Relic neutrino detection:
from an impossible idea to a challenging project

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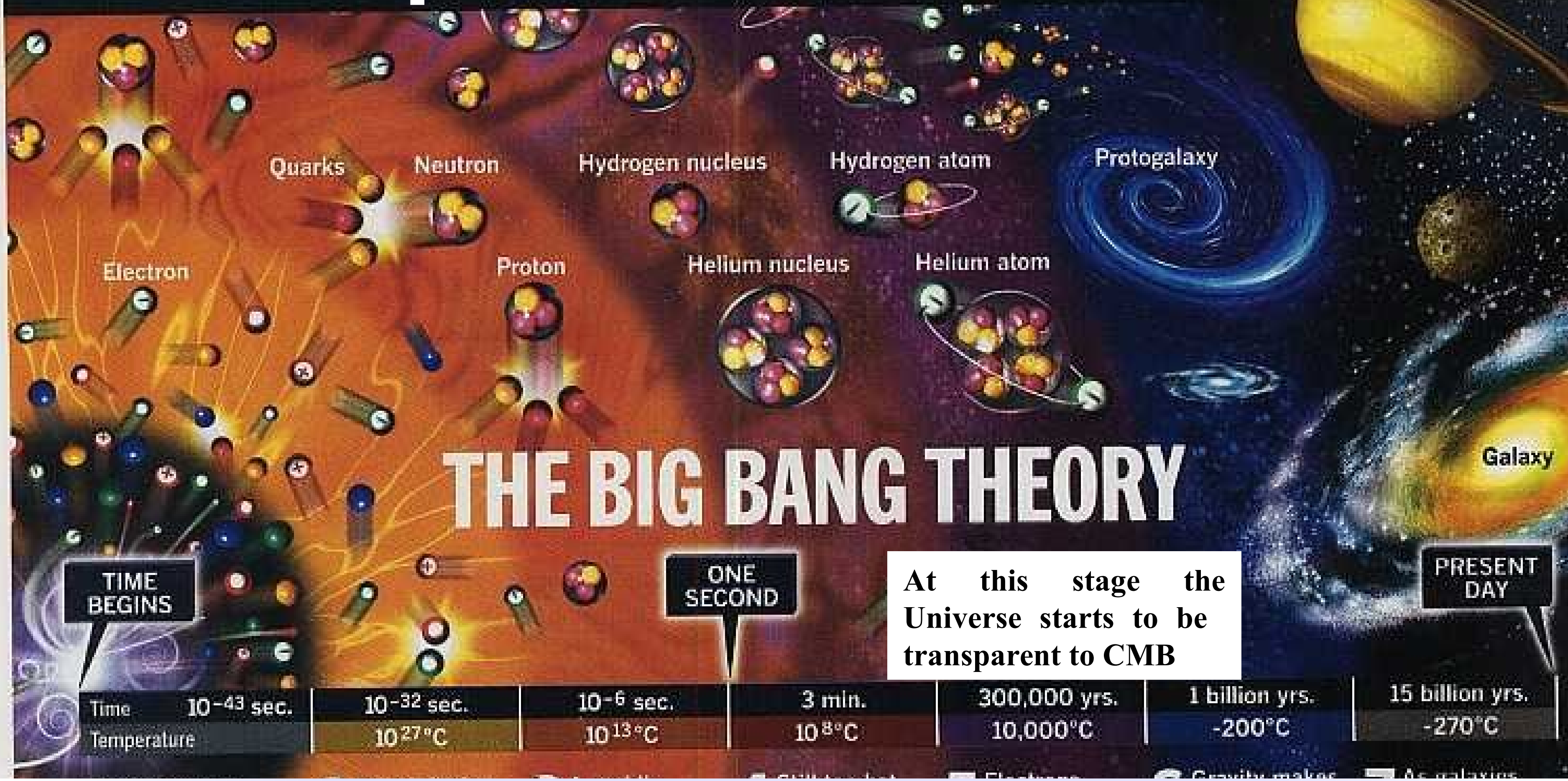
OUTLINE

- Some features and the state of art
- Phenomenology of relic neutrinos on beta instable elements
- Some other effects that might enhance the rate.
- A Possible experimental technique for relic neutrinos detection
- Conclusions and outlook

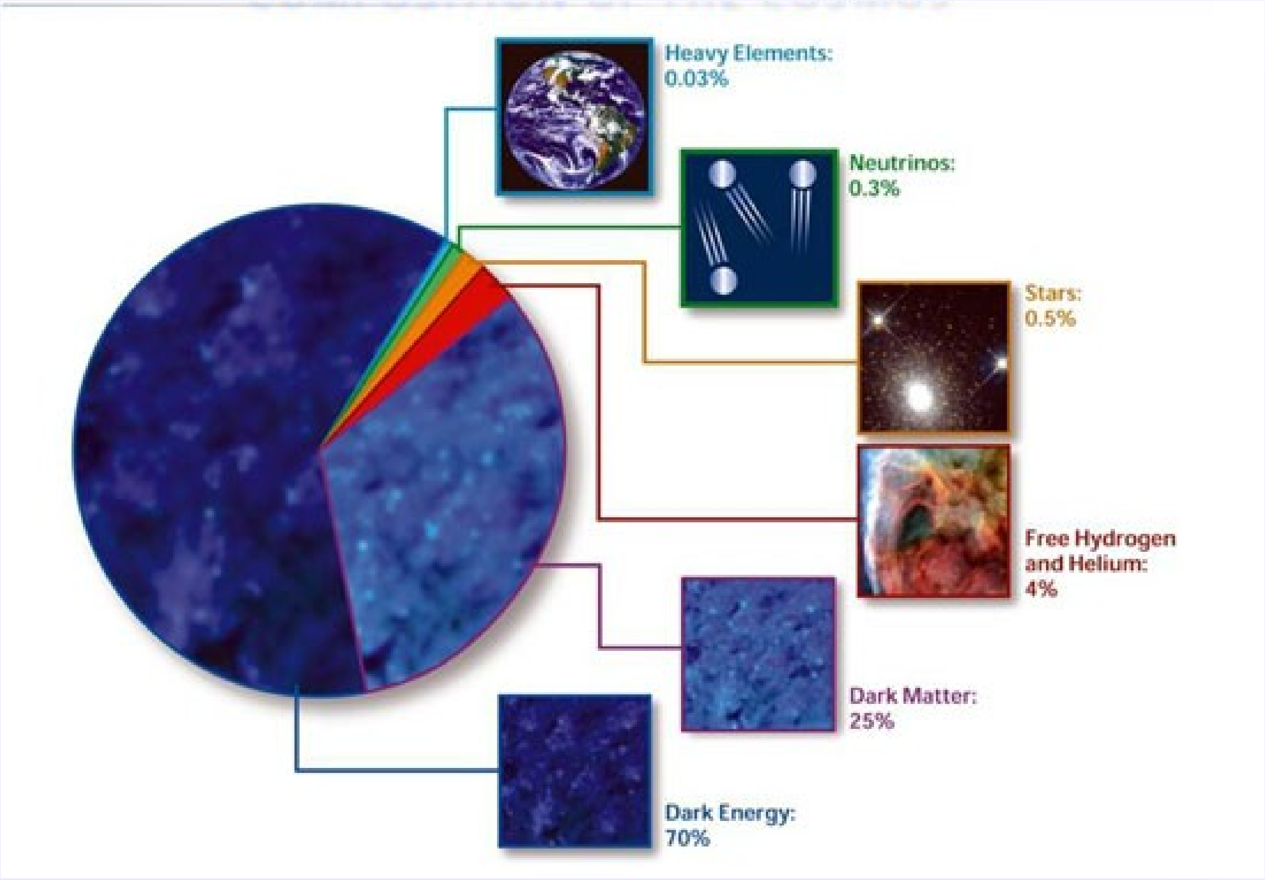
The expansion of the Universe



At this stage the Universe starts to be transparent to CMB

The relic neutrinos are produced with a $T_n \sim 10^{10}$ K (1 MeV).

Why relic neutrinos are so important



Even if relic neutrinos are among the most abundant components of the Universe and the oldest witness of the beginning of the Universe they have never been detected.

The Cosmological Relic Neutrinos

We know that Cosmological Relic Neutrinos (CRN) are weakly-clustered

$$\sim 1\sec > BigBang$$

Date of birth

$$\bar{n}_{\nu_i 0} = \bar{n}_{\bar{\nu}_i 0} = \frac{3}{22}\bar{n}_{\gamma 0} = 53 cm^{-3}$$

density per flavour

$$T_{\nu,0} = \left(\frac{4}{11}\right)^{1/3} T_{\gamma 0} = 1.95K$$

temperature

$$\bar{p}_{\nu_i 0} = \bar{p}_{\bar{\nu}_i 0} = 3T_{\nu,0} = 5\times 10^{-4}\, eV$$

mean kinetic energy

$$\Delta = \frac{1}{\bar{p}_{\nu_i}} = \frac{0.12 cm}{\left\langle p/T_{\nu,0 \bar{p}_{\nu_i 0}} \right\rangle}$$

Wave function extension

Detection methods proposed so far

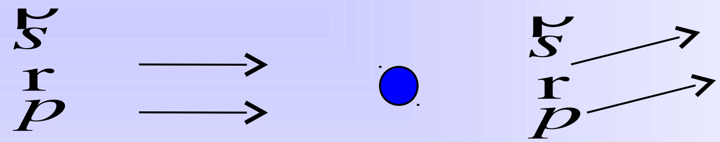
The longstanding question (I)

Is it possible to measure the CRN?

Method 1

The first method proposed for the detection of CRN was based on the fact that given the null mass of the neutrinos (today we know it is small) any variation of the ν momentum (Δp) implies a variation of the ν spin (ΔJ) (R. R. Lewis Phy. Rev. D**21** 663, 1980):

$$\left\langle \frac{\Delta J}{\Delta t} \right\rangle = mD \left\langle \frac{\Delta p}{\Delta t} \right\rangle$$



<u>Neutrino and anti-neutrino with the same momentum transfer opposite sign Δp and so the same ΔJ</u>. This is due to the fact that the opposite sign of the scattering amplitude implies different refraction index for ν (n>1) and anti-ν (n<1) and so a different scattering angle.

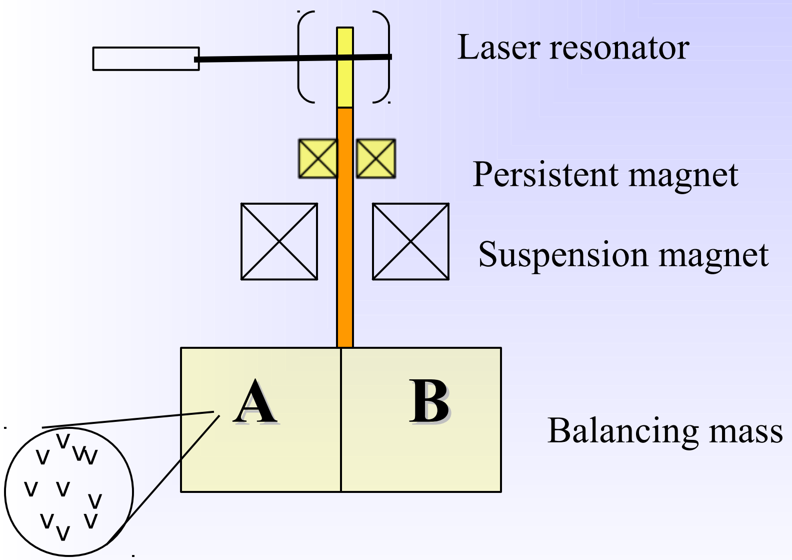
Then if we use a torque-balance to detect the angular acceleration due to the CRNs scattering we exploit the major advantage to be sensitive to any mixture of neutrino and anti-neutrino.

The longstanding question (II)

Is it possible to measure the CRN?

Method 1

Unfortunately what assumed by Lewis was shown by Cabibbo and Maiani (Phys. Lett. **B114** 115,1982) to vanish at first order in Fermi constant G_F.



Given the ν wavelength (~ 1 mm) an enhancement of the interaction rate due to a coherent sum of the ν scattering amplitudes is expected. Under this assumption:

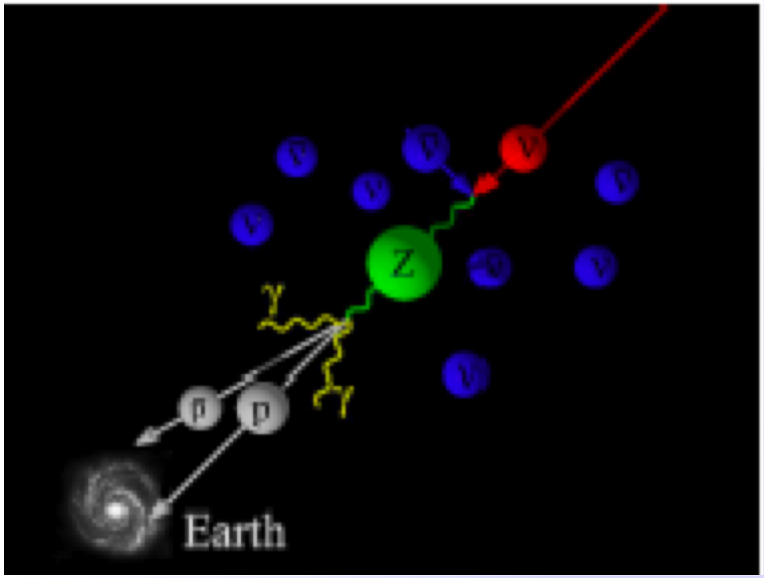
$$a_{G_F} \approx 10^{-27} \frac{cm}{\sec^2} f\left(\frac{\beta_{earth}}{10^{-3} c}\right)$$

This value is almost 15 orders of magnitude below the sensitivity of any "Cavendish" apparatus conceived so far.

The longstanding question

Is it possible to measure the CRN ?

Method 2



The second method was based on the a resonant annihilation of EECν off CRN into a Z-boson.
The annihilation occurs at energy:

$$E_{\nu_i}^{res} = \frac{m_Z^2}{2m_{\nu_i}} \approx 4x10^{21}\left(\frac{eV}{m_{\nu_i}}\right)eV$$

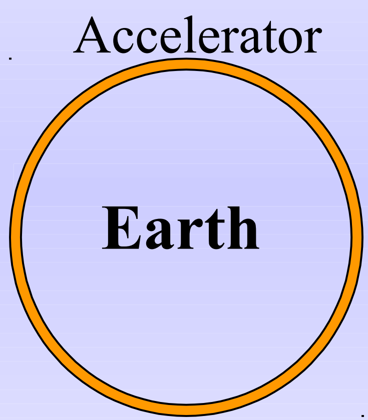
The signature might be a deep in the cosmological neutrino flux around 10^{22} eV or an excess of events of photons or protons beyond the GKZ deep (where the photons of CMB are absorbed by protons). Such energetic neutrino sources are unknown so far.

The longstanding question

Is it possible to measure the CRN ?

Method 3

The third method was based on the observation of interactions of extremely high energy protons from terrestrial accelerator with the relic neutrinos.



In this case even with an accelerator ring (VLHC) of $\sim 4 \times 10^{4}$ km length (Earth circumference) with $E_{beam} \sim 10^{7}$ TeV the interaction rate would still be negligible.

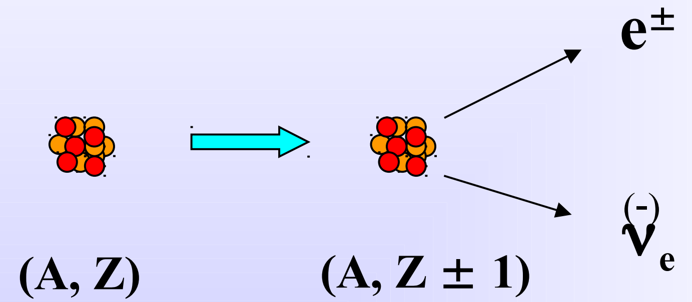
Detection methods proposed so far!

All those methods require unrealistic experimental apparatus or astronomical neutrino sources not yet observed and not even hypothesized.

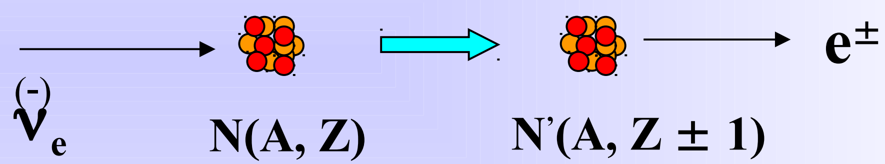
For reviews on the topic see:
A.Ringwald "Neutrino Telescopes" 2005 – hep-ph/0505024
G.Gelmini G. B. Gemini Phys.Scripta T121:131-136,2005

How to detect relic neutrinos

Beta decay



Neutrino Capture on a
Beta decaying nucleus



Since $M(N)-M(N')=Q_{\beta}>0$ the ν interaction on beta instable nuclei is always energetically allowed no matter the value of the incoming ν energy.

In this case the phase space does not put any energetic constraint to the neutrino CC interaction on a beta instable nucleus (NCB).

PHYSICAL REVIEW VOLUME 128, NUMBER 3 NOVEMBER 1, 1962

Universal Neutrino Degeneracy

STEVEN WEINBERG*
Imperial College of Science and Technology, London, England
(Received March 22, 1962)

In the original idea a large neutrino chemical potential (μ) in the Fermi-Dirac momentum distribution could distort the electron (positron) spectrum near the endpoint energy

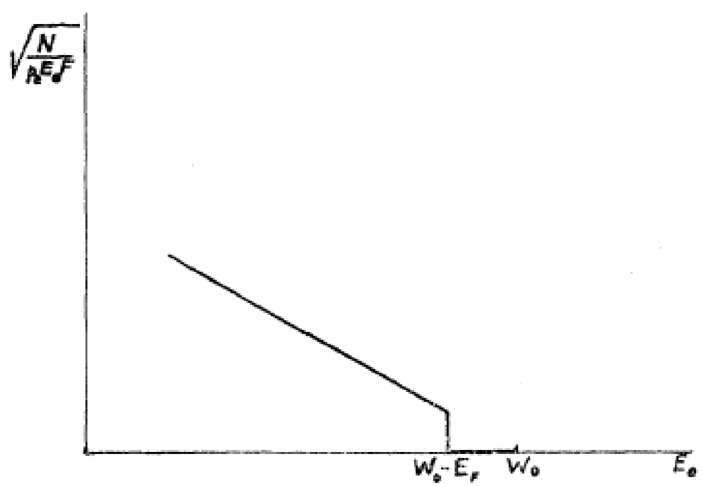


FIG. 1. Shape of the upper end of an allowed Kurie plot to be expected in a β^+ decay if neutrinos are degenerate up to energy E_F, or in a β^- decay if antineutrinos are degenerate.

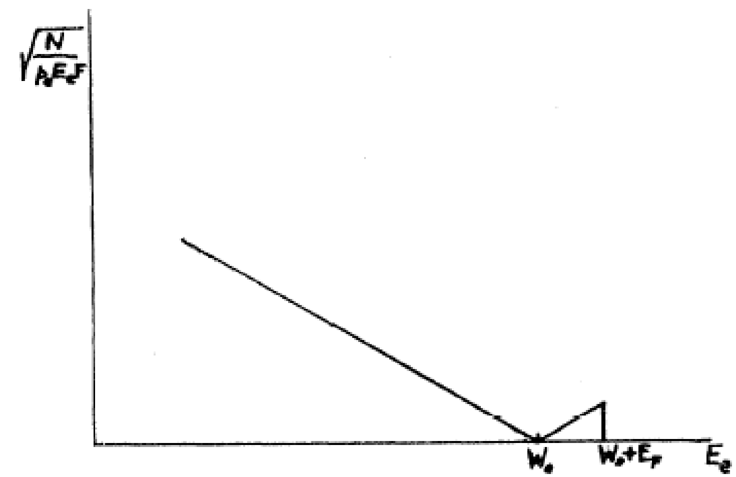


FIG. 2. Shape of the upper end of an allowed Kurie plot to be expected in a β^- decay if neutrinos are degenerate up to energy E_F, or in a β^+ decay if antineutrinos are degenerate.

NCB Cross Section (I)

NCB

$$\sigma_{\rm NCB} v_\nu = \frac{G_\beta^2}{\pi} p_{\rm e} E_{\rm e} F(Z, E_{\rm e}) C(E_{\rm e}, p_\nu)_\nu$$

$$E_{\rm e} = E_\nu + Q_\beta + m_{\rm e} = E_\nu + m_\nu + W_{\rm o}$$

Where $F(Z, E_{\rm e})$ the Fermi function and $C(E_{\rm e}, p_\nu)_\nu$ the nuclear shape factor which is an angular momentum weighted average of nuclear state transition amplitudes.

It is more convenient to focus our attention on the interaction rate:

$$\lambda_\nu = \frac{G_\beta^2}{2\pi^3} \int_{W_{\rm o}+2m_\nu}^{\infty} p_{\rm e} E_{\rm e} F(Z, E_{\rm e}) C(E_{\rm e}, p_\nu)_\nu \cdot E_\nu p_\nu f(p_\nu)\, {\rm d}E_{\rm e},$$

NCB Cross Section (II)

The most difficult part of the rate estimation is the nuclear shape factor calculation:

$$C(E_e, p_\nu)_\beta = \sum_{k_e, k_\nu, K} \lambda_{k_e} [M_K^2(k_e, k_\nu) + m_K^2(k_e, k_\nu) - \frac{2\mu_{k_e} m_e \gamma_{k_e}}{k_e E_e} M_K^2(k_e, k_\nu) m_K^2(k_e, k_\nu)]$$

Where λ_{ke}, μ_{ke} and γ_{ke} are the Coulomb coefficients, k_e and k_ν are the electron and neutrino radial wave function indexes ($k=j+1/2$), $K=L-1$ represents the nuclear transition multipolarity ($|k_e - k_\nu| \leq K \leq |k_e + k_\nu|$) and, M^2 and m^2 are nuclear matrix elements. Their calculation is the main source of uncertainty for σ_{NCB}.

On the other hand, the NCB (see previous slide) and the corresponding beta decay rates are strongly related as can be seen in the following:

$$\lambda_\beta = \frac{G_\beta^2}{2\pi^3} \int_{m_e}^{W_o} p_e E_e F(Z, E_e) C(E_e, p_\nu)_\beta E_\nu p_\nu \, dE_e$$

$$C(E_e, p_\nu)_\nu = C(E_e, -p_\nu)_\beta$$

NCB Cross Section (III)

The beta decay rate provides a relation that allows to express the mean shape factor:

$$\overline{C}_\beta = \frac{1}{f}\int_{m_e}^{W_o} p_e E_e F(Z, E_e) C(E_e, p_\nu)_\beta E_\nu p_\nu \, dE_e,$$

in terms of observable quantities: $ft_{1/2} = \frac{2\pi^3 \ln 2}{G_\beta^2 \overline{C}_\beta}$, $f = \int_{m_e}^{W_o} F(Z, E_e) p_e E_e E_\nu p_\nu \, dE_e$.

then if we derive G_β in terms of $\overline{C}_\beta$ and of $ft_{1/2}$ and replace it in the expression of the NCB cross section:

$$\sigma_{NCB} v_\nu = \frac{G_\beta^2}{\pi} p_e E_e F(Z, E_e) C(E_e, p_\nu)_\nu$$

we obtain

$$\sigma_{NCB} v_\nu = 2\pi^2 \ln 2 \, p_e E_e F(Z, E_e) \frac{C(E_e, p_\nu)_\nu}{ft_{1/2} \overline{C}_\beta}$$

So the σ_{NCB} can be calculated in terms of well measured quantities and of $\overline{C}(E_e, p_\nu)_\nu$ and C_β which depend on the same nuclear transition matrix elements.

NCB Cross Section
a new parameterization

It is convenient to introduce

$$\mathcal{A} = \int_{m_e}^{W_o} \frac{C(E'_e, p'_\nu)_\beta}{C(E_e, p_\nu)_\nu} \frac{p'_e}{p_e} \frac{E'_e}{E_e} \frac{F(E'_e, Z)}{F(E_e, Z)} E'_\nu p'_\nu dE'_e$$

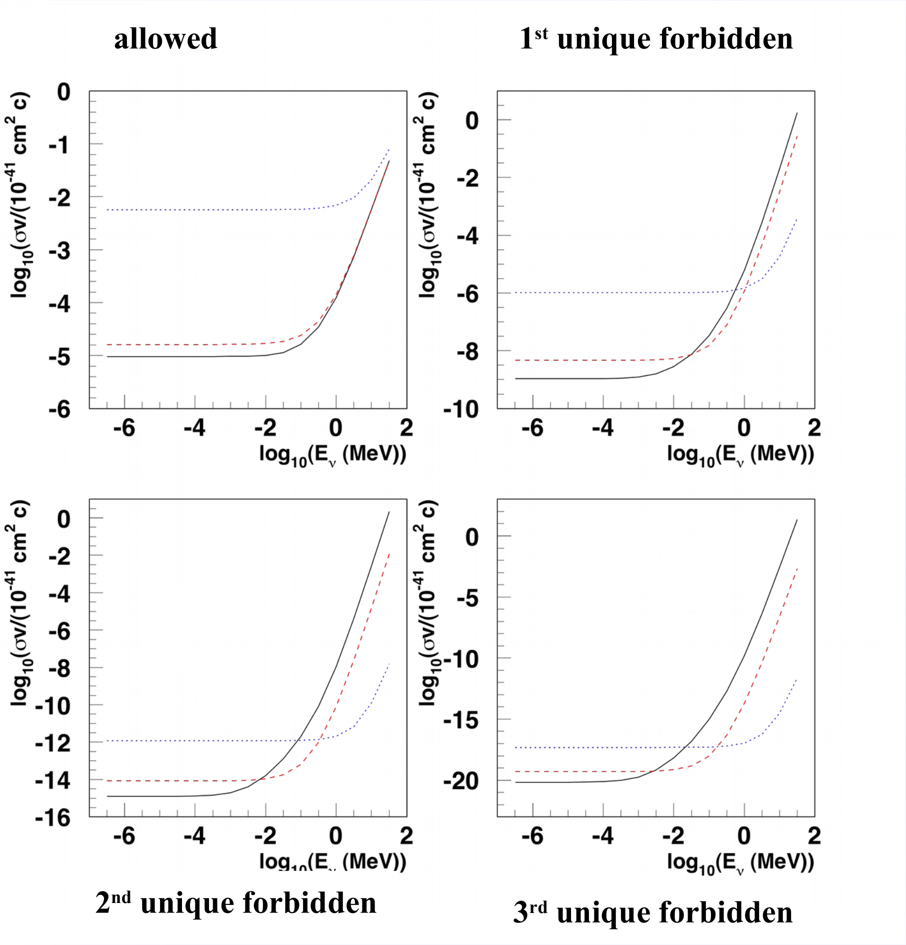
where A depends only by E_ν . Then if we introduce A in the cross section expression we have:

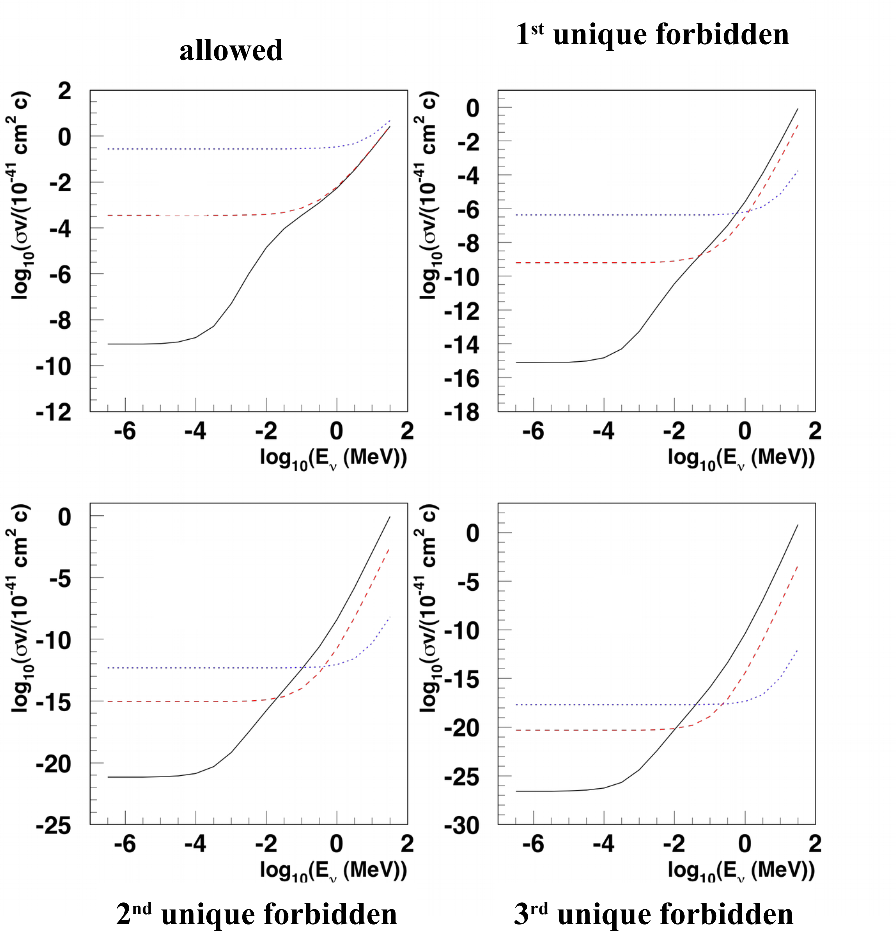
$$\boxed{\sigma_{\mathrm{NCB}} v_\nu = \frac{2\pi^2 \ln 2}{\mathcal{A}\, t_{1/2}}}$$

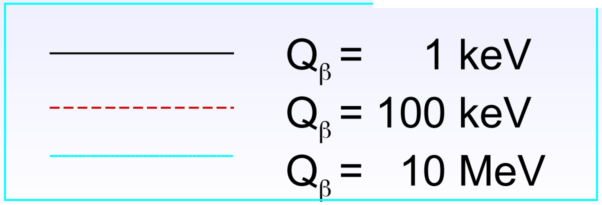
Thus σ_{NCB} can be easily calculated in terms of the decay half-life of the corresponding beta decay process and of the quantity A where the neutrino energy dependency is hidden.

NCB Cross Section

as a function of E_ν, Q_β and multipolarity







NCB Cross Section Evaluation

specific cases

Isotope	Q_β (keV)	Half-life (sec)	$\sigma_{\rm NCB}(v_\nu/c)$ (10^{-41} cm^2)
^{10}C	885.87	1320.99	5.36×10^{-3}
^{14}O	1891.8	71.152	1.49×10^{-2}
^{26m}Al	3210.55	6.3502	3.54×10^{-2}
^{34}Cl	4469.78	1.5280	5.90×10^{-2}
^{38m}K	5022.4	0.92512	7.03×10^{-2}
^{42}Sc	5403.63	0.68143	7.76×10^{-2}
^{46}V	6028.71	0.42299	9.17×10^{-2}
^{50}Mn	6610.43	0.28371	1.05×10^{-1}
^{54}Co	7220.6	0.19350	1.20×10^{-1}

Super-allowed $0^+ \to 0^+$

Isotope	Decay	Q (keV)	Half-life (sec)	$\sigma_{\rm NCB}(v_\nu/c)$ (10^{-41} cm^2)
^{3}H	β^-	18.591	3.8878×10^8	7.84×10^{-4}
^{63}Ni	β^-	66.945	3.1588×10^9	1.38×10^{-6}
^{93}Zr	β^-	60.63	4.952×10^{13}	2.39×10^{-10}
^{106}Ru	β^-	39.4	3.2278×10^7	5.88×10^{-4}
^{107}Pd	β^-	33	2.0512×10^{14}	2.58×10^{-10}
^{187}Re	β^-	2.64	1.3727×10^{18}	4.32×10^{-11}
^{11}C	β^+	960.2	1.226×10^3	4.66×10^{-3}
^{13}N	β^+	1198.5	5.99×10^2	5.3×10^{-3}
^{15}O	β^+	1732	1.224×10^2	9.75×10^{-3}
^{18}F	β^+	633.5	6.809×10^3	2.63×10^{-3}
^{22}Na	β^+	545.6	9.07×10^7	3.04×10^{-7}
^{45}Ti	β^+	1040.4	1.307×10^4	3.87×10^{-4}

Nuclei having the highest product $\boldsymbol{\sigma}_{\mathbf{NCB}}\, \boldsymbol{t}_{\mathbf{1/2}}$

NCB Cross Section
the major results of our papers

- Exist a process (NCB) that allows in principle the detection of neutrino of vanishing energy!

- The cross section (times the neutrino velocity) does not vanish when the neutrino energy becomes negligible!

- We evaluated thousands of cross section for neutrino interaction on beta unstable nuclei!

- The detection of the relic neutrinos has been downscaled from a principle problem to a technological challenge.

Probing low energy neutrino backgrounds with neutrino capture on beta decaying nuclei JCAP 0706:015,2007,
Low Energy Antineutrino Detection Using Neutrino Capture on EC Decaying Nuclei: Phys. Rev. D 79, 053009 (2009)

Relic Neutrino Detection

signal to background ratio

The ratio between capture (λ_ν) and beta decay rate (λ_β) is obtained using the previous expressions:

$$\frac{\lambda_\nu}{\lambda_\beta} = \frac{2\pi^2 n_\nu}{\mathcal{A}}$$

Then, if we evaluate $\lambda_\nu/\lambda_\beta$ for ^3H in the full energy range of the β decay spectrum, with the assumption that $m_\nu=0$, $n_\nu \sim 53/cm^3$ we get a value to small to be considered in an experimental framework ($0.66\ 10^{-23}$).

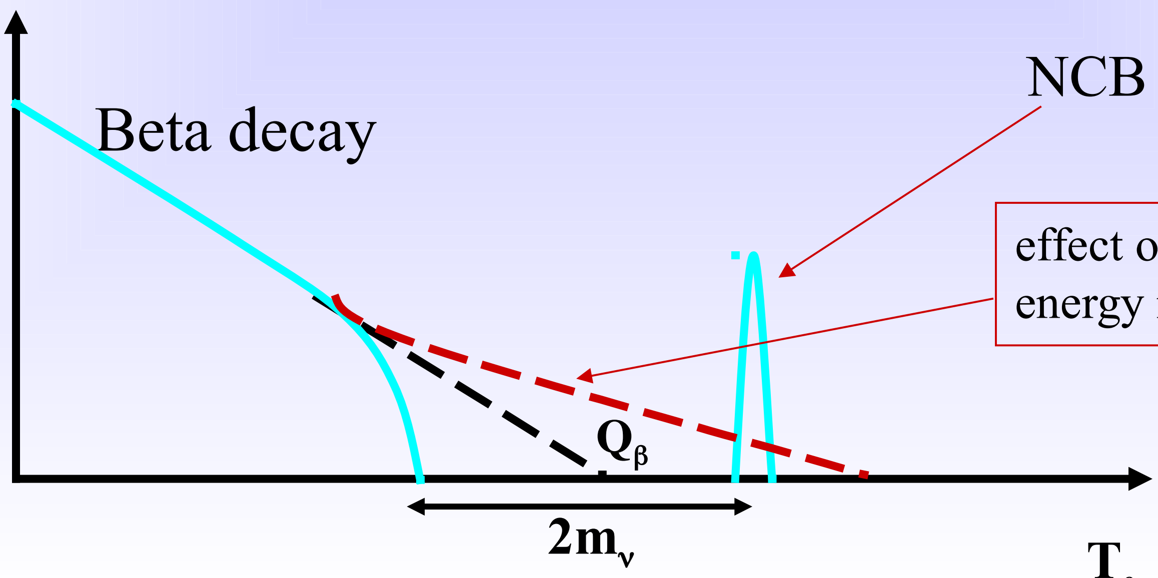
So far we considered the worst condition to calculate the CRN interaction rate. In fact, any experiment with a given energy resolution will enhance the signal over background ratio and furthermore, the Fermi momentum distribution, assumed so far, does not include any gravitational clustering that will happen in case of non zero neutrino mass

Relic Neutrino Detection (III)
signal to background ratio

As a general result for a given experimental resolution Δ the signal (λ_ν) to background (λ_β) ratio is given by

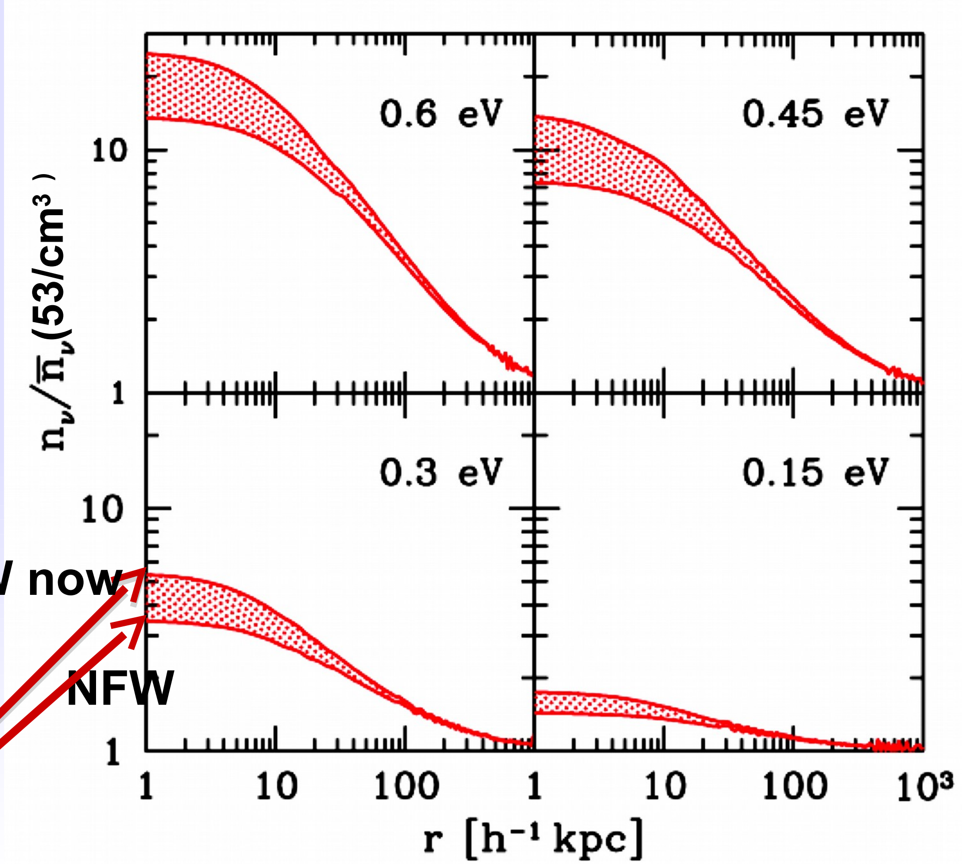
$$\frac{S}{B} = \frac{9}{2}\zeta(3)\left(\frac{T_\nu}{\Delta}\right)^3 \frac{1}{(1+2m_\nu/\Delta)^{3/2}}\left[\frac{1}{\sqrt{2\pi}}\int_{\frac{2m_\nu}{\Delta}-\frac{1}{2}}^{\frac{2m_\nu}{\Delta}+\frac{1}{2}} e^{-x^2/2}dx\right]^{-1}$$

where the last term is the probability for a beta decay electron at the endpoint to be measured in the $2m_\nu$ gap.



Possible effects enhancing the NCB (I)

A.Ringwald and Y.Y.Wong (JCAP12(2004)005) made predictions about the CRN density by using an N-body simulation under two main assumptions. In one they considered the clustering of the CRN under the gravitational potential given by the Milky Way matter density as it is today. The second prediction was made considering a gravitational potential evolving during the Universe expansion (Navarro, Franck White). In both cases the neutrinos were considered as spectators and not participating to the potential generation.



Neutrino density enhancement

Possible effects enhancing the NCB (II)

In table the number of events per year are reported if we assume the target mass of 100 g of Tritium

m_ν(eV	FD (events/yr)	NFW (events/yr)	MW (events/yr)
0.6	7.5	90	150
0.3	7.5	23	33
0.15	7.5	10	12

No background has been considered so far!

A possible experimental solution

PTOLEMY project

started thanks to the effort of C. Tully at the Princeton University

Xiv:1307.4738v2 [astro-ph.IM] 26 Aug 2013

Development of a Relic Neutrino Detection Experiment at PTOLEMY:
Princeton Tritium Observatory for Light, Early-Universe, Massive-Neutrino Yield

S. Betts[1], W. R. Blanchard[1], R. H. Carnevale[1], C. Chang[2], C. Chen[3], S. Chidzik[3], L. Ciebiera[1], P. Cloessner[4], A. Cocco[5], A. Cohen[1], J. Dong[1], R. Klemmer[3], M. Komor[3], C. Gentile[1], B. Harrop[3], A. Hopkins[1], N. Jarosik[3], G. Mangano[5], M. Messina[6], B. Osherson[3], Y. Raitses[1], W. Sands[3], M. Schaefer[1], J. Taylor[1], C. G. Tully[3], R. Woolley[1], and A. Zwicker[1]

[1]Princeton Plasma Physics Laboratory
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[3]Department of Physics, Princeton University
[4]Savannah River National Laboratory
[5]Istituto Nazionale di Fisica Nucleare – Sezione di Napoli
[6]Department of Physics, Columbia University

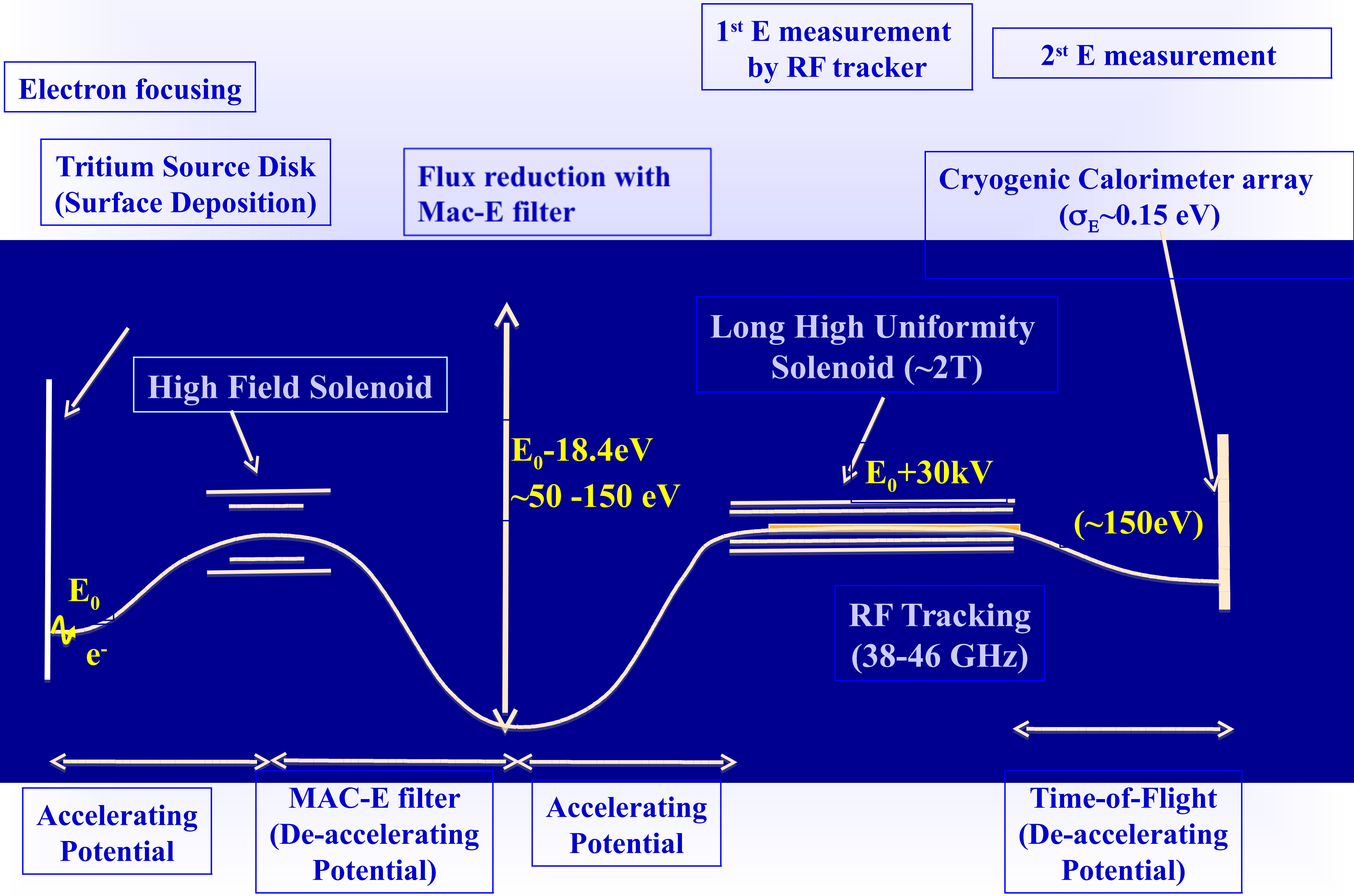
Project Summary

The direct detection of relic neutrinos from the Big Bang was proposed in a paper by Steven Weinberg in 1962 [*Phys. Rev.* 128:3 (1962) 1457]. The signal for relic neutrino capture on tritium is the observation of electron kinetic energies emitted from a tritium target that are above the β-decay endpoint. The requirements on the experimental energy resolution for relic neutrino identification are constrained by the thermal model for neutrino decoupling in the early universe that predicts a present-day average neutrino kinetic energy of 1.7×10^{-4}eV, neutrino mass mixing parameters that indicate mass eigenstates at least as massive as 0.05eV, and cosmological input from WMAP+SPT, and other sources, on the sum of the masses of the light neutrino species in thermal equilibrium in the early universe to be constrained to less than approximately 0.3eV. The parameters for a relic neutrino experiment require 100 grams of weakly-bound atomic tritium, sub-eV energy resolution commensurate with the most massive neutrinos with electron-flavor content, and below microHertz of background rate in a narrow energy window above the tritium endpoint. The PTOLEMY experiment (Princeton Tritium Observatory for Light, Early-Universe, Massive-Neutrino Yield) aims to

PTOLEMY Conceptual Design

- High precision on endpoint
  - Cryogenic calorimetry energy resolution
  - **Goal: 0.1eV resolution**
- Signal/Background suppression
  - RF tracking and time-of-flight system
  - **Goal: sub-microHertz background rates above endpoint**
- High resolution tritium source
  - Surface deposition (tenuously held) on conductor in vacuum
  - **Goal: for CNB: maintains 0.1eV signal features with high efficiency**
  - **For sterile nu search: maintains 10eV signal features w/ high eff.**
- Scalable mass/area of tritium source and detector
  - **Goal: relic neutrino detection at 100g**
  - **Sterile neutrino (w/ % electron flavor) at ~1g**

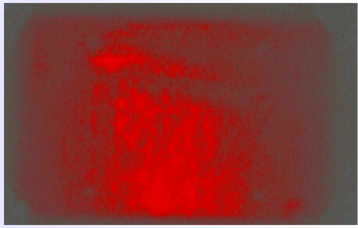
PTOLEMY Experimental Layout



Surface Deposition Sources

- At PPPL we are commissioning with samples of amorphous-Silicon:H:T plates
  - Experience with "tenuously held" tritium

Image of Carbon tile loaded with T



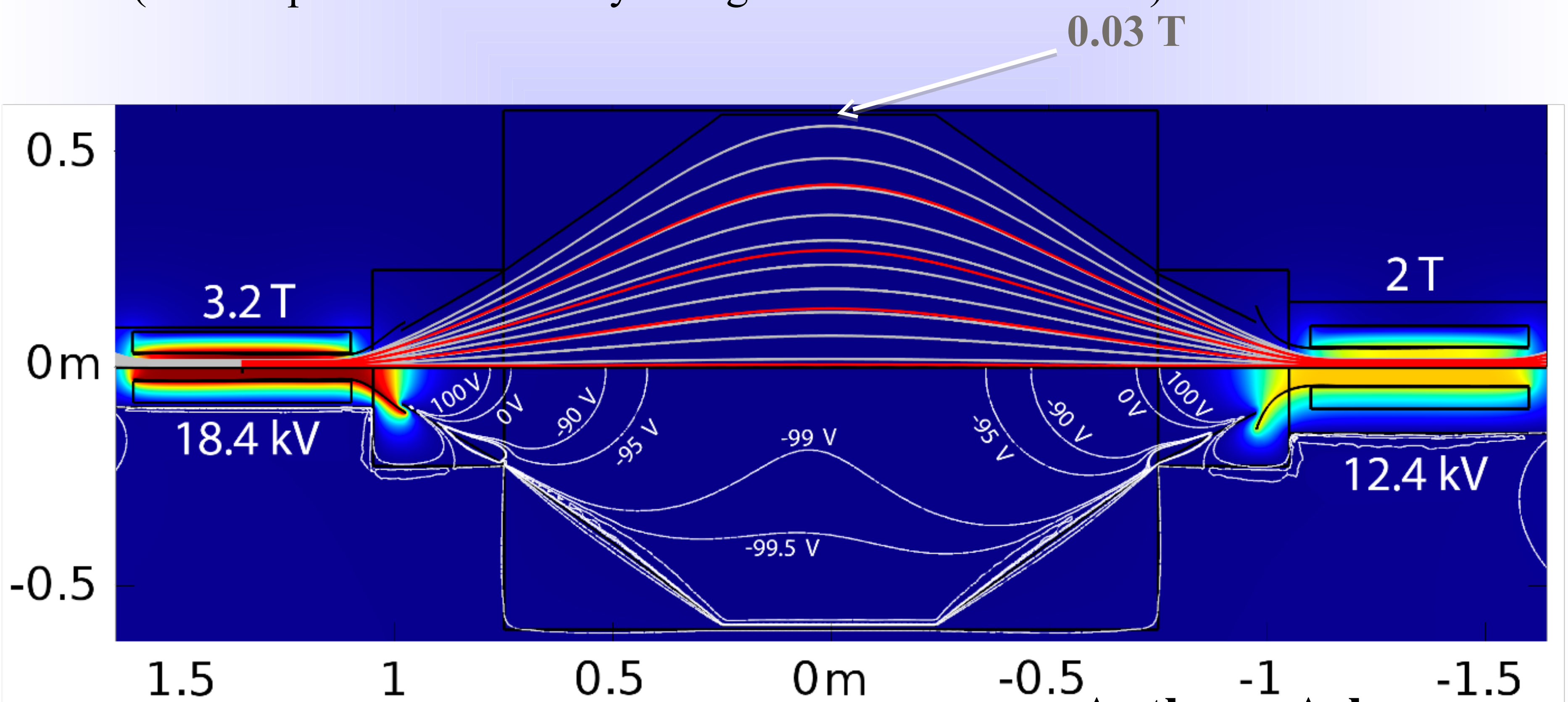
- Depositions on titanium, gold, diamond, and graphene are being investigated (done by Canadian firms and Savannah River National Lab (SRNL) in collaboration with PPPL)
  - SRNL has titanium samples that we have requested for testing
- Source strength surface densities of ~1Ci/cm^2 (100micrograms/cm^2) are possible, but energy spread from source scattering needs to be measured
  - Required resolution ~0.1eV for CNB and ~10eV for sterile nu search

Ref: Lin, C. *et al. Nano Lett.* 15, 903–908 (2015).

MAC-E filter

- MAC-E filter cutoff of 10^{-2} to 10^{-3} precision on electron energy
  - 2π acceptance
  - Voltage of filter cut-off threshold to ~10 eV: Φ reduction~ $(\Delta E/Q)^3 = 1.55\ 10^{-10}$

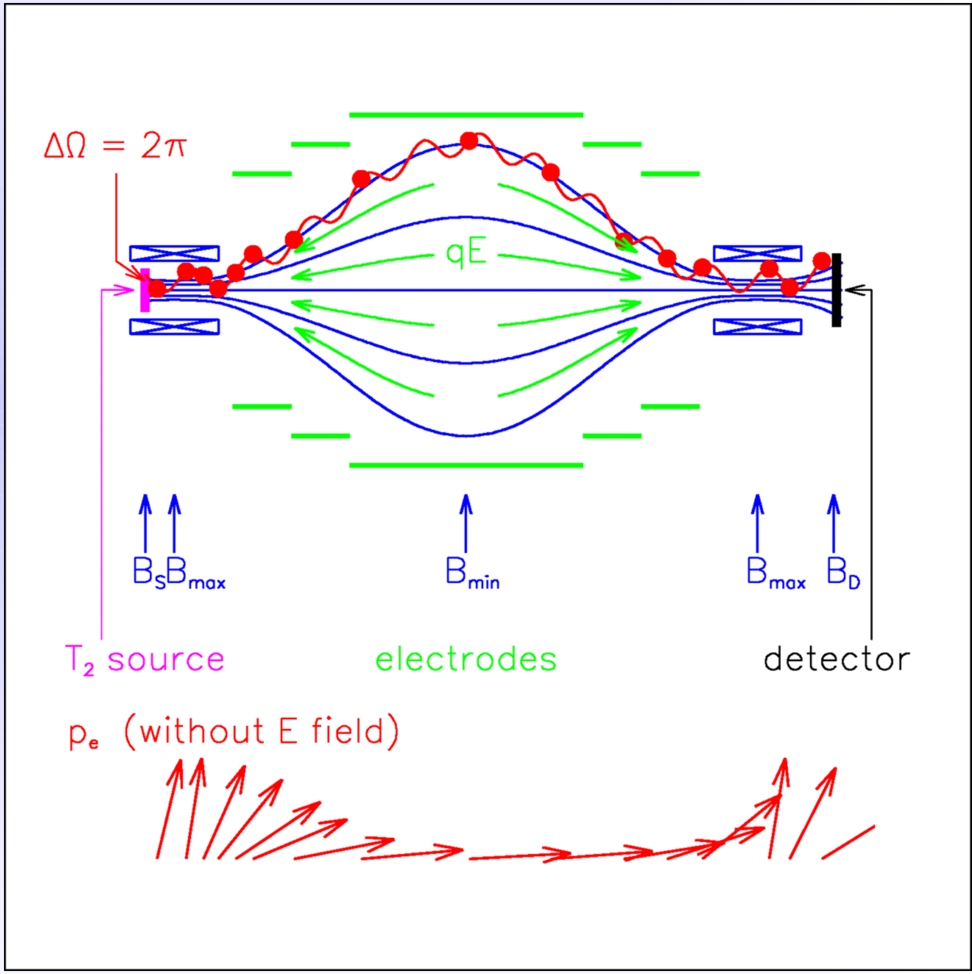
    (for comparison the activity of 1 g of T is of $3.6\ 10^{+14}$ Hz)



Anthony Ashmore

The principle of the Mac-E filter*

Two superconducting solenoids produce a magnetic field B. The beta electrons, which are starting from the tritium source in the left solenoid, are guided magnetically on a cyclotron motion around the magnetic field lines into the spectrometer (2π solid angle).



***from Katrin webpage**

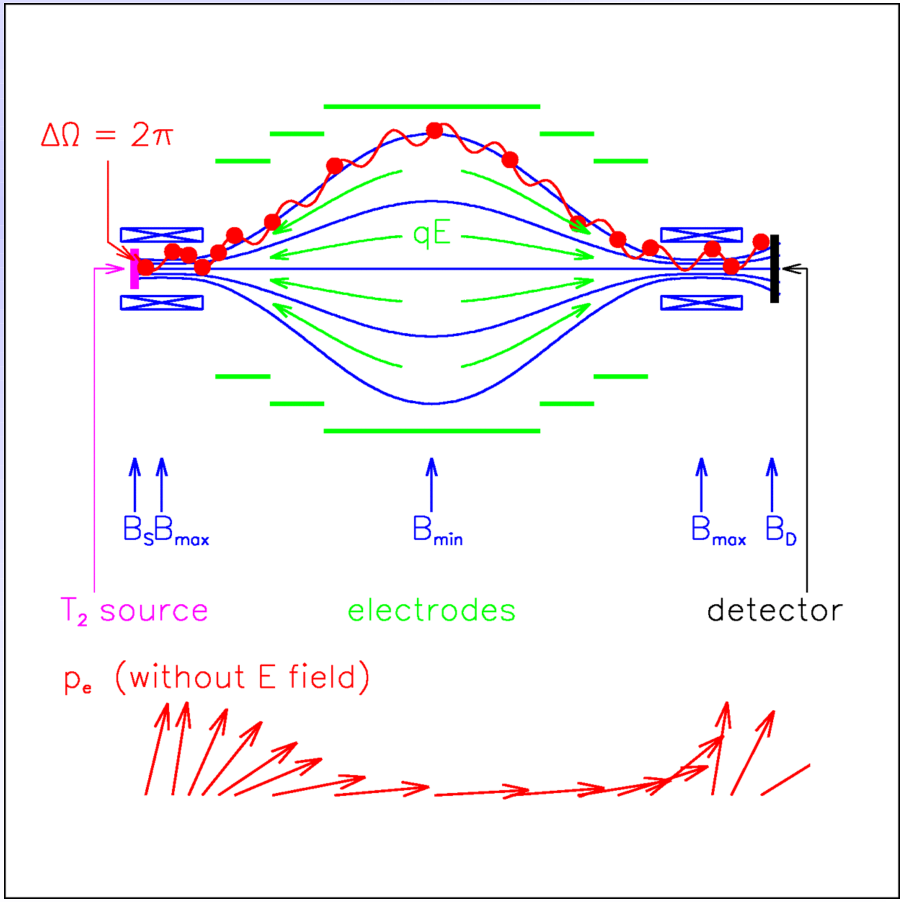
The principle of the Mac-E filter (I)

On their way into the center of the spectrometer the magnetic field B drops by many orders of magnitude. Therefore, the magnetic gradient force

$$F_{grad} = -(\vec{m}\cdot\vec{\nabla})\cdot\vec{B}$$

transforms most of the cyclotron energy into longitudinal motion. because of the slowly varying magnetic field B the momentum transforms adiabatically, therefore the magnetic moment μ is maintained constant and in non-relativistic approximation:

$$\boxed{\mu = \frac{E_\perp}{B}}$$



The principle of the Mac-E filter (II)

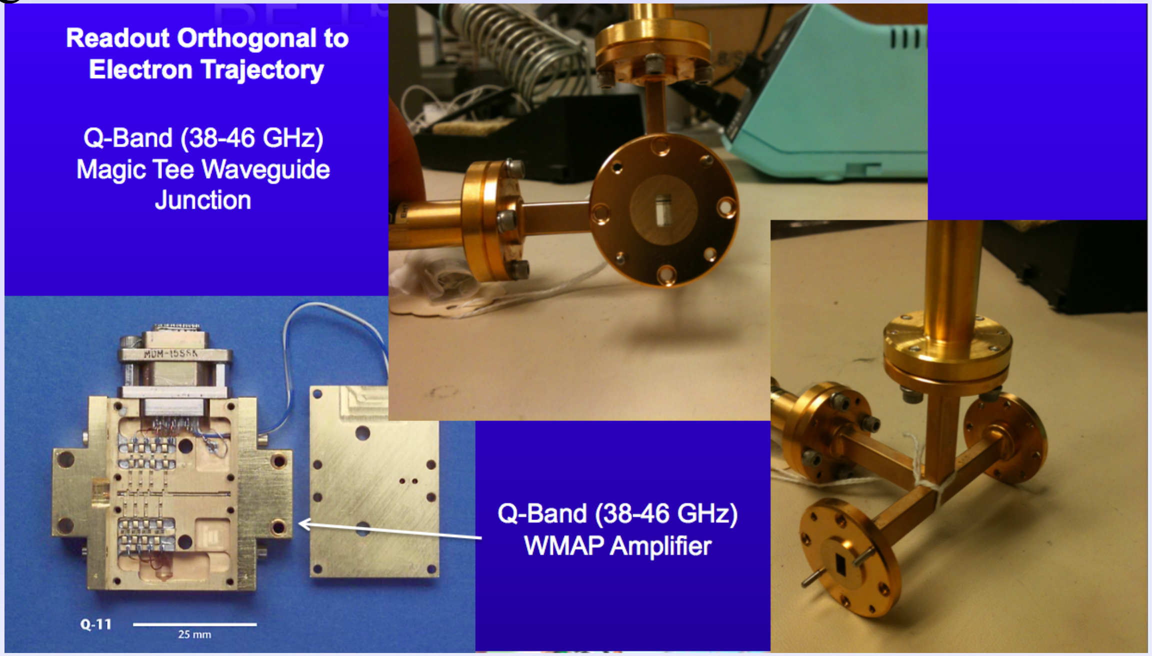
The beta electrons, isotropically emitted at the source, are transformed into a broad beam of electrons flying almost parallel to the magnetic field lines. This parallel beam of electrons is running against an electrostatic potential. All electrons with enough energy to pass the electrostatic barrier are reaccelerated and collimated onto a detector, all others are reflected. Therefore the spectrometer acts as an integrating high-energy pass filter. The relative sharpness of this filter is:

$$\boxed{\frac{\Delta E}{E} = \frac{B_{\min}}{B_{\max}}}$$

In the case of PTOLEMY experiment this is is further improved by the RF tracking devices capable to measure the high frequency cyclotron emission and eventually by the calorimetric measurement.

Signal/Background suppression

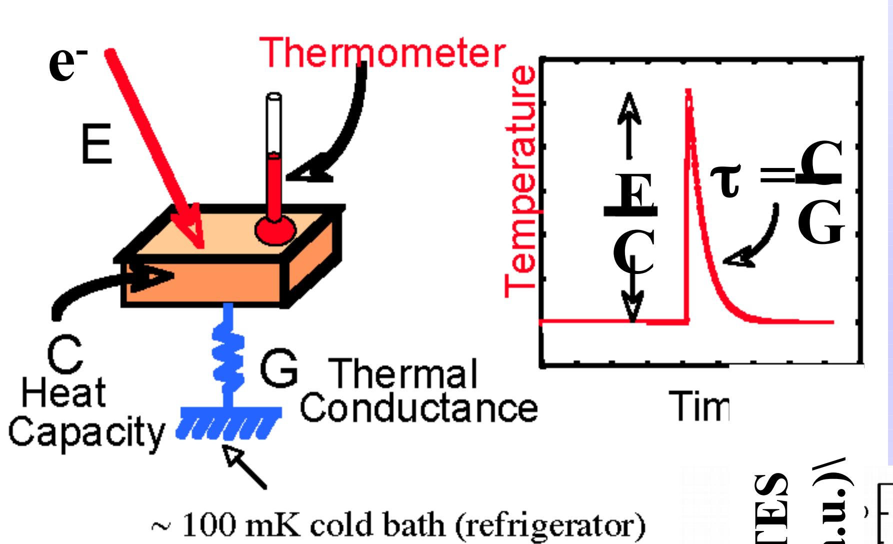
- RF tracking and time-of-flight
  - Thread electron trajectories (magnetic field lines) through an array of parallel plate Project-8 type antennas with wide bandwidth (few x10[-5]) to identify cyclotron RF signal in transit times of order 0.2μsec. Expected resolution of 10 ns depending on the TES.

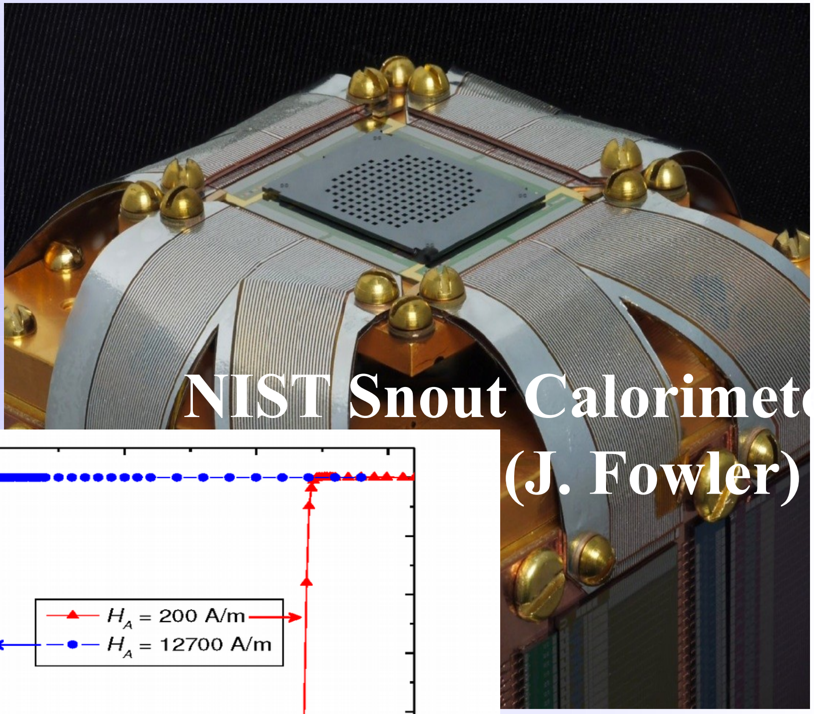


- Currently using WMAP (Norm Jarosik) HEMT amplifiers with 1K/GHz noise and operating in the range 38-46 GHz (~1.9T)
- Accelerate electrons to E_0+30keV in antenna region to increase electron cyclotron radiation – record in long uniform field

TES Calorimetry

- NIST and ANL are leaders in the development of these sensors (driven by X-ray source astrophysics)





TES sensitive to magnetic field

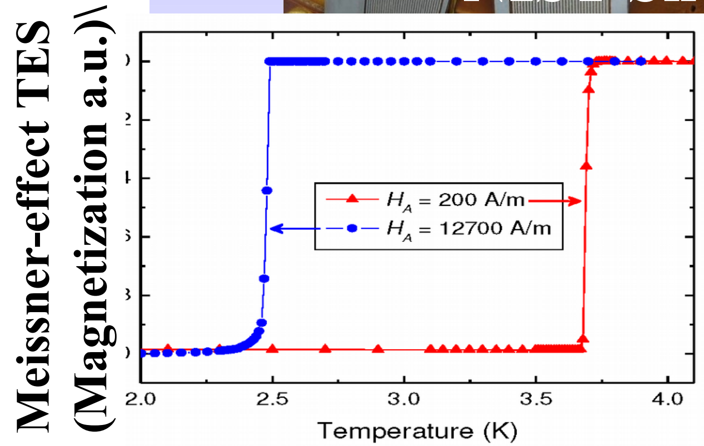


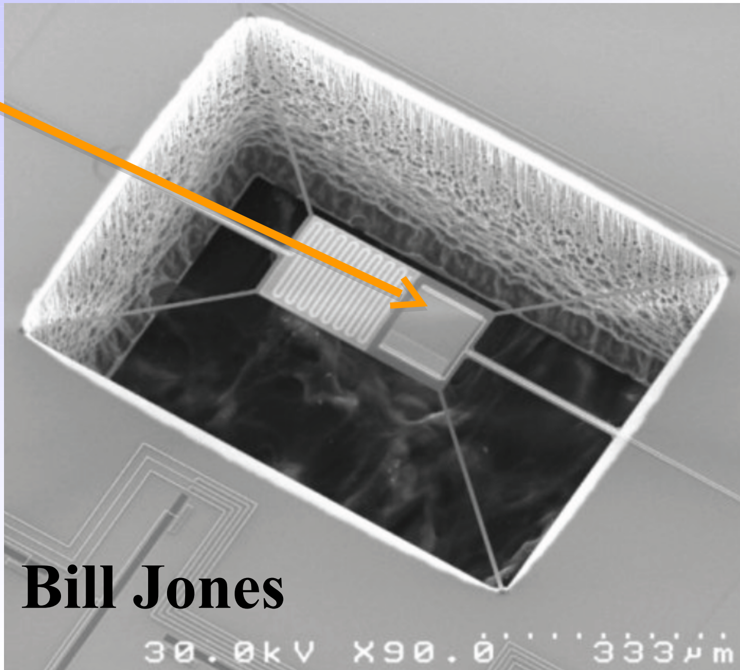
FIG. 1. (Color online) Magnetic superconducting transition for tin wire at two magnetic fields. For an applied field (H_A) of 1.3×10^4 A/m (160 Oe) applied parallel to the wire axis, the T_c is reduced from 3.7 to 2.5 K and the width of the transition remains below 30 mK.

High precision on Endpoint

- Transition-Edge Sensors for Calorimetry
  - Resolution of ~0.55eV at 1keV and ~0.15eV at 0.1keV operating at 70-100mK under investigation (Clarence Chang ANL)
  - New design introduces periodic pattern of normal regions in the TES to increase stability
    - **Magnetic fields of few hundred Gauss may be able to thread through normal regions**

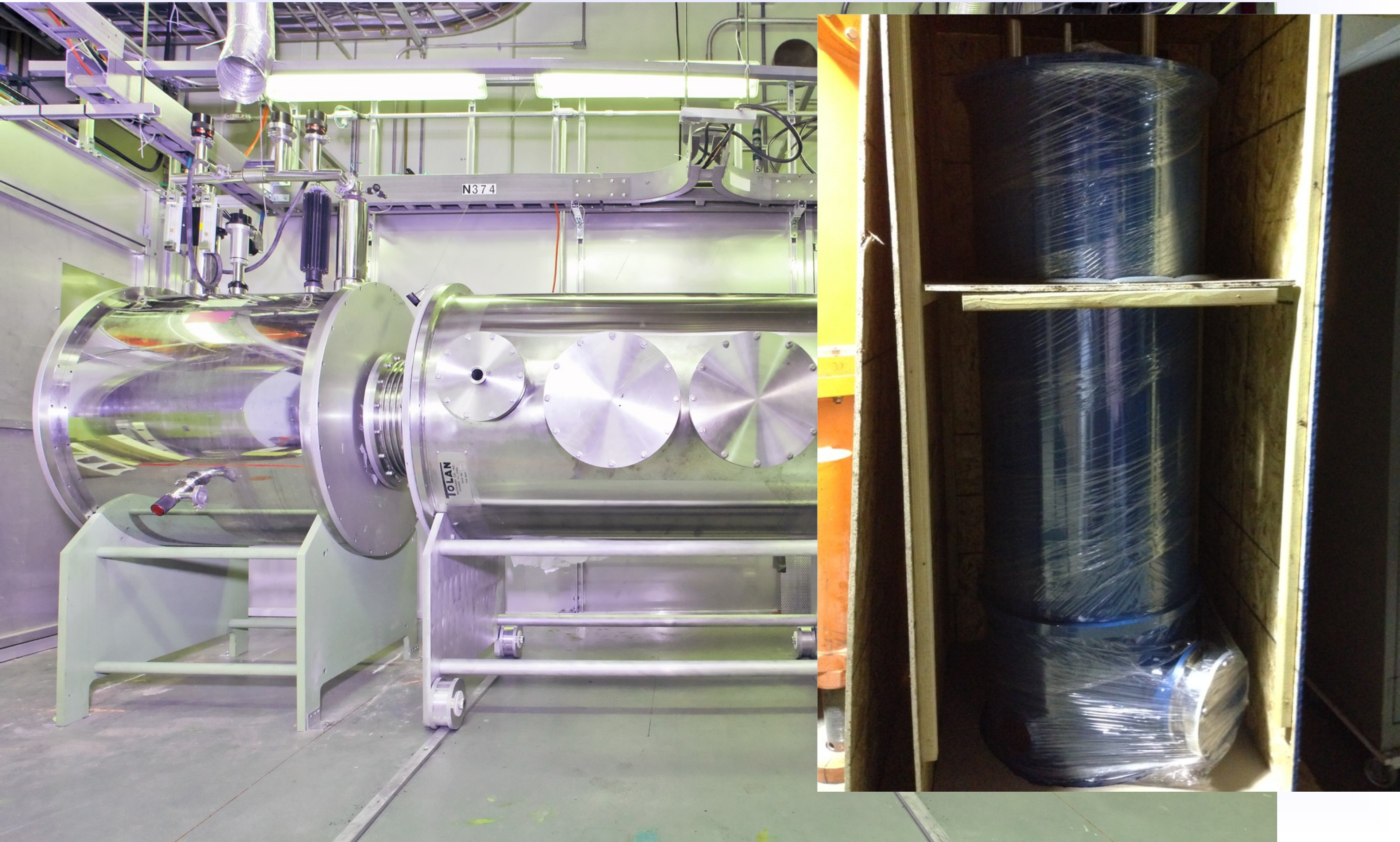
(example) SPIDER Island TES

Important points for the experiment:
1)Need to truncate 18.570 keV energy spectrum and de-accelerate to within ~150eV of endpoint
2) Spatially segmented source disks to map efficiently into finite TES sensor area (little capacitance) of order ~1cm²/channel



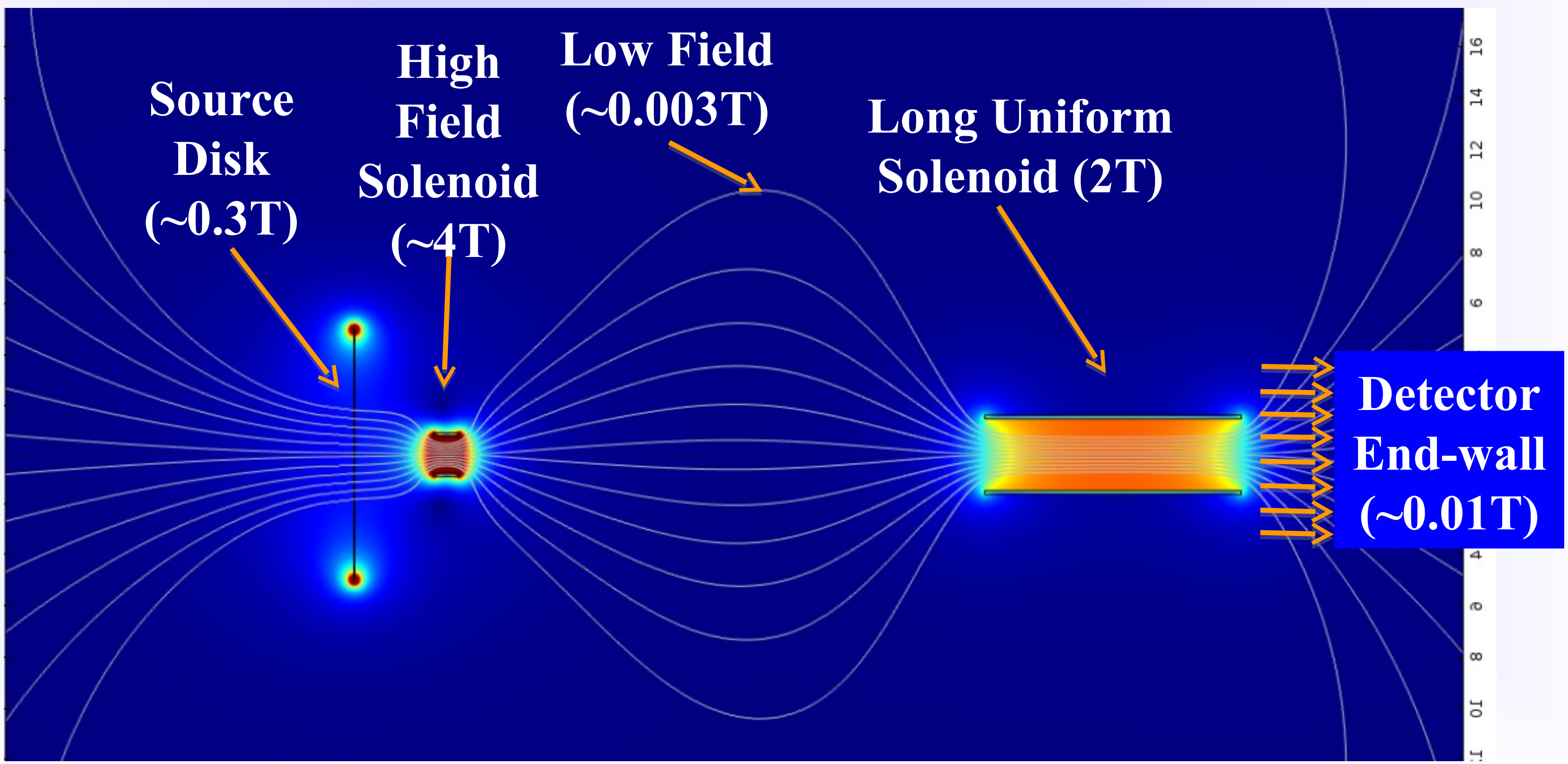
PTOLEMY

schematic drawing

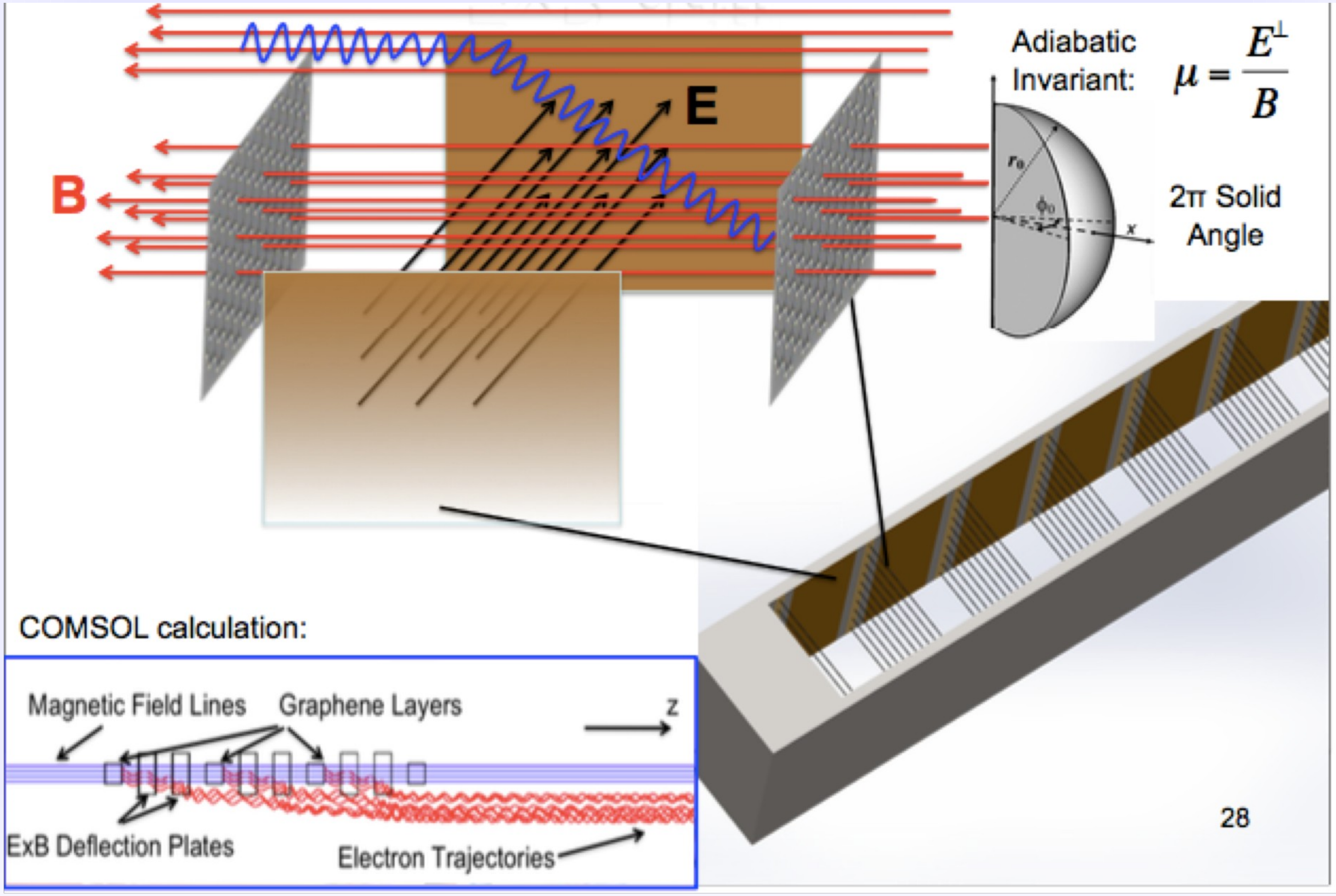


100g PTOLEMY

- Different geometries were investigated
  - Example configuration places a 12m diameter disk at the input to the 1st MAC-E magnet (accelerated to ~90 keV)
  - Source disk will consist of 10^4-10^5 individual plates



Special arrangement of the T source



Experimental Program for PTOLEMY Prototype

1st Milestone: ✓(done) Commission small test vacuum chamber with APD readout of tritium spectrum in magnetic field
- Chamber arrived, Vacuum fittings completed.
-Electrical fittings, APD windowless from CERN cleaned at PRISM.
-2nd Milestone: (in progress) Tritium spectrum taken under full magnetic transport
- Installation of full-scale vacuum chamber.
- Commissioning of vacuum for 2 weeks, Electrical fittings for vacuum with installation of detector.
- Tritium spectrum taken with magnetic transport in full-scale vacuum chamber.
3rd Milestone: Detect RF signal in coincidence with APD trigger in vacuum.
- Re-energize 1.9T magnet with few $x10^{-5}$ field uniformity
- Install WMAP 40-50 GHz amplifier with parallel-plate/BalUn and 100 MHz mixer
- Install APD trigger system and APD/antenna digital readout in vacuum
- Observe 3-5 Sigma RF signals

Experimental Program for PTOLEMY Prototype

4th Milestone: Commission MAC-E filter.
- **Finish fabrication of copper tubes**
- **Install in Vac-tank with HV stand-offs and 50kV cable/connectors.**
- **Evaluate performance of filter cut-off with APD data in vacuum.**

5th Milestone: First physics dataset analyzed for sterile nu search.
- **Measure magnetic aperture of source to detector with MAC-E filter applied**
- **Scan EM cutoff and measure sharpness of low energy cutoff across aperture**
- **Optimize readout system and DAQ for 24/7 operation**
- **Upgrade source strength in to 1 Curie or as large as possible**
- **Take calibration data and background runs interspersed with data runs**

6th Milestone: Validate technologies for 100g PTOLEMY.
- **Introduce disk source feeding source magnet aperture.**
- **Introduce TES micro-calorimeter with sub-eV resolution.**
- **Benchmark system performance.**

Is there anything in the keV region ?

("what we see" vs "what we think it should be")

Everything "above" the endpoint is at zero background

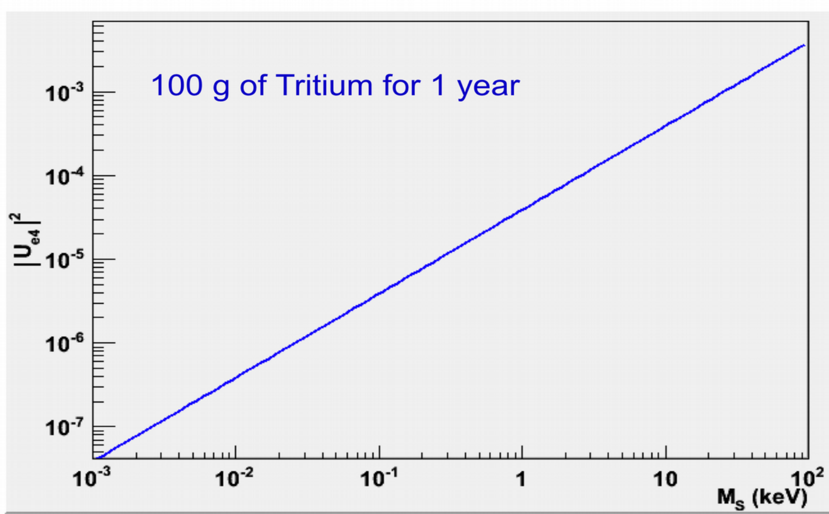
(no need for sub-eV resolution ! Only E_x or $m_x > \Delta$)

Example:

Using ν capture...

If Dark Matter is made by sterile neutrino ➔ $\rho_S \sim \frac{0.4\times10^6}{M_S[keV]}$ cm^{-3}

Looking beyond the beta decay endpoint energy (background free region)



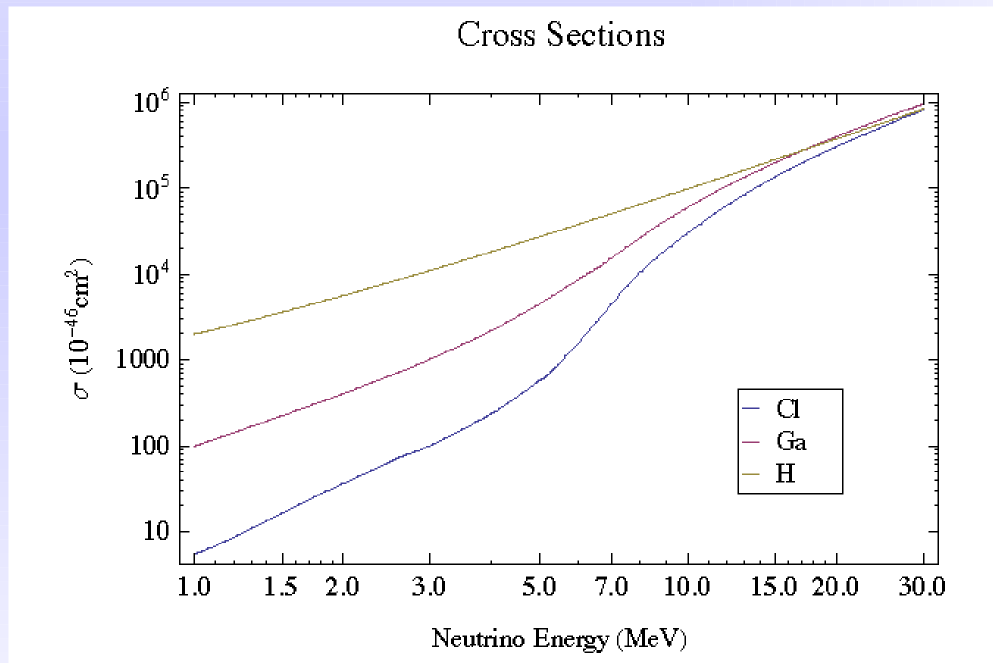
Solar Neutrino Capture Rates at PTOLEMY

Source	Integrated flux (cm^{-2} s^{-1})	$\overline{\sigma}$ (10^{-45} cm^2)	Events per year
p-p	5.90×10^{10}	4.56×10^{1}	1.87
^{8}B	5.50×10^{6}	5.33×10^{3}	0.02
^{13}N	2.98×10^{8}	1.30×10^{2}	0.02
^{15}O	2.25×10^{8}	2.08×10^{2}	0.03
^{17}F	5.69×10^{6}	2.09×10^{2}	0.0008
pep	1.51×10^{8}	3.38×10^{2}	0.03
^{7}Be	4.69×10^{8}	6.38×10^{1}	0.02
^{7}Be	4.54×10^{9}	1.63×10^{2}	0.51
hep	7.38×10^{3}	1.02×10^{4}	0.00005
All	6.46×10^{10}	5.60×10^{1}	2.53 ± 0.08

Solar Neutrino Capture Experiments

- PTOLEMY ~3618 SNU with 100g (10^{25} nuclei) 2.5 evts/year
- Gallex 70 SNU with 30 tons (10^{29} nuclei) 1200 evts/year
- Homestake (Chlorine) 8 SNU with 600 tons (10^{31} nuclei) 2500 evts/year

Hard to compete with Tritium for sub-MeV neutrino energies



SNU=10^{-36} neutrino interaction per second per atom

Summary

- Relic neutrino detection is has been promoted from “impossible” to “challenging”
- Important R&D still to be done on source, detector, background levels
- PPPL prototype is an excellent test bench for validating the technologies for a multi-grams PTOLEMY
- KATRIN will hopefully provide more input on the neutrino mass(es)

Outlook

- The fact that neutrino has a nonzero mass has renewed the interest on Neutrino Capture on Beta decaying nuclei as a <u>unique tool to detect very low energy neutrino</u>
- The relatively high NCB cross section when considered in a favourable scenario could bring cosmological relic neutrino detection within reach in a near future if:
  - neutrino mass is in the eV range
  - an electron energy resolution of 0.1 – 0.2 eV will be achieved