

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

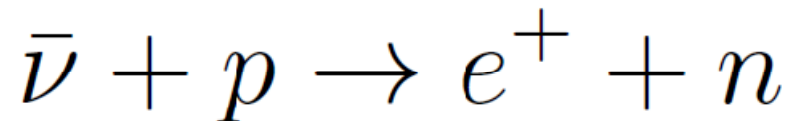
- Квантовый подход к описанию нейтрино в веществе

Необычные и удивительные свойства



«незаметная» или «мелкая» частица :

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



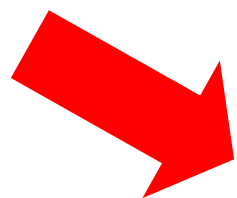
$$\sigma \sim 10^{-43} \text{ cm}^2$$

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

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

... 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 ✓
в современной физике*

«ОКНО»
В
«Новую физику»

Взаимодействия элементарных частиц

«Новая физика»

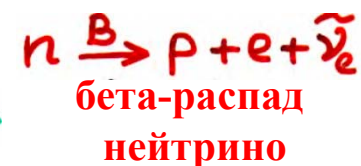
Стандартная модель

Электрослабое взаимодействие

- Электромагнитное взаимодействие



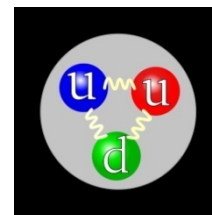
- Слабое взаимодействие



- Сильное взаимодействие

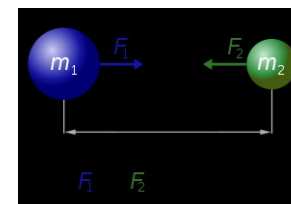


протон $p =$

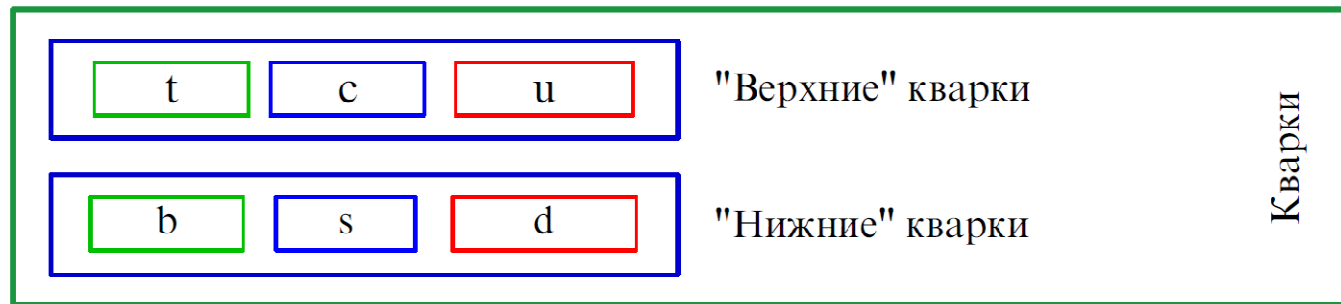
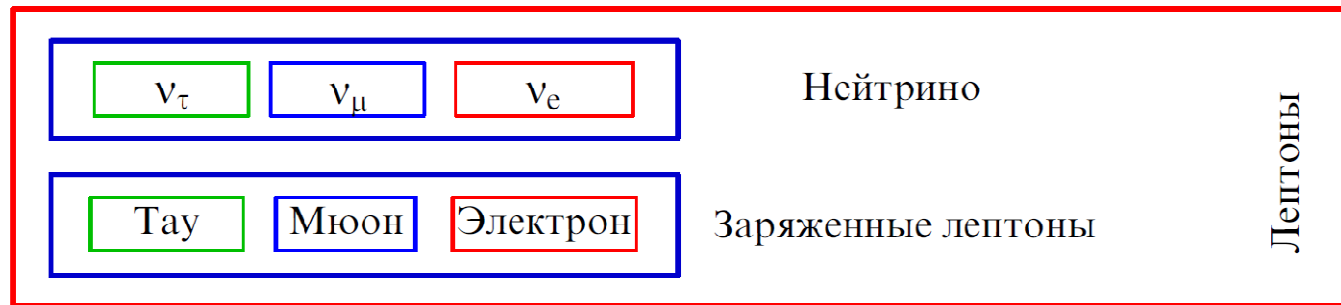


три кварка,
связанные
глюонами

- Гравитационное взаимодействие



Элементарные частицы Стандартной модели



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

Бозон Хиггса

Окружающий нас мир (обычно) $\Rightarrow$ атомы + свет

p (uud) n (udd) e

γ

роль нейтрино

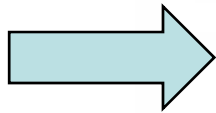
?

История нейтрино



познание фундаментальных
законов природы:

Нейтрино – уникальная элементарная частица



Вольфганг Паули
(1890-1958)

в 1930 году выдвинул
гипотезу
о существовании
нейтрино,
назвав эту частицу
«**нейтроном**»

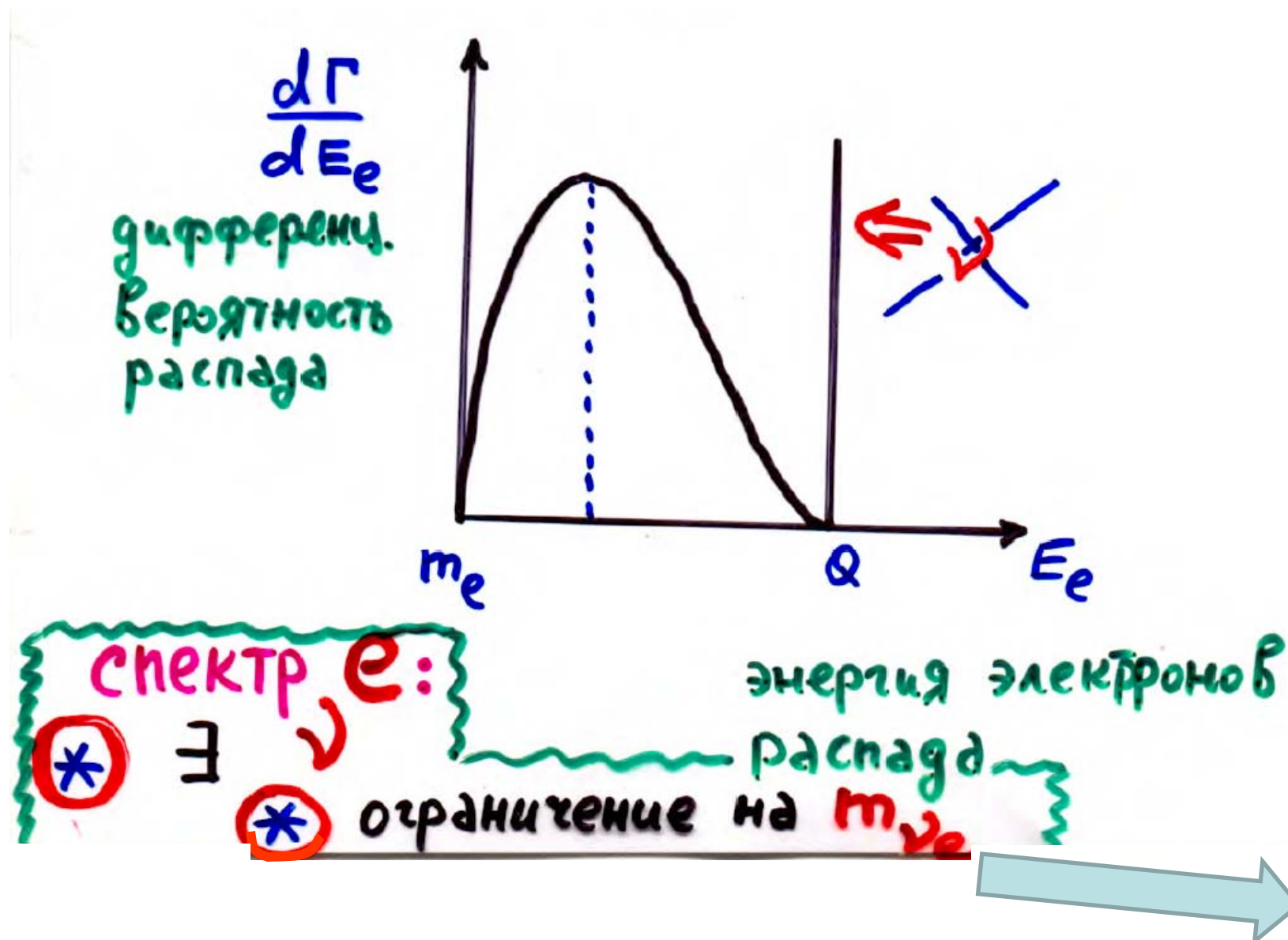
В. Паули (1930г.) – открытое письмо
Тюбингенскому физическому
обществу:

ν – «нейтрон»
 $m_\nu < m_e$ или 0
 $S = 1/2$

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

Существование ν «спасает»
закон сохранения энергии в
 β -распаде ядер Н. Бор ...

Спектр энергий электронов распада



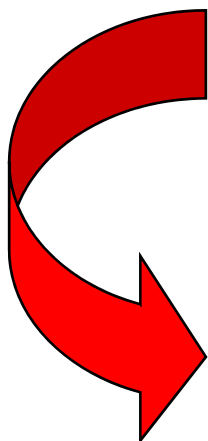


История **нейтрино** – череда парадоксов и сюрпризов !

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 $\bar{\nu}$:
 $\bar{\nu} + p \rightarrow n + e^+$ (1956)
Ф. Райнес - Н.н. 1996
С. Кован

- Экспер. открытие
 $\nu_\mu \neq \nu_e$:

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

$\downarrow \mu, \cancel{e}$

Л. Ледерман
М. Цувару
Дж. Стейнберг

} - Н.н.
1988

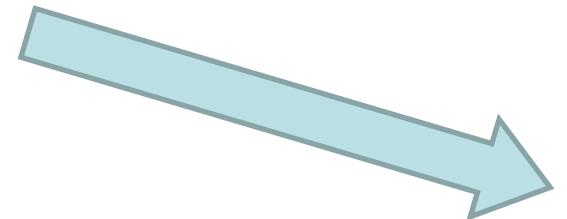
- DONUT (ДАНУТ, 2000 г.)
(Direct Observation
of the NU Tau)

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

- готовятся новые
измерения 

эффективная масса



$m_{\nu_e} < 2.2 \text{ эВ}$

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

... это очень мало :

$$m_n = 939,6 \text{ МэВ}$$

$$m_p = 938,3 \text{ МэВ}$$

$$m_e = 0,5 \text{ МэВ}$$

 $m_{\nu_\mu} < 170 \text{ keV}$

 $m_{\nu_\tau} < 18.2 \text{ MeV}$

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

$$(\pi^+ \rightarrow \mu^+ + \nu_\mu)$$

$$(\tau^\pm \rightarrow \nu_\tau + \pi^\pm + \pi^\pm + \pi^\mp)$$

Эксперимент по прямому измерению массы нейтрино КАТРИН

KATRIN
Karlsruhe Tritium





История нейтрино

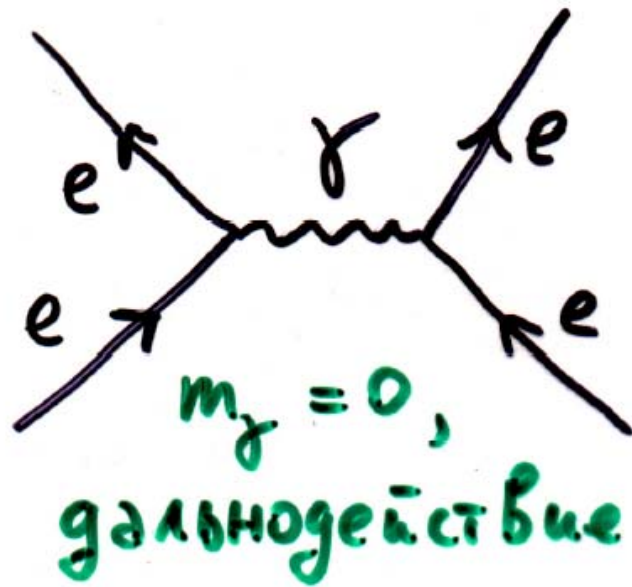


познание фундаментальных
законов природы:

* Теория слабых взаимодействий

Э. Ферми (1933) — аналогия с
моделью Дирака

электромагнитных
взаимодействий



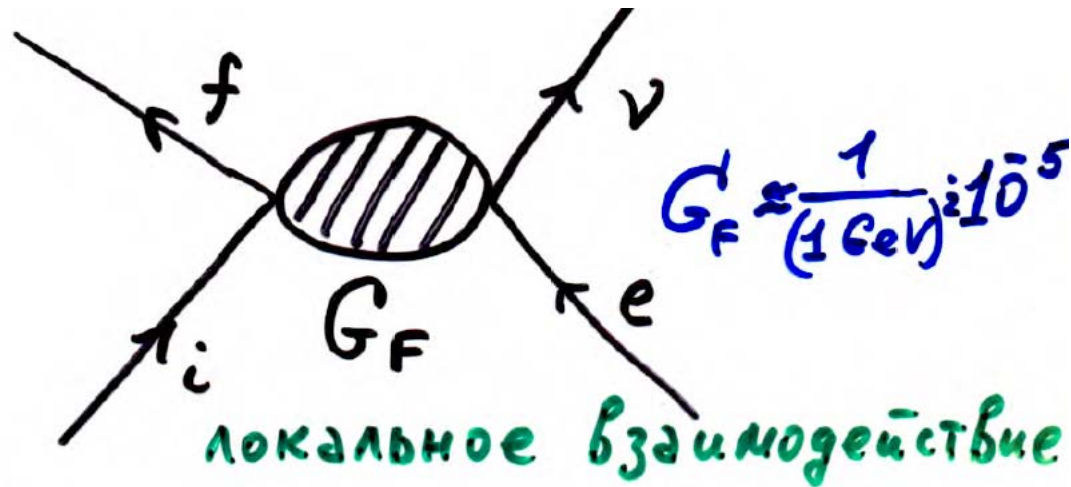
"ТОК" $\times$ "ТОК"





Энрико Ферми
(1901-1954)

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



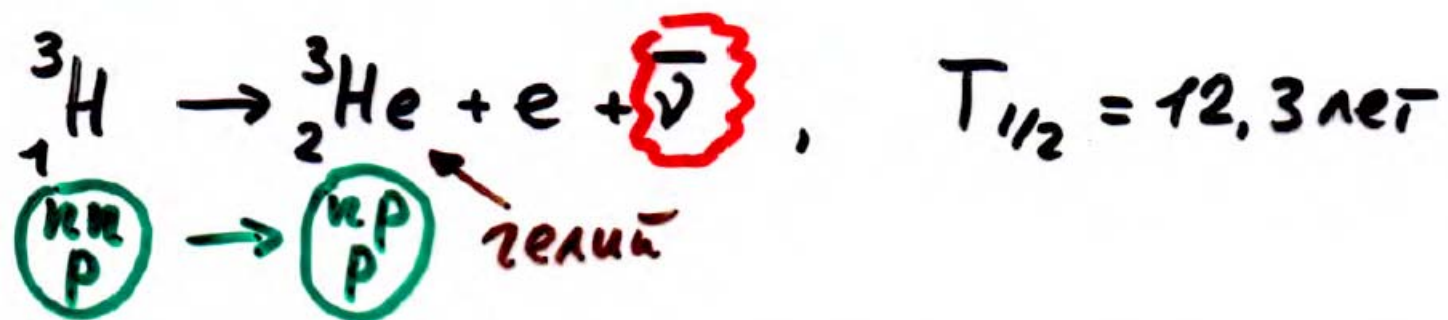
$$H = \frac{G_F}{\sqrt{2}} \psi_p^\dagger O_\mu \psi_n \psi_e^\dagger O^\mu \psi_\nu.$$

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

$$(A, z) \rightarrow (A, z \pm 1) + e^{\mp} + \nu(\bar{\nu})$$

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

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

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

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



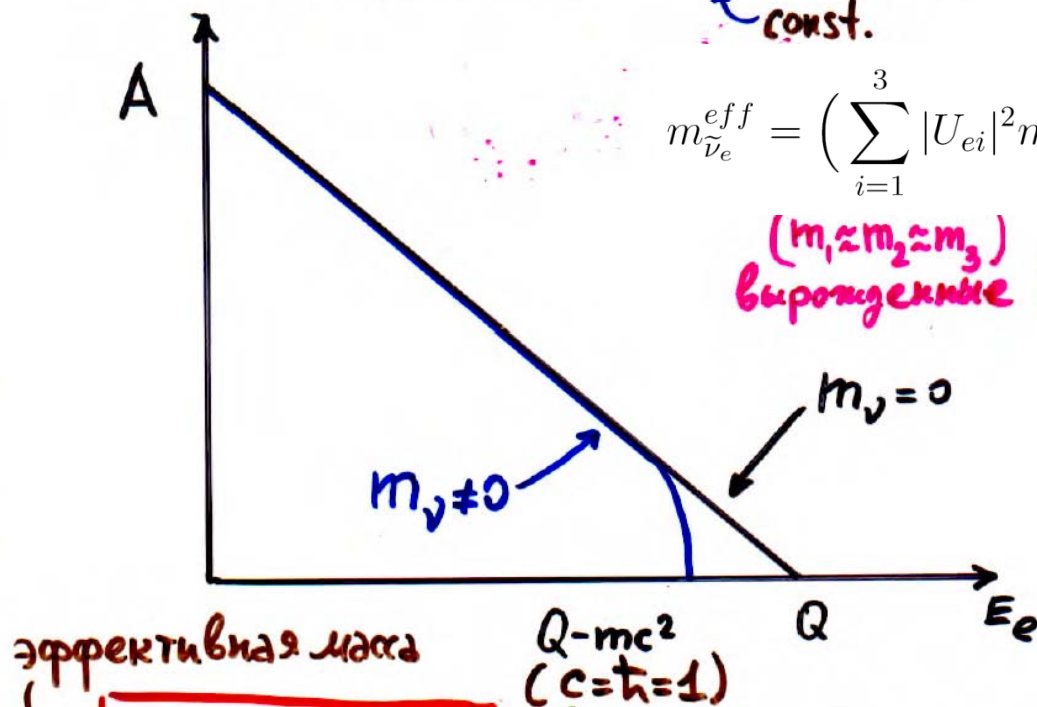
$$A = \sqrt{N(p_e) / p_e^2 F(z, E_e)} = B \cdot (Q - E_e)$$

const.

энергия кинетическая
электрона

$$m_{\tilde{\nu}_e}^{eff} = \left(\sum_{i=1}^3 |U_{ei}|^2 m_i^2 \right)^{\frac{1}{2}}$$

$(m_1 \approx m_2 \approx m_3)$
вырожденные ν



История нейтрино



познание фундаментальных
законов природы:

несохранение

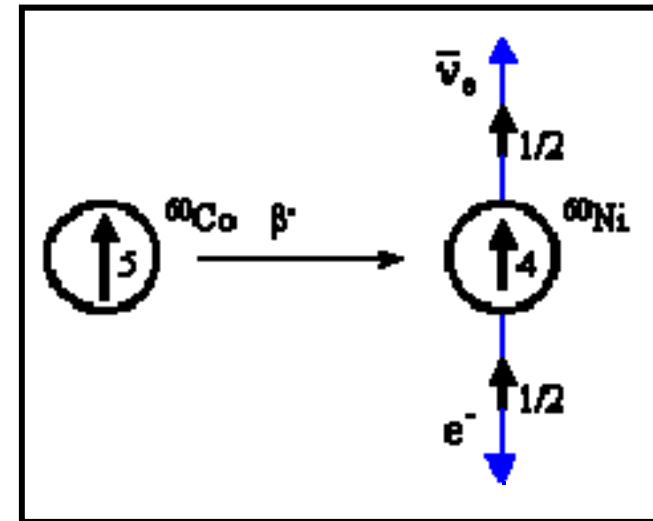
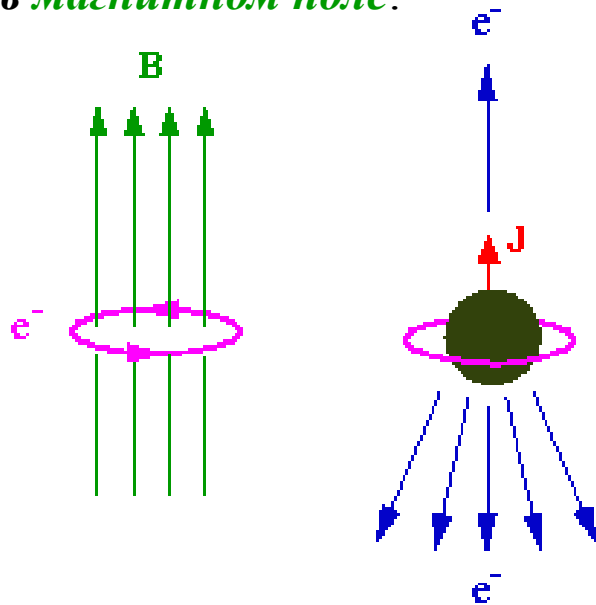
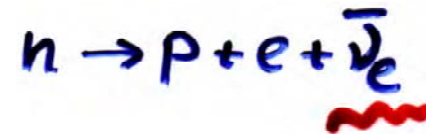
пространственной чётности

в слабых взаимодействиях



Несохранение пространственной четности в слабых взаимодействиях (эксперимент Ву и др., 1957 г.)

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

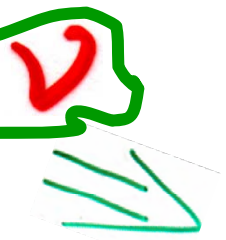


Взглянув на процесс через зеркало
– такого процесса **нет в природе!**

несохранение четности

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

свойства



Нейтрино, являясь

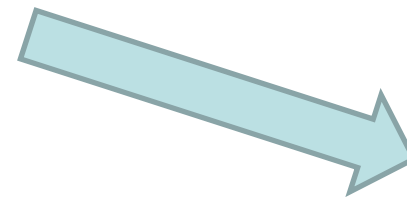
практически «незаметной» частицей и крайне

слабо взаимодействующей с другими

элементарными частицами, вместе с тем

играет чрезвычайно важную роль

на всех этапах эволюции нашей Вселенной



Без  невозможно объяснить:

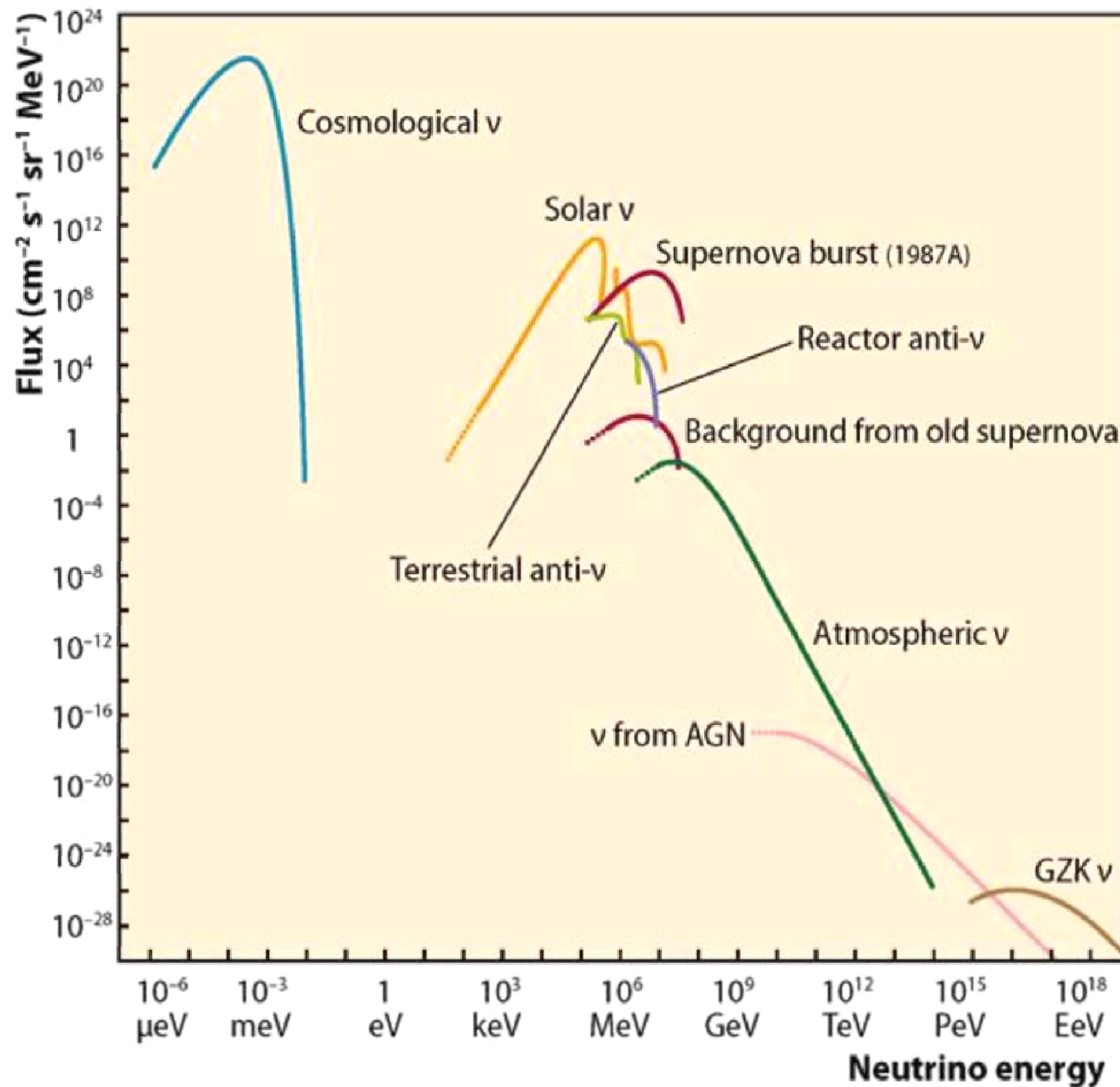
- процессы на ранней стадии эволюции Вселенной,*
- остывание звезд,*
- возникновение и разнообразие химических элементов,*
- как работает Солнце, дающее энергию для нашего существования на Земле*

Мы знаем, что

нейтрино было всегда и

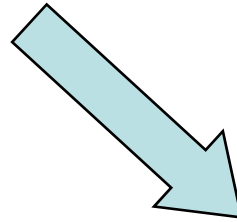
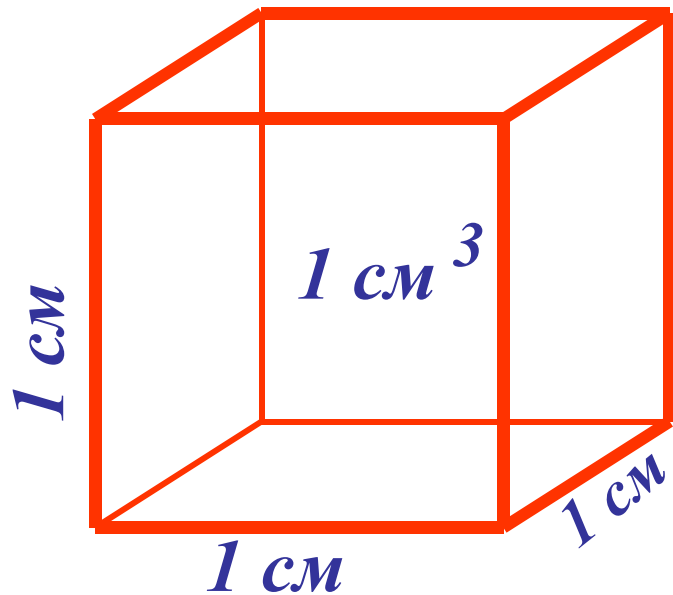
присутствует везде

Спектры
энергий
потоков
нейтрино



В каждом кубическом сантиметре
- 300 нейтрино

от Большого взрыва

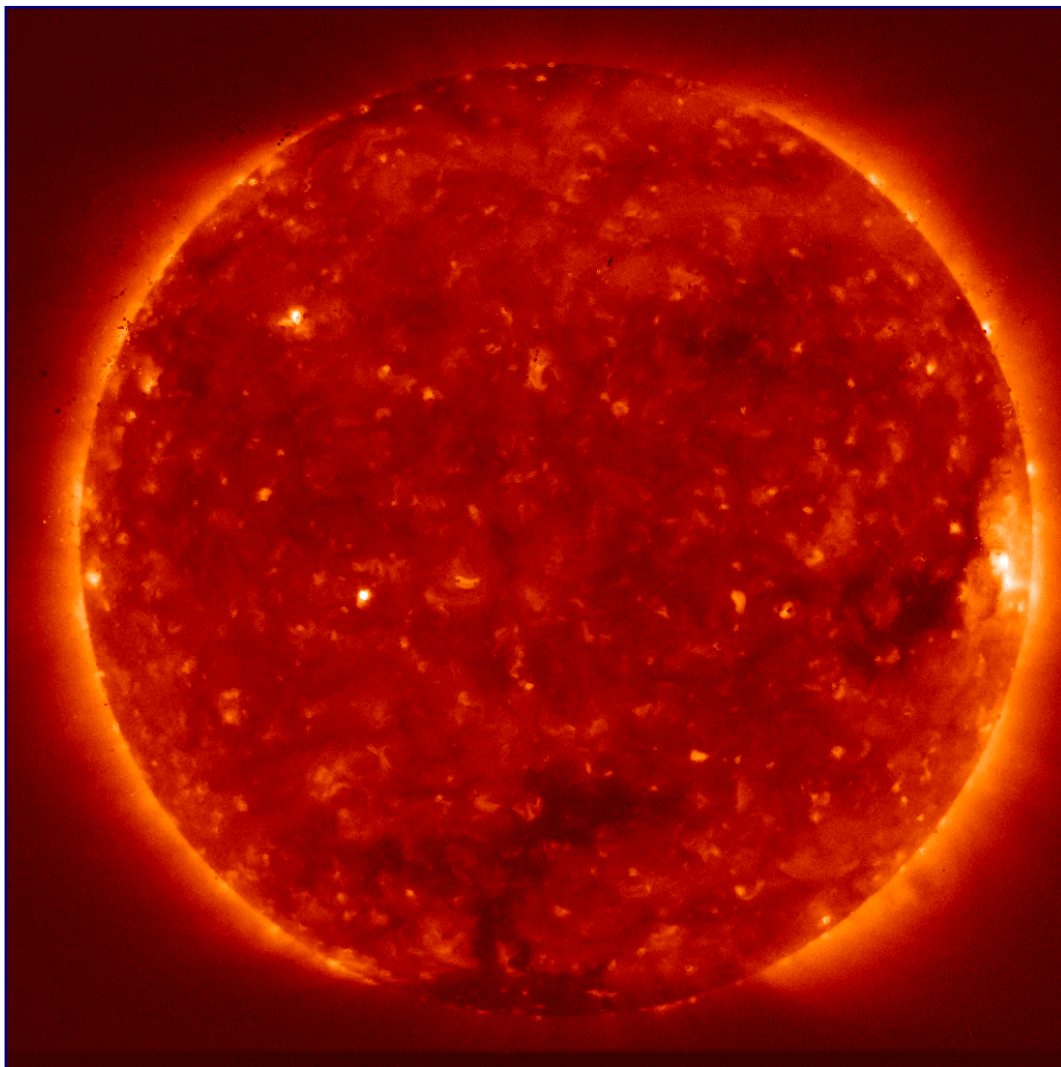


или
30 000 000 нейтрино
в каждом из нас



вездесущи и неуловимы !

*Солнце – тоже источник **нейтрино***

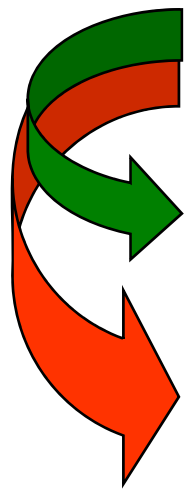


$$R_{\odot} = 7 \cdot 10^8 \text{ м}$$

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

**Плотность
ядра ($1/4 R_{\odot}$)**

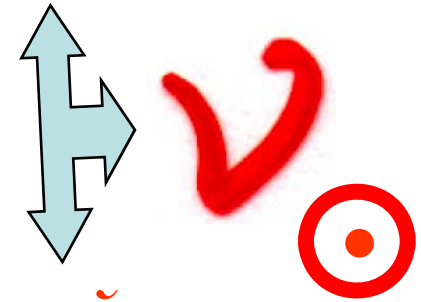
$$\rho = 20\text{-}158 \text{ г/см}^3$$



Реакция ядерного синтеза внутри Солнца

*генерация **тепловой энергии** и*

*интенсивного потока электронных **нейтрино**:*



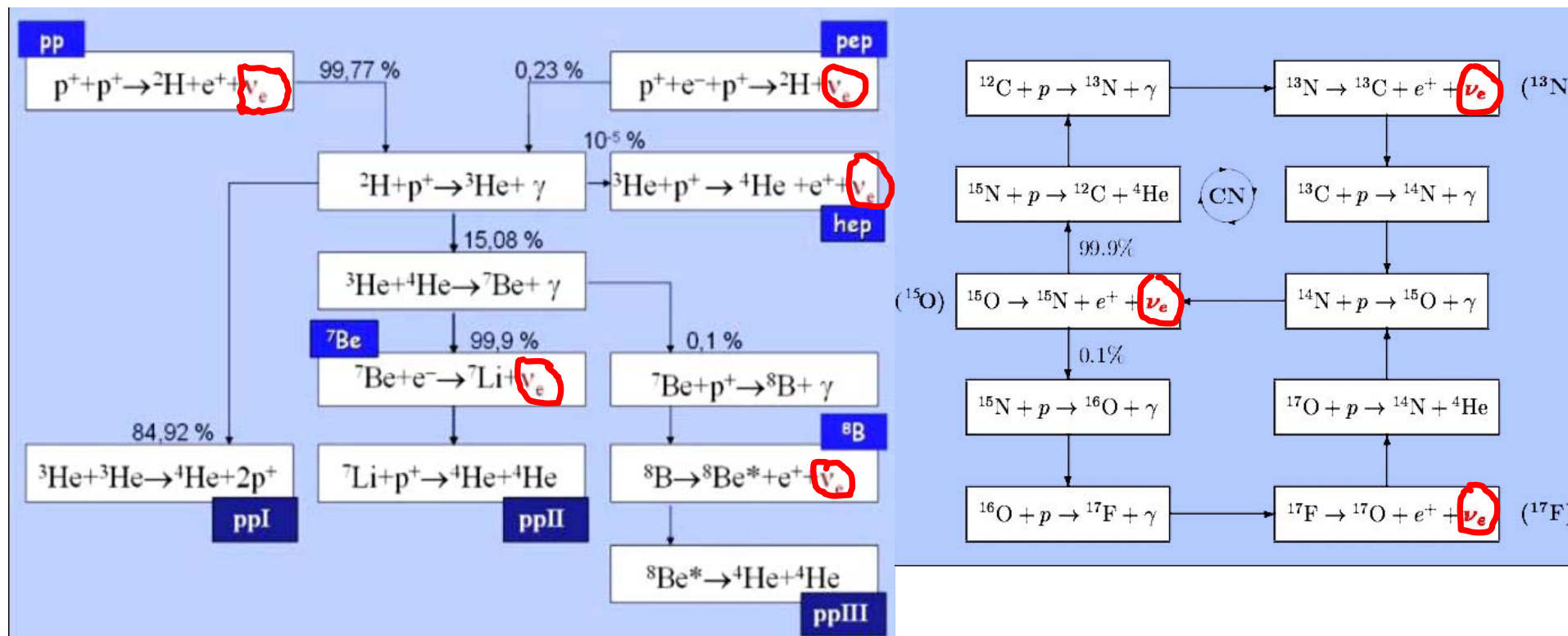
*E_{ν} – энергия, которую уносят **нейтрино**,
со средним значением (E_{ν}) $\sim 0.6 \text{ МэВ}$*

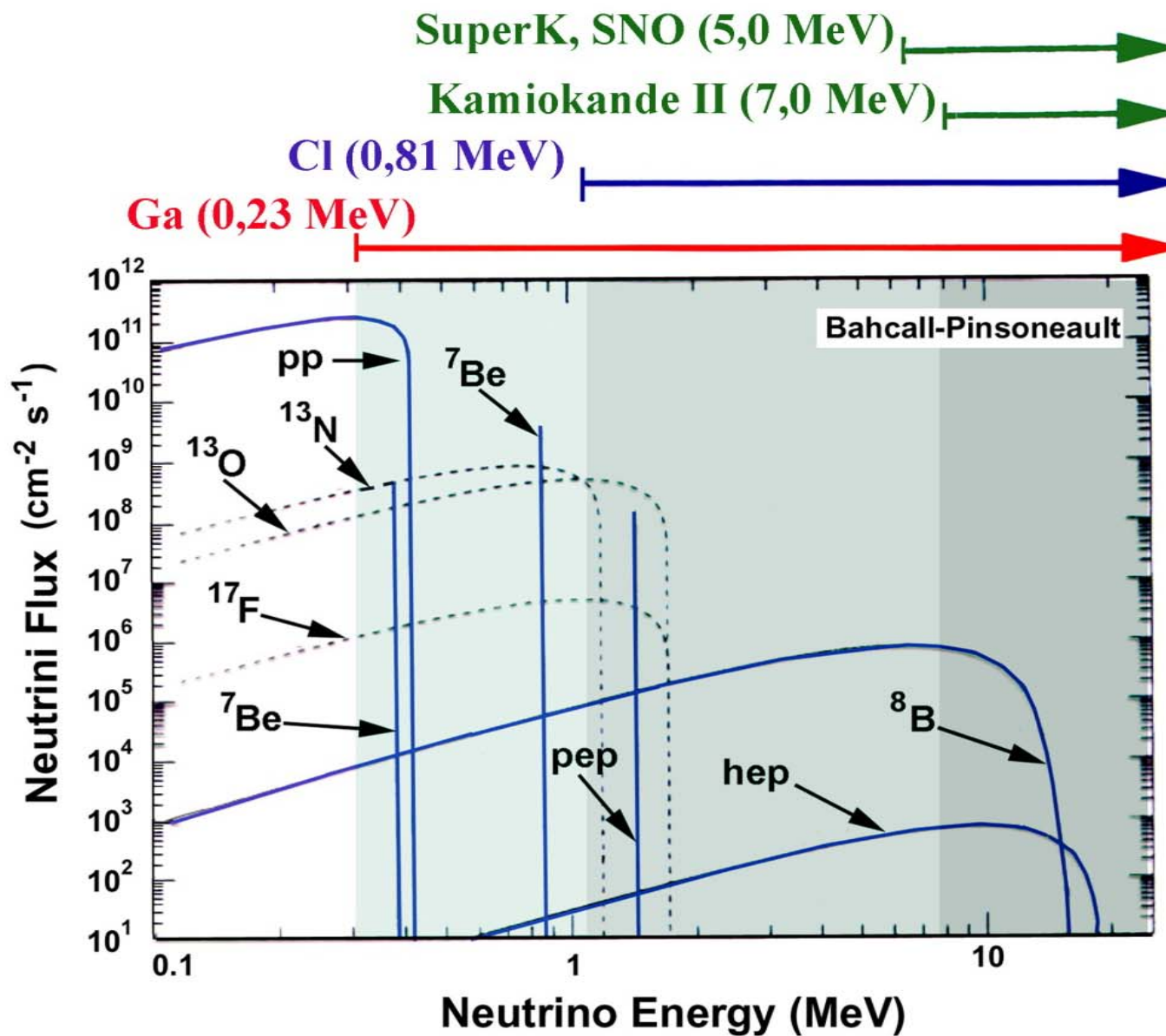


Механизмы генерации энергии и нейтрино в Солнце

pp цепочка реакций (> 99 % энергии)

CNO цикл





✓

«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 для нас ?



... наш
обычный
вид ...



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



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

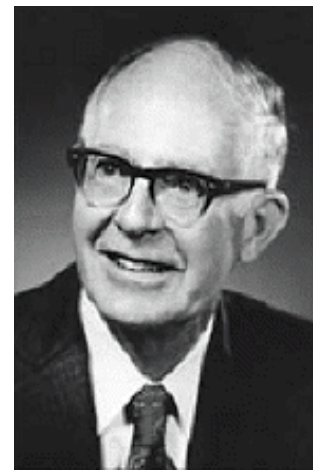
Только один человек (через которого прошло нейтрино) из
 $10\ 000\ 000\ 000\ 000\ 000\ 000\ 000 = 10^{19}$ почувствует это .

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



... нет проблемы с

солнечными **нейтрино** ?



Рей Дэвис
(1914-2006)

Проблемы = парадоксы и сюрпризы :

Число



в детекторе



$$= \frac{1}{3}$$

Число



Стандартная **солнечная** модель





SAGE (ИЯИ РАН)

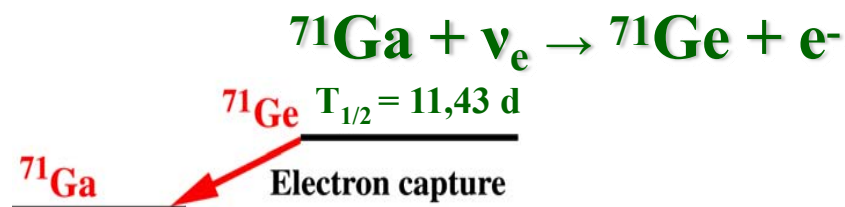
Баксанская нейтринная обсерватория, Северный Кавказ, 3.5 км от входа в горизонтальный туннель
Глубина заложения 2100 м (4700 м.в.э.)

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 $\sim 90\%$



эксперимент

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

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

теория

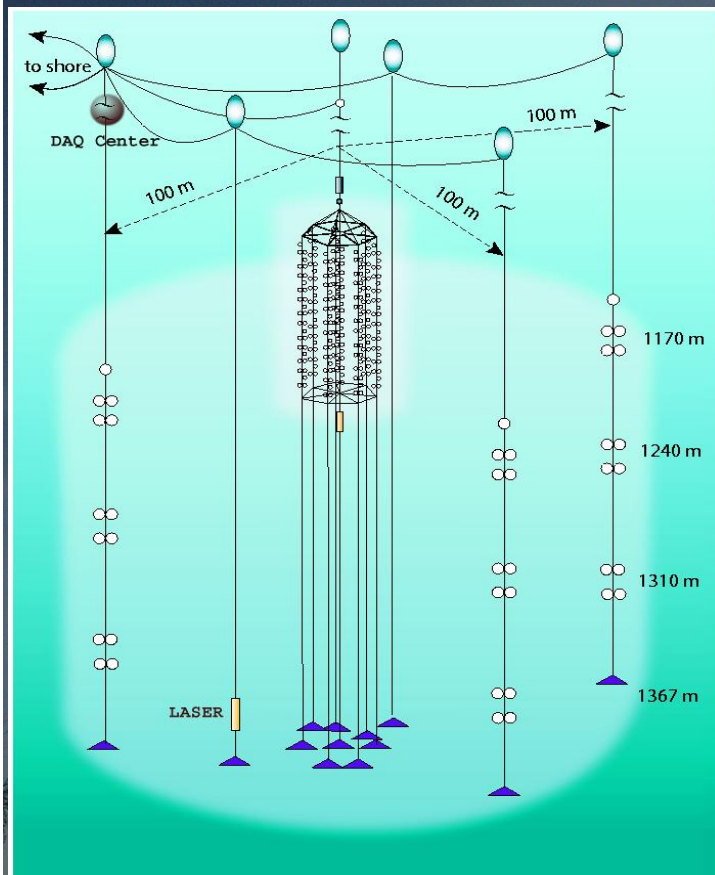
SSM:(Ga) $127.9^{+8.1}_{-8.2}$ $120.5^{+6.9}_{-7.1}$

BPS08(GS)

BPS08(AGS)

Наличие дефицита солнечных нейтрино во всем диапазоне энергии нейтрино !

Байкальская нейтринная обсерватория (ИЯИ РАН)



~ 3.6 km to shore,
1070 m depth



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

NT200: 8 strings (192 optical modules)
Height x $\varnothing$ = 70m x 40m, $V_{\text{inst}}=10^5\text{m}^3$
Effective area: 1 TeV~2000m²
Eff. shower volume: 10 TeV~ 0.2 Mton

Status of NT200+

NT200+ is operating now in Baikal lake

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

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

Eff. shower volume: 10⁴ TeV ~ 10 Mton

→ ~4 times better sensitivity

→ Improve cascade reconstruction

NT200

Atmospheric muon
background

Magnetic
Monopoles

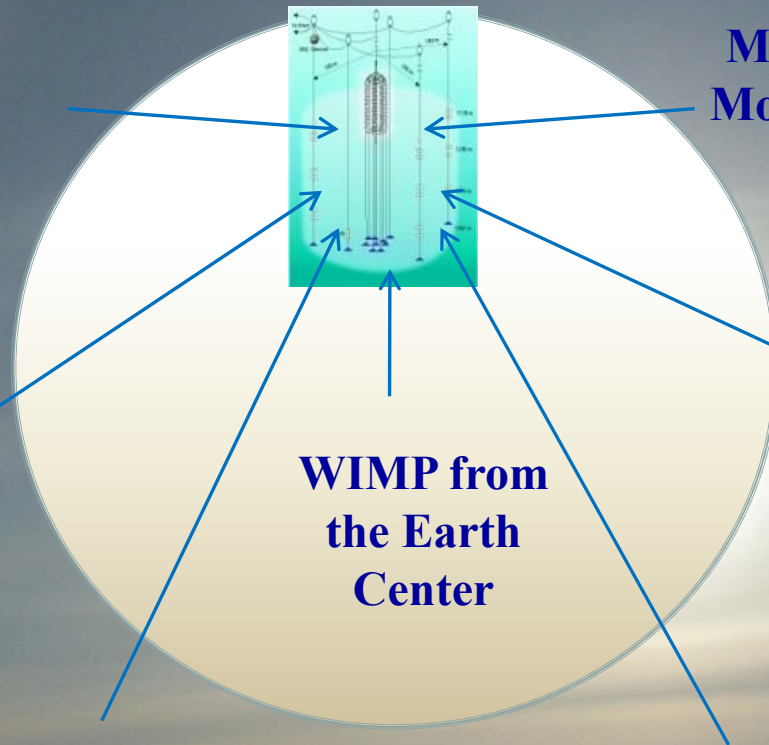
Atmospheric
neutrinos

WIMP from
the Earth
Center

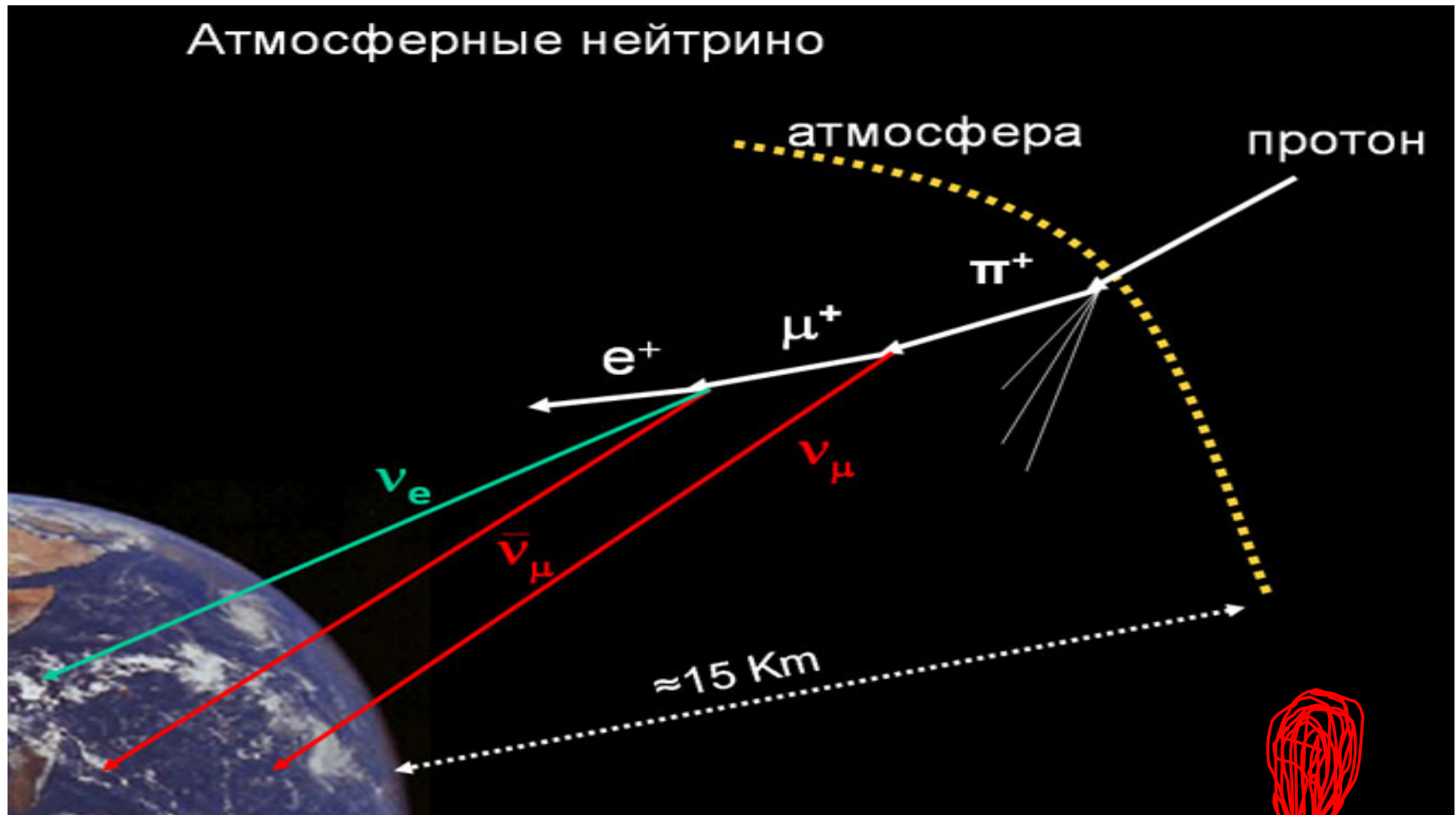
WIMP from
the Sun

Diffuse neutrino
flux

Neutrinos
from GRB



... 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

нейтрино

электрон

e



ν_e

электронное нейтрино

мюон

μ



ν_μ

мюонное нейтрино

тау-лептон

τ



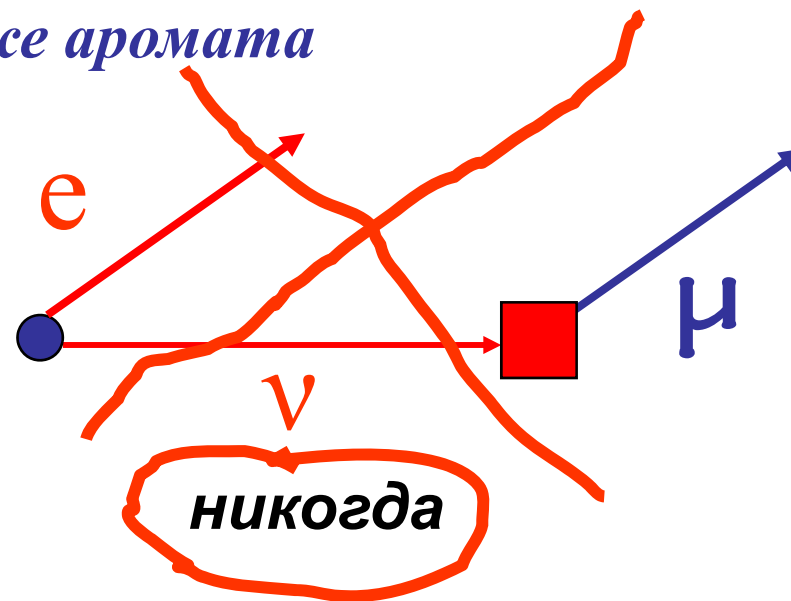
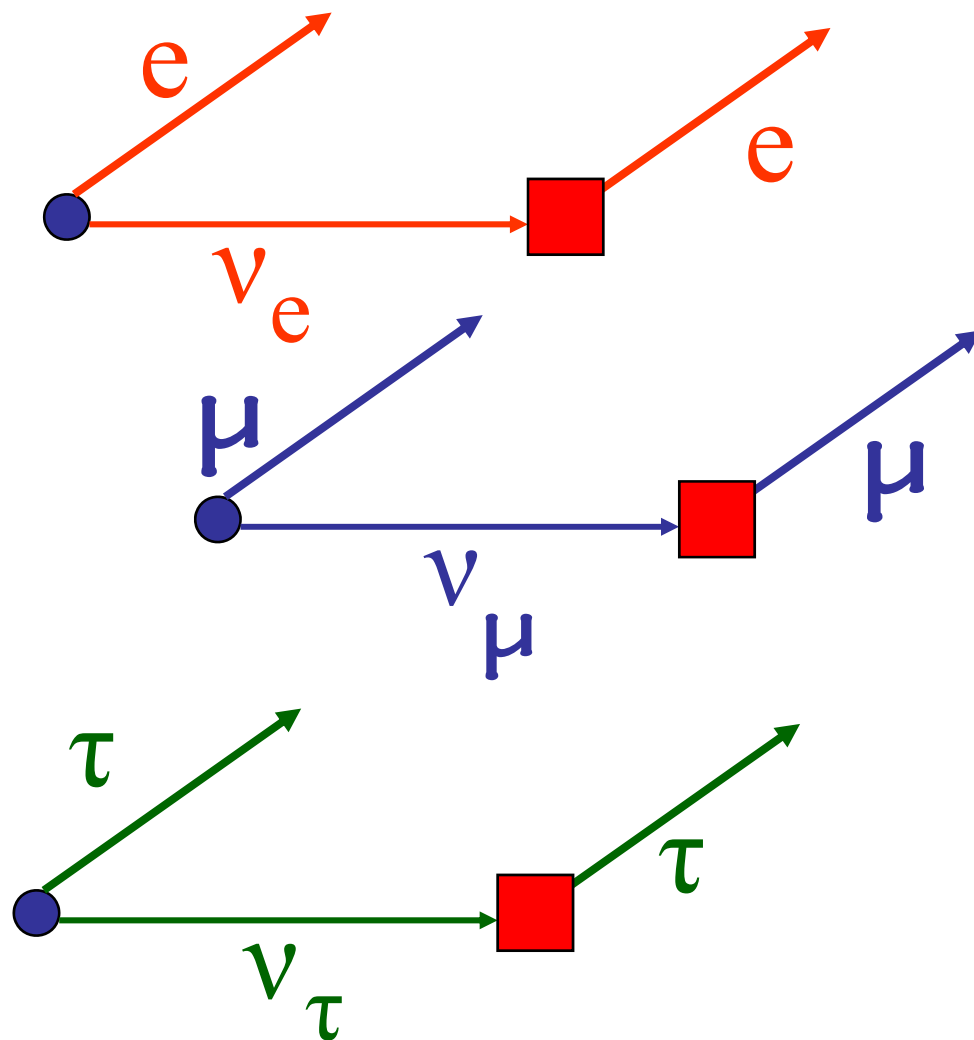
ν_τ

тау-нейтрино

Три типа частиц или три типа аромата или флейвора

Решение проблем ...

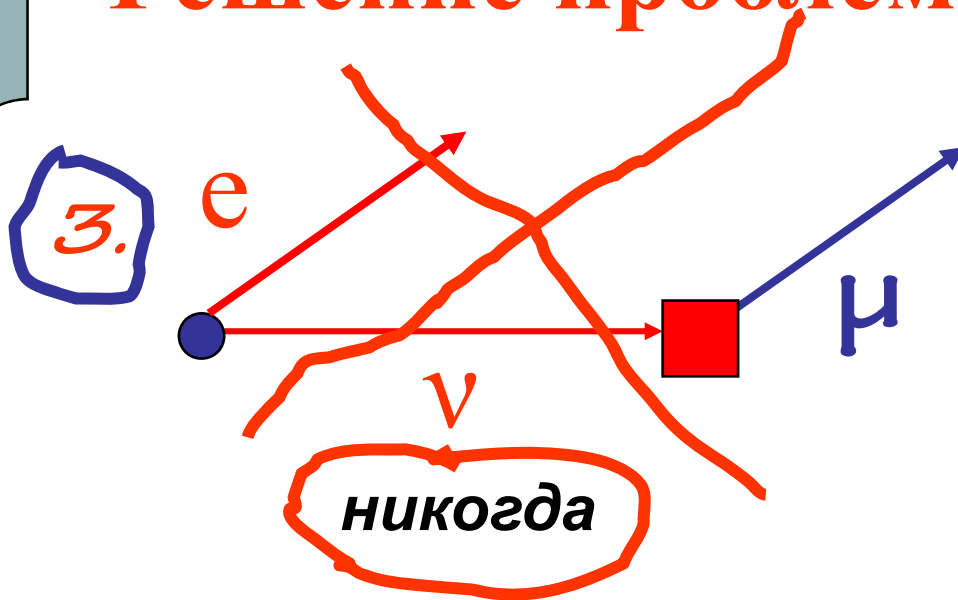
2. *Нейтрино определенного аромата взаимодействуют с заряженными лептонами того же аромата*



● источник нейтрино

■ детектор нейтрино

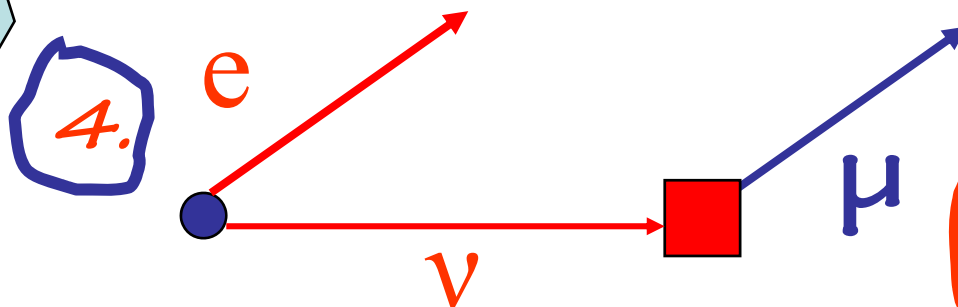
Решение проблем ...



*ароматы сохраняются,
ароматы не смешиваются*

*для малых расстояний
пролёта нейтрино*

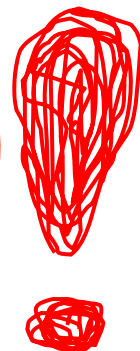
L/E



● 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* ...

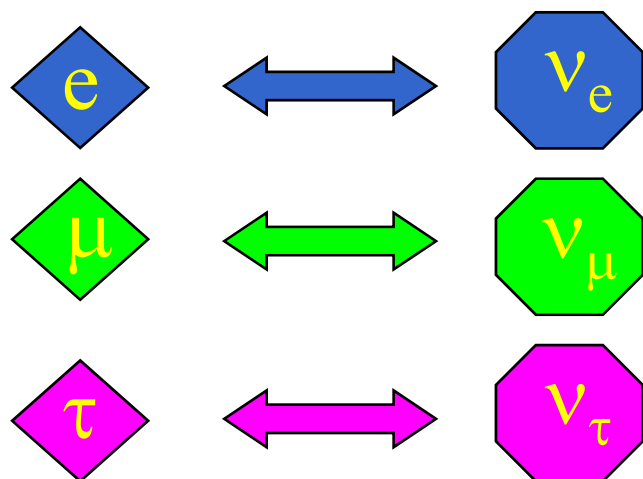
● *Нейтрино* может быть ν_e , а может – ν_μ ...

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

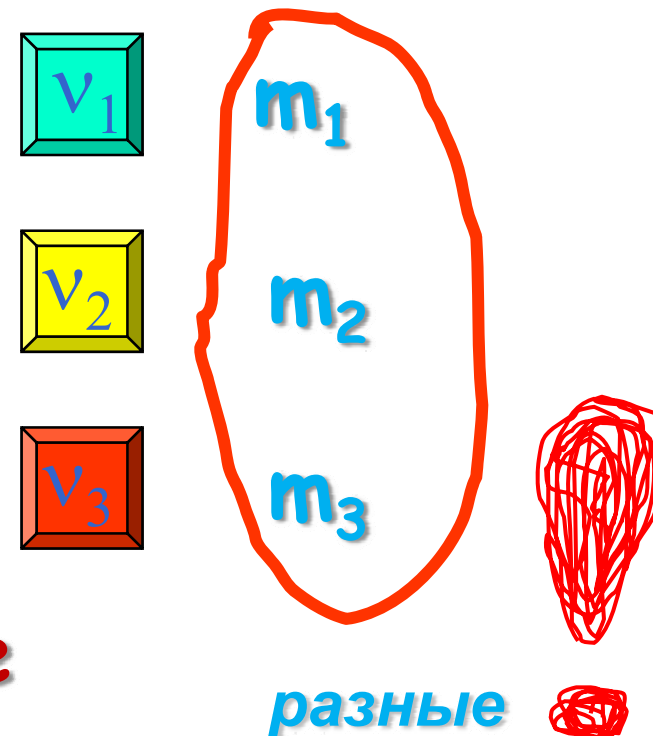


Нейтринные состояния

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:

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

neutrino oscillations (1957)

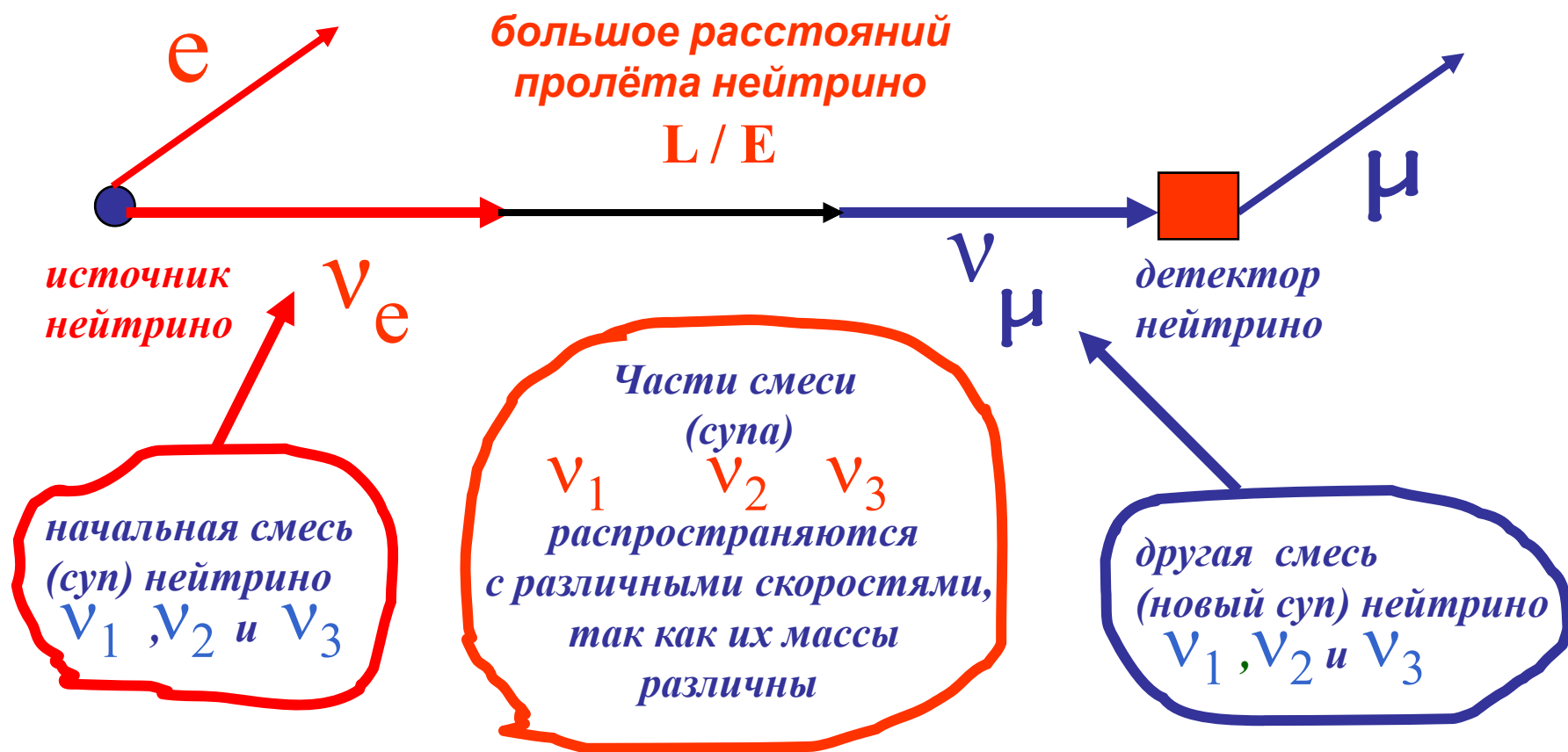
$$\nu \leftrightarrow \bar{\nu}$$



Бруно Понтекорво
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

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

В. Грибов, Б. Понтекорво (1969)
 С. Биленкий, Б. Понтекорво (1976)

* Осцилляции ν в вакууме

$$\underbrace{\nu^{\dagger} = \begin{pmatrix} \nu_e \\ \nu_{\mu} \end{pmatrix}}_{\substack{\text{состояния} \\ \text{взаимодействия}}} \longleftrightarrow \underbrace{\nu^P = \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}}_{\substack{\text{массовые состояния} \\ (m_1, m_2)}}$$

$\left(\begin{array}{l} \pi^+ \rightarrow \mu^+ + \nu_{\mu} \\ n \rightarrow p + e + \bar{\nu}_e \end{array} \right)$

$$\nu_e = \nu_1 \cos \theta_{\nu} + \nu_2 \sin \theta_{\nu}$$

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

угол смешивания
 нейтрино в
 вакууме

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

$$\nu_e = \nu_1 \cos \theta_\nu + \nu_2 \sin \theta_\nu$$

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

угол смешивания
нейтрино в
вакууме

матрица
смешивания

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

Эволюция пучка ν во времени (пространстве)

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

✓

$$P_{\nu_e \rightarrow \nu_\mu}(x) = \sin^2 2\theta_\nu \sin^2 \frac{\pi x}{L}$$

путь,
пройденный
нейтрино

энергия
нейтрино

Осциллирующее
нейтрино

амплитуда
осцилляций

$$L = \frac{4\pi E}{\Delta m^2}$$

$$\Delta m^2 = m_2^2 - m_1^2$$

длина осцилляций

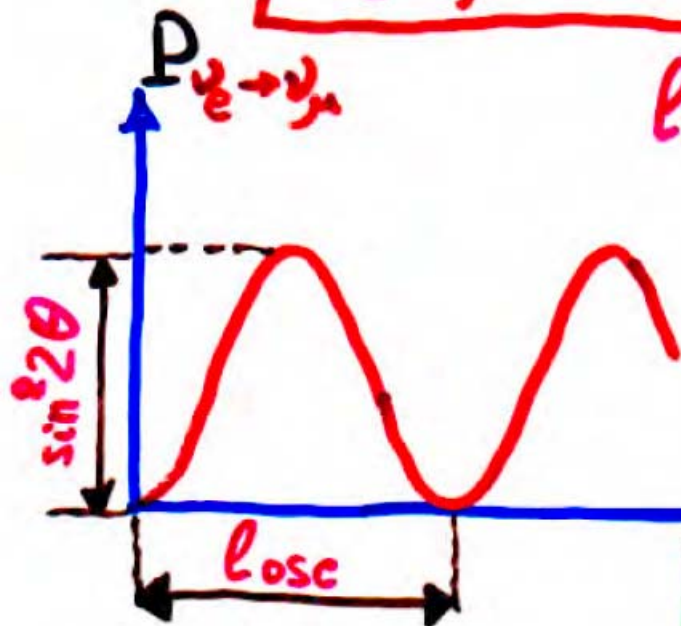
Типы экспериментов – детектирование
осцилляций по:

- ⊙ возникновению ν „нового“ флейвора ($\nu_e \rightarrow \nu_\mu$)
- ⊙ исчезновению ν „назального“ флейвора ($\nu_e \rightarrow \nu_\mu$).

Вероятность флейворных осцилляций:

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

$$\sin^2 \pi \frac{\chi}{l_{osc}}$$



$$l_{osc} = 4\pi \frac{E}{\Delta m^2} = 2.5 \mu \frac{E}{1 \text{ MeV}} \cdot \frac{1 \text{ eV}^2}{\Delta m^2}$$

При заданных E и L (расстояние от точки рождения до детектора) эксперимент чувствителен к:

$$\Delta m^2 / m_{\min}^2 \sim \frac{E}{L}$$

$$\Delta m^2 = m_2^2 - m_1^2$$



Нейтринные состояния

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \quad \text{← угол смешивания}$$

Когерентная смесь собственных массовых состояний

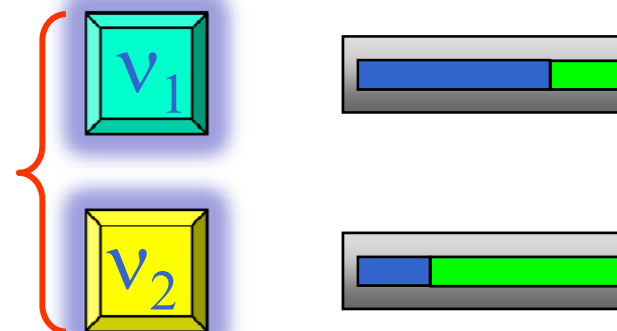
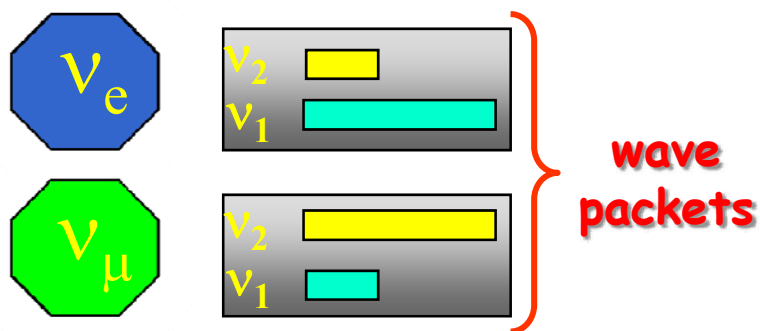
$$\nu_e = \cos\theta \nu_1 + \sin\theta \nu_2$$

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

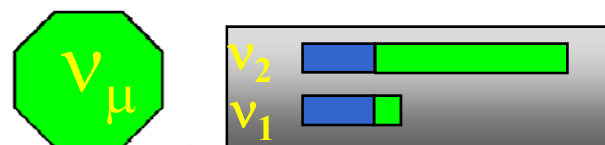
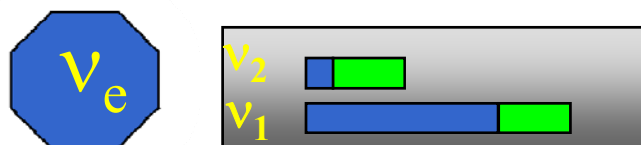
Ароматный состав собственных массовых состояний

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

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



«Портрет» нейтрино:





mixing and oscillations

3 families

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

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{-i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

atmospheric

solar

link between atmospheric and solar

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

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

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

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

?? θ_{13} , mass hierarchy , δ ??

Осцилляции нейтрино в веществе

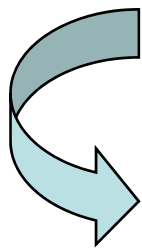
- Распространение ν в веществе ($\nu_e, \nu_{\mu}, \nu_{\tau}, \nu_s \dots$)

... аналогия с фотоном:

- ① вакуум $\rightarrow$ закон дисперсии $E_\gamma = |\vec{p}|c, v_\gamma = c,$
- 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 **нейтринного пучка**

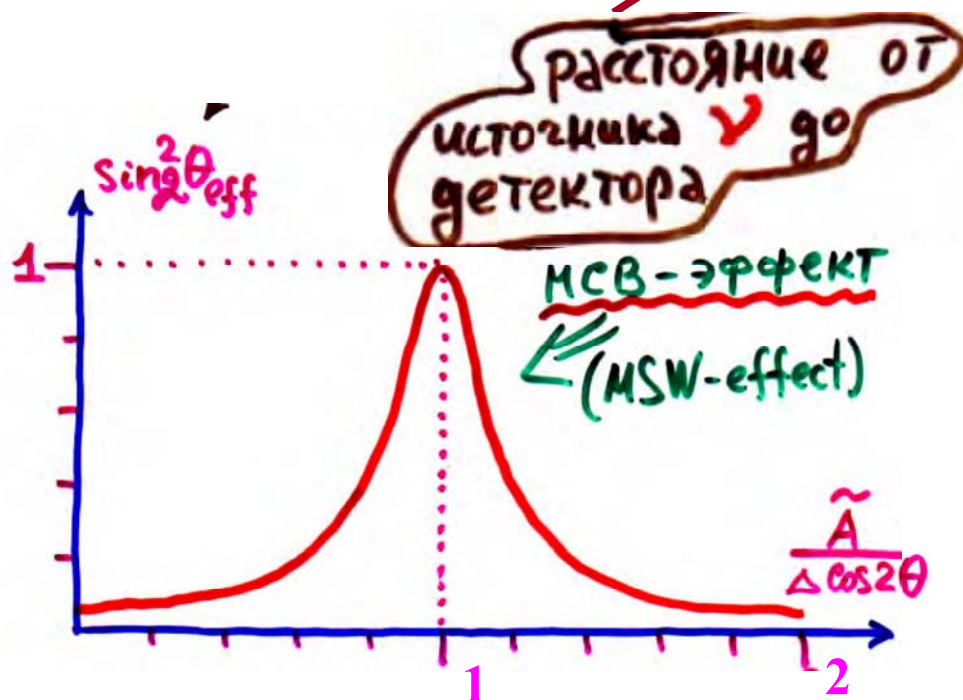
L. Wolfenstein 1978



Резонансное усиления осцилляций в веществе эффект Михеева-Смирнова-Вольфенштейна, 1985

Флейворные осцилляции
в *покоящейся* среде:

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



$$\begin{aligned}\nu_e &= \nu_1 \cos \theta + \nu_2 \sin \theta, \\ \nu_\mu &= -\nu_1 \sin \theta + \nu_2 \cos \theta,\end{aligned}$$

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

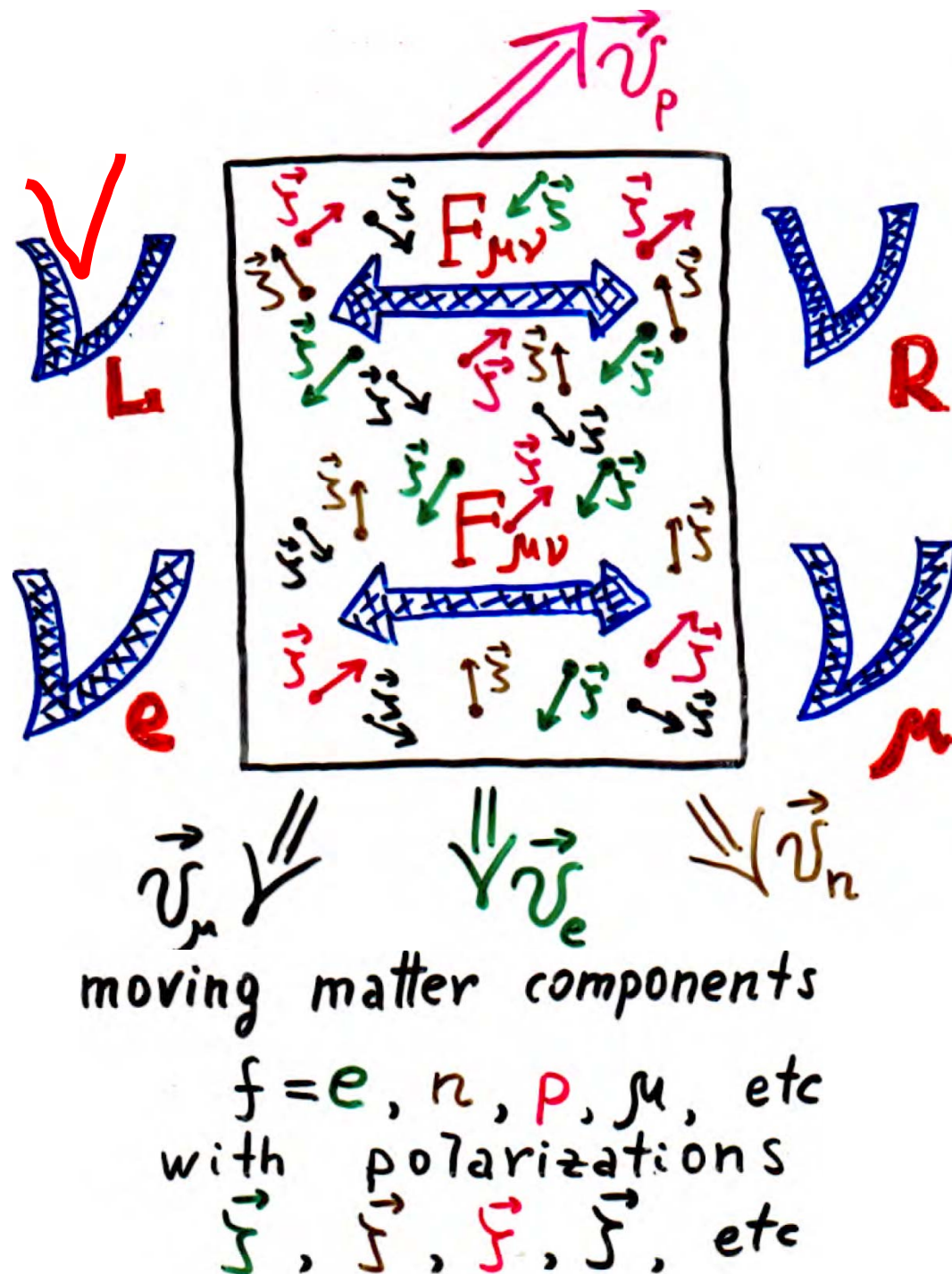
...резонанс...

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

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

плотность вещества

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



✓ 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
 ($\vec{\zeta}_e = 0, v_e \neq 0$)

Resonance condition:

$$\bullet \frac{\delta m_{\nu}^2}{2|\vec{p}|} \cos 2\theta = \sqrt{2} G_F n_e^{(0)} \frac{1 - \vec{\beta}_{\nu} \vec{v}_e}{\sqrt{1 - v_e^2}}$$

invariant matter density in r.f.

If

$\vec{\beta}_{\nu}$
 $\vec{v}_e$:

$$\bullet \left. \frac{1 - \vec{\beta}_{\nu} \vec{v}_e}{\sqrt{1 - v_e^2}} \right|_{\beta_{\nu} \approx 1} = \begin{cases} \left| \sqrt{\frac{1 - v_e}{1 + v_e}} \right|_{v_e \approx 1} \approx \frac{\sqrt{1 - v_e}}{\sqrt{2}} & \begin{array}{c} \nu \rightarrow \vec{\beta}_{\nu} \\ \text{matter} \rightarrow \vec{v}_e \end{array} \\ \left| \sqrt{\frac{1 + v_e}{1 - v_e}} \right|_{v_e \approx 1} \approx \frac{\sqrt{2}}{\sqrt{1 - v_e}} & \begin{array}{c} \nu \rightarrow \vec{\beta}_{\nu} \\ \text{matter} \leftarrow \vec{v}_e \end{array} \end{cases}$$

**MSW
effect**

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 $\nu \leftrightarrow \bar{\nu}$ if matter density
 $n_e^{(0)}$ is too high (low) for resonance
 appearance in non-moving matter.
 {in rest frame of matter}

★ **Resonance condition in Lorentz invariant form :**

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

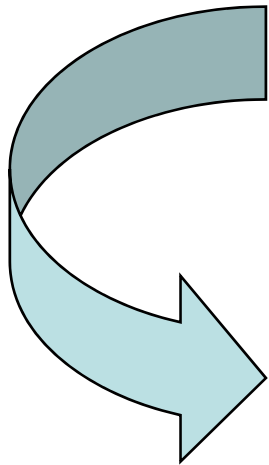
$$\Delta \cos 2\theta = \sqrt{2} G_F n_0 p_\mu u^\mu, \quad \Delta = \delta m_\nu^2 / 2E,$$

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

История нейтрино

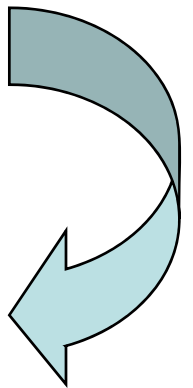


познание фундаментальных
законов природы



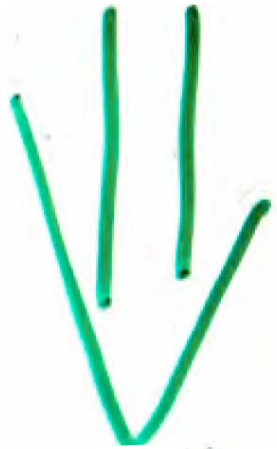
"Новая физика" (экспериментальные
указания на $m_\nu \neq 0$
смешивание ν)

т.е., осциллирующие нейтрино
существуют



$$m_\nu \neq 0$$

Neutrino mass



$$m_\nu \neq 0 !$$

Neutrino magnetic moment

$$\mu_\nu \neq 0$$

 $\left\{ \begin{array}{l} \text{Lee} \\ \text{Shrock} \\ \text{Fujikawa} \end{array} \right\} \begin{array}{l} 1977 \\ 1980 \end{array}$

... 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
Shrock, 1977; Fujikawa
Shrock, 1980

In the Standard Model : $m_\nu = 0$,
there is no $\nu_R \Rightarrow$
 ν magnetic moment $\mu_\nu = 0$.

Thus, $\mu_\nu \neq 0 \leftarrow$ beyond the SM.



$$m_\nu \neq 0$$

... beyond
Standard Model

Theory (Standard Model with ν_R)

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

Lee Shrock, 1977; Fujikawa Shrock, 1980

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

anomalous
magnetic
moment of
electron

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

visualization of μ_ν

Astrophysical bounds

$$\mu_\nu \leq 3 \cdot 10^{-12} \mu_B \quad (\text{Red Giant Lumin.})$$

etc.

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

Theory (Standard Model with ν_R)

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

Lee
Shrock, 1977; Fujikawa
Shrock, 1980

3

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

3.1 ✓ vertex function

The most general study of the
massive neutrino vertex function

(including electric and magnetic
form factors) in arbitrary R_ξ gauge
in the context of the SM + $SU(2)$ -singlet



γ_R accounting for masses of particles
in polarization loops

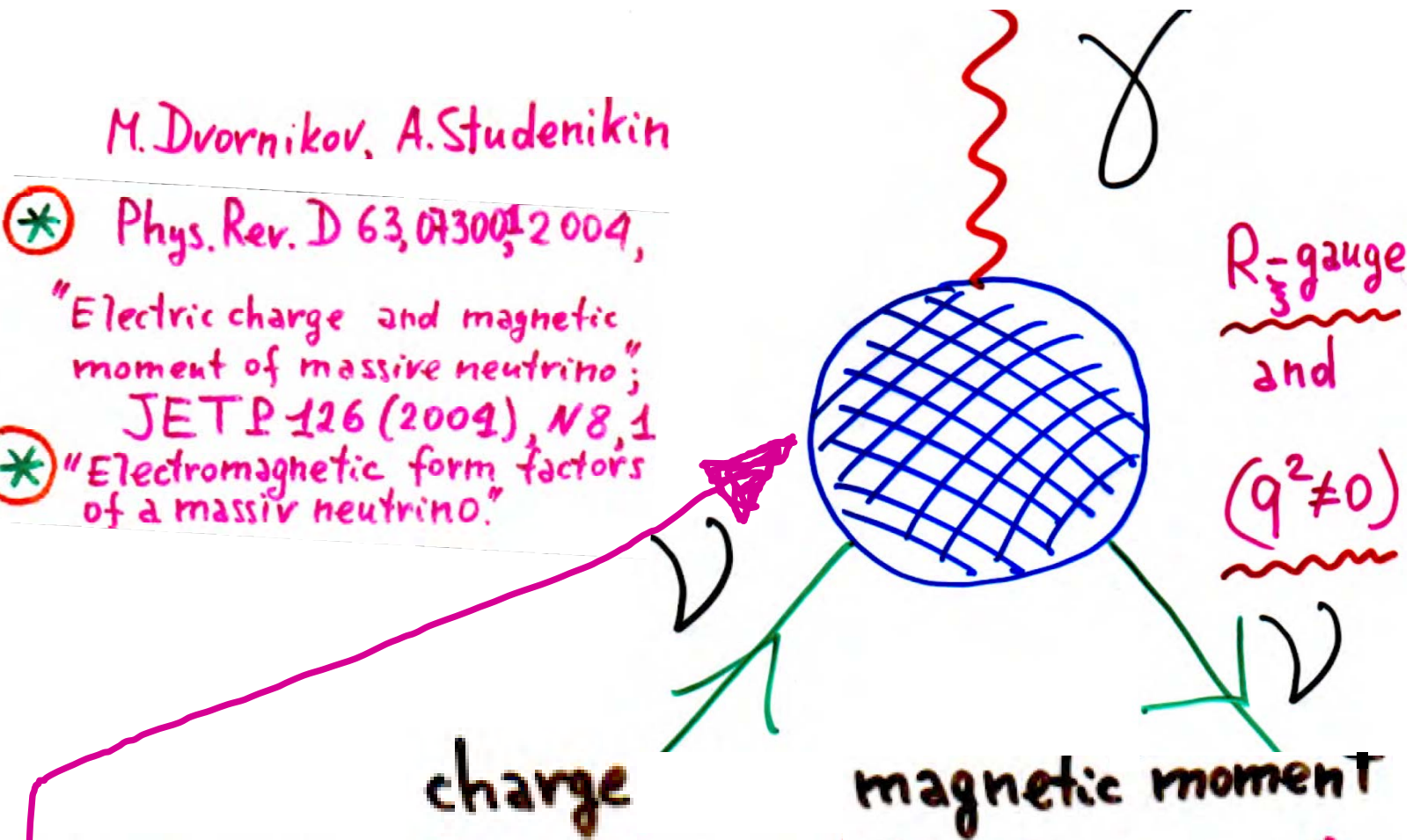


M. Dvornikov, A. Studenikin

* Phys. Rev. D 63, 073001, 2004,

"Electric charge and magnetic moment of massive neutrino";
JETP 126 (2004), N 8, 1

* "Electromagnetic form factors of a massive neutrino."



$$\Delta_\mu(q) = \underbrace{f_Q(q^2)}_{\text{charge}} \gamma_\mu + \underbrace{f_M(q^2)}_{\text{magnetic moment}} i \sigma_{\mu\nu} q^\nu -$$

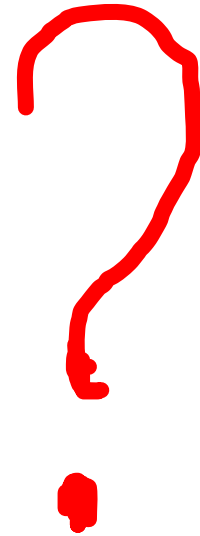
$$- \underbrace{f_E(q^2)}_{\text{electric moment}} i \sigma_{\mu\nu} q^\nu \gamma_5 - \underbrace{f_A(q^2)}_{\text{anapole moment}} (q^\nu \gamma_\mu - q_\mu \gamma^\nu) \gamma_5$$

Magnetic moment dependence

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



on neutrino mass





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

light ✓

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

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

*Dvornikov,
Studenikin,*

*Phys.Rev.D 69
(2004) 073001;*

JETP 99 (2004) 254



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

intermediate ✓

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

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



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

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

heavy ✓

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

... подробно об электромагнитных свойствах ν ...

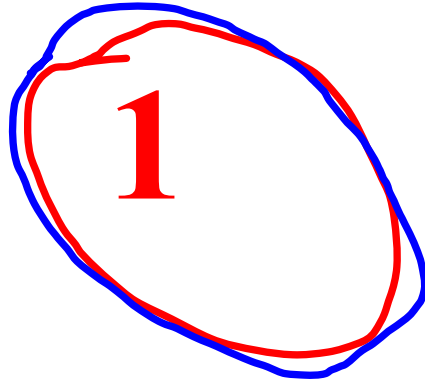
① Carlo Giunti, Alexander Studenikin :
“Neutrino electromagnetic properties”
Phys.Atom.Nucl. 73, 2089-2125 (2009)
arXiv:0812.3646 v5, Apr 12, 2010

... within the agreement
on cooperation between
Moscow University and
Istituto 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.*



*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 $\checkmark$ 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:

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

where the Standard Model contribution

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

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

T is the electron recoil energy

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

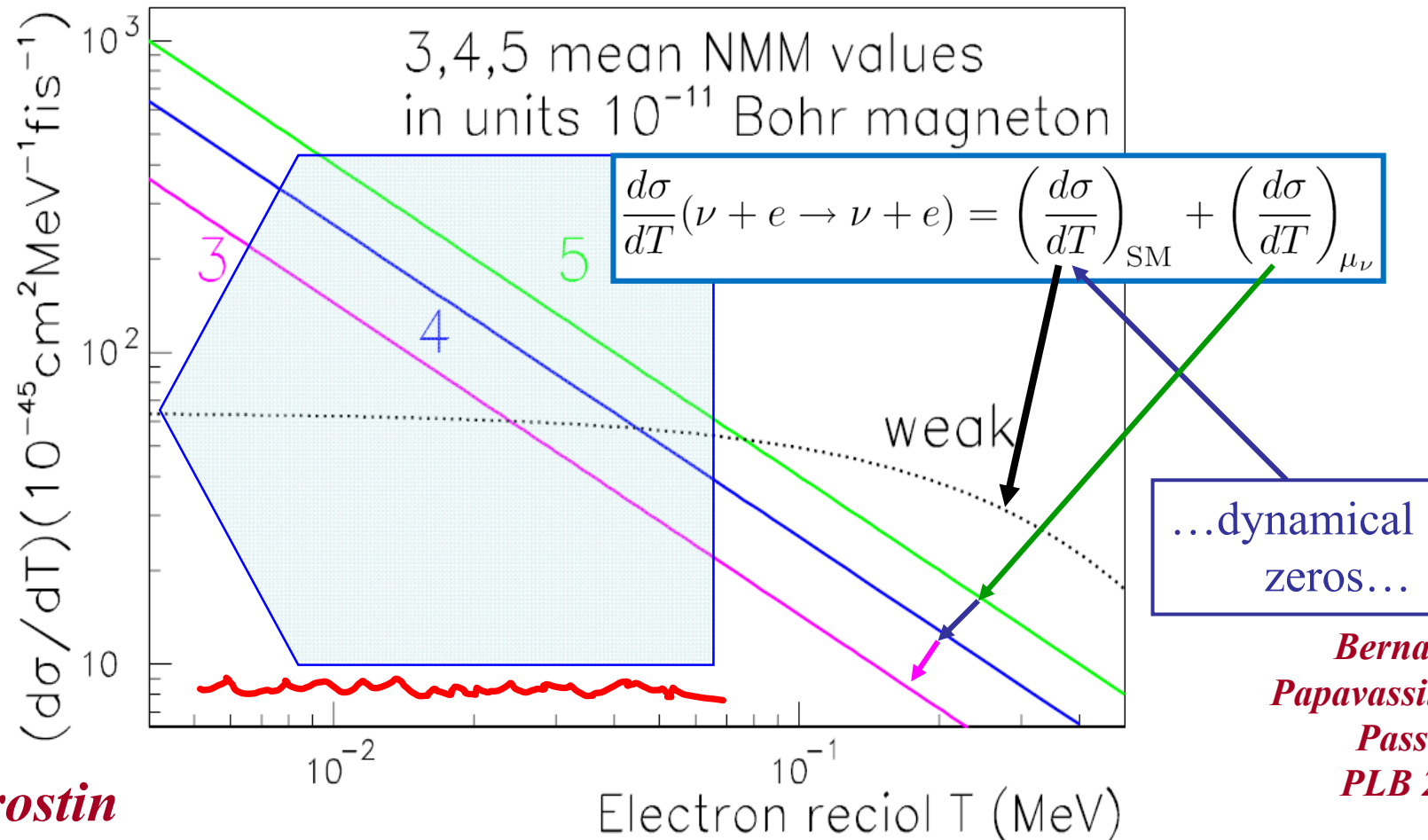
$$g_V = \begin{cases} 2 \sin^2 \theta_W + \frac{1}{2} & \text{for } \nu_e, \\ 2 \sin^2 \theta_W - \frac{1}{2} & \text{for } \nu_\mu, \nu_\tau, \end{cases} \quad g_A = \begin{cases} \frac{1}{2} & \text{for } \nu_e, \\ -\frac{1}{2} & \text{for } \nu_\mu, \nu_\tau \end{cases} \quad \begin{array}{l} \text{for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

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 $\frac{T}{m_e} < \frac{\pi^2 \alpha_{em}}{G_F^2 m_e^4} \mu_\nu^2$

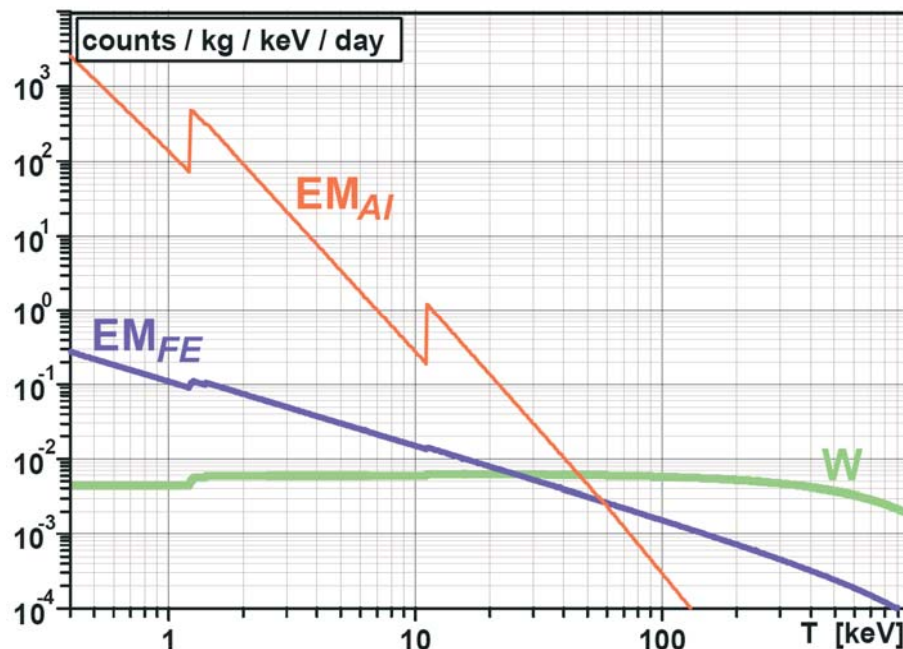
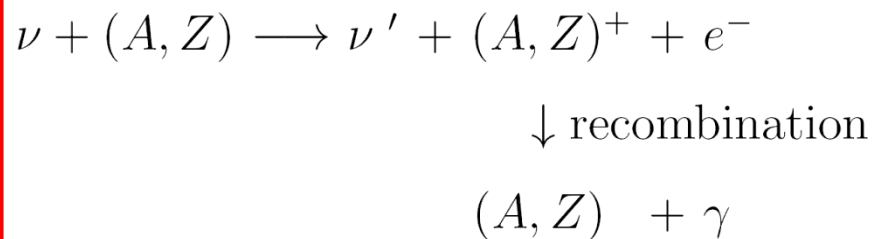
... the **lower** the smallest measurable electron recoil energy is,
the **smaller** values of μ_ν^2 can be probed in scattering experiments ...



from
A. Starostin

*Bernabeu,
Papavassiliou,
Passera,
PLB 2005*

... quite recent *claim*
 that ν - e cross section
 should be increased by
Atomic Ionization effect:

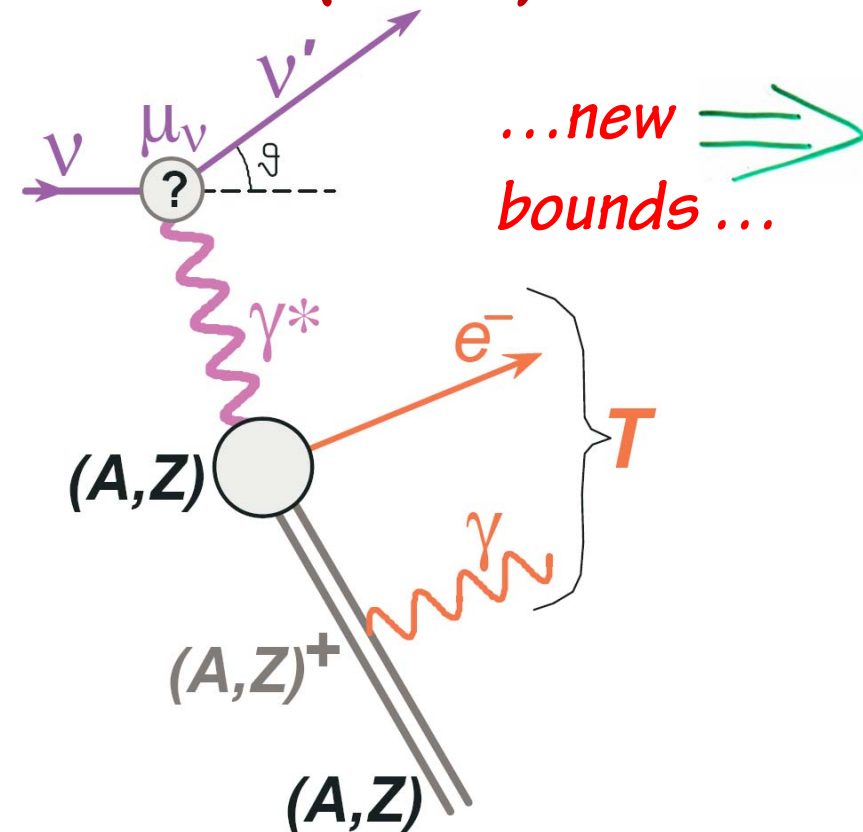


?

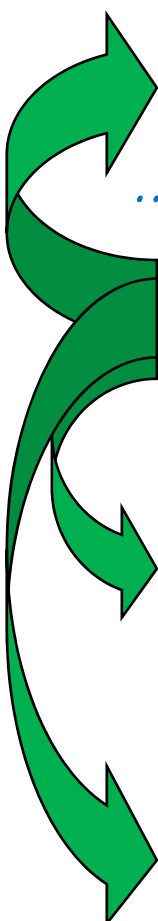
H.Wong et al. (TEXONO Coll.), arXiv:
 1001.2074,
 13 Jan 2010,
 reported at

Neutrino 2010 Conference
 (Athens, June 2010),

PRL 105 (2010) 061801



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


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

... *atomic ionization* effect accounted for ...

?

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

Neutrino 2010 Conference, Athens

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

... *atomic ionization* effect accounted for ...

?

... *however* ...

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

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

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

K.Kouzakov, A.Studenikin,

- “Magnetic neutrino scattering on atomic electrons revisited” ●
Phys.Lett. B 105 (2011) 061801, 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

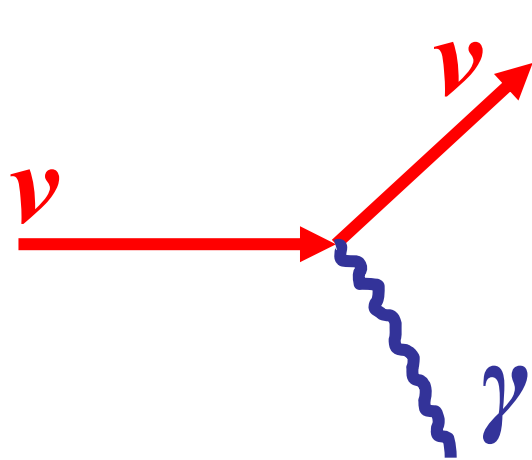
K.Kouzakov, A.Studenikin, M.Voloshin,

- “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.Suppl.) 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

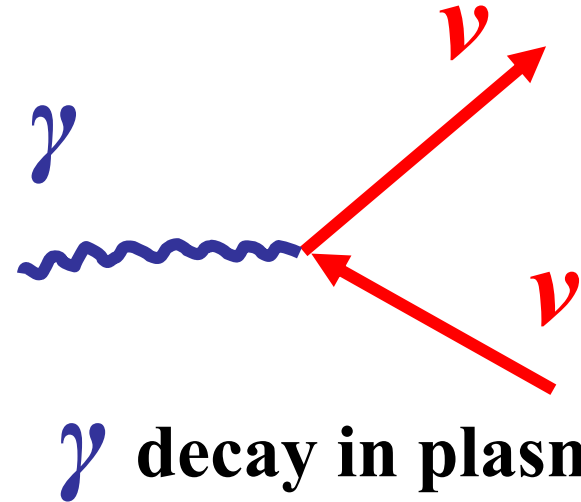
M.Voloshin,

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

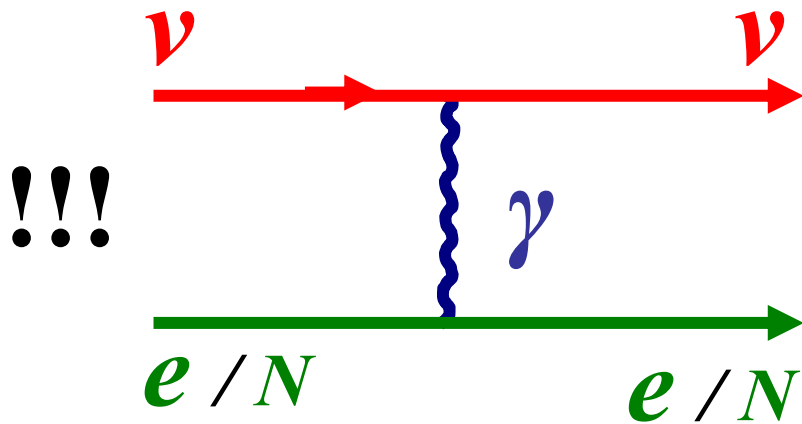
Neutrino-photon couplings



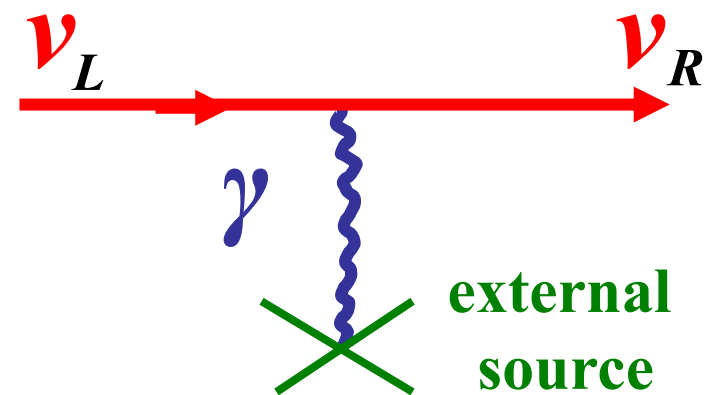
ν decay, Cherenkov radiation



γ decay in plasma



Scattering



Spin precession

New mechanism of electromagnetic radiation

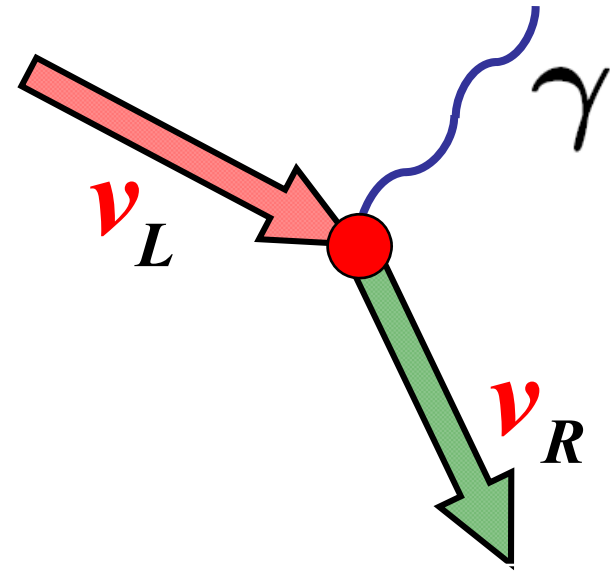


Spin Light of Neutrino

спиновый свет нейтрино



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

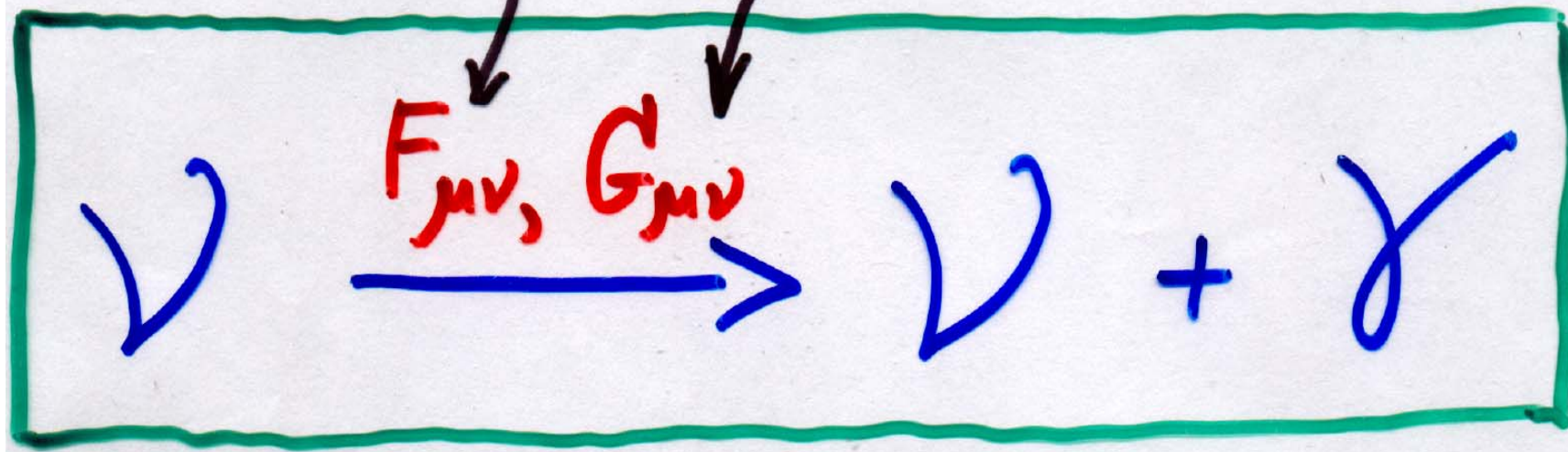
A.Grigoriev, A.S., A.Ternov, Phys.Lett. B 622 (2005) 199

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 ν



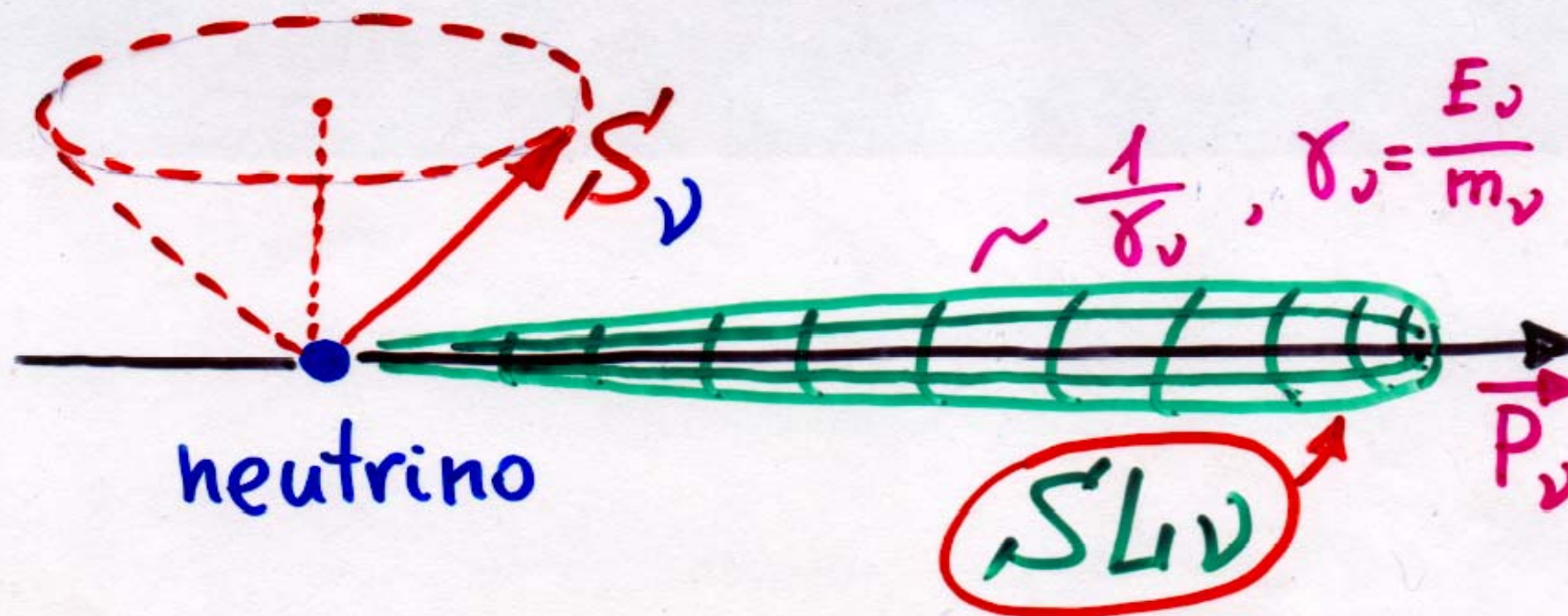
Quasi-classical theory of spin light of neutrino in matter and gravitational field



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** precession in background environment



✓ spin evolution in presence of general external fields

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

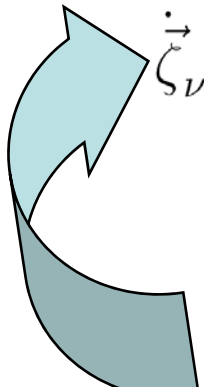
General types non-derivative interaction with external fields

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

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:*



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

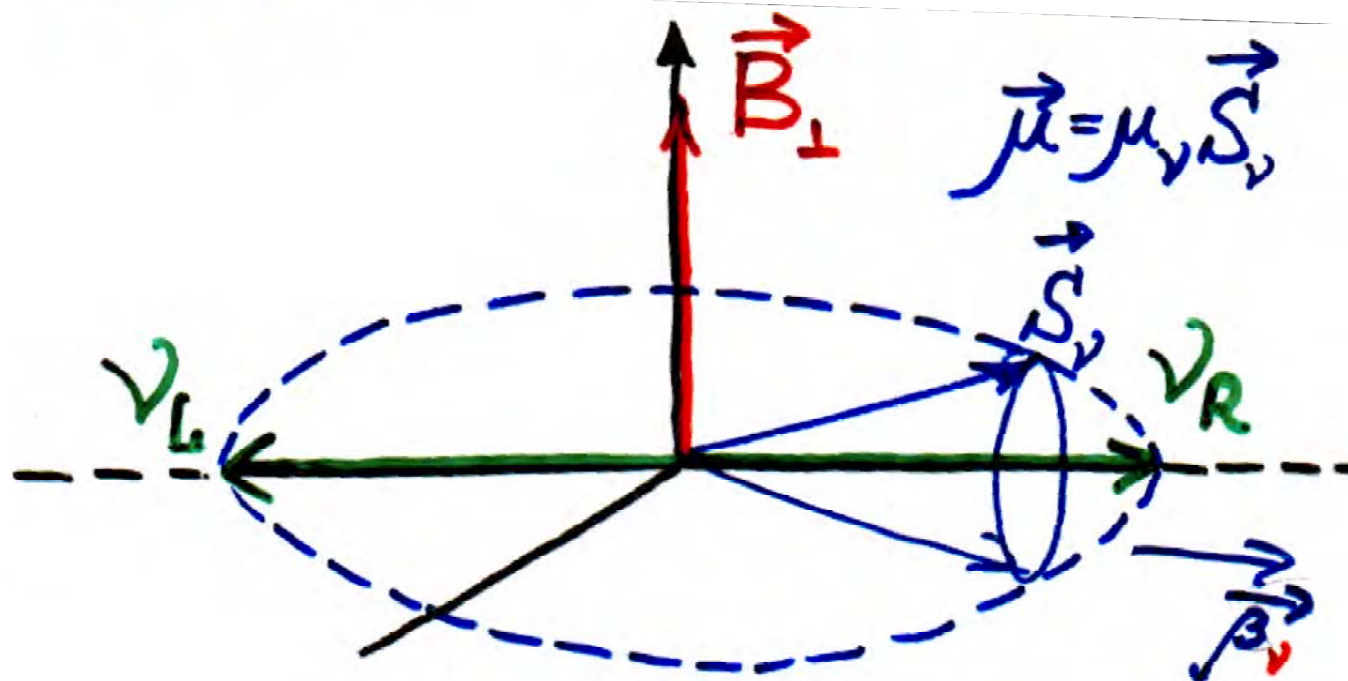
● *Neither S nor π nor V contributes to spin evolution*

● **Electromagnetic interaction**

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

● **SM weak interaction**

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



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

electromagnetic
interaction with
e.m. field

weak interaction
with matter

New mechanism of electromagnetic radiation

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

Analogies with:

* classical electrodynamics

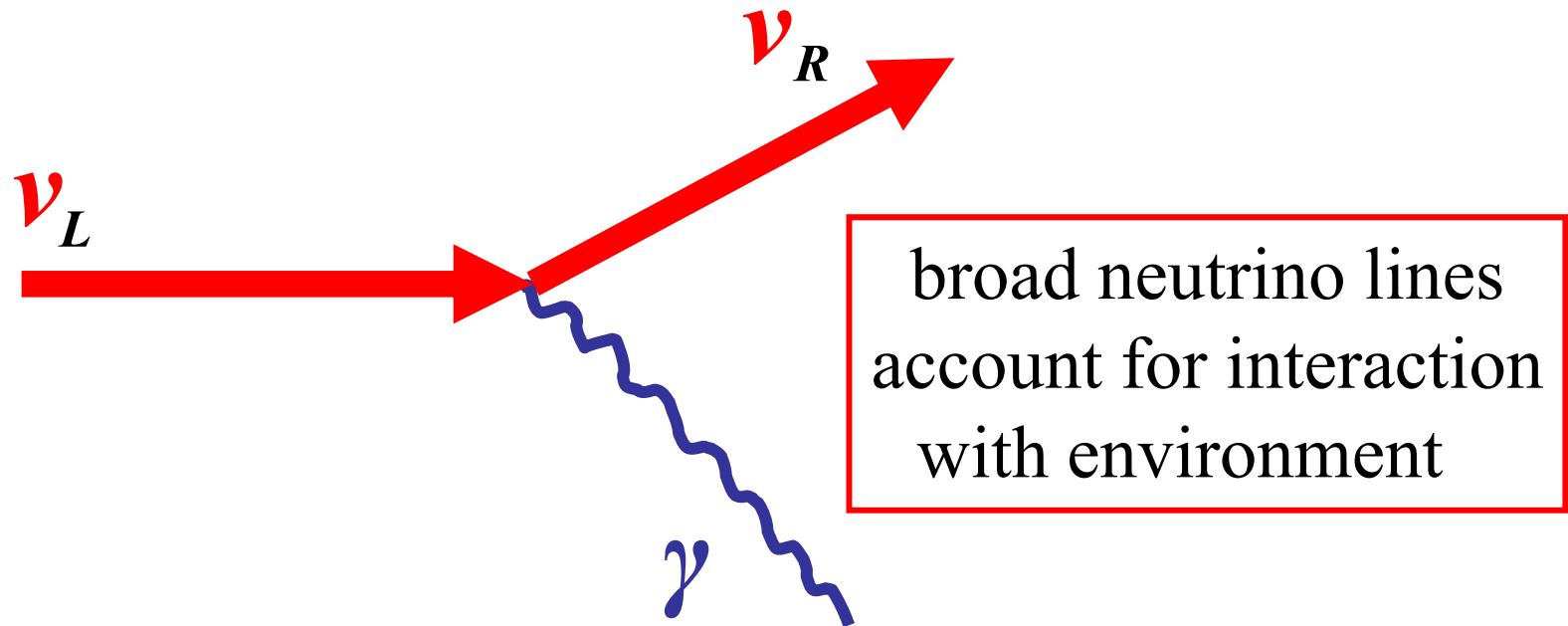
an object with charge $Q=0$ and

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

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

← 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

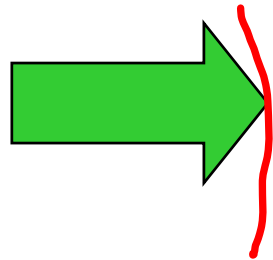
$$\Delta L_{eff} = \Delta L_{eff}^{CC} + \Delta L_{eff}^{NC} = -f^\mu \left(\bar{\nu} \gamma_\mu \frac{1 + \gamma^5}{2} \nu \right)$$

matter
current

where

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

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 wave length. Therefore, **the interaction of a neutrino with the matter (electrons) is coherent.**

L.Chang, R.Zia,'88; J.Pantaleone,'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

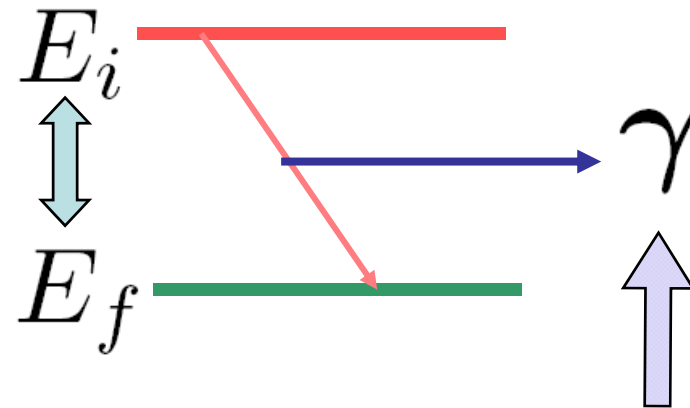
shows that this process originates from the **two subdivided phenomena**:



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

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

$$s = \pm 1$$



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

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

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

Grav. & Cosm. 14 (2005) 132;

neutrino-spin self-polarization effect in the matter

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

Phys.Lett.B 601 (2004) 171

It is possible to have

$$\tau = \frac{1}{\Gamma_{SL\nu}} \ll \text{age of the Universe ?}$$

For ultra-relativistic ✓
 with momentum $p \sim 10^{20} \text{ eV}$
 and magnetic moment $\mu \sim 10^{-10} \mu_B$
 in very dense matter $n \sim 10^{40} \text{ cm}^{-3}$
 from

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

$$p \gg m_{\text{plasmon}}$$

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

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

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 $\nu\bar{\nu}$ 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 ✓ 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 $B = |B_\perp| e^{i\phi(t)}$ ← for solar ✓ etc ...

✓ 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

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



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



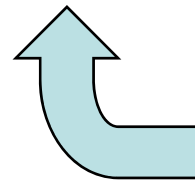
$$U' = \begin{pmatrix} -e^{-i\phi} & 0 \\ 0 & e^{i\phi} \end{pmatrix}, \quad U^\dagger = \begin{pmatrix} e^{i\phi} & 0 \\ 0 & e^{-i\phi} \end{pmatrix}$$

conjugated

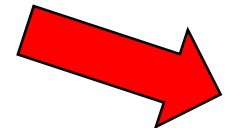
$$U^\dagger U' = \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix}$$

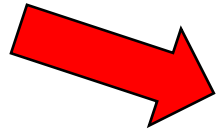
$$i \frac{d}{dt} \nu' = (U^\dagger \tilde{H} U + \frac{\dot{\phi}}{2} U^\dagger U') \nu'$$

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



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





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



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

For relativistic  : $\frac{d}{dt} \rightarrow \frac{d}{dz}$ 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

$$\Delta_{LR} = \frac{\Delta m^2}{2} (\cos 2\theta + 1) - 2E \underline{V_{\nu e}} + 2E \dot{\phi}$$

... **Flavour oscillations** $\longleftrightarrow$ **Spin oscillations...**

$$P_{\nu_e \nu_\mu} = \sin^2 2\theta \sin^2 \frac{\Delta m^2}{4E} z \longleftrightarrow P_{\nu_L \nu_R} = \sin^2 \beta \sin^2 \Omega z$$

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

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

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

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



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

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

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

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 $\nu_\odot$ -problem

⑤ $\nu_{eL} \xleftrightarrow{B_\perp} \nu_{eR}$, A. Cisneros, 1977
M. Voloshin, M. Vysotsky, L. Okun, 1986, $\nu_\odot$

⑥ $\nu_{eL} \xleftrightarrow{B_\perp} \nu_{eR}, \nu_{\mu R}$, 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

● (*) ν ⊙ problem

$$\begin{matrix} B \\ \nu_L \leftrightarrow \nu_R \end{matrix}$$

Cisneros, 1971

* { Voloshin, Vysotsky, Okun, 1986
Barbieri, Fiorentini, 1988

⊙ twisting B { Smirnov, 1991
Akhmedov, Petcov, Smirnov, 1993

● (*) **Supernova** $\nu_L \xleftrightarrow{B} \nu_R$

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 (???)

← ...for recent analysis see

J. Pulido, 2006,

TAUP-09; ●

A. Balantekin,

C. Volpe, 2005

...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 $\odot$ ν 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 $B_\odot \rightarrow$ large $\mu_\nu B_\odot \rightarrow$ 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...



Pulsar kick and ν oscillations in B

{Kusenko,
Serge, 1996

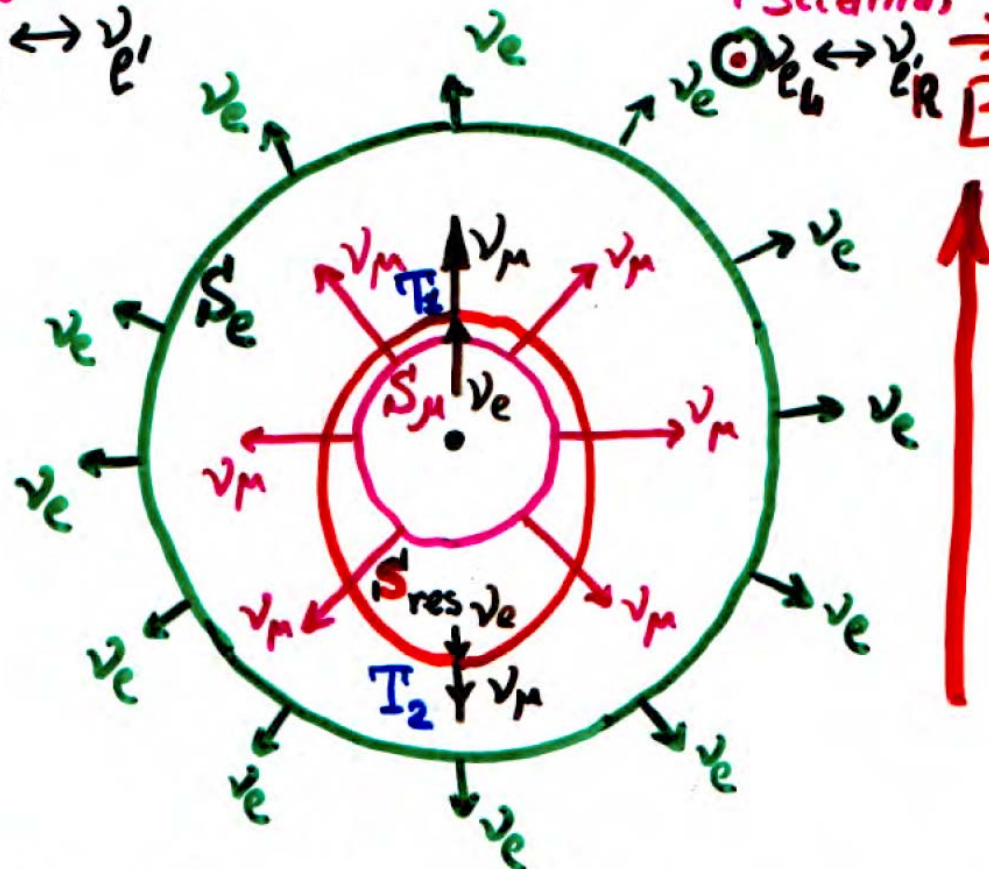
$$\nu_e \leftrightarrow \nu_{e'}$$

{Akhmedov,
Lanza, 1997
Sciama,

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

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

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



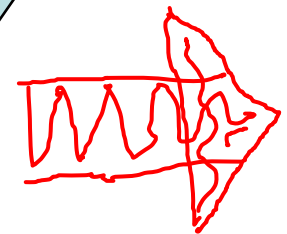
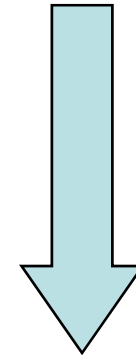
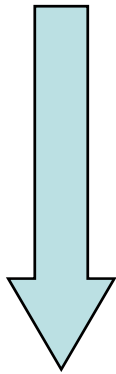
{ In directions where **RS** is close (far)
to center $\rightarrow$ larger (smaller) ν momentum,
since $T_1 > T_2$.

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** ...

β -decay of neutron in magnetic field

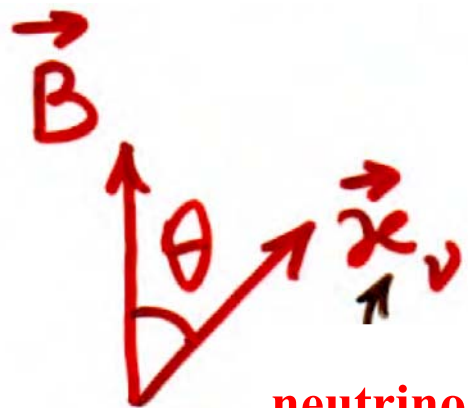
{Birth of γ astrophysics in B}



- * L. Korovina, " β -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

$$\frac{W(\theta)}{W_0} = \frac{1}{2} \int \sin \theta_{\tilde{\nu}} d\theta_{\tilde{\nu}} \left\{ 1 + \frac{2(\alpha^2 + \alpha)}{1 + 3\alpha^2} S_n \cos \theta_{\tilde{\nu}} \right. \\ \left. - 4.9 \frac{eB}{\Delta^2} \left(\frac{\alpha^2 - 1}{1 + 3\alpha^2} \cos \theta_{\tilde{\nu}} + \frac{2(\alpha^2 - \alpha)}{1 + 3\alpha^2} S_n \right) \right\}$$



neutrino momentum

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. Lecoine, J. Phys. Radium **8**, 238 (1947)

$$\frac{w_{\tilde{h}}}{w_{\tilde{c}}} \cong 4.2 \times 10^{-6}$$

$$\tau_c \sim 15 \text{ min}$$

$$\tau_b \sim 7 \text{ years}$$

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

* $n \xrightarrow{B} p + e + \tilde{\nu}_e$
* $\nu + n \xrightarrow{B} p + e$
* 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 B

* magnetic moment $\mu_\nu = \mu_\nu(B)$
* induced electric charge of ν in magnetized matter

Egorov, Sludnikov, 1994

Borisov, Zhukovskiy, Kurilin, Ternov, 1985



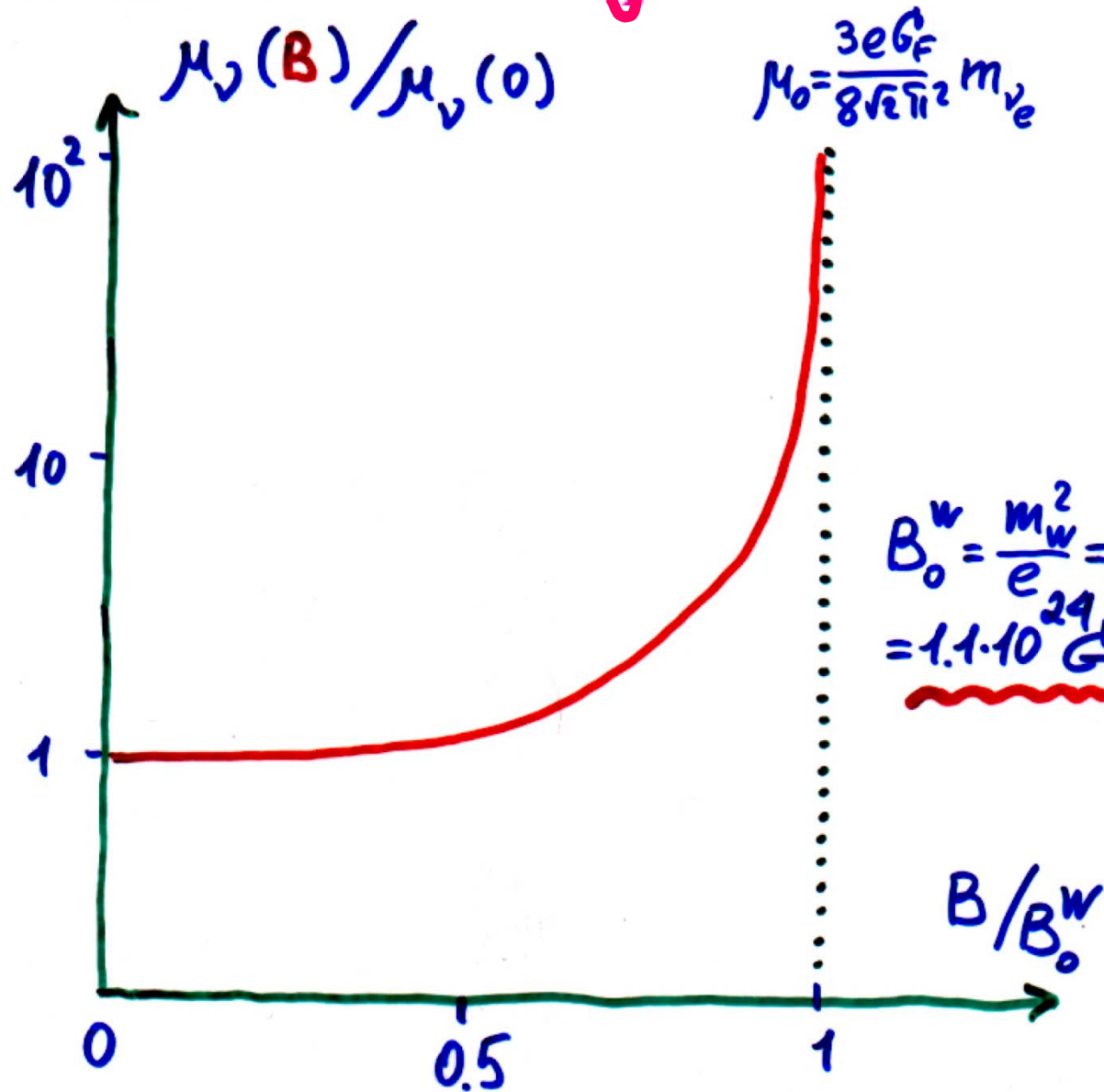
Oraevsky, Semikoz

Smorodinsky, 1986

Bhattacharaya, Ganguly, Konar, 2002

Nieves, 2003

Neutrino magnetic moment



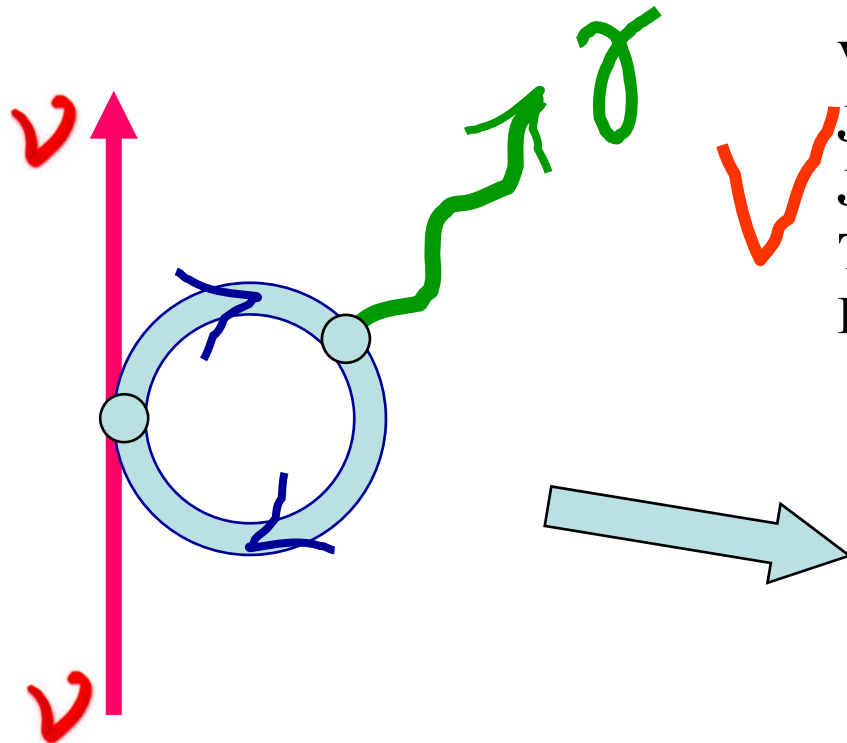
Borisov,
Zhukovskiy,
Kurilin,
Ternov, 1985;

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

✓ “effective electric charge” in magnetized plasma

● ✓ ν s do not couple with γ s in vacuum,
... however, when

● ✓ 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

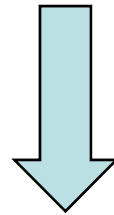
...different ✓ γ interactions in
astrophysical and cosmological media

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

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

quantized part
of potential

charged particles **current**

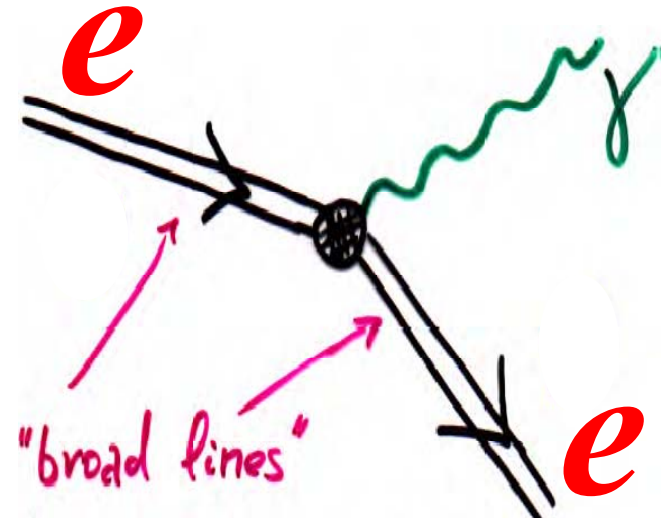
$$j_\mu(x) = \frac{e}{2} [\bar{\Psi}_F \gamma_\mu, \Psi_F],$$

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...

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



ν and e

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

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

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

The background of the slide is a photograph of the main building of Moscow State University, a large, ornate, light-colored stone structure with multiple towers and a central spire topped with a golden orb. The building is set against a clear blue sky. A red L-shaped graphic element is in the top-left corner.

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

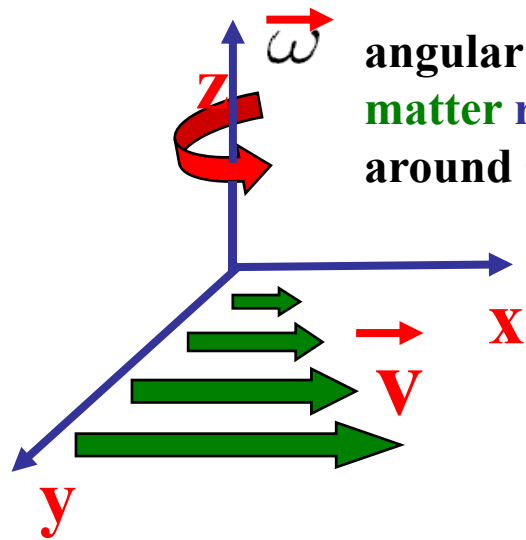
Neutrino'08,
Christchurch,
May 25-31, 2008

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



angular speed of
matter rotation
around **OZ**

A. Grigoriev, A. Savochkin, A. Studenikin (2007)

A. Studenikin (2008)

I. Balantsev, Yu. Popov, A. Studenikin (2011)

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

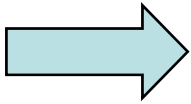
 wave function 

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

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  **speed of matter**  **angular speed of rotation** 

 **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**

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

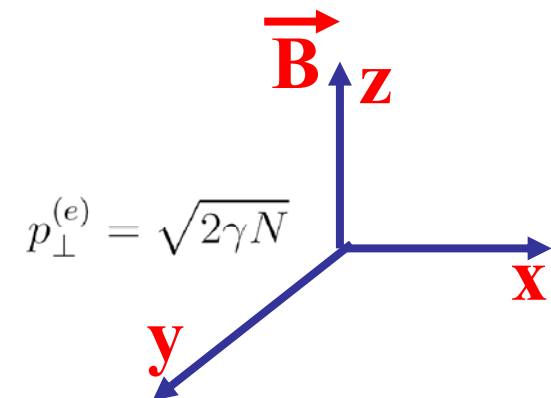
$$\tilde{p}_0 = \sqrt{p_3^2 + 2\rho N} + Gn, \quad N = 0, 1, 2, \dots$$



 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  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

$$p_0 = \sqrt{m^2 + p_3^2 + 4N\rho - Gn}$$

for 

$$\tilde{p}_0 = \sqrt{m^2 + p_3^2 + 4N\rho + Gn}$$

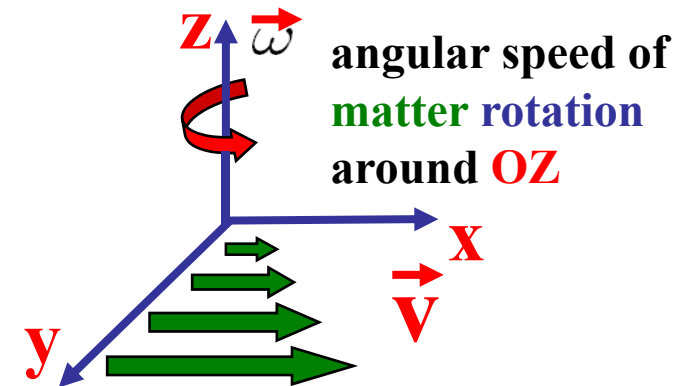
for 

$$N = 0, 1, 2, \dots$$

$$\rho = Gn\omega$$

One example: consider antineutrino $\bar{\nu}$
 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:

$$R = \sqrt{\frac{2N}{Gn\omega}} \Rightarrow \text{binding orbits inside a Neutron Star !?}$$

NS:

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

for this set

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

radius of trajectory

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

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

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

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

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

$$\boxed{\mathbf{F}_m^{(\nu)} = q_m^{(\nu)} \boldsymbol{\beta} \times \mathbf{B}_m} \quad \mathbf{B}_m = \nabla \times \mathbf{A}_m, \quad \mathbf{A}_m = n \mathbf{v} \quad \begin{array}{l} \text{"magnetic field"} \\ \text{vector potential} \end{array} \quad \begin{array}{l} \text{"charge"} \\ q_m^{(\nu)} = -G \end{array}$$

matter-induced "Lorentz force",

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

Generalization to non-constant matter density:

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

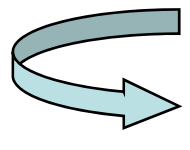
*L.Silva, R.Bingham,
J.Dawson, J.Mendoca,
P.Shukla, Phys.Plasma 7
(2000) 2166*

"magnetic field"

$$\boxed{\mathbf{B}_m = n \nabla \times \mathbf{v} - \mathbf{v} \times \nabla n}$$

"electric field"

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

 ***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”

✓ *e.m. vertex function* $\Rightarrow$ *4 form factors* A Feynman diagram showing a neutrino vertex. A blue circle with a cross-hatch pattern represents the vertex. A red wavy line labeled with a Greek letter gamma (γ) enters from the top. Two green lines labeled with ν enter from the bottom left and bottom right.

charge **dipole** **magnetic** and **electric**

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

anapole

- **EM** properties $\Rightarrow$ a way to distinguish **Dirac** and **Majorana** ✓

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

- *In extensions of SM* $\Rightarrow$ enhancement of **✓** magnetic moment, *even* electrically millicharged **✓**

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

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

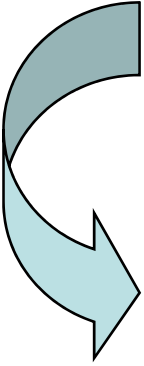
*A.Beda et al.
(GEMMA Coll.)*

- *Limits from astrophysics, star cooling (1990):*

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

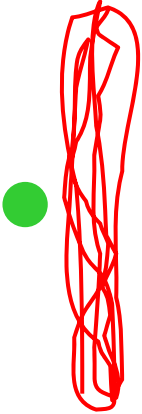
G.Raffelt

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****



**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
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JETP **99** (2004) 254; **JHEP** **09** (2002) 016
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 A.Egorov, A.Lobanov, A.Studenikin, **Phys.Lett.B** **491** (2000) 137

Faculty of Physics

Moscow State University

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

FIFTEENTH LOMONOSOV CONFERENCE ON ELEMENTARY PARTICLE PHYSICS



Mikhail Lomonosov
1711-1765

Moscow, August 18 - 24, 2011

Electroweak Theory
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

NINTH
INTERNATIONAL
MEETING
ON
August 24, 2011
PROBLEMS
OF INTELLIGENTSIA

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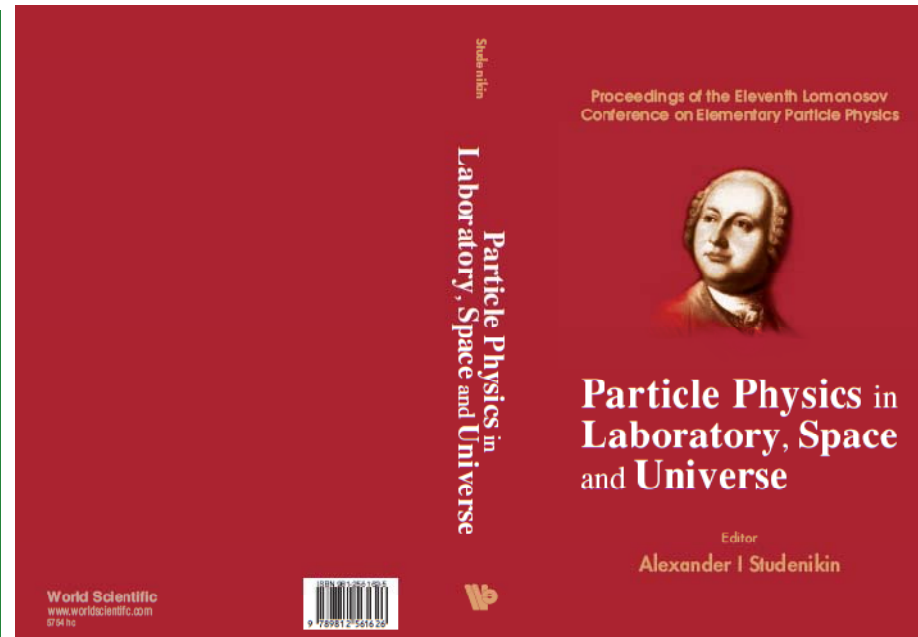
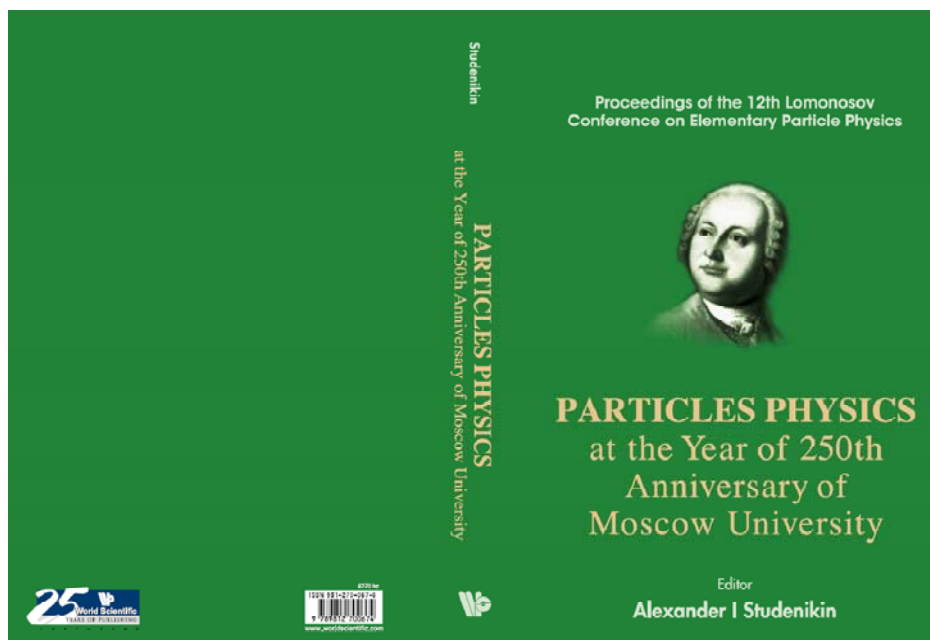
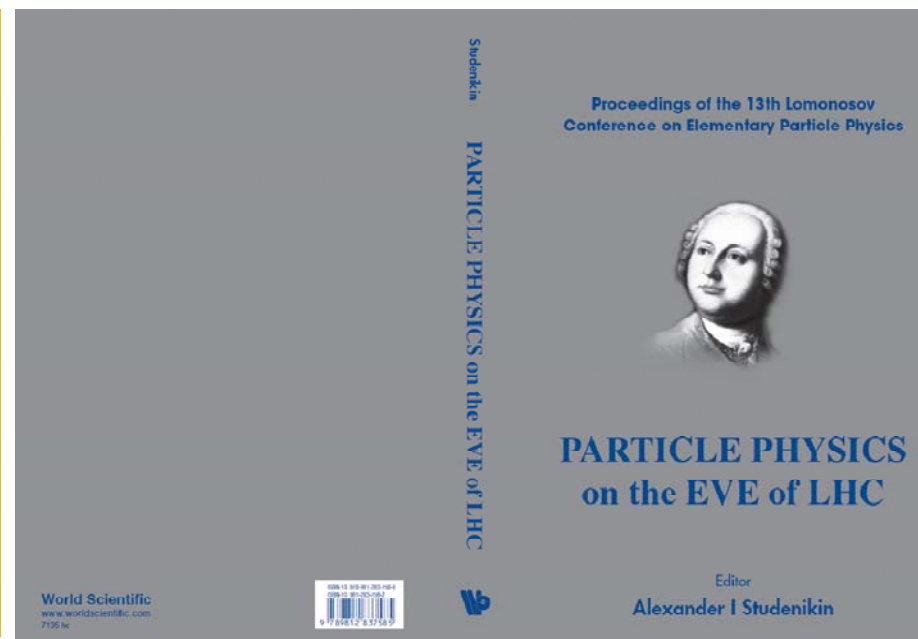
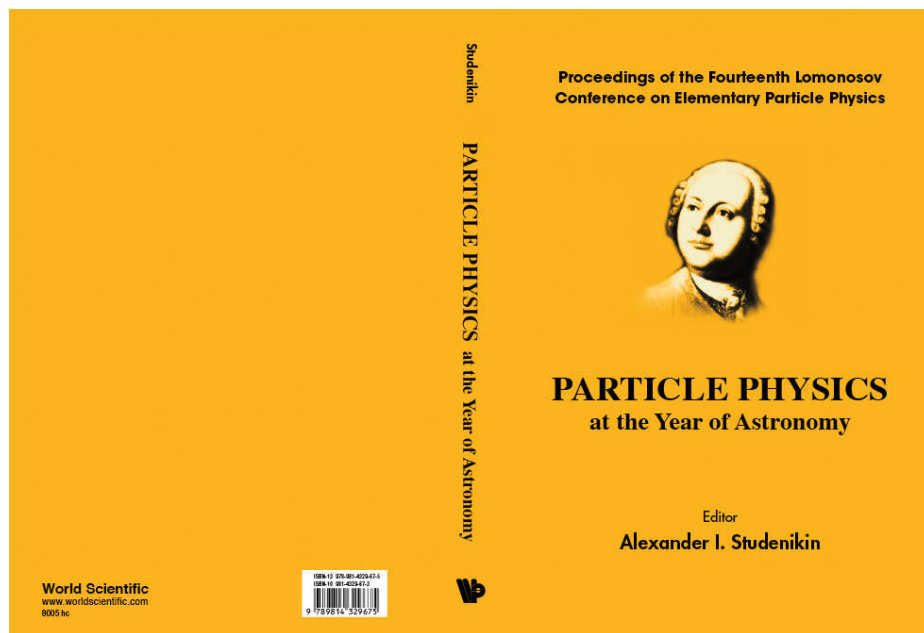
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по физике
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... взаимодействия частиц
во внешних полях ...



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.

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

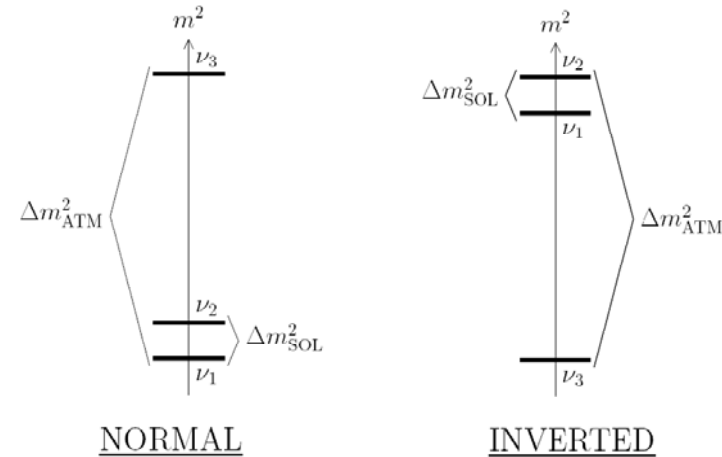
$$\Delta m_{\text{ATM}}^2 \simeq |\Delta m_{31}^2| \simeq |\Delta m_{32}^2|$$

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



Квази-вырожденный 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: $m_{e2\beta} = \left| \sum_{k=1,2,3} U_{ek}^2 m_k \right| < 0.3 - 0.5 \text{ eV}$

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**

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

1. electric

dipole

2. magnetic

3. electric

$$+ f_A(q^2) (q^2 \gamma_\mu - q_\mu \not{q}) \gamma_5$$

4. anapole

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

Dirac

- 1) CP invariance + hermiticity $\Rightarrow f_E = 0$,
- 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 $\Rightarrow$ three form factors are real: $\text{Im} f_Q = \text{Im} f_M = \text{Im} f_A = 0$.

Majoran

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

$$f_Q = f_M = f_E = 0$$

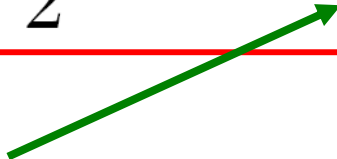
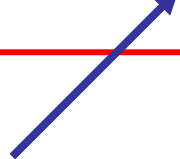
...as early as 1939, W. Pauli...

EM properties $\Rightarrow$ a way to distinguish **Dirac** and **Majorana**

Effective Lagrangian for the spin component of  vertex

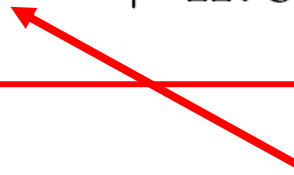
$$L = \frac{1}{2} \bar{\nu}_j \sigma_{\eta\xi} (\beta_{ij} + \varepsilon_{ij} \gamma_5) \nu_i F^{\eta\xi} + \text{h.c.},$$

... 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 

E.M. properties

 a way to distinguish Dirac and Majorana 

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**

1) **CP invariance + hermiticity**

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

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

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

are relatively real (no relative phases).

... quite different EM properties ...

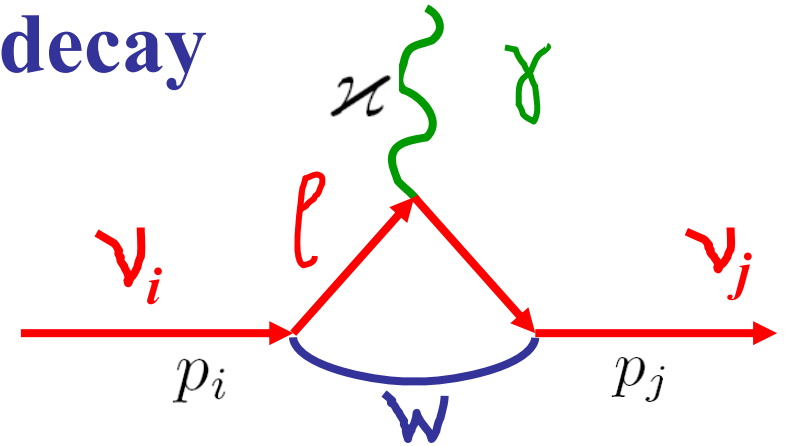
3.7

Neutrino radiative decay

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

$$m_i > m_j$$

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



Radiative decay rate

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

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

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

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

- 1) reactor $\bar{\nu}_e$ and solar ν_e fluxes,
- 2) SN 1987A ν burst (all flavours),
- 3) spectral distortion of CMBR

Raffelt 1999

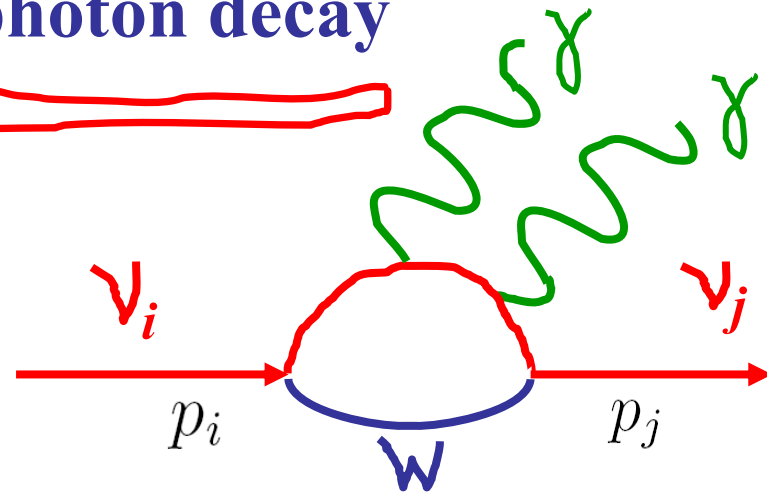
*Kolb, Turner 1990;
Ressell, Turner 1990*

3.8

Neutrino radiative two-photon decay

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

$m_i > m_j$

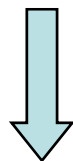


fine structure constant $\ll 1$

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



... there is no GIM cancellation...



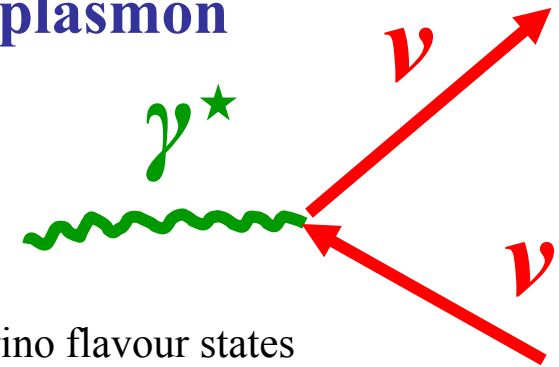
... can be of interest for certain range of ν masses...

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

Nieves, 1983; Ghosh, 1984

3.9 The tightest astrophysical bound on μ_{ν} G. Raffelt, PRL 1990

comes from cooling of **red giant** stars by plasmon decay $\gamma^* \longrightarrow \nu \bar{\nu}$



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

neutrino flavour states

Matrix element

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

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

Decay rate

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

= 0 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

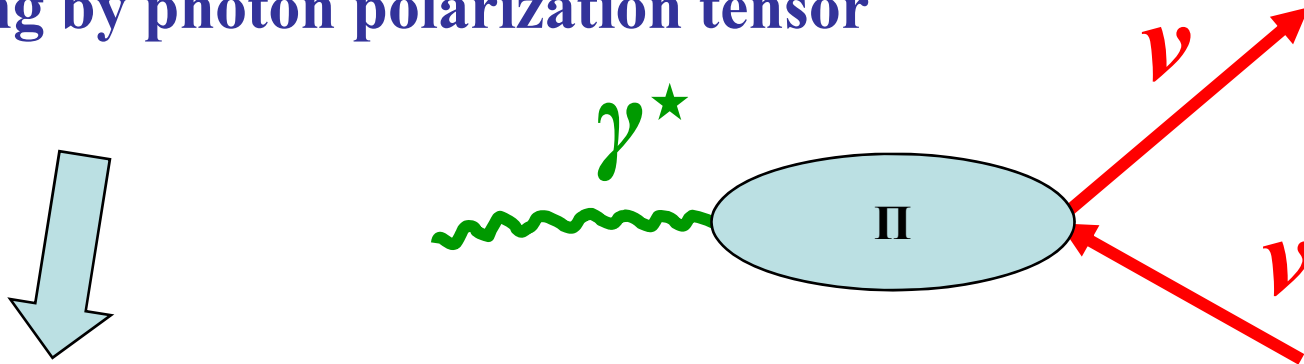
$$\mu^2 \rightarrow \sum_{a,b} (|\mu_{a,b}|^2 + |\epsilon_{a,b}|^2)$$

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

distribution function of plasmons

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

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



more fast cooling of the star.

In order not to delay helium ignition ($\leq 5\%$ in Q)



*... best
astrophysical
limit on*

✓ magnetic moment...

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

**G.Raffelt,
PRL 1990**

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

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.

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

Bounds depend on

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

● Generic assumption:

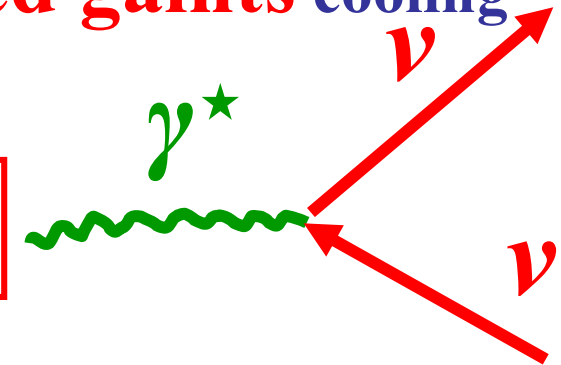
- absence of other nonstandard interactions except for μ_ν .

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

3.10

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

● Constraints on neutrino **millicharge** from **red gaints** cooling



Interaction Lagrangian

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

Decay rate

millicharge

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

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

*Halt, Raffelt,
Weiss, PRL 1994*

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

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

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

**Приглашаем всех участников
настоящего заседания
продолжить научные дискуссии
по теме**

**«  в электромагнитных полях и средах»
за чашкой чая**