

Нейтрино в сильных электромагнитных полях и плотных средах

Школа по физике нейтрино
и астрофизике,
физический факультет МГУ,

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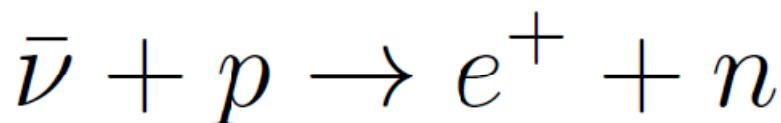
-  **Вступление**
-  **История нейтрино**
-  **Осцилляций нейтрино**
-  **Электромагнитные свойства нейтрино**
-  **Новые эффекты (1, 2, 3, 4) в нейтринных осцилляциях**
-  **Квантовый подход к описанию нейтрино в веществе**

Необычные и удивительные свойства

ν

«незаметная» или «мелкая» частица :

- **очень легкая** $m_{\nu_f} \ll m_f, f = e, \mu, \tau$
- **нейтральная** $q_\nu = 0 \quad q_\nu < 4 \times 10^{-17} e$
- **магнитный момент** $\mu_\nu \quad ?$
- **очень слабо связана (взаимодействует)
с окружающим миром (другими частицами)**



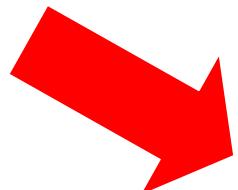
$$\sigma \sim 10^{-43} \text{ cm}^2$$

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

$$E_\nu \sim 3 \text{ MeV}$$

... пробег в воде ...

*Поэтому **нейтрино** обращает на себя пристальное внимание на завершающих этапах развития исследований в рамках конкретной теоретической парадигмы, когда основные закономерности взаимодействия элементарных частиц уже хорошо теоретически осмыслены и экспериментально исследованы*

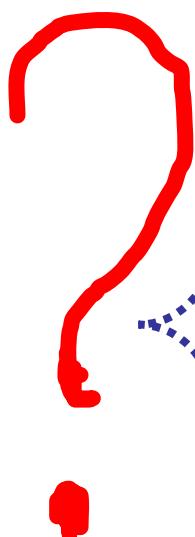


особая роль ν в современной физике

«ОКНО»
в
«Новую физику»

Взаимодействия элементарных частиц

«Новая
физика»



Стандартная
модель

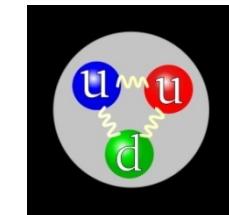
Электрослабое
взаимодействие

• Сильное
взаимодействие

• Гравитационное взаимодействие

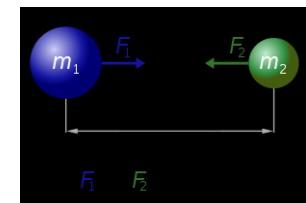
• Электромагнитное
взаимодействие

• Слабое
взаимодействие

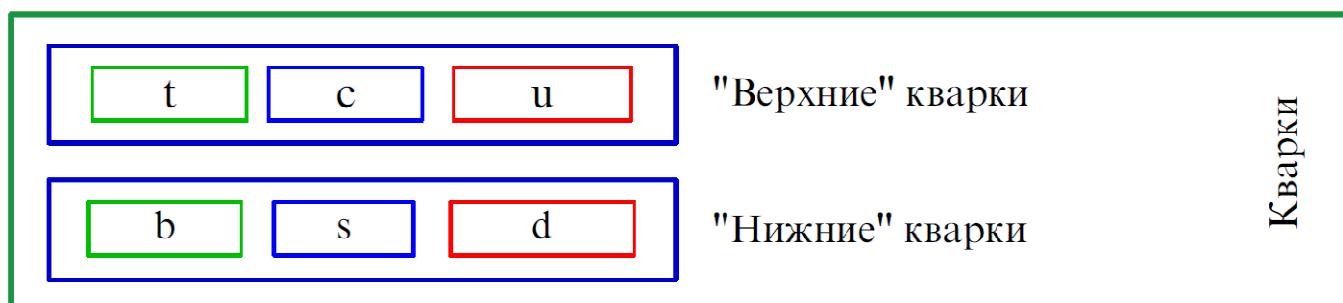
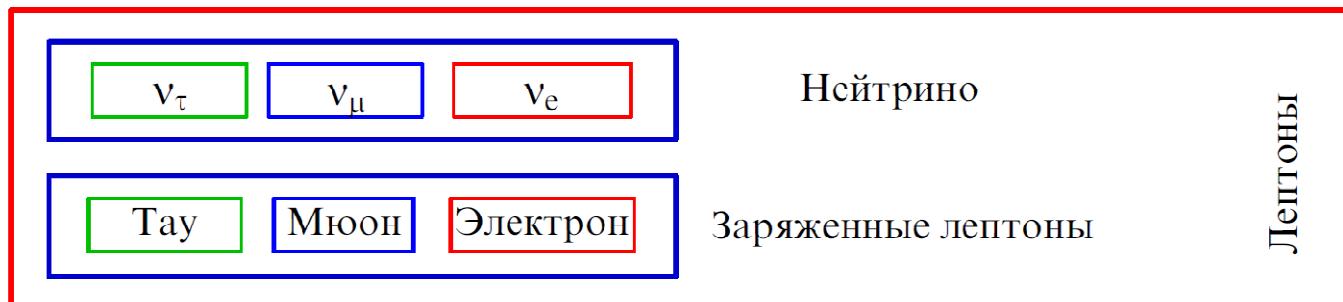


$n \xrightarrow{\beta} p + e + \bar{\nu}_e$
бета-распад
нейтрино

три кварка,
связанные
глюонами



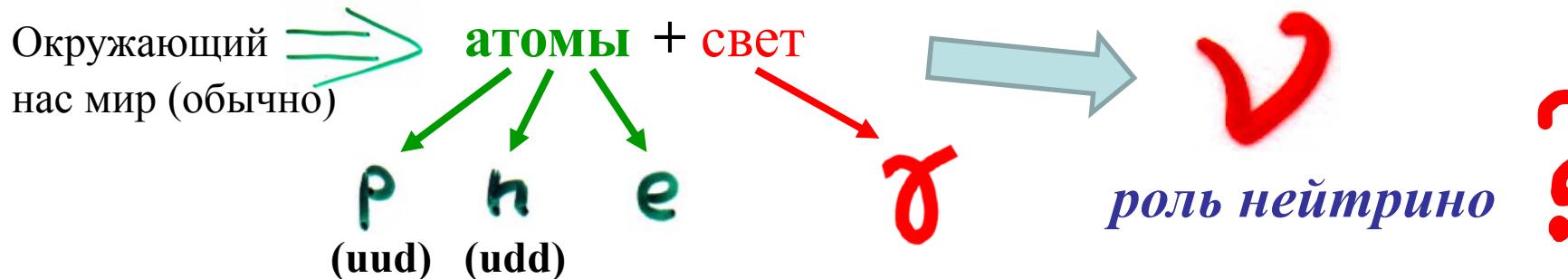
Элементарные частицы Стандартной модели



Частицы — переносчики взаимодействий:
электрослабого — фотон, W^+ , W^- , Z ;
сильного — глюоны

Бозон Хиггса

?



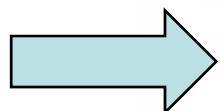
История нейтрино



познание фундаментальных
законов природы :

Нейтрино – уникальная элементарная частица

ν



В. Паули (1930г.) – открытое письмо



Тюбенгенскому физическому
обществу:

ν – „нейтрон“

$m < m_e$ или 0

$S = 1/2$

«настоящий» **нейtron**
был открыт
Дж. Чедвиком
в 1932 г.

Вольфганг Паули
(1890-1958)
в 1930 году выдвинул
гипотезу
о существовании
нейтрино,
назав эту частицу
«нейтроном»

Существование ν „спасает“
закон сохранения энергии в
 β -распаде ядер Н. Бор ...

Спектр энергий электронов распада



спектр e^- :
* E ν_e
* ограничение на m_{ν_e}

энергия электронов
распада

\rightarrow

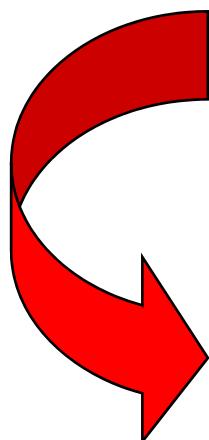


История нейтрино – череда парадоксов и сюрпризов !

Вольфганг Паули
Wolfgang Pauli



Вальтер Бааде
Walter Baade
(1893-1960)

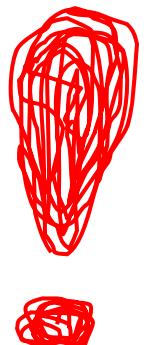


- “Today I did something a physicist should never do.
I predicted something which will never be observed experimentally..”

w. Pauli, 1930

- «Сегодня я совершил то,
что физик не должен делать никогда.

Я предсказал нечто,
что никогда не будет наблюдаться экспериментально»

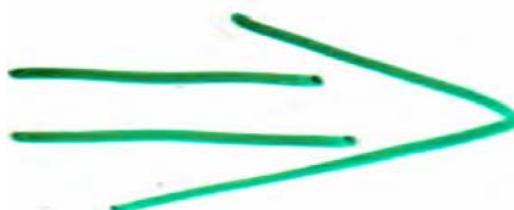


H.Bethe, R.Peierls, «The ‘neutrino’»

Nature 133 (1934) 532,

- «*There is no practically possible way of observing the neutrino*»
- «*Не существует практической возможности обнаружения нейтрино*»

... однако ...



Обнаружение **нейтрино** в экспериментах

ν_e - электронное нейтрино,

ν_μ - мюонное нейтрино

- Экспериментальное открытие $\bar{\nu}$:

$$\bar{\nu} + p \rightarrow n + e^+ \quad (1956)$$

Ф. Райнес - Н.н.
С. Кобан

- Экспер. открытие

$$\nu_\mu \neq \nu_e :$$

$$\pi^+ \rightarrow \mu^+ + \nu \leftarrow n \quad (1962)$$

$\downarrow \mu, e$

Л. Ледерман
М. Шварц
Дж. Стенберг

{ - Н.н.
1988

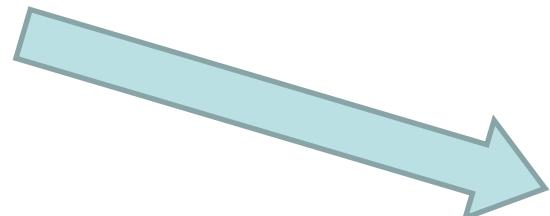
- DONUT (ДАНУТ, 2000 г.)
(Direct Observation of the NU Tau)

ν_τ

- тау-нейтрино

Нейтрино – одна из самых загадочных и уникальных элементарных частиц

*Несмотря на значительные усилия,
предпринимаемые физиками
(как экспериментаторами,
так и теоретиками)
на протяжении более чем 80 лет,
до сих пор многие вопросы о свойствах
нейтрино остаются открытыми*



Например,

*мы не знаем какова величина
массы нейтрино*

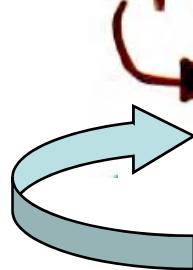
*(а это – главная характеристика любой
элементарной частицы)!*

Ограничения на массу нейтрино

- Эксперимент «Троицк-ню-масс»
в Институте ядерных исследований РАН

эффектная масса

$m_{\nu_e} < 2.2 \text{ эВ}$



... это очень мало :

$$m_n = 939,6 \text{ МэВ}$$
$$m_p = 938,3 \text{ МэВ}$$
$$m_e = 0,5 \text{ МэВ}$$

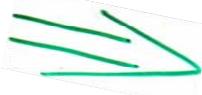


$$m_{\nu_\mu} < 170 \text{ кэВ}$$



$$m_{\nu_\tau} < 18.2 \text{ МэВ}$$

- готовятся новые
измерения



(В.М. Лобашов, Троицк, 2003)
(Ch. Weinheimer, Mainz, 2003)

$$1 \text{ МэВ} = 10^6 \text{ эВ} = 1,8 \times 10^{-27} \text{ г}$$

$$(\pi^+ \rightarrow \mu^+ + \nu_\mu)$$
$$(\tau^\pm \rightarrow \nu_\tau + \bar{\nu}^\pm + \pi^\pm + \bar{\pi}^\mp)$$

Эксперимент по прямому измерению массы нейтрино КАТРИН

KATRIN
Karlsruhe Tritium





История нейтрино



познание фундаментальных
законов природы :



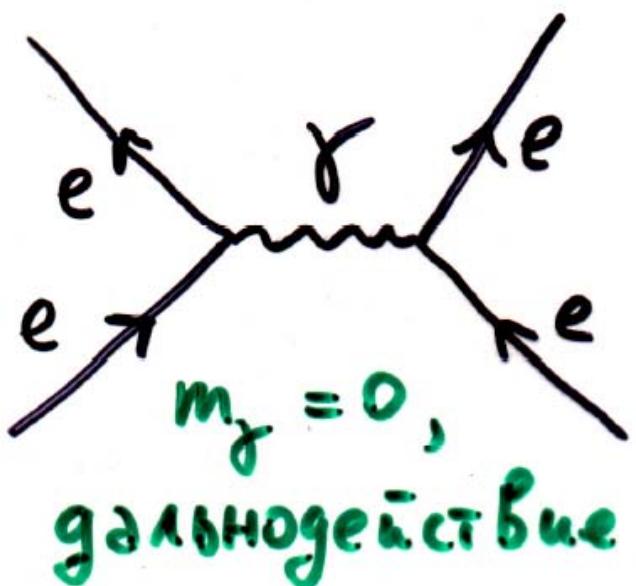
Теория слабых взаимодействий

Э.Ферми (1933) – аналогия с

моделью Дирака

электромагнитных
взаимодействий

„ток“ × „ток“



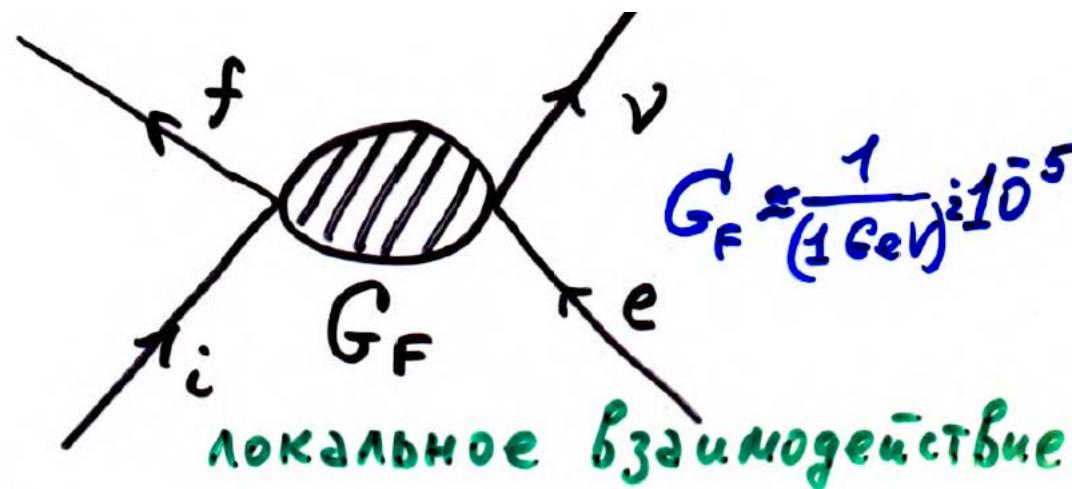
$$m_\gamma = 0,$$

дальнодействие



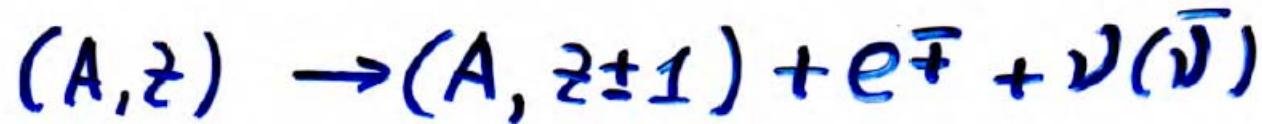
В 1934 году построил первую теорию радиоактивного бета-распада, включив в рассмотрение новую частицу, которую назвал на итальянский манер «нейтрино»

Энрико Ферми
(1901-1954)

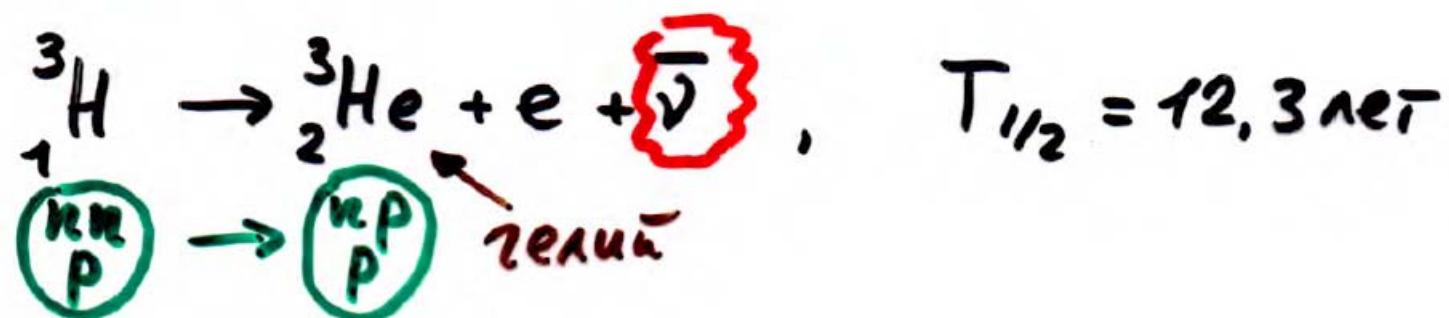


$$H = \frac{G_F}{\sqrt{2}} \Psi_p^+ O_\mu \Psi_n \Psi_e^+ O^\mu \Psi_\nu.$$

Э.Ферми, Ф.Перрен (1934) – метод прямого измерения массы ν по β -спектру вблизи его конца.



Тритий:



$$Q = M(A, z) - M(A, z+1) = 18.6 \text{ keV}$$

разность масс родительского и
дочернего ядер

Диаграмма Кюри
 (спектр электронов распада) функция Ферми

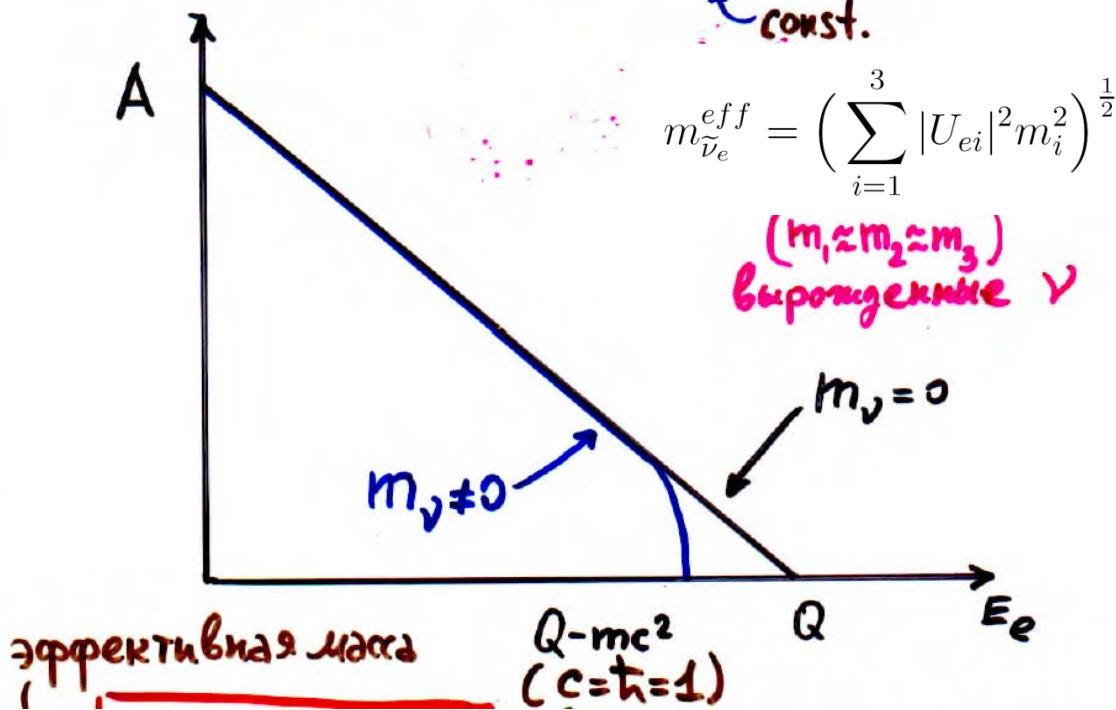
$$N(p_e) dp_e \sim |\langle f | H_B | i \rangle|^2 F(z, E_e) \times$$

$$\times p_e (Q - E_e)^2 \sqrt{1 - \left(\frac{m_e c^2}{Q - E_e}\right)^2} dp_e$$

⇓

$$A = \sqrt{N(p_e) / p_e^2 F(z, E_e)} = B \cdot (Q - E_e) \text{ const.}$$

энерговыделение кинетической энергии электрона



История нейтрино



познание фундаментальных
законов природы :

несохранение

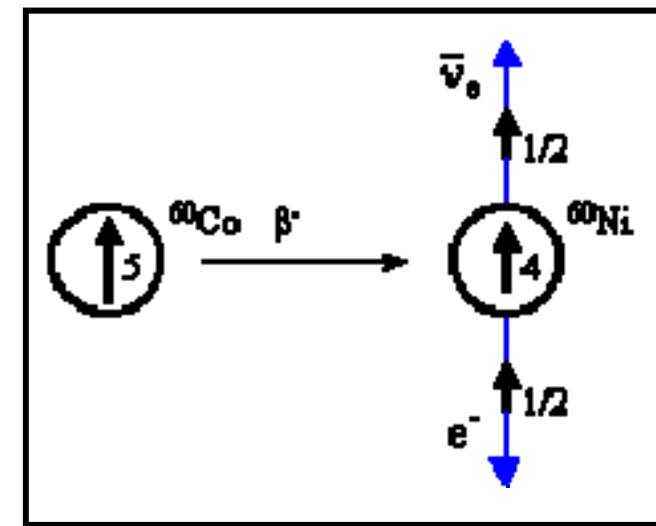
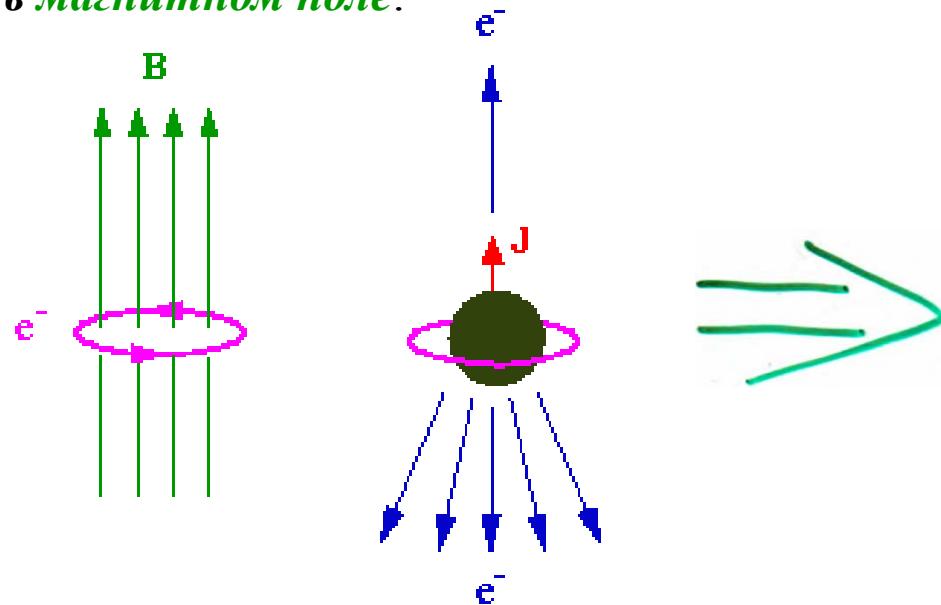
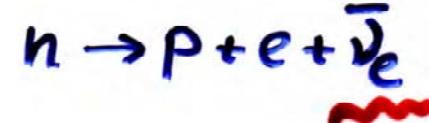
*пространственной чётности
в слабых взаимодействиях*



Несохранение пространственной четности в слабых взаимодействиях

(эксперимент *By и др.*, 1957 г.)

*Бета-распад ядер радиоактивного кобальта
в магнитном поле:*



Взглянув на процесс через зеркало
– такого процесса **нет в природе!**

несохранение четности

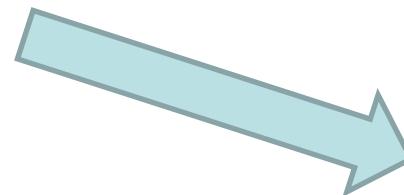


*Если бы пространственная четность сохранялась
(симметрия относительно зеркального отражения),
то одинаковое количество электронов **по** и **против** магнитного поля*

свойства **v**



*Нейтрино, являясь
практически «незаметной» частицей и крайне
слабо взаимодействующей с другими
элементарными частицами, вместе с тем
играет чрезвычайно важную роль
на всех этапах эволюции нашей Вселенной*



Без

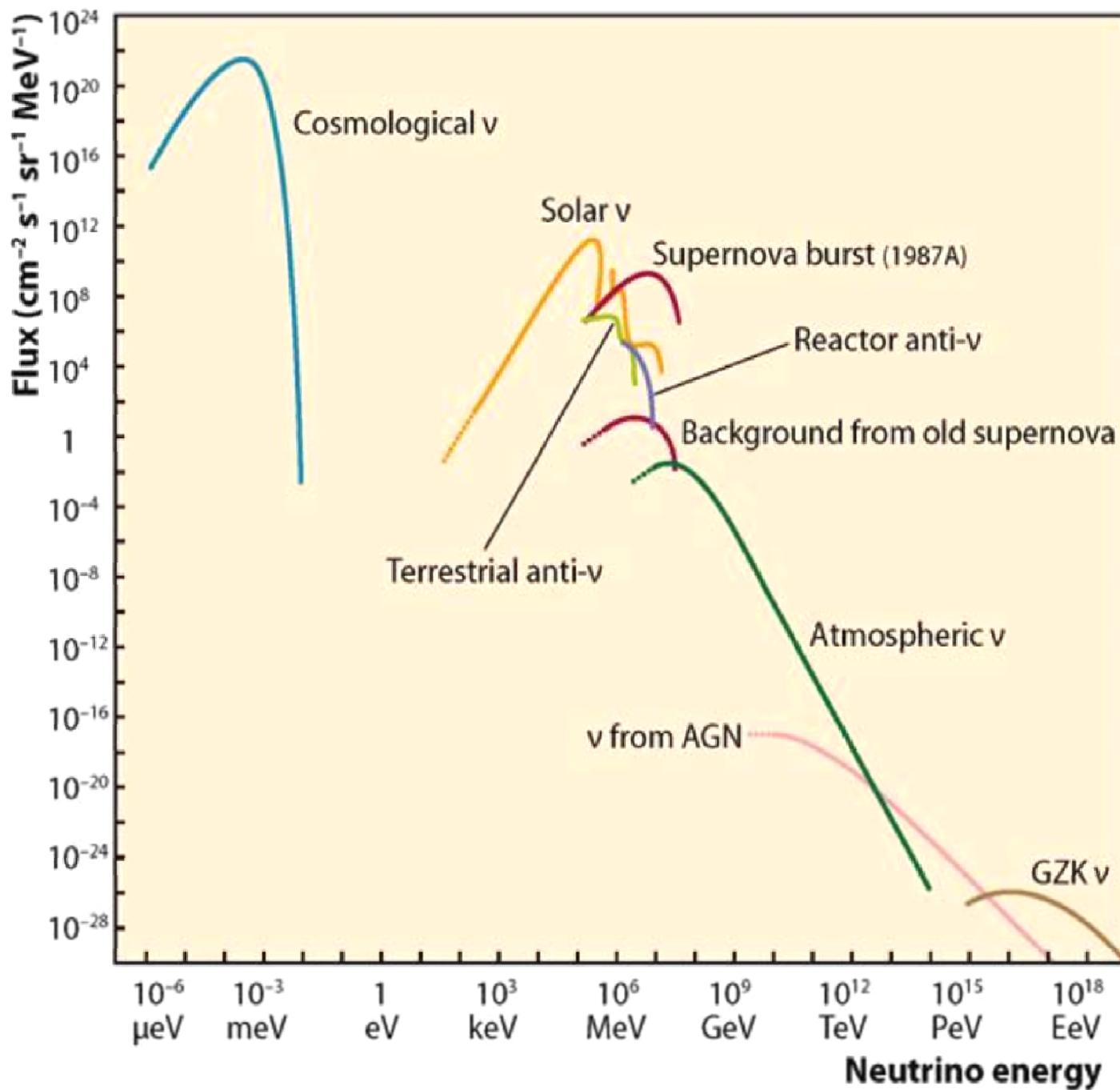


невозможно объяснить:

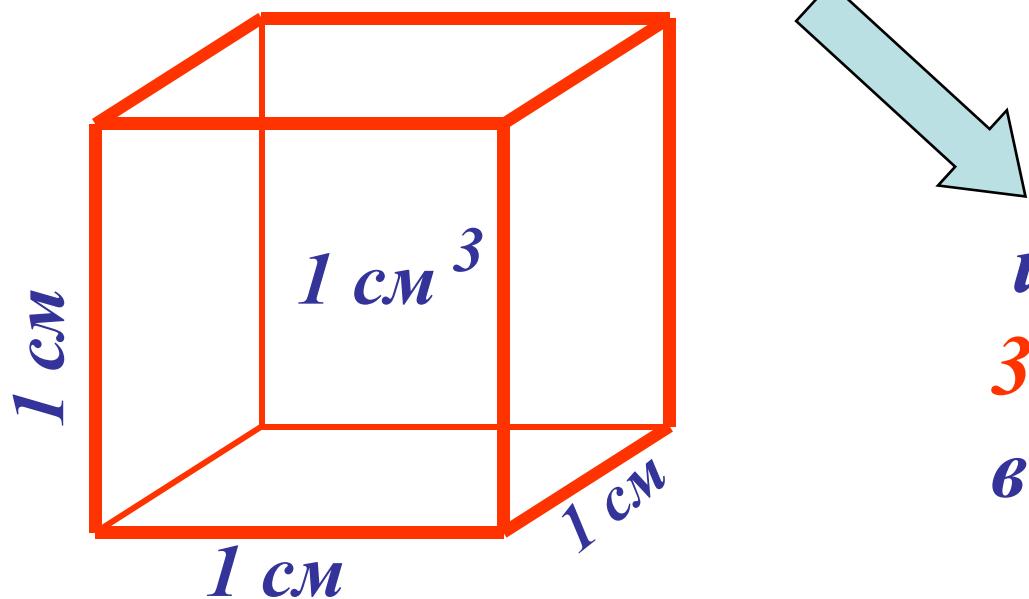
- *процессы на ранней стадии эволюции Вселенной,*
- *остывание звезд,*
- *возникновение и разнообразие химических элементов,*
- *как работает Солнце, дающее энергию для нашего существования на Земле*

*Мы знаем, что
нейтрино было всегда и
присутствует везде*

Спектры энергий потоков нейтрино



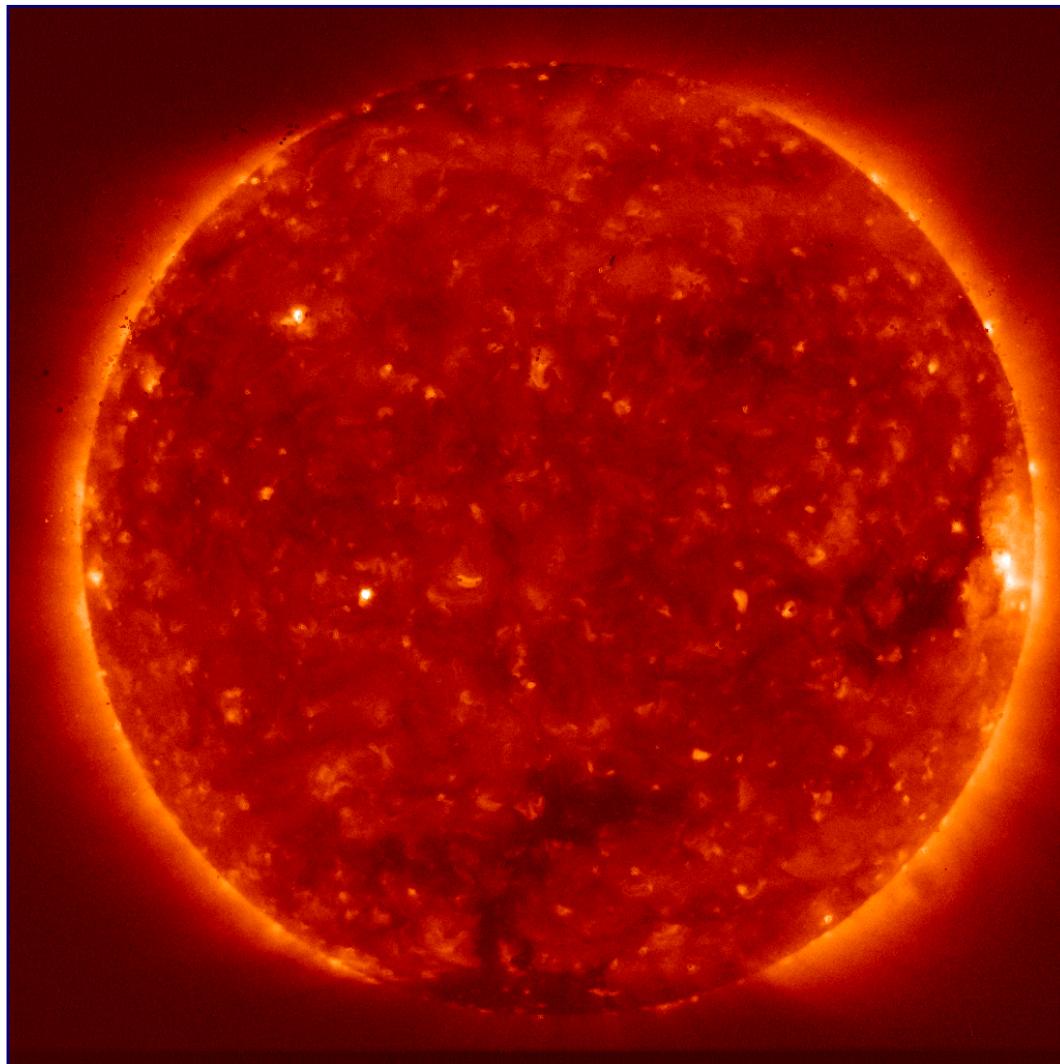
В каждом кубическом сантиметре
- *300 нейтрино*
от Большого взрыва



или
30 000 000 нейтрино
в каждом из нас

ν *вездесущи и неуловимы !*

Солнце – тоже источник нейтрино

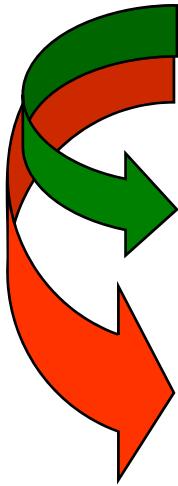


$$R_{\odot} = 7 \cdot 10^8 \text{ м}$$

$$M_{\odot} = 2 \cdot 10^{33} \text{ г/см}^3$$

**Плотность
ядра ($1/4 R_{\odot}$)**

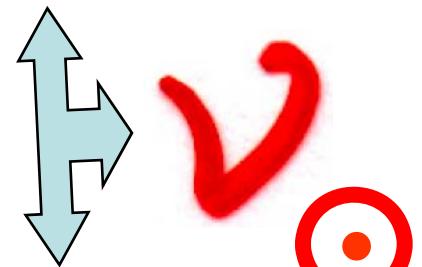
$$\rho = 20-158 \text{ г/см}^3$$



Реакция ядерного синтеза внутри Солнца

генерация тепловой энергии и

интенсивного потока электронных нейтрино:



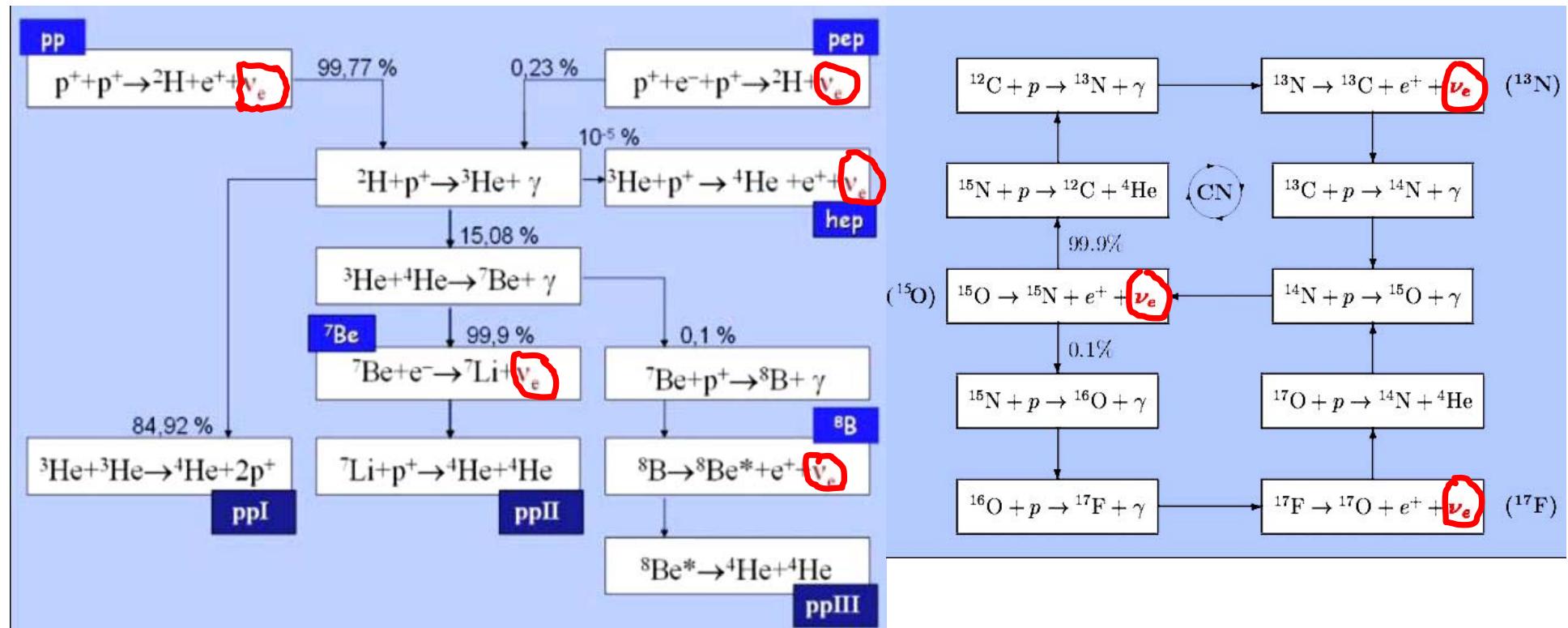
*E_ν – энергия, которую уносят нейтрино,
со средним значением (E_ν) ~ 0.6 МэВ*

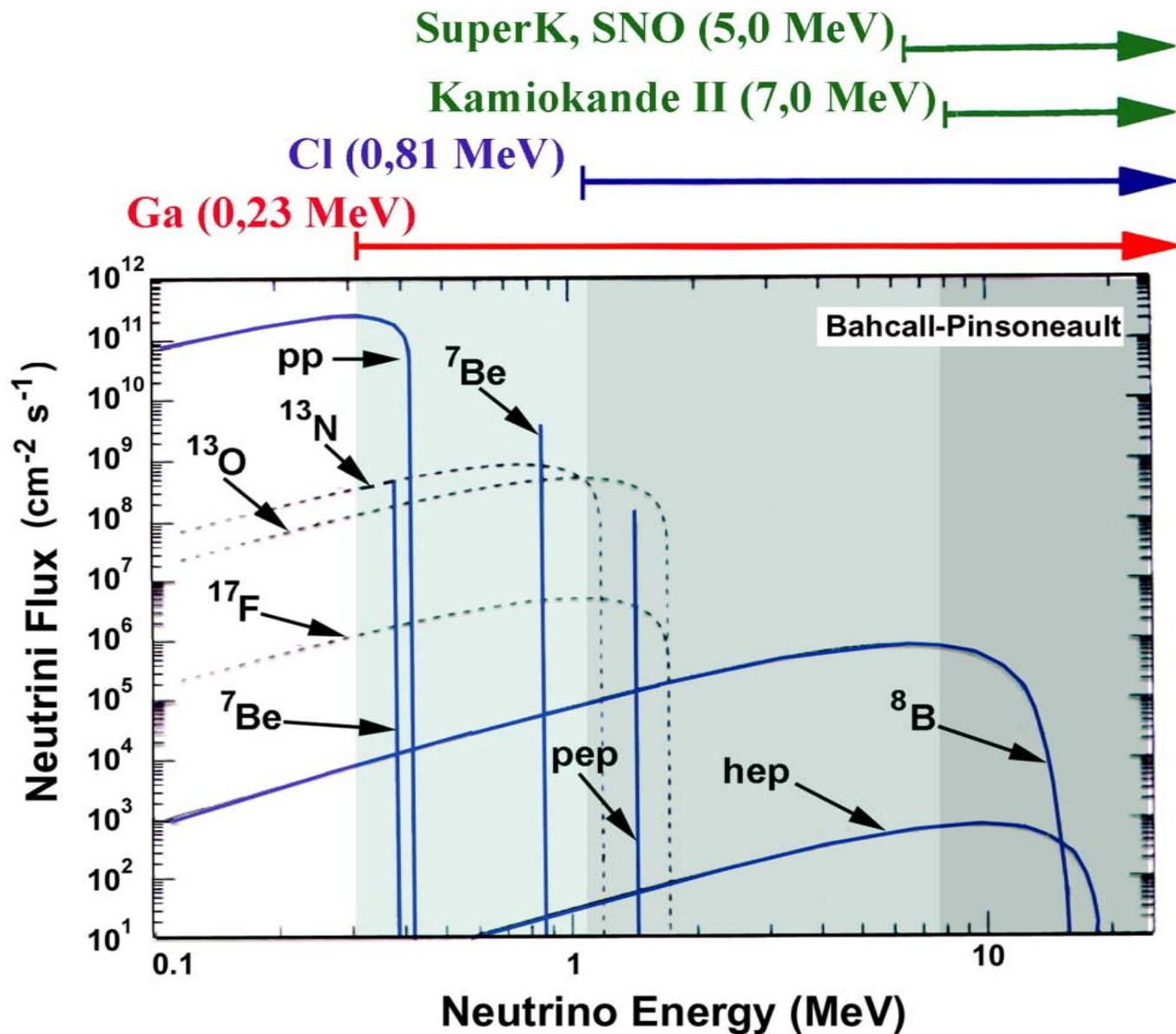


Механизмы генерации энергии и нейтрино в Солнце

pp цепочка реакций (> 99 % энергии)

CNO цикл





ν

«Стандартная
солнечная
модель»



Джон Бакалл
(1934-2005)

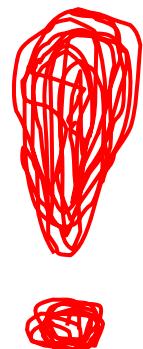
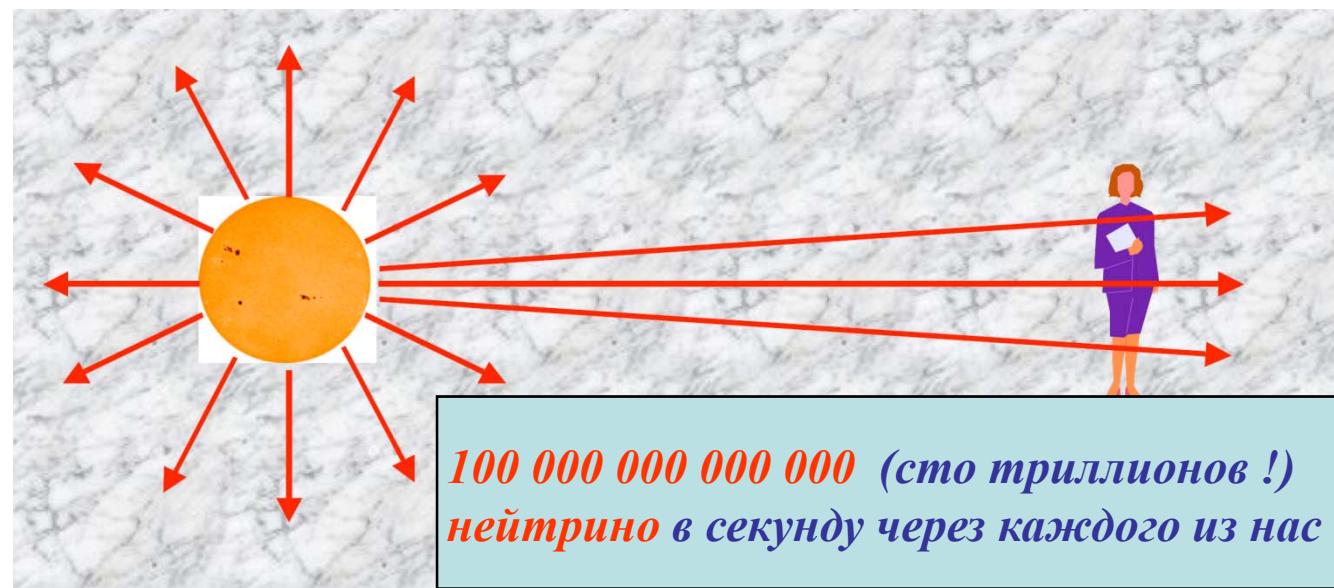
- 1 SNU = 1 interaction/sec in a target that contains 10^{36} atoms of the neutrino absorbing isotope.

Стандартная солнечная модель



*60 000 000 000 нейтрино
через 1 см² на Земле в секунду*

или



Взаимодействие нейтрино с веществом: опасно ли нейтринное проникающее излучение



... наш
обычный
вид ...

для нас ?



... наш
нейтринный
вид
(очень тусклый)...



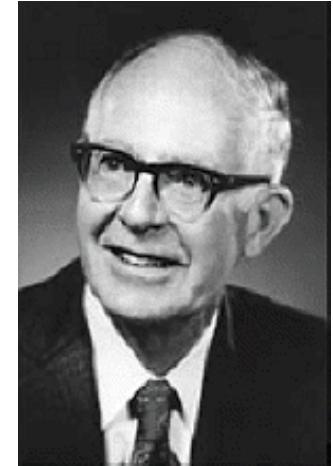
*Практически все солнечные нейтрино
пронизывают нас не причиняя никакого вреда:*

Только один человек (через которого прошло нейтрино) из
 $10\ 000\ 000\ 000\ 000\ 000 = 10^{19}$ почувствует это .

*Вероятность солнечному нейтрино оказаться
воздействие на нас = $1 / 10\ 000\ 000\ 000\ 000\ 000$*



*... нет проблемы с
солнечными нейтрино ?*



Проблемы = парадоксы и сюрпризы :

*Рей Дэвис
(1914-2006)*





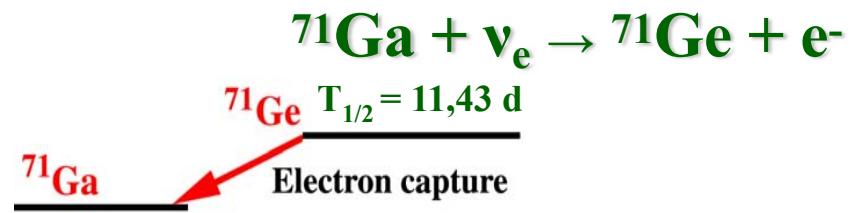
SAGE (ИЯИ РАН)

Баксанская нейтринная обсерватория, Северный Кавказ, 3.5 км от входа в горизонтальный туннель
Глубина заложения 2100 м (4700 м.в.э.)

50 тонн металлического Ga

Атомы ^{71}Ge химически извлекаются и их распад регистрируется в пропорциональных счетчиках.
Чувствительность: один атом ^{71}Ge из $5 \cdot 10^{29}$

атомов Ga с эффективностью ~90%



эксперимент

SAGE : $[pp + ^7\text{Be} + \text{CNO} + pep + ^8\text{B} | \text{Ga}]$

$= 64.6 \pm 3.8 \text{ SNU}$

теория

$127.9^{+8.1}_{-8.2}$

$120.5^{+6.9}_{-7.1}$

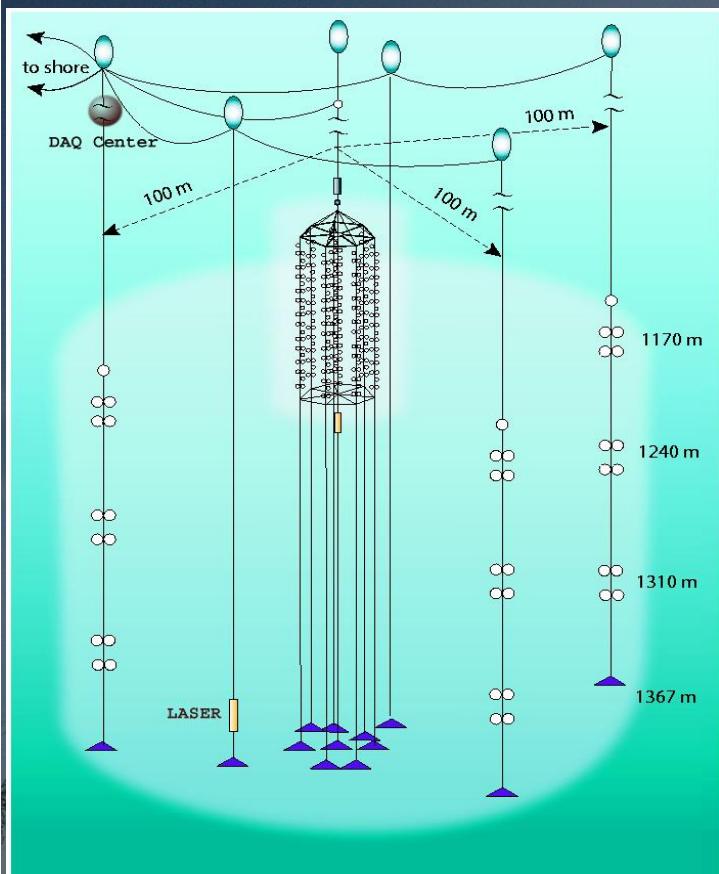
SSM:(Ga)

BPS08(GS)

BPS08(AGS)

Наличие дефицита солнечных нейтрино во всем диапазоне энергии нейтрино!

Байкальская нейтринная обсерватория (ИЯИ РАН)



NT200: 8 strings (192 optical modules)
Height $\times \varnothing = 70\text{m} \times 40\text{m}$, $V_{\text{inst}}=10^5\text{m}^3$
Effective area: $1\text{ TeV} \sim 2000\text{m}^2$
Eff. shower volume: $10\text{ TeV} \sim 0.2\text{ Mton}$

Status of NT200+

NT200+ is operating now in Baikal lake

NT200+ = NT200 + 3 outer stringw (36 optical modules)

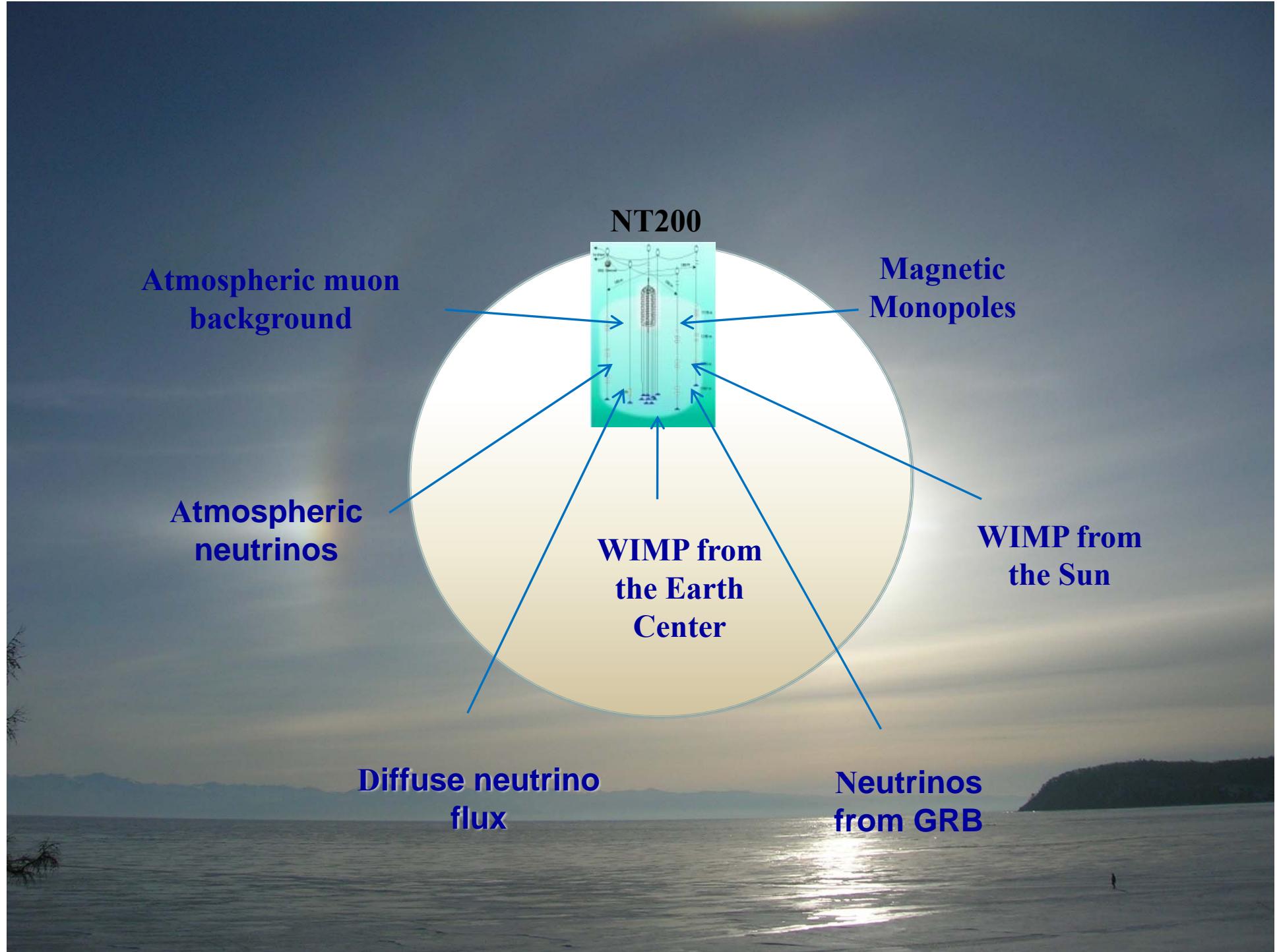
Height $\times \varnothing = 210\text{m} \times 200\text{m}$, $V_{\text{inst}}=4 \times 10^6\text{m}^3$

Eff. shower volume: $10^4\text{ TeV} \sim 10\text{ Mton}$

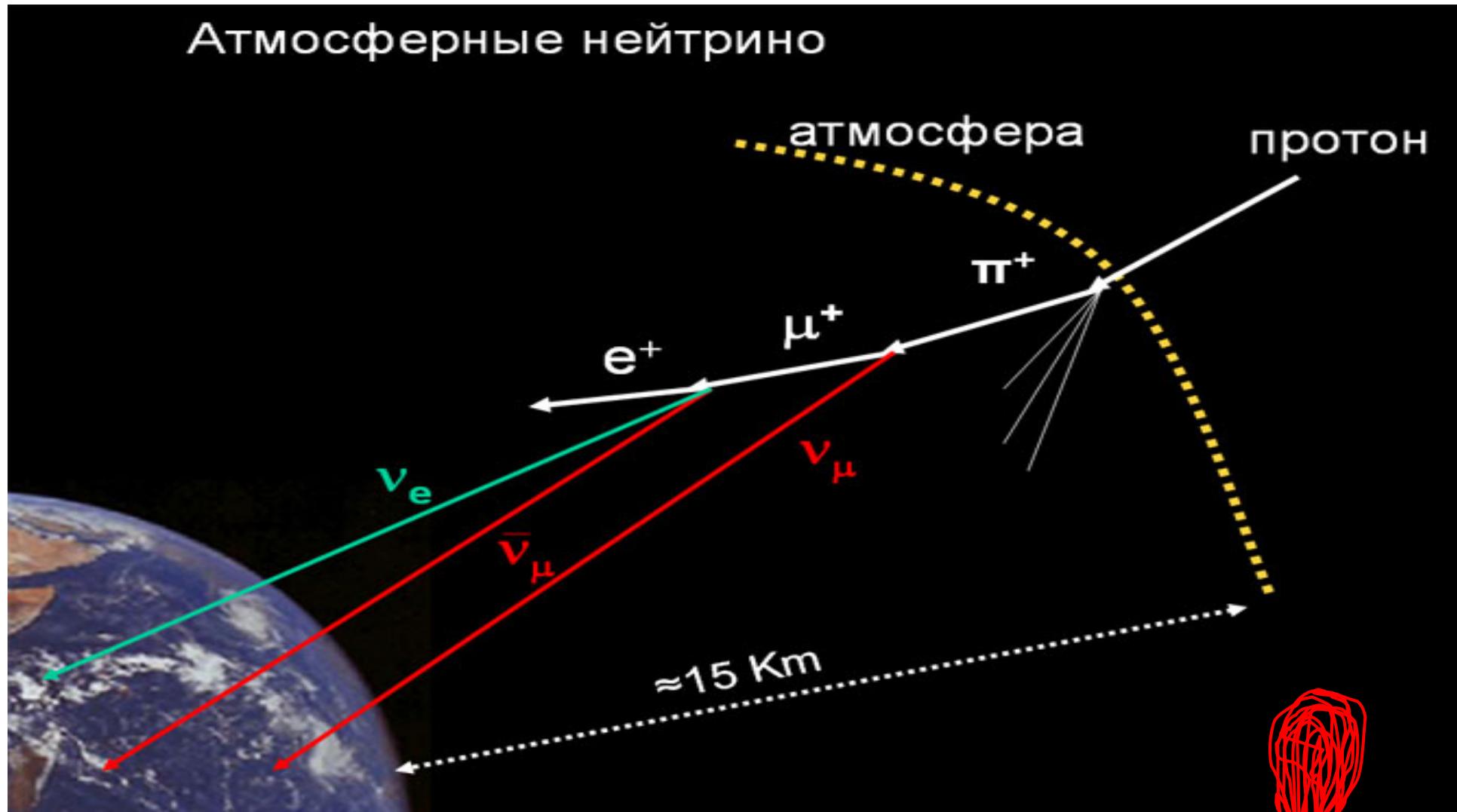
→ ~4 times better sensitivity

→ Improve cascade reconstruction
Quasar

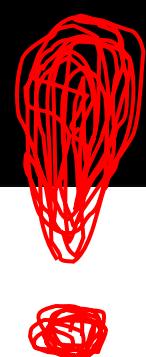
photodetector
($\varnothing=37\text{cm}$)



... Проблема атмосферных нейтрино



$$R = \frac{\text{число } \nu_\mu \text{ в детекторе}}{\text{число } \nu_e \text{ в детекторе}} < 2$$



Решение проблем ...

1.

Нейтрино в природе встречаются разные:

заряженные
лептоны

электрон

e

нейтрино

ν_e электронное нейтрино

мюон

μ

ν_μ мюонное нейтрино

тая-лептон

τ

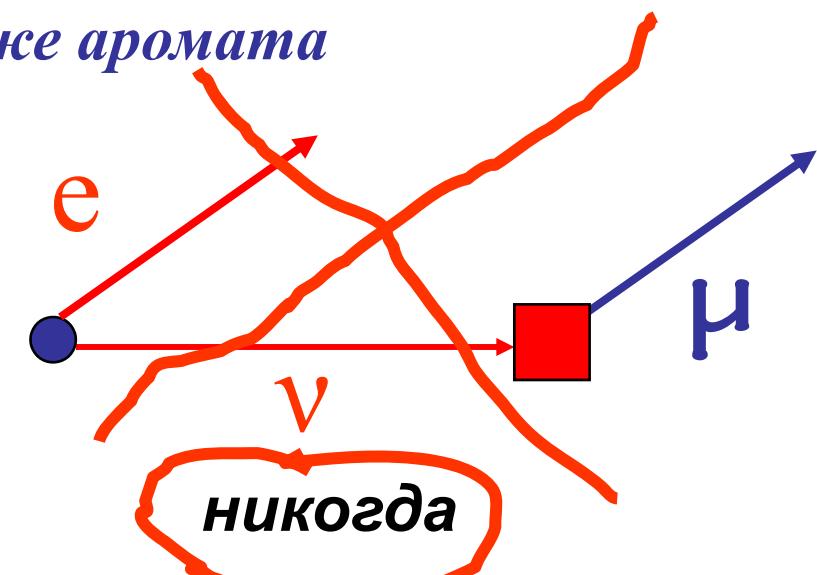
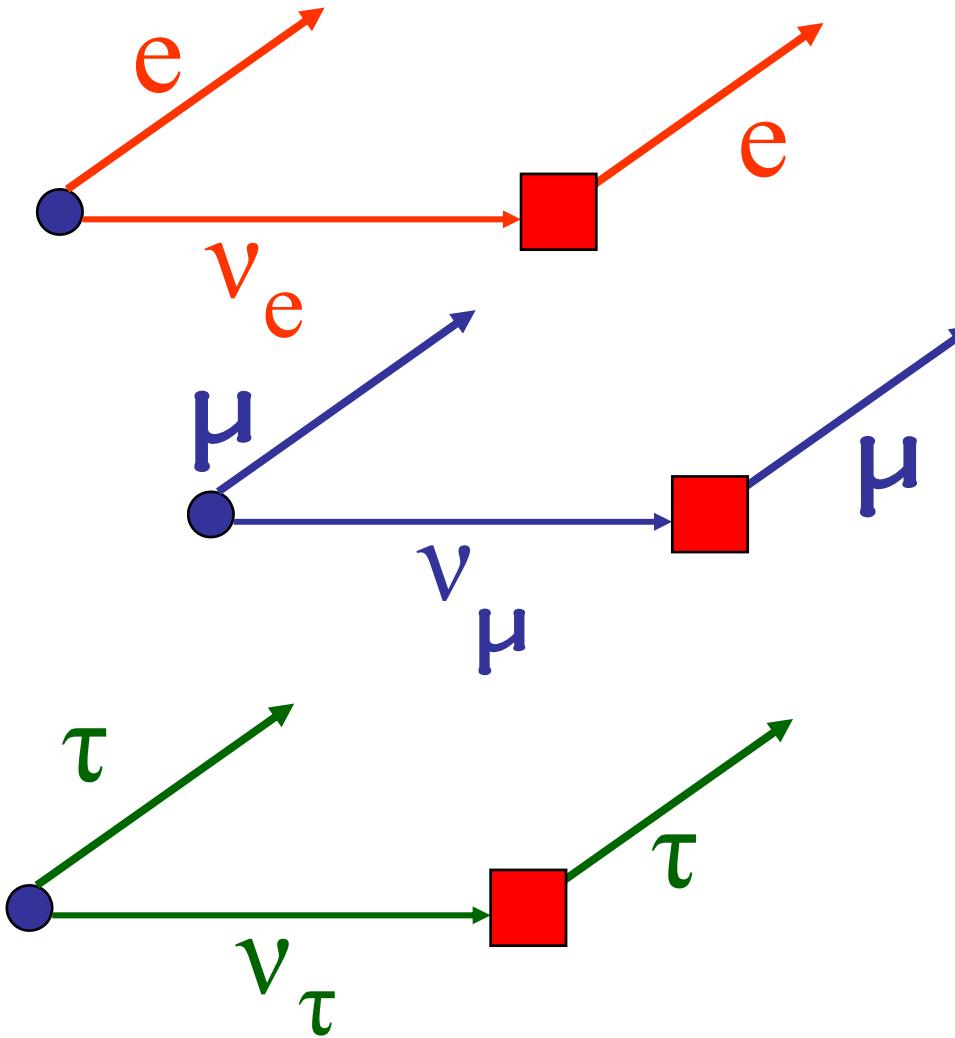
ν_τ тая-нейтрино

Три типа частиц или три типа аромата или флейвора

Решение проблем ...

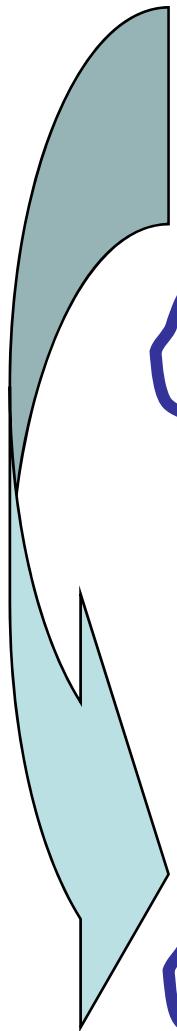
2.

Нейтрино определенного аромата взаимодействуют с заряженным лептоном того же аромата

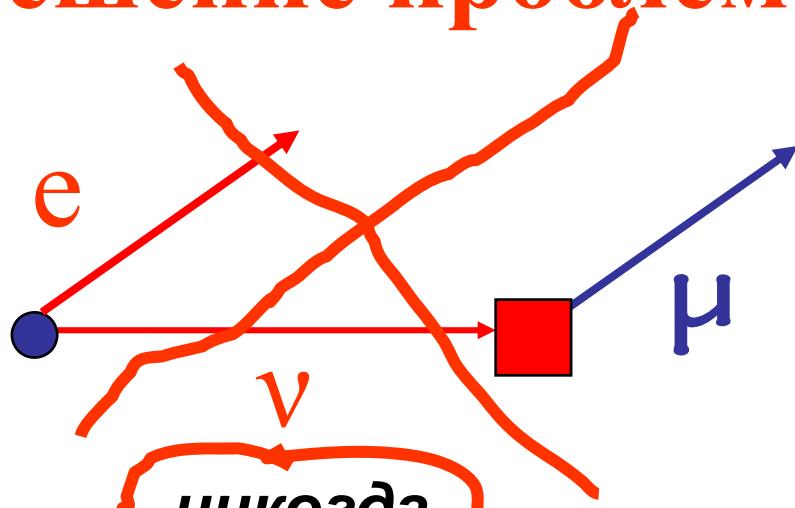


- *источник нейтрино*
- *датчик нейтрино*

Решение проблем ...



3.

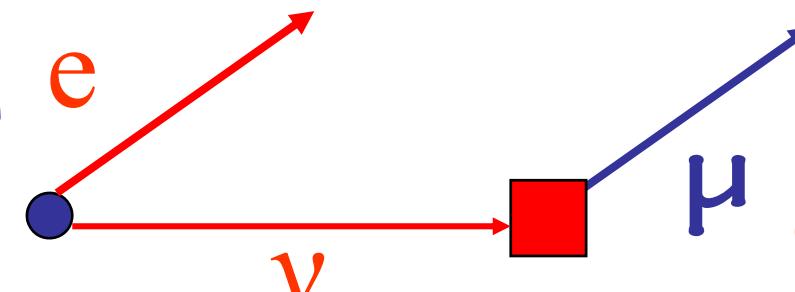


ароматы сохраняются,
ароматы не смешиваются

для малых расстояний
пролёта нейтрино

L/E

4.



ароматы **НЕ** сохраняются,
ароматы **смешиваются**

для больших расстояний
пролёта нейтрино

L/E

Решение проблем ...

5.

Мир элементарных частиц живет по законам квантовой механики

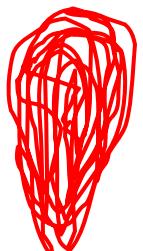


принцип неопределенности:

● *Объект (частица) может находиться здесь, а может там ...*

● *Частица может быть такой, а может – другой ...*

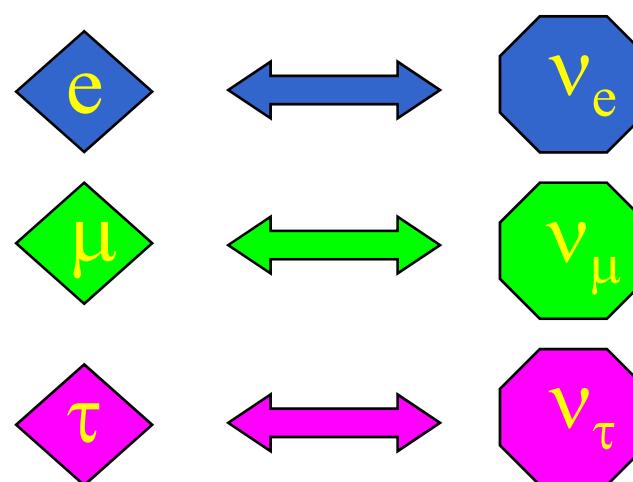
● *Нейтрино может быть ν_e , а может – ν_μ ...*



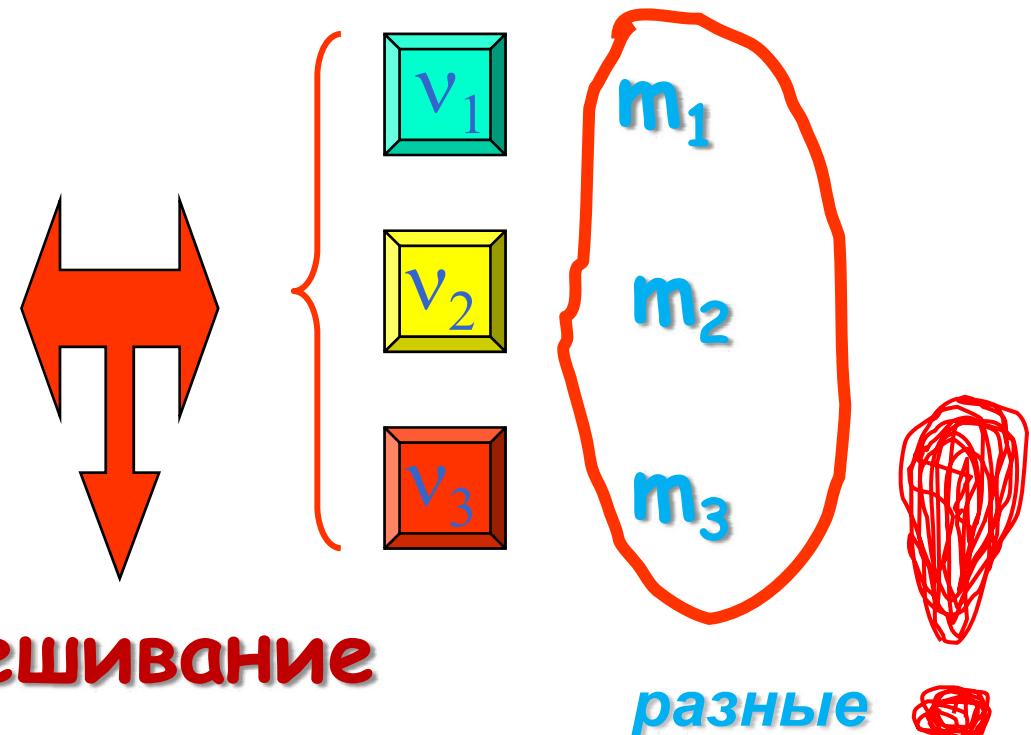
ароматы НЕ сохраняются, ароматы смешиваются ???

Нейтринные состояния

**Собственные состояния
слабых взаимодействий
(заряженные токи)**



**Собственные массовые
состояния**



смешивание

$$|\nu_f\rangle = \sum_i U_{fi} |\nu_i\rangle$$

... впервые о нейтринных осцилляциях...

Bruno Pontecorvo:

neutrino oscillations

(1957)

$$\nu \leftrightarrow \bar{\nu}$$

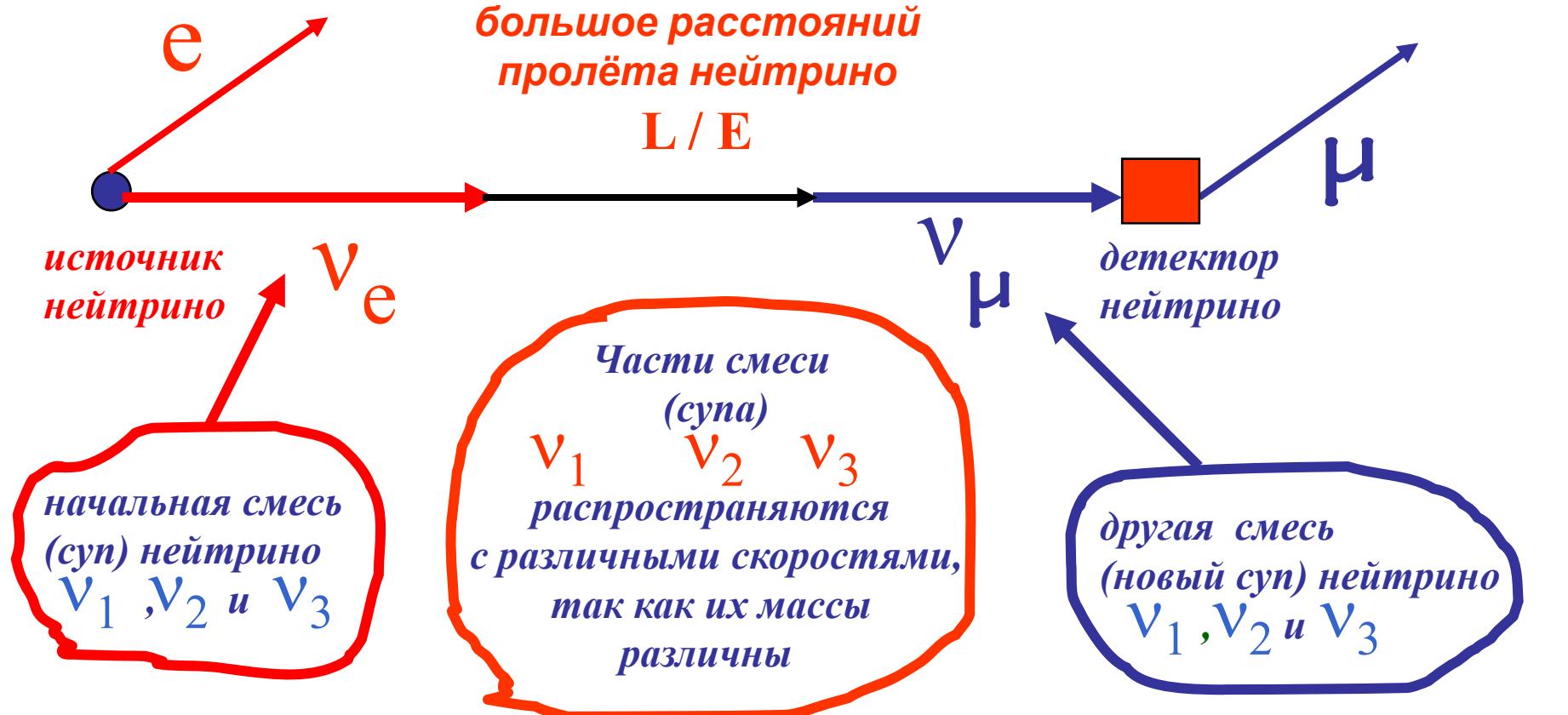
J. Exptl. Theoret. Phys.
34 (1957), p. 549.



Бруно Понтеорво
1913-1993

- С 1950 г. **Бруно Максимович Понтекорво**, выдающийся итальянский физик, жил в Дубне и работал в Объединенном институте ядерных исследований
- **Бруно Понтекорво** возглавлял кафедру Физики элементарных частиц физического факультета МГУ и был членом Ученого совета физического факультета МГУ

Решение проблем ...



Смешивание и осцилляции нейтрино различных типов возможно только если у частицы ненулевая масса

$v \leftrightarrow \bar{v}$
Бруно Понтекорво,
1957

В. Грибов, Б. Понтеорво (1965)

С. Биленкин, Б. Понтеорво (1976)

* Осциляции ν в вакууме

$$\nu \quad \nu^f = \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} \quad \longleftrightarrow \quad \nu^P = \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \quad \nu$$

состояния
взаимодействия

массовые состояния
(m_1, m_2)

$(\pi^+ \rightarrow \mu^+ + \nu_\mu)$
 $n \rightarrow p + e + \bar{\nu}_e$)

$$\nu_e = \nu_1 \cos \theta_\nu + \nu_2 \sin \theta_\nu$$
$$\nu_\mu = -\nu_1 \sin \theta_\nu + \nu_2 \cos \theta_\nu$$

угол смешивания
нейтрино в
вакууме

$$U = \begin{pmatrix} \cos \vartheta & \sin \vartheta \\ -\sin \vartheta & \cos \vartheta \end{pmatrix}$$

$$v_e = v_1 \cos \theta + v_2 \sin \theta$$

$$v_\mu = -v_1 \sin \theta + v_2 \cos \theta$$

угол смешивания
нейтрин в
вакууме
матрица
смешивания

$$U = \begin{pmatrix} \cos \vartheta & \sin \vartheta \\ -\sin \vartheta & \cos \vartheta \end{pmatrix}$$

Эволюция нутка v во времени (пространстве)

$$i \frac{d}{dt} v^P(t) = H v^P(t), \quad H = \begin{pmatrix} E_1 & 0 \\ 0 & E_2 \end{pmatrix}, \quad E_i \approx |\vec{p}_i| + \frac{m_i^2}{2|\vec{p}_i|}$$

V

$$P_{v_e \rightarrow v_\mu} = \sin^2 2\theta \sin^2 \frac{\pi x}{L}$$

путь,
пройденный
нейтрином
энергия
нейтрин

осциляции
нейтрин

амплитуда
осциляций

$$L = \frac{4\pi E}{\Delta m^2}, \quad \Delta m^2 = m_2^2 - m_1^2$$

длина осциляций

Типы экспериментов – детектирование
осциляций по:

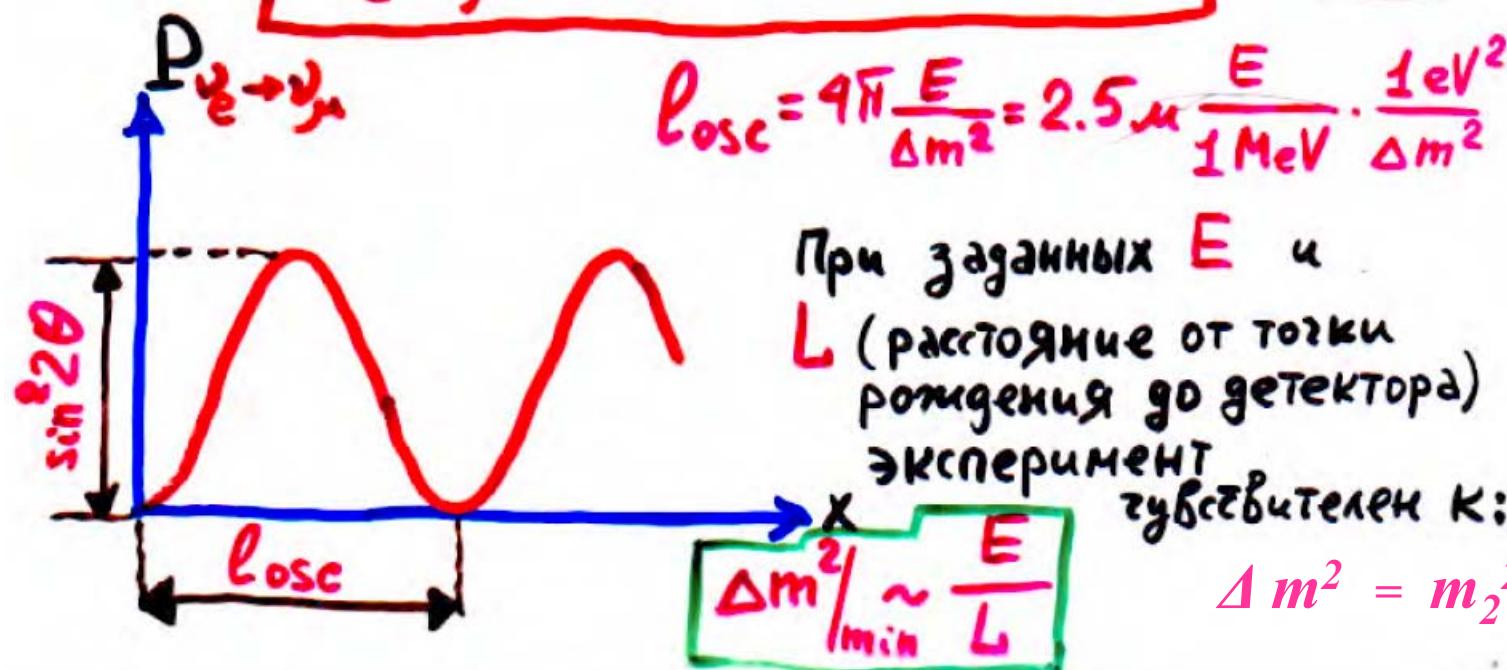
- Возникновению „нового“ флаг-борда ($\nu_e \rightarrow \nu_\mu$)
- исчезновению ν „известного“ флаг-борда ($\nu_e \rightarrow \nu_\mu$).

Вероятность флаг-бордовых осциляций:

$$P_{\nu_e \rightarrow \nu_\mu} = \sin^2 2\theta \cdot \sin^2 \frac{X \Delta m^2}{4E}$$

$$\sin^2 \frac{X \Delta m^2}{4E} \rho_{osc}$$

$$\rho_{osc} = 9\pi \frac{E}{\Delta m^2} = 2.5 \cdot \frac{E}{1 \text{ MeV}} \cdot \frac{1 \text{ eV}^2}{\Delta m^2}$$





Нейтринные состояния

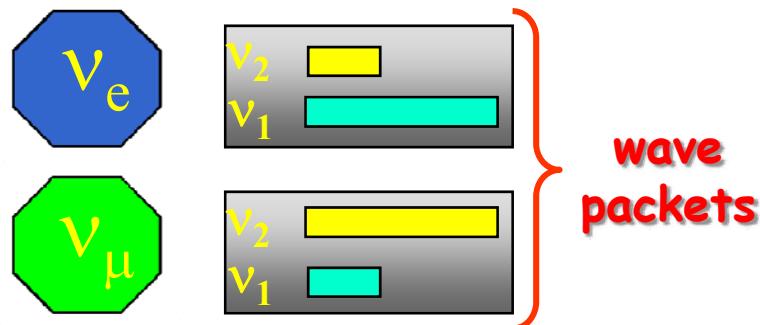
$$2\nu \quad U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

угол смещивания

Когерентная смесь собственных
массовых состояний

$$\nu_e = \cos\theta \nu_1 + \sin\theta \nu_2$$

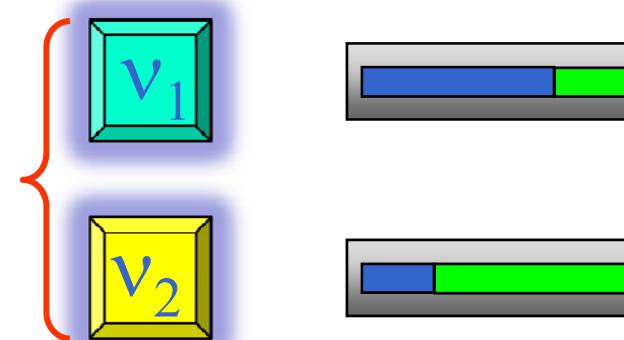
$$\nu_\mu = -\sin\theta \nu_1 + \cos\theta \nu_2$$



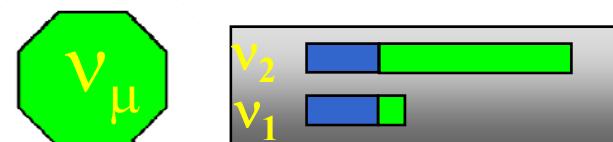
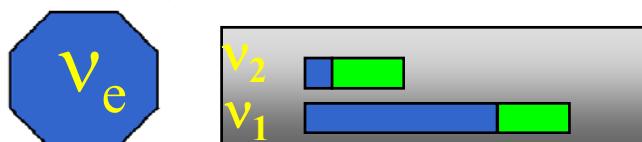
Ароматный состав собственных
массовых состояний

$$\nu_2 = \sin\theta \nu_e + \cos\theta \nu_\mu$$

$$\nu_1 = \cos\theta \nu_e - \sin\theta \nu_\mu$$



«Портрет» нейтрино:



V

mixing and oscillations

3 families

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

atmospheric

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

$$\begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{-i\delta} & 0 & \cos\theta_{13} \end{pmatrix}$$

solar

$$\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

link between atmospheric and solar

U parameterization: three mixing angles θ_{12} θ_{23} θ_{13} and CP violating phase δ

$$\Delta m_{ij}^2 = m_i^2 - m_j^2 \quad \Delta m_{12}^2 + \Delta m_{23}^2 + \Delta m_{31}^2 = 0 \quad \rightarrow \text{two independent } \Delta m^2$$

$$\Delta m_{12}^2 = \Delta m_{sol}^2 \approx 7.5 \times 10^{-5} \text{ eV}^2 \quad \Delta m_{23}^2 \approx \Delta m_{31}^2 = \Delta m_{atm}^2 \approx 2.4 \times 10^{-3} \text{ eV}^2$$

$$\theta_{12} \sim 34^\circ \quad \theta_{23} \sim 45^\circ$$

?? θ_{13} , mass hierarchy, δ ??

Осилиляции нейтрино в веществе

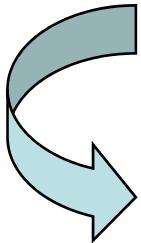
● Распространение ν в веществе ($\nu_0, \nu_{NS\dots}$)

... аналогия с фотоном:

- ① vacuum \rightarrow закон дисперсии $E_\gamma = |\vec{p}|, v_\gamma = c,$
- ② matter $\rightarrow m_\gamma^{\text{eff}} \neq 0, v_\gamma < c.$

\Rightarrow взаимодействие с веществом изменяет закон дисперсии \Rightarrow изменяется гамильтониан системы \Rightarrow изменяется временная эволюция нейтриноного пучка

L. Wolfenstein, 1978

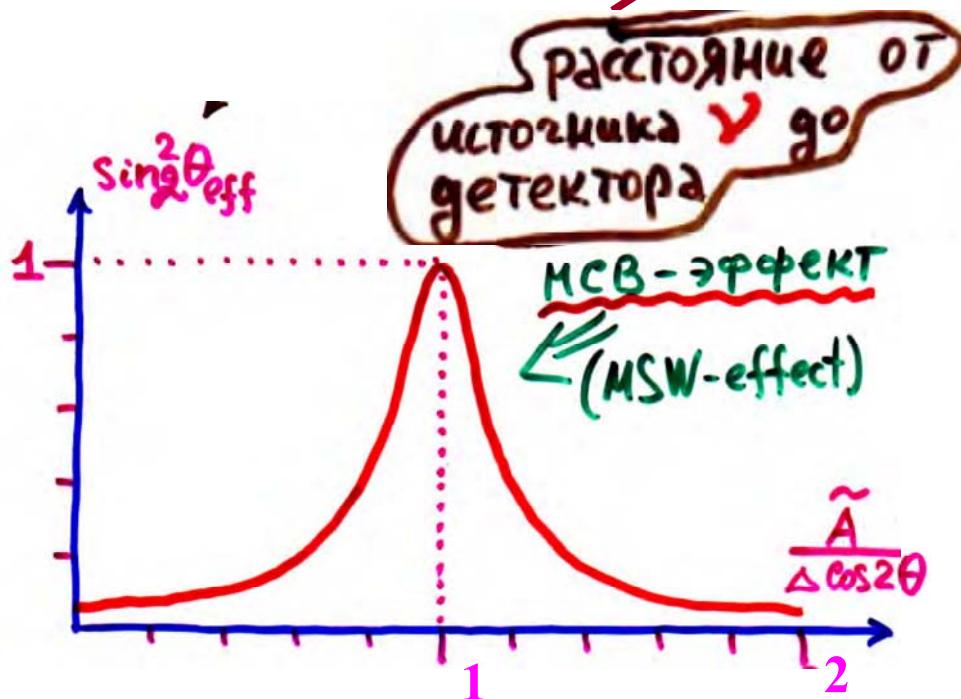


Резонансное усиления осцилляций ν в веществе

эффект Михеева-Смирнова-Вольфенштейна, 1985

*Флайворные осцилляции
в покоящейся среде:*

$$P(\nu_e \rightarrow \nu_\mu) = \sin^2 2\theta_{eff} \sin^2 \left(\frac{\pi x}{L_{eff}} \right),$$



$$\nu_e = \nu_1 \cos \theta + \nu_2 \sin \theta, \\ \nu_\mu = -\nu_1 \sin \theta + \nu_2 \cos \theta,$$

$$\sin^2 2\theta_{eff} = \frac{\Delta^2 \sin^2 2\theta}{(\Delta \cos 2\theta - A)^2 + \Delta^2 \sin^2 2\theta},$$

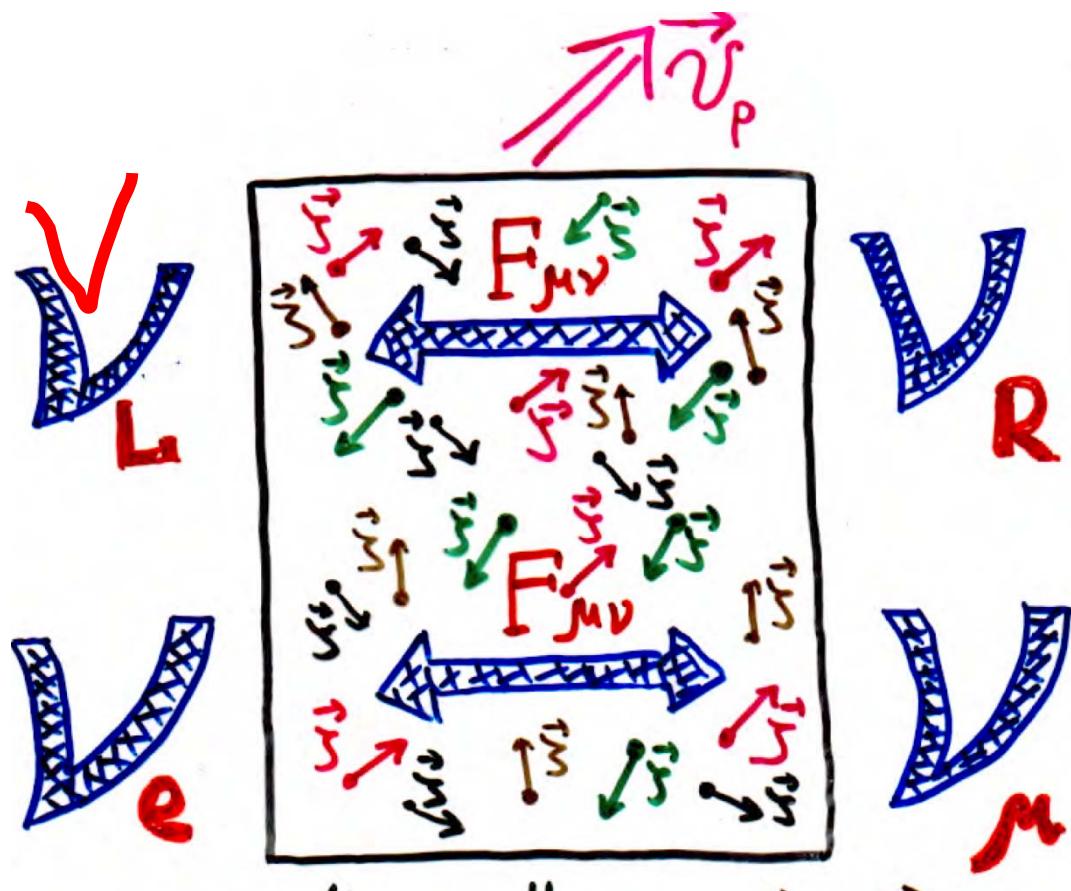
...резонанс...

$$\Delta \cos 2\theta = A$$

$$\Delta = \delta m_\nu^2 / 2E$$

плотность вещества

$$A = \sqrt{2} G_F n_{eff}, \quad n_{eff} = n_e$$



moving matter components

$f = e, n, p, \mu, \text{etc}$
with polarizations
 $\vec{s}, \vec{s}, \vec{s}, \vec{s}, \text{etc}$

V oscillations in strong magnetic field and moving matter

G.Likhachev,
A.Studenikin,
JETP 81 (1995) 419

A.Egorov, A.Lobanov,
A.Studenikin,
Phys.Lett.B 491 (2000) 137

A.Lobanov, A.Studenikin,
Phys.Lett.B 515 (2001) 94

A.Lobanov, A.Grigoriev,
A.Studenikin,
Phys.Lett.B 535 (2002) 187

Unpolarized but moving matter ($\vec{\zeta}_e = 0, \vec{v}_e \neq 0$)

MSW effect

Resonance condition:

- $$\frac{sm_\nu^2}{2|\vec{p}|} \cos 2\theta = \sqrt{2} G_F n_e^{(0)} \frac{1 - \beta_\nu \vec{v}_e}{\sqrt{1 - v_e^2}}$$

invariant matter density in r.f.

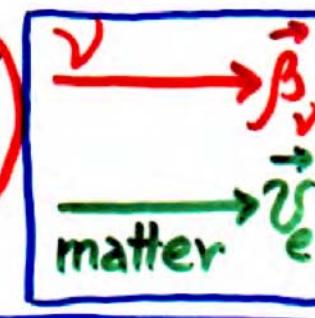
If

$$\begin{array}{c} \leftrightarrow \\ \vec{\beta}_\nu \\ \leftrightarrow \\ \vec{v}_e \end{array} :$$

- $$\left| \frac{1 - \beta_\nu \vec{v}_e}{\sqrt{1 - v_e^2}} \right|$$

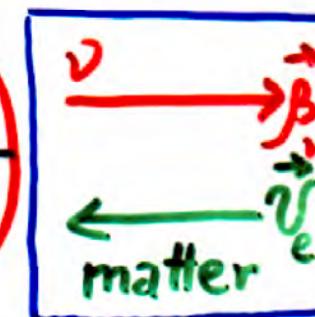
$$= \left| \frac{\sqrt{\frac{1 - v_e}{1 + v_e}}}{\sqrt{1 - v_e^2}} \right| \approx \frac{\sqrt{1 - v_e}}{\sqrt{2}}$$

$$\beta_\nu \approx 1$$



$$\left| \frac{\sqrt{\frac{1 + v_e}{1 - v_e}}}{\sqrt{1 - v_e^2}} \right| \approx \frac{\sqrt{2}}{\sqrt{1 - v_e}}$$

$$v_e \approx 1$$



G.Likhachev,
A.Studenikin,
(1995)

A.Lobanov,
A.Grigoriev,
A.Studenikin:

«Effect of matter motion and polarization in neutrino flavour oscillations»,

Phys.Lett.B 535
(2002) 187

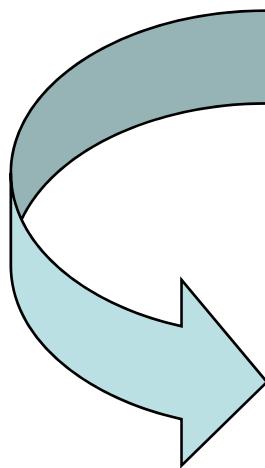
{ Relativistic motion of matter along (against) neutrino propagation could provide resonance in $\nu \leftrightarrow \nu$ if matter density $n_e^{(0)}$ is too high (low) for resonance appearance in non-moving matter.
 in restframe of matter

★ Resonance condition in Lorentz invariant form :

A.S., Phys.Atom.Nucl.2004

$$\boxed{\Delta \cos 2\theta = \sqrt{2}G_F n_0 p_\mu u^\mu}, \quad \Delta = \delta m_\nu^2 / 2E,$$

$$p_\mu = m\gamma(1, \beta), \quad u_\mu = \gamma_e(1, \mathbf{v}_e), \quad \gamma_e = (1 - v_e^2)^{1/2}$$



История нейтрино



познание фундаментальных
законов природы

"Новая физика" (экспериментальные
указания на $m_\nu \neq 0$
смещивание ν)



Т.е., осциляции нейтрино
существуют

$$m_v \neq 0$$

Neutrino mass



$m_\nu \neq 0 !$

Neutrino magnetic moment

$\mu_\nu \neq 0$

* { Lee Shrock } 1977
{ Fujikawa } 1980

... Massive neutrino electromagnetic properties ...

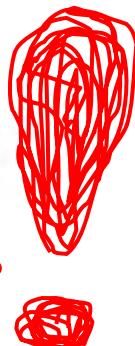


Theory (Standard Model with ν_R)

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

Lee Fujikawa
Shrock, 1977; Shrock, 1980

In the Standard Model : $m_{\nu} = 0$,
there is no $\nu_R \Rightarrow$
 ν magnetic moment $\mu_{\nu} = 0$.
Thus, $\mu_{\nu} \neq 0 \rightarrow$ beyond the SM.



$m_\nu \neq 0$

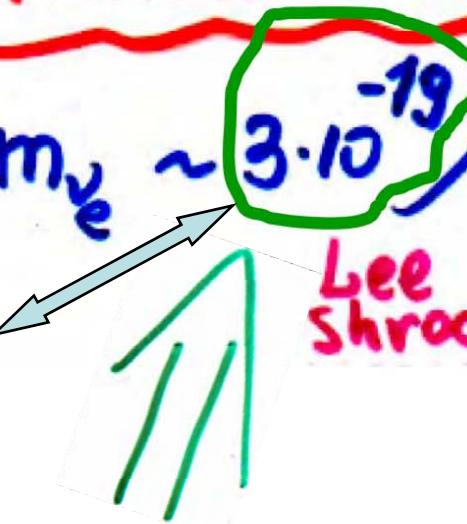
*... beyond
Standard Model*

Theory (Standard Model) with ν_R

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

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

anomalous
magnetic
moment of
electron



$3 \cdot 10^{-19} \mu_B \left(\frac{m_\nu}{3\text{eV}} \right)$,
Lee Shrock, 1977; Fujikawa Shrock, 1980

*... much greater values are desired
for astrophysical or cosmology*

visualization of μ_ν

Astrophysical bounds

$$\mu_\nu \leq 3 \cdot 10^{-12} M_B$$

(Red Giant lumin.)
etc.

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

Theory (Standard Model with ν_R)

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

Lee Shrock, 1977; Fujikawa Shrock, 1980

3

*... a bit of **V** electromagnetic
properties theory*

3.1

V

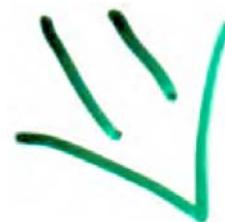
vertex function

The most general study of the
massive neutrino vertex function

(including electric and magnetic
form factors) in arbitrary R₅ gauge

in the context of the SM + SU(2)-singlet

γ_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 (2009), N8, 1

* "Electromagnetic form factors of a massive neutrino."

The diagram shows a blue sphere with a grid pattern, representing a massive neutrino. Four arrows point from the text labels below to specific parts of the sphere:

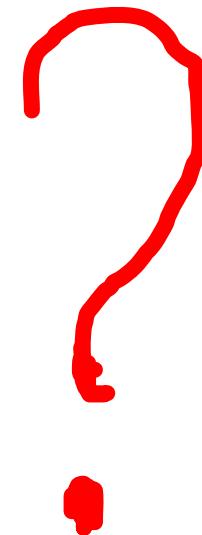
- A pink arrow labeled "charge" points to the top left of the sphere.
- A green arrow labeled "magnetic moment" points to the bottom right of the sphere.
- A green arrow labeled "electric moment" points to the bottom left of the sphere.
- A green arrow labeled "anapole moment" points to the bottom right of the sphere.

At the top right, there is a red wavy line labeled "R-gauge" and "and" above it, followed by "(q² ≠ 0)" in red.

$$\Delta_\mu(q) = \underbrace{f_Q(q^2)\gamma_\mu}_{\text{charge}} + \underbrace{f_M(q^2)i\sigma_{\mu\nu}q^\nu}_{\text{magnetic moment}} - \underbrace{f_E(q^2)i\sigma_{\mu\nu}q^\nu\gamma_5}_{\text{electric moment}} - \underbrace{f_A(q^2)(q^2\gamma_\mu - q_\mu\gamma)}_{\text{anapole moment}}\gamma_5$$

Magnetic moment dependence

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



on neutrino mass



$$m_\nu \ll m_e \ll M_W$$

light ν

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

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

Dvornikov,
Studenikin,

Phys.Rev.D 69
(2004) 073001;

JETP 99 (2004) 254



$$m_e \ll m_\nu \ll M_W$$

intermediate ν

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

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



$$m_e \ll M_W \ll m_\nu$$

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

heavy ν
 $\sim 10^{-19} \mu_e \left(\frac{m_\nu}{1\text{eV}}\right)$

... подробно об электромагнитных свойствах ✓

1

Carlo Giunti, Alexander Studenikin :
“Neutrino electromagnetic properties”
Phys.Atom.Nucl. 73, 2089-2125 (2009)
arXiv:0812.3646 v5, Apr 12, 2010

... within the agreement
on cooperation between
Moscow University and
Instituto Nazionale di
Fisica Nucleare (INFN)

2

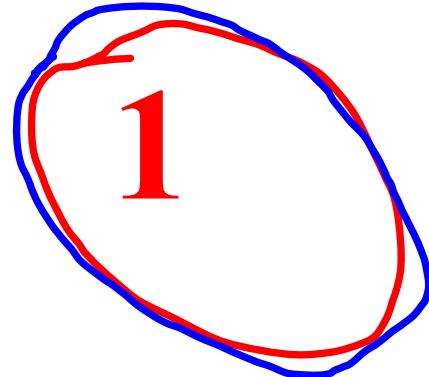
A.Studenikin :
“Neutrino magnetic moment: a window to new physics”
Nucl.Phys.B (Proc.Supl.) 188, 220 (2009)

3

C. Giunti, A. Studenikin :
“Electromagnetic properties of neutrinos”
J.Phys.: Conf.Series. 203 (2010) 012100
arXiv:1006.1502 June 8, 2010

4

C.Giunti, A.Studenikin : “Theory and phenomenology
of neutrino electromagnetic properties”
to appear in *Rev.Mod.Phys.*



v magnetic moment in experiments

Samuel Ting

(wrote on the wall at Department of Theoretical Physics of Moscow State University) :

“Physics is an experimental science”

GEMMA (2005-2008)

Germanium Experiment on measurement of Magnetic Moment of Antineutrino



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

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



... till 13 January 2010 and again since 23 August 2010
best limit on ν magnetic moment

A.Beda et al, Phys.Part.Nucl.Lett. 7 (2010) 406
result known since 2009:

A.Beda, E.Demidova, A.Starostin et al,
arXiv:09.06.1926, June 10, 2009,

A.Beda, V.Brudanin, E.Demidova et al,
in: "Particle Physics on the Eve of LHC",
ed. A.Studenikin, World Scientific (Singapore),
p.112, 2009 (13th Lomonosov Conference) www.icas.ru

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

Cross-section:

$$\bullet \quad \frac{d\sigma}{dT}(\nu + e \rightarrow \nu + e) = \left(\frac{d\sigma}{dT} \right)_{\text{SM}} + \left(\frac{d\sigma}{dT} \right)_{\mu_\nu},$$



where the Standard Model contribution

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

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

T is the electron recoil energy

$$0 \leq T \leq \frac{2E_\nu^2}{2E_\nu + m_e},$$

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

for anti-neutrinos

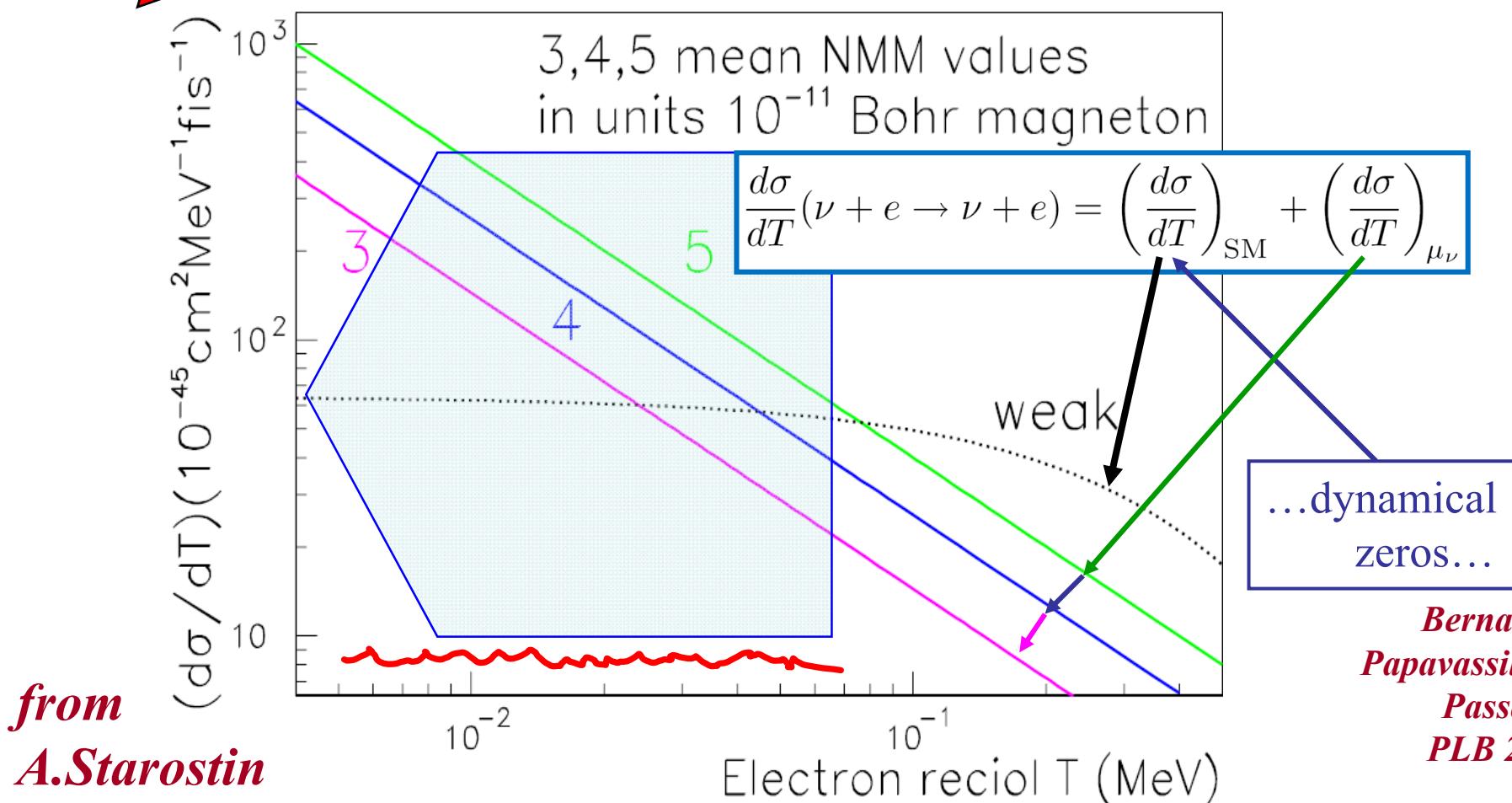
$$g_A \rightarrow -g_A$$

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

Magnetic moment contribution is dominated at low electron recoil energies

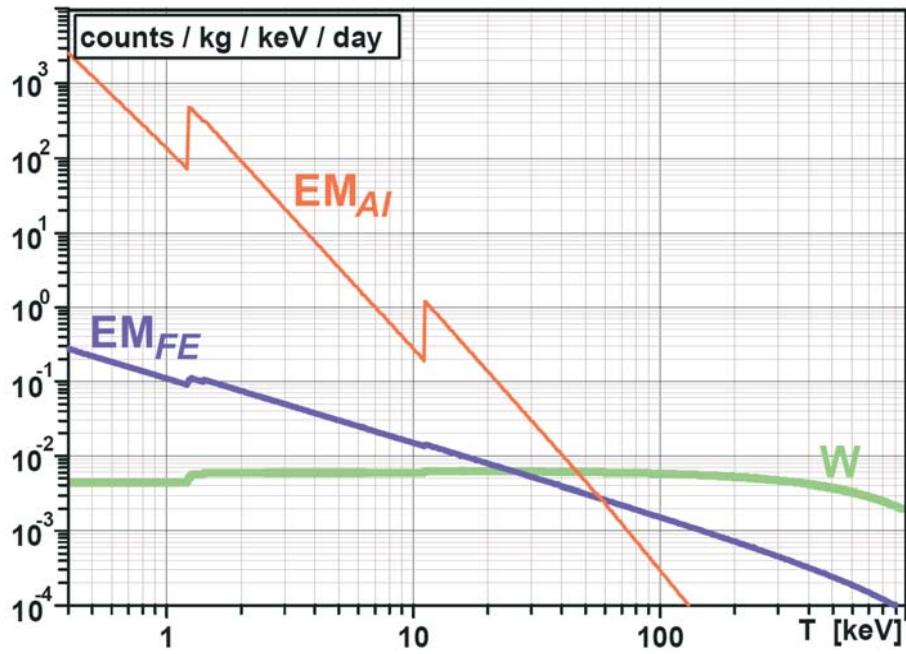
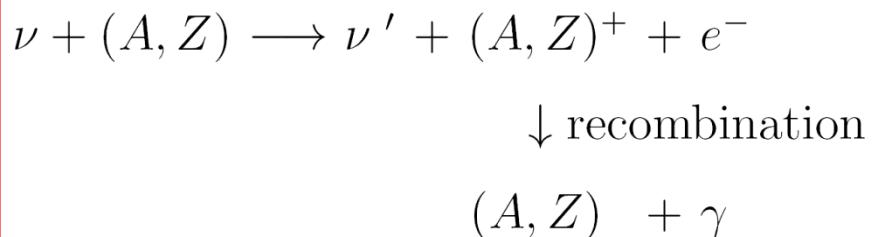
and $\left(\frac{d\sigma}{dT}\right)_{\mu_\nu} > \left(\frac{d\sigma}{dT}\right)_{SM}$ when $\frac{T}{m_e} < \frac{\pi^2 \alpha_{em}}{G_F^2 m_e^4} \mu_\nu^2$

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



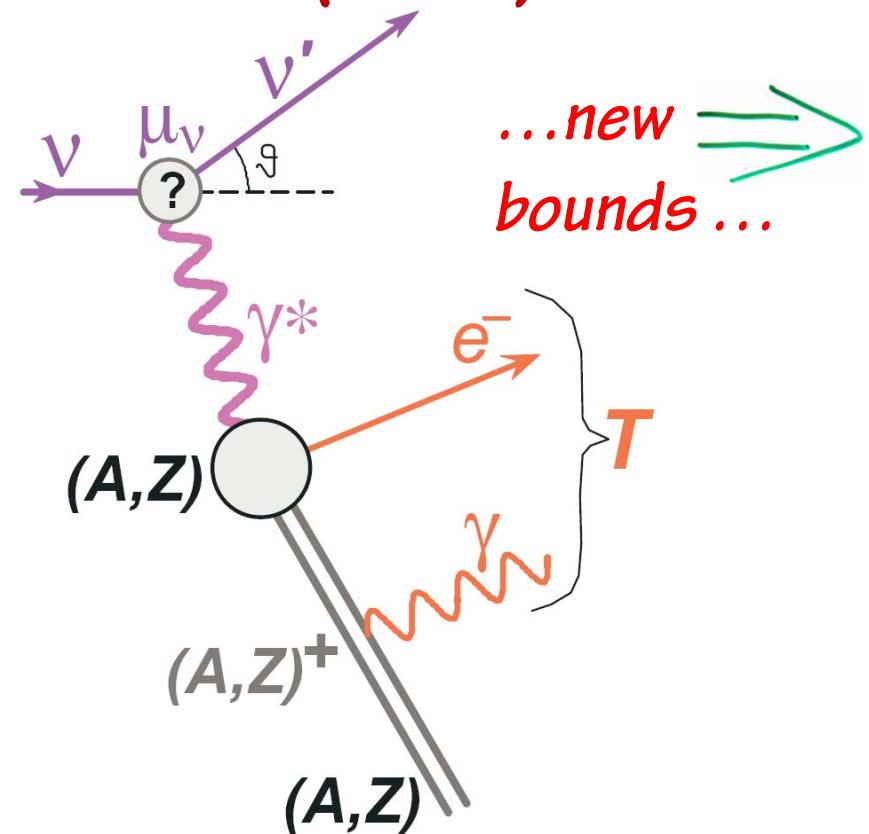
... quite recent claim
that ν -e cross section
should be increased by ?

Atomic ionization effect:

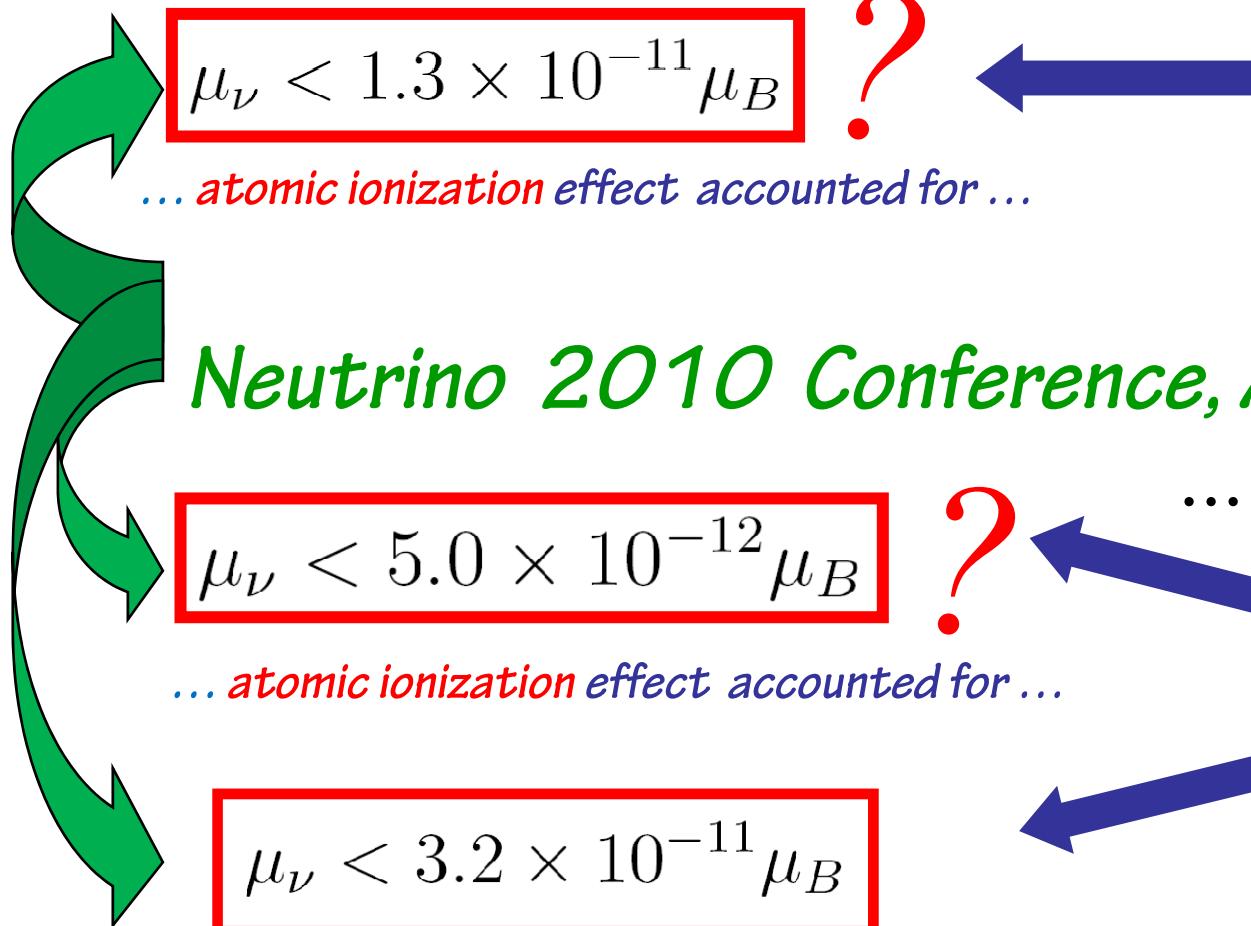


H.Wong et al. (TEXONO Coll.), arXiv:
1001.2074,
13 Jan 2010,
reported at

Neutrino 2010 Conference
(Athens, June 2010),
PRL 105 (2010) 061801



...much better limits on ν effective magnetic moment ...



Neutrino 2010 Conference, Athens

H.Wong et al.,
(*TEXONO Coll.*),
arXiv: 1001.2074,
13 Jan 2010,
PRL 105 (2010)
061801

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

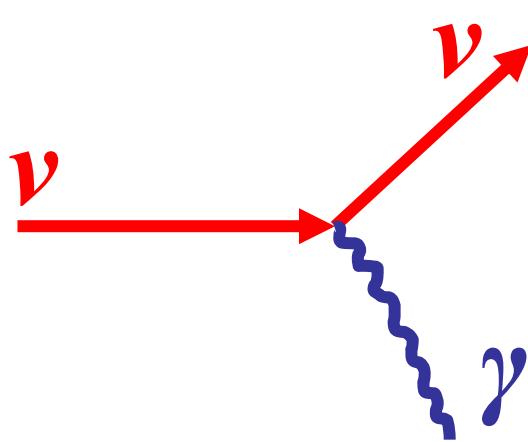
*... ν -e scattering on free electrons ...
(without atomic ionization)*

- K.Kouzakov, A.Studenikin,
- “Magnetic neutrino scattering on atomic electrons revisited” ●
Phys.Lett. B 105 (2011) 061801, arXiv: 1011.5847
 - “Electromagnetic neutrino-atom collisions: The role of electron binding”
to appear in **Nucl.Phys.B (Proc.Suppl.) 217 (2011) 353**
arXiv: 1108.2872, 14 Aug 2011

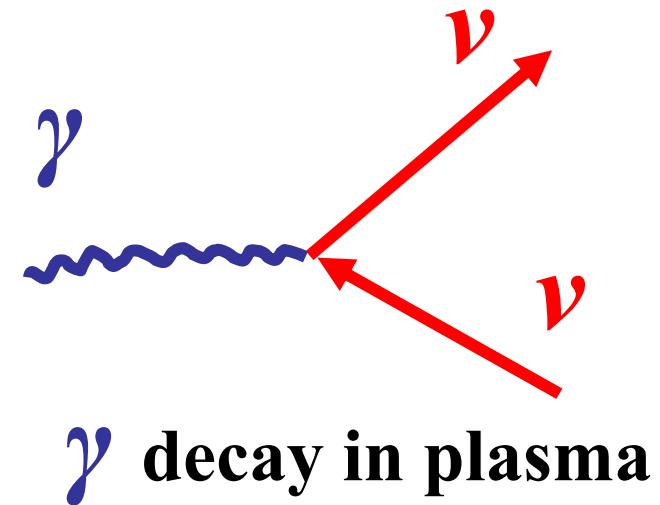
- K.Kouzakov, A.Studenikin, M.Voloshin,
- “Neutrino-impact ionization of atoms in search for neutrino magnetic moment”, arXiv: 1101.4878, 25 Jan 2011
Phys.Rev.D 83 (2011) 113001
 - “On neutrino-atom scattering in searches for neutrino magnetic moments” arXiv: 1102.0643, 3 Feb 2011
Nucl.Phys.B (Proc.Supp.) 2011 (Proc. of Neutrino 2010 Conference)
 - “Testing neutrino magnetic moment in ionization of atoms by neutrino impact”, arXiv: 1105.5543, 27 May 2011
JETP Lett. 93 (2011) 699

- M.Voloshin,
- “Neutrino scattering on atomic electrons in search for neutrino magnetic moment”
Phys.Rev.Lett. 105 (2010) 201801, arXiv: 1008.2171

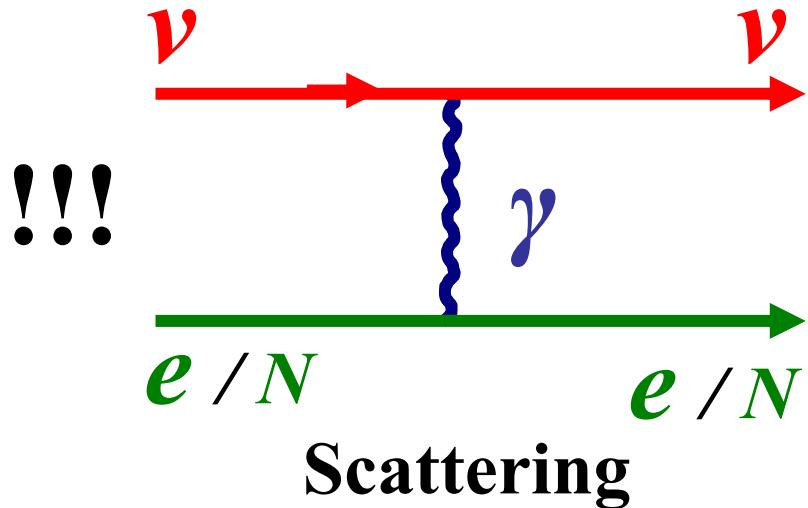
Neutrino–photon couplings



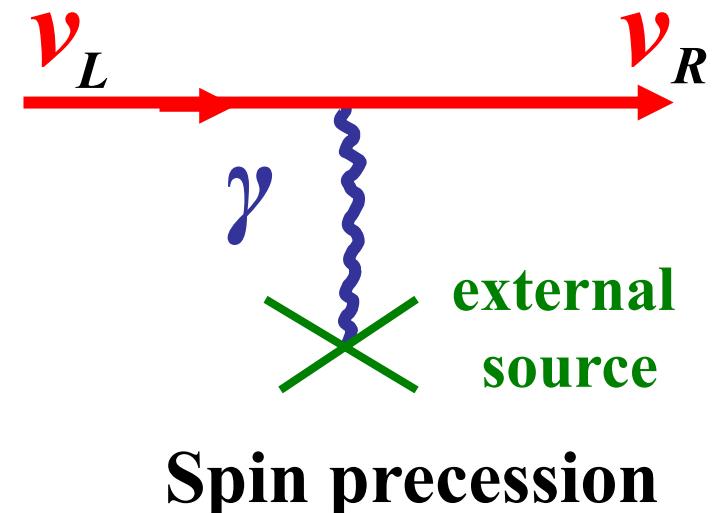
ν decay, Cherenkov radiation



γ decay in plasma



Scattering



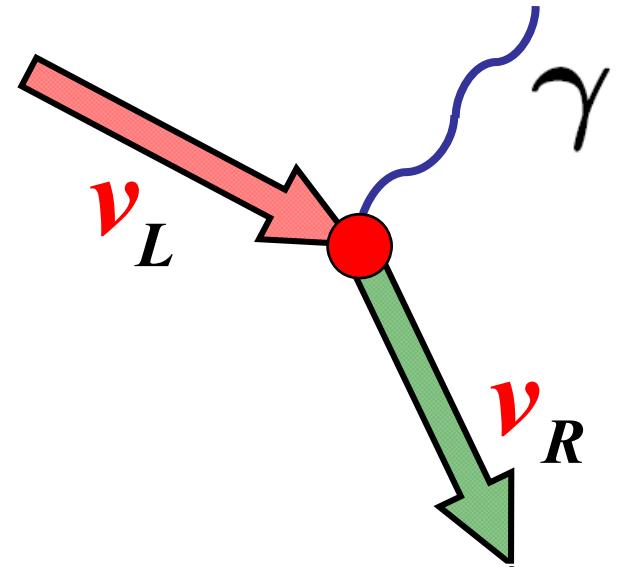
Spin precession

New mechanism of electromagnetic radiation



Spin Light of Neutrino
спиновый свет нейтрино

$SL\nu$



Spin light of neutrino

- *new mechanism of the electromagnetic process stimulated by the presence of background environment, in which neutrino with nonzero magnetic moment emits light*

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

Phys.Lett. B 601 (2004) 171

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

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

A.S., J.Phys.A: Math.Gen. 39 (2006) 6769

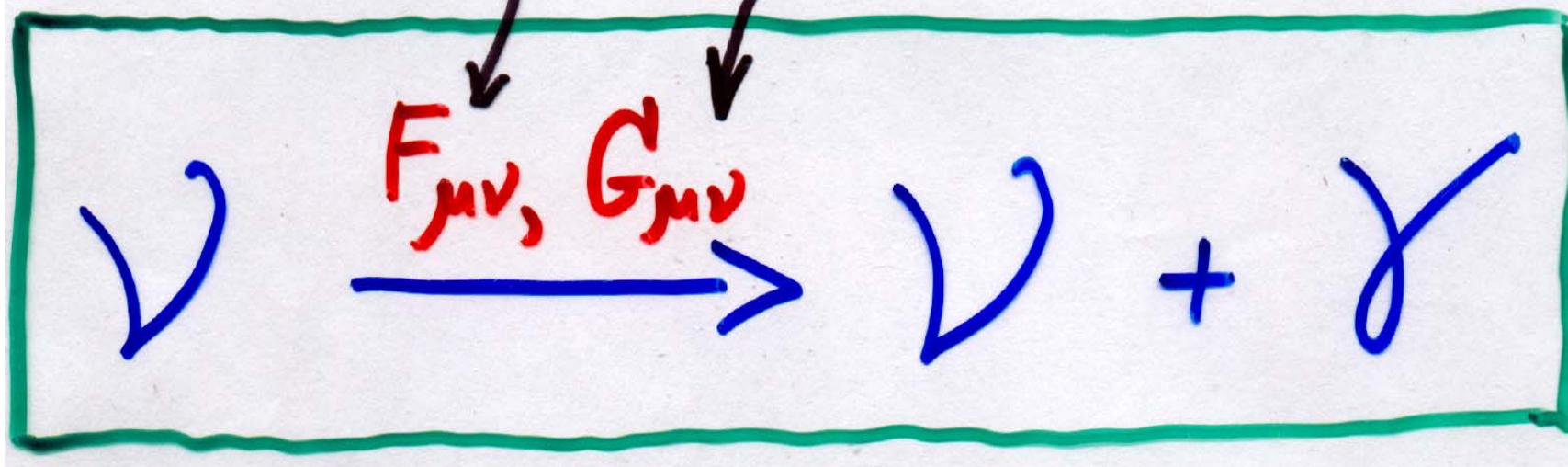
A.S., J.Phys.A: Math.Theor. 41 (2008) 16402

"Spin light of neutrino"

in matter and

electromagnetic fields

$SL\nu$



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

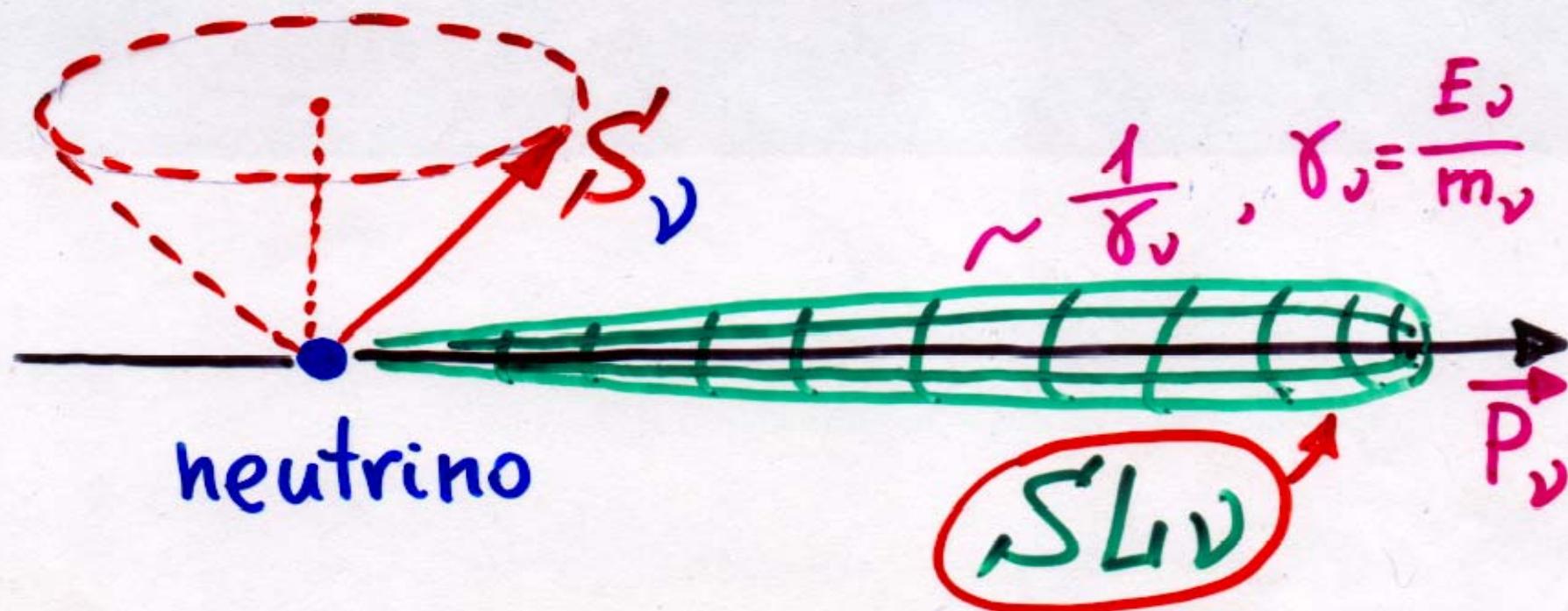
SL ν

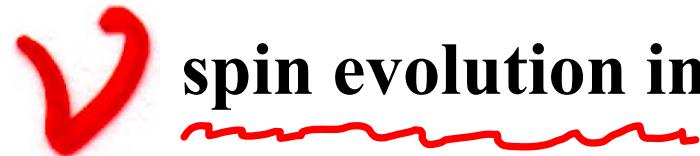
A.Lobanov, A.Studenikin, Phys.Lett. B 564 (2003) 27,

Phys.Lett. B 601 (2004) 171;

M.Dvornikov, A.Grigoriev, A.Studenikin, Int.J.Mod.Phys. D 14 (2005) 309

Neutrino spin procession in background environment





spin evolution in presence of general external fields

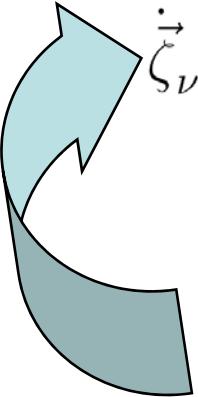
M.Dvornikov, A.Studenikin,
JHEP 09 (2002) 016

General types non-derivative interaction with external fields

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

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 equation (quasiclassical) for  *spin vector:*



$$\dot{\vec{\zeta}}_\nu = 2g_a \left\{ A^0 [\vec{\zeta}_\nu \times \vec{\beta}] - \frac{m_\nu}{E_\nu} [\vec{\zeta}_\nu \times \vec{A}] - \frac{E_\nu}{E_\nu+m_\nu} (\vec{A} \vec{\beta}) [\vec{\zeta}_\nu \times \vec{\beta}] \right\} \\ + 2g_t \left\{ [\vec{\zeta}_\nu \times \vec{b}] - \frac{E_\nu}{E_\nu+m_\nu} (\vec{\beta} \vec{b}) [\vec{\zeta}_\nu \times \vec{\beta}] + [\vec{\zeta}_\nu \times [\vec{a} \times \vec{\beta}]] \right\} + \\ + 2ig'_t \left\{ [\vec{\zeta}_\nu \times \vec{c}] - \frac{E_\nu}{E_\nu+m_\nu} (\vec{\beta} \vec{c}) [\vec{\zeta}_\nu \times \vec{\beta}] - [\vec{\zeta}_\nu \times [\vec{d} \times \vec{\beta}]] \right\}.$$

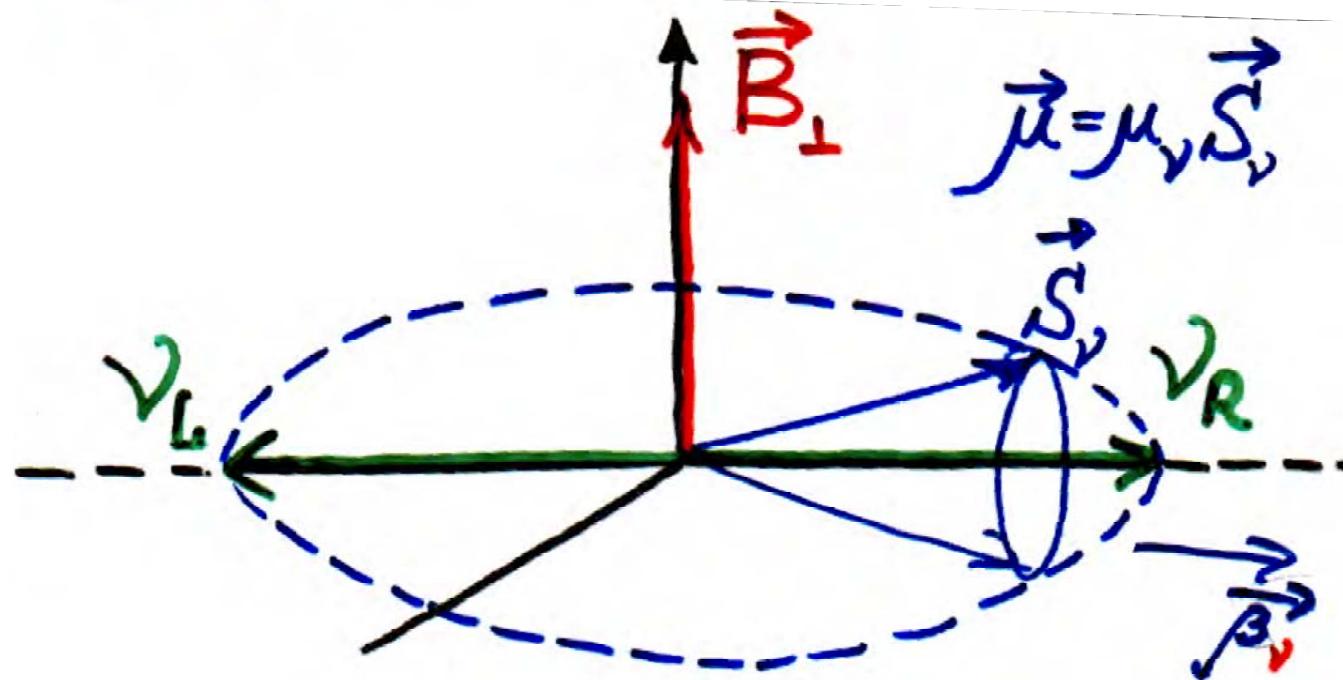
● **Neither S nor π nor V contributes to spin evolution**

- Electromagnetic interaction

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

- SM weak interaction

$$G_{\mu\nu} = (-\vec{P}, \vec{M}) \quad \vec{M} = \gamma(A^0 \vec{\beta} - \vec{A}) \\ \vec{P} = -\gamma[\vec{\beta} \times \vec{A}],$$



$$\frac{d\vec{S}_y}{dt} = 2\mu_y [\vec{S}_y \times \vec{B}] + 2\mu_y [\vec{S}_y \times \vec{G}]$$

electromagnetic interaction with e.m. field

Weak interaction with matter

New mechanism of electromagnetic radiation

of neutrino $SL\nu$
? Why Spin Light in matter.
of electron SLe

Analogies with :

* classical electrodynamics

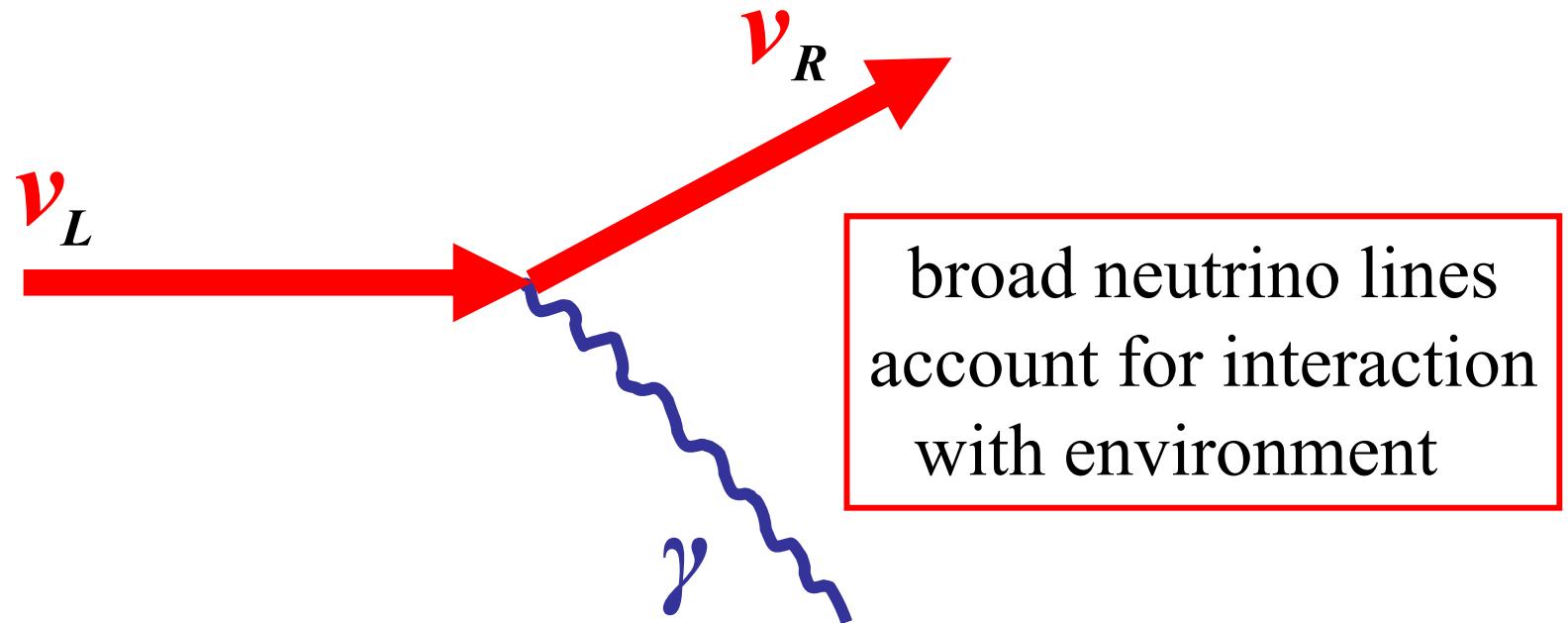
an object with charge $Q = 0$ and

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

$$I^{\text{cl. el.}} = \frac{2}{3} \vec{m}^2$$

magnetic dipole
radiation power

Neutrino – photon couplings (II)



“Spin light of neutrino in matter”



... within the quantum treatment based on
method of exact solutions ...

Modified Dirac equation for neutrino in matter

Addition to the vacuum neutrino Lagrangian

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

where

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

matter current

matter polarization

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

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

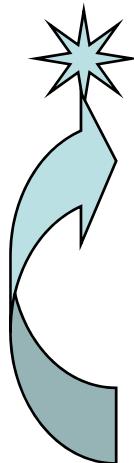
L.Chang, R.Zia,'88; J.Panteleone,'91; K.Kiers, N.Weiss,
M.Tytgat,'97-'98; P.Manheim,'88; D.Nötzold, G.Raffelt,'88;
J.Nieves,'89; V.Oraevsky, V.Semikoz, Ya.Smorodinsky,'89;
W.Naxton, W-M.Zhang'91; M.Kachelriess,'98;
A.Kusenko, M.Postma,'02.

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

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)

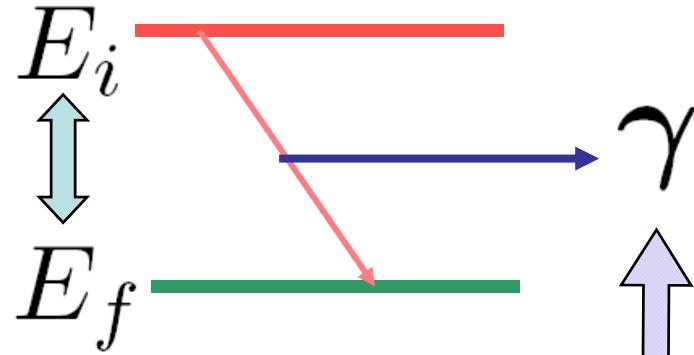
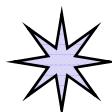
Quantum treatment of *spin light of neutrino* in matter shows that this process originates from the **two subdivided phenomena**:



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

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

$$s = \pm 1$$



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,

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

Phys.Lett.B 608 (2005) 107;

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

$$\tau = \frac{1}{\Gamma} \ll \text{age of the Universe ?}$$

SL ν

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

$$\Gamma_{SL\nu} = 4\mu^2 \alpha^2 m_\nu^2 p$$

$$p \gg m_{plasmon}$$

recently also
discussed by
**A.Kuznetsov,
N.Mikheev, 2006**

A.Lobanov, A.S., PLB 2003; PLB 2004

A.Grigoriev, A.S., PLB 2005

A.Grigoriev, A.S., A.Ternov, PLB 2005

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

it follows that

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

- A.Studenikin, **J.Phys.A: Math.Theor.** **41** (2008) 164047
- A.Studenikin, **J.Phys.A: Math.Gen.** **39** (2006) 6769; **Ann.Fond. de Broglie** **31** (2006) 289
- A.Studenikin, **Phys.Atom.Nucl.** **70** (2007) 1275; *ibid* **67** (2004) 1014
- A.Grigoriev, A.Savochkin, A.Studenikin, **Russ.Phys. J.** **50** (2007) 845
- A.Grigoriev, S.Shinkevich, A.Studenikin, A.Ternov, I.Trofimov, **Russ.Phys. J.** **50** (2007) 596
- A.Studenikin, A.Ternov, **Phys.Lett.B** **608** (2005) 107; **Grav. & Cosm.** **14** (2008)
- A.Grigoriev, A.Studenikin, A.Ternov, **Phys.Lett.B** **622** (2005) 199
Grav. & Cosm. **11** (2005) 132 ; **Phys.Atom.Nucl.** **69** (2006) 1940
- K.Kouzakov, A.Studenikin, **Phys.Rev.C** **72** (2005) 015502
- M.Dvornikov, A.Grigoriev, A.Studenikin, **Int.J Mod.Phys.D** **14** (2005) 309
- S.Shinkevich, A.Studenikin, **Pramana** **64** (2005) 124
- A.Studenikin, **Nucl.Phys.B** (Proc.Suppl.) **143** (2005) 570
- M.Dvornikov, A.Studenikin, **Phys.Rev.D** **69** (2004) 073001
Phys.Atom.Nucl. **64** (2001) 1624
Phys.Atom.Nucl. **67** (2004) 719
JETP **99** (2004) 254; **JHEP** **09** (2002) 016
- A.Lobanov, A.Studenikin, **Phys.Lett.B** **601** (2004) 171
Phys.Lett.B **564** (2003) 27
Phys.Lett.B **515** (2001) 94
- A.Grigoriev, A.Lobanov, A.Studenikin, **Phys.Lett.B** **535** (2002) 187
- A.Egorov, A.Lobanov, A.Studenikin, **Phys.Lett.B** **491** (2000) 137

Direct

and
influence

Indirect

of electromagnetic fields

on ν

through non-trivial
neutrino electromagnetic
properties (magnetic moment):

★ neutrino spin

★ spin-flavour oscillations...

★ different $\nu\gamma$ processes

due to e.m. field influence on
charged particles coupled
to neutrinos

- ★ neutron beta-decay in B
- ★ change of ν oscillation pattern
due to matter polarization under
influence of external e.m. fields ...

4

ν spin and spin-flavour oscillations in

 B_{\perp} 

Consider two different neutrinos: $\nu_{eL}, \nu_{\mu R}, m_L \neq m_R$
with magnetic moment interaction

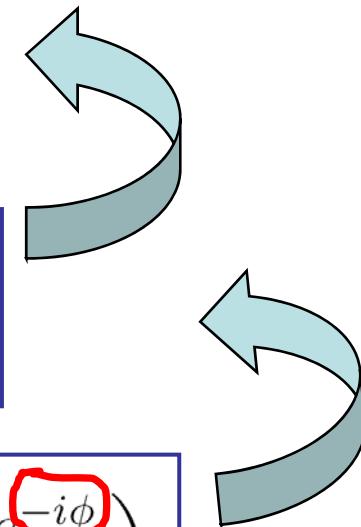
$$L \sim \bar{\nu} \sigma_{\lambda\rho} F^{\lambda\rho} \nu' = \bar{\nu}_L \sigma_{\lambda\rho} F^{\lambda\rho} \nu'_R + \bar{\nu}_R \sigma_{\lambda\rho} F^{\lambda\rho} \nu'_L.$$

Twisting magnetic field $B = |\mathbf{B}_{\perp}| e^{i\phi(t)}$ for solar ν etc ...

 ν

evolution equation

$$i \frac{d}{dt} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix} = H \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$$

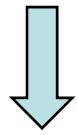


$$H = \begin{pmatrix} E_L & \mu_{e\mu} B e^{-i\phi} \\ \mu_{e\mu} B e^{+i\phi} & E_R \end{pmatrix} = \dots \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + \tilde{H}$$

!

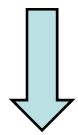
$$\tilde{H} = \begin{pmatrix} -\frac{\Delta m^2}{4E} \cos 2\theta + \frac{V_{\nu_e}}{2} & \mu_{e\mu} B e^{-i\phi} \\ \mu_{e\mu} B e^{+i\phi} & \frac{\Delta m^2}{4E} - \frac{V_{\nu_e}}{2} \end{pmatrix}$$

After unitary transformation



$$\nu = U\nu', \quad U = \begin{pmatrix} e^{-i\phi} & 0 \\ 0 & e^{i\phi} \end{pmatrix}$$

$$i\left[\frac{i}{2}\begin{pmatrix} -e^{-i\phi} & 0 \\ 0 & e^{i\phi} \end{pmatrix}\dot{\phi}\nu' + \begin{pmatrix} e^{-i\phi} & 0 \\ 0 & e^{i\phi} \end{pmatrix}\frac{d}{dt}\nu'\right] = H\begin{pmatrix} e^{-i\phi} & 0 \\ 0 & e^{i\phi} \end{pmatrix}\nu'$$



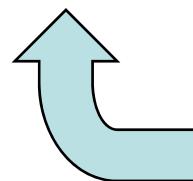
$$U^\dagger U' = \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix}$$

$$U' = \begin{pmatrix} -e^{-i\phi} & 0 \\ 0 & e^{i\phi} \end{pmatrix}, \quad U^\dagger = \begin{pmatrix} e^{i\phi} & 0 \\ 0 & e^{-i\phi} \end{pmatrix}$$

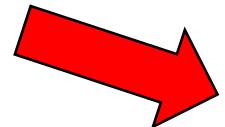
conjugated

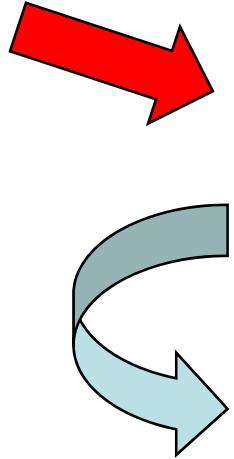
$$i\frac{d}{dt}\nu' = (U^\dagger \tilde{H} U + \frac{\dot{\phi}}{2} U^\dagger U')\nu'$$

$$U^\dagger \tilde{H} U = \tilde{H}_{|\phi=0}$$



$$\tilde{H} = \begin{pmatrix} -\frac{\Delta m^2}{4E} \cos 2\theta + \frac{V_{\nu_e}}{2} & \mu_{e\mu} B e^{-i\phi} \\ \mu_{e\mu} B e^{+i\phi} & \frac{\Delta m^2}{4E} - \frac{V_{\nu_e}}{2} \end{pmatrix}$$





$$i \frac{d}{dt} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix} = \begin{pmatrix} -\frac{\Delta m^2}{4E} \cos 2\theta + \frac{V_{\nu_e}}{2} - \frac{\dot{\phi}}{2} & \mu_{e\mu} B \\ \mu_{e\mu} B & \frac{\Delta m^2}{4E} - \frac{V_{\nu_e}}{2} + \frac{\dot{\phi}}{2} \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$$

$$i \frac{d}{dt} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix} = \left(-\frac{\Delta_{LR}}{4E} \sigma_3 + \mu_{e\mu} B \sigma_1 \right) \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix} \quad \sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_3 = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

For relativistic \mathcal{V} : $\frac{d}{dt} \rightarrow \frac{d}{dz}$ and solution is

$$\nu(z) = e^{-i\Omega z(\mathbf{n}\sigma)} \nu(0)$$

where

$$\mathbf{n} = \frac{\mathbf{k}}{\Omega}, \quad \mathbf{k} = \left(\mu_{e\mu} B, 0, -\frac{\Delta_{LR}}{4E} \right)$$

$$\Omega^2 = (\mu_{e\mu} B)^2 + \left(\frac{\Delta_{LR}}{4E} \right)^2$$

and

$$\Delta_{LR} = \frac{\Delta m^2}{2} (\cos 2\theta + 1) - 2EV_{\nu_e} + 2E\dot{\phi}$$

... Flavour oscillations \longleftrightarrow Spin oscillations...

$$P_{\nu_e \nu_\mu} = \sin^2 2\theta \sin^2 \frac{\Delta m^2}{4E} z$$

$$P_{\nu_L \nu_R} = \sin^2 \beta \sin^2 \Omega z$$

$$\Omega^2 = (\mu_{e\mu} B)^2 + \left(\frac{\Delta_{LR}}{4E} \right)^2$$

$$\sin^2 2\theta$$

$$\frac{(\mu_{e\mu} B)^2}{(\mu_{e\mu} B)^2 + \left(\frac{\Delta_{LR}}{4E} \right)^2} = \sin^2 \beta$$

$$\frac{\Delta m^2}{4E}$$

$$\sqrt{(\mu_{e\mu} B)^2 + \left(\frac{\Delta_{LR}}{4E} \right)^2}$$

Probability of $\nu_{eL} \leftrightarrow \nu_{\mu R}$ oscillations in $B = |\mathbf{B}_\perp| e^{i\phi(t)}$ and matter



$$P_{\nu_L \nu_R} = \sin^2 \beta \sin^2 \Omega z, \quad \sin^2 \beta = \frac{(\mu_{e\mu} B)^2}{(\mu_{e\mu} B)^2 + \left(\frac{\Delta_{LR}}{4E} \right)^2}$$

$$\Delta_{LR} = \frac{\Delta m^2}{2} (\cos 2\theta + 1) - 2EV_{\nu_e} + 2E\dot{\phi}$$

$$\Omega^2 = (\mu_{e\mu} B)^2 + \left(\frac{\Delta_{LR}}{4E} \right)^2$$



Resonance amplification of oscillations in matter:

$$\Delta_{LR} \rightarrow 0$$



$$\sin^2 \beta \rightarrow 1$$

Akhmedov, 1988
Lim, Marciano

In magnetic field

$\nu_{eL} \quad \nu_{\mu R}$

$$i \frac{d}{dz} \nu_{eL} = -\frac{\Delta_{LR}}{4E} \nu_{eL} + \mu_{e\mu} B \nu_{\mu R}$$

$$i \frac{d}{dz} \nu_{\mu L} = \frac{\Delta_{LR}}{4E} \nu_{\mu L} + \mu_{e\mu} B \nu_{eR}$$

① $\nu_e \xleftrightarrow{\text{vac}} \bar{\nu}_e$, B. Pontecorvo, 1957

② $\nu_e \xleftrightarrow{\text{vac}} \nu_\mu$, Z. Maki, M. Nakagawa, S. Sakata, 1962

③ $\nu_e \xleftrightarrow{\text{matter, } g = \text{const}} \nu_\mu$, L. Wolfenstein, 1978

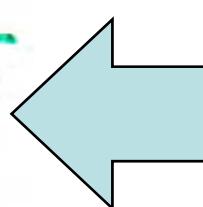
④ $\nu_e \xleftrightarrow{\text{matter, } g \neq \text{const}} \nu_\mu$, S. Mikheev, A. Smirnov, 1985

- resonances in ν flavour oscillations \Rightarrow MSW-effect, solution for ν_0 -problem

⑤ $\nu_{e_L} \xleftrightarrow{B_\perp} \nu_{e_R}$, A. Cisneros, 1971
M. Voloshin, M. Vysotsky, L. Okun, 1986, ν_0

⑥ $\nu_{e_L} \xleftrightarrow{B_\perp} \nu_{e_R}, \nu_{\mu_R}$, E. Akhmedov, 1988
C.-S. Lim & W. Marciano, 1988

- resonances in ν spin (spin-flavour) oscillations in matter



in
and
matter at rest

B_\perp

Neutrino conversions and oscillations in magnetic field

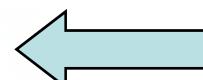
- \cancel{V}_0 problem

$$V_L \xleftrightarrow{B} V_R$$

Cisneros, 1971

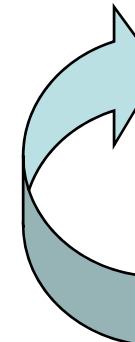
* { Voloshin, Vysotsky, Okun, 1986
Barbieri, Fiorentini, 1988
Smirnov, 1991
Akhmedov, Petcov, Smirnov, 1993

• twisting B



...for recent analysis see

J.Pulido, 2006,
TAUP-09;
A.Balantekin,
C.Volpe, 2005



- $\cancel{*}$ Supernova

$$V_L \xleftrightarrow{B} V_R$$

Dar, 1987

Fujikawa, Shrock, 1988

Voloshin, 1988

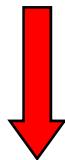


Spin-flavour oscillations in early universe – strong B_\perp
→ population of ν wrong-helicity states (r.h.) would
accelerate expansion of universe (???)

...subdominant
contribution to
LMA – MSW
solution...

Periodicity of the active solar neutrino flux is probably the most important issue to be investigated after LMA has been ascertained as the dominant solution to the $\odot \nu$ problem. If confirmed it will imply the existence of a sizable neutrino magnetic moment μ_ν and hence a wealth of new physics.

Idea was introduced in 1986 by



Voloshin, Vysotsky and Okun

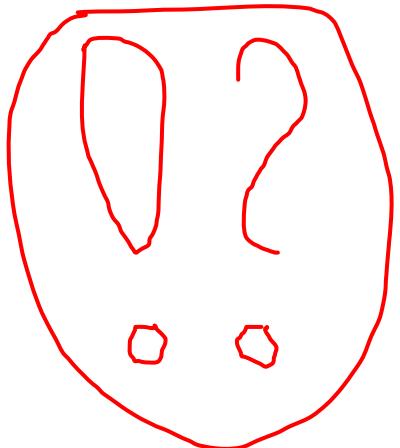


Strong $B_\odot \rightarrow \text{large } \mu_\nu B_\odot \rightarrow \text{large conversion}$

- For recent analysis see **J.Pulido, TAUP-2009** ●
J.Pulido, 2006 ...see also A.Balantekin and C.Volpe, 2005



... **Spin-flavour precession resonance** and **MSW resonance** take place very close to each other inside sun...



S_μ , S_e , S_{res}
are muon, electron
neutrino-spheres

and $\nu_e \leftrightarrow \nu_\mu$
resonance Surface
(ellipsoid)

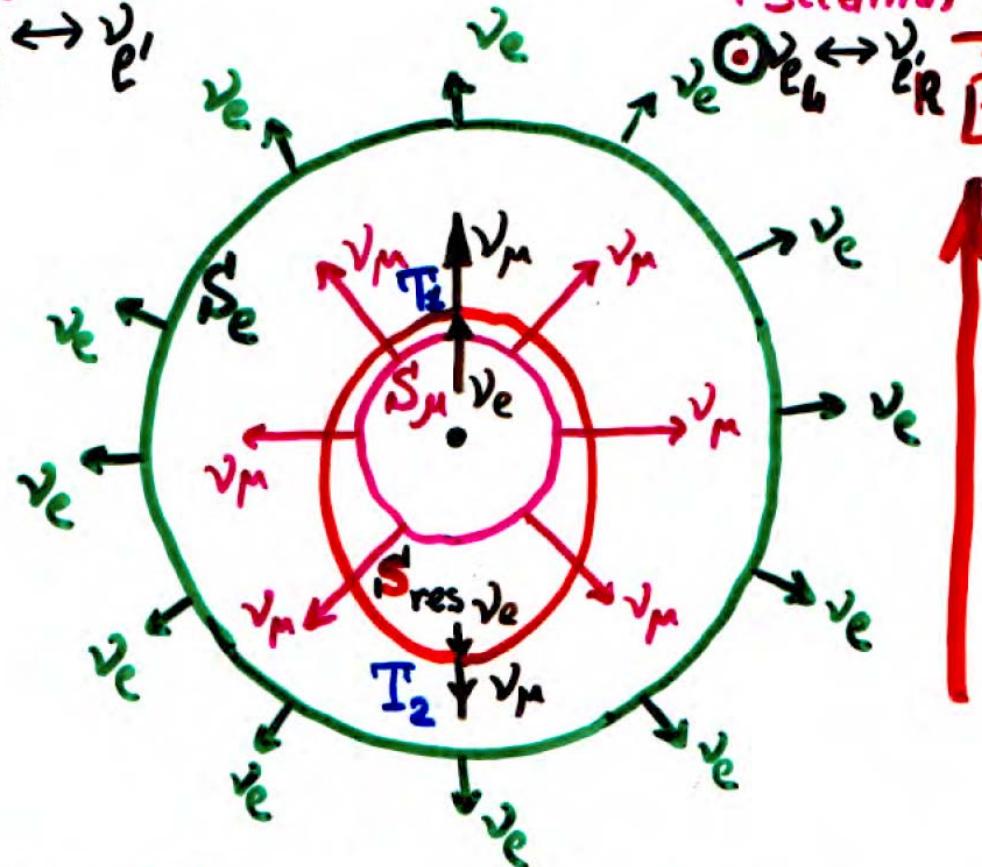
Pulsar kick and ν oscillations in B

{Kusenko,
Serge, 1996}

$$\nu_e \leftrightarrow \nu_{e'}$$

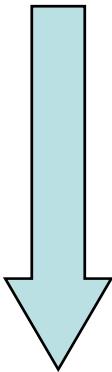
{Akhmedov,
Lanza, Sciamma,
1997}

$$\nu_e \leftrightarrow \nu_{eR} B$$



{ In directions where RS is close (far)
to center →
larger (smaller) ν momentum,
since $T_1 > T_2$.

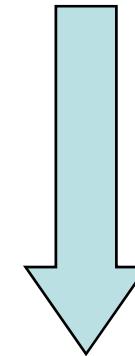
Direct and influence of electromagnetic fields on ν



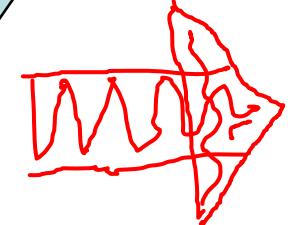
through non-trivial
neutrino electromagnetic
properties (magnetic moment):

- ★ neutrino spin
- ★ spin-flavour oscillations...
- ★ different $\nu\gamma$ processes

Indirect



due to e.m. field influence on
charged particles coupled
to neutrinos



- ★ neutron beta-decay in B
- ★ change of ν oscillation pattern
due to matter polarization under
influence of external e.m. fields ...

β -decay of neutron in magnetic field

{Birth of ν astrophysics in B }



- * L. Korovina, "Beta-decay of polarized neutron in magnetic field", Sov.Phys.J., # 6 (1964) 86
- * I.Ternov, B.Lysov, L.Korovina, Mosc.Univ.Bull.,Phys.,Astron., #5 (1965) 58
"On the theory of neutron β -decay in external magnetic field".
- * J.Matese, R.O'Connell, "Neutron beta decay in a uniform magnetic field", Phys.Rev.180 (1969) 1289
- * L.Fassio-Canuto, "Neutron beta decay in a strong magnetic field" Phys.Rev.187 (1969) 2141
- * G.Greenstein, Nature 223 (1969) 938

* Asymmetry in $\tilde{\nu}$ emission

$$\frac{W(B)}{W_0} = \frac{1}{2} \int \sin\theta \, d\theta \left\{ 1 + \frac{2(\alpha^2 - \alpha)}{1 + 3\alpha^2} S_n \underline{\cos\theta} \right.$$

$$\left. - 4.9 \frac{eB}{\Delta^2} \left(\frac{\alpha^2 - 1}{1 + 3\alpha^2} \underline{\cos\theta} + \frac{2(\alpha^2 - \alpha)}{1 + 3\alpha^2} S_n \right) \right\}$$



astrophysical applications



K.Kouzakov, A.Studenikin
Phys.Rev.C 72 (2005) 015502



“Bound-state beta-decay
of neutron in strong
magnetic field”

Usual (continuum - state) β decay $n \rightarrow p + e^- + \bar{\nu}_e$
"Rare" (bound - state) β decay $n \rightarrow (pe^-) + \bar{\nu}_e$

R. Daudel, M. Jean, and M. Lecoin, J. Phys. Radium **8**, 238 (1947)

$$\frac{w_b}{w_c} \cong 4.2 \times 10^{-6}$$

$$\begin{aligned}\tau_c &\sim 15 \text{ min} \\ \tau_b &\sim 7 \text{ years}\end{aligned}$$

J.N. Bahcall, Phys. Rev. **124**, 495 (1961) [Dirac equation]

L.L. Nemenov, Sov. J. Nucl. Phys. **15**, 582 (1972) [Schrödinger equation]

X. Song, J. Phys. G: Nucl. Phys. **13**, 1023 (1987) [Bethe-Salpeter equation]

K.A. Kouzakov and A.I. Studenikin, Phys. Rev. C **72**, 015502 (2005)
<http://arxiv.org/hep-ph/0412134>

Summary

First analysis of bound-state β decay in a strong magnetic field ($B \sim 10^{13}$ - 10^{18} G)

✓ $w_b/w_c \sim 0.1$ - 0.4 in contrast to the field-free case, where $w_b/w_c \sim 10^{-6}$

✓ A logarithmiclike behavior

$$w_b/w_c \propto \log_{10}(B/B_e) + b \quad (b > 0)$$

Outlook: Astrophysical applications?

...remark on How can ν
Be affected
By \vec{B} ?

1) "direct influence"

non-trivial
electromagnetic
properties

* $\mu_\nu \neq 0 (m_\nu \neq 0)$

- * spin and
- * spin-flavour
oscillations
in B



2) "indirect influence"
of B on

interacting with ν
particles

- * $n \xrightarrow[B]{\gamma} p^+ e^- \bar{\nu}_e$
- * $\nu + n \xrightarrow[B]{\gamma} p^+ e^-$
- * flavour and spin ν
oscillations in
polarized (by B)
matter (e, n, p, \dots)

3) "direct-indirect influence"

Spin light of ν in matter and e.m.fields

3.12

✓ e.m. form factors are affected by matter and $\underline{\underline{B}}$

* magnetic moment $\mu_{\nu} = \mu_{\nu}(B)$

* induced electric charge of ν in magnetized matter

Egorov
Studenikin
1992

Borisov,
Zhukovsky,
Kurilin,
Ternov,
1985

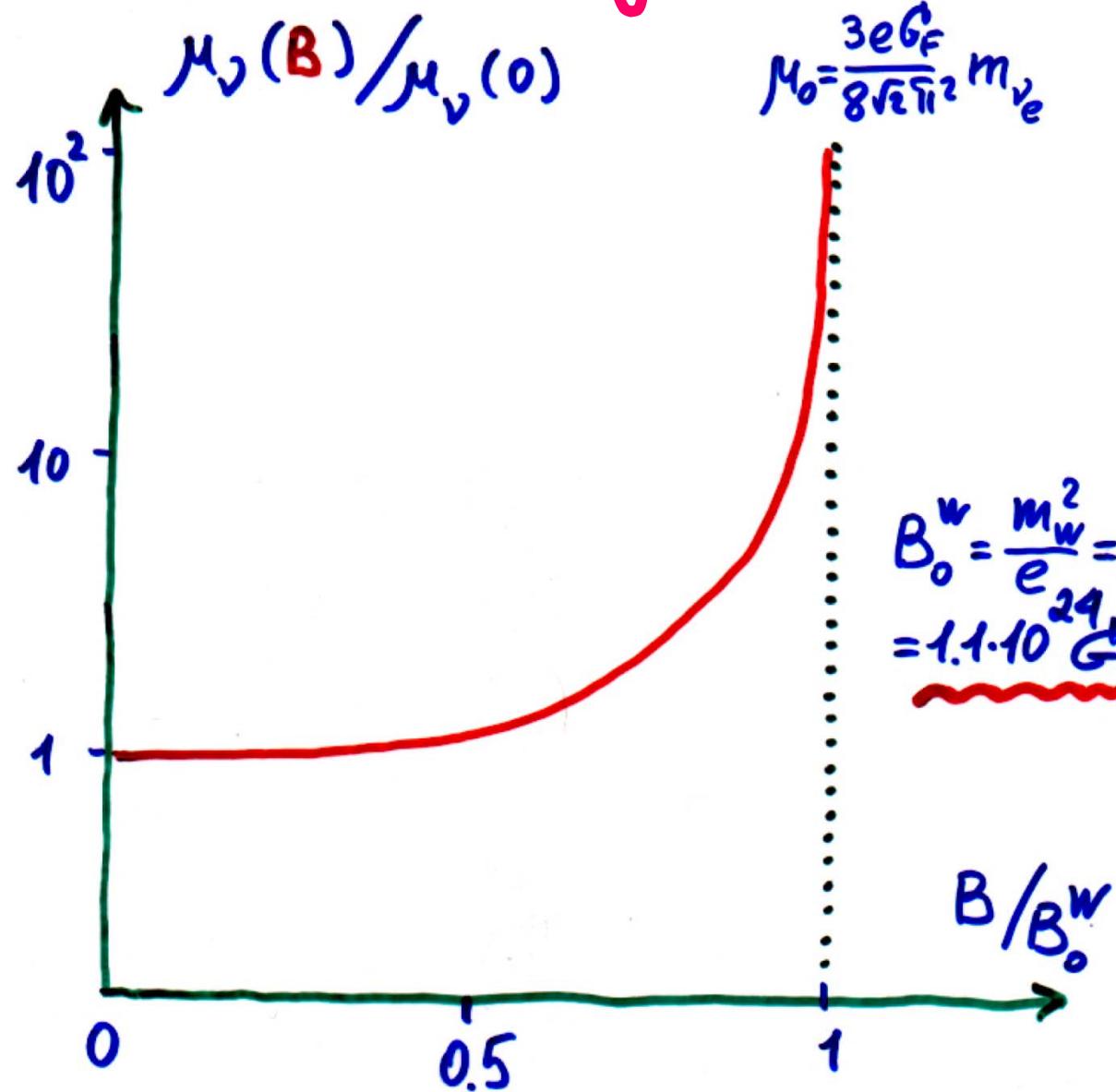
* Oraevsky, Semikoz

Smorodinsky, 1986

Bhattacharya, Ganguly, Konar, 2002

Nieves, 2003

Neutrino magnetic moment



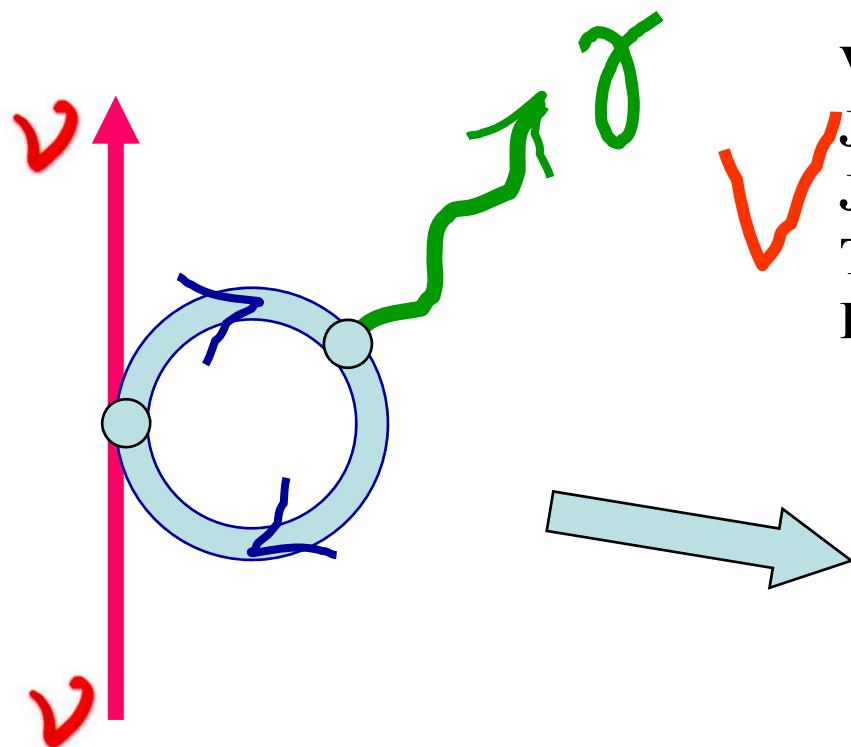
Borisov,
Zhukovskiy,
Kurilin,
Ternov, 1985;

Masood,
Perez Rojas,
Gaitan,
Rodrigues-Romo,
1999

ν

“effective electric charge” in magnetized plasma

- ν_s do not couple with γ_s in vacuum,
... however, when
- ν in thermal medium (e^- and e^+)



V.Oraevsky, V.Semikoz, Ya.Smorodinsky,
JETP Lett. 43 (1986) 709;
J.Nieves, P.Pal, Phys.Rev.D 49 (1994) 1398;
T.Altherr, P.Salati, Nucl.Phys.B421 (1994) 662;
K.Bhattacharya, A.Ganguly, 2002

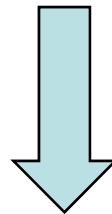
...different $\nu\gamma$ interactions in
astrophysical and cosmological media

Method of exact solutions

Modified **Dirac equations** for ν
(containing the correspondent effective matter potentials)



exact solutions (particles wave functions)



a basis for investigation of different phenomena which
can proceed when **neutrinos** and **electrons** move in
dense 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

$$A_\mu(x) = A_\mu^q(x) + A_\mu^{ext}(x),$$

evolution operator

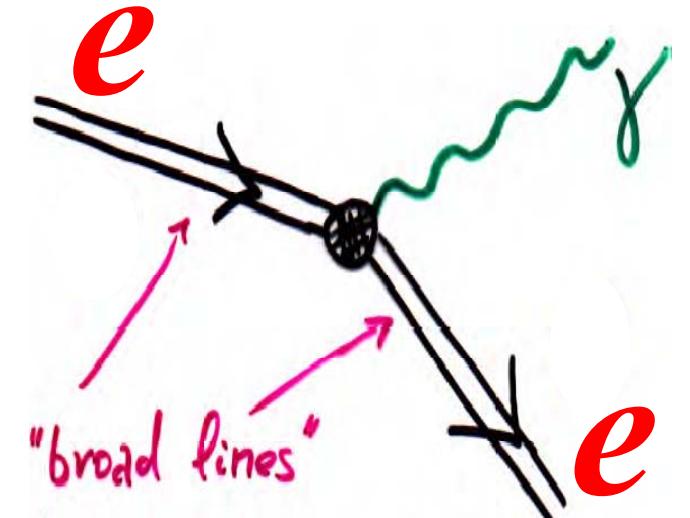
quantized part
of potential

$$U_F(t_1, t_2) = T \exp \left[-i \int_{t_1}^{t_2} j^\mu(x) A_\mu^q(x) dx \right],$$

charged particles current

$$j_\mu(x) = \frac{e}{2} [\Psi_F \gamma_\mu, \Psi_F],$$

B_\perp
 $e \rightarrow e + \gamma$
synchrotron radiation



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

$$\left\{ \gamma^\mu \left(i \partial_\mu - e A_\mu^{ext}(x) \right) - m_e \right\} \Psi_F(x) = 0$$



...beyond perturbation series expansion,
strong fields and non linear effects...

ν and e

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

hep-ph/0410297,
“Neutrino quantum states in matter”;

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

A.Grigoriev, A.Studenikin,
A.Ternov,
Phys.Lett.B 608 622 (2005) 199

in matter being treated within
the method of exact solutions
of quantum wave equations -
«method of exact solutions»

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,
“Relativistic particles motion in strong
magnetic field and dense matter”,
J.Phys.A: Math.Theor.44 (2011) 255301

Neutrino energy quantization in rotating media: new mechanism for neutrino trapping inside dense rotating stars

Neutrino'08,
Christchurch,
May 25-31, 2008

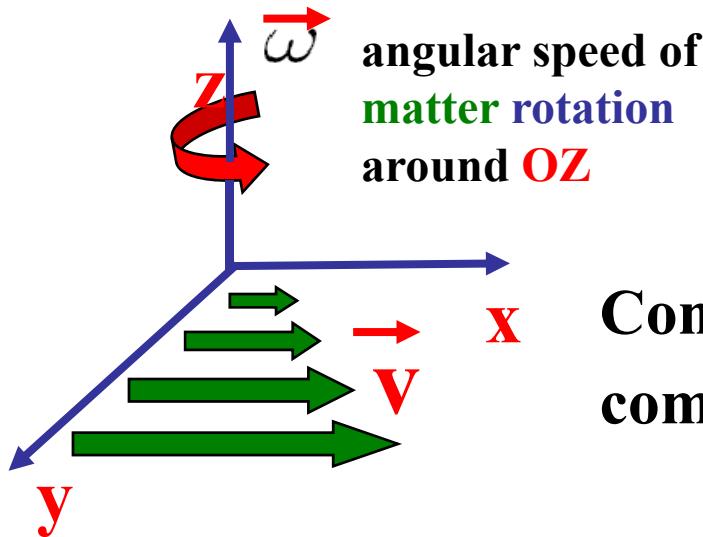
Alexander Studenikin

Moscow State
University

A.Studenikin, “Method of exact solutions in
studies of neutrinos and electrons in dense matter”
J.Phys.A:Math.Theor. 41 (2008) 164047 (20 pp)



Neutrino energy quantization in matter



Consider ν moving in **rotating** medium composed of neutrons (generalization s.f.):

ν wave function

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

where **matter** potential $f^\mu = -G(n, n\mathbf{v})$, $\mathbf{v} = (\omega y, 0, 0)$, $\rho = Gn\omega$ $G = \frac{G_F}{\sqrt{2}}$
neutron number density

$$\nu \text{ energy spectrum } \tilde{p}_0 = \sqrt{p_3^2 + 2\rho N} + Gn, \quad N = 0, 1, 2, \dots$$

circular orbits **trapping inside dense stars**

*A. Grigoriev, A. Savochkin, A. Studenikin (2007)
A. Studenikin (2008)
I. Balantsev, Yu. Popov, A. Studenikin (2011)*

Energy spectrum of active left-handed neutrino

$$p_0 = \sqrt{p_3^2 + 2\rho N} - Gn, \quad N = 0, 1, 2, \dots$$

$$\rho = Gn\omega$$

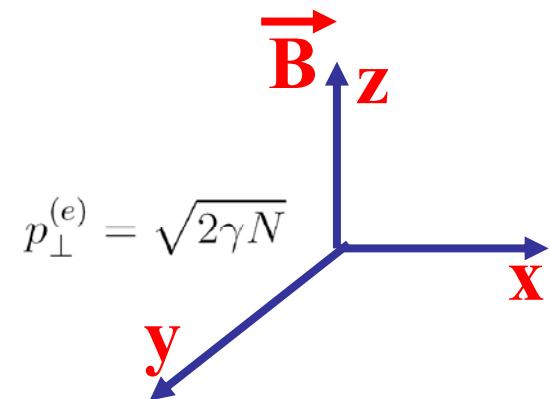
Antineutrino \longrightarrow “negative sign” energy eigenvalues

$$\tilde{p}_0 = \sqrt{p_3^2 + 2\rho N} + Gn, \quad N = 0, 1, 2, \dots$$

 energy quantization

Transversal motion of active relativistic 
is quantized in rotating medium
like electron motion is quantized
in magnetic field (Landau energy levels):

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



... consistent model of a rotating matter with account for \check{V} mass

*I.Balantsev, Yu.Popov, A.Studenikin,
Nuov.Cim.B 32 (2009) 53,
arXiv: 0906.2391*

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

$$f^\mu = -G(n, n\mathbf{v}), \quad \mathbf{v} = (-\omega y, \omega x, 0)$$

Energy spectra

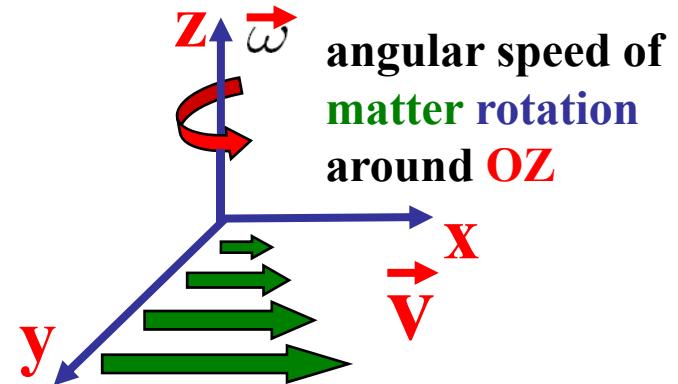
$$p_0 = \sqrt{m^2 + p_3^2 + 4N\rho} - Gn \quad \text{for } \check{V}$$

$$\tilde{p}_0 = \sqrt{m^2 + p_3^2 + 4N\rho + Gn} \quad \text{for } \widetilde{\check{V}}$$

$$N = 0, 1, 2, \dots \quad \rho = Gn\omega$$

One example: consider antineutrino $\tilde{\nu}$ in **rotating neutron matter**, then energy of transversal motion

$$\tilde{p}_\perp = \sqrt{2\rho N} \quad \rho = Gn\omega$$



Quantum number N also determines **radius** of antineutrino quasi-classical orbit in moving matter:

$$R = \sqrt{\frac{2N}{Gn\omega}}$$

binding orbits inside a Neutron Star !?

NS:

$$R_{NS} = 10 \text{ km} \\ n = 10^{37} \text{ cm}^{-3} \\ \omega = 2\pi \times 10^3 \text{ s}^{-1}$$

for this set

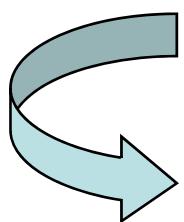
radius of trajectory

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

if $N \leq N_{max} = 10^{10}$, $\tilde{\nu}$ with $N \leq 10^{10}$ can be bound inside the star

thus, $\tilde{\nu}$ with energy $\tilde{p}_0 \sim 1 \text{ eV}$ can be bound inside NS

$$N \gg 1 \text{ and } p_3 = 0$$



✓ quantum states in rotating matter

A.Studenikin,
J.Phys.A: Math.Theor. 41
(2008) 164047

quasi-classical circular orbits due to central force

$$\mathbf{F}_m^{(\nu)} = q_m^{(\nu)} \boldsymbol{\beta} \times \mathbf{B}_m$$

$\mathbf{B}_m = \nabla \times \mathbf{A}_m, \quad \mathbf{A}_m = n\mathbf{v}$
“magnetic field” vector potential

“charge”
 $q_m^{(\nu)} = -G$

matter-induced “Lorentz force”,

$$\mathbf{F}_m^{(\nu)} \perp \boldsymbol{\beta}$$

Generalization to non-constant matter density:

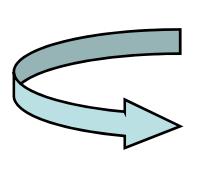
$$\mathbf{F}_m^{(\nu)} = q_m^{(\nu)} \mathbf{E}_m + q_m^{(\nu)} \boldsymbol{\beta} \times \mathbf{B}_m,$$

L.Silva, R.Bingham,
J.Dawson, J.Mendoza,
P.Shukla, *Phys.Plasma* 7
(2000) 2166

“magnetic field” $\mathbf{B}_m = n\nabla \times \mathbf{v} - \mathbf{v} \times \nabla n$

“electric field”

$$\mathbf{E}_m = -\nabla n - \mathbf{v} \frac{\partial n}{\partial t} - n \frac{\partial \mathbf{v}}{\partial t}$$



e quantum states in rotating matter quasi-classical circular orbits due to central force

Matter-induced “Lorentz force” on electron

A.Studenikin,
J.Phys.A:Math.Theor. 41
(2008) 164047

$$\mathbf{F}_m^{(e)} = q_m^{(e)} \mathbf{E}_m + q_m^{(e)} \boldsymbol{\beta} \times \mathbf{B}_m$$

We predict that there could be an electromagnetic radiation emitted by
an electron moving in radial direction inside a neutrino flow ($m = \nu$)
emitted from a central part of a star (dipole radiation):

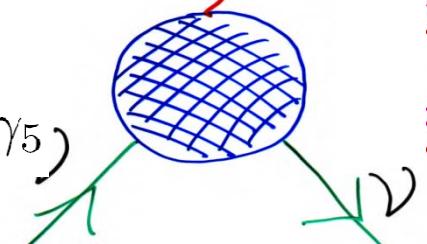
$$I = \frac{2}{3} q_\nu^{(e)} \left[\frac{\mathbf{a}^2}{(1 - \beta^2)^2} + \frac{(\mathbf{a}\boldsymbol{\beta})^2}{(1 - \beta^2)^3} \right]$$

acceleration of electron
due to mater-induced “Lorentz force”

V e.m. vertex function \rightarrow 4 form factors γ

charge dipole magnetic and electric

- $\Lambda_\mu(q) = f_Q(q^2)\gamma_\mu + f_M(q^2)i\sigma_{\mu\nu}q^\nu + f_E(q^2)\sigma_{\mu\nu}q^\nu\gamma_5 + f_A(q^2)(q^2\gamma_\mu - q_\mu q^\nu)\gamma_5$ **anapole**



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

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

In extensions of SM

enhancement of ν, even

electrically
millicharged ν

- Limits from reactor ν-e scattering experiments (2010):

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

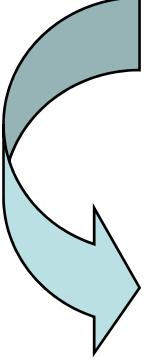
A.Beda et al.
(GEMMA Coll.)

- Limits from astrophysics, star cooling (1990):

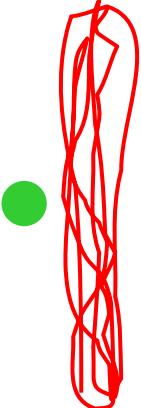
$$\mu \leq 3 \times 10^{-12} \mu_B$$

G.Raffelt

μ_{ν} is presently known to be in the range


$$10^{-20} \mu_B \leq \mu_{\nu} \leq 10^{-11} \mu_B$$

μ_{ν} provides a tool for exploration possible physics beyond the Standard Model



Due to smallness of neutrino-mass-induced magnetic moments,

$$\mu_{ii} \approx 3.2 \times 10^{-19} \left(\frac{m_i}{1 \text{ eV}} \right) \mu_B$$

any indication for non-trivial electromagnetic properties of ν , that could be obtained within reasonable time in the future, would give evidence for interactions beyond extended Standard Model



v

manifests itself most vividly
under the influence of
extreme external conditions:

- **dense background matter**
and
- **strong external electromagnetic fields**

**Инициативный проект РФФИ
№ 11-02-01509-а (2011-2013 гг.)**

***«Взаимодействие элементарных частиц
в экстремальных внешних условиях»***

***9 ученых и аспирантов
(физический факультет и НИИЯФ МГУ,
ФКЦ ФИАН, ФИЗТЕХ,
Университета Дружбы народов)***

средний возраст исполнителей – 36 лет

- ***... работа с молодёжью ...***

- C.Giunti, A.Studenikin, **J.Phys.: Conf.Series** **203** (2010) 1012100, arXiv: 1006.xxxx
 I.Balantsev, Yu.Popov, A.Studenikin, **Nuov.Cim.B** (2009) arXiv: 0906.2391
- C.Giunti, A.Studenikin, **Phys.Atom.Nucl.** **73** (2009) 1089, arXiv: 0812.3646v5, Apr 12 2010
 A.Grigoriev, A.Studenikin, A.Ternov, **Phys.Atom.Nucl.** **72** (2009) 718
- A.Studenikin, **J.Phys.A: Math.Theor.** **41** (2008) 16402
- A.Studenikin, **J.Phys.A: Math.Gen.** **39** (2006) 6769; **Ann.Fond. de Broglie** **31** (2006) 289
- A.Studenikin, **Phys.Atom.Nucl.** **70** (2007) 1275; *ibid* **67** (2004) 1014
- A.Grigoriev, A.Savochkin, A.Studenikin, **Russ.Phys. J.** **50** (2007) 845
- A.Grigoriev, S.Shinkevich, A.Studenikin, A.Ternov, I.Trofimov, **Russ.Phys. J.** **50** (2007) 596
- A.Studenikin, A.Ternov, **Phys.Lett.B** **608** (2005) 107; **Grav. & Cosm.** **14** (2008)
- A.Grigoriev, A.Studenikin, A.Ternov, **Phys.Lett.B** **622** (2005) 199
Grav. & Cosm. **11** (2005) 132 ; **Phys.Atom.Nucl.** **69** (2006) 1940
- K.Kouzakov, A.Studenikin, **Phys.Rev.C** **72** (2005) 015502
- M.Dvornikov, A.Grigoriev, A.Studenikin, **Int.J Mod.Phys.D** **14** (2005) 309
- S.Shinkevich, A.Studenikin, **Pramana** **64** (2005) 124
- A.Studenikin, **Nucl.Phys.B** (Proc.Suppl.) **143** (2005) 570
- M.Dvornikov, A.Studenikin, **Phys.Rev.D** **69** (2004) 073001
Phys.Atom.Nucl. **64** (2001) 1624
Phys.Atom.Nucl. **67** (2004) 719
JETP **99** (2004) 254; **JHEP** **09** (2002) 016
- A.Lobanov, A.Studenikin, **Phys.Lett.B** **601** (2004) 171; *ibid* **564** (2003) 27, **515** (2001) 94
- A.Grigoriev, A.Lobanov, A.Studenikin, **Phys.Lett.B** **535** (2002) 187
- A.Egorov, A.Lobanov, A.Studenikin, **Phys.Lett.B** **491** (2000) 137

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Dedicated to the 300th Anniversary of the birth of Mikhail Lomonosov

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Moscow, August 18 - 24, 2011

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Tests of Standard Model & Beyond
Neutrino Physics
Astroparticle Physics
Gravitation and Cosmology
Developments in QCD (Perturbative and Non-Perturbative Effects)
Heavy Quark Physics
Physics at the Future Accelerators

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ON PROBLEMS OF INTELLIGENTSIA
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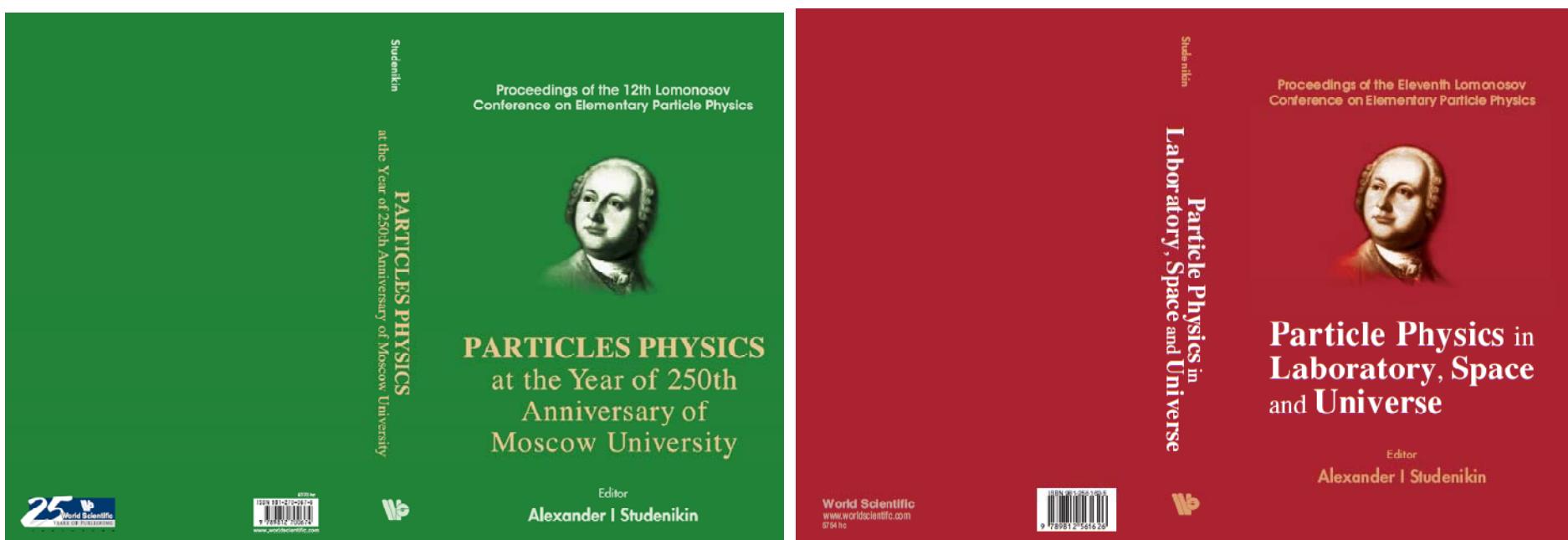
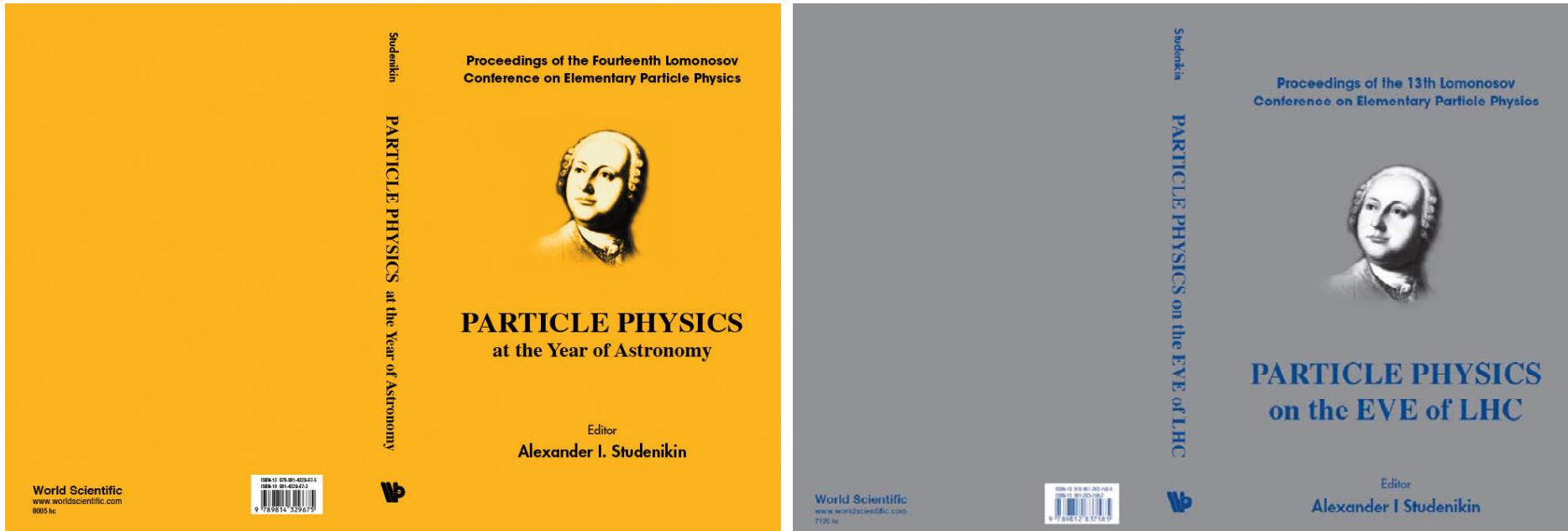
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*16th Lomonosov Conference on Elementary Particle Physics
Faculty of Physics. MSU, Moscow, August 22-28, 2013*



*August 22, 2013
is the centenary of
Bruno Pontecorvo birth*

- One of the focuses of 16LomCon programme is planned to be neutrino and astroparticle physics

*Бруно Понтекорво
1913-1993*

Ограничения на массу нейтрино

Осцилляторные эксперименты позволяют определять только разности квадратов масс нейтрино.

$$\Delta m_{\text{SOL}}^2 = \Delta m_{21}^2,$$

$$\Delta m_{\text{ATM}}^2 \simeq |\Delta m_{31}^2| \simeq |\Delta m_{32}^2|$$

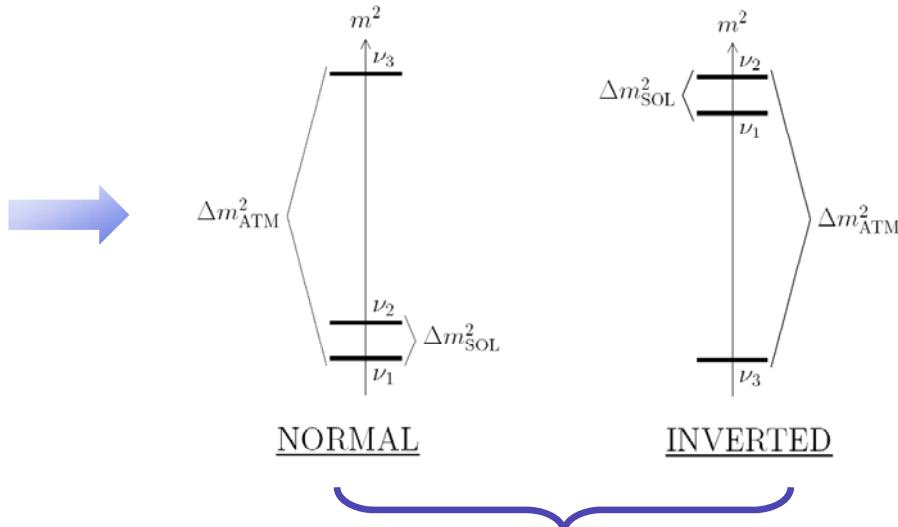
$$\Delta m_{\text{ATM}}^2 \simeq 30 \Delta m_{\text{SOL}}^2$$



Квазивырожденный спектр:

$$m_3 \gtrsim m_2 \gtrsim m_1 \gg \sqrt{\Delta m_{\text{ATM}}^2} \simeq 5 \times 10^{-2} \text{ eV}$$

$$(m_2 \gtrsim m_1 \gtrsim m_3)$$



Различаются знаком Δm_{31}^2

- Бета-распад: $m_{\nu_e} \simeq \sqrt{\sum_{k=1,2,3} |U_{ek}|^2 m_k^2} < 2.3 \text{ eV} \quad (95\% \text{ C.L.})$

- Космологические наблюдения: $\sum m_\nu < 0.2 - 0.4 \text{ eV} \quad (95\% \text{ C.L.})$

- Двойной безнейтринный бета-распад: $m_{e_{2\beta}} = \left| \sum_{k=1,2,3} U_{ek}^2 m_k \right| < 0.3 - 0.5 \text{ eV}$



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

$$\Lambda_\mu(q) = f_Q(q^2) \gamma_\mu + f_M(q^2) i \sigma_{\mu\nu} q^\nu - f_E(q^2) \sigma_{\mu\nu} q^\nu \gamma_5 + f_A(q^2) (q^2 \gamma_\mu - q_\mu q^\nu) \gamma_5$$

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 $\implies f_E = 0$,
- 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 \implies three form factors are real: $Im f_Q = Im f_M = Im f_A = 0$.



Majoran ν

- 1) from CPT invariance (regardless CP or ~~CP~~).

$$f_Q = f_M = f_E = 0$$



...as early as 1939, W.Pauli...

EM properties \implies a way to distinguish Dirac and Majorana ν

Effective Lagrangian for the spin component of ν vertex

$$L = \frac{1}{2} \bar{\nu}_j \sigma_{\eta\xi} (\beta_{ij} + \varepsilon_{ij} \gamma_5) \nu_i F^{\eta\xi} + \text{h.c.},$$

... beyond
SM...

magnetic and electric moments

which couple together mass eigenstates

$(\nu_i)_L$ and $(\nu_j)_R$  change of the helicity states

e.m. field tensor

- $\nu_i = \nu_j$  diagonal moments
- $\nu_i \neq \nu_j$  transitional moments

• $\varepsilon_{ii} = \beta_{ii} = 0$ for Majorana ν

E.M. 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 $p^2 = m_i^2$, $p'^2 = m_j^2$:

$$\langle \psi_j(p') | J_\mu^{\text{EM}} | \psi_i(p) \rangle = \bar{u}_j(p') \Lambda_\mu(q) u_i(p)$$

... beyond
SM...

and

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



form factors are matrices in mass eigenstates space.



Dirac

(off-diagonal case $i \neq j$)

Majorana

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

2) CP invariance + hermiticity

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

are relatively real (no relative phases).

1) CP invariance + hermiticity

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

or

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

... quite different
EM properties ...

3.7

Neutrino radiative decay

$$\nu_i \rightarrow \nu_j + \gamma$$

$$m_i > m_j$$

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

Radiative decay rate

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

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

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

- Radiative decay has been constrained from absence of decay photons:

1) reactor $\bar{\nu}_e$ and solar ν_e fluxes,

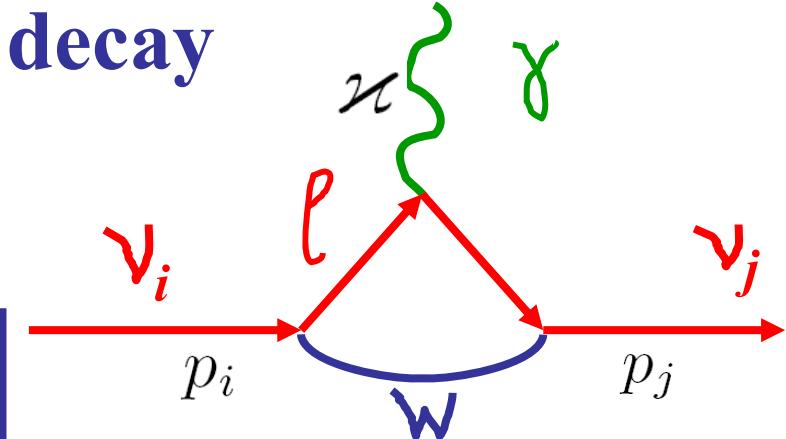
Raffelt 1999

2) SN 1987A ν burst (all flavours),

Kolb, Turner 1990;

3) spectral distortion of CMBR

Ressell, Turner 1990

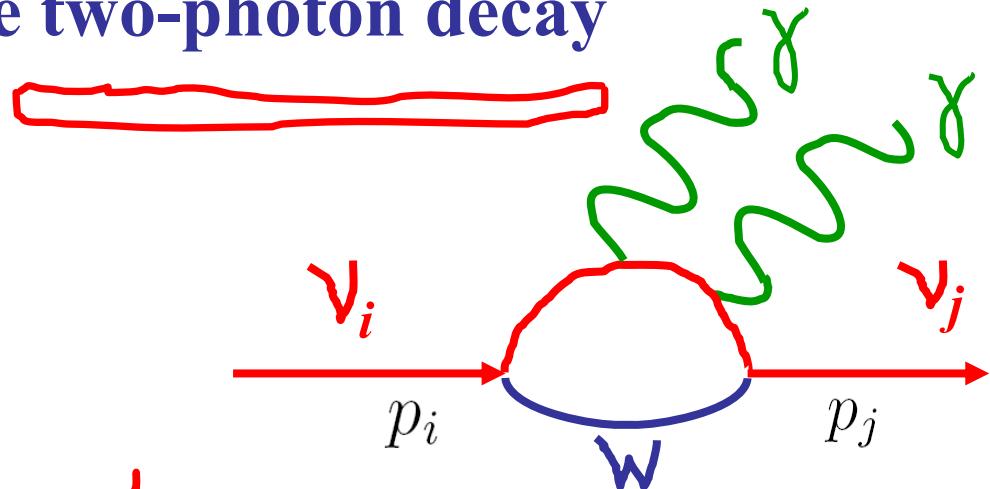


3.8

Neutrino radiative two-photon decay

$$\nu_i \rightarrow \nu_j + \gamma + \gamma$$

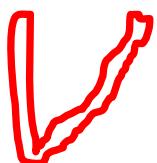
$$m_i > m_j$$



fine structure constant



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



... there is no GIM cancellation...

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

Nieves, 1983; Ghosh, 1984

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

3.9

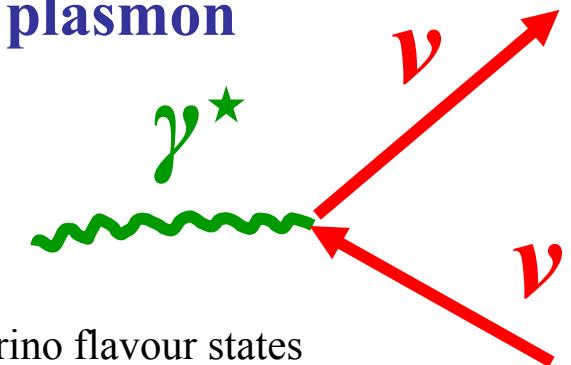
The tightest astrophysical bound on μ_ν

G.Raffelt,
PRL 1990

comes from cooling of red giant stars by plasmon decay

$$\gamma^* \rightarrow \nu \bar{\nu}$$

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



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

$$\Gamma_{\gamma \rightarrow \nu \bar{\nu}} = \frac{\mu^2}{24\pi} \frac{(\omega^2 - k^2)^2}{\omega} = 0 \text{ in vacuum } \omega = k$$

In the classical limit γ^*

- like a massive particle with $\omega^2 - k^2 = \omega_{pl}^2$

Energy-loss rate per unit volume

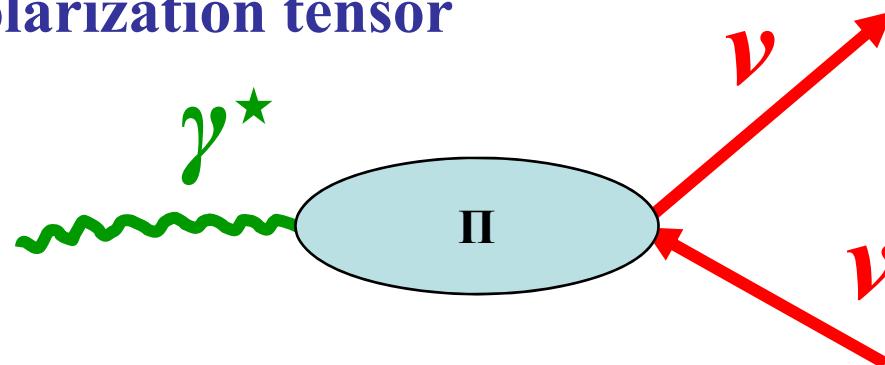
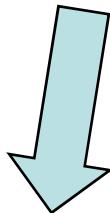
$$\mu^2 \rightarrow \sum_{a,b} \left(|\mu_{a,b}|^2 + |\epsilon_{a,b}|^2 \right)$$

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

distribution function of plasmons

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

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 ($\leq 5\%$ in Q)



*... best
astrophysical
limit on
 ν magnetic moment...*

$$\mu \leq 3 \times 10^{-12} \mu_B$$

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

**G.Raffelt,
PRL 1990**

Astrophysics bounds on μ_ν

$$\mu_\nu(\text{astro}) < 10^{-10} - 10^{-12} \mu_B$$

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.

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

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

3.10

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

- Constraints on neutrino **millicharge** from **red giants cooling**

Interaction Lagrangian

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

Decay rate

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

...to avoid helium ignition in
low-mass **red giants**

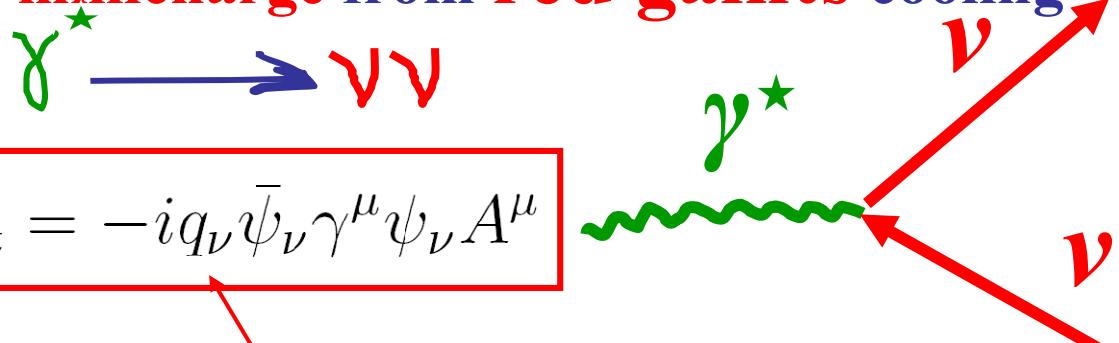
*Halt, Raffelt,
Weiss, PRL 1994*

$$q_\nu \leq 2 \times 10^{-14} e$$

... absence of anomalous energy-dependent
dispersion of SN1987A ν signal, most model independent

● ... from “charge neutrality” of neutron...

$$q_\nu \leq 3 \times 10^{-21} e$$



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