Direct Detection of Neutrinos with KATRIN and PTOLEMY

Diogo Miguel nº53096

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Introduction

- Cosmic neutrino Background (CνB) is a relic from the early Universe.
- It dates as far as 350 000 years before the Cosmic Microwave Background.
- It is the Universe's background particle radiation composed of neutrinos.
- Measuring the properties of these neutrinos will be important to unfold the mysteries of the Universe.

Neutrinos

- Have weak interactions, making them slower than the Hubble rate instantaneously in the decoupling limit.
- The average number density per neutrino state today, n_0, is:

$$n_0 = \frac{3\zeta(3)}{4\pi^2} T_{\nu,0}^3 = 56cm^{-3}$$

- $T_{\nu,0}$ is the neutrino temperature in the present, $T_{\nu,0} \approx 1.95K$.

Neutrinos

- The final stages of neutrino decoupling overlap with the beginning of the electron-positron annihilations in the primeval plasma.
- The effective number of relativistic neutrino families are:

$$N_{eff} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\frac{\rho_\nu}{\rho_\gamma} = 3.045$$

- ρ_γ e ρ_ν are the photon and neutrino energy densities, respectively.

- 2 of the 3 neutrino families are massive, however, the mass scale is still unknown.

Direct detection of Neutrinos

- The best way to measure the neutrinos mass is through:
    - β-decay endpoint;
    - Electron capture decay.
- Some current and future projects are going to attempt to take these measurements:
    - KATRIN;
    - ECHo;
    - HOLMES;
    - Project-8;
    - PTOLEMY.

β-decay endpoint

- Effective neutrino β-decay mass:

$$m_\beta^2 = \sum_i |U_{ei}|^2 m_i^2$$

- $|U_{ei}|$ are the elements of the mixing matrix which describe the electron flavor for each of the eigenstates.
- m_i is the mass of the i-th neutrino eigenstate.
- Considering that the mass m_i is similar to the neutrino mass itself, m_ν, then:

$$m_\beta \approx m_\nu$$

Neutrino Mass Ordering

- Another unknown is the mass ordering of neutrinos. It can be normal or inverted.
- Normal ordering happens when the lightest neutrino has the biggest mixing with the electron flavors.
- Inverted ordering is the exact opposite.
- Super–Kamiokande experiment suggests that the normal order is the most favorable.

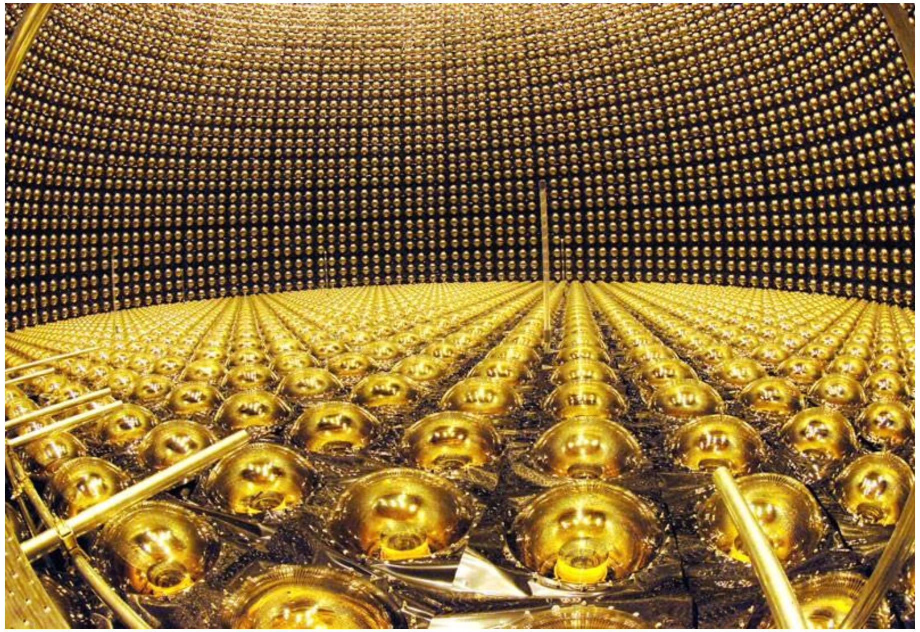

Fig.1: Image of the interior of super-Kamiokande experiment.

It is an important factor in the interpretation of the event counts.

Cosmology of the Neutrino Background

- Hubble constant, H, is given by:

$$H = \frac{\dot{a}}{a} = \sqrt{\frac{8\pi G}{3}\rho_{total}} = \sqrt{\frac{8\pi\rho}{3M_{Planck}^2}} \propto a^{-4}$$

- Reaction rate for relativistic neutrinos, Γ:

$$\Gamma = n_\nu < \sigma v > \approx T_0^3 G_{Fermi} T_0^2 = G_F T_0^5 \propto a^{-5}$$

The decoupling of neutrinos is a competition between these two factors.

β-decay of Tritium

- Reaction:

$$\nu_e + {}^3H \rightarrow {}^3He + e^-$$

Why Tritium?

- Availability;
- Adequate lifetime;
- Large neutrino cross section capture;
- Reaction has a low Q values ($\approx 18{,}562\ KeV$).

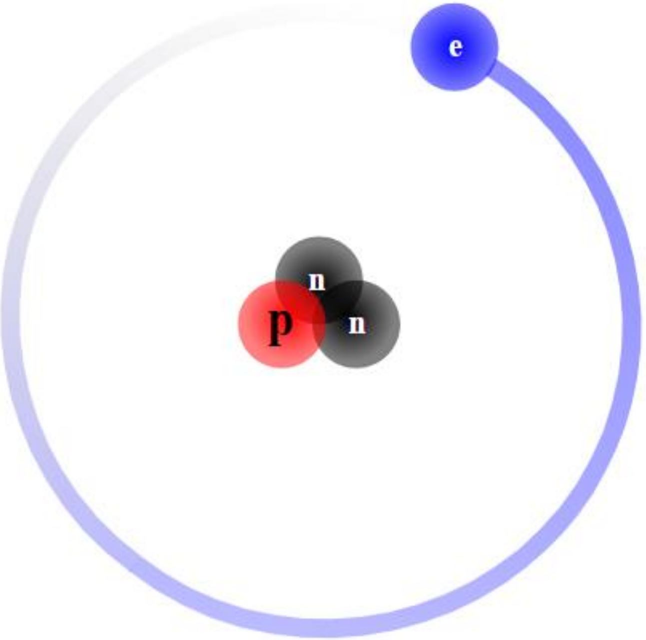

Fig.2: Scheme of the composition of a Tritium atom.

Neutrino capture with KATRIN

- According to Fermi's Golden Rule, Tritium β-decay probability is given by:

$$\Gamma^{\beta}_{decay}(^3H) = \frac{1}{2\pi^3} \cdot \sum \int | < {}^3He|T|^3H > |^2 \cdot 2\pi\delta(E_\nu + E_e + E_f - E_i)\frac{d\vec{p}_e}{2\pi^3} \cdot \frac{d\vec{p}_\nu}{2\pi^3}$$

- $\sum | < {}^3He|T|^3H > |^2$ is the beta decay matrix element.
- Integrating over the phase space and finding $\Gamma^{\beta}_{decay}(^3H)$, one finds the half-life of tritium:

$$T^{\beta}_{1/2} = \frac{ln2}{\Gamma^{\beta}_{decay}(^3H)} = 12.32 \quad years$$

- This result agrees with the values obtained experimentally.

Fig.3: KATRIN

Neutrino capture with KATRIN

- The induced relic neutrino capture reaction is:

$$\Gamma^{\beta}_{capture}(^{3}H) = 4.2 \cdot 10^{-25} \frac{n_{\nu,e}}{< n_{\nu,e} >} \quad , \qquad \text{with} \quad < n_{\nu,e} >= 56cm^{-3}$$

Gives the relic neutrino capture rate per year for 1 Tritium atom.

- The effective mass of the tritium source of KATRIN considered is 20 µg.

→ $2 \cdot 10^{18}$ Tritium$_2$ molecules

- The capture rate of relic neutrinos at KATRIN, N_{ν}^{K}, is then: $N_{\nu}^{k} = 1.7 \cdot 10^{-6} \cdot \frac{n_{\nu,e}}{< n_{\nu,e} >}$

Corresponds to 1 count for every 590 000 years.

Neutrino capture with KATRIN

- The number density of relic neutrinos is larger by gravitational clustering in our solar system or in our galaxy.
- Gravitational clustering of neutrinos is possible on the scale of galaxies of around 1 Mpc and their halos. The values obtained for the upper limit are:

$$n_{\nu,e}/ < n_{\nu,e} > \leq 10^6$$

- The new value for the capture rate of relic neutrinos is:

$$N_\nu^k = 1.7 \cdot 10^{-6} \cdot \frac{n_{\nu,e}}{< n_{\nu,e} >} \approx 1.7$$

Corresponds to 1.7 counts per year.

Neutrino capture with PTOLEMY

- The capture rate of relic neutrinos by Tritium nuclei is:

$$\Gamma_{C\nu B} = \sum_{i=1}^{N_\nu} \Gamma_i$$

- Γ_i is the capture rates from all the different neutrino mass eigenstates, ν_i. Γ_i depends on the number of Tritium nuclei,

$$N_T = M_T / m_{^3H}$$

- M_T is the mass of the sample of the element.

Neutrino capture with PTOLEMY

- Γ_i is given by:

$$\Gamma_i = N_T |U_{ei}|^2 \int \frac{d^3 p_\nu}{(2\pi)^3} \sigma(p_\nu) v_\nu f_{\nu_i}(p_\nu)$$

- $|U_{ei}|$ is the mixing matrix elements, ρ_ν and v_ν are the neutrinos momentum and velocity, respectively. $\sigma(\rho_\nu)$ is the cross-section and $f_{\nu_i}(\rho_\nu)$ is the momentum distribution function of the respective neutrino eigenstate.
- This distribution is very slender and so, the integral can be reduced to:

$$\int \frac{d^3 p_\nu}{(2\pi)^3} \sigma(p_\nu) v_\nu f_{\nu_i}(p_\nu) = \bar{\sigma} v_\nu f_{c,i} n_0$$

Neutrino capture with PTOLEMY

- The capture rate can then be modified to:

$$\Gamma_i = N_T |U_{ei}|^2 \bar{\sigma} v_\nu f_{c,i} n_0$$

- Energy resolution is finite so, most of the background in the neutrino capture process is from the most energetic electrons of the β-decay of Tritium. This happens because they can be measured with energies that go beyond the endpoint.
- Taking in account the β-decay spectrum, the rate of this background is:

$$\frac{d\Gamma_\beta}{dE_e} = \frac{\bar{\sigma}}{\pi^2} N_T \sum_{i=1}^{N_\nu} |U_{ei}|^2 H(E_e, m_i)$$

Neutrino capture with PTOLEMY

- A smearing is introduced in the electron spectrum, to account for the energy resolution Δ.
- Implemented through a convolution between the $C\nu B$ and the β-decay spectrum with a Gaussian of FWHM Δ.
- Therefore, the new neutrino capture rate is:

$$\frac{d\tilde{\Gamma}_{C\nu B}}{dE_e}(E_e) = \frac{1}{\sqrt{2\pi}(\Delta/\sqrt{8ln2})}\sum_{i=1}^{N_\nu}\Gamma_i \times exp\left[-\frac{[E_e-(E_{endpoint}+m_i+m_{lightest})]^2}{2(\Delta/\sqrt{8ln2})^2}\right]$$

- And applying the same principle to the smeared β-decays,

$$\frac{d\tilde{\Gamma}_{\beta}}{dE_e}(E_e) = \frac{1}{\sqrt{2\pi}(\Delta/\sqrt{8ln2})}\int_{-\infty}^{+\infty} dE'\frac{d\tilde{\Gamma}_{\beta}}{dE_e}(E')exp\left[-\frac{(E_e-E')^2}{2(\Delta/\sqrt{8ln2})^2}\right]$$

The number of signal events to be expected is around 4 counts per year.

Expected events rates with PTOLEMY

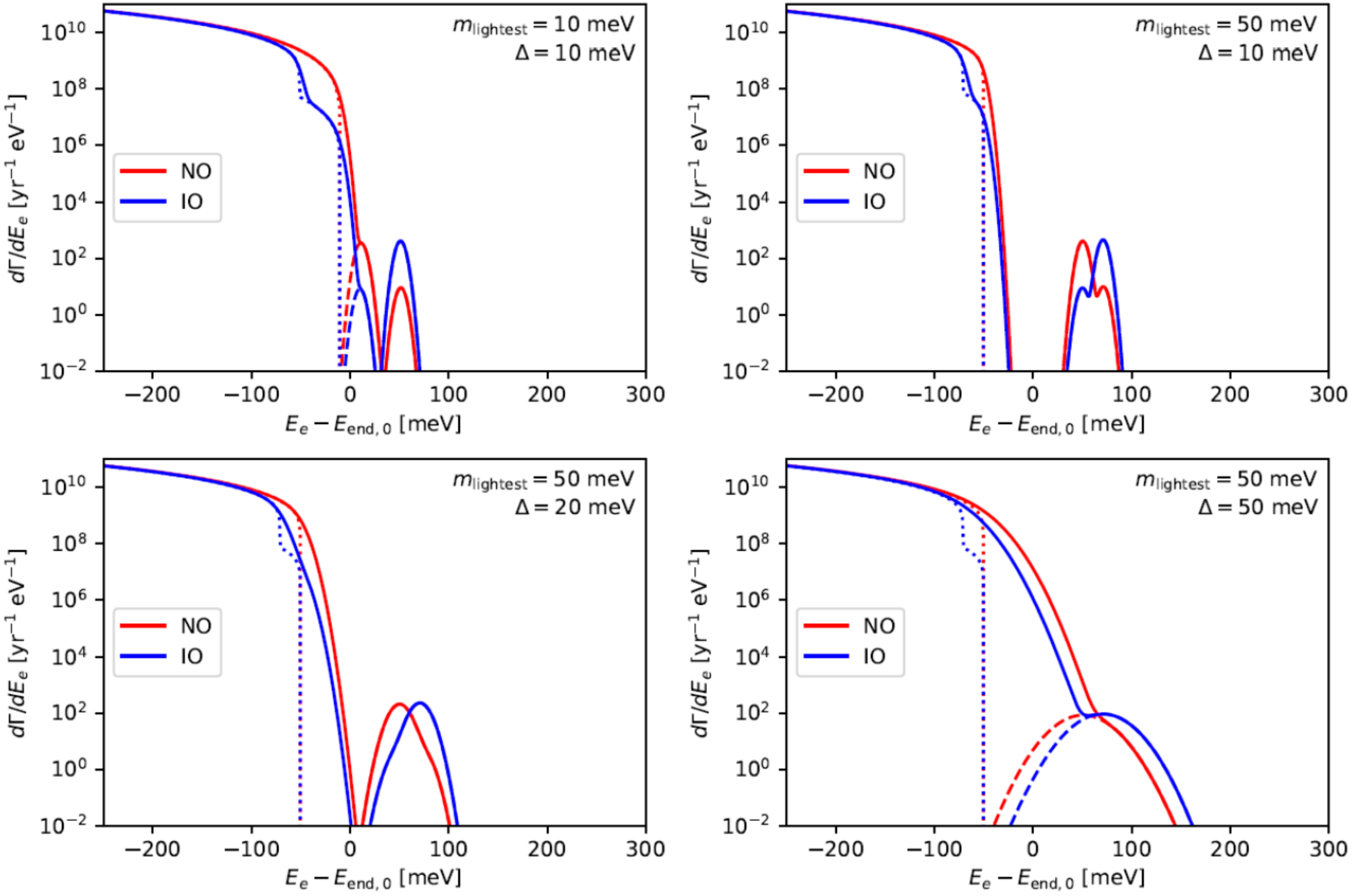

Fig.4: Expected event rates as a function of electron energy E_e in the PTOLEMY experiment (assuming 100g of tritium source) near the β-decay endpoint for different lightest neutrino masses and energy resolutions. Solid lines represent the total event rates convolved with a Gaussian envelope and dashed lines represent the signal event rates as it would be measured by the experiment without the background while dotted lines show the background (β-decay) event rates without the convolution.

Neutrino mass sensitivity

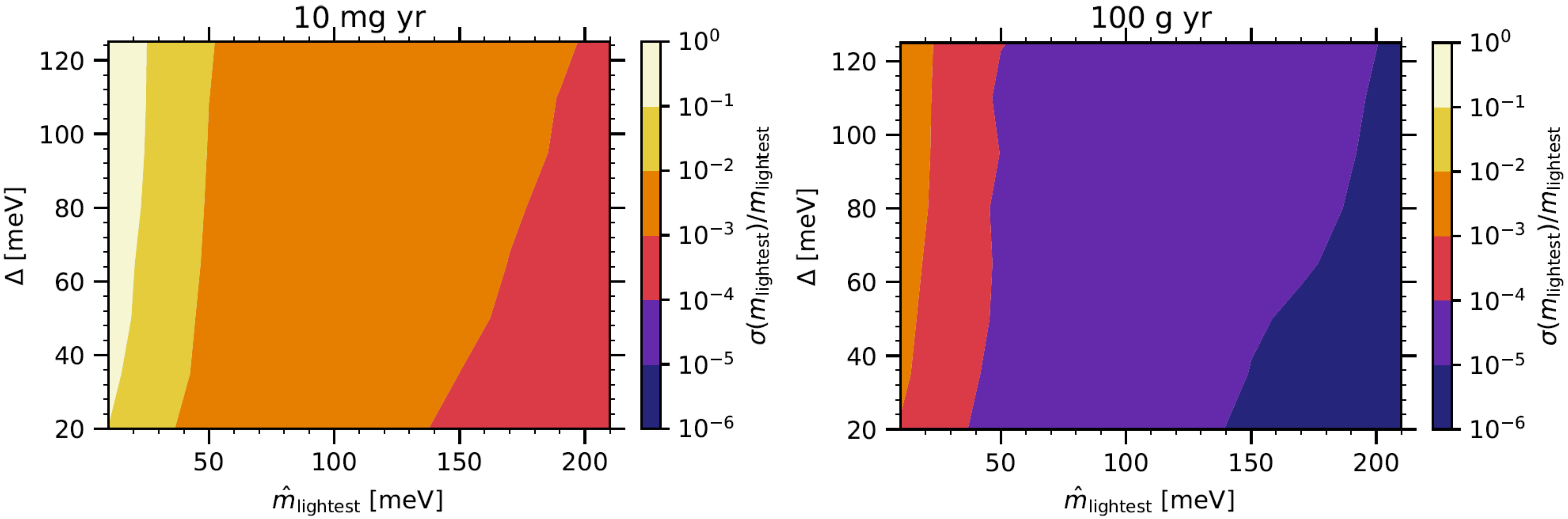

Fig.5: Relative error of the reconstructed lightest neutrino mass as a function of the lightest neutrino mass and the energy resolution, considering two different values for tritium mass of PTOLEMY data and normal ordering.

Mass ordering-PTOLEMY

- PTOLEMY will be able to determine the neutrino mass ordering.
- Best-fit mixing parameters of NO and IO to compute the Bayesian evidence $\mathcal{Z}$.
- Using Bayes factor, one obtains PTOLEMY sensitivity to mass ordering.

$$ln\mathcal{B}_{ij} = ln\mathcal{Z}_i - ln\mathcal{Z}_j$$

If $ln\mathcal{B}_{ij} > 0$ → Case i is preferred

If $ln\mathcal{B}_{ij} < 0$ → Case j is preferred

Conclusions

- Measuring the Cosmic Neutrino Background can give us a way to look back in time. More than with the Cosmic Microwave Background.

Problem:

  - Low neutrino number density, resulting in low counts of the $C\nu B$.

Solution:

  - Look in local overdensities in our galaxy.

- PTOLEMY has a good potential in neutrino physics, can detect very low energy fluxes and provides constrains on neutrino properties.

- Without Tritium, PTOLEMY could also be useful to observe dark matter particles.

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