Neutrino Physics with Cold Atoms

Melissa Jerkins
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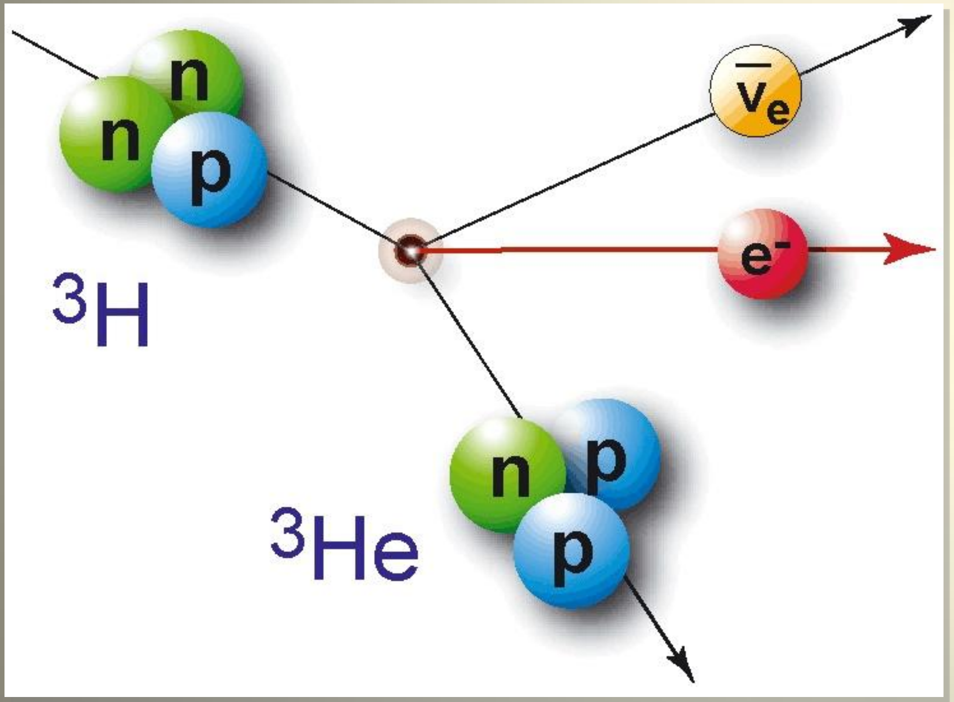
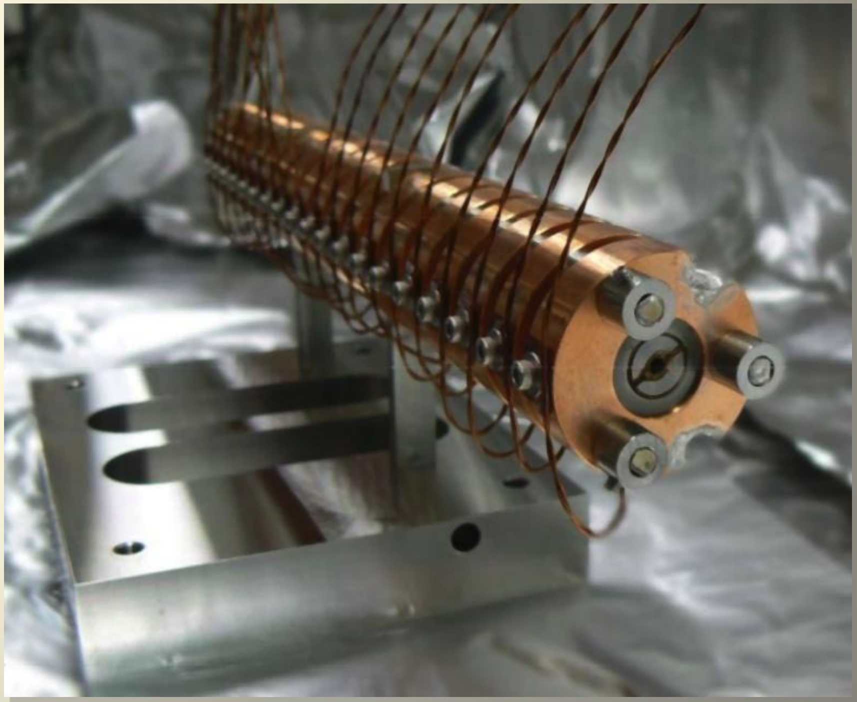
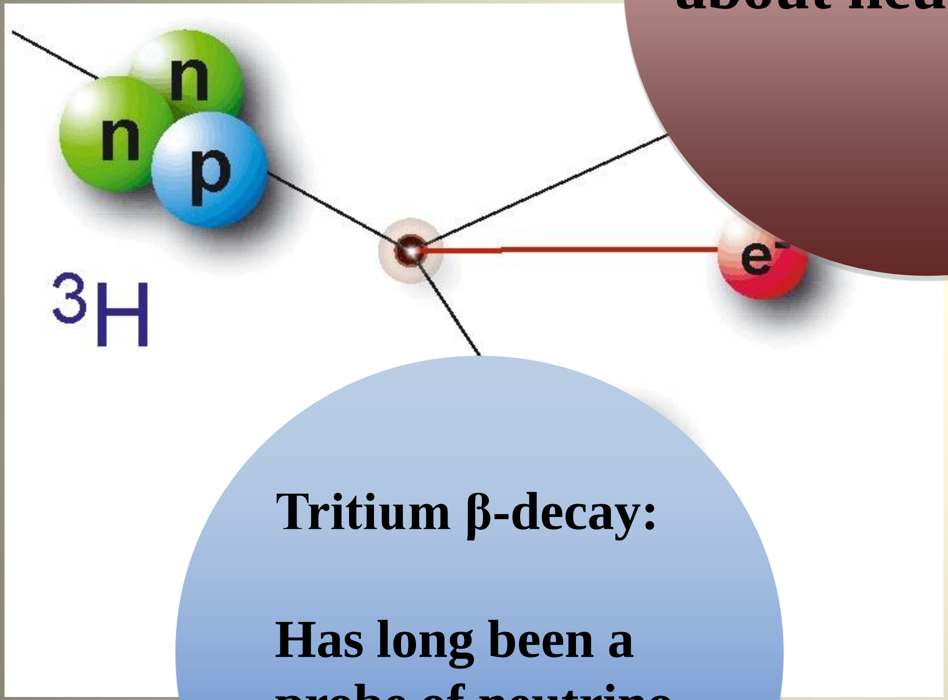




Tuesday June 2nd, 2009
Workshop for Atomic Physics on Rare Atoms
Collaborators include Dr. Mark Raizen, Dr. Joshua Klein, Dr. Francis Robicheaux, and Julia Majors

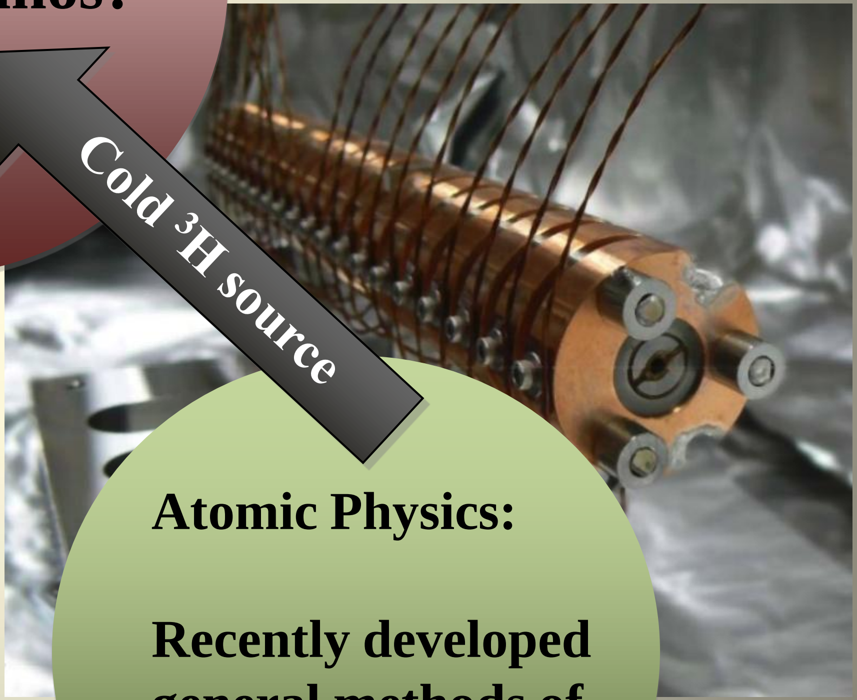
Neutrino Physics with Cold Atoms

What can we learn about neutrinos?



Tritium β-decay:

Has long been a probe of neutrino properties



Atomic Physics:

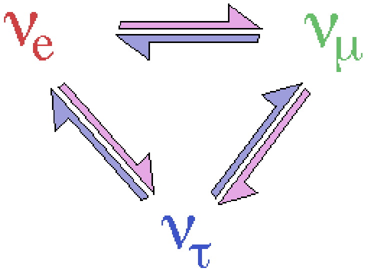
Recently developed general methods of slowing & cooling

Cold ^{3}H source

Neutrino Mass

Maki-Nakagawa-Sakata matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \times \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



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

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2(2\theta)\sin^2(1.27\Delta m^2 L/E)$$

The probability of flavor change depends on the mass differences between states, not on absolute masses

Oscillations only provide a lower limit on the ν-mass scale!

$$\boldsymbol{m_3 \geq \mathrm{sqrt}(|\Delta m_{atm}^2|) \sim (0.04 - 0.07\ \mathrm{eV})}$$

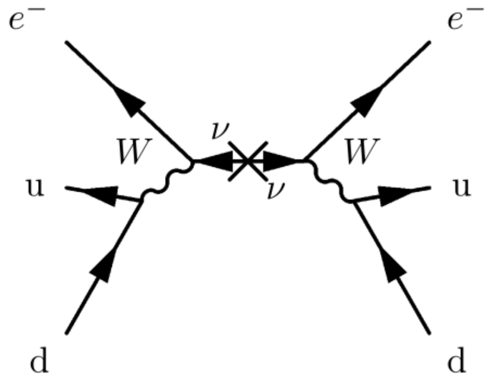
$\Delta m_{21}^2 = \Delta m_{sol}^2 = 8.0 \times 10^{-5}\ \mathrm{eV}^2$ (KamLAND)

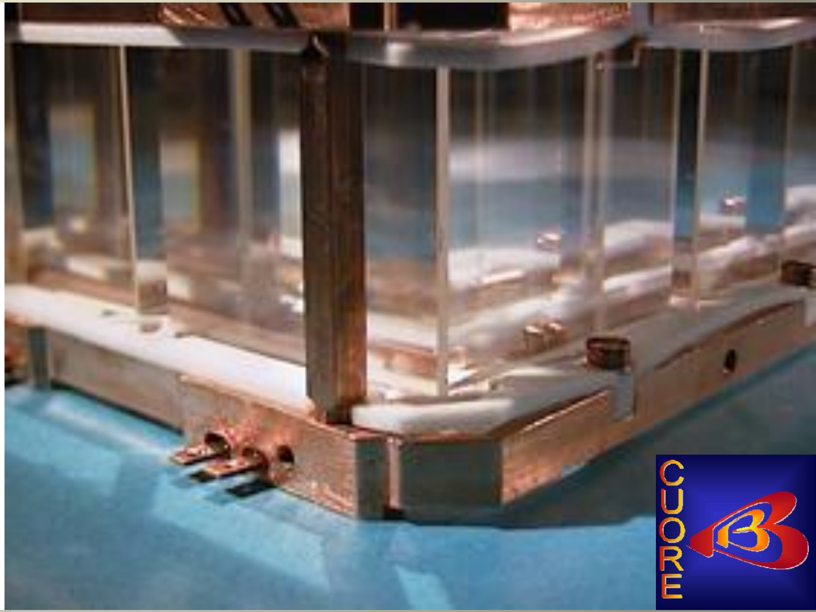
$\Delta m_{31}^2 \approx \Delta m_{32}^2 = \Delta m_{atm}^2 = 2.4 \times 10^{-3}\ \mathrm{eV}^2$ (Super-K)

Experimental options

Neutrinoless Double Beta Decay Experiments

- Neutrino emitted at one beta decay vertex has to be absorbed by the second decay vertex as an antineutrino





- CUORE plans to reach a limit of 20-50 meV on neutrino mass
- **Only possible if neutrinos are massive and Majorana**, meaning they are their own antiparticles
- Double beta decay experiments actually measure: $m_\nu = \Sigma |U_{ek}|^2 e^{i\alpha_{ek}} m_k$
  Majorana CP-phases are unknown ⇒ cancellations could occur

SuperNEMO
GERDA
EXO
CUORE
MOON II
COBRA

Majorana
CANDLES
XMASS
CARVEL
SNO+
many more …

Experimental options

Tritium beta decay

$$^{3}\mathrm{H} \rightarrow {}^{3}\mathrm{He}^{+} + e^{-} + \bar{\nu}_{e}$$

Half life: $t_{1/2}$ = 12.3 years

Endpoint energy: E_o=18.6 keV

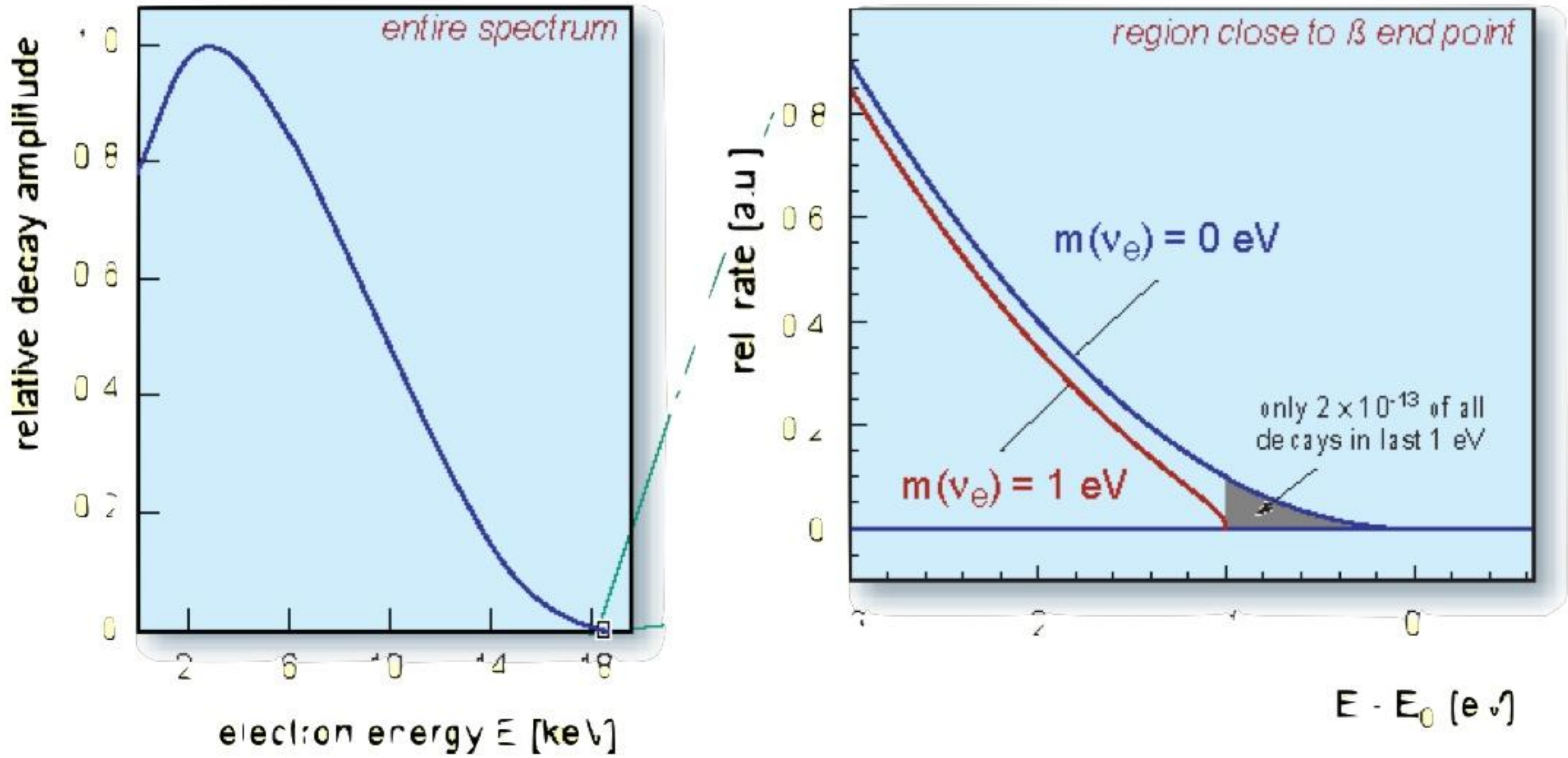


Figure: Osipowicz, A. et al. (KATRIN), arXiv:hep-ex/0109033

Experimental options

Tritium beta decay

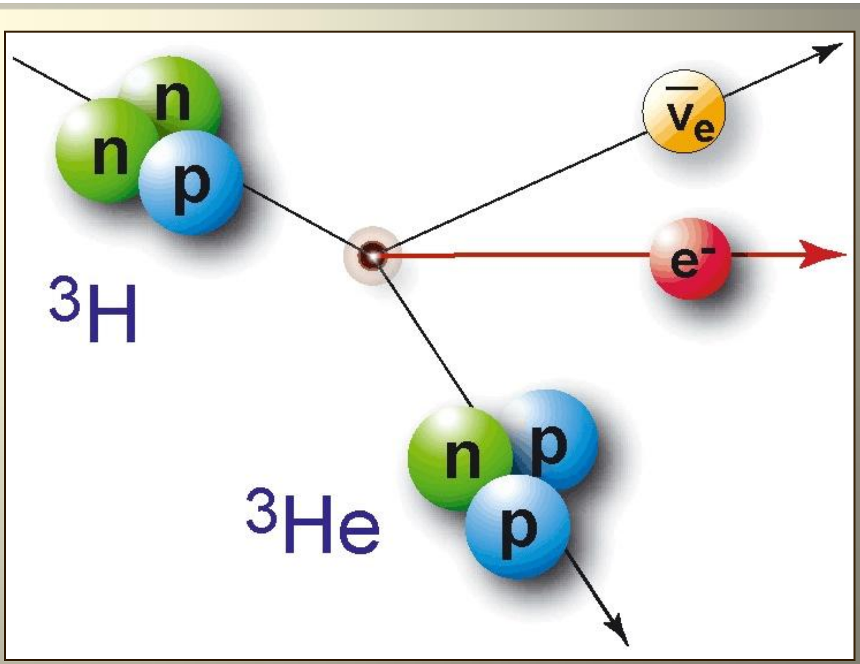
Electron energy spectrum of tritium β decay:

Experimental observable

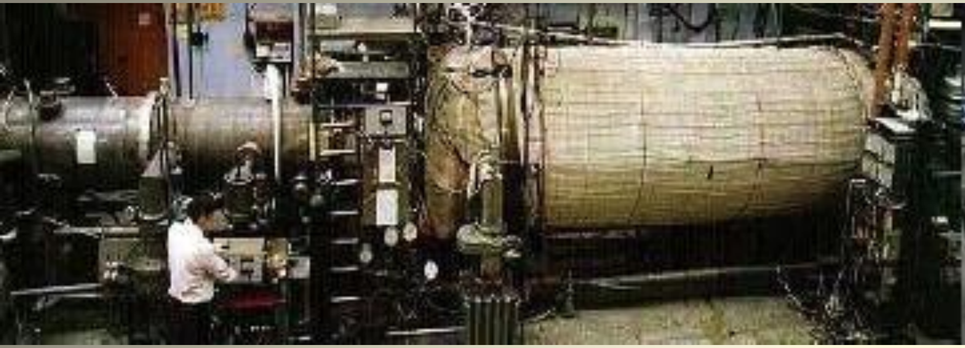
$$N(E) = \frac{dN}{dE} = K \times F(E,Z) \times p_e \times E_e \times p_\nu \times E_\nu$$

$$= K \times F(E,Z) \times p \times W \times \sqrt{(E_0 - E)^2 - m_\nu^2} \times (E_0 - E)$$

- m_ν^2 = “mass” of the $\overline{\nu}_e = \boldsymbol{\Sigma \,|U_{ei}|^2 m_i^2}$
- W = electron total energy
- E_o = endpoint energy = 18.6 keV
- F(Z,E) = Fermi function, accounting for Coulomb interaction of the outgoing electron in the final state
- $K = G_F^2\,(m_e^5/2\pi^3)\cos^2\theta_C\,|M|^2$



Previous Experiments

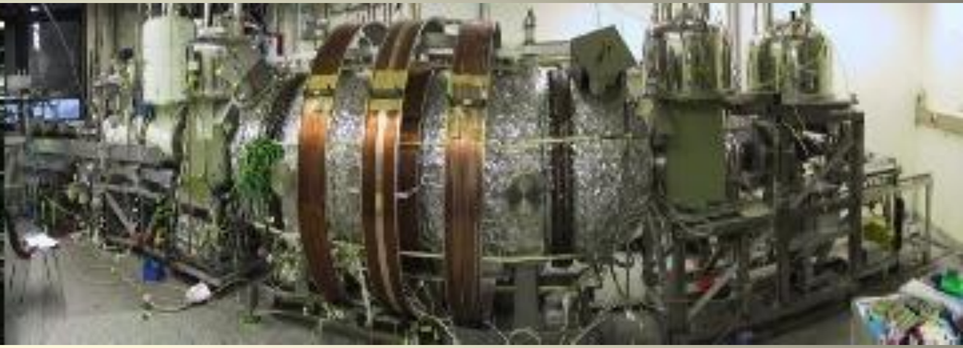


Troitsk

$m_\nu^2 = -1.0 \pm 3.0 \pm 2.5$ eV^2

$m_\nu \leq 2.5$ eV (95% CL)

Source = Windowless gaseous T^2



Mainz

$m_\nu^2 = -1.6 \pm 2.5 \pm 2.1$ eV^2

$m_\nu \leq 2.2$ eV (95% CL)

Source = Quench condensed T^2 film on graphite

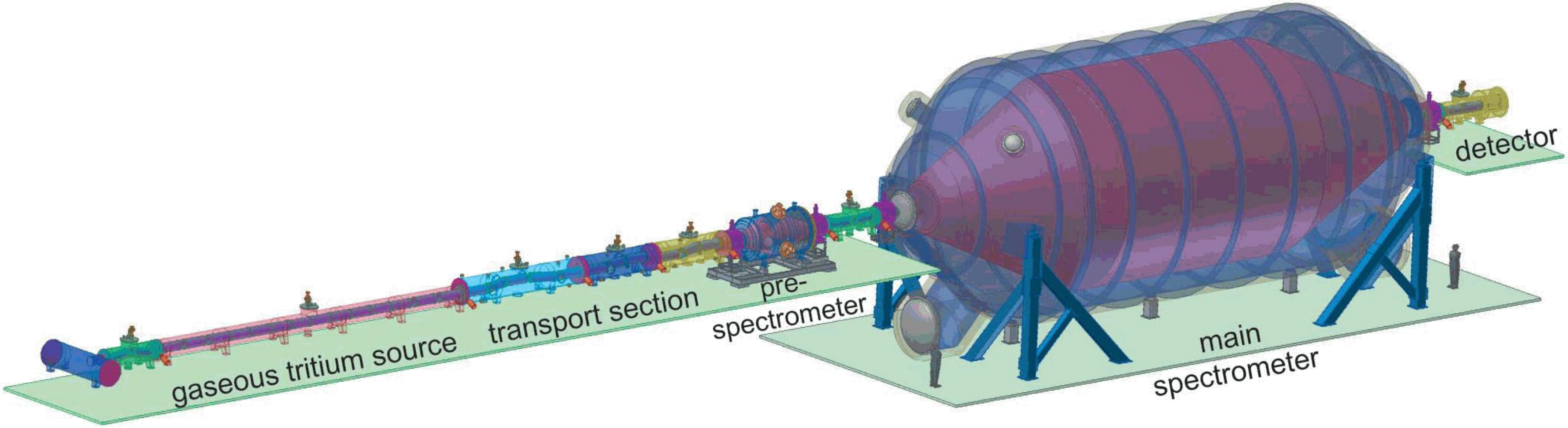
Limiting Factors:

- Statistics
- Scattering in source
- Backgrounds
- Energy resolution
- Electronic final state effects
- Tritium source uncertainties

Current Experiments

KATRIN

- Scaled-up version of Troitsk experiment
- Low background of $< 10^{-2}$ counts/s is required
- Plans to reach a neutrino mass sensitivity of 0.2 eV after 5-6 years of data taking



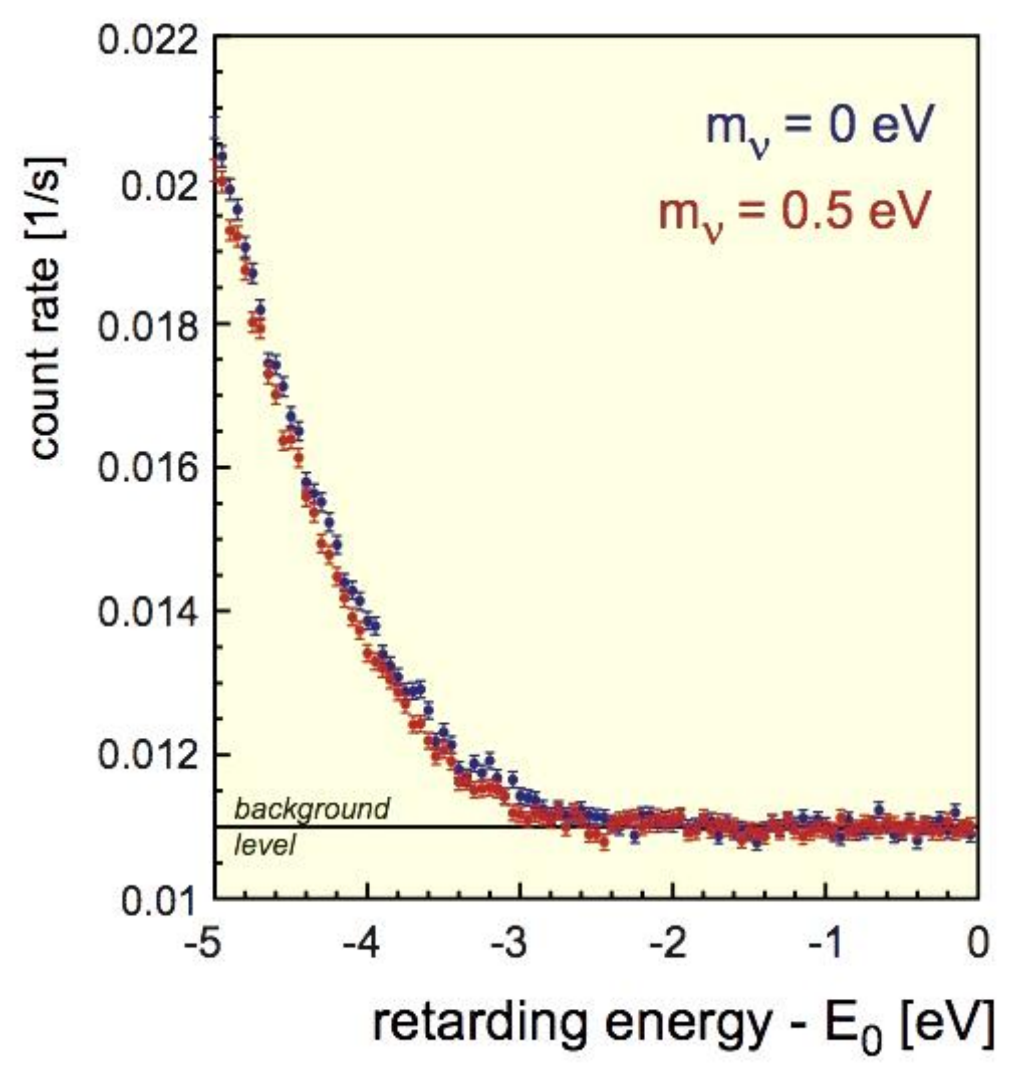
- Windowless Gaseous Tritium Source is a 10m long cylinder (80x stronger source)
- Main spectrometer is 23m long and 10m in diameter (4x better energy resolution)

Current Experiments

KATRIN

Monte Carlo spectra:

- Run time = 3 years
- $\Delta E = 1$ eV
- WGTS column density = $5 \times 10^{17}/\mathrm{cm}^2$
- Final state effects included
- Analysis window = 5 eV below endpoint

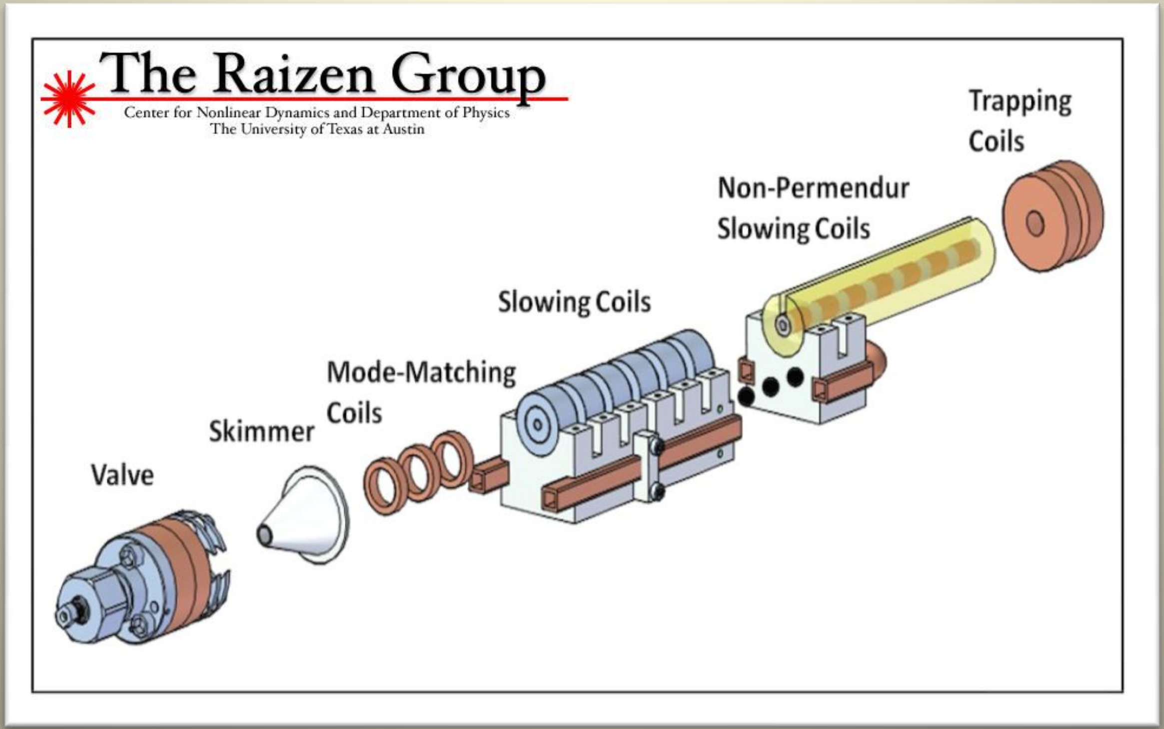


Is there another approach to directly measuring m_ν?

Magnetic Slowing of Atoms

Slowing and trapping cold atomic tritium would create a new kind of source for tritium β-decay.

- Supersonic nozzle → beam of atoms moving at ~400m/s
- Temperature of beam is very cold (~50mK in co-moving frame)
- Tritium can be entrained into the beam and then slowed for trapping

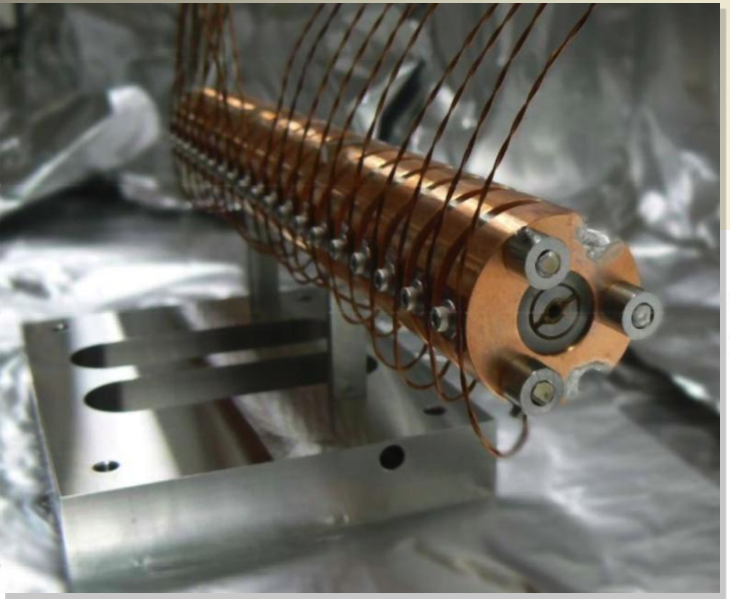


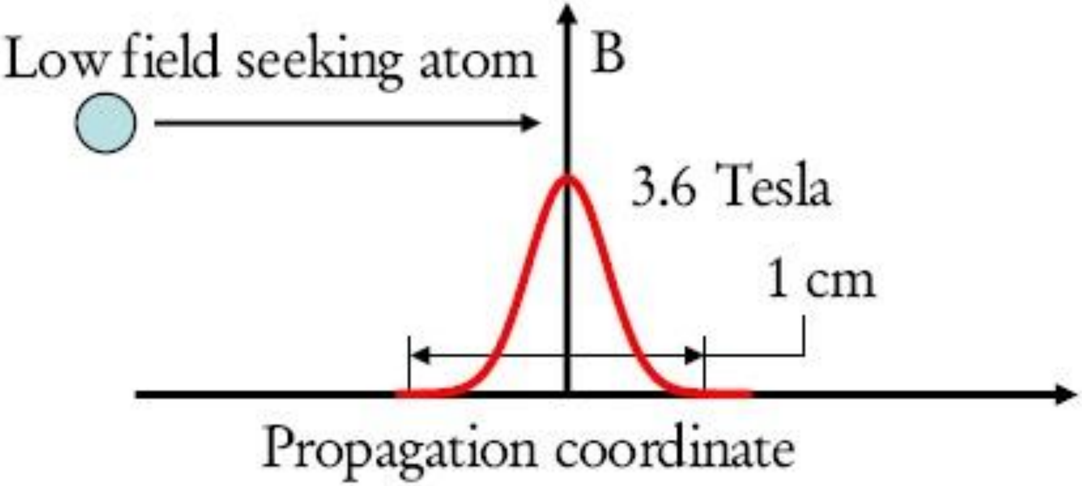
E. Narevicius, A. Libson, C. Parthey, I. Chavez, J. Narevicius, U. Even, and M. G. Raizen, Phys. Rev. Lett. 100, 093003 (2008)

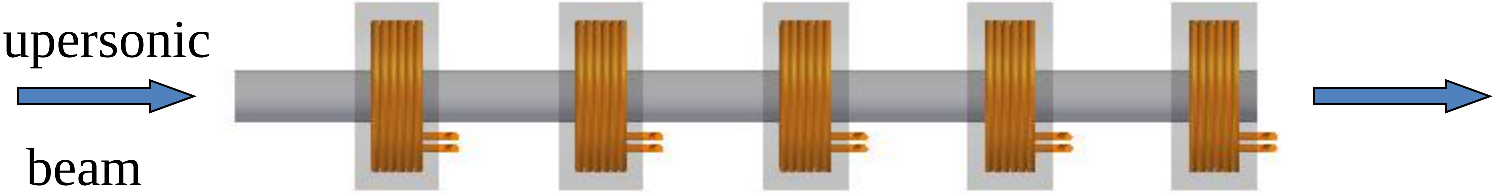
Magnetic Slowing of Atoms

Use pulsed magnetic fields to decelerate tritium atoms

- Zeeman effect: $\Delta E = -\,\boldsymbol{\mu}\cdot\mathbf{B}$
- Low-field seekers are repelled in high field regions and lose kinetic energy







Supersonic

beam

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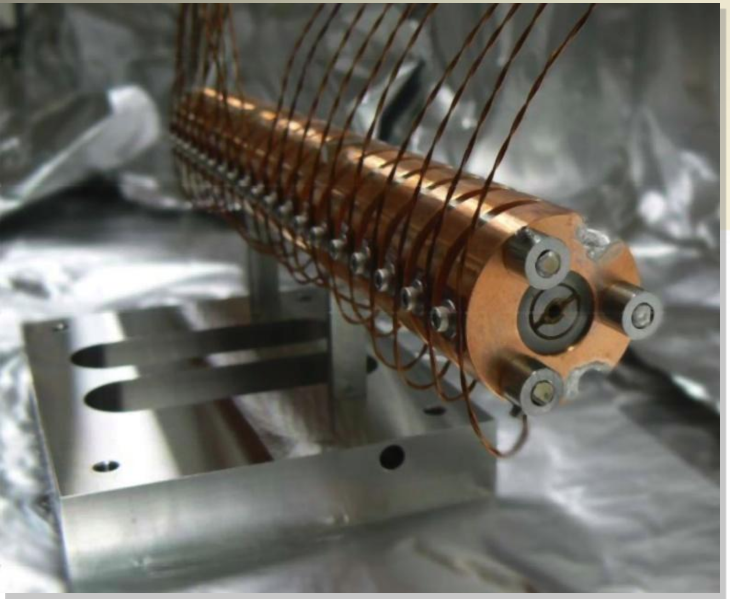

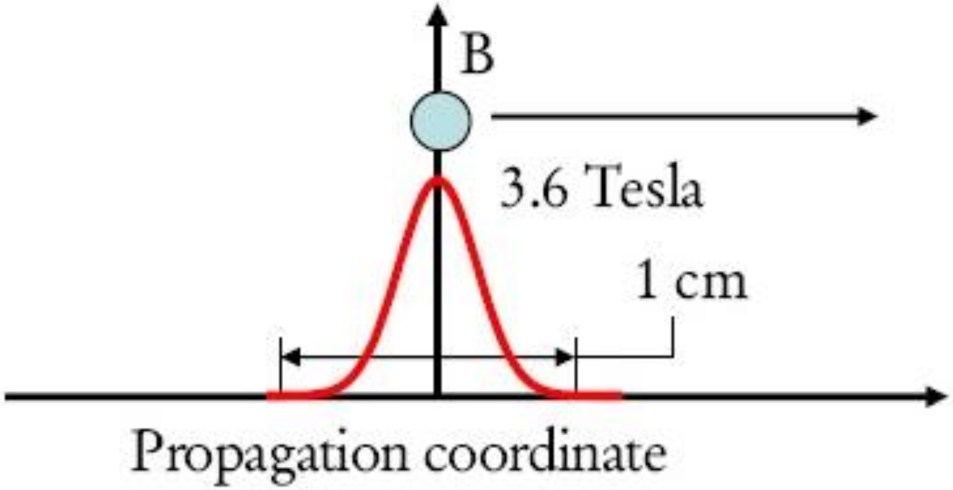

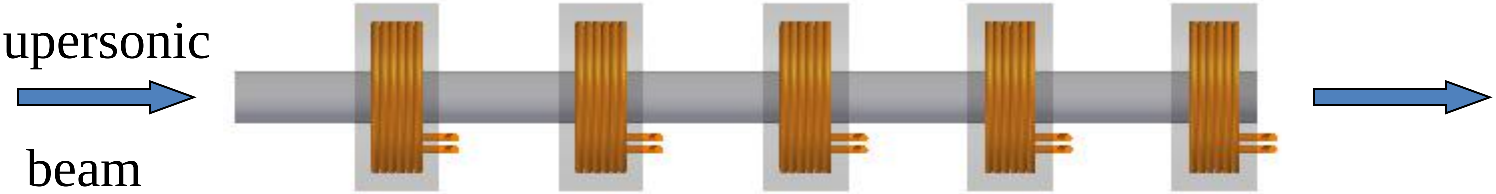

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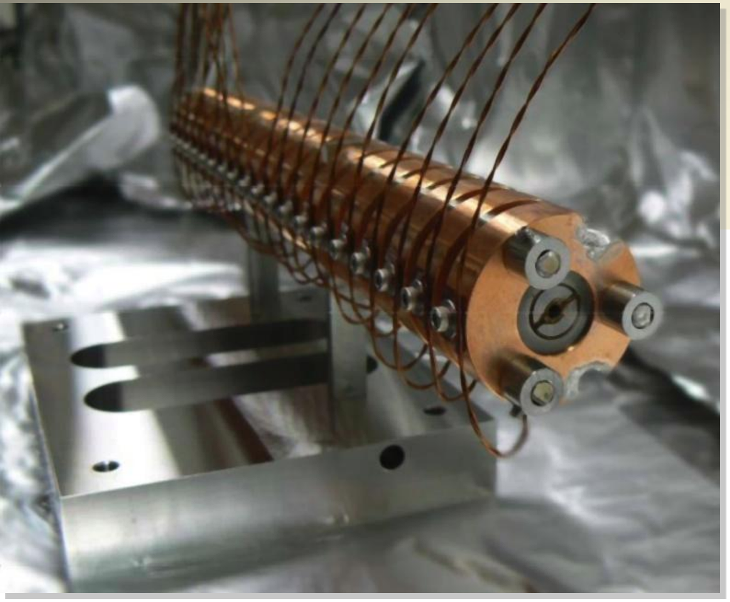
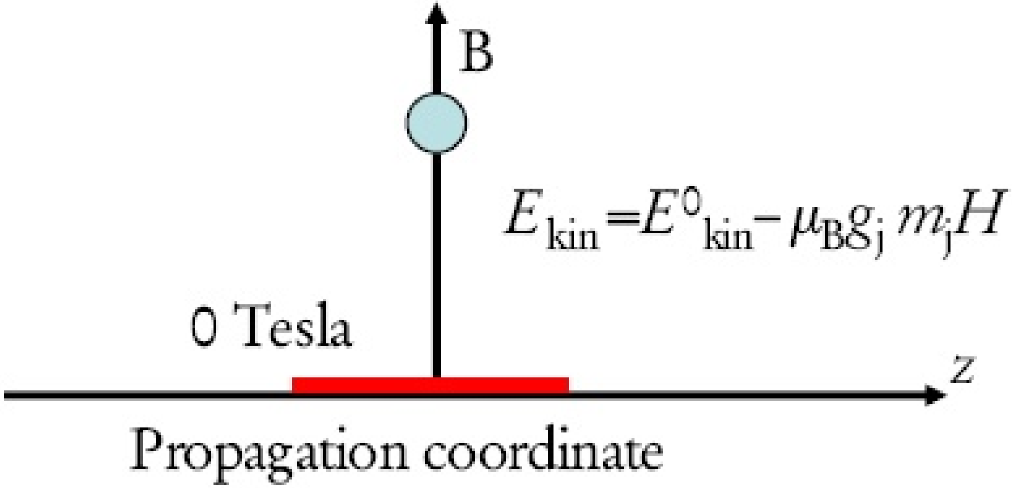
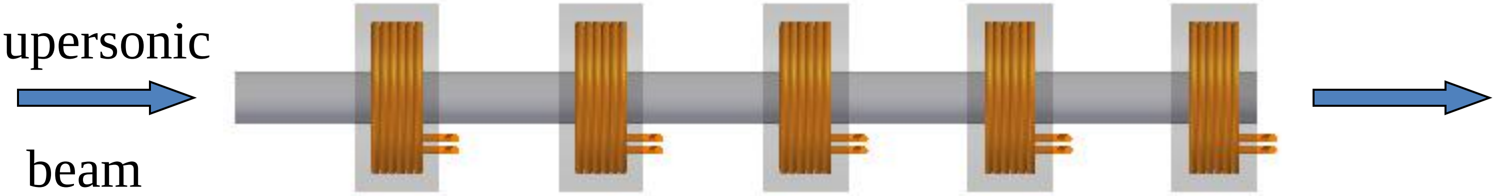






Supersonic

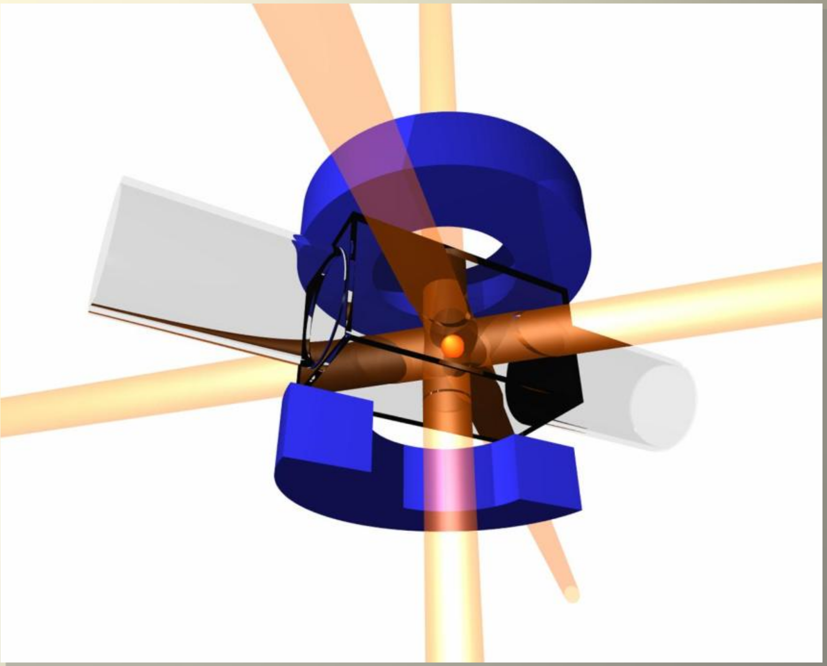
beam

Single Photon Cooling

Can we further cool tritium once we've trapped it?

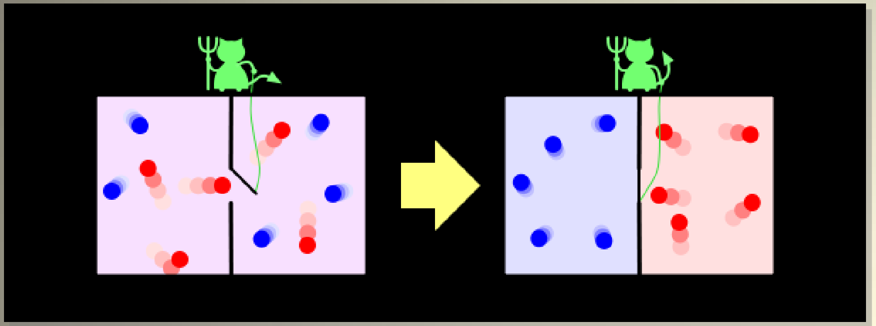
Laser cooling: Highly effective but limited to a small group of atoms

- 1997 Nobel Prize: Chu, Cohen-Tannoudji, Phillips
- Repeated scattering of photons reduces atomic momentum
- Requires a cycling transition
- Hydrogen cannot be laser cooled



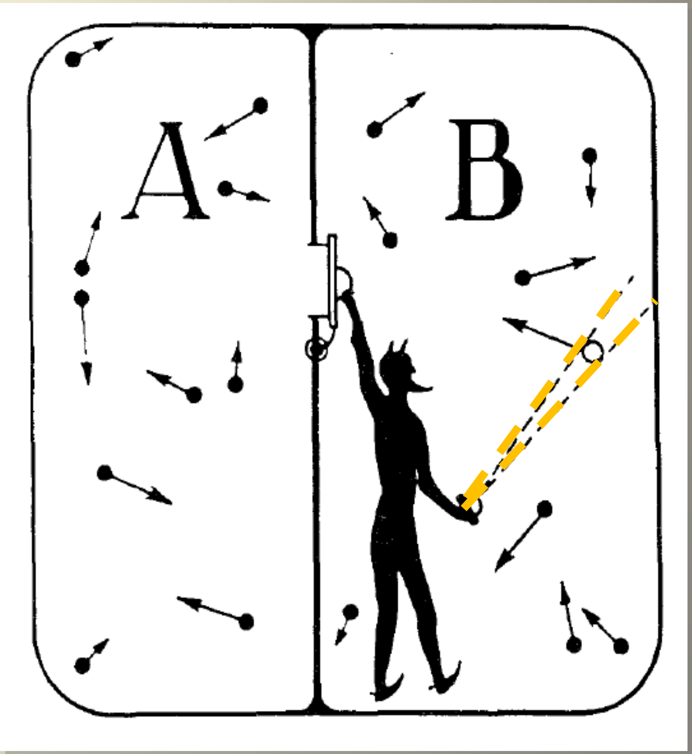
Is there a more general cooling method?

Single Photon Cooling



Thought-experiment by Maxwell (1867)

Entropy reduced without expenditure of work



2^{nd} law is saved by information carrying entropy

Szilard (1929)

- Demon makes a measurement
- Information entropy

Demon’s jobs:

- Measure **r**, **p**
- Operate gate

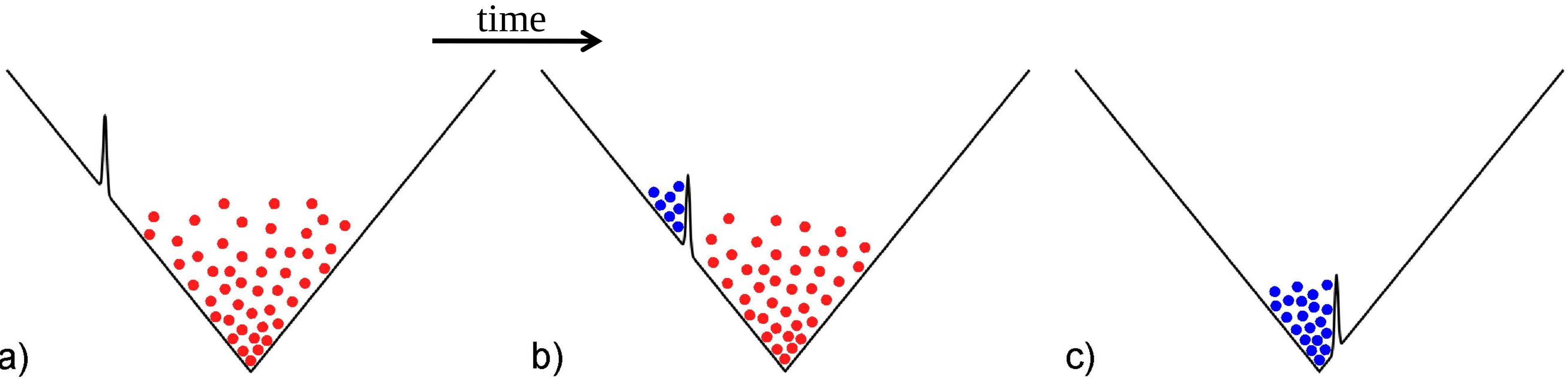
Single-photon cooling realizes Maxwell’s demon:
“Demon” discriminates coldest atoms and releases this info in a single scattered photon

Single Photon Cooling

Goal: Transfer atoms from a magnetic to an optical trap via emission of a single photon

- Slowly translate 1-way barrier so that you catch atoms at their classical turning points
- A spontaneous Raman emission could be such a 1-way barrier
- This cooling technique has been demonstrated on ^{87}Rb

G.N. Price, S.T. Bannerman, K. Viering, E. Narevicius, and M.G. Raizen. Phys. Rev. Lett. 100, 093004 (2008)

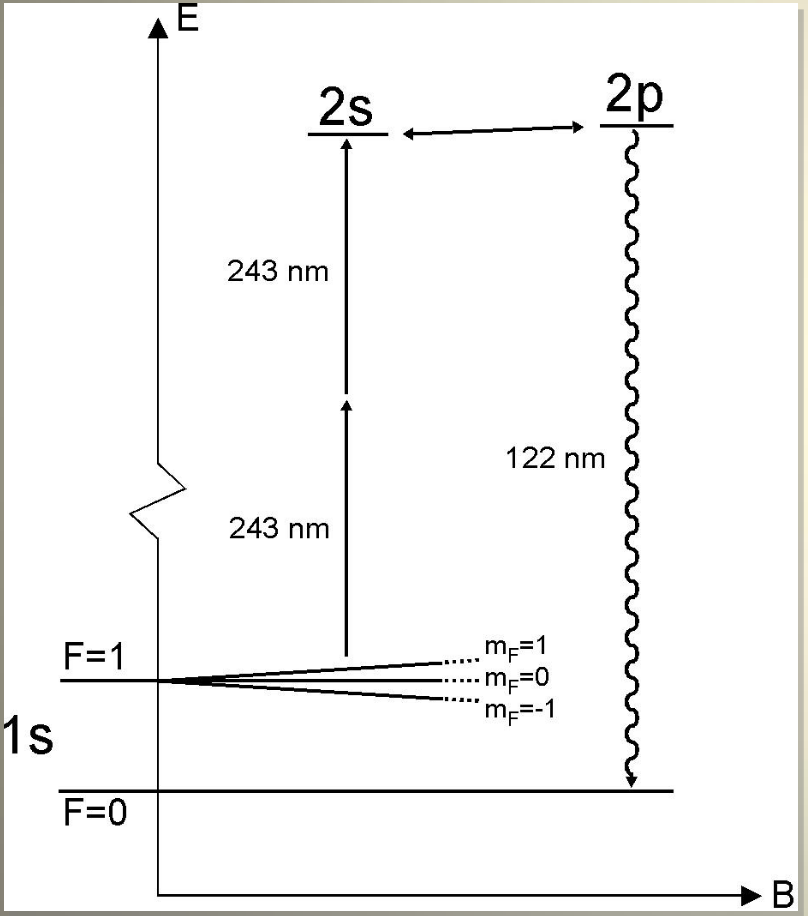


Correlation between position and momentum for $|\vec{v}_{dem}| \ll |\vec{v}_{ini}|$

10^{-1} cm s^{-1} 10^{2} cm s^{-1}

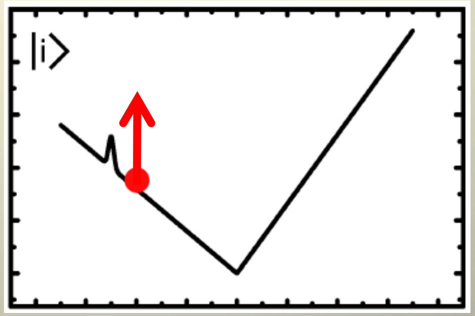
Single Photon Cooling

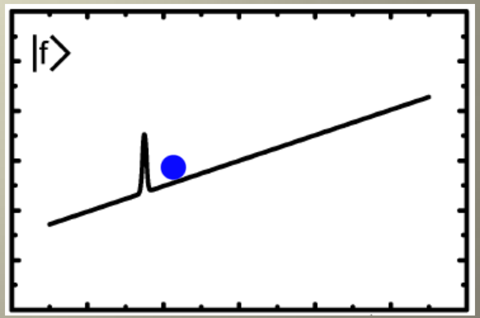
Allows creation of a tritium source with ~μK temperature



- "Demon" = gravito-optical trap + resonant pump beam
- Approach classical turning points slowly from the left
- If final state has weaker or opposite magnetic coupling, atom is trapped in optical trap

$$U = \mu_B g_F m_F \,|B| + mgz$$





Experimental options

A low-density source of trapped atoms allows the ion to escape as well as the β.

$$^{3}\mathrm{H} \rightarrow {}^{3}\mathrm{He}^{+} + e^{-} + \bar{\nu}_{e}$$

Source density < 10^{15} atoms/cm^{3}

Source column density < 10^{13} atoms/cm^{2}

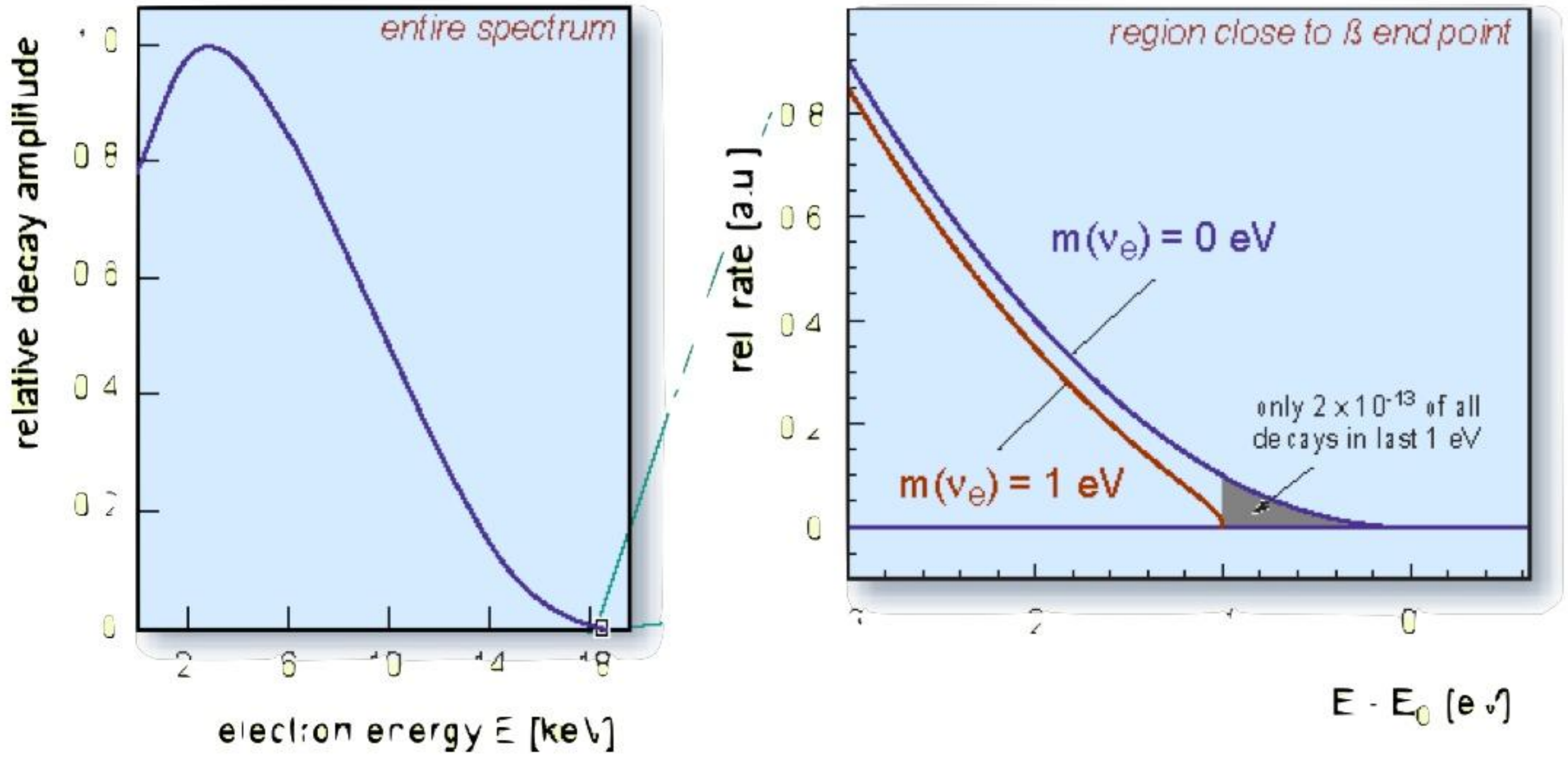
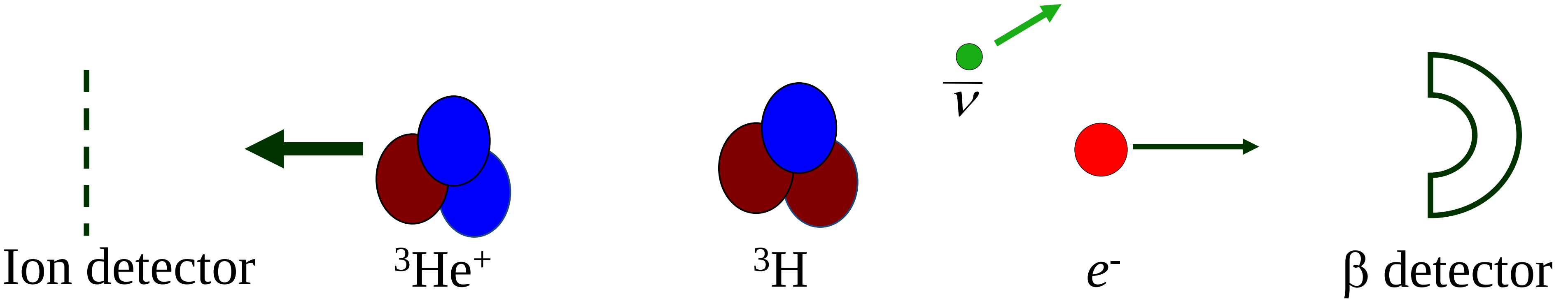


Figure: Osipowicz, A. et al. (KATRIN), arXiv:hep-ex/0109033

Tritium β-Decay

Direct reconstruction of the neutrino mass!



$$m_\nu^2 = (W - E_{ion} - E_\beta)^2 - (p_{x_{ion}} + p_{x_\beta})^2 - (p_{y_{ion}} + p_{y_\beta})^2 - (p_{z_{ion}} + p_{z_\beta})^2$$

- Thin source allows ion detection!
- Don’t have to rely only on beta spectrum
- Coincidence measurement ⇒ low backgrounds
- Atomic tritium ⇒ well-known final state corrections

Tritium β-Decay

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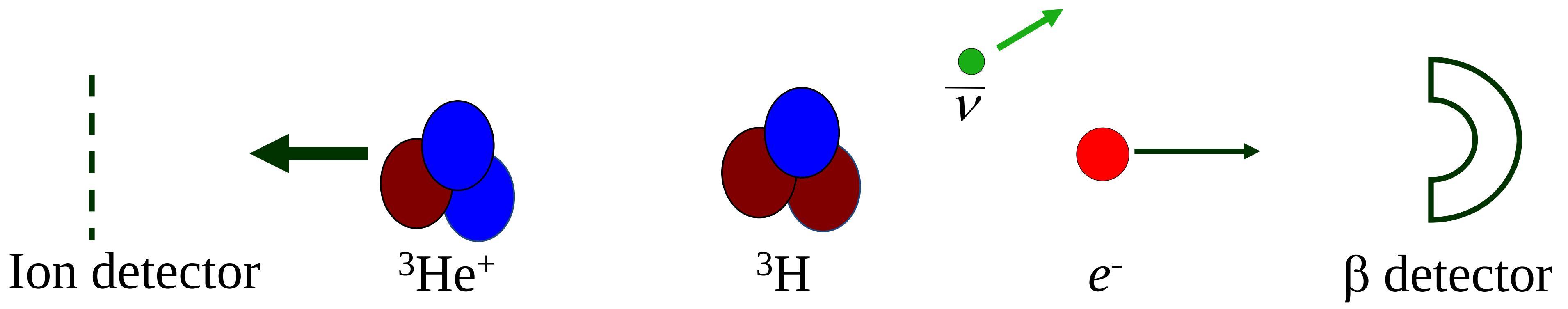


$$m_\nu^2 = (W - E_{ion} - E_\beta)^2 - (p_{x_{ion}} + p_{x_\beta})^2 - (p_{y_{ion}} + p_{y_\beta})^2 - (p_{z_{ion}} + p_{z_\beta})^2$$

Ion detector = Microchannel Plate

Ion detector

- θ and ϕ of ion
- TOF for ion

$p_{x_{ion}}$ $p_{y_{ion}}$ $p_{z_{ion}}$

(E_{ion} reconstructed from energy conservation)

β detector: hemispherical analyzer + optical lattice of Rydberg atoms

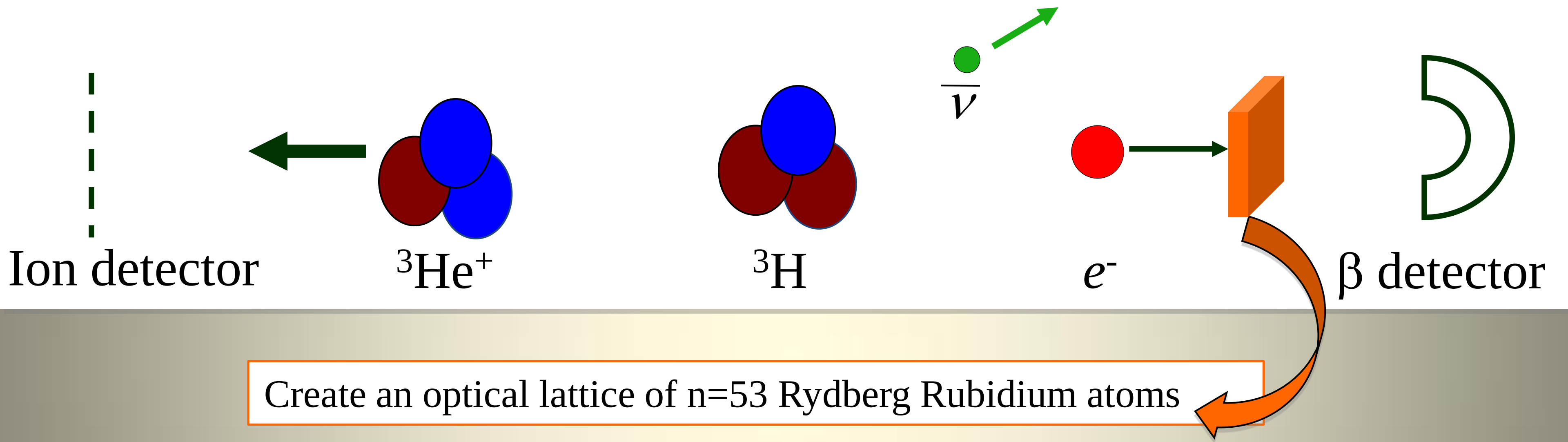
β spectrometer + Rydberg atoms

E_β p_{x_β} p_{y_β}

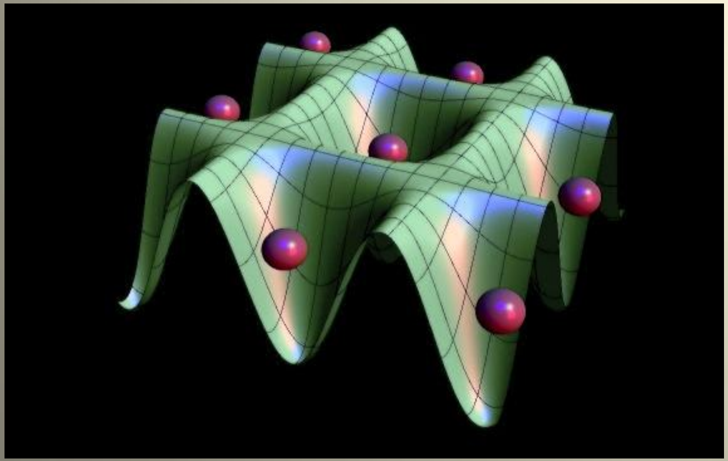
(p_{z_β} reconstructed from energy conservation)

Tritium β-Decay

Use Rydberg atoms to measure β momentum non-invasively:



Create an optical lattice of n=53 Rydberg Rubidium atoms

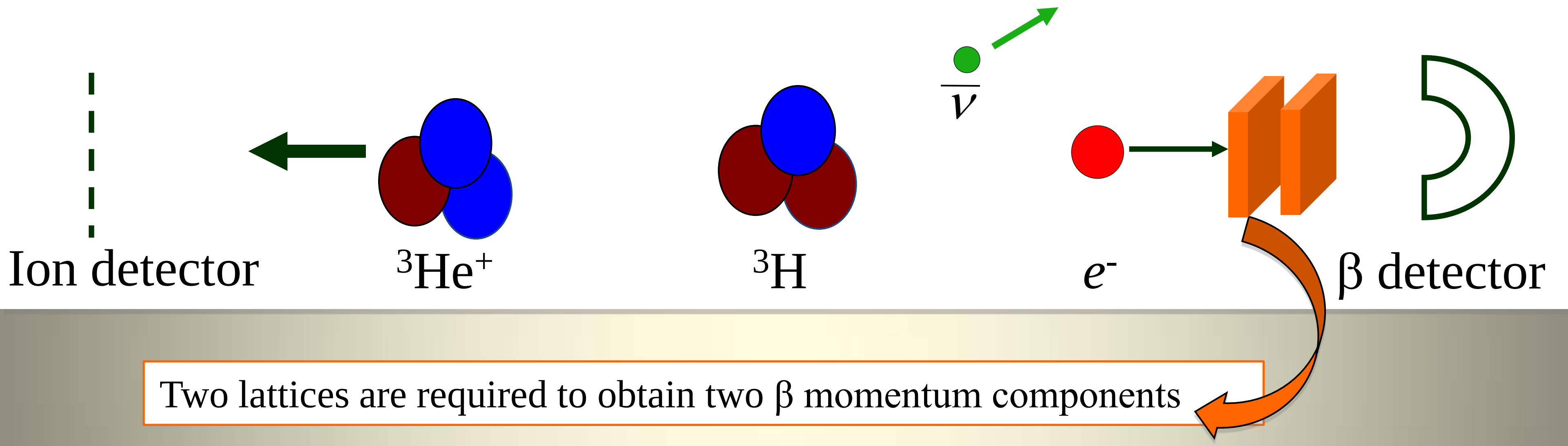


How do we measure the β's momentum?

1) Slow β down to < 900 eV after leaving source
2) Cross section for passing β to excite atom from 53s to 53p is: 0.36×10^{-9} cm^2
3) When spectrometer detects the β, the 53s atoms are optically de-excited using STIRAP
4) 100 V/cm is ramped to ionize the 53p atoms
5) MCP detects the ionized Rydberg atoms, giving us a 1D track projection of the β's path

Tritium β-Decay

Use Rydberg atoms to measure β momentum non-invasively:



Two lattices are required to obtain two β momentum components

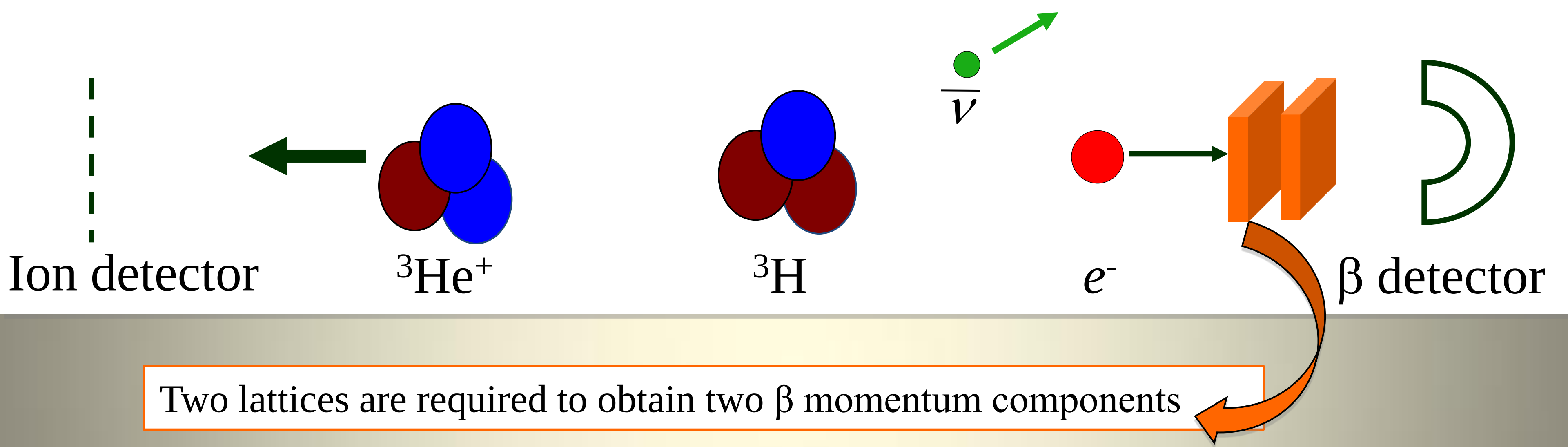
Combining θ and φ (from the lattice tracks) with β energy from spectrometer, we get β's x and y momentum components.

What about background events?

- Collisions ➔ Solved by putting the atoms in an optical lattice
- Blackbody radiation ➔ Solved by surrounding the lattice with a wire mesh whose spacing is small compared to microwave wavelength
- Additionally ➔ Atoms can be periodically cycled between the ground state and the n=53s state to avoid accumulating 53p backgrounds

Tritium β-Decay

Use Rydberg atoms to measure β momentum non-invasively:



Two lattices are required to obtain two β momentum components

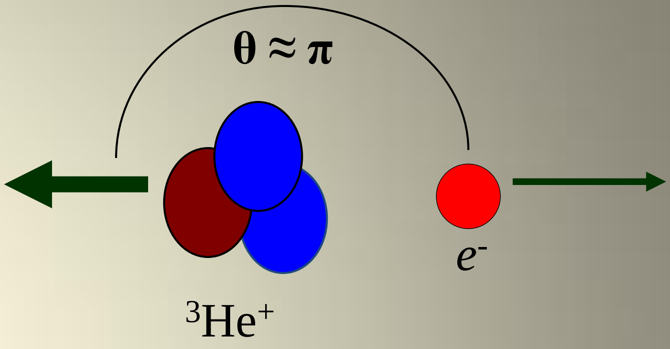
Lattice Specifications:

- Density of Rydberg atoms ~10^{11} atoms/cm^3
- Optical lattice size: 10 cm x 10 cm x 1 cm
- β excites an atom within ~5 microns as it transverses lattice
- Lattice positioned 2 m from the tritium source
- Momentum resolution varies from 40 meV/c to 2.7 eV/c

This non-invasive method may find other applications in the detection of low-energy β's.

Tritium β-Decay

What about the opening angle uncertainty?



$$\tilde{p}_\nu \cdot \tilde{p}_\nu = m_\nu^2 \qquad \tilde{p}_\nu + \tilde{p}_{ion} + \tilde{p}_\beta = \tilde{p}_{3H}$$

$$m_\nu^2 = \tilde{p}_\nu \cdot \tilde{p}_\nu = (\tilde{p}_{3H} - \tilde{p}_{ion} - \tilde{p}_\beta) \cdot (\tilde{p}_{3H} - \tilde{p}_{ion} - \tilde{p}_\beta)$$

$$m_\nu^2 = W^2 - 2WE_{ion} - 2WE_\beta + m_{ion}^2 + m_\beta^2 + 2|p_{ion}||p_\beta|\cos\theta$$

$$\delta\theta \frac{\partial m_\nu^2}{\partial\theta} = -2|p_{ion}||p_\beta|\sin\theta \qquad \sim \delta\theta \sin(\theta) 10^{10} (eV/c)^2$$

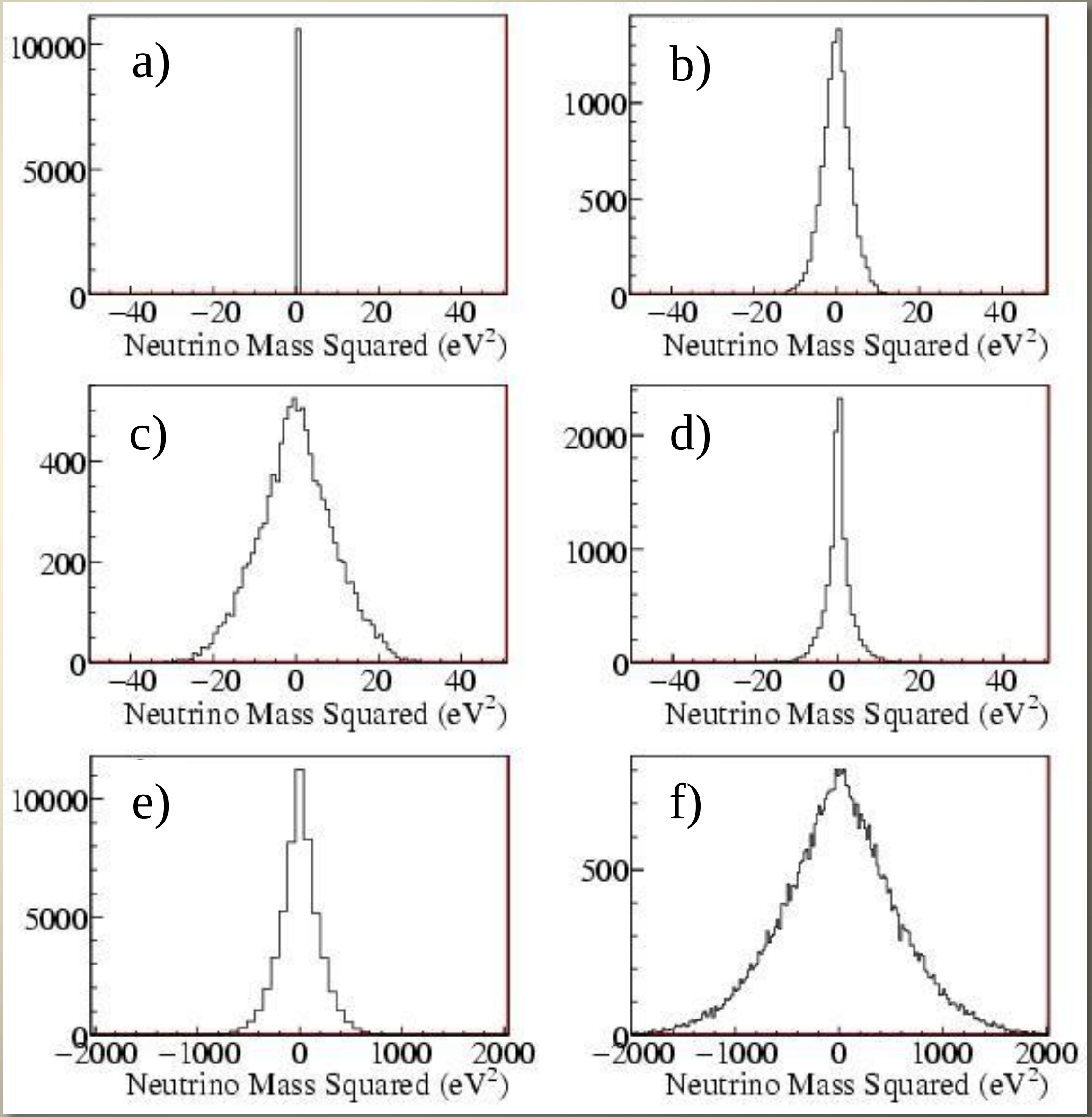
How do we avert disaster?

- Opening angle is almost π, which makes sinθ small
- The uncertainty of the mean goes like $1/N^{1/2}$
- $\delta\theta\sin(\theta)10^{10}\,(eV/c)^2 = 10^{-5}(\sin(\pi-10^{-4}))10^{10}\,(eV/c)^2 = 10\,(eV/c)^2$

Tritium β-Decay

Detector smearings of m_ν^2 peak:

a) No Smearing
b) β Energy Resolution
c) Ion's MCP binning
d) Ion's MCP timing
e) β Momentum Resolution
f) Initial tritium temperature



Tritium β-Decay

ROOT simulation: based on kinematics (no particle tracking)

What's in the simulation?

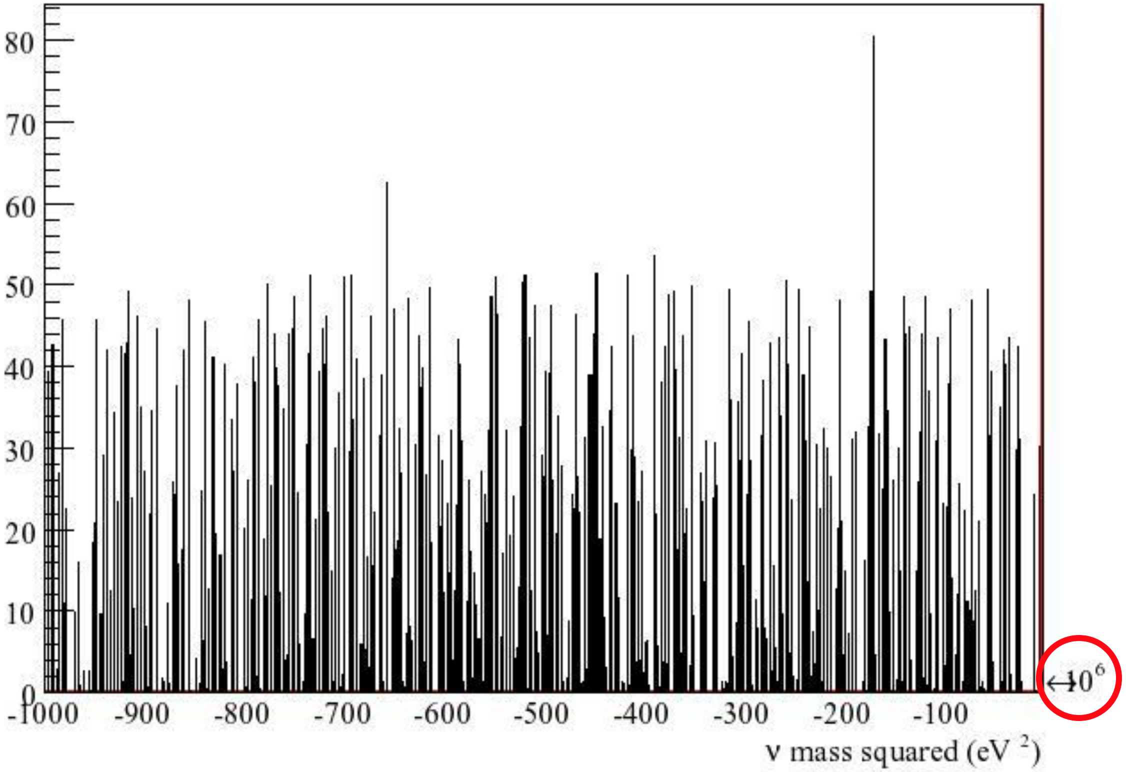
- atomic tritium source is 100μm diameter sphere
- Tritium source atoms at 1μK with a Gaussian momentum smear of width mkT
- Electron TOF Gaussian smear of 20ps
- Electron energy resolution of 5 meV
- Final state effects: ground state 70%, 1st excited state 30%
- 1 year assumed runtime
- Electron momentum resolution of 40 meV/c to 2.7 eV/c
- Geometrical acceptance for the β limited by optical lattice of Rydberg atoms 10 x 10 x 1 cm placed 2m from source
- MCP: 2 micron binning, 44% geometrical acceptance, 15 x 15 cm, placed 5m from source
- Ion TOF Gaussian smear of 20ps
- Gravity correction for the ion ~0.5 microns

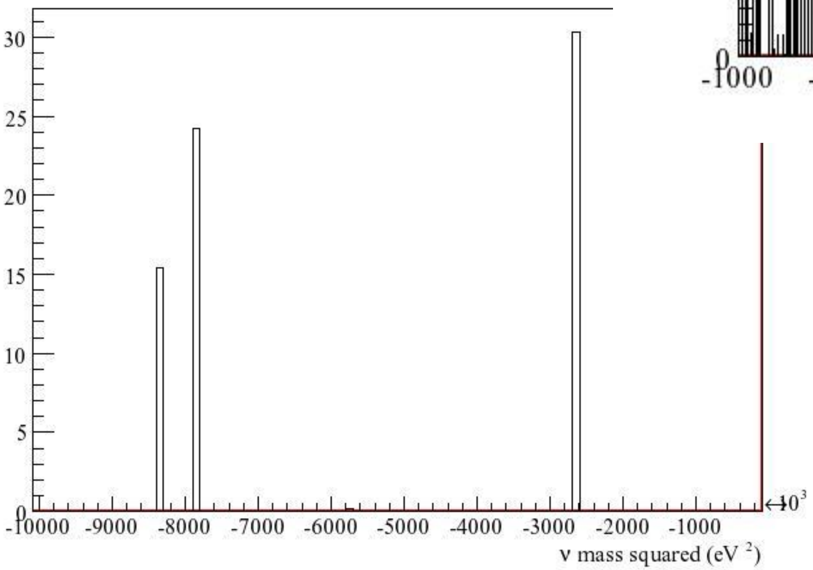
Tritium β-Decay

Background test:

- Randomize MCP hits
- Randomize ion TOF
- Leave beta unchanged

10^{-5} background rejection, not including β-coincidence
Coincidence time ~3 ms

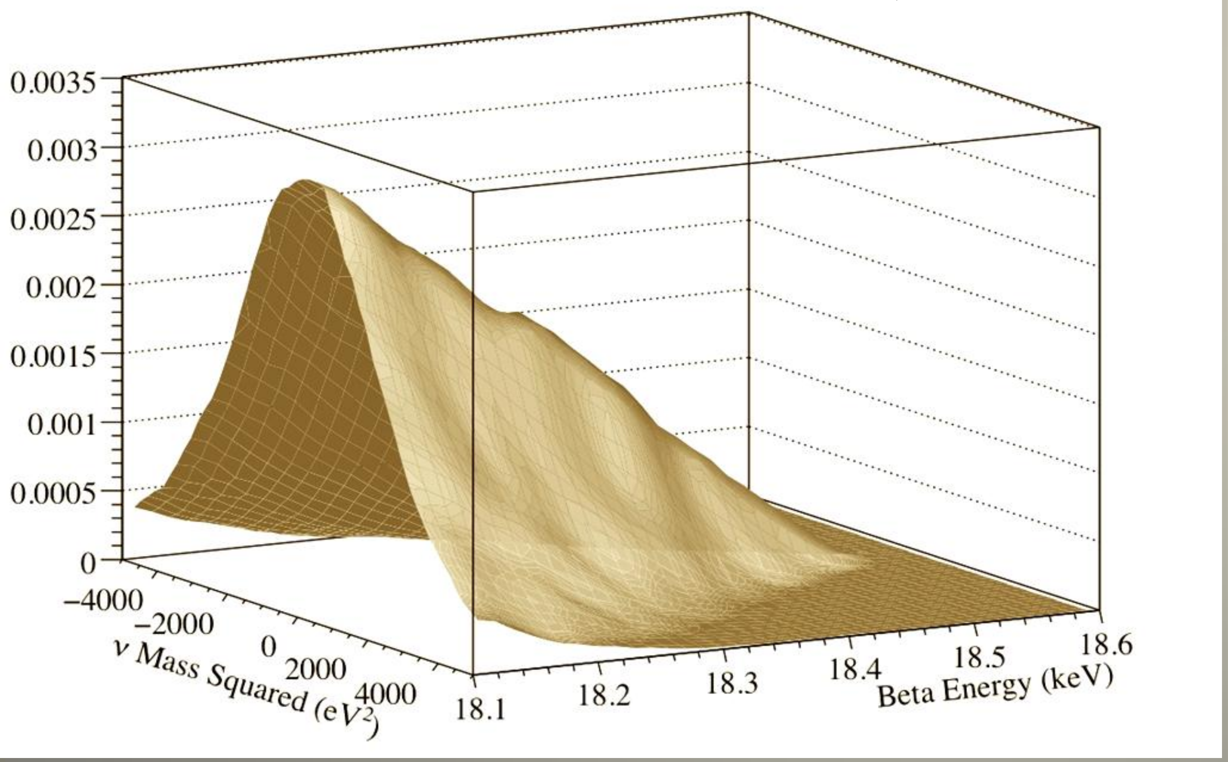




Magnitude of p_ν is increased 2-3 times, while E_ν changes only slightly → m_ν always reconstructs extremely negative for background events

Tritium β-Decay

- Fit utilizes data up to **500eV** away from the endpoint energy
- Minuit log-likelihood fit using 2D probability density functions (pdf)
- Find m_ν by interpolating between pdfs of different neutrino masses

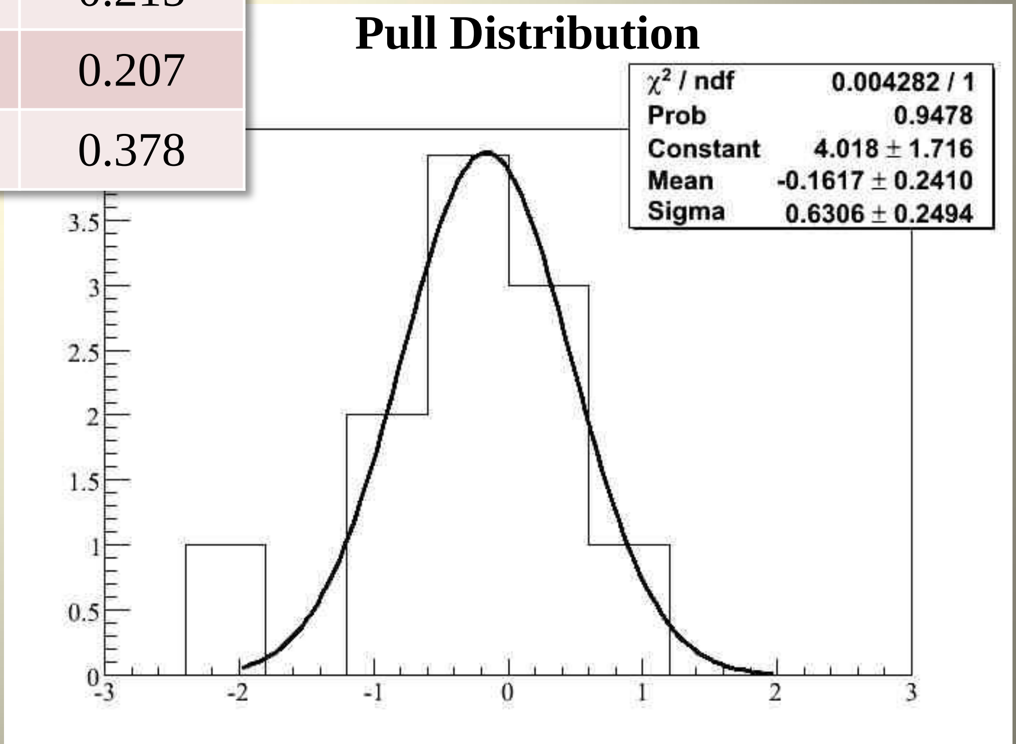


Probability distribution function with m_ν = 0eV

Statistics gained by moving far from the endpoint improve precision on m_ν even though the spread in reconstructed mass gets broader.

Tritium β-Decay

Assumed m_ν (eV)	Fit m_ν	(+) error	(-) error
0.2	0.239	0.174	0.153
0.4	0.354	0.166	0.150
0.6	0.690	0.270	0.203
0.8	0.794	0.247	0.215
1.0	0.813	0.246	0.207
5.0	5.188	0.402	0.378

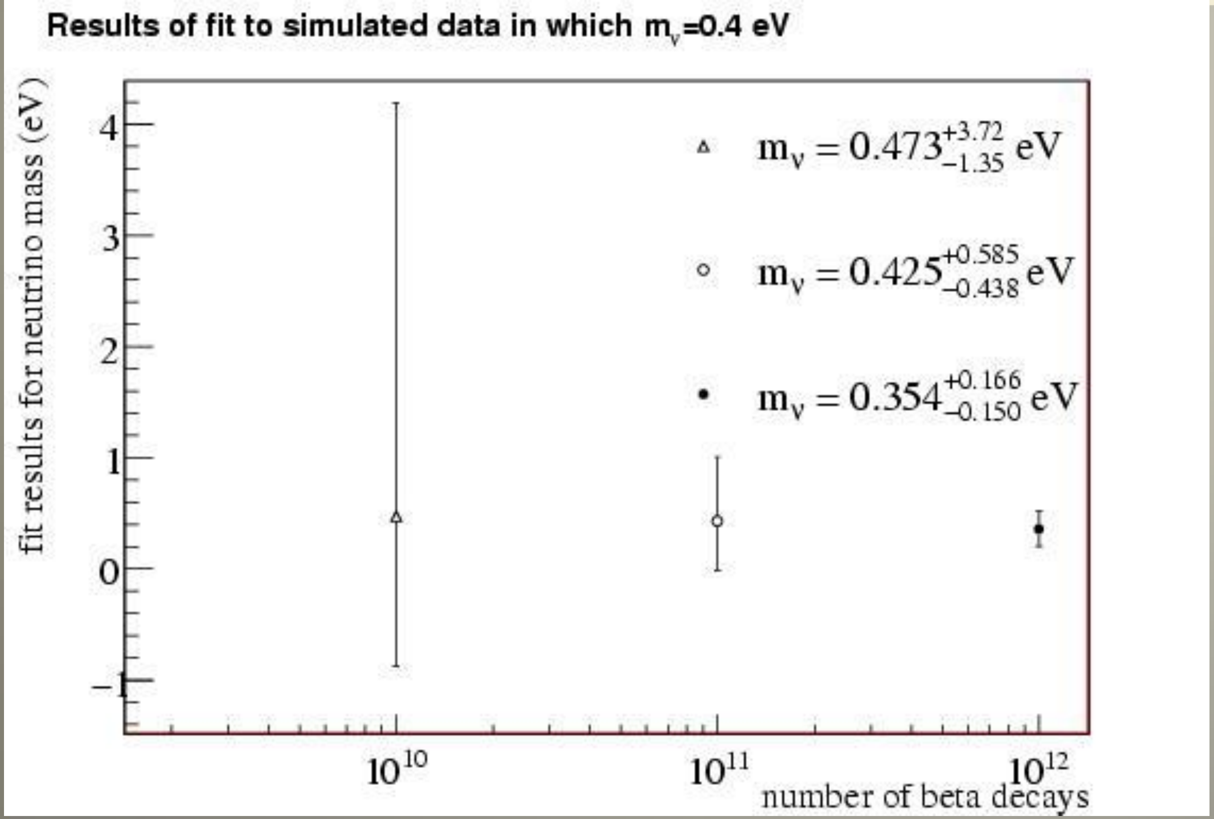


Results of a pull distribution of the neutrino mass fit results are consistent with a normal Gaussian.

Tritium β-Decay

What are the strengths of this technique?

- Extremely thin source → low scattering
- Atomic tritium → simpler final state effects
- β coincidence → low backgrounds
- Direct m_ν reconstruction & β-spectrum
- Utilizing data 500 eV from endpoint
- Valid for Dirac and Majorana neutrinos



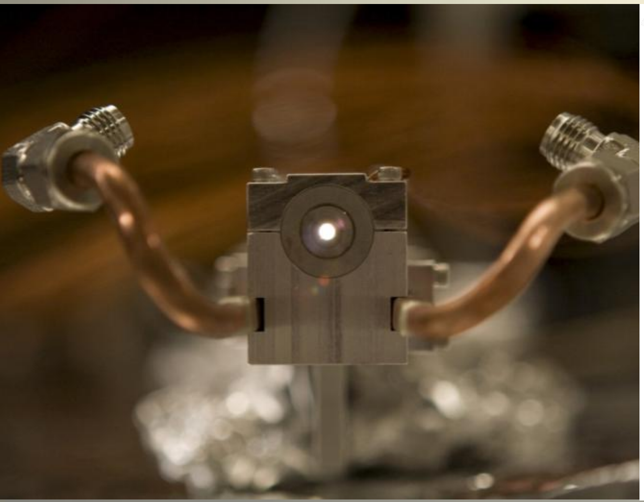
Trapping $2\text{x}10^{13}$ tritium atoms:

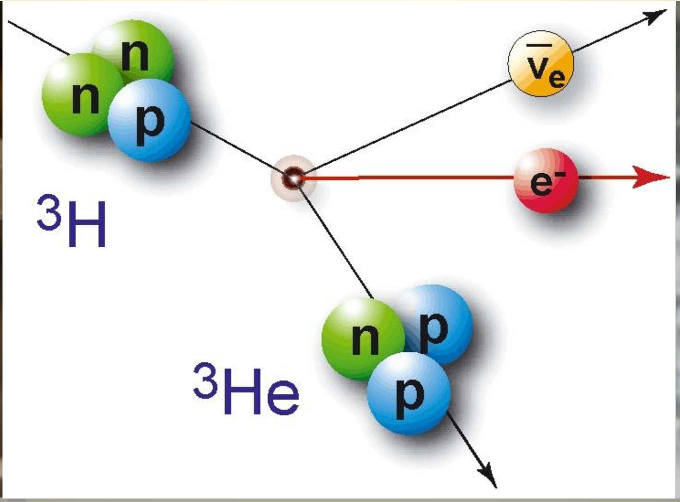
- Stack sources along a line by repeated launching & trapping
- Trap lifetimes of 5-10 minutes with cryogenic cold fingers and chamber bake-out
- Optical lattice of Rydberg atoms could be placed to aid in distinguishing sources for reconstruction

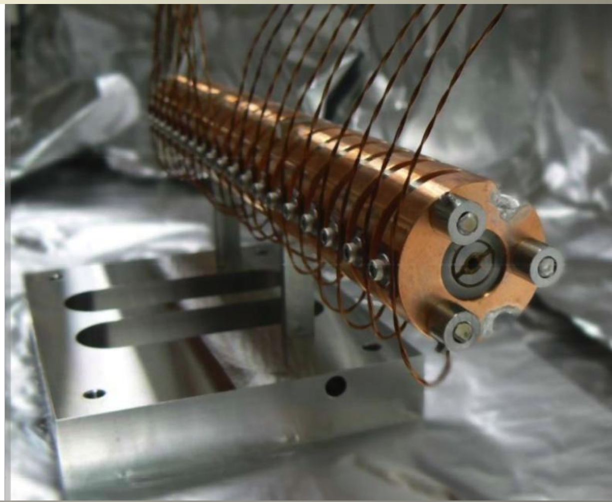
Conclusions

Slowing and trapping cold ^{3}H atoms $\rightarrow$ Fundamentally new way of measuring m_ν

- General slowing, trapping, & cooling methods present new opportunities
- Working towards the first atomic source ever utilized in tritium beta decay
- Rydberg atoms offer an innovative non-invasive momentum measurement technique
- Our proposed experiment could compete with KATRIN’s goal of limiting $m_\nu < 0.2$ eV





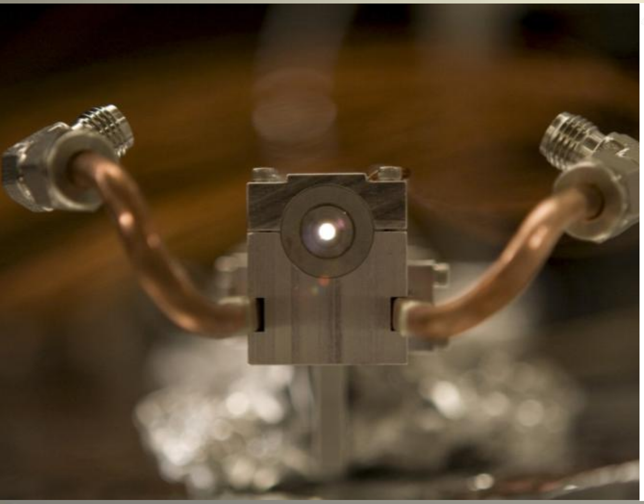


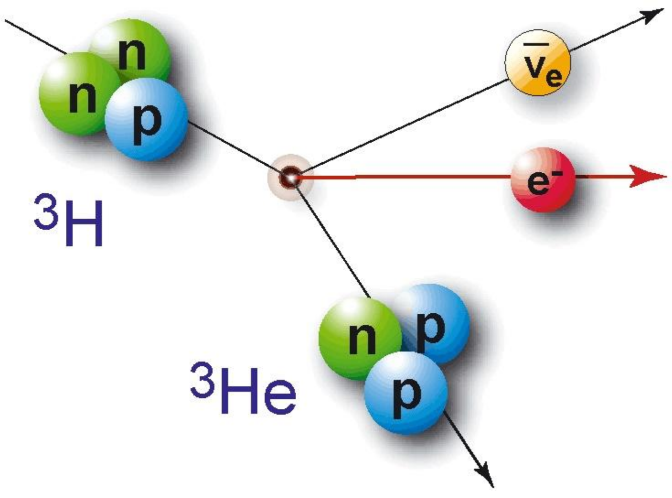
M. Jerkins, J. R. Klein, F. Robicheaux, J. H. Majors, and M. G. Raizen, arXiv:0901.3111v3

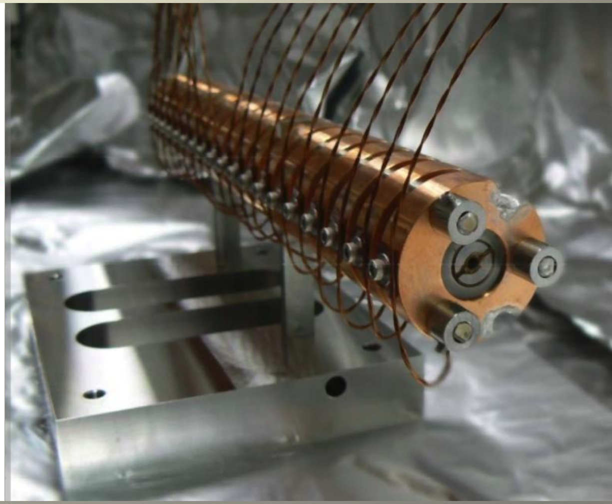
Special Thanks

Mark Raizen
Josh Klein
Francis Robicheaux
Julia Majors
Ed Narevicius

The Raizen Group
Center for Nonlinear Dynamics and Department of Physics
The University of Texas at Austin

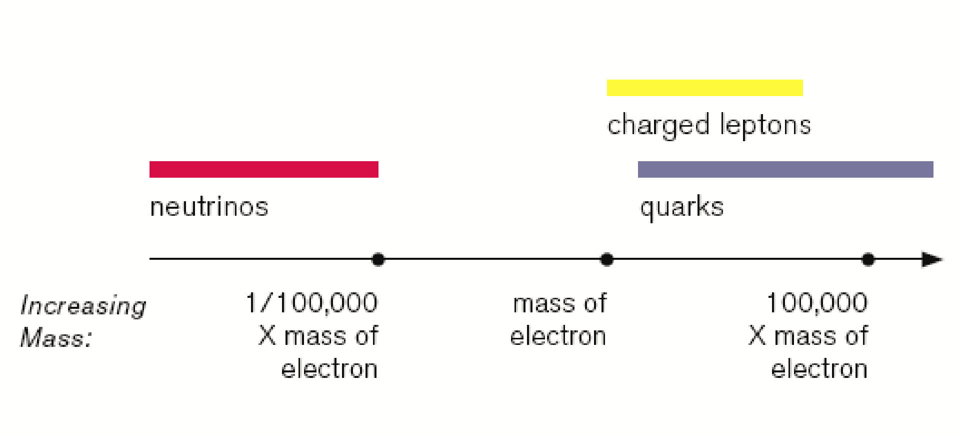


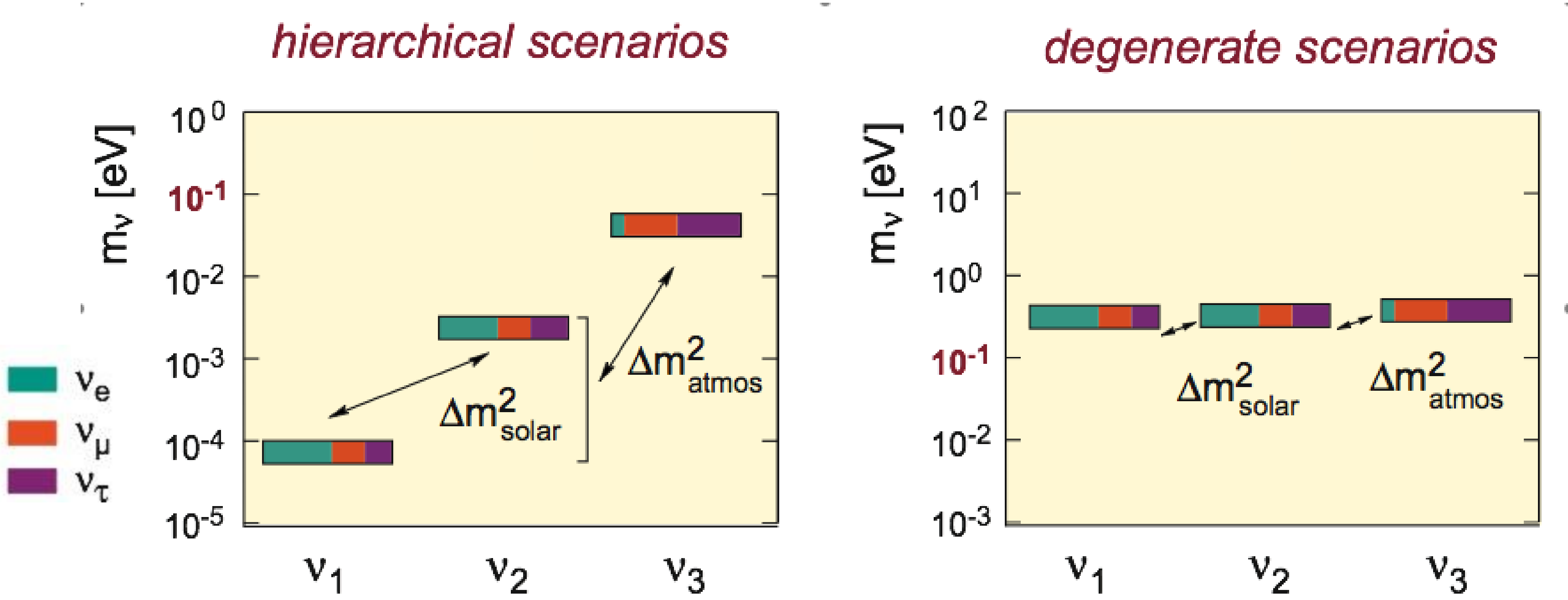




Neutrino Mass

- Are neutrino masses hierarchical or degenerate?
- Are neutrinos Dirac or Majorana particles?
- Why are neutrino masses so relatively small?

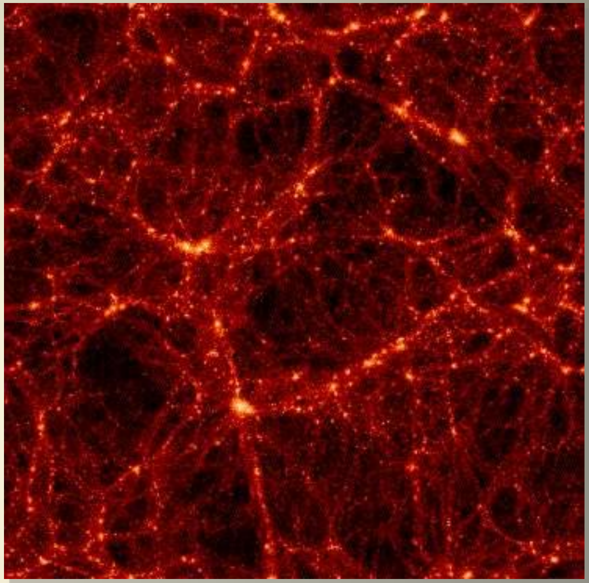




Neutrino Mass

Cosmology

Evolution of large scale structures

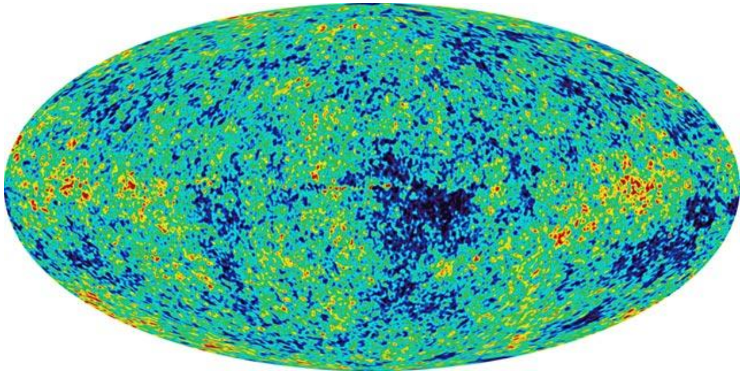


- Neutrinos = hot dark matter in the early universe

- Energy density parameter Ω of the universe: Experimental limits: $\Omega_\nu = 0.003 - 0.25$

- Fits for m_ν depend sensitively on other cosmological parameters

WMAP data has been fit with cosmological models that estimate $\sum m_\nu \leq 0.6$ eV



Experimental options

Tritium beta decay

What about neutrino mixing?

$$N(E) = \frac{dN}{dE} = K \times F(E,Z) \times p \times E \times \sqrt{(E_0 - E)^2 - m_\nu^2} \times (E_0 - E)$$

$$|U_{ei}|^2 = |\langle \nu_e | \nu_i \rangle|^2$$

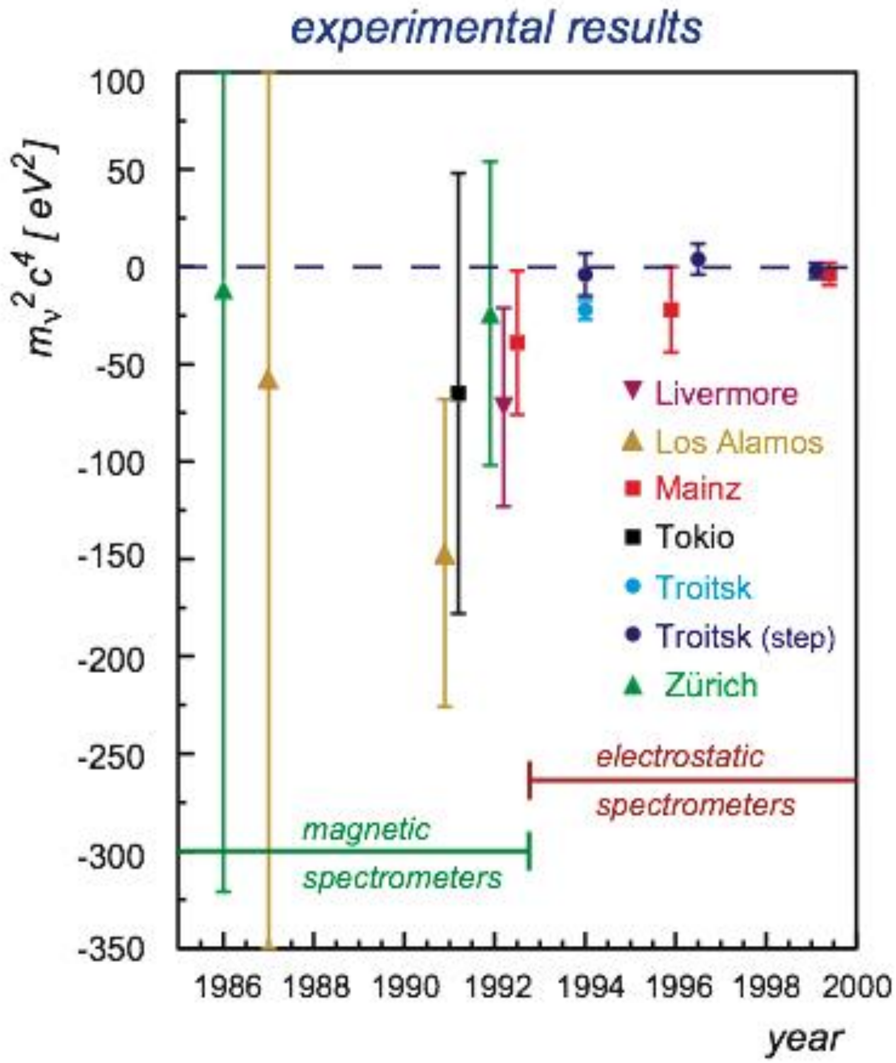
m_ν^2 = “mass” of the electron (anti-)neutrino = $\boldsymbol{\Sigma\, |U_{ei}|^2\, m_i^2}$

The measured neutrino mass from tritium beta decay would **fix the absolute neutrino mass scale** in a degenerate model

Double beta decay experiments actually measure: $m_\nu = \left|\Sigma\, |U_{ek}|^2\, e^{i\alpha_{ek}} m_k\right|$
Majorana CP-phases are unknown ⇒ cancellations could occur

Previous Experiments

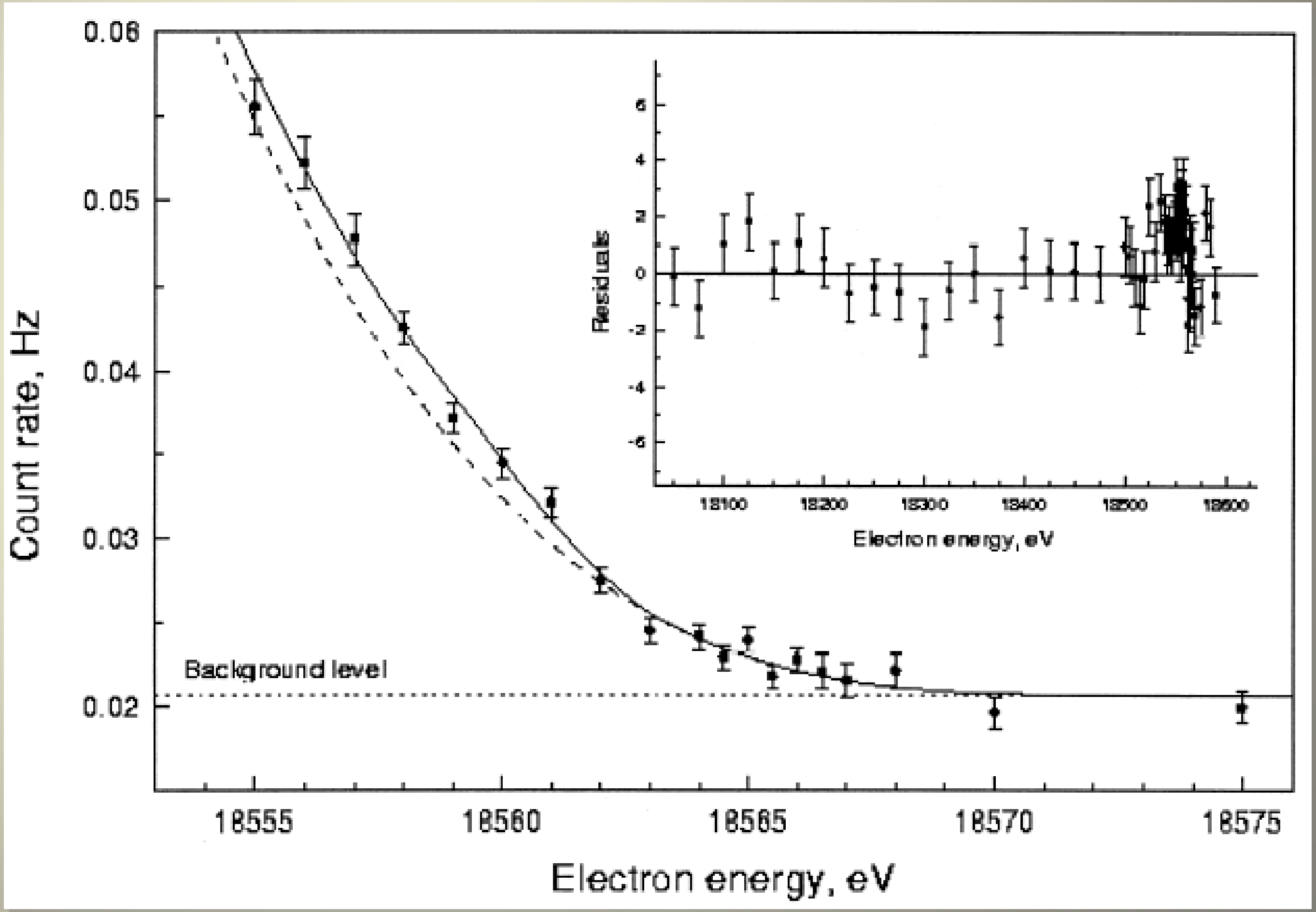
	m_ν
ITEP *T_2 in complex molecule* *magn. spectrometer (Tret'yakov)*	17-40 eV
Los Alamos *gaseous T_2 - source* *magn. spectrometer (Tret'yakov)*	< 9.3 eV
Tokio *T - source* *magn. spectrometer (Tret'yakov)*	< 13.1 eV
Livermore *gaseous T_2 - source* *magn. spectrometer (Tret'yakov)*	< 7.0 eV
Zürich *T_2 - source impl. on carrier* *magn. spectrometer (Tret'yakov)*	< 11.7 eV
Troitsk (1994-today) *gaseous T_2 - source* *electrostat. spectrometer*	< 2.5 eV
Mainz (1994-today) *frozen T_2 - source* *electrostat. spectrometer*	< 2.2 eV



Previous Experiments

Troitsk and Mainz

- Obtained m_ν by fitting the beta spectrum
- Parameters were m_ν, endpoint energy, background, and normalization

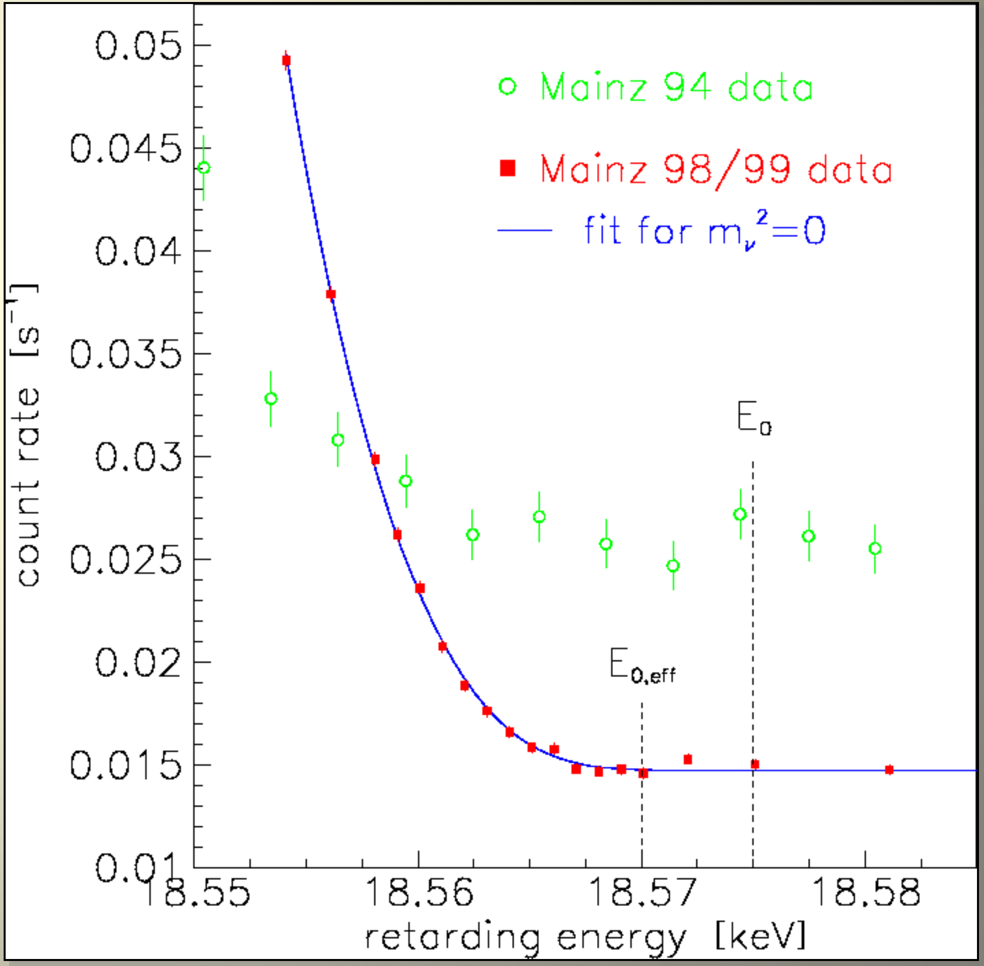


Previous Experiments

Troitsk and Mainz: $m_\nu < 2.2$ eV

Limiting Factors:

- Statistics
- Scattering in source
- Backgrounds
- Energy resolution
- Electronic final state effects
- Tritium source uncertainties



Previous Experiments

Troitsk & Mainz breakthrough technology: MAC-E-Filter

guiding by magnetic fields

(*magnetic adiabatic collimation*)

$\Delta\Omega \sim 2\pi$

electric (retarding-) field :

analysis of electron energies

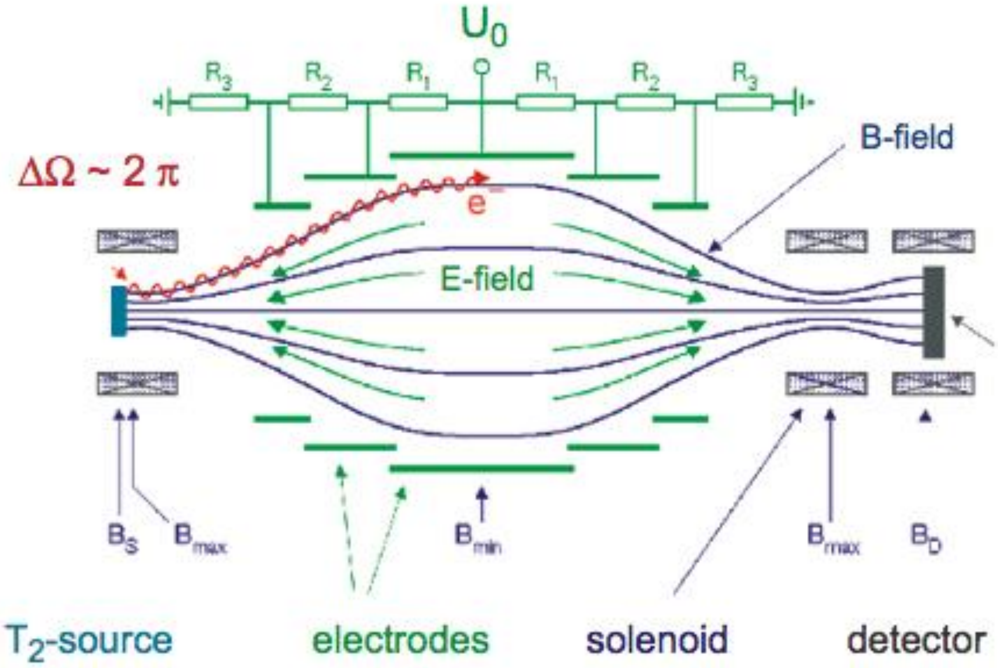
(*electrostatic filter*)

integral transmission : $E > U_0$

$$\vec{F} = (\vec{\mu} \cdot \vec{\nabla})\,\vec{B} + q\,\vec{E}$$

$$\mu = E_\perp / B = \text{const}$$

adiabatic motion



E || B

adiabatic transformation $E_\perp \rightarrow E_{||}$

Current Experiments

KATRIN

- Factor of 4 improvement in energy resolution over Troitsk and Mainz
- Increased T_2 source strength (factor 80)
- Low background of 10^{-2} counts/s or less is required
- Reduced inelastic scattering events to 2% of signal rate by looking only at the last 25 eV below the endpoint
- Pre-spectrometer rejects all electrons except those close to the endpoint, reducing the count rate to ~ 1000/s

Sensitivity (90% CL)
$m_\nu < 0.2$ eV

Discovery (95% CL)
$m_\nu < 0.35$ eV

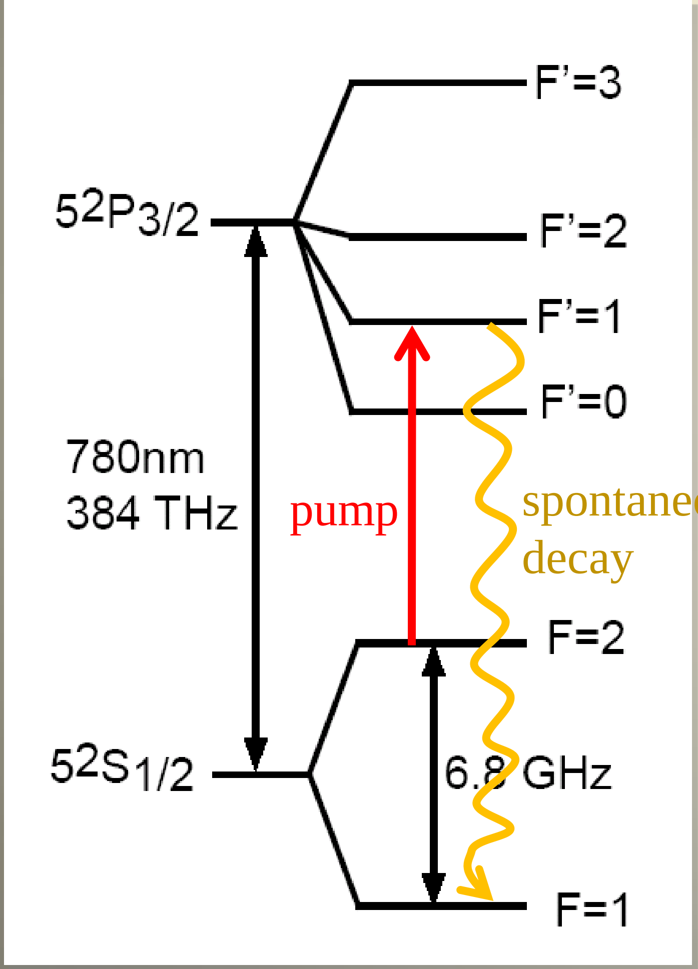
Current Experiments

KATRIN: Karlsruhe Tritium Neutrino Experiment	**MARE:** Microcalorimeter Arrays for a Rhenium Experiment
External β-source (^{3}H)	β-source = detector (^{187}Re)
^{3}H endpoint = 18.6 keV	^{187}Re endpoint = 2.6 keV
^{3}H half-life = 12.3 years	^{187}Re half-life = $5\text{x}10^{10}$ years
Energy: electrostatic spectrometer	Energy: single crystal bolometer
Measures kinetic energy of β	Measure entire decay energy
Narrow interval close to E_o	Measure entire spectrum
Integrated β-energy spectrum	Differential β-energy spectrum
Integral design, size limits	Modular size, expandable
$\Delta E_{expected} = 0.93$ eV	$\Delta E_{expected} \sim 5$ eV (FWHM)

Is there another approach to directly measuring m_ν?

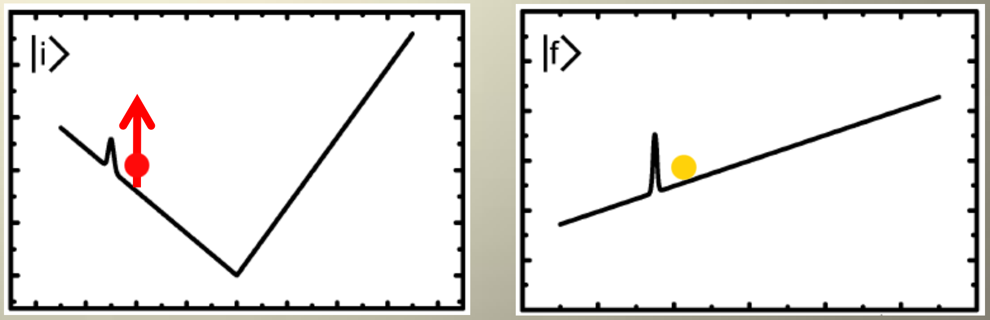
Single Photon Cooling

Allows creation of a tritium source with ~μK temperature



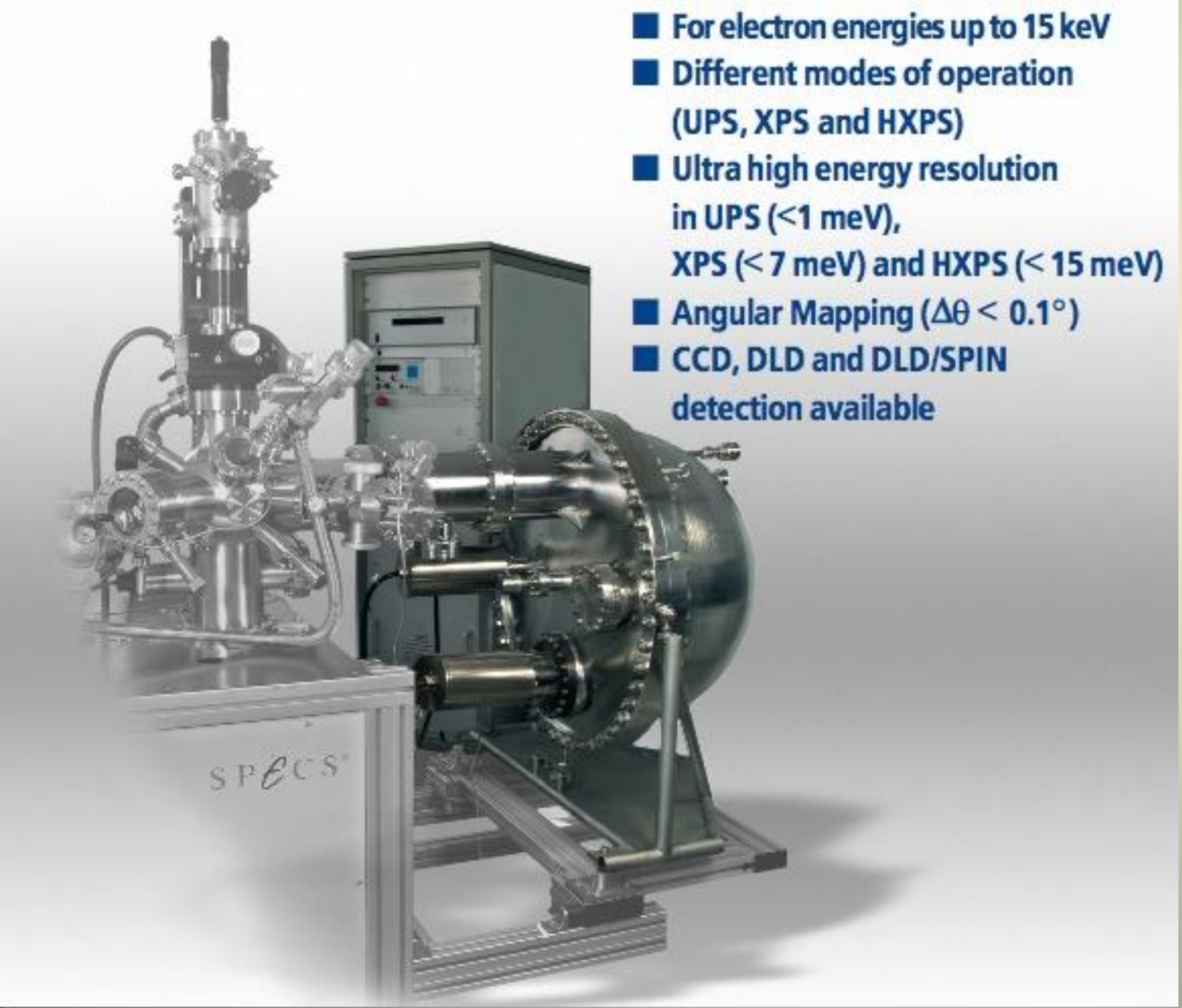
- "Demon" = gravito-optical trap + resonant pump beam
- Approach classical turning points slowly from the left
- If final state has weaker or opposite magnetic coupling, atom is trapped in optical trap

$$U=\mu_B g_F m_F\,|B|+mgz$$



Tritium β-Decay: 3-Body

PHOIBOS hemispherical analyzer 225 HV



- For electron energies up to 15 keV
- Different modes of operation (UPS, XPS and HXPS)
- Ultra high energy resolution in UPS (<1 meV), XPS (< 7 meV) and HXPS (< 15 meV)
- Angular Mapping ($\Delta\theta < 0.1°$)
- CCD, DLD and DLD/SPIN detection available

- 15 keV energy
- Small geometrical acceptance
- Potential calibration source: ^{83m}Kr conversion electron with energy of 17.8 keV and width of 2.7 eV

Tritium β-Decay: 3-Body

Burle 2-micron MCP detector

We need:

- 2-10 μm spacing
- ~20ps timing
- Large area: ~ 1m wide x 20cm tall

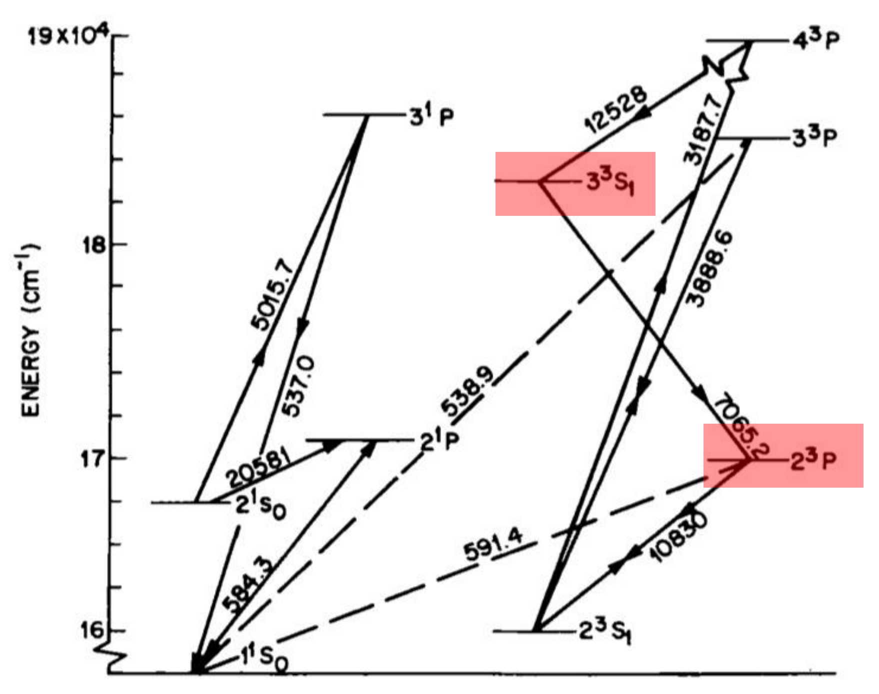
- Detects position and time-of-flight (TOF)
- 2 micron holes spaced 3 microns center-to-center
- 350 ps pulse width resolution

Boundstate β-Decay: 2-Body

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

$$v_{Recoil} = \frac{\left[\,(M_{^3\mathrm{H}} - M_{^3\mathrm{He}})^2 \; - \; (\boldsymbol{m_\nu}\, c^2)^2\,\right]^{1/2}}{M_{^3\mathrm{He}}\, c}$$

- Measure ^{3}He recoil velocity
- 0.69% of all ^{3}H decays are boundstate
- 3% of boundstate He^3 atoms are in an excited state and emit a 706.52nm photon



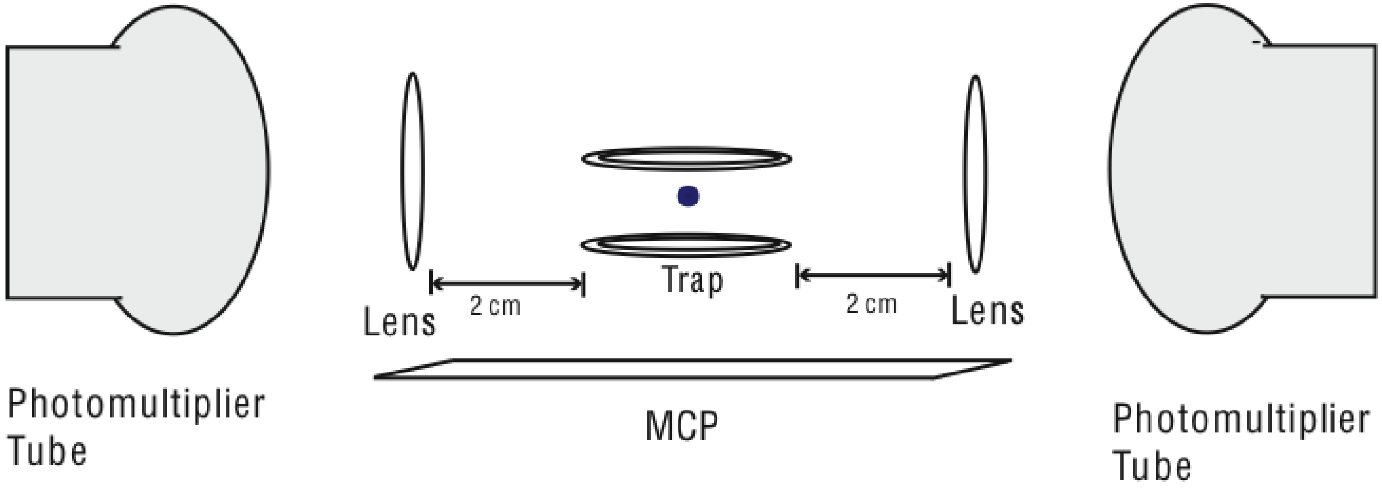
Boundstate β-Decay: 2-Body

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

$$v_{Recoil} = \frac{\left[\,(M_{^3\mathrm{H}} - M_{^3\mathrm{He}})^2 \;-\; (m_\nu c^2)^2\,\right]^{1/2}}{M_{^3\mathrm{He}}\,c}$$

- Measure ^{3}He recoil velocity
- 0.69% of all ^{3}H decays are boundstate
- 3% of boundstate He^{3} atoms are in an excited state and emit a 706.52nm photon

Detect photon from ^{3}He atom & ^{3}He TOF to MCP



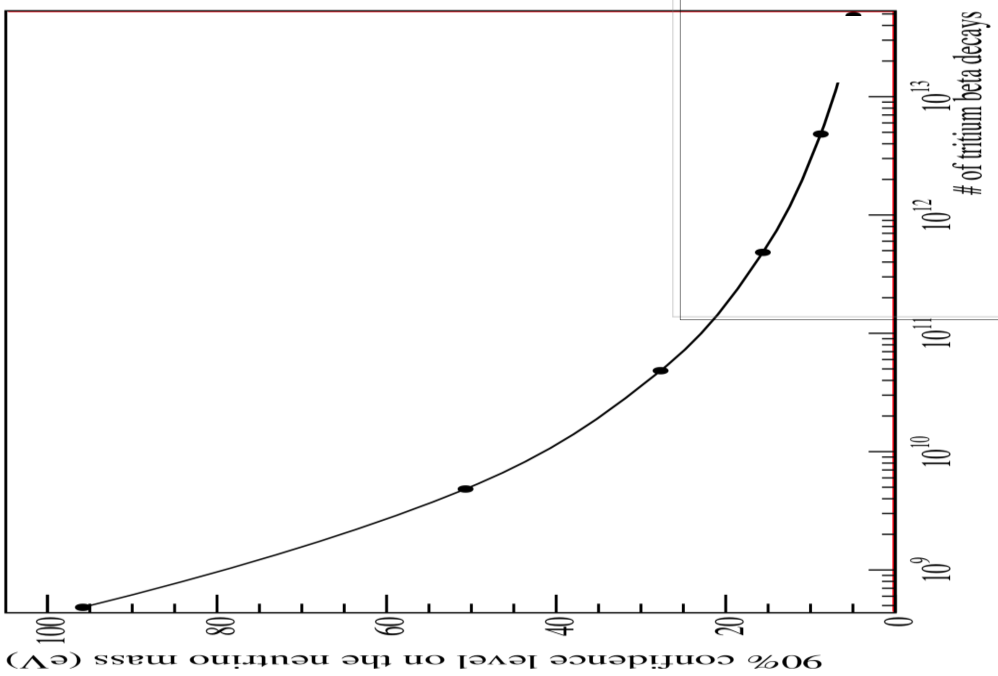
Boundstate β-Decay: 2-Body

Boundstate beta decay does not currently offer a competitive limit on m_ν.

90%CL on m_ν vs. # of tritium β decays

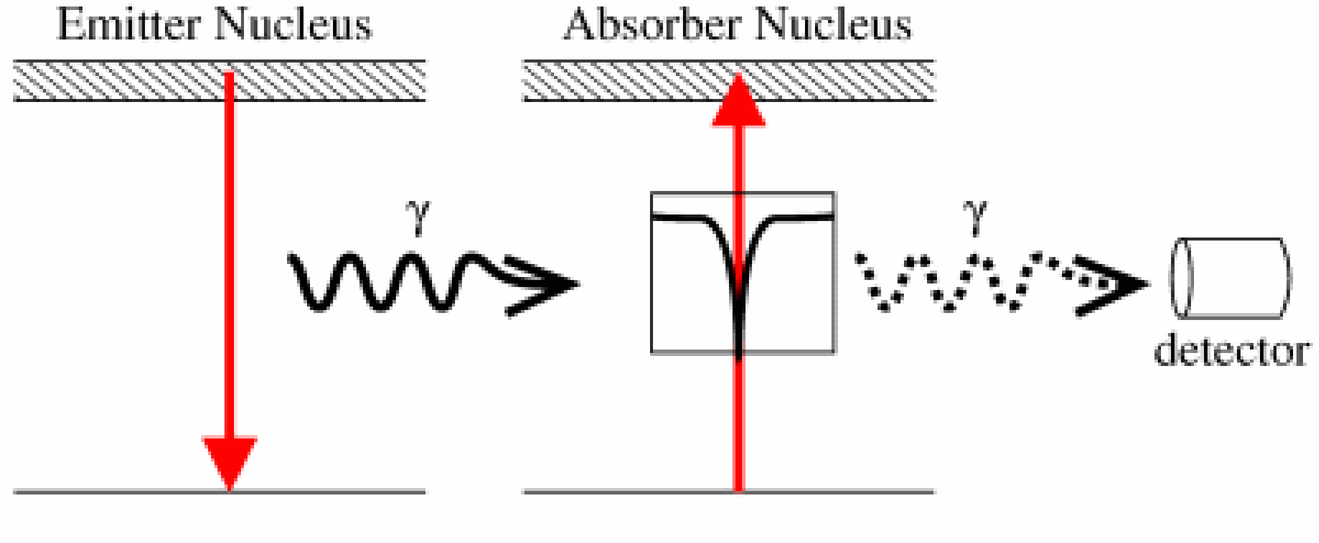
- Given sufficient statistics, the fit is very accurate
- But even with 10^{13} decays, the 90%CL is only 8.8eV

Simulation m_ν=20eV,   Fit m_ν=19.6eV



Mössbauer Neutrinos: 1-Body

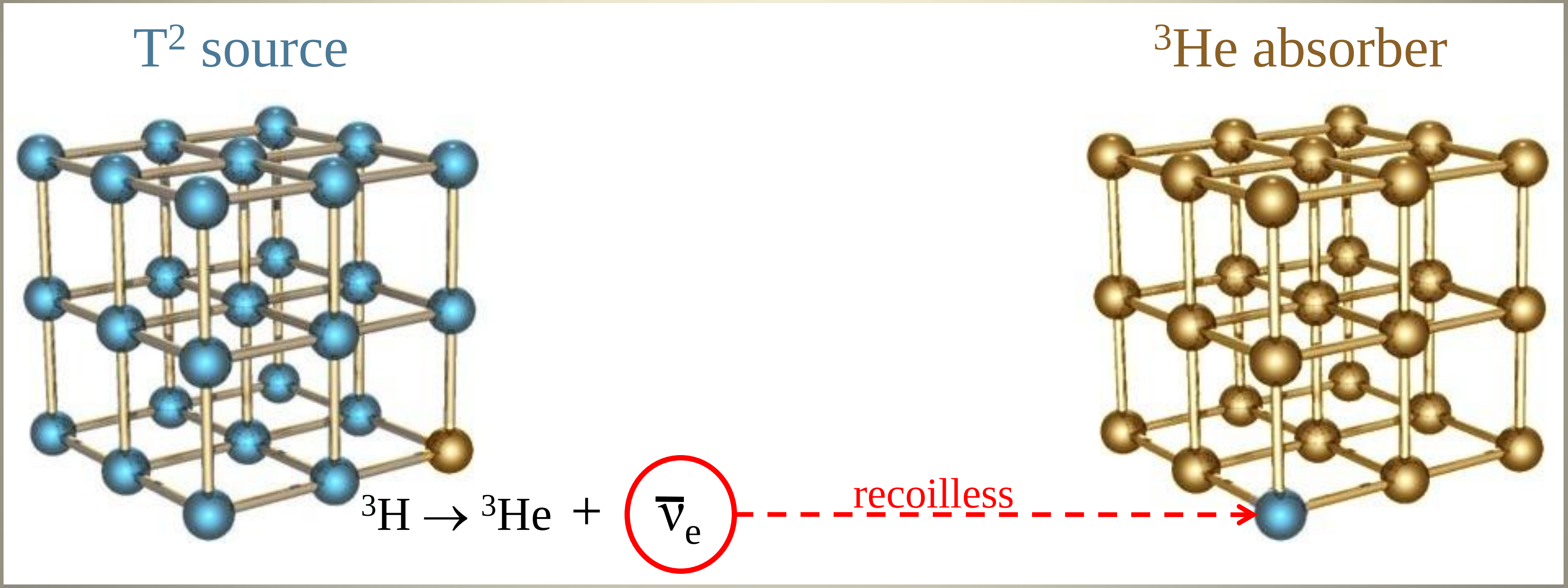
Ordinary Mossbauer effect: photons emitted recoillessly by one nucleus can be resonantly absorbed by another nucleus of the same type



Nuclei must be bound in a lattice for significant recoilless emission or absorption.

Mössbauer Neutrinos: 1-Body

ν's emitted recoillessly from boundstate decay of ^{3}H can be resonantly absorbed by ^{3}He



Boundstate tritium beta decay:

$$^3\text{H} \rightarrow {}^3\text{He} + \bar{\nu}_e$$

Reverse tritium beta decay:

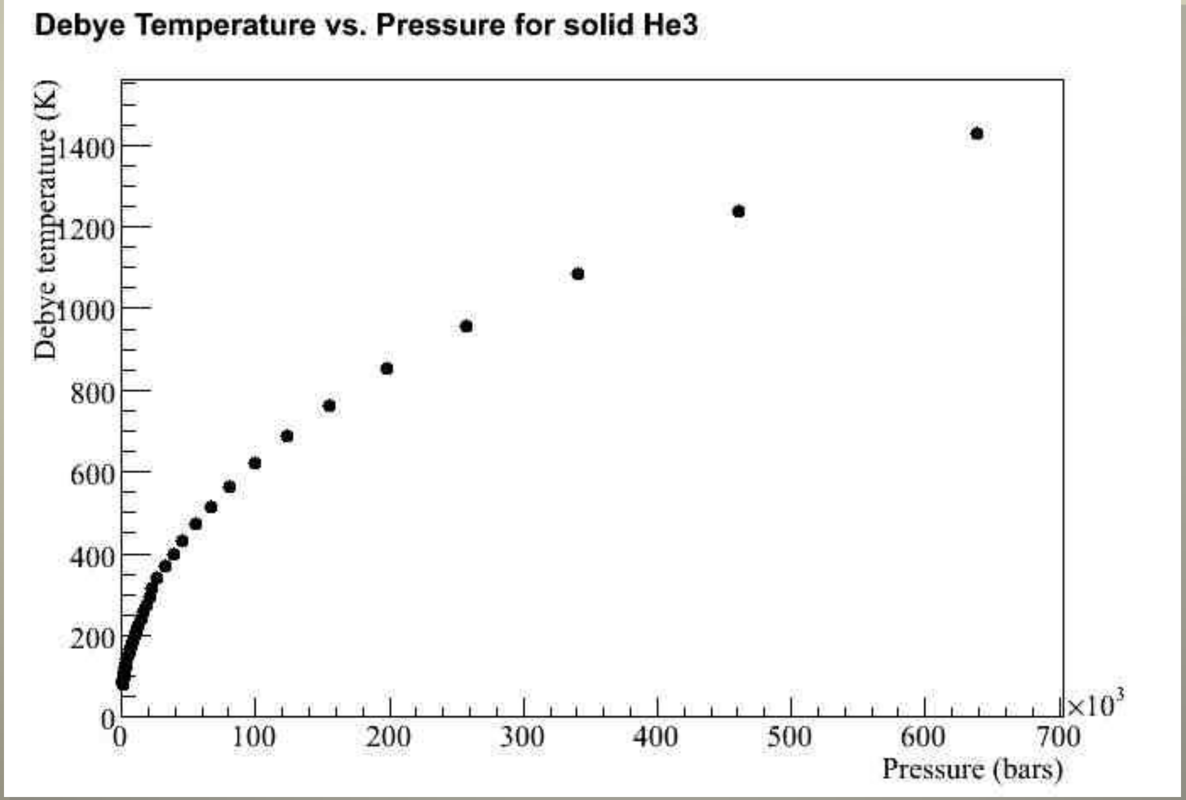
$$\bar{\nu}_e + {}^3\text{He} \rightarrow {}^3\text{H}$$

Mössbauer Neutrinos: 1-Body

Debye temperature = temperature of a crystal's highest normal mode of vibration

$f_{recoilless} = \exp\{ (-E^2/(2Mc^2))*(3/2k_B\theta_D) \}$ where θ_D is the Debye temperature

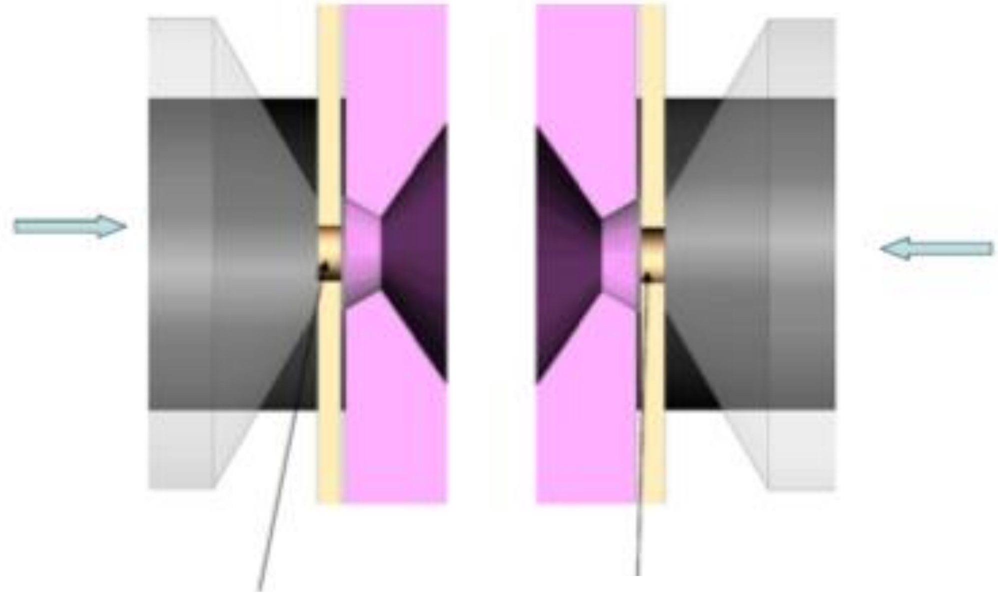
We can get a very high Debye temperature by going to high pressures



Mössbauer Neutrinos: 1-Body

- High pressures raise the Debye temperature, which increases $f_{recoilless}$
- Volume not likely to exceed $0.004 cm^3$

2 Diamond Anvil Cells placed ~1-4cm apart



^{3}He detector @10GPa
V = $0.004 cm^3$

T_2 source @10GPa
Source ~29Cu

Mössbauer Neutrinos: 1-Body

Tuning the pressure allows us to align emission & absorption peaks!

$\sigma_{resonant} = 4.18 * 10^{-41} * g_o^{\;2} * \rho(E^{res}{}_{\nu_e}) / ft_{1/2} \approx \mathbf{10^{-32} cm^2}$

(assuming linewidth ~10^{-12}eV)

- Linewidth dominated by inhomogeneous broadening (impurities, lattice defects, ect.)

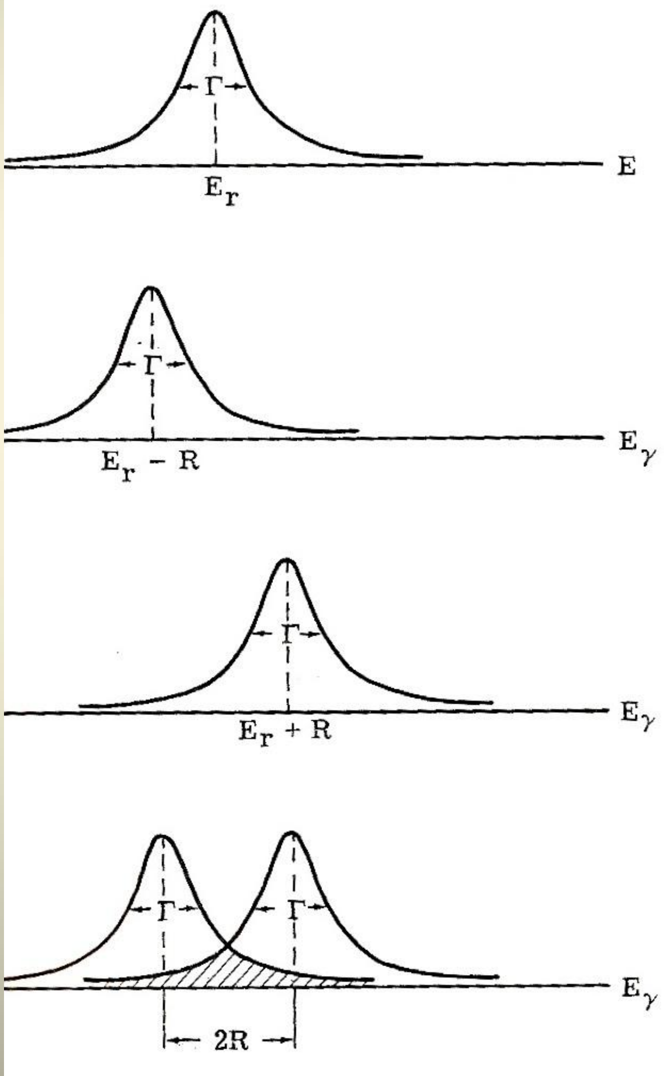
- Narrow linewidth implies we must be able to tune energy shifts to observe resonance

- Very cold temperatures reduce Doppler shifts

- Isomer shift (from changes in atomic radius) can be canceled by zero-point energy shift:

$$\Delta E/E = (9k_B/16Mc^2) * (\theta_{emitter} - \theta_{absorber})$$

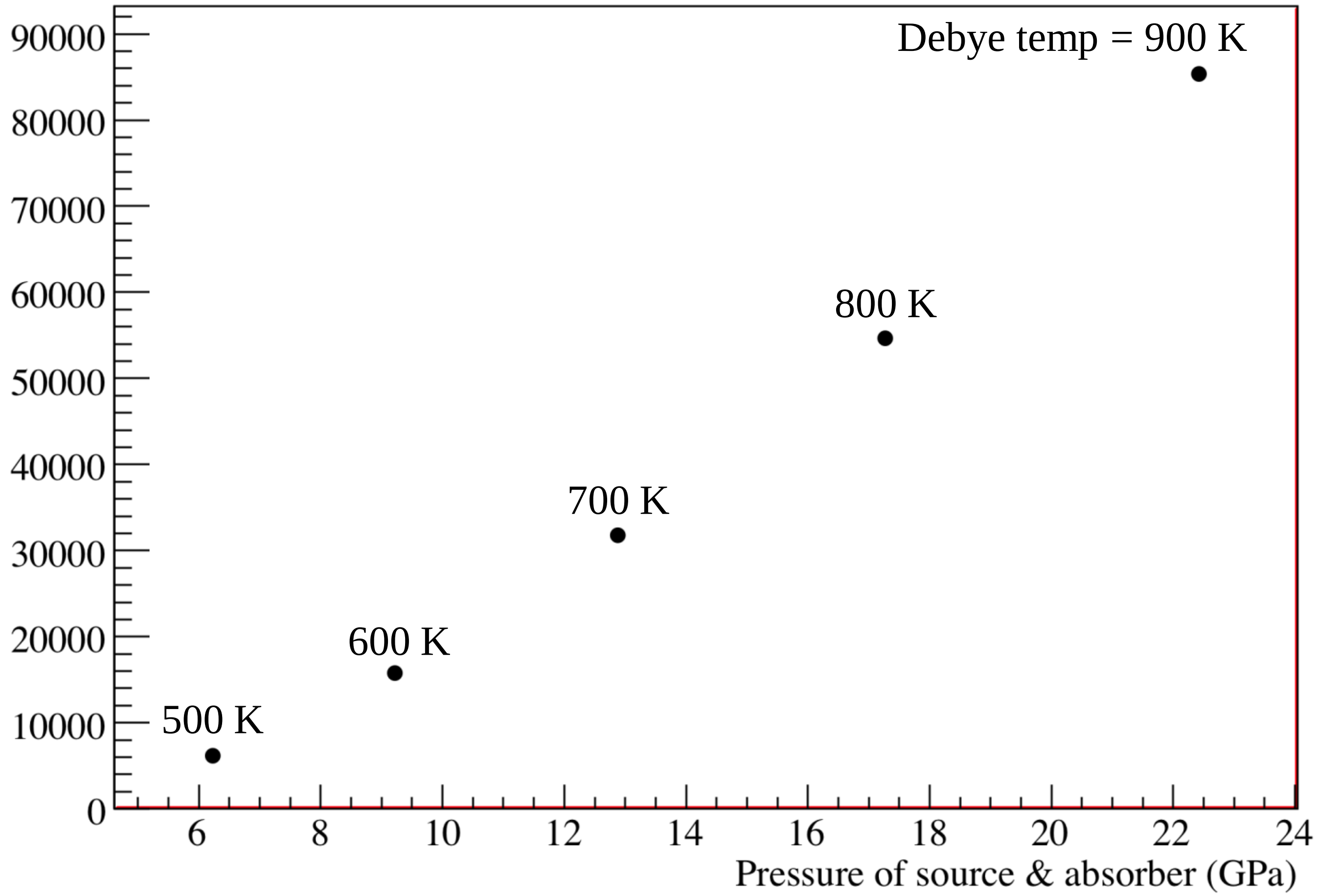
Energy shifts can destroy resonance



Mössbauer Neutrinos: 1-Body

We estimate a Debye temperature of ~700K
Simulation results: ~31755 events per week

Eventrate vs. Pressure (assuming a DAC volume of 0.004cm^3)



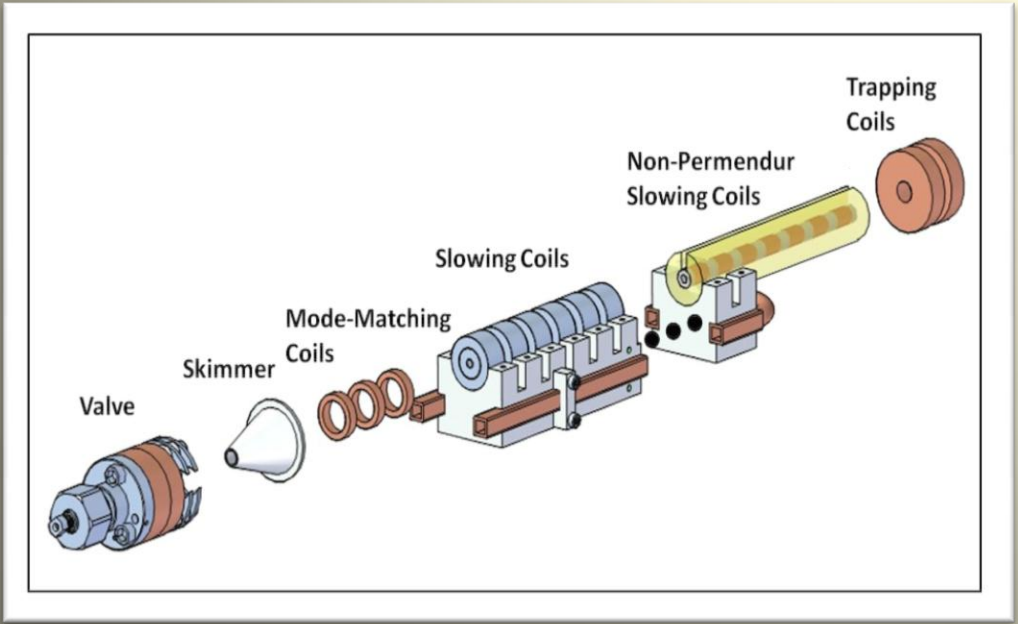
Mössbauer Neutrinos: 1-Body

But how do you detect the tritium in the helium-3 absorber?

- **Magnetic slowing enables trace element detection** so we can actually detect the ^{3}H in the ^{3}He absorber! (~1/1000 detection efficiency)

Physics motivation:

- θ_{13} measurement from rates taken at distances 1cm-10m



$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta)\sin^2(1.27\Delta m^2 L/E)$$

A large L is unnecessary if E=18.6keV