KATRIN: A next generation neutrino mass experiment

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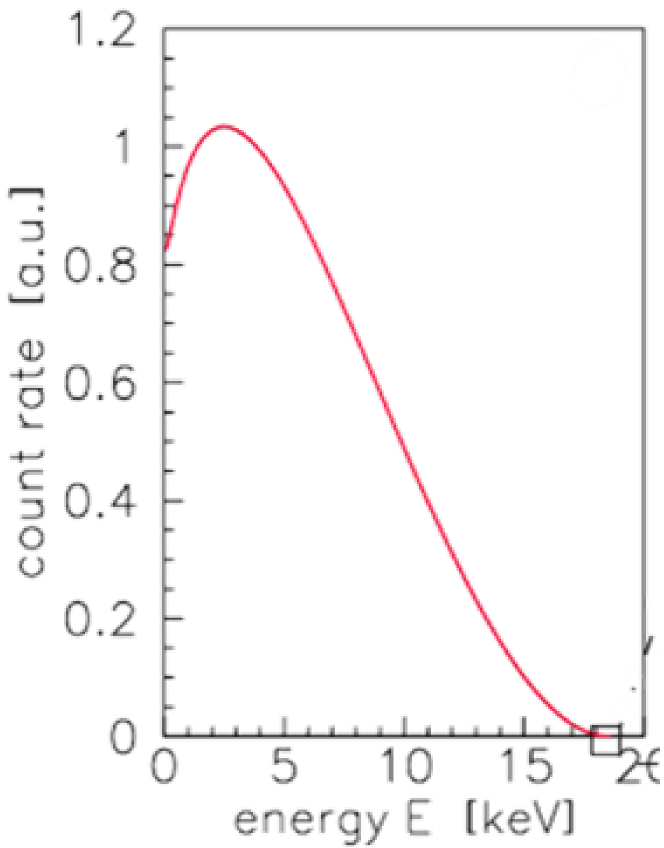
Outline

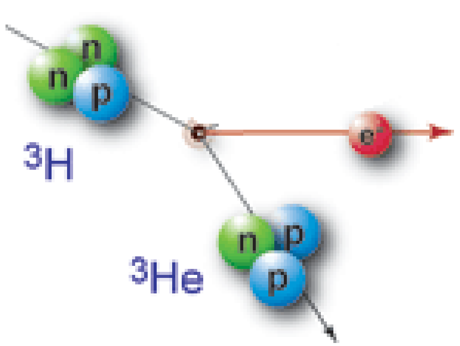
- What is a neutrino and why is its mass interesting?
- What techniques can measure neutrino mass?
- Overview of the KATRIN tritium β-decay experiment
  - Principle of MAC-E filter
- Detector region design
  - Backgrounds simulations for KATRIN

1930: Missing Energy

Nuclear ß-decay:

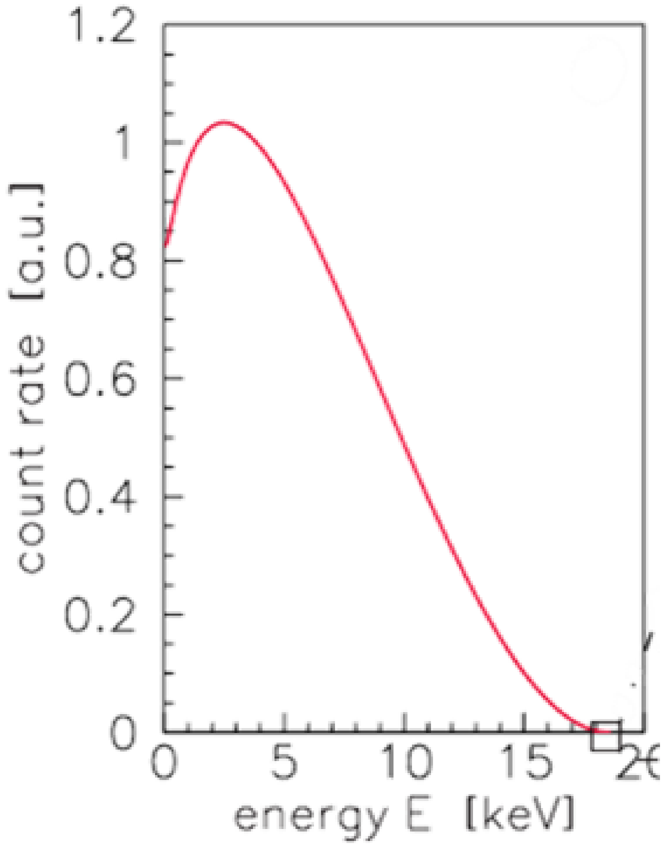


- Two particles observed in the final state
- Energy and momentum appear to not be conserved



The Neutrino Postulated

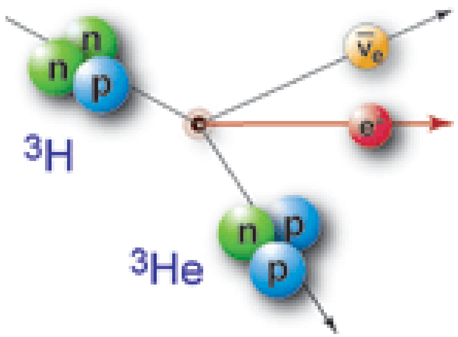
Nuclear ß-decay:



Pauli postulates a third particle is emitted

- Electrically neutral
- Light: $m_\nu << M_p$
- Spin 1/2

$$^{A}_{Z}X \rightarrow ^{A}_{Z+1}X' + e^- + \bar{\nu}_e$$

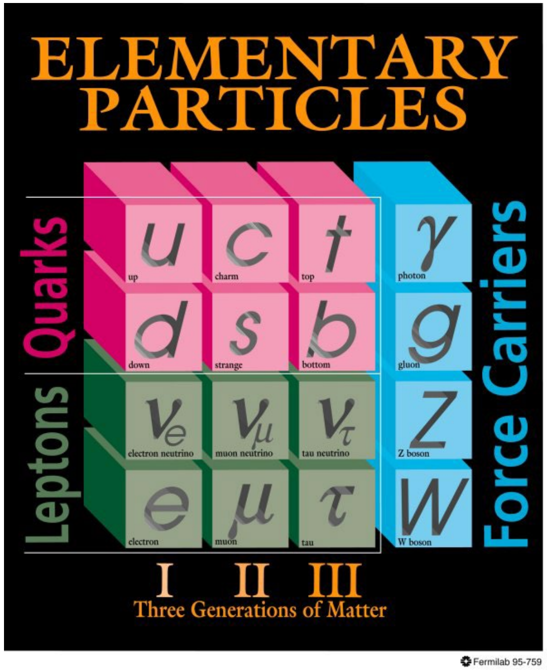


Standard Model of Particle Physics

- Three flavors of neutrinos interact via the weak interaction mediated by $W^{\pm}$ and Z^0
- Interaction projects out left-handed particle states to violate parity maximally

$$\bar{\psi}\gamma^{\mu}(1-\gamma^5)\psi$$

- In SM neutrinos are only left-handed and massless!



However...

Solar and atmospheric neutrino experiments observe flavor oscillations

If neutrinos have different mass and flavor eigenstates

$$|\nu_l\rangle = U_{lj}|\nu_j\rangle$$

(like CKM) then neutrinos can oscillate to other flavors

$$P(\nu_e \rightarrow \nu_\mu) = sin^2 2\theta sin^2(\frac{\pi L \Delta m^2}{2.5 E_\nu})$$

$$\Delta m^2 = m_1^2 - m_2^2$$

Oscillations show neutrinos are not massless!

But cannot measure the absolute mass scale

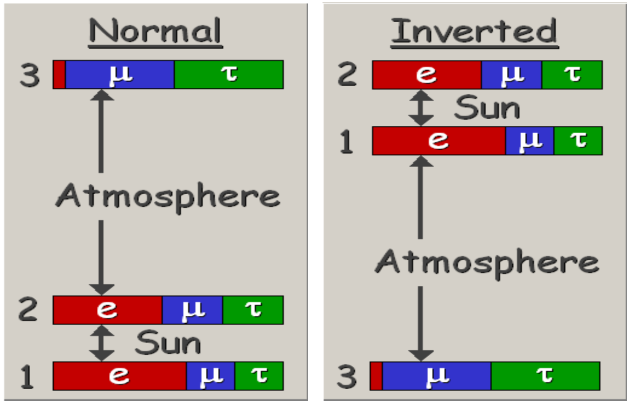


Figure from Scott Dodelson

Why is neutrino mass important?

- Particle Physics:
  - Neutrino mass is much smaller than other fermion masses
  - Neutrinos are uncharged and have the possibility to be their own antiparticle
  - Do neutrinos acquire mass differently than other particles?
  - New physics?

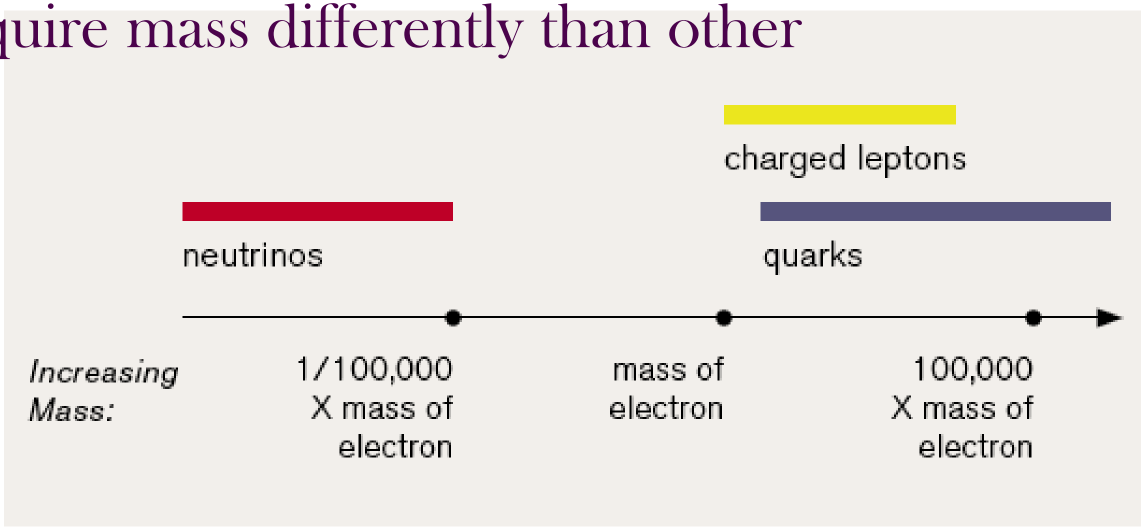


Figure from APS “Neutrino Matrix”

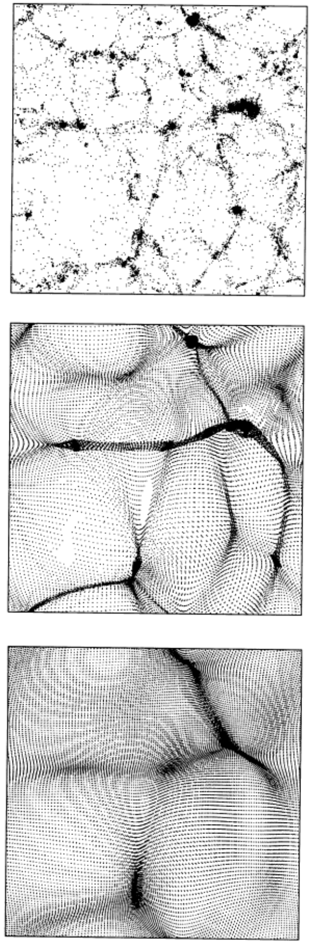
Why is neutrino mass important?

- Cosmology
  - 10^9 more neutrinos than baryons in the universe
  - Large Scale Structure
  - Leptogenesis
    - Might be able to explain the abundance of matter over antimatter in the universe
  - Supernovae

Cold Dark Matter
(no neutrino mass)

Hot + Cold Dark Matter
(non-zero neutrino mass)

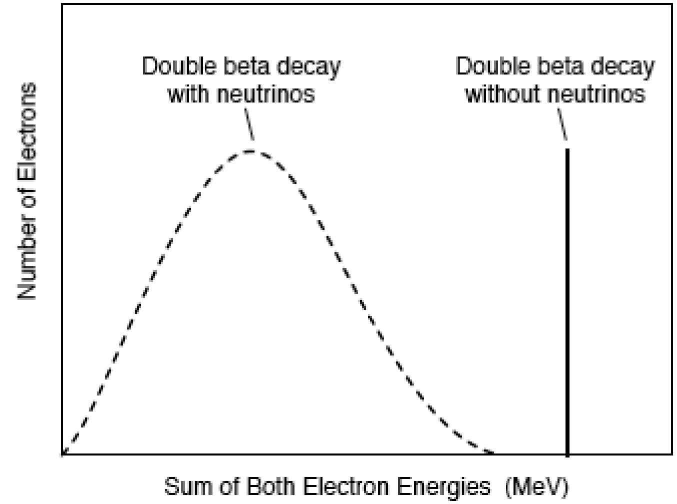
Matter distribution in the universe

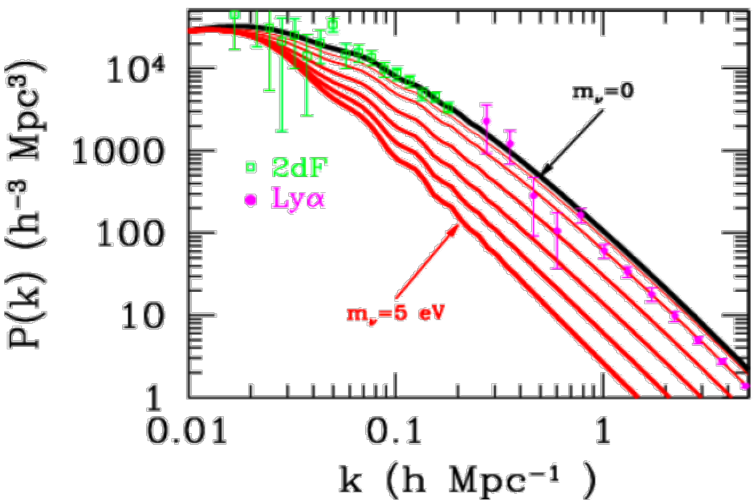


Colombi, Dodelson, & Widrow 1995

Measuring Neutrino Mass

- Cosmology:
  - Massive neutrinos suppress matter power spectrum at small scales
  - Model dependent





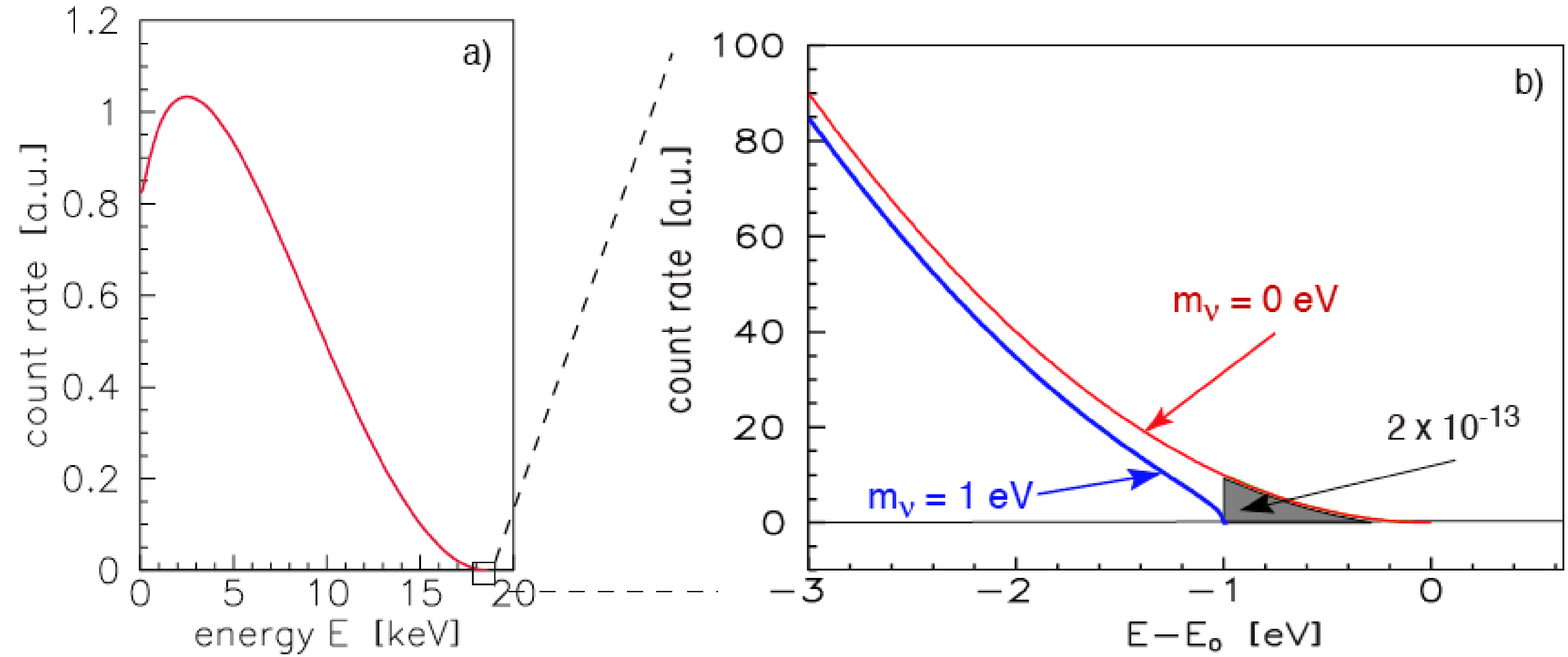
More clumpy

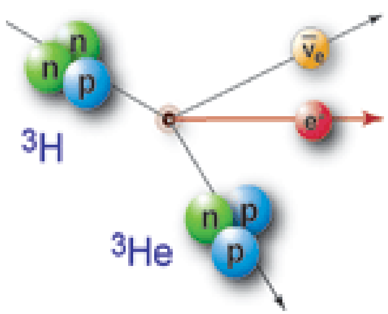
Smaller scales

Figure from Scott Dodelson

- Neutrinoless Double Beta Decay:
  - If neutrinos are Majorana particles
  - Rate depends on effective mass and nuclear matrix element
  - Model dependent

Measuring Neutrino Mass: Beta Decay





Neutrinos with mass modify the shape of the electron’s energy spectrum near the endpoint (18.6 keV)

Beta Decay

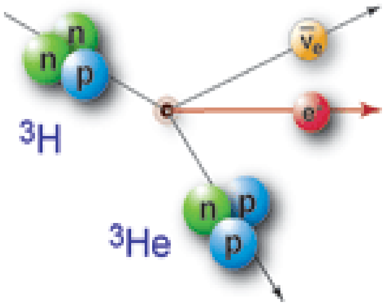
Electron's energy spectrum:

$$\frac{dN}{dE_e} = CF(Z, E_e)p_e(E_e + m_e c^2)(E_0 - E_e)\sum_j |U_{ej}|^2[(E_0 - E_e)^2 - m_{\nu_j}^2]^{1/2}$$

$$C = \frac{1}{2\pi^3 c^4 \hbar^7} G_F^2 cos^2\Theta_C |M_{fi}|^2$$

For degenerate neutrino mass region (3 flavors) measure an effective mass:

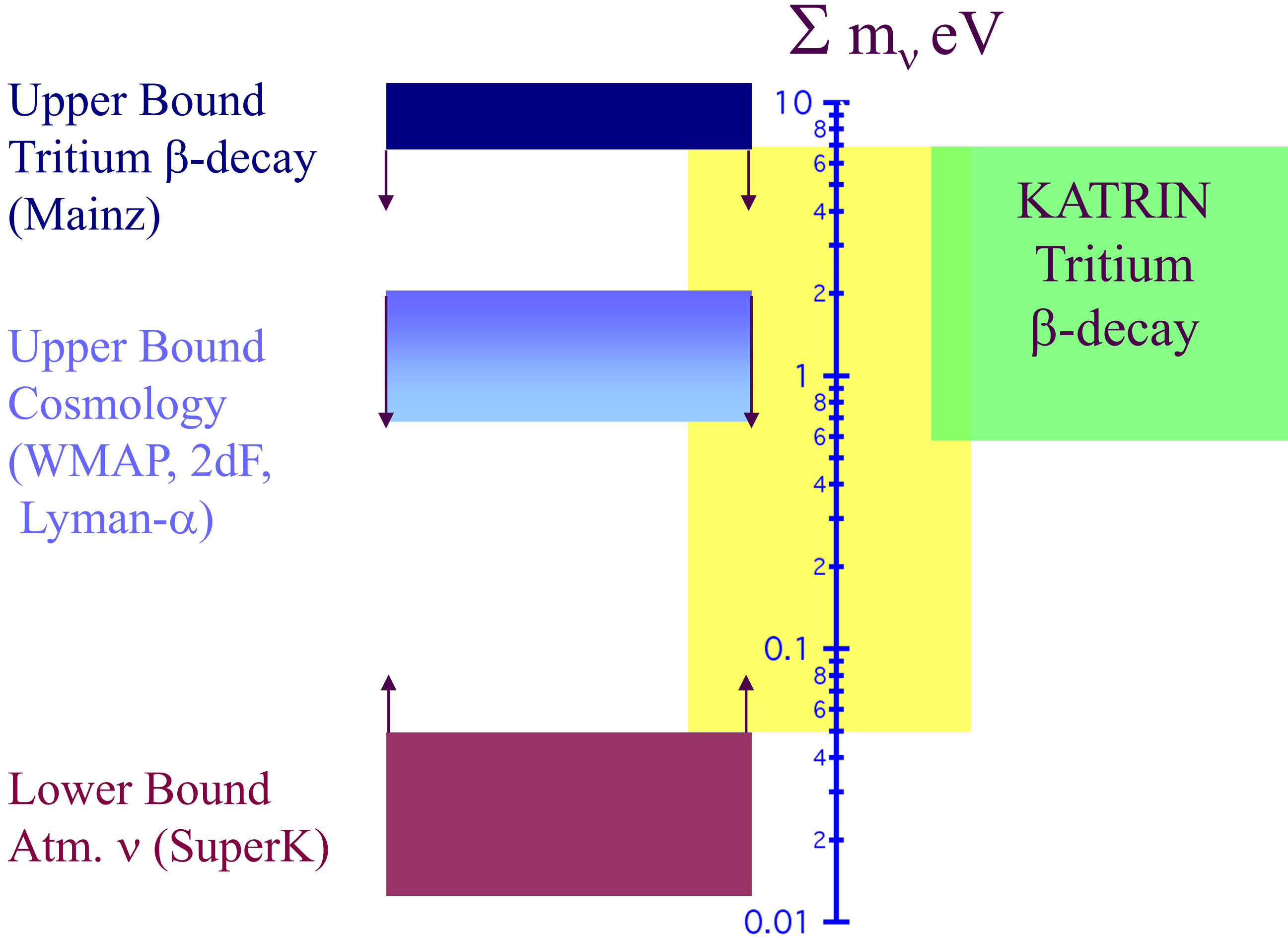
$$\langle m(\nu_e)^2 \rangle = \sum_j |U_{ej}|^2 m_j^2$$



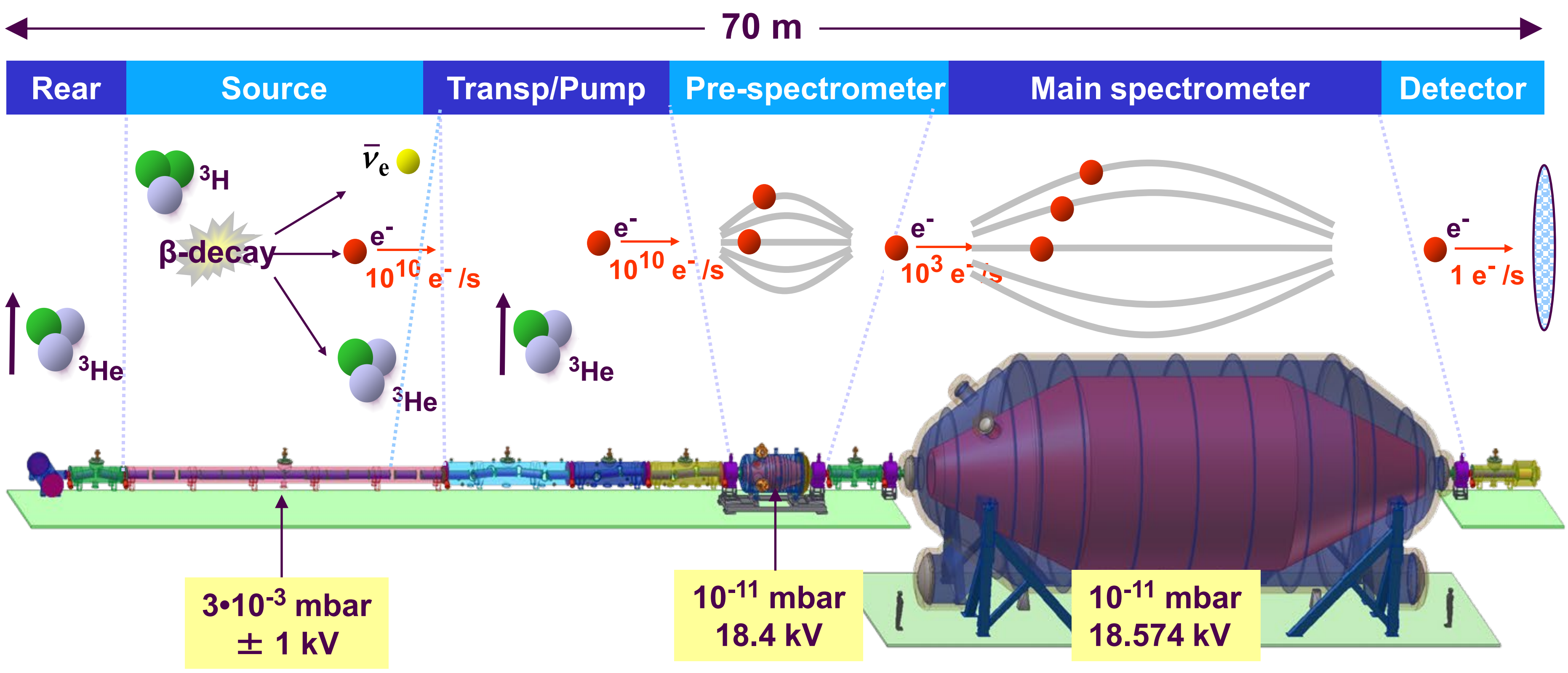
Constraints on ν mass

What we know

Future Experiments



Overview of KATRIN



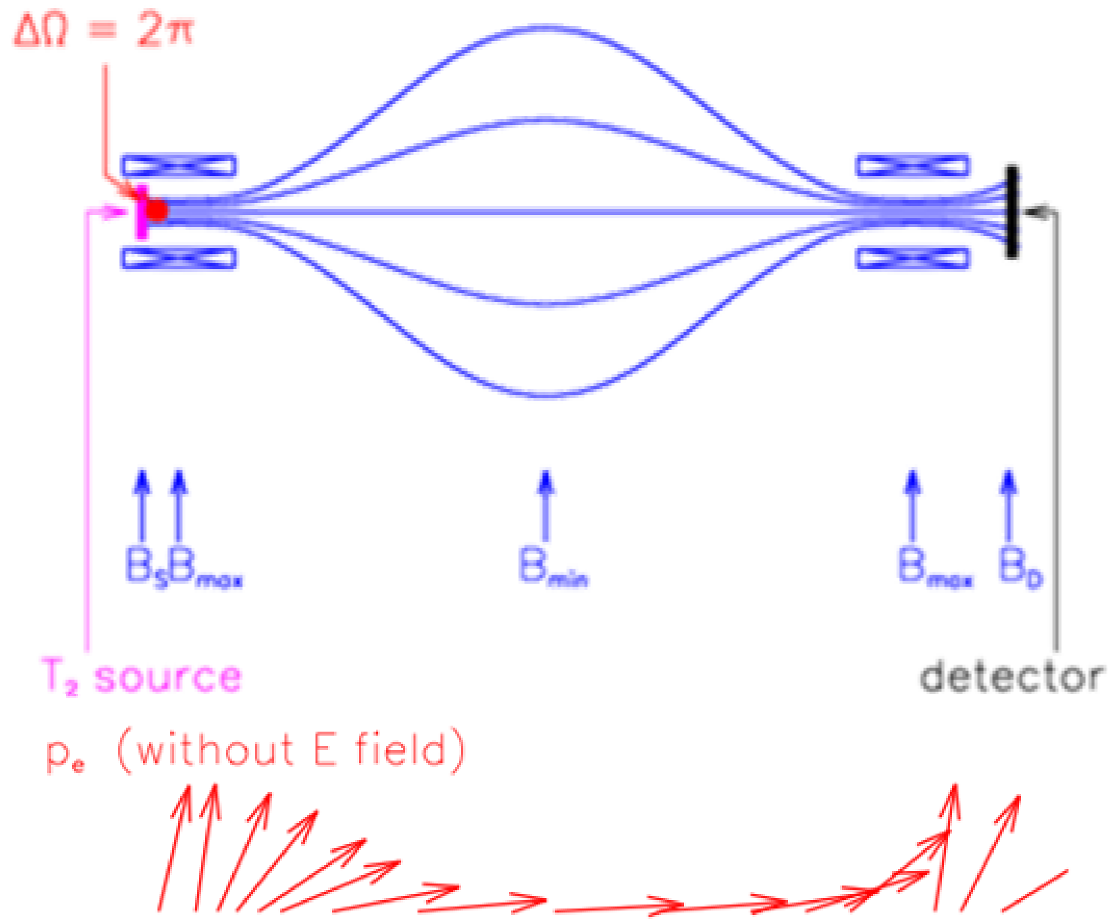
Principle of a MAC-E Filter

Magnetic Adiabatic Collimation + Electrostatic Filter

- Two superconducting solenoids make a guiding magnetic field
- Electron source in left solenoid
- Electrons emitted in forward direction are magnetically guided
- Adiabatic transformation:

$$\mu = \frac{T_\perp}{B} = const$$

$\Rightarrow$ Parallel beam at analyzing plane

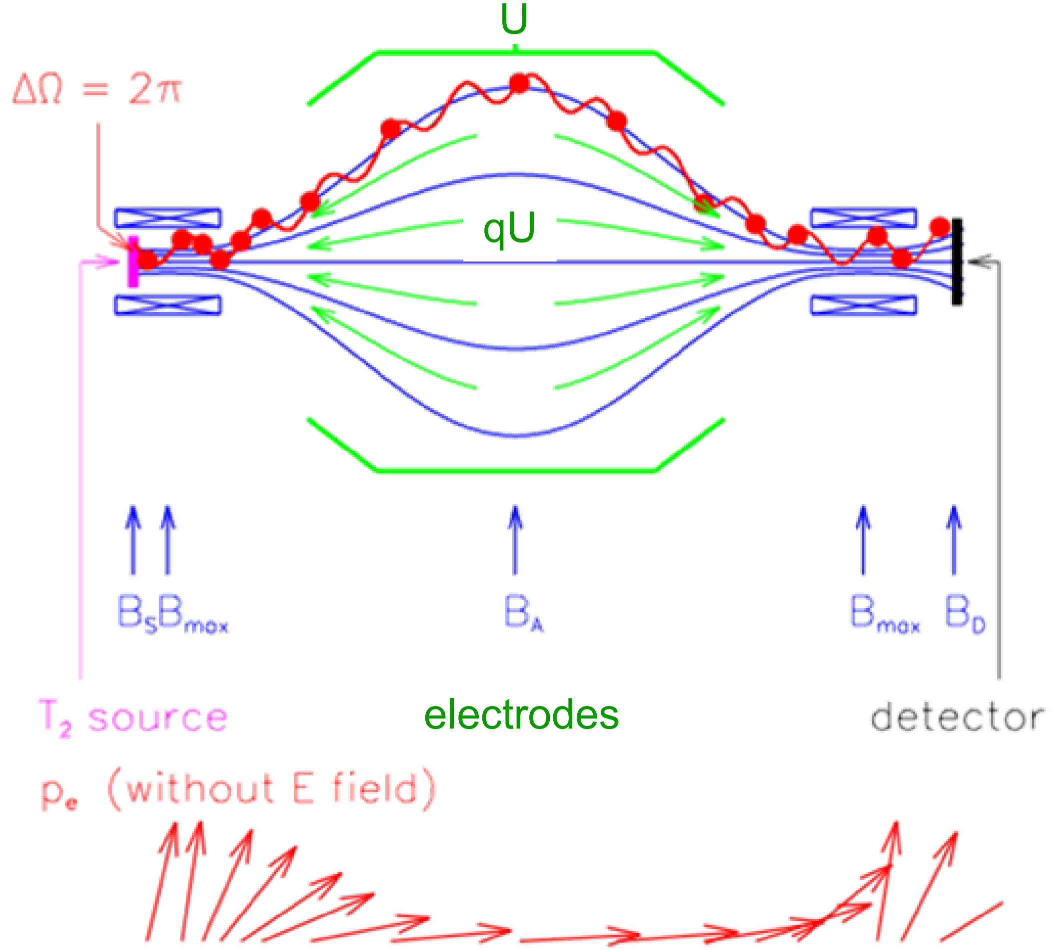


Principle of a MAC-E Filter

Magnetic Adiabatic Collimation + Electrostatic Filter

- Retarding electrostatic potential is an integrating high-energy pass filter
- Parallel energy analysis

$$T_{||} > qU$$

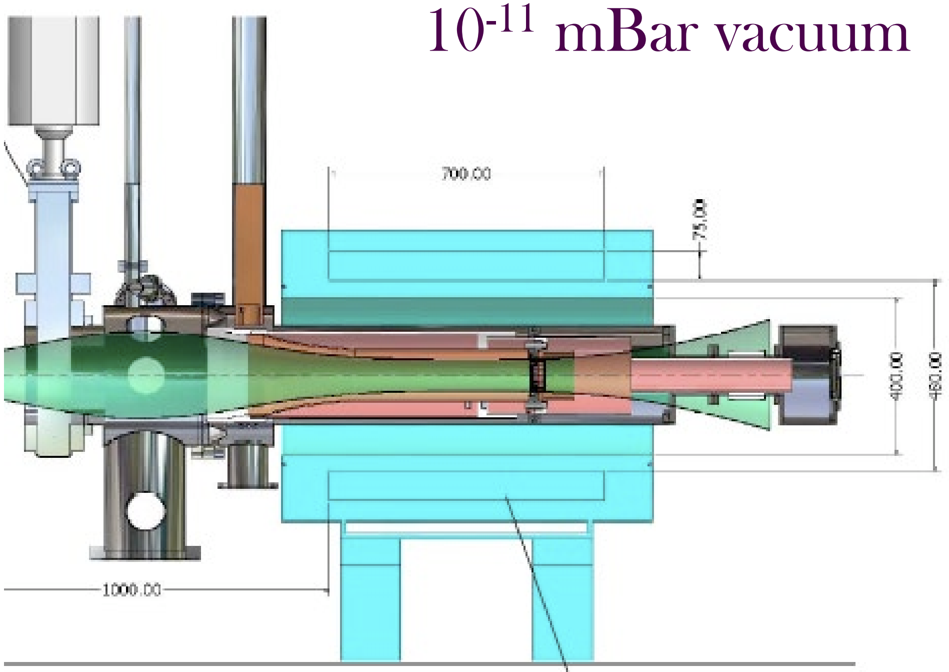


Main Spectrometer Delivery

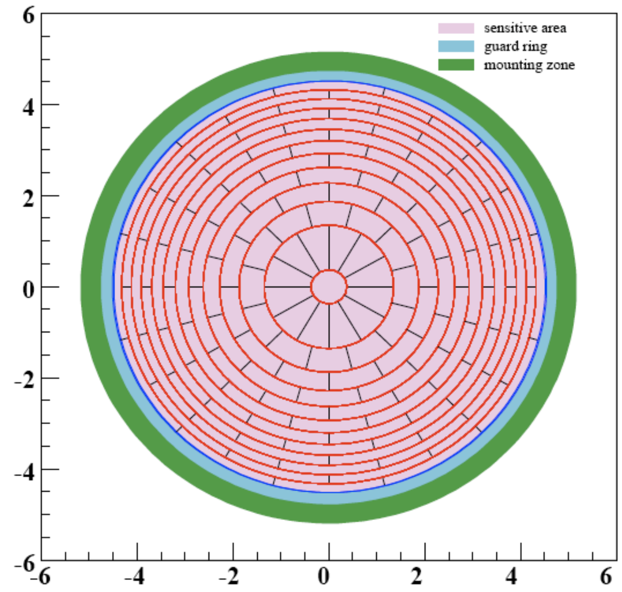
KATRIN's Detector Region

30 kV post-acceleration electrode

10^{-11} mBar vacuum



3 Tesla magnet



5 cm Silicon Detector

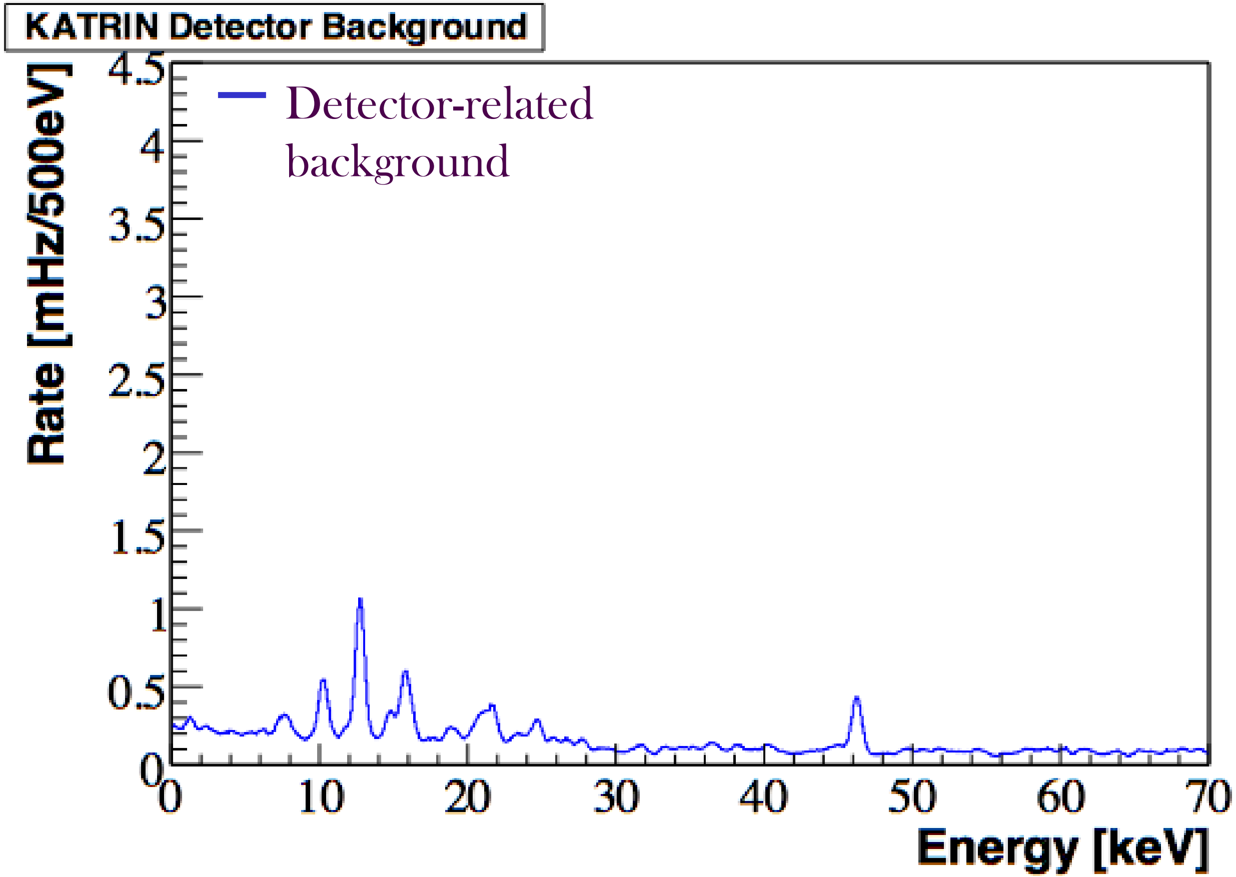
500 μm thick

148 segments

Detector Background

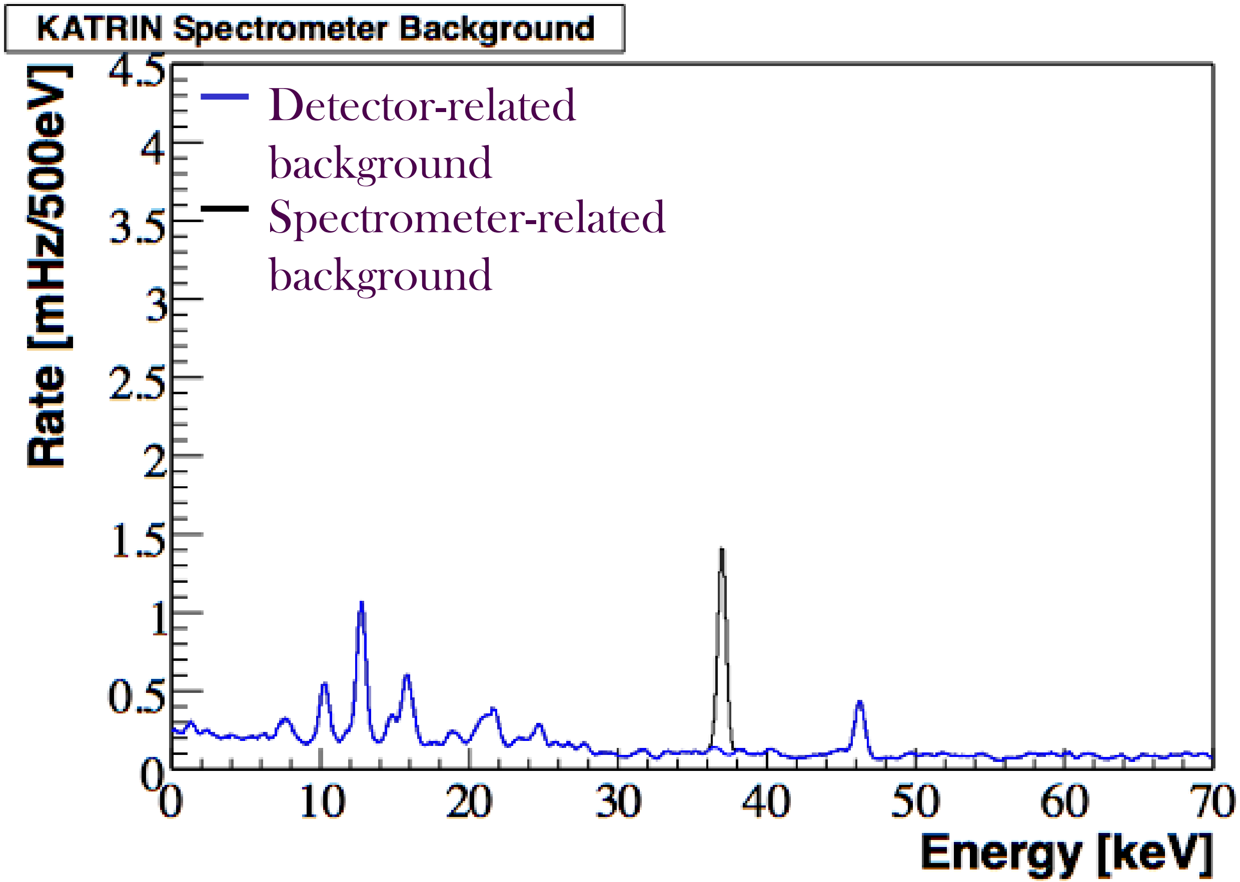
Region Of Interest (ROI) depends on

- Post-acceleration
- Energy resolution



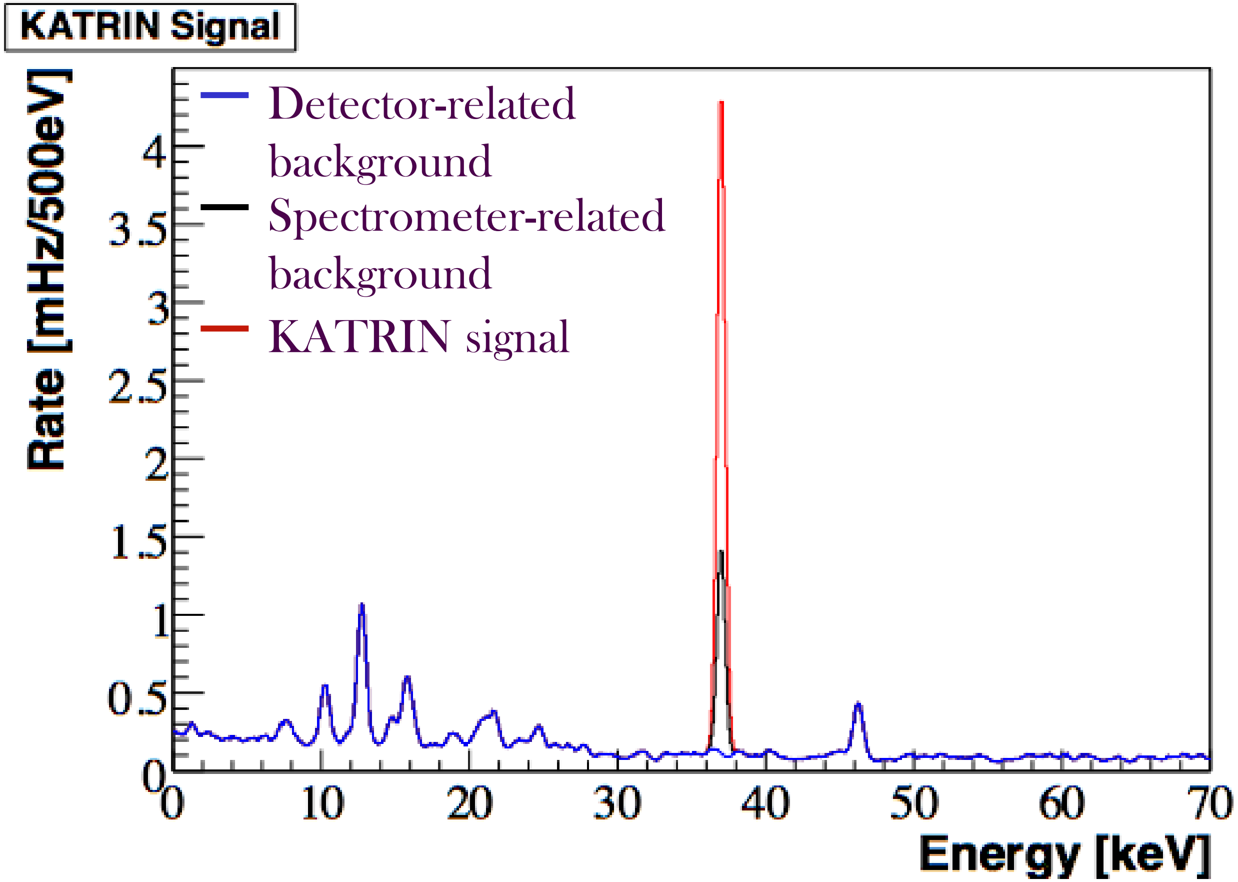
Spectrometer-related Background

- Electrons produced in the spectrometer
- Mimics the signal
- Position determined by post-acceleration



KATRIN Signal

- Position determined by post-acceleration
- 0-100 Hz rate depending on retarding voltage



KATRIN Signal

Signal rate:

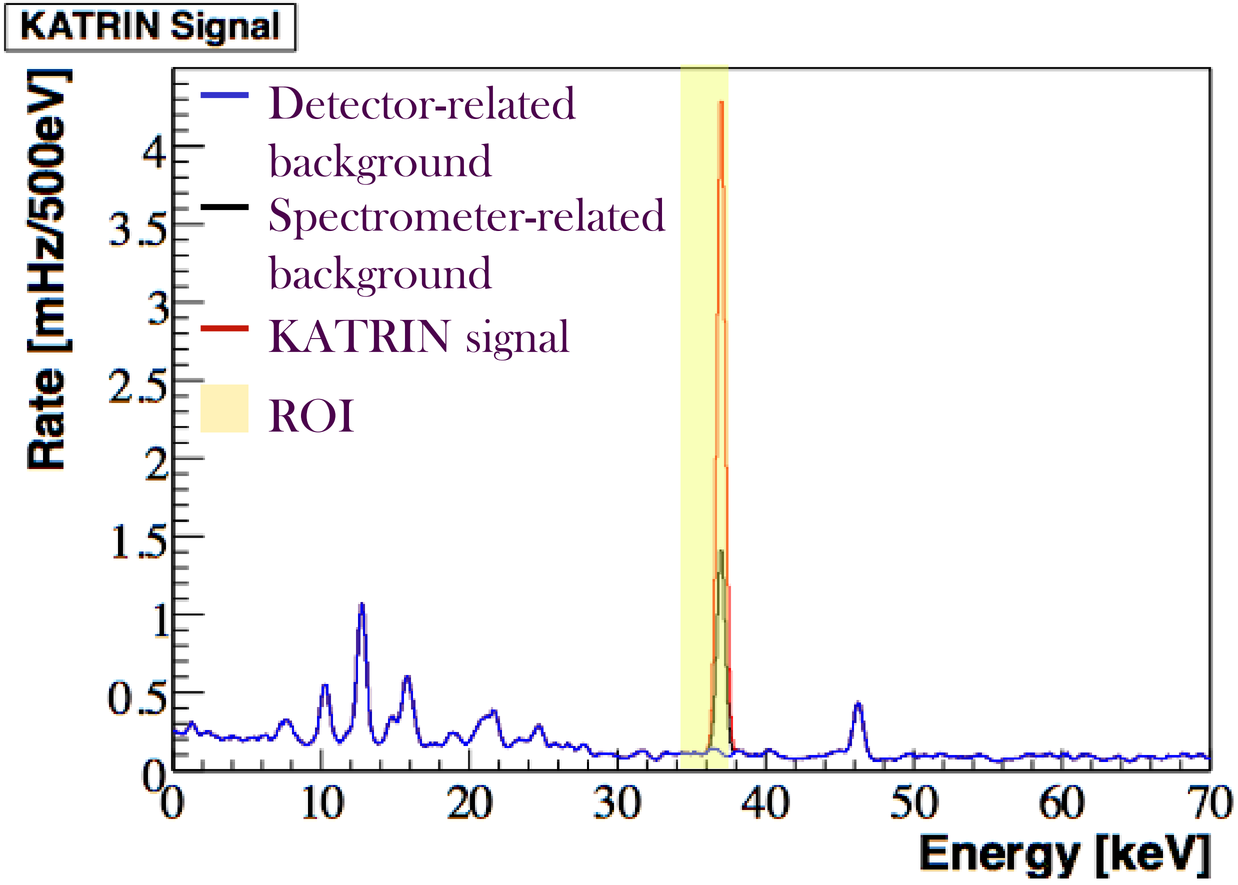
0-100 Hz

Spectrometer Background:

10 mHz

Detector background:

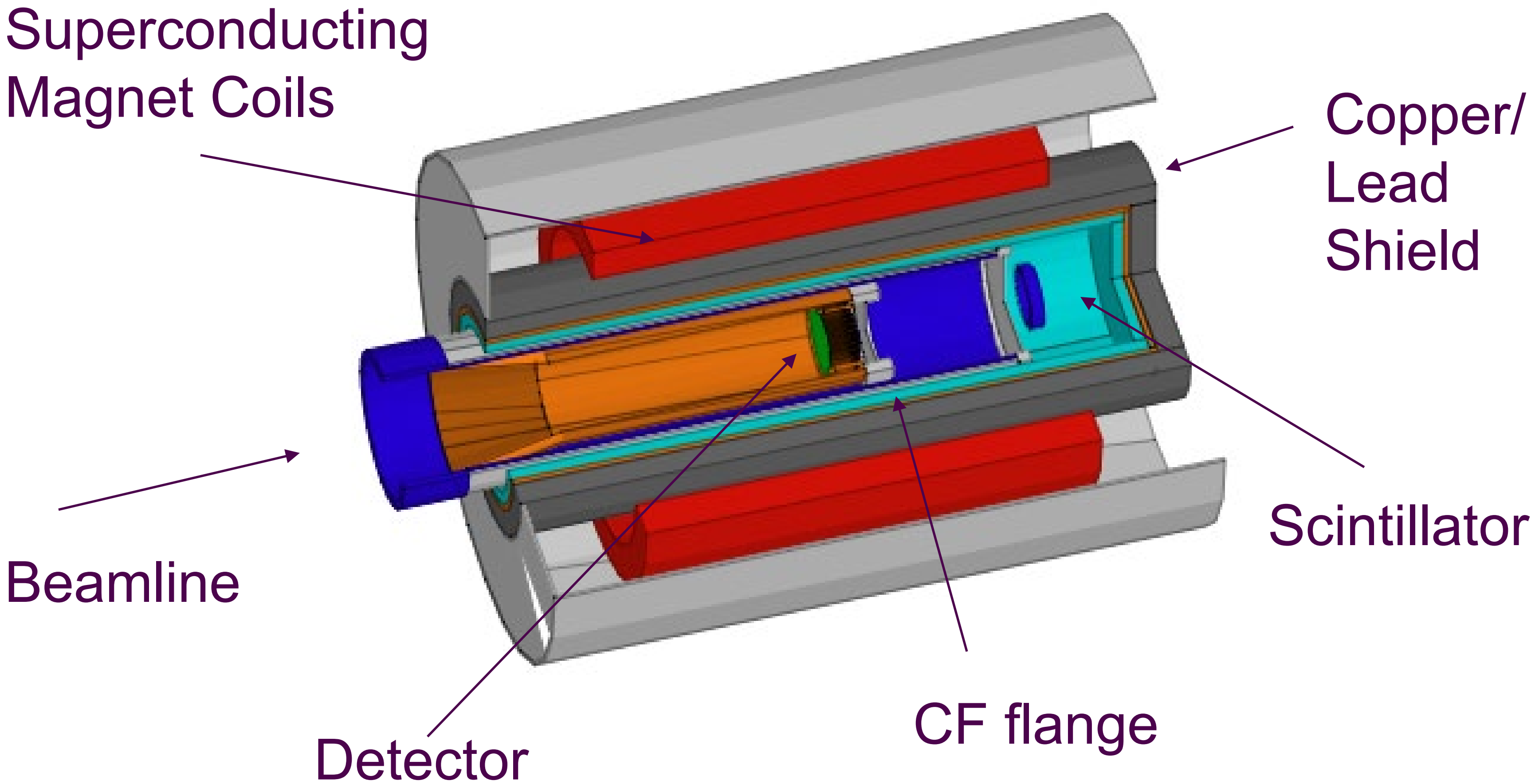
1 mHz



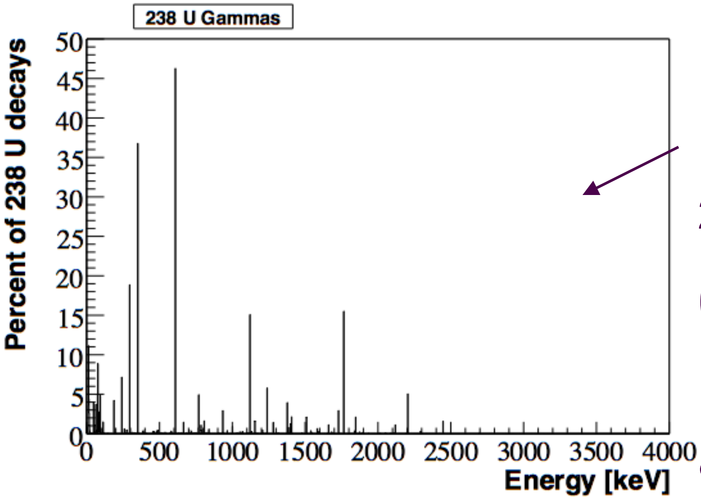
Detector-related Backgrounds

- Sources
  - Cosmic Rays
    - Muons, protons, and neutrons
  - Natural Radioactivity
    - ^{238}U, ^{232}Th
  - Cosmogenics
    - Copper, Stainless Steel, Silicon, Ceramic

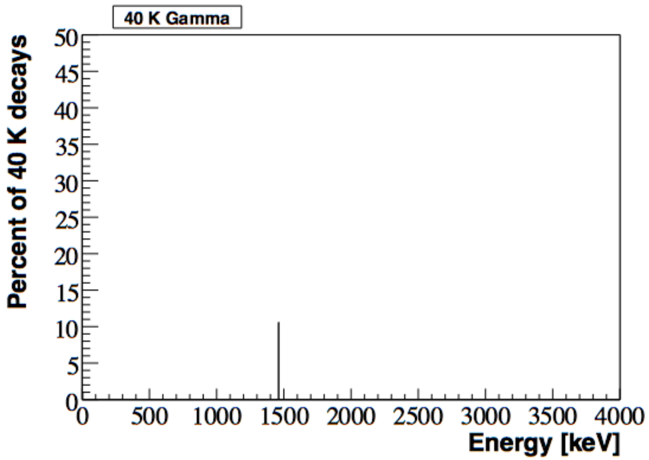
Detector Area



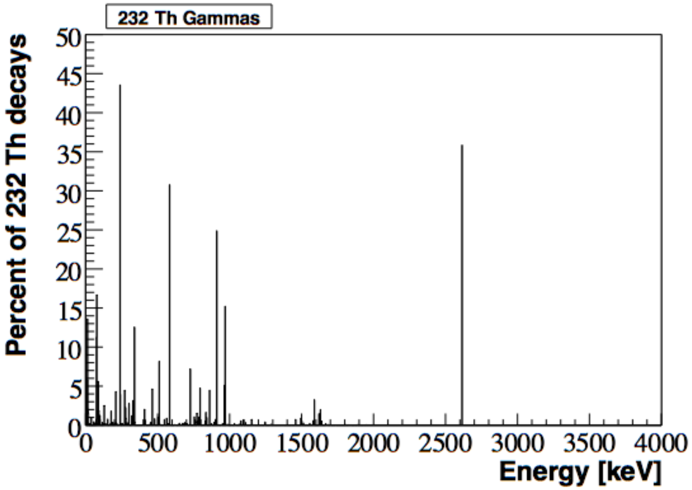
Natural Radioactivity



Uranium Chain:
^{214}Bi releases
0.7 gammas
per decay
above 1 MeV

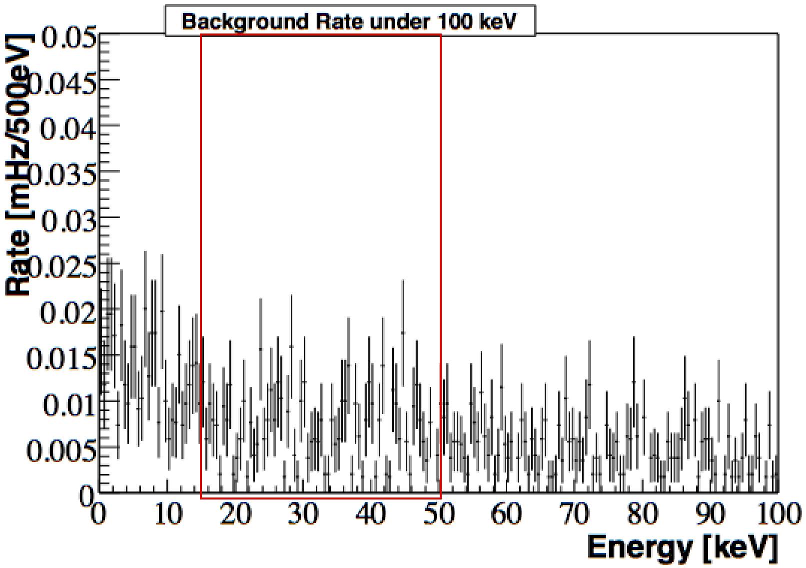


Thorium Chain:
^{228}Ac and ^{208}Tl
release
0.5 gammas per
decay above
1 MeV



Potassium-40
releases 0.1
gammas per
decay above
1 MeV

Backgrounds from Magnet Coils

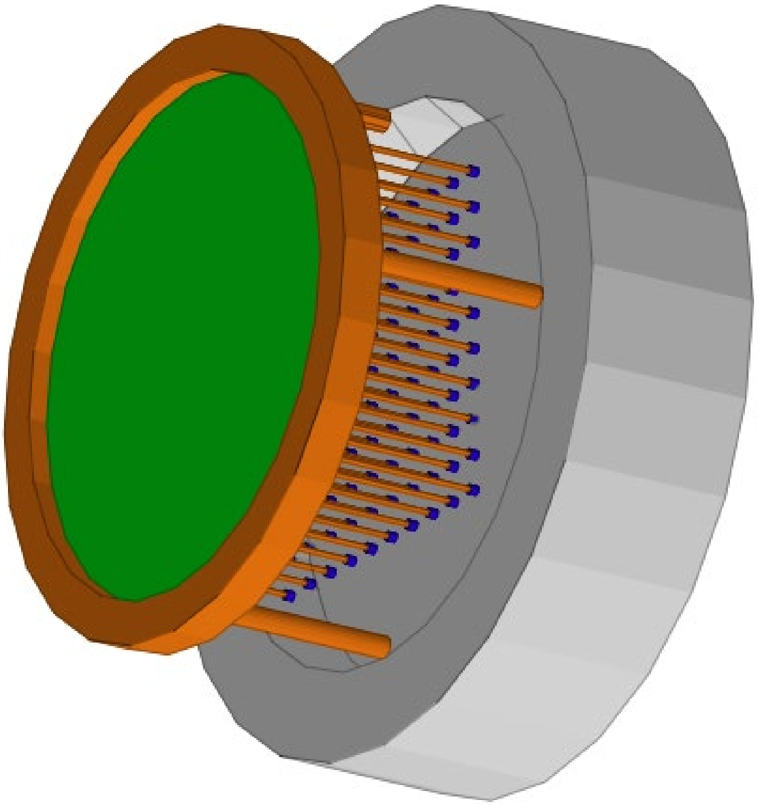


High energy photons compton scatter within the detector

	Activity Bq/kg	Rate 15.9-19.4
Uranium	0.74	0.023 $\pm$ 0.006 mHz
Thorium	0.89	0.034 $\pm$ 0.008 mHz
Potassium	3.0	0.01-0.02 mHz

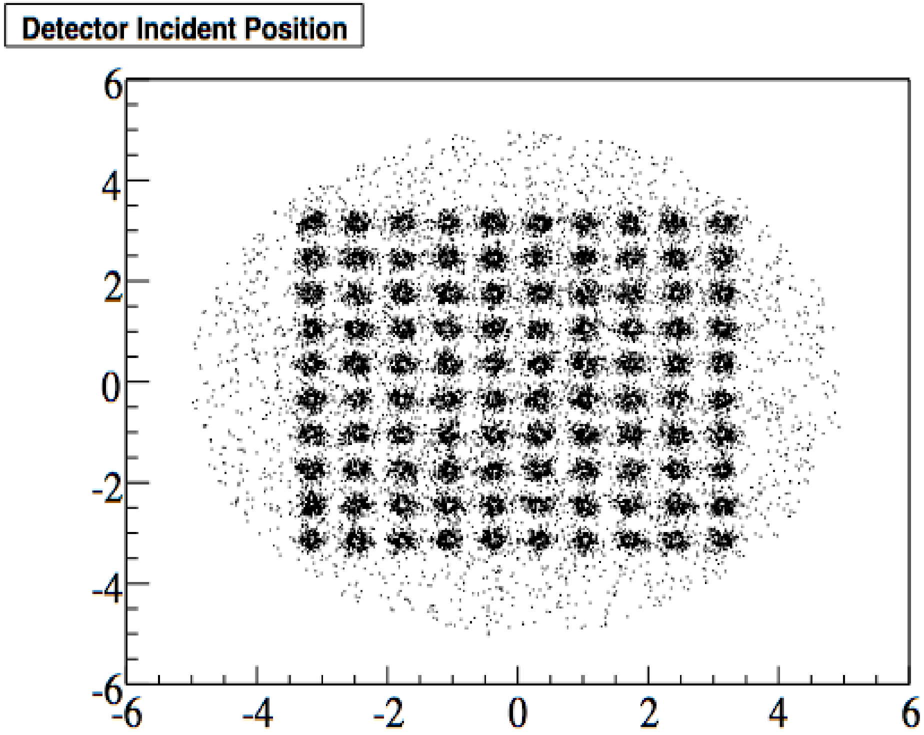
Simulation Detector

- 500 μm, 5 cm radius Silicon Wafer
- Copper cooling ring
- Mounted on
  CF flange
- Feed through
  Insulators



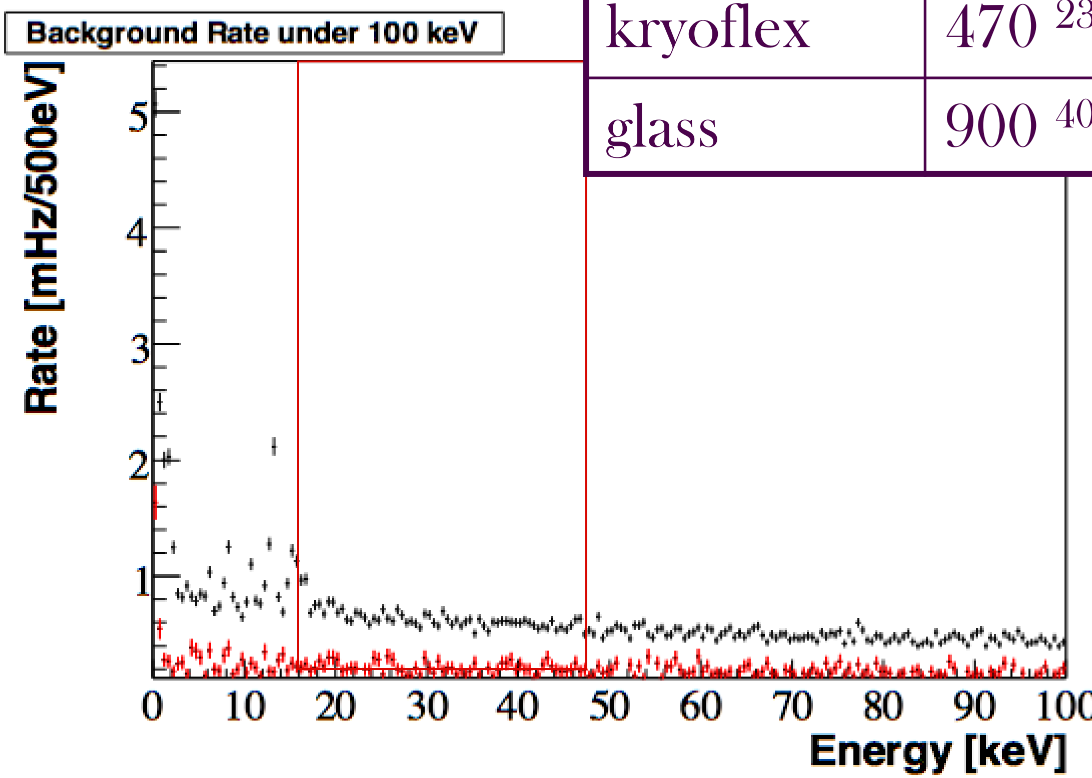
Feed-through Insulators

- Uranium:
  - 6 βs per decay max endpoint ~3 MeV
- Thorium
  - 4 βs per decay max endpoint ~2 MeV
- Potassium
  - 1 β per decay max endpoint 1.5 MeV



Feed-through Insulators

material	Activity Bq/kg	Mass g	Rate 15.9-19.4 mHz
kryoflex	470 ^{238}U	3.2	5.6 ± 0.1
glass	900 ^{40}K	3.2	1.5 ± 0.2



Remaining Background Work

- <u>Verification</u>
  - Short term:
    - Detector response to photons (^{241}Am)
    - Measure the cosmic ray spectrum
    - Electron Gun
  - During Commissioning:
    - Effect of magnetic field on detector backgrounds

Conclusions

- The KATRIN experiment will investigate an interesting region of neutrino mass
- Largest detector backgrounds are starting to be understood
  - Cosmic Rays
  - βs originating close to the detector
- Neutrino mass measurements will start end of 2009-2010

Thanks!

Massachusetts Institute of Technology

John Wilkerson, Peter Doe, Hamish Robertson, Joe Formaggio, Markus Steidl, Ferenc Glück, Brent VanDevender, Brandon Wall, Jessica Dunmore

Parity Violation

- Polarized ^{60}Co nuclei ß-decay, emitting electrons preferentially away from the magnetic field
- Under parity, spin does not change sign, but the electron's momentum does

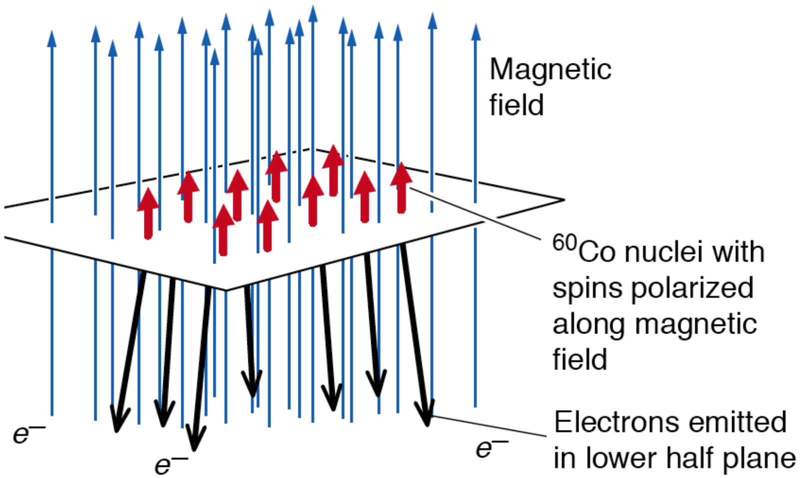


Figure from Los Alamos Science

Helicity vs. Chirality

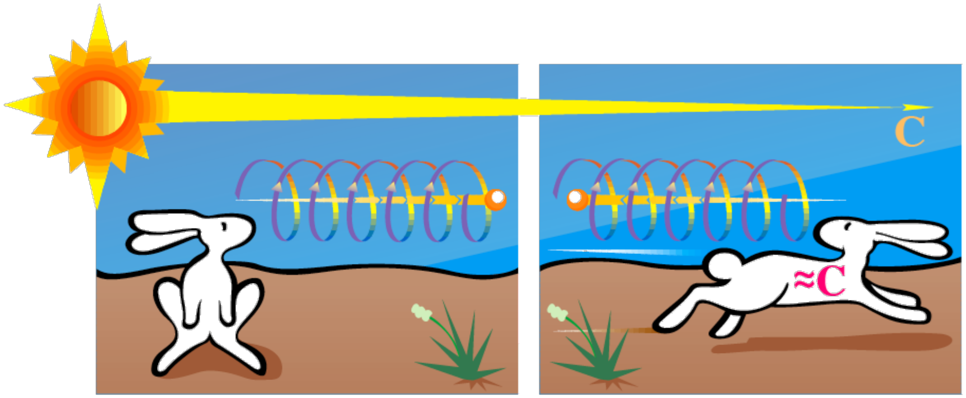


Figure from Los Alamos Science

- Helicity $= \frac{\mathbf{s} \cdot \mathbf{p}}{|\mathbf{p}|}$

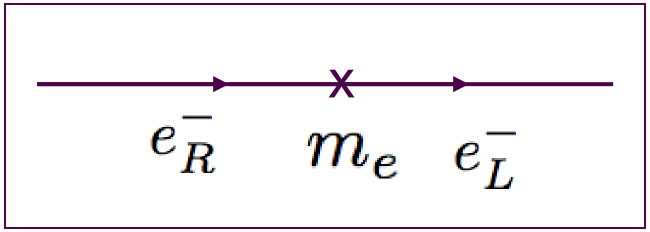
  Conserved

  Frame dependent

- Chirality $= \gamma^5$

  Frame independent

  Not conserved



In the Standard Model, only massless, left-chirality neutrinos exist.

Current State of Neutrino Physics

Oscillations show neutrinos are not massless!
But cannot measure the mass scale

Solar Experiments and KamLAND measure

$$\Delta m^2_{12} = 8 \times 10^{-5} eV^2{}^{+0.6}_{-0.4}$$

$$\theta_{12} = 33.9^{+2.4}_{-2.2} degrees$$

SNO Collaboration, Phys. Rev. C72 (2005)

Atmospheric Experiments measure

$$\Delta m^2_{23} = 2.4 \times 10^{-3} eV^2{}^{+0.6}_{-0.5}$$

$$\theta_{23} > 32.1 degrees (90\% CL)$$

Super Kamiokande Collaboration,
Phys. Rev. Lett. 93(2004)

Bounds from cosmology

Case	$\sum m_\nu$ (95% C.L.)
1: 11 parameters, CMB, LSS, SNI-a	2.3 eV
2: 11 parameters, CMB, LSS, SNI-a, BAO	0.48 eV
3: 8 parameters, CMB, LSS, SNI-a, BAO	0.44 eV
4: 8 parameters, CMB, LSS, SNI-a, BAO, Ly-α	0.30 eV
Other recent bounds	
8 parameters, WMAP only (87)	2 eV
8 parameters, WMAP, SDSS (49)	1.8 eV
8 parameters, WMAP, SDSS, SNI-a, Ly-α (52)	0.42 eV

S. Hannestad, Annu. Rev. Nucl. Part. Phys. (2006) 1

Bounds fluctuate because of model dependencies

KATRIN's Sensitivity

KATRIN will probe the degenerate mass regions with projected sensitivity

0.2 eV (90% CL)