NEUTRINO OSCILLATIONS IN GRAVITATIONAL FIELDS AND ASTROPHYSICAL APPLICATIONS

Maxim Dvornikov

IZMIRAN, Russia

Plan of the talk

- Neutrino spin oscillations in a scattering off a black hole (BH)
- Neutrino flavor oscillations in stochastic gravitational waves (GWs)
- Summary

Publications

- **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**, *Flavor ratios of astrophysical neutrinos interacting with stochastic gravitational waves having arbitrary spectra*, JCAP 12 (2020) 022, arXiv:2009.02195.
- **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**, *Neutrino flavor oscillations in stochastic gravitational waves*, Phys. Rev. D **100**, 096014 (2019), arXiv:1906.06167.

SPIN OSCILLATIONS IN GRAVITATIONAL SCATTERING

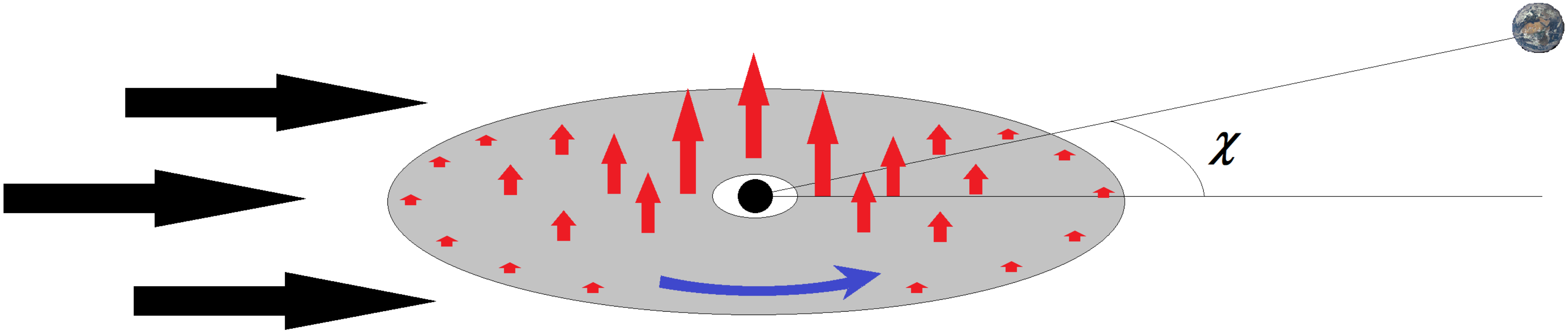
Introduction and motivation

- 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 shadow in M87 was observed. What happens if we look at this SMBH in a neutrino telescope?

Formulation of the problem

- Uniform flux of left-polarized neutrinos
- Gravitational scattering off BH rotating BH: Kerr metric
- Electroweak interaction of neutrinos with dense matter of an accretion disk, which, as a rule surrounds BH
- Accretion disk with realistic radial density distribution
- Neutrino has nonzero magnetic moment
- Accretion disk is permeated by the magnetic field
- Neutrino motion in the equatorial plane only

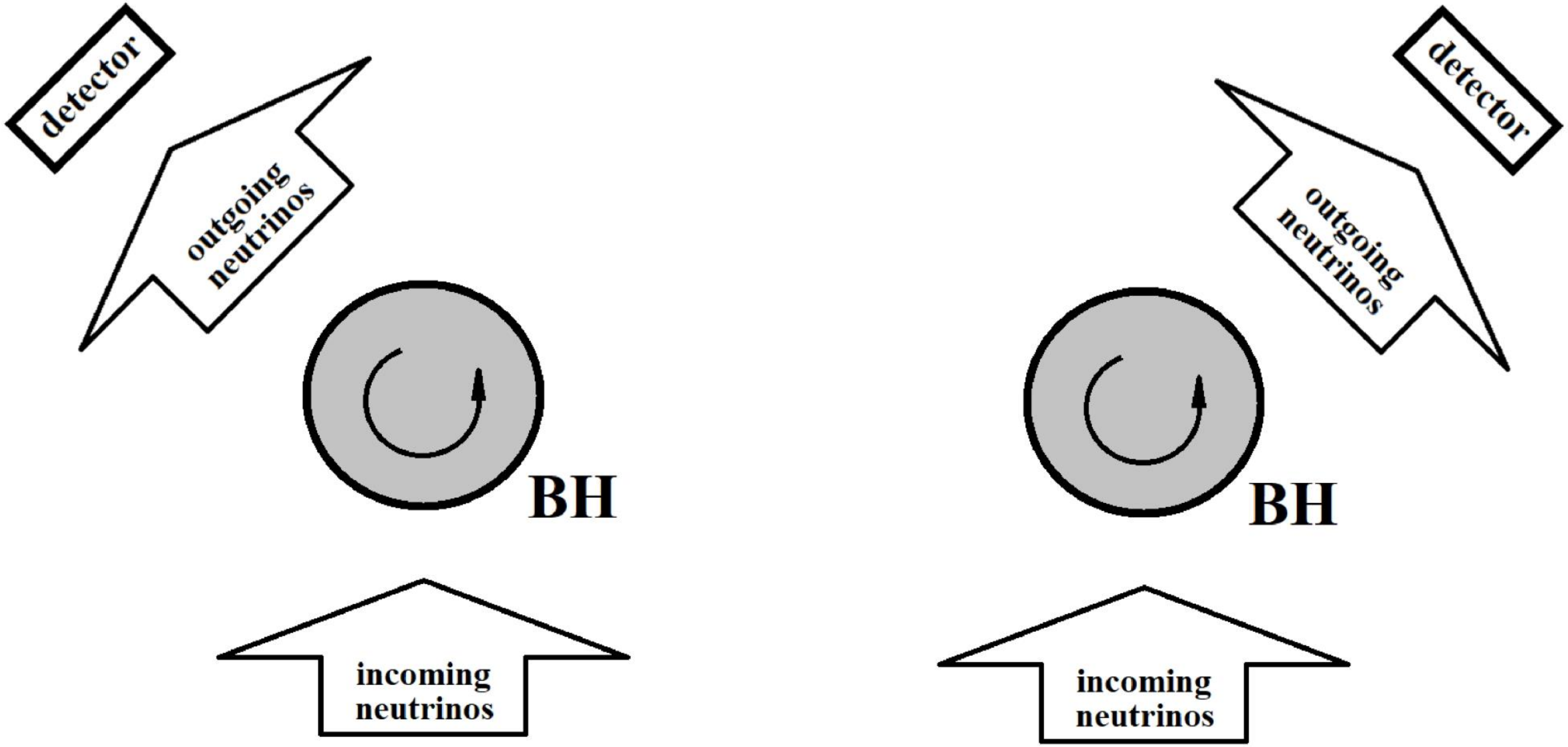
Schematic illustration of neutrino scattering



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. We take that only poloidal exists. Toroidal component does not contribute significantly to neutrino spin-flip
- Blandford & Payne (1982) assumed the equipartition of the energy between the magnetic field and accreting plasma. If $B \propto B_0 r^{-\kappa}$ and $n \propto n_0 r^{-\beta}$, $\kappa = (\beta + 1)/2$.
- Narayan & Yi (1994) found that $\beta = 3/2$ in an advection dominated accretion disk. Thus $\kappa = 5/4$.
- Jiang et al. (2019) obtained that $n_0 = 10^{18} cm^{-3}$ for $M = 10^8 M_\odot$
- 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: $\mu = 10^{-14} \mu_B$

Direct and retrograde scatterings



Neutrino spin evolution in the locally Minkowskian frame

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

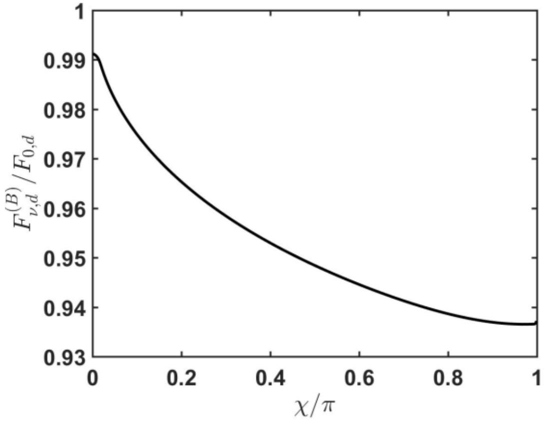
$$\frac{d\vec{\zeta}}{dt} = 2(\vec{\Omega} \times \vec{\zeta})$$

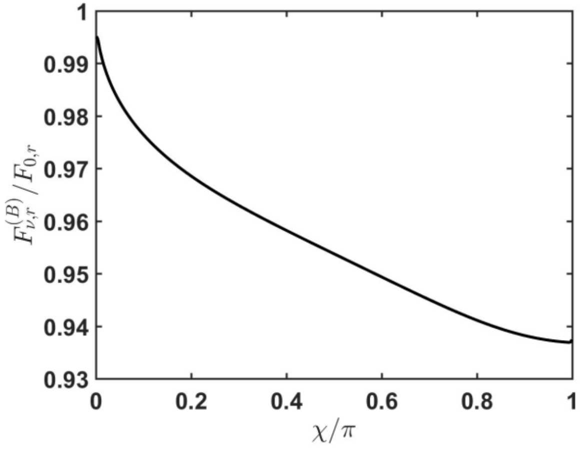
- Neutrino velocity in the locally Minkowskian frame changes its direction in gravitational scattering
- Transition and survival probabilities are

$$P_{LR,LL} = \frac{1}{2}(1 \pm \cos \alpha_{+\infty})$$

- If a neutrino interacts only with gravity and a magnetic field, $\alpha_{+\infty}$ can be expressed in quadratures

Transition probability for ultrarelativistic neutrinos in Kerr metric





- If ultrarelativistic neutrinos interact only with gravity, $\alpha_{+\infty} = -\pi$. Thus $P_{LR} = 0$. Thus result is in agreement with Lambiase et al. (2005), who studies the neutrino scattering off a Kerr BH in the weak field limit
- If a neutrino has nonzero magnetic moment, $P_{LR} \neq 0$ even for ultrarelativistic particles
- Transition/survival probabilities versus the impact parameter are not measurable because of multiple revolutions of a neutrino around BH
- The flux of particles versus the scattering angle is measured
- Only left-polarized neutrinos interact with a detector. The measured flux $\propto P_{LL} F_0$
- The interaction with magnetic field and/or accretion disk changes the flux compared to “scalar” neutrinos and when only magnetic scattering is accounted for

Electroweak interaction with accretion disk

- Neutrino forward scattering in plasma

$$L_{matt} = -\frac{G_F}{\sqrt{2}}\bar{\nu}\gamma^{\mu}(1-\gamma^5)\nu \cdot G_{\mu}$$

- Modification of the precession equation

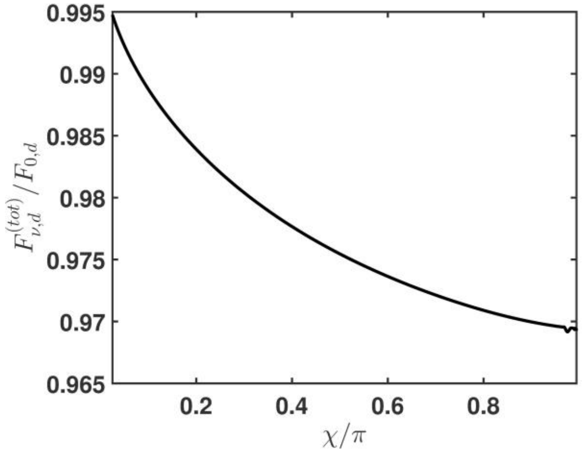
$$\vec{\Omega} = \vec{\Omega}_g + \vec{\Omega}_B + \vec{\Omega}_{matt} \qquad \vec{\Omega}_{matt} \propto G_F n_{eff}$$

- Rotating accretion disk (Bardeen et al., 1972)

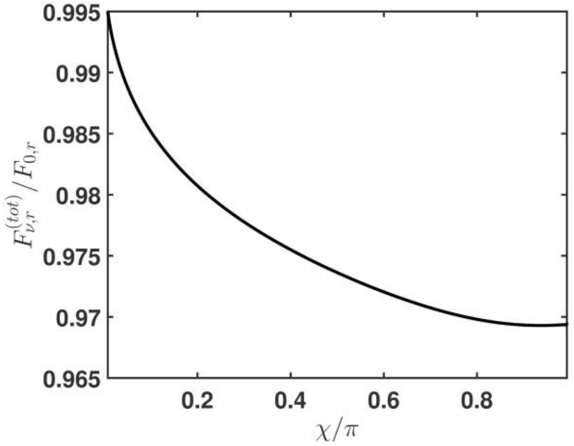
$$U_f^t = \frac{\sqrt{2}x^{3/2} + \lambda z}{\sqrt{2x^3 - 3x^2 + 2\lambda\sqrt{2}zx^{3/2}}}, \qquad U_f^{\phi} = \frac{1}{r_g}\frac{\lambda}{\sqrt{2x^3 - 3x^2 + 2\lambda\sqrt{2}zx^{3/2}}}$$

- Corotating disk: $\lambda = +1$; counter-rotating disk: $\lambda = -1$
- The problem cannot be solved in quadratures. The effective Schrodinger equation should be integrated numerically

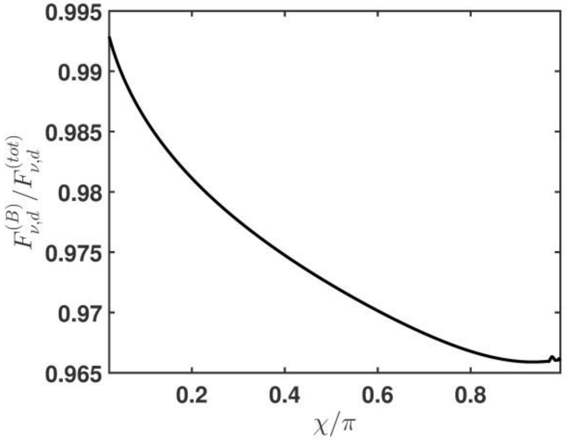
Fluxes of scattered neutrinos accounting for spin oscillations: corotating disk



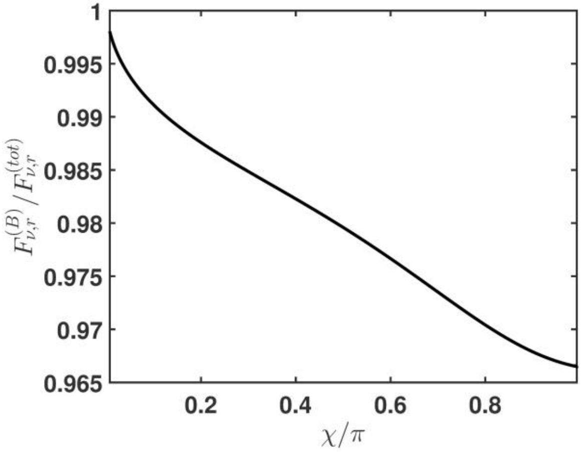
(a) Direct scattering



(b) Retrograde scattering



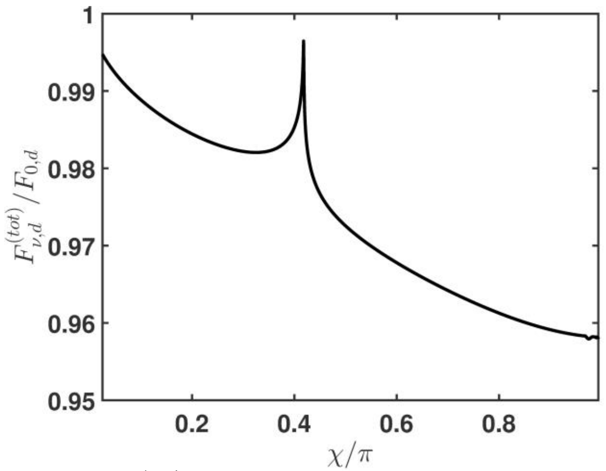
(c) Direct scattering



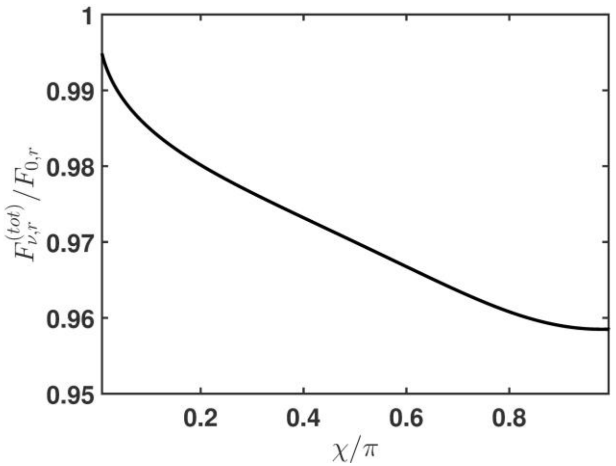
(d) Retrograde scattering

- Maximally rotating SMBH with $a = M$
- $\lambda = +1$
- The maximal effect is for the backward scattering $\chi = \pi$. The glory flux of neutrinos experience maximal (several %) reduction

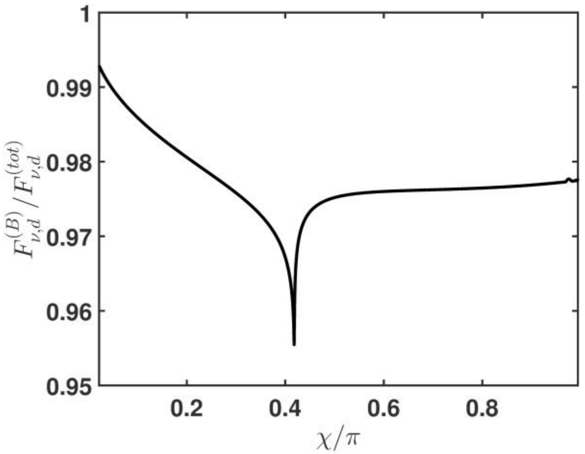
Fluxes of scattered neutrinos accounting for spin oscillations: counter-rotating disk



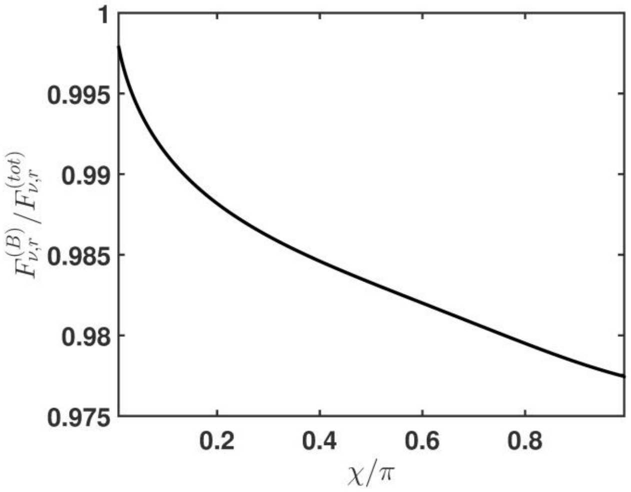
(a) Direct scattering



(b) Retrograde scattering



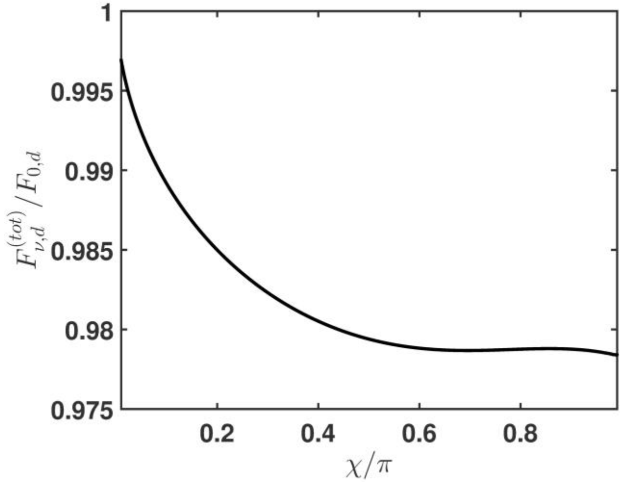
(c) Direct scattering



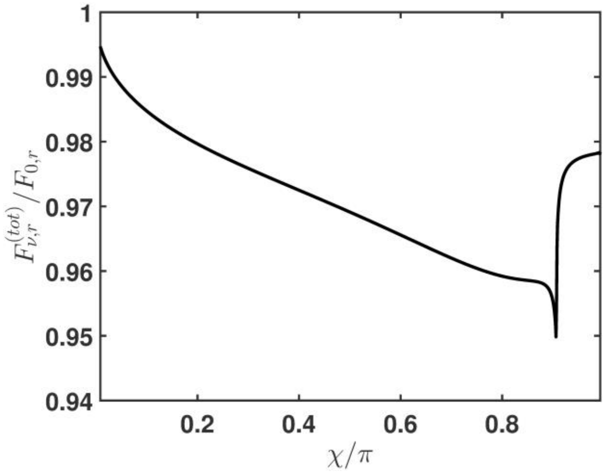
(d) Retrograde scattering

- Maximally rotating SMBH with $a = M$
- $\lambda = -1$
- There is an upward spike in the total flux in the direct scattering
- P_{LL} is great

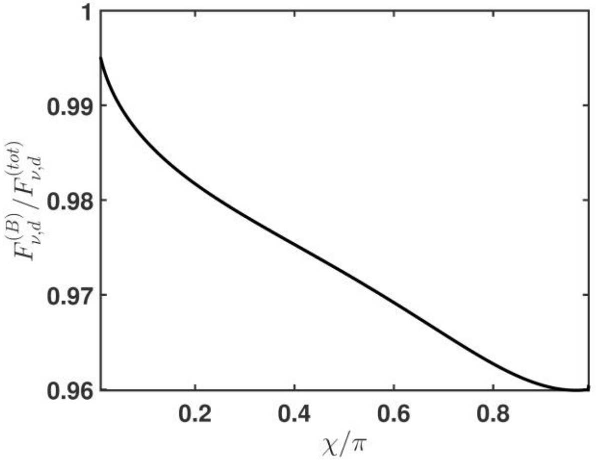
Fluxes of scattered neutrinos accounting for spin oscillations: counter-rotating disk



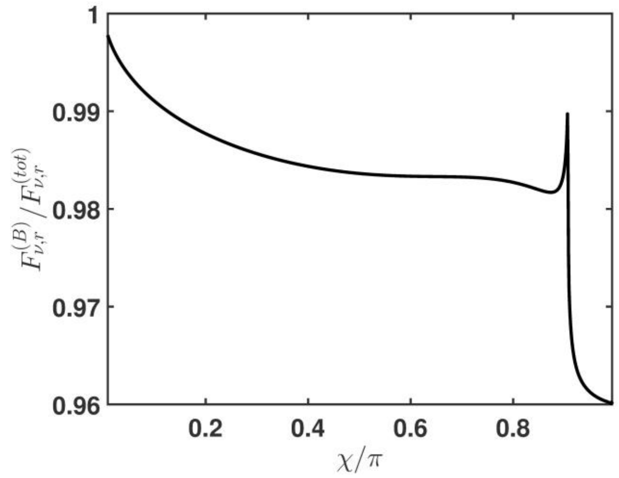
(a) Direct scattering



(b) Retrograde scattering



(c) Direct scattering



(d) Retrograde scattering

- SMBH with $a = 0.2M$
- $\lambda = -1$
- There is a downward spike in the total flux in the retrograde scattering
- P_{LR} grows

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 form and the size of a BH shadow is unchanged since spin oscillations do not contribute to the flux at $\chi = 0$
- The major modification of the flux is for backwardly scattered neutrinos $\chi = \pi$
- The electroweak interaction with counter-rotating disks result in the up- or downward spikes in the total fluxes in direct or retrograde scatterings
- Possible interpretation: neutrinos interact with matter of a disk which moves with relativistic velocities. Moving matter is known to affect spin oscillations including causing the spin-flip

FLAVOR OSCILLATIONS 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

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

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

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

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

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

$$\left(H_m^{(g)}\right)_{aa} = -\frac{p^2h}{2\sqrt{p^2 + m_a^2}}\sin^2\vartheta\cos(2\varphi - \phi_a)$$

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

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

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 $(F_e, F_\mu, F_\tau)_S = (1:0:0)$

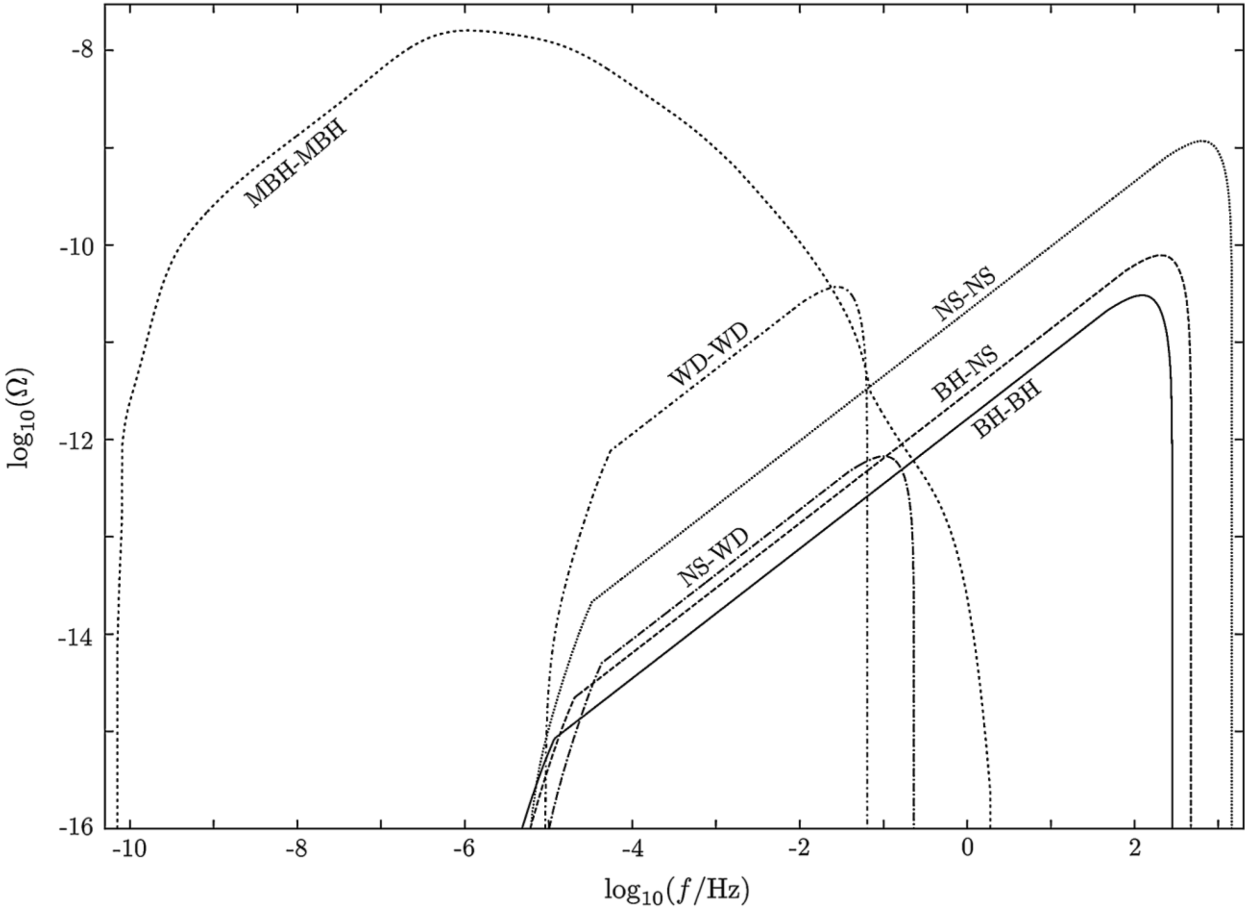
Initial condition $\rho_{11}(0) = 1, \rho_{22}(0) = 0, \rho_{33}(0) = 0$

GW emitted by randomly coalescencing supermassive BHs (SMBH)

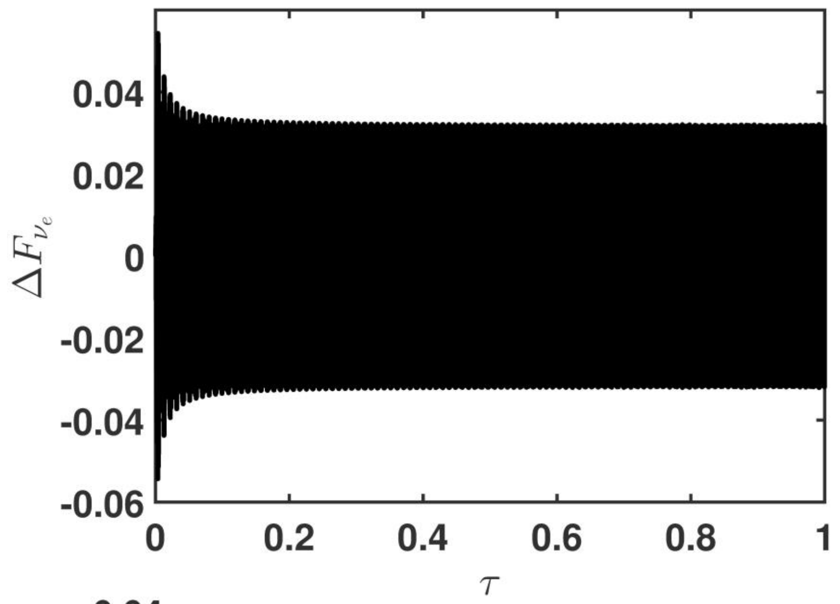
- Spectral function for GW from different types of merging BHs is calculated by Rosado (2011)
- Ω is the energy density of stochastic GWs per logarithmic frequency interval with respect to the closure density of the universe

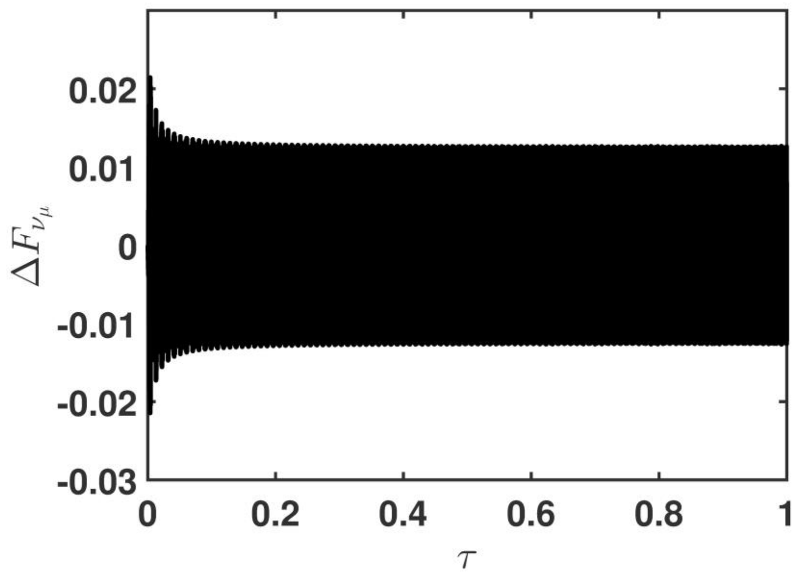
$$\Omega \propto f^{\alpha}$$

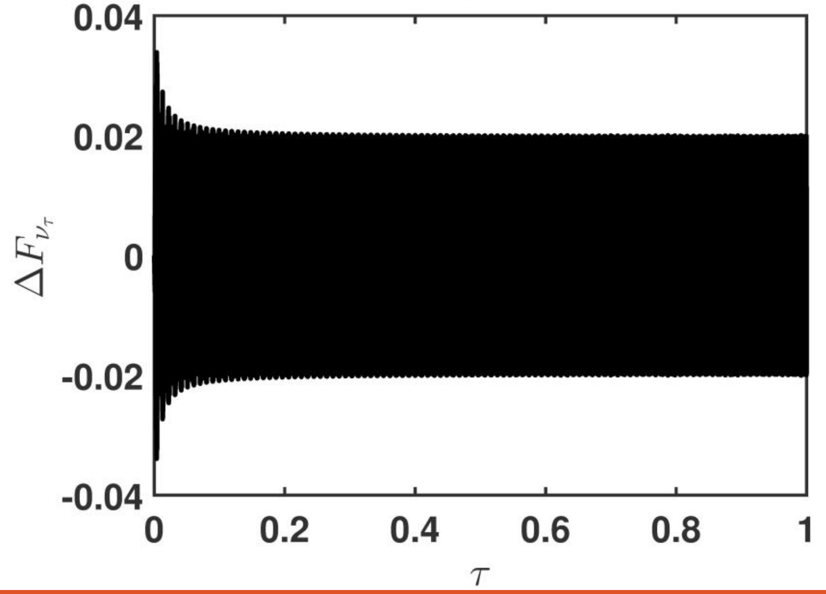
- We will study the case of SMBH since they produce stochastic GWs with the major effect on neutrino oscillations



Fluxes of flavor neutrinos





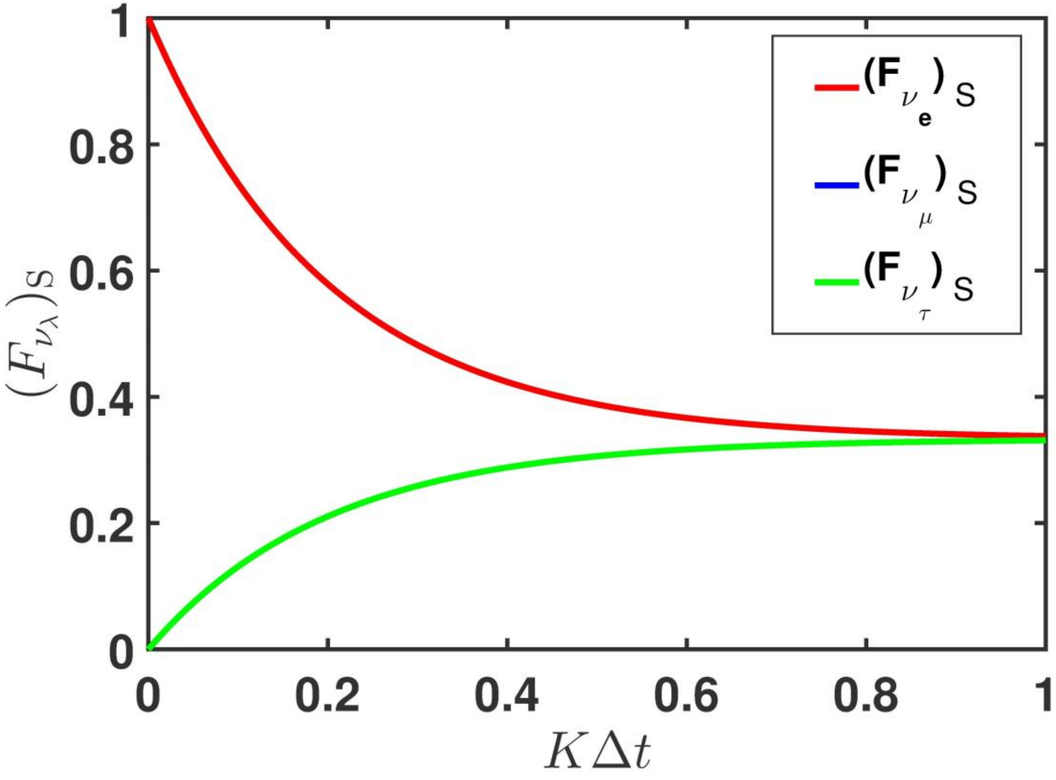


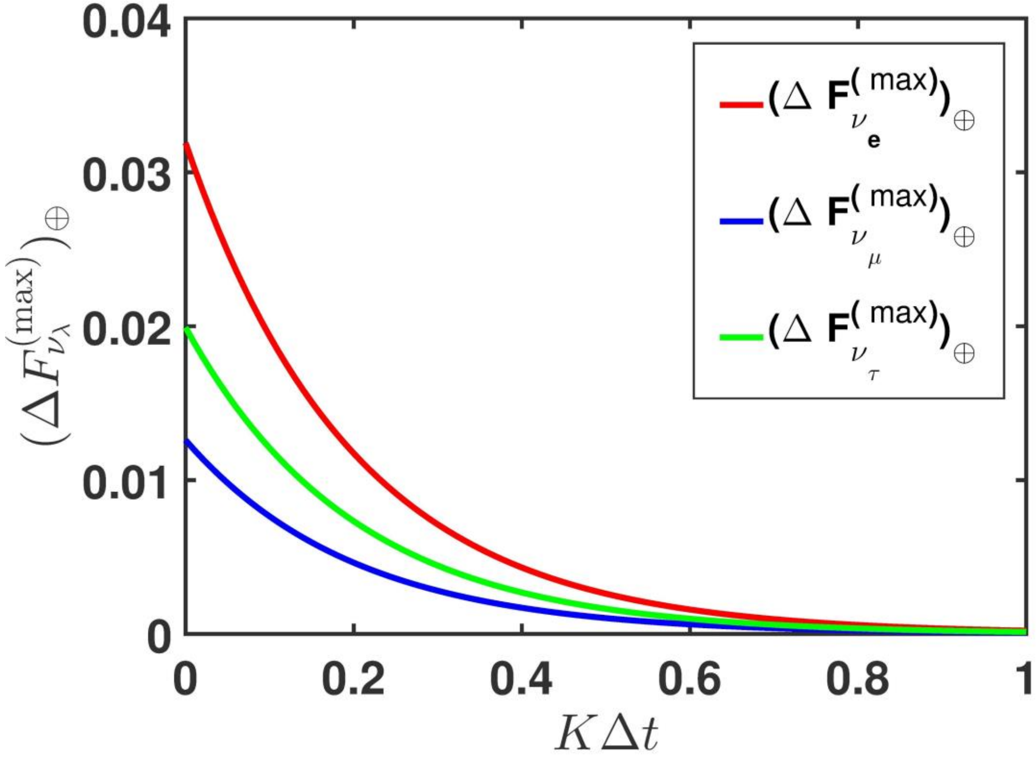
E = 10 MeV

$$\tau = x/L$$

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 disk
- There is a reduction of fluxes mainly for the backward scattering
- The interaction of neutrinos with an accretion disk also modifies the fluxes. There are spikes in the total fluxes, which can result from the neutrino interaction with moving matter of a disk
- 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