What Next
ν cross sections

Bologna
9 Novembre 2015

Rivelazione di Neutrini Relici (CνB)
PTOLEMY e oltre…

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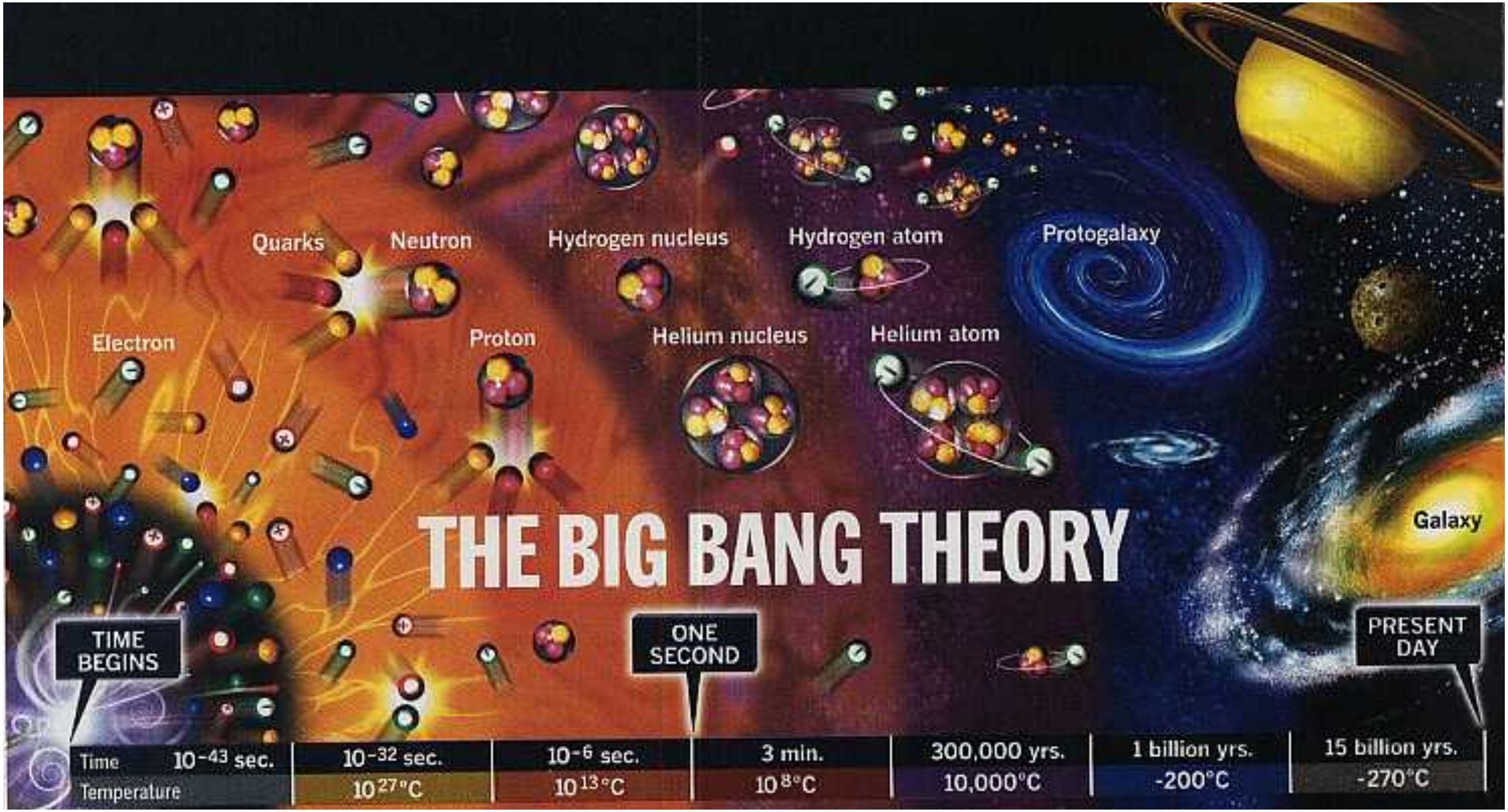


Decoupling dei Neutrini
(CνB)

Decoupling dei gamma
(CMB)
Atomi neutri

Cosmological relic neutrino Background (CνB)

In the Big-Bang scenario neutrinos decoupled when T ~ MeV

This happened about 1 s after the Universe was born

$\Rightarrow$ ν are the oldest "detectable" relics !!

"Thermal" spectrum $$f_\nu(p,T) = \frac{1}{e^{p/T_\nu}+1} \qquad p_\nu \approx 10^{-4}\ \mathrm{eV}$$

Number density today

$$n_\nu = \int \frac{d^3p}{(2\pi)^3} f_\nu(p,T_\nu) = \frac{3}{11} n_\gamma = \frac{6\zeta(3)}{11\pi^2} T^3_{CMB} \cong \left(56\ \mathrm{cm}^{-3}\right) \times 6$$

Energy density today $$\Omega_\nu h^2 = \frac{\sum_i m_i}{94.1\ \ \mathrm{eV}}$$

Detection: G_F

Bulk acceleration: due to refractive index the CνB could produce a torque on a torsion balance:

the effect vanishes for an equal mixture of ν and $\bar{\nu}$

requires breaking of isotropy (Earth velocity)

$$F = S\rho_\nu \beta_\oplus c p_\nu (n-1) = SV\rho_\nu \propto G_F$$

Unfortunately, Cabibbo and Maiani in 1982 proved that for *vector* forces the effect is only order G_F^2 even for pure ν or $\bar{\nu}$ fluxes !!

$$\vec{F} = -\frac{\Delta\vec{p}_\nu}{\Delta t} \simeq G_F \int d^3x \rho_A(x) \vec{\nabla} n_\nu(x)$$

Detection: G_F

Stodolsky effect: energy split of electron spin states in the ν background

requires ν chemical potential (Dirac) or net helicity (Majorana)

requires breaking of isotropy (Earth velocity)

results depend on Dirac/Majorana,relativistic/non relativistic, clustered/unclustered

Duda et al ‘01

$$\Delta E \approx G_F g_A \vec{s} \cdot \vec{\beta}_\oplus (n_\nu - \bar{n}_\nu)$$

Torque on frozen magnetized macroscopic piece of material of dimension R

$$a \approx 10^{-27} \left(\frac{100}{A}\right)\left(\frac{\mathrm{cm}}{R}\right)\left(\frac{\beta_\oplus}{10^{-3}}\right)\left(\frac{n_\nu - \bar{n}_\nu}{100\ \mathrm{cm}^{-3}}\right) \mathrm{cm\ s}^{-2}$$

Detection: G_F^2

ν-Nucleus collision: net momentum transfer due to Earth peculiar motion

$$\sigma_{\nu N} = G_F^2 \, E_\nu^2$$

$$a = n_\nu v_\nu \frac{N_A}{A} \sigma_{\nu N} \Delta p$$

$$\Delta p = \beta_\oplus E_\nu$$

$$\Delta p = \beta_\oplus m_\nu$$

$$\Delta p = \beta_\oplus T_\nu \quad \Longrightarrow \quad \mathbf{a \approx (10^{-46} - 10^{-54}) \frac{A}{100}\, cm\ s^{-2}}$$

Coherence enhancement

$$\lambda_\nu \approx 1/T_\nu \ \ \text{-}\ \ 1/\mathrm{m}_\nu \approx mm \qquad N_c = \frac{N_A}{A} \rho \lambda_\nu^3$$

Zeldovich and Khlopov ’81

Smith and Lewin ‘83

The Quantum Limit

Uncertainty principle limits the smallest measurable acceleration to

$$a_{QL} \approx 10^{-24}\,\mathrm{cm\,s^{-2}}$$

relic neutrino effects, both G_F and G_F^2, are 3 to 4 orders of magnitude below this limit !!!

Still: seismic, gravitational variations (Moon), solar neutrinos, WIMPs….

Since the energy of relic neutrino is so small collective effects are (were) a natural choice

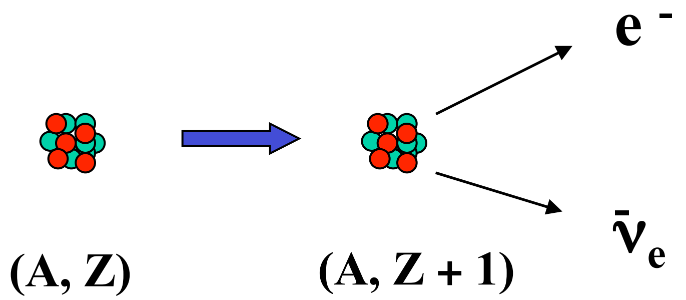
but…..

is direct detection possible ?

Neutrino capture on β± decaying nuclei

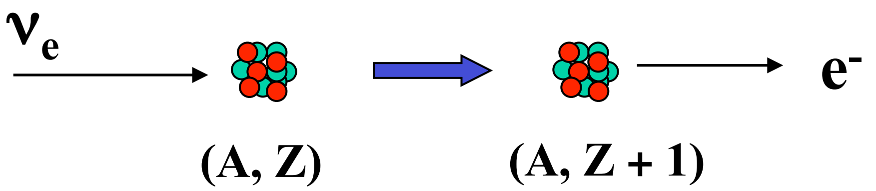
Known

Nuclear Beta decay



Possible

Neutrino Capture on a Beta Decaying Nucleus (NCB)

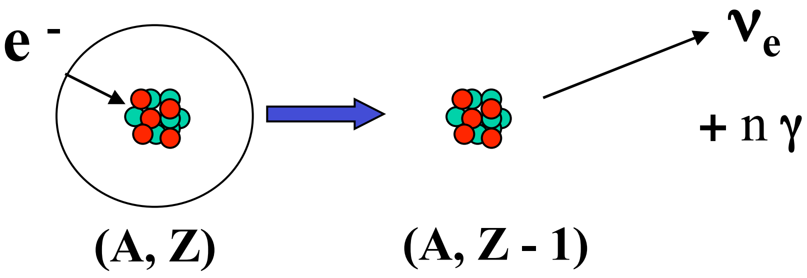


This process has no energy threshold !

Antineutrino capture on EC decaying nuclei (a)

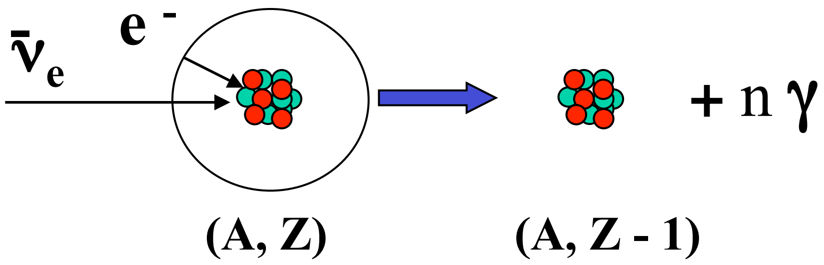
Known

Electron Capture



Possible

Simultaneous $\bar{\nu}$ and electron Capture

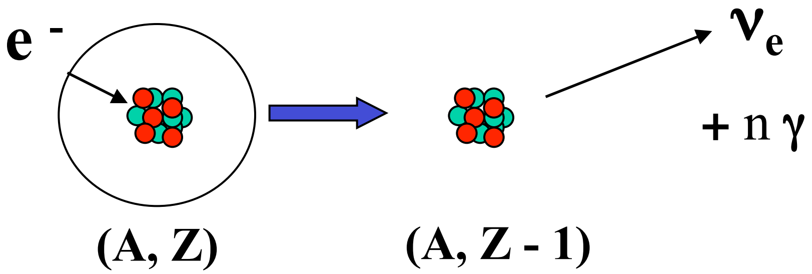


This process has no energy threshold !

Antineutrino capture on EC decaying nuclei (b)

Known

Electron Capture



e^-

ν_e

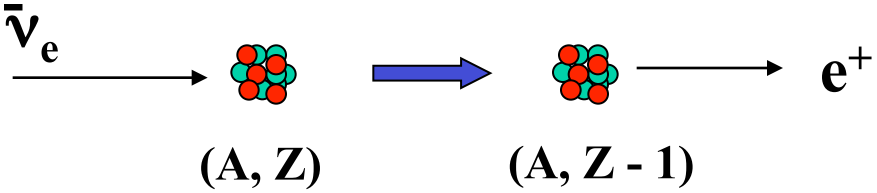
$+ n\gamma$

(A, Z)

(A, Z - 1)

Possible

Antineutrino Capture



$\bar{\nu}_e$

e^+

(A, Z)

(A, Z - 1)

E_ν threshold = $2m_e$ **- Q_{EC}**

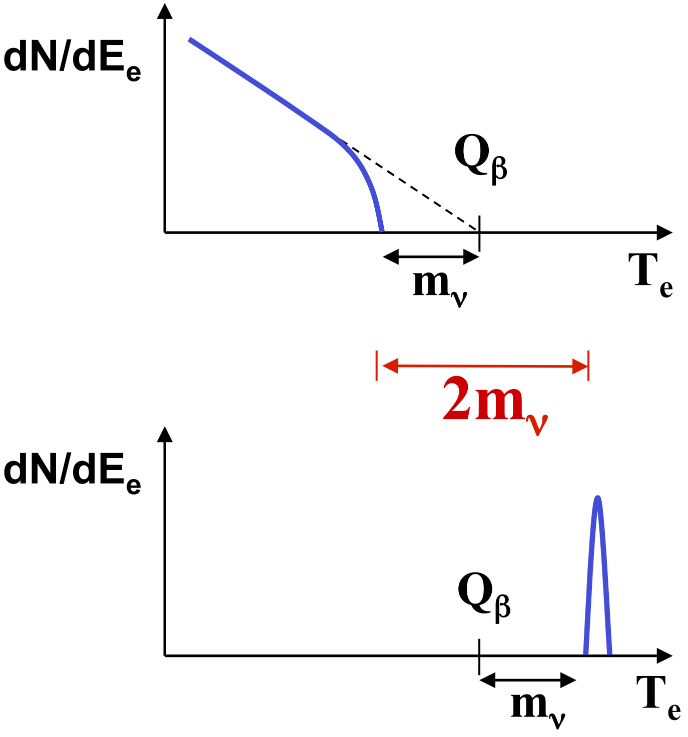
The effect of $m_\nu \neq 0$

Neutrino masses of the order of 1 eV are compatible with the present picture of our Universe

Neutrino capture on $\beta^\pm$ decaying nuclei

Nuclear Beta decay

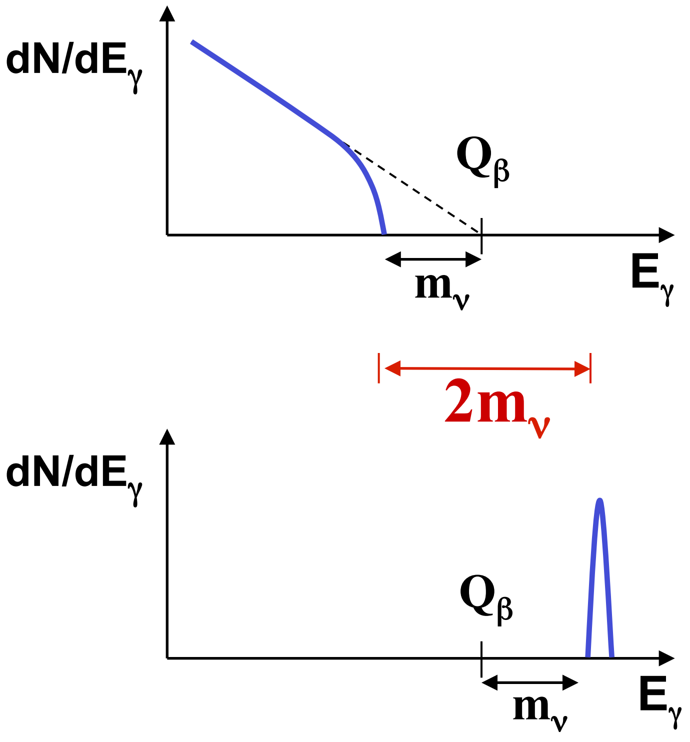
Neutrino Capture on a Beta Decaying Nucleus



The events induced by Neutrino Capture have a unique signature: there is a gap of $2m_\nu$ (centered at Q_β) between “signal” and “background”

exploiting $m_\nu \neq 0$

Neutrino capture on EC decaying nuclei



Electron Capture

Neutrino and Electron Capture

The events induced by Neutrino Capture have a unique signature:
there is a gap of $2m_\nu$ (centered at Q_β) between “signal” and “background”

The interactions exist…..
….but what about cross sections ?

If $\sigma_{NCB} \propto E_{\nu}$

then $\sigma_{NCB} \xrightarrow{E_{\nu} \to 0} 0$

NCB Cross Section

a new parametrization

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

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

The nuclear shape factors C_β and C_ν both depend on the same nuclear matrix elements

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

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

NCB Cross Section

a new parametrization

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

This is valid for both $\beta^\pm$ and EC decaying nuclei

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

$\overset{(-)}{\nu}$ capture on $\beta^\pm$ nuclei

$$\mathcal{A} = \frac{\sum_x n_x C_x(q_\nu) f_x(q_\nu)}{p_e E_e F(Z, E_e) C(p_e, p_\nu)_\nu}$$

$\bar{\nu}$ capture on EC nuclei

$$\mathcal{A}' = \frac{\sum_x n_x C_x(q_\nu) f_x(q_\nu)}{\sum_x n_x C_x(E_\nu) g_x \rho_x(E_\nu)}$$

$\bar{\nu}$ + e^- capture on EC nuclei

In a large number of cases $\mathcal{A}$ can be evaluated in an exact way and NCB cross section depends only on Q_β and $t_{1/2}$ (measurable)

Example: NCB Cross Section

on $\beta^{\pm}$ nuclei for different types of decay transitions

- Superallowed transitions

$$\sigma_{\mathrm{NCB}} v_\nu = 2\pi^2 \ln 2 \frac{p_e E_e F(Z, E_e)}{f t_{1/2}}$$

- This is a very good approximation also for allowed transitions since

$$\frac{C(E_e, p_\nu)_\beta}{C(E_e, p_\nu)_\nu} \simeq 1$$

- *i-th* unique forbidden

$$C(E_e, p_\nu)^i_\beta = \left[\frac{R^i}{(2i+1)!!}\right]^2 \left|{}^A F^{(0)}_{(i+1)\,i\,1}\right|^2 u_i(p_e, p_\nu)$$

$$\mathcal{A}_i = \int_{m_e}^{W_o} \frac{u_i(p'_e, p'_\nu) p'_e E'_e F(Z, E'_e)}{u_i(p_e, p_\nu) p_e E_e F(Z, E_e)} E'_\nu p'_\nu \mathrm{d}E'_e$$

NCB Cross Section Evaluation

The case of Tritium

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

we obtain $\sigma_{\mathrm{NCB}}(^3\mathrm{H}) \frac{v_\nu}{c} = (\ 7.7 \pm 0.2\ ) \times 10^{-45}\ \mathrm{cm}^2$

where the error is due to Fermi and Gamow-Teller matrix element uncertainties

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Using shape factors ratio $\sigma_{\mathrm{NCB}} v_\nu = 2\pi^2 \ln 2 \frac{p_e E_e F(Z, E_e)}{f t_{1/2}}$

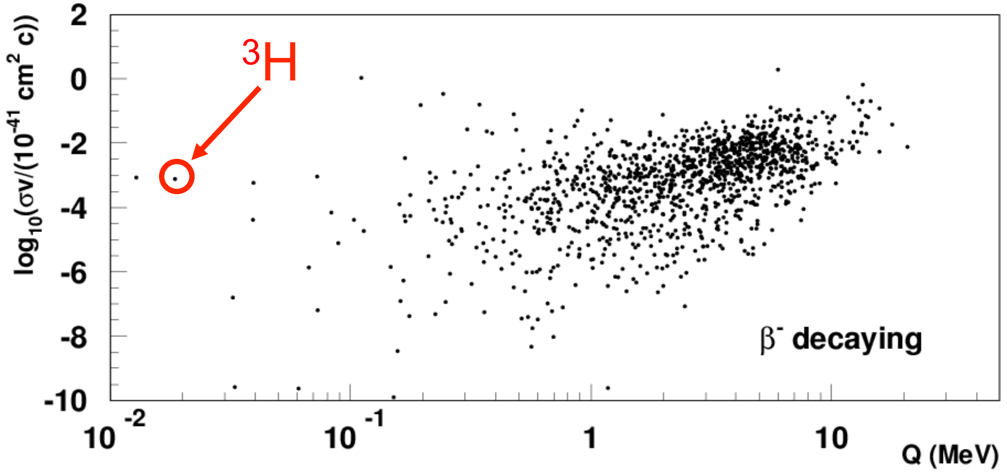
$$\sigma_{\mathrm{NCB}}(^3\mathrm{H}) \frac{v_\nu}{c} = (\ 7.84 \pm 0.03\ ) \times 10^{-45}\ \mathrm{cm}^2$$

where the error is due only to uncertainties on Q_β and $t_{1/2}$

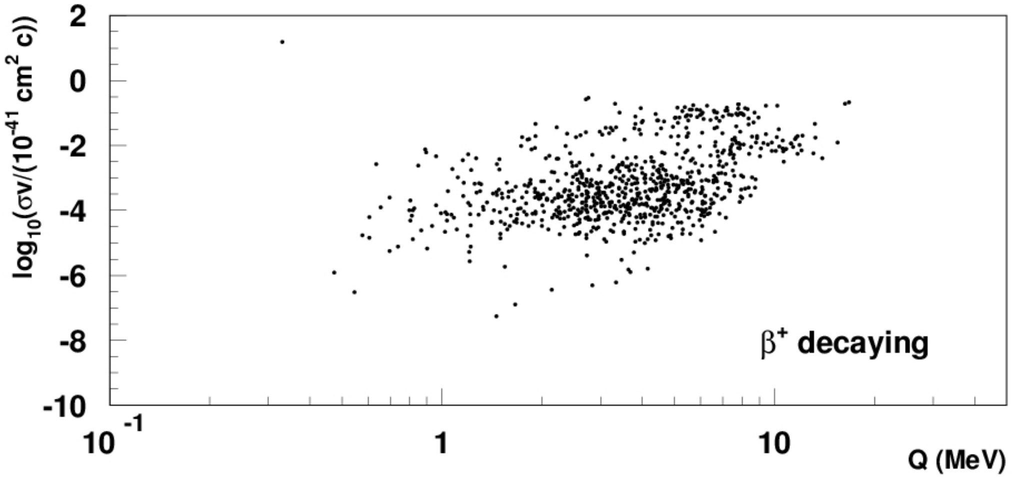
NCB Cross Section Evaluation

using measured values of Q_β and $t_{1/2}$

1272 β^- decays



799 β^+ decays



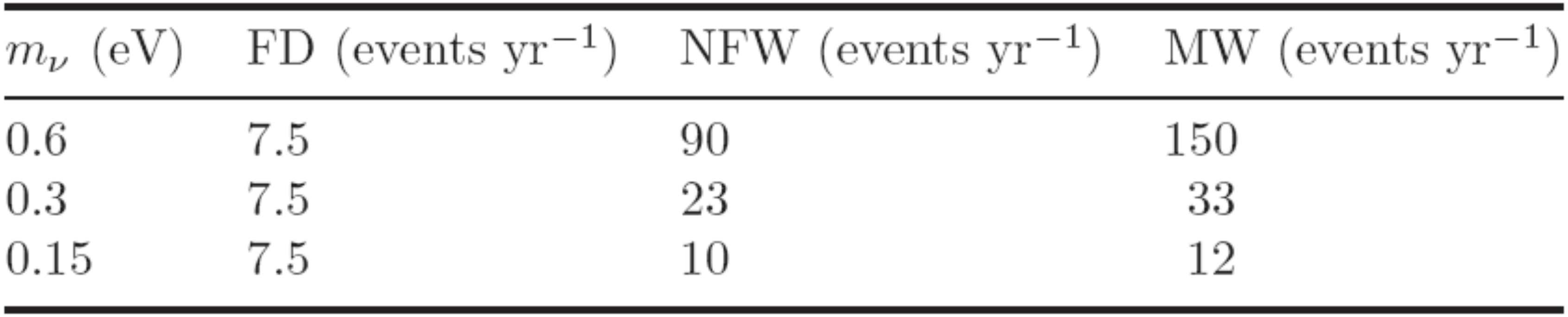
Beta decaying nuclei having BR($\beta^\pm$) > 5 %
selected from 14543 decays listed in the ENSDF database

Relic Neutrino Detection

using $\beta^{\pm}$ decaying nuclei

In the case of Tritium we estimate that 7.5 neutrino capture events per year are obtained using a total mass of 100 g

In case of CνB gravitational clustering we expect a significant signal enhancement



m_ν (eV)	FD (events yr^{-1})	NFW (events yr^{-1})	MW (events yr^{-1})
0.6	7.5	90	150
0.3	7.5	23	33
0.15	7.5	10	12

FD = Fermi-Dirac NFW= Navarro,Frenk and White
MW=Milky Way (Ringwald, Wong)

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

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

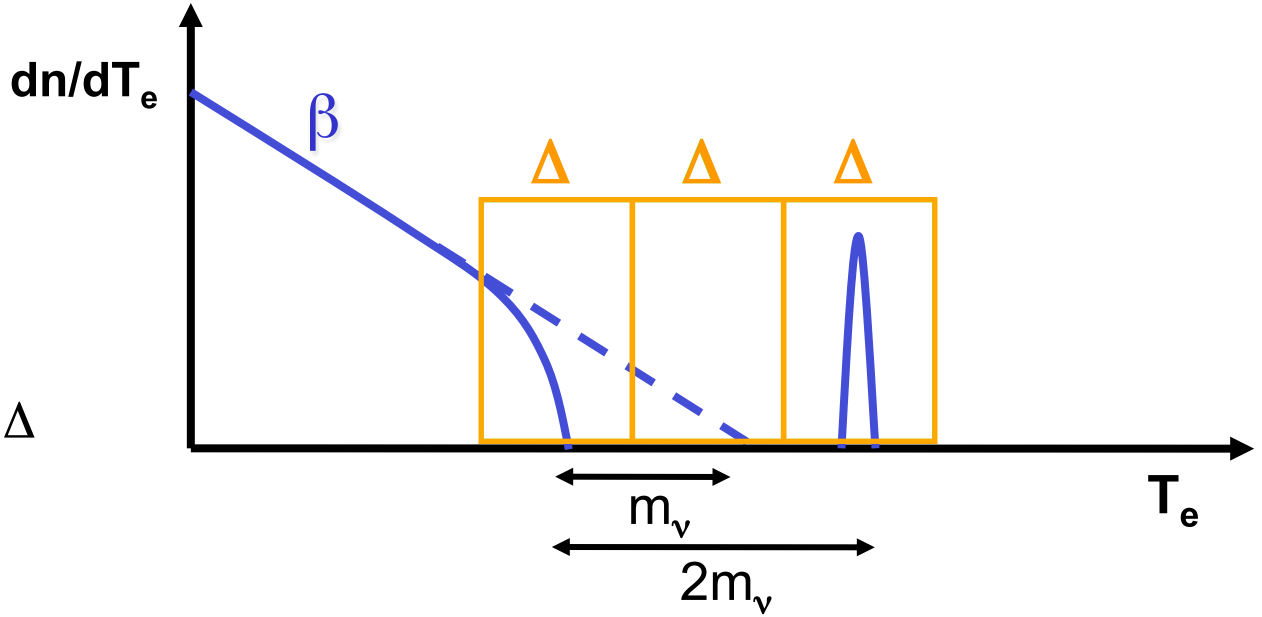
In the case of Tritium (and using n_ν=50) we found that

$$\lambda_\nu(^3\mathrm{H}) = 0.66 \cdot 10^{-23} \lambda_\beta(^3\mathrm{H})$$

Relic Neutrino Detection

signal to background ratio

Observing the last energy bins of width Δ



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

where the last term is the probability for a beta decay electron at the endpoint to be measured beyond the 2m$_\nu$ gap

It works for $\Delta<m_\nu$

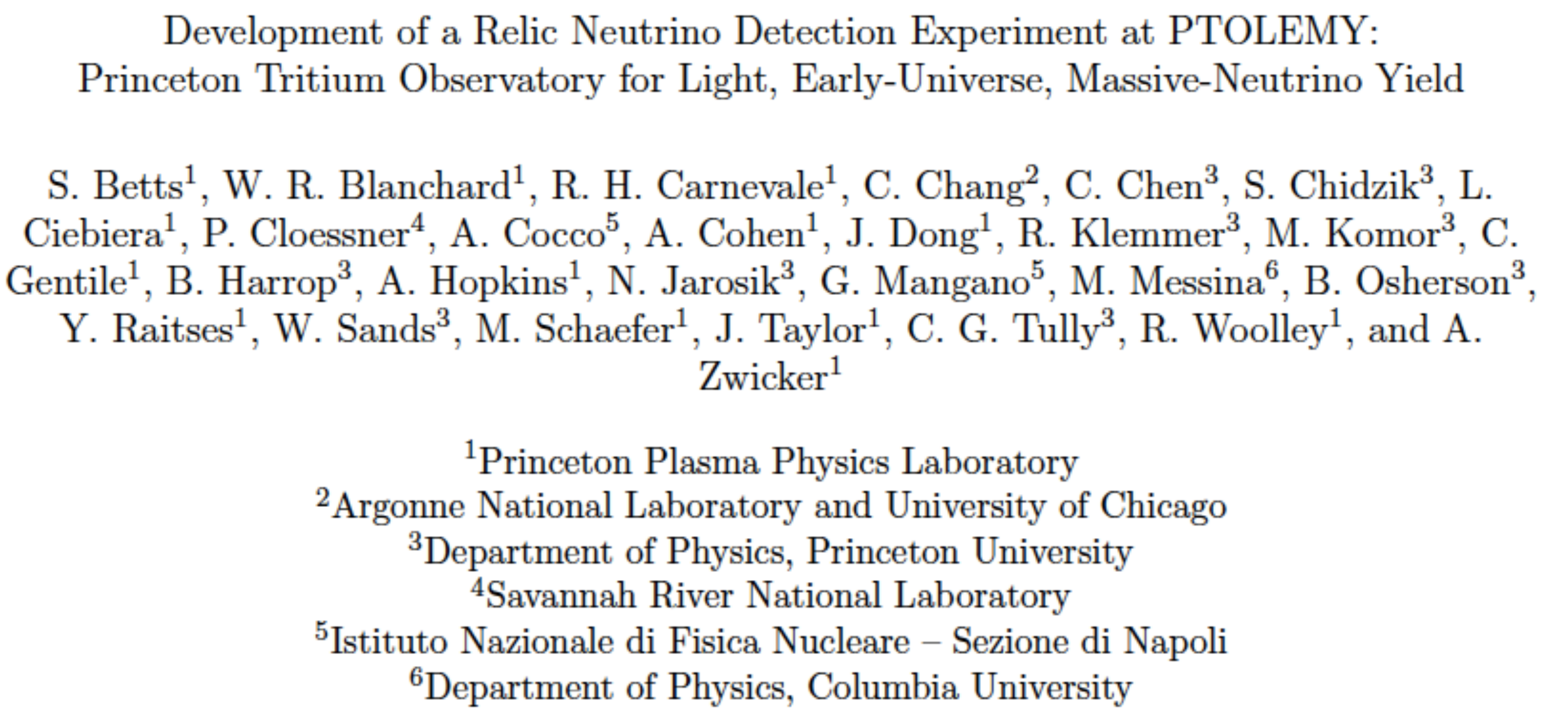
CνB detection using Tritium

Signal to background ratio depends crucially on the energy resolution (Δ) at the beta decay endpoint (It works only if $\Delta < m_\nu$)

As an example, given a neutrino mass of 0.7 eV and an energy resolution at the beta decay endpoint of Δ=0.2 eV a signal to background ratio of 3 is obtained. In the case of 100 g mass target of Tritium it would take one and a half year to observe a 5σ effect

More details in: AGC, M.Messina and G.Mangano JCAP 06(2007)015

Il progetto PTOLEMY



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

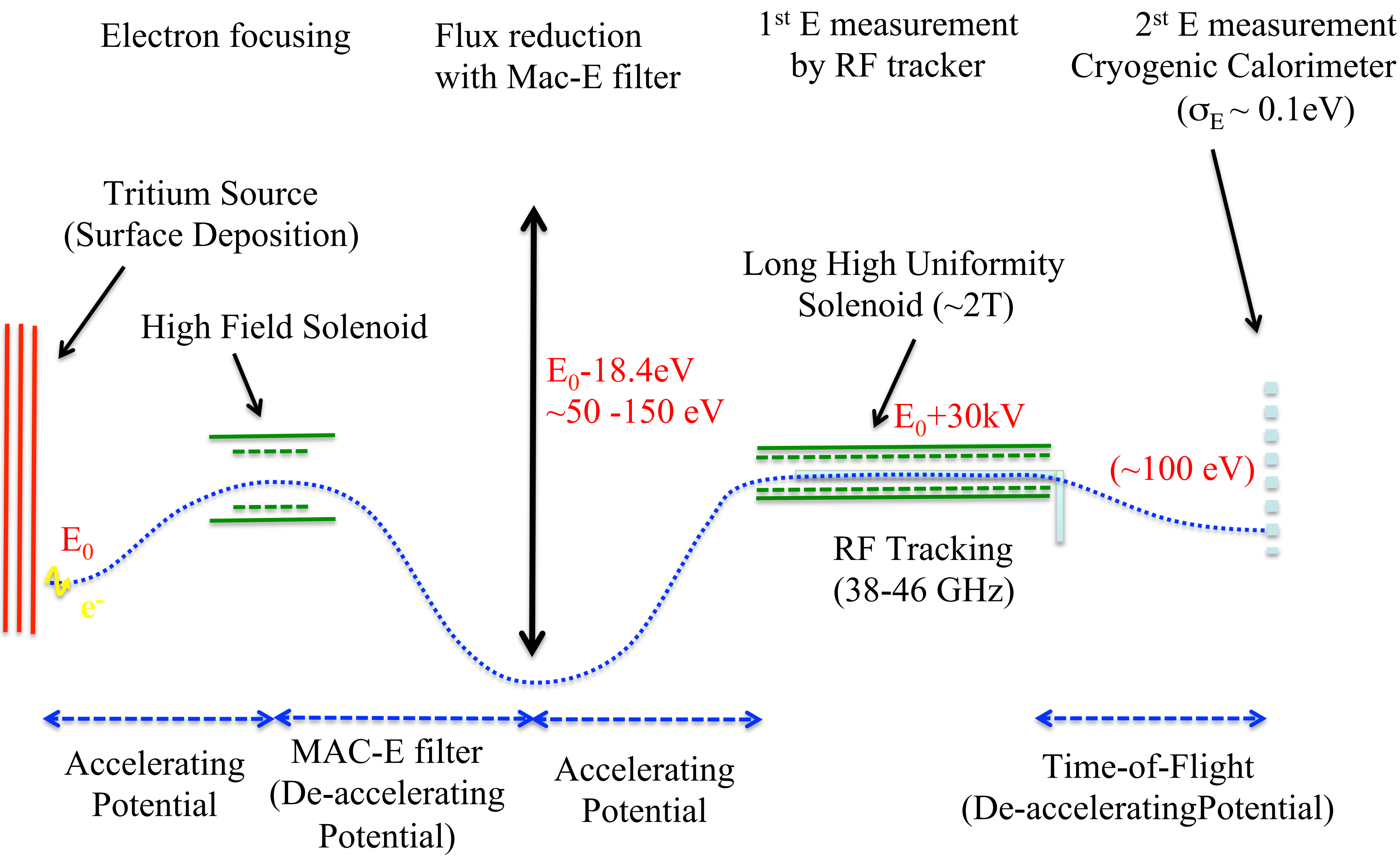
S. Betts[1], W. R. Blanchard[1], R. H. Carnevale[1], C. Chang[2], C. Chen[3], S. Chidzik[3], L. Ciebiera[1], P. Cloessner[4], A. Cocco[5], A. Cohen[1], J. Dong[1], R. Klemmer[3], M. Komor[3], C. Gentile[1], B. Harrop[3], A. Hopkins[1], N. Jarosik[3], G. Mangano[5], M. Messina[6], B. Osherson[3], Y. Raitses[1], 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
[2]Argonne National Laboratory and University of Chicago
[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

100 g di Trizio + filtro MAC-E + RF tracking + calorimetro con risoluzione < eV

arXiv:1307.4738v2

PTOLEMY



Electron focusing

Flux reduction
with Mac-E filter

1st E measurement
by RF tracker

2st E measurement
Cryogenic Calorimeter
($\sigma_E \sim 0.1$eV)

Tritium Source
(Surface Deposition)

High Field Solenoid

E_0-18.4eV
~50 -150 eV

Long High Uniformity
Solenoid (~2T)

E_0+30kV

(~100 eV)

E_0

e^-

RF Tracking
(38-46 GHz)

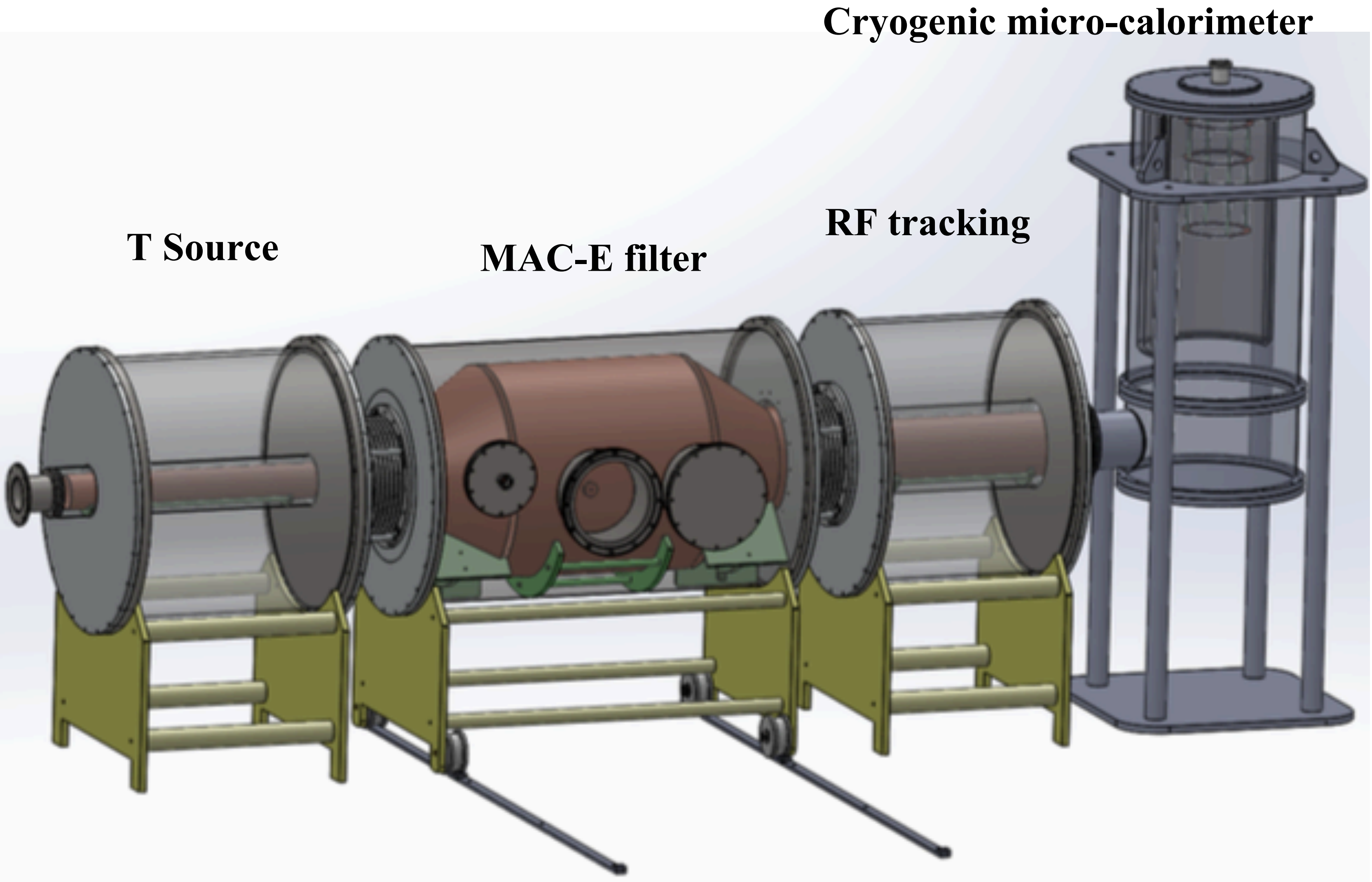
Accelerating
Potential

MAC-E filter
(De-accelerating
Potential)

Accelerating
Potential

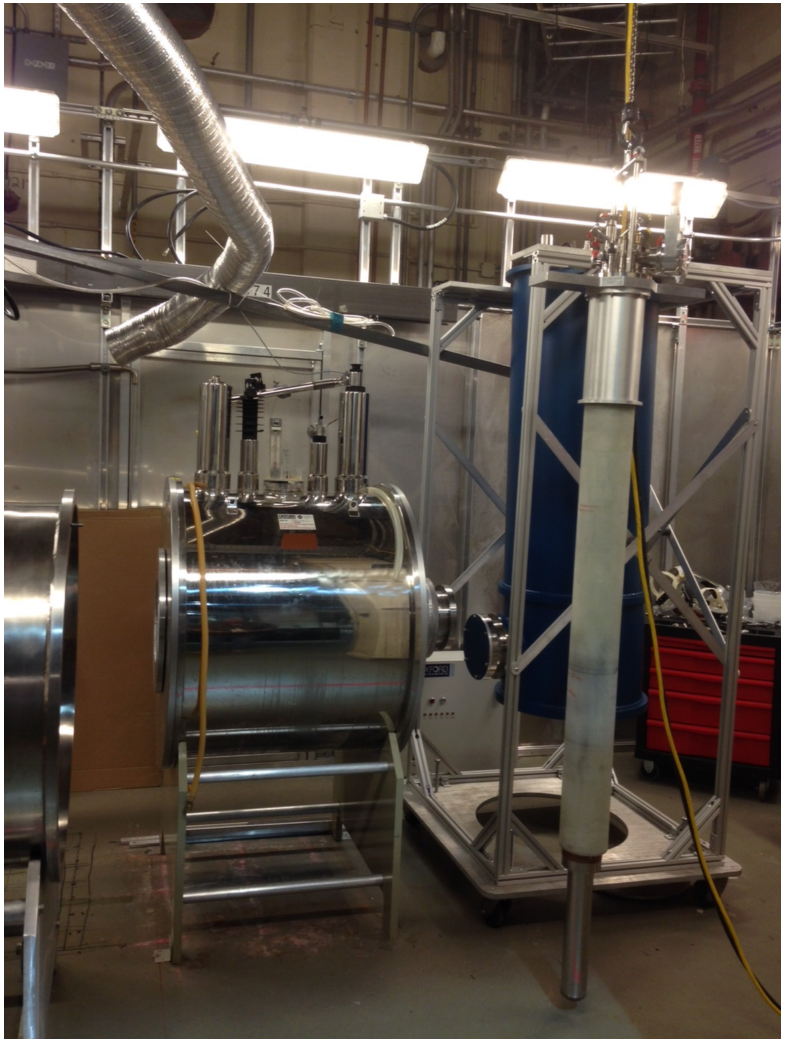
Time-of-Flight
(De-acceleratingPotential)

Prototipo di PTOLEMY in costruzione a Princeton



Prototipo di PTOLEMY in costruzione a Princeton

Prototipo di PTOLEMY in costruzione a Princeton



Sept 29, 2015

Tritium target

Challenges:
- Permissions (!)
- High density and packing factor
- Weakly bound
- Low interaction probability
- Electron adiabatically focused to match the MAC-E filter

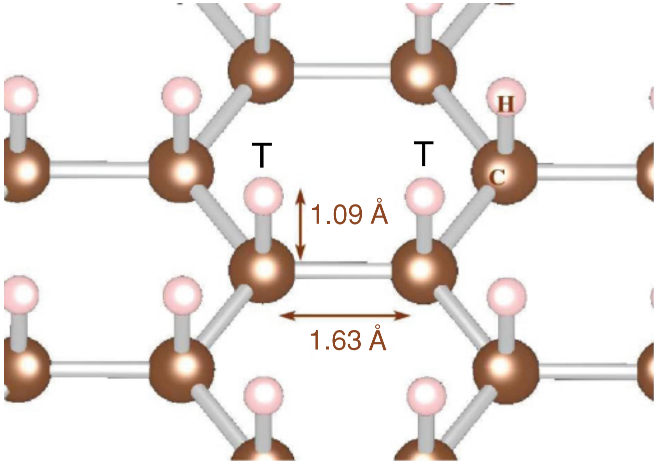
Cold plasma T deposition on Graphene (PPPL)

Single atomic graphene layer weakly bound in sp-3 configuration

Source strength with surface densities of ~1Ci/cm^2 (100 μg/cm^2)

Energy spread from source scattering needs to be measured

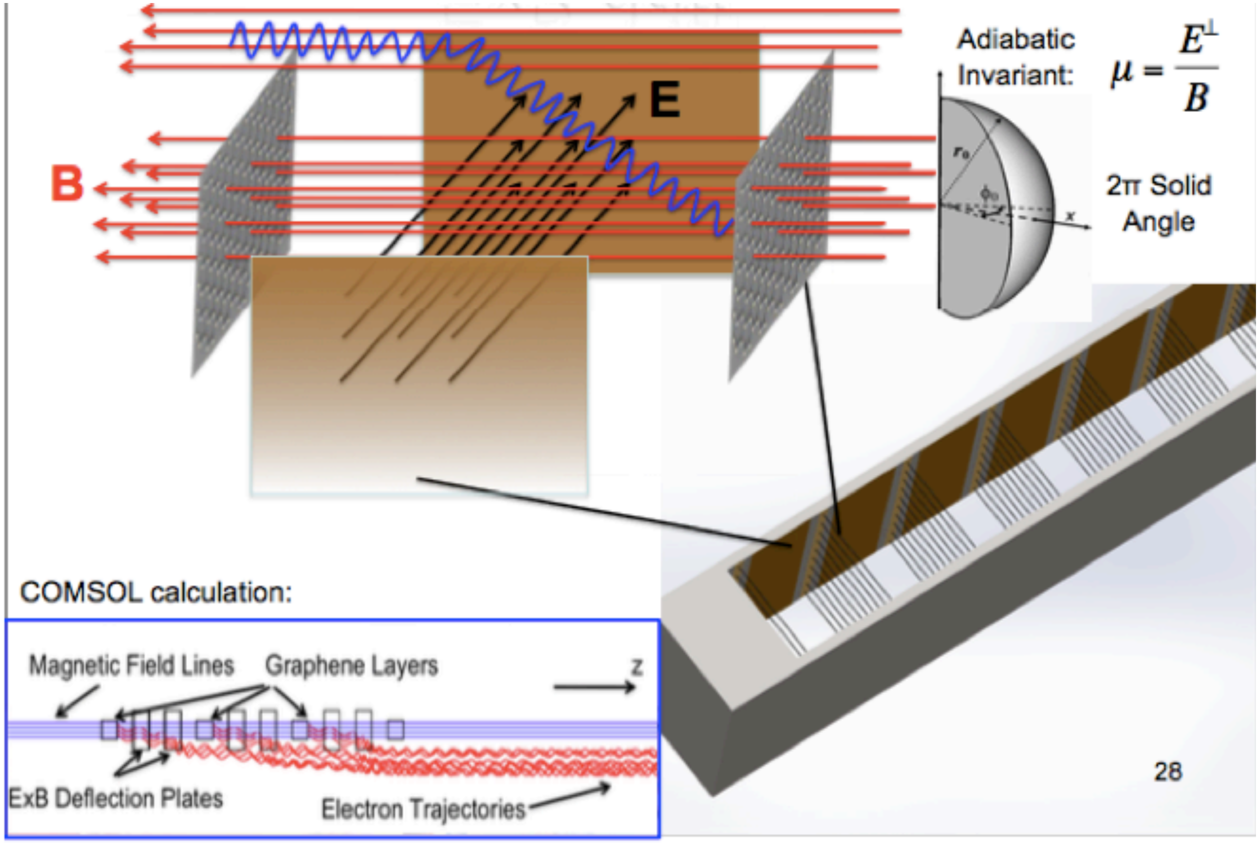
First samples available by end 2015



Tritium target

PTOLEMY 100g

Source disk made of 10^4-10^5 plates



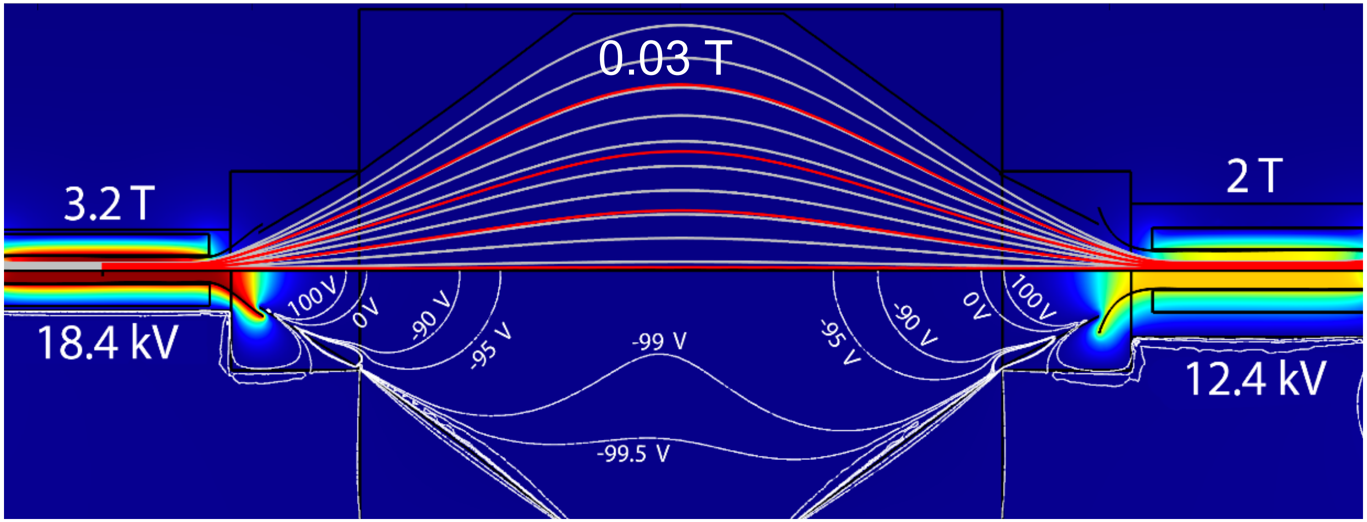
Under study…

MAC-E filter

Low magnetic gradient adiabatically transforms cyclotron trajectories into longitudinal motion

$$\mu = \frac{E_\perp}{B} \qquad \frac{\Delta E}{E} = \frac{B_{\min}}{B_{\max}}$$

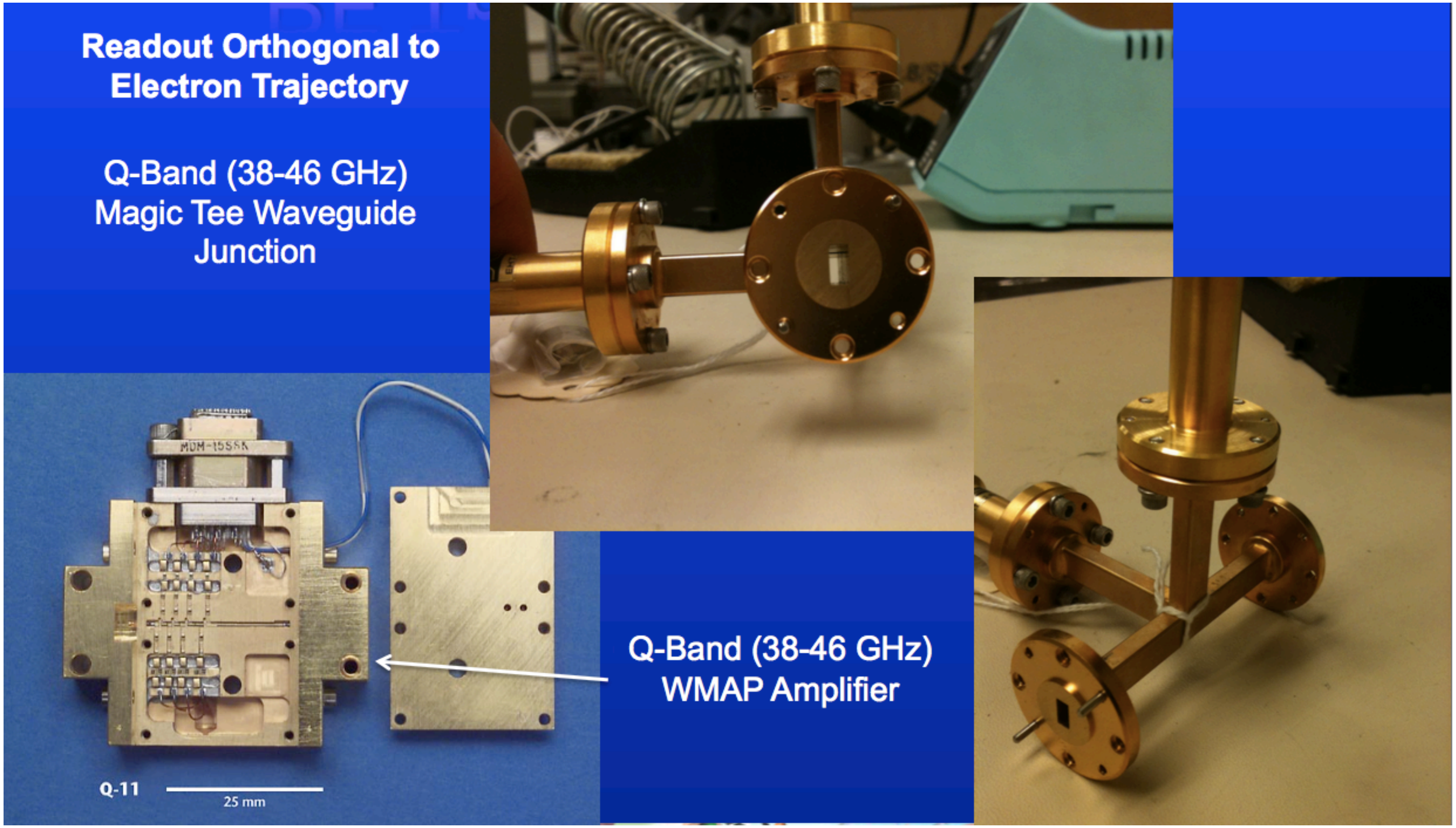
Electric field sets the energy cutoff



If the threshold is set at ~1eV the event rate reduction is ~ $(\Delta E/Q)^3 = 1.55\ 10^{-13}$
(for comparison, the activity of 1 g of T is of $3.6\ 10^{+14}$ Hz)

RF tracking and time-of-flight

Thread electron trajectories (magnetic field lines) through an array of Project-8 type antennas with wide bandwidth (few x10^{-5}) to identify cyclotron RF signal in transit times of order 0.2 msec. The timing resolution expected is ~ 10ns depending on micro-calorimeter response.



Readout Orthogonal to Electron Trajectory

Q-Band (38-46 GHz)
Magic Tee Waveguide Junction

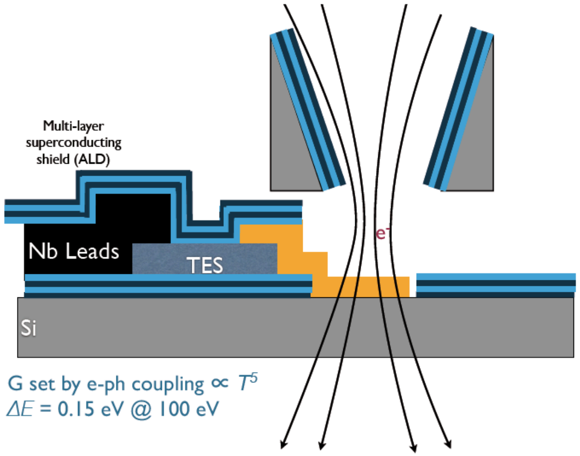
Q-Band (38-46 GHz)
WMAP Amplifier

Cryogenic micro-calorimeters
based on Transition Edges Sensors technology

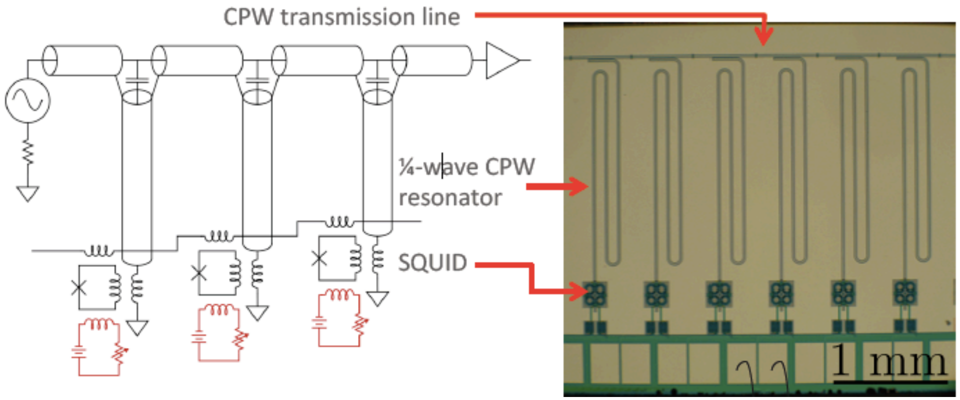
Operating TES in magnetic field is a major technical challenge.TES readout systems are typically operated in low magnetic field environments due to a downward shifting of the transition-edge temperature in high fields

The design for PTOLEMY incorporates magnetic shielding for the TES and the microwave-readout massive SQUID multiplexer (MMSM)

Resolution of ~0.55eV at 1keV and ~0.15eV at 0.1keV operating at 70-100mK under investigation (Clarence Chang ANL, Moseley et. al. GSFC/NASA)



G set by e-ph coupling $\propto T^5$
ΔE = 0.15 eV @ 100 eV



PTOLEMY prototype programme

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

2nd Milestone:(done) Complete the construction of MAC-E filter

- Installation of full-scale vacuum chamber
- Install nine copper electrodes under HV

3rd Milestone: Install 100mK Oxford Instruments Dilution Refrigerator and commission TES calorimeter

4th Milestone: Install Tritium-loaded Graphene Sample and commission MAC-E filter with APD readout

5th Milestone: Collect data at tritium endpoint with cryogenically cooled tritium and TES calorimeter and verify that the energy resolution is better than diatomic tritium.

Most precise study of tritium endpoint spectrum!

6th Milestone: Validate technologies for 100g PTOLEMY

Summary

Relic neutrino detection has been promoted from "impossible" to "challenging"

Important R&D still to be done on source, detector and background levels

PTOLEMY prototype @ PPPL is an excellent test bench for validating the technologies for a 100g detector

First grant from Simons Foundation started on Sep. 1st

Kick-off meeting of the PTOLEMY collaboration will take place before end 2015

Enthusiastic collaborators are welcome !

beyond…

There is a way to detect any particle having a mixing with electron neutrino (ie has some electron flavor)

In addition, if this particle has a “large” mass (>1eV) there are no background events due to the beta decay process

In the neutrino mass/energy range [1 eV ÷ 100 keV] (“terra incognita”) this is maybe the only realistic detection method

Sterile neutrino as a detectable “relic” ?

Does it exists ?

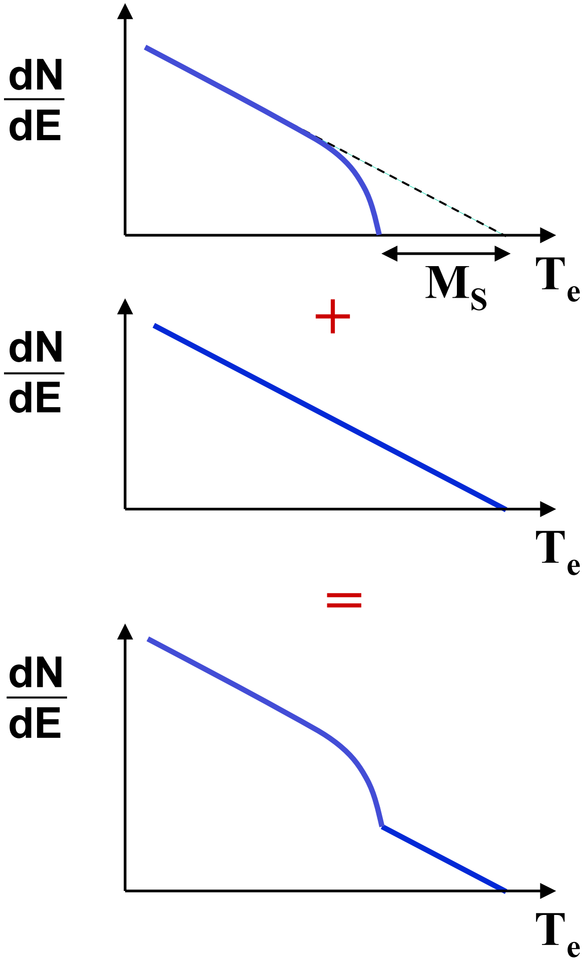
Constraints on the number of “standard” neutrino families come from Big Bang Nucleosynthesis (^{4}He abundance) and from the CMB power spectrum shape analysis

Is it a viable Dark Matter candidate ?

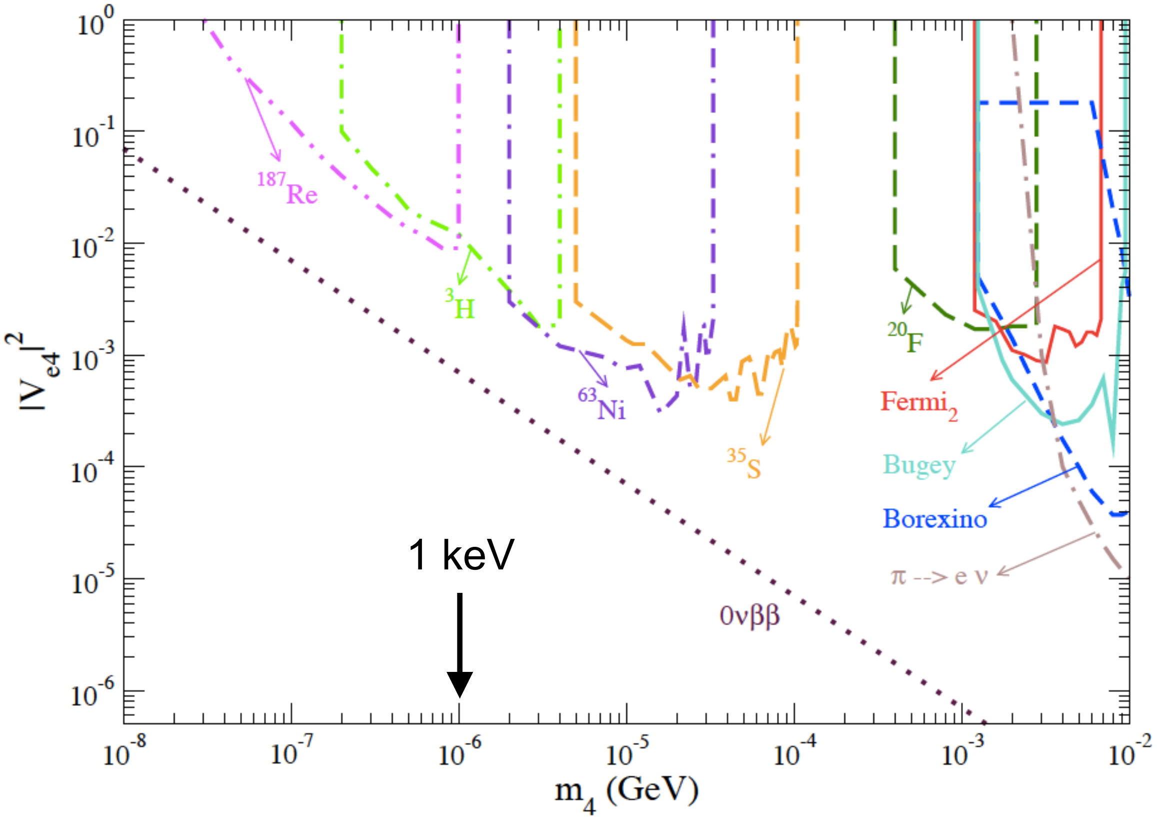
Dark Matter could indeed be just “Warm” instead of “Cold”

Mass around 1 keV are compatible with cosmological and particle physics models

Sterile neutrino kink searches in β decay spectra



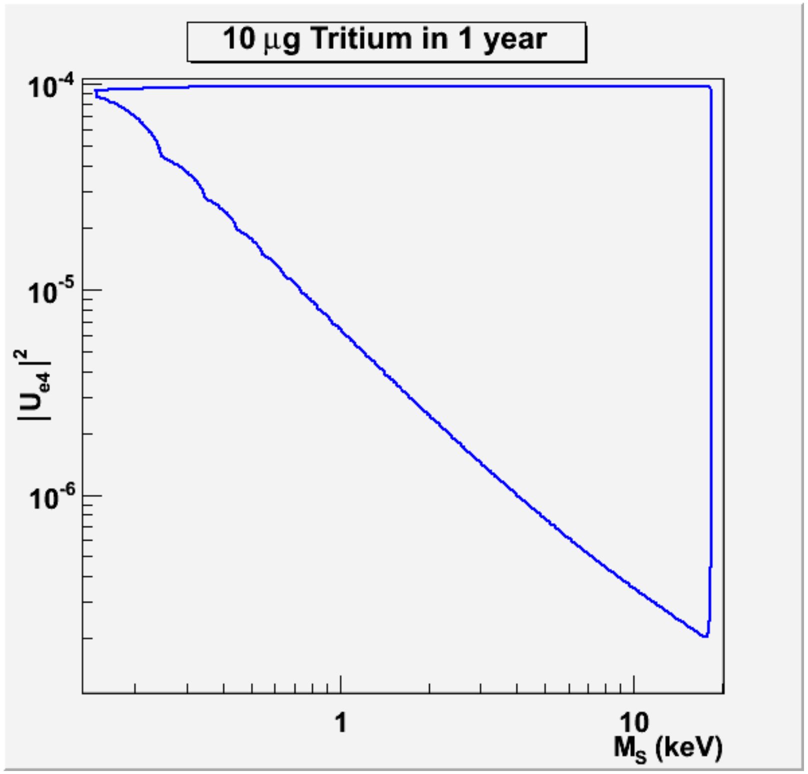
A.Atre et al. JHEP05(2009)030

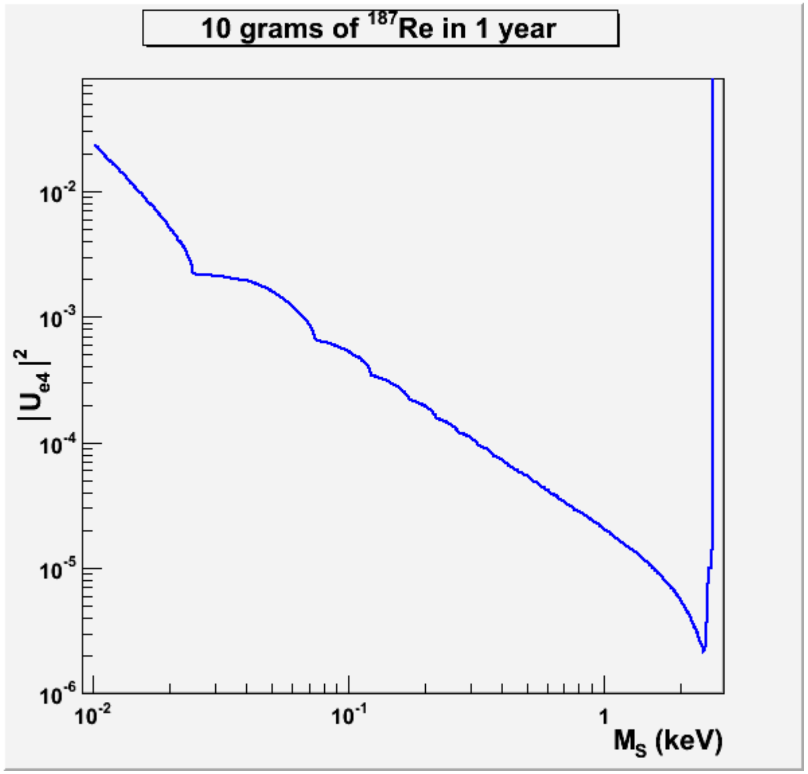


It works only if $M_S < Q_\beta$

Brute-force approach to increase sensitivity

Aim: $|U_{e4}|^2 < 1.0\times10^{-5}$ 90% CL





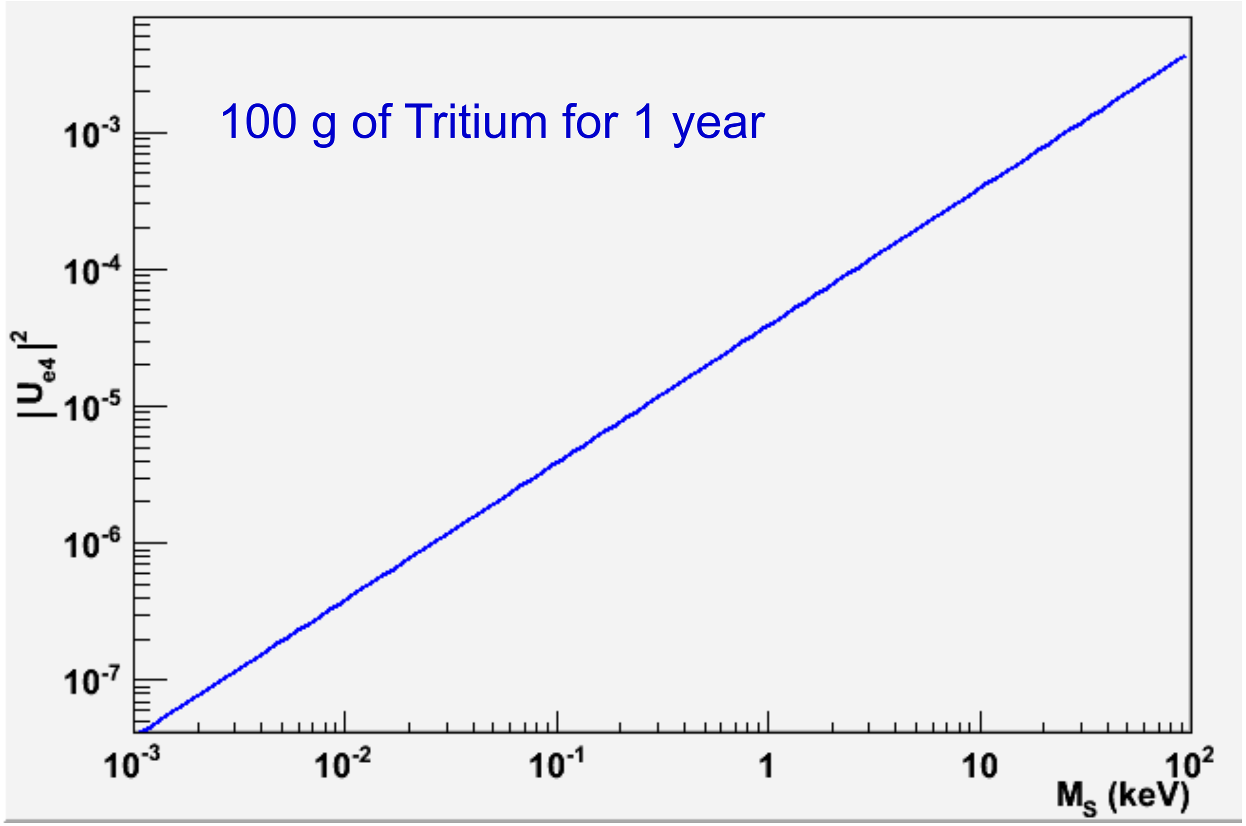
10^{17} events
Trigger rate ~ 10^9 Hz

10^{11} events
Trigger rate ~ 10^4 Hz
10000 x 1 mg crystals

Using ν capture...

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

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



CνB detection using ^{163}Ho

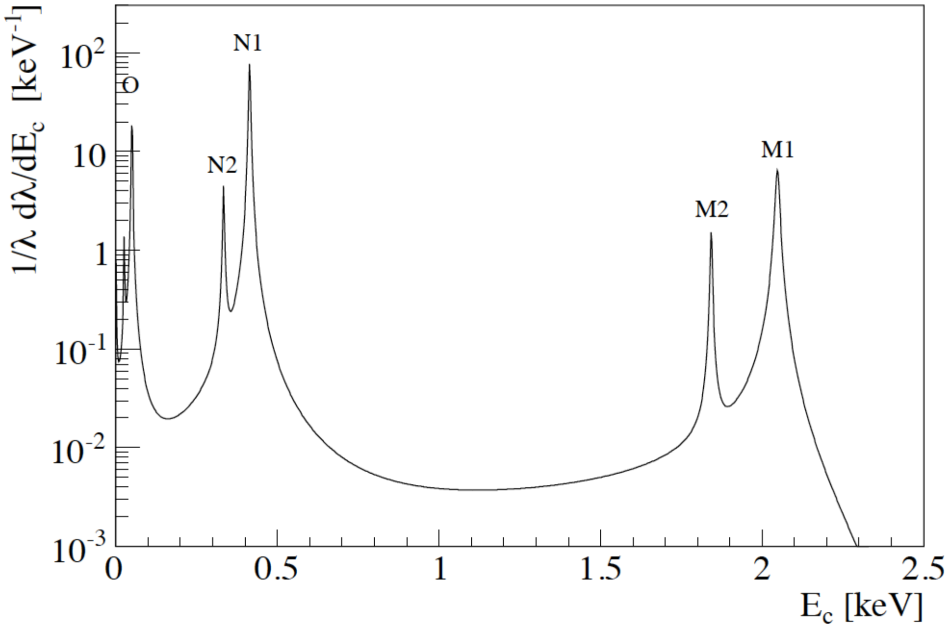
M.Lusignoli and M.Vignati arXiv:1012.0760v1 (2010)

Q_{EC} ~ 2.6 keV $T_{1/2}$ = 4570 years

$$\bar{\nu} + {}^{163}\mathrm{Ho} \rightarrow {}^{163}\mathrm{Dy}^{*} \rightarrow {}^{163}\mathrm{Dy} + n\,\gamma$$

$$\lambda_{\bar{\nu}} = n_{\bar{\nu}} \frac{G_\beta^2}{2} \sum_i n_i\, C_i\, \beta_i^2 B_i\, \rho_i(E_{\bar{\nu}})$$

$$\rho_i(E_{\bar{\nu}}) = \frac{1}{\pi} \cdot \frac{\Gamma_i/2}{(E_{\bar{\nu}} + Q - E_i)^2 + \Gamma_i^2/4}$$



$$\frac{\lambda_{\bar{\nu}}}{\lambda_{EC}} = (7.7 \cdot 10^{-22}, 5.8 \cdot 10^{-23}, 1.4 \cdot 10^{-23}) \text{ for } Q = (2.3, 2.5, 2.8) \text{ keV}$$

10 events in 30 kg of ^{163}Ho in 1 year

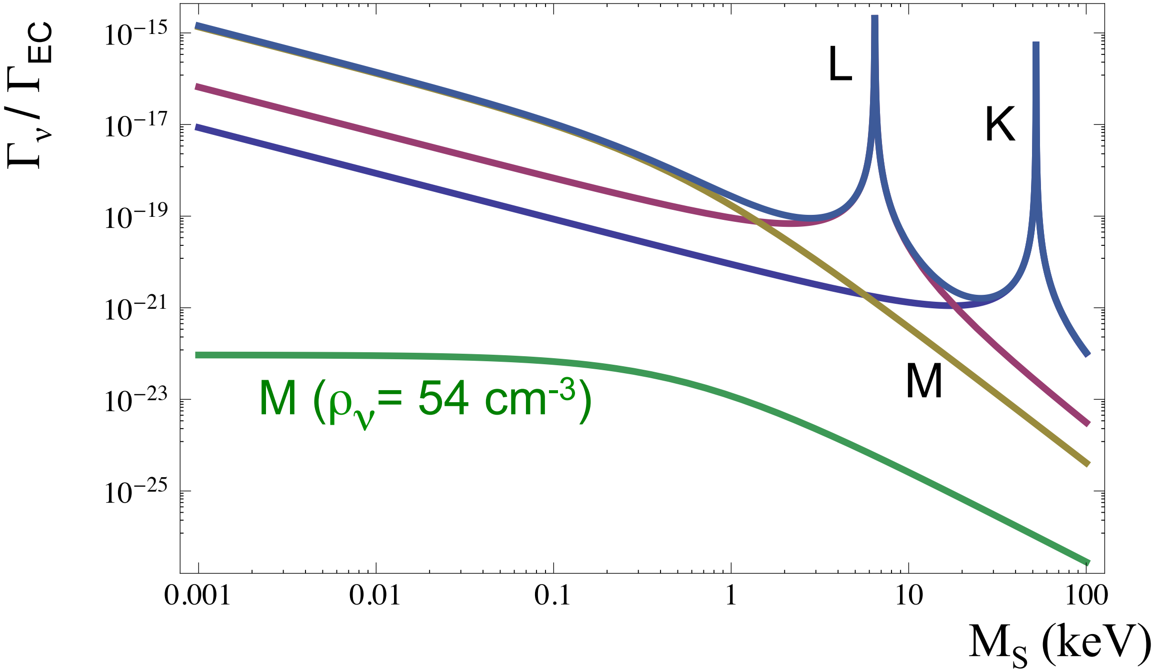
A 5σ discovery evidence could be achieved in case of
m_ν=0.5 eV and Δ=0.3 eV

^{163}Ho as a target for sterile neutrino

Q_{EC} ~ 2.6 keV $T_{1/2}$ = 4570 years

K and L Capture are forbidden since E_K=54 keV and E_L=9 keV)

$\bar{\nu} + {}^{163}\text{Ho} \rightarrow {}^{163}\text{Dy}^* \rightarrow {}^{163}\text{Dy} + n\,\gamma$



Assuming M_S~ 0.1 ÷ 1 keV and $|U_{e4}|^2$ ~ 10^{-4}

7 ν_S induced capture events using 1 kg in 1 year of data taking

…further beyond…

Are we missing something ?

…further beyond…

Are we missing something ?

I neutrini relici hanno una lunghezza d’onda di DeBroglie ordine millimetri, hanno cioè una funzione d’onda “macroscopica”. Fenomeni tipicamente quantistici potrebbero avere luogo….

Provocazione 1

Data la reazione $\nu + A \rightarrow B$

Relic neutrino interagente in corrente carica con un bersaglio di materiale composto da nuclei (A) e (B)

ν + |ABBAA…..ABAAA> $\rightarrow$ |ABBAB…..ABAAA>

esistono casi in cui e' impossibile misurare (anche in linea di principio) quale degli (A) sia diventato (B) ?

Provocazione 2

Data la reazione $\nu + A \longrightarrow B^*$

Relic neutrino interagente in corrente carica con un bersaglio di materiale composto da nuclei (A) e (B)

$$\begin{tikzcd}
\nu + A^1 \arrow[r] & B^{1*} \arrow[dr, dotted] & & \\
& & B^{2*} \arrow[r] & A^2 + \nu
\end{tikzcd}$$

B^1 e B^2 sono distinti e separati da una distanza $d < \lambda_\nu$ ma il ν può essere lo stesso….

Grazie !

Grazie !

PLEASE DO NOT SHOOT

THE PIANO PLAYER

Trigger and data acquisition

The raw rate of electron production from tritium decay for 100 grams of tritium is roughly 10^{16} electrons/second

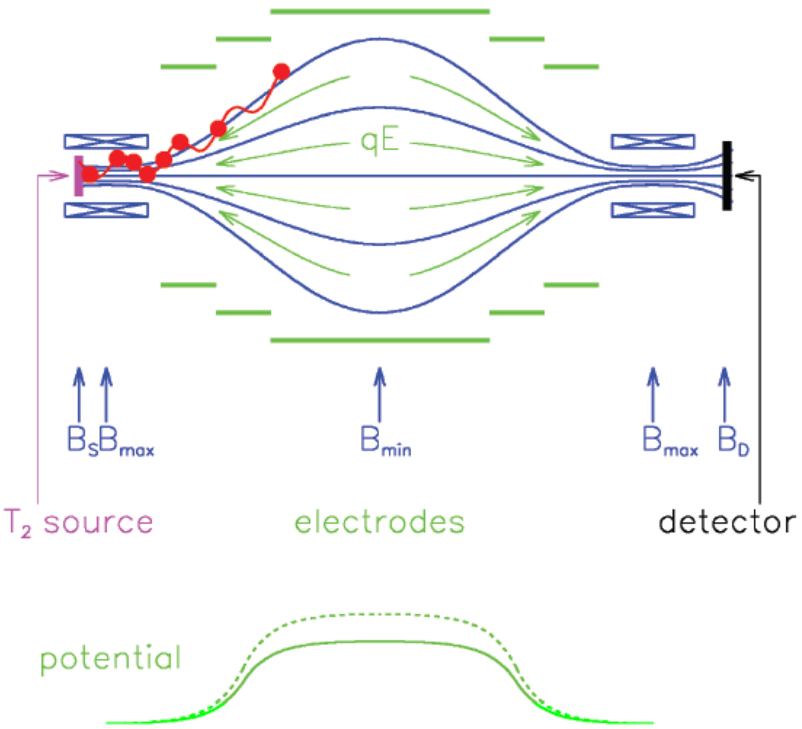
The fraction of -decays within 100 eV of the endpoint is approximately $2\mathrm{x}10^{-7}$

With 10^{5} readout channels, the average rate per channel is 10-20 kHz

KATRIN
Karlsruhe Tritium Neutrino Experiment

Aim at direct neutrino mass measurement through the study of the ^{3}H endpoint (Q_β =18.59 keV, $t_{1/2}$=12.32 years)

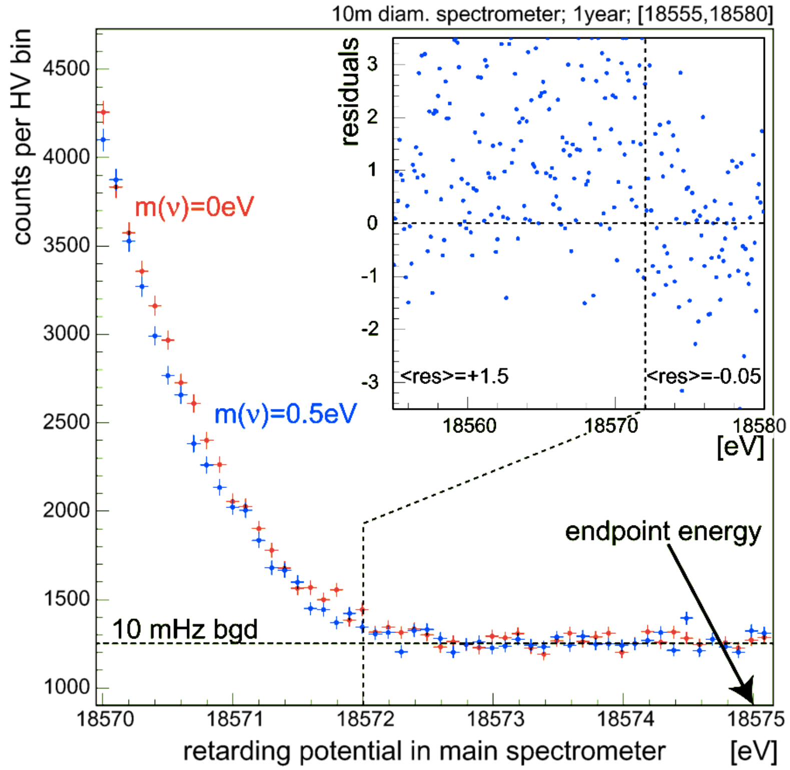
Phase I
- Energy resolution: 0.93 eV
- Tritium mass: ~ 0.1 mg
- Noise level 10 mHz
- Sensitivity to ν_e mass: 0.2 eV



Magnetic Adiabatic Collimator + Electrostatic filter

KATRIN
Karlsruhe Tritium Neutrino Experiment

MonteCarlo simulation of phase I data

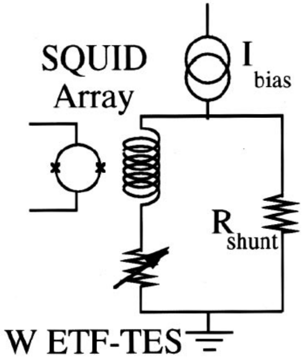


First results in 2011
End of Phase I data taking: 2015

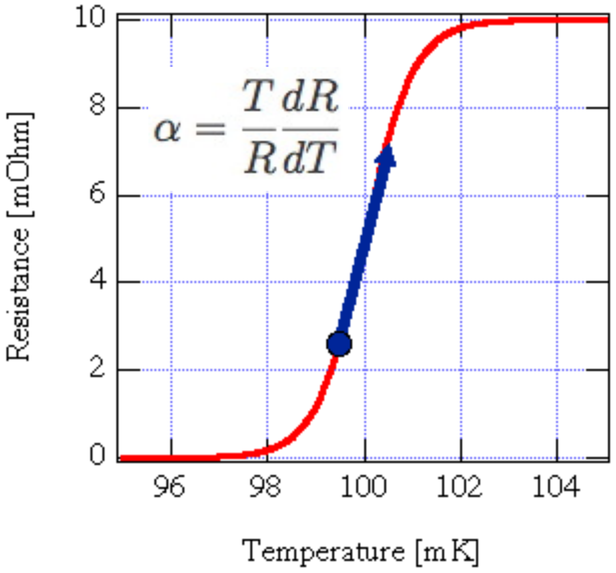
Phase II
- Energy resolution: 0.2 eV
- Noise level 1 mHz

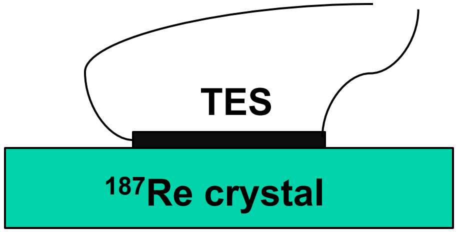
MARE

Aim at direct neutrino mass measurement through the study of the ^{187}Re endpoint (Q_β =2.66 keV, $t_{1/2}$=4.3 x 10^{10} years) using TES+micro-bolometers @ 10 mK temperature



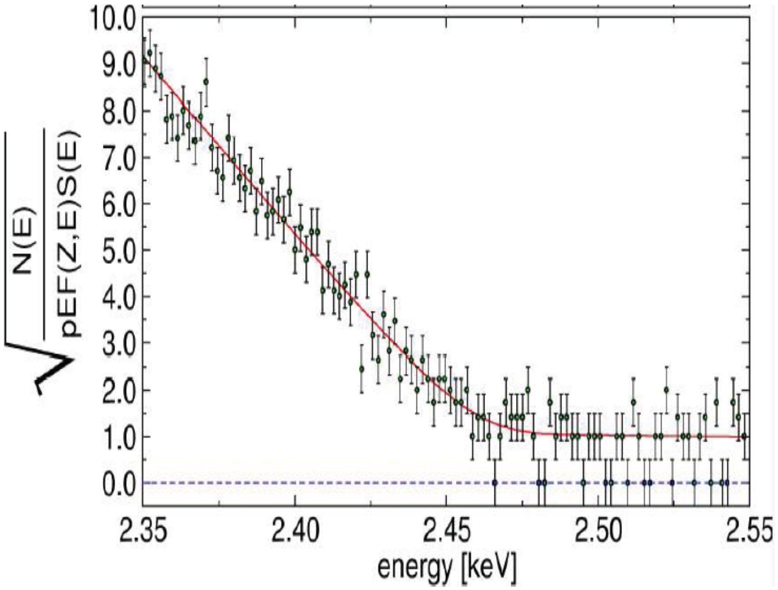
$$\Delta E \simeq 2.35\sqrt{4kT^2\frac{C}{\alpha}}$$





MARE

Energy resolution: 2÷3 eV
Total ^{187}Re mass: ~ 100 g



Phase II
Energy resolution: < 1 eV(?)

Relic Antineutrino Detection

using EC decaying nuclei (a)

$\bar{\nu}_e + e^- + (A,Z) \rightarrow (A,Z\text{-}1) + X$

The lack of a suitable final state prevents the use of this reaction to detect CνB unless either:

1) there exist an excited level (either atomic or nuclear) with energy
$E_o = Q_{EC} - E_K + m_\nu$

2) the captured electron is “off-mass” shell $m_{eff} = m_e - E_o$

3) it exist a nucleus A (stable) for which $Q_{EC} = E_K - m_\nu$

Relic Antineutrino Detection

using EC decaying nuclei (b)

$\bar{\nu}_e$ + (A,Z) → (A,Z-1) + e^+

The energy threshold prevents the use of this reaction to detect CνB unless:

1) use CνB as a target for accelerated fully ionized beam

- EC decay is inhibited (no electrons to be captured)
- Ions should have $\gamma_{\min} = \dfrac{E_{\rm thr}}{m_\nu}$
- Interaction rate is given by $\lambda_{\rm NCB} = \dfrac{n_{\bar{\nu}}\, 2\pi^2 \ln 2}{\mathcal{A} \cdot t_{1/2}^{\rm EC}}\, \mathcal{N}$

For allowed transitions and using n_ν= 56, E_{thr}=10 eV :

$$\mathcal{N} = 10^{13}$$
$$\gamma = 100$$

$$\lambda_{\rm NCB} \simeq 10^{-18}\ {\rm s}^{-1}$$

Too slow to be detected !

Relic Antineutrino Detection

using EC decaying nuclei (b)

$\bar{\nu}_e + (A,Z) \rightarrow (A,Z-1) + e^+$

2) there exist a nucleus for which

$$2m_e - m_\nu < Q_{EC} < 2m_e + m_\nu$$

In this case:

- the reaction has no energy threshold on the incoming antineutrino
- unique signature since β^+ decay is forbidden
- cross section is evaluated using EC decay observables

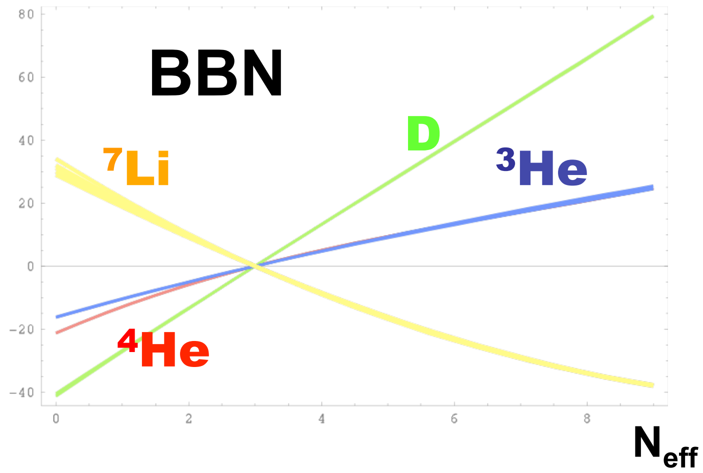
More details in: AGC, M.Messina and G.Mangano Phys. Rev. D79(2009)053009

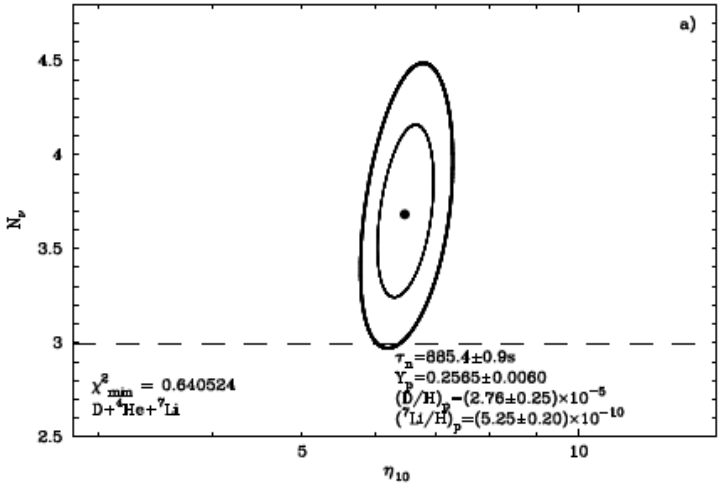
Question: “Is it possible to detect/measure the CνB ?”

Short answer: In the most favourable scenario it depends
on the value of m_ν and
on the experimental energy resolution Δ

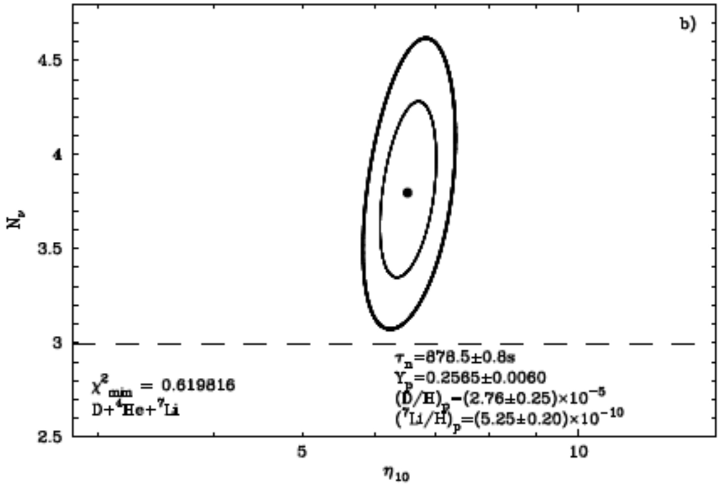
BBN constraints on the number of ν families

The number of relativistic degrees of freedom affects Universe expansion rate in the radiation dominated phase





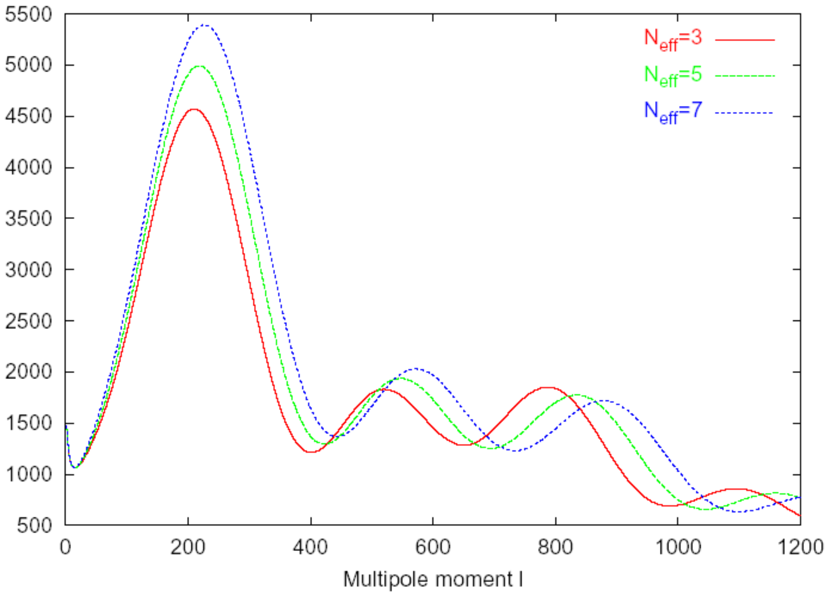
$$N_\nu = 3.68^{+0.80}_{-0.70}$$



$$N_\nu = 3.80^{+0.80}_{-0.70}$$

CMB constraints on the number of ν families

The number of degrees of freedom at radiation-matter decoupling time affects CMB lineshape



N_{eff} = 4.34 + 0.86 – 0.88 (“WMAP 7” arxiv:1001.4538v3)

Conclusions

The fact that neutrino has a nonzero mass has renewed the interest on Netrino Capture on $\beta^{\pm}$ and EC decaying nuclei as a tool to measure very low energy neutrino

A detailed study of NCB cross section has been performed for a large sample of known beta decays avoiding the uncertainties due to nuclear matrix elements evaluation

The relatively high NCB cross section when considered in favourable scenarios could bring cosmological relic neutrino detection within reach in a few years

NCB as a tool to investigate Dark Matter sterile neutrino hypothesis

Thank you

exploiting $m_\nu \neq 0$

Antineutrino capture on EC decaying nuclei

reaction (a)

Electron Capture

$e^- + (A,Z) \rightarrow (A,Z\text{-}1) + \nu_e + n\,\gamma$

$E_\nu = Q_{EC} - E_K$
$E_\gamma = E_K$

E_K = captured electron binding energy

$\bar{\nu}_e + e^- + (A,Z) \rightarrow (A,Z\text{-}1) + X$

Always energetically allowed

IF: $E_K - m_\nu \leq Q_{EC} < E_K + m_\nu$

(in the limit $E_\nu \rightarrow m_\nu$)

the EC decay is forbidden (no background)

exploiting $m_\nu \neq 0$

Antineutrino capture on EC decaying nuclei

reaction (b)

Electron Capture

$e^- + (A,Z) \rightarrow (A,Z\text{-}1) + \nu_e + n\,\gamma$

$E_\nu = Q_{EC} - E_K$

$E_\gamma = E_K$

E_K = captured electron binding energy

$\bar{\nu}_e + (A,Z) \rightarrow (A,Z\text{-}1) + e^+$

$E_{thr} = 2m_e - Q_{EC}$

But, in case $2m_e - m_\nu \leq Q_{EC} < 2m_e + m_\nu$

no threshold and the β^+ decay is forbidden (no background)

The longstanding question

Is it possible to detect/measure the Cosmological Relic Neutrino background (CνB) ?

The answer is: no

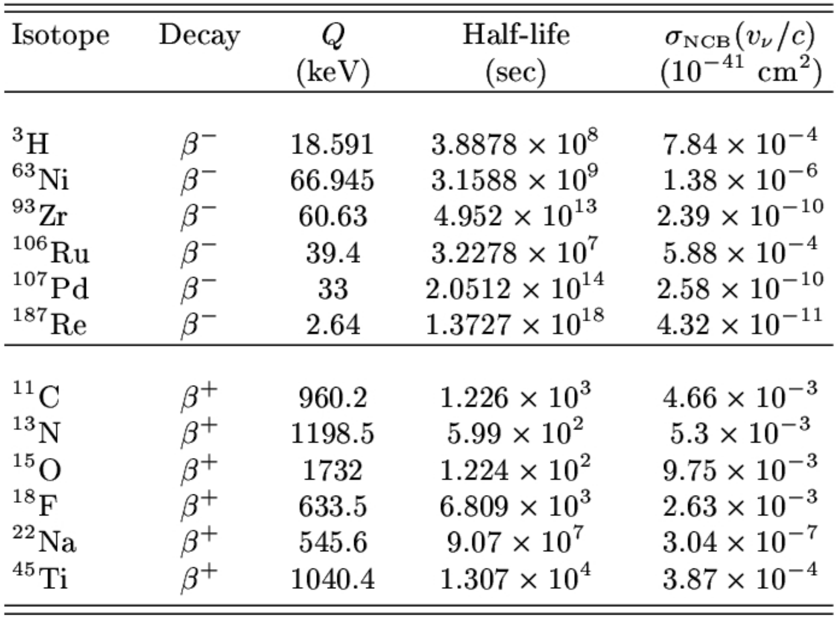
All the methods proposed so far require either strong theoretical assumptions or experimental apparatus having unrealistic performances

A.Ringwald "Neutrino Telescopes" 2005 – hep-ph/0505024
G.Gelmini hep-ph/0412305

NCB Cross Section Evaluation

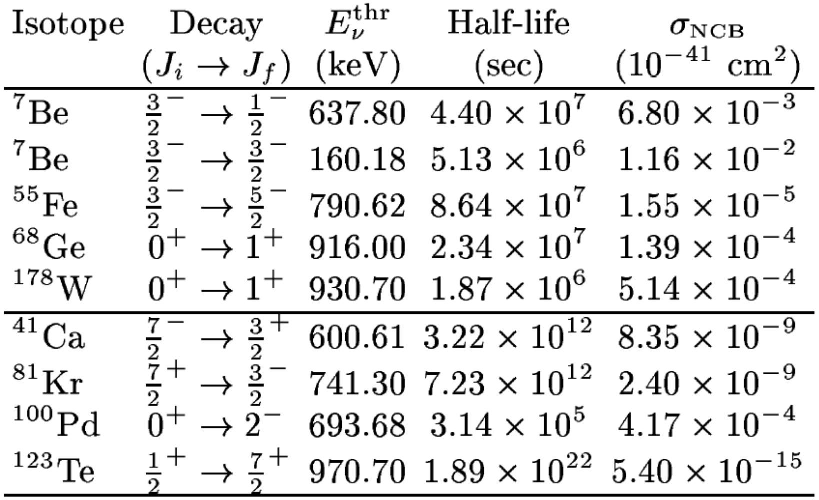
specific cases

$\beta^{\pm}$



Isotope	Decay	Q (keV)	Half-life (sec)	$\sigma_{\mathrm{NCB}}(v_\nu/c)$ (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}

EC



Isotope	Decay ($J_i \to J_f$)	E_ν^{thr} (keV)	Half-life (sec)	σ_{NCB} (10^{-41} cm^2)
^{7}Be	$\frac{3}{2}^- \to \frac{1}{2}^-$	637.80	4.40×10^7	6.80×10^{-3}
^{7}Be	$\frac{3}{2}^- \to \frac{3}{2}^-$	160.18	5.13×10^6	1.16×10^{-2}
^{55}Fe	$\frac{3}{2}^- \to \frac{5}{2}^-$	790.62	8.64×10^7	1.55×10^{-5}
^{68}Ge	$0^+ \to 1^+$	916.00	2.34×10^7	1.39×10^{-4}
^{178}W	$0^+ \to 1^+$	930.70	1.87×10^6	5.14×10^{-4}
^{41}Ca	$\frac{7}{2}^- \to \frac{3}{2}^+$	600.61	3.22×10^{12}	8.35×10^{-9}
^{81}Kr	$\frac{7}{2}^+ \to \frac{3}{2}^-$	741.30	7.23×10^{12}	2.40×10^{-9}
^{100}Pd	$0^+ \to 2^-$	693.68	3.14×10^5	4.17×10^{-4}
^{123}Te	$\frac{1}{2}^+ \to \frac{7}{2}^+$	970.70	1.89×10^{22}	5.40×10^{-15}

$E_\nu = E_{thr}$ + 1 MeV
K capture

Nuclei having the highest product

$\sigma_{\mathrm{NCB}}\, t_{1/2}$

Detection: G_F

Stodolsky effect: energy split of electron spin states in the ν background

requires ν chemical potential (Dirac) or net helicity (Majorana)

requires breaking of isotropy (Earth velocity)

results depend on Dirac/Majorana,relativistic/non relativistic, clustered/unclustered

Duda et al ‘01

$$\Delta E \approx G_F g_A \vec{s} \cdot \vec{\beta}_{\oplus} (n_\nu - \overline{n}_\nu)$$

Torque on frozen magnetized macroscopic piece of material of dimension R

$$\mathbf{a} \approx 10^{-27} \left(\frac{100}{\mathrm{A}}\right)\left(\frac{\mathrm{cm}}{\mathrm{R}}\right)\left(\frac{\beta_{\oplus}}{10^{-3}}\right)\left(\frac{n_\nu - \overline{n}_\nu}{100\,\mathrm{cm}^{-3}}\right)\mathrm{cm\,s}^{-2}$$

Presently Cavendish torsion balances: $\mathbf{a} \approx 10^{-12}\,\mathrm{cm\,s}^{-2}$

Detection: G_F^2

ν-Nucleus collision: net momentum transfer due to Earth peculiar motion

$$\sigma_{\nu N} = G_F^2 E_\nu^2$$

$$a = n_\nu v_\nu \frac{N_A}{A} \sigma_{\nu N} \Delta p$$

$$\Delta p = \beta_\oplus E_\nu$$

$$\Delta p = \beta_\oplus m_\nu$$

$$\Delta p = \beta_\oplus T_\nu$$

$$\Rightarrow \quad \mathbf{a \approx (10^{-46} - 10^{-54}) \frac{A}{100}\, cm\ s^{-2}}$$

Coherence enhancement

$$\lambda_\nu \approx 1/T_\nu \quad - \quad 1/\mathrm{m}_\nu \approx mm$$

$$N_c = \frac{N_A}{A} \rho \lambda_\nu^3$$

Zeldovich and Khlopov ’81

Smith and Lewin ‘83

Quantum limit