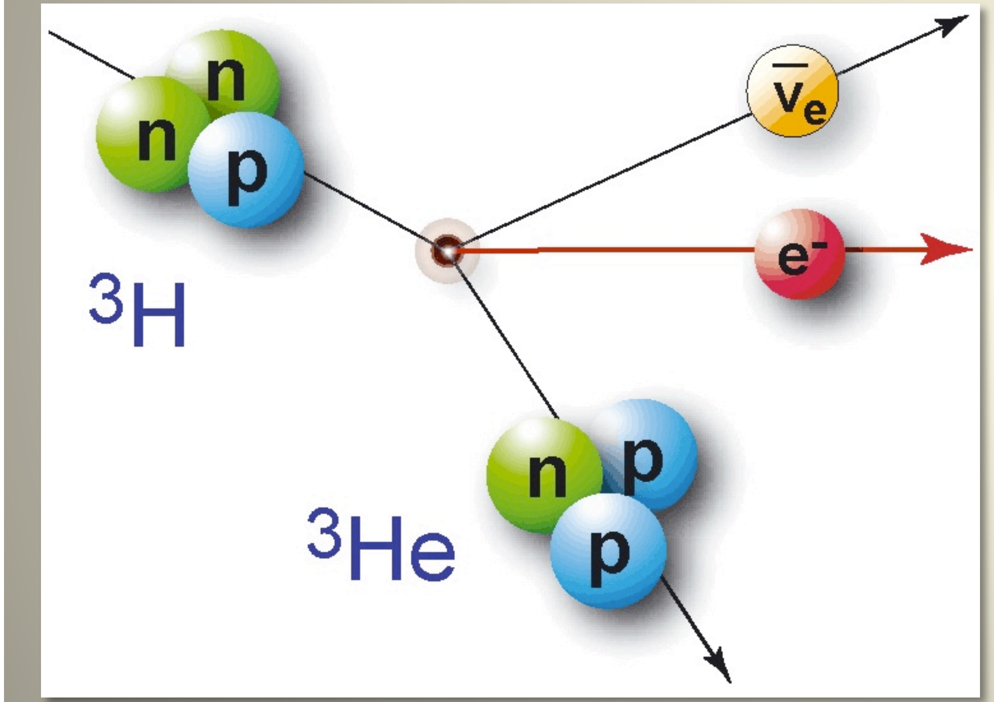
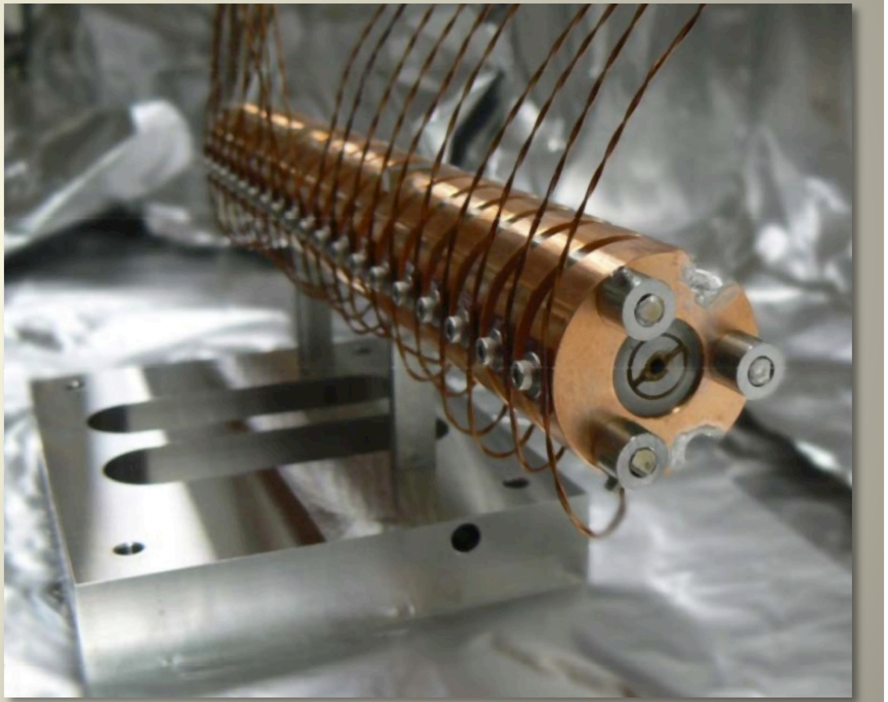
Neutrino Physics with Cold Atoms

Melissa Jerkins
University of Texas at Austin

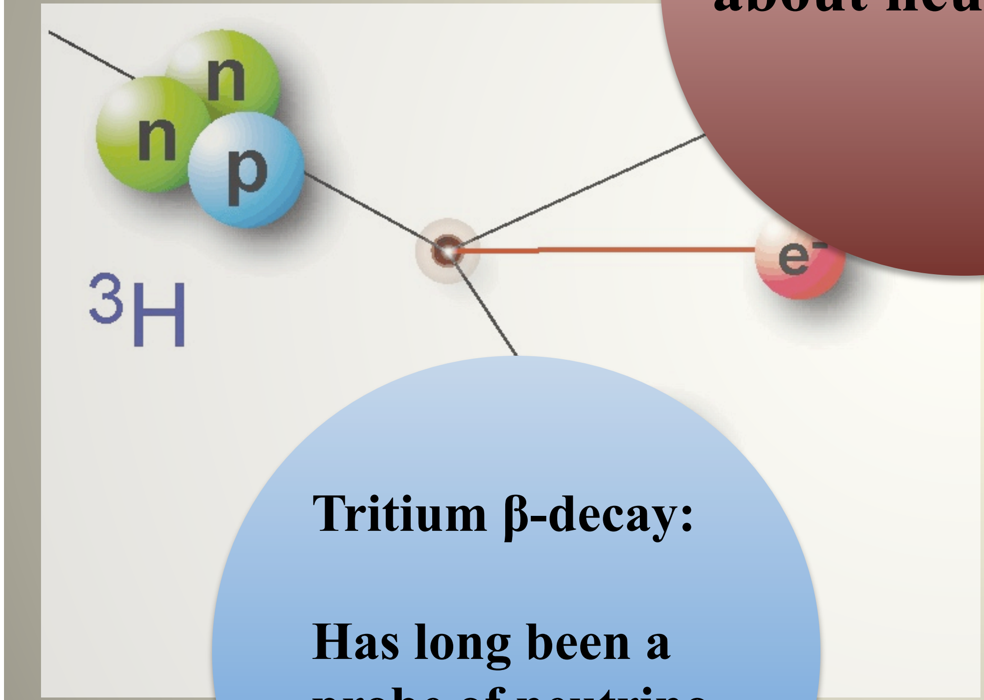




Tuesday February 3rd, 2009
Collaborators include Dr. Mark Raizen, Dr. Joshua Klein, and Julia Majors

Neutrino Physics with Cold Atoms

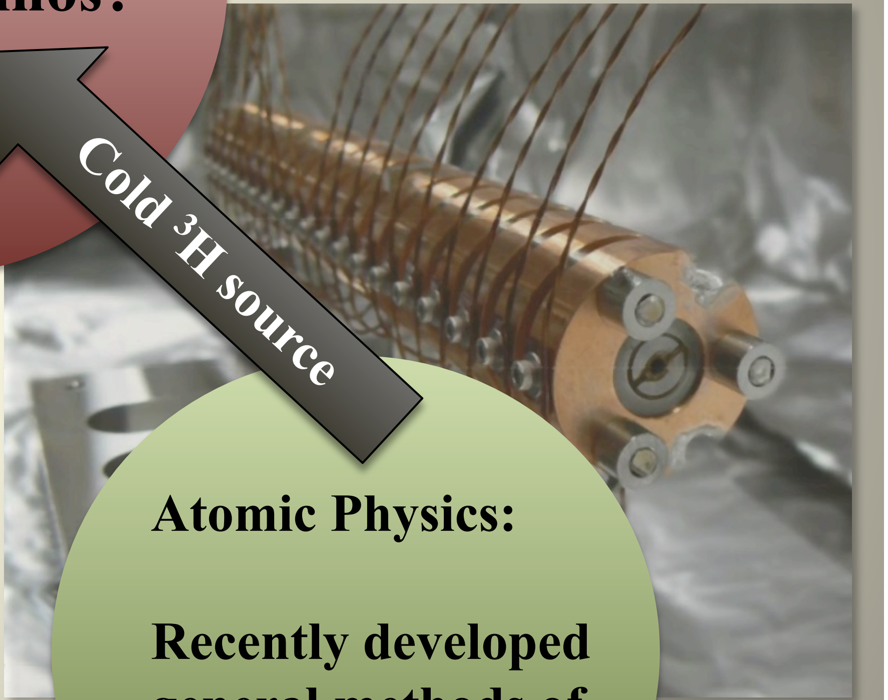
What can we learn about neutrinos?



Tritium β-decay:

Has long been a probe of neutrino properties

Cold ^{3}H source



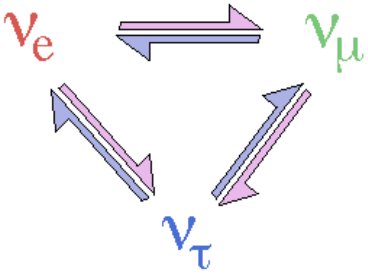
Atomic Physics:

Recently developed general methods of slowing & cooling

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!

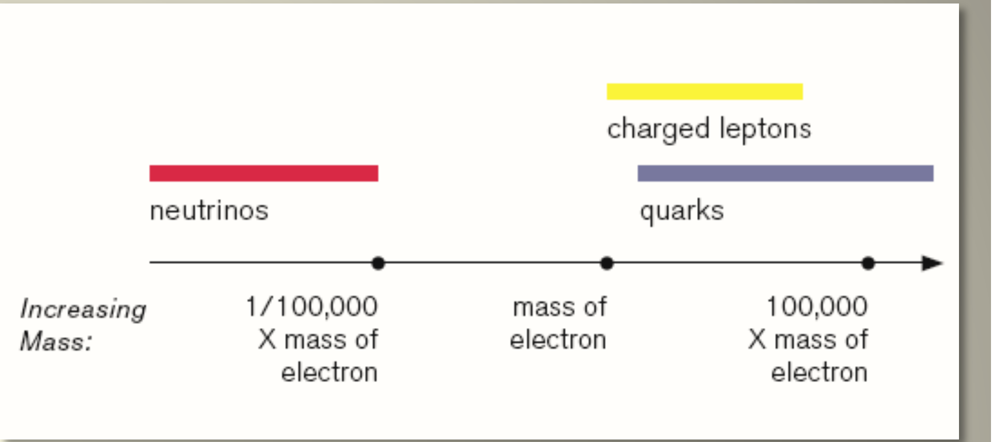
$$\boldsymbol{m_3 \geq \mathrm{sqrt}(|\Delta m_{\mathrm{atm}}{}^2|) \sim (0.04 - 0.07\ \mathrm{eV})}$$

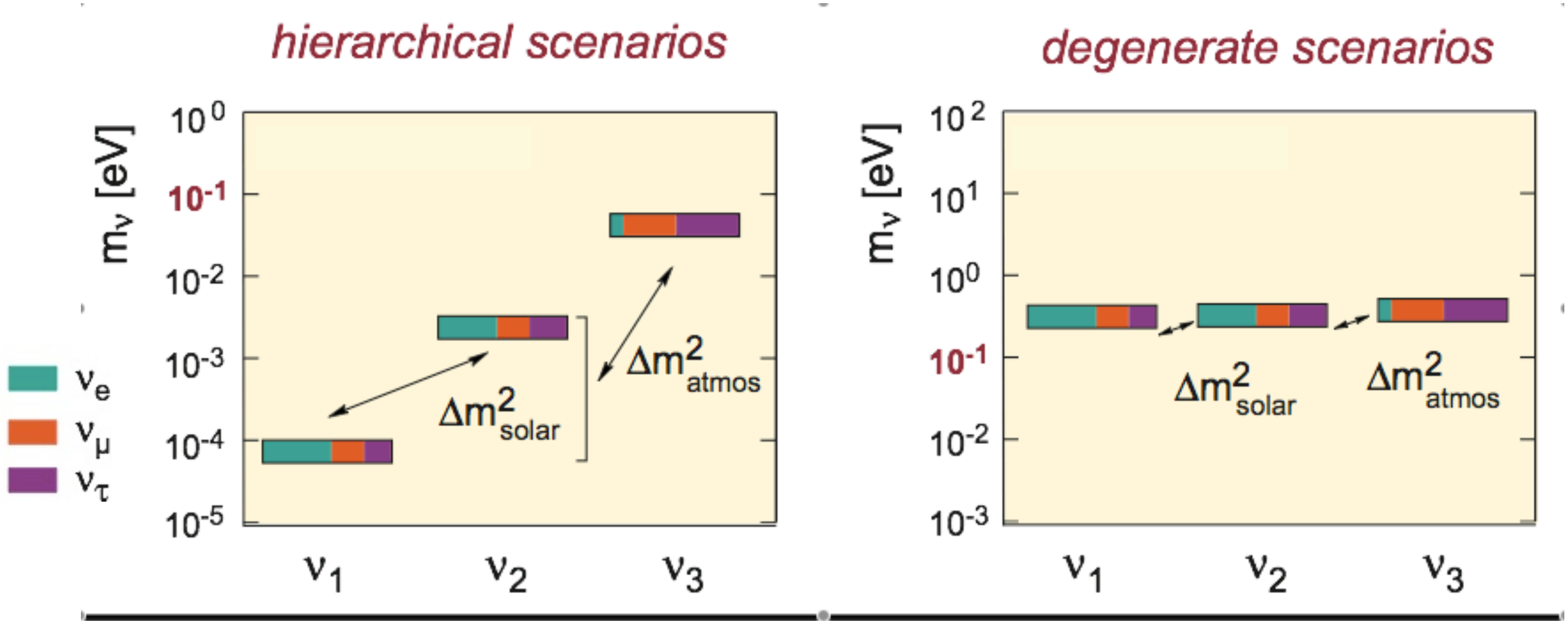
$\Delta m_{21}{}^2 = \Delta m_{sol}{}^2 = 8.0 \times 10^{-5}\ \mathrm{eV}^2$ (KamLAND)

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

Neutrino Mass

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

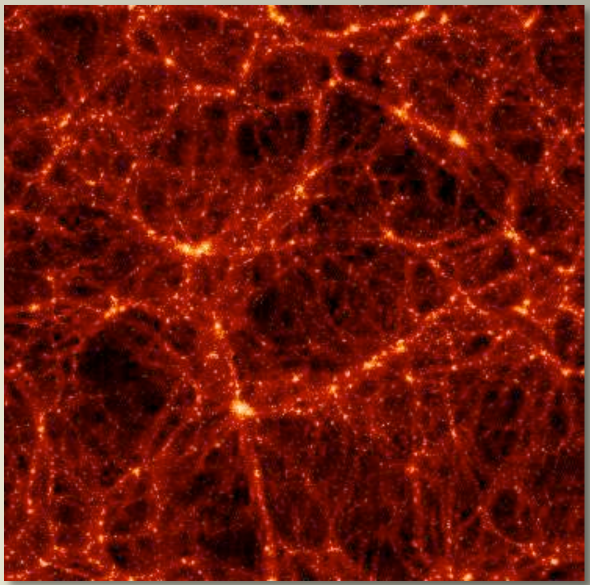




Neutrino Mass

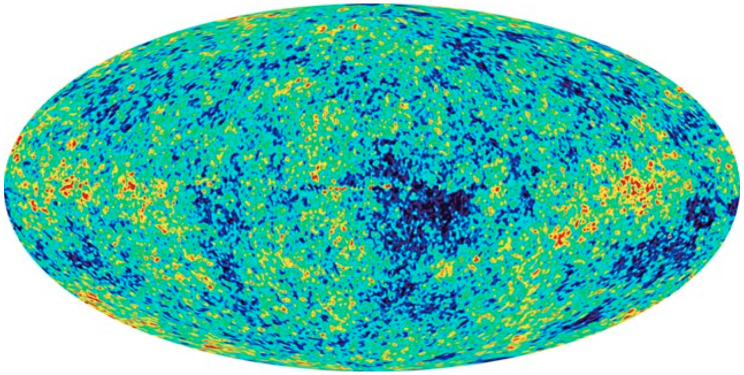
Cosmology

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

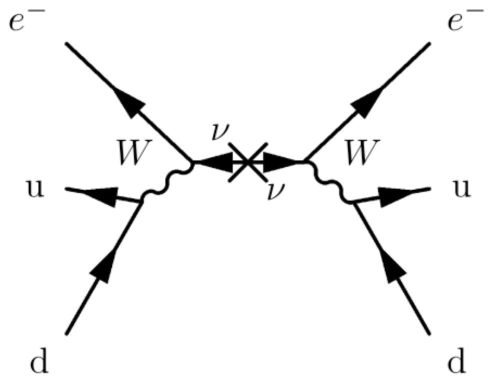
WMAP data has been fit with cosmological models that estimate $\sum m_\nu \leq 0.6$ eV

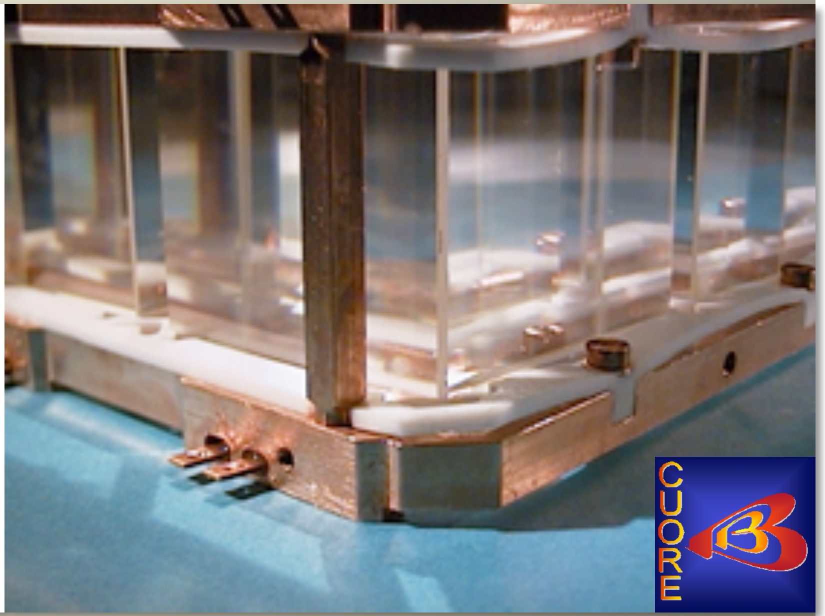


Experimental options

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

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

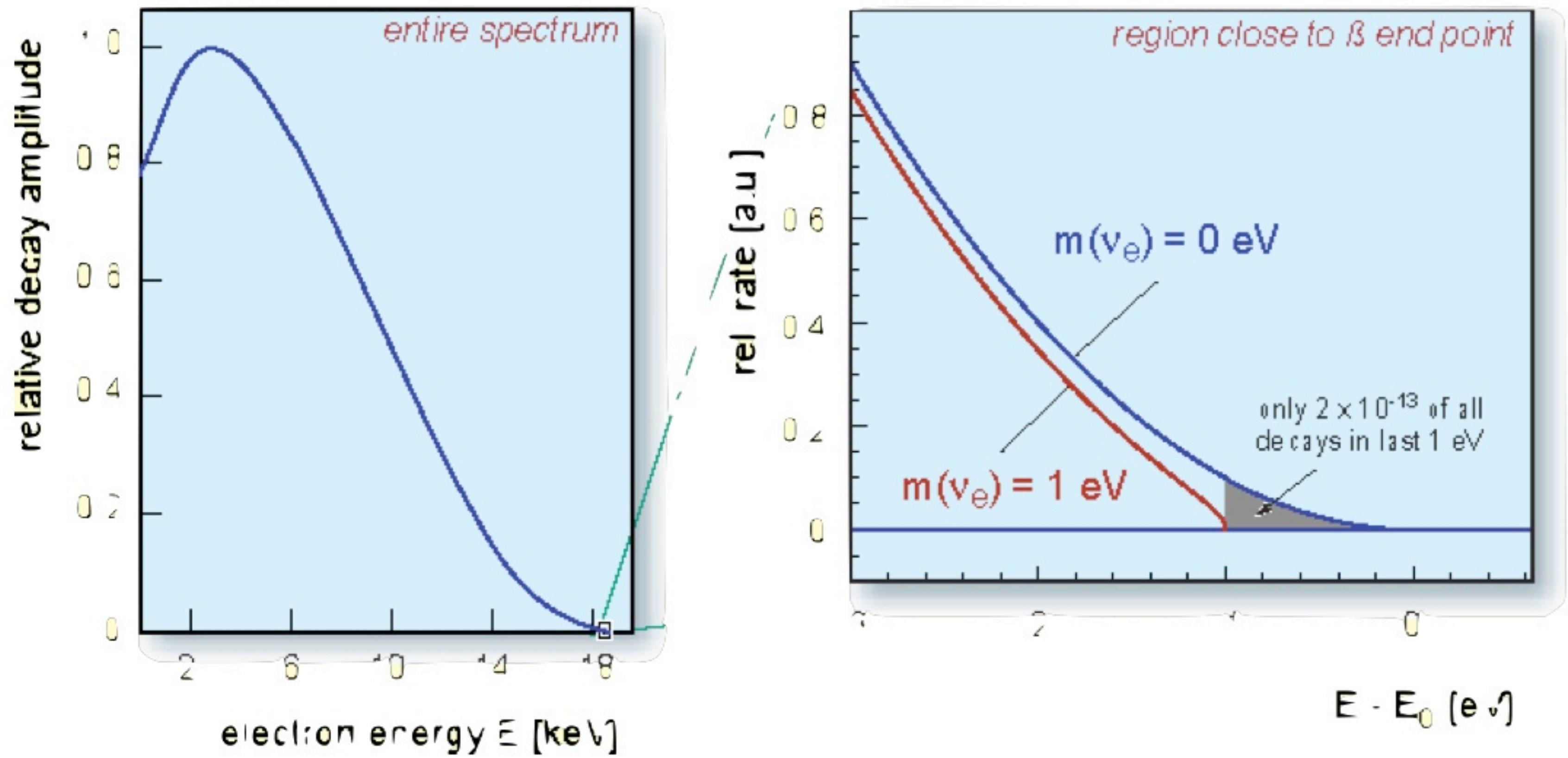


Figure: Osipowicz, A. et al. (KATRIN), arXiv:hep-ex/0109033

Experimental options

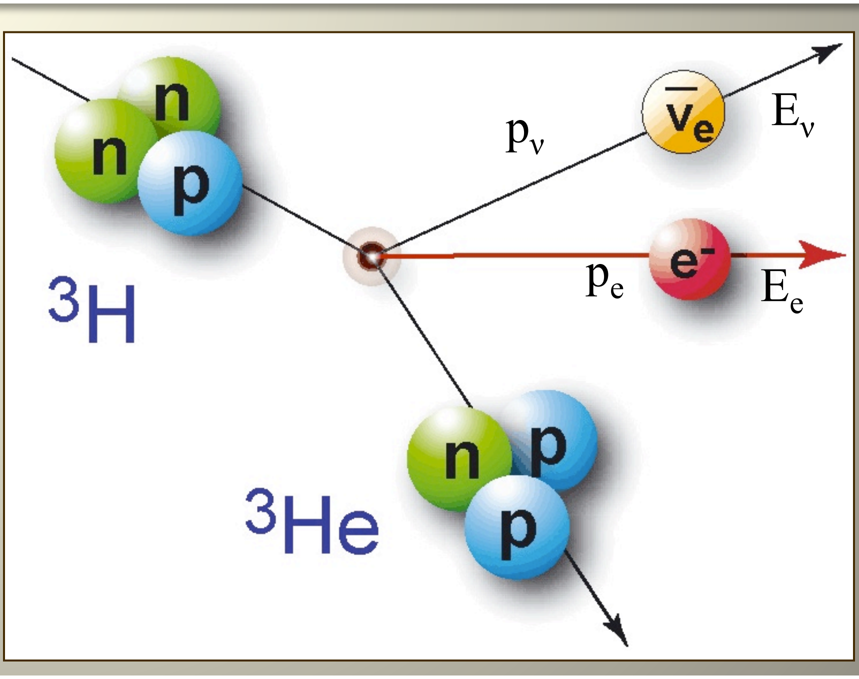
Tritium beta decay

Electron energy spectrum of tritium β decay:

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

$$= K \times F(E,Z) \times p \times W \times \sqrt{(E_0 - E)^2 - \overset{\substack{\text{Experimental observable}\\ \uparrow}}{\boxed{m_\nu^2}}} \times (E_0 - E)$$

- p = electron momentum
  W = electron total energy
- E = electron kinetic 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
- $K = G_F^2\,(m_e^5/2\pi^3)\cos^2\theta_C\,|M|^2$



Experimental options

Tritium beta decay

What about neutrino mixing?

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

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

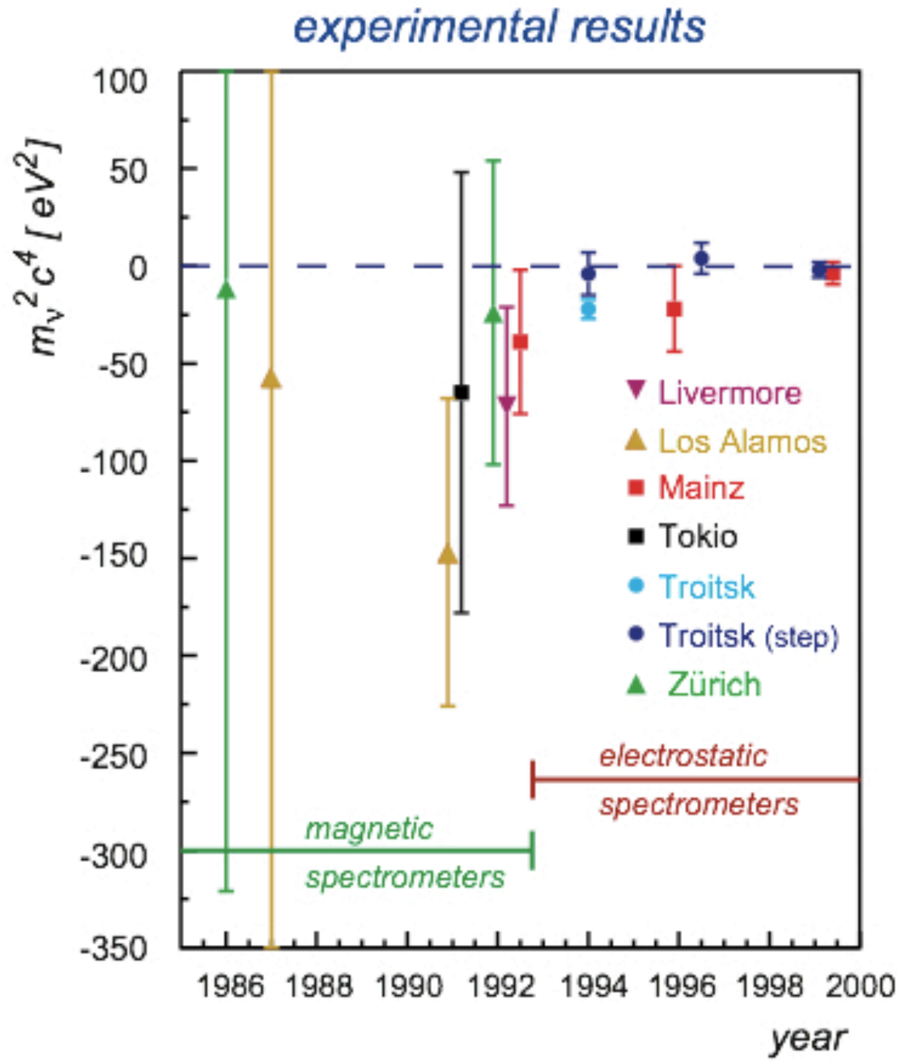
m_ν^2 = “mass” of the electron (anti-)neutrino = $\boldsymbol{\Sigma\, |U_{ei}|^2\, m_i^2}$

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 & 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

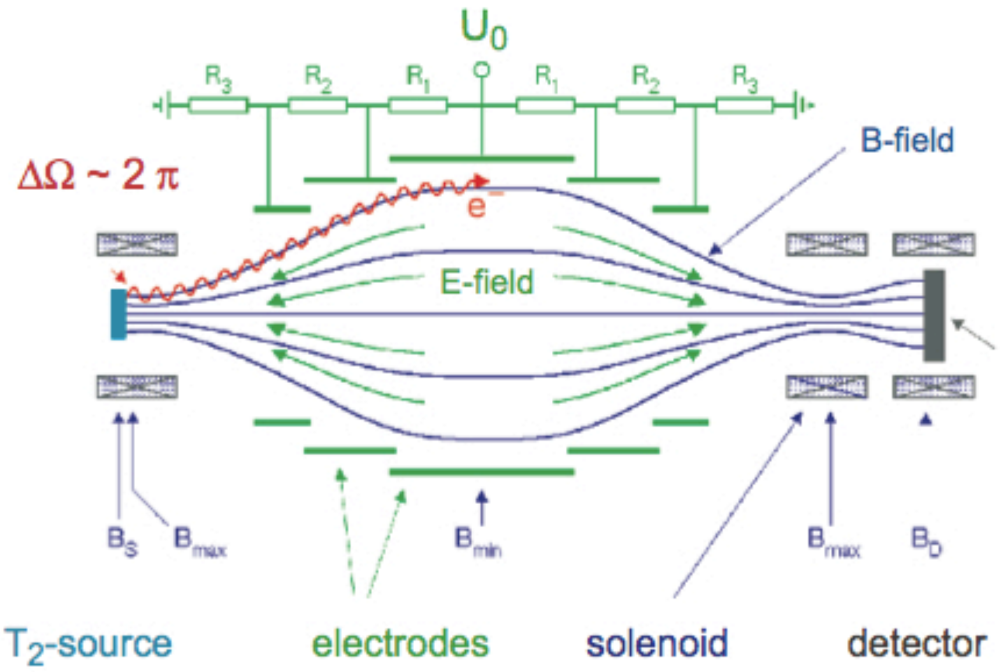
(*electrostatic filter*)

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



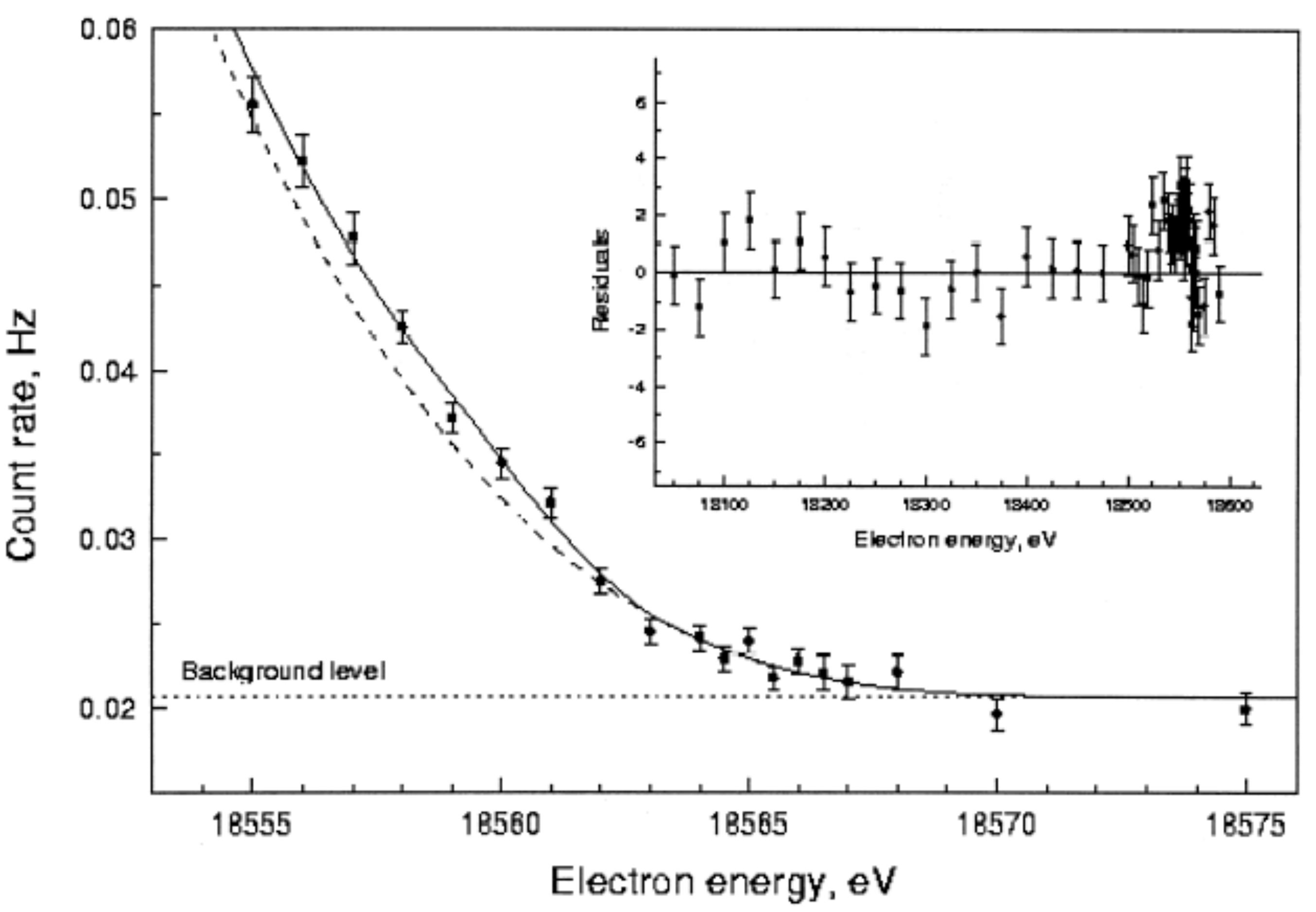
$E \parallel B$

adiabatic transformation $E_\perp \rightarrow E_\parallel$

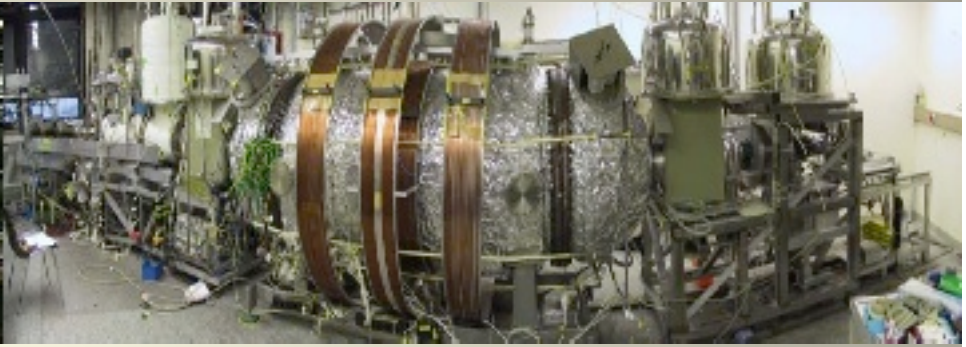
Previous Experiments

Troitsk and Mainz

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



Previous Experiments

Troitsk

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

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

Source = Windowless gaseous T^2

Mainz

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

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

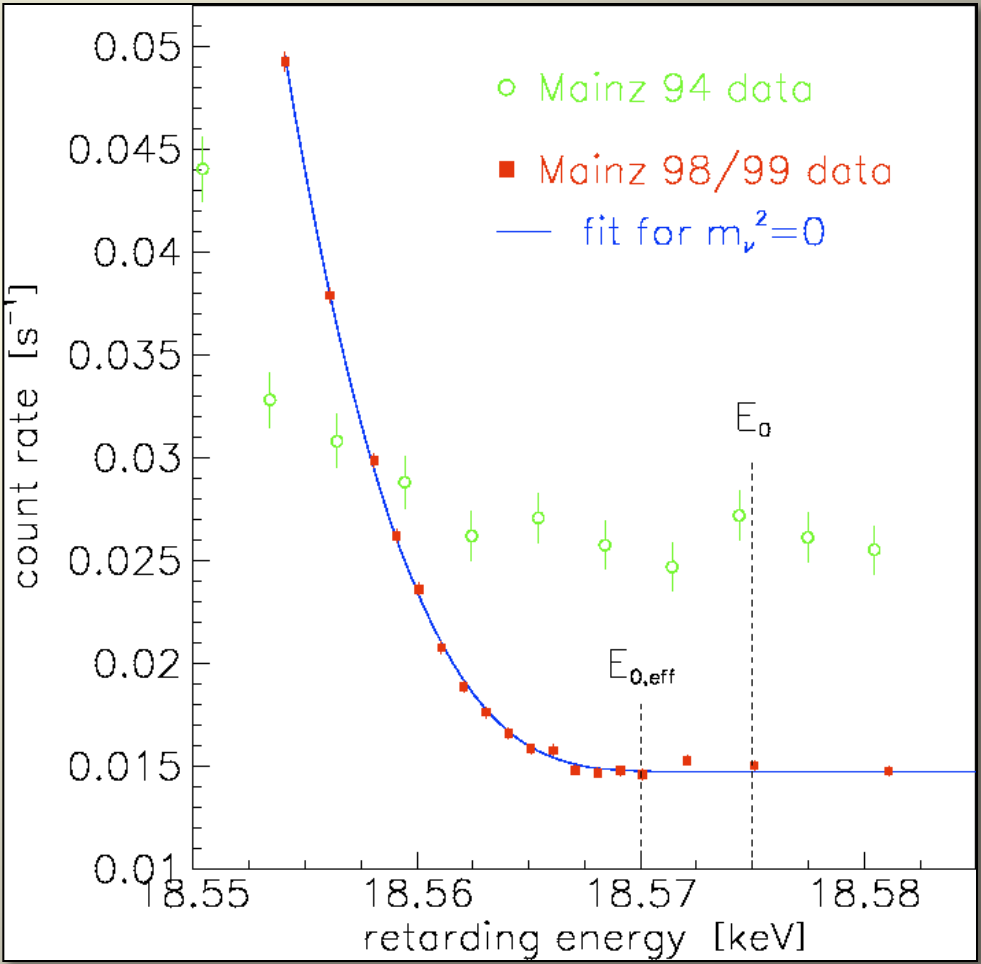
Source = Quench condensed T^2 film on graphite

Previous Experiments

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

Limiting Factors:

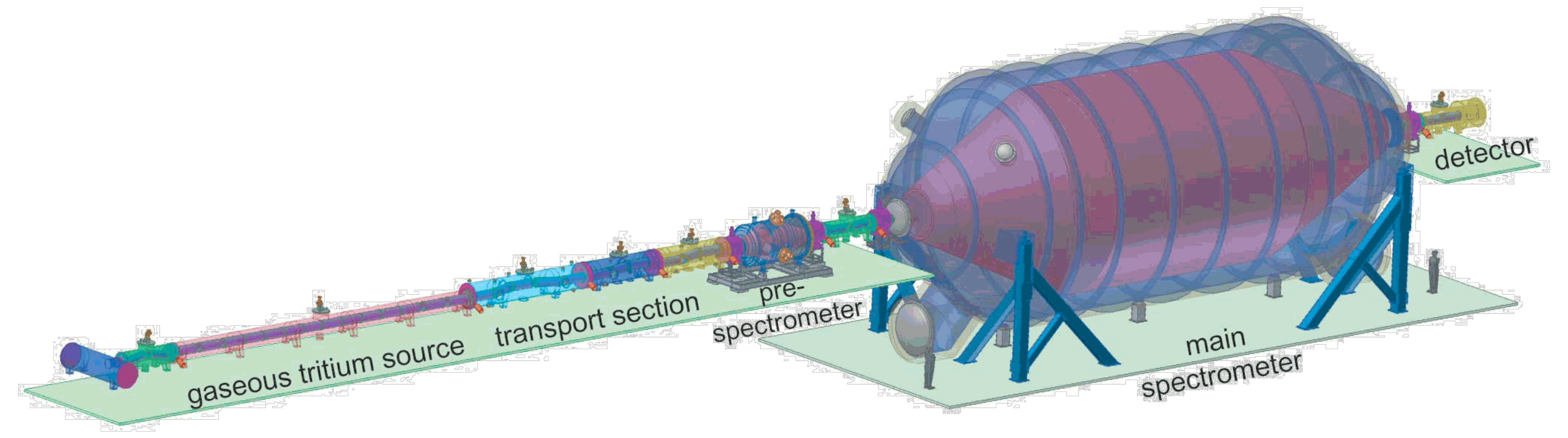
- Statistics
- Scattering in source
- Backgrounds
- Energy resolution
- Electronic final state effects
- Tritium source uncertainties



Current Experiments

KATRIN

- Scaled-up version of Troitsk experiment
- 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
- Main spectrometer is 23m long and 10m in diameter

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

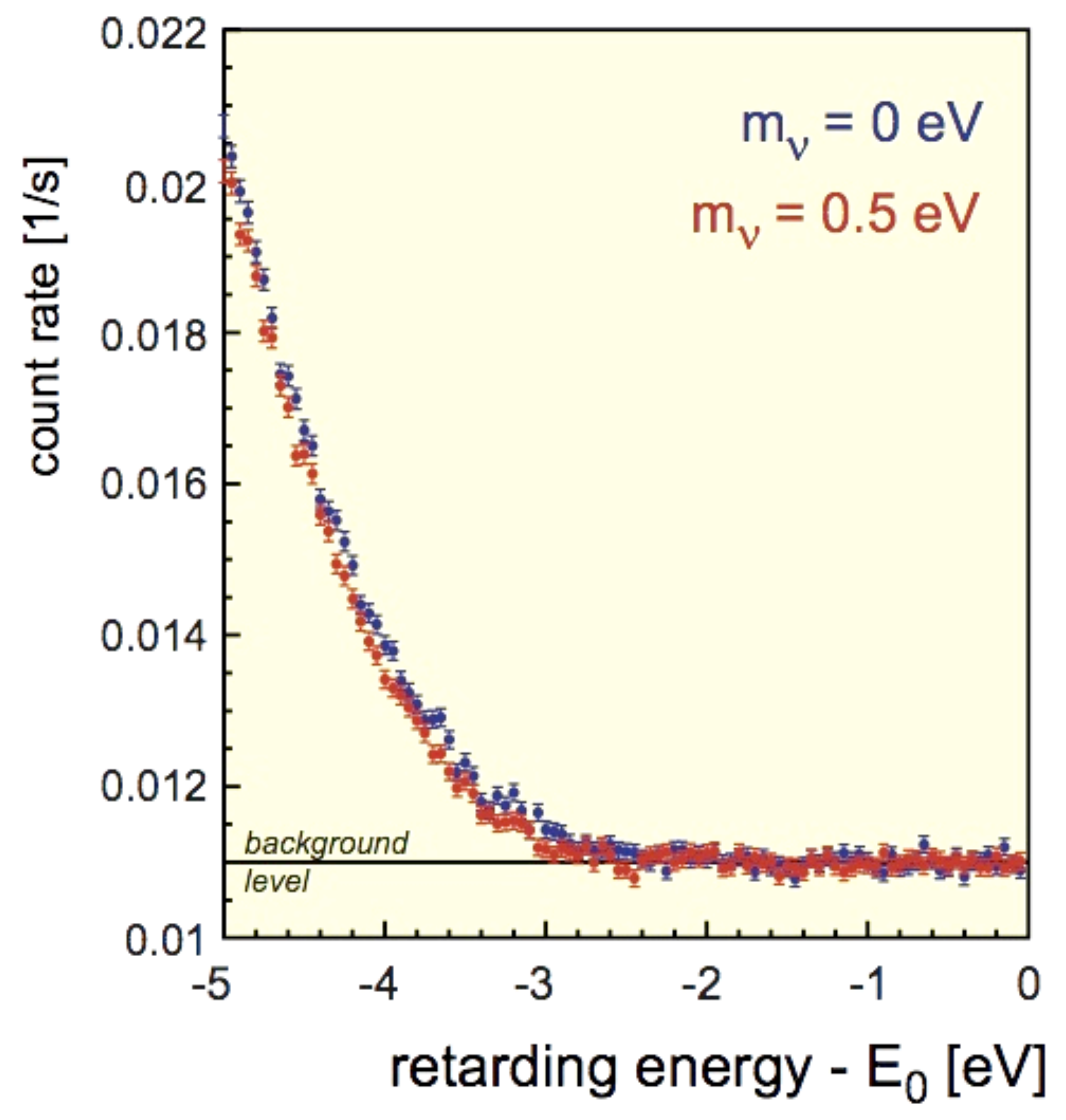
Discovery (95% CL)
$m_\nu < 0.35$ eV

Current Experiments

KATRIN

Monte Carlo spectra:

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



Current Experiments

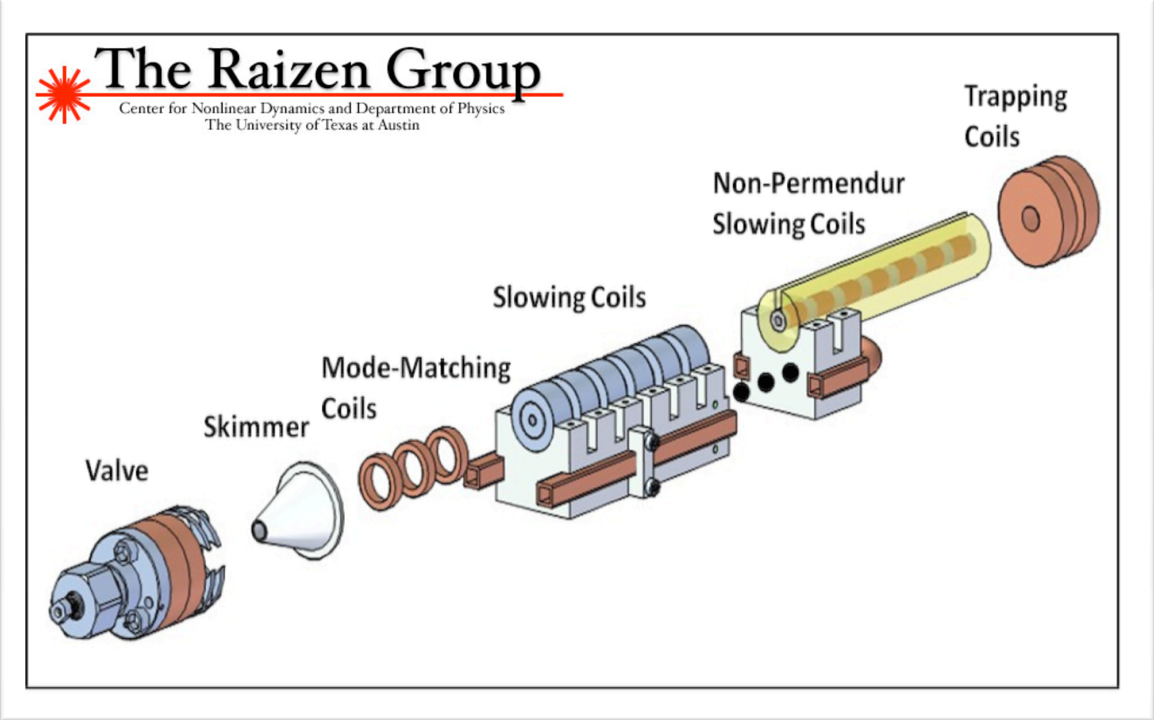
KATRIN:	**MARE:**
Karlsruhe Tritium Neutrino Experiment	Microcalorimeter Arrays for a Rhenium Experiment
• External β-source (^{3}H)	• β-source = detector (^{187}Re)
• ^{3}H endpoint = 18.6 keV	• ^{187}Re endpoint = 2.6 keV
• ^{3}H half-life = 12.3 years	• ^{187}Re half-life = $5\text{x}10^{10}$ years
• 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
• $\Delta E_{\text{expected}} = 0.93$ eV	• $\Delta E_{\text{expected}} \sim 5$ eV (FWHM)

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

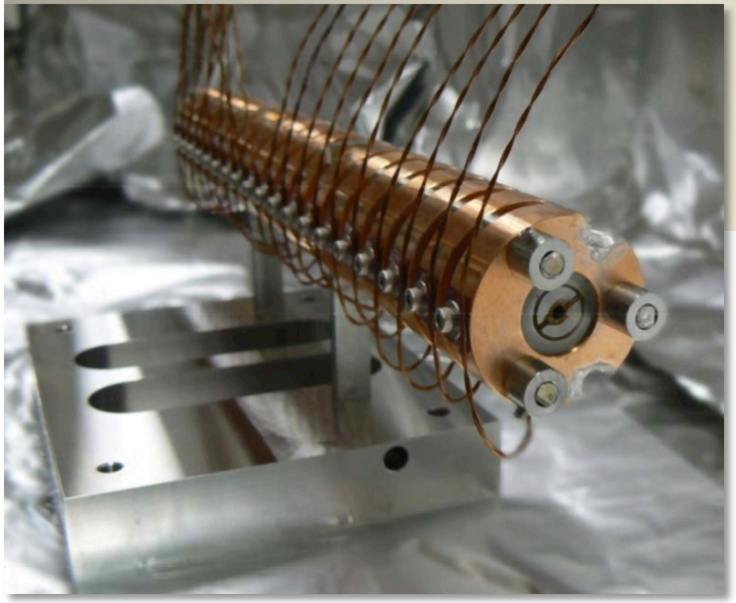


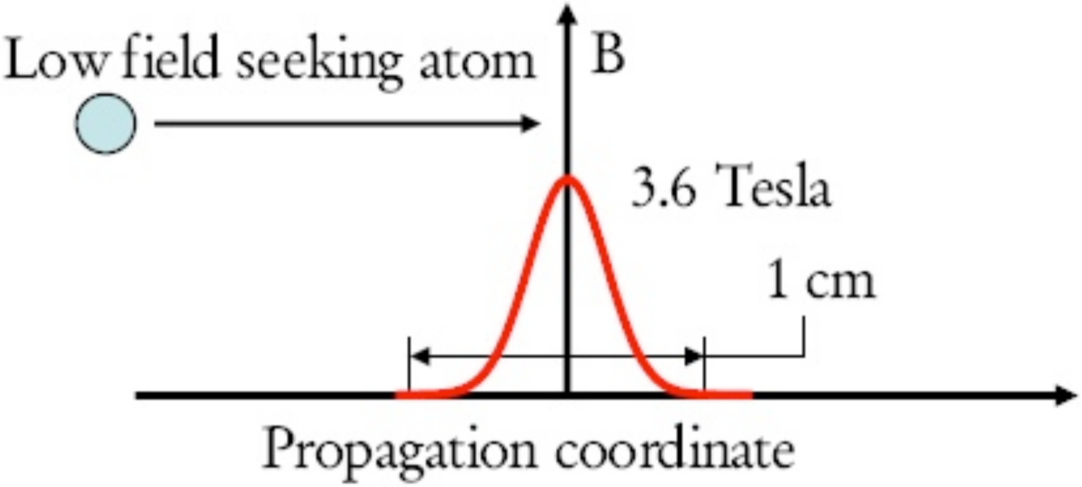
E. Narevicius, A. Libson, C. Parthey, I. Chavez, J. Narevicius, U. Even, and M. G. Raizen, Phys. Rev. Lett. 100, 093003 (2008)

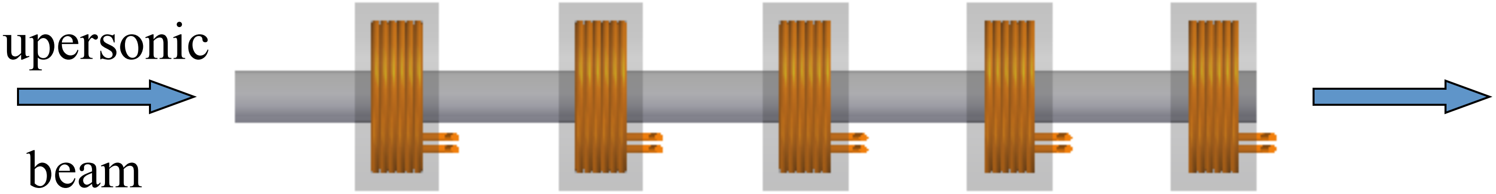
Magnetic Slowing of Atoms

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





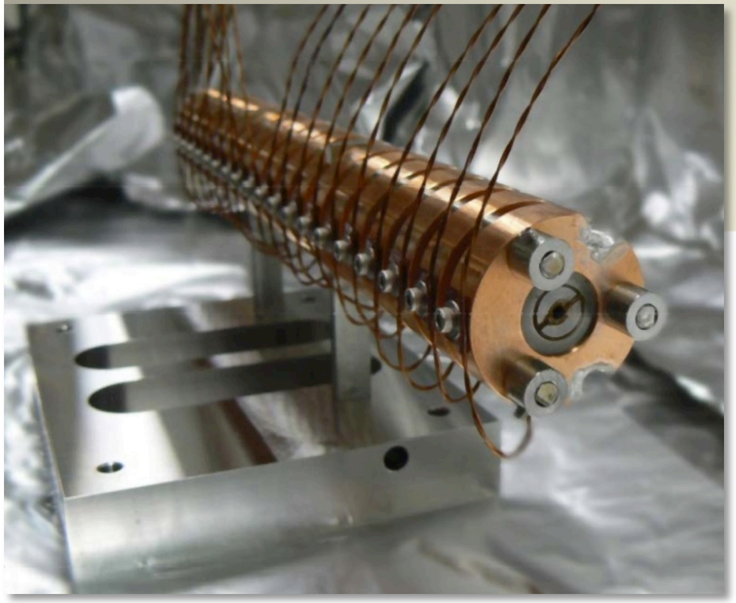


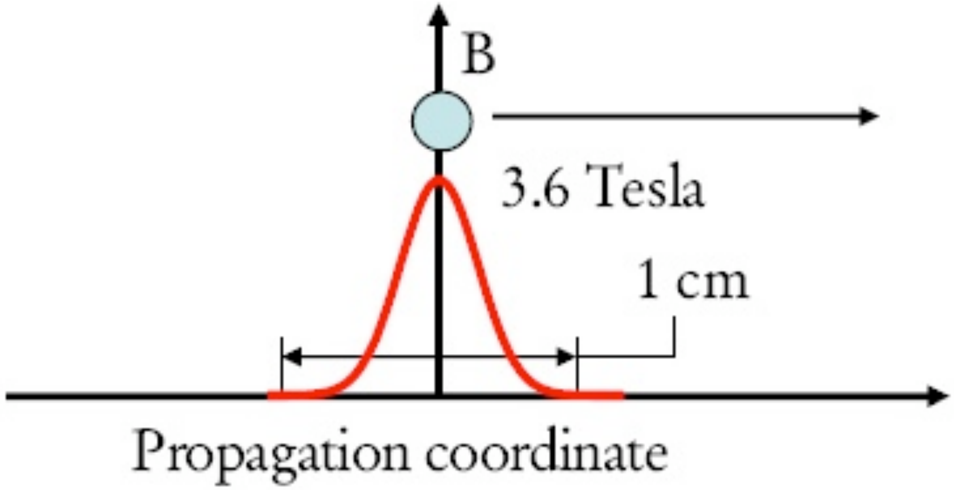
Supersonic beam

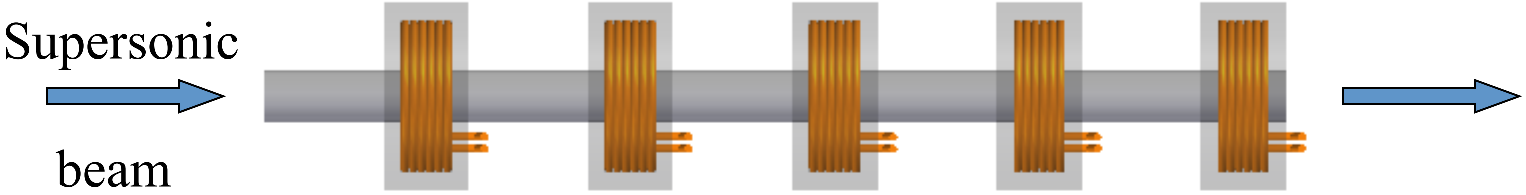
Magnetic Slowing of Atoms

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



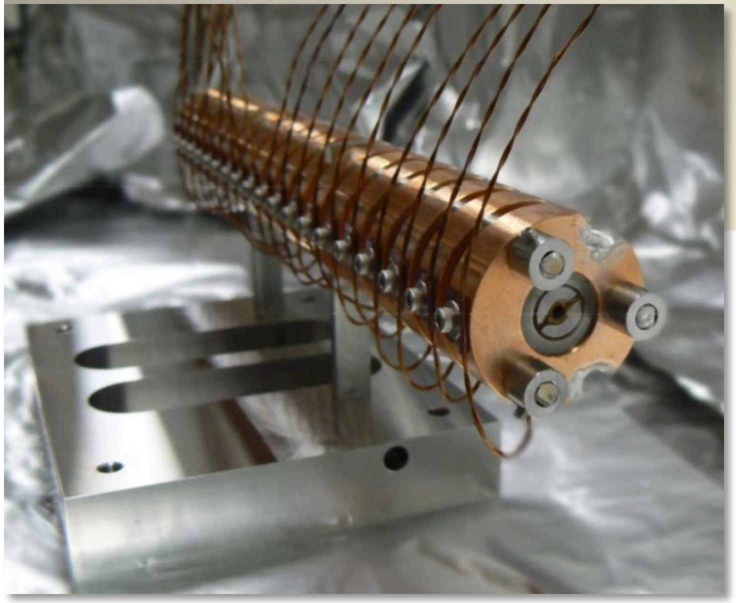


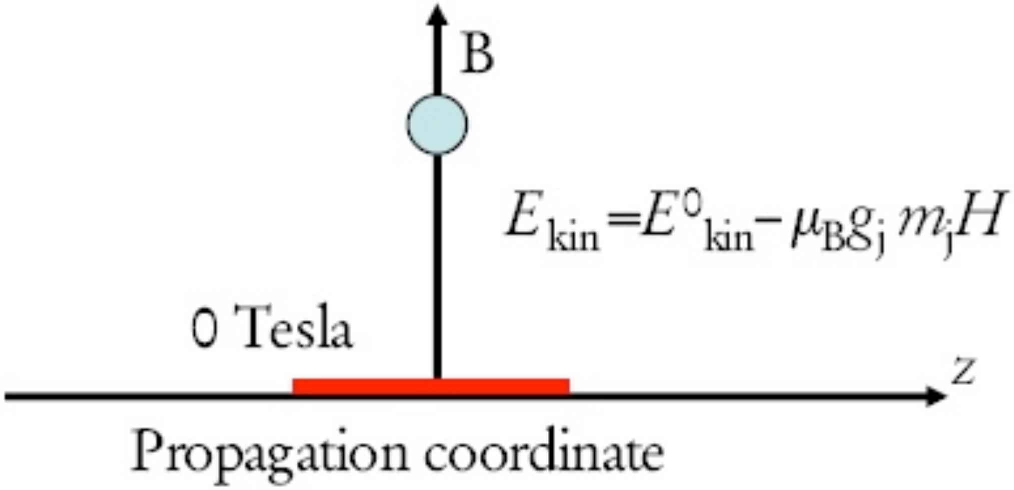


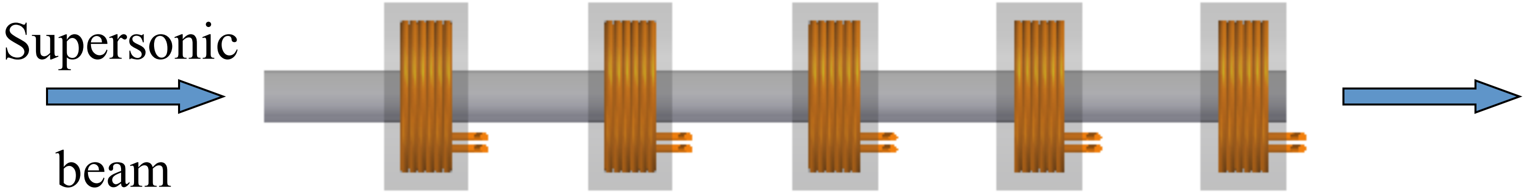
Magnetic Slowing of Atoms

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





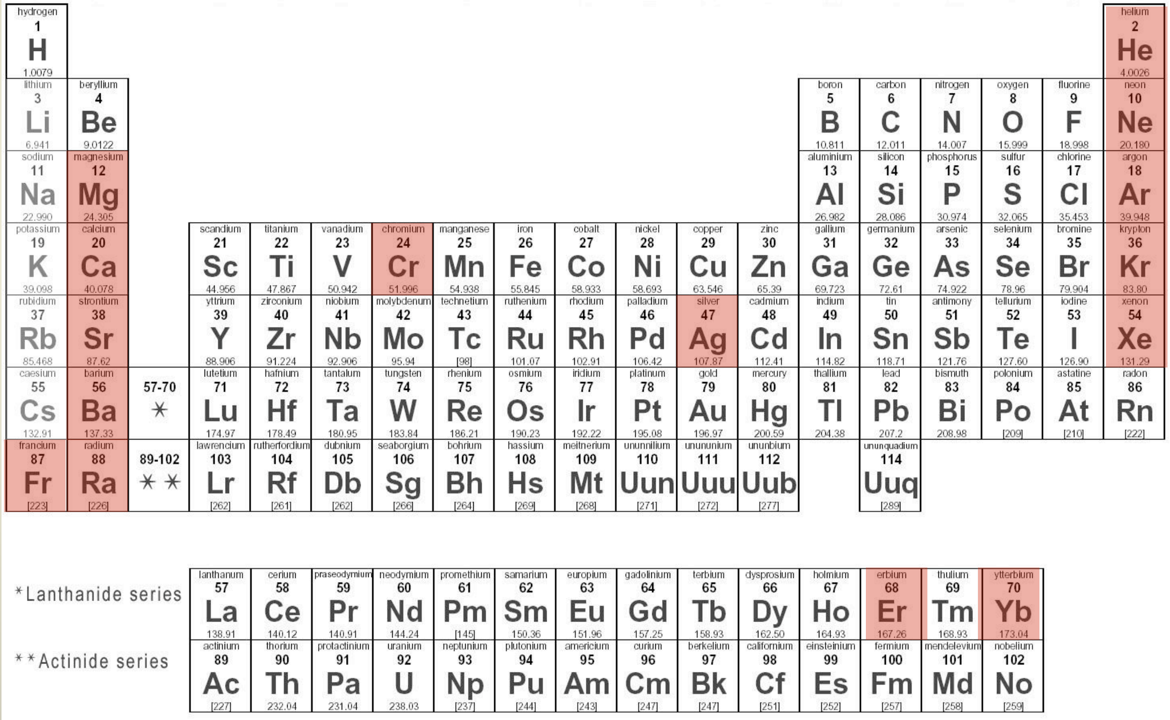


Single Photon Cooling

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

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

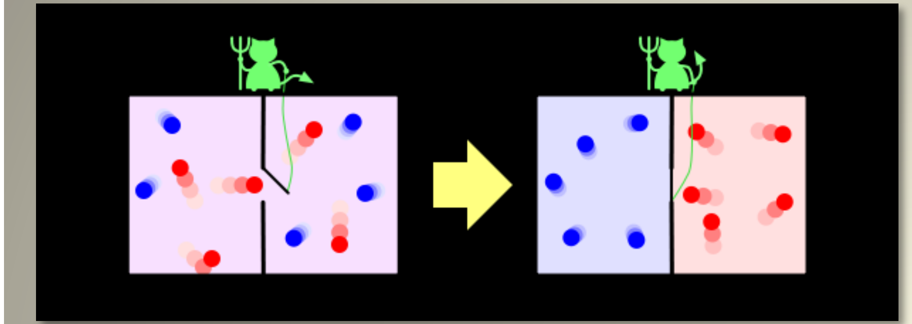
- 1997 Nobel Prize: Chu, Cohen-Tannoudji, Phillips
- Repeated scattering of photons reduces atomic momentum
- Requires a cycling transition
- Hydrogen cannot be laser cooled



hydrogen 1 H 1.0079																		helium 2 He 4.0026
lithium 3 Li 6.941	beryllium 4 Be 9.0122												boron 5 B 10.811	carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluorine 9 F 18.998	neon 10 Ne 20.180
sodium 11 Na 22.990	magnesium 12 Mg 24.305												aluminium 13 Al 26.982	silicon 14 Si 28.086	phosphorus 15 P 30.974	sulfur 16 S 32.065	chlorine 17 Cl 35.453	argon 18 Ar 39.948
potassium 19 K 39.098	calcium 20 Ca 40.078		scandium 21 Sc 44.956	titanium 22 Ti 47.867	vanadium 23 V 50.942	chromium 24 Cr 51.996	manganese 25 Mn 54.938	iron 26 Fe 55.845	cobalt 27 Co 58.933	nickel 28 Ni 58.693	copper 29 Cu 63.546	zinc 30 Zn 65.39	gallium 31 Ga 69.723	germanium 32 Ge 72.61	arsenic 33 As 74.922	selenium 34 Se 78.96	bromine 35 Br 79.904	krypton 36 Kr 83.80
rubidium 37 Rb 85.468	strontium 38 Sr 87.62		yttrium 39 Y 88.906	zirconium 40 Zr 91.224	niobium 41 Nb 92.906	molybdenum 42 Mo 95.94	technetium 43 Tc [98]	ruthenium 44 Ru 101.07	rhodium 45 Rh 102.91	palladium 46 Pd 106.42	silver 47 Ag 107.87	cadmium 48 Cd 112.41	indium 49 In 114.82	tin 50 Sn 118.71	antimony 51 Sb 121.76	tellurium 52 Te 127.60	iodine 53 I 126.90	xenon 54 Xe 131.29
caesium 55 Cs 132.91	barium 56 Ba 137.33	57-70 *	lutetium 71 Lu 174.97	hafnium 72 Hf 178.49	tantalum 73 Ta 180.95	tungsten 74 W 183.84	rhenium 75 Re 186.21	osmium 76 Os 190.23	iridium 77 Ir 192.22	platinum 78 Pt 195.08	gold 79 Au 196.97	mercury 80 Hg 200.59	thallium 81 Tl 204.38	lead 82 Pb 207.2	bismuth 83 Bi 208.98	polonium 84 Po [209]	astatine 85 At [210]	radon 86 Rn [222]
francium 87 Fr [223]	radium 88 Ra [226]	89-102 * *	lawrencium 103 Lr [262]	rutherfordium 104 Rf [261]	dubnium 105 Db [262]	seaborgium 106 Sg [266]	bohrium 107 Bh [264]	hassium 108 Hs [269]	meitnerium 109 Mt [268]	ununnilium 110 Uun [271]	unununium 111 Uuu [272]	ununbium 112 Uub [277]		ununquadium 114 Uuq [289]				
*Lanthanide series			lanthanum 57 La 138.91	cerium 58 Ce 140.12	praseodymium 59 Pr 140.91	neodymium 60 Nd 144.24	promethium 61 Pm [145]	samarium 62 Sm 150.36	europium 63 Eu 151.96	gadolinium 64 Gd 157.25	terbium 65 Tb 158.93	dysprosium 66 Dy 162.50	holmium 67 Ho 164.93	erbium 68 Er 167.26	thulium 69 Tm 168.93	ytterbium 70 Yb 173.04		
* *Actinide series			actinium 89 Ac [227]	thorium 90 Th 232.04	protactinium 91 Pa 231.04	uranium 92 U 238.03	neptunium 93 Np [237]	plutonium 94 Pu [244]	americium 95 Am [243]	curium 96 Cm [247]	berkelium 97 Bk [247]	californium 98 Cf [251]	einsteinium 99 Es [252]	fermium 100 Fm [257]	mendelevium 101 Md [258]	nobelium 102 No [259]		

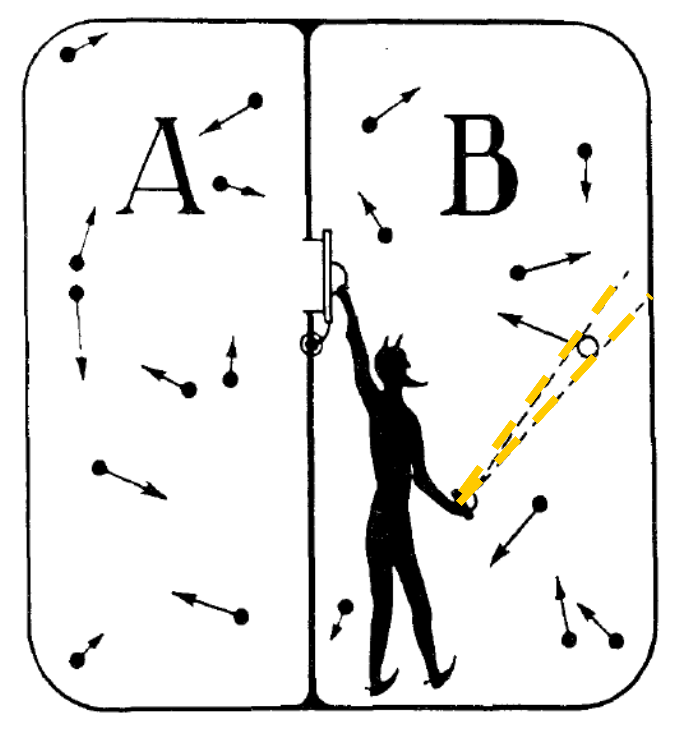
Is there a more general cooling method?

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

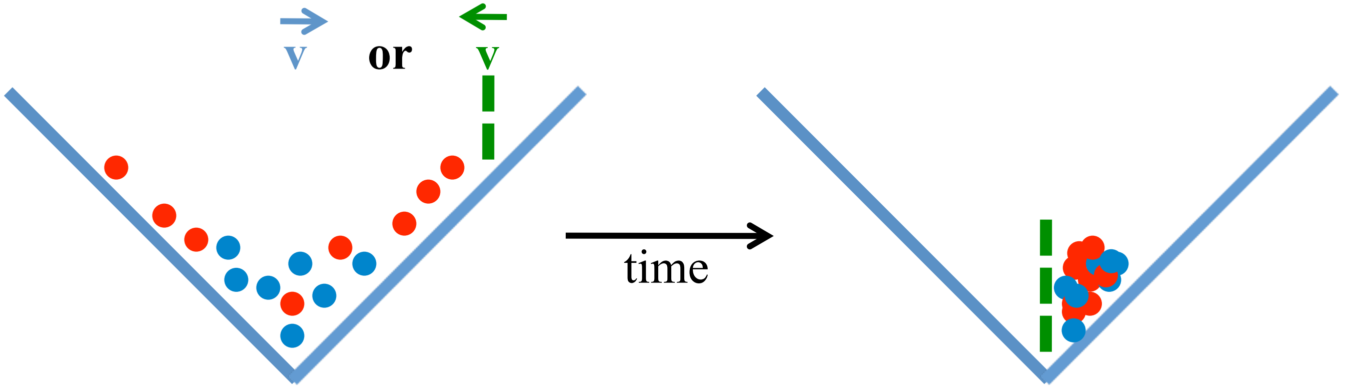
Single-photon cooling realizes Maxwell's demon:
"Demon" discriminates coldest atoms and releases this info in a single scattered photon

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

(T. Bannerman, G. N. Price, K. Viering, and M. G. Raizen, arXiv:08102239v1)

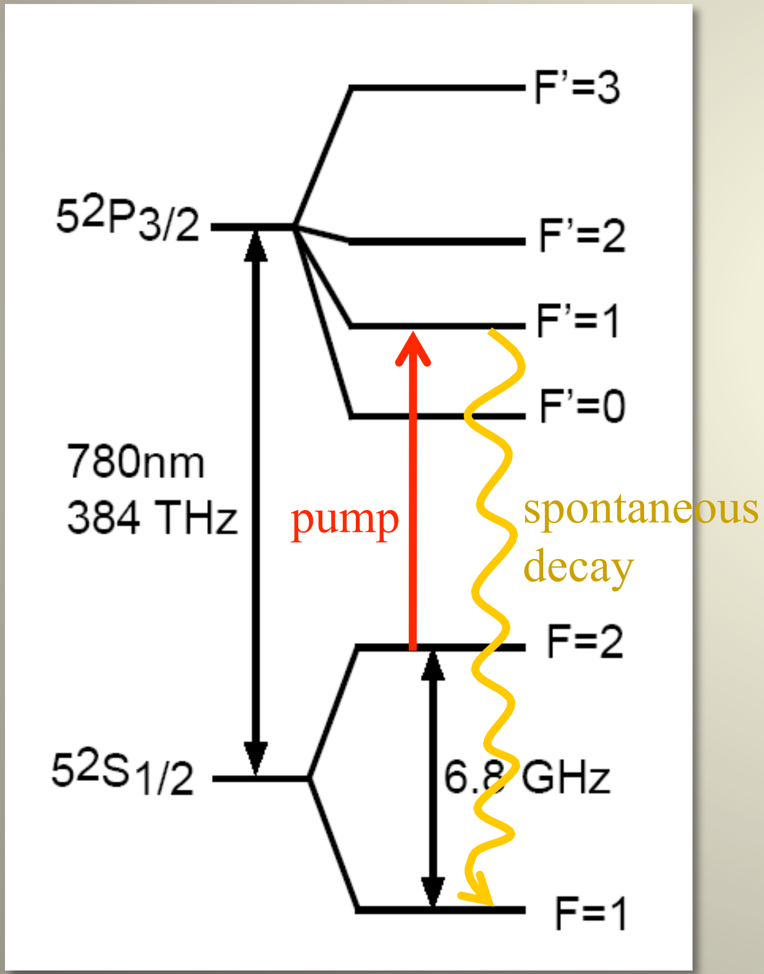


Correlation between position and momentum for $\vec{v}_{demon} << \langle \vec{v}_{atom} \rangle$

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

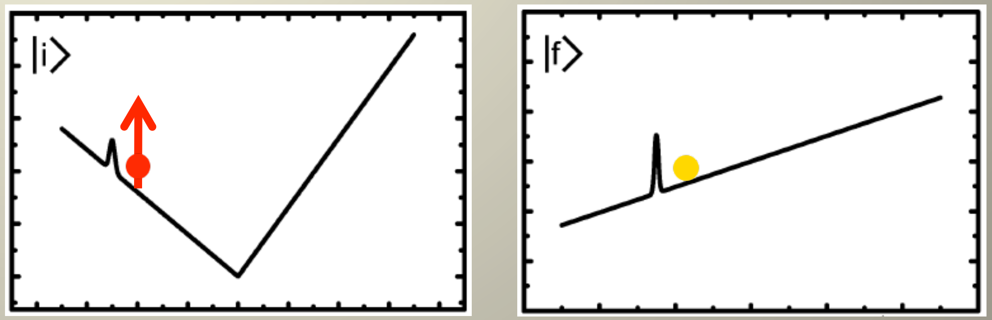
Single Photon Cooling

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 source of ~10^{11} trapped atoms allows the ion to escape as well as the β.

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

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

Endpoint energy: E_o=18.6 keV

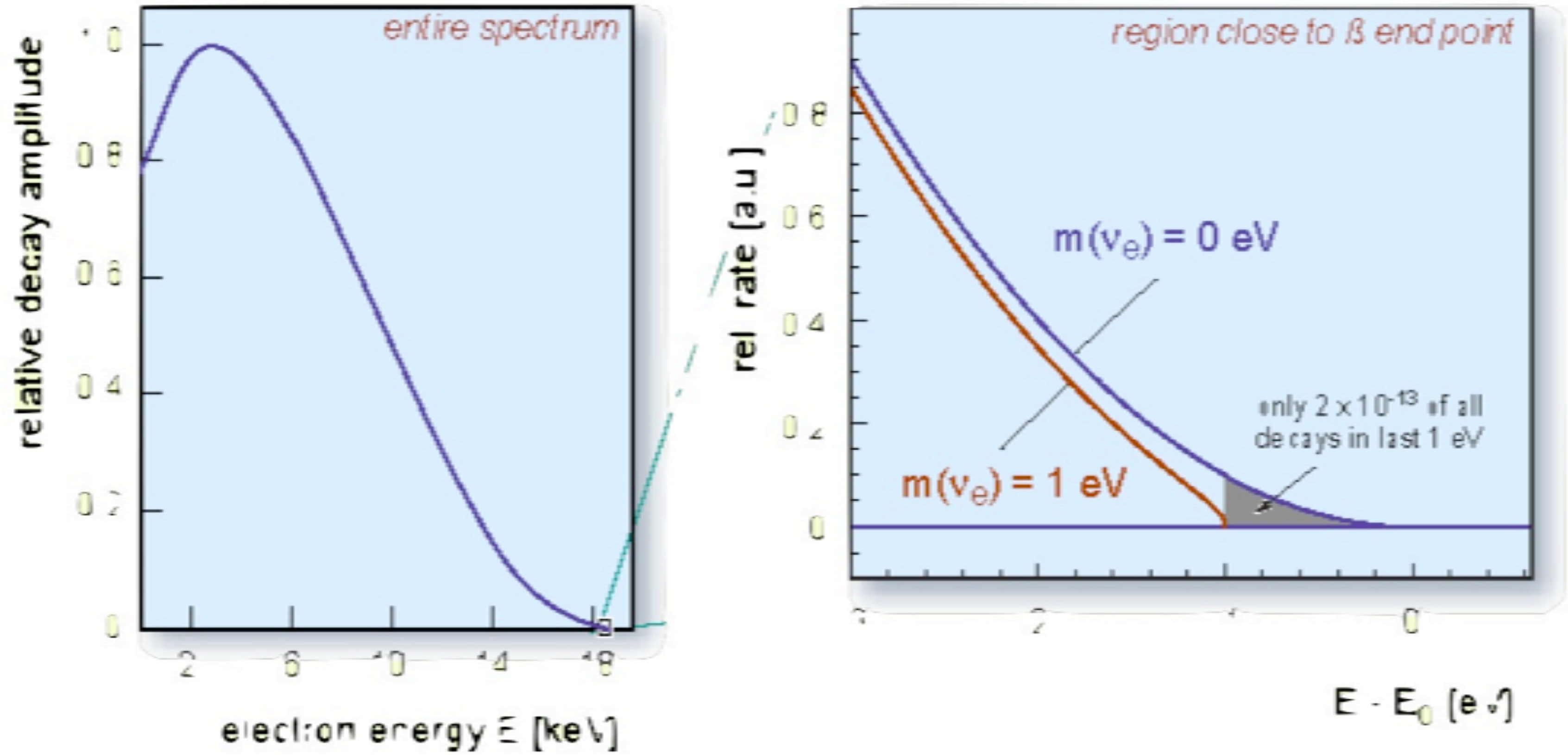
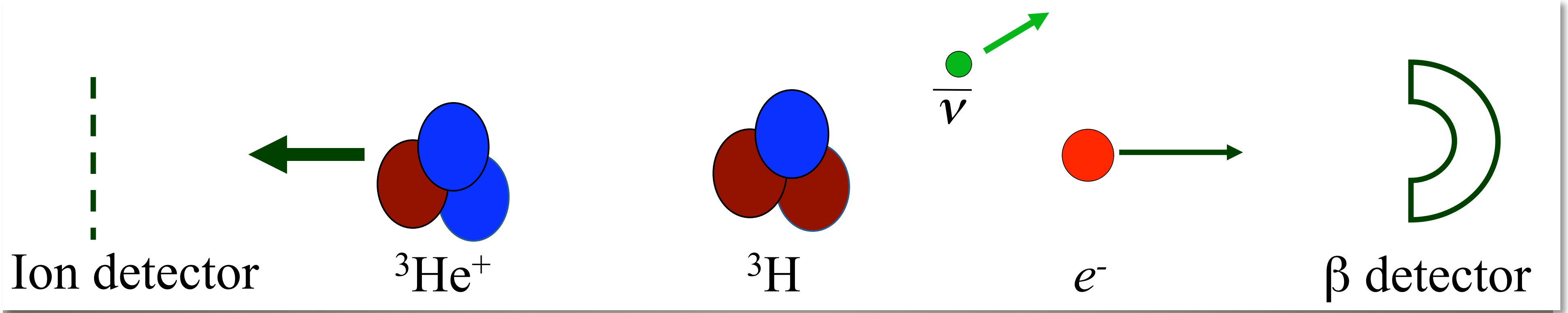


Figure: Osipowicz, A. et al. (KATRIN), arXiv:hep-ex/0109033

Tritium β-Decay: 3-Body

Direct reconstruction of the neutrino mass!

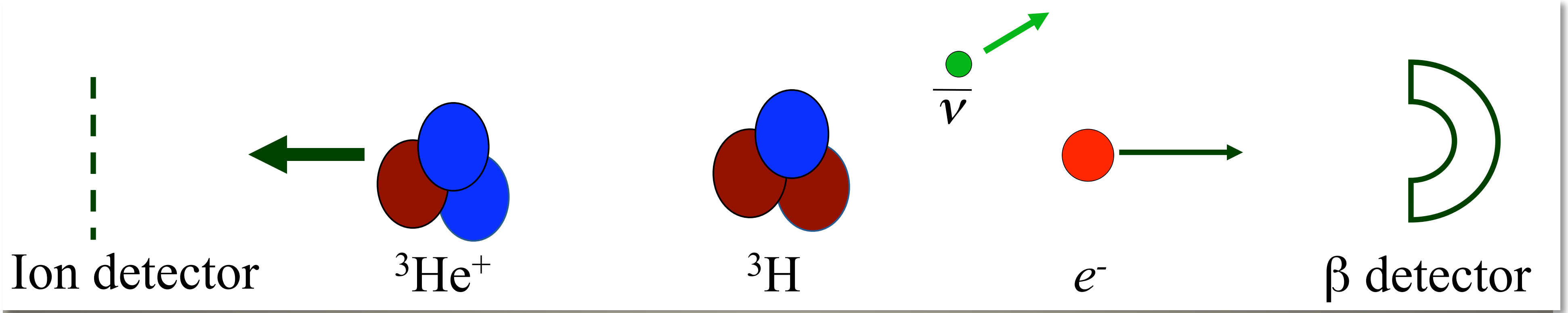


$$m_\nu^2 = (W - E_{ion} - E_\beta)^2 - (p_{x_{ion}} + p_{x_\beta})^2 - (p_{y_{ion}} + p_{y_\beta})^2 - (p_{z_{ion}} + p_{z_\beta})^2$$

- 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: 3-Body

Direct reconstruction of the neutrino mass!



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

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 + momentum measurement obtained using Rydberg atoms

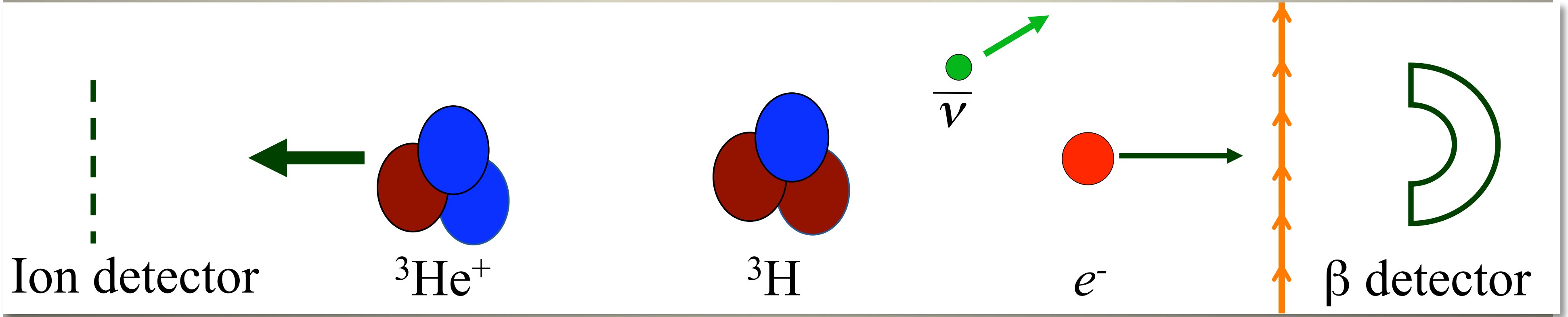
β spectrometer + Rydberg atoms

E_β p_{x_β} p_{y_β}

(p_{z_β} reconstructed from energy conservation)

Tritium β-Decay: 3-Body

Use Rydberg atoms to measure β momentum non-invasively:



Create a transverse beam of slow-moving Rydberg Rubidium atoms

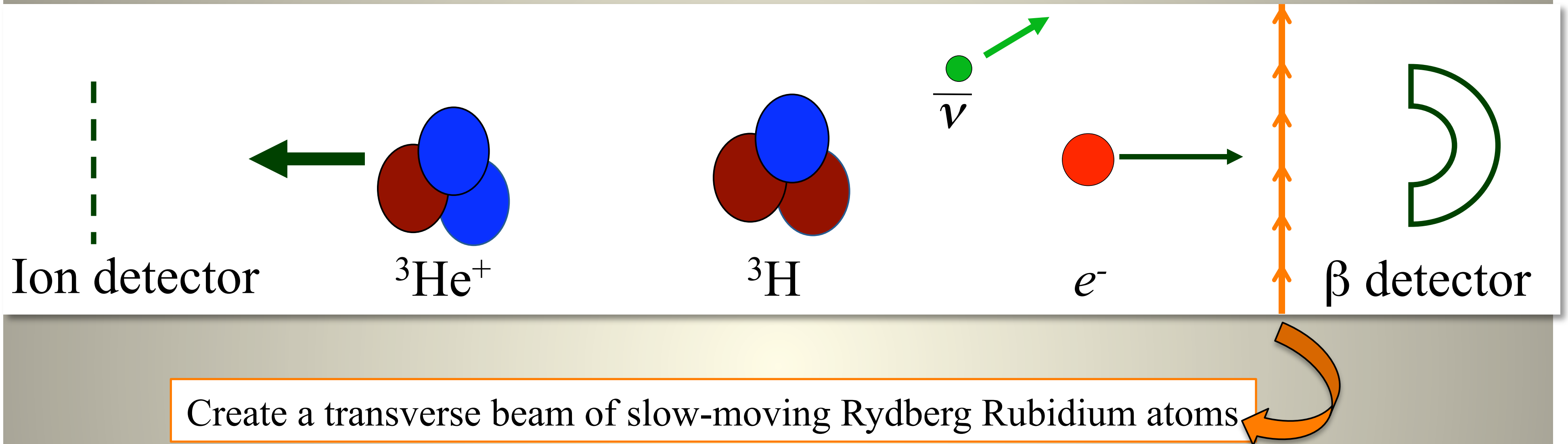
Rydberg atoms have valence electrons with high principle quantum number:

$$r = \frac{n^2\hbar^2}{kZe^2m} \quad \longrightarrow$$

High n implies large orbital radius and easily perturbed or ionized electrons

Tritium β-Decay: 3-Body

Use Rydberg atoms to measure β momentum non-invasively:



Create a transverse beam of slow-moving Rydberg Rubidium atoms

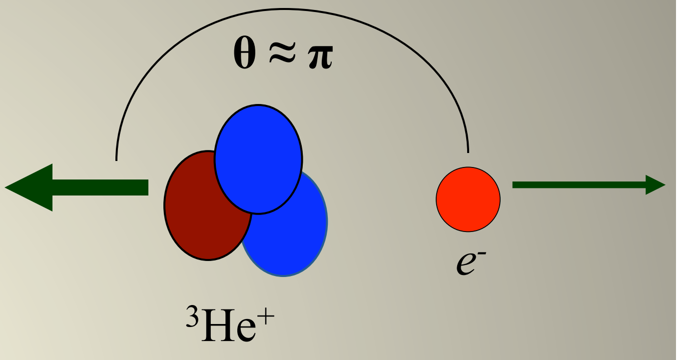
1) β passing near a Rydberg atom excites/ionizes it above n=50
2) Small applied E field accelerates only atoms above n=50
3) MCP detects atom, giving x position of the β that passed
4) TOF of atom to MCP gives y position of the β that passed

Combining with β energy from spectrometer, we get β's x, y, and z momentum components

Technique's resolution varies from 15meV/c to 2.7eV/c

Tritium β-Decay: 3-Body

What about the opening angle uncertainty?



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

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

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

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

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: 3-Body

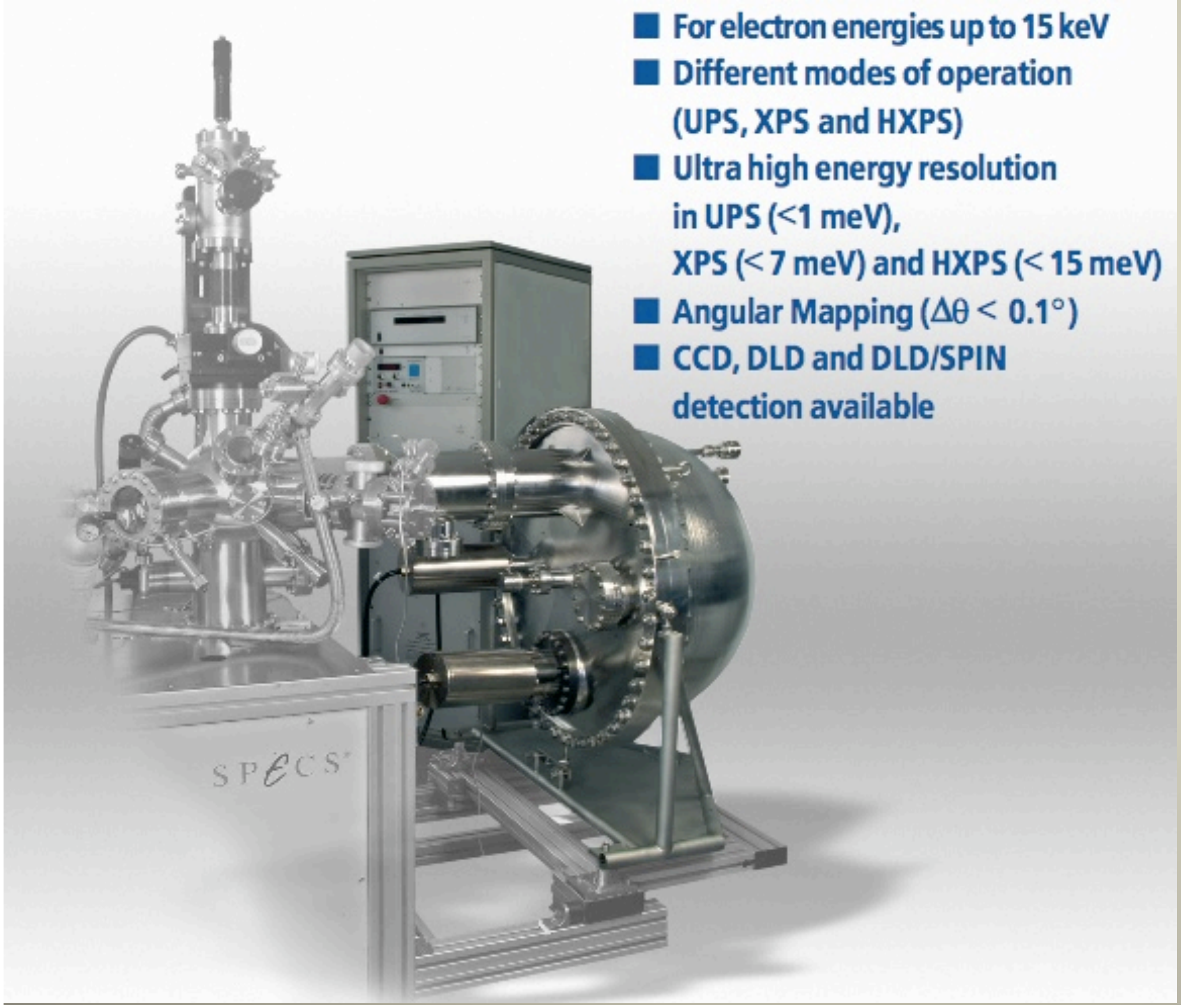
ROOT simulation: based on kinematics (no particle tracking)

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 15meV/c to 2.7 eV/c
- Geometrical acceptance for the β limited by 10 beams of Rydberg atoms (width 1cm) placed 5m from source
- MCP: 2 micron binning, 44% geometrical acceptance, 100cm wide and 20cm tall, placed 5m from source
- Ion TOF Gaussian smear of 20ps
- Gravity correction for the ion ~0.5 microns

Tritium β-Decay: 3-Body

PHOIBOS hemispherical analyzer 225 HV

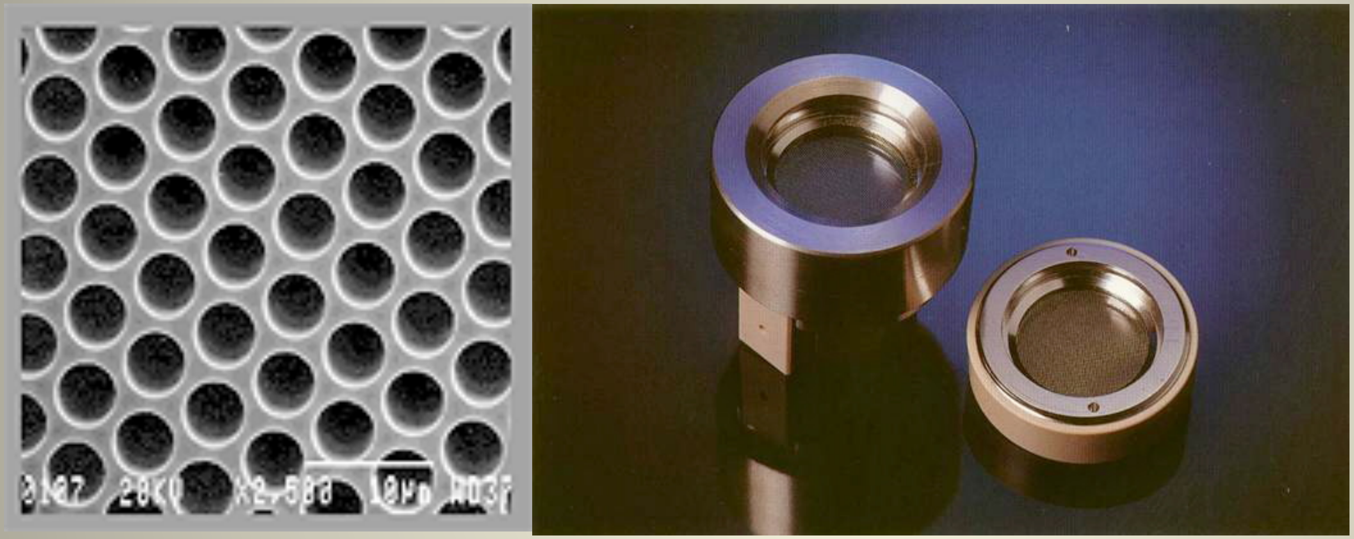


- For electron energies up to 15 keV
- Different modes of operation (UPS, XPS and HXPS)
- Ultra high energy resolution in UPS (<1 meV), XPS (< 7 meV) and HXPS (< 15 meV)
- Angular Mapping ($\Delta\theta < 0.1°$)
- CCD, DLD and DLD/SPIN detection available

- 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

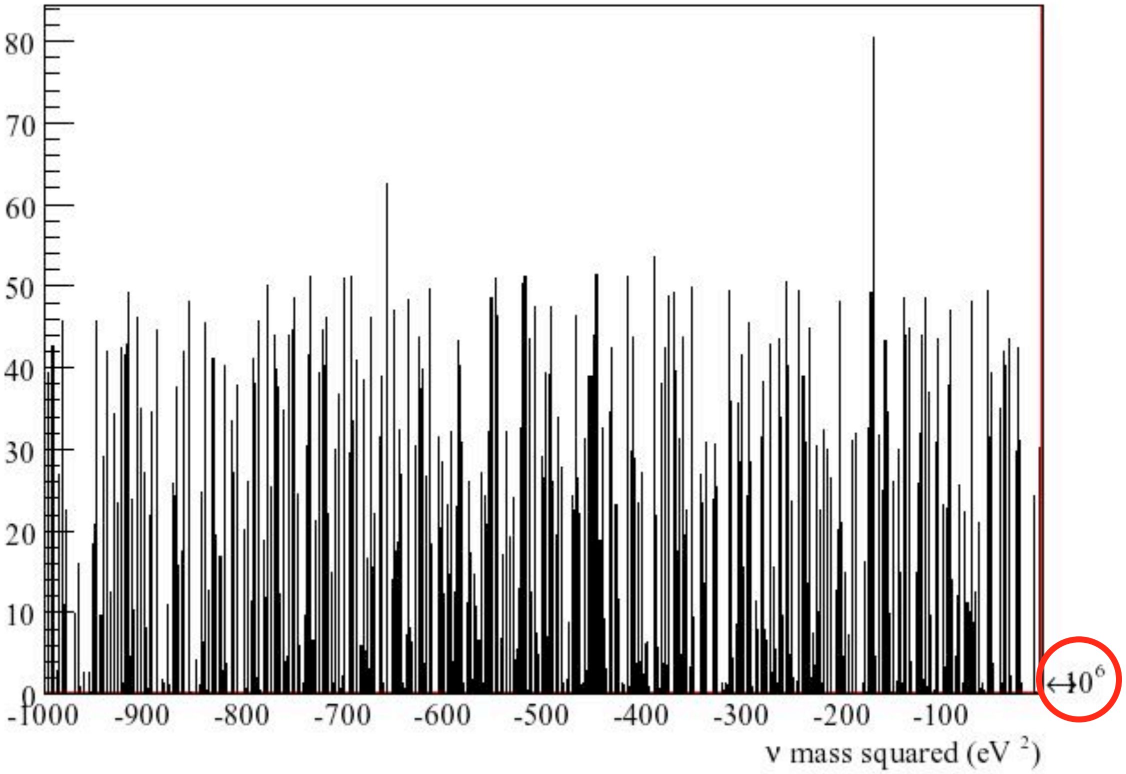
- Detects position and time-of-flight (TOF)
- 2 micron holes spaced 3 microns center-to-center
- 350 ps pulse width resolution

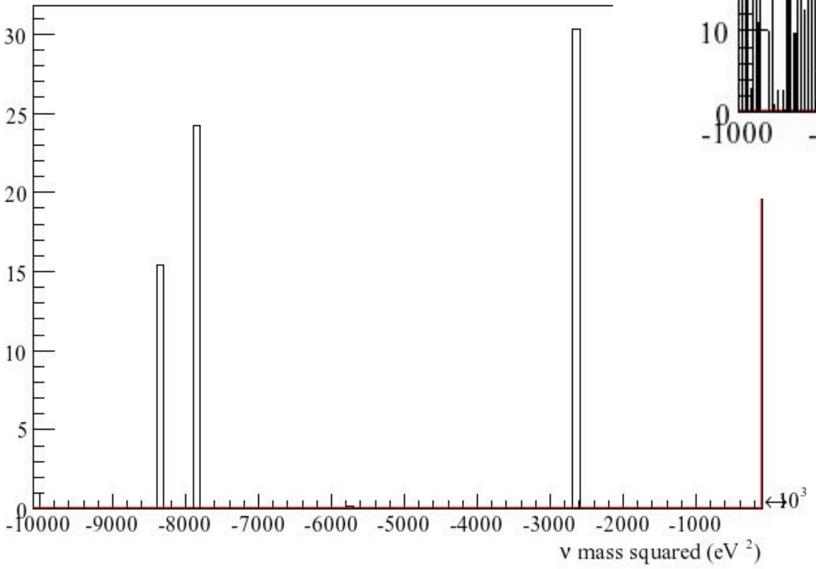
Tritium β-Decay: 3-Body

Background test:

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

10^{-5} background rejection, not including β-coincidence

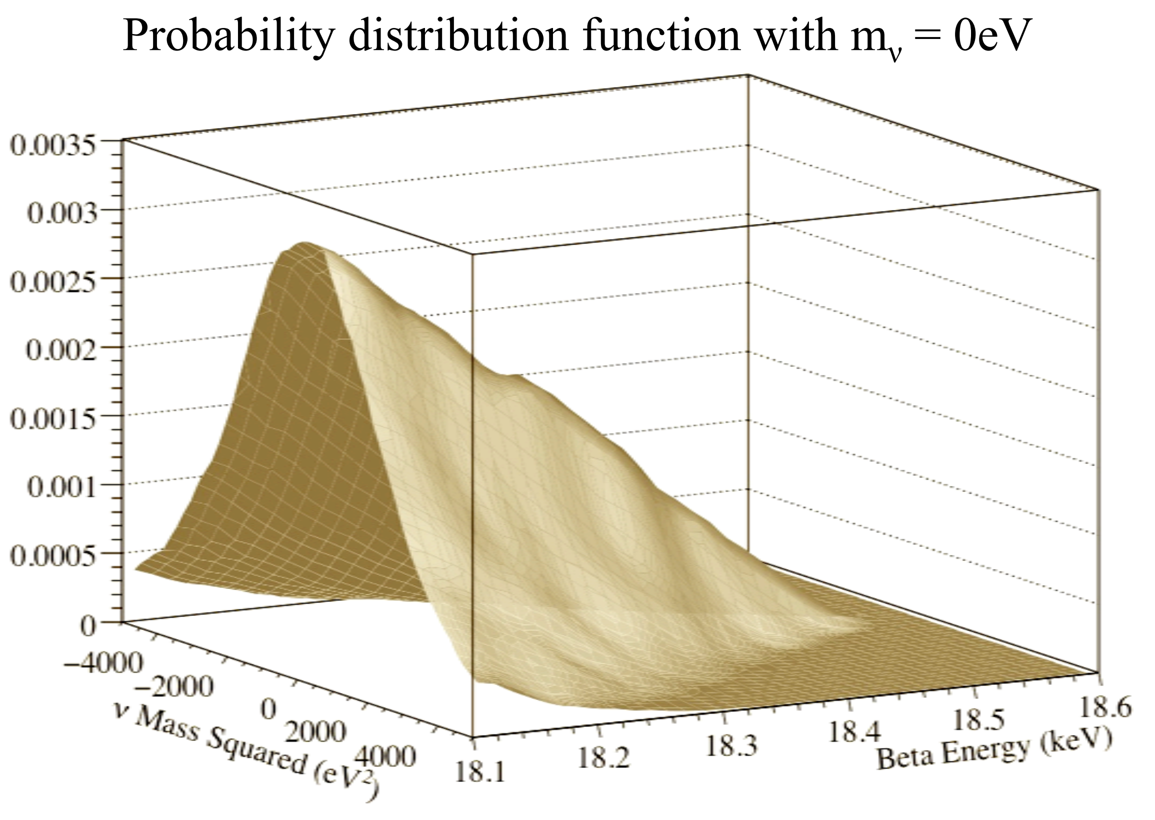




Magnitude of p_ν is increased 2-3 times, while E_ν changes only slightly → m_ν always reconstructs extremely negative for background events

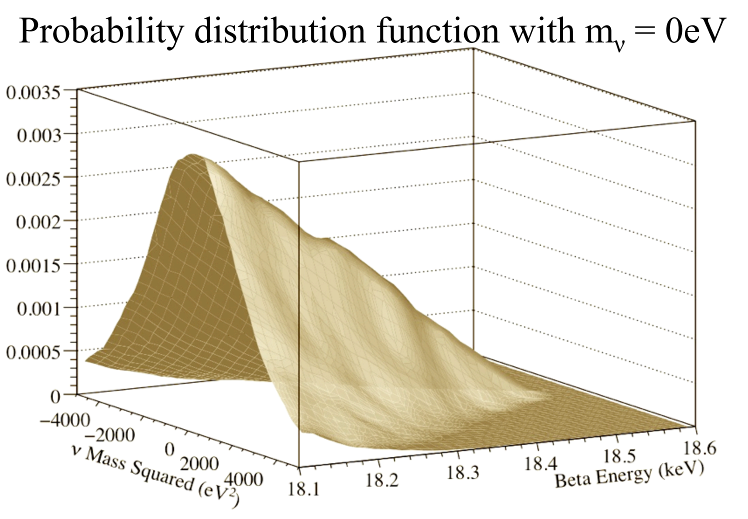
Tritium β-Decay: 3-Body

- 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



Tritium β-Decay: 3-Body

Assumed m_ν (eV)	Fit m_ν	(+) error	(-) error
0.2	0.190	0.166	0.139
0.4	0.407	0.211	0.160
1.0	0.778	0.268	0.240



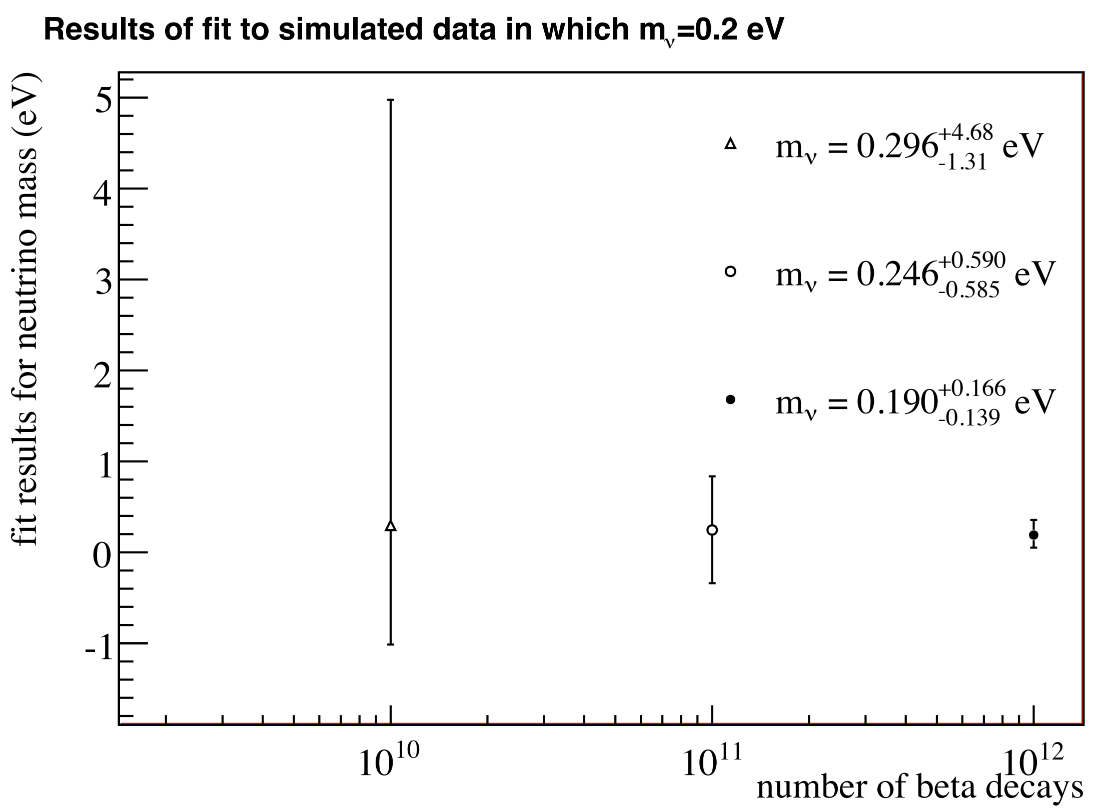
Probability distribution function with m_ν = 0eV

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: 3-Body

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 500eV from endpoint
- Valid for Dirac and Majorana neutrinos



Experimental challenges:

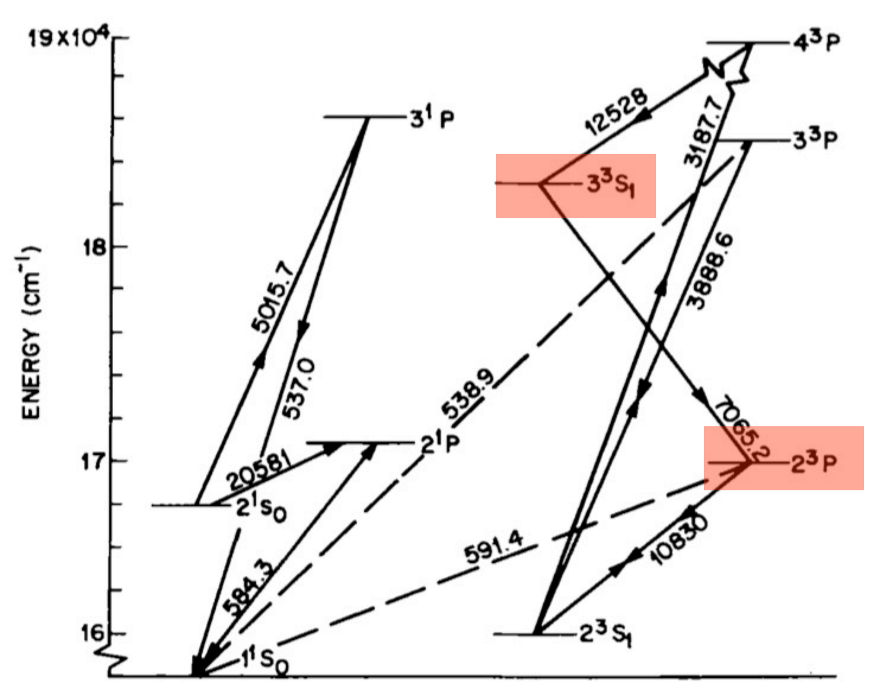
- Trapping $2x10^{13}$ tritium atoms
- Large MCP with binning 2-10μm
- 5-50meV energy resolution
- Non-invasive momentum measurement for β

Boundstate β-Decay: 2-Body

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

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

- 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



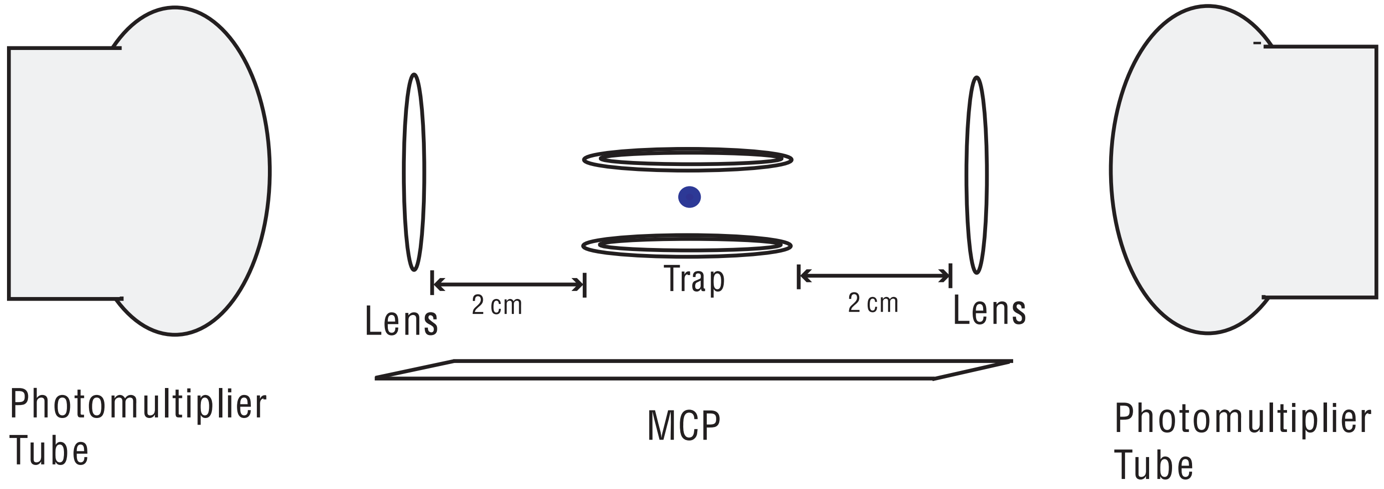
Boundstate β-Decay: 2-Body

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

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

- 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

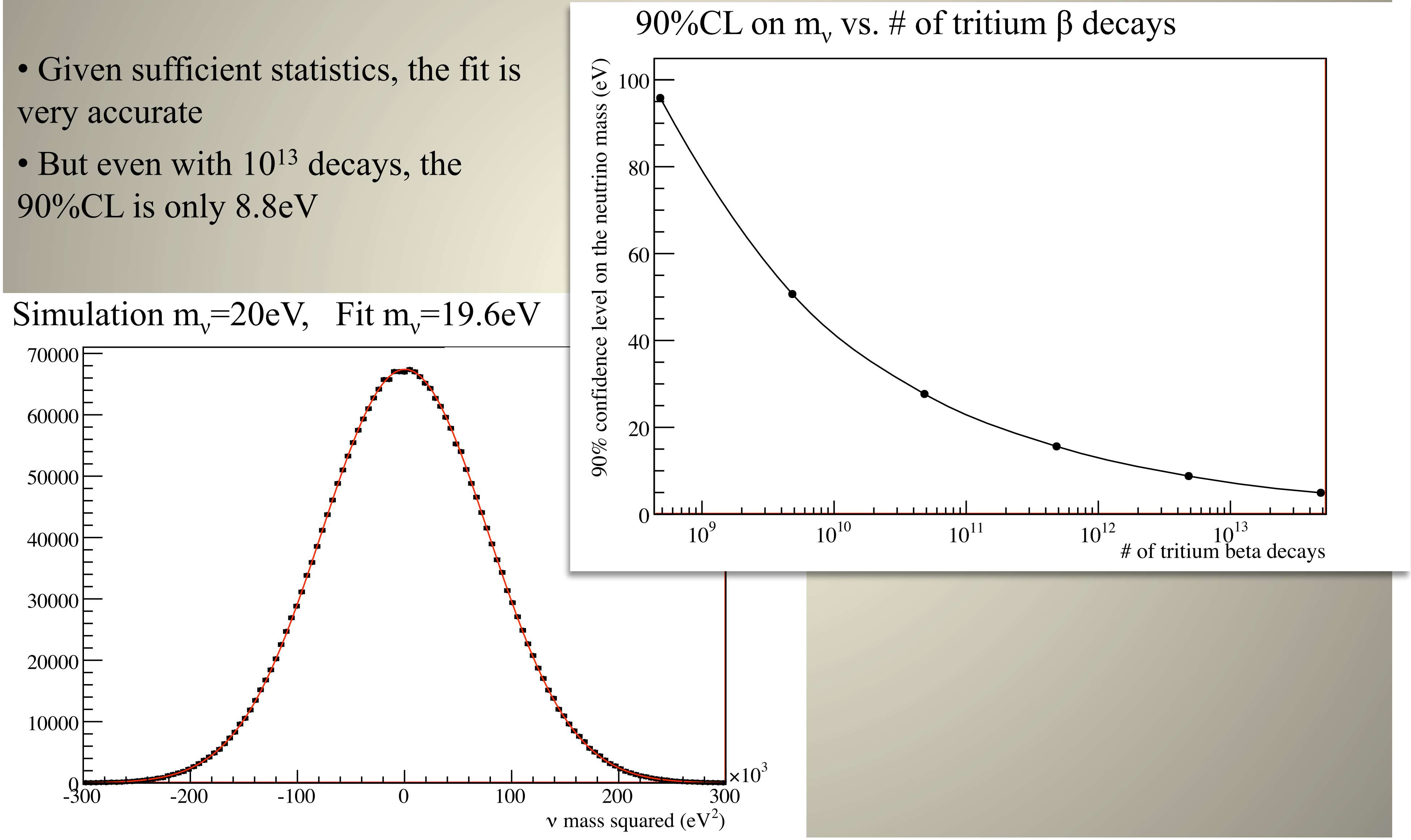
Detect photon from ^{3}He atom & ^{3}He TOF to MCP



Boundstate β-Decay: 2-Body

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

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

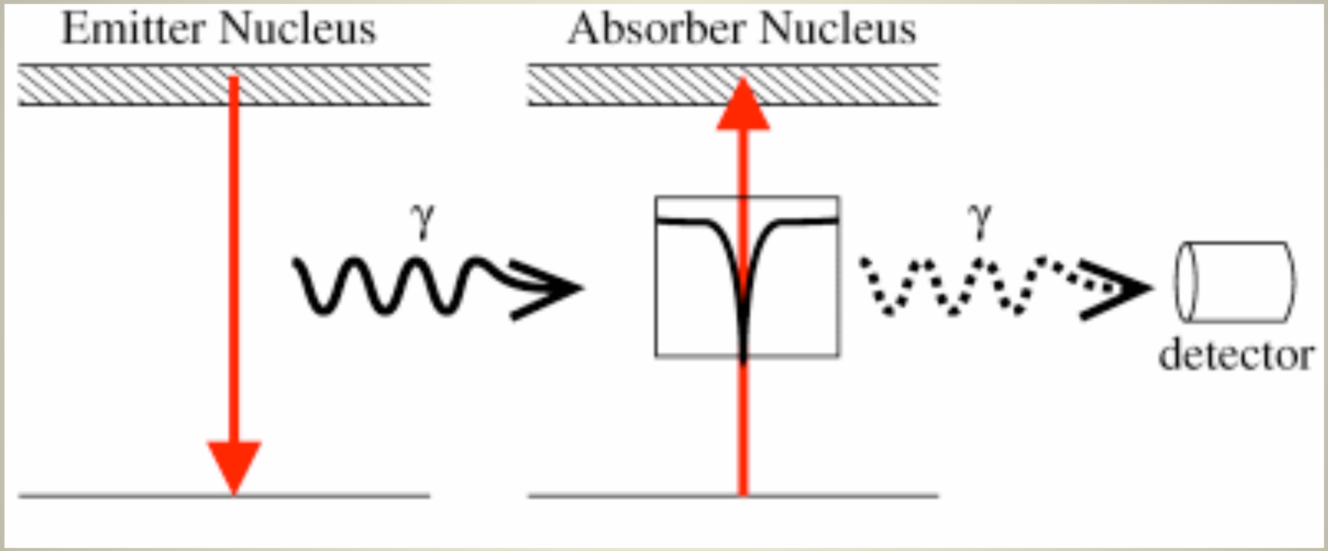


90%CL on m_ν vs. # of tritium β decays

Simulation m_ν=20eV, Fit m_ν=19.6eV

Mössbauer Neutrinos: 1-Body

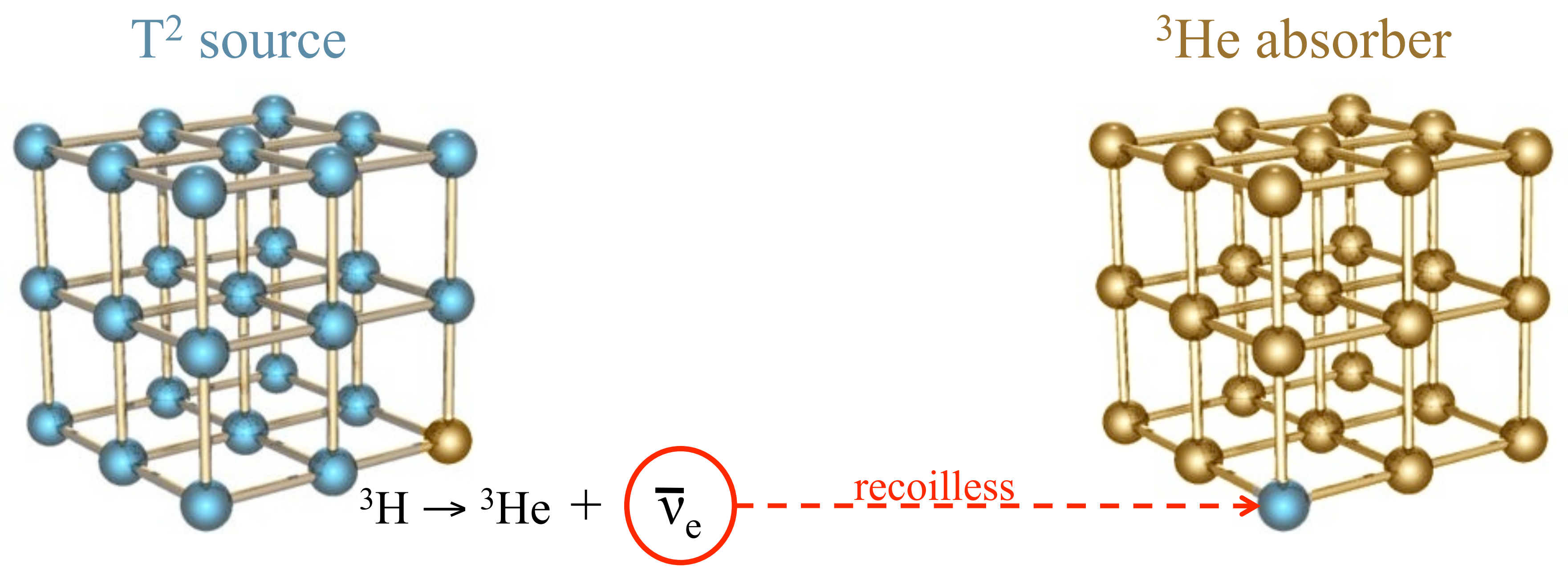
Ordinary Mossbauer effect: photons emitted recoillessly by one nucleus can be resonantly absorbed by another nucleus of the same type



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:

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

Reverse tritium beta decay:

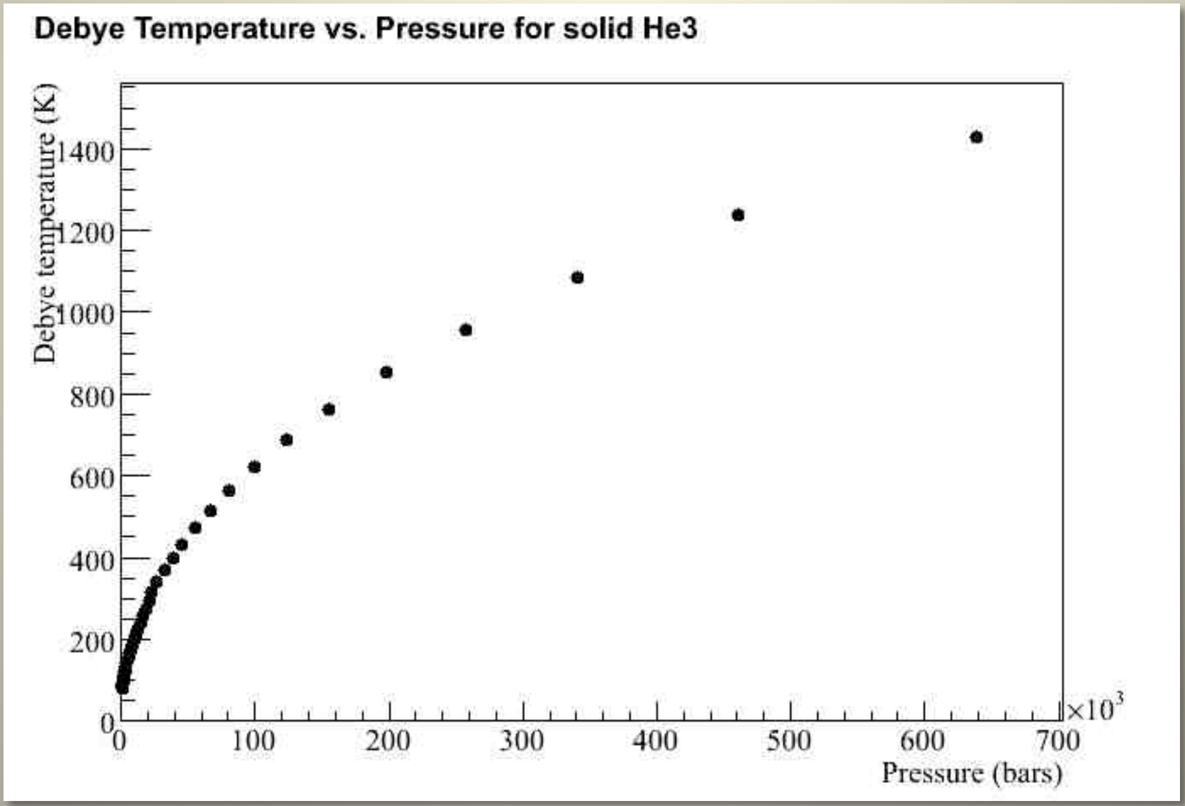
$$\bar{\nu}_e + {}^3He \rightarrow {}^3H$$

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

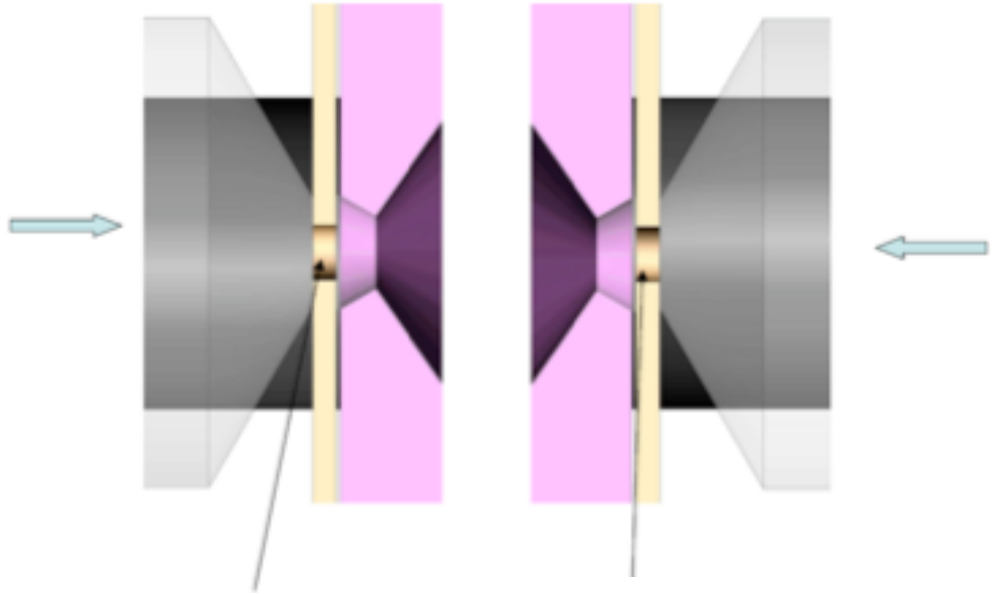
We can get a very high Debye temperature by going to high pressures



Mössbauer Neutrinos: 1-Body

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

2 Diamond Anvil Cells placed ~1-4cm apart



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

T_2 source @10GPa
Source ~29Cu

Mössbauer Neutrinos: 1-Body

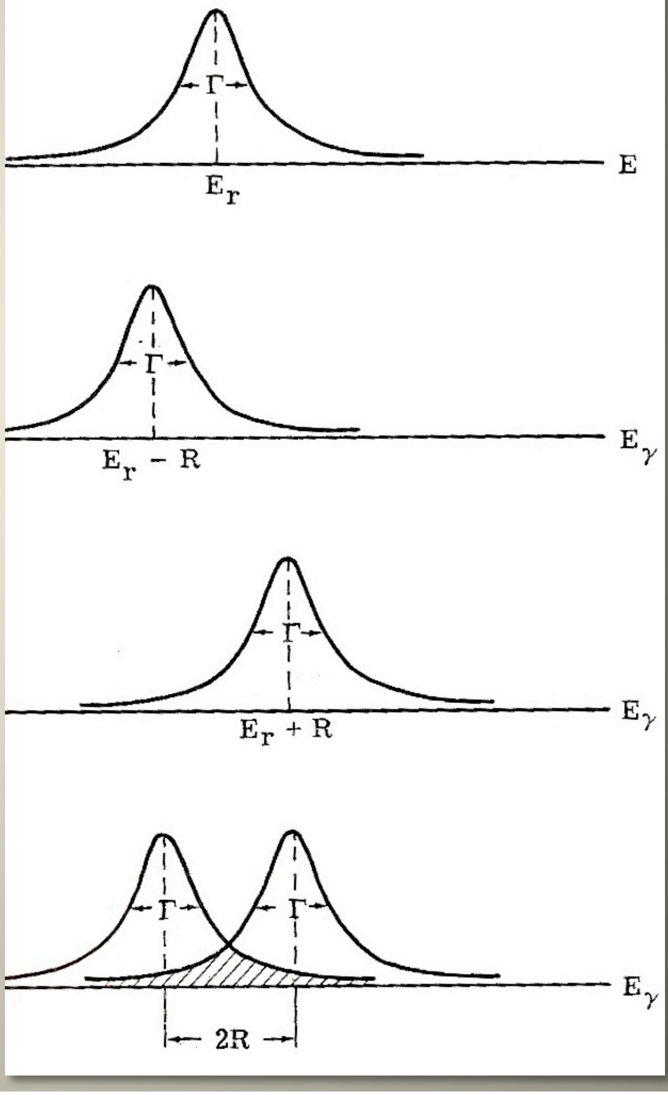
Tuning the pressure allows us to align emission & absorption peaks!

$\sigma_{\text{resonant}} = 4.18 * 10^{-41} * g_o^{\,2} * \rho(E^{\text{res}}_{\nu_e})/ft_{1/2} \approx \mathbf{10^{-32} cm^2}$
(assuming linewidth $\sim 10^{-12}$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:

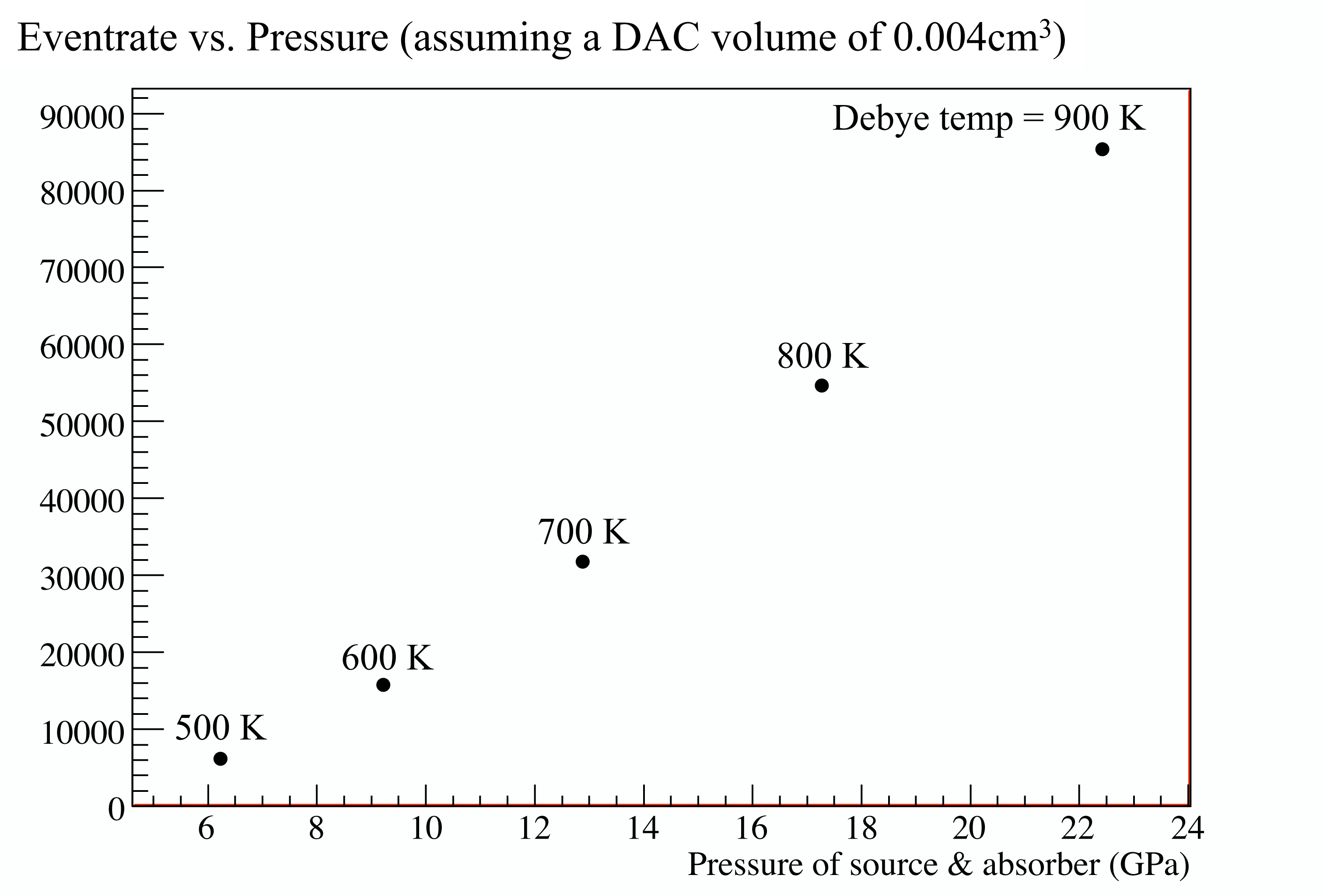
$\Delta E/E = (9k_B/16Mc^2) * (\theta_{\text{emitter}} - \theta_{\text{absorber}})$

Energy shifts can destroy resonance



Mössbauer Neutrinos: 1-Body

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



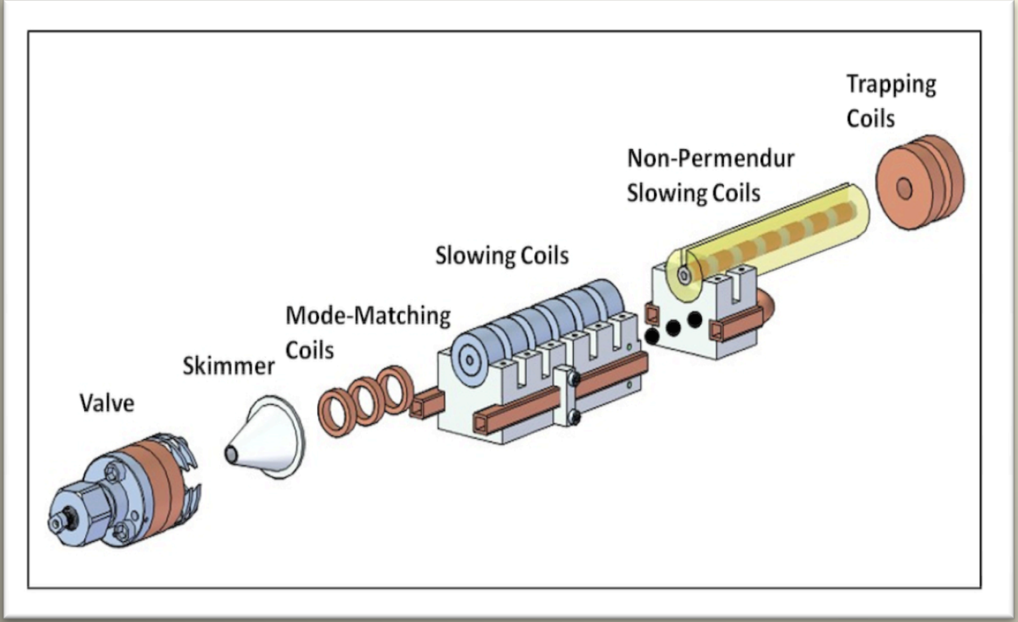
Mössbauer Neutrinos: 1-Body

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

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

Physics motivation:

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



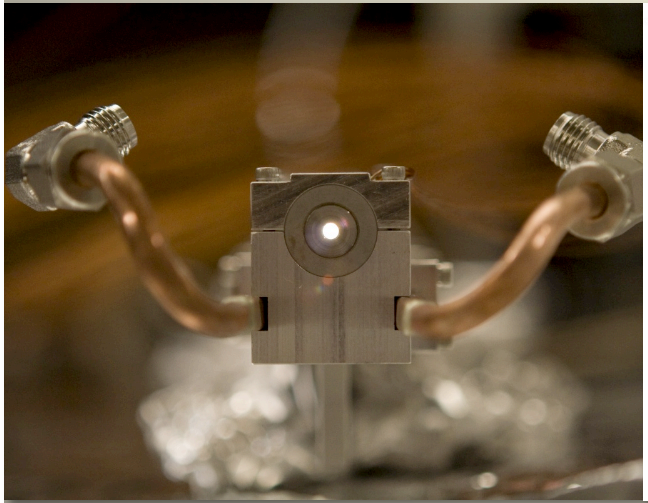
$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta)\sin^2(1.27\Delta m^2 L/E)$$

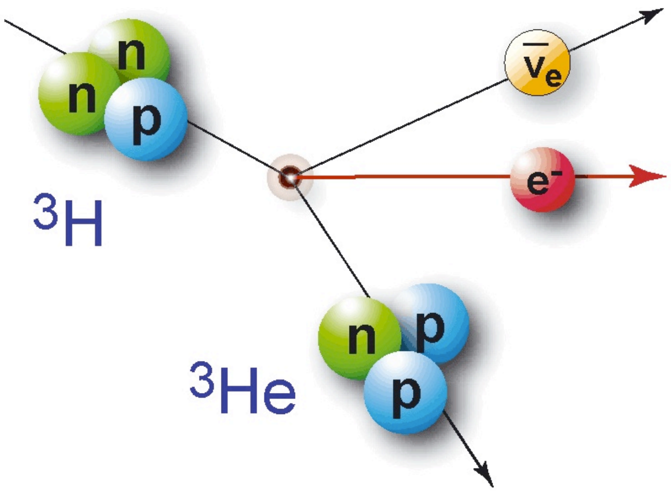
A large L is unnecessary if E=18.6keV

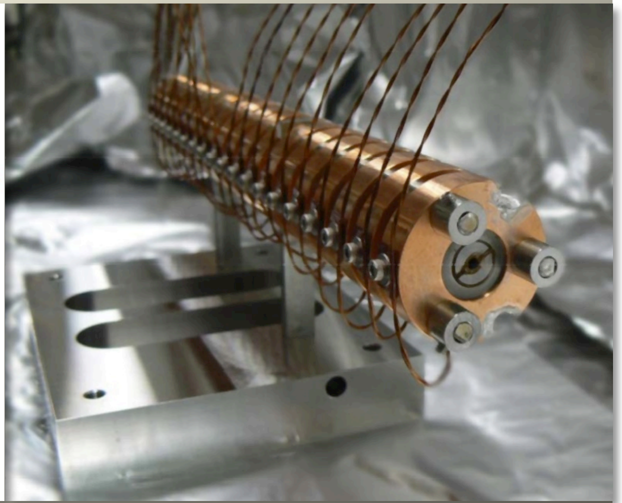
Conclusions

Slowing and trapping cold ^{3}H atoms → exciting potential ν experiments:

- First atomic source ever utilized in tritium β-decay
- **Three-body β-decay:** Fundamentally new way of measuring ν mass
- **Boundstate β-decay:** Unique (if uncompetitive) constraint on the neutrino mass
- **Neutrino Mössbauer effect:** Trace element detection through magnetic slowing may enable ν research at tabletop scales







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

Special Thanks

Josh Klein
Mark Raizen
Paul Loubey
Julia Majors
Francis Robicheaux
Ed Narevicius

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