EMISSION AND ANNIHILATION OF $\nu\bar{\nu}$ PAIRS AS THE GENERATION ENGINE OF LONG GRBs UNDER THE IGC MODEL

Eduar A. Becerra[1,2,3]

In collaboration Whit

Juan D. Uribe[2]

Advisor

Prof. Jorge Rueda[2,4] and **Prof. Guillermo González**[1]

Postgraduate Seminaries

[1] Escuela de Física, Universidad Industrial de Santander

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[2] International Center for Relativistic Astrophysics Network

[3] Dipartimento di Fisica, Sapienza Università di Roma

[4] Dipartimento di Fisica e Scienze della Terra, Università degli Studi di Ferrara

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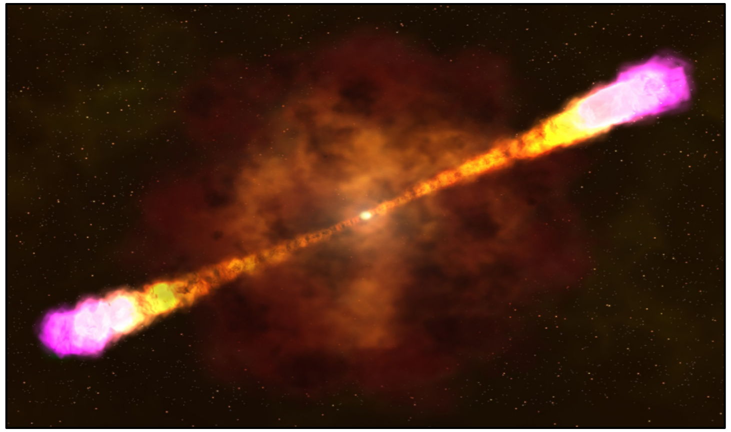
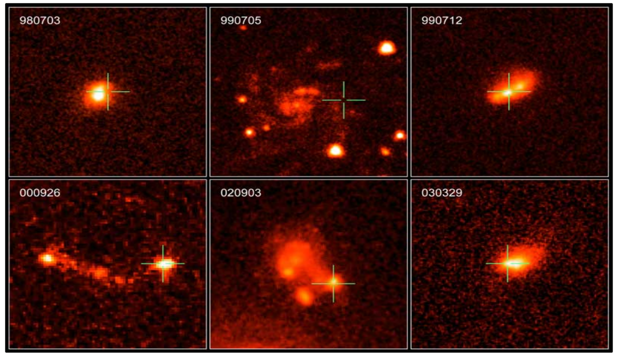
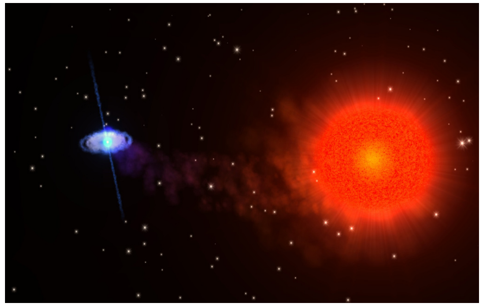
IGC and GRBs



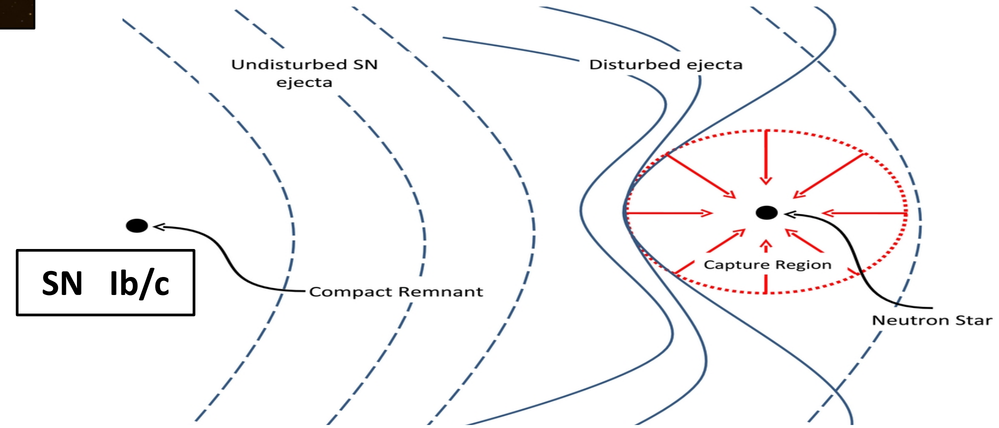


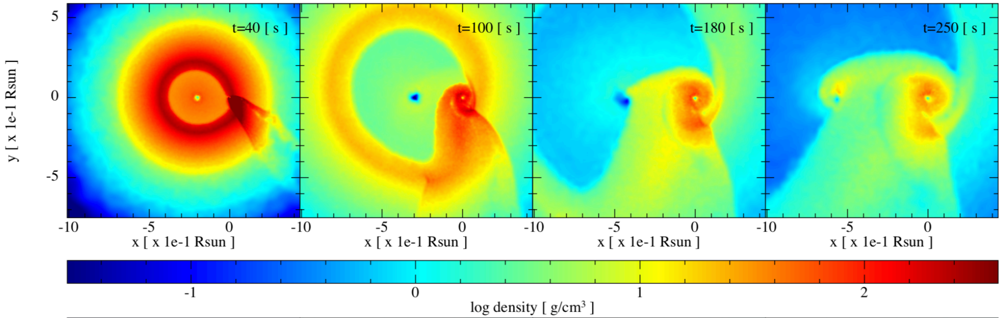
$$10^{47} - 10^{54} \; erg \; s^{-1}$$

IGC



- Core ⟶ C,O
- NS companion





- $10^{-2} \; M_{\odot} \; s^{-1}$
- $10 - 10^{4} \; s$

Super-Accretion

$\geq 10^{-4} \; M_{\odot} \; s^{-1}$

↓

Collapse into BH

↓

GRB emission

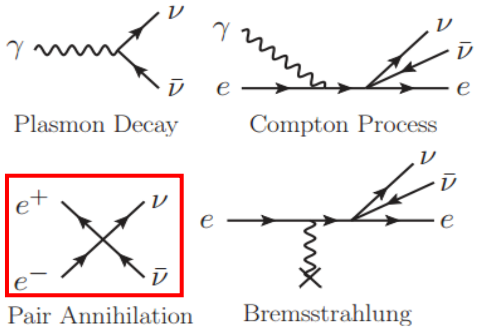
Becerra, L., F. Cipolletta, C. L. Fryer, J. A. Rueda, and R. Ruffini. ApJ, 812(2):100 (201
Becerra, L. and Bianco, C.L. and Fryer, C.L. and Rueda, J.A. and Ruffini, R., *ApJ*, 833(
Becerra, L. and Ellinger, C.L. and Fryer, C.L. and Rueda, J.A. and Ruffini, R., ApJ, 871

Importance of the Neutrinos

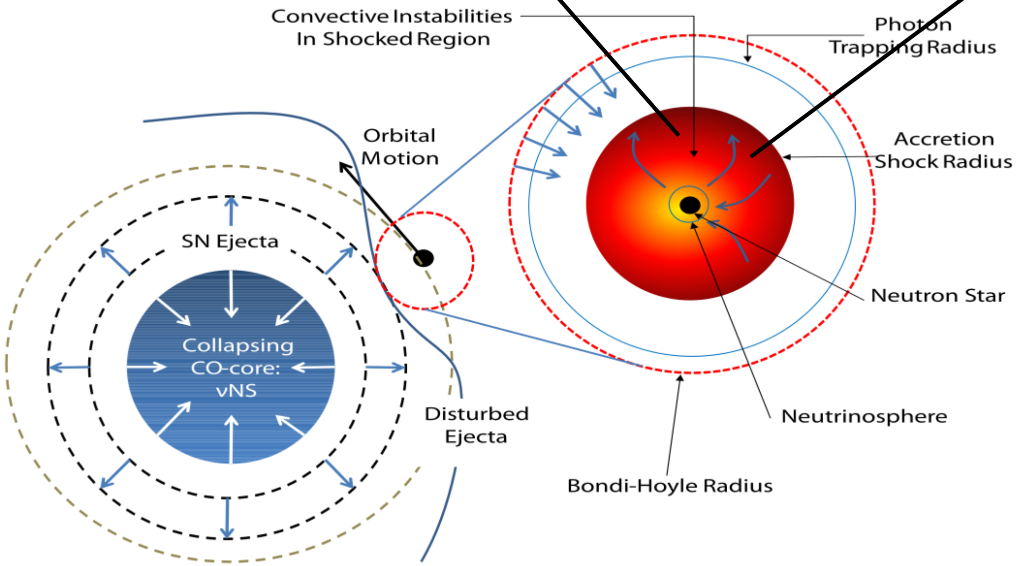
$\rho \sim 10^{10} - 10^{13}\ cm^{-3}$

$T \sim 10^{10} - 10^{11}\ K$

- γ ⟶ trapped
- $\nu\bar{\nu}$ ⟶ emision



- luminosities up to $10^{57}\ MeV\ s^{-1}$
- Average neutrino energies of $20\ MeV$
- Neutrino densities of $10^{31}\ cm^{-3}$



Neutrino dominated accretion fluxes

↓

Annihilation

$\nu\bar{\nu} \rightarrow e^- + e^+ \rightarrow \gamma + \gamma$

↓

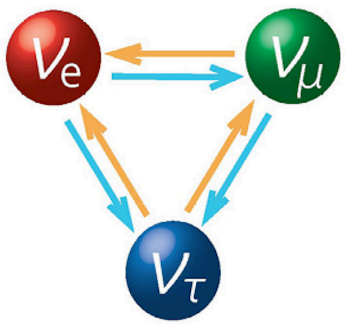
A plasma dominated by e^-e^+ is created → can generate a relativistic jet

↓

GRB

Becerra, Laura, et al. Neutrino Oscillations within the Induced Gravitational Collapse Paradigm of Long Gamma-Ray Bursts. *The Astrophysical Journal* 852.2 (2018): 120.
Popham, R., S. E. Woosley, and C. Fryer. Hyperaccreting black holes and gamma-ray bursts. The Astrophysical Journal, 518(1):356 (1999).
Aloy, M. A., H.-T. Janka, and E. Muller. Relativistic outflows from remnants of compact object mergers and their viability for short gamma-ray bursts. Astronomy & Astrophysics, 436(1):273–311 (2005).

Neutrino Oscillations



$$-\frac{\partial \rho_{\mathbf{p}}}{\partial t} = i\,[H_{\mathbf{p}}, \rho_{\mathbf{p}}]\,, \qquad -\frac{\partial \bar{\rho}_{\mathbf{p}}}{\partial t} = i\,[\bar{H}_{\mathbf{p}}, \bar{\rho}_{\mathbf{p}}]$$

→ $\rho_{\mathbf{p}}$ occupation number matrix

two-flavor approximation → $\nu_e \leftrightharpoons \nu_x = \nu_\mu + \nu_\tau$ →

$$\rho_{\mathbf{p}} = \begin{pmatrix} \rho_{ee} & \rho_{ex} \\ \rho_{xe} & \rho_{xx} \end{pmatrix}_{\mathbf{p}} = \frac{1}{2}\left(f_{\mathbf{p}}\mathbb{1} + \mathsf{P}_{\mathbf{p}} \cdot \vec{\sigma}\right)$$

can occur at length as small as 0.05 a 1 km.

$$f_p = \mathrm{Tr}[\rho_p] = f_{\nu_e}(p) + f_{\nu_x}(p)$$

$$\mathsf{H} = \mathsf{H}_{\text{vacuum}} + \mathsf{H}_{\text{matter}} + \mathsf{H}_{\nu\nu}$$

$$\mathsf{H}_{\nu\nu} = \sqrt{2}G_F \left[\int \frac{d^3\mathbf{q}}{(2\pi)^3}\left(\mathbf{P}_{\mathbf{q}} - \bar{\mathbf{P}}_{\mathbf{q}}\right)\left(1 - \cos\theta_{\mathbf{pq}}\right)\right] \cdot \vec{\sigma}$$

$$\mathsf{H}_{\text{vacuum}} = \frac{\omega_{\mathbf{p}}}{2}\begin{pmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix} = \frac{\omega_{\mathbf{p}}}{2}\vec{B}\cdot\vec{\sigma}$$

$$\mathsf{H}_{\text{matter}} = \frac{\lambda}{2}\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} = \frac{\lambda}{2}\vec{L}\cdot\vec{\sigma}$$

P_{p} → Polarization vector in flavor space

$\vec{\sigma}$ → Pauli matrices

$$\omega_{\mathbf{p}} = \Delta m^2/2p,\ \vec{B} = (\sin 2\theta, 0, -\cos 2\theta)$$

$$\lambda = \sqrt{2}G_F\,(n_{e^-} - n_{e^+}) \qquad \vec{L} = (0, 0, 1)$$

θ → mixing angle in vacuum

$$\partial_t \mathbf{P}_{\mathbf{p}} = +\left\{\omega_{\mathbf{p}}\mathbf{B} + \lambda\mathbf{L} + \sqrt{2}G_F \int \frac{d^3\mathbf{q}}{(2\pi)^3}\left(\mathbf{P}_{\mathbf{q}} - \bar{\mathbf{P}}_{\mathbf{q}}\right)\left(1 - \cos\theta_{\mathbf{pq}}\right)\right\} \times \mathbf{P}_{\mathbf{p}}$$

$$\partial_t \bar{\mathbf{P}}_{\mathbf{p}} = -\left\{\omega_{\mathbf{p}}\mathbf{B} - \lambda\mathbf{L} + \sqrt{2}G_F \int \frac{d^3\mathbf{q}}{(2\pi)^3}\left(\mathbf{P}_{\mathbf{q}} - \bar{\mathbf{P}}_{\mathbf{q}}\right)\left(1 - \cos\theta_{\mathbf{pq}}\right)\right\} \times \bar{\mathbf{P}}_{\mathbf{p}}$$

→ If the z component of the polarization vector obeys: →

$$\mathsf{P}^z_{\mathbf{p}} = f_{\nu_e}(\mathbf{p}) - f_{\nu_x}(\mathbf{p})$$

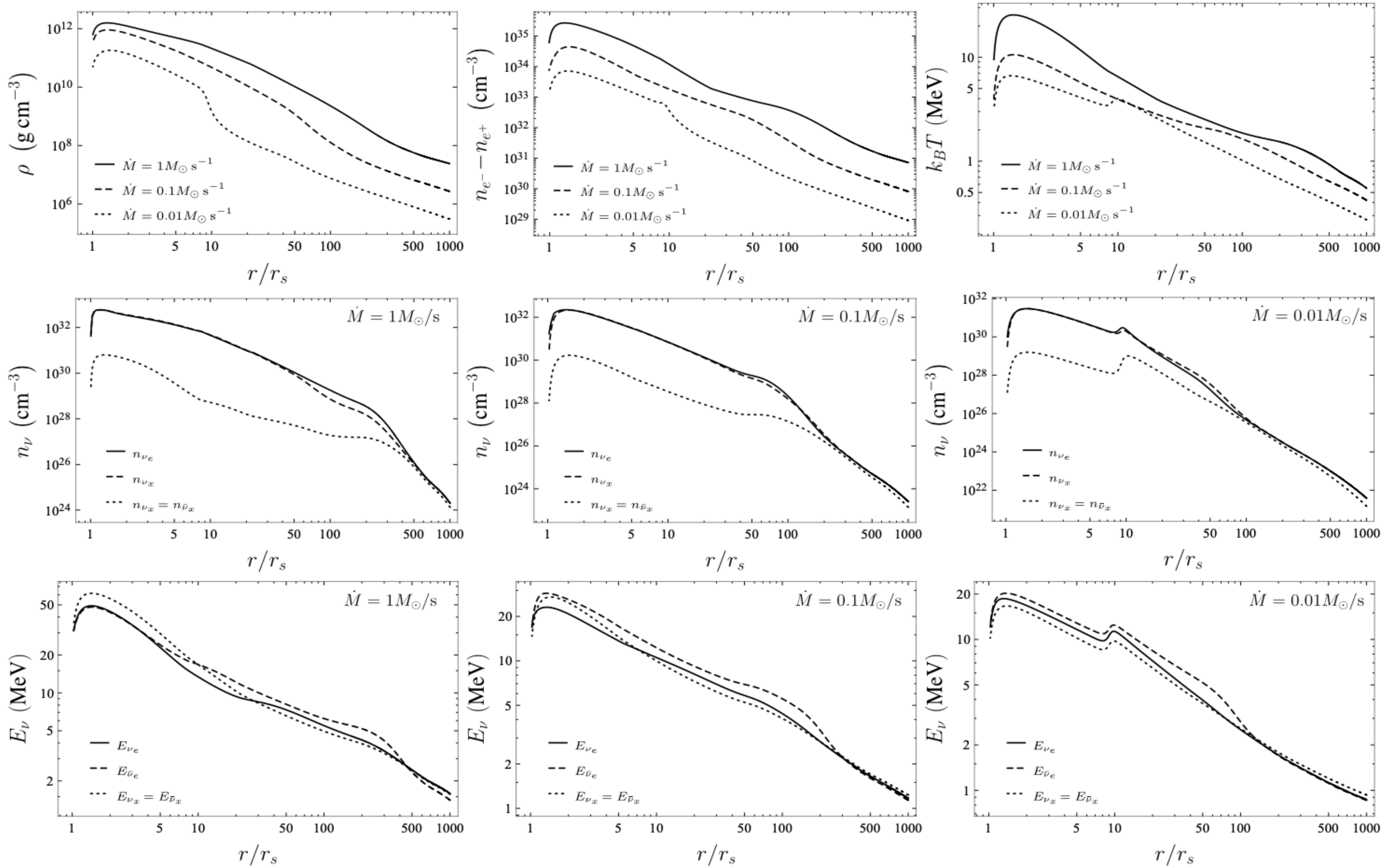
$$P_{\nu_e \leftrightarrow \nu_e} = \frac{1}{2}\left(1 + \mathsf{P}^z_{\mathbf{p}}\right)$$

$$P_{\nu_e \leftrightarrow \nu_x} = \frac{1}{2}\left(1 - \mathsf{P}^z_{\mathbf{p}}\right)$$

→ **survival and mixing probability**

Becerra, L., M. M. Guzzo, F. Rossi-Torres, J. A. Rueda, R. Ruffini, and J. D. Uribe. Neutrino oscillations within the induced gravitational collapse paradigm of long gamma-ray bursts. The Astrophysical Journal, 852(2):120 (2018).

What has been do?



Properties of accretion disks in absence of oscillations

M = 3M⊙

a = 0.95

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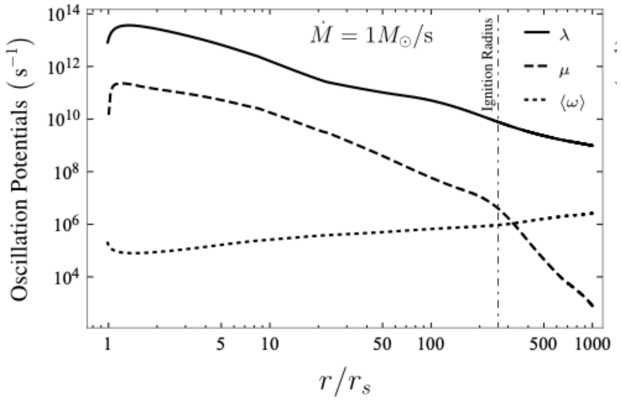
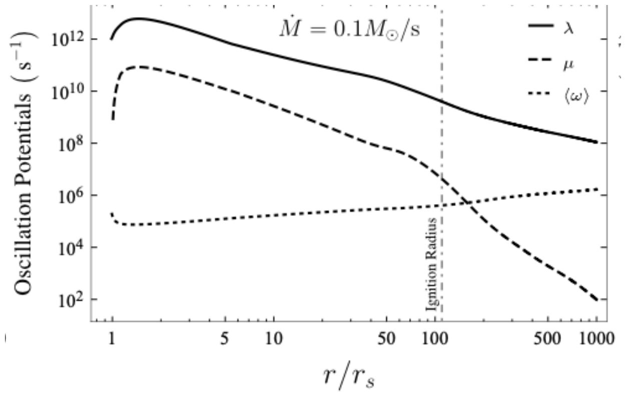
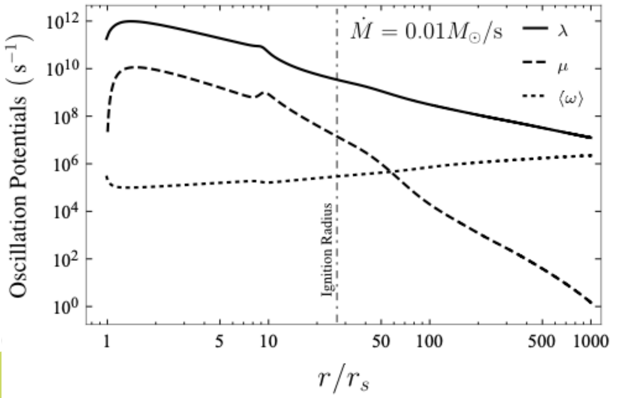
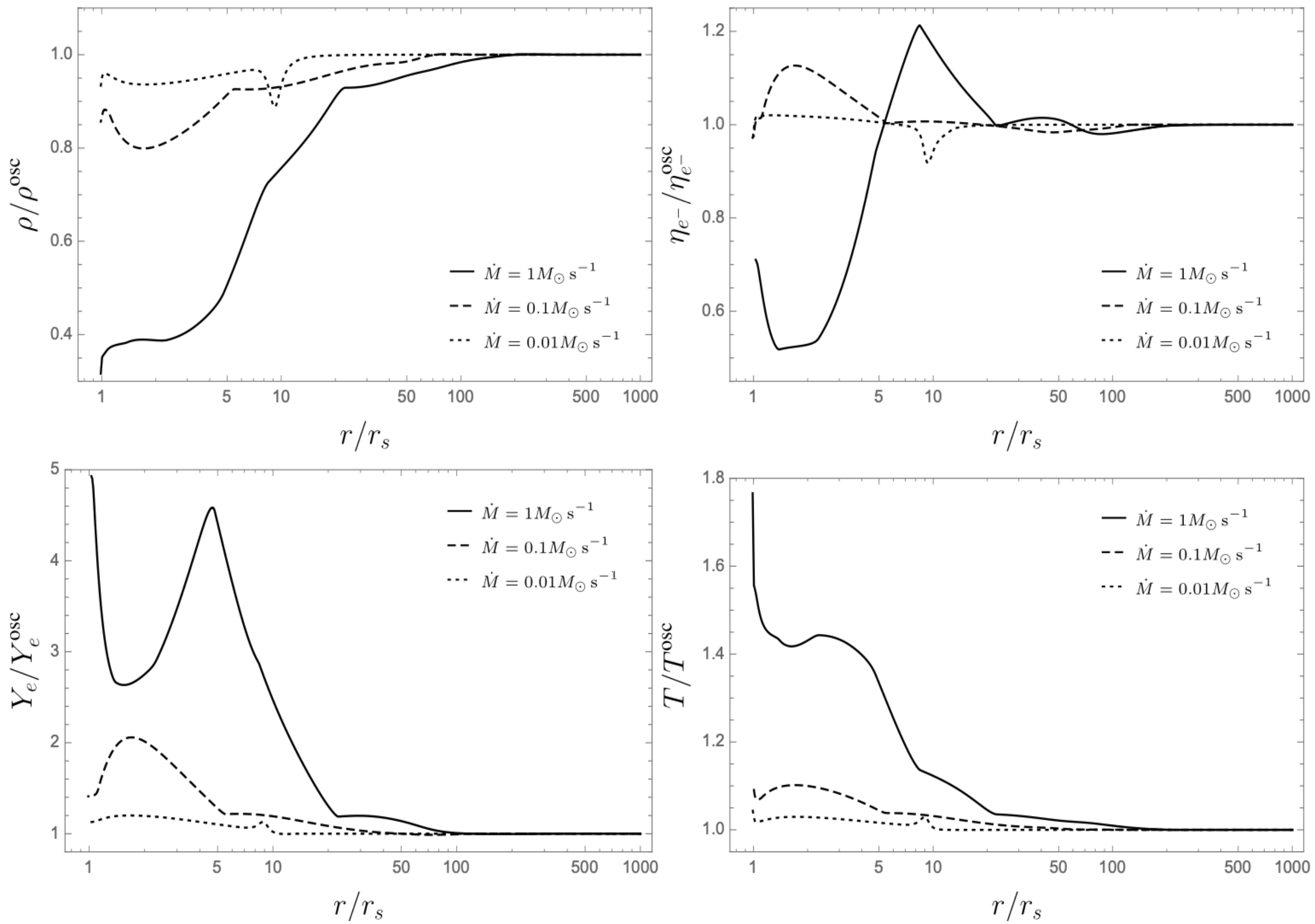
Comparison between the main variables with and without neutrino oscillations









L_{ν_e} ↓ ~ 3

$L_{\bar{\nu}_e}$ ↓ ~ 2

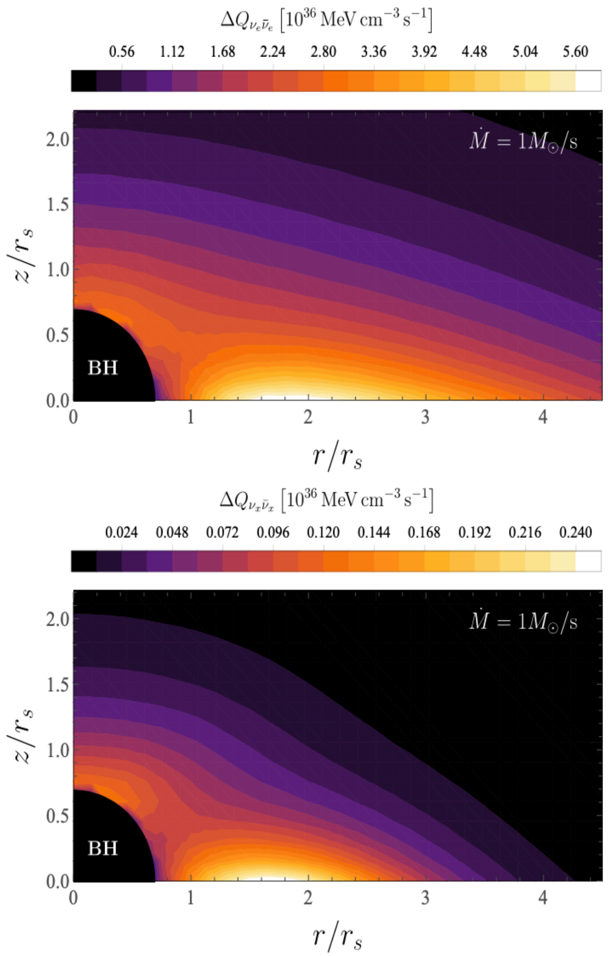
L_{ν_x}, $L_{\bar{\nu}_x}$ ↑ ~ 10

Total L_ν ↓ $\sim 3-5$

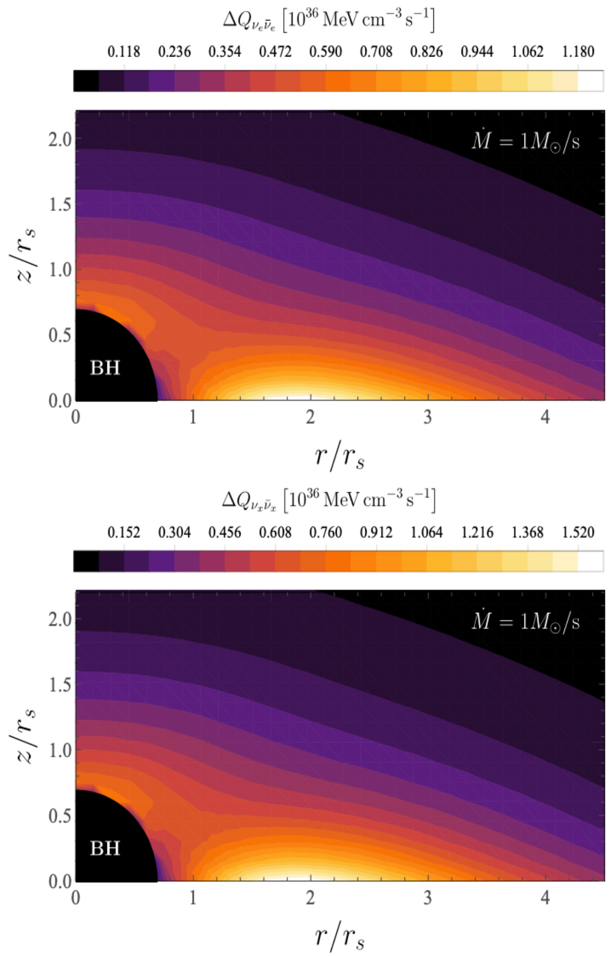
$[\mathrm{MeV}\ \mathrm{s}^{-1}]$ / $[M_\odot\ \mathrm{s}^{-1}]$	Without oscillations						With oscillations (flavour equipartition)					
	L_{ν_e}	$L_{\bar{\nu}_e}$	L_{ν_x}	$L_{\bar{\nu}_x}$	$L_{\nu_e\bar{\nu}_e}$	$L_{\nu_x\bar{\nu}_x}$	L_{ν_e}	$L_{\bar{\nu}_e}$	L_{ν_x}	$L_{\bar{\nu}_x}$	$L_{\nu_e\bar{\nu}_e}$	$L_{\nu_x\bar{\nu}_x}$
1	6.46×10^{58}	7.33×10^{58}	1.17×10^{58}	1.17×10^{58}	1.25×10^{57}	1.05×10^{55}	1.87×10^{58}	4.37×10^{58}	7.55×10^{58}	5.44×10^{58}	1.85×10^{56}	2.31×10^{56}
0.1	9.19×10^{57}	1.08×10^{58}	8.06×10^{55}	8.06×10^{55}	1.62×10^{55}	1.27×10^{50}	2.47×10^{57}	4.89×10^{57}	7.75×10^{57}	5.27×10^{57}	1.78×10^{54}	1.64×10^{54}
0.01	1.05×10^{57}	1.12×10^{57}	2.43×10^{55}	2.43×10^{55}	1.78×10^{53}	8.68×10^{48}	4.29×10^{56}	5.48×10^{56}	6.71×10^{56}	5.70×10^{56}	3.53×10^{52}	1.23×10^{52}

Comparison of total neutrino luminosities

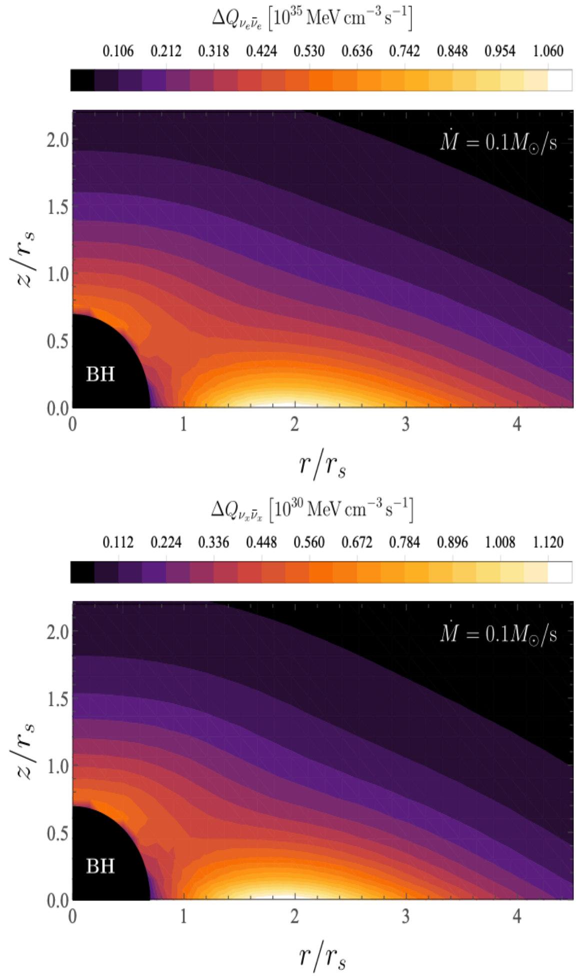
Neutrino annihilation luminosity per volume unit



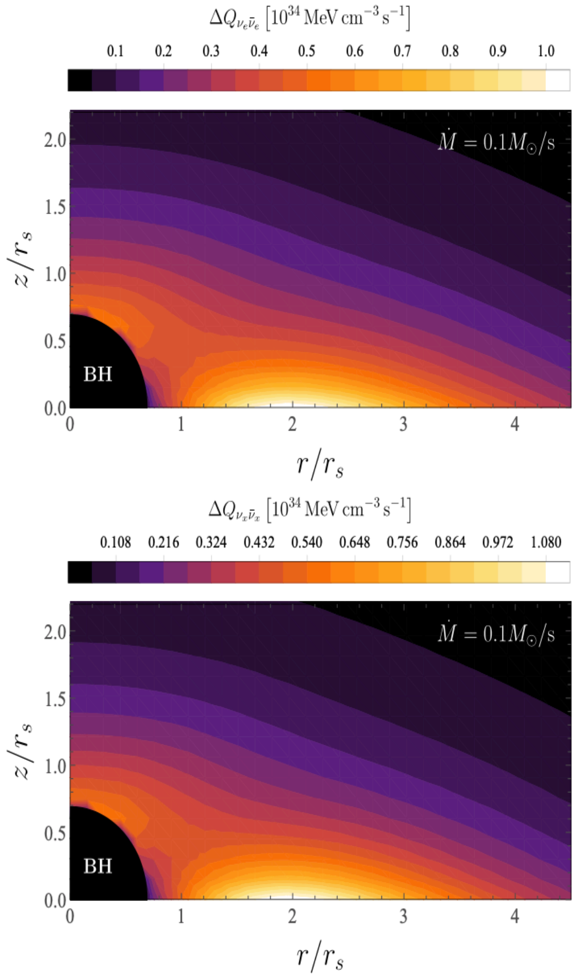
Without oscillations



With oscillations



Without oscillations

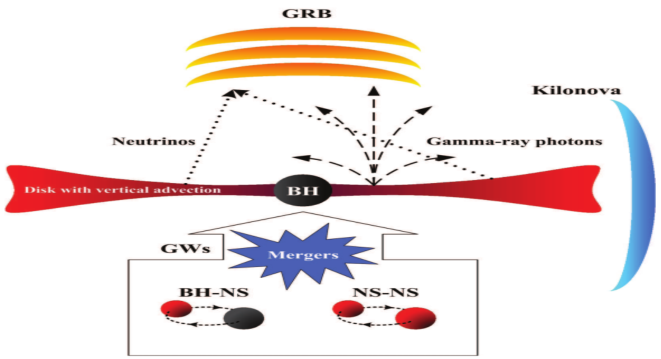


With oscillations

$$\Delta Q_{\nu_i\bar{\nu}_i kk'} = A_{1,i}\frac{\Delta\ell^k_{\nu_i}}{r_k^2}\frac{\Delta\ell^{k'}_{\bar{\nu}_i}}{r_{k'}^2}\left(\langle E_{\nu_i}\rangle^k + \langle E_{\bar{\nu}_i}\rangle^{k'}\right)\left(1-\frac{\mathbf{r}_k\cdot\mathbf{r}_{k'}}{r_k r_{k'}}\right)^2 + A_{2,i}\frac{\Delta\ell^k_{\nu_i}}{r_k^2}\frac{\Delta\ell^{k'}_{\bar{\nu}_i}}{r_{k'}^2}\left(\frac{\langle E_{\nu_i}\rangle^k + \langle E_{\bar{\nu}_i}\rangle^{k'}}{\langle E_{\nu_i}\rangle^k\langle E_{\bar{\nu}_i}\rangle^{k'}}\right)\left(1-\frac{\mathbf{r}_k\cdot\mathbf{r}_{k'}}{r_k r_{k'}}\right)$$

$$L_{\nu_i\bar{\nu}_i} = 4\pi\int_{\mathcal{A}}\sum_{k,k'}\Delta Q_{\nu_i\bar{\nu}_i kk'}d^3\mathbf{r}$$

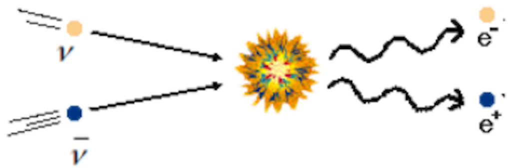
What needs to be done?



$$\frac{d^2x^\alpha}{d\lambda^2} + \Gamma^\alpha_{\beta\gamma}\frac{dx^\beta}{d\lambda}\frac{dx^\gamma}{d\lambda} = 0$$

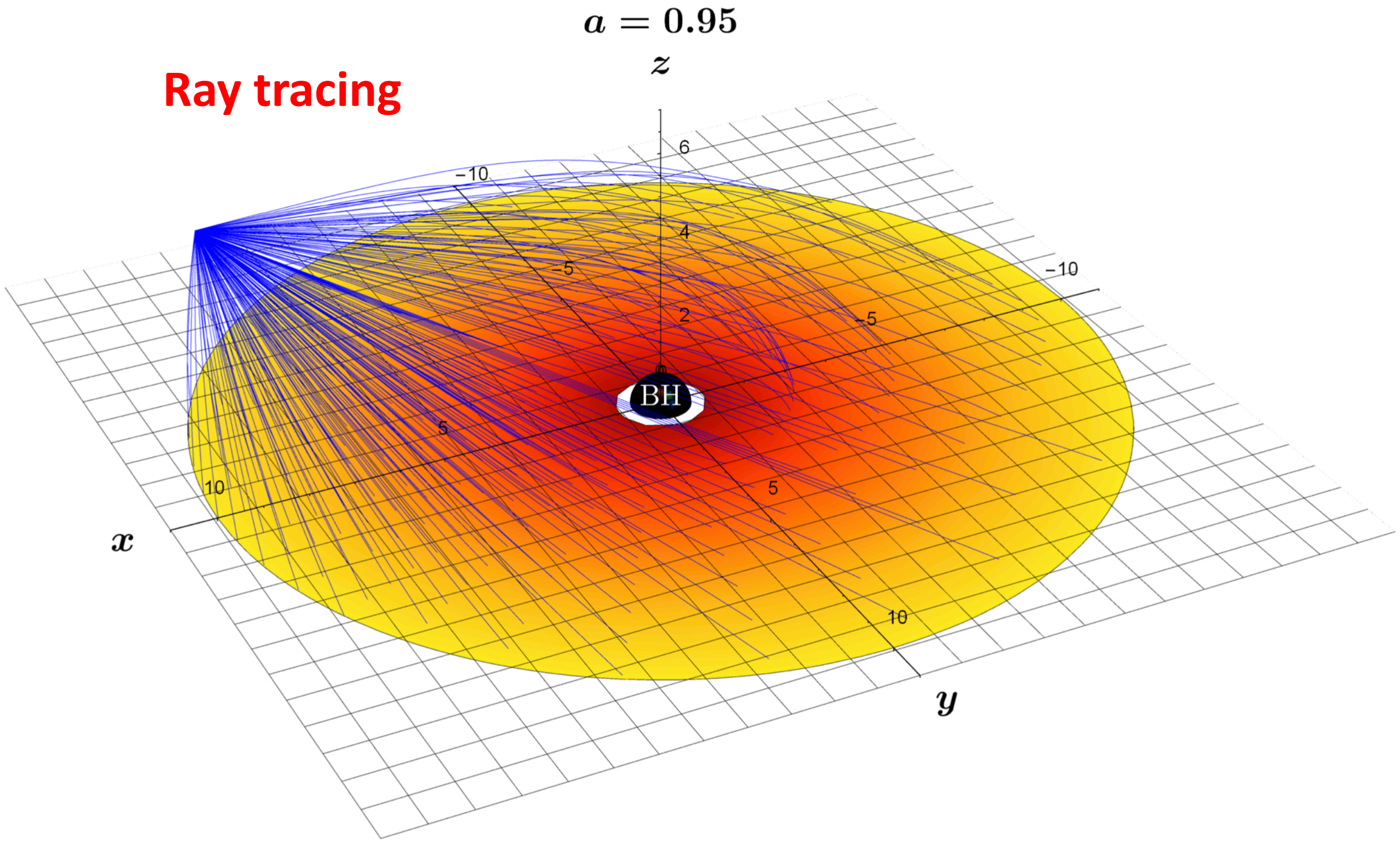
$$\frac{\mathrm{d}f\,(t(\lambda), \bar{x}(\lambda), \bar{p}(\lambda))}{\mathrm{d}\lambda} = 0$$

$$Q_i^\alpha = \int d^3p_{\nu_i} d^3p_{\bar{\nu}_i}\ A_i^\alpha(p^\alpha_{\nu_i}, p^\alpha_{\bar{\nu}_i}) f_{\nu_i} f_{\bar{\nu}_i}$$



$$A_i^\alpha(p^\alpha_{\nu_i}, p^\alpha_{\bar{\nu}_i}) = \frac{\sigma_0\ c^2}{4h^6}\left[C^\dagger_{\nu_i\bar{\nu}_i}\frac{p^0_{\nu_i}p^0_{\bar{\nu}_i}}{m_e^2c^2}(1-\cos\theta)^2 + C^*_{\nu_i\bar{\nu}_i}(1-\cos\theta)\right](p^\alpha_{\nu_i} + p^\alpha_{\bar{\nu}_i})$$

Ray tracing



$$Q_i^\alpha = \frac{1}{4}\frac{\sigma_0}{m_e^2h^6}\Bigg\{C^\dagger_{\nu_i\bar{\nu}_i}\int_0^\infty dE_{\nu_i}\int_0^\infty dE_{\bar{\nu}_i}\,(p^\alpha_{\nu_i} + p^\alpha_{\bar{\nu}_i})\,E^3_{\nu_i}E^3_{\bar{\nu}_i} \oint_{4\pi} d\Omega_{\nu_i}\oint_{4\pi} d\Omega_{\bar{\nu}_i}\,(1-\cos\theta)^2 f_{\nu_i}f_{\bar{\nu}_i}\ + C^*_{\nu_i\bar{\nu}_i}m_e^2c^2\int_0^\infty dE_{\nu_i}\int_0^\infty dE_{\bar{\nu}_i}\,(p^\alpha_{\nu_i} + p^\alpha_{\bar{\nu}_i})\,E^2_{\nu_i}E^2_{\bar{\nu}_i} \oint_{4\pi} d\Omega_{\nu_i}\oint_{4\pi} d\Omega_{\bar{\nu}_i}\,(1-\cos\theta)\, f_{\nu_i}f_{\bar{\nu}_i}\Bigg\},$$

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¡Gracias!

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