Cosmic Neutrino Background telescope

The PTOLEMY experiment

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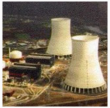
Neutrino sources

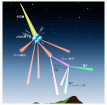
Nuclear Reactors
E_ν = 1 - 10 MeV
Detected ✓



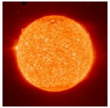
Accelerators
E_ν up to 12 GeV
Detected ✓

CERN
J-PARC
Fermilab
KEK

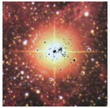
Atmosphere (Cosmic Rays)
E_ν up to 1 GeV
Detected ✓



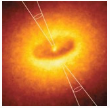
Terrestrial radioactivity
E_ν up to 1 MeV
Detected ✓



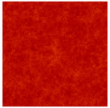
Sun
E_ν = 10.4 MeV
Detected ✓



Supernovae (SN 1987A)
E_ν = 10 MeV
Detected ✓

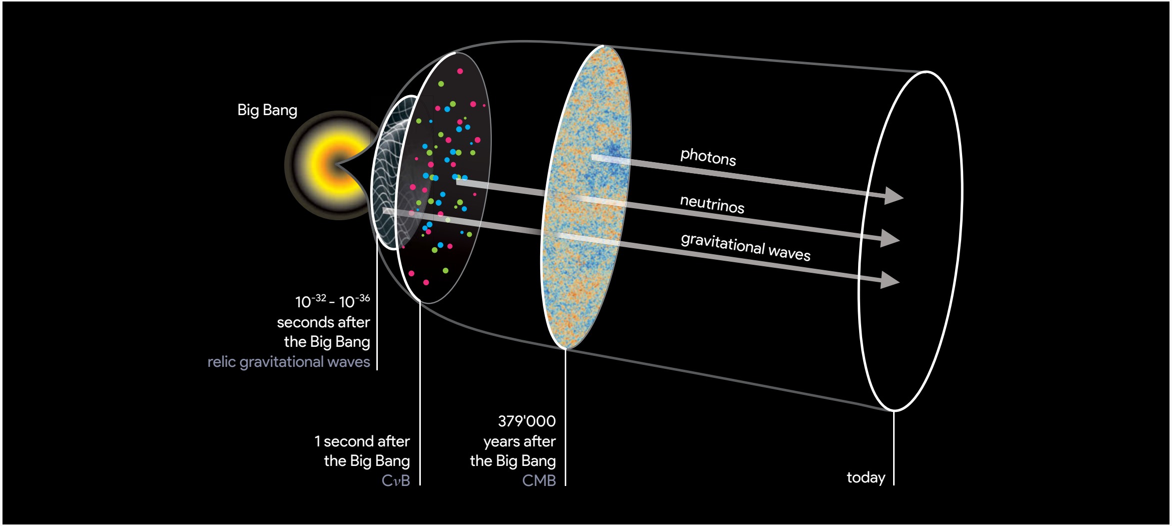


Astrophysical accelerators
E_ν ~ TeV - PeV
Detected ✓

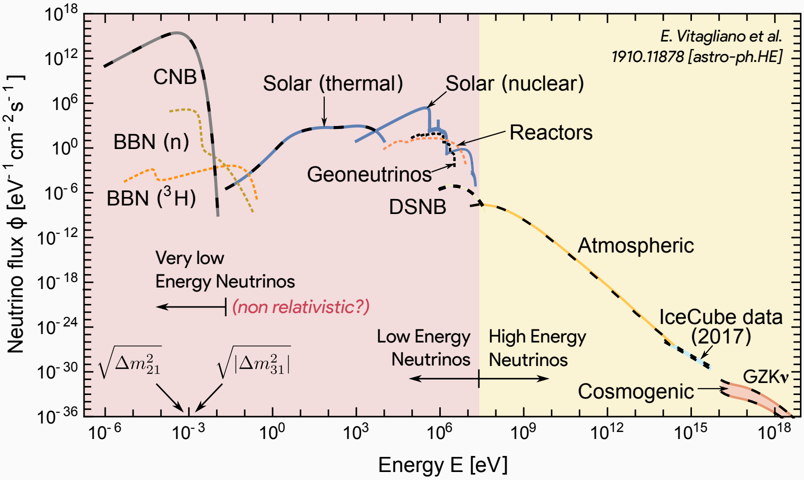


Early Universe
E_ν ~ 10^{-4} eV
Detected ✗ → Indirect evidence

Last Scattering Surfaces



Grand Unified Neutrino Spectrum at Earth

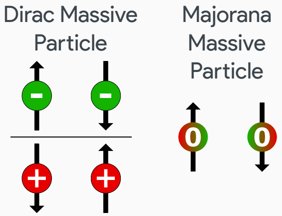


CνB is the largest neutrino density at Earth: 56 ν/cm^3 per type ($\nu/\overline{\nu}$) per flavour (e/μ/τ)

Direct detection of CνB is the *holy grail* of neutrino physics

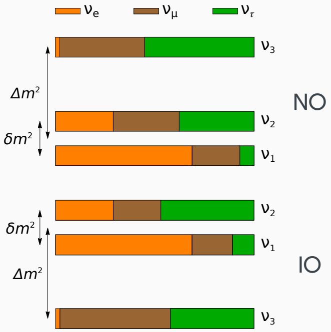
CνB is the largest neutrino density at Earth but yet it has never been measured;

- Detection of relic neutrino is a significant test of standard cosmology
- Observation of CνB would:
  - provide a window into the 1st second of creation;
  - constitute the first probe of non-relativistic neutrinos;
  - reveal the neutrino nature (through measurement of modulations/asymmetries);



In particular

- Neutrino mass nature: the capture rates of non-relativistic neutrinos (on beta decaying nuclei) depends on whether their mass nature is Dirac ($\overline{\nu} \neq \nu$) or Majorana ($\overline{\nu} = \nu$)
- Neutrino mass ordering: relic neutrinos with an enhanced (suppressed) detection rate for normal (inverted) neutrino ordering
  (since the lightest mass eigenstate contains a large (small) fraction of the electron-neutrino flavor eigenstate)



Relic Neutrino Direct Detection

The decoupling of neutrinos occurred just before $e^{\pm}$ annihilated and reheated photons, leading to the following ratio between the photon (γ) and neutrino (ν) temperatures

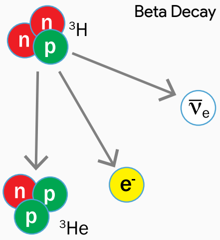
$$\frac{T_\gamma}{T_\nu} = \left(\frac{4}{11}\right)^{\frac{1}{3}} \Rightarrow \text{today } T_\nu = 1.95\,K = 0.168\,\text{meV} \quad \text{(for massless neutrinos)}$$

Is it possible to detect non-relativistic neutrinos?

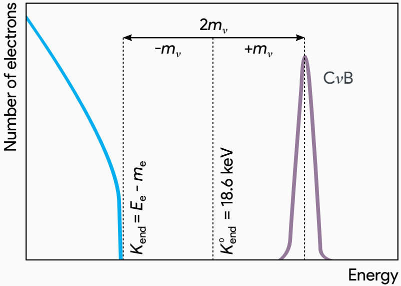
Several methods have been proposed:

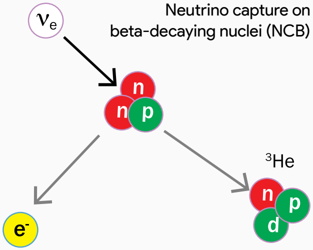
- absorption dips in the ultra-high-energy (UHE) neutrino fluxes due to their annihilation with relic neutrinos at the Z boson resonance;
- forces generated by coherent scattering of the relic bath on a pendulum and measured by laser interferometers;
- observation of interactions of extremely high energy protons from terrestrial accelerator beams with the relic neutrinos;
- Most of these proposed methods are impractical from the experimental point of view;

Neutrino capture in a β-decaying nucleus



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

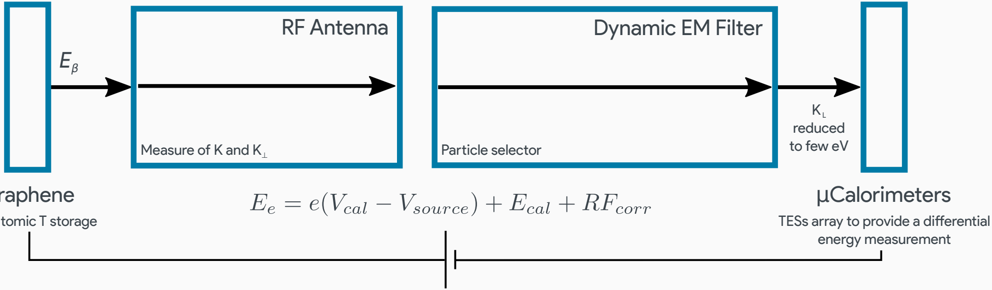




$$\nu_e + {}^3\mathrm{H} \rightarrow {}^3\mathrm{He} + e^-$$

- No energy thresholds on the value of the incoming neutrino energy;
- Smoking gun signature: peak in the electron spectrum at an energy of $2m_\nu$ above the beta decay endpoint;
- Tritium (^{3}H) represent the best candidate since it has a high neutrino capture cross section, low Q-value and it is long-lived;
- Detecting this peak requires an energy resolution below the level of $m_\nu = \mathcal{O}(0.1\,\mathrm{eV})$;
- For a 100 gram target, the expected capture rate is approximately 10 events per year.

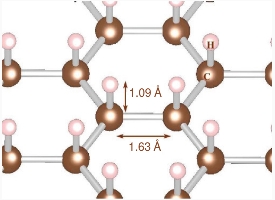
PonTecorvo Observatory for Light Early-Universe Massive-Neutrino Yield: PTOLEMY

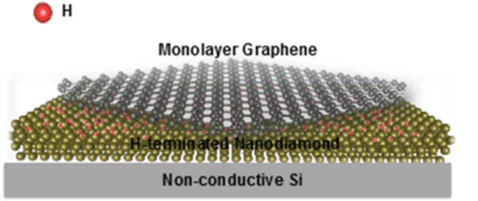


$$E_e = e(V_{cal} - V_{source}) + E_{cal} + RF_{corr}$$

- Electrons from weakly-bound tritium originate from a cold target surface.
- Electrons drift through an RF Antenna region where the electron momentum components are measured to few eV resolution.
- Filter electrodes are set around 1 msec in advance of electrons entering filter.
- Kinetic energy of electrons drained as they climb a potential under gradient-B drift.
- Electrons of few eV in a low B field region are transported into a microcalorimeter array.

Tritium-doped graphene (GRT) electron source (ESR)





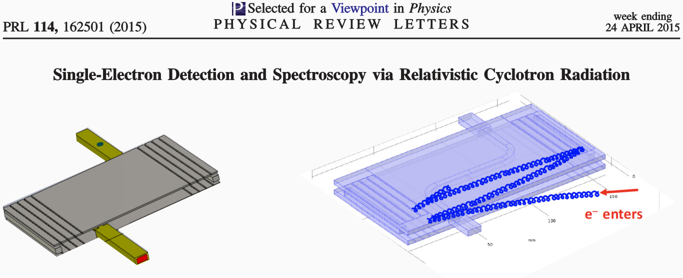
- Monolayer graphene consists of carbon atoms arranged in a two-dimensional honeycomb lattice;
- Graphene substrates are suitable to hold monoatomic Tritium layer through chemical absorption;

Advantages

- Use of atomic T $\Rightarrow$ no vibrational modes in final state like for ^{3}He-^{3}T final state;
- The binding energy of tritium on graphene is an order of magnitude weaker than (molecular or gaseous) tritium$_2$ binding energy;
- Cold plasma loading of atomic tritium onto monolayer graphene would reduce smearing and eliminate noise at the source itself;

RF antenna (RFA)

Original idea from the Project8 collaboration



Selected for a Viewpoint in *Physics*
PRL **114,** 162501 (2015)
PHYSICAL REVIEW LETTERS
week ending
24 APRIL 2015

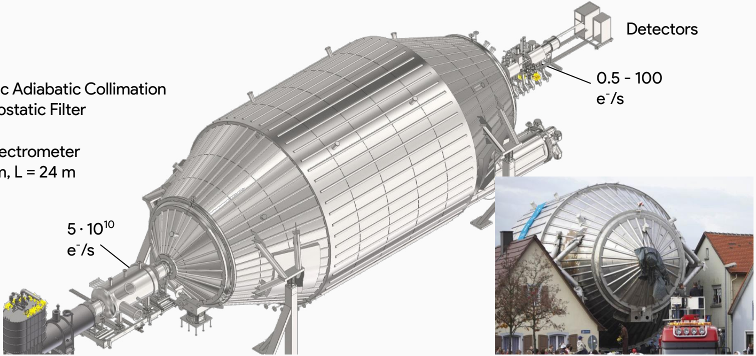
Single-Electron Detection and Spectroscopy via Relativistic Cyclotron Radiation

- Rectangular waveguide sized to capture and transmit the microwave radiation to the input of a low-noise radio-frequency receiver;
- Signal amplified by a cryogenics low noise amplifier (HEMT) in the K_a-band (26.5–40 GHz) and then down-converted to a lower band for digitization;

The RF antenna measures for every single electron:

- the frequency of the RF radiation;
- the power associated with its signal;
- a time series of Doppler-shifted frequencies that can be used to decompose the momentum components of the electron.
- Target RFA energy resolution in the ROI: < 10 eV @ 27 GHz;
- Antenna simulation and design in progress;

Dynamic EM filter (EMF)



Magnetic Adiabatic Collimation
& Electrostatic Filter

Main Spectrometer
Ø = 10 m, L = 24 m

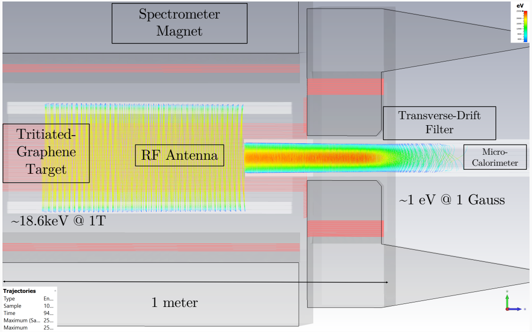
$5 \cdot 10^{10}$
e^{-}/s

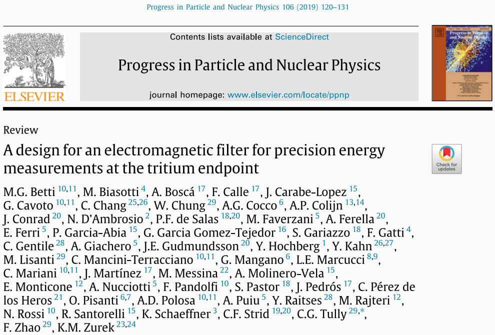
Detectors

0.5 - 100
e^{-}/s

- The goal is to decimate the electrons flux preserving the ones with energy close to the relic neutrino capture signature;
- To date, the only device capable of achieving similar results is the KATRIN MAC-E filter spectrometer;
- The large tritium mass needed for the PTOLEMY experiment cannot be accommodated in a classical MAC-E filter
- PTOLEMY tritium target cannot be in a gaseous form

Dynamic EM filter (EMF) (cont.)





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journal homepage: www.elsevier.com/locate/ppnp

Review

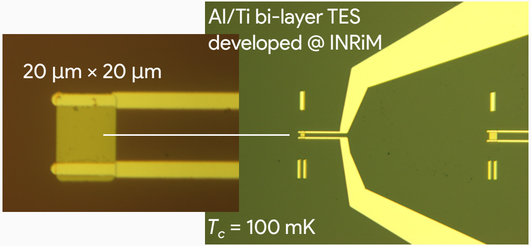
A design for an electromagnetic filter for precision energy measurements at the tritium endpoint

M.G. Betti [10,11], M. Biasotti [4], A. Boscá [17], F. Calle [17], J. Carabe-Lopez [15], G. Cavoto [10,11], C. Chang [25,26], W. Chung [29], A.G. Cocco [6], A.P. Colijn [13,14], J. Conrad [20], N. D'Ambrosio [2], P.F. de Salas [18,20], M. Faverzani [5], A. Ferella [20], E. Ferri [5], P. Garcia-Abia [15], G. Garcia Gomez-Tejedor [16], S. Gariazzo [18], F. Gatti [4], C. Gentile [28], A. Giachero [5], J.E. Gudmundsson [20], Y. Hochberg [1], Y. Kahn [26,27], M. Lisanti [29], C. Mancini-Terracciano [10,11], G. Mangano [6], L.E. Marcucci [8,9], C. Mariani [10,11], J. Martínez [17], M. Messina [22], A. Molinero-Vela [15], E. Monticone [12], A. Nucciotti [5], F. Pandolfi [10], S. Pastor [18], J. Pedrós [17], C. Pérez de los Heros [21], O. Pisanti [6,7], A.D. Polosa [10,11], A. Puiu [5], Y. Raitses [28], M. Rajteri [12], N. Rossi [10], R. Santorelli [15], K. Schaeffner [3], C.F. Strid [19,20], C.G. Tully [29,*], F. Zhao [29], K.M. Zurek [23,24]

- New concept design for the transverse drift filter;
- Combination of higher-order transverse drifts from a region of high magnetic field into low magnetic field
- Simulation showed that an 18.6 keV electron is reduced to 0.01 eV in 0.7 m
- The final determination of the absolute neutrino mass combines the calorimeter measurements with corrections for losses from RF radiation: $E_e = e(V_{\text{cal}} - V_{\text{source}}) + E_{\text{cal}} + RF_{\text{corr}}$

Cryogenic microcalorimeter (MCA)

A key point for the project success is the development of a device capable to detect low energy electrons with an energy resolution lower than 0.05 eV



- Micro-calorimeters based on transition-edge sensors (TES) are among the best candidates since they already;
- The PTOLEMY baseline are the TESs developed by INRiM for IR applications:

$$\Delta E_{\text{FWHM}} = (0.113 \pm 0.001)\,\text{eV} \,@\, 0.8\,\text{eV}$$

(Record Resolution, Appl. Phys. Lett. 103 (2013) 041107)

- PTOLEMY requires a 0.05 eV microcalorimetric resolution for electron energies below 10 eV;
- The TES energy resolution is proportional to $\Delta E \propto T_c^{3/2} \quad \Rightarrow \quad \text{if } T_c \downarrow \quad \Rightarrow \quad \Delta E \downarrow$
- A critical temperature of 42 mK have been recently achieved with Ti/Au bilayer films with 38 nm thick; *(J. Low Temp. Phys. 199 (2020) 138–142)*

PTOLEMY Program

micro-PTOLEMY (Phase-0)

- Proof-of-Principle
- R&D activities for the five sub-systems:
  - Electron Sources for Calibration (ESC);
  - GRaphene Target (GRT);
  - RF Antenna (RFA);
  - Transverse EM Filter (EMF)
  - Micro-Calorimeter Array (MCA)

mini-PTOLEMY or PTOLEMY-0 (Phase-1)

- Building and running of the demonstrator
- $\sim \mu$g of Tritium;
- Key step towards the proposal of a full-scale experiment
- Neutrino mass measurement;

PTOLEMY (Phase-2)

- Full-scale experiment
- 100 g of Tritium;
- Relic neutrino telescope;
- around 10 events/y expected

PTOLEMY @ MIB

The INFN-MIB

- is collaborating with INRiM at the TESs design and is responsible for the cryogenics and for TESs read out;
- has a leading role in the TESs characterization;

Characterization with low energy photons: SPD (single photon detector)

- optimize design and material to improve energy resolution and detector area;
- optimize readout electronics and multiplexing;

Characterization with electron source: SED (single electron detector):

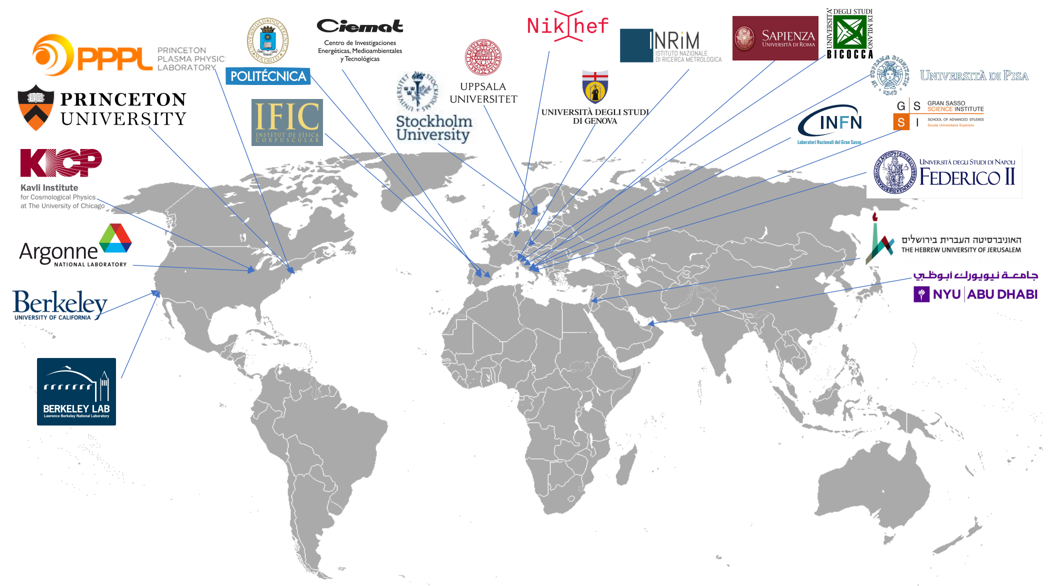
- Develop low energy high resolution high stability cryogenic single electron source
- Characterize energy resolution with electron energy < 100 eV
- Characterize detector energy response: resolution, backscattering and secondary electron emission
- Optimize design and material to improve the detector energy response.
- Develop devices to reduce the secondary emission and backscattering probability.

Design and integration of the stage to transport the low energy electrons from the EMF to the MCA and to possibly focus the electrons onto the MCA pixels

Conclusion

- Relic neutrino detection has been promoted from ”impossible” to ”challenging”;
- … but important R&Ds still to be done;
- The PTOLEMY collaboration plans to finalize these R&Ds, and then to realize a full scale relic neutrino telescope, through a 3-phase research activity;
- The MIB unit is playing a crucial role in the micro-calorimeters design, realization and characterization;
- Innovative tools for characterization, read out, simulations and analysis will be developed…
- … and M.Sc and Ph.D students could give important contributions at all of these activities;

PTOLEMY Collaboration



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