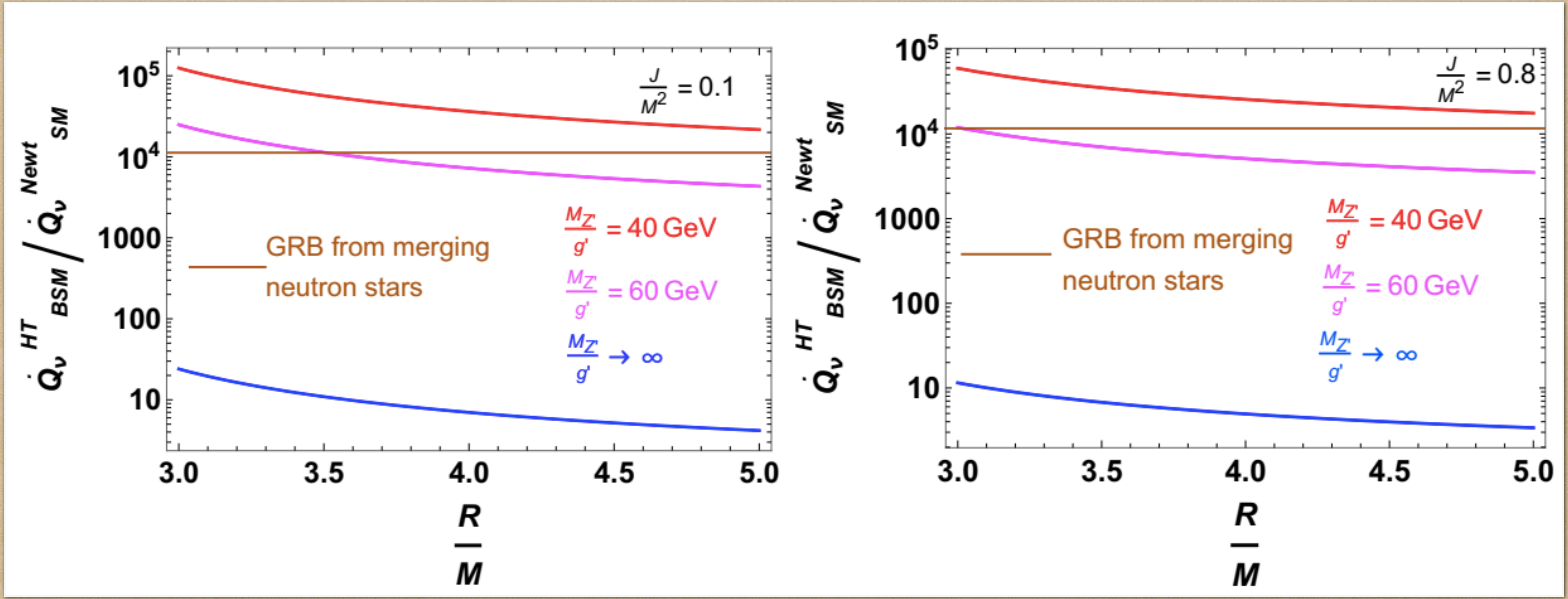
Hartle-Thorne background



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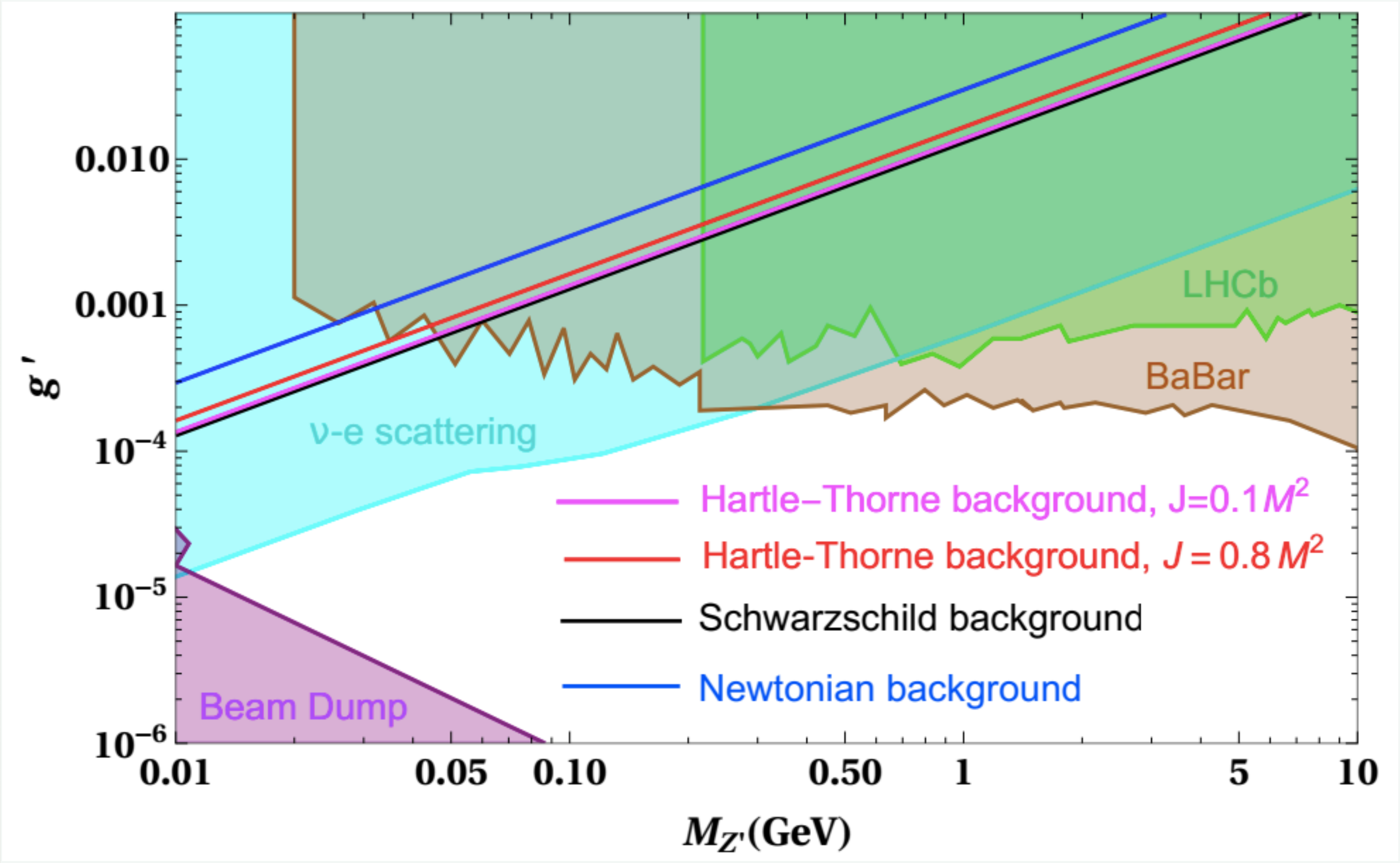

0.010
0.001
10^{-4}
10^{-5}
10^{-6}
g'
0.01
0.05
0.10
0.50
1
5
10
$M_{Z'}$(GeV)
ν-e scattering
LHCb
BaBar
Beam Dump
Hartle–Thorne background, J=0.1M^2
Hartle-Thorne background, $J = 0.8\,M^2$
Schwarzschild background
Newtonian background

Conclusions

- The neutrino annihilation process is important since it can deposit energy in Several violent explosions and a possible source of powering GRB
- The energy deposition due to neutrino pair annihilation is enhanced in Schwarzschild, and Hartle-Thorne backgrounds compared to the Newtonian.
- However, the enhancement is not sufficient to explain the observed energy in GRB
- The contribution of Z' gauge boson in $U(1)$ extended SM can significantly enhance the energy deposition rate
- We obtain constraints on Z' from GRB

Thank You !