Towards the detection of relic neutrinos

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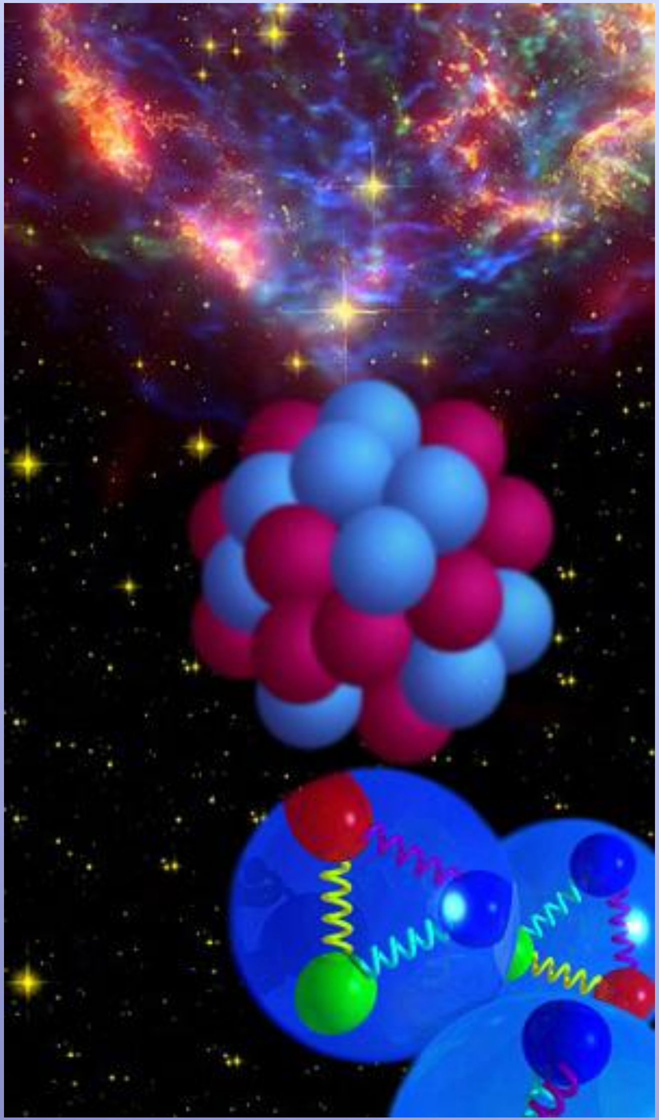
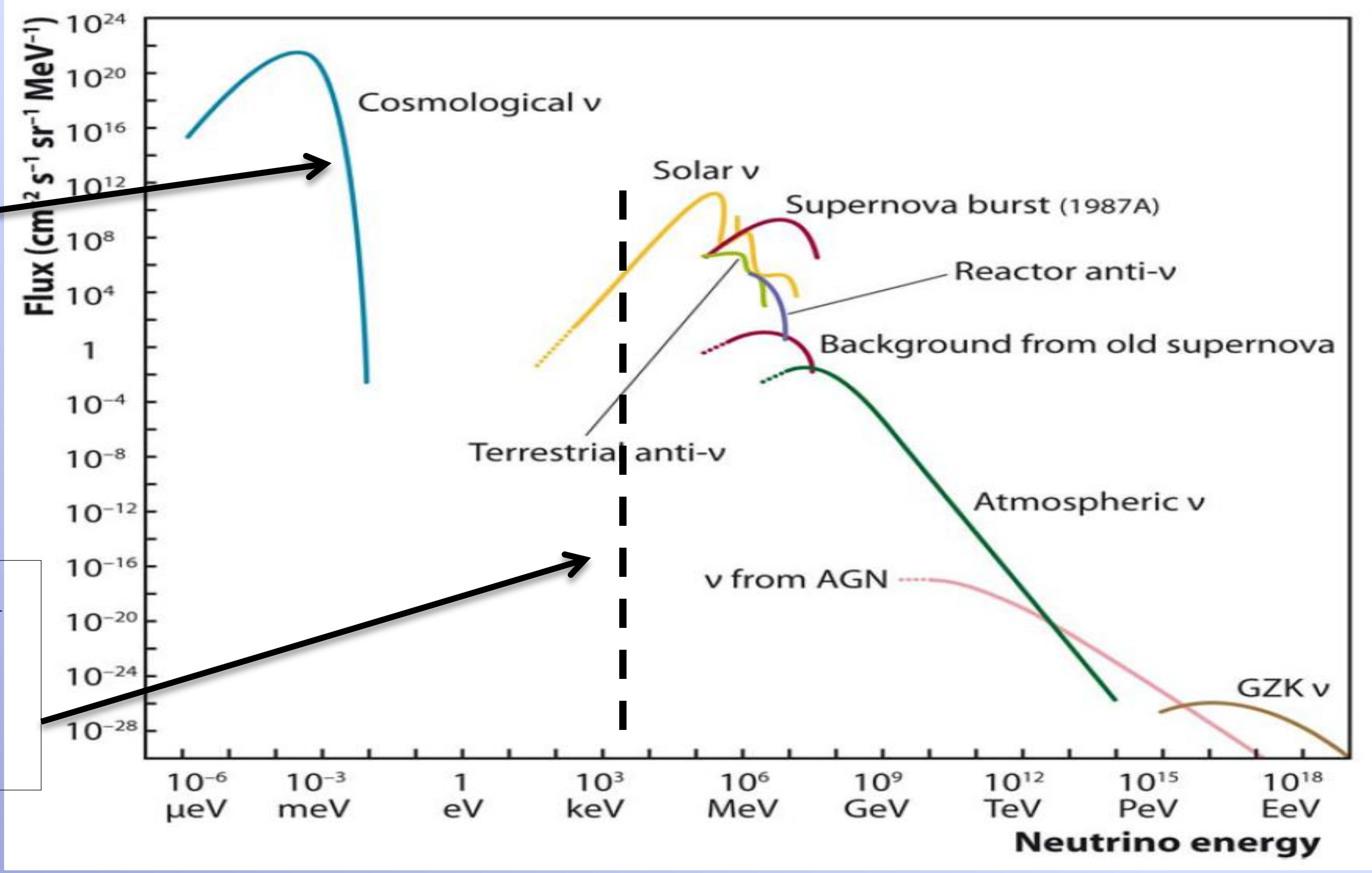
International School of Nuclear Physics, Particle and Nuclear Astrophysics
Erice - Sicily, Sept. 16-24, 2010

Introduction



- Neutrinos are probably one of the most important structural constituents and one of the most abundant components of the Universe (**10^{87}** relic neutrinos per flavour in the visible universe)
- Inside our body are more than 10^7 neutrino relics from the early Universe
- So far, relic neutrinos have not been observed
- Investigation of the possibilities to detect cosmological relic neutrinos with **neutrino capture on β -decaying** (^{3}H - KATRIN experiment, ^{187}Re - MARE experiment) and **double β -decaying** (^{100}Mo - MOON experiment) **nuclei**
- **Heavy sterile neutrino:** Towards the detection
- **Gravitational clustering** of neutrinos in our galaxy or galaxy cluster may enhance the relic neutrino density making its detection more realistic

Sources of neutrinos



Abundant but challenging detection

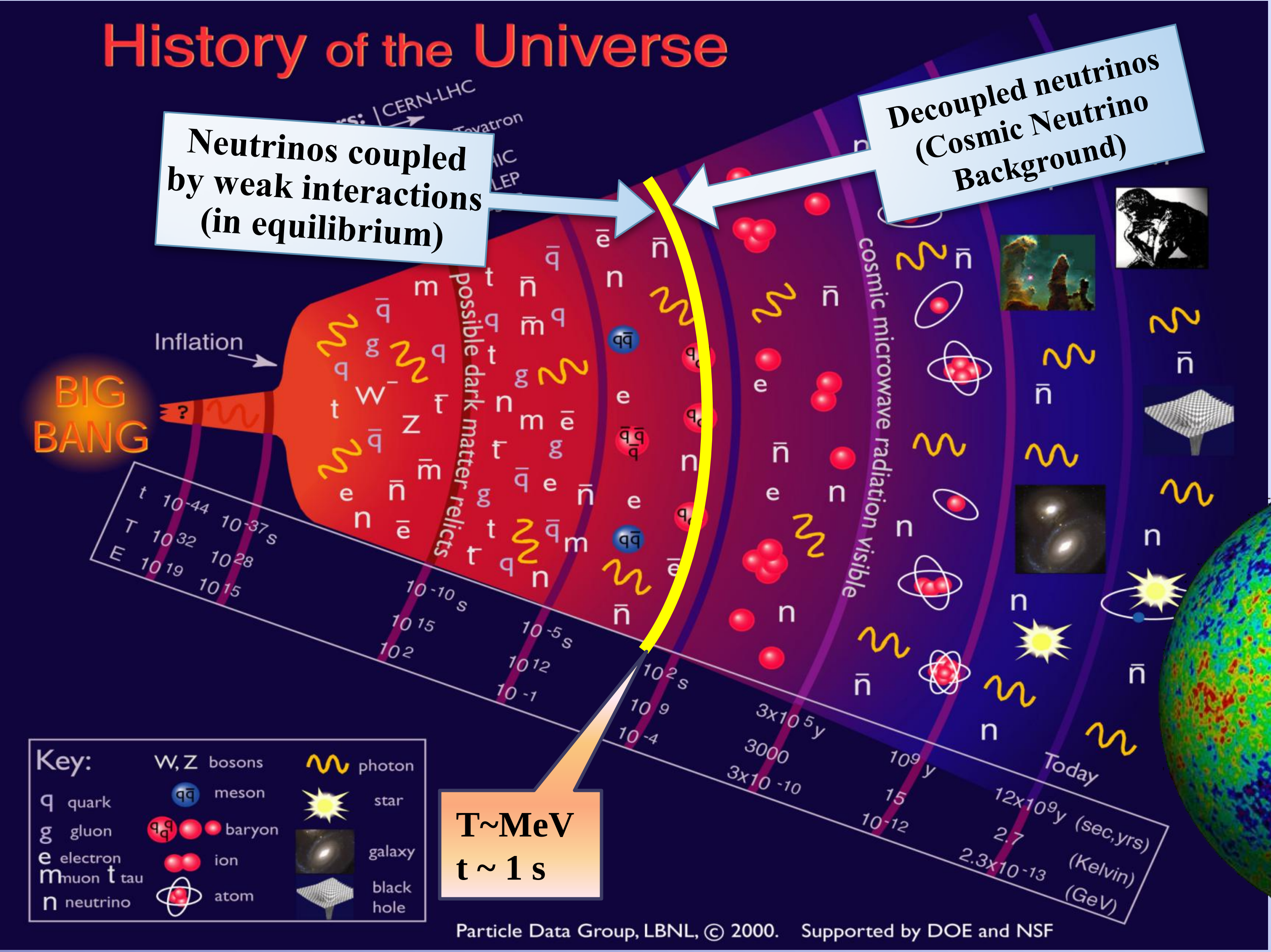
Below detection threshold of current experiments

- ➢ Flux of neutrinos on Earth from different sources as a function of energy

Ref.: D. Vignaud and M. Spiro, Nucl. Phys.A 654 (1999) 350

Relic neutrinos

- lepton era (≈ **1s** after BB, $\mathbf{10^{10}\ K \leq T_{\gamma} \leq 10^{12}\ K \rightarrow \approx\ 1 - 100\ MeV}$)

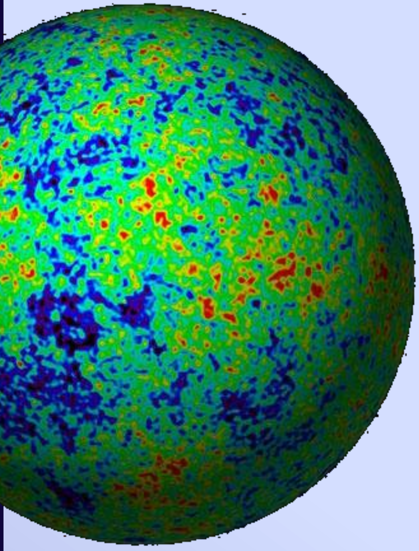


Neutrinos coupled by weak interactions (in equilibrium)

Decoupled neutrinos (Cosmic Neutrino Background)

T~MeV
t ~ 1 s

- The existence of a **cosmic neutrino background** – the analogue of the cosmic microwave background – is a fundamental prediction of Standard Cosmological Model

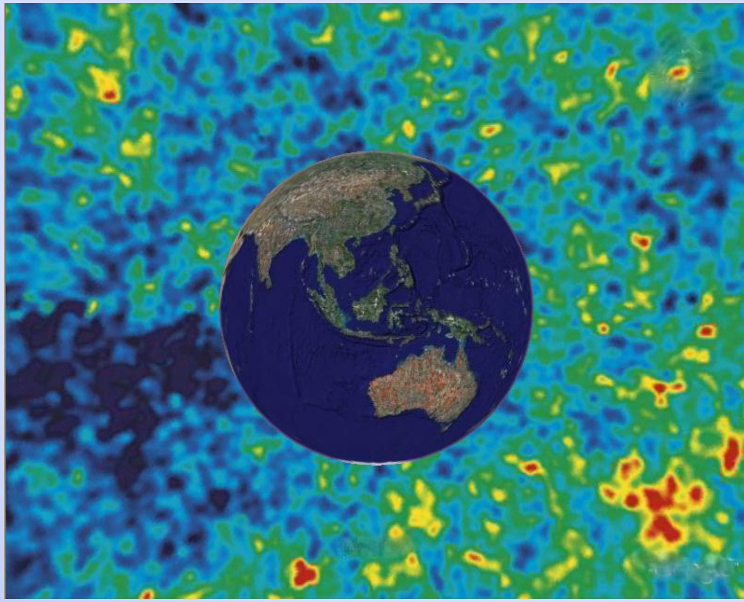


Properties of relic neutrino background

- Present relic neutrino **temperature**

$$T_\nu^{\,0} = \left(\frac{4}{11}\right)^{1/3} T_\gamma^{\,0} \approx (1.945\pm0.001)K \rightarrow \mathrm{k_B}T_\nu \approx (1.676\pm0.001)\times10^{-4}eV$$

$$\rightarrow T_\gamma^{\,0} = (2.725\pm0.001)K = (2.348\pm0.001)\times10^{-4}eV$$



- Present **number density** of each neutrino generation

$$n_\nu^0 + n_{\bar\nu}^0 = \frac{3}{2}\frac{\zeta(3)}{\pi^2} g_\nu (T_\nu^0)^3 = \frac{6}{11}\frac{\zeta(3)}{\pi^2}(T_\nu^0)^3 =$$

$$= \frac{3}{11} n_\gamma^0 = (111.9\pm0.1)cm^{-3}$$

$\zeta(3) \approx 1.20206$
Riemann´s zeta function and **g_ν =1**

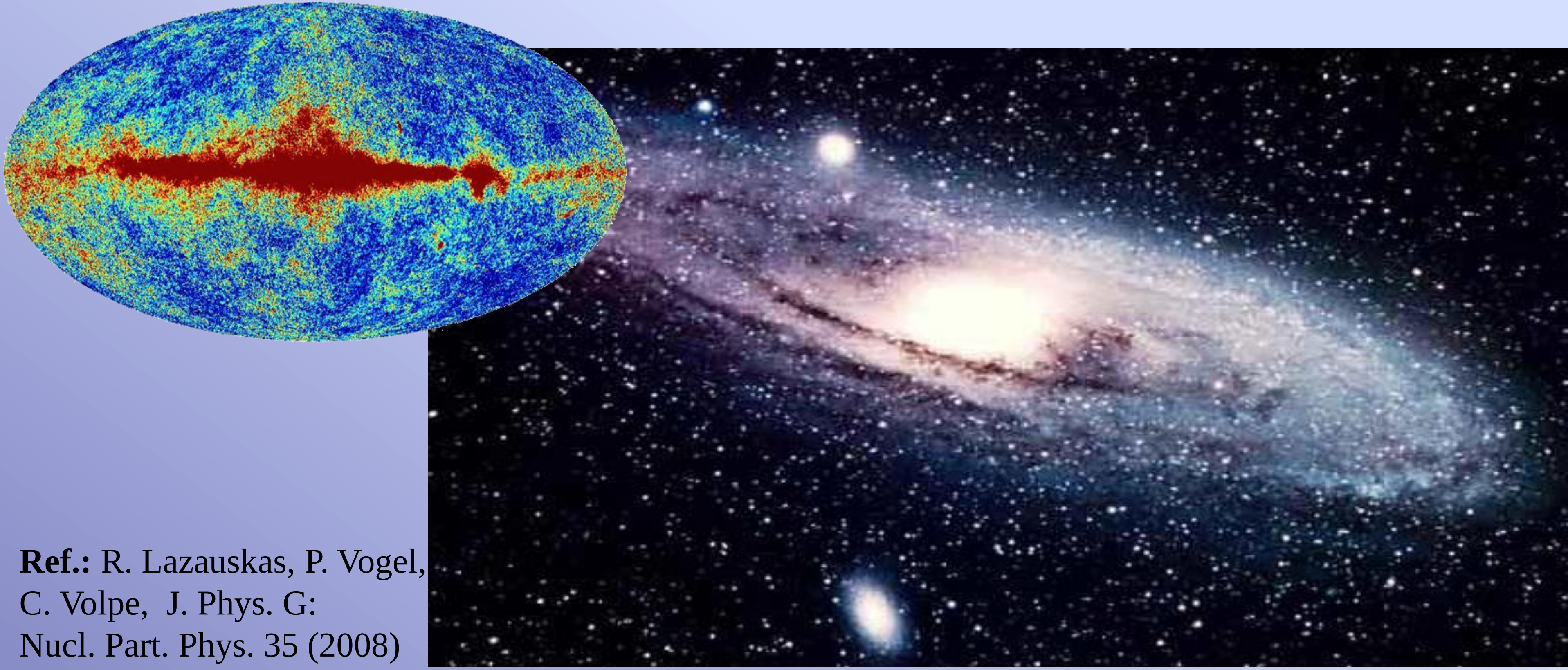
- Present **mean momentum** of relic neutrinos

$$\left\langle p_\nu^0 \right\rangle = \frac{7}{2}\frac{\zeta(4)}{\zeta(3)} T_\nu^0 \approx 3.151 T_\nu^0 \approx 5.314\times10^{-4}eV$$

$\zeta(4) = \pi^4/90 \approx 1.08232$

Ref.: C. Giunti, C. W. Kim, Fundamentals of Neutrino Physics and Astrophysics, Oxford U. Press, (2007)

- We know that neutrinos of CνB are now **non-relativistic** and **weakly-clustered**
- Massive neutrinos (**m_ν ~ 1 eV)** will be **gravitationally clustered** on the **scale** of **~Mpc** (~3×10^{19}km) → the scale of galaxy clusters
- The expected over-densities with respect to the average CνB neutrinos density **~ 10^3–10^4**



Ref.: R. Lazauskas, P. Vogel, C. Volpe, J. Phys. G: Nucl. Part. Phys. 35 (2008)

Relic neutrino detection using ν capture on β^- decaying nuclei → feasibility to detect ν in

KATRIN experiment (Karlsruhe TRItium Neutrino)

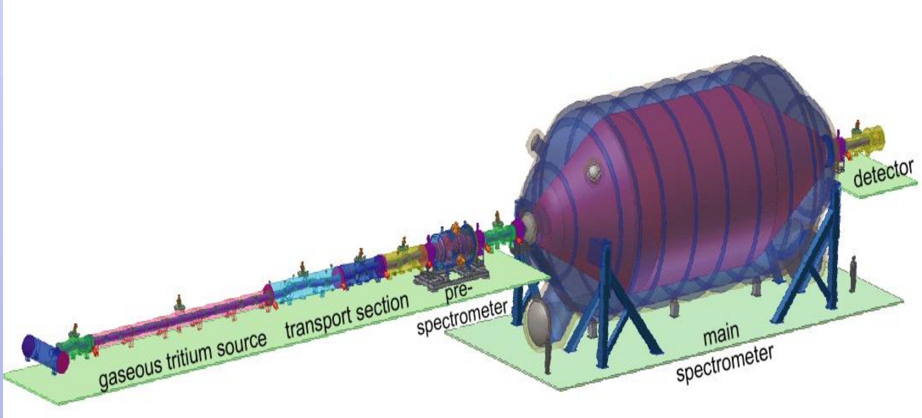
$$\nu + {}^{3}H^{\frac{1}{2}^{+}} \rightarrow {}^{3}He^{\frac{1}{2}^{+}} + e^{-}$$

- Measuring **m_ν** with sensitivity of **0.2 eV**
- For single neutrino in a **volume V** and by assuming a **local density** of relic neutrinos **η_ν** the **capture rate per atom** is

$$\boxed{\Gamma^{\nu}({}^{3}H) = \frac{1}{\pi} G_{\beta}^{2}.F_{0}(2,p).p.p_{0}\left(|M_{F}|^{2} + g_{A}^{2}|M_{GT}|^{2}\right)\frac{\eta_{\nu}}{\langle\eta_{\nu}\rangle}\langle\eta_{\nu}\rangle = 4.2\times10^{-25}\,y^{-1}}$$

- Using about **50 μg** of **^{3}H ($T_{1/2}^{\beta}$ = 12.35 y)** (corresponding to 5×10^{18} T_2 molecules)
- For **number of neutrino capture events**

$$\boxed{N_{capt}^{\nu}(KATRIN) \approx 4.2\times10^{-6}\,\frac{\eta_{\nu}}{\langle\eta_{\nu}\rangle}\,y^{-1}}$$



Ref.: A. G. Cocco, G. Mangano, M. Messina, arXiv:0711.1762v1, 12 Nov 2007

Experiment MARE (The Microcalorimeter Arrays for a Rhenium Experiment)

$$\nu + {}^{187}\mathrm{Re}^{5/2^{+}} \rightarrow {}^{187}Os^{1/2^{-}} + e^{-}$$

- Measuring neutrino mass in the sub-eV range with the unique first **forbidden** β - decay of ^{187}Re
- For the **capture rate** of this process we derive

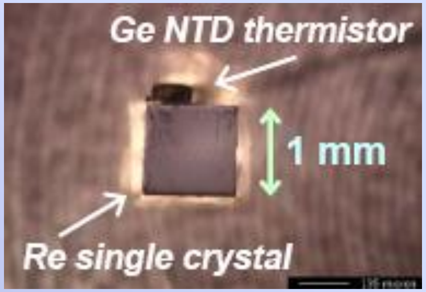
$$\boxed{\Gamma^{\nu}({}^{187}\mathrm{Re}) = \frac{1}{\pi} G_{\beta}^{2} \frac{1}{3} F_{1}(76, p)\left(pR\right)^{2} B.p.p_{0} \frac{\eta_{\nu}}{\langle \eta_{\nu} \rangle} \langle \eta_{\nu} \rangle = 2.75 \times 10^{-32} y^{-1}}$$

Beta strength

$$\boxed{B = \frac{g_{A}^{2}}{6} \left| \left\langle {}^{187}Os^{1/2^{-}} \left\| \sqrt{\frac{4\pi}{3}} \sum_{n} \tau_{n}^{+} \frac{r_{n}}{R} \left\{ \sigma_{n} \otimes Y_{1}(\Omega_{r_{n}} \right\}_{2} \right\| {}^{187}\mathrm{Re}^{5/2^{+}} \right\rangle \right|^{2}}$$

- Investigation the β -decay of ^{187}Re with absorbers of **$\mathbf{AgReO_4}$ crystals**
- Using about **760 g** of **^{187}Re** **($T_{1/2}^{\beta}$ = 4.35 x10^{10} y)** for **number of neutrino capture events**

$$\boxed{N_{capt}^{\nu}(MARE) \approx 7.6 \times 10^{-8} \frac{\eta_{\nu}}{\langle \eta_{\nu} \rangle} y^{-1}}$$



- For the **ratio of capture rate** and **decay rate** we have

$$\boxed{\frac{\Gamma^{\nu}(^{3}H)}{\Gamma^{\beta}(^{3}H)} = 7.5\times10^{-24}} \qquad \boxed{\frac{\Gamma^{\nu}(^{187}\mathrm{Re})}{\Gamma^{\beta}(^{187}\mathrm{Re})} = 1.7\times10^{-21}}$$

- Factor of 200
- The MARE detector technology can be **scaled up**
- In the case of clustering of relic neutrinos there is a chance for a reasonable relic neutrino capture rate with 2-4 orders of magnitude heavier detector.

Relic neutrino detection using ν capture on $\beta\beta$ decaying nuclei

Single capture

$$\nu + (A,Z) \to (A,Z+2) + 2e^- + \bar{\nu}$$

Double capture

$$2\nu + (A,Z) \to (A,Z+2) + 2e^-$$

Capture rate

$$\boxed{\Gamma^{\nu\beta\beta\bar{\nu}} = \frac{1}{2\pi^5} G_\beta^4 g_A^4 \left|M_{GT}^{2\nu}\right|^2 I^{\nu\bar{\nu}} \frac{\eta_\nu}{\langle\eta_\nu\rangle}\langle\eta_\nu\rangle}$$

$$\boxed{\Gamma^{\nu\nu\beta\beta} = \frac{1}{2\pi^3} G_\beta^4 g_A^4 \left|M_{GT}^{2\nu}\right|^2 I^{\nu\nu} \left(\frac{\eta_\nu}{\langle\eta_\nu\rangle}\right)^2 \left|\langle\eta_\nu\rangle\right|^2}$$

NME of 2νββ - decay

MOON experiment (Molybdenum Observatory Of Neutrinos)

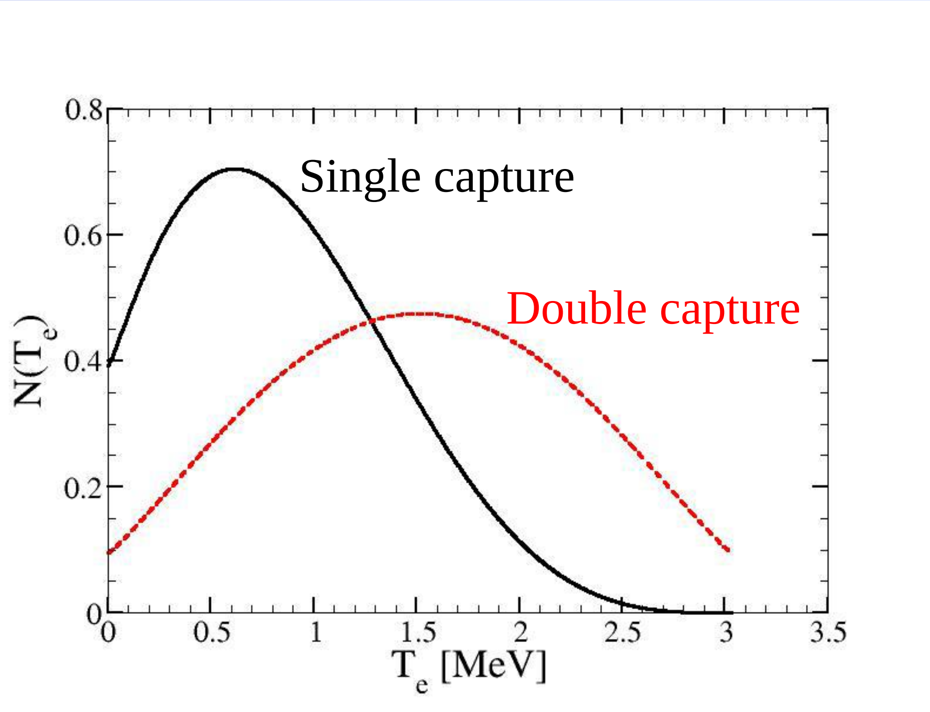
- Measuring directly **m**$^{M}_{\nu}$ by neutrino-less double beta decay with sensitivity of 0.01 ~ 0.06 eV
- Let us consider an example of a detector with 1 ton of **^{100}Mo** **($T_{1/2}^{\beta}$ = 7.1 x 10^{18}y)**

→ capture rate

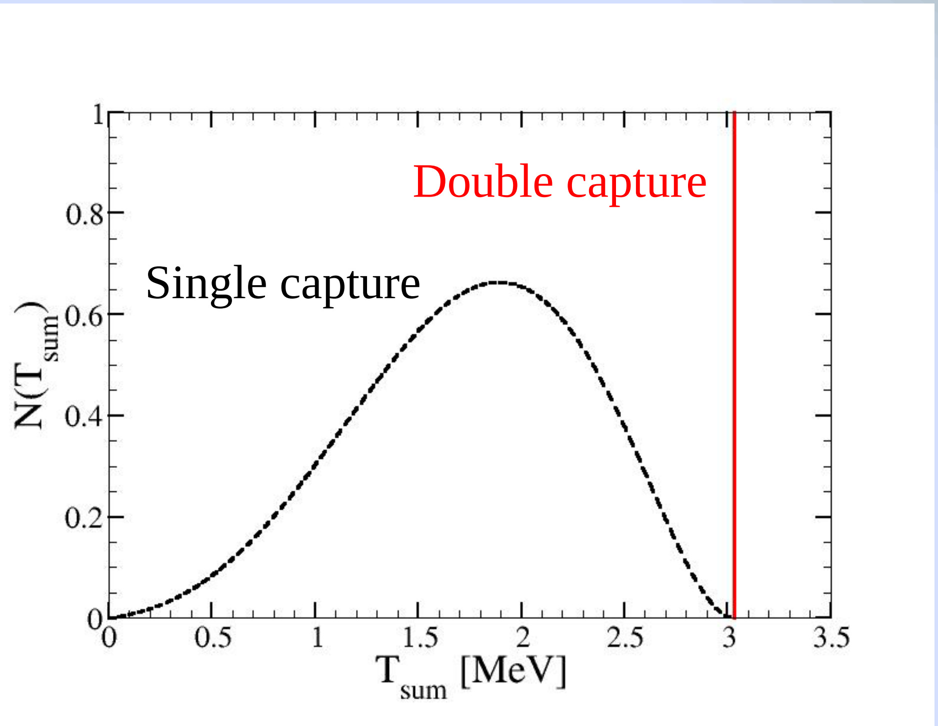
$$\boxed{N^{\nu\bar{\nu}}_{capt}(MOON) \approx 8.8\times10^{-20} \frac{n_\nu}{\langle n_\nu\rangle}\langle n_\nu\rangle y^{-1}}$$

$$\boxed{N^{\nu\nu}_{capt}(MOON) \approx 1.0\times10^{-48} \left(\frac{\eta_\nu}{\langle\eta_\nu\rangle}\right)^2 \left|\langle\eta_\nu\rangle\right|^2 y^{-1}}$$

Differential electron spectra normalized to the total capture rates for single and double relic neutrino capture on ^{100}Mo



Single electron energy T_e



Sum of kinetic energy of outgoing electrons T_{sum}

Sterile neutrinos

$$\nu_{k(=e,\mu,\tau)} = \sum_{i=1}^{3} \mathrm{U}_{\mathrm{k}i}\nu_i + \nu_4 = \nu_h$$

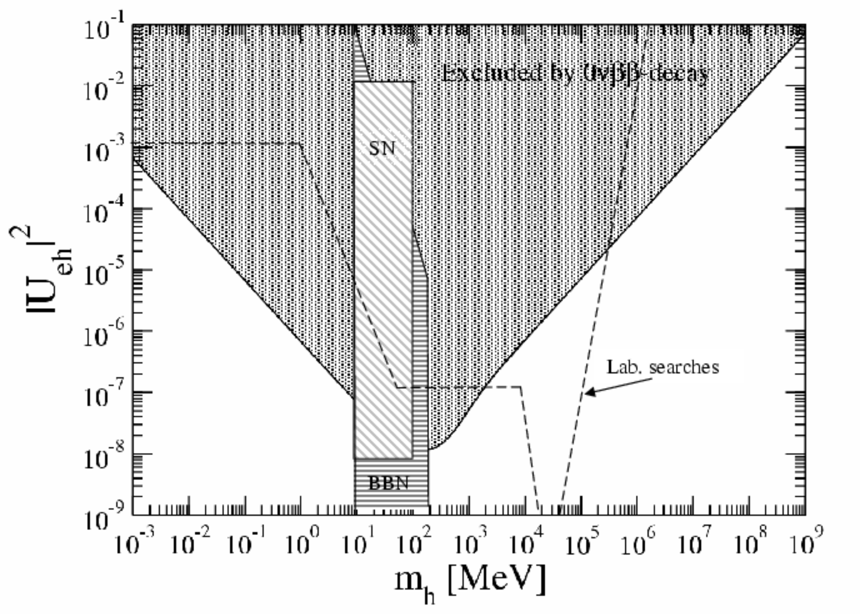
Heavy sterile neutrino

$$\nu_{k(=e,\mu,\tau,h)} = \sum_{i=1}^{4} \mathrm{U}_{\mathrm{k}i}\nu_i$$

Each *flavor* eigenstate (ν_e, ν_μ, ν_τ and ν_S) is a linear superposition of four *mass* eigenstates ν_1, ν_2 ,ν_3 and ν_4 described by ***unitary mixing matrix*** **(Pontecorvo-Maki-Nakagawa-Sakata).**

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_S \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{S1} & U_{S2} & U_{S3} & U_{S4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

$$\sum_{i=1}^{4} \mathrm{U}_{\mathrm{e}i}^2 = 1 \qquad U_{eh}^2 = 1 - \sum_{i=1}^{3} \mathrm{U}_{\mathrm{e}i}^2$$



Ref.: Beneš, Faessler, Šimkovic, Kovalenko, PRD 71 (2005) 077901

Sterile relic neutrino detection using ν_h capture on ^{3}He

$$\nu_h + {}^3He \rightarrow {}^3H + e^+$$

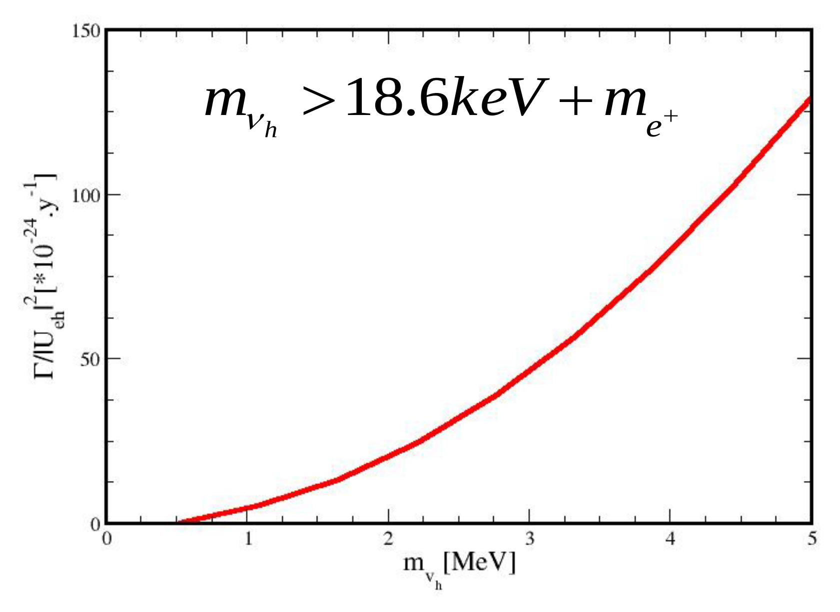
- Capture rate per atom

$$\boxed{\Gamma^{\nu_h}({}^3He) = |U_{eh}|^2 \frac{1}{\pi} G_\beta^2 . F_0(1,p) . p_{e^+} . p_0 \left(|M_F|^2 + g_A^2 |M_{GT}|^2 \right) \frac{\eta_\nu}{\langle \eta_\nu \rangle} \langle \eta_\nu \rangle}$$

$$\boxed{p_{e^+} = \sqrt{E_e^2 - m_e^2} = \sqrt{(m_{\nu_h} - 18.6 keV)^2 - m_e^2}}$$

- Using about **1kg** of **^{3}He** (corresponding to **2×10^{26}** molecules) → **production rate**

m_{ν_h} [MeV]	$N_{\nu_h} . \lvert U_{eh}\rvert^2 . \frac{\eta_\nu}{\langle \eta_\nu \rangle}$.[$*10^{-24}$ y^{-1}]
0.6	1
1	5
5	130



Sterile relic neutrino detection using ν_h capture on ^{187}Os

- Capture rate per atom

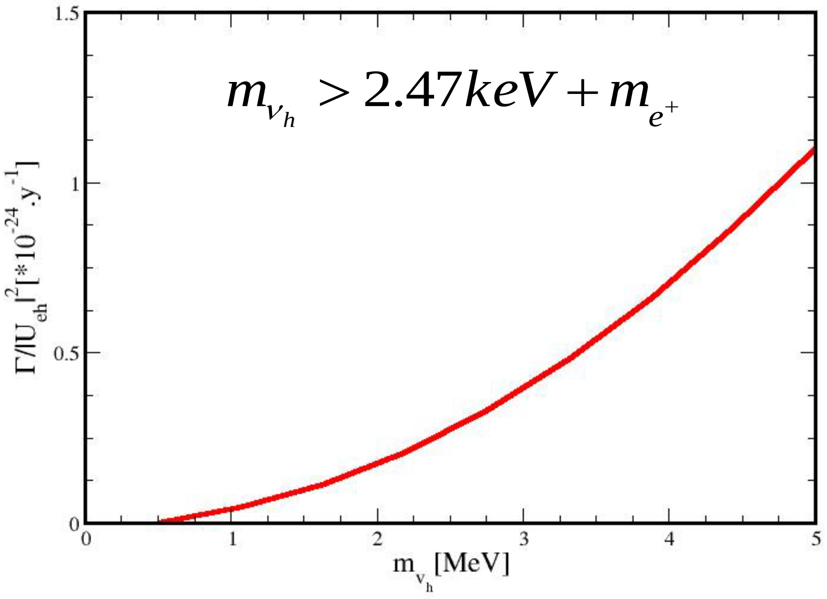
$$\nu_h + {}^{187}Os \rightarrow {}^{187}\mathrm{Re} + e^+$$

$$\boxed{\Gamma^{\nu_h}({}^{187}Os) = |U_{eh}|^2 \frac{1}{\pi} G_\beta^2 \frac{1}{3} \underset{\downarrow}{F_1}(75, p)(pR)^2 . B . p_{e^+} . p_0 \frac{\eta_\nu}{\langle \eta_\nu \rangle} \langle \eta_\nu \rangle}$$

Relativistic coulombic factor

- Using about **1kg** of **^{187}Os** (corresponding to **3×10^{24}** molecules) → **production rate**

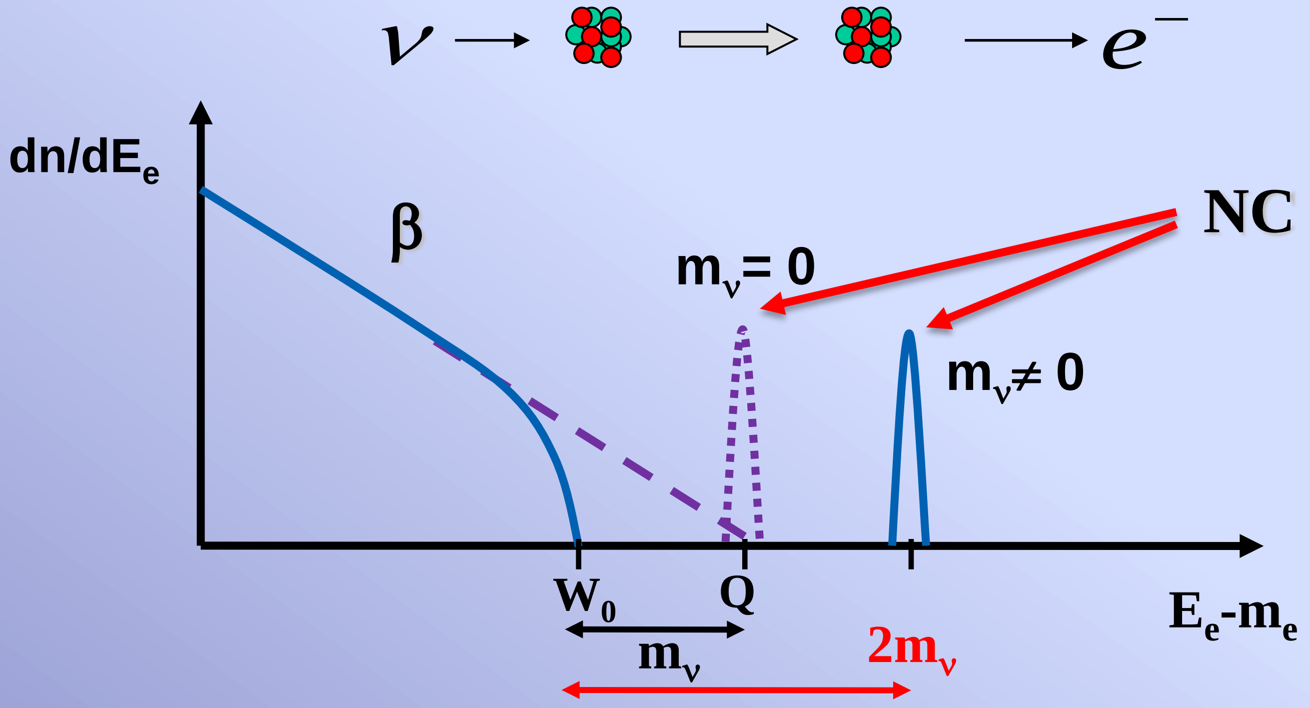
m_{ν_h} [MeV]	$N_{\nu_h} . \lvert U_{eh}\rvert^2 . \frac{\eta_\nu}{\langle \eta_\nu \rangle}$.[$*10^{-24}$ y^{-1}]
0.6	0.008
1	0.04
5	1



Ref.: M. Doi, T Kotani and E. Takasugi, Prog. Theor Phys. (Supp.) 83, 1 (1985)

Conclusions

- In single neutrino capture process on **50 μg** of **^{3}H (Q=18.6 keV)** we calculated the number of events equal to **4.2 x10^{-6}** events per year and in **^{187}Re (Q=2.47 keV)** case equal to **7.6 x10^{-8}** events per year (without considering gravitational clustering)



- Processes of single and double neutrino capture with double beta decaying nuclei (on 1 ton of **^{100}Mo, Q=3MeV**) are strongly suppressed (**8.8 x10^{-20}** and **1.0 x10^{-48}** events per year respectively)
- The double relic neutrino capture, due to smallness of its rate, can be excluded as a background for the 0νββ -decay experiment

- Case of heavy sterile neutrino capture on nuclei (^{3}He...) need to be also investigated in the future experiments.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