Relic Neutrinos

(and other Holy Grails)

Institute for Nuclear Theory
February 2010

J. A. Formaggio
MIT

New Connections

- With the launch of the Planck satellite, the connection between neutrino physics and cosmology becomes even stronger.
- A strong verification of the existence of the relic neutrino background (via direct detection) may provide strong validation of our current cosmological model(s),
- Can direct detection of relic neutrinos be accomplished?

The Triumph of Cosmology

- The combination of the standard model of particle physics and general relativity allows us to relate events taking place at different epochs together.
- Observation of the cosmological neutrinos would then provide a window into the 1st second of creation

Signal Properties

$$f_i(p,T) = \frac{1}{e^{\frac{E_i(p)-\mu_i}{T}}+1}$$

- Cosmological neutrinos (or the CνB) are inherently connected to the photon microwave background. However, there are significant differences between the two.

- Some characteristics:

    - The CνB **temperature** is related to the photon temperature (including reheating).

    - The CνB is inherently a gas of spin 1/2 particles: obey **Fermi-Dirac statistics** rather than Bose-Einstein).

    - The CνB **density** is predicted directly from the photon density.

	Bose-Einstein (γ's)	Fermi-Dirac (ν's)
Temperature (Now)	2.725 K	1.945 K
Number density	$\frac{\zeta\{3\}}{\pi^2} g T_\gamma^3$	$\frac{3}{4}\frac{\zeta\{3\}}{\pi^2} g T_\nu^3$
Energy Density	$\frac{\pi^2}{30} g T_\gamma^4$	$\frac{7}{8}\frac{\pi^2}{30} g T_\nu^4$

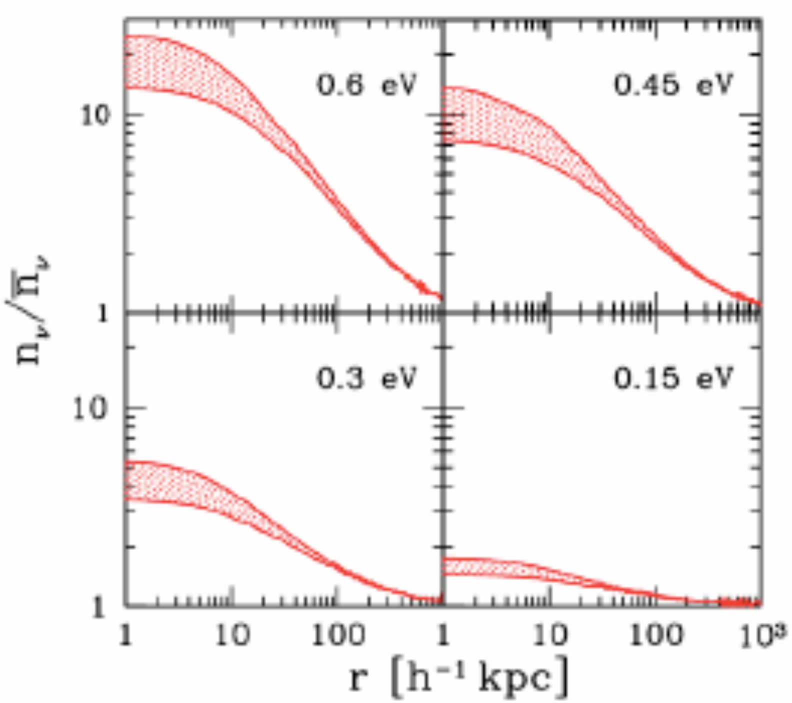
From CMB, the neutrino density is ~110 ν's/cm³ per flavor.

(neutrino and anti-neutrino)

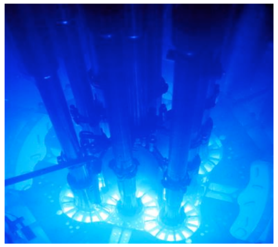
Local Enhancement

- Because neutrinos have a small (but non-zero) mass, they feel the force of gravity and are thereby affected by it.

- Given the present-day cosmological neutrinos are non-relativistic, one could expect a *local* enhancement of the density of neutrinos in our galaxy.



We have a good track record...



Neutrinos from reactors.

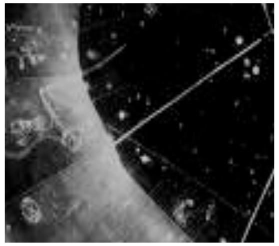
Detected (1950s)

Neutrinos from the sun.

Detected (1960s)

Neutrinos from the atmosphere.

Detected (1960s)

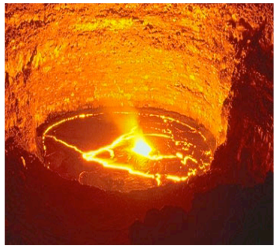


Neutrinos from accelerators.

Created & detected (1960s)

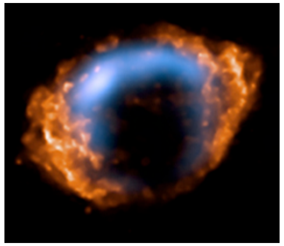
Neutrinos from supernovae.

Detected (1980s)



Neutrinos from the Earth.

Detected (2000s)



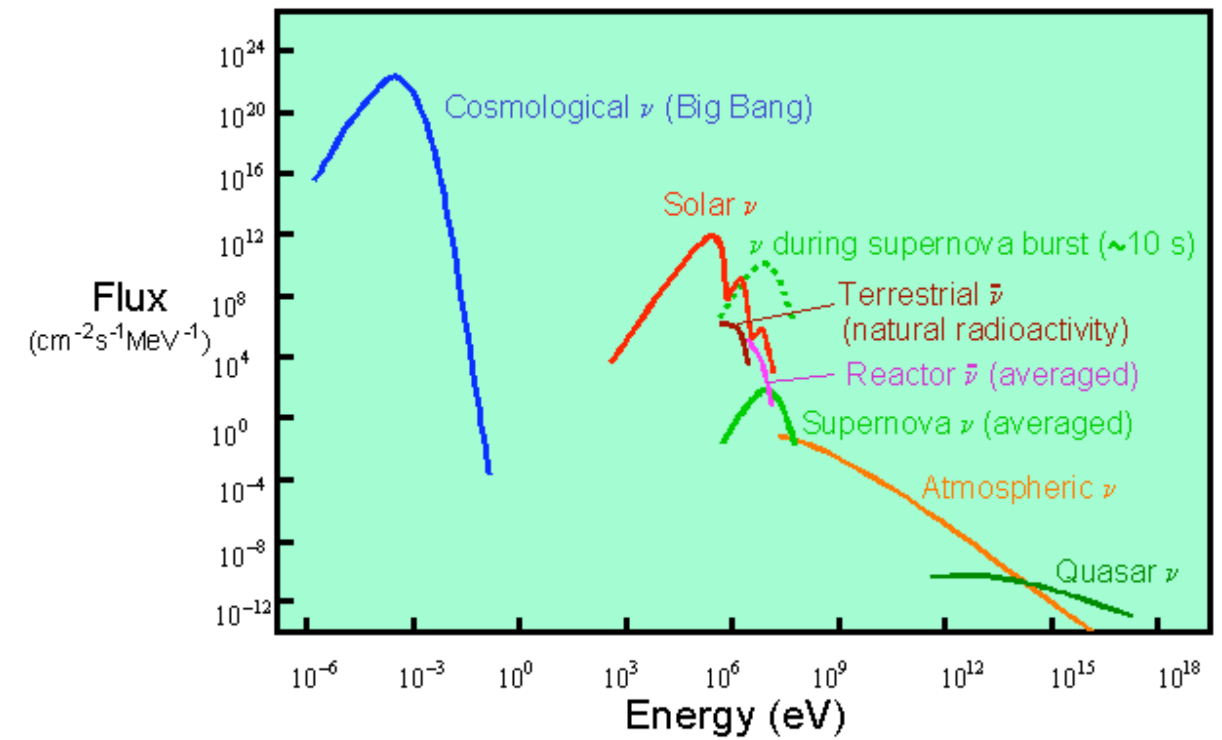
Neutrinos from galactic sources.

Not yet (but close!)

Neutrinos from the Big Bang.

Not even close...

Why is it so hard???



Flux on earth of neutrinos from various sources, in function of energy

- Cosmological neutrinos comprise the most intense natural source of neutrinos available to us from nature.

- The cosmological photon background has been measured incredibly well. The noise from the early big bang still rings today.

So??

What's the problem?!

Why is it so hard?

"Choice. The problem is choice."

- Actually, the problem is THRESHOLD.

- Consider, for example, ordinary inverse beta decay.

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$$E_\nu + m_p \geq m_e + m_n$$

- Since energy is conserved, you need the neutrino to have enough energy to initiate the process.

- But here the kinetic energy from relics is very small.

$$< K >= 6.5T_\nu^2/m_\nu \text{ or } 3.15T_\nu$$

- For most nuclei, you just do not have enough energy. You need a threshold-less process.

Some quotes....

"About every neutrino physicist goes through a phase in his or her career and asks 'There's got to be a way to measure the relic neutrino background...'" *P. Fisher*

Coherent Scattering

- Consider the scattering of a macroscopic object against the neutrino *wind*.
- This wind is actually the motion of the earth with respect to the neutrinos (similar to moving through a dark matter halo).
- Consider the coherent scattering of neutrinos against an object (spheres) and look at the force imposed by the neutrino wind.

$$\sigma = G_F^2 m_\nu^2 \frac{k_L^2}{\pi} \quad \text{(scattering)}$$

$$\frac{d\vec{p}}{dt} = F_\nu \sigma \Delta p \quad \text{(mom. trans.)}$$

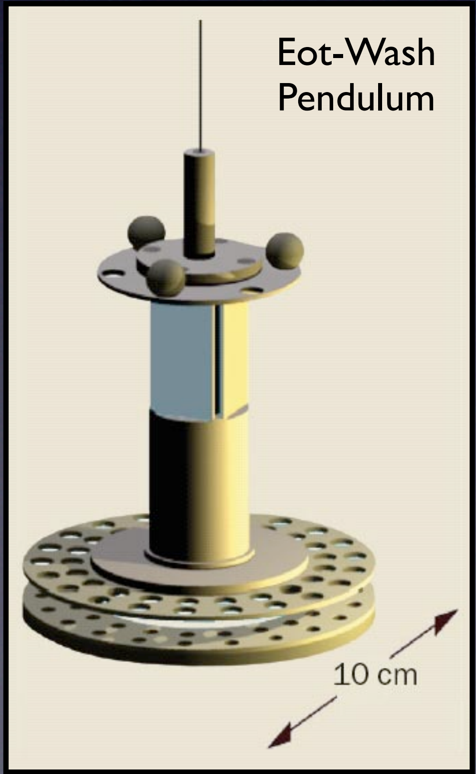
Coherent Elastic Scattering

- Effect takes advantage of a macroscopic de Broglie wavelength (for these momenta).

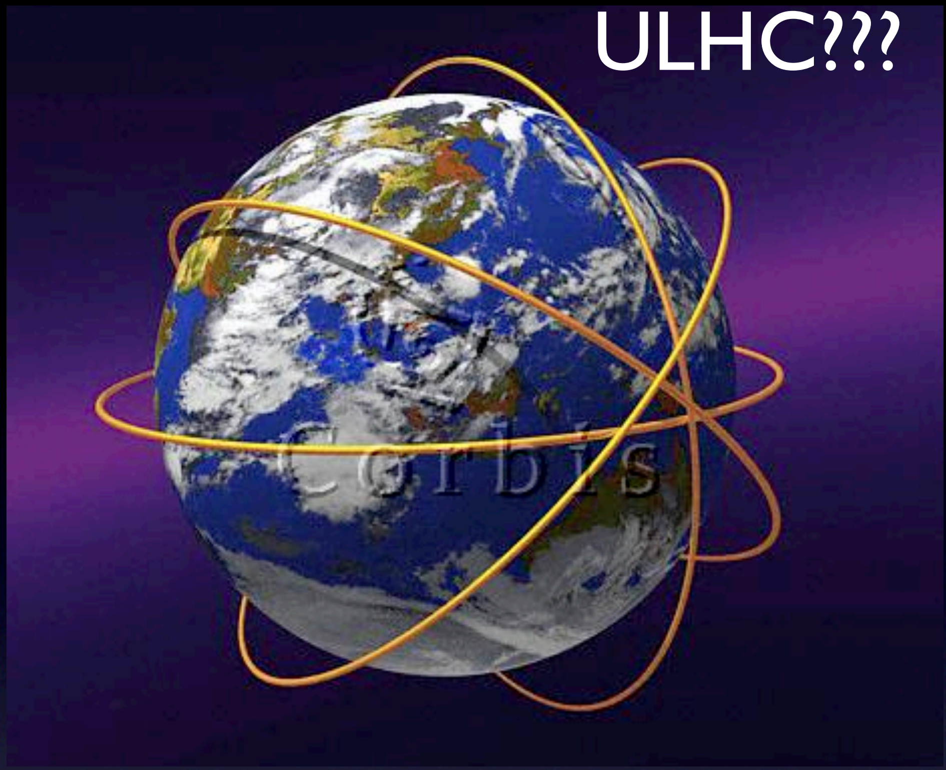
- Equivalent to measuring a small acceleration on a macroscopic object.

- Currently can measure accelerations down to 10^{-13} cm/s^2. Can push this down to 10^{-23} cm/s^2 in the future.

$$a_t \simeq (10^{-46} - 10^{-54}) \frac{A}{100} \text{ cm s}^{-2}$$



High Energy Scattering : Beams



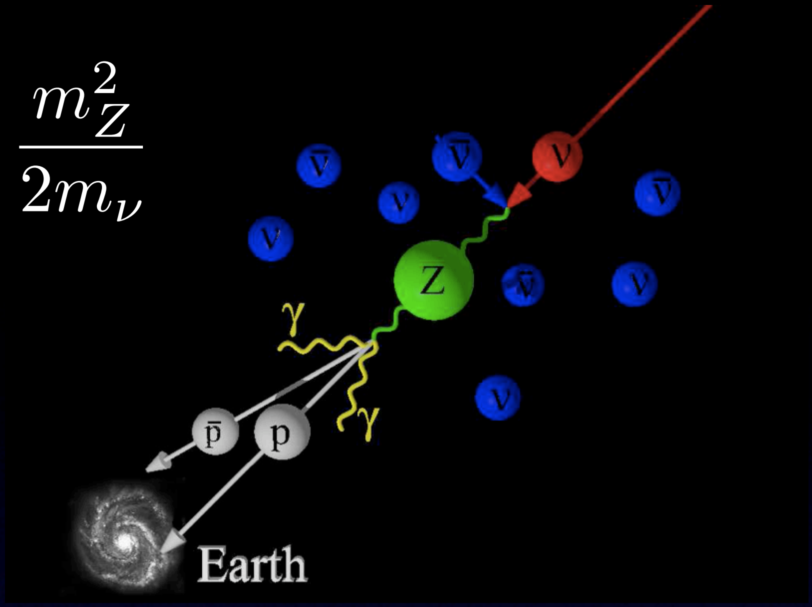
- Take advantage of cross-section growth with energy, using very high energy isotopes as probes.
- Two possible sources: high energy accelerators & cosmic rays.
- Most parameters necessary for relic neutrino detection beyond scope of conventional machines.

accel.	N	E_N [TeV]	L [km]	I [A]	$\frac{R_\nu A}{\left[\frac{n_\nu}{\bar{n}_\nu}\frac{m_\nu}{\mathrm{eV}}\right]}$ [yr^{-1}]
LHC	p	7	26.7	0.6	2×10^{-8}
	Pb	574	26.7	0.006	1×10^{-5}
VLHC	p	87.5	233	0.06	2×10^{-7}
	Pb	7280	233	0.0006	1×10^{-4}
ULHC	p	10^7	40 000	0.1	10

$$R_\nu = 2\times10^{-9}\cdot\frac{m_\nu}{\mathrm{eV}}\frac{A^2}{Z}\frac{E_n}{10\mathrm{TeV}}\frac{L}{\mathrm{km}}\frac{I}{\mathrm{A}}[\mathrm{yr}^{-1}]$$

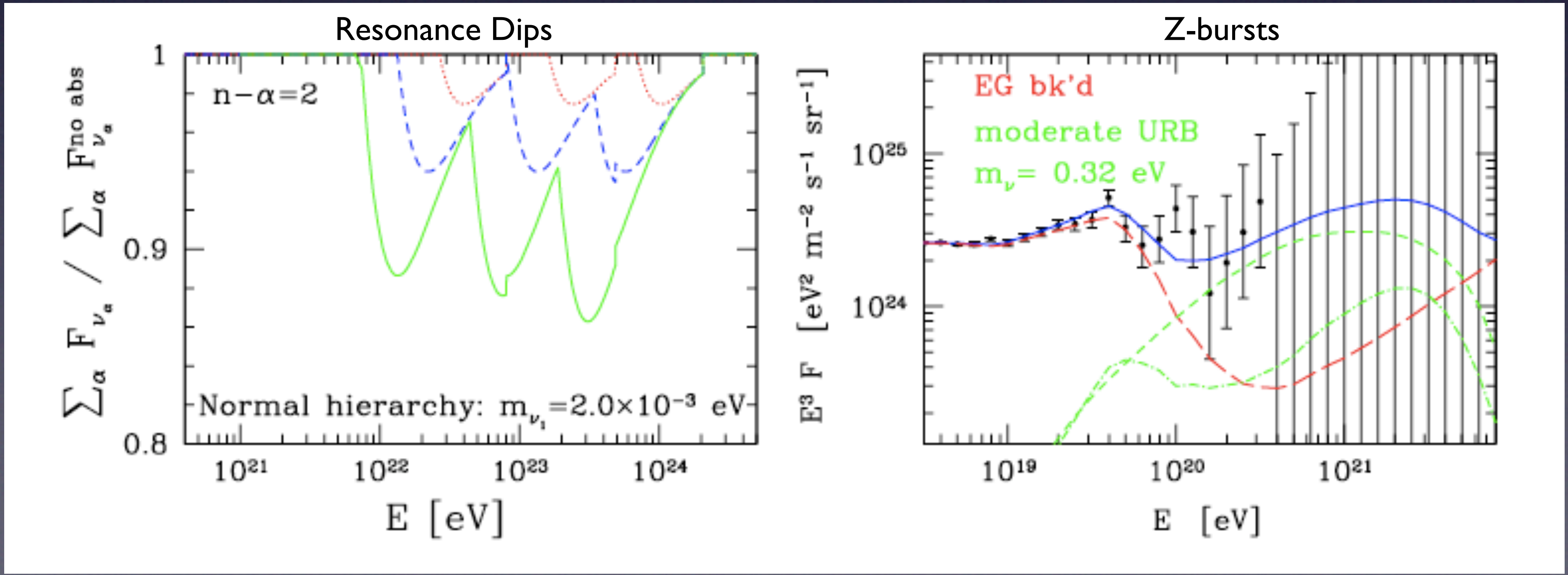
High Energy Scattering : Cosmic Rays

$$E_\nu^{\rm res} = \frac{m_Z^2}{2m_\nu}$$



- Conversely, one can use cosmic rays as the high energy source.

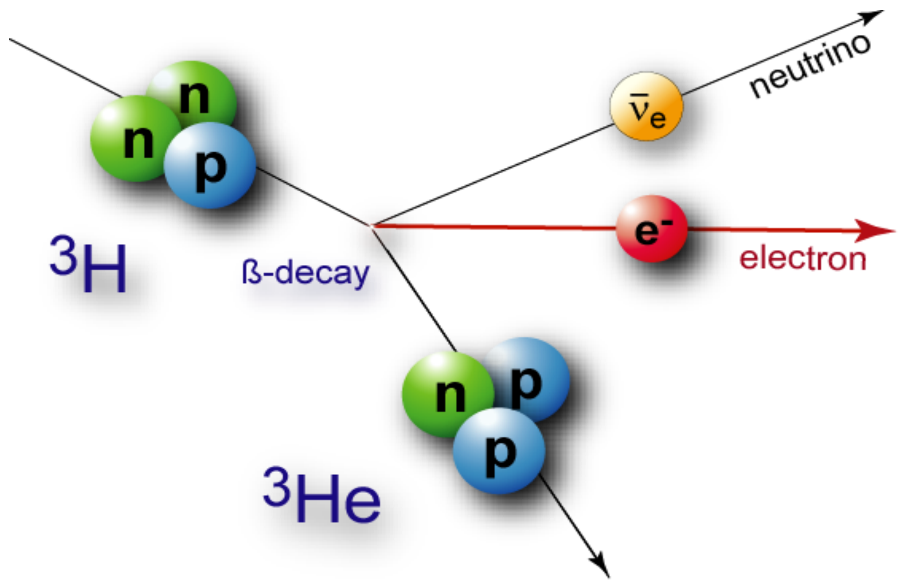
- One can look at absorption of extremely high energy neutrinos near the Z-resonance, or for emission features above the natural GZK cutoff.



Neutrino Capture

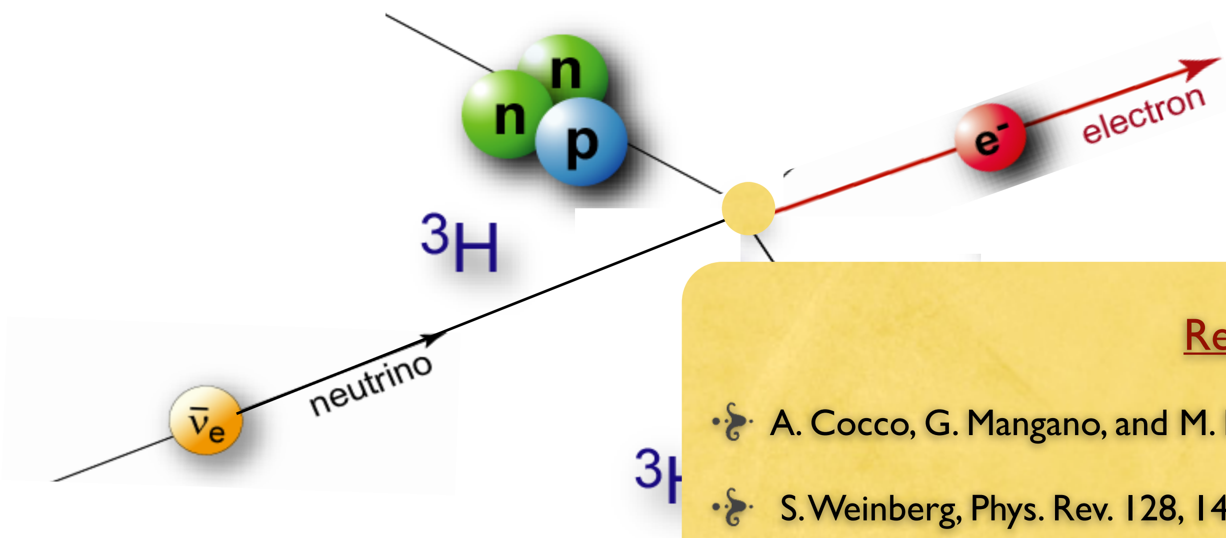
Instead of beta decay...

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



Neutrino Capture

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



__References__

- A. Cocco, G. Mangano, and M. Messina, hep-ph/0703075 (2007).
- S. Weinberg, Phys. Rev. 128, 1457 (1962).
- T. W. Donnell and J. D. Walecka, Ann. Rev. Nucl. Sci. 25, 329 (1975).

The process is energetically allowed even at zero momentum.

This threshold-less reaction allows for relic neutrino detection

Detecting the Impossible...

- The rate is determined by the neutrino density in our galaxy (n_ν) and the cross-section for the process to occur.

- Cross-section can be calculated from the ordinary beta-decay matrix elements.

- Because neutrino temperature is small (1.9 K), the energy distribution is also narrow and near zero.

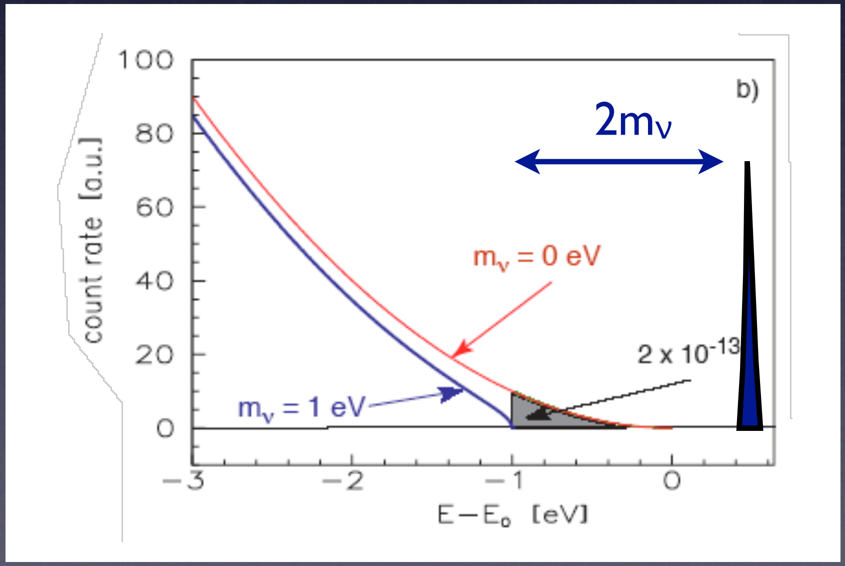
- This results in a unique signature: a mono-energetic electron removed from the endpoint energy of beta decay.

$$\lambda_\nu = \int \sigma_\nu \cdot v \cdot f(p_\nu)(\frac{dp}{2\pi})^3$$

Neutrino Capture Rate

$$\sigma_\nu \cdot \frac{v}{c} = (7.84 \pm 0.03) \times 10^{-45} cm^2$$

Tritium Cross-Section



The Targets

- The half-life of the beta-decay isotope essentially determines the rate at which the neutrino capture reaction occurs.
- Rate (for nominal neutrino density) can therefore be computed.
- Tritium emerges as the one isotope adaptable for relic neutrino detection.

Isotope	Endpoint (keV)	Half-Life (s)	Cross-Section (10^{-41} cm^2)	Rate (yr^{-1} kg^{-1})
^{3}H	18.591	3.89×10^{8}	7.84×10^{-4}	75
^{106}Ru	39.4	3.23×10^{7}	5.88×10^{-4}	1.6
^{187}Re	2.64	1.37×10^{18}	4.32×10^{-11}	4.7×10^{-11}
$^{11}\mathrm{C}^{\dagger}$	960.	1.27×10^{3}	4.66×10^{-3}	120.8
$^{13}\mathrm{N}^{\dagger}$	1199.	5.99×10^{2}	9.75×10^{-3}	116.2
$^{15}\mathrm{O}^{\dagger}$	1732.	1.22×10^{2}	9.75×10^{-3}	185.3

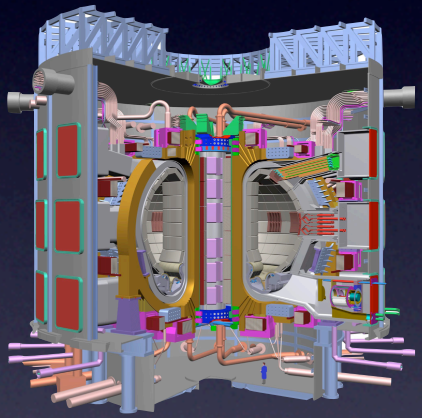
Bottom Line: 100 g of ^{3}H provides ~10 events/year

Intense Tritium Sources

KATRIN:

~100 μg (target)

ITER:



~3 kg (initial)

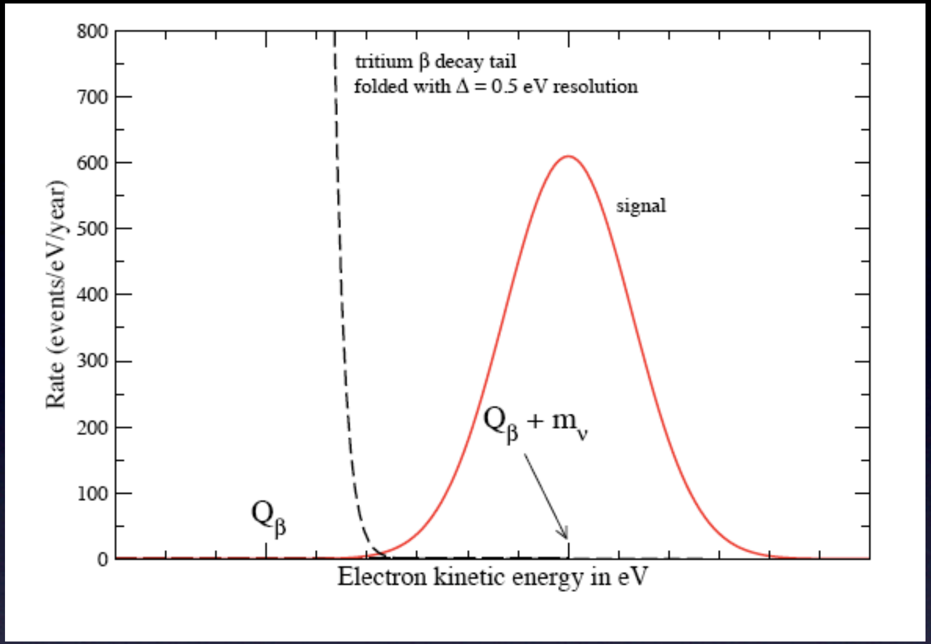
Exit Signs:

~1 μg

Intense tritium sources (order ~100 g) are obtainable

The Need for Resolution...

- Resolution is a key ingredient in the tagging of this process.
- As in neutrinoless double beta decay, one must separate the (more abundant) beta decay rate from the (rare) neutrino capture signal.
- The only separation stems from the energy difference (i.e. $2m_\nu$).
- Even if achieved, the background in the signal region must be < 1 event/year.



R. Lazauskas, P. Vogel, C. Volpe arXiv:0710.5312

In general, we want $\Delta \leq m_\nu$

Some More Quotes....

"About every neutrino physicist goes through a phase in his or her career and asks 'There's got to be a way to measure the relic neutrino background...'" *P. Fisher*

"... In all fairness, this method [neutrino capture] appears to have survived the longest." *P. Fisher*

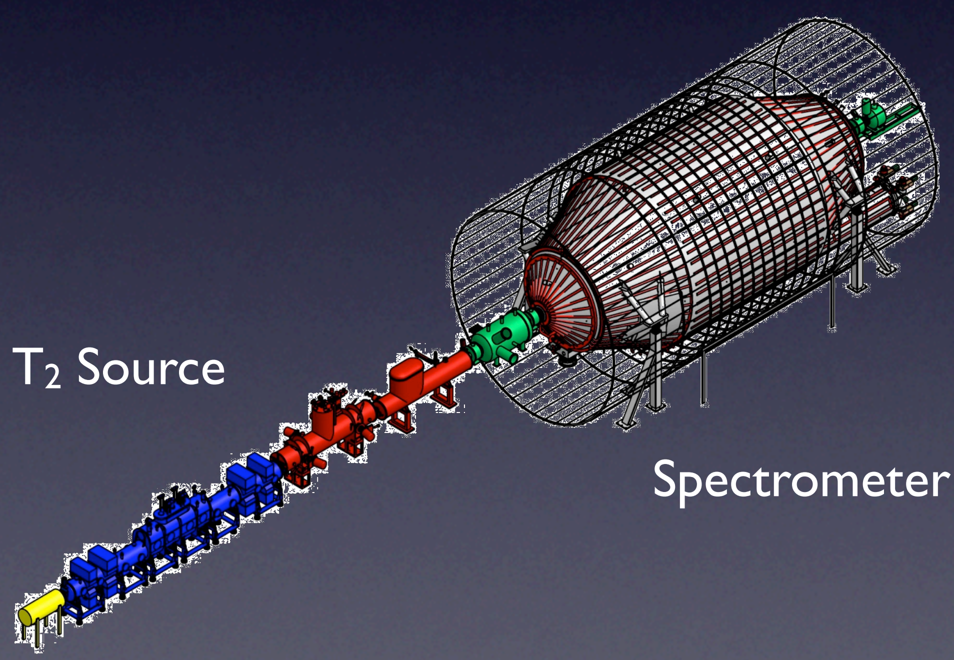
"Anyone who can measure relic neutrinos via neutrino capture will have made an amazing neutrino mass measurement..." *G. Drexlin*

"If it were easy, we'd be done by now..." *my translation*

The KATRIN Experiment

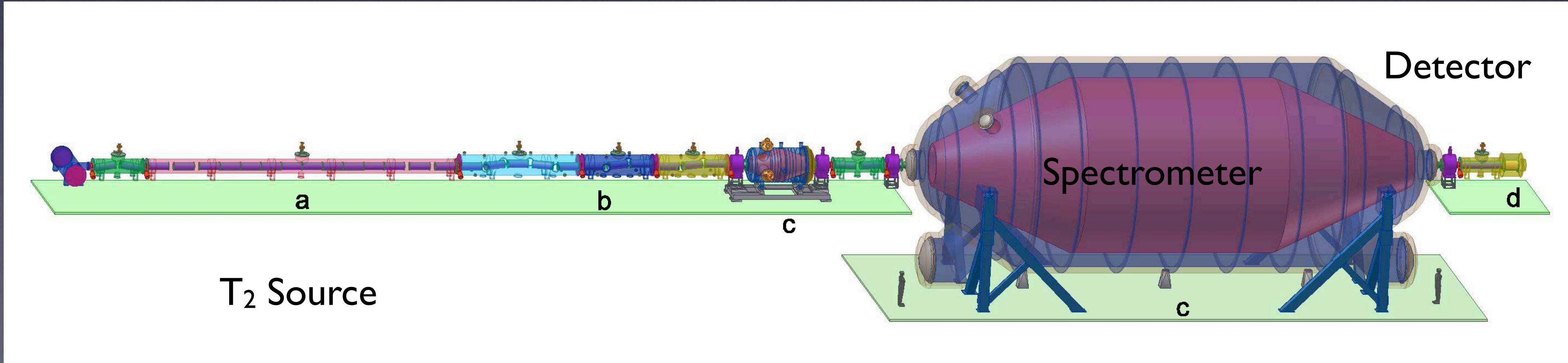
- The KATRIN experiment uses *magnetic adiabatic collimation* with *electrostatic filtering* to achieve its energy resolution.

- Target activity is approximately 4.7 Ci. Energy resolution from spectrometer is 0.93 eV.



KATRIN = Liouville's Theorem + Jackson problem

- Electrons from tritium decay need to overcome a known potential Φ in order to be counted to the detector. Measures an integrated spectrum.
- Problem: decays are isotropic, but filter acts on cos(θ).
- Solution: adiabatically rearrange their phase space.

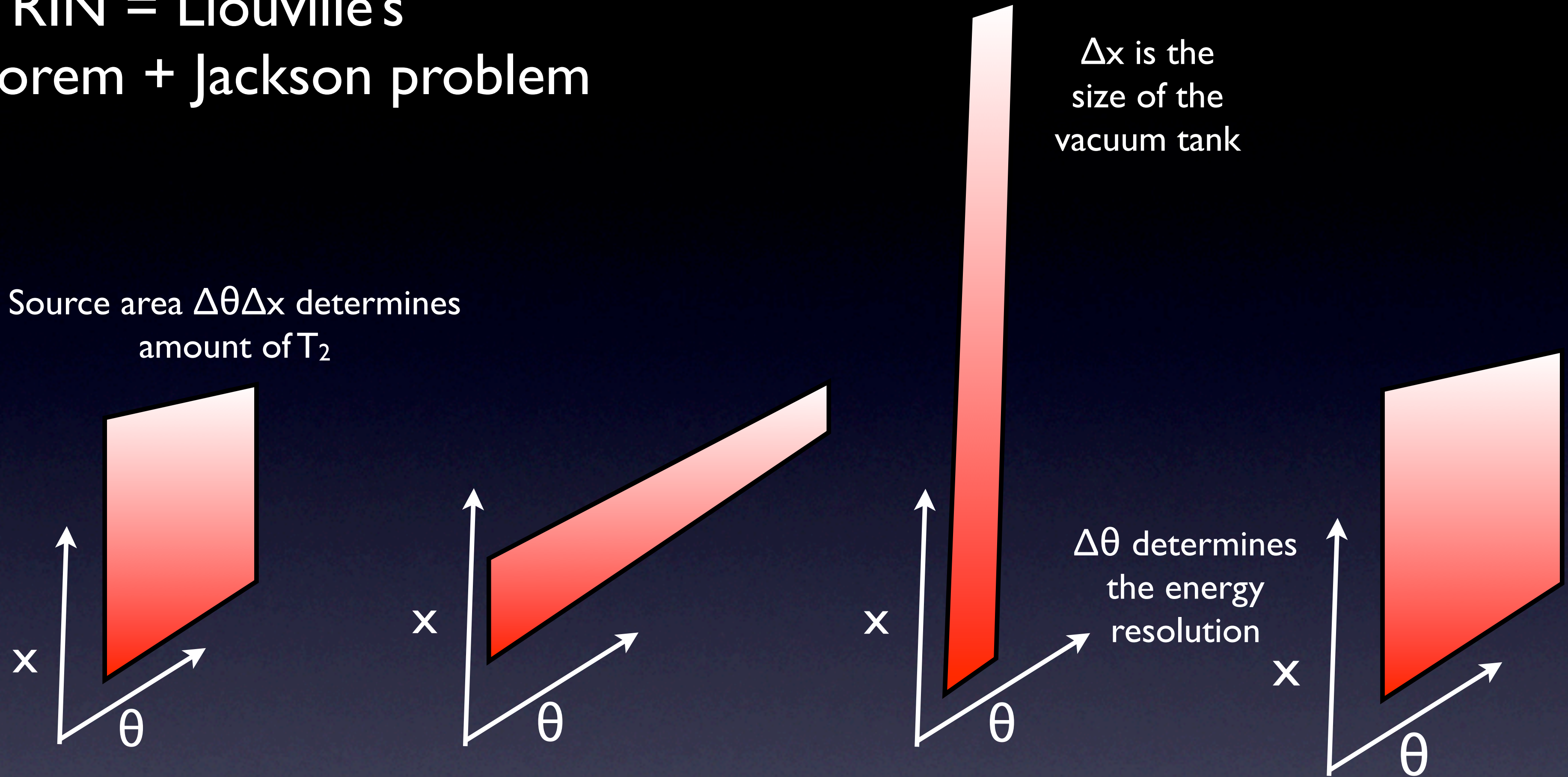


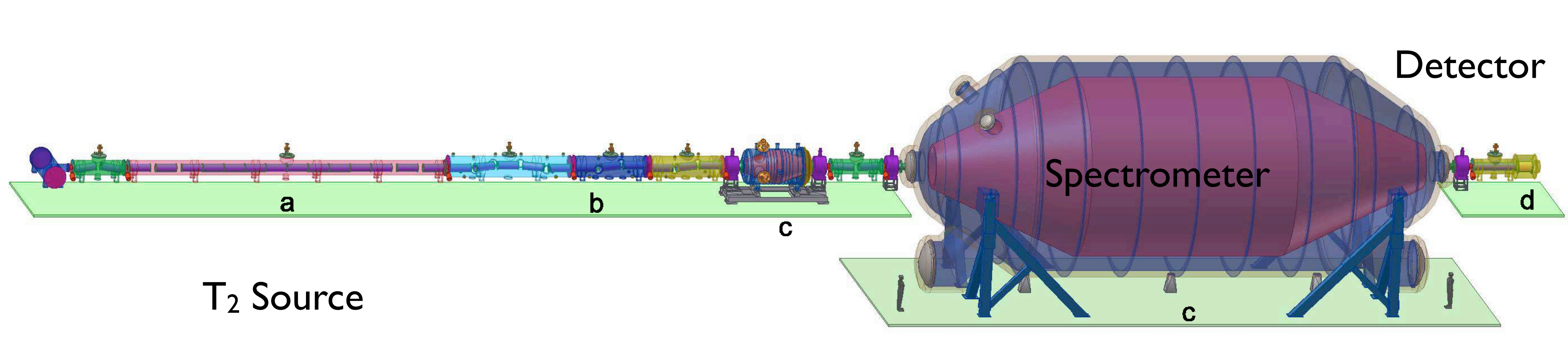
KATRIN = Liouville's Theorem + Jackson problem

Source area $\Delta\theta\Delta x$ determines amount of T_2

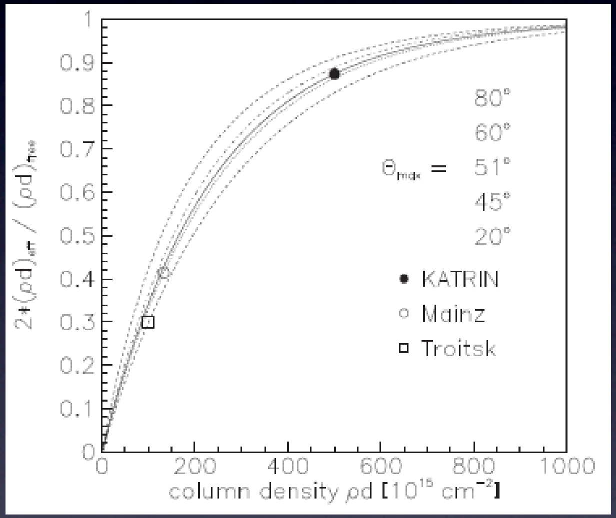
Δx is the size of the vacuum tank

$\Delta\theta$ determines the energy resolution



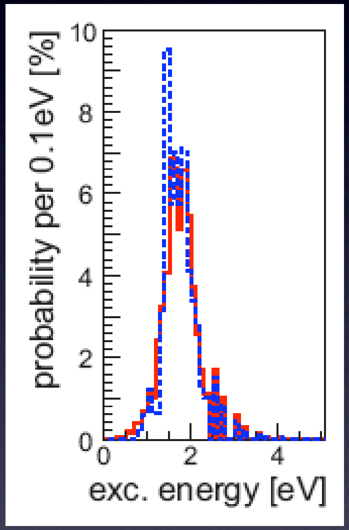


Can KATRIN be Scaled?



Source Strength

Size



Final States

There are three main obstacles for improving KATRIN to a better neutrino mass or relic neutrino measurement:

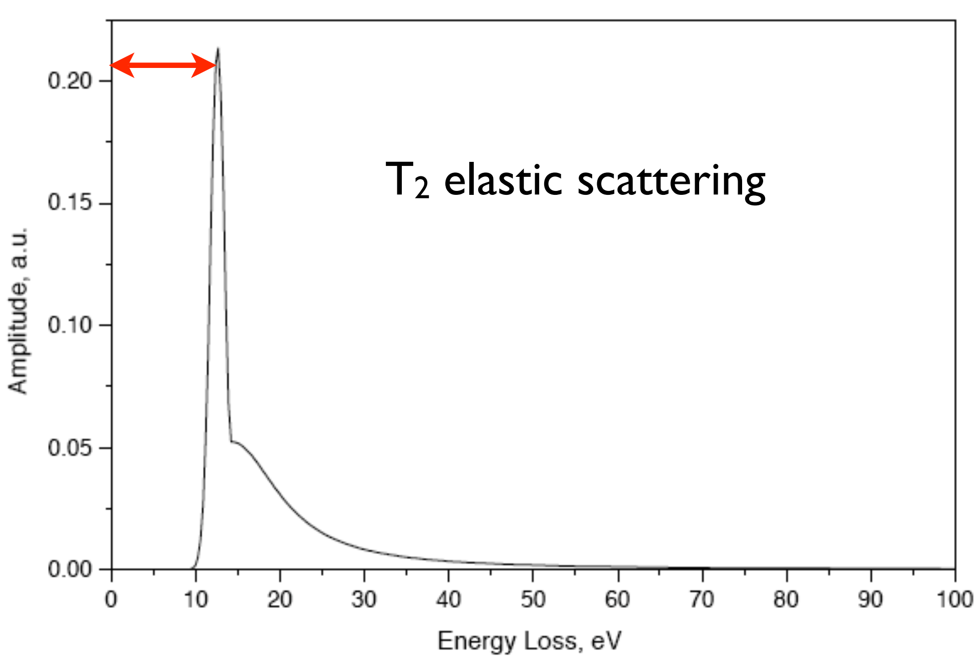
Scaling KATRIN: Source Strength

- For a fixed resolution, the luminosity of KATRIN is dictated by the flux of electrons created from the source.

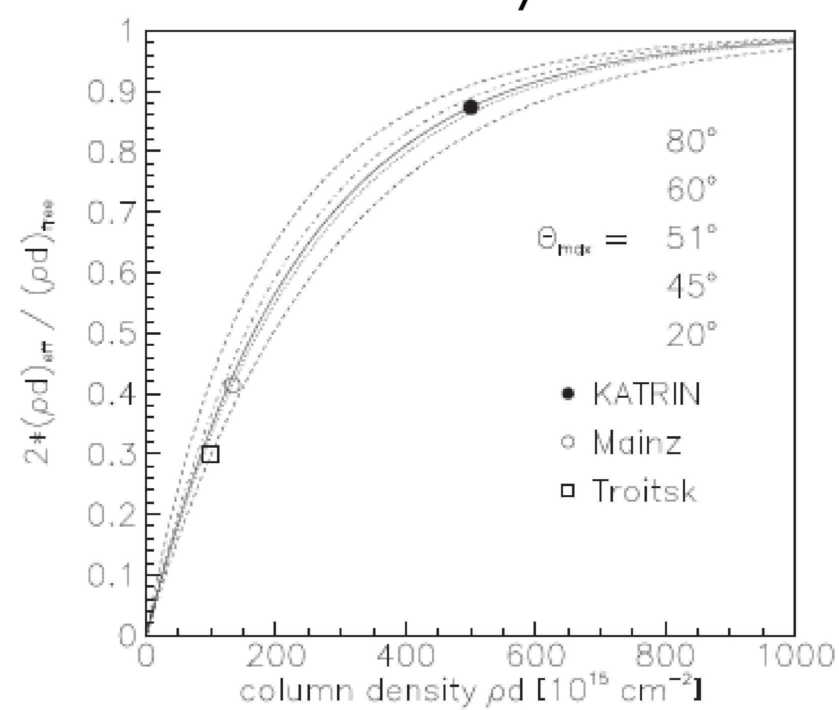
- Therefore, scaling the source strength requires either scaling the area of the source or its column density (ρd).

- Here, the source and the detector are distinct. Increasing the column density does not help in this case, since inelastic cross-section limits the opacity of the source.

Minimum energy loss

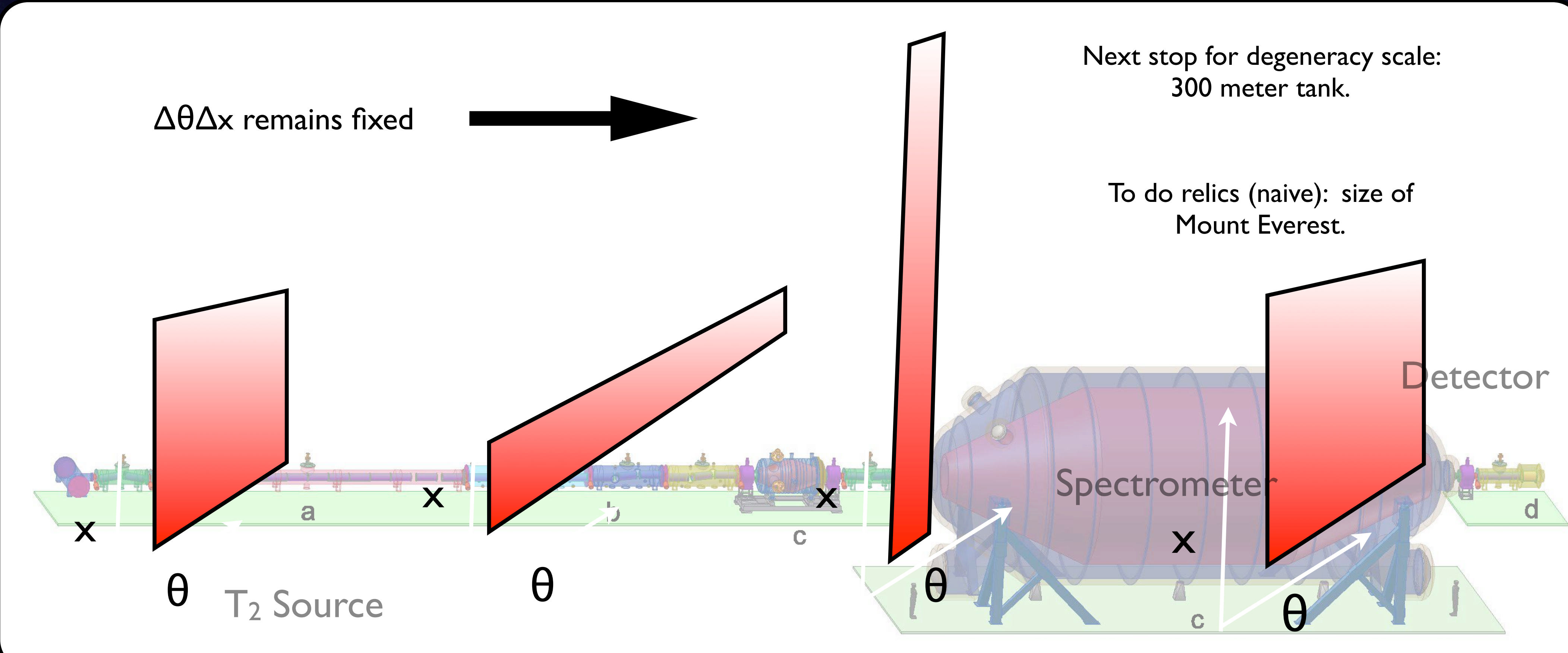


Ratio of effective versus free column density



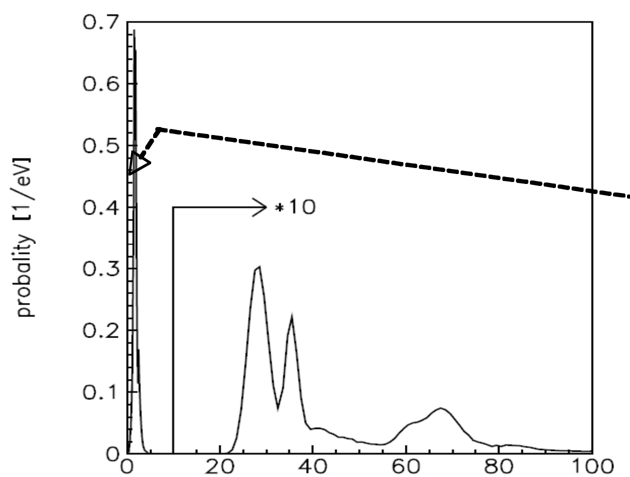
Scaling KATRIN: Area

- To improve resolution (at fixed source strength), spectrometer area must increase.
- To increase source strength (at fixed resolution) source area, hence spectrometer area must increase as well.



Scaling KATRIN: Final States

- Most effective tritium source achieved so far involves the use of gaseous *molecular* tritium.
- Method will eventually hit a resolution "wall" which is dictated by the roto-vibrational states of T_2. This places a resolution limit of 0.36 eV.
- One needs to either switch to (extremely pure) atomic tritium or other isotope with equivalent yield.



Electronic excitation of $^3HeT^+$ (43%)

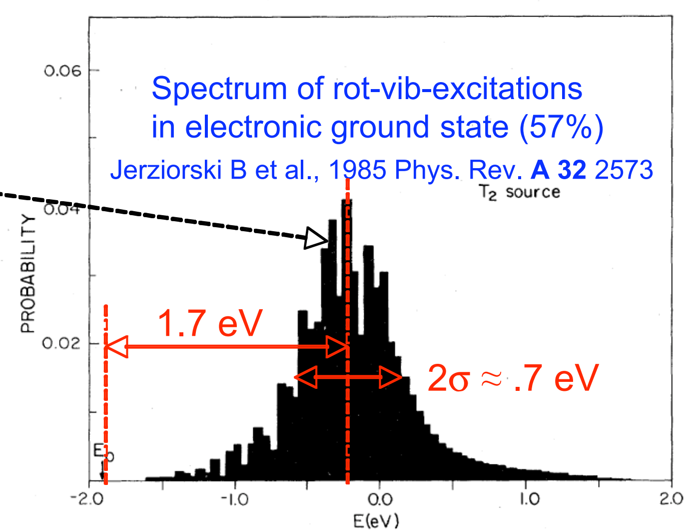
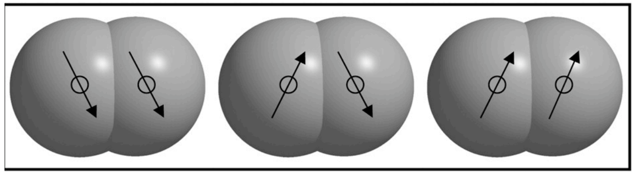
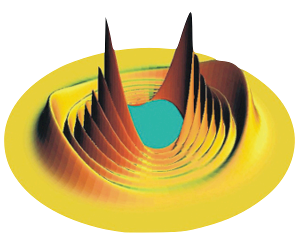
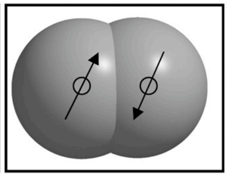


FIG. 1. Probability histogram for transitions to the first (ground) electronic state of the $^3HeT^+$ molecular ion. The energy "zero" is the energy of the ground-state He atom and the T^+ nucleus at infinity. This energy is 1.897 42 eV above the ground rovibronic state of $^3HeT^+$.



ortho-hydrogen





para-hydrogen

Some Hope for Atomic Tritium

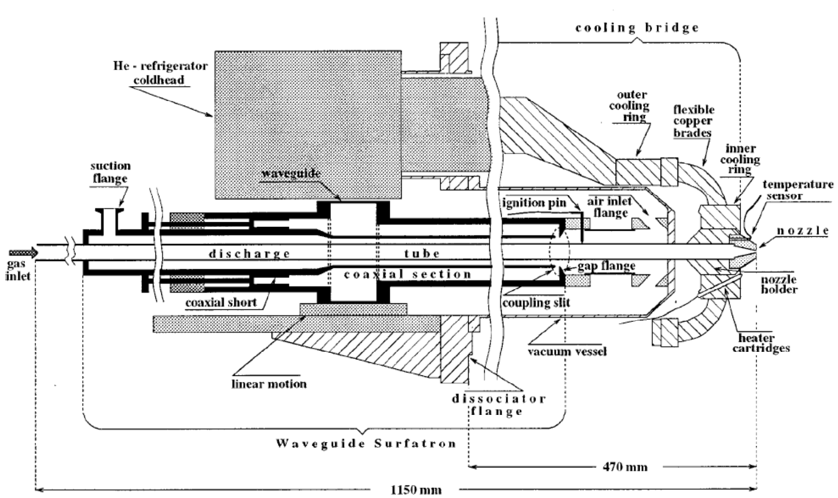
- High intensity sources of tritium might be achievable using similar techniques as employed in H/D production.
- Main challenge is achieving the *purity* and transport of atomic tritium. Requires heavy R&D.

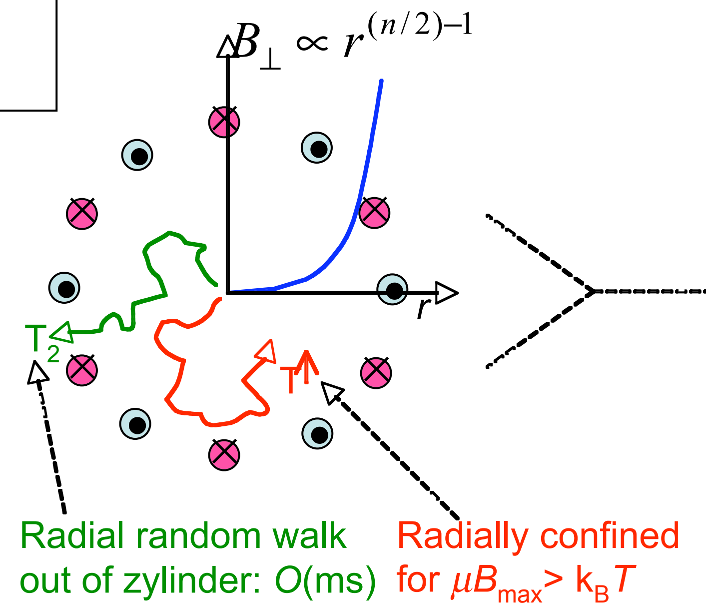
from E. Otten, 2007

REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 70, NUMBER 3 MARCH 1999

High intensity source for cold atomic hydrogen and deuterium beams

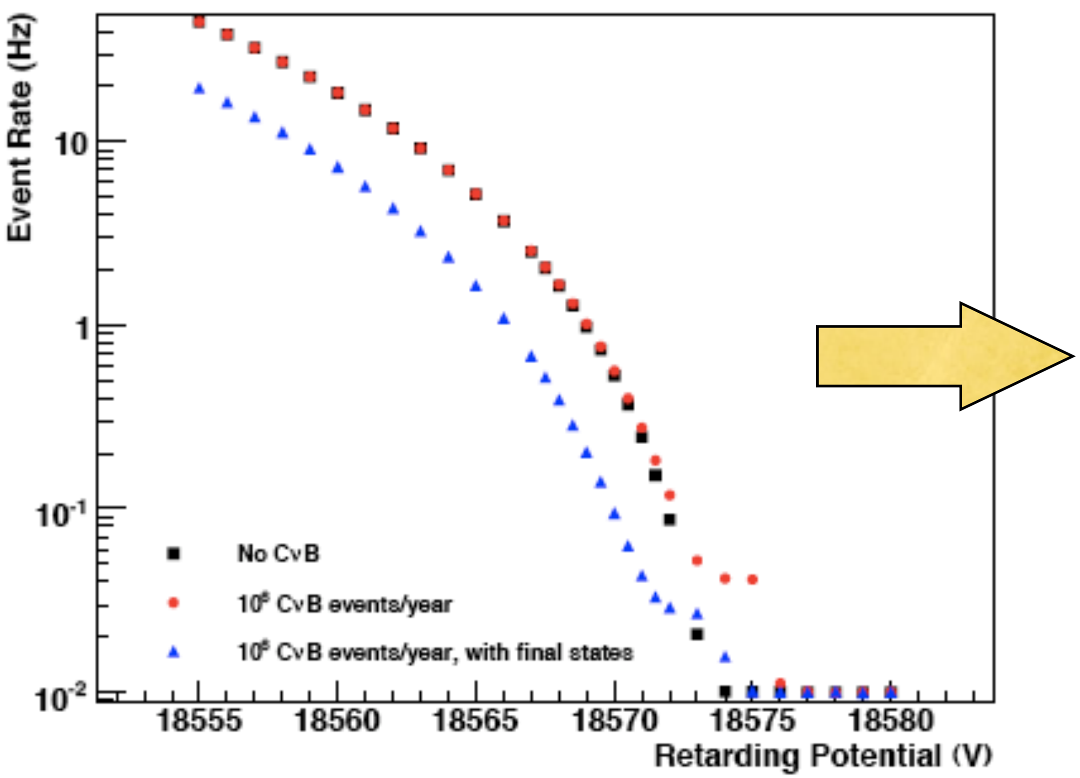
N. Koch[a] and E. Steffens[b]

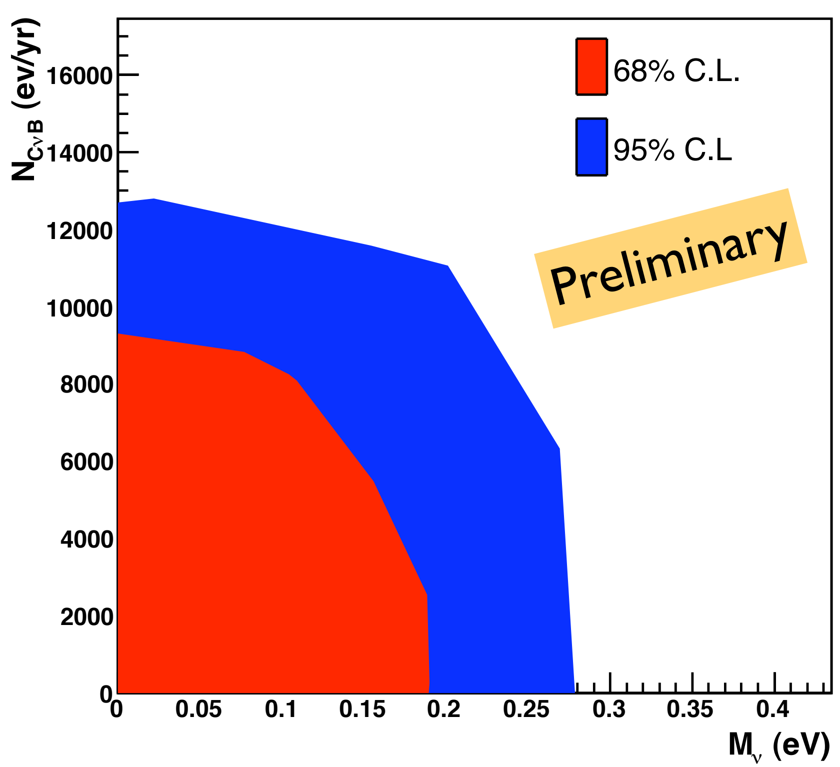




What can KATRIN do?

- KATRIN is sensitive to the relic neutrino density, but only if significant deviations from standard cosmology are manifest.
- Illustrates limits due to target mass, backgrounds, and energy resolution.





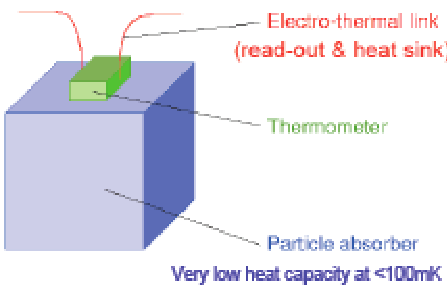
Direct Neutrino Probes: MARE

- Use bolometers to measure the full energy deposit from beta decay,
- Use ^{187}Re as the beta decay isotope ($\tau_{1/2} = 4.3 \times 10^{10}$ y, $Q = 2.46$ keV)

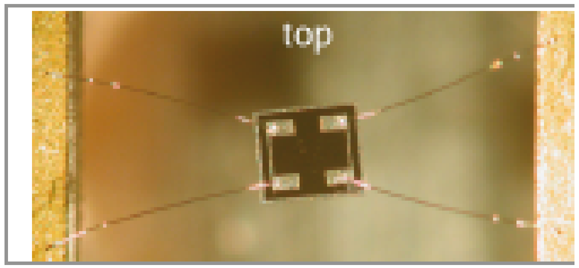
Main Advantages	Challenges
No final state issues (all energy is measured) Scales with volume/mass	Both cross-section and lifetime is far too low. Mass requirements too high to achieve positive sensitivity

Bolometry

MIBETA
&
MARE



$$^{187}\mathrm{Re} \rightarrow {}^{187}\mathrm{Os} + e^{-} + \bar{\nu}_e$$



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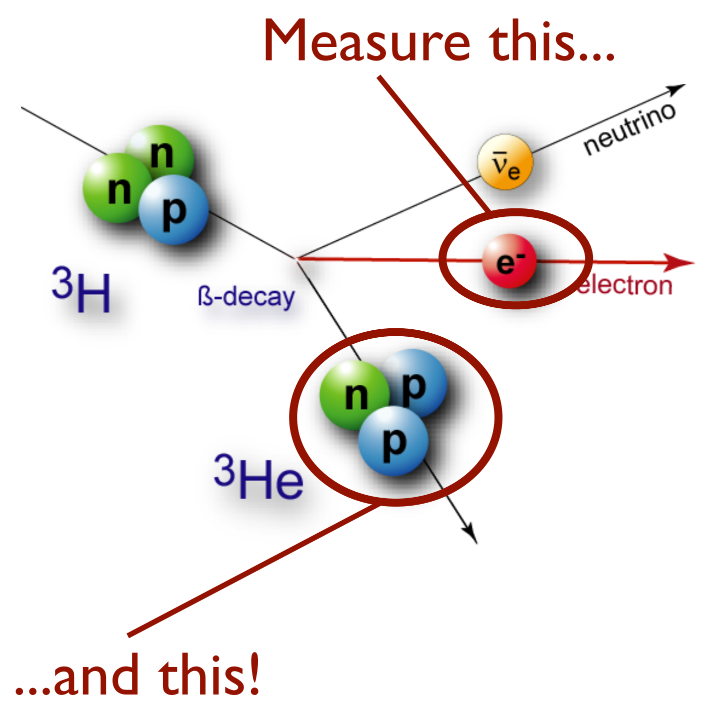
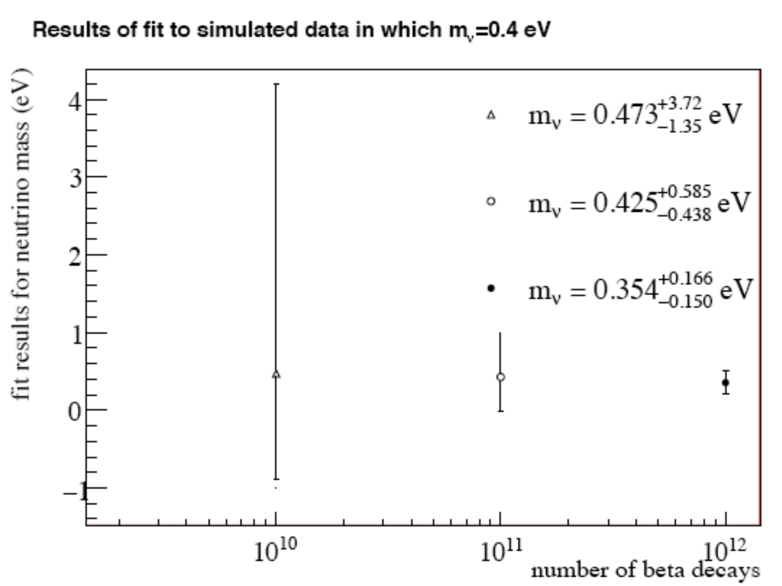
Atomic Trapping of Tritium

- Trap atomic tritium by magnetically cooling an atomic beam of tritium. Technique demonstrated on oxygen and hydrogen. Being extended to tritium next.
- Measure both the ion ($^3He+$) and the electron to reconstruct the neutrino mass kinematically.

Main Advantages	Challenges
Full reconstruction of mass; need for targets less than needed for KATRIN	Atomic targets have little activity. Too little for relic neutrino detection.
Use of atomic (rather than molecular) tritium.	





M. Jerkins, J. Klein, J. Majors, F. Robichaeux, M. Raizen, arXiv:0901:3111

Measuring Energy with Frequency (Project 8)

"Never measure anything but frequency."

I. I. Rabi

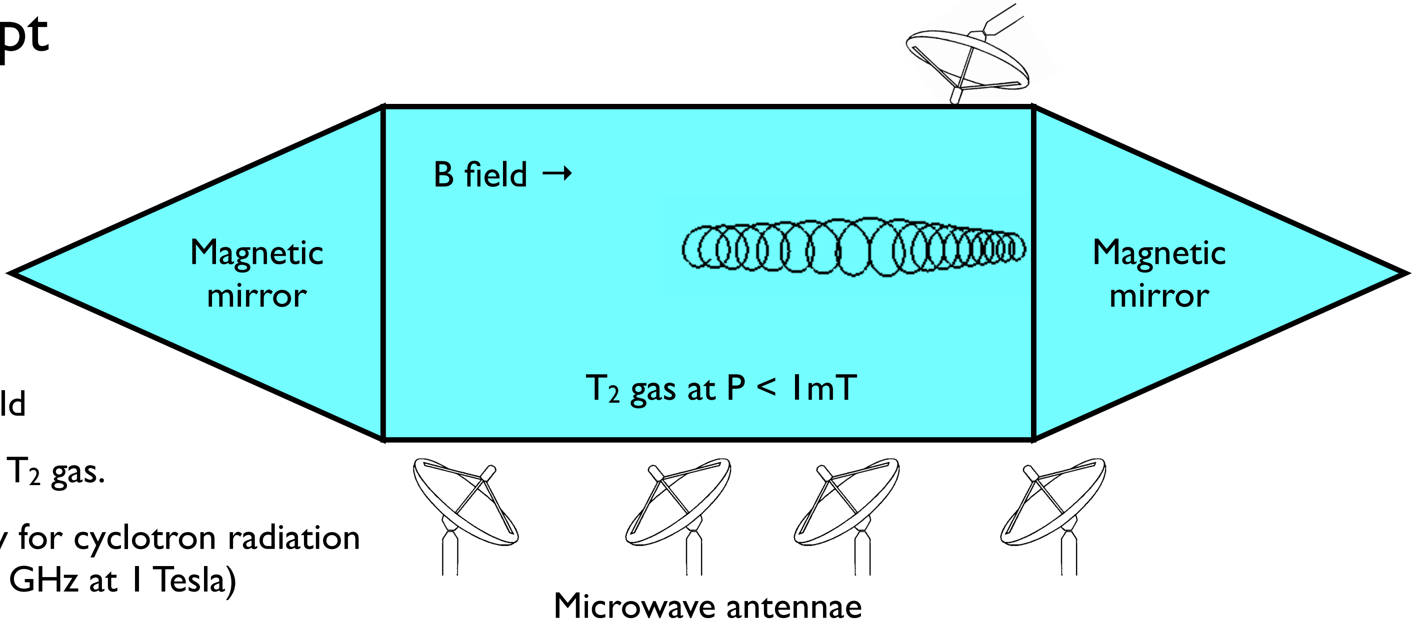
- Take advantage of cyclotron radiation created by a relativistic electron moving in a uniform magnetic field.

$$\omega = \frac{eB}{\gamma m_e}$$

- Non-destructive means of measuring the electron energy. Using frequency may allow extremely high precision.

B. Monreal and J. Formaggio
Published in Phys. Rev. D80:051301 (2009).

The Concept



- Uniform B field
- Low pressure T_2 gas.
- Antenna array for cyclotron radiation detection (26 GHz at 1 Tesla)

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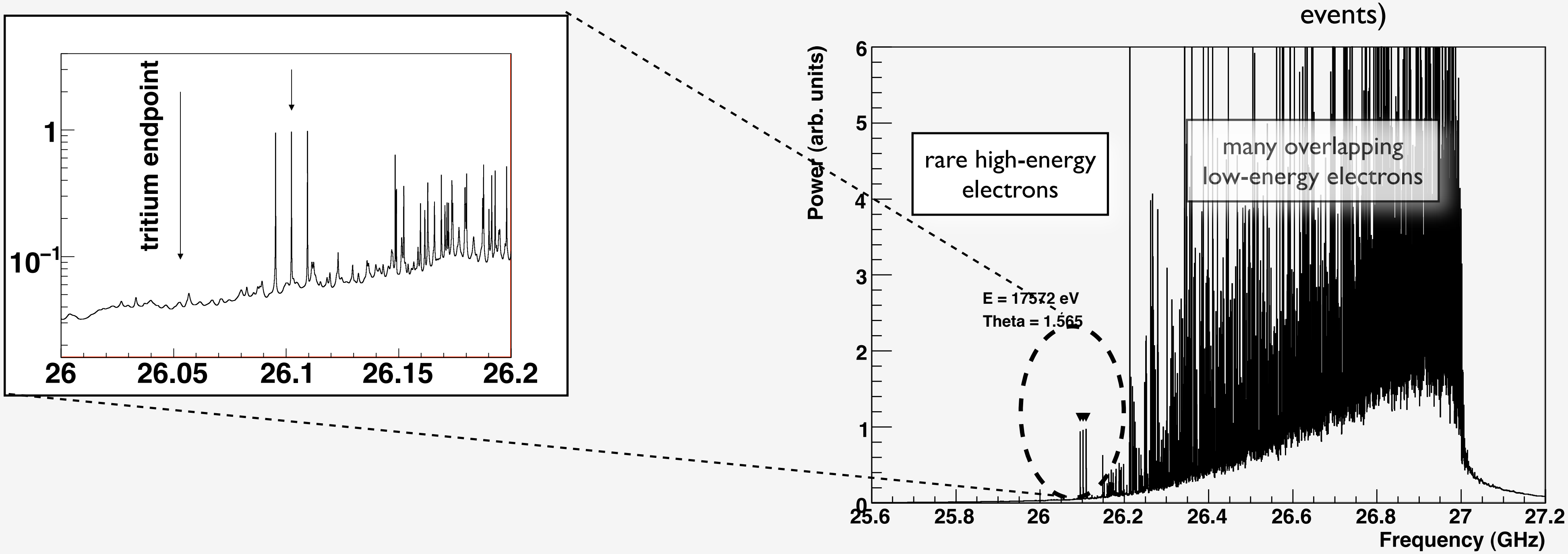
Simulation run (10^5 events)



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$$\omega = \frac{eB}{\gamma m_e}$$

- Non-destructive means of measuring the electron energy. Using frequency may allow extremely high precision.

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Main Advantages

Target mass scales with volume; resolution with *time*

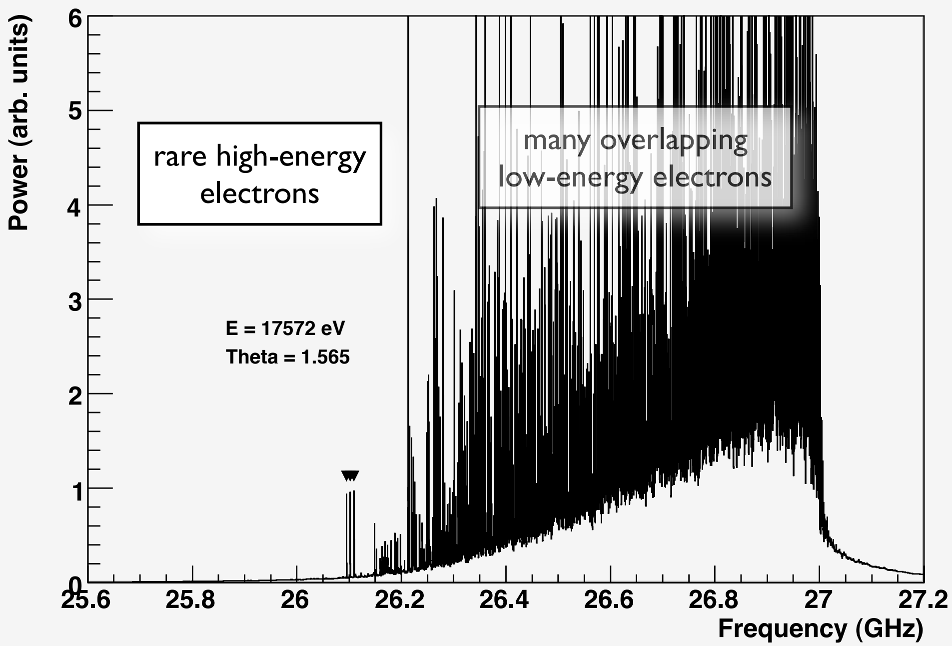
Potential high precision achievable.

Challenges

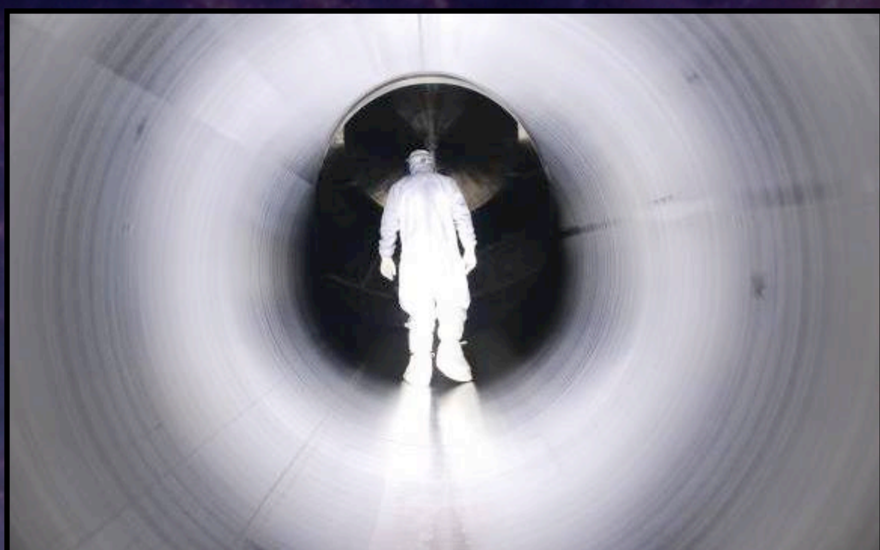
Currently still based on molecular rather than atomic tritium.

Low and high energy regions still within same system.

Simulation run (10^5 events)



Obstacles for a Relic Neutrino Measurement



Target:

Tritium appears still as most favorable isotope. High activity targets (~1 MCi) of tritium necessary. Eventually need to switch to atomic tritium to push resolution.

Energy Resolution:

Need to achieve high resolution ($\Delta < m_\nu$) for any chance of signal background separation. One order of magnitude desirable.

Backgrounds:

Need to achieve less that few events/year in region of interest. Cosmic rays and other activity will eventually play a role.

Summary

The issue of relic neutrino detection still remains a great challenge to our community.

From a purely "what is within our technological reach", neutrino capture appears the most viable approach, albeit still very challenging.