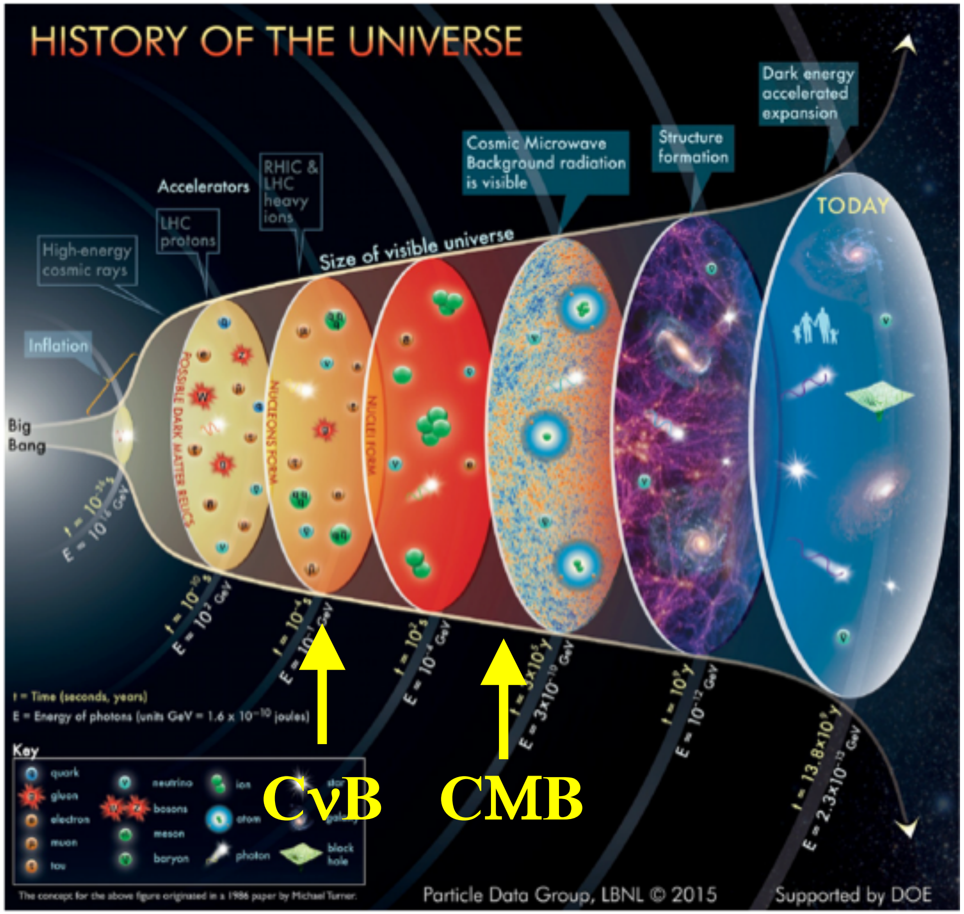
Detection of CνB

1



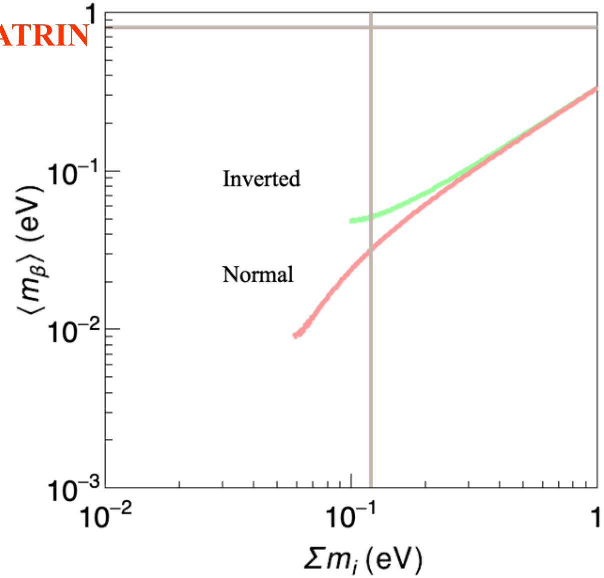
“Darkness on the Table”

Yeongduk Kim, CUP, IBS

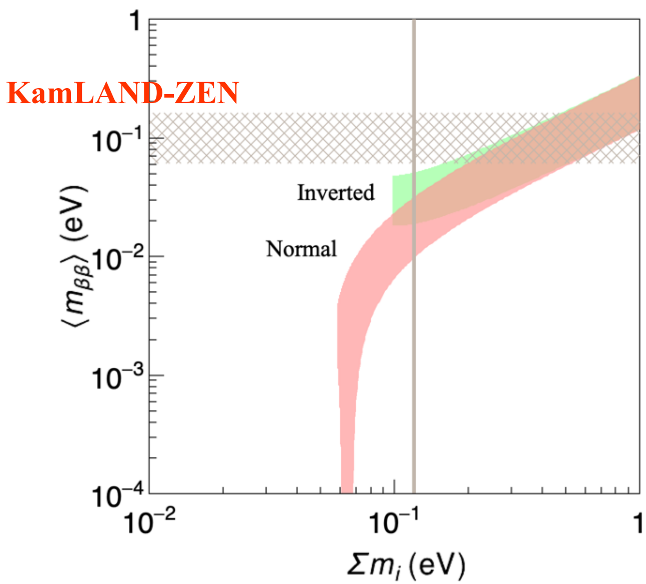
Neutrino mass

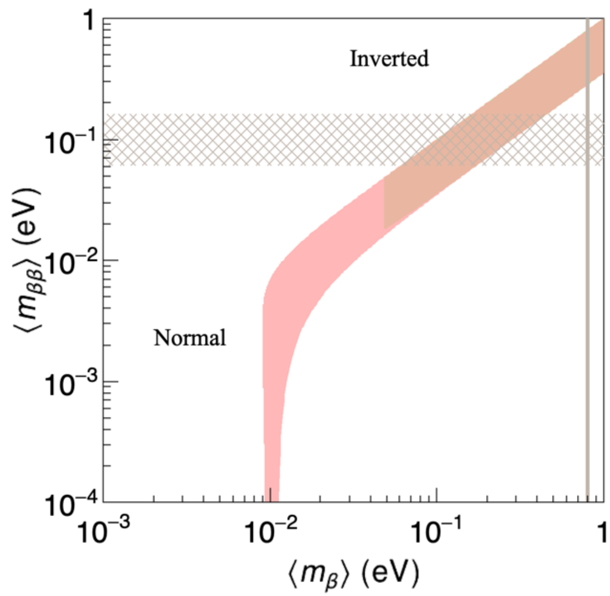
PLANCK

KATRIN



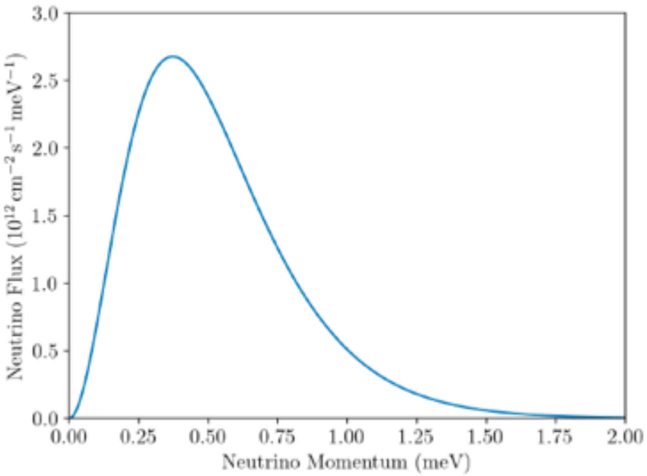
- Neutrino mass is ultra small, and we don’t understand its origin.
- Neutrino mass is constrained by beta decays and cosmology.
- Cosmological measurements may soon give finite neutrino mass.





CνB properties

$$\sum_i \rho_{\nu_i} = N_{eff}\left[\frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\rho_\gamma\right]$$



Number density $n_\nu = 56/cm^3$

We expect overdensity in our galaxy, $\leq 10^4$

Dark Matter density ~0.4GeV/cm^3 >> Neutrino density

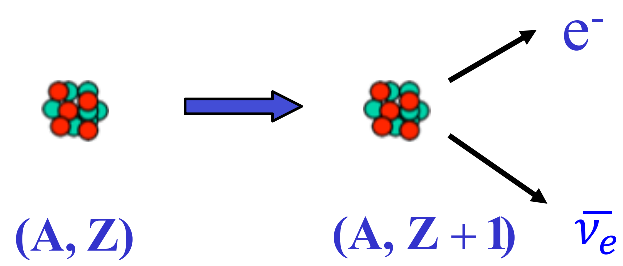
Extremely difficult to detect CνB.

Ringwald & Wong, JCAP 0412, 005 (2004)

Neutrino capture on β decaying nuclei

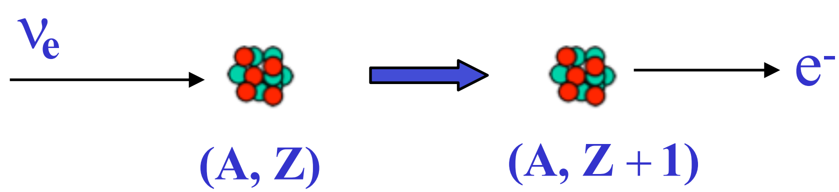
Known

Nuclear Beta decay



Possible

Neutrino Capture on a Beta Decaying Nucleus (NCB)



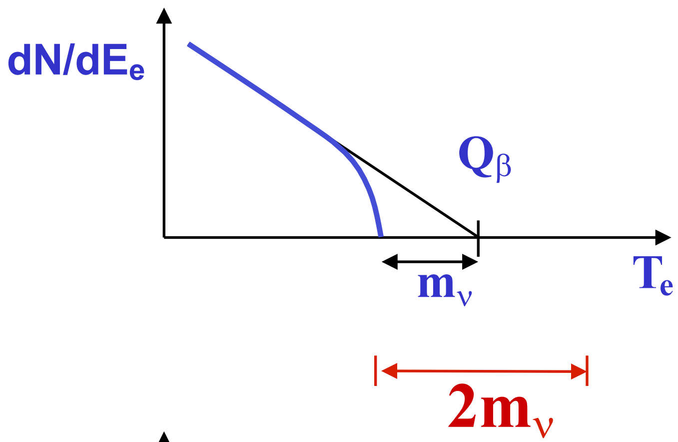
This process has no energy threshold !
Cross section is non vanishing !
e^- in final state has fixed energy (2 body decay) !

Direct detection IS possible !!

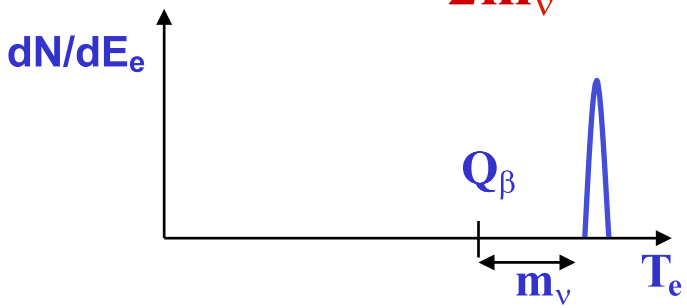
A.G.Cocco, G.Mangano and M.Messina JCAP 06(2007)015

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

Nuclear Beta decay



Neutrino Capture on a Beta Decaying Nucleus



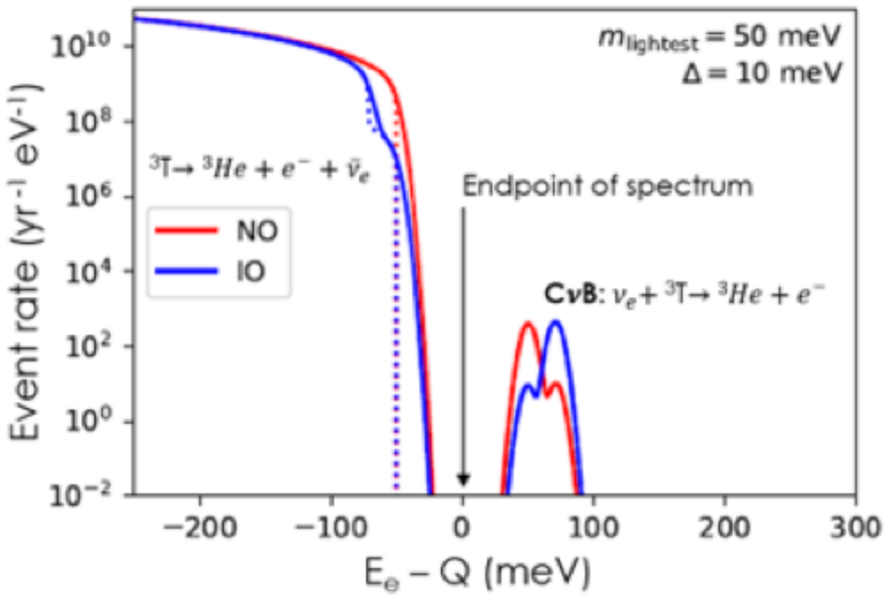
The events induced by Neutrino Capture have a unique signature: there is a gap of $2m_\nu$ (centered at Q_β) between "signal" and "background"

As s "side result": measurement of the neutrino mass !

PTOLEMY

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

- High cross section (~10^{-44} cm^2)
- Sizeable lifetime ($T_{1/2}$ = 12 y)
- Low Q value (18.6 keV)
- Nuclear and atomic physics effects can be evaluated analytically

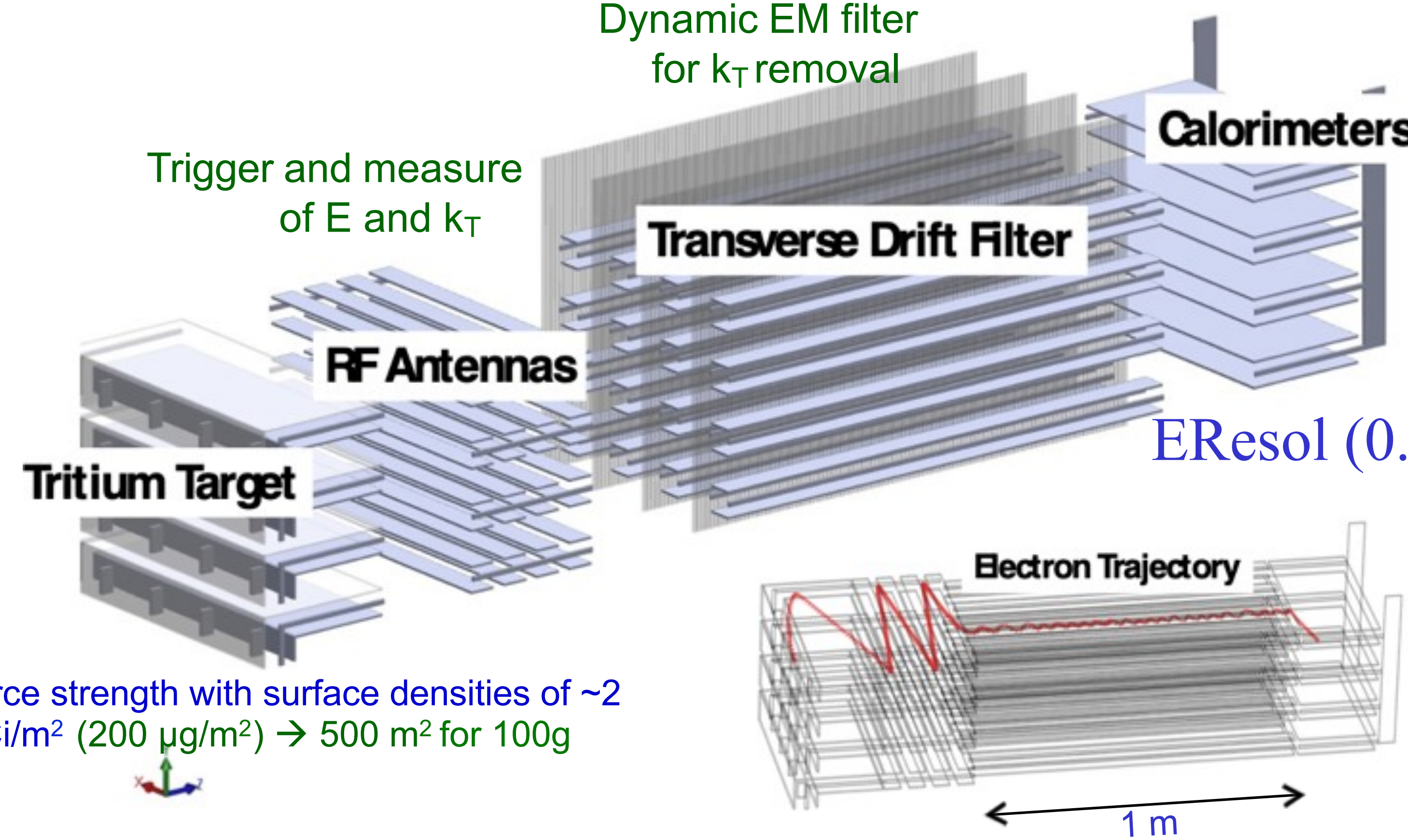


100 g T source + EM filter + RF tagging + sub-eV resolution calorimeter

→ 7 capture events per year

PTOLEMY Collaboration M.G.Betti et al., JCAP 07(2019)047

PTOLEMY prototype layout



EResol (0.05 eV)

Source strength with surface densities of ~2 Ci/m^2 (200 μg/m^2) → 500 m^2 for 100g

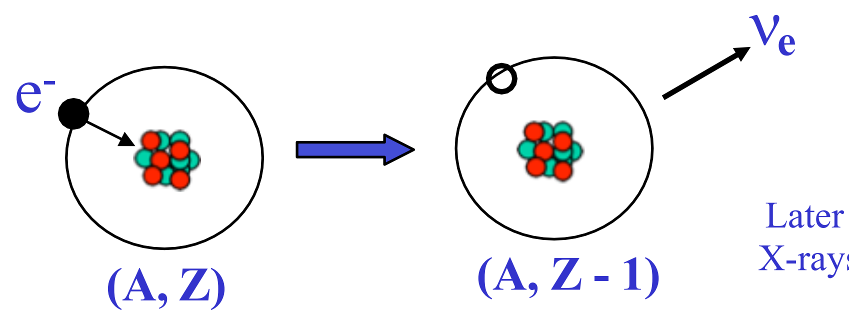
Static electric and magnetic fields are used

$$\boxed{E_{tot} = q(V_{cal} - V_{source}) + E_{cal}}$$

CνB detection w/ EC decaying nuclei

Known

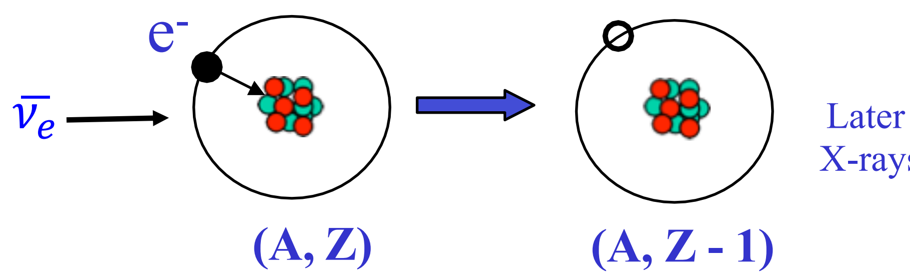
Electron Capture



Possible

Simultaneous ν and electron Capture

Resonant process



This process has no energy threshold !

A.G.Cocco, G.Mangano and M.Messina Phys. Rev. D79 (2009) 053009

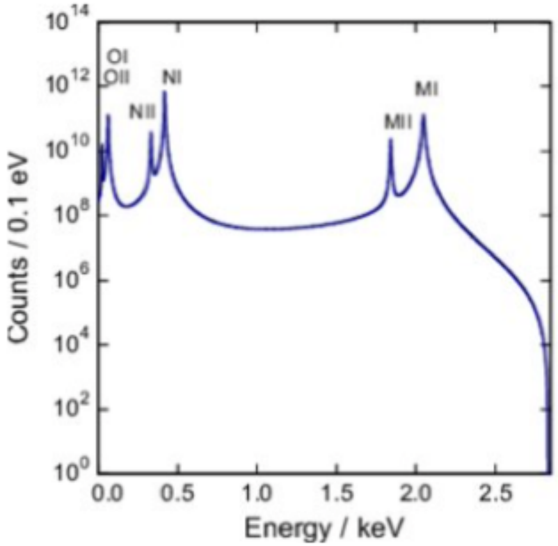
- Lusignoli & Vignati, "Lusignoli"
  'Relic $\bar{\nu}$ capture on ^{163}Ho decaying nuclei'
  [PLB 697, 11 (2011) & PLB 701, 673 (2011) (E)]

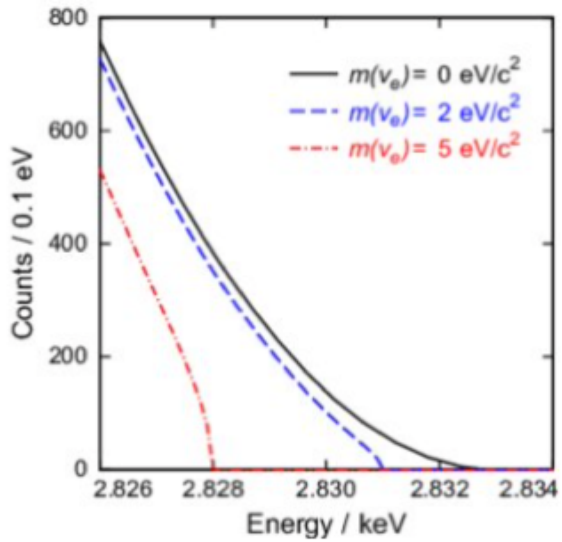
- Vergados et al.,
  'Prospects of detection of relic antineutrinos by resonant absorption in electron capturing nuclei.' [J. Phys. G. Phys. 41 (2014)]

- Jeong-Yeon Lee, Satoshi Chiba, Yeongduk Kim. "Lee"
  "New targets for relic antineutrino capture", arXiv:1811.05183

^{163}Ho EC spectra vs neutrino mass

"Lusignoli"





$$\frac{d\lambda_{EC}}{dE_c} = \frac{G_\beta^2}{4\pi^2}(Q - E_c)\sqrt{(Q - E_c)^2 - m_\nu^2} \times \sum_i n_i C_i \beta_i^2 B_i \frac{\Gamma_i}{2\pi} \frac{1}{(E_c - E_i)^2 + \Gamma_i^2/4}.$$

The neutrino mass in fact affects the capture rates from different levels, and it modifies the spectra of inner bremsstrahlung photons and emitted electrons near to their endpoints.

$$S = \frac{\lambda_{\bar{\nu}}}{\lambda_{EC}} \frac{\log 2}{T_{1/2}} N_A n_{\mathrm{mol}} t,$$

# of signals at the end point

Need energy resolution < 0.5 eV

Reaction rates of $\bar{\nu}$ induced EC capture

"Lusignoli"

$$\frac{\lambda_{\bar{\nu}}}{\lambda_{EC}} \cong 2\pi^2 n_{\bar{\nu}} \frac{\sum_i n_i \beta_i^2 B_i \rho_i(E_{\bar{\nu}})}{\sum_i n_i \beta_i^2 B_i (Q - E_i)^2}$$

$n_{\bar{\nu}}$: # density of incoming $\bar{\nu}$
n_i : fraction of occupancy of i-th atomic shell
β_i : Coulomb amplitude of electron radial wave function
B_i : atomic correction for electron exchange and overlap (~1)
$\rho_i(E_{\bar{\nu}})$: density of final state per energy.

Q-value	2.2 keV	2.5 keV	2.8 keV	2.833 keV
$\lambda_{\bar{\nu}}/\lambda_{EC}$	7.6×10^{-22}	5.8×10^{-23}	1.4×10^{-23}	1.2×10^{-23}

For 10 events, a minimum quantity of ^{163}Ho of (23.2, 307, 1274) kg y for Q = (2.3, 2.5, 2.8) keV. Q=2.833 keV ! Too large mass is required.

Closer to the resonant condition.

- Search resonant states including nuclear excited states.
- For all s state electron levels.
- Q_{EC}<60 keV

"Lee"

$$Q'_{EC} = \Delta m_{(Z)} - \Delta m_{(Z-1)}{}^{*'}$$ → How close to the resonant condition

(' : atomic excitation, *: nuclear excitation)

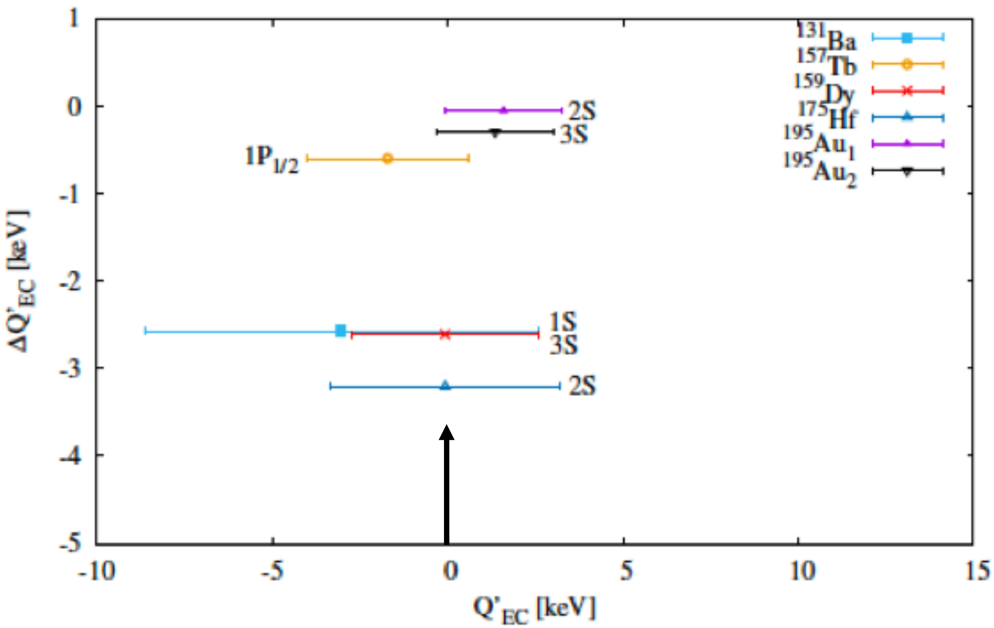
$$dQ'_{EC} = \sqrt{\Delta m_{(Z)}^2 + \Delta m_{(Z-1)}^2}$$ → Uncertainty of the Q value

$$\Delta Q'_{EC} = |Q'_{EC}| - dQ'_{EC}$$ → How close to the resonant condition

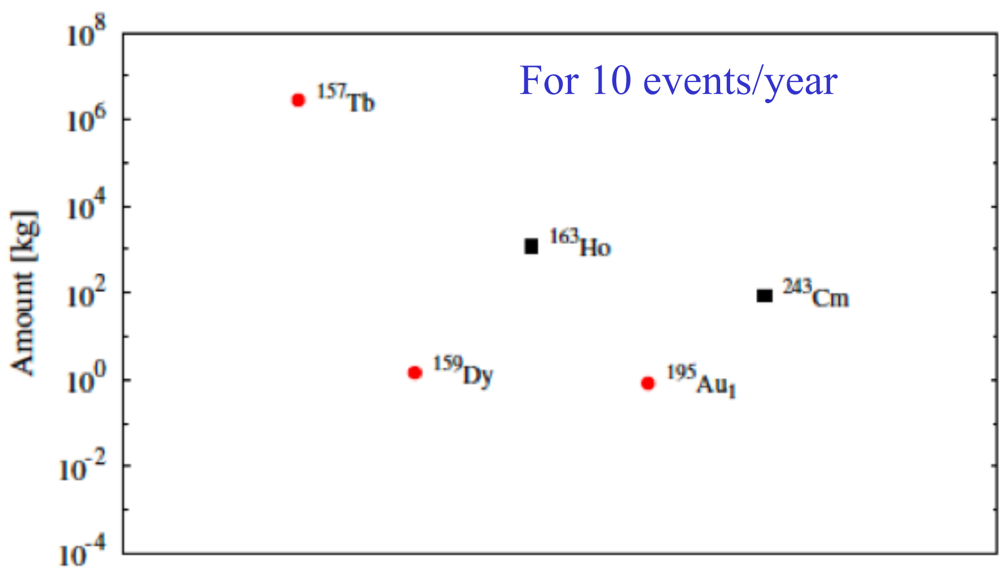
Conditions: $T_{1/2}$ >10 days,

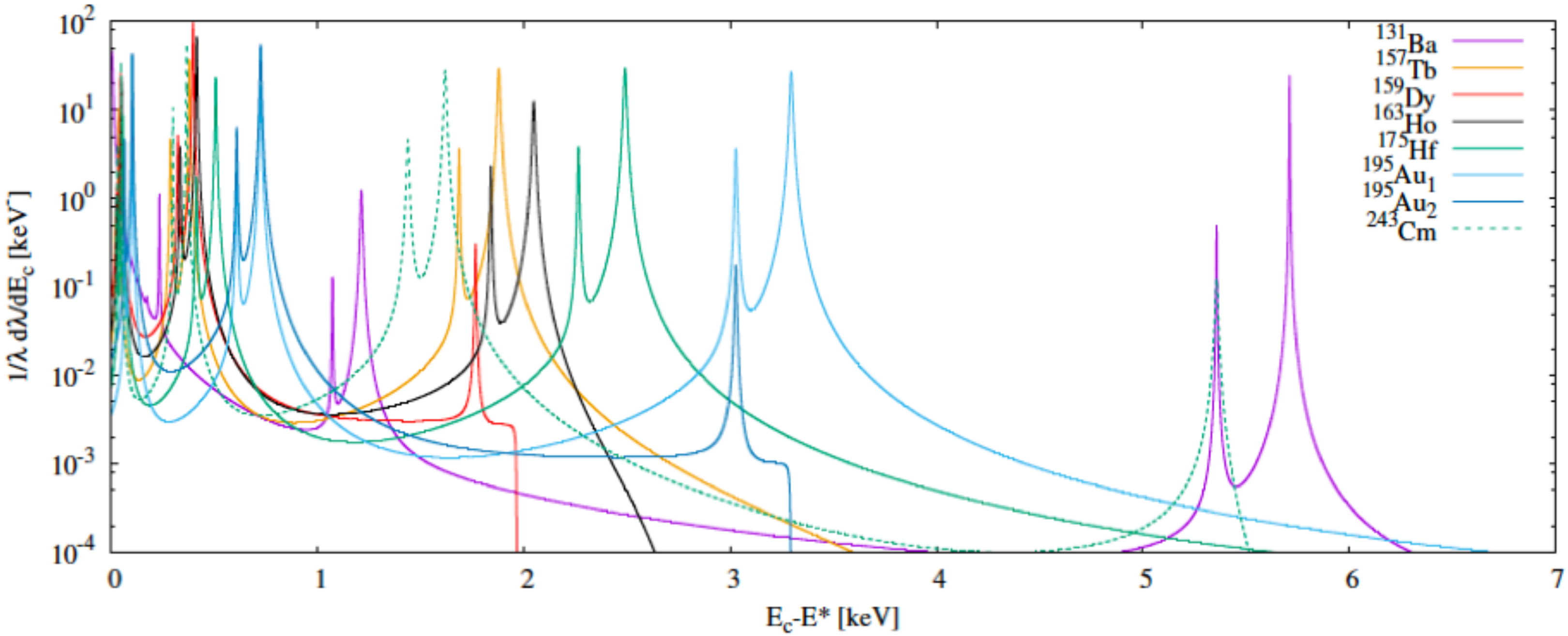
Q'_{EC}<10 keV, dQ'_{EC}<10 keV, $\Delta Q'_{EC}$<10 keV

Results



A few candidates are found.
But, still the best candidates need ~ kg for 10 events/year

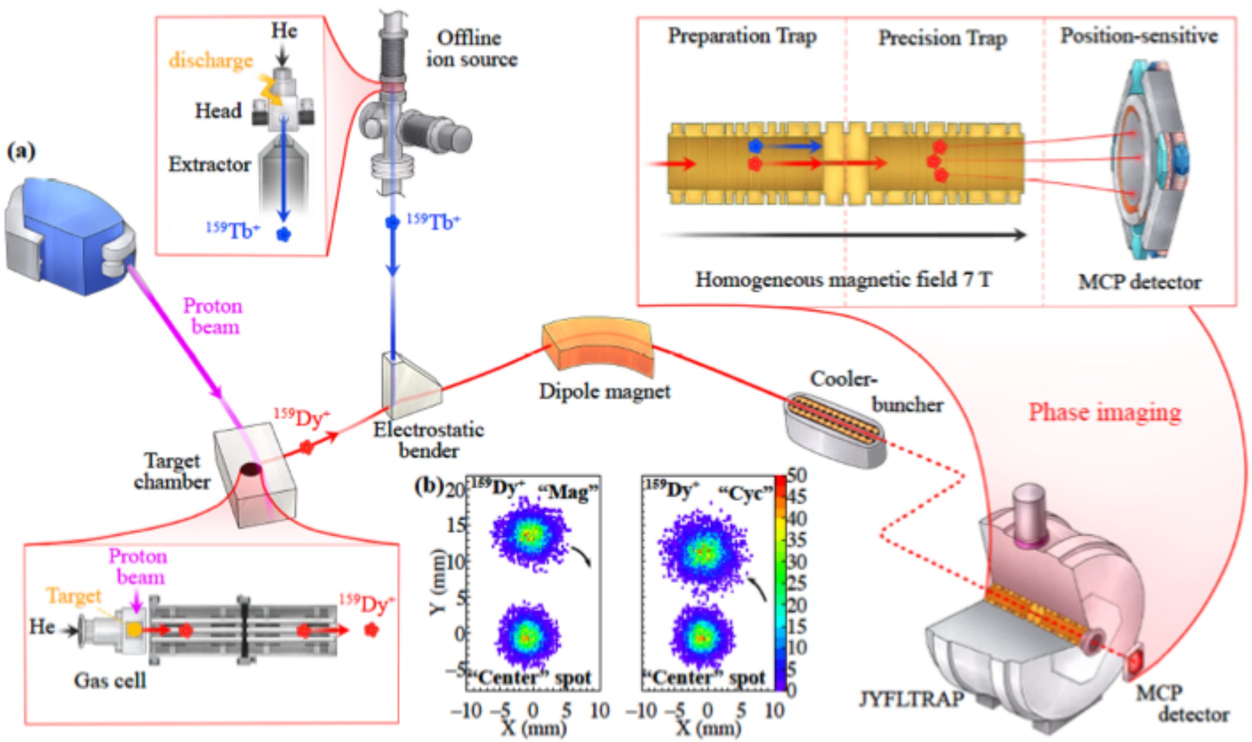


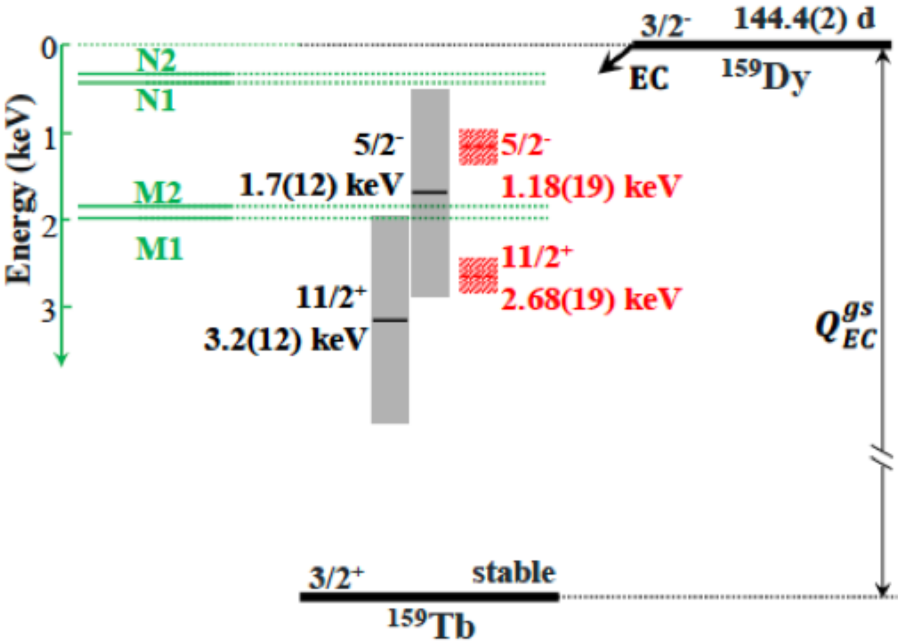

10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$1/\lambda\ d\lambda/dE_c$ [keV^{-1}]
0
1
2
3
4
5
6
7
E_c-E^* [keV]
^{131}Ba
^{157}Tb
^{159}Dy
^{163}Ho
^{175}Hf
^{195}Au$_1$
^{195}Au$_2$
^{243}Cm

New mass measurements

"^{159}Dy electron-capture: a strong new candidate for neutrino mass determination", Z. Ge et al., arXiv:2106.06626

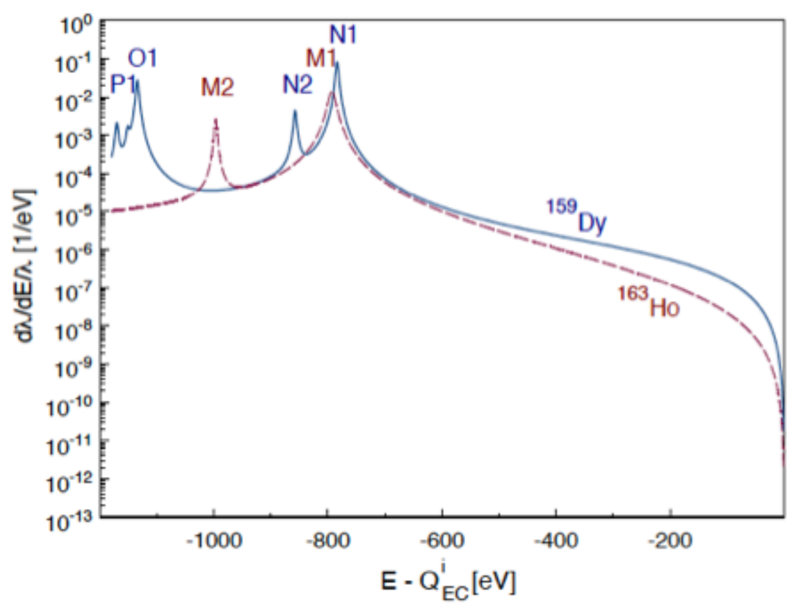
^{159}Dy is measured with Penning Trap since it could have ~ 0 Q value.





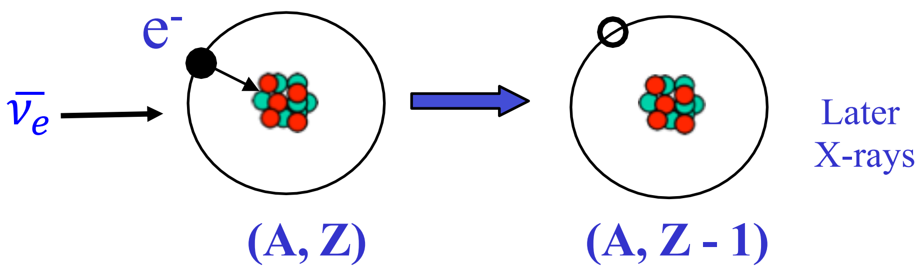
- smallest Q-value of any known electron capture, 1.18(19) keV
- 0.47 keV smaller than previous Q value.

Much more events @ end points.

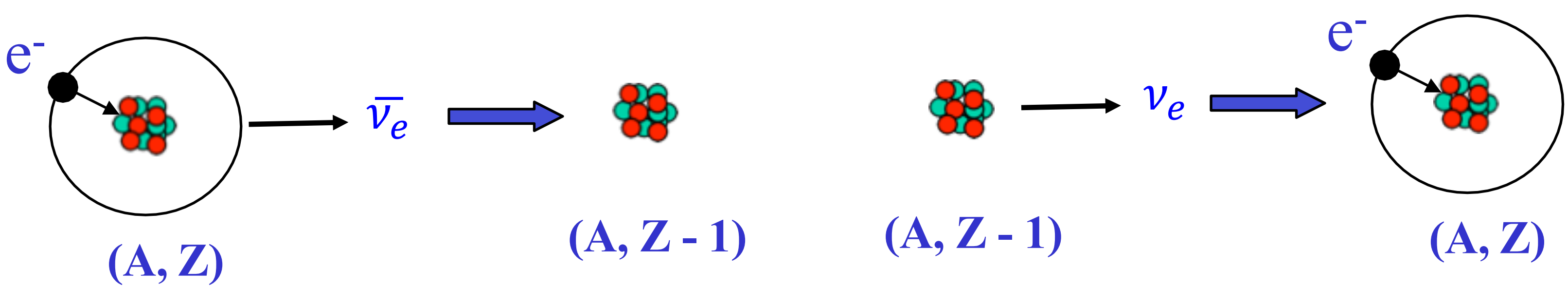


CνB w/ accelerator

"Observing relic neutrinos with an accelerator experiment", Martin Bauer et al. arXiv:2104.12784



Accelerate Hydrogen-like ion(left) or fully stripped ion to the resonant velocity.



Neutrino induced electron capture

Bound-state beta decay

Unlikely to stationary target, there is no decay without neutrino absorption, since it needs threshold energy. → In principle, no background.

Candidates

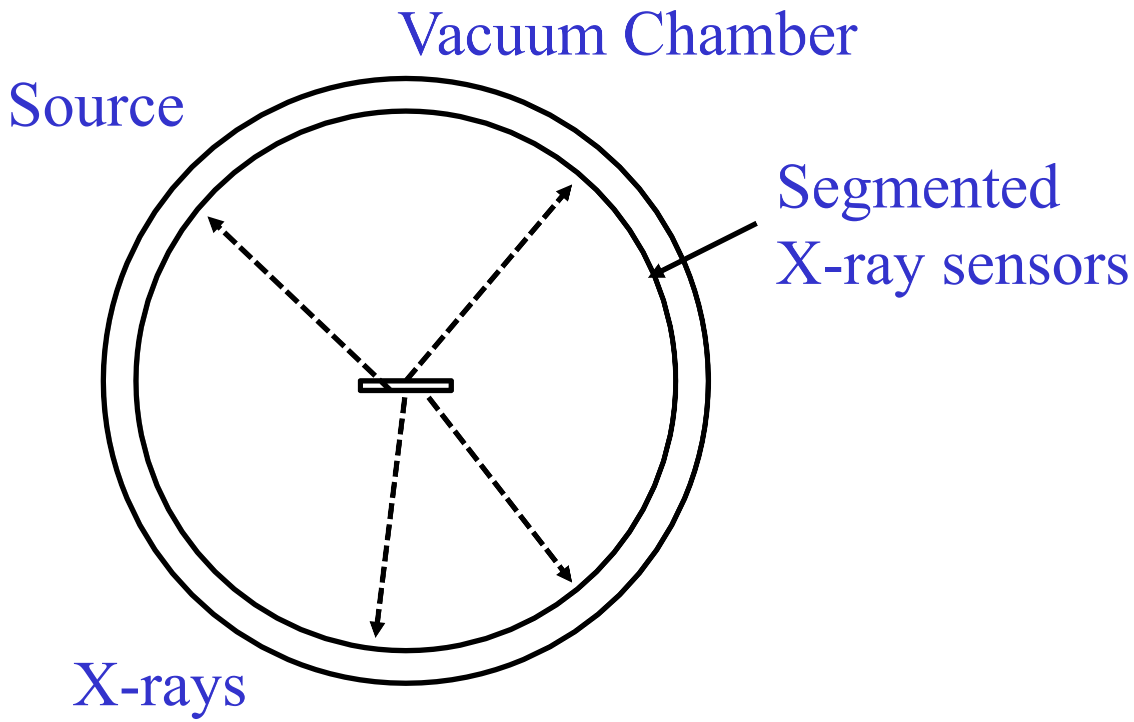
System	$Q\,(\mathrm{keV})$	$E/A\,(\mathrm{TeV})$	$\mathcal{B}_{DP}$ / $\mathcal{B}_{DF}$	$x\,(t=1\,\mathrm{y})$	$N_D(x)/N_0$ / $N_F(x)/N_0$
${}^{193}\mathrm{Ir} \xrightarrow{\mathrm{RB}\beta} {}^{193}\mathrm{Pt}$	5.55	51.69	1	$2.50 \cdot 10^{-7}$	$2.36 \cdot 10^{-23}$
${}^{3}\mathrm{He} \xrightarrow{\mathrm{REC}} {}^{3}\mathrm{H}$	18.58	174.00	0.031	$3.03 \cdot 10^{-7}$	$1.58 \cdot 10^{-25}$

- The required energies for the resonance are too high.
- Yet, the production is too small.
- Need to look at other alternatives.
- Atomic mass accuracy ~ 10 eV at best, yet the total binding energy for fully stripping has error of ~ 100 eV.

Summary

- Neutrino is one of the best too for BSM physics.
- Cosmological neutrino mass may be determined in near future.
- Resonant reaction is studied for direct CnB detection, yet shows no strong candidate. There are rooms to be explore yet.
- PTOLEMY has a definite plan with much improvements, yet a lot of technical questions.

Experimental Realization



This configuration has an advantage that we can have a strong source. Bend all the electrons from the source by magnet. Only photons(x-rays) are emitted from the source and