OSCILLATIONS OF ASTROPHYSICAL NEUTRINOS IN VARIOUS GRAVITATIONAL BACKGROUNDS

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Plan of the talk

- Neutrino spin oscillations in a scattering off a black hole (BH)
- Flavor oscillations of SN neutrinos in stochastic gravitational waves (GWs)
- Summary

Publications

- **M. Dvornikov**, *Gravitational scattering of spinning neutrinos by a rotating black hole with a slim magnetized accretion disk, Class. Quantum Gravity* **40**, 015002 (2023) arXiv:2206.00042.
- **M. Dvornikov**, *Interaction of supernova neutrinos with stochastic gravitational waves*, Phys. Rev. D **104**, 043018 (2021), arXiv:2103.15464.
- **M. Dvornikov**, *Neutrino scattering off a black hole surrounded by a magnetized accretion disk*, JCAP 04 (2021) 005, arXiv:2102.00806.
- **M. Dvornikov**, *Spin oscillations of neutrinos scattered off a rotating black hole*, Eur. Phys. J. C **80**, 474 (2020), arXiv:2006.01636.
- **M. Dvornikov**, *Spin effects in neutrino gravitational scattering*, Phys. Rev. D **101**, 056018 (2020), arXiv:1911.08317.
- **M. Dvornikov**, *Flavor ratios of astrophysical neutrinos interacting with stochastic gravitational waves having arbitrary spectra*, JCAP 12 (2020) 022, arXiv:2009.02195.
- **M. Dvornikov**, *Neutrino flavor oscillations in stochastic gravitational waves*, Phys. Rev. D **100**, 096014 (2019), arXiv:1906.06167.

SPIN OSCILLATIONS IN GRAVITATIONAL SCATTERING

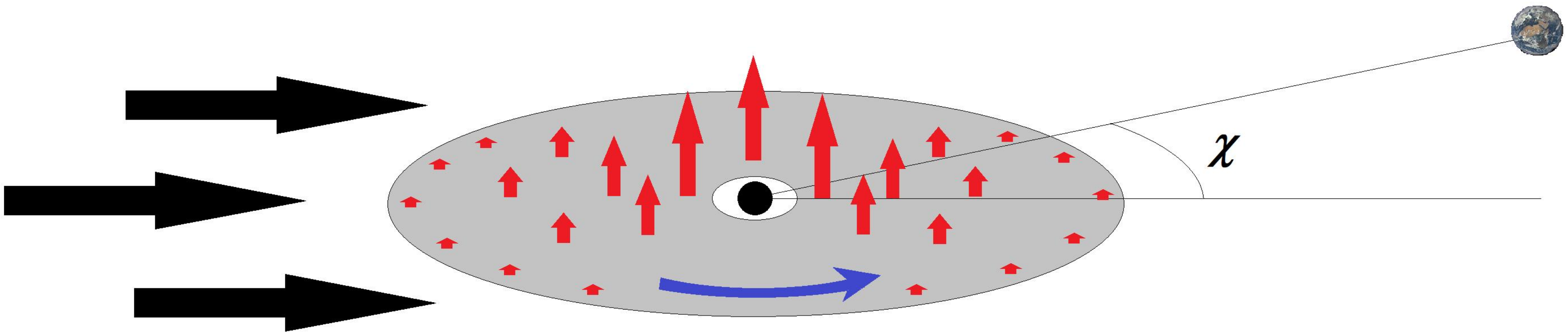
Introduction and motivation

- Neutrinos are left-handed in the standard model, i.e. their spin is opposite to the neutrino momentum
- If the neutrino spin precesses in an external field, i.e. changes its direction with respect to the neutrino momentum, particles become right-handed
- Right-handed neutrinos are sterile in the standard model
- We will observe the effective reduction of the initial neutrino flux
- This process is called neutrino spin oscillations
- External fields, including gravity, can change polarization of fermions
- Recently, the supermassive BH shadows in M87 and Milky Way were observed. What happens if we look at this SMBH in a neutrino telescope?

Formulation of the problem

- Uniform flux of left-polarized neutrinos is parallel to the equatorial plane
- Gravitational scattering off BH rotating BH: Kerr metric
- BH is surrounded by a thin accretion disk
- Magnetic field in the accretion disk is generated by the plasma motion
- Neutrino has nonzero magnetic moment

Neutrino scattering



Parameters of an accretion disk and a neutrino

- Wald (1974) found an electromagnetic field in the vicinity of a Kerr BH which asymptotically approaches to a constant and uniform magnetic field. It acquires an electric component. However, such magnetic field is unphysical since B should disappear at the edge of a disk
- Beskin (2010) reviewed numerous models of magnetic fields in a disk. Both poloidal and toroidal components are present. If the disk is thin, only poloidal magnetic field contributes the neutrino spin precession
- Blandford & Payne (1982) assumed the equipartition of the energy between the magnetic field and accreting plasma. Then, $B \propto B_0 r^{-5/4}$.
- Magnetic field near BH is constrained by the Eddington limit B_{Edd}. We take that $B_0 = 10^{-2} B_{Edd}$. One gets that $B_0 = 3.2 \times 10^2 G$. Daly (2019) reports that such magnetic fields are not excluded by observations
- Bell et al. (2005) suggests a model independent constraint on the Dirac neutrino magnetic moment: $\mu = 10^{-14} \mu_B$. Viaux et al. (2013) found best astrophysical constraint on the neutrino magnetic moment: $\mu {\sim} 10^{-13} \mu_B$

Neutrino spin evolution in the locally Minkowskian frame

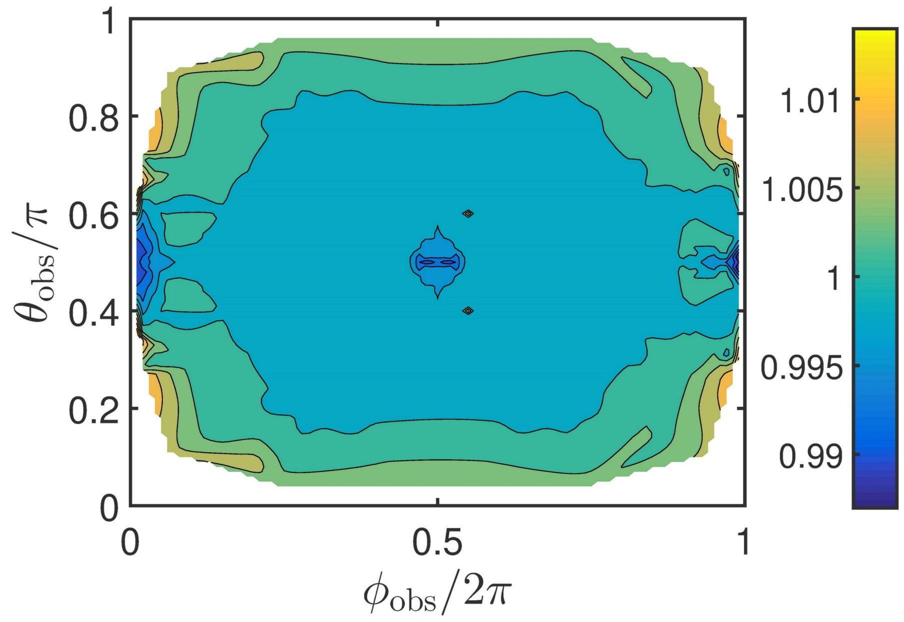
- 3D neutrino spin in curved spacetime (Pomeranskii & Khriplovich, 1998; Dvornikov 2006, 2013):

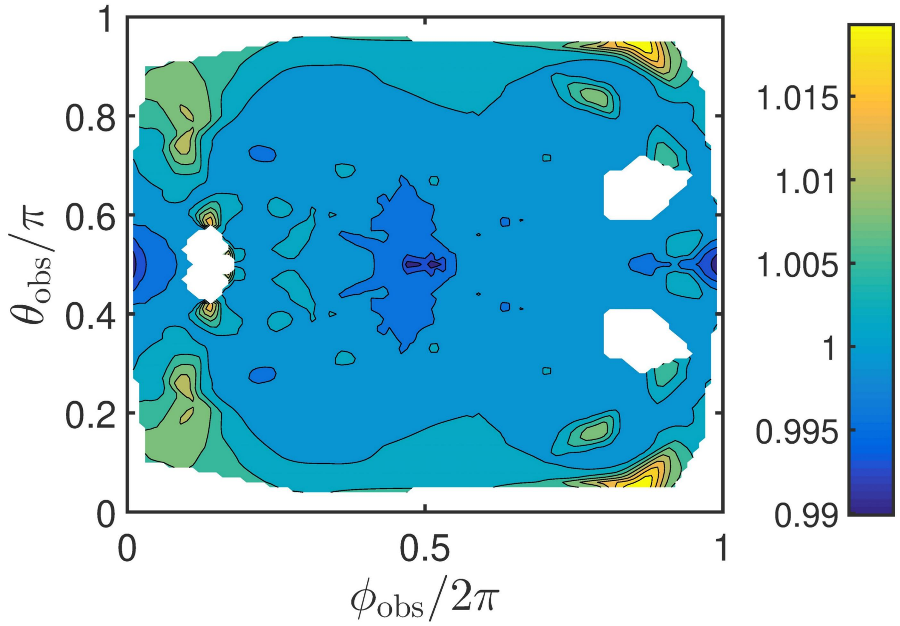
$$\frac{d\vec{\zeta}}{dt} = 2(\vec{\Omega} \times \vec{\zeta})$$

- Neutrino velocity in the locally Minkowskian frame changes its direction in gravitational scattering

Contribution of gravity to the neutrino fluxes

- Only left-polarized neutrinos interact with a detector. The measured flux ∝ $P_{LL}F_0$, where F_0 is the flux of scalar particles
- We show the ratio F_ν/F_0 for nonrotating and maximally rotating BHs
- Gravity only does not contribute to the neutrino spin-flip

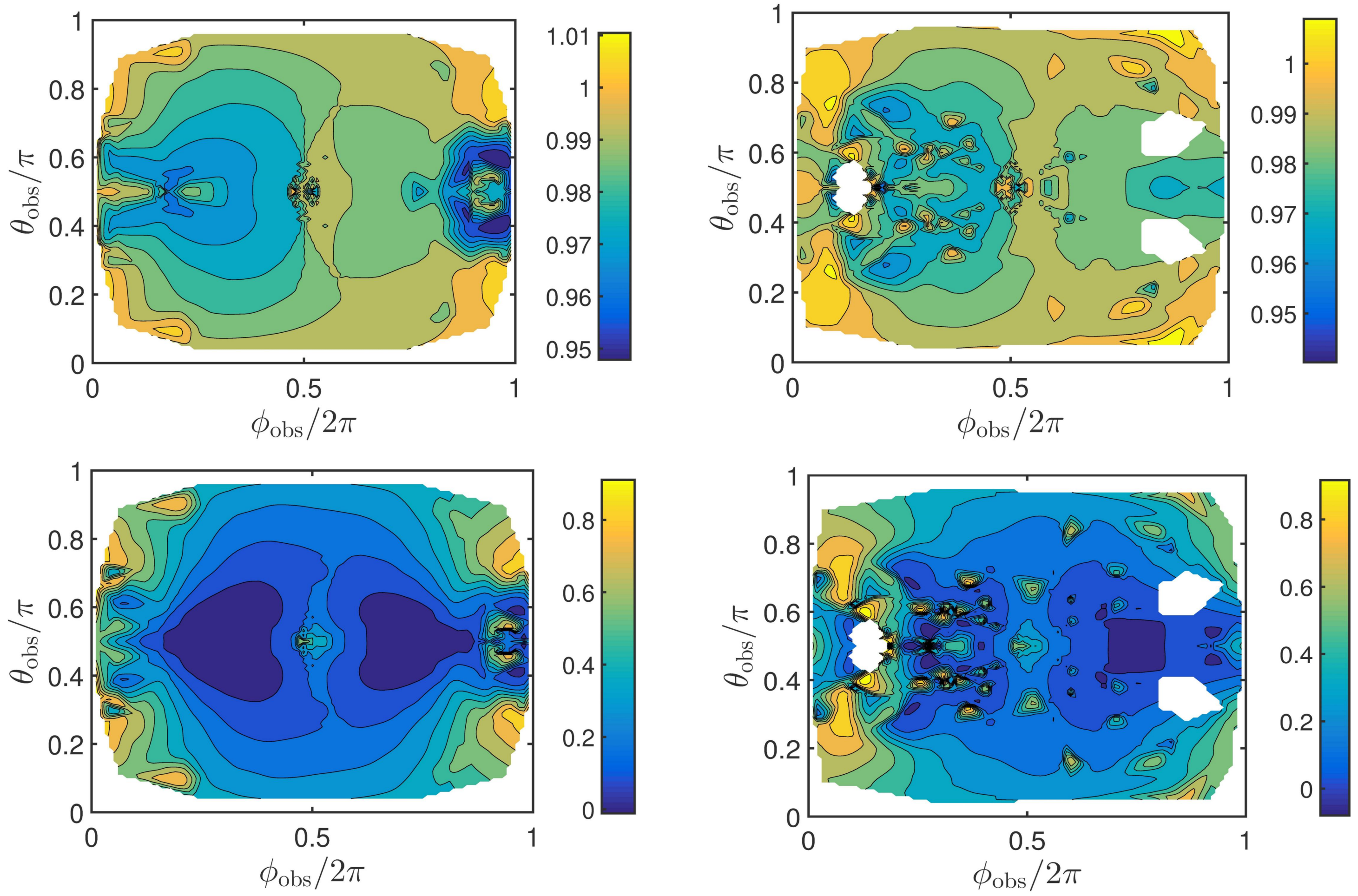




Contribution of magnetic field to neutrino fluxes

$$\mu = 10^{-14}\mu_B$$

$$\mu = 10^{-13}\mu_B$$



Discussion

- There is spin-flip of ultrarelativistic neutrinos in their scattering off a rotating BH only if they have a magnetic moment and there is a magnetic field in the disk
- Solely gravitational scattering does not make a spin-flip of ultrarelativistic neutrinos
- The interaction neutrino magnetic moment $\mu = 10^{-13}\mu_B$ with realistic magnetic field in a slim accretion disk can almost completely reduce the observed neutrino fluxes

FLAVOR OSCILLATIONS OF SN NEUTRINOS IN STOCHASTIC GWS

Introduction and motivation

- Neutrinos interact with other leptons (e,μ,τ) as flavor eigenstates:
  $\nu = (\nu_e, \nu_\mu, \nu_\tau)$
- Flavor eigenstates do not have definite masses
- We introduce mass eigenstates $\psi = (\psi_1, \psi_2, \psi_3)$
- These bases are related by the unitary matrix transformation

$$\nu = U\psi$$

- These neutrino properties result in neutrino flavor oscillation, i.e. the change of a flavor content of the neutrino beam, which can happen even in vacuum
- External fields, including gravity, can influence neutrino flavor oscillations
- It is interesting to check if nonstationary gravitational field, like GWs, which were directly detected by LIGO-Virgo, can contribute to neutrino flavor oscillations
- NANOGrav (2020) reported about a strong evidence of stochastic GWs

Evolution of a mass eigenstate in GW

Ahluwalia & Burgard (1996); Fornengo et al (1997) established the evolution of neutrino mass eigenstates in a gravitational field

$$\psi_a(x,t) \sim \exp\left[-iS_a(x,t)\right]$$

$$g_{\mu\nu}\frac{\partial S_a}{\partial x_\mu}\frac{\partial S_a}{\partial x_\nu} = m_a^2$$

$$ds^2 = g_{\mu\nu}dx^\mu dx^\nu = dt^2 - (1 - h_+\cos\phi)dx^2 - (1 + h_+\cos\phi)dy^2 + 2dxdyh_\times\sin\phi - dz^2$$

Dvornikov (2021) found the perturbative solution of the Hamilton-Jacobi equation in a plane GW

Schrodinger equation and the effective Hamiltonian for neutrino flavor eigenstates

$$i\dot{\nu} = H_f\nu \qquad H_f = UH_mU^+$$

$$\left(H_m^{(+)}\right)_{aa} = -\frac{p^2h_+}{2\sqrt{p^2+m_a^2}}\sin^2\vartheta\cos(2\varphi) \times \cos(\omega t[1 - v_a\cos\vartheta])$$

GW does not contribute to neutrino oscillations if neutrino beam propagates along GW ($\vartheta = 0$)

Stochastic GWs

- Neutrino interacts with randomly emitted GWs
- Density matrix (Loreti & Balantekin, 1994)
- Averaging over angles
- Gaussian distribution of strain with arbitrary correlator: $\langle h_{+,\times}(t_1) h_{+,\times}(t_2) \rangle = f_{+,\times}(|t_1 - t_2|)$
- We can find the correction to the probabilities of vacuum oscillations caused by GWs

$$\Delta P_\lambda(x) = 2 \sum_\sigma P_\sigma(0) \sum_{a>b} \left\{ \mathrm{Re}[U_{\lambda a} U^*_{\lambda b} U^*_{\sigma a} U_{\sigma b}] \cos\left(2\pi \frac{x}{L_{ab}}\right) + \mathrm{Im}[U_{\lambda a} U^*_{\lambda b} U^*_{\sigma a} U_{\sigma b}] \sin\left(2\pi \frac{x}{L_{ab}}\right) \right\} \left\{ 1 - \exp\left[-\frac{4\pi^2}{L_{ab}^2} \int_0^x \widetilde{g}(t) dt \right] \right\}$$

Initial condition

We study neutrinos emitted in ν_e-burst in core-collapsing SN
SN is almost point-like source
The size of neutrinosphere is ~ 100 km
The contribution of solar oscillations channel is not smeared

Fluxes at a source are $(F_e, F_\mu, F_\tau)_S = (1:0:0)$

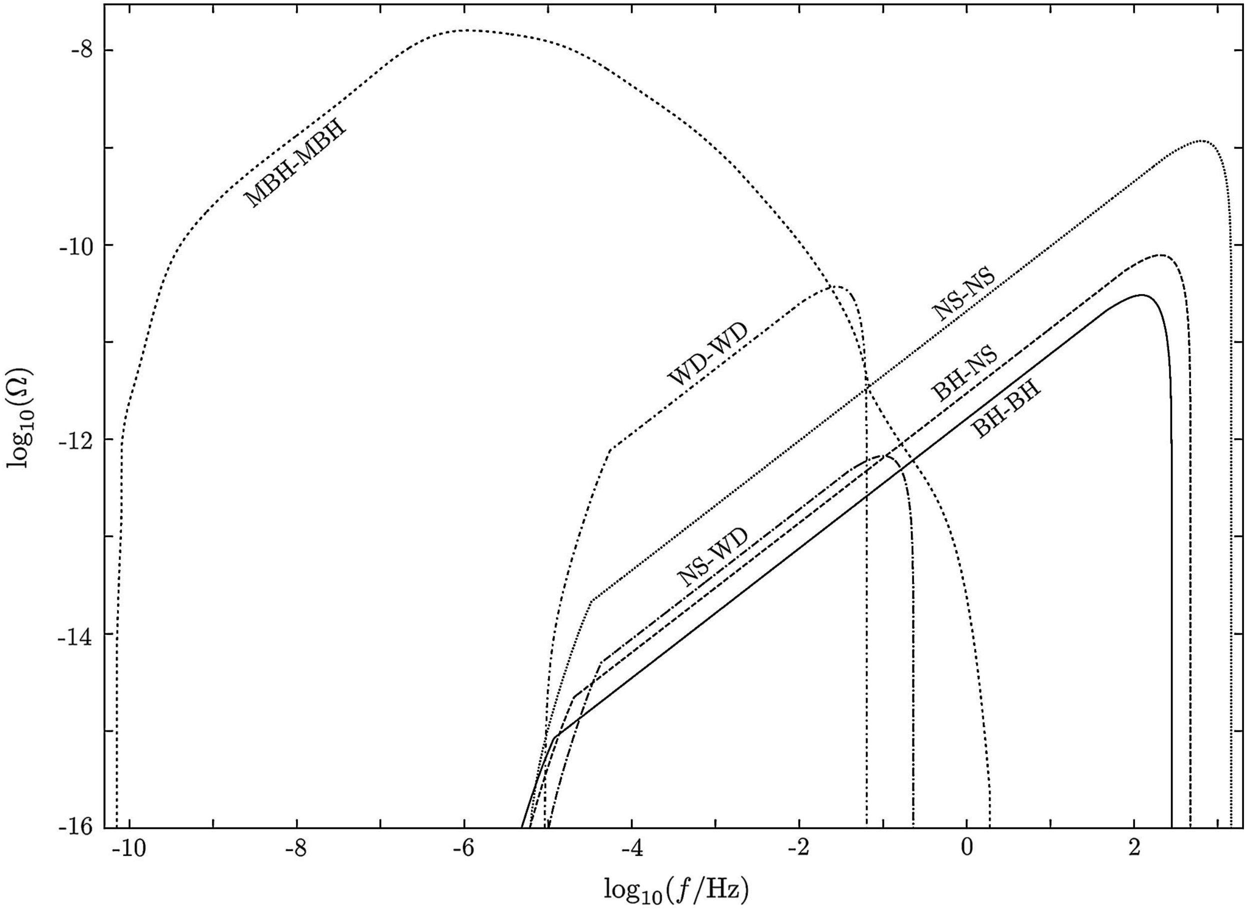
Initial condition $\rho_{11}(0) = 1, \rho_{22}(0) = 0, \rho_{33}(0) = 0$

GW emitted by randomly coalescencing supermassive BHs (SMBH)

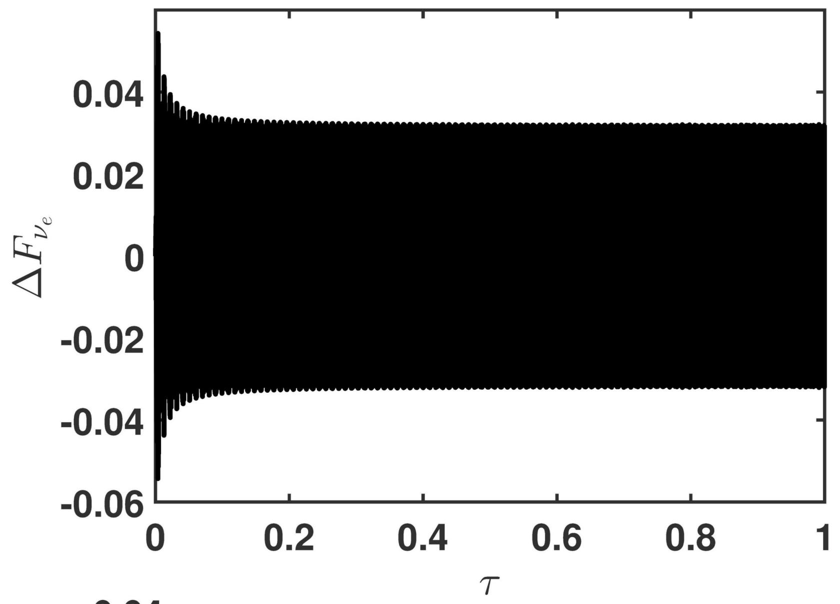
- Spectral function for GW from different types of merging BHs is calculated by Rosado (2011)
- Ω is the energy density of stochastic GWs per logarithmic frequency interval with respect to the closure density of the universe

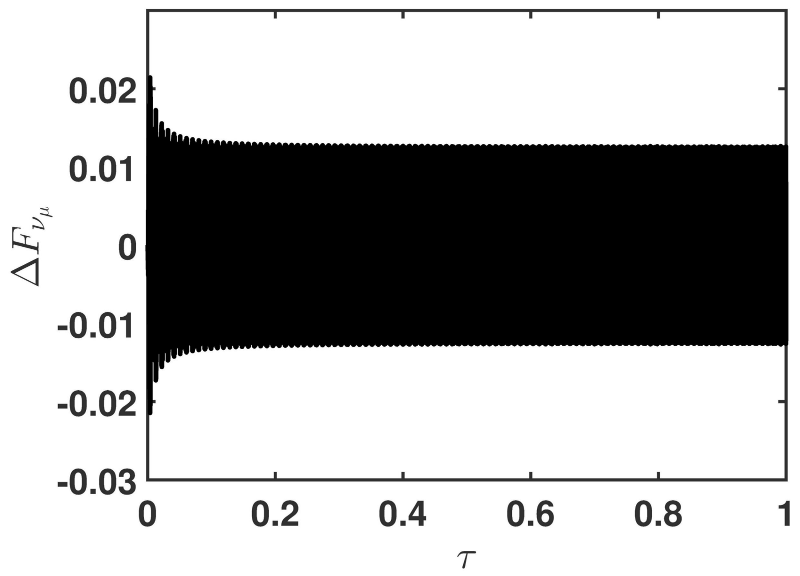
$$\Omega \propto f^{\alpha}$$

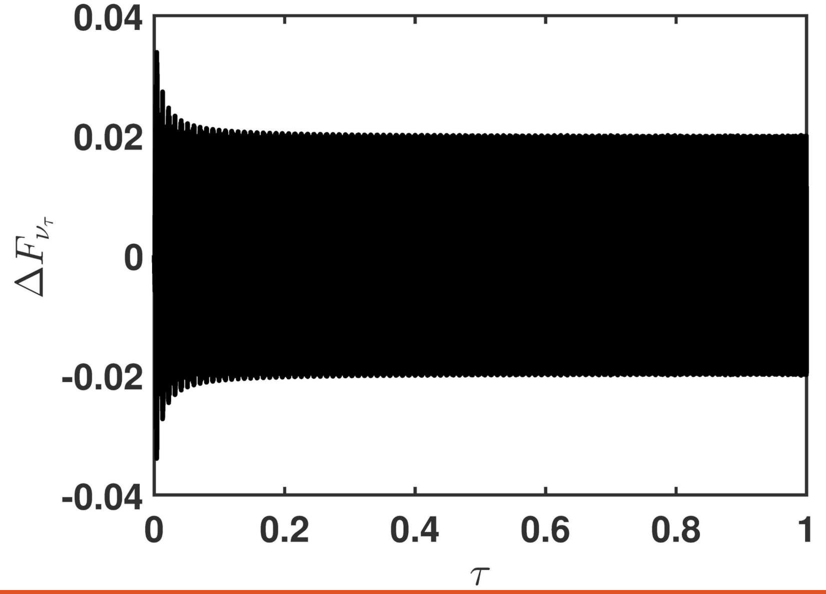
- We will study the case of SMBH since they produce stochastic GWs with the major effect on neutrino oscillations



Fluxes of flavor neutrinos





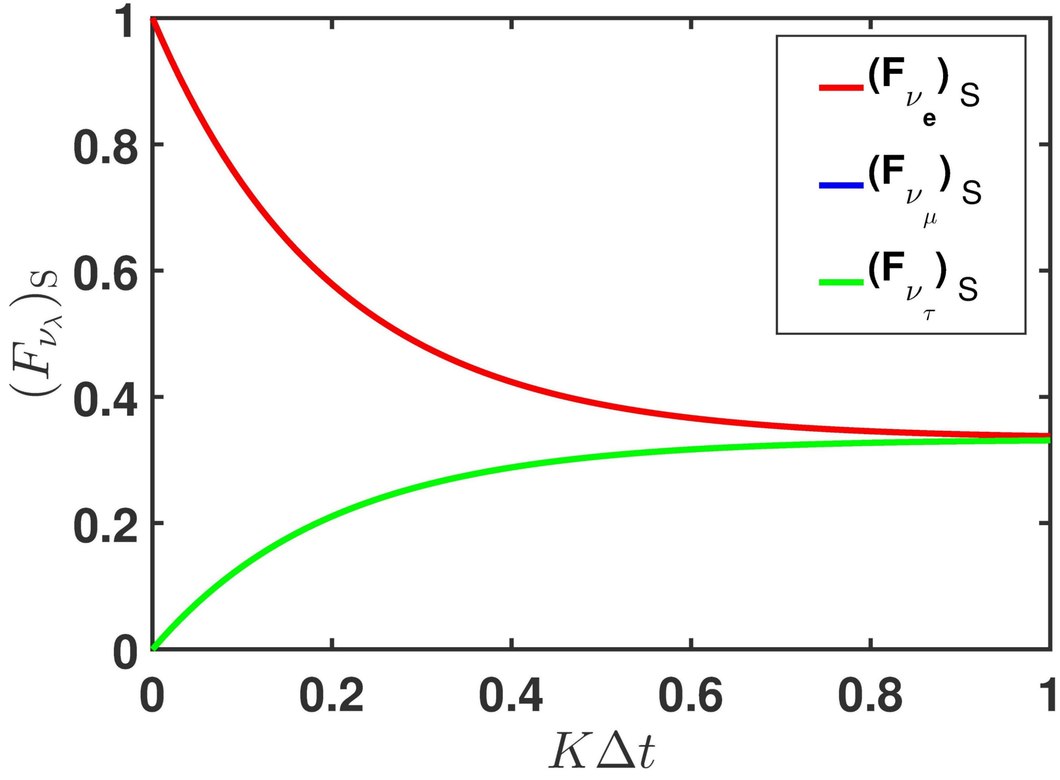


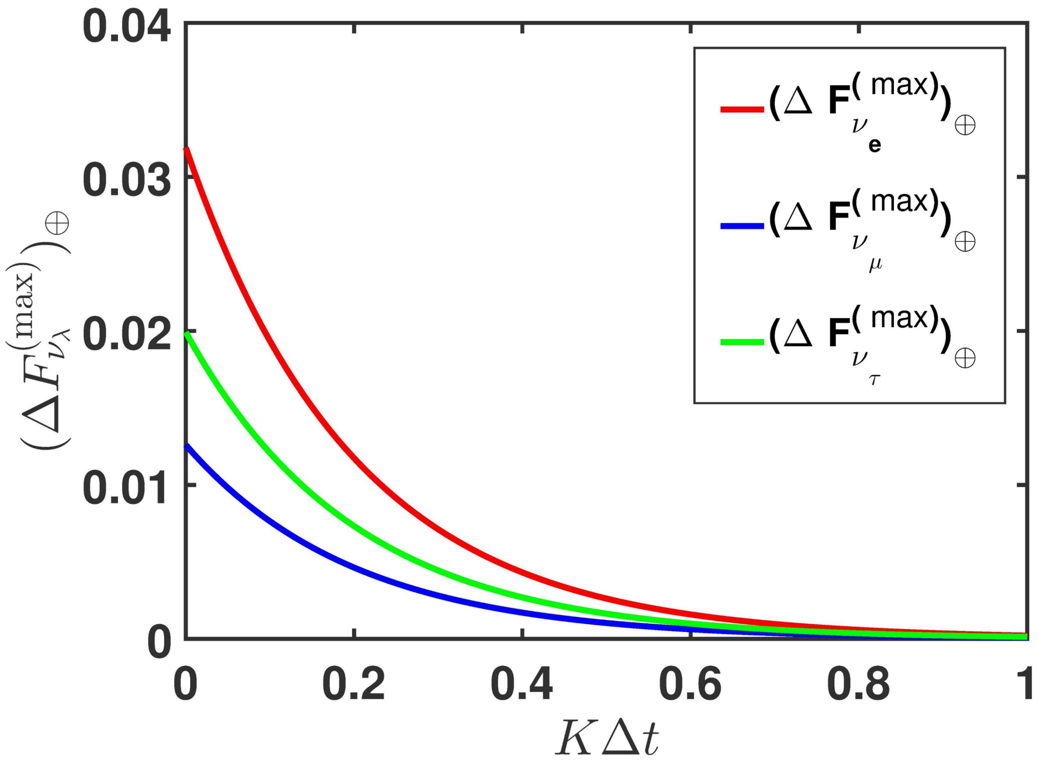
E = 10 MeV

$$\tau = x/L$$

L = 10 kpc

Neutrino fluxes after ν_e-burst





- Significant number of neutrinos of different flavors is emitted after ν_e-burst
- We study oscillations of such neutrinos in stochastic GWs
- $0 < \Delta t < 0.1\ s$ is the time after ν_e-burst. We approximate the fluxes at a source (SN) by exponents
- The contributions to the fluxes from stochastic GWs in a detector are vanishing at $\Delta t \sim 0.1\ s$

Discussion

- We have the analytic expression for the probabilities for all neutrino flavors interacting with stochastic GWs
- Two independent polarizations of GWs are accounted for
- The correlators of amplitudes are arbitrary
- The results are applied for oscillations of SN neutrinos
- The major effect is for neutrinos emitted in ν_e-burst. At subsequent moments of time, the contribution of stochastic GWs is vanishing
- The interaction with stochastic GWs can results in the change of the SN neutrinos fuxes by ±350 events, in case of the Super-Kamiokande, and by ±3750 events, for the Hyper-Kamiokande

Summary

- We have studied the influence of spin oscillations on the observed fluxes of neutrinos scattered off a rotating BH
- There is a spin-flip of ultrarelativistic neutrinos in scattering in the Kerr metric caused by the interaction of the neutrino magnetic moment with the magnetic field in an accretion disk
- Observed fluxes can be almost completely reduced in some cases
- We have examined the relaxation of the fluxes of flavor neutrinos owing to their interaction with stochastic GWs
- The major contribution is from GWs emitted by merging SMBHs
- This effect can be potentially observed for SN neutrinos with E = 10 MeV in our Galaxy with the propagation length L = 10 kpc