Constraints on light vector gauge boson from GRB observation

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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 a huge number of neutrinos make stellar objects cool, $L_\nu \sim 10^{53}$erg/s

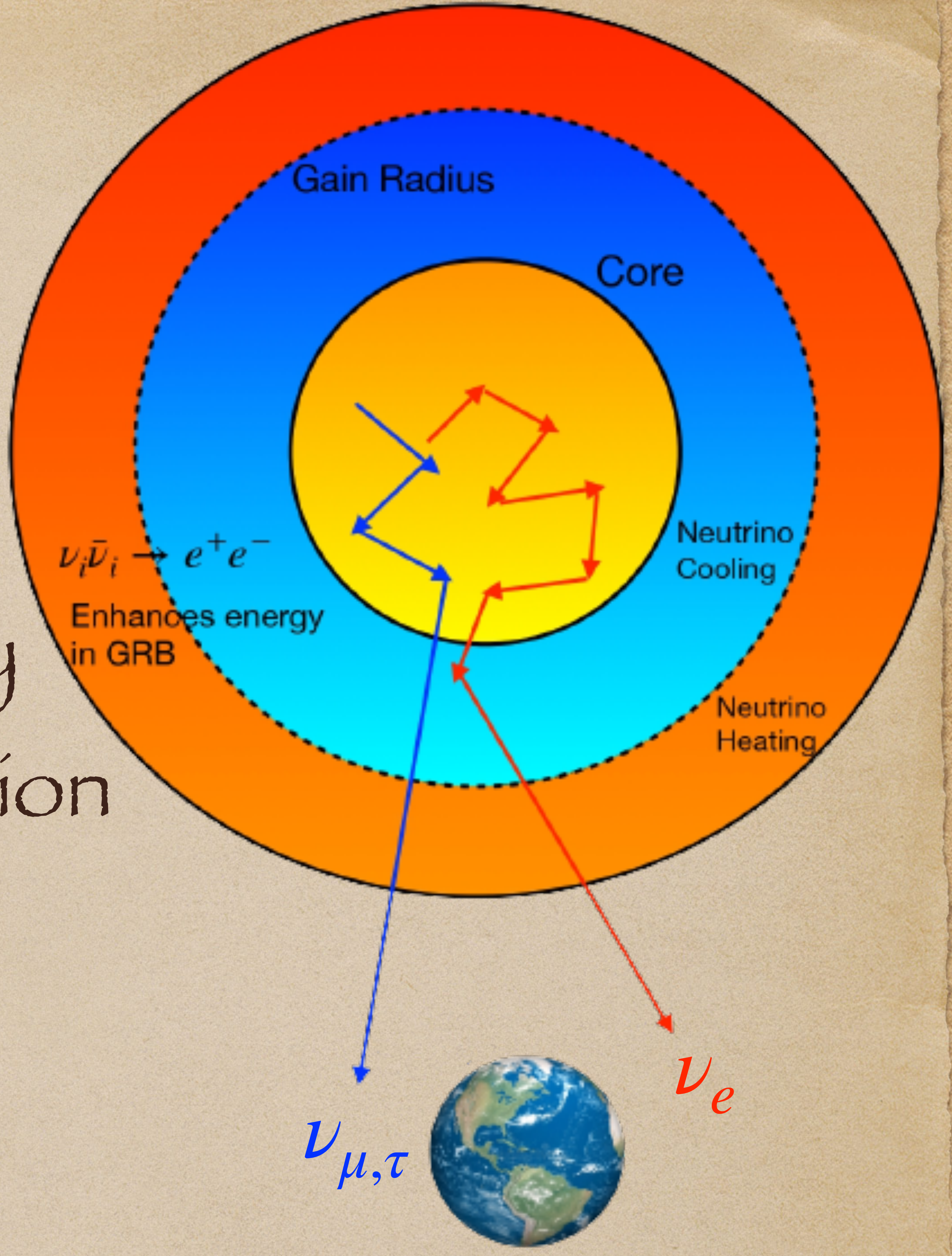
- Neutrino Heating: Neutrino flux can also deposit energy into the stellar envelope through neutrino pair annihilation

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

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

$E_{GRB}^{\rm Theory} \sim 1.5 \times 10^{50}$erg (Newtonian)

$E_{GRB}^{\rm Theory} \sim 4.3 \times 10^{51}$erg (Schwarzschild)



Could not match with the observations!!

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Extension in the gravity sector

- Modified gravity models
- Quintessence model
- Temperature gradient model etc…

Scope for extending 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

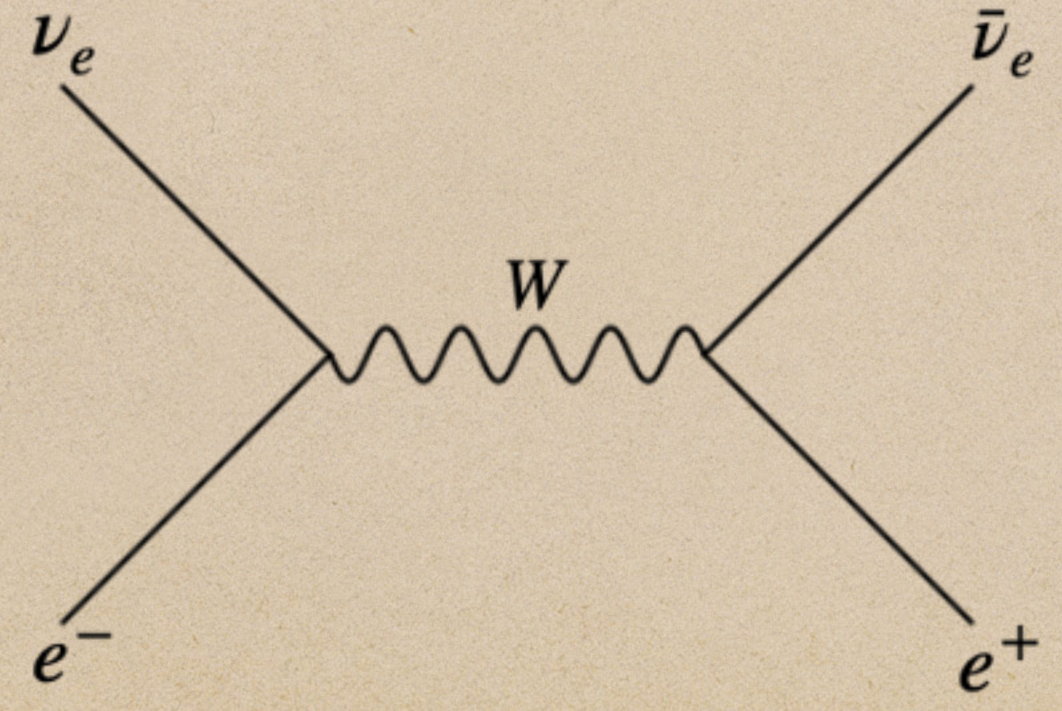
$$\dot{q}(r) = \int\int f_\nu(\mathbf{p}_\nu, r) f_{\bar{\nu}}(\mathbf{p}_{\bar{\nu}}, r)(\sigma|\mathbf{v}_\nu - \mathbf{v}_{\bar{\nu}}|E_\nu E_{\bar{\nu}}) \times \frac{E_\nu + E_{\bar{\nu}}}{E_\nu E_{\bar{\nu}}} d^3\mathbf{p}_\nu d^3\mathbf{p}_{\bar{\nu}},$$

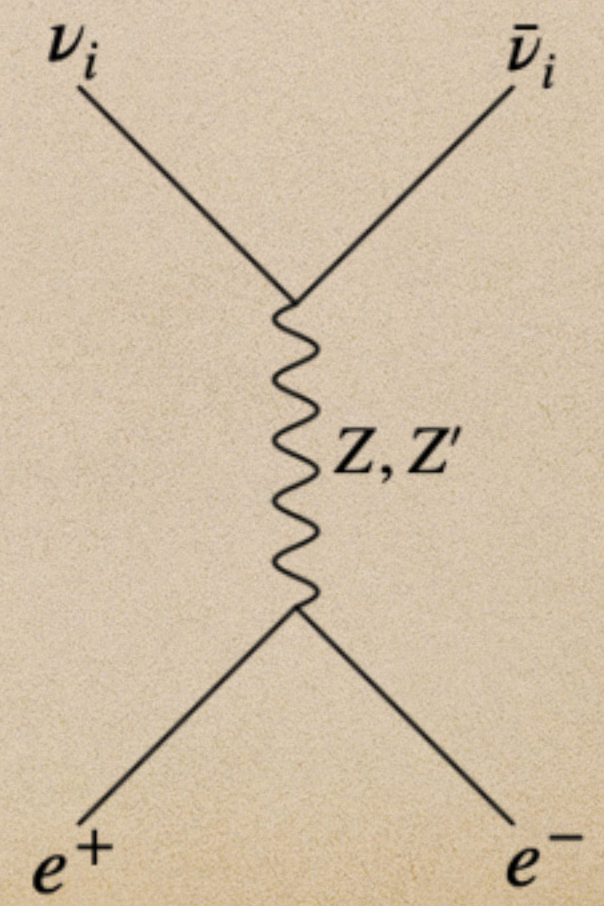
Also,

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

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

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





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$U(1)_X$:

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

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

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

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

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

$J \to 0$ 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 $\dot{q}$

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

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

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

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

Combined effects (Z′+background spacetimes)

Hartle-Thorne background

The total energy deposition rate

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

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

Contd…

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

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

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

$$\dot{Q}_{\mathrm{HT}} \sim 3.6 \times 10^{51} \mathrm{erg/s}, \frac{\mathrm{J}}{\mathrm{M}^2} = 0.1, \frac{\mathrm{R}}{\mathrm{M}} = 3$$

Born-Infeld generalisation of Reissner-Nordstrom (BIRN) solution

The metric

$$ds^2 = -f(r)dt^2 + f(r)^{-1}dr^2 + r^2 d\Omega^2$$

$$f(r) = 1 - \frac{2M}{r} + \frac{2}{3}b^2r^2\left(1 - \sqrt{1 + \frac{Q^2}{b^2r^4}}\right) + \frac{2Q^2}{3r}\sqrt{\frac{b}{Q}}F\left(\arccos\left(\frac{br^2/Q - 1}{br^2/Q + 1}\right), \frac{1}{\sqrt{2}}\right)$$

$$x_{\nu_i}^{BIRN} = \left[1 - \frac{R^2}{r^2}\left(\frac{1 - \frac{2M}{r} + \frac{2}{3}b^2r^2\left(1 - \sqrt{1 + \frac{Q^2}{b^2r^4}}\right) + \frac{2Q^2}{3r}\sqrt{\frac{b}{Q}}F\left(\arccos\left(\frac{br^2/Q - 1}{br^2/Q + 1}\right), \frac{1}{\sqrt{2}}\right)}{1 - \frac{2M}{R} + \frac{2}{3}b^2R^2\left(1 - \sqrt{1 + \frac{Q^2}{b^2R^4}}\right) + \frac{2Q^2}{3R}\sqrt{\frac{b}{Q}}F\left(\arccos\left(\frac{bR^2/Q - 1}{bR^2/Q + 1}\right), \frac{1}{\sqrt{2}}\right)}\right)\right]^{\frac{1}{2}}$$

Quintessence

The metric

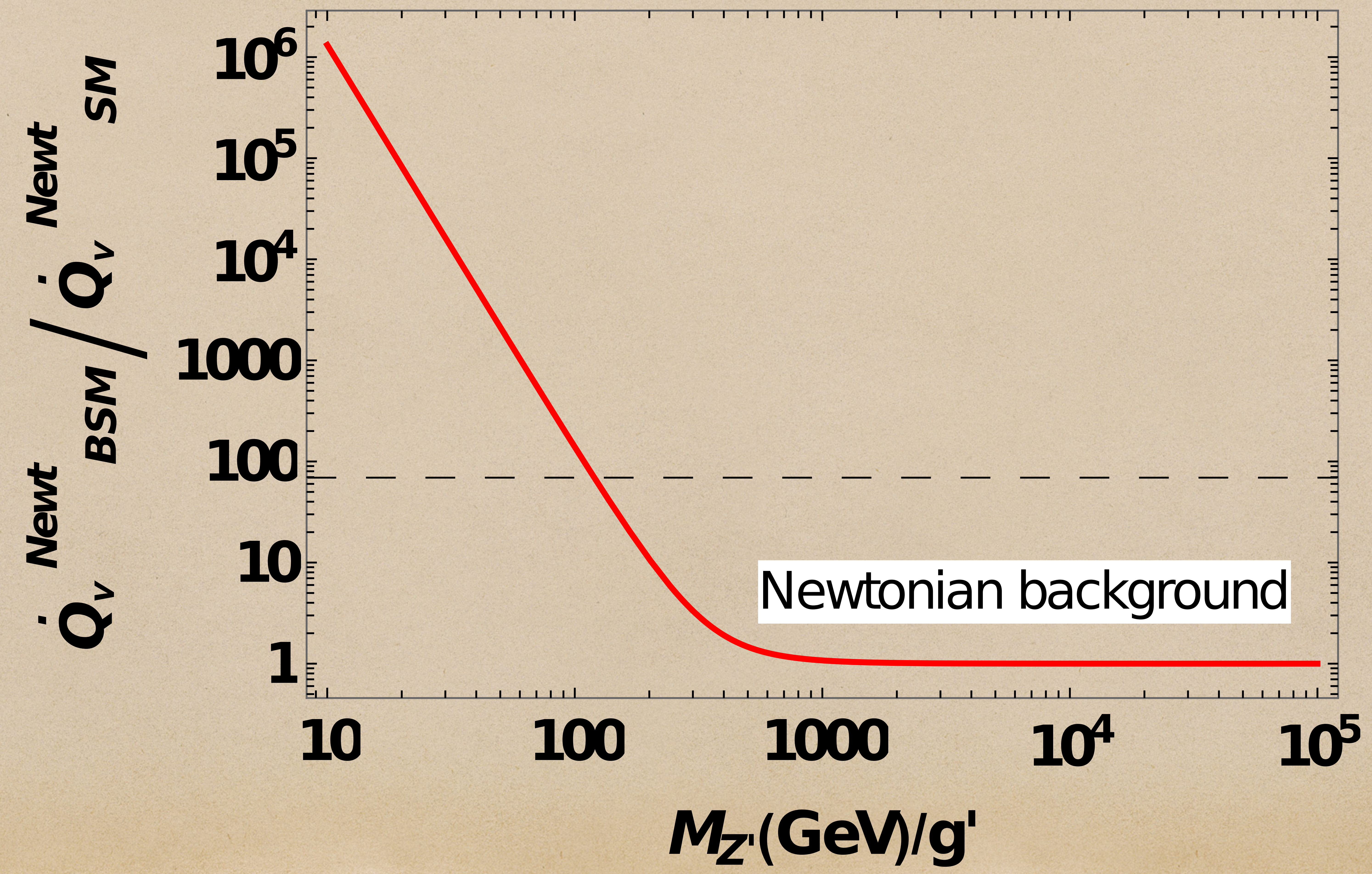
$$ds^2 = -f(r)dt^2 + f(r)^{-1}dr^2 + r^2 d\Omega^2$$

$$f(r) = 1 - \frac{2M}{r} - \frac{c}{r^{3\omega+1}}$$

$$x_{\nu_i}^{Quint} = \left[1 - \frac{R^2}{r^2}\left(\frac{1 - \frac{2M}{r} - \frac{c}{r^{3\omega+1}}}{1 - \frac{2M}{R} - \frac{c}{R^{3\omega+1}}}\right)\right]^{\frac{1}{2}}$$

Constraints on Z′: Results and Analysis

Newtonian background



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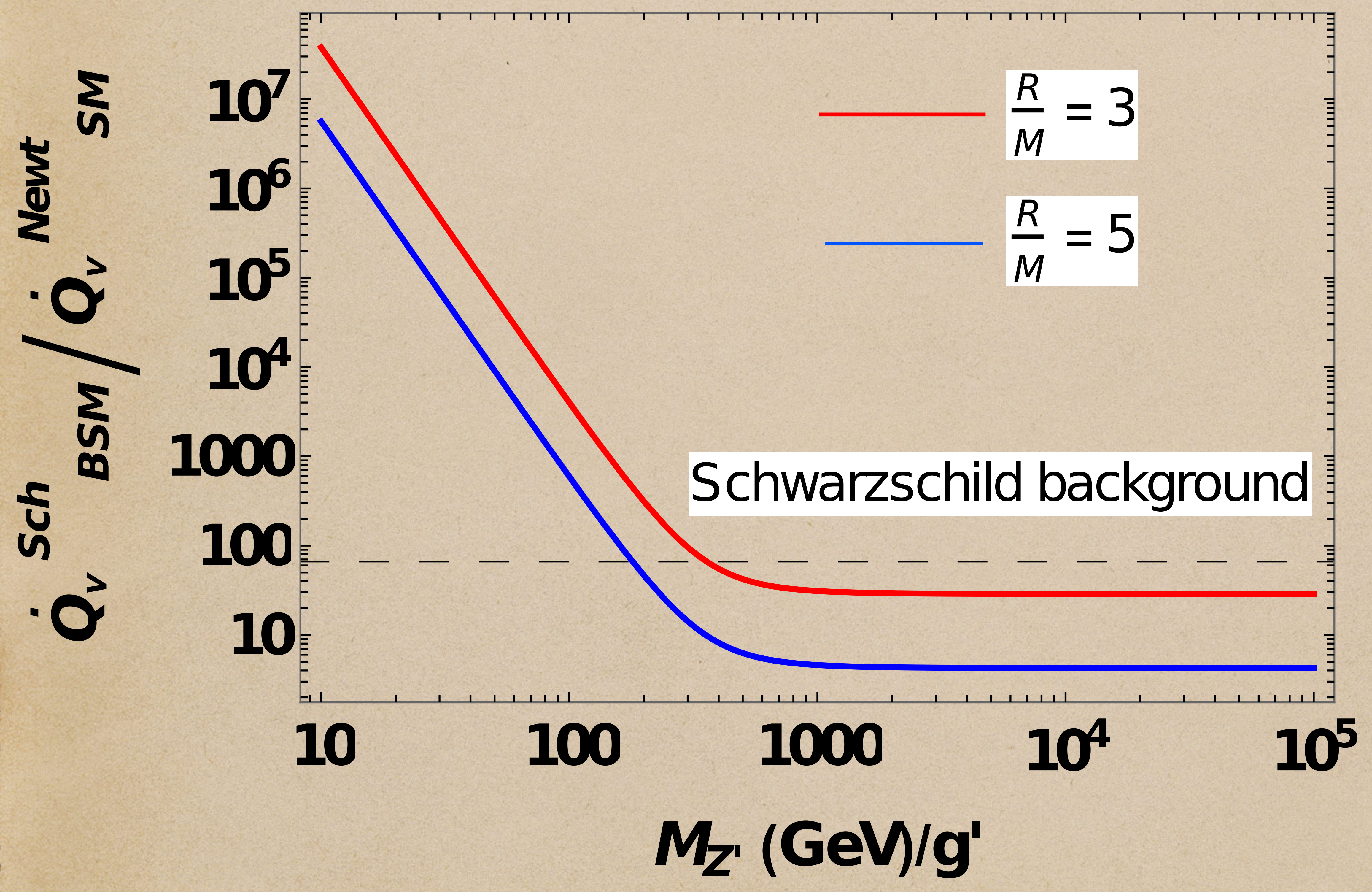
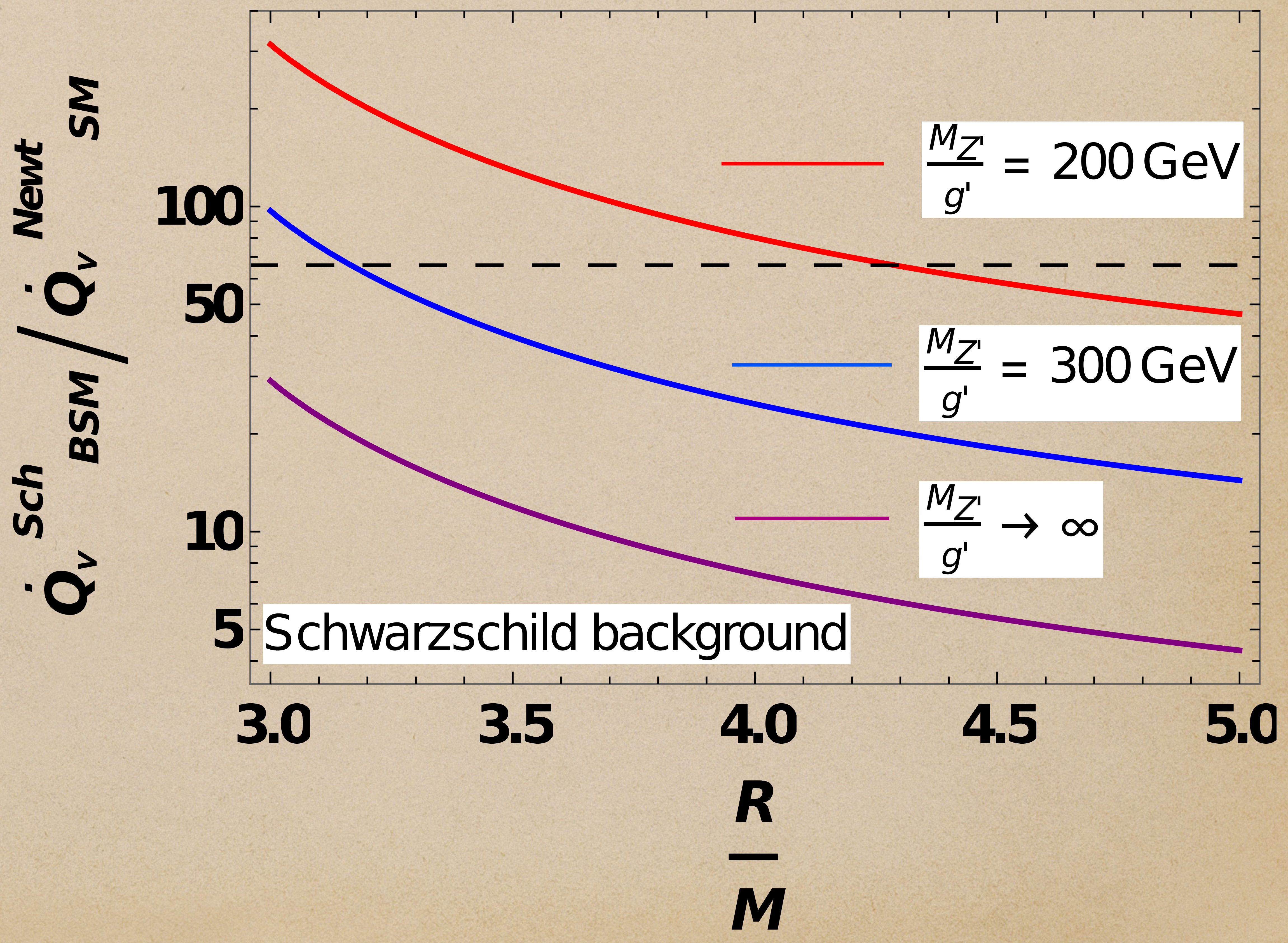
Schwarzschild background





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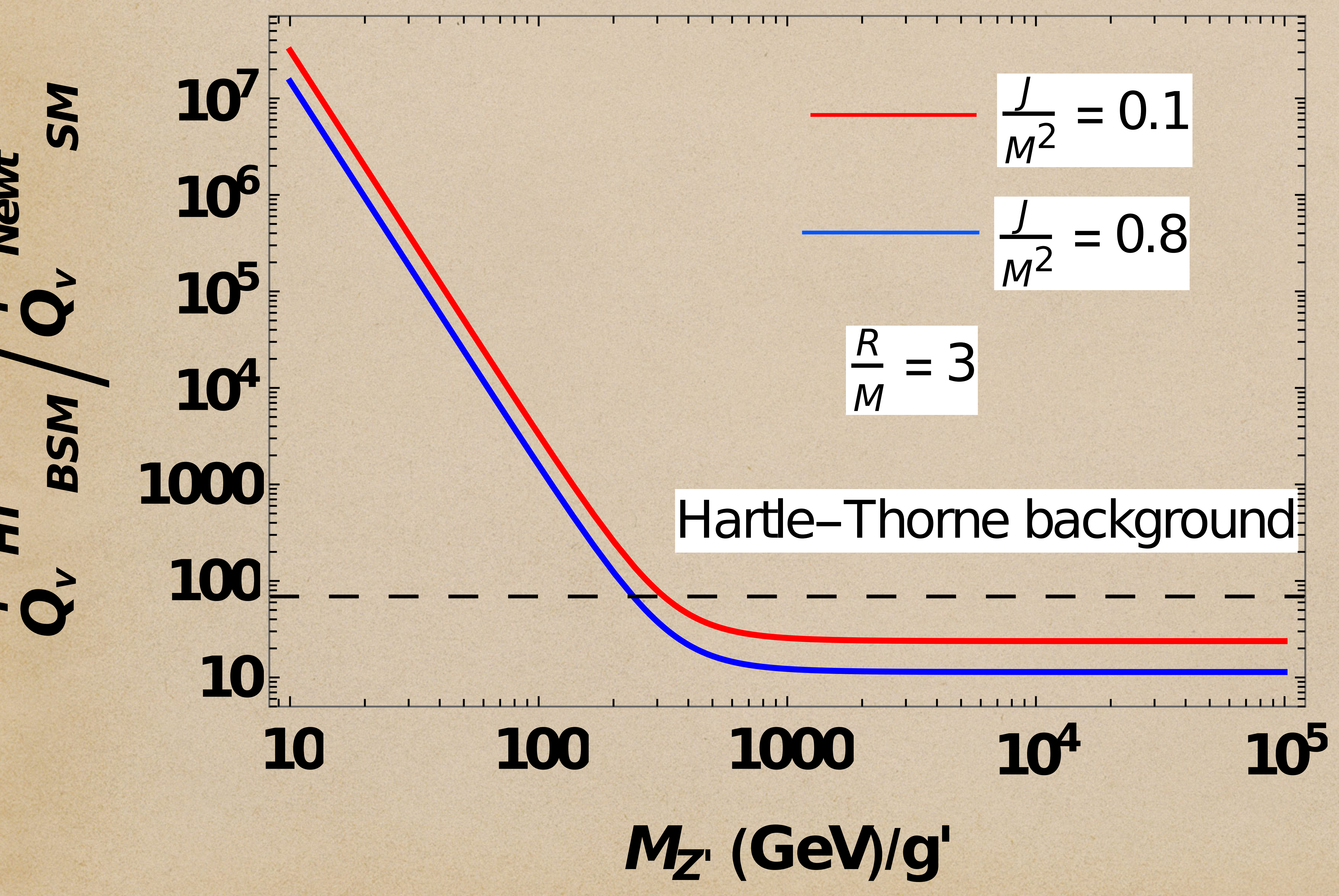
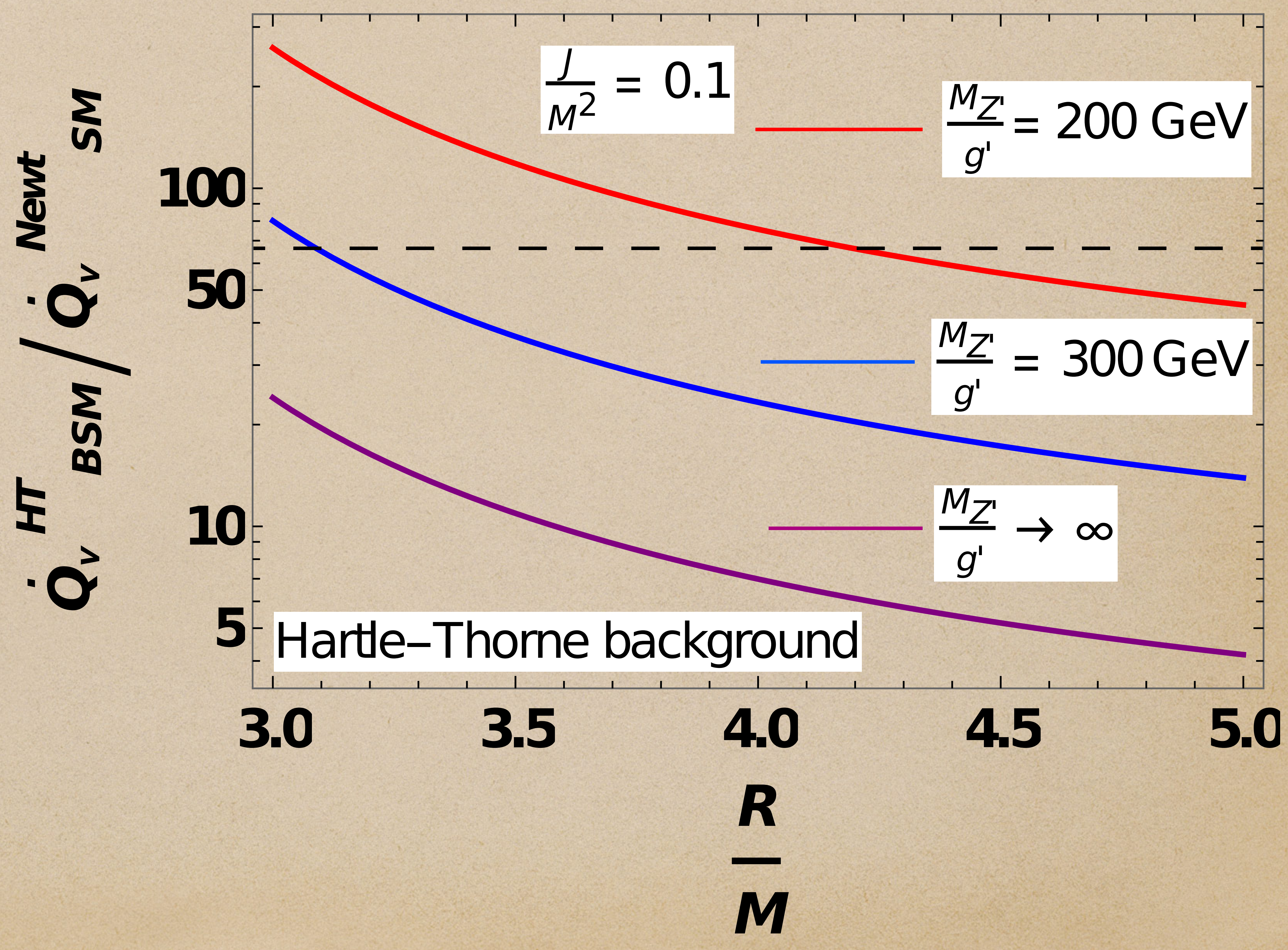
Hartle-Thorne background





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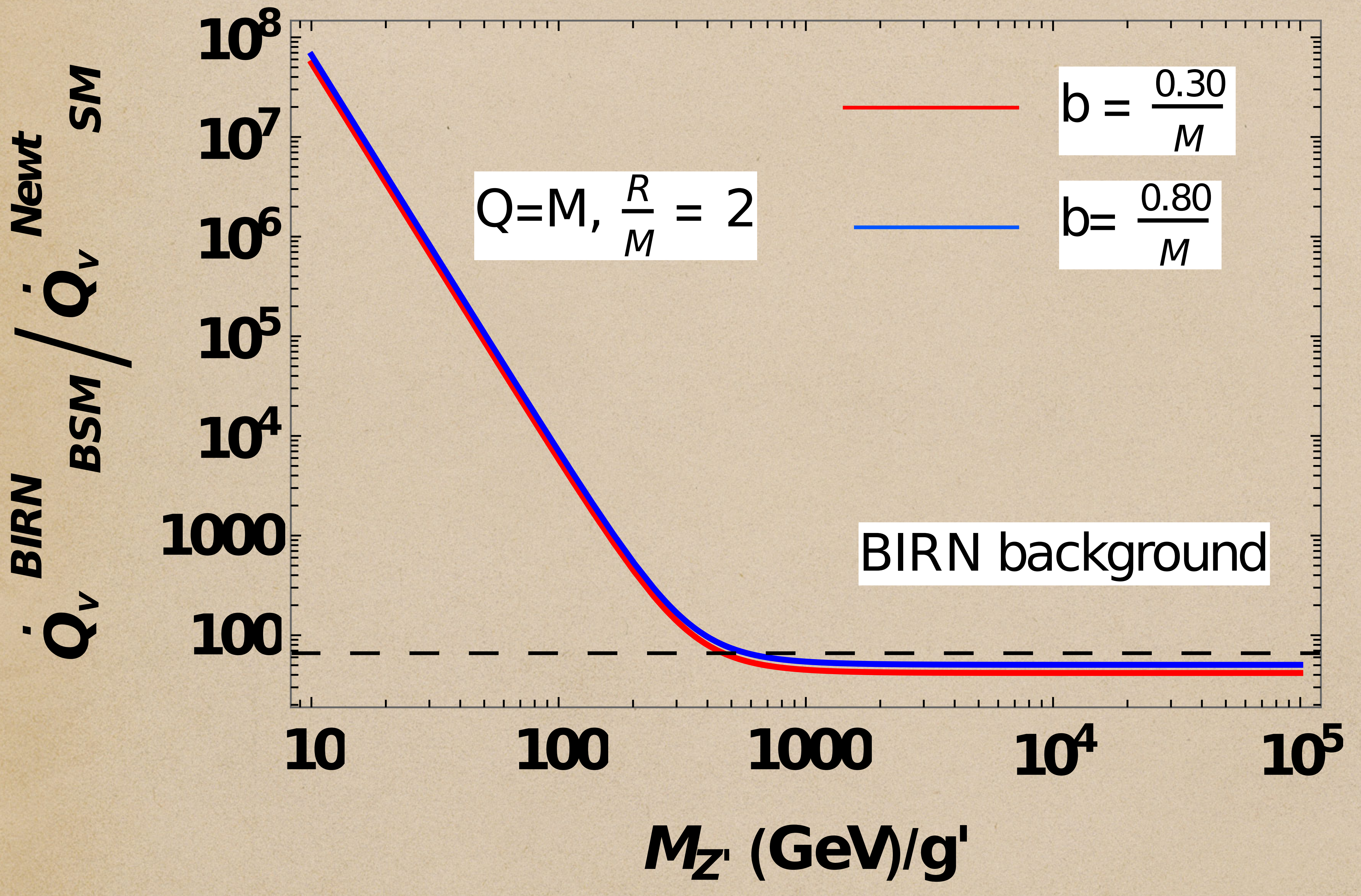
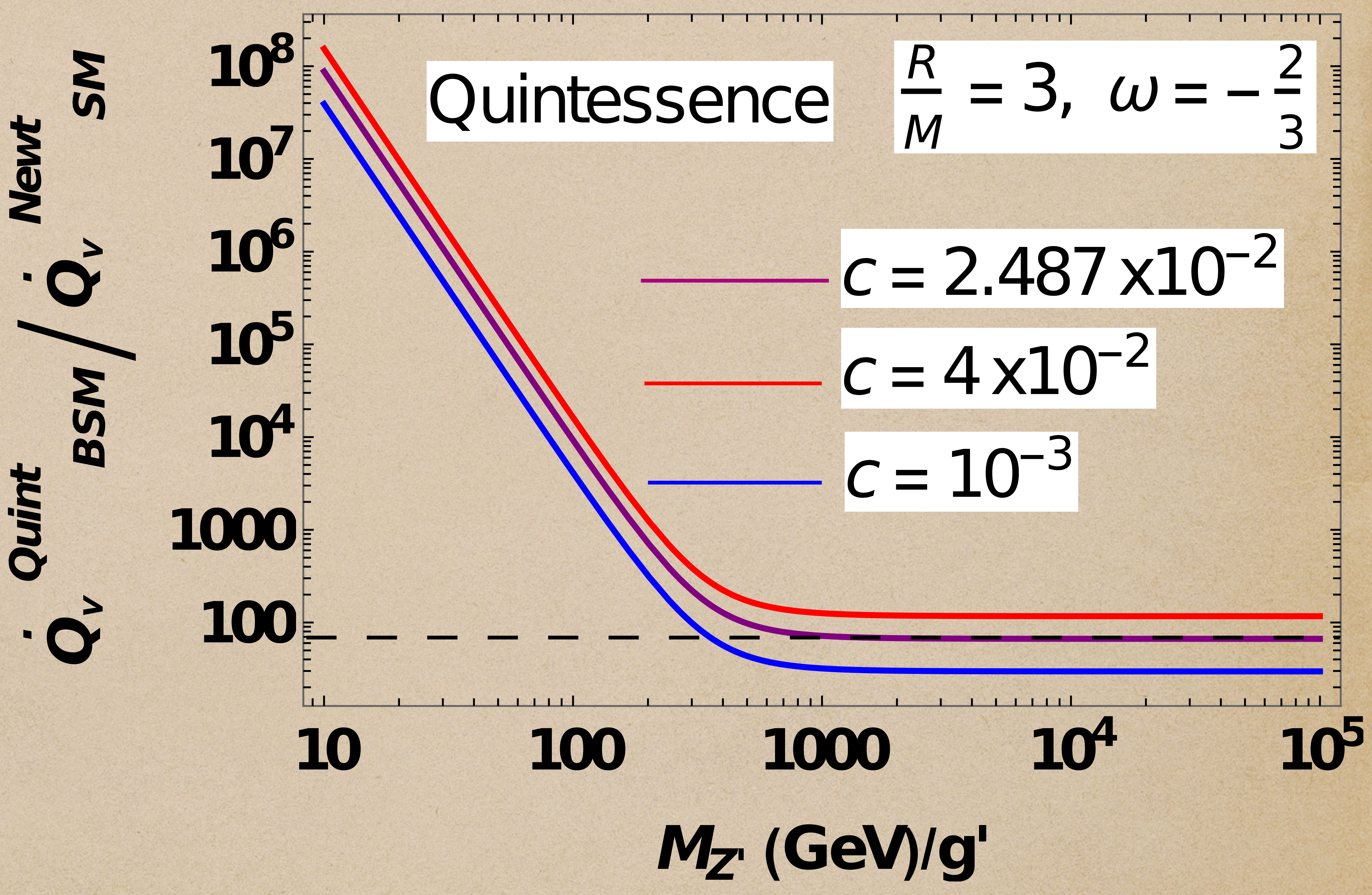
BIRN and Quintessence background





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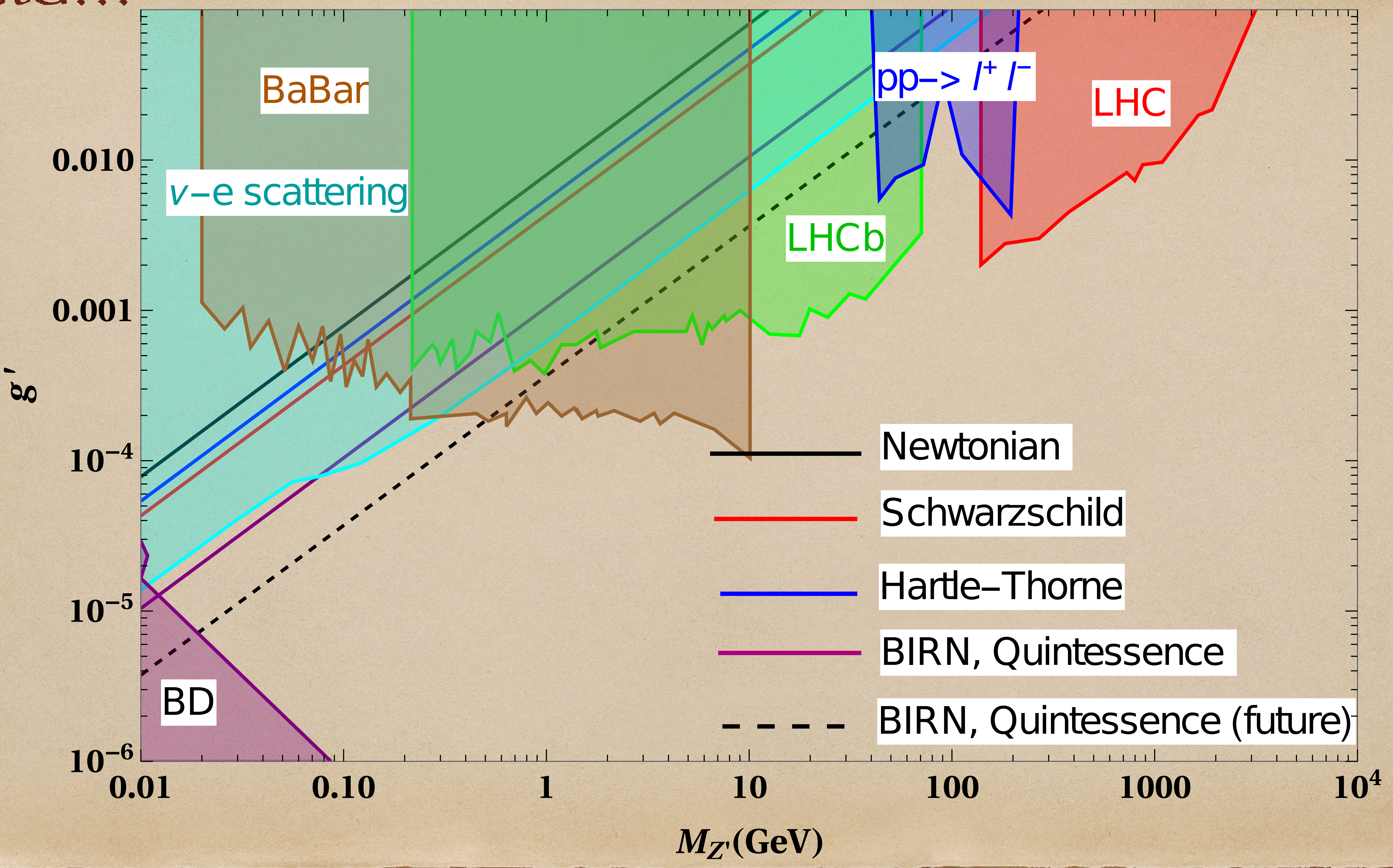
BaBar
ν−e scattering
LHCb
pp−> l⁺ l⁻
LHC
BD
Newtonian
Schwarzschild
Hartle−Thorne
BIRN, Quintessence
BIRN, Quintessence (future)
0.010
0.001
10⁻⁴
10⁻⁵
10⁻⁶
g′
0.01
0.10
1
10
100
1000
10⁴
M_Z′(GeV)

Conclusions

- We obtain constraints on Z' gauge bosons from neutrino pair annihilation in energizing GRB.

- The bound on Z' depends on the background spacetime. We obtain stronger bound on Z' from BIRN and Quintessence backgrounds.

- The effects of any trapping of neutrinos and nonlinear magnetic field can significantly change the energy deposition rate.

- Measurements of GRB energy with increased precision can strengthen the bound on Z'.

Thank You !