Излучение безмассовых частиц и ограничения классической ОТО

Д.В. Гальцов

Физфак МГУ

XIV Марковские чтения

13 мая 2016 г. ИЯИ, Москва

М.А. МАРКОВ и нейтрино

- 1960: Идея использования озер и океанов для регистрации нейтрино (Дюманд – Баксан -- Байкал)

- 1967: Предсказание роста сечений то сечение нейтринных многочастичных процессов с энергией (доклад на семинаре CERN-JINR в Риге).

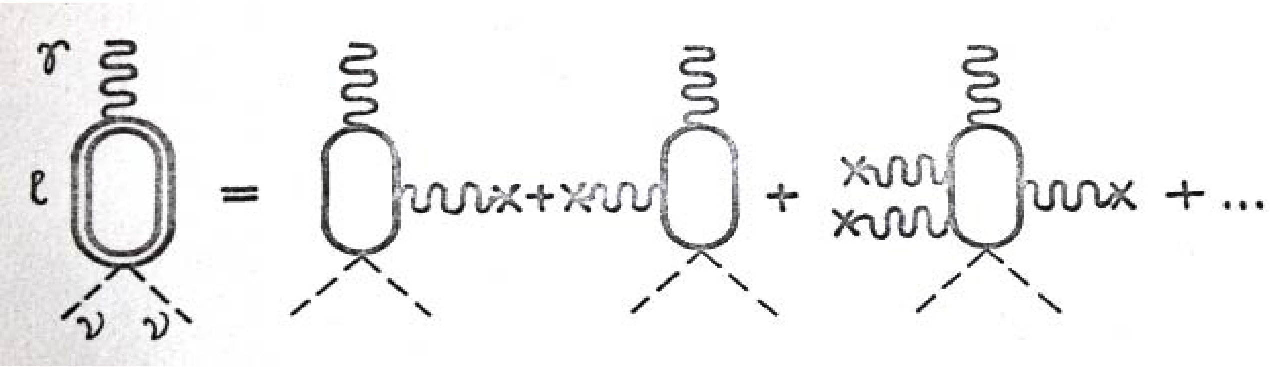
- Книга «Нейтрино» (1964)

Аннотация:

«Предлагаемый обзор ограничен физическими явлениями в нейтринных пучках и рядом проблем слабых взаимодействий, связанных с физикой нейтрино. Все более и более становится ясным, что нейтринные процессы играют существенную роль в природе, раскрывается богатейшее разнообразие эффектов с участием нейтрино. Есть основание полагать, что ряд астрофизических проблем может найти свое решение при дальнейшем изучении закономерностей нейтринной физики. Не исключено, что нейтринные процессы имеют существенное значение для космологии и космогонии. Нейтринная астрономия может стать делом не такого уж далекого будущего.

Электромагнитные свойства нейтрино

- **Излучение фотона нейтрино в постоянном поле (** ***Д.Г. и Н. Никитина, ЖЭТФ, т. 62, с. 2008 (1972)).*** **Четырехфермионная теория с точным учетом внешнего поля в картине Фарри** $\nu_\ell(q) + F \to \nu_\ell(q') + \gamma(k,e) + F$



В низшем порядке теории возмущений излучение фотона и однофотонное рождение пары нейтрино-антинейтрино

$\gamma(k,e) + F \to \nu_\ell(q) + \tilde{\nu}_\ell(q') + F$ **обусловлено треугольной аномалией**

$$M = -i\,\frac{\sqrt{2}\,G}{k^0}\int dx\, e^{-i(q-q')x}\langle \gamma(k,e)|\partial_\mu J_5^\mu(x)|0\rangle$$

$$\partial_\mu \partial_\mu J_5^\mu(x) = -2im J_5(x) + \frac{e^2}{8\pi}\tilde{\mathcal{F}}_{\mu\nu}\mathcal{F}^{\mu\nu}$$

где $\mathcal{F}_{\mu\nu} = F_{\mu\nu} + f_{\mu\nu}$. Кинематически процесс коллинеарнен, т.е.

излучение происходит в направлении вперед. При этом отсутствует коллинеарная расходимость, возникающая, когда фотон испускается из внешней линии (ср. Вайнберг, Киношита-Ли-Науенберг… 60-е гг)

$$w_{\nu\to\nu\gamma} = \frac{e^2 G m_\ell^6}{4\pi^4 q^0}\tilde{\chi}^2 \begin{cases} \chi^4/15^3, & \chi^2 \ll 1 \\ 1, & \chi^2 \gg 1 \end{cases}$$

где $\tilde{\chi}^2 = -e^2 m_\ell^{-6}(q_\mu \tilde{F}^{\mu\nu})^2$

Заметим, что вероятность испускания фотона остается конечной при нулевой массе заряженного лептона.

Вероятность однофотонного рождения пары нейтрино-антинейтрино в пределе сильного поля также не зависит от массы лептона

$$w_{\gamma\to\nu\bar{\nu}} = \frac{e^4 G_F^2 B^2 E_\gamma}{24\pi^4}$$

The rest is based on:

- **DG, Synchrotron radiation from massless charge, Physics Letters B 747, 400 (2015)**

- **DG, Electromagnetic and gravitational radiation from massless particles, arXiv:1512.06826**

- **DG, P. Spirin and Th. Tomaras**

  Gravitational radiation form massless particle orbiting a circle (in preparation)

Massless particles interacting with massless fields

- Photons, neutrino, gravitons in GR +
- Gluons in QCD +
- Massless charges (MC) in QED -?
  - Collinear divergences +
  - Charge screening - +
  - $e(\mu)$ → 0 in the IR - +
- But: classical motion in external field +
- Massless QED in external magnetic field +
- MC exists, but unobservable: do not radiate ?
- Radiation from massless particles in GR ?

QUESTIONS

- Is Minkowski space QED with massless charged particles non-contradictory? (Вакс, Грибов, Смилга…)
- Can classical ED describe radiation from massless charges?
- Are ultrarelativistic limit and massless limit for radiating particle identical?
- Whether quantum radiation power from massless charge have classical limit?
- Whether radiation from massless particle moving along geodesic in curved space be described classically?

Larmor formula for radiation in classical ED in the massless limit

Power emitted by a classical charge in magnetic field

$$P_{\rm cl} = \frac{2e^4 H^2}{3m^2}\left(\frac{E}{m}\right)^2$$

diverges as m→0

Is this formula applicable to a «true» massless charge?

Lienard-Wiechert potential has singularity along the line parallel to the velocity

$$A^\mu = \left.\frac{ev^\mu}{R(1-\cos\theta)}\right|_{\rm ret}$$

reminiscent to collinear singularities in QFT.

Radical claims (Kosyakov, Lechner): **NO RADIATION**

BUT: spectral decomposition is correct,

Schott remains right!

Schott formula is valid for v=c

$$\frac{dP}{d\Omega} = \sum_{\nu=0}^{\infty} \frac{e^2\nu^2\omega_H^2}{2\pi} \left[\tan^2\theta J_\nu^2(\nu\beta\cos\theta) + \beta^2 J_\nu'^2(\nu\beta\cos\theta)\right] \qquad \beta \to 1$$

but the harmonic number $\omega = \nu\omega_H, \quad \omega_H = \frac{eH}{E}$ is no more bounded at high frequencies:

$$\nu \lesssim \nu_{\rm cr} \sim (1-\beta^2)^{-3/2} = (E/m)^3$$

so the total power diverges. But passing to continuous spectral distribution, integrating over angles, and taking the limit m → 0 one obtains the non-singular spectral distribution

$$\frac{dP}{d\omega} = \frac{e^2\omega_H 3^{1/6}\Gamma(2/3)}{\pi}\left(\frac{\omega}{\omega_H}\right)^{1/3}$$

which has the only problem to be non-integrable at high frequences, so a cutoff has to be introduced. This classical formula is relevant as low-frequency limit of en exact quantum formula.

Total power with quantum cutoff

Absence of classical cutoff corresponds to shrinking to zero of radiation formation length for massless charge. In quantum theory formation length can not be shorter than de Broglie length $\lambda_B = \hbar c/E$ therefore we cut on the quantum bound

$$\omega_{\max} = E/\hbar$$

obtaining

$$P_{\text{cut}} = \frac{e^2\sqrt{3}\Gamma(2/3)}{4\pi\hbar^2}(3e\hbar HE)^{2/3}$$

This expression differs from the true quantum result only by numerical factor. It diverges as Planck's constant goes to zero as

$$\hbar^{-4/3}$$

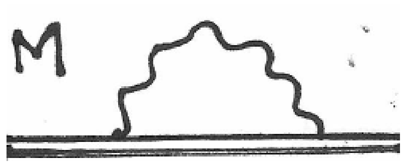
Non-analyticity in e and $\hbar$ indicates on non-perturbative nature of this result

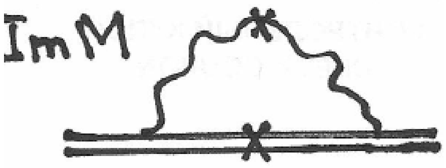
SR in quantum theory

- Start with exact solution of the Klein-Gordon (Dirac) equation in magnetic field producing the Landau spectrum (macroatom)

$$E = \sqrt{eH(2n+1) + p_z^2}$$

- Consider radiative transitions from n to n'
- Sum up over final states to get spectral-angular distribution and the total power
- For massive charges the detailed theory was developed by Sokolov, Klepikov, Ternov, Bagrov, Zhukovski, Borisov in 50--70-ies
- Later approaches: Schwinger, Baier, Ritus… -- using mass operator, summing over final quantum numbers implicitly





SR in massless QED: Schwinger approach

Exact calculation of one loop mass operator in massless scalar QED

The corresponding term in the action $-\frac{1}{2}\int \phi(x)M(x,x')\phi(x')dxdx'$

In Schwinger sympbolic notation the exact in H one-loop mass-operator of the massless charge reads

$$M = ie^2\int\left[(\Pi-k)^\mu\frac{1}{k^2}\frac{1}{(\Pi-k)^2}(\Pi-k)_\mu\right]\frac{dk}{(2\pi)^4} - M_0$$

where $\Pi_\mu = -i\partial_\mu - eA_\mu,\;\; A_\mu$ stands for constant magnetic field H, and M_0 is the subtraction term. Exponentiating two propagators

$$\frac{1}{k^2}\frac{1}{(\Pi-k)^2} = -\int_0^\infty sds\int_0^1 \mathrm{e}^{-is\mathcal{H}}$$

, with $\mathcal{H} = (k-u\Pi)^2 - u(1-u)\Pi^2$

one replaces integration over k is by averaging over states of the fictituos particle

$$M = ie^2\int_0^\infty sds\int_0^1 du\langle\xi\big|(\Pi-k)^\mu \mathrm{e}^{-is\mathcal{H}}(\Pi-k)_\mu\big|\xi\rangle$$

treating $\mathcal{H}$ as Hamiltonian

Operator products are disentangled in Heisenberg representation for fictitious particle, and are taken on shell, i.e. $\phi(x) = \phi(\mathbf{r})\mathrm{e}^{-iEt}$ satisfying $\Pi^2\phi = 0$ with $E = \sqrt{eH(2n+1)}$. The result reads

$$M = \frac{e^2}{4\pi}\int_0^1 du \int_0^\infty \frac{ds}{s}\left[\mathrm{e}^{-i\psi}\Delta^{-1/2}\left(E^2\Phi_1 + 4ieH\Phi_2 + i\Phi_3/s\right) - 2i/s\right]$$

$$\Phi_1 = 3 - 4u + u^2 - \frac{(1-u)^2}{\Delta}(4\cos 2x - 1) - \frac{u(1-u)}{x\,\Delta}\sin 2x\,,$$

$$\Phi_2 = \sin 2x - \frac{2u(1-u)\sin^2 x}{x\,\Delta}\cos 2x\,,$$

$$\Phi_3 = 1 + \frac{1-u}{\Delta}(2\cos 2x - 1) + \frac{u\sin 2x}{2x\,\Delta}(4\cos 2x - 3)\,,$$

where $x = eHsu$ and $\Delta = (1-u)^2 + u(1-u)\dfrac{\sin 2x}{x} + u^2\left(\dfrac{\sin x}{x}\right)^2$

$$\psi = (2n+1)[\beta - (1-u)x]\,, \quad \tan\beta = \left(\cot x + \frac{u}{x(1-u)}\right)^{-1}$$

This is true for all Landau levels n.

Quasiclassical motion n>>1

Simple analytical result can be obtained for high initial Landau levels n>>1. The imaginary part Im M (divided by -E) gives the total probability of radiation summed over all final n'. The integrals over x are computed in the leading approximation in $n^{-1/3}$ expanding the exponential and the rest of the integrand in powers of x. One gets

$$\Gamma = \frac{e^2}{4\pi E}\int_0^1 du \int_0^\infty \frac{dx}{x}\left(E^2\Phi_1 \sin\psi \; + 2\frac{eHu}{x}(1-\cos\psi)\right)$$

where $\psi \approx (2n+1)\alpha x^3$. After x-integration one finds

$$\Gamma = \frac{e^2\Gamma\left(2/3\right)\left(3eHE\right)^{2/3}}{8\pi\sqrt{3}E}\int_0^1 \frac{8-32u/3+19u^2/3-3u^3}{u^{2/3}(1-u)^{1/3}}du$$

and finally $\Gamma = \frac{4e^2}{9E}\Gamma\left(2/3\right)\left(3eHE\right)^{2/3}$ Decaying levels acquire the Imaginary parts of energy levels E - i Γ/2, so the spacing must be << Γ This gives upper restriction $n \ll \frac{81}{16\left[\Gamma\left(2/3\right)\right]^3}\frac{1}{\alpha^3} \approx 0.5\cdot 10^7$

Radiation spectrum

To get the spectral power of radiation one has to perform Fourrier decomposition inside the mass operator

$$P(\omega) = -\frac{\omega}{E}\,\mathrm{Im}\left(\int_{-\infty}^{\infty} \mathrm{e}^{i\omega\tau}\, M'\, \frac{d\tau}{2\pi}\right)$$

where the modified M is

$$M' = -ie^2 \int_0^{\infty} sds \int_0^1 du \langle\xi\big|(\Pi-k)^{\mu}\mathrm{e}^{-is\mathcal{H}}\mathrm{e}^{-ik^0\tau}(\Pi-k)_{\mu}\big|\xi\rangle$$

Calculations in the quasiclassical regime n>>1 give

$$P(\omega) = \frac{e^2 v}{4\pi E}\int_0^{\infty}\left(E^2(8-v^2)(1-v)^2 x\sin\psi \;+\frac{eHv}{x^2}(1-\cos\psi)\right)dx$$

where $v = \omega/E$. Integrating over x as before, one gets

$$P(\omega) = \frac{2e^2\,\Gamma\left(2/3\right)}{27\hbar E}\,\left(3e\hbar H E\right)^{2/3}\mathcal{P}\left(\hbar\omega/E\right)$$

where the normalized spectral distribution is introduced (red curve)

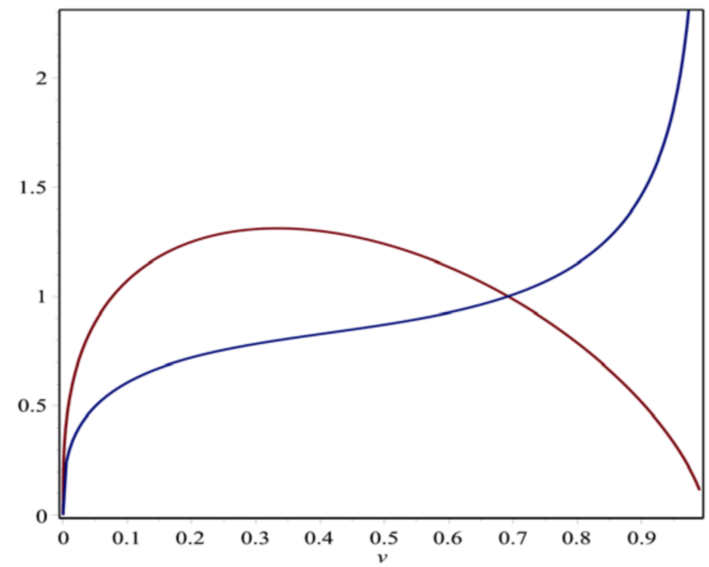
$$\mathcal{P}\left(v\right) = \frac{27}{2\pi\sqrt{3}}\,v^{1/3}(1-v)^{2/3}$$

The curve has maximum at $\hbar\omega_{\mathrm{max}} = \frac{1}{3}E$

The average photon energy

$$\langle\hbar\omega\rangle = E\int_0^1 v\mathcal{P}\left(v\right)dv = \frac{4}{9}E$$

For small frequencies spectrum coincides with classical result.



In the case of spin 1/2 calculations are essentially similar and lead to the following expression for the spectral power:

$$\mathcal{P}_{1/2}(v) = \frac{81\sqrt{3}}{64\pi}\, v^{1/3}(1-v)^{-1/3}(v^2 - 2v + 2)\,. \qquad (14)$$

At the upper limit $v \to 1$ the spin 1/2 spectral power has an integrable divergence. The low-frequency limits are identical for both spins and coincide with the classical spectrum ($\hbar$ disappears):

$$P_{\rm cl}(\omega) = e^2\frac{3^{1/6}}{\pi}\Gamma(2/3)\left(\frac{\omega}{\omega_H}\right)^{1/3}\omega_H\,, \qquad \omega_H = \frac{eH}{E}\,. \quad (15)$$

This power-low dependence exhibits ultraviolet catastrophe (no high-frequency cutoff), which is cured in quantum theory.

One can also investigate the case of vector massless particles, $s = 1$, but then the result is infinite: magnetized vector QED fails to describe radiation from massless vector charges. This could be expected in view of the results of Case and Gasiorovich,[5] who gave the arguments that electromagnetic interaction of massless charged particles with spin one and higher is controversial.

The total power is obtained integrating over the spectrum

$$P = \int_0^{E/\hbar} P(\omega)d\omega = \frac{2e^2\,\Gamma\left(2/3\right)}{27\hbar^2}\ \left(3e\hbar HE\right)^{2/3}$$

It has exactly the same functional form as the result of intergration of classical spectrum with quantum cut-off, differing only by the numerical factor of the order ½.

This quantity diverges for zero Planck's constant. Thus, synchrotron radiation form massless charge is essentially quantum, consisting of hard quanta of the order of particle energy. Remarkably, this does not depend on the value of magnetic field and the particle energy. Even in weak magnetic field of the Earth such particles would be observable by their radiation with universal spectrum.

No classical radiation reaction

- One consequence of quantum nature of SR from massless charge is that the radiation reaction problem becomes meaningless. Such an equation derived by Kazinski et al ('02) has strange features like non-lagrangian divergent terms and fifth derivative in the finite term. Meanwhile, massless limit in the usual Lorentz -Dirac equation diverges, like the Larmor formula. The reason is that quantum recoil makes the reaction problem stochastic.
- Moreover, in the sinchrotron radiation theory there is stronger restriction on the validity of classical radiation reaction equation due to excitation of the so-called betatron oscialltions. The threshold is

$$E_{\text{fluct}} \sim E_{1/5} = m \left(\frac{H_0}{H} \right)^{1/4}$$

- It is lower than the recoil treshold

$$E_{\text{recoil}} \sim m \frac{H_0}{H}$$

SR emission of gravitons (flat space)

The charge also emits gravitons in Minkowski space in the framework of the linearized gravity $g_{\mu\nu} = \eta_{\mu\nu} + \varkappa h_{\mu\nu}$, with interaction

$$S_{\rm int} = -\frac{\varkappa}{2} \int h_{\mu\nu} T^{\mu\nu}$$

where $T^{\mu\nu} = T^{\mu\nu}_{\rm p} + T^{\mu\nu}_{F}$

Second term is Maxwell, it is needed to ensure conservation equation $\partial_\mu T^{\mu\nu} = 0$. The Maxwell field must be the sum of the external (magnetic) field and the retarded field of the charge

$$T^{\mu\nu}_{F} = \frac{1}{4\pi} \left(F^{\mu\lambda} \mathcal{F}_{\lambda}^{\ \nu{\rm ret}} + \mathcal{F}^{\mu\lambda{\rm ret}} F_{\lambda}^{\ \nu} - \frac{1}{2} \eta^{\mu\nu} F^{\kappa\lambda} \mathcal{F}^{\rm ret}_{\kappa\lambda} \right)$$

The retarded field has to be further split as $\mathcal{F}^{\rm ret}_{\mu\lambda} = \mathcal{F}^{\rm self}_{\mu\lambda} + \mathcal{F}^{\rm rad}_{\mu\lambda}$ to account for resonant transformation of EM wave to GW in the homogeneous magnetic field. One needs to keep only linear term in the retarded field of the charge (quadratic is self-energy like)

EM-GW tansformation (Gerzenshtein effect)

- Due to linearity of the Maxwell source term in the retarded field is splits as $T_F^{\mu\nu} = t^{\mu\nu} + S^{\mu\nu}$ where

$$t^{\mu\nu} = \frac{1}{4\pi}\left(F^{\mu\lambda}\mathcal{F}_{\lambda}^{\ \nu\mathrm{rad}} + \mathcal{F}^{\mu\lambda\mathrm{rad}}F_{\lambda}^{\ \nu} - \frac{1}{2}\eta^{\mu\nu}F^{\kappa\lambda}\mathcal{F}_{\kappa\lambda}^{\mathrm{rad}}\right)$$

$$S^{\mu\nu} = \frac{1}{4\pi}\left(F^{\mu\lambda}\mathcal{F}_{\lambda}^{\ \nu\mathrm{self}} + \mathcal{F}^{\mu\lambda\mathrm{self}}F_{\lambda}^{\ \nu} - \frac{1}{2}\eta^{\mu\nu}F^{\kappa\lambda}\mathcal{F}_{\kappa\lambda}^{\mathrm{self}}\right)$$

- The first is trivially conserved, while the second is conserved together with the mass term, i.e. S acts the non-local source of GW.
- The corresponding two GW amplitudes do not interfere and can be considered separately. The first source is EM-GW transformation
- In the magnetic field (Gertsenshtein effect),

$$\frac{dP_{\mathrm{res}}}{d\Omega} = GB^2R^2\,\frac{dP_{\mathrm{em}}}{d\Omega}$$

- so the same considerations apply to it: radiation is quantum.

Proper gravitational radiation

The second part of gravitational radiation (genuine GW) is generated by the sum of the sources $T^{\mu\nu} = T^{\mu\nu}_{\rm p} + S^{\mu\nu}$ has the spectrum falling with frequency

$$\frac{dP_{GW}}{d\omega} = \frac{\Gamma\,(1/3)\,3^{5/6} G E^2 \omega_H}{2\pi} \left(\frac{\omega_H}{\omega}\right)^{1/3}$$

which is falling with frequency, but is still non-integrable, and quantum cut-off is thus needed.

“Quantum” spectrum

- The normalized graviton spectrum is

$$\mathcal{P}_{GW} = \frac{2}{3}\left(\frac{\hbar}{E}\right)^{2/3}\theta(E-\hbar\omega)\,\omega^{-1/3}$$

- and the average energy of emitted graviton

$$\langle\hbar\omega\rangle = \int_0^{E/\hbar}\hbar\omega\mathcal{P}_{GW}\,d\omega = \frac{2}{5}E$$

so radiation is again hard.

Thus, graviton emission by massless non-gravitating source computed within the linearized gravity in Minkowski space-time is essentially quantum process. Large recoil precludes possibility of classical description of back reaction a la Lorentz-Dirac.

Relastivistic orbits near black holes

Time-like geodesics $\left(\frac{dr}{d\tau}\right)^2 + U(r) = 0 \quad U(r) = \left(1 - \frac{2M}{r}\right)\left(\frac{L^2}{r^2} + 1\right) - \gamma^2$

$$\frac{d\phi}{d\tau} = \frac{L}{r^2}, \qquad \frac{dt}{d\tau} = \gamma\left(1 - \frac{2M}{r}\right)^{-1}$$

Circular orbits: $U(r_{\rm p}) = 0 = U'(r_{\rm p})$ lead to

$$\gamma = \left(1 - \frac{2M}{r_{\rm p}}\right)\left(1 - \frac{3M}{r_{\rm p}}\right)^{-1/2}, \quad \frac{L}{\gamma} = (Mr_{\rm p})^{1/2}\left(1 - \frac{2M}{r}\right)^{-1}$$

and

$$\omega_0 = \frac{d\phi}{dt} = \left(\frac{M}{r_{\rm p}}\right)^{1/2}, \quad \frac{dt}{d\tau} = \left(1 - \frac{3M}{r_{\rm p}}\right)^{-1/2}$$

, orbits $3M < r_{\rm p} < 4M$

are unstable and jump to large angle scattering orbits with impact

$$b = \frac{L}{(\gamma^2 - 1)^{1/2}} = r_{\rm p}\left(\frac{4M}{r_{\rm p}} - 1\right)^{-1/2}$$

For $\gamma \gg 1$ unbound orbits close to $b = 3\sqrt{3}M$ make multiple revolutions

GSR from massive bodies

- Null circular orbit is at $r_{\rm ph} = 3M$ (photon orbit).
- Massive ultrarelativistic orbit are close $r_{\rm p} = (3+\delta)M$
  so that $\gamma^2 = \dfrac{1}{3\delta}$

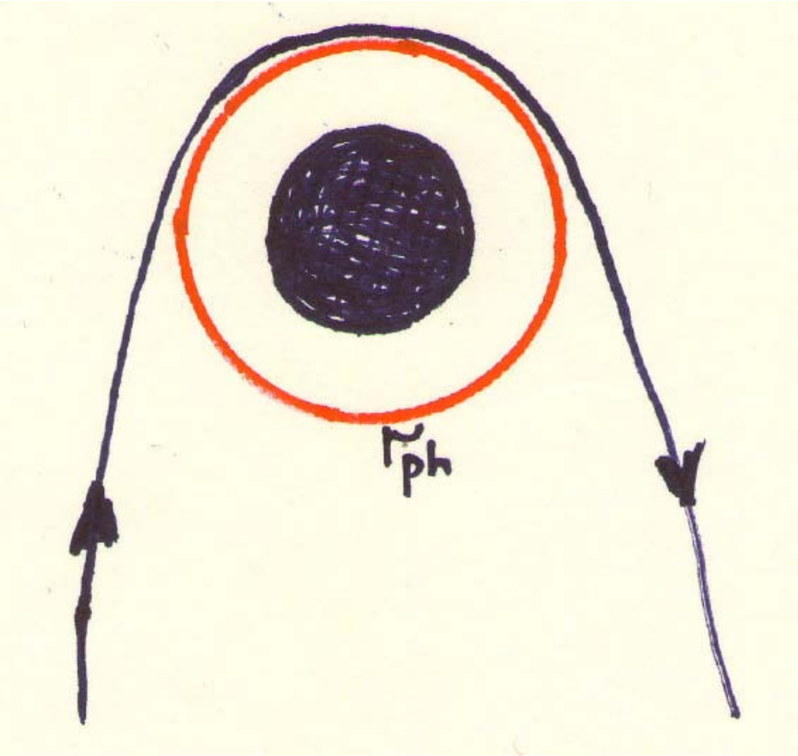
- For massive ultrarelativistic particle aiming to explain gravitational wave flux reported by Weber (Misner, Brill, Ruffini, Breuer, Chrzanowsky …) in 70-ies, The spectrum has a cut-off at the harmonic $m_{\rm cr} = \dfrac{12}{\pi}\gamma^2$ of the rotation frequency. The total power was computed in
  DG and Matiukhin, Sov J Nucl Phys v.45,555 ('87)

$$P_{GSR} = \frac{6\mathrm{e}^{-\pi/4}(r_{\rm p} - M)\left|\Gamma(1/4 + i/4)\right|^2}{\pi^{3/2} r_{\rm p}^2 (r_{\rm p} + 3M)} (\mu\gamma)^2 \ln(\gamma)$$

GSR from massless particles

- One can imagine flows of neutrinos or photons scattered at large angle on black holes, their radiation can be estimated knowing power of GSR

- Gravitational radiation is described by the solution of the Teukolsky equation. Fluxes going to infinity and to black hole are the same, so we need to calculate only the Weyl Newman-Penrose scalar ψ_4



Total radiation power from massless point particle at a circular orbit

$$P_{\rm GSR} = k\frac{E^2\omega_0}{M}\sum_1^{\infty}\frac{1}{m}$$

where the sum has no frequency cut-off and diverges

Introducing quantum cut-off $m_{\rm max} = \frac{E}{\hbar\omega_0}$ we get

$$P_{\rm GSR} = k\frac{E^2\omega_0}{M}\sum_1^{m_{\rm max}}\frac{1}{m} = k\frac{E^2\omega_0}{M}\ln\left(\frac{E}{\hbar\omega_0}\right)$$

Energy loss per revolution is

$$\Delta E_{\rm GSR} = k_1\frac{E^2}{M}\ln\left(\frac{E}{\hbar\omega_0}\right)$$

and the efficiency is

$$\epsilon = \frac{\Delta E}{E} = k_1\frac{E}{M}\ln\left(\frac{E}{\hbar\omega_0}\right)$$

It may be non-small within the limits of validity

$$E < M\,, \qquad \ln\left(\frac{E}{\hbar\omega_0}\right) \gg 1$$

Conclusions

- While motion of massless point particles is unambiguosly prescribed by classical GR as null geodecis, their gravitational radiation **is not**
- Gravitational radiation from massless particles in classical GR exhibits **ultraviolet catastrophe,** appealing to quantization of gravity. This is an independent argument apart of the problem of singularities.
- Quasi-quantum GSR power obtained integrating classical spectrum up to the quantum cut-off $\hbar\omega = E$ is likely to indicate that ***efficiency of graviton emission for large angle scattering of massless particles from black hole can be non-small*** (partly applicable to LED transplanckian problem), but it is small in the case of lensing (and deflection by Sun). Thus lensing proves not only classical GR, but also quantum gravity!
- Gravitational smoothening in the spectrum of GSR vs SR is manifest, but the effect is not enough to ensure the UV finiteness

Congratulations to winners

and thanks for attention!