Electromagnetic properties of neutrinos: a window to New Physics

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&

JINR -Dubna

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Stockholm,
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2013

- the standard Higgs boson
  (... probably ...)
- the Standard Model
  experimental status
  confirmation

ν is the only
known
particle with properties
Beyond
Standard
Model

ν exhibits unexpected properties (puzzles)

W. Pauli, 1930

- neutral "neutron" $\Longrightarrow$ ν

E.Fermi,
1933

- probably $\mu_\nu \neq 0$!?

…recent claim for
new experimental
bound on μ_ν
(with atomic ionization
effect) continue
chain of puzzles…

- Pauli himself wrote to Baade:

"Today I did something a physicist should never do. I predicted something which will never be observed experimentally…".

H.Bethe, R.Peierls, «The 'neutrino'»
Nature 133 (1934) 532,

- «There is no practically possible way of observing the neutrino»

… puzzles …

- …up to now absolute value ?

$m_\nu \neq 0$ after 80 years left !

… however … ⇒

… an optimistic view on the present and future of ν

Бруно Понтекорво

1913-1993

In 1946
Bruno Pontecorvo:

"… observation of neutrinos is not out of question…"

$$\nu + (A, Z) \rightarrow e^{-} + (A, Z+1)$$

$$^{37}\mathrm{Cl} + \nu \rightarrow {}^{37}\mathrm{Ar} + e^{-}$$

August 22, 2013
Centenary of the birth of
Bruno Pontecorvo

… problem and puzzle

ν is quite

invisible

particle

weak interactions are indeed weak

$\boxed{L \sim 10^{15} km}$

… free path in water…

$\bar{\nu} + p \rightarrow e^{+} + n$

$E_{\nu} \sim 3MeV$

$\sigma \sim 10^{-43} \ cm^{2}$

ν manifests itself most clearly under the influence of **extreme external conditions**:

- strong external electromagnetic fields

and

- dense background matter

Outline (I)

ν electromagnetic properties

(short review)

⇒ ① Carlo Giunti, Alexander Studenikin :
"Neutrino electromagnetic properties"
Phys.Atom.Nucl. 73, 2089-2125 (2009)

② A.Studenikin : "Neutrino magnetic moment: a window to new physics"
Nucl.Phys.B (Proc.Supl.) 188, 220 (2009)

③ C. Giunti, A. Studenikin : "Electromagnetic properties of neutrino"
J.Phys.: Conf.Series. 203 (2010) 012100

④ C.Broggini, C.Giunti, A.Studenikin :
"Electromagnetic properties of neutrinos", ●
in: Special issue "Neutrino Physics"
(Adv. iHigh Energy Phys. 2012 (2012) 459526 (49 pp)
arXiv: 1207.3980 July 17, 2012

⑤ C.Giunti, A.Studenikin : "Theory and phenomenology
of neutrino electromagnetic properties"
Rev.Mod.Phys. (in preparation)

Outline (II)

(ii a)

- results of recent experimental searches for upper bound on μ_ν

(GEMMA Coll. JINR - ITEP)

(ii b)

- our corresponding theoretical studies of ν-e scattering

- proper treatment of "atomic ionization effect"

K.Kouzakov, A.Studenikin,

- “Magnetic neutrino scattering on atomic electrons revisited” **Phys.Lett. B** 105 (2011) 061801,
- “Electromagnetic neutrino-atom collisions: The role of electron binding” **Nucl.Phys.B** (Proc.Suppl.) 217 (2011) 353

K.Kouzakov, A.Studenikin, M.Voloshin,

- “Neutrino electromagnetic properties and new bounds on neutrino magnetic moments” **J.Phys.: Conf.Ser.** 375 (2012) 042045
- “Neutrino-impact ionization of atoms in search for neutrino magnetic moment”, **Phys.Rev.D** 83 (2011) 113001
- “On neutrino-atom scattering in searches for neutrino magnetic moments” **Nucl.Phys.B** (Proc.Supp.) 2011 (Proc. of Neutrino 2010 Conf.)
- “Testing neutrino magnetic moment in ionization of atoms by neutrino impact”, **JETP Lett.** 93 (2011) 699

M.Voloshin,

- “Neutrino scattering on atomic electrons in search for neutrino magnetic moment” **Phys.Rev.Lett.** 105 (2010) 201801

Outline (III)

- ν quantum states in magnetized matter

… new effect of …

Spin Light of ν in matter

$\boxed{SL\nu}$

⇒

ν energy quantization in rotating matter

… phenomenological consequences in astrophysics (pulsars)

ν in matter treated within «method of exact solutions» of quantum wave equations for wave function

Studenikin,
"Method of wave equations exact solutions in studies of neutrinos and electrons interaction in dense matter",
J.Phys. A: Math.Theor. 41 (2008) 164047

Balantsev, Popov, Studenikin,
J.Phys. A:Math.Theor. 44 (2011) 255301

Balantsev, Studenikin, Tokarev, Phys.Part.Nucl. 43 (2012), 727
Phys.Atom.Nucl. 76 (2013) 489

Studenikin, Tokarev,
Millicharged neutrino with anomalous magnetic moment in rotating magnetized matter,
arXiv: 1209.3245 v 2, May 28, 2013

(1)

. . . basics of ν electromagnetic properties

… in spite of

- results of terrestrial laboratory experiments on ν EM properties

as well as

- data from astrophysics and cosmology are

in agreement with "ZERO" ν EM properties

… However, in course of recent development of knowledge on ν mixing and oscillations,

$$m_\nu \neq 0$$

… a tool for studying physics
Beyond Standard Model…

$$m_\nu \neq 0$$

Theory (Standard Model with ν_R)

$$\mu_{\nu_e} = \frac{3eG_F}{8\sqrt{2}\pi^2}\, m_{\nu_e} \sim \boxed{3\cdot 10^{-19}}\,\mu_B\left(\frac{m_{\nu_e}}{1\,eV}\right), \quad \mu_B = \frac{e}{2m_e}$$

Lee, Shrock, 1977; Fujikawa, Shrock, 1980

$$\boxed{a_e = \frac{\alpha_{QED}}{2\pi} \sim 10^{-3}}$$

… much greater values are desired

for astrophysical or cosmology

visualization of μ_ν

- **Astrophysical bounds**

$$\mu_\nu \lesssim 3\cdot 10^{-12}\mu_B$$

G. Raffelt, D. Dearborn,
J. Silk, 1989.

- **Theory (Standard Model with ν_R)**

$$\mu_e = \frac{3eG_F}{8\sqrt{2}\pi^2}\, m_{\nu_e} \sim 3\cdot 10^{-19}\mu_B\left(\frac{m_{\nu_e}}{1\,eV}\right), \quad \mu_B = \frac{e}{2m_e}$$

Lee
Shrock, 1977; Fujikawa
Shrok, 1980

- **Limits from reactor ν-e scattering experiments**

A.Beda et al. (GEMMA Coll.)
(2012):

$$\boxed{\mu_\nu < 2.9\times 10^{-11}\mu_B}$$

...the present status...

to have visible $m_\nu \neq 0$

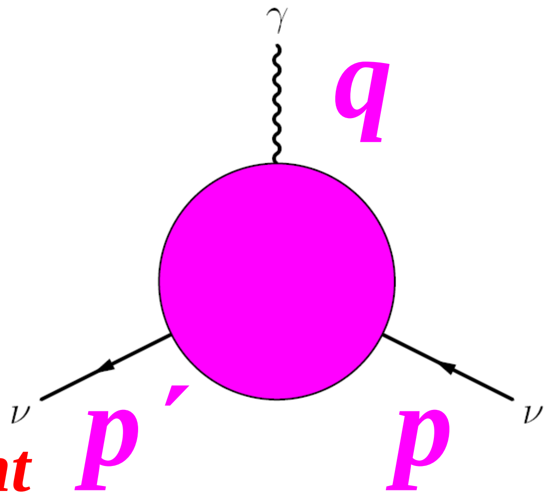
is not an easy task for

theoreticians

and experimentalists

. . . a bit of ν electromagnetic properties theory . . .

electromagnetic vertex function



$$< \psi(p')|J_\mu^{EM}|\psi(p) >= \bar{u}(p')\Lambda_\mu(q,l)u(p)$$

Matrix element of electromagnetic current is a Lorentz vector

$\Lambda_\mu(q,l)$ ***should be constructed using***

matrices $\hat{1}, \quad \gamma_5, \quad \gamma_\mu, \quad \gamma_5\gamma_\mu, \quad \sigma_{\mu\nu},$

tensors $g_{\mu\nu}, \quad \epsilon_{\mu\nu\sigma\gamma}$

vectors q_μ ***and*** l_μ

$$\boxed{q_\mu = p'_\mu - p_\mu, \; l_\mu = p'_\mu + p_\mu}$$

Lorentz covariance (1)
and electromagnetic
gauge invariance (2) ⇒

Matrix element of electromagnetic current between neutrino states

$$\langle \nu(p')|J_\mu^{EM}|\nu(p)\rangle = \bar{u}(p')\Lambda_\mu(q)u(p),$$

where vertex function generally contains 4 *form factors*

$$\Lambda_\mu(q) = f_Q(q^2)\gamma_\mu + f_M(q^2) i\sigma_{\mu\nu}q^\nu - f_E(q^2)\sigma_{\mu\nu}q^\nu\gamma_5 + f_A(q^2)(q^2\gamma_\mu - q_\mu \not{q})\gamma_5$$

1. electric

dipole

2. magnetic

3. electric

4. anapole

- **Hermiticity and discrete symmetries of EM current J_μ^{EM} put constraints on form factors**

Dirac ν

1) *CP invariance + hermiticity* ⟹ $f_E = 0$,

2) *at zero momentum transfer* ***only*** *electric charge $f_Q(0)$ and magnetic moment $f_M(0)$ contribute to $H_{int} \sim J_\mu^{EM} A^\mu$,*

3) *hermiticity itself* ⟹ *three form factors are real:* $Im f_Q = Im f_M = Im f_A = 0$

Majorana ν

1) *from CPT invariance (regardless CP or $\cancel{CP}$).*

$$f_Q = f_M = f_E = 0$$

…as early as 1939, W.Pauli…

EM properties ⟹ a way to distinguish Dirac and Majorana ν

In general case matrix element of J_μ^{EM} can be considered between different initial $\psi_i(p)$ and final $\psi_j(p')$ states of different masses

$p^2 = m_i^2, \ p'^2 = m_j^2$:

$$\boxed{< \psi_j(p')|J_\mu^{EM}|\psi_i(p) >= \bar{u}_j(p')\Lambda_\mu(q)u_i(p)}$$

… beyond SM…

and

$$\boxed{\begin{aligned}\Lambda_\mu(q) = \Big(f_Q(q^2)_{ij} + f_A(q^2)_{ij}\gamma_5\Big)(q^2\gamma_\mu - q_\mu \not{q}) +& \\ f_M(q^2)_{ij} i\sigma_{\mu\nu}q^\nu + f_E(q^2)_{ij}\sigma_{\mu\nu}q^\nu\gamma_5&\end{aligned}}$$

form factors are matrices in ν mass eigenstates space.

Dirac ν ***(off-diagonal case*** $i \neq j$ ***)*** **Majorana** ν

1) ***hermiticity itself does not apply restrictions on form factors,***

2) ***CP invariance + hermiticity***

$\Downarrow$

$f_Q(q^2), \ f_M(q^2), \ f_E(q^2), \ f_A(q^2)$

are relatively real (no relative phases) .

… quite different EM properties …

1) ***CP invariance + hermiticity***

$\boxed{\mu_{ij}^M = 2\mu_{ij}^D \ \ and \ \ \epsilon_{ij}^M = 0}$ ***or***

$\boxed{\mu_{ij}^M = 0 \ \ and \ \ \epsilon_{ij}^M = 2\epsilon_{ij}^D}$

… importance of μ_ν studies…

If diagonal $\mu_\nu \neq 0$

were confirmed

then ν^{Dirac}

… for ν^{Majorana}
non-diagonal = transitional
$\mu_\nu \neq 0$

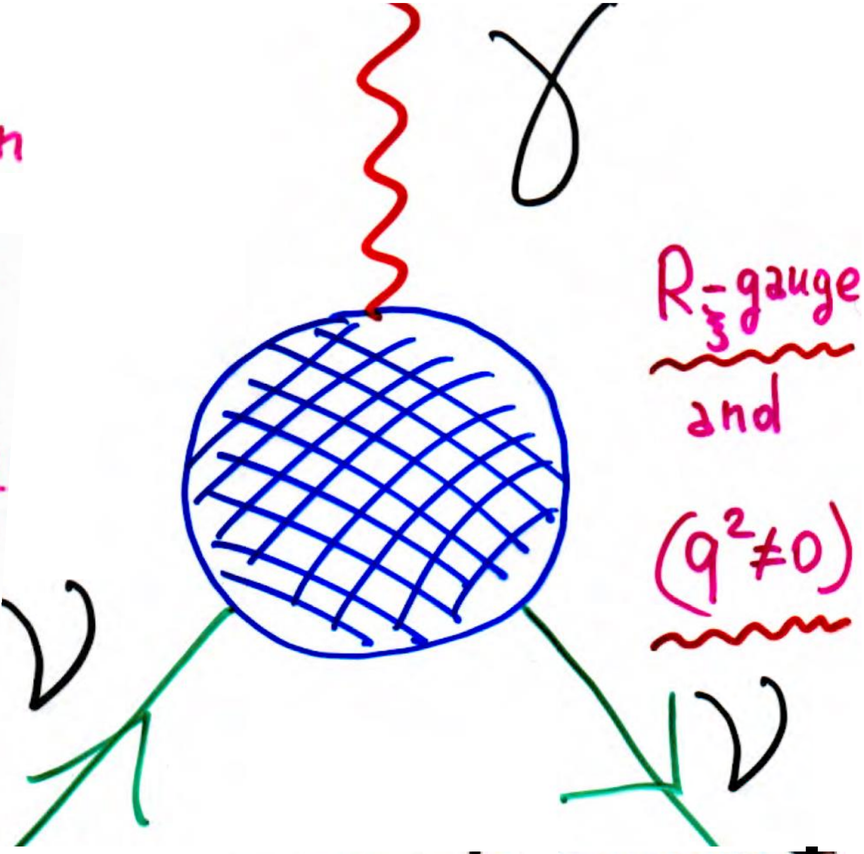
… progress
in experimental
studies of μ_ν ⇒

ν vertex function

The most general study of the massive neutrino vertex function (including electric and magnetic form factors) in arbitrary R_ξ gauge in the context of the SM + SU(2)-singlet ν_R accounting for masses of particles in polarization loops

M. Dvornikov, A. Studenikin

(*) Phys. Rev. D 63, 073001, 2004,
"Electric charge and magnetic moment of massive neutrino";
JETP 126 (2004), N8, 1
(*) "Electromagnetic form factors of a massiv neutrino."



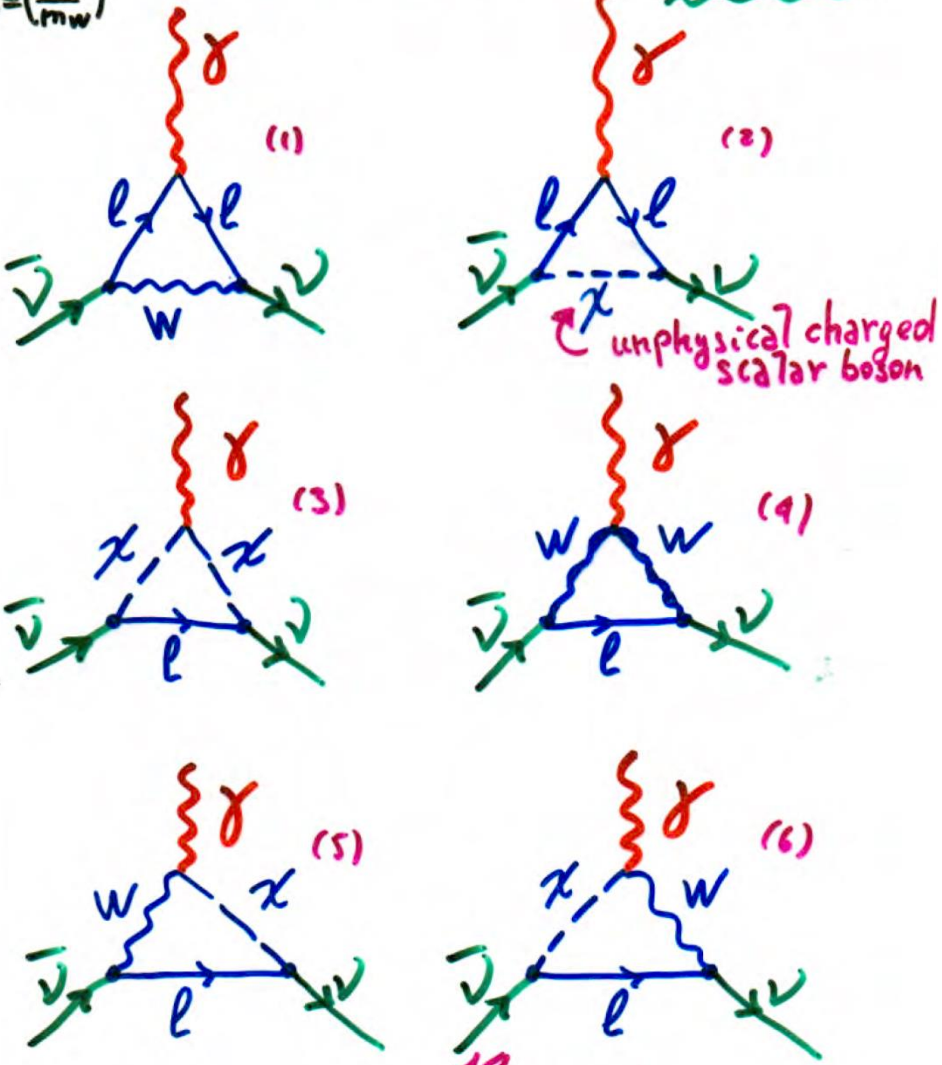
R_ξ-gauge
and
$(q^2 \neq 0)$

$$\Delta_\mu(q) = \overset{\text{charge}}{\underbrace{f_Q}}(q^2)\gamma_\mu + \overset{\text{magnetic moment}}{\underbrace{f_M}}(q^2)\, i\sigma_{\mu\nu} q^\nu - \underbrace{f_E}_{\text{electric moment}}(q^2)\, i\sigma_{\mu\nu} q^\nu \gamma_5 - \underbrace{f_A}_{\text{anapole moment}}(q^2)(q^2\gamma_\mu - q_\mu \not{q})\gamma_5$$

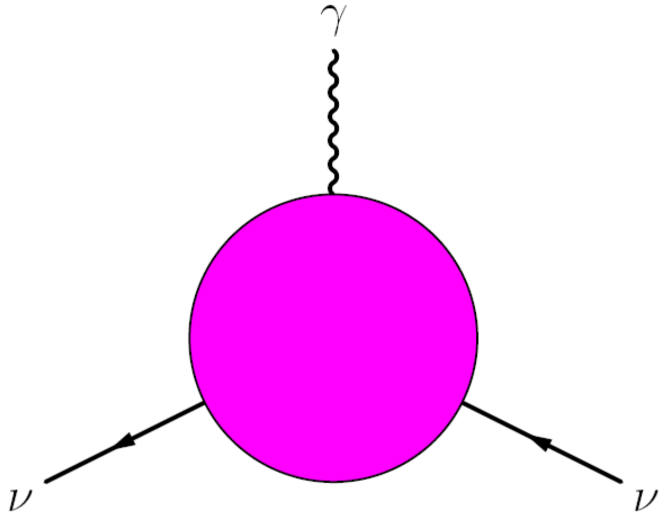
$a = \left(\frac{m_\ell}{m_W}\right)^2,$

$b = \left(\frac{m_\nu}{m_W}\right)^2$

Proper vertices R_ξ-gauge



$$\Lambda_\mu(q) = \sum_{i=1}^{14} \Lambda_\mu^i(q)$$



$$\Lambda_\mu(q)$$

Contributions of proper vertices diagrams

(dimensional-regularization scheme)

- $$\Lambda_\mu^{(1)}=i\frac{eg^2}{2}\int\frac{d^Nk}{(2\pi)^N}\left[g^{\kappa\lambda}-(1-\alpha)\frac{k^\kappa k^\lambda}{k^2-\alpha M_W^2}\right]\times\frac{\gamma_\kappa^L(\not{p}\,'-\not{k}+m_\ell)\gamma_\mu(\not{p}-\not{k}+m_\ell)\gamma_\lambda^L}{[(p'-k)^2-m_\ell^2][(p-k)^2-m_\ell^2][k^2-M_W^2]},$$

- $$\Lambda_\mu^{(2)}=i\frac{eg^2}{2M_W^2}\int\frac{d^Nk}{(2\pi)^N}\frac{(m_\nu P_L-m_\ell P_R)(\not{p}\,'-\not{k}+m_\ell)\gamma_\mu(\not{p}-\not{k}+m_\ell)(m_\ell P_L-m_\nu P_R)}{[(p'-k)^2-m_\ell^2][(p-k)^2-m_\ell^2][k^2-\alpha M_W^2]},$$

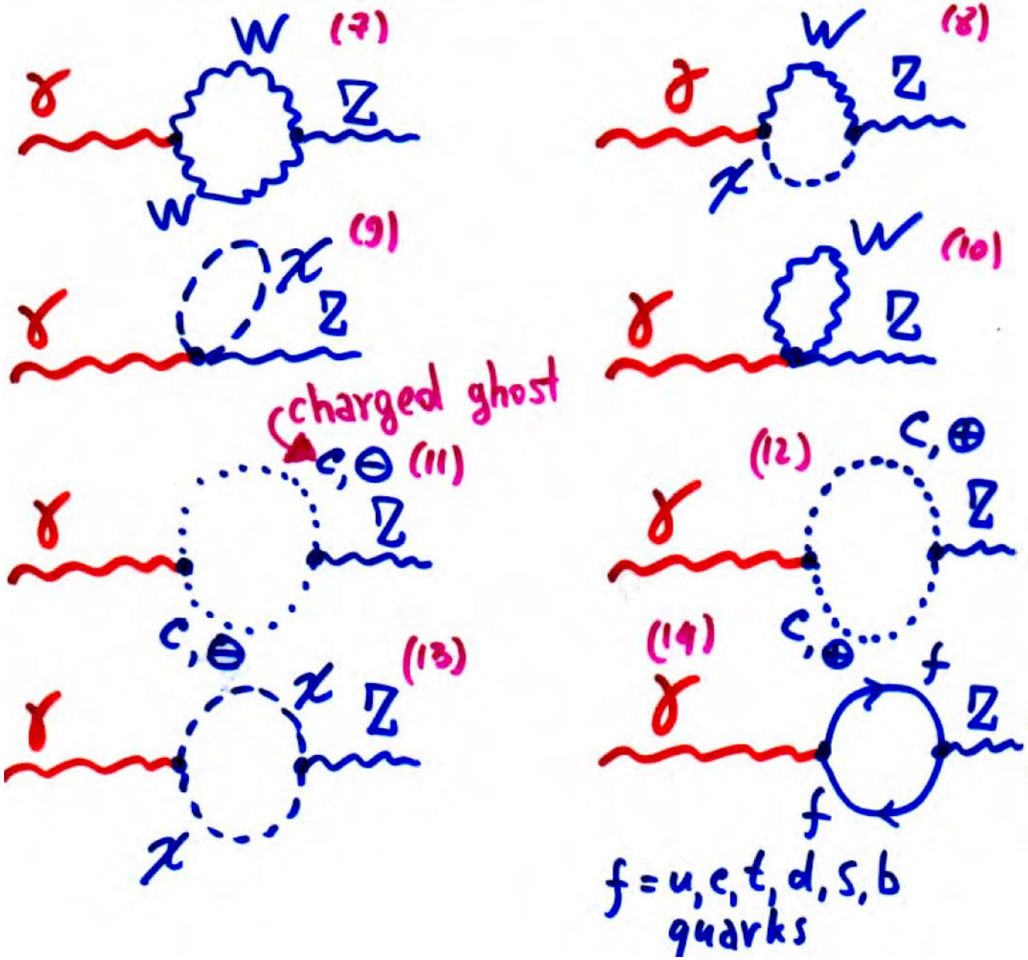
- $$\Lambda_\mu^{(3)}=i\frac{eg^2}{2M_W^2}\int\frac{d^Nk}{(2\pi)^N}(2k-p-p')_\mu\frac{(m_\nu P_L-m_\ell P_R)(\not{k}+m_\ell)(m_\ell P_L-m_\nu P_R)}{[(p'-k)^2-\alpha M_W^2][(p-k)^2-\alpha M_W^2][k^2-m_\ell^2]},$$

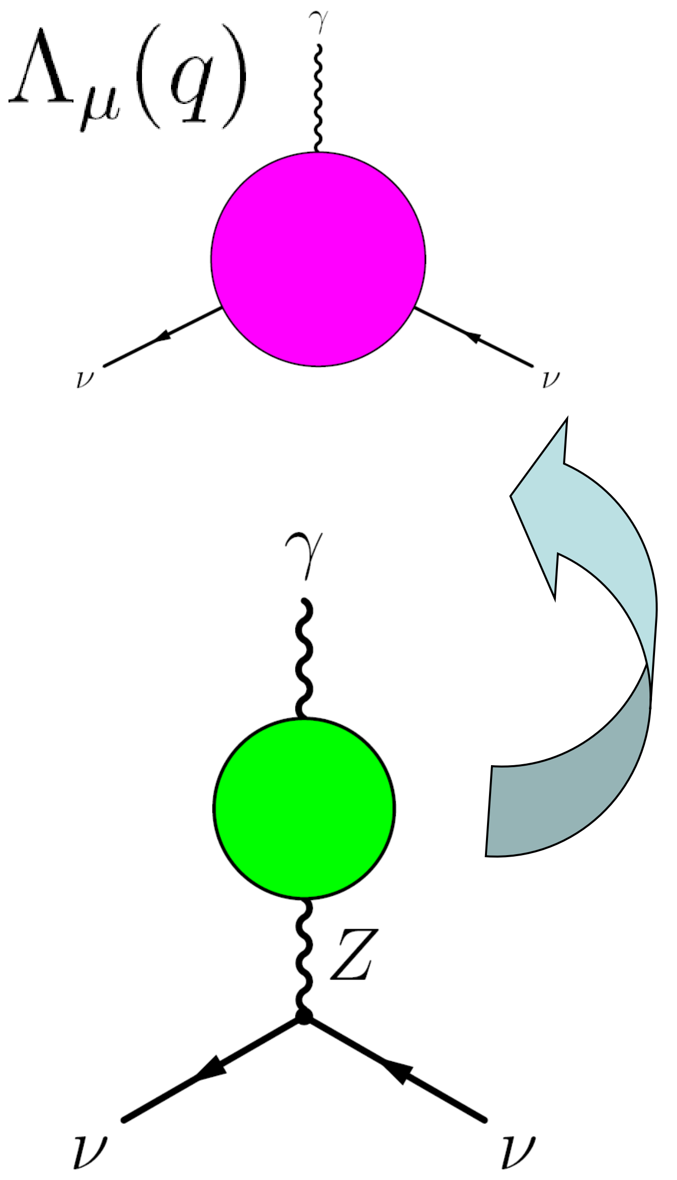
- $$\Lambda_\mu^{(4)}=i\frac{eg^2}{2}\int\frac{d^Nk}{(2\pi)^N}\gamma_\kappa^L(\not{k}+m_\ell)\gamma_\lambda^L\left[\delta_\beta^\kappa-(1-\alpha)\frac{(p'-k)^\kappa(p'-k)_\beta}{(p'-k)^2-\alpha M_W^2}\right]\left[\delta_\gamma^\lambda-(1-\alpha)\frac{(p-k)^\lambda(p-k)_\gamma}{(p-k)^2-\alpha M_W^2}\right]$$
  $$\times\frac{\delta_\mu^\beta(2p'-p-k)^\gamma+g^{\beta\gamma}(2k-p-p')_\mu+\delta_\mu^\gamma(2p-p'-k)^\beta}{[(p'-k)^2-M_W^2][(p-k)^2-M_W^2][k^2-m_\ell^2]},$$

- $$\Lambda_\mu^{(5)+(6)}=i\frac{eg^2}{2}\int\frac{d^Nk}{(2\pi)^N}$$
  $$\times\left\{\frac{\gamma_\beta^L(\not{k}-m_\ell)(m_\ell P_L-m_\nu P_R)}{[(p'-k)^2-M_W^2][(p-k)^2-\alpha M_W^2][k^2m_\ell^2]}\left[\delta_\mu^\beta-(1-\alpha)\frac{(p'-k)^\beta(p'-k)_\mu}{(p'-k)^2-\alpha M_W^2}\right]\right.$$
  $$\left.-\frac{(m_\nu P_L-m_\ell P_R)(\not{k}-m_\ell)\gamma_\beta^L}{[(p'-k)^2-\alpha M_W^2][(p-k)^2-M_W^2][k^2-m_\ell^2]}\left[\delta_\mu^\beta-(1-\alpha)\frac{(p-k)^\beta(p-k)_\mu}{(p-k)^2-\alpha M_W^2}\right]\right\}$$

$$\Lambda^{j}_{\mu}(q) = \frac{g}{2\cos\theta_W}\,\Pi^{(j)}_{\mu\nu}(q)\,\frac{1}{q^2-M_Z^2} \times \left\{ g^{\nu\alpha} - (1-\alpha_Z)\frac{q^\nu q^\alpha}{q^2-\alpha_Z M_Z^2} \right\} \gamma^{L}_{\alpha}, \; j=7,\dots,14$$

γ-Z self-energy diagrams





$\gamma - Z$ self-energy diagrams

Direct calculations of complete set of one-loop contributions to ν vertex function in minimally extended Standard Model

for a massive Dirac neutrino:

M.Dvornikov,
A.Studenikin,
PRD, 2004

… in case CP conservation

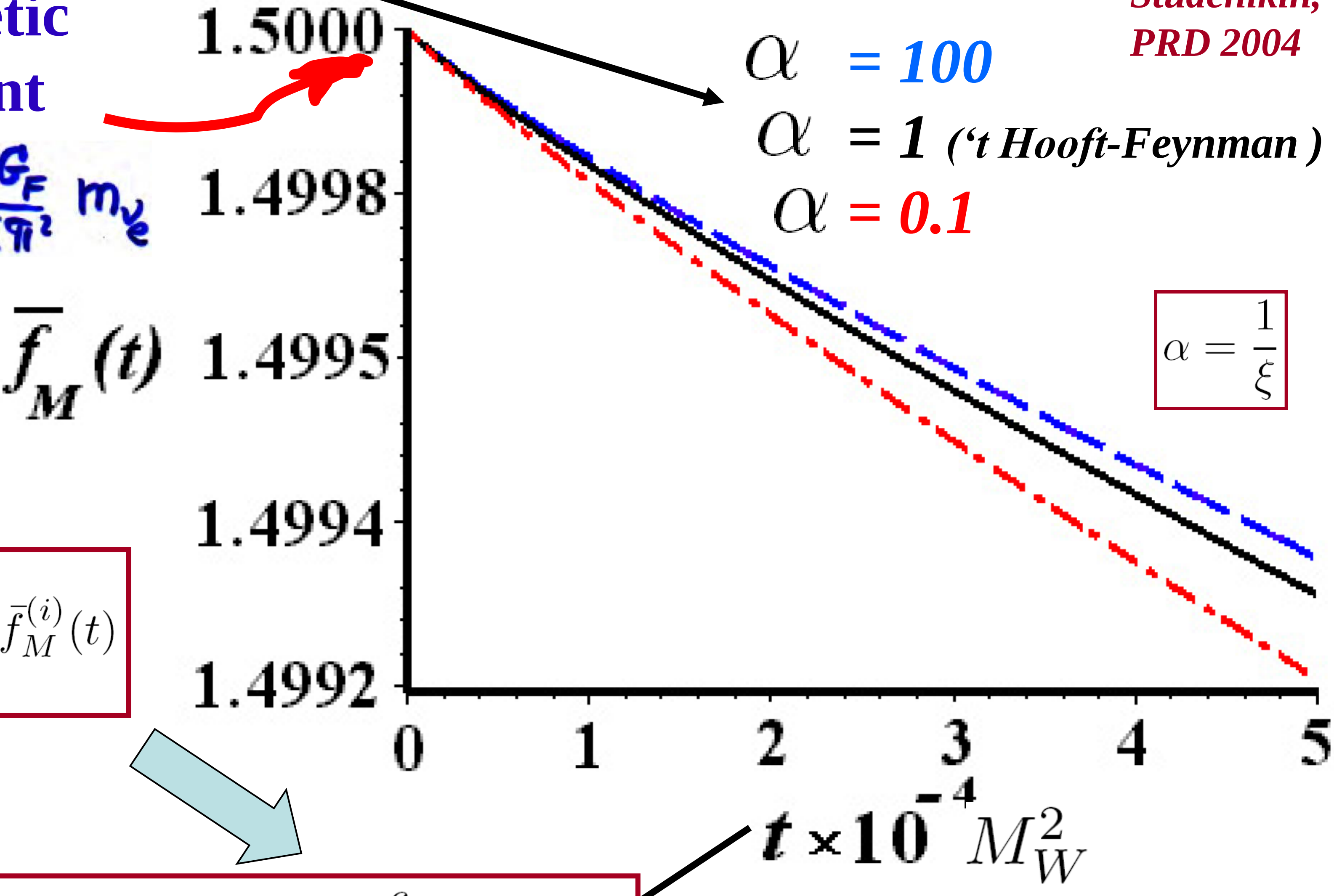
- $\Lambda_\mu(q) \Longrightarrow f_Q(q^2),\ f_M(q^2),\ \cancel{f_E(q^2)},\ f_A(q^2)$
- **Electric charge** $f_Q(0) = \mathbf{0}$ **and is gauge-independent**
- **Magnetic moment** $f_M(0)$ **is finite and gauge-independent**
- **Gauge and** $\boldsymbol{q}\times\boldsymbol{q}$ **dependence …**

Gauge and $q \times q$ dependence …

Dvornikov, Studenikin, PRD 2004

ν magnetic moment

- $\mu_e = \frac{3eG_F}{8\sqrt{2}\pi^2} m_\nu$



$$\bar{f}_M(t) = \sum_{i=1}^{6} \bar{f}_M^{(i)}(t)$$

$$f_M(q^2) = \frac{eG_F}{4\pi^2\sqrt{2}} m_\nu \sum_{i=1}^{6} \bar{f}_M^{(i)}(q^2)$$

ν dipole magnetic form factor

Magnetic moment dependence

$$\mu_\nu = \mu_\nu(m_\nu)$$

on neutrino mass

3.2

Calculation of ν magnetic moment (massive ν, arbitrary R_ξ - gauge)

Dvornikov, Studenikin, PRD 2004

$$\Lambda_\mu(q)=f_Q(q^2)\gamma_\mu+f_M(q^2)i\underline{\sigma_{\mu\nu}q^\nu}-f_E(q^2)\sigma_{\mu\nu}q^\nu\gamma_5+f_A(q^2)(q^2\gamma_\mu-q_\mu\not{q})\gamma_5$$

magnetic moment

$$\mu(a,b,\alpha)=f_M(q^2=0)$$

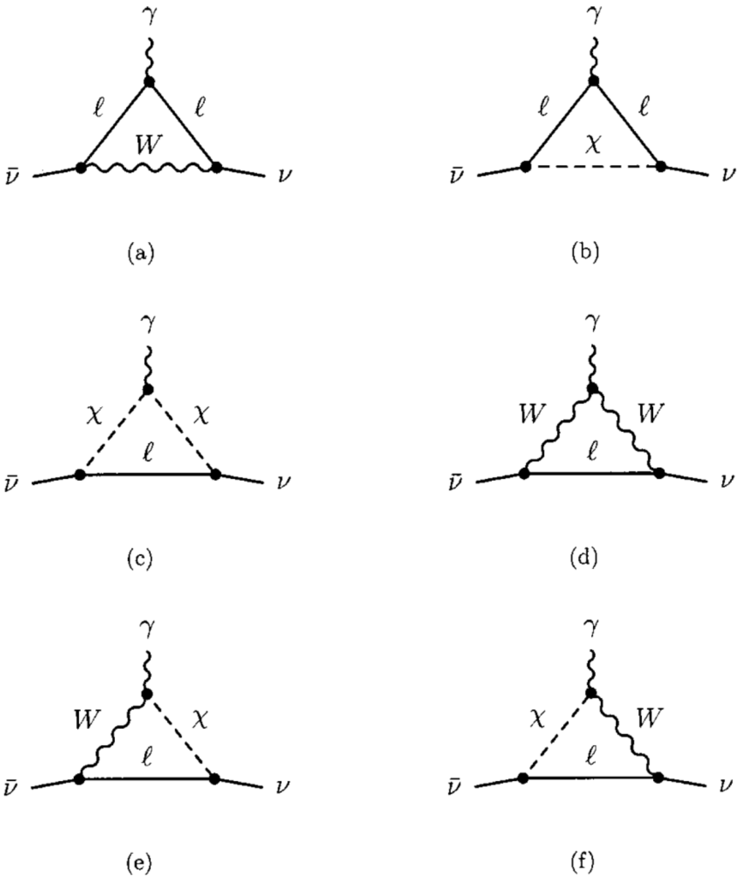
two mass parameters ● $a=\left(\frac{m_\ell}{M_W}\right)^2$ $b=\left(\frac{m_\nu}{M_W}\right)^2$ ●

$$\mu(a,b,\alpha)=\sum_{i=1}^{6}\mu^{(i)}(a,b,\alpha)$$

and gauge-fixing parameter $\alpha=\frac{1}{\xi}$ ●

$\xi=0$ **- unitary gauge,** $\xi=1$ **- 't Hooft-Feynman gauge**

Proper vertices



ν magnetic moment

(for arbitrary neutrino mass, heavy neutrino…)

- LEP data →

only 3 light νs coupled to Z^0,

for any additional neutrino

$$\boxed{m_{\nu} < 45\ Gev}$$

● $m_\nu \ll m_e \ll M_W$ **light** ν

$$\mu_e = \frac{3eG_F}{8\sqrt{2}\pi^2} m_{\nu_e}$$

$$\boxed{\mu_\nu = \frac{eG_F}{4\pi^2\sqrt{2}} m_\nu \frac{3}{4(1-a)^3}\left(2 - 7a + 6a^2 - 2a^2 \ln a - a^3\right)} \, , \quad a = \left(\frac{m_e}{M_W}\right)^2$$

Gabral-Rosetti, Bernabeu, Vidal, Zepeda, Eur.Phys.J C 12 (2000) 633

Dvornikov, Studenikin, Phys.Rev.D 69 (2004) 073001; JETP 99 (2004) 254

● $m_e \ll m_\nu \ll M_W$ **intermediate** ν

$$\boxed{\mu_\nu = \frac{3eG_F}{8\pi^2\sqrt{2}} m_\nu \left\{1 + \frac{5}{18} b\right\}} \, , \quad b = \left(\frac{m_\nu}{M_W}\right)^2$$

● $m_e \ll M_W \ll m_\nu$

$$\boxed{\mu_\nu = \frac{eG_F}{8\pi^2\sqrt{2}} m_\nu}$$

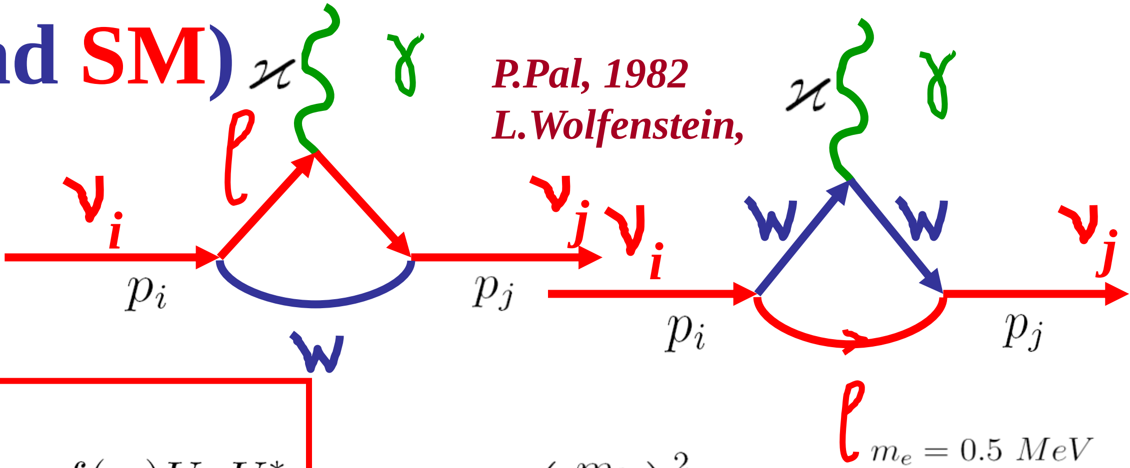
heavy ν

$$\sim 10^{-19} \mu_B \left(\frac{m_{\nu_e}}{1eV}\right)$$

. . . μ_ν *in case of mixing . . .*

3.5 Neutrino (beyond SM) dipole moments

(+ transition moments)



P.Pal, 1982
L.Wolfenstein,

- **Dirac neutrino**

$$\left.\begin{matrix}\mu_{ij}\\ \epsilon_{ij}\end{matrix}\right\} = \frac{eG_F m_i}{8\sqrt{2}\pi^2}\left(1 \pm \frac{m_j}{m_i}\right)\sum_{l=\ e,\ \mu,\ \tau} f(r_l)U_{lj}U^*_{li}$$

$$r_l = \left(\frac{m_l}{m_W}\right)^2$$

$m_e = 0.5\ MeV$
$m_\mu = 105.7\ MeV$
$m_\tau = 1.78\ GeV$
$m_W = 80.2\ GeV$

- $m_i, m_j \ll m_l, m_W$

$$f(r_l) \approx \frac{3}{2}\left(1 - \frac{1}{2}r_l\right), \quad r_l \ll 1$$

transition moments vanish because unitarity of ***U*** implies that its rows or columns represent orthogonal vectors

- **Majorana neutrino only for** $i \cancel{\neq} j$

$$\mu^M_{ij} = 2\mu^D_{ij} \quad and \quad \epsilon^M_{ij} = 0$$

or

$$\mu^M_{ij} = 0 \quad and \quad \epsilon^M_{ij} = 2\epsilon^D_{ij}$$

- **transition moments are suppressed, Glashow-Iliopoulos-Maiani cancellation,**
- **for diagonal moments there is no GIM cancellation**

… depending on relative ***CP*** phase of ν_i and ν_j

The first nonzero contribution from neutrino transition moments

$$f_{r_l} \to -\cancel{\frac{3}{2}} + \frac{3}{4}\left(\frac{m_l}{m_W}\right)^2$$ << 1

GIM cancellation

$$\left.\begin{matrix}\mu_{ij}\\ \epsilon_{ij}\end{matrix}\right\} = \frac{3eG_F m_i}{32\sqrt{2}\pi^2}\left(1 \pm \frac{m_j}{m_i}\right)\left(\frac{m_\tau}{m_W}\right)^2 \sum_{l=\ e,\ \mu,\ \tau}\left(\frac{m_l}{m_\tau}\right)^2 U_{lj}U^*_{li}$$

$$\mu_B = \frac{e}{2m_e}$$

- $$\left.\begin{matrix}\mu_{ij}\\ \epsilon_{ij}\end{matrix}\right\} = 4 \times 10^{-23}\mu_B\left(\frac{m_i \pm m_j}{1\ eV}\right) \sum_{l=\ e,\ \mu,\ \tau}\left(\frac{m_l}{m_\tau}\right)^2 U_{lj}U^*_{li}$$

… neutrino radiative decay is very slow

- **Dirac ν diagonal *(i=j)* magnetic moment**

$\epsilon^D_{ii} = 0$ **for CP-invariant interactions**

$\mu^M_{ii} = \epsilon^M_{ii} = 0$

$$\mu_{ii} = \frac{3eG_F m_i}{8\sqrt{2}\pi^2}\left(1 - \frac{1}{2}\sum_{l=\ e,\mu,\tau} r_l \mid U_{li} \mid^2\right) \approx 3.2 \times 10^{-19}\left(\frac{m_i}{1\ eV}\right)\mu_B$$

$$r_l = \left(\frac{m_l}{m_W}\right)^2$$

- ***no GIM cancellation***

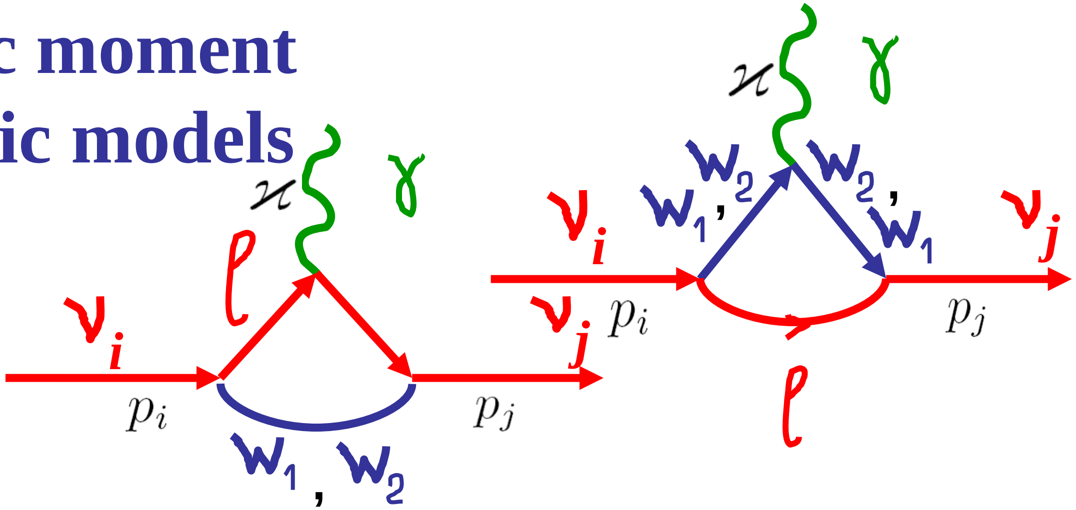
Lee, Shrock, Fujikawa, 1977

- μ^D_{ii} **- to leading order - independent on U_{li} and $m_{\ l=e,\ \mu,\ \tau}$**
- $\mu_e^2 = \sum_{i=1,2,3} \mid U_{ie} \mid^2 \mu_{ii}^2$ **…possibility to measure fundamental** μ^D_{ii}

$\mu^D_{ii} = 0$ **for massless ν (in the absence of right-handed charged currents)**

3.6 Neutrino magnetic moment in left-right symmetric models

$SU_L(2) \times SU_R(2) \times U(1)$



Gauge bosons mass states $W_1 = W_L \cos\xi - W_R \sin\xi$

$W_2 = W_L \sin\xi + W_R \cos\xi$

with mixing angle ξ **of gauge bosons** $W_{L,R}$ **with pure** $(V \pm A)$ **couplings**

Kim, 1976; Marciano, Sanda, 1977; Beg, Marciano, Ruderman, 1978

$$\boxed{\mu_{\nu_l} = \frac{eG_F}{2\sqrt{2}\pi^2}\left[\underline{m_l}\left(1-\frac{m^2_{W_1}}{m^2_{W_2}}\right)\sin 2\xi + \frac{3}{4}\underline{m_{\nu_l}}\left(1+\frac{m^2_{W_1}}{m^2_{W_2}}\right)\right]}$$

… charged lepton mass …

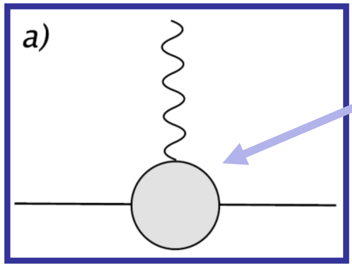
… neutrino mass …

3.3 Naïve relationship between the size of m_ν and μ_ν

… problem to get large μ_ν *and still acceptable* m_ν

If μ_ν is generated by physics beyond the SM at energy scale Λ ,

P.Vogel e.a., 2006

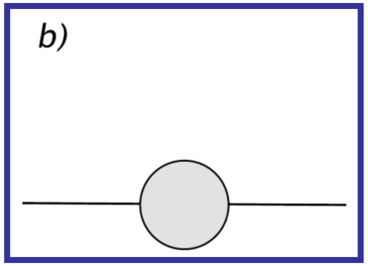


then

$$\boxed{\mu_\nu \sim \frac{eG}{\Lambda},}$$

…combination of constants and loop factors…

contribution to m_ν given by



, then $\boxed{m_\nu \sim G\Lambda}$

$$m_\nu \sim \frac{\Lambda^2}{2m_e}\frac{\mu_\nu}{\mu_B} \sim \frac{\mu_\nu}{10^{-18}\mu_B}[\Lambda(\mathrm{TeV})]^2 \quad \mathrm{eV}$$

Voloshin, 1988;
Barr, Freire,
Zee, 1990

Large magnetic moment

$\mu_\nu = \mu_\nu(m_\nu, m_{B^+}, m_{e^-})$

⇑

- In the L-R symmetric models $(SU(2)_L \times SU(2)_R \times U(1))$

Kim, 1976
Beg, Marciano, Ruderman, 1978

- *Voloshin, 1988*

“On compatibility of small m_ν with large μ_ν of neutrino”, Sov.J.Nucl.Phys. 48 (1988) 512

… there may be $SU(2)_\nu$ symmetry that forbids m_ν but not μ_ν

- ***Bar, Freire, Zee, 1990***
- **supersymmetry**
- **extra dimensions**
- **model-independent constraint μ_ν**

considerable enhancement of μ_ν to experimentally relevant range

$\boxed{\mu_\nu^D \le 10^{-15}\mu_B}$

$\boxed{\mu_\nu^M \le 10^{-14}\mu_B}$

for BSM ($\Lambda \sim 1\ \mathrm{TeV}$) without fine tuning and under the assumption that $\boxed{\delta m_\nu \le 1\ \mathrm{eV}}$

Bell, Cirigliano, Ramsey-Musolf, Vogel, Wise, 2005

ν magnetic moment in experiments

Studies of ν-e scattering
- most sensitive method for experimental investigation of μ_ν

Cross-section:

- $$\frac{d\sigma}{dT}(\nu + e \to \nu + e) = \left(\frac{d\sigma}{dT}\right)_{\rm SM} + \left(\frac{d\sigma}{dT}\right)_{\mu_\nu}$$

where the Standard Model contribution

- $$\left(\frac{d\sigma}{dT}\right)_{\rm SM} = \frac{G_{\rm F}^2 m_e}{2\pi}\left[(g_V + g_A)^2 + (g_V - g_A)^2\left(1 - \frac{T}{E_\nu}\right)^2 + (g_A^2 - g_V^2)\frac{m_e T}{E_\nu^2}\right],$$

T is the electron recoil energy and

- $$\left(\frac{d\sigma}{dT}\right)_{\mu_\nu} = \frac{\pi\alpha_{em}^2}{m_e^2}\left[\frac{1 - T/E_\nu}{T}\right]\mu_\nu^2$$

$$\mu_\nu^2 = \sum_{j = \nu_e,\, \nu_\mu,\, \nu_\tau} |\, \mu_{ij} - \epsilon_{ij}\, |^2$$

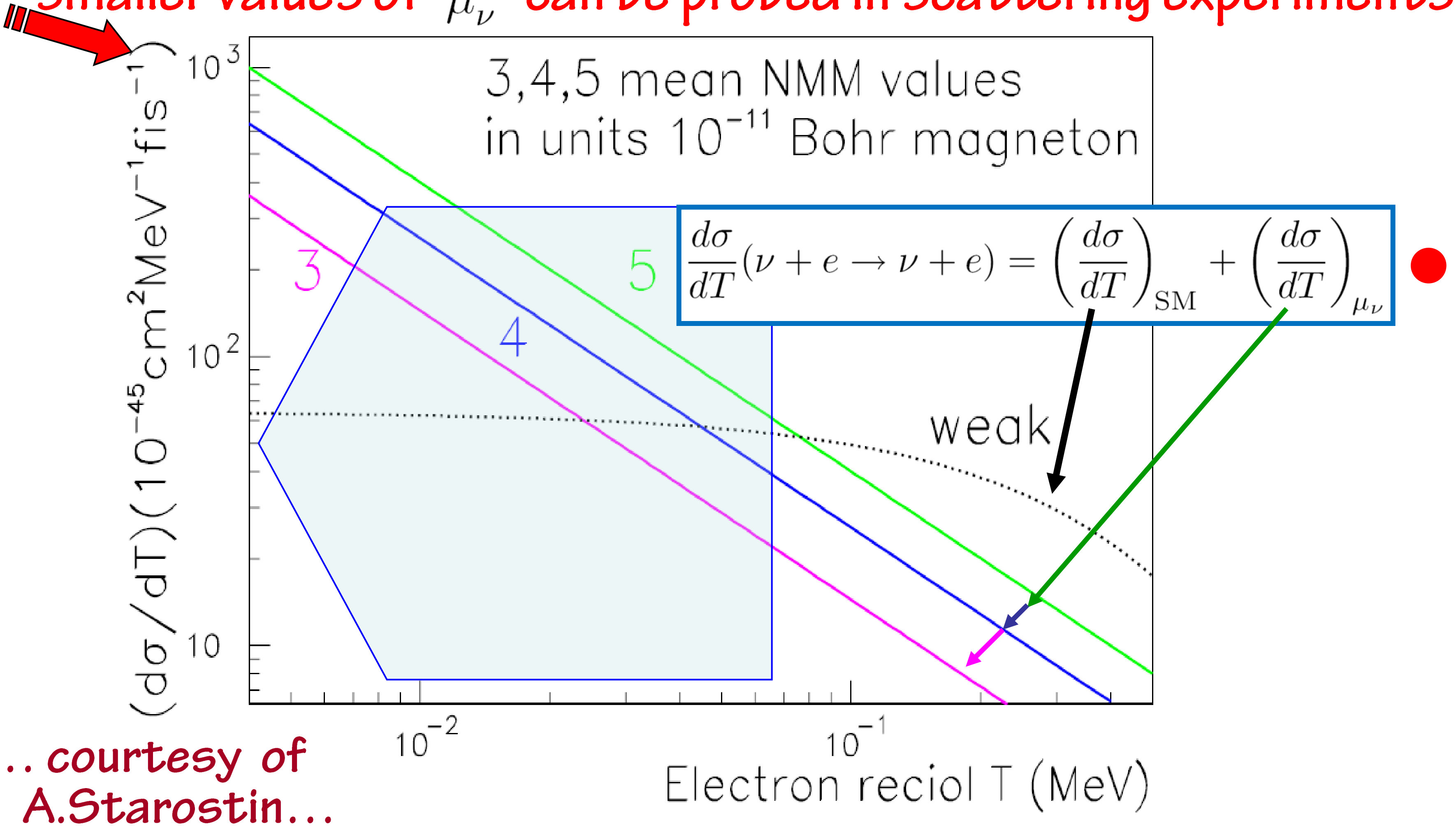
$$g_V = \begin{cases} 2\sin^2\theta_W + \frac{1}{2} & \text{for} \quad \nu_e\,, \\ 2\sin^2\theta_W - \frac{1}{2} & \text{for} \quad \nu_\mu, \nu_\tau\,, \end{cases} \qquad g_A = \begin{cases} \frac{1}{2} & \text{for} \quad \nu_e\,, \\ -\frac{1}{2} & \text{for} \quad \nu_\mu, \nu_\tau \end{cases}$$

for anti-neutrinos $g_A \to -g_A$

to incorporate charge radius: $g_V \to g_V + \boxed{\frac{2}{3} M_W^2 \langle r^2 \rangle \sin^2\theta_W}$

Magnetic moment contribution dominates at low electron recoil energies when $\boxed{\left(\frac{d\sigma}{dT}\right)_{\mu_\nu} > \left(\frac{d\sigma}{dT}\right)_{SM}}$ and $\boxed{\frac{T}{m_e} < \frac{\pi^2 \alpha_{em}}{G_F^2 m_e^4}\mu_\nu^2}$

… the lower the smallest measurable electron recoil energy is, smaller values of μ_ν^2 can be probed in scattering experiments …



$$\frac{d\sigma}{dT}(\nu + e \to \nu + e) = \left(\frac{d\sigma}{dT}\right)_{\rm SM} + \left(\frac{d\sigma}{dT}\right)_{\mu_\nu}$$

… courtesy of A.Starostin…

Effective ν_e magnetic moment measured in ν-e scattering experiments ? $\boxed{\mu_e^2}$

Two steps:

1) consider ν_e as superposition of mass eigenstates (*i=1,2,3*) at some distance *L* from the source, and then sum up magnetic moment contributions to ν-e scattering amplitude (of each of mass components) induced by their magnetic moments

$$\boxed{A_j \sim \sum_i U_{ei} e^{-iE_iL} \mu_{ji}}$$

J.Beacom, P.Vogel, 1999

2) amplitudes combine incoherently in total cross section

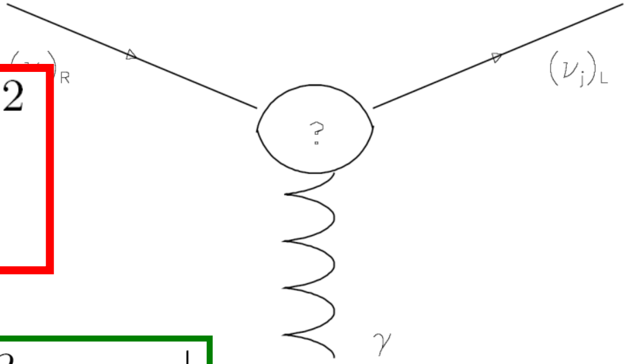
$$\boxed{\sigma \sim \mu_e^2 = \sum_j \left| \sum_i U_{ei} e^{-iE_iL} \mu_{ji} \right|^2}$$

C.Giunti, A.Studenikin, 2009

NB! Summation over ***j=1,2,3*** is outside the square because of **incoherence** of different final mass states contributions to cross section.

Effective ν magnetic moment in experiments

(for neutrino produced as ν_l with energy $\boldsymbol{E_\nu}$
and after traveling a distance $\boldsymbol{L}$)



$$\mu_\nu^2(\nu_l, L, E_\nu) = \sum_j \left| \sum_i U_{li} e^{-iE_iL} \mu_{ji} \right|^2$$

where U_{li}: neutrino mixing matrix

$$\mu_{ij} \equiv |\beta_{ij} - \varepsilon_{ij}|$$

β_{ij}, ε_{ij}: **magnetic** and **electric** moments

- Observable μ_ν is an effective parameter that depends on neutrino flavour composition at the detector.

- Implications of μ_ν limits from different experiments (reactor , solar $^8\mathrm{B}$ and $^7\mathrm{Be}$) are different.

MUNU experiment at Bugey reactor (2005)

$$\boxed{\mu_\nu \leq 9 \times 10^{-11} \mu_B}$$

TEXONO collaboration at Kuo-Sheng power plant (2006)

$$\boxed{\mu_\nu \leq 7 \times 10^{-11} \mu_B}$$

GEMMA (2007) $\boxed{\mu_\nu \leq \ 5.8 \times 10^{-11} \mu_B}$

GEMMA I 2005 - 2007

BOREXINO (2008) $\boxed{\mu_\nu \leq \ 5.4 \times 10^{-11} \mu_B}$

...was considered as the world best constraint...

$$\boxed{\mu_\nu \leq \ 8.5 \times 10^{-11} \mu_B \quad (\nu_\tau, \ \nu_\mu)}$$

Montanino,
Picariello,
Pulido,
PRD 2008

based on first release of
BOREXINO data

... attempts to
improve bounds

… quite recent claim that ν-e cross section should be increased by Atomic Ionization Effect:

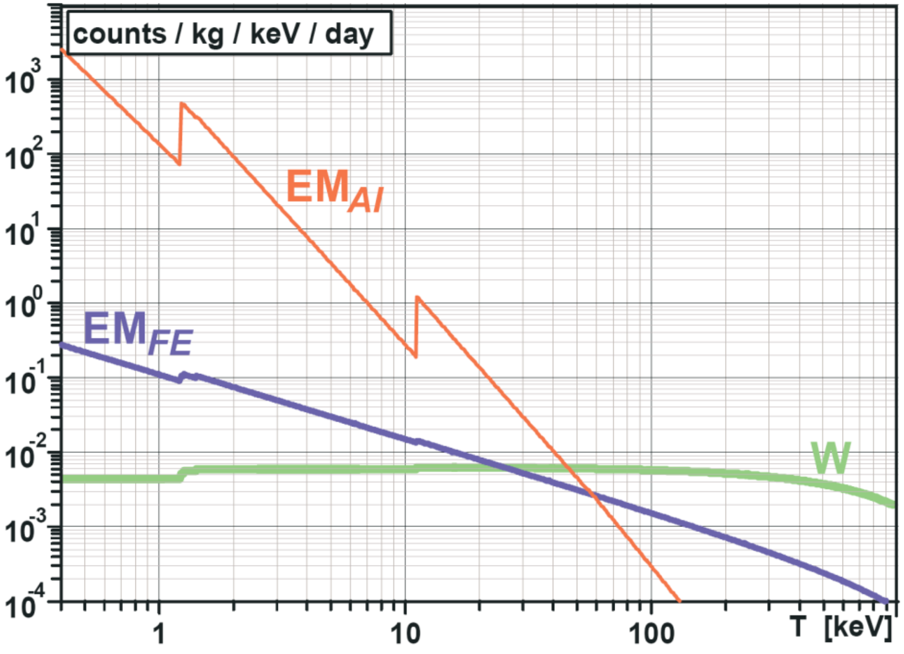
?

H.Wong et al. (TEXONO Coll.), PRL 105 (2010) 061801

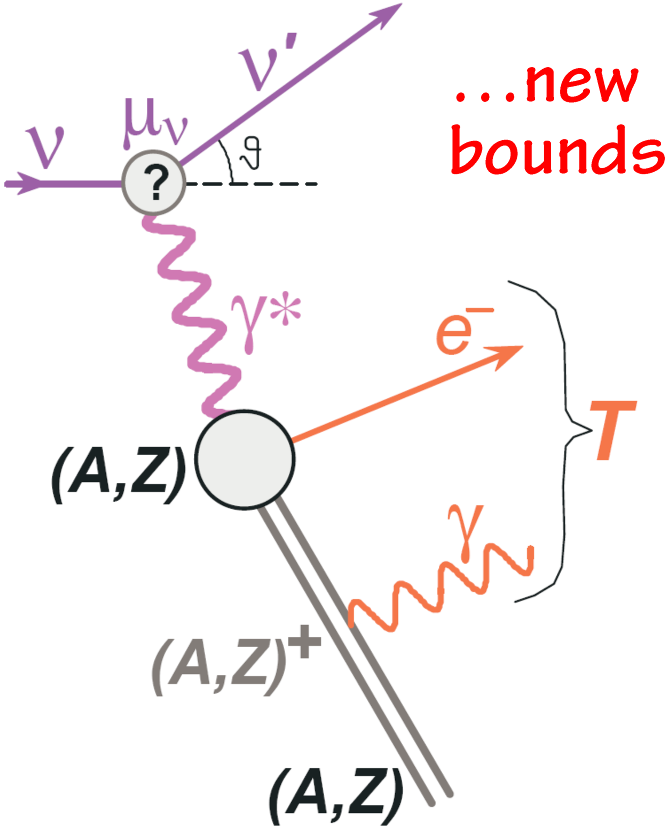
$$\nu + (A,Z) \longrightarrow \nu\,' + (A,Z)^+ + e^-$$

$$\downarrow \text{recombination}$$

$$(A,Z) \quad + \gamma$$



… an interesting hypothetical possibility to improve bounds…



…new bounds …

… better limits on ν effective magnetic moment …

$$\boxed{\mu_\nu < 1.3 \times 10^{-11} \mu_B}$$?

H.Wong et al.,
(TEXONO Coll.),
PRL 105 (2010) 061801

… atomic ionization effect
accounted for …

… however …

$$\boxed{\mu_\nu < 5.0 \times 10^{-12} \mu_B}$$?

… atomic ionization effect
accounted for …

A.Beda et al.
(GEMMA Coll.),
arXiv: 1005.2736,
16 May 2010

$$\boxed{\mu_\nu < 3.2 \times 10^{-11} \mu_B}$$

… ν-e scattering on free electrons …
(without atomic ionization)

- K.Kouzakov, A.Studenikin,
  "Magnetic neutrino scattering on atomic electrons revisited"
  Phys.Lett. B 105 (2011) 061801,

- "Electromagnetic neutrino-atom collisions: The role of electron binding"
  Nucl.Phys.B (Proc.Suppl.) 217 (2011) 353

- K.Kouzakov, A.Studenikin, M.Voloshin,
  "Neutrino-impact ionization of atoms in search for neutrino
  magnetic moment", **Phys.Rev.D** 83 (2011) 113001

- "On neutrino-atom scattering in searches for neutrino magnetic
  moments" **Nucl.Phys.B** (Proc.Supp.) 2012

- "Testing neutrino magnetic moment in ionization of atoms
  by neutrino impact", **JETP Lett.** 93 (2011) 699

- M.Voloshin,
  "Neutrino scattering on atomic electrons in search for neutrino
  magnetic moment"
  Phys.Rev.Lett. 105 (2010) 201801

No important effect of Atomic Ionization on cross section in μ_ν experiments once all possible final electronic states accounted for

…free electron approximation …

- M.Voloshin, 23 Aug 2010;
  K.Kouzakov, A.Studenikin, 26 Nov 2010;
  H.Wong et al, arXiv: 1001.2074 V3, 28 Nov 2010

GEMMA (2005-2012)

JINR (Dubna) + ITEP (Moscow) at Kalinin Nuclear Power Plant

World best experimental limit

$$\boxed{\mu_\nu < 2.9 \times 10^{-11} \mu_B}$$

June 2012

A. Beda et al, in: Special Issue on "Neutrino Physics" , Advances in High Energy Physics (2012) 2012,

editors: J.Bernabeu, G. Fogli, A.McDonald, K. Nishikawa

… quite realistic prospects of the near future

$$\boxed{\mu_\nu \sim 1 \times 10^{-11} \mu_B}$$

(V.Brudanin, A.Starostin, priv. comm.)

… A remark on electric charge of ν …

Beyond Standard Model…

ν **neutrality** ***Q=0*** **is attributed to**

gauge invariance
+
anomaly cancellation constraints

imposed in SM of electroweak interactions

Foot, Joshi, Lew, Volkas, 1990;
Foot, Lew, Volkas, 1993;
Babu, Mohapatra, 1989, 1990

- ***…General proof:***
- ***In SM :*** $SU(2)_L\times U(1)_Y$

$$\boxed{Q = I_3 + \frac{Y}{2}}$$

- ***In SM (without*** ν_R***) triangle anomalies cancellation constraints → certain relations among particle hypercharges*** Y***, that is enough to fix all*** Y ***so that they, and consequently Q, are quantized***

$\boxed{Q=0}$

- $\boxed{Q=0}$ ***is proven also by direct calculation in SM within different gauges and methods***

Bardeen, Gastmans, Lautrup, 1972;
Cabral-Rosetti, Bernabeu, Vidal, Zepeda, 2000;
Beg, Marciano, Ruderman, 1978;
Marciano, Sirlin, 1980; Sakakibara, 1981;
- ***M.Dvornikov, A.S., 2004 (for extended SM in one-loop calculations)***

- ***… However, strict requirements for*** **Q** ***quantization may disappear in extensions of standard*** $SU(2)_L\times U(1)_Y$ ***EW model if*** ν_R ***with Y ≠ 0 are included : in the absence of Y quantization electric charges Q gets dequantized*** →

millicharged ν

Bounds on ν millicharge q_ν from μ_ν (GEMMA Coll. Data)

A.S.,
arXiv: 1302.1168,
May 13, 2013

ν-e cross-section

$$\boxed{\left(\frac{d\sigma}{dT}\right)_{\nu-e} = \left(\frac{d\sigma}{dT}\right)_{SM} + \left(\frac{d\sigma}{dT}\right)_{\mu_\nu} + \left(\frac{d\sigma}{dT}\right)_{q_\nu}}$$

two not seen contributions:

$$\left(\frac{d\sigma}{dT}\right)_{\mu_\nu^a} \approx \pi\alpha^2 \frac{1}{m_e^2 T}\left(\frac{\mu_\nu^a}{\mu_B}\right)^2$$

$$\left(\frac{d\sigma}{dT}\right)_{q_\nu} \approx 2\pi\alpha \frac{1}{m_e T^2} q_\nu^2$$

Bounds on q_ν from

$$R = \frac{\left(\frac{d\sigma}{dT}\right)_{q_\nu}}{\left(\frac{d\sigma}{dT}\right)_{\mu_\nu^a}} = \frac{2m_e}{T}\frac{\left(\frac{q_\nu}{e_0}\right)^2}{\left(\frac{\mu_\nu^a}{\mu_B}\right)^2} \ll 1$$

… no observable effects of New Physics

Constraints on μ_ν from GEMMA :

now $\mu_\nu^a < 2.9 \times 10^{-11} \mu_B$ $(T \sim 2.8\ keV)$

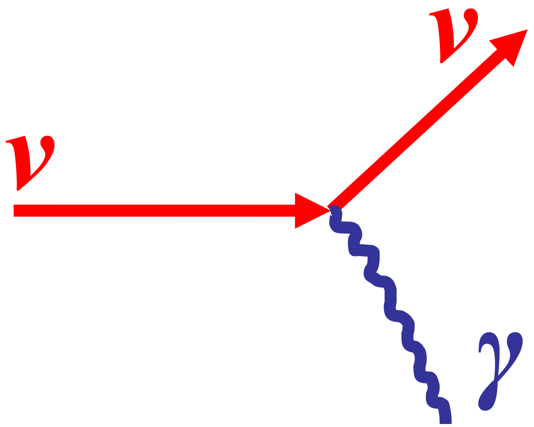
Constraints on q_ν

$\boxed{\mid q_\nu \mid < 1.5 \times 10^{-12} e_0}$

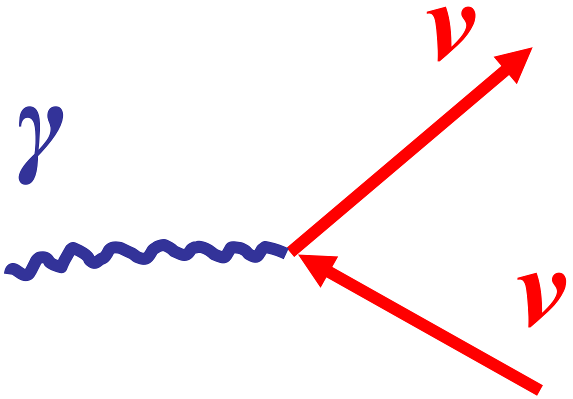
2015 (expected) $\mu_\nu^a \sim 1.5 \times 10^{-11} \mu_B$ $(T = 1.5\ keV)$ $\boxed{\mid q_\nu \mid < 3.7 \times 10^{-13} e_0}$

2017 (expected) $\mu_\nu^a \sim 0.9 \times 10^{-12} \mu_B$ $(T = 400\ eV)$ $\boxed{\mid q_\nu \mid < 2 \times 10^{-13} e_0}$

ν electromagnetic interactions

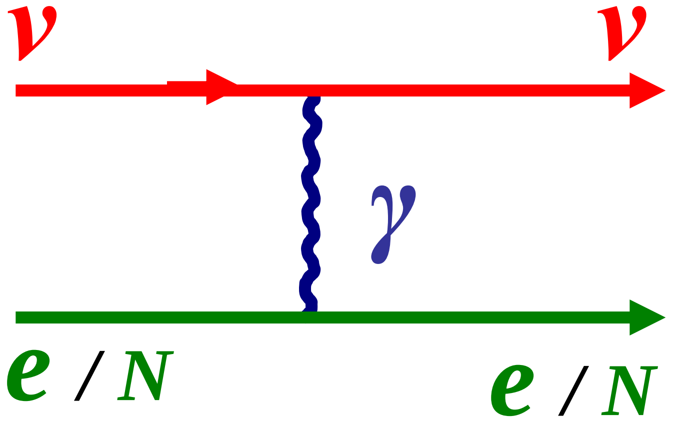


ν decay, Cherenkov radiation

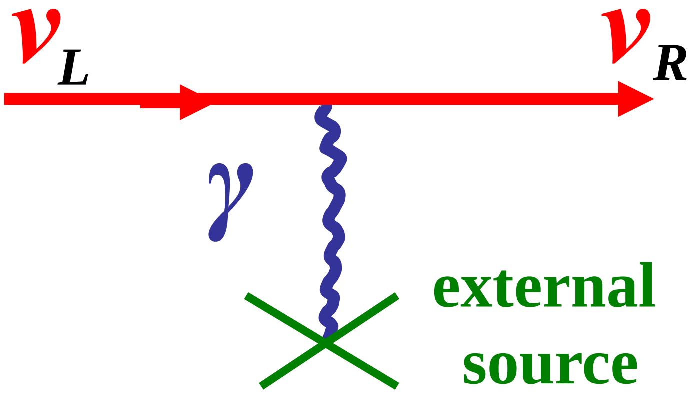


γ decay in plasma

!!!



Scattering



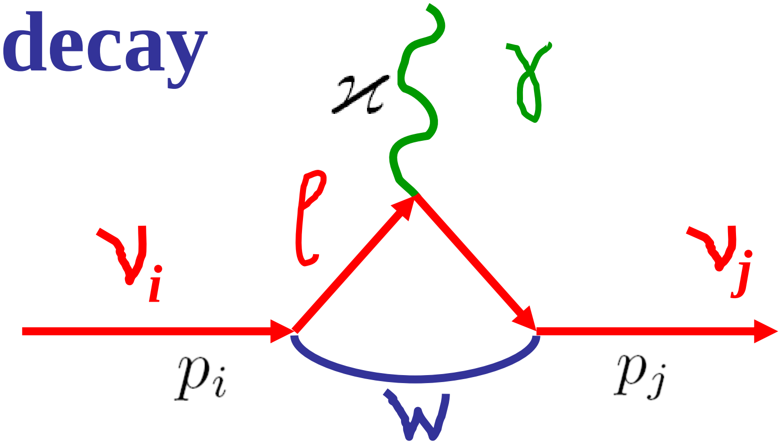
Spin precession

3.7 Neutrino radiative decay

$$\nu_i \longrightarrow \nu_j + \gamma$$

$$m_i > m_j$$

$$\boxed{L_{int} = \frac{1}{2}\bar{\psi}_i \sigma_{\alpha\beta}(\sigma_{ij} + \epsilon_{ij}\gamma_5)\psi_j F^{\alpha\beta} + h.c.}$$



Radiative decay rate

Petkov 1977; Zatsepin, Smirnov 1978;
Bilenky, Petkov 1987; Pal, Wolfenstein 1982

$$\boxed{\Gamma_{\nu_i \to \nu_j + \gamma} = \frac{\mu_{eff}^2}{8\pi}\left(\frac{m_i^2 - m_j^2}{m_i^2}\right)^3} \approx 5\left(\frac{\mu_{eff}}{\mu_B}\right)^2\left(\frac{m_i^2 - m_j^2}{m_i^2}\right)^3\left(\frac{m_i}{1\ eV}\right)^3 s^{-1}$$

$$\boxed{\mu_{eff}^2 = \mid \mu_{ij} \mid^2 + \mid \epsilon_{ij} \mid^2}$$

- Radiative decay has been constrained from absence of decay photons:
  1) reactor $\bar{\nu}_e$ and solar ν_e fluxes,
  2) SN 1987A ν burst (all flavours),
  3) spectral distortion of CMBR

Raffelt 1999

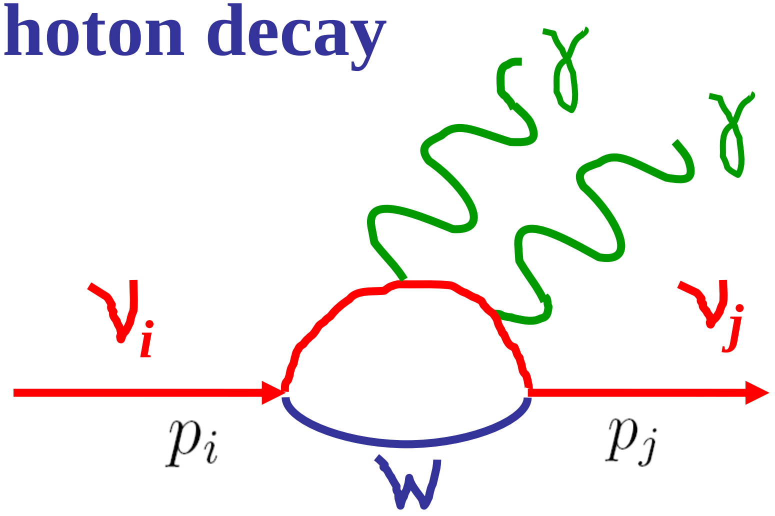
Kolb, Turner 1990;
Ressell, Turner 1990

3.8

Neutrino radiative two-photon decay

$\nu_i \longrightarrow \nu_j + \gamma + \gamma$

$m_i > m_j$



fine structure constant

$$\boxed{\Gamma_{\nu_i \to \nu_j + \gamma + \gamma} \sim \frac{\alpha_{QED}}{4\pi} \Gamma_{\nu_i \to \nu_j + \gamma}}$$

$$\boxed{f(r_l) \approx \frac{3}{2}\left(\cancel{1} - \frac{1}{2}\left(\frac{m_l}{m_W}\right)^2\right) \to (m_i/m_l)^2}$$

… there is no GIM cancellation…

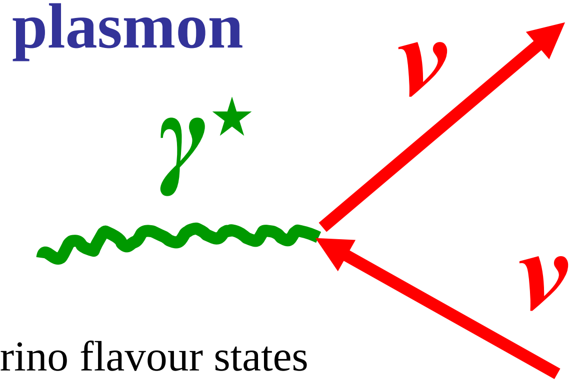
Nieves, 1983; Ghosh, 1984

… can be of interest for certain range of ν masses…

The tightest astrophysical bound on μ_ν

G.Raffelt, PRL 1990

comes from cooling of red **gaint** stars by plasmon decay $\gamma^\star \longrightarrow \nu\nu$



$$\boxed{L_{int} = \frac{1}{2}\sum_{a,b}\left(\mu_{a,b}\bar{\psi}_a\sigma_{\mu\nu}\psi_b + \epsilon_{a,b}\bar{\psi}_a\sigma_{\mu\nu}\gamma_5\psi_b\right)}$$

neutrino flavour states

Matrix element

$$\epsilon_\alpha k^\alpha = 0$$

$$|M|^2 = M_{\alpha\beta}p^\alpha p^\beta, \quad M_{\alpha\beta} = 4\mu^2(2k_\alpha k_\beta - 2k^2\epsilon^*_\alpha\epsilon_\beta - k^2 g_{\alpha,\beta}),$$

Decay rate

$$\boxed{\Gamma_{\gamma\to\nu\bar{\nu}} = \frac{\mu^2}{24\pi}\frac{(\omega^2 - k^2)^2}{\omega}}$$

= 0 in vacuum $\omega = k$

In the classical limit $\gamma^\star$ - like a massive particle with $\omega^2 - k^2 = \omega^2_{pl}$

Energy-loss rate per unit volume

$$\boxed{Q_\mu = g\int \frac{d^3k}{(2\pi)^3}\omega f_{BE}\Gamma_{\gamma\to\nu\bar{\nu}}}$$

$$\mu^2 \to \sum_{a,b}\left(|\mu_{a,b}|^2 + |\epsilon_{a,b}|^2\right)$$

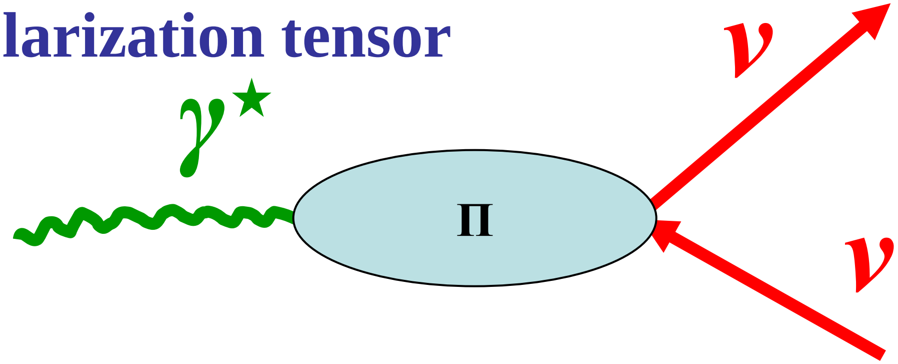
distribution function of plasmons

Astrophysical bound on μ_ν

$$Q_\mu = g\int \frac{d^3k}{(2\pi)^3}\omega f_{BE}\Gamma_{\gamma\to\nu\bar{\nu}}$$

Energy-loss rate per unit volume

Magnetic moment plasmon decay enhances the Standard Model photo-neutrino cooling by photon polarization tensor



more fast cooling of the star.

In order not to delay helium ignition (≤5% in Q)

… best astrophysical limit on ν magnetic moment…

$$\boxed{\mu \le 3\times10^{-12}\mu_B}$$

$$\mu^2 \to \sum_{a,b}\left(|\mu_{a,b}|^2 + |\epsilon_{a,b}|^2\right)$$

G.Raffelt, PRL 1990

Astrophysics bounds on μ_ν

$$\boxed{\mu_\nu(\text{astro}) < 10^{-10}\text{–}10^{-12}\ \mu_\text{B}}$$

Mostly derived from consequences of helicity-state change in astrophysical medium:

- **available degrees of freedom in BBN.**
- **stellar cooling via plasmon decay,**
- **cooling of SN1987a.**

Red Giant lumin.
$\mu_\nu \leqslant 3 \cdot 10^{-12} \mu_B$
G. Raffelt, D. Dearborn,
J. Silk, 1989.

Bounds depend on

- **modeling of astrophysical systems,**
- **on assumptions on the neutrino properties.**

Generic assumption:

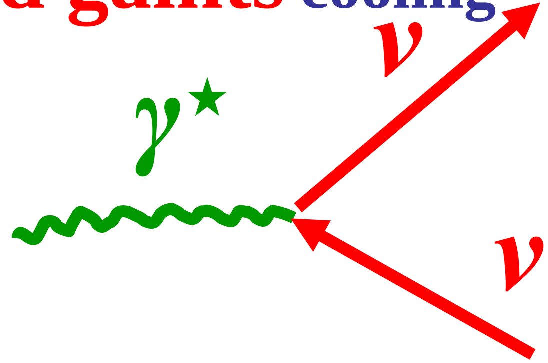
- **absence of other nonstandard interactions except for μ_ν .**

A global treatment would be desirable, incorporating oscillation and matter effects as well as the complications due to interference and competitions among various channels.

Dobroliubov, Ignatiev (1990); Babu, Volkas (1992);
Mohapatra, Nussinov (1992) …

Constraints on neutrino millicharge from red gaints cooling

$\gamma^{\star} \longrightarrow \nu\nu$



Interaction Lagrangian

$$\boxed{L_{int} = -iq_{\nu}\bar{\psi}_{\nu}\gamma^{\mu}\psi_{\nu}A^{\mu}}$$

millicharge

Decay rate

$$\boxed{\Gamma_{q_{\nu}} = \frac{{q_{\nu}}^{2}}{12\pi}\omega_{pl}\left(\frac{\omega_{pl}}{\omega}\right)}$$

- $\boxed{q_{\nu} \leq 2 \times 10^{-14} e}$ …to avoid helium ignition in low-mass **red gaints**

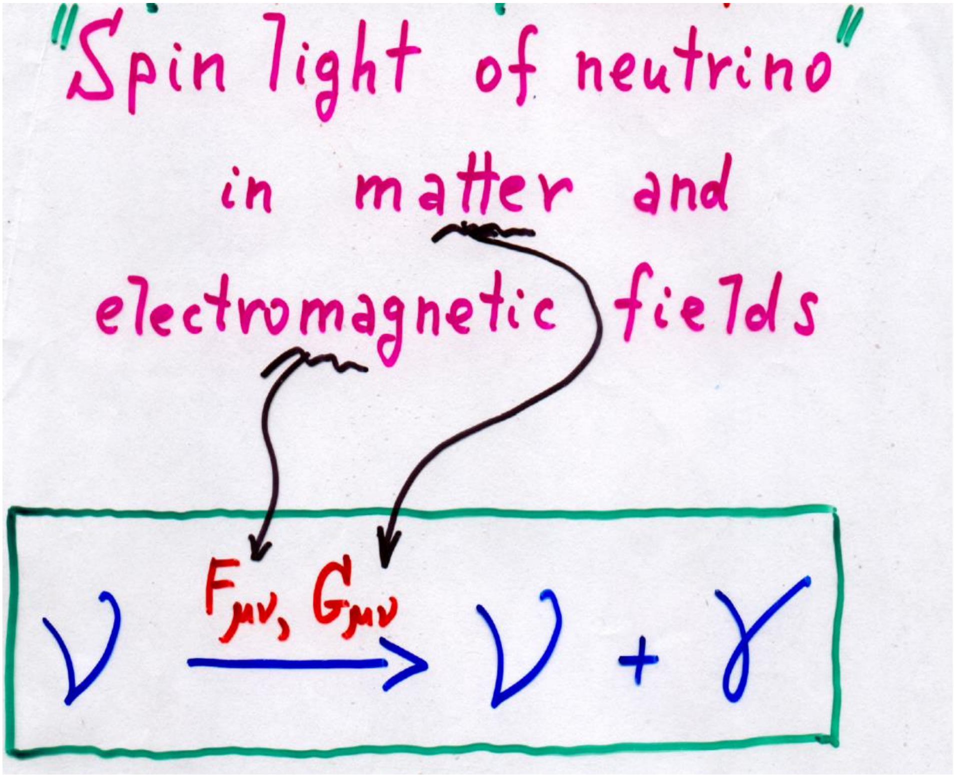
Halt,Raffelt, Weiss, PRL1994

- $\boxed{q_{\nu} \leq 3 \times 10^{-17} e}$ … absence of anomalous energy-dependent dispersion of SN1987A ν signal, most model independent

- **… from “charge neutrality” of neutron…** $\boxed{q_{\nu} \leq 3 \times 10^{-21} e}$

• New mechanism of electromagnetic radiation

SLν



A.Lobanov, A.Studenikin,
Phys.Lett. B 564 (2003) 27
Phys.Lett. B 601 (2004) 171

Studenikin, A.Ternov,
Phys.Lett. B 608 (2005) 107

A.Grigoriev, A.S., Ternov,
Phys.Lett. B 622 (2005) 199

Studenikin,

J.Phys.A: Math.Gen. 39 (2006) 6769,
J.Phys.A: Math.Theor. 41 (2008) 16402,

A.Grigoriev, A.Lokhov,
A.Studenikin, A.Ternov,
Nuovo Cim. 35 C (2012) 57,
Phys.lett.B 718 (2012) 512

"Spin light of neutrino" in matter and electromagnetic fields

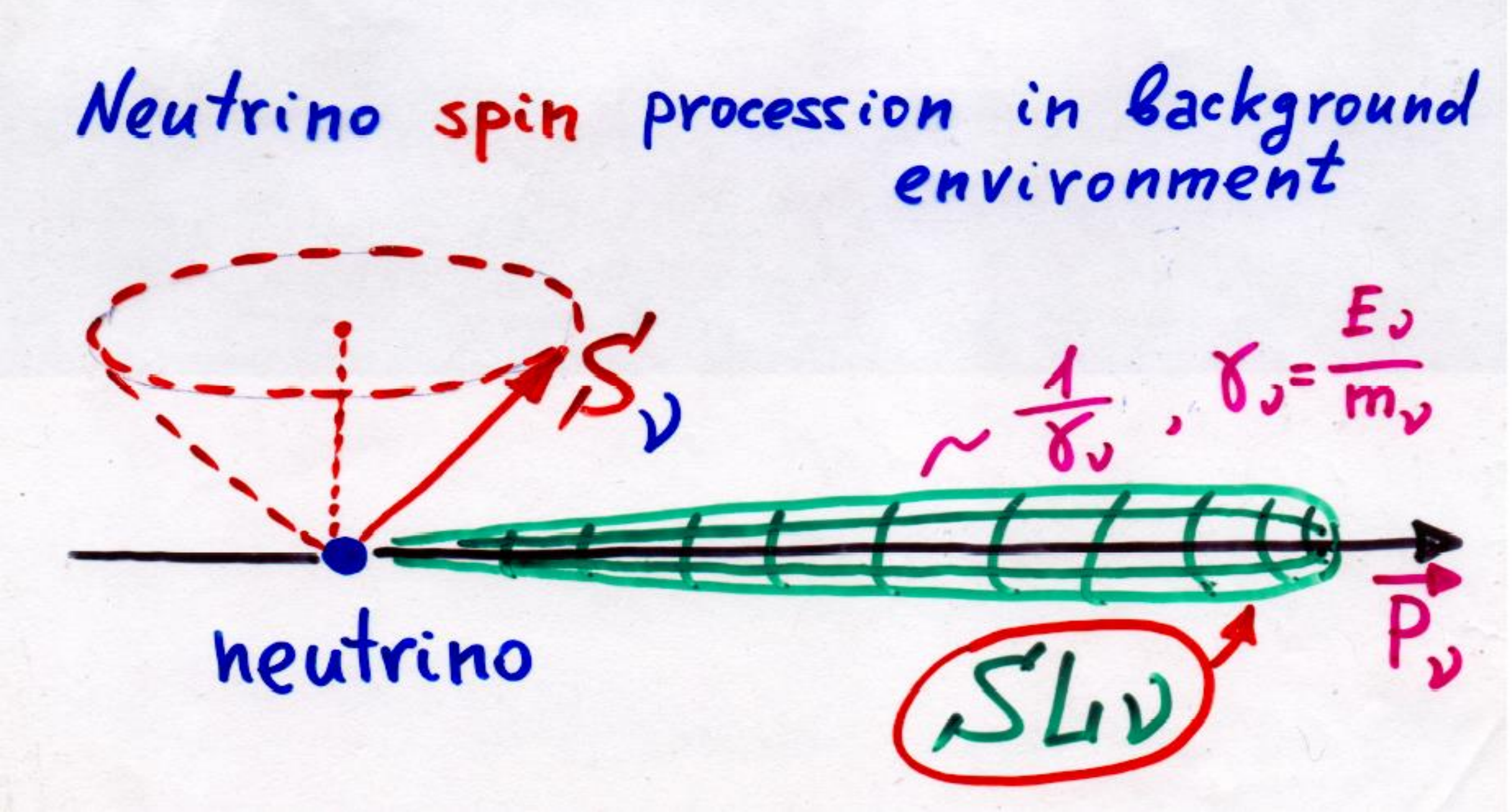
$SL\nu$

$$\nu \xrightarrow{F_{\mu\nu},\ G_{\mu\nu}} \nu + \gamma$$

Quasi-classical theory of spin light of neutrino in matter and gravitational field

$SL\nu$

A.Lobanov, A.Studenikin, Phys.Lett. B 564 (2003) 27,
Phys.Lett. B 601 (2004) 171;
M.Dvornikov, A.Grigoriev, A.Studenikin, Int.J.Mod.Phys. D 14 (2005) 309



ν spin evolution in presence of general external fields

M.Dvornikov, A.Studenikin,
JHEP 09 (2002) 016

General types non-derivative interaction with external fields

$$\boxed{\begin{gathered}-\mathcal{L} = g_s s(x)\bar\nu\nu + g_p\pi(x)\bar\nu\gamma^5\nu + g_v V^\mu(x)\bar\nu\gamma_\mu\nu + g_a A^\mu(x)\bar\nu\gamma_\mu\gamma^5\nu + \\ +\tfrac{g_t}{2}T^{\mu\nu}\bar\nu\sigma_{\mu\nu}\nu + \tfrac{g'_t}{2}\Pi^{\mu\nu}\bar\nu\sigma_{\mu\nu}\gamma_5\nu,\end{gathered}}$$

scalar, pseudoscalar, vector, axial-vector, tensor and pseudotensor fields:

$$s,\pi, V^\mu = (V^0,\vec V), A^\mu = (A^0,\vec A),$$
$$T_{\mu\nu} = (\vec a,\vec b), \Pi_{\mu\nu} = (\vec c,\vec d)$$

Relativistic (quasiclassical) equation for ν spin vector:

$$\begin{aligned}\dot{\vec\zeta}_\nu = 2g_a\Big\{&A^0[\vec\zeta_\nu\times\vec\beta] - \tfrac{m_\nu}{E_\nu}[\vec\zeta_\nu\times\vec A] - \tfrac{E_\nu}{E_\nu+m_\nu}(\vec A\vec\beta)[\vec\zeta_\nu\times\vec\beta]\Big\}\\ &+2g_t\Big\{[\vec\zeta_\nu\times\vec b] - \tfrac{E_\nu}{E_\nu+m_\nu}(\vec\beta\vec b)[\vec\zeta_\nu\times\vec\beta] + [\vec\zeta_\nu\times[\vec a\times\vec\beta]]\Big\} + \\ &+2ig'_t\Big\{[\vec\zeta_\nu\times\vec c] - \tfrac{E_\nu}{E_\nu+m_\nu}(\vec\beta\vec c)[\vec\zeta_\nu\times\vec\beta] - [\vec\zeta_\nu\times[\vec d\times\vec\beta]]\Big\}.\end{aligned}$$

- ***Neither s nor π nor V contributes to spin evolution***

- **Electromagnetic interaction**

$$T_{\mu\nu} = F_{\mu\nu} = (\vec E,\vec B)$$

- **SM weak interaction**

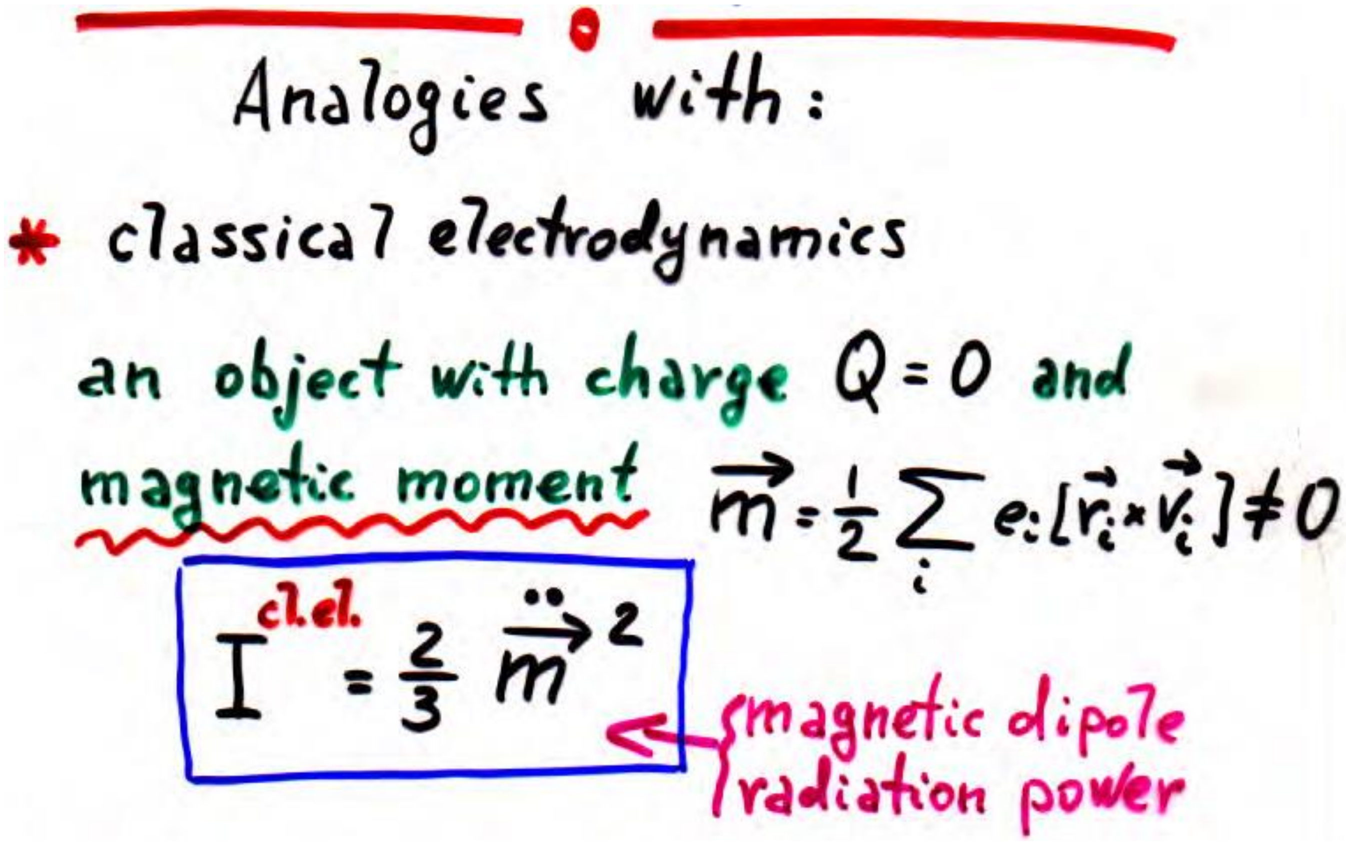
$$G_{\mu\nu} = (-\vec P,\vec M)$$

$$\vec M = \gamma(A^0\vec\beta - \vec A)$$
$$\vec P = -\gamma[\vec\beta\times\vec A],$$

New mechanism of electromagnetic radiation

? Why **Spin Light** of neutrino $\boxed{SL\nu}$ in matter.

? Why **Spin Light** of electron $\boxed{SLe}$ in matter.



Analogies with:

* classical electrodynamics

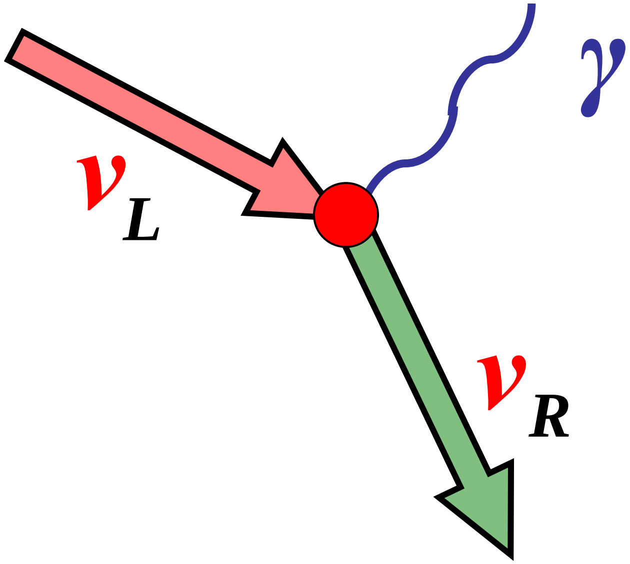
an object with charge $Q=0$ and

magnetic moment $\vec{m} = \frac{1}{2} \sum_i e_i [\vec{r}_i \times \vec{v}_i] \neq 0$

$$\boxed{I^{cl.el.} = \frac{2}{3} \ddot{\vec{m}}^2} \longleftarrow$$

magnetic dipole radiation power

Neutrino – photon couplings



broad neutrino lines account for interaction with environment

"Spin light of neutrino in matter"

$SL\nu$

- … within the quantum treatment based on method of exact solutions …

Method of exact solutions

Modified Dirac equations for ν (and e)

(containing effective electromagnetic and matter potentials)

+

exact solutions (particles wave functions)

⇓

a basis for investigation of different phenomena which can proceed when neutrinos (and electrons) move in dense magnetized media (astrophysical and cosmological environments) «method of exact solutions »

Interaction of particles in external electromagnetic fields

(Furry representation in quantum electrodynamics)

Potential of electromagnetic field

$$\boxed{A_\mu(x) = A^q_\mu(x) + A^{ext}_\mu(x)},$$

quantized part of potential

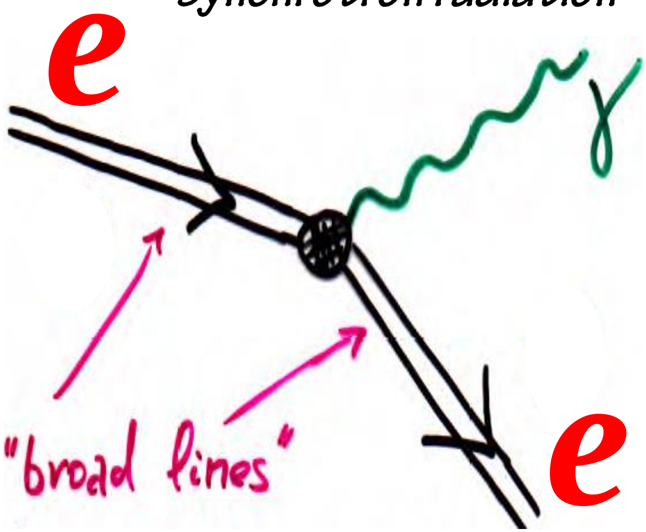
$$e \xrightarrow{\mathbf{B}_\perp} e + \gamma$$

synchrotron radiation

evolution operator

$$\boxed{U_F(t_1,t_2) = Texp\Big[- i \int\limits_{t_1}^{t_2} j^\mu(x) A^q_\mu(x) dx \Big]},$$

charged particles current $\boxed{j_\mu(x) = \frac{e}{2}\left[\overline{\Psi}_F \gamma_\mu, \Psi_F\right]}$,



Dirac equation in external classical (non-quantized) field $A^{ext}_\mu(x)$

$$\boxed{\Big\{ \gamma^\mu \Big(i\partial_\mu - eA^{ext}_\mu(x) \Big) - m_e \Big\} \Psi_F(x) = 0}$$

…beyond perturbation series expansion,

strong fields and non linear effects…

ν *and* e *in matter treated within*

«method of exact solutions»

(of quantum wave equations)

A.Studenikin, A.Ternov, "Neutrino quantum states in matter", Phys.Lett.B 608 (2005) 107;

"Generalized Dirac-Pauli equation and neutrino quantum states in matter" hep-ph/0410296,

A.Grigoriev, A.Studenikin, A.Ternov, Phys.Lett.B 608 622 (2005)19

A.Studenikin,"Method of wave equations exact solutions in studies of neutrino and electron interactions in dense matter",

- J.Phys.A:Math.Theor. 41 (2008) 16402

"Neutrinos and electrons in background matter: a new approach",

- Ann. Fond. de Broglie 31 (2006) 289,
- J.Phys.A: Math.Gen.39 (2006) 6769

I.Balantsev, Yu.Popov, A.Studenikin, "On a problem of relativistic particles motion in a strong magnetic field and dense matter"

- J .Phys.A: Math.Theor.44 (2011)255301

A.Studenikin, I.Tokarev, "Millicharged neutrino with anomalous magnetic moment in rotating magnetized matter",

- arXiv : 1209.3245 v2, May 27, 2013

- ν *energy quantization in rotating matter …*

Modified Dirac equation for neutrino in matter

Addition to the vacuum neutrino Lagrangian

$$\Delta L_{eff} = \Delta L_{eff}^{CC} + \Delta L_{eff}^{NC} = -f^{\mu}\left(\bar{\nu}\gamma_{\mu}\frac{1+\gamma^{5}}{2}\nu\right)$$

matter current

where $$f^{\mu} = \frac{G_F}{\sqrt{2}}\left((1+4\sin^{2}\theta_W)j^{\mu} - \lambda^{\mu}\right)$$

matter polarization

$$\boxed{\left\{i\gamma_{\mu}\partial^{\mu} - \frac{1}{2}\gamma_{\mu}(1+\gamma_5)f^{\mu} - m\right\}\Psi(x) = 0}$$

A.Studenikin, A.Ternov, hep-ph/0410297;
Phys.Lett.B **608 (2005) 107**

It is supposed that there is a macroscopic amount of electrons in the scale of a neutrino de Broglie wave length. Therefore, **the interaction of a neutrino with the matter (electrons) is coherent.**

L.Chang, R.Zia,'88; J.Panteleone,'91; K.Kiers, N.Weiss, M.Tytgat,'97-'98; P.Manheim,'88; D.Nötzold, G.Raffelt,'88; J.Nieves,'89; V.Oraevsky, V.Semikoz, Ya.Smorodinsky,89; W.Naxton, W-M.Zhang'91; M.Kachelriess,'98; A.Kusenko, M.Postma,'02.

This is the most general equation of motion of a neutrino in which the effective potential accounts for both the **charged** and **neutral-current** interactions with the background matter and also for the possible effects of the matter **motion** and **polarization**.

Quantum theory of spin light of neutrino (I)

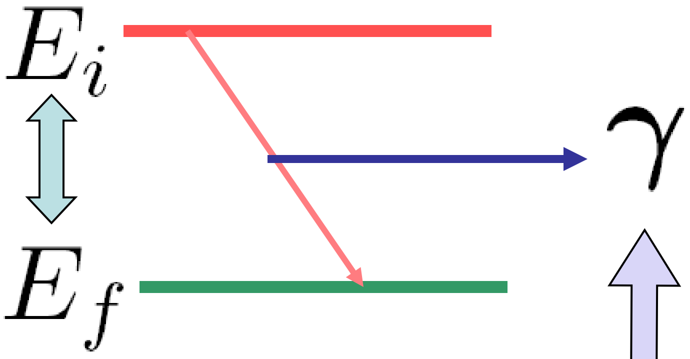
Quantum treatment of *spin light of neutrino* in matter
showns that this process originates from the **two subdivided phenomena:**

$SL\nu$

the **shift** of the neutrino **energy levels** in the presence of the background matter, which is different for the two opposite **neutrino helicity states**,

$$E = \sqrt{\mathbf{p}^2\left(1 - s\alpha\frac{m}{p}\right)^2} + m^2 + \alpha m$$

$$s = \pm 1$$



the radiation of the photon in the process of the neutrino transition from the **"excited" helicity state** to the **low-lying helicity state** in matter

A.Studenikin, A.Ternov, Phys.Lett.B 608 (2005) 107;
A.Grigoriev, A.Studenikin, A.Ternov, Phys.Lett.B 622 (2005) 199;
Grav. & Cosm. 14 (2005) 132;

neutrino-spin self-polarization effect in the matter

A.Lobanov, A.Studenikin, Phys.Lett.B 564 (2003) 27;
Phys.Lett.B 601 (2004) 171

It is possible to have $\tau = \frac{1}{\Gamma_{SL\nu}} << $ age of the Universe ?

$p \gg m_{plasmon}$

also discussed by
A.Kuznetsov,
N.Mikheev, 2007

For ultra-relativistic ν
with momentum $p \sim 10^{20} eV$
and magnetic moment $\mu \sim 10^{-10} \mu_B$
in very dense matter $n \sim 10^{40} cm^{-3}$
from $\Gamma_{SL\nu} = 4\mu^2 \alpha^2 m_\nu^2 p$

A.Lobanov, A.S., PLB 2003; PLB 2004
A.Grigoriev, A.S., PLB 2005
A.Grigoriev, A.S., A.Ternov, PLB 2005

$$\alpha m_\nu = \frac{1}{2\sqrt{2}} G_F n \left(1 + sin^2\theta_W\right)$$

it follows that

$$\tau = \frac{1}{\Gamma_{SL\nu}} = 1.5 \times 10^{-8} s$$

A.Grigoriev, A.Lokhov,
A.Ternov, A.Studenikin

The effect of plasmon mass on Spin Light of Neutrino in dense matter

Phys.Lett. B 718
(2012) 512-515

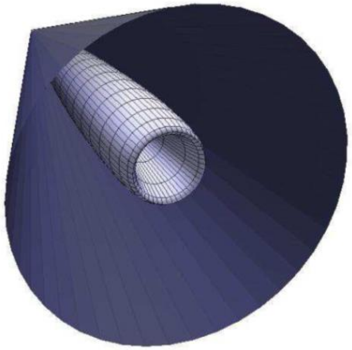


Figure 1: 3D representation of the radiation power distribution.

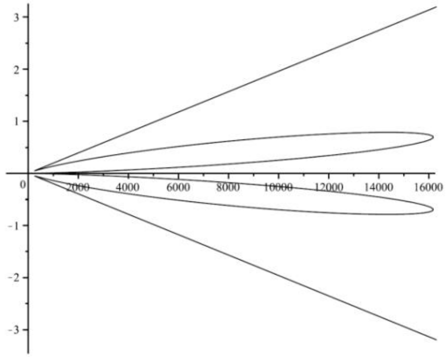


Figure 2: The two-dimensional cut along the symmetry axis. Relative units are used.

4. Conclusions

We developed a detailed evaluation of the spin light of neutrino in matter accounting for effects of the emitted plasmon mass. On the base of the exact solution of the modified Dirac equation for the neutrino wave function in the presence of the background matter the appearance of the threshold for the considered process is confirmed. The obtained exact and explicit threshold condition relation exhibit a rather complicated dependance on the matter density and neutrino mass. The dependance of the rate and power on the neutrino energy, matter density and the angular distribution of the $SL\nu$ is investigated in details. It is shown how the rate and power wash out when the threshold parameter $a = m_\gamma^2/4\tilde{n}p$ approaching unity. From the performed detailed analysis it is shown that the $SL\nu$ mechanism is practically insensitive to the emitted plasmon mass for very high densities of matter (even up to $n = 10^{41} cm^{-3}$) for ultra-high energy neutrinos for a wide range of energies starting from $E = 1$ TeV. This conclusion is of interest for astrophysical applications of $SL\nu$ radiation mechanism in light of the recently reported hints of $1 \div 10$ PeV neutrinos observed by IceCube [17].

(III) ν energy quantization in rotating media: new mechanism for ν trapping inside compact objects

Grigoriev, Savochkin, Studenikin, Russ.Phys.J. 50 (2007) 845
Studenikin, J.Phys. A: Math.Theor. 41 (2008) 164047
Balantsev, Popov, Studenikin,
J.Phys. A:Math.Theor. 44 (2011) 255301
Balantsev, Studenikin, Tokarev, Phys.Part.Nucl. 43 (2012), 727
Phys.Atom.Nucl. 76 (2013) 489
Studenikin, Tokarev, arXiv: 1209.3245 v 2, May 28, 2013

… evaluation of the method

- within a project of research on ν

in dense matter and external fields

A. Studenikin,

- "Quantum treatment of neutrino in background matter", J. Phys. A: Math. Gen. 39 (2006) 6769-6776

- "Method of wave equations exact solutions in studies of neutrinos and electron interactions in dense matter", J.Phys.A: Math.Theor. 41 (2008) 164047

- "Neutrinos and electrons in background matter: a new approach", Ann.Fond. de Broglie 31 (2006) 289-316

…«method of exact solutions»

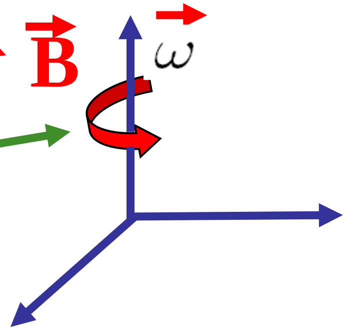
Millicharged magnetic ν in rotating magnetized matter

Balatsev, Tokarev, Studenikin,
Phys.Part.Nucl., 2012,
Phys.Atom.Nucl., Nucl.Phys. B, 2013,
● Studenikin, Tokarev, arXiv: 1209.3245, V 2, May 27, 2013

Modified Dirac equation for ν wave function

$$\boxed{\left(\gamma_\mu(p^\mu + q_0 A^\mu) - \frac{1}{2}\gamma_\mu(c_l + \gamma_5)f^\mu - \frac{i}{2}\mu\sigma_{\mu\nu}F^{\mu\nu} - m\right)\Psi(x) = 0}$$

external magnetic field



$$\boxed{V_m = \tfrac{1}{2}\gamma_\mu(c_l + \gamma_5)f^\mu} \qquad c_l = 1$$

matter potential

rotating matter

$$\boxed{f^\mu = -Gn_n(1, -\epsilon y\omega, \epsilon x\omega, 0)}$$

rotation
angular
frequency

✓ energy is quantized in rotating matter

$$G = \frac{G_F}{\sqrt{2}}$$

$$\boxed{p_0 = \sqrt{p_3^2 + 2N|2Gn_n\omega - \epsilon q_\nu B| + m^2} - Gn_n - q\phi}$$

$$\boxed{N = 0, 1, 2, \ldots}$$

matter rotation frequency

scalar potential of electric field

✓ energy is quantized in rotating matter like electron energy in magnetic field (Landau energy levels):

$$\boxed{p_0^{(e)} = \sqrt{m_e^2 + p_3^2 + 2\gamma N}, \quad \gamma = eB, \quad N = 0, 1, 2, \ldots}$$

In quasi-classical approach

- ✓ quantum states in rotating matter
- ✓ motion in circular orbits

$$\boxed{R = \int_0^\infty \Psi_L^\dagger \, \mathrm{r} \, \Psi_L \, d\mathbf{r} = \sqrt{\frac{2N}{|2Gn_n\omega - \epsilon q_0 B|}}}$$

due to effective Lorentz force

$$\boxed{\mathbf{F}_{eff} = q_{eff}\mathbf{E}_{eff} + q_{eff}\,[\boldsymbol{\beta} \times \mathbf{B}_{eff}]}$$

$$q_{eff}\mathbf{E}_{eff} = q_m\mathbf{E}_m + q_0\mathbf{E} \qquad q_{eff}\mathbf{B}_{eff} = |q_m B_m + q_0 B|\mathbf{e}_z$$

where $\boxed{q_m = -G, \quad \mathbf{E}_m = -\boldsymbol{\nabla} n_n, \quad \mathbf{B}_m = 2n_n\boldsymbol{\omega}}$

matter induced “charge”, “electric” and “magnetic” fields

. . . we predict :

$E \sim 1\ eV$

1) low-energy ν are trapped in circular orbits inside rotating neutron stars

$$R = \sqrt{\frac{2N}{Gn\omega}} < R_{NS} = 10\ km$$

$$\boxed{\begin{aligned} R_{NS} &= 10\ km \\ n &= 10^{37} cm^{-3} \\ \omega &= 2\pi \times 10^{3}\ s^{-1} \end{aligned}}$$

2) rotating neutron stars as filters for low-energy relic ν ?

$T_\nu \sim 10^{-4}$ eV

Studenikin, Tokarev,
arXiv:1209.3245
May 28, 2013

… we predict :

3) high-energy ν are deflected inside a rotating astrophysical transient sources (GRBs, SNe, AGNs)

absence of light in correlation with ν signal reported by ANTARES Coll.

M.Ageron et al,
Nucl.Instrum.Meth. A692 (2012) 184

Neutrino Star Turning (νST) mechanism

...Due to effective Lorentz force

Studenikin, Tokarev,
arXiv:1209.3245
May 28, 2013

feedback of neutrinos on rotating star

Escaping ν s move on curved orbits inside rotating star should effect initial rotation of star

... To avoid contradiction between impact νST mechanism on pulsar rotation and observational data on pulsars

...the shift of rotation frequency (for realistic choice of the star characteristics)

$$\boxed{\frac{|\Delta\omega_0|}{\omega_0} \simeq 10^{17}\varepsilon\left(\frac{P_0}{10\ \mathrm{s}}\right)}$$

$\varepsilon = q_\nu/e_0$

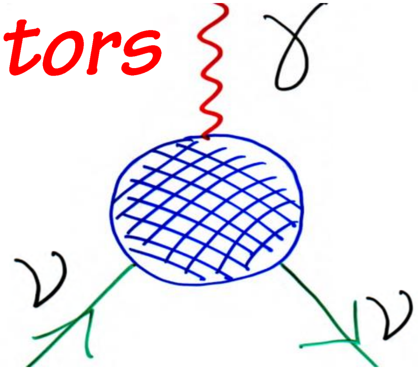
From $|\Delta\omega_0| < \omega_0$ (for slowly rotating stars $P_0 \sim 10\ s$)

new astrophysical limit

$$\boxed{q_\nu < 10^{-17}e_0}$$

Conclusions

ν e.m. vertex function → 4 form factors



charge dipole magnetic and electric

- $$\Lambda_\mu(q) = f_Q(q^2)\gamma_\mu + f_M(q^2) i\sigma_{\mu\nu}q^\nu + f_E(q^2)\sigma_{\mu\nu}q^\nu\gamma_5$$
  $$f_A(q^2)(q^2\gamma_\mu - q_\mu \not{q})\gamma_5$$ anapole

- **EM properties → a way to distinguish Dirac and Majorana ν**

- Standard Model with ν_R $(m_\nu \neq 0)$: $\mu_e = \frac{3eG_F}{8\sqrt{2}\pi^2} m_{\nu_e} \sim 3 \cdot 10^{-19} \mu_B \left(\frac{m_{\nu_e}}{1eV}\right)$

- In extensions of SM → enhancement of ν magnetic moment, even electrically millicharged ν

- Limits from reactor ν-e scattering experiments (2012):

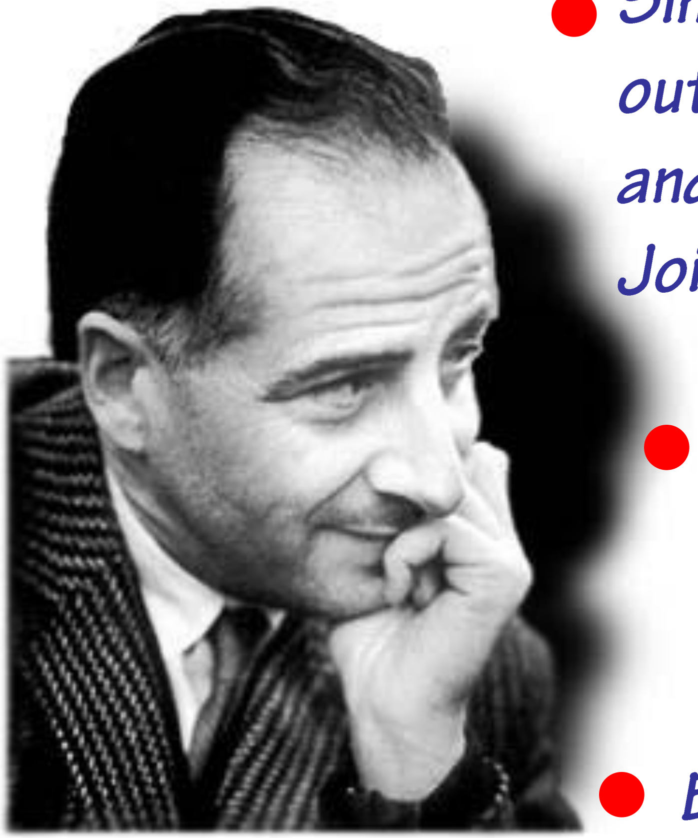
  $$\boxed{\mu_\nu < 2.9 \times 10^{-11} \mu_B}$$ A.Beda et al. (GEMMA Coll.)

  $$\boxed{\mid q_\nu \mid < 1.5 \times 10^{-12} e_0}$$

- Limits from astrophysics, star cooling (1990):

  $$\boxed{\mu_\nu < 3 \times 10^{-12} \mu_B}$$ G.Raffelt

  $$\boxed{q_\nu < 10^{-17} e_0}$$ νST mechanism



Бруно Понтекорво

- Since 1950 Bruno Pontecorvo, outstanding Italian scientist, lived in Russia and was staff member of Joint Institute for Nuclear Research, Dubna
- Bruno Pontecorvo was Head of Department of Particle Physics and member of Scientific Council of Faculty of Physics of Moscow State University
- Bruno Pontecorvo Laboratory on Neutrino Physics and Astrophysics (PLN)

  has been recently established at Faculty of Physics of Moscow State University

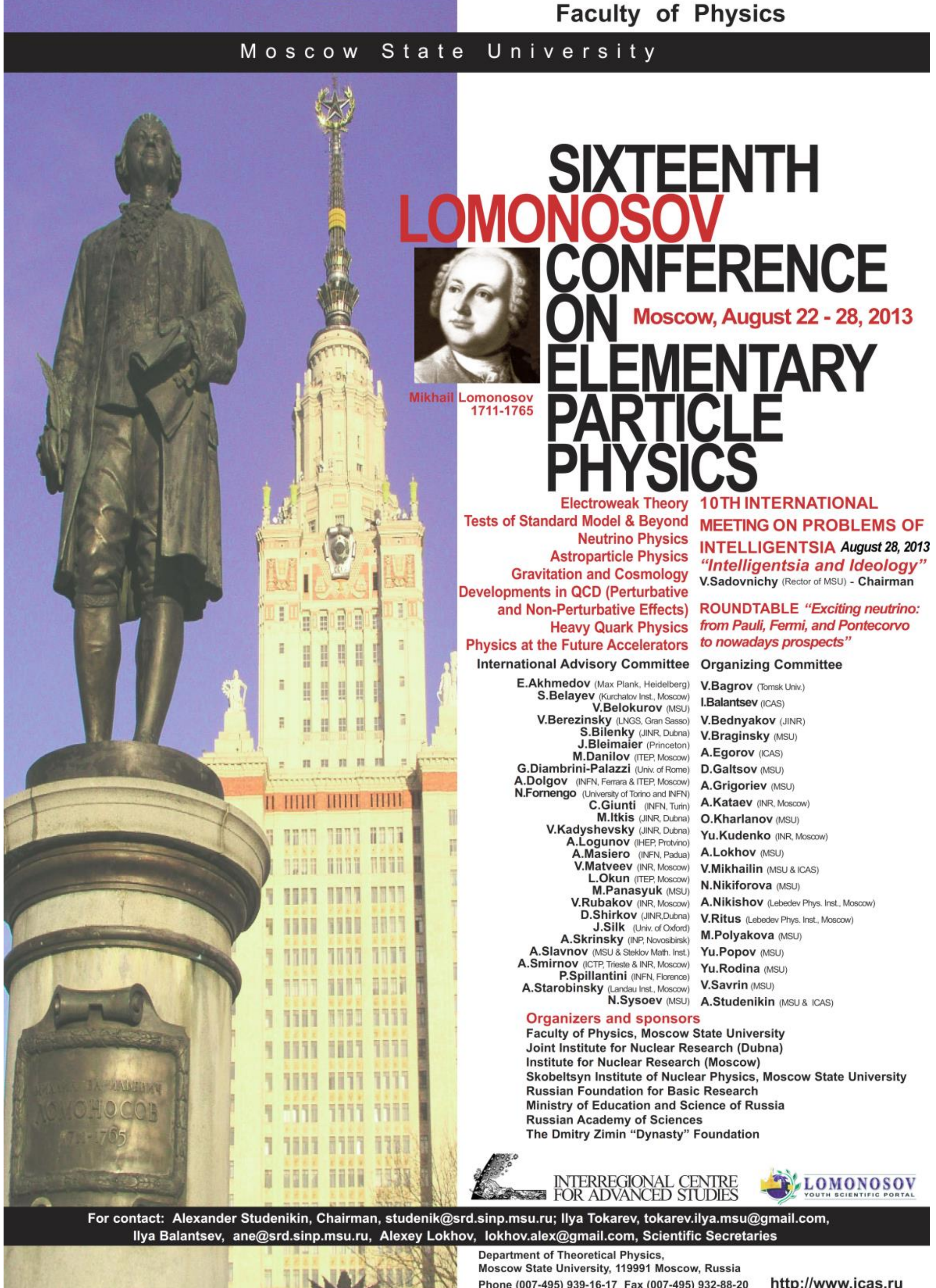
… to provide continuation of long-standing traditions in teaching and performing scientific researches of neutrinos of related issues…

16th Lomonosov Conference on Elementary Particle Physics, www.icas.ru Moscow State University, August 22-27, 2013

Бруно Понтекорво

1913-1993

centennial anniversary



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1711-1765

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