The Future of Neutrino Mass Measurements with Tritium Beta Decay

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MIT

LBNL
September 2, 2010

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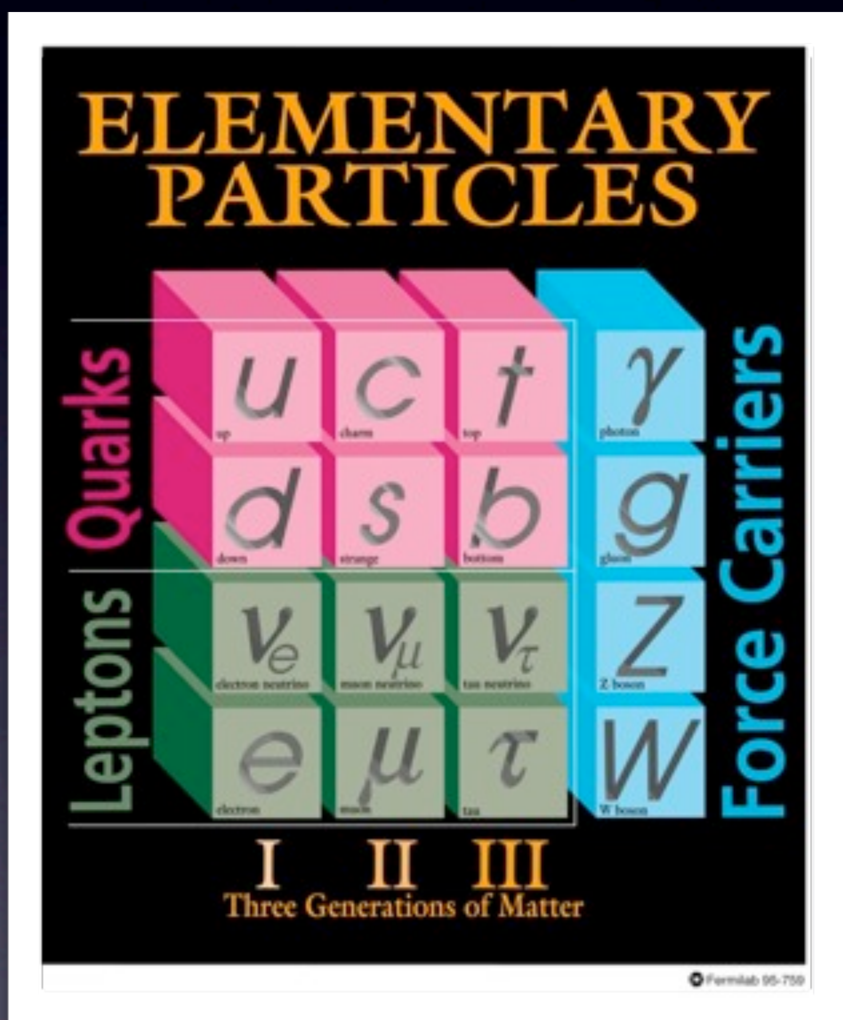
What we do and don’t know about neutrino mass

Using tritium beta decay to study neutrino mass

The next-generation experiment: KATRIN

The next-next-generation experiment: Project 8

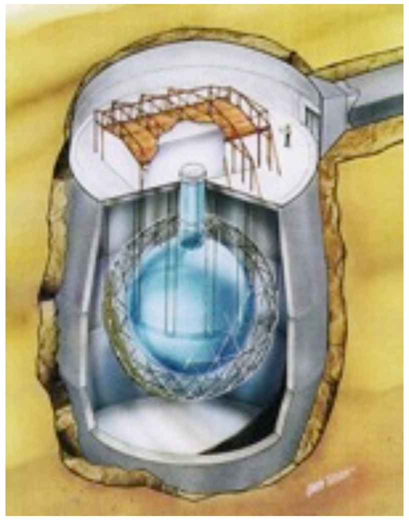
Beyond the Standard Model



- Solid evidence of physics beyond the Standard Model
  - Neutrino oscillation experiments have shown that neutrinos have mass
- Questions remain
  - Are neutrinos their own antiparticles?
  - Why are neutrinos so light?
  - What is the absolute neutrino mass scale?

Probing Neutrino Mass

Neutrino Oscillations



Sensitive to mass differences

Uses quantum mechanical effects

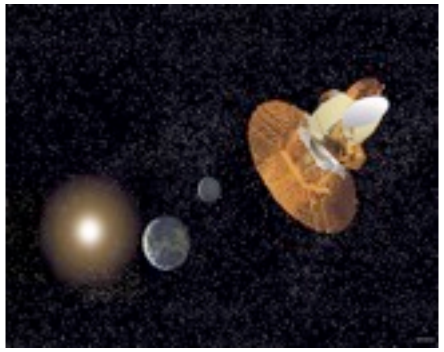
Sources: Reactor, solar, atmospheric, beams

Cosmology

Sensitive to the total neutrino mass

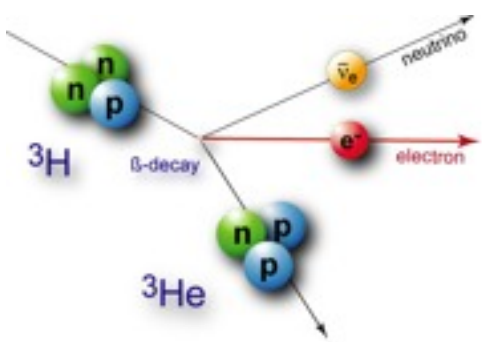
Uses General Relativity

Measured by satellites & ground-based observatories



ν

Single Beta Decay



Sensitive to the absolute mass scale

Uses conservation of energy

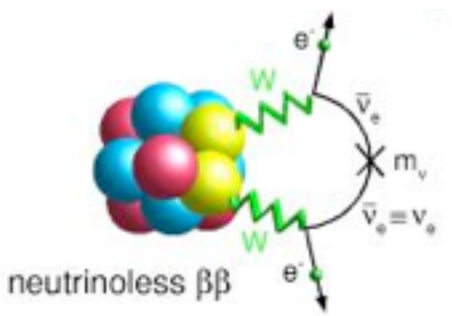
Model independent

0ν Double Beta Decay

Sensitive to the Majorana masses

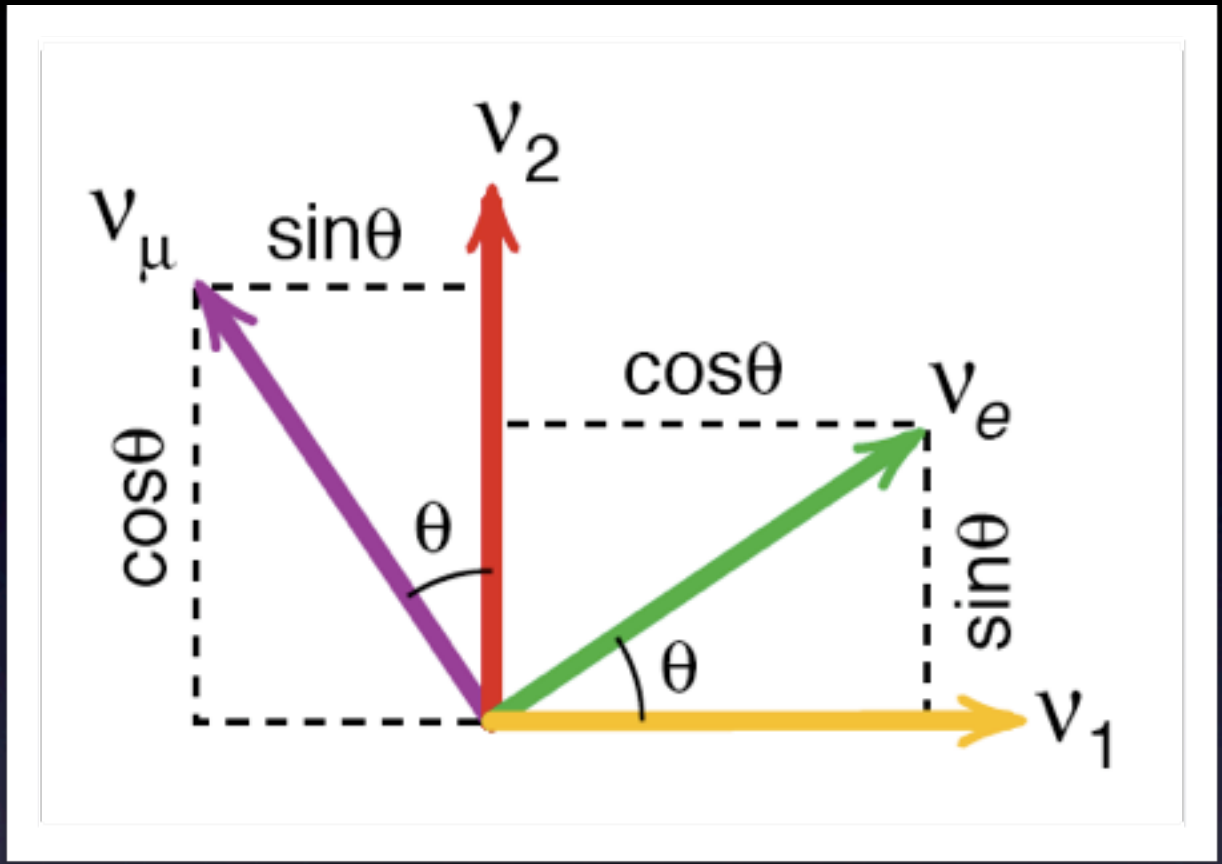
Uses the rarest decays

Probes the nature of neutrinos



Neutrino Oscillations

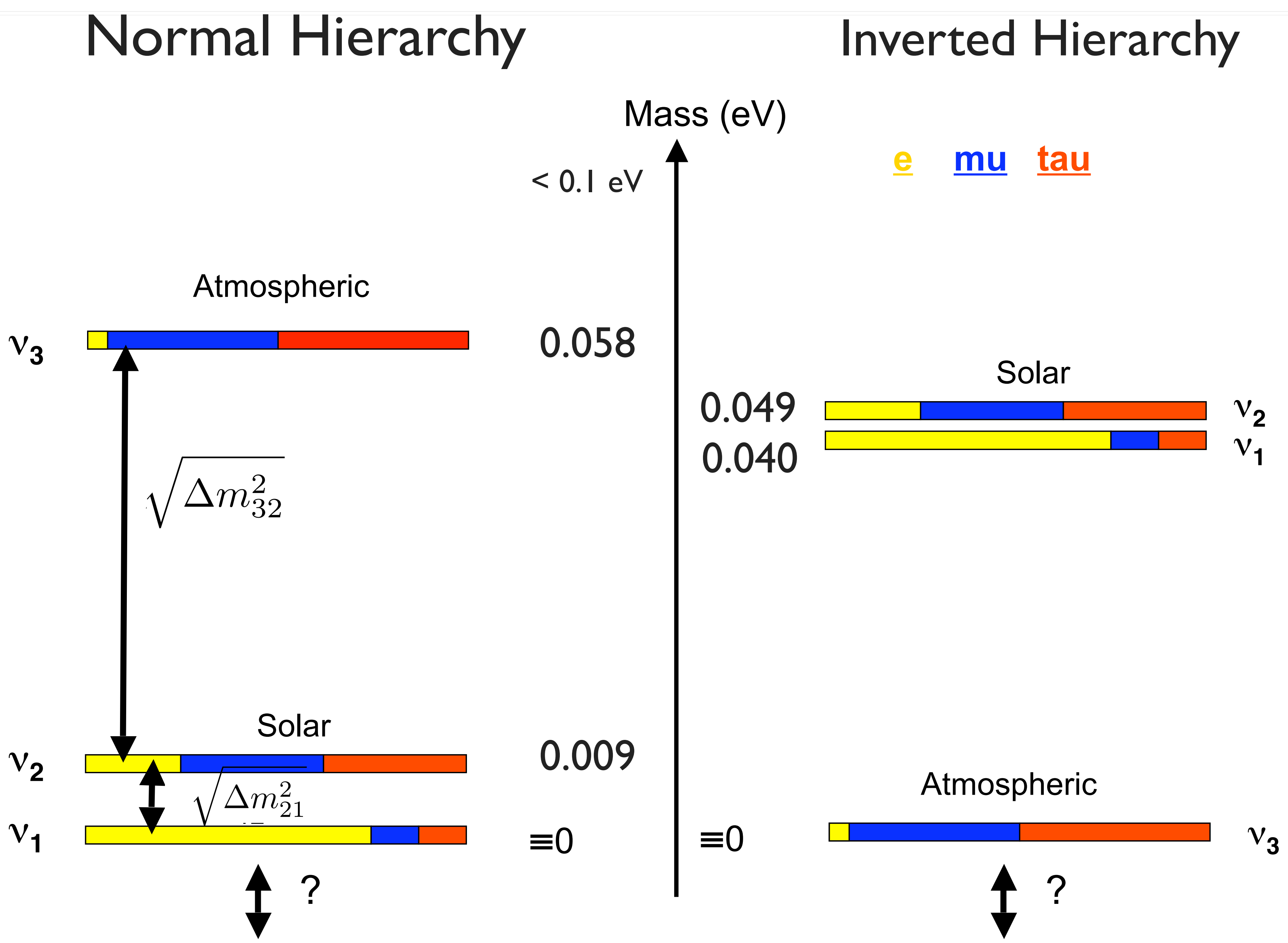
- The first evidence of neutrino masses comes from oscillation experiments
- Neutrinos that start out as one flavor are observed to have changed flavor when detected
- Oscillation probability depends on the mass splittings, and the mixing angles



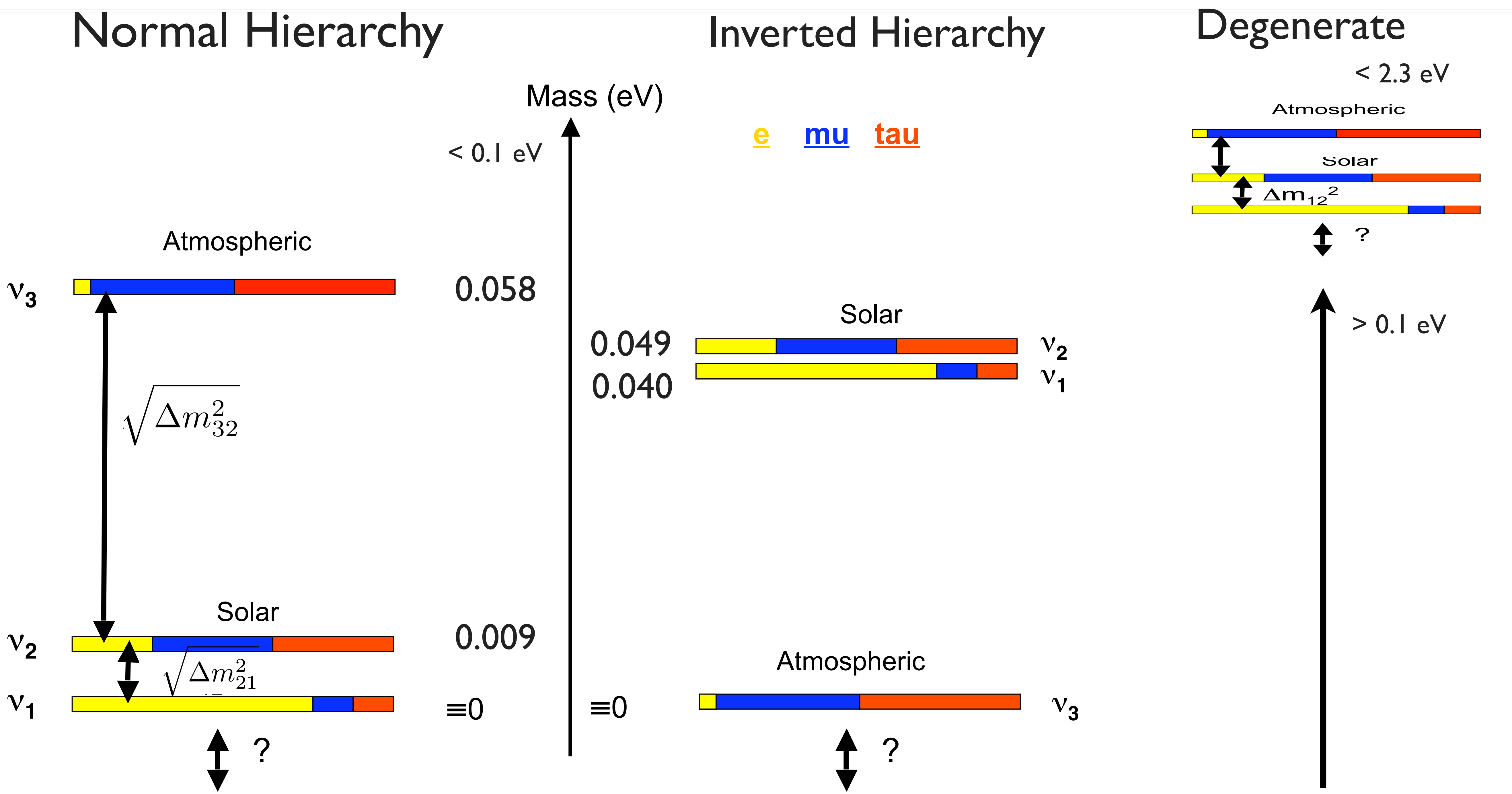
$$P(\nu_e \to \nu_\mu) = \sin^2 2\theta \sin^2 \left(\frac{2\pi L \Delta m^2}{5 E_\nu} \right)$$

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

Learning from Oscillations



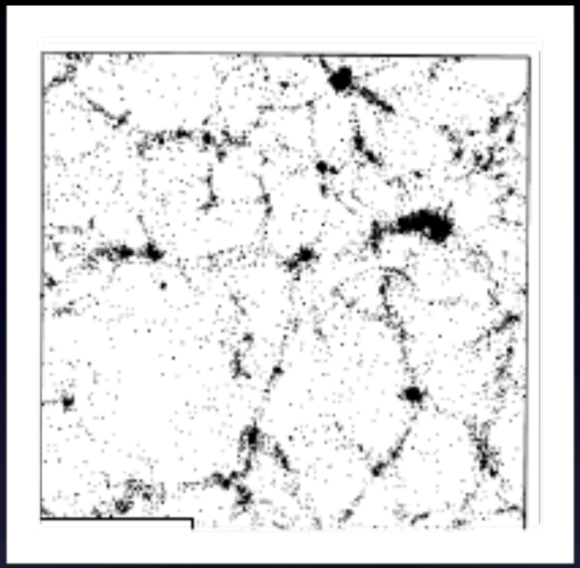
Learning from Oscillations



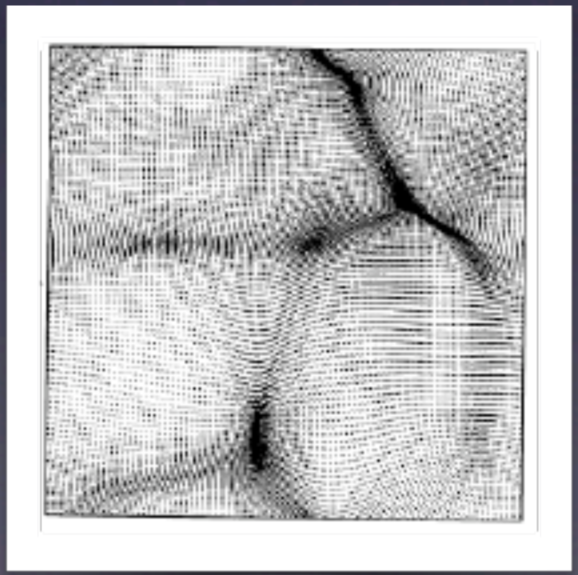
Cosmological Effects

- Neutrinos are abundant in the universe
- Sufficient numbers of neutrinos can affect structure formation
- Suppress matter density fluctuations, especially on small scales

clumpy universe
$m_\nu = 0$



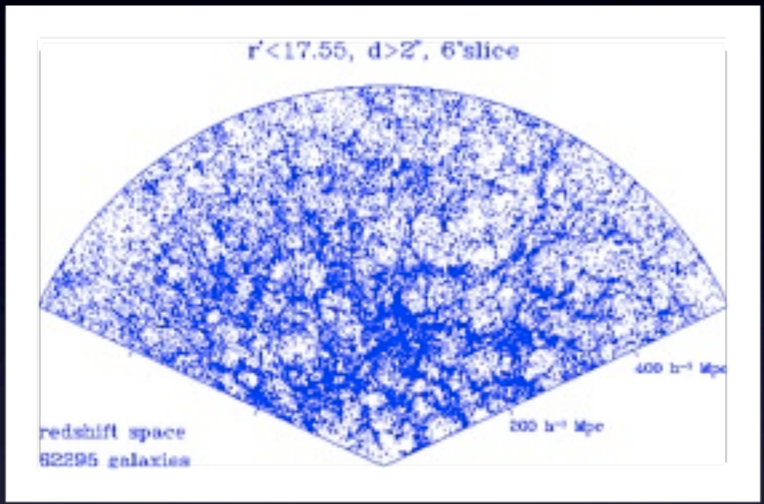
less clumpy universe
$m_\nu > 0$

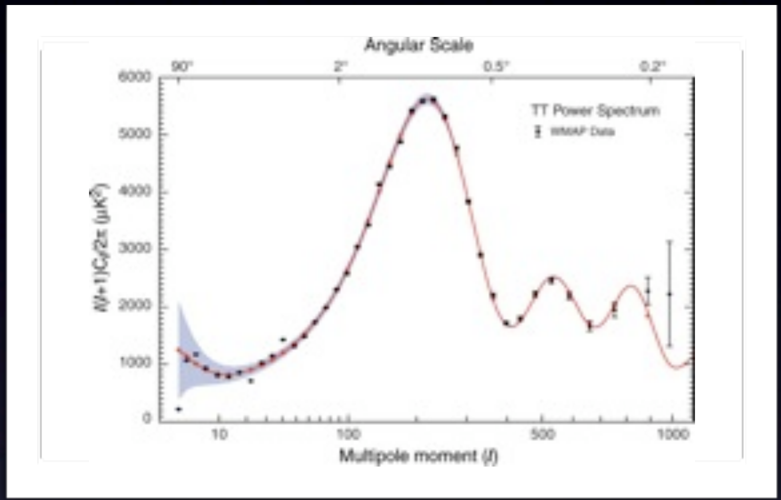


Mass Limits from Cosmology

Observable:

$$\Sigma m_\nu = m_1 + m_2 + m_3$$





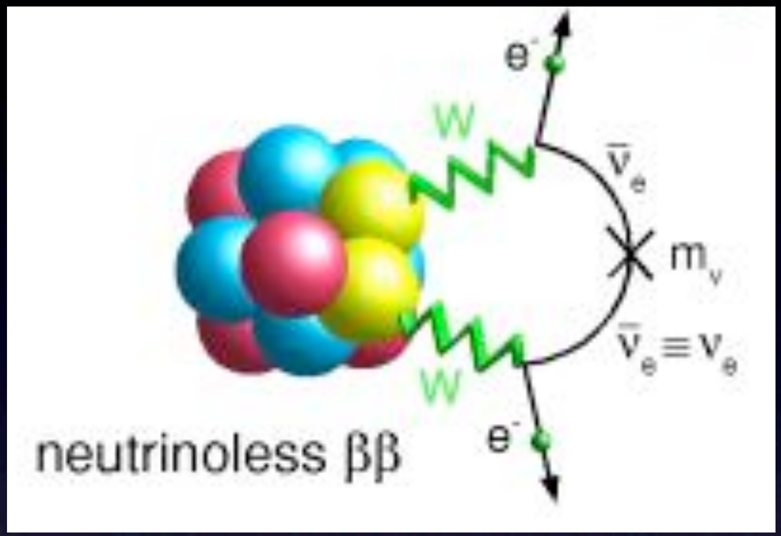
Case	Cosmological data set	Σ (at 2σ)
(i)	CMB	<1.19 eV
(ii)	CMB + LSS	<0.71 eV
(iii)	CMB + HST + SN-Ia	<0.75 eV
(iv)	CMB + HST + SN-Ia + BAO	<0.60 eV
(v)	CMB + HST + SN-Ia + BAO + Lyα	<0.19 eV

Results are highly dependent on

- Data sets included
- Cosmological model
- Systematic uncertainties

Fogli, et. al., Phys.Rev., D78:033010 (2008)

0ν Double-Beta Decay



Observable:

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)|M_{0\nu}|^2 \langle m_{\beta\beta}\rangle^2$$

$$m_{\beta\beta} = |\Sigma_i U^2_{ei} m_i|$$

If observed:

- Neutrinos are Majorana
- Lepton number is violated
- If mediated by a light Majorana neutrino, can measure $m_{\beta\beta}$ . . .
- . . . or it could be mediated by another lepton-number violating process

If not observed:

- Neutrinos could be Dirac
- Neutrinos could be Majorana and the complex phases are canceling
- Neutrinos could be Majorana and the matrix element is small

Limits from 0νββ

Limits from 0νββ

KKDC claim: ^{76}Ge

$0.16\ eV < m_{\beta\beta} < 0.52\ eV$ (95% CL)

Fogli, et. al., Phys.Rev.D78:033010 (2008)

Cuoricino Limit: ^{130}Te

$m_{\beta\beta} < 0.3\ eV$ (95% CL)

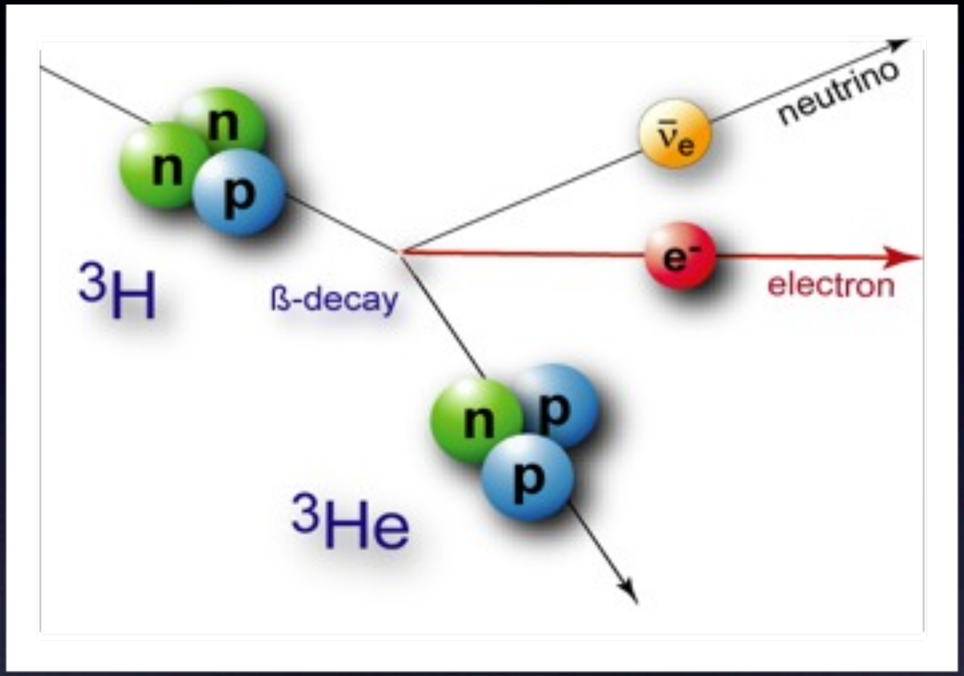
(favorable NME)

$m_{\beta\beta} < 0.7\ eV$ (95% CL)

(unfavorable NME)

M. Pavan, Neutrinos 2010, Athens, Greece

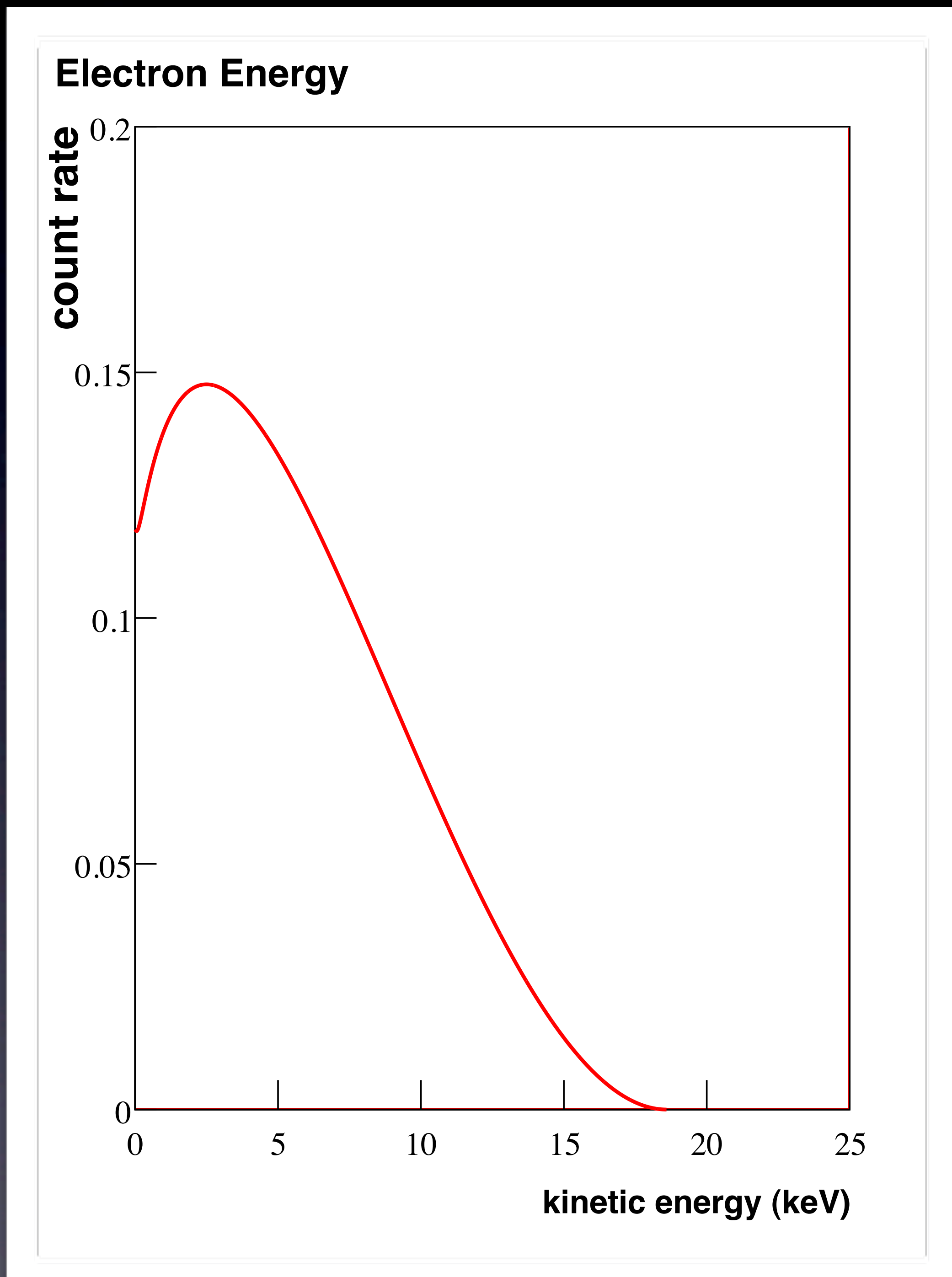
Single Beta Decay



. . . from which we detect the electron

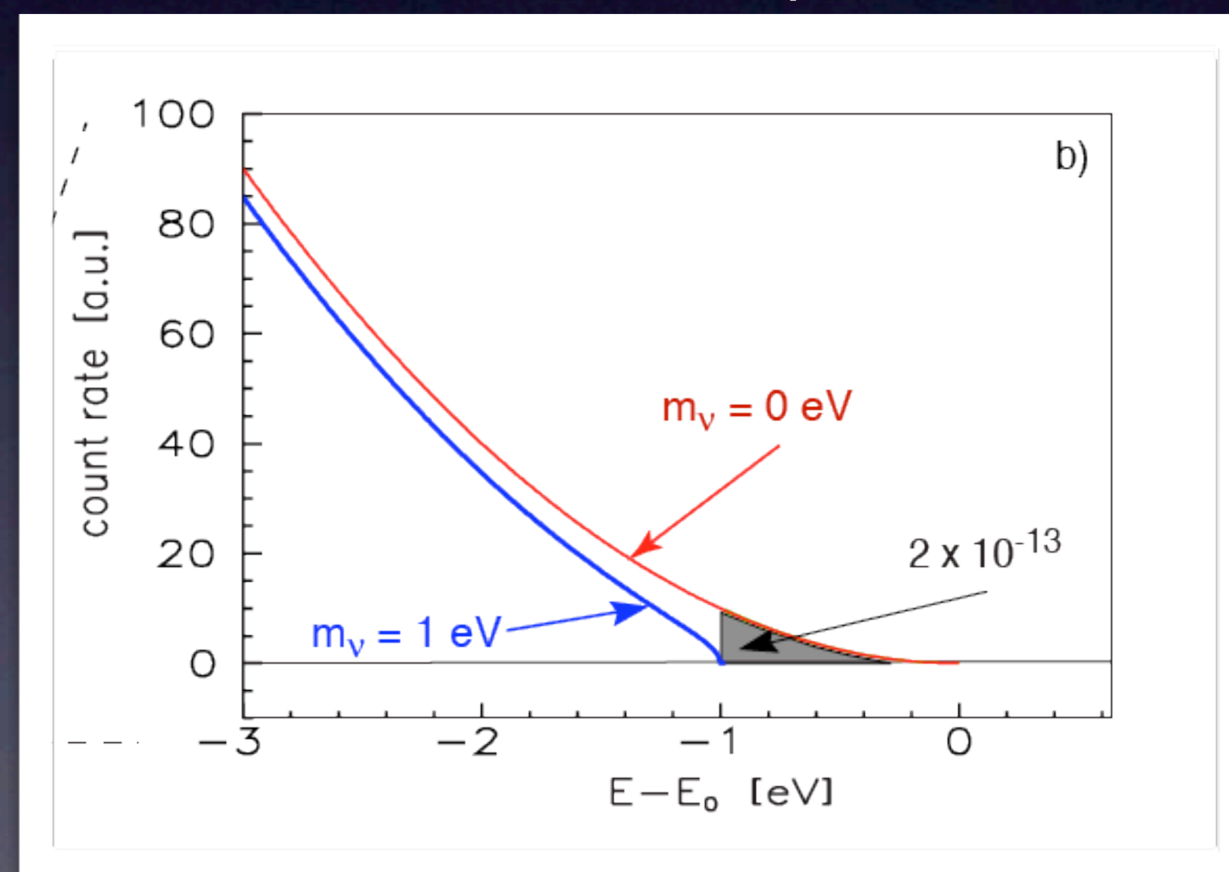
Beta decay allows precise measurement of the absolute neutrino mass scale.

Energy Spectrum

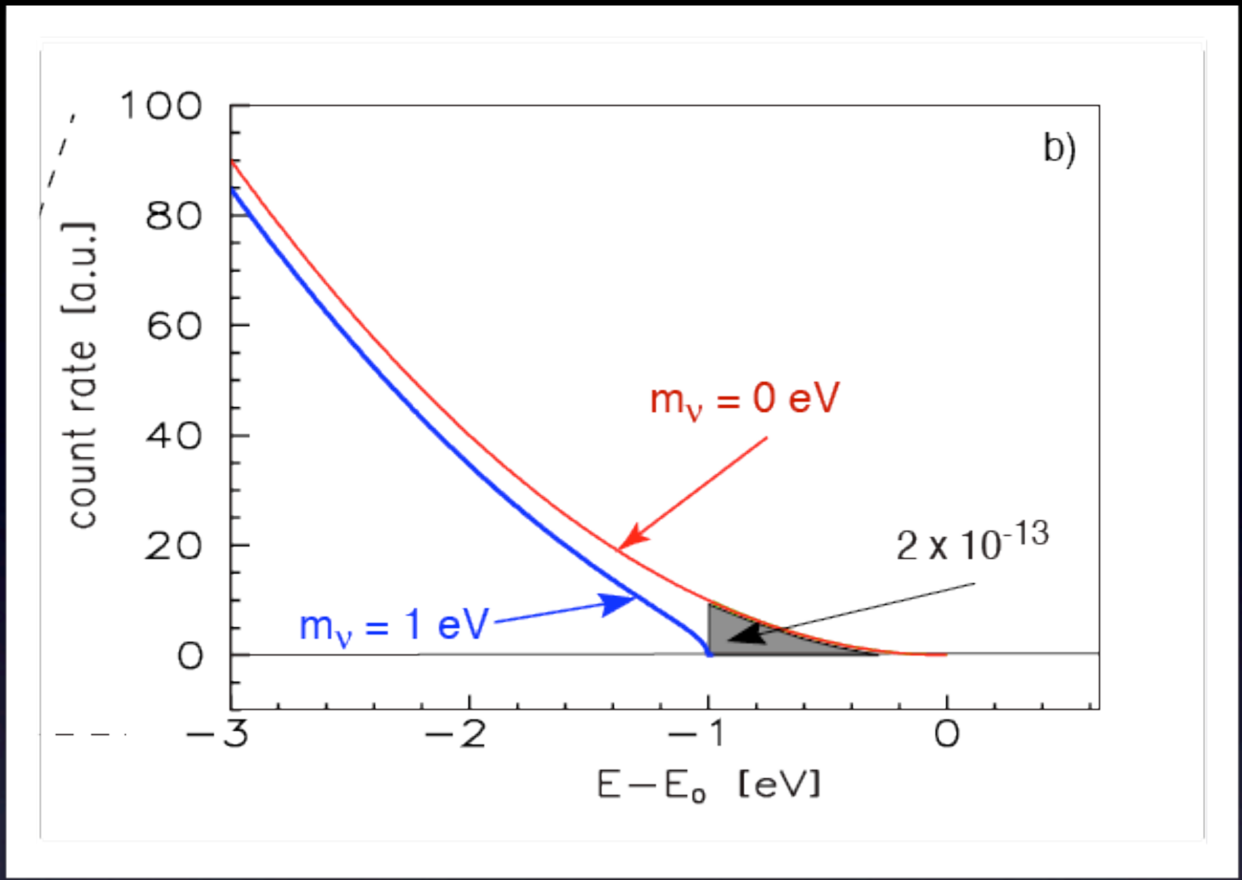


The shape is modified by neutrino mass, squared

Zoom in on the endpoint . . .



Energy Spectrum



$$\frac{dN}{dE} = KF(Z,E)p(E+m_e c^2)\sum_j (E_0 - E)|U_{ej}|^2 \sqrt{(E_0-E)^2 - m_{\nu_j}^2}$$

$$m_\nu = \sqrt{\Sigma_i |U_{ei}|^2 m_i^2} \approx m_i$$ in the degenerate region

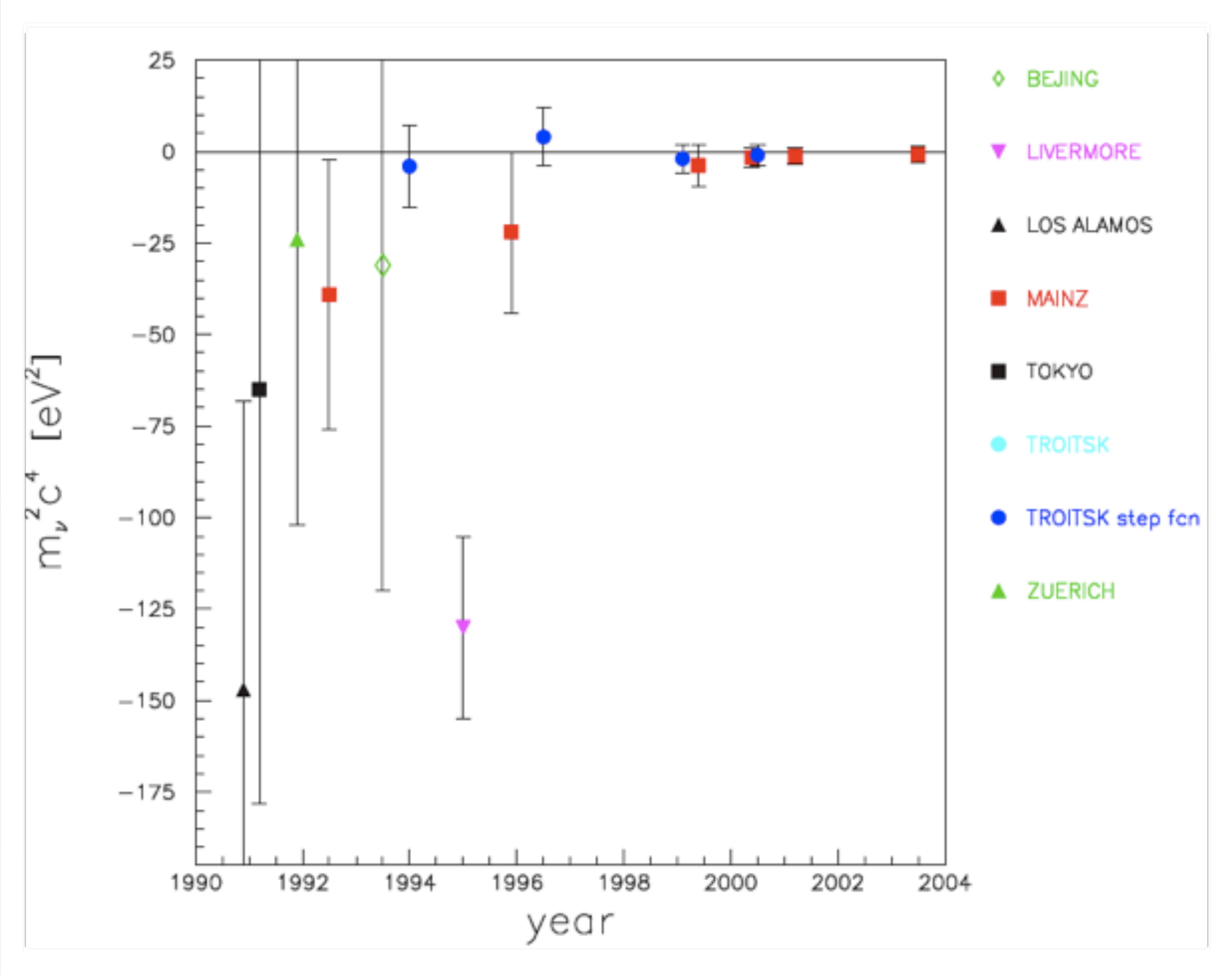
K = Nuclear Matrix Element
F(Z, E) = Fermi Function

Advantages of Tritium

- Low endpoint energy (18.6 keV) and relatively short half life (12.3 yrs) maximize counts near the endpoint
- Super allowed nuclear transition makes matrix element easy to calculate
- Low charge of the source reduces scattering
- Molecular structure of the final state ^3He-^3H is simple

Previous Tritium Measurements

- Many direct measurements with tritium
- Present Limit: Mainz experiment (similar to KATRIN) $m_\nu < 2.3$ eV (95% CL)
- KATRIN Sensitivity: 200 meV (90% CL), 350 meV at 5σ

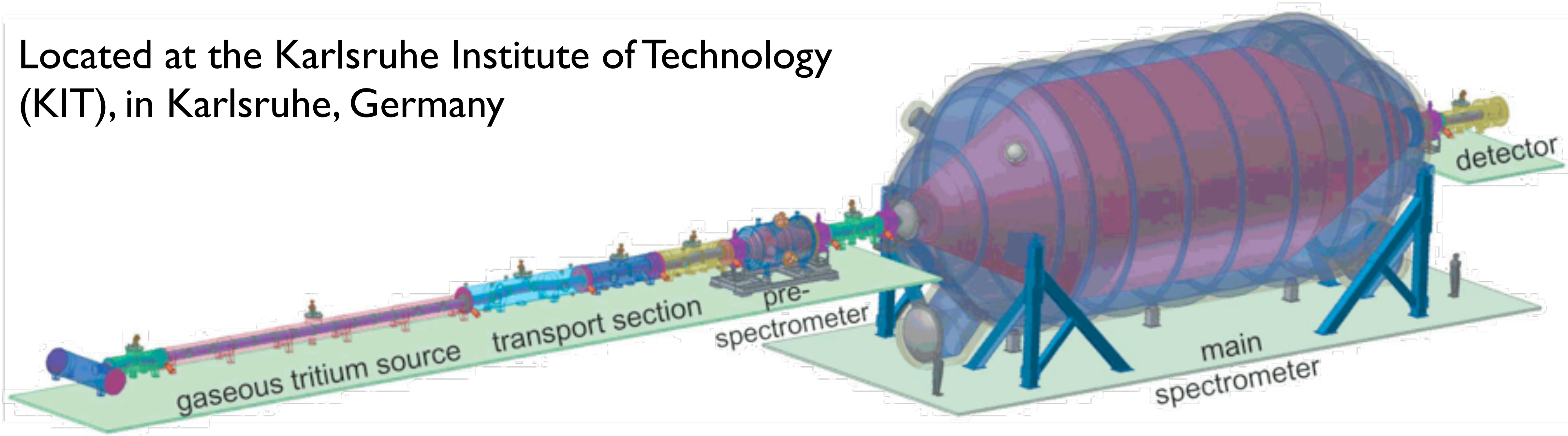


Thursday, September 2, 2010

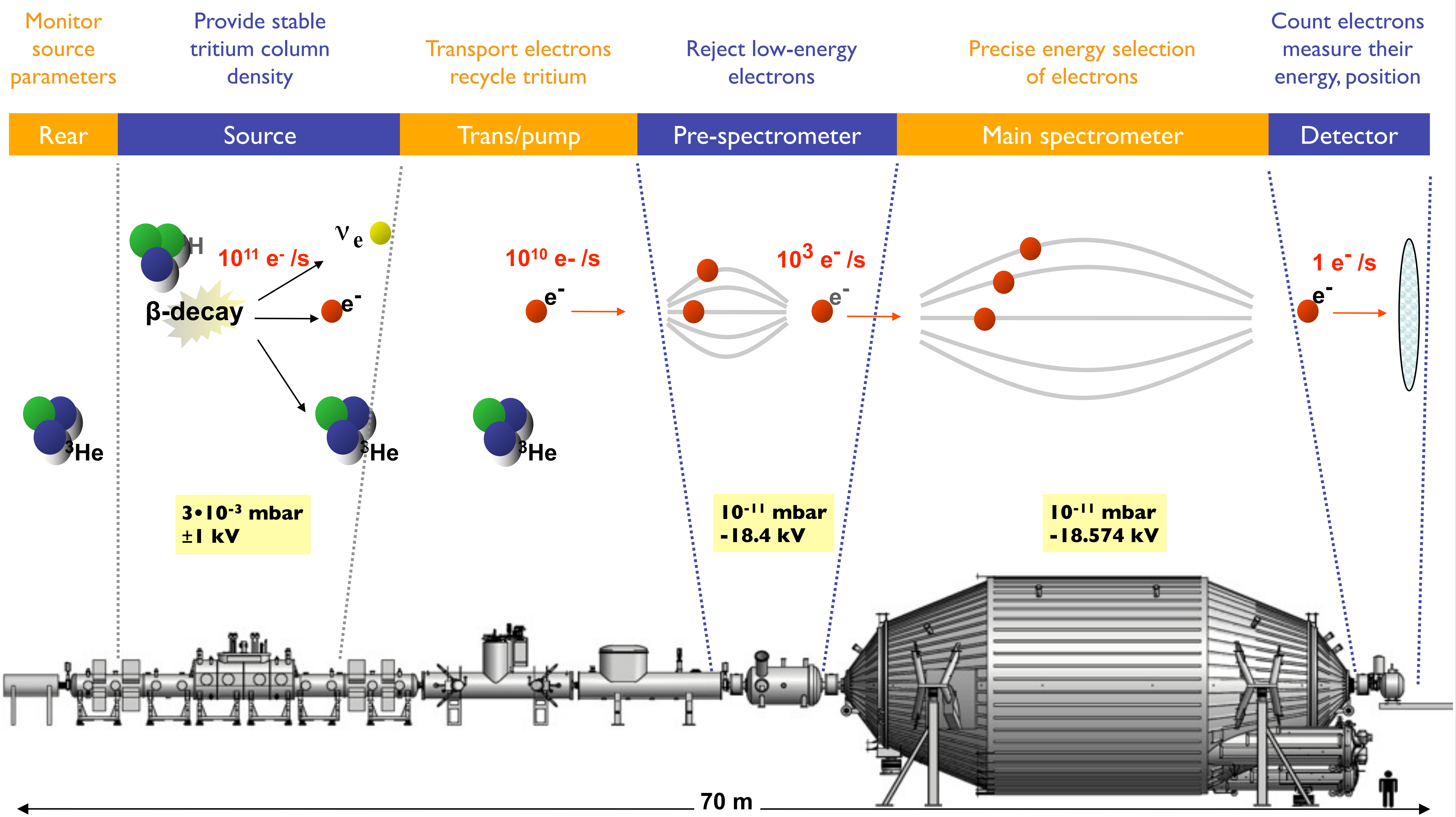
The Next Generation: KATRIN

- Collaboration includes ≈150 scientists from 5 countries
- US collaborators are MIT, LBNL, UW, UCSB, and UNC-Chapel Hill

Located at the Karlsruhe Institute of Technology (KIT), in Karlsruhe, Germany



How it Works



Monitor source parameters
Provide stable tritium column density
Transport electrons recycle tritium
Reject low-energy electrons
Precise energy selection of electrons
Count electrons measure their energy, position
Rear
Source
Trans/pump
Pre-spectrometer
Main spectrometer
Detector
10^{11} e⁻ /s
10^{10} e- /s
10^{3} e⁻ /s
1 e⁻ /s
β-decay
ν_e
e⁻
^{3}H
^{3}He
3•10^{-3} mbar
±1 kV
10^{-11} mbar
-18.4 kV
10^{-11} mbar
-18.574 kV
70 m

What Makes it so Hard?

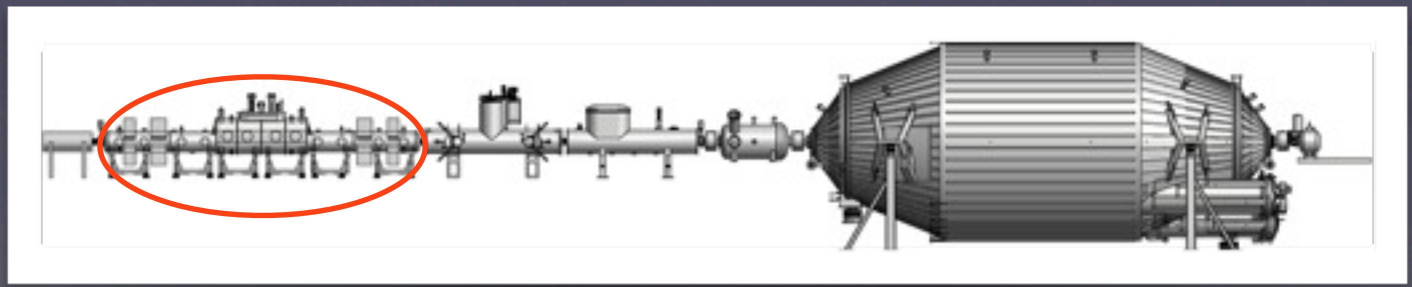
- Windowless, gaseous tritium source
  - High purity tritium
  - Column density known to 0.1%
- Transport/Pumping
  - Move electrons 70 m without energy loss
  - Reduce T_2 pressure by a factor of 10^7
- Spectrometers
  - Reduce e- flux by a factor of 10^{11}
  - Energy resolution of < 1eV
- Detector
  - Achieve a background rate of 1-10 mHz
  - Capable of detection rates from mHz to kHz

Windowless Tritium Source

- No physical separation between the source region and the vacuum vessels
- Use of injection & differential pumping to provide a well-controlled gas column density.
- Monitoring of purity of gas via laser Raman spectroscopy.

T_2 Specifications

Tritium throughput	40 g/day
Temperature stability	30 mk @ 27 K
Electron flux	10^{11} β/s
Column density	5 x 10^{17} cm^{-2}



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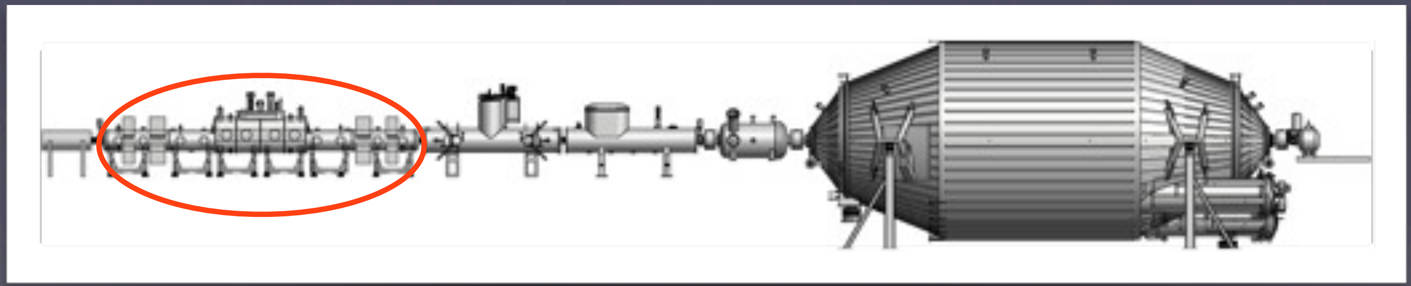
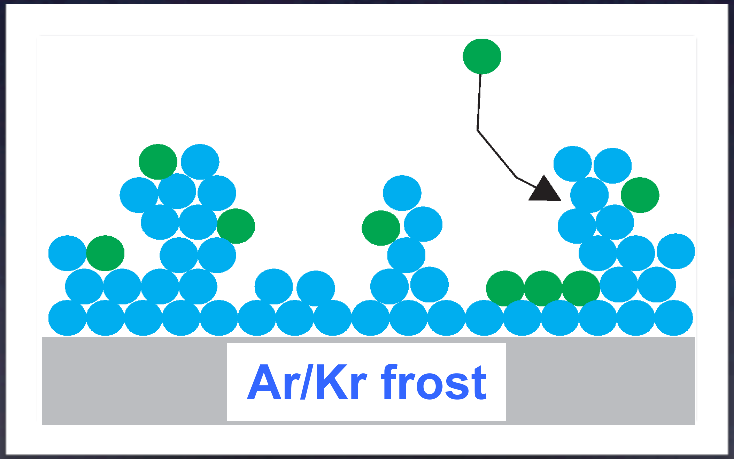
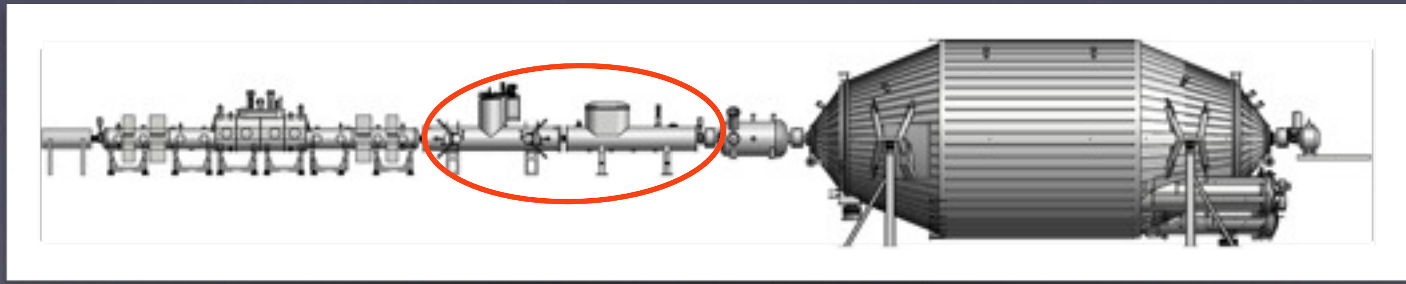


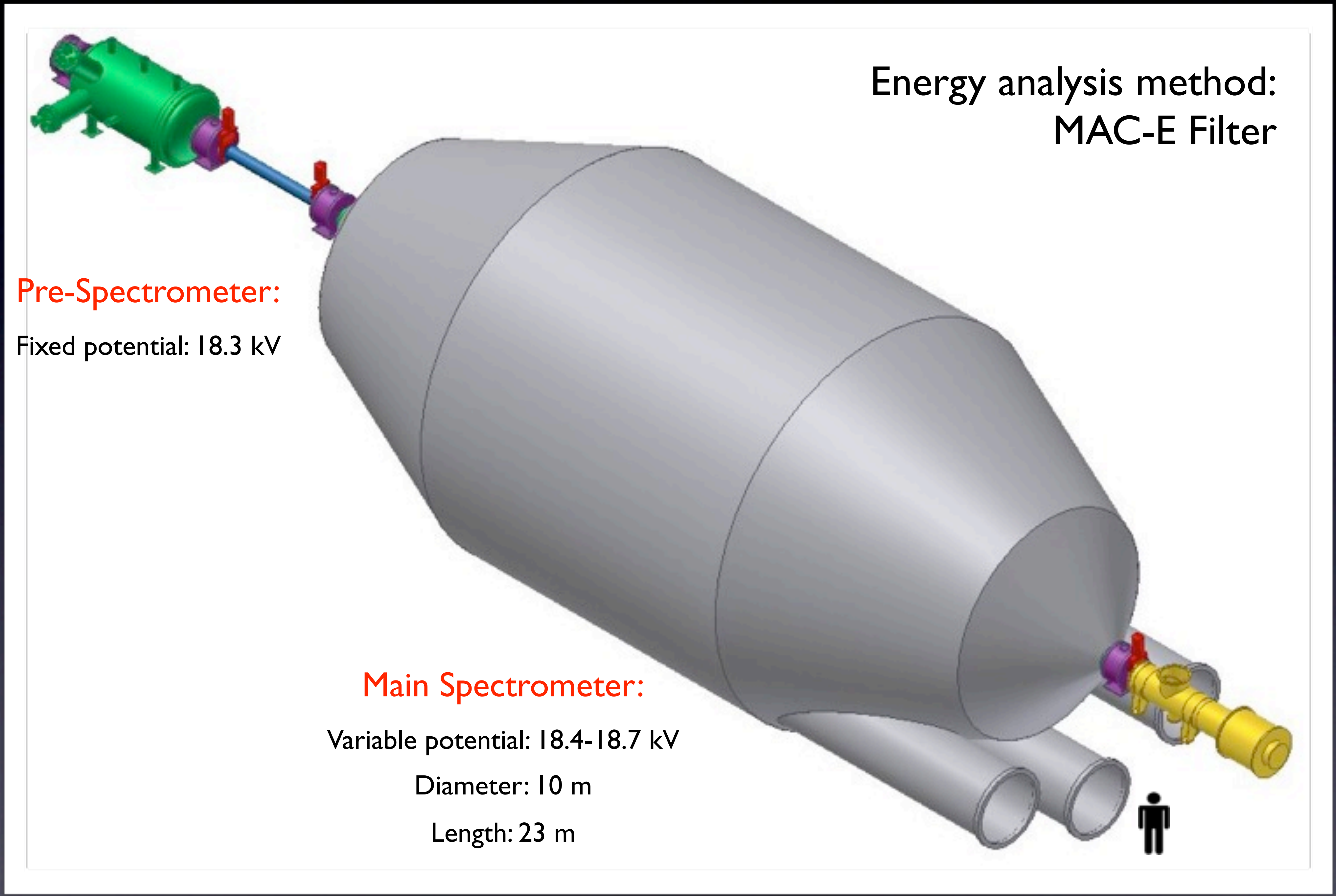
Transport/Pumping

- Magnetic field generated with superconducting solenoids
- Goal is to reduce tritium pressure by a factor of $>10^7$
- T_2 gas recycled with turbo pumps
- Final pumping with an Ar/Kr frost at 3-4 K to trap residual tritium gas





Spectrometers



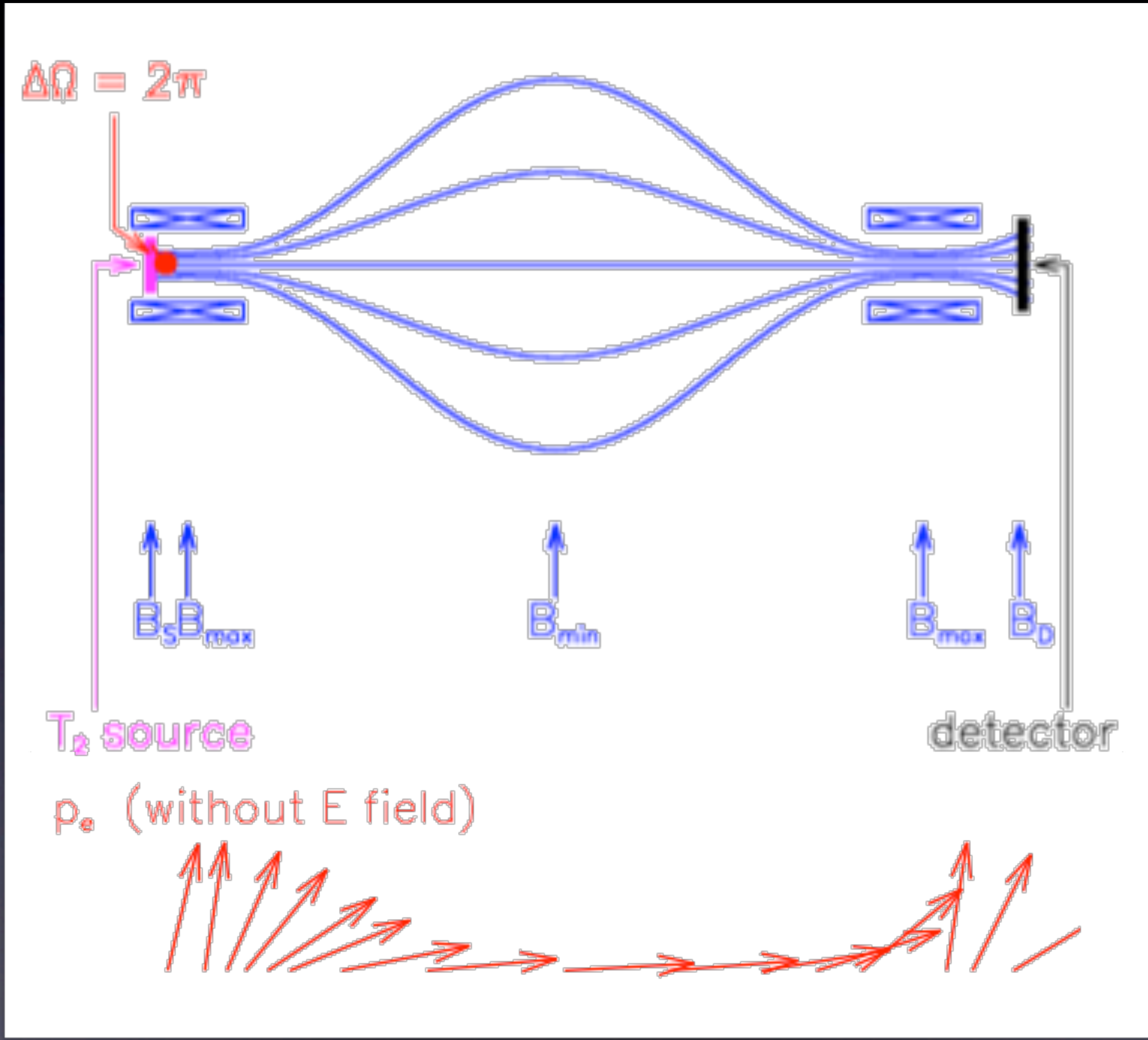
The MAC-E Filter Technique

MAC = Magnetic Adiabatic Collimation

- Two superconducting solenoids make a guiding magnetic field
- Isotropic Electron source in left solenoid
- Electrons emitted in the forward direction are magnetically guided
- Cyclotron energy is converted to longitudinal energy

$$\mu = \frac{p_\perp^2}{B} = \mathrm{const}$$

- Broad, parallel beam at the analyzing plane



A. Picard et al., Nucl. Instr. Meth. 63 (1992) 345

The MAC-E Filter Technique

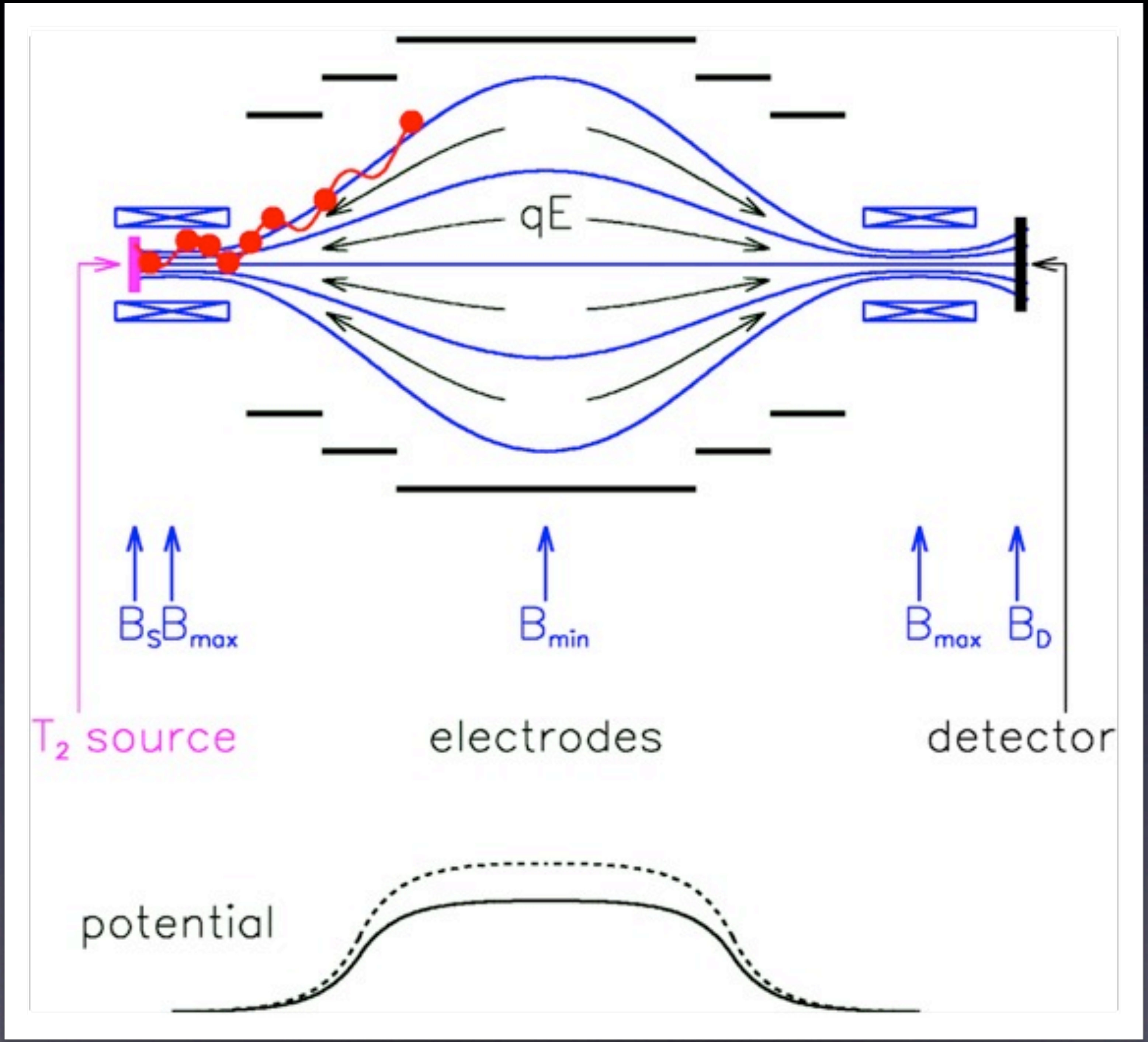
E = Electrostatic (Filter)

- Add electric field parallel to magnetic field
- Retarding electrostatic potential is an integrating high-pass energy filter

➡ Parallel energy analysis

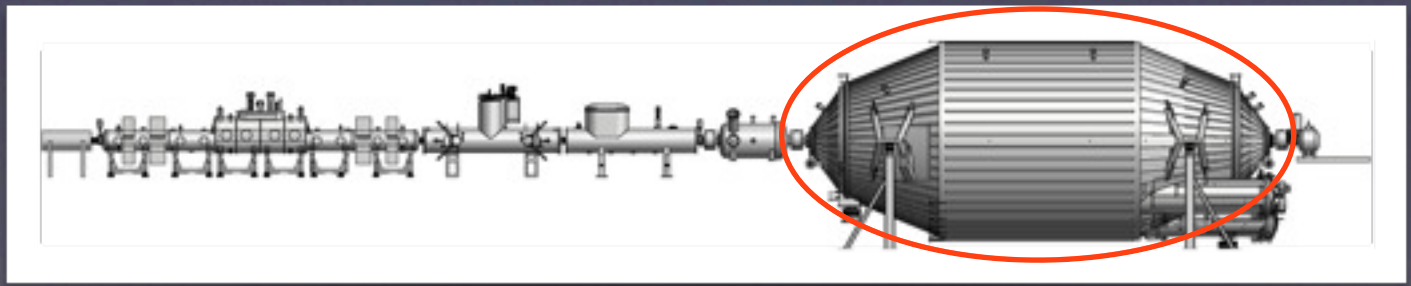
$$\frac{p_{\parallel}^2}{2m} = E_{\parallel} > qU$$

$$\Delta E = \frac{B_{\min} E}{B_{\max}} = 0.93\,\mathrm{eV}$$



Main Spectrometer

- High-pass energy filter calibrated to high precision
- Small transmission resolution achieved with large size and high precision HV stability
- Wire electrodes used to reduce the cosmic ray background



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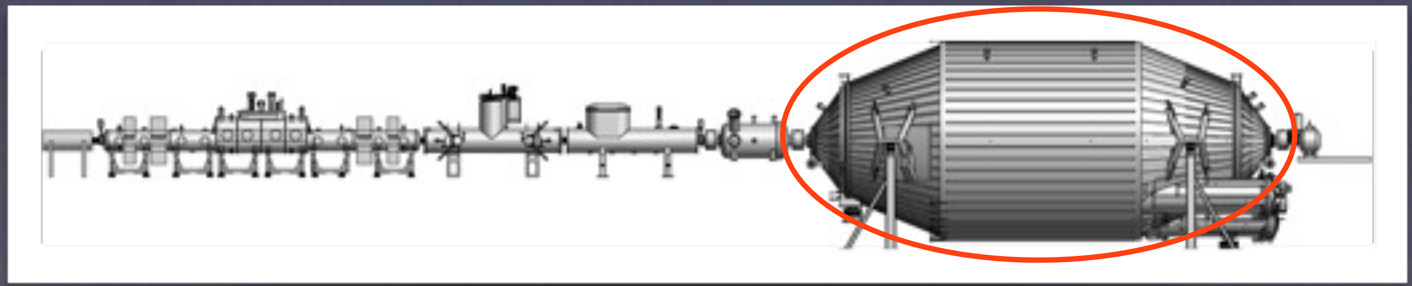


Delivery of the Main Spectrometer

Constructed near Deggendorf, about 400 km from Karlsruhe.

Shipped 9000 km around western Europe!

Delivery of the Main Spectrometer

Constructed near Deggendorf, about 400 km from Karlsruhe.

Shipped 9000 km around western Europe!

Transport through Leopoldshafen

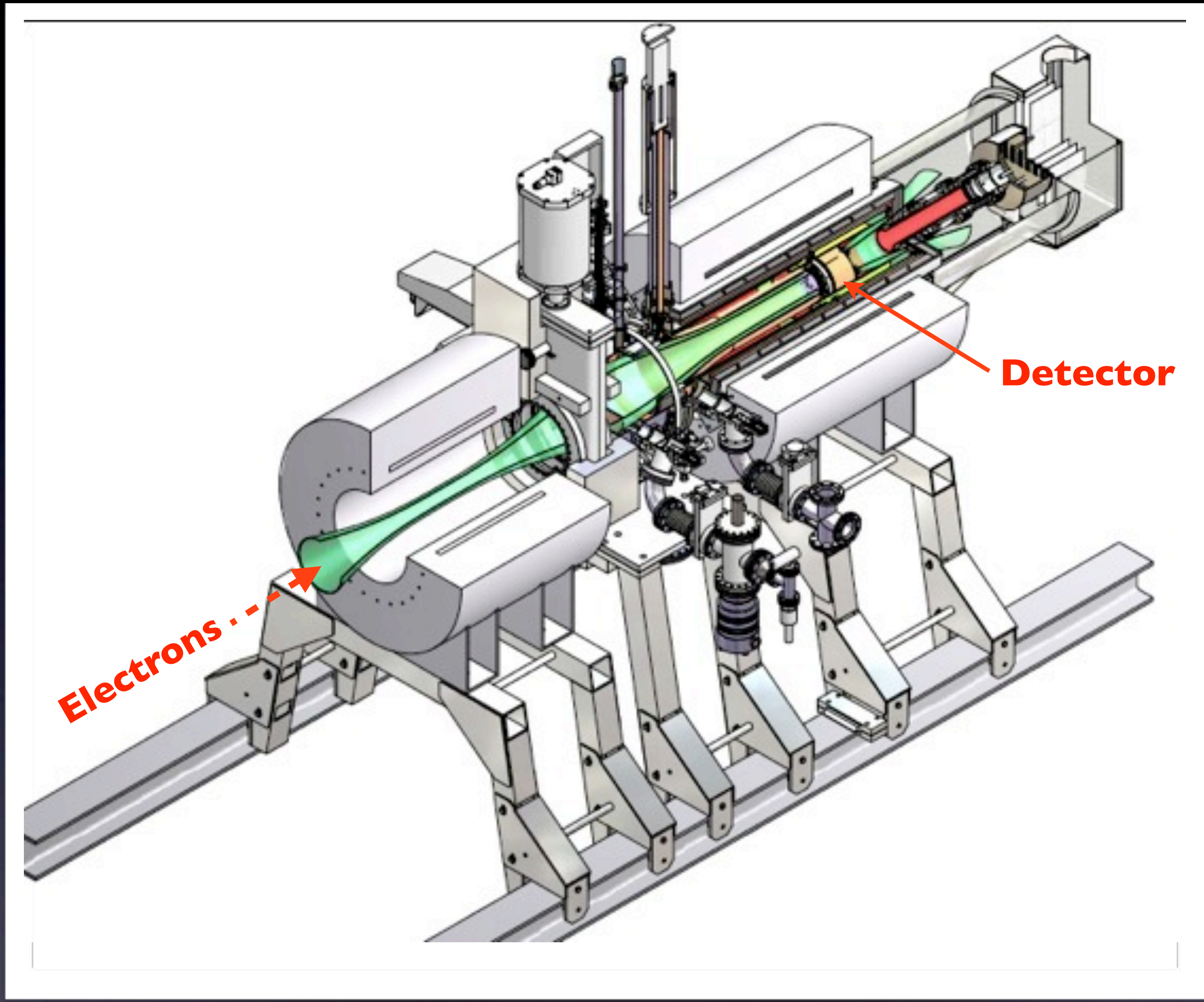
Delivery of the Main Spectrometer

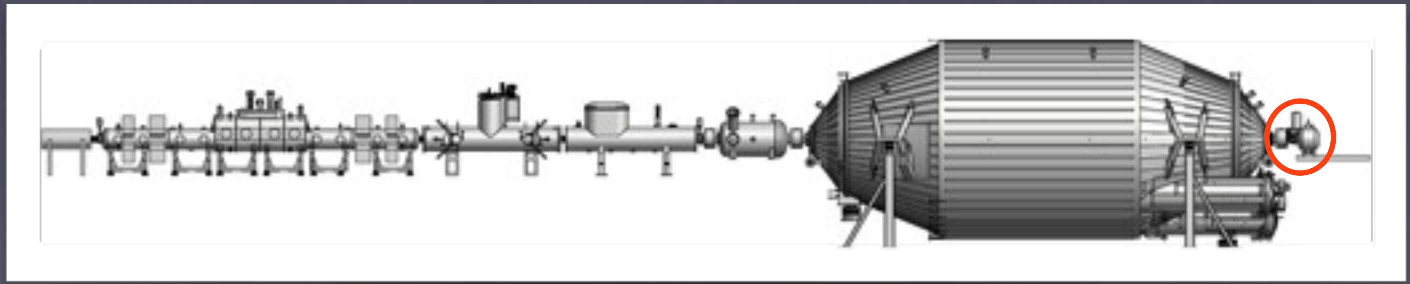
Arriving at KIT

Transport through Leopoldshafen

Detector Section

- High magnetic field collimation
- Segmented silicon PIN detector for electron detection
- Background reduction techniques include passive shield and active veto





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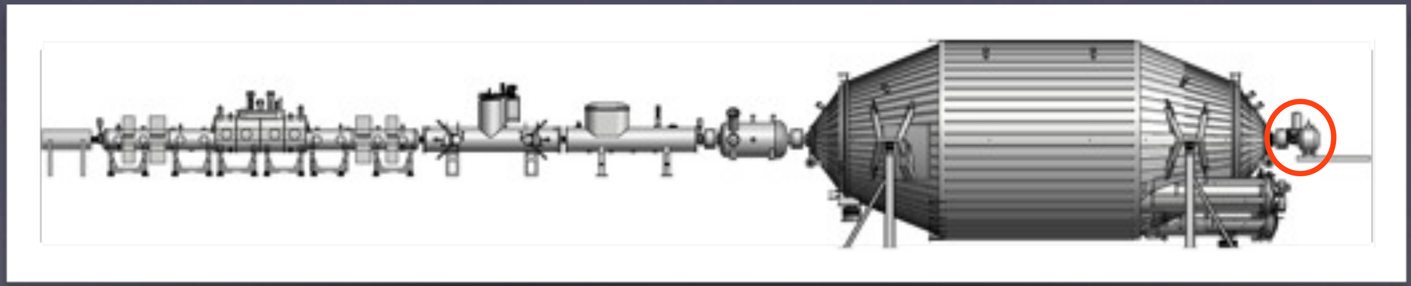
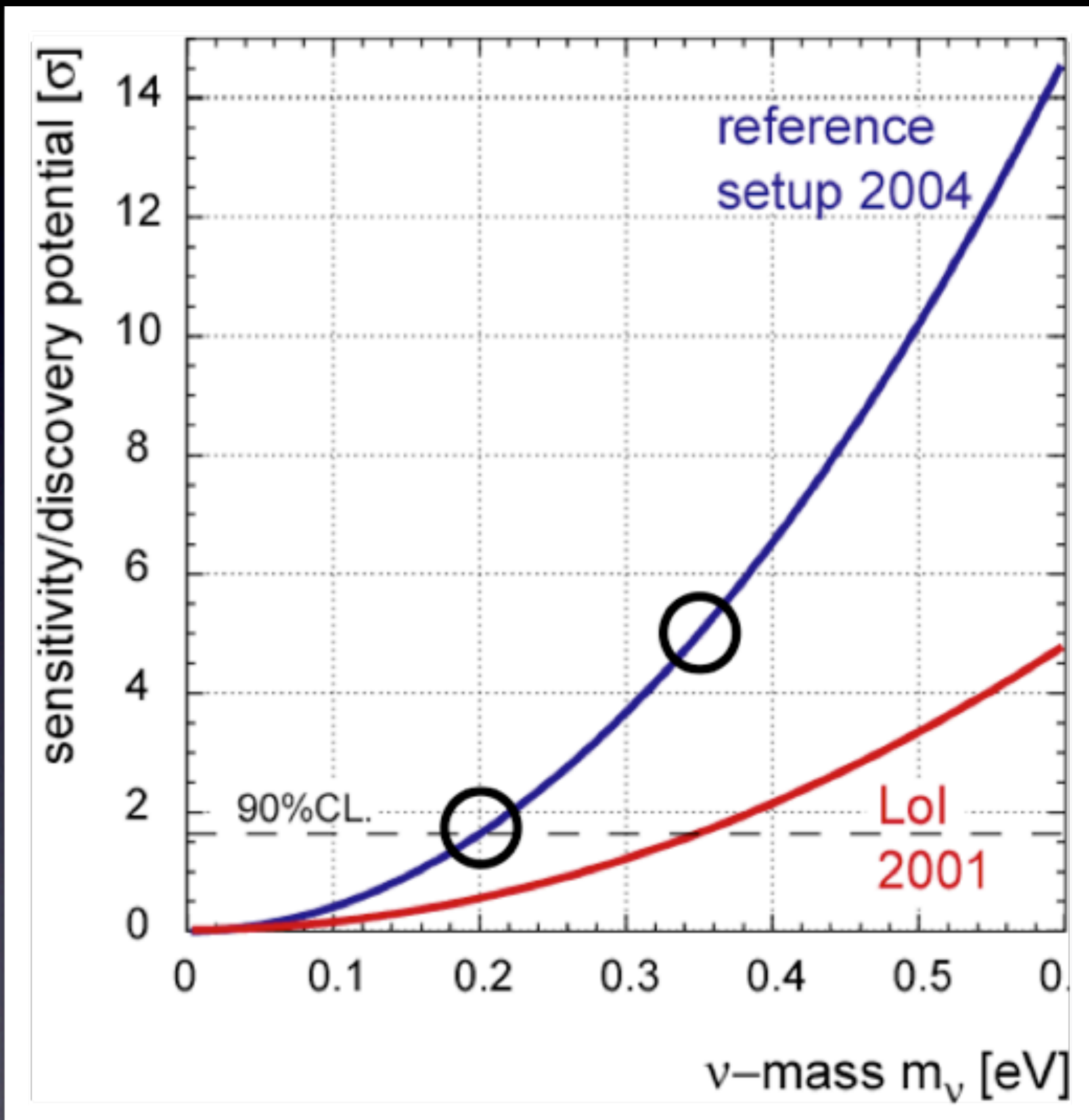


Current Status

- Detector section shipping to Karlsruhe in December
- Main Spectrometer commissioning begins in early 2011
- Data taking begins in 2012

Final Sensitivities



After 3 years of data
(5 years real time)

$\Delta m^2_{stat} \approx \Delta m^2_{syst} \approx 0.018\ eV^2$

Discovery Potential (5σ)

- m_ν = 350 meV

Sensitivity (90% CL)

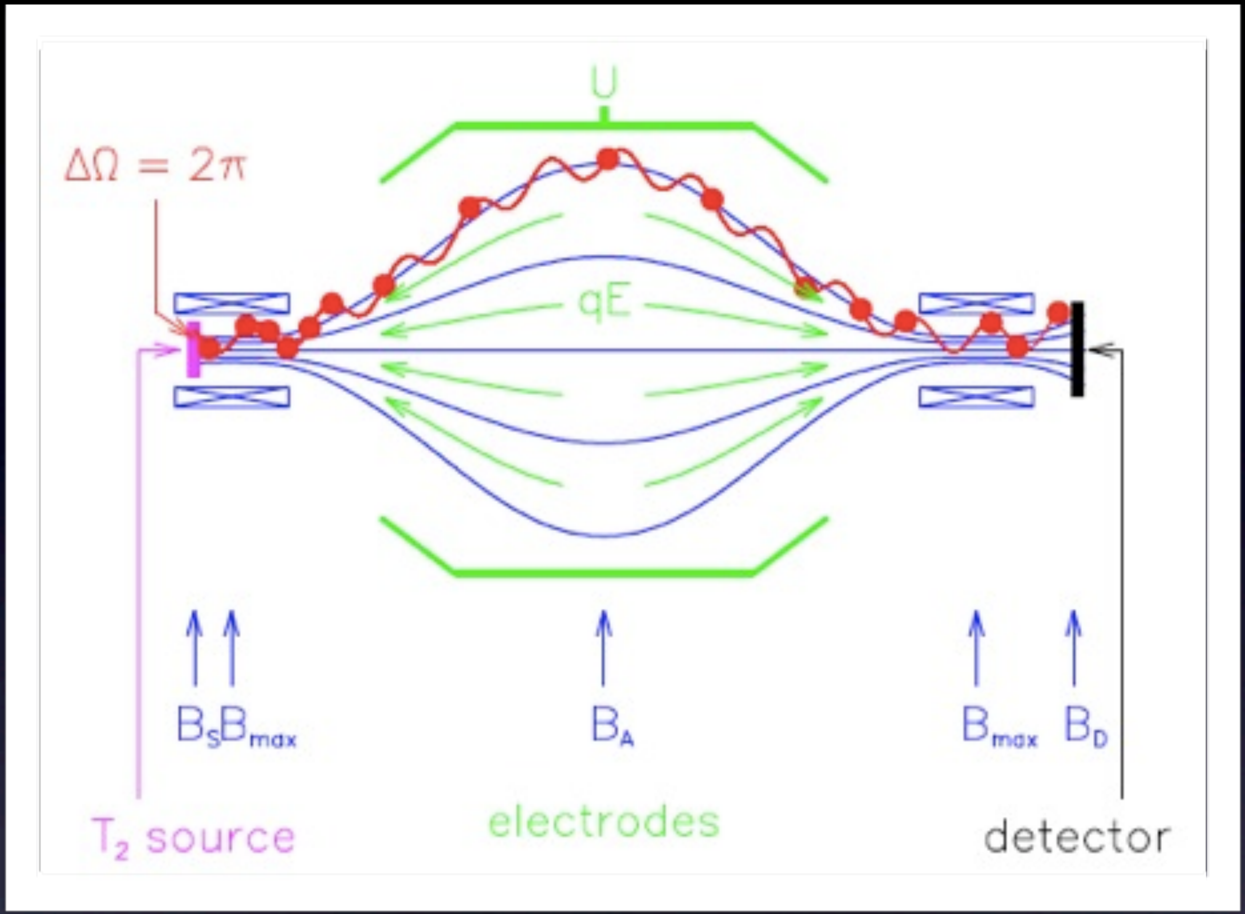
- m_ν < 200 meV

Comparison to Rhenium

	^{187}**Re**	**T$_2$**
Experiment	MARE	KATRIN
Type	Calorimeter	Spectrometer
Endpoint	2.47 keV	18.6 keV
Half-life	4.3×10^{10} y	12.3 y
Spectrum	Differential	Integral
Resolution	MARE-I: 15 eV MARE-II: 5 eV	0.93 eV
Mass Limit	MARE-I: 2 eV MARE-II: 0.2 eV	0.2 eV

Can We Do Better?

- Flux: Cannot increase source column density; can only scale up the area
- Resolution: Cannot reasonably scale up the size of the spectrometer



A new technique is necessary to achieve desired target and resolution

PROJECT 8

A small proto-collaboration has formed to explore this experimental possibility

Massachusetts Institute of Technology & Haystack Observatories

J.A. Formaggio, N. S. Oblath, D. Furse, P. Fisher,

A. Rogers and S. Doelman

University of Washington

R.G.H. Robertson, P. Doe, L. Rosenberg, M. Miller, G. Rybka, B. VanDevender, L. Bodine

University of California, Santa Barbara

B. Monreal and M. Leber

National Radio Astronomy Observatory

R. Bradley

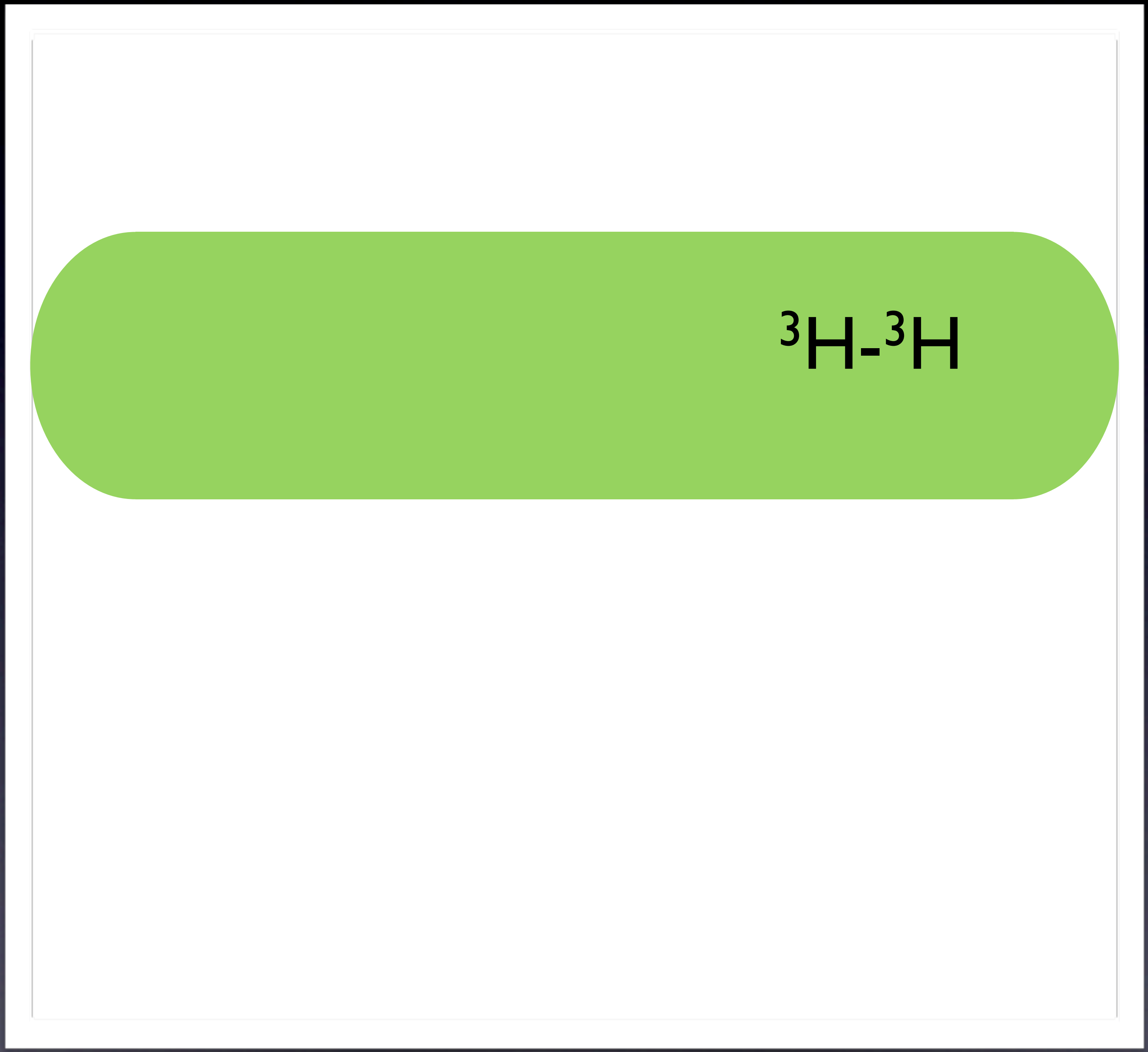
The Concept

- Enclosed volume

For details on this technique, see B. Monreal and J. Formaggio, Phys. Rev. D80 051301 (2008)

The Concept

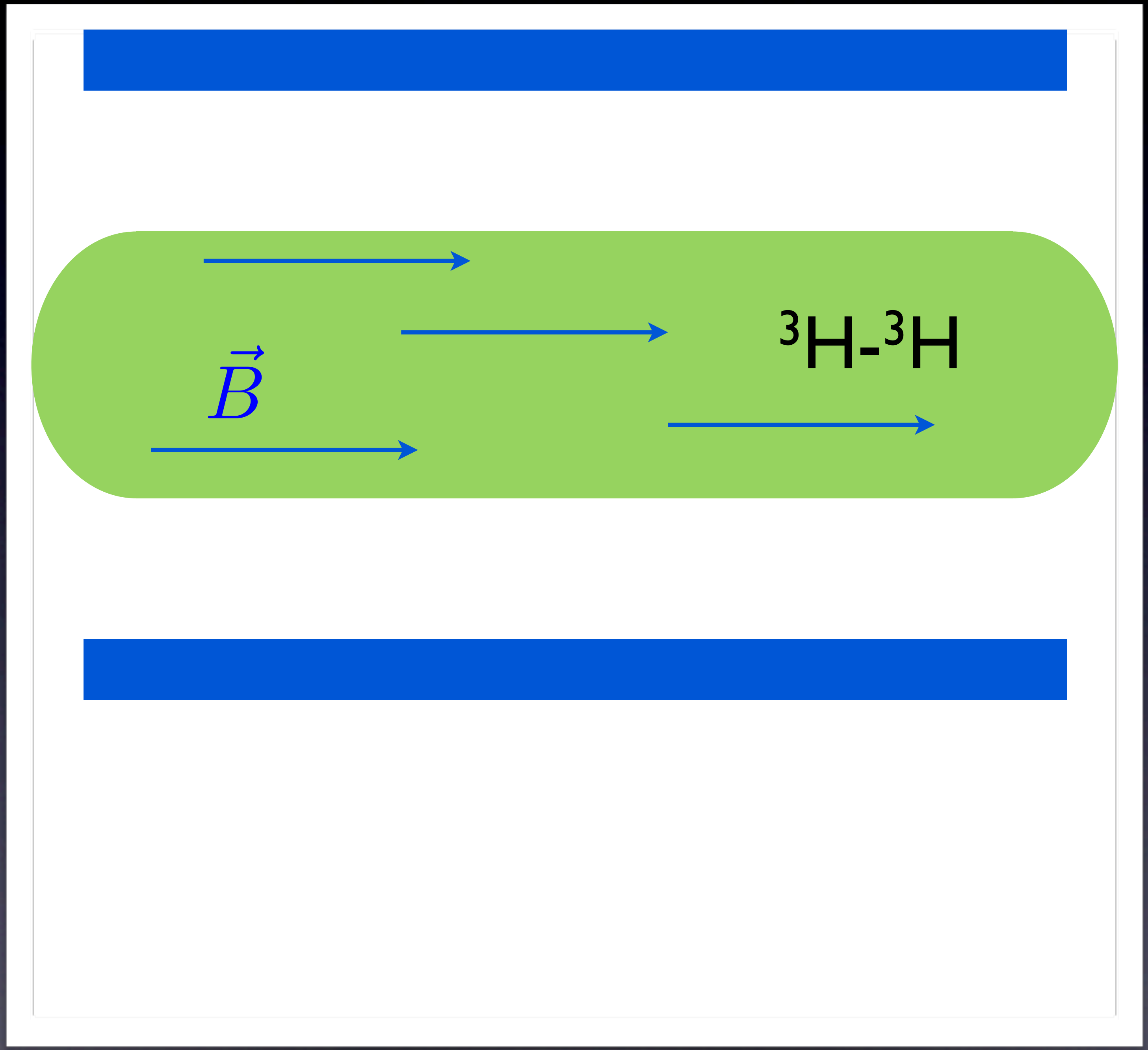
- Enclosed volume
- Fill with tritium gas



For details on this technique, see B. Monreal and J. Formaggio, Phys. Rev. D80 051301 (2008)

The Concept

- Enclosed volume
- Fill with tritium gas
- Add a magnetic field



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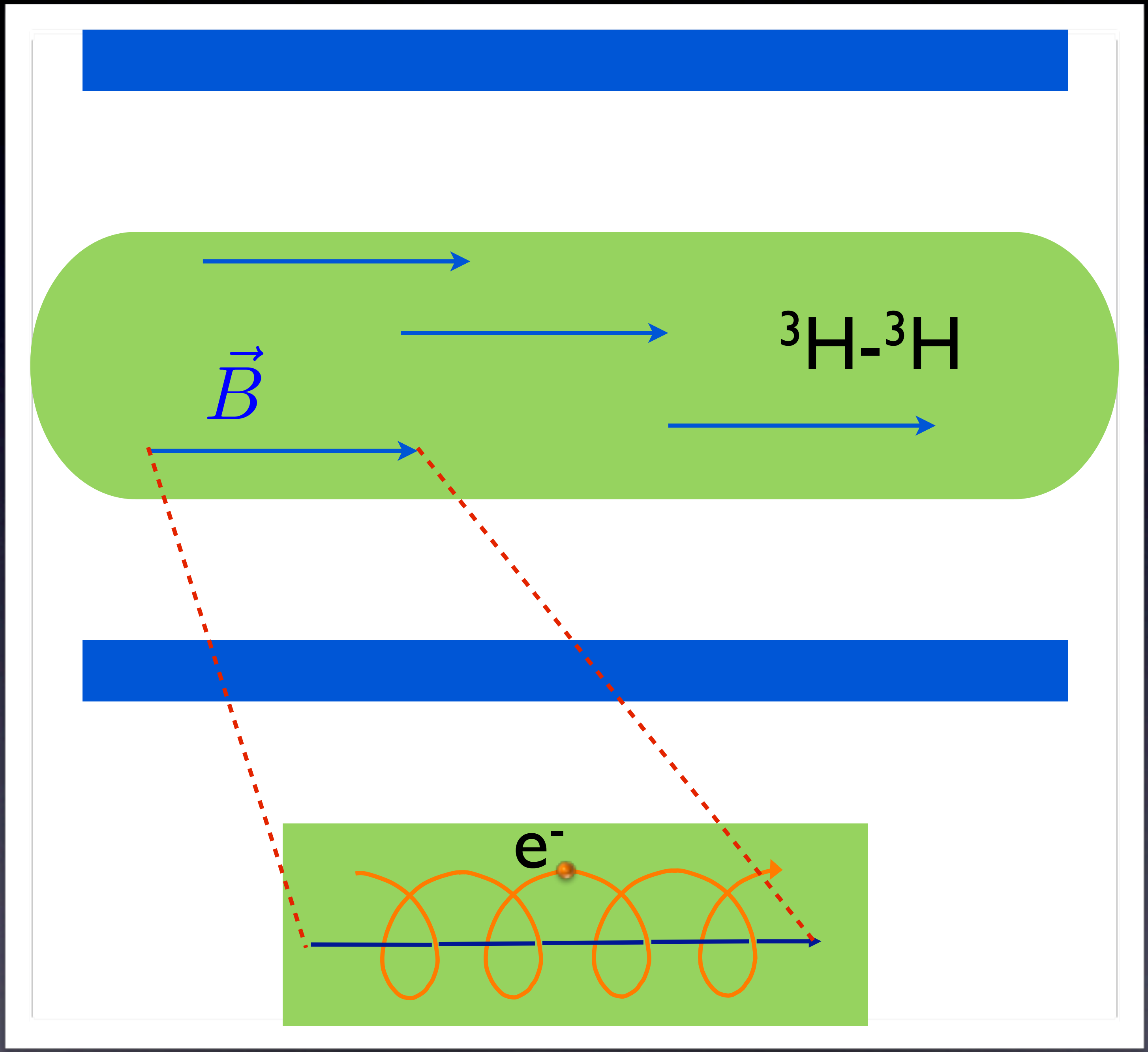

- Decay electrons spiral around field lines

For details on this technique, see B. Monreal and J. Formaggio, Phys. Rev. D80 051301 (2008)

The Concept

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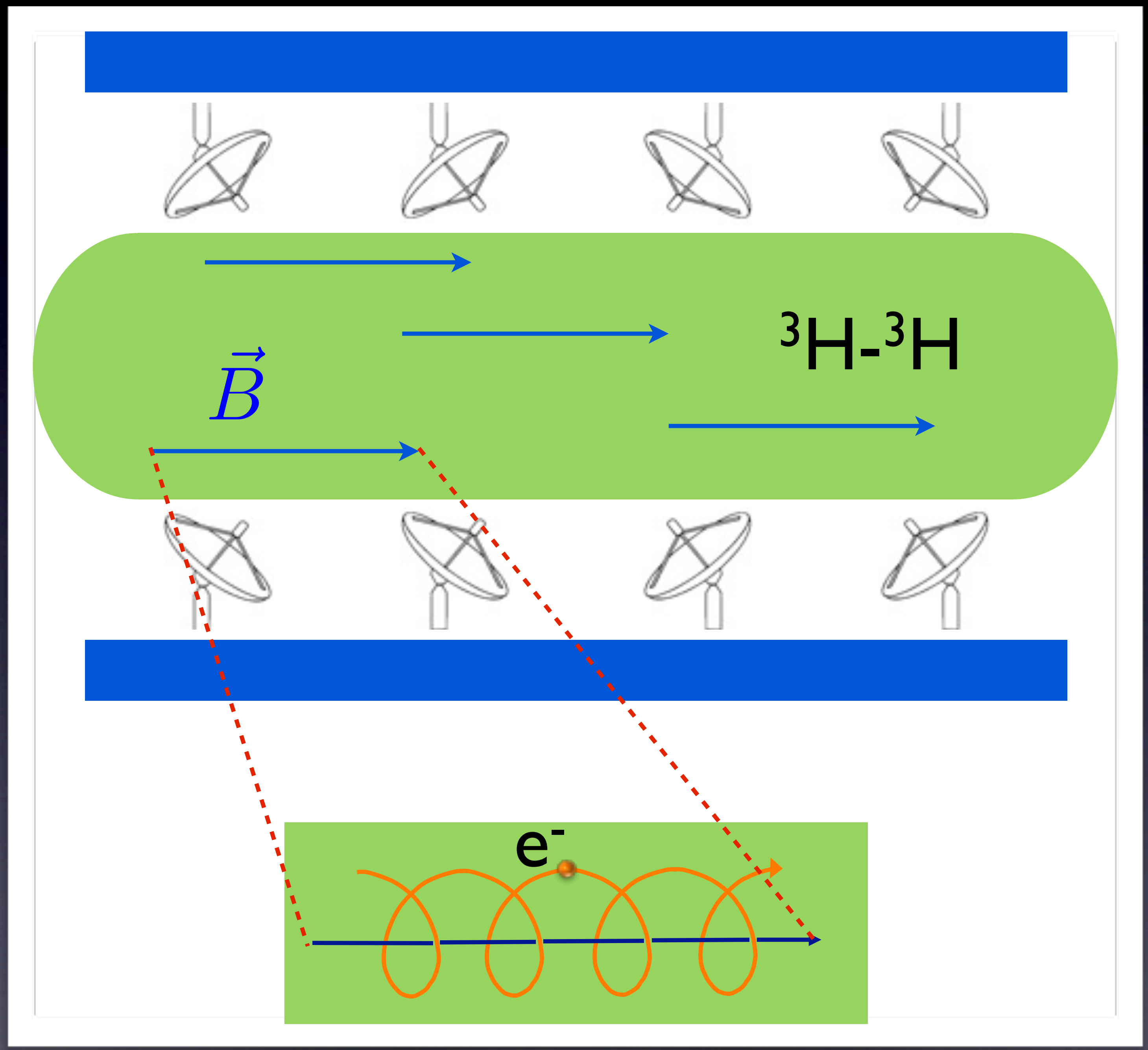
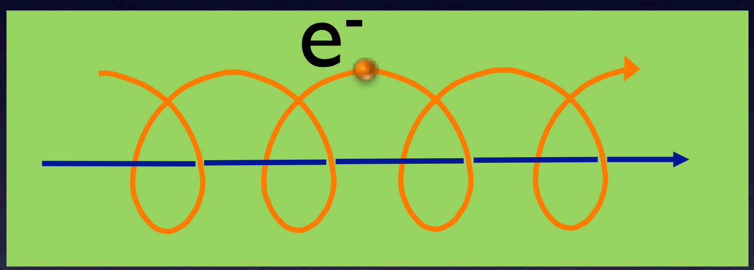


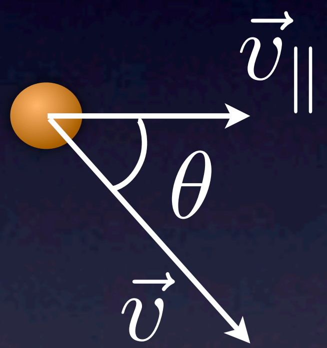
- Decay electrons spiral around field lines
- Add antennas to detect the cyclotron radiation

For details on this technique, see B. Monreal and J. Formaggio, Phys. Rev. D80 051301 (2008)

Cyclotron Radiation

- The frequency of the emitted radiation (ω) depends on the relativistic boost (γ and β dependence), and is independent of the pitch angle of the electron (θ)





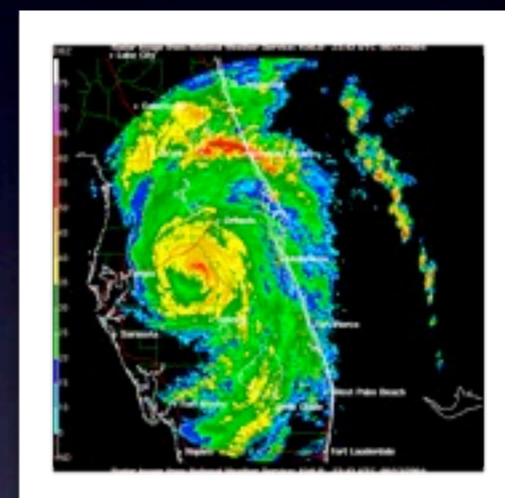
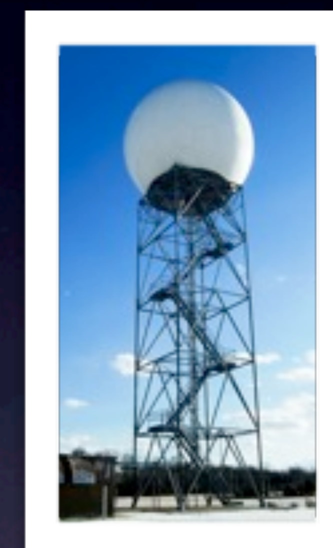
$$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e}$$

$$P_{\text{tot}} = \frac{1}{4\pi\epsilon_0}\frac{2q^2\omega_c^2}{3c}\frac{\beta_\perp^2}{1-\beta^2}$$

- The radiation emitted can be collected to measure the electron energy in a non-destructive manner

Some Numbers

- Frequency @ B = 1 T: ≈26 GHz

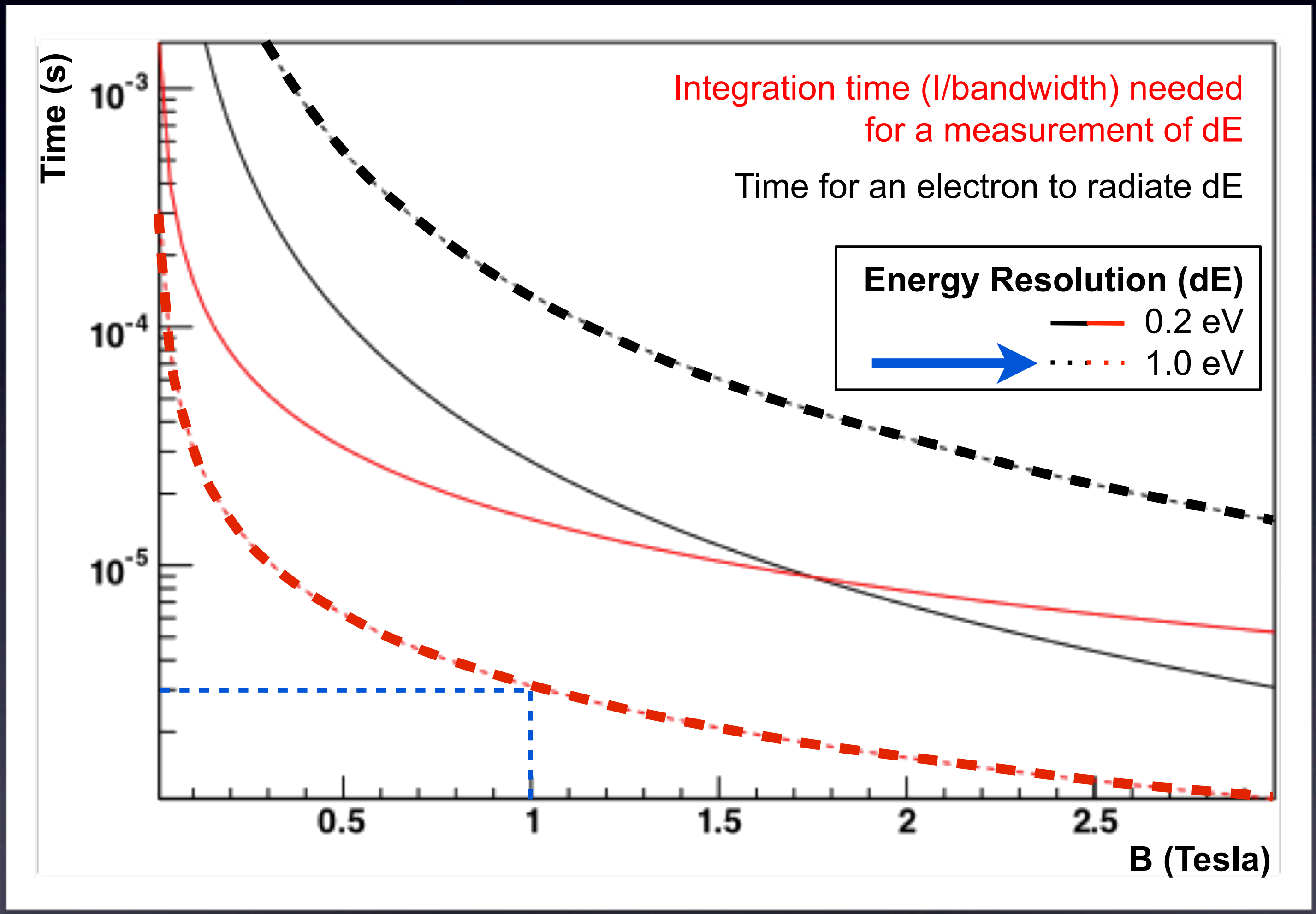




- Power radiated: 10^{-15} W
  - 18.6 keV = 3×10^{-15} J
  - Measurement time: ~10^{-5} s

Energy Resolution

- The energy resolution (dE) is determined by how long one can observe the radiation (T)

$$dE \propto \frac{1}{T}$$

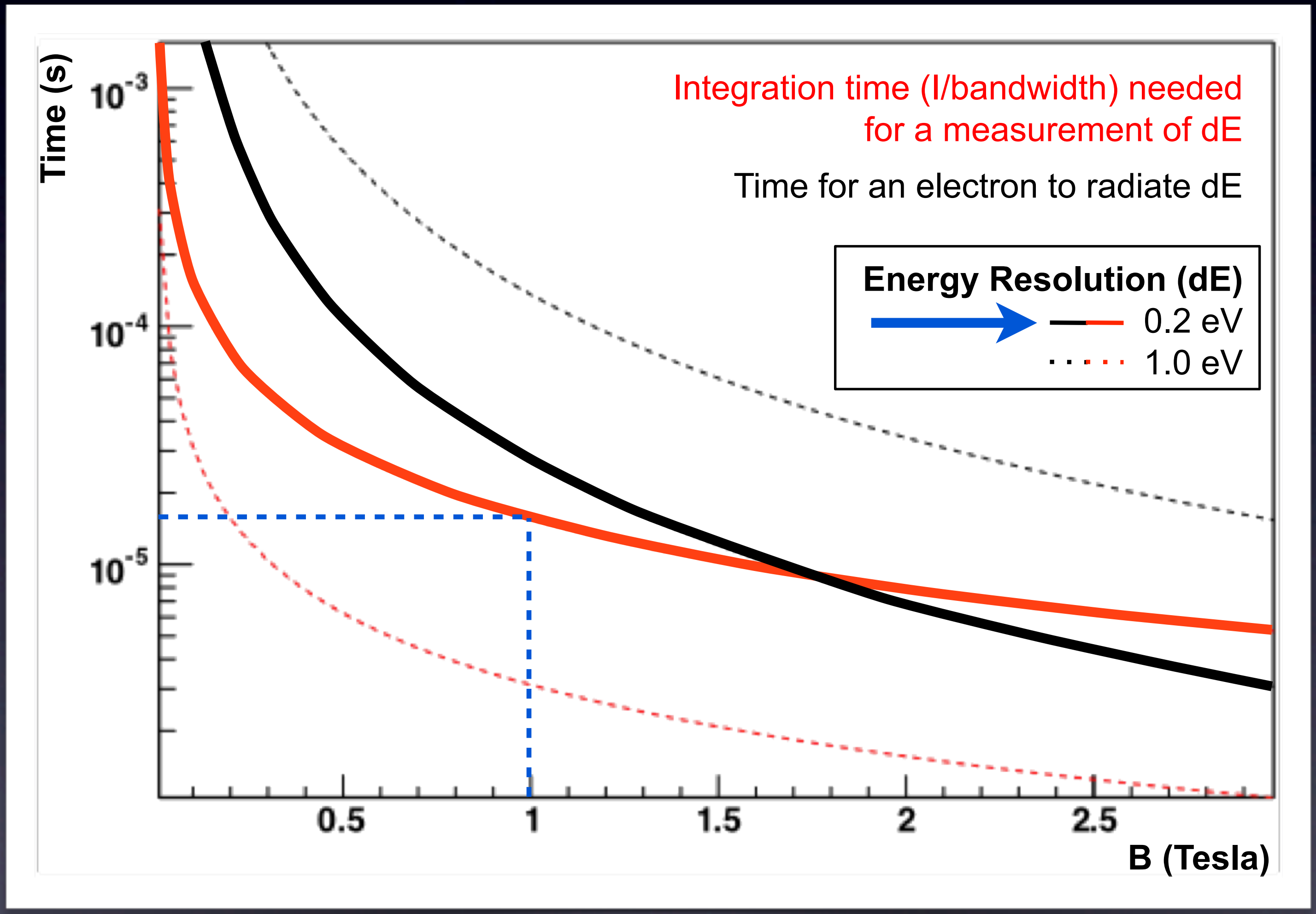


- For dE=1 eV , the measurement length must be $T \approx 3$ μs

Energy Resolution

- The energy resolution (*dE*) is determined by how long one can observe the radiation (*T*)

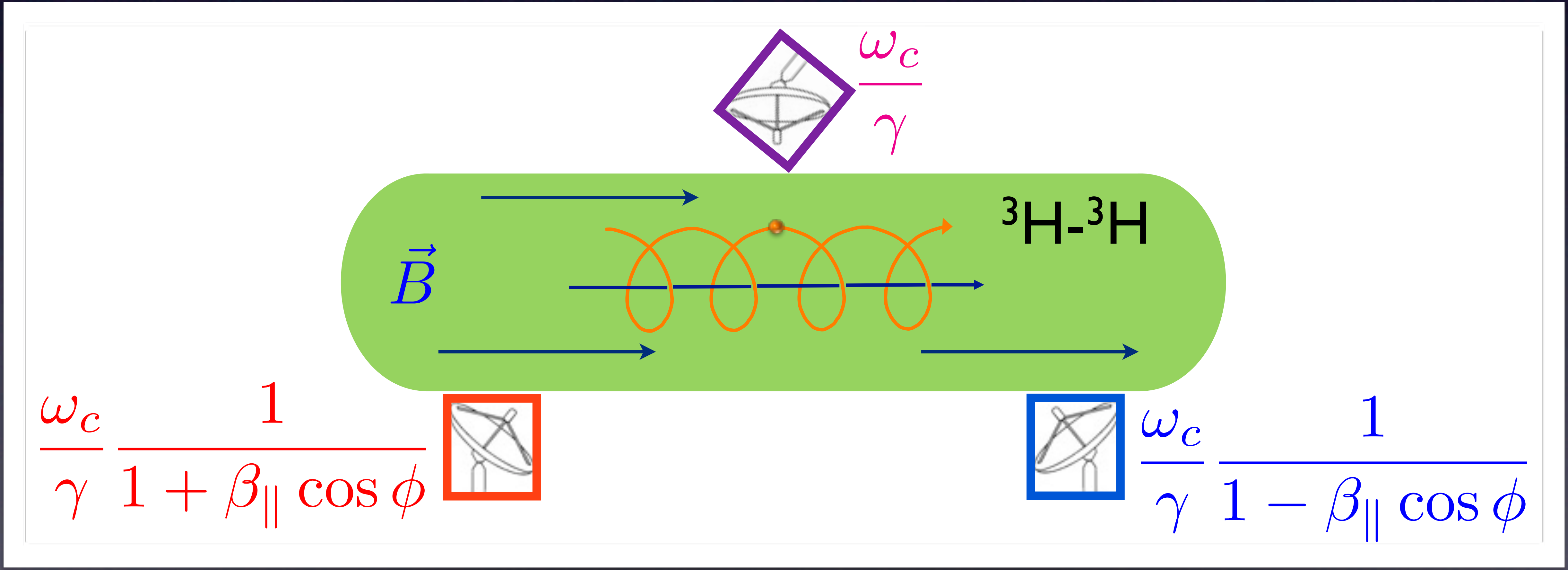
$$dE \propto \frac{1}{T}$$



- For *dE*=0.2 eV, the measurement length must be *T*≈15 μs

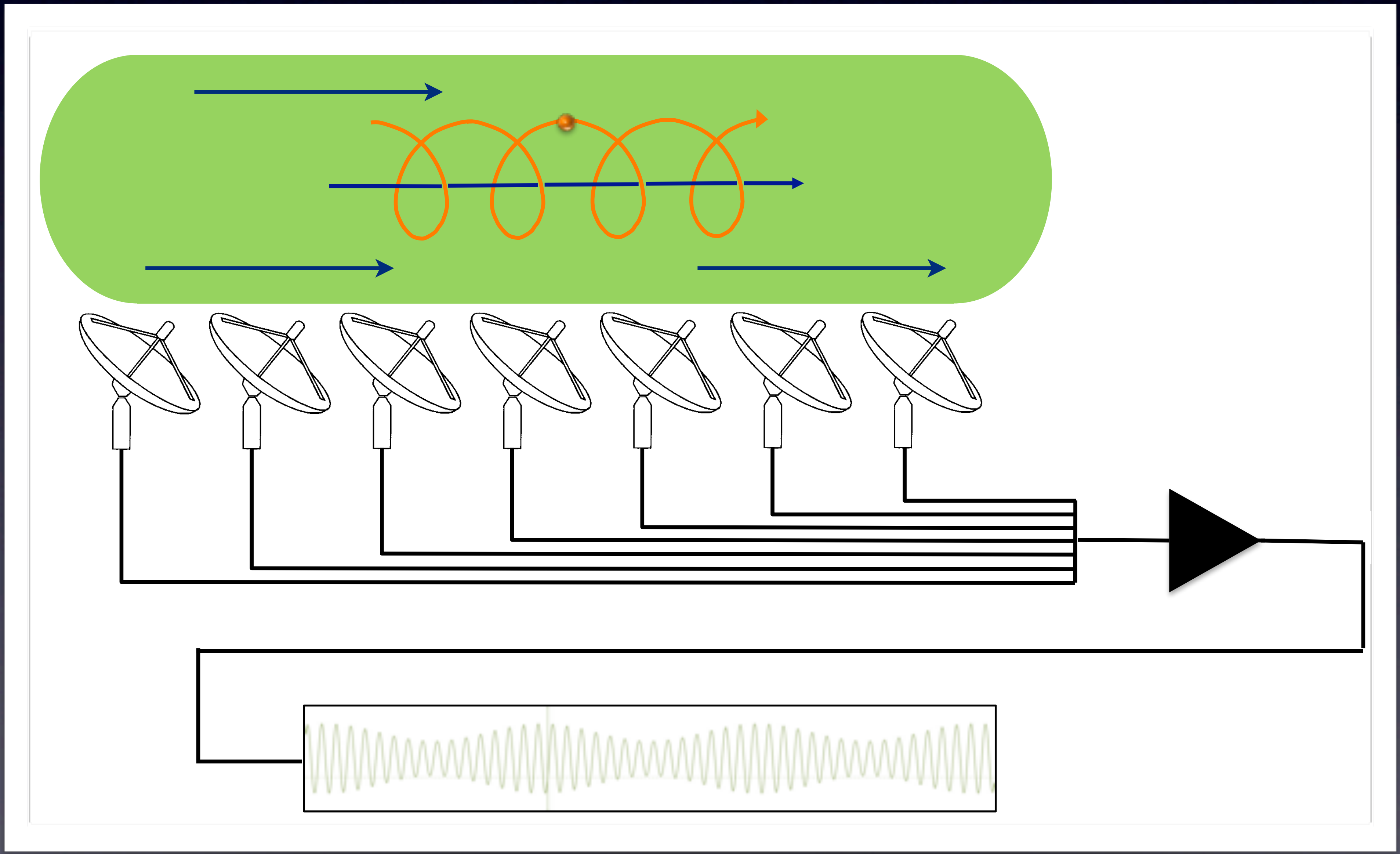
Doppler Shift

- A single antenna will see a sweep of frequency as the electron passes by: Doppler shift
- The detected frequency will therefore depend on both the electron energy and the Doppler shift



Interferometry

- Use an evenly-spaced antenna array
- Signals partially cancel, separating $\beta_{||}$-dependent sidebands from the energy-dependent central frequency



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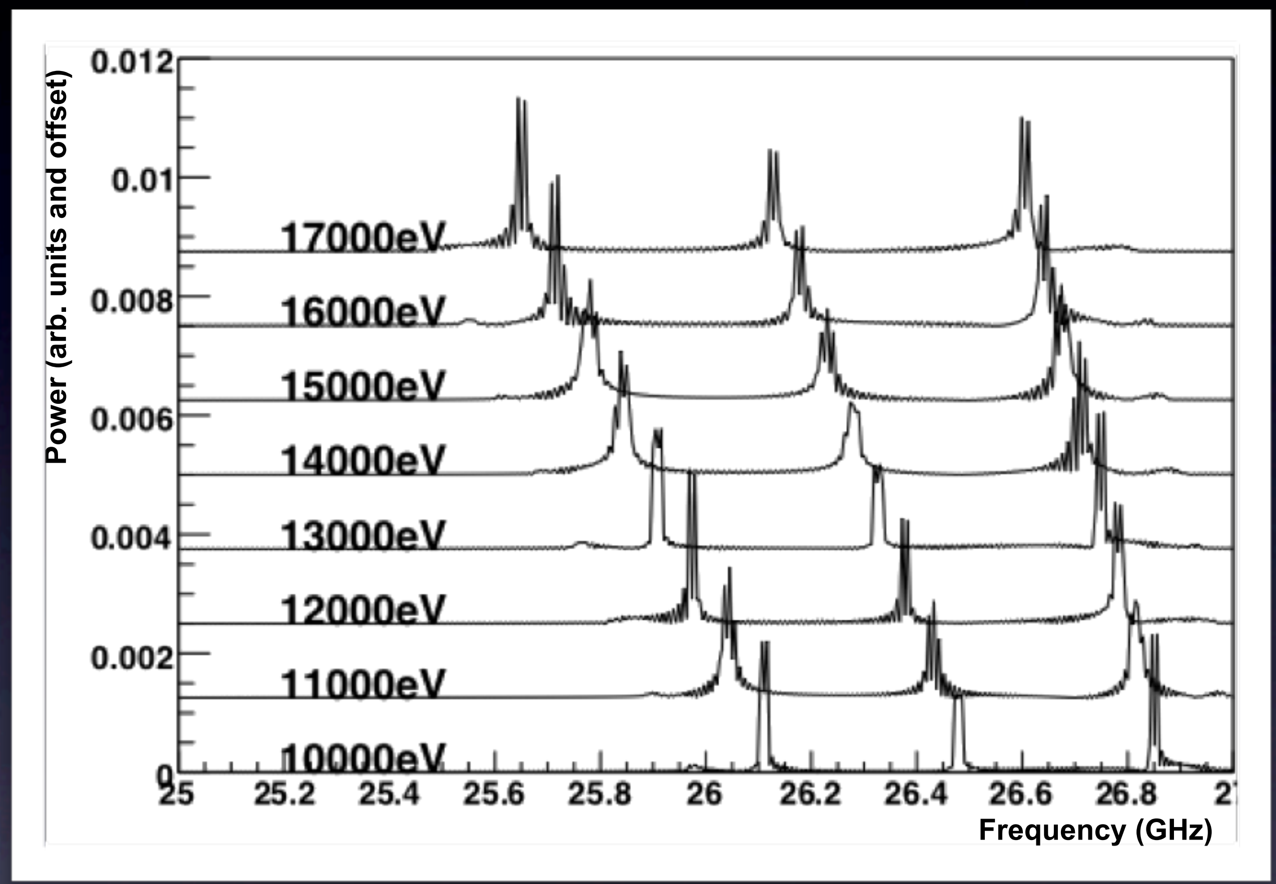
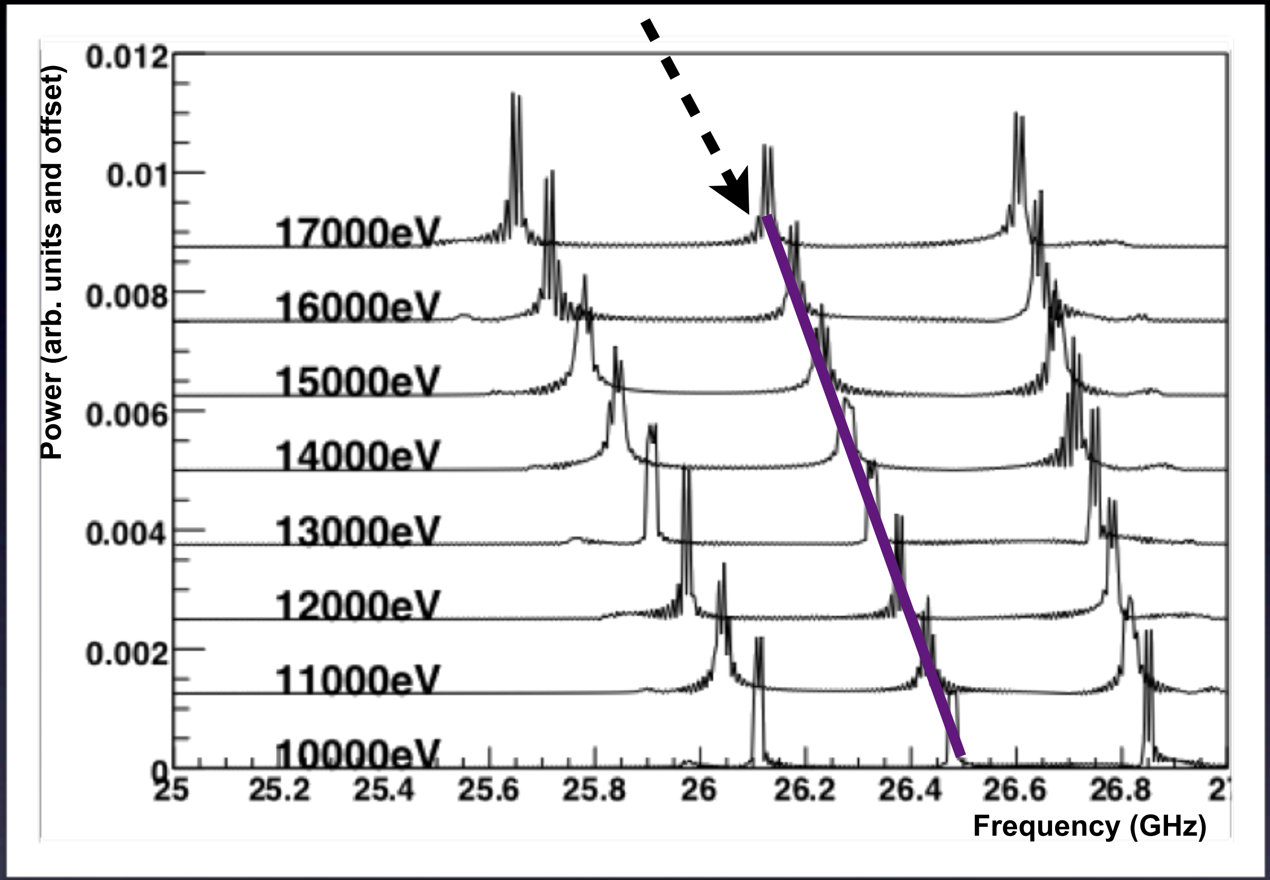


This effect is highly dependent on the antenna configuration

Interferometry

Central frequency
Dependent on the electron energy



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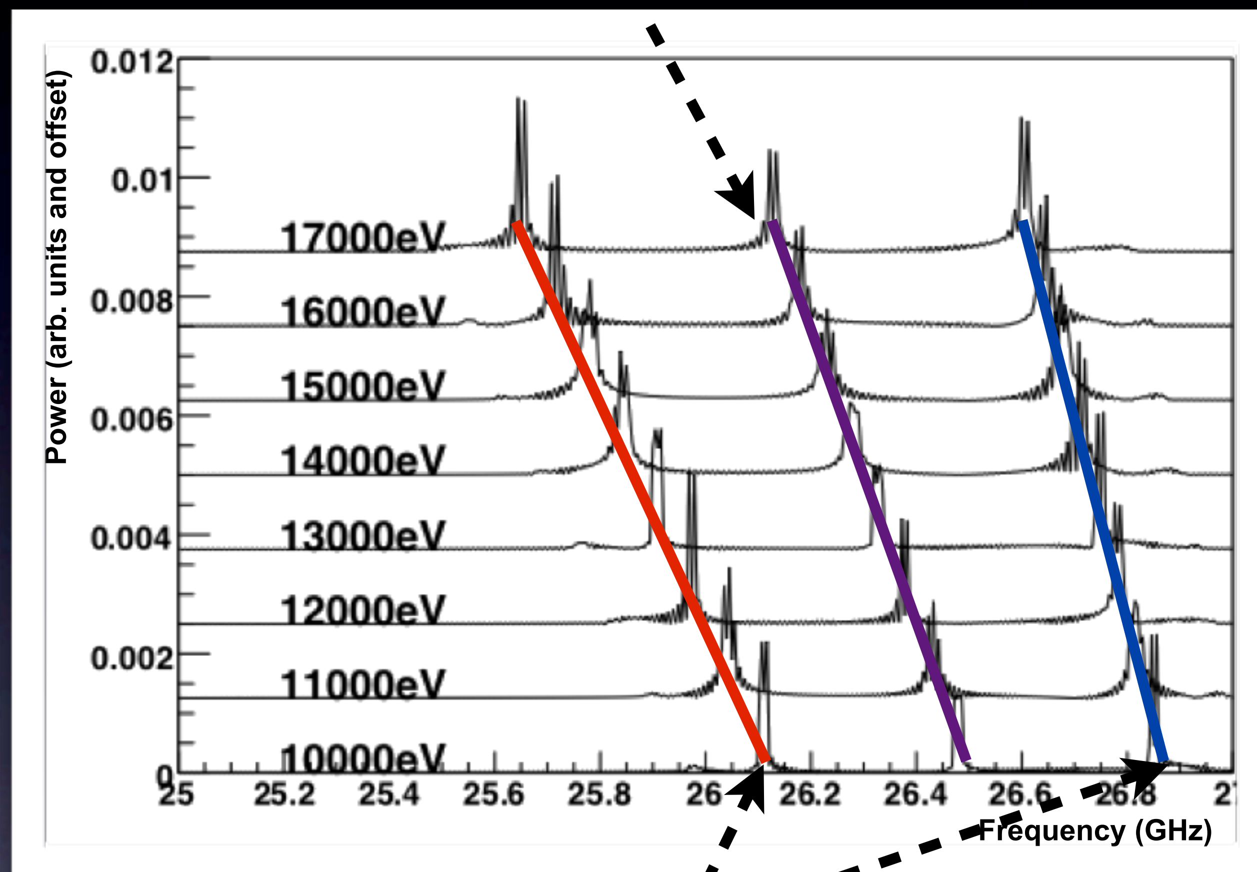
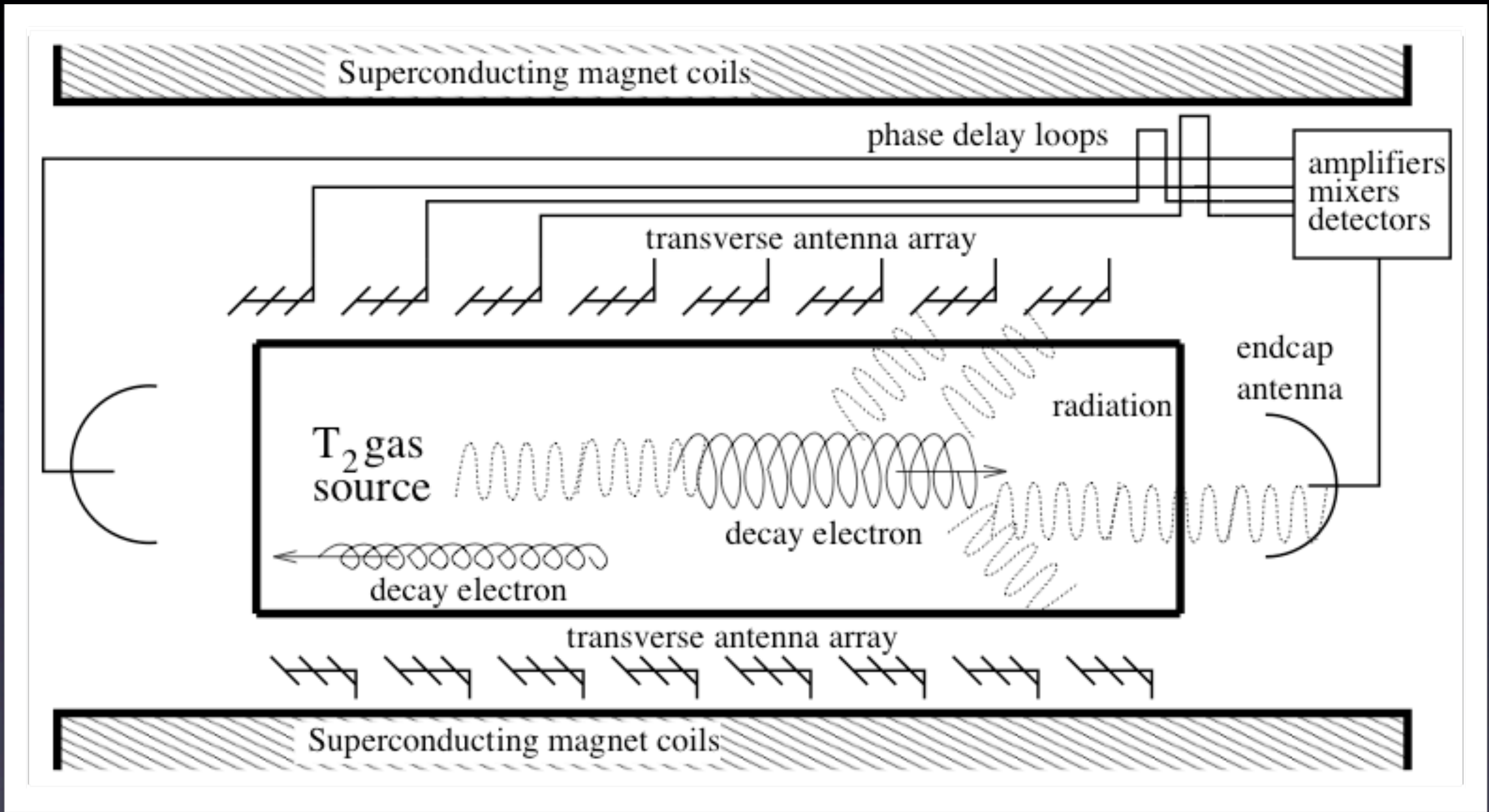


Sidebands
Dependent on the momentum parallel to the magnetic field

This effect is highly dependent on the antenna configuration

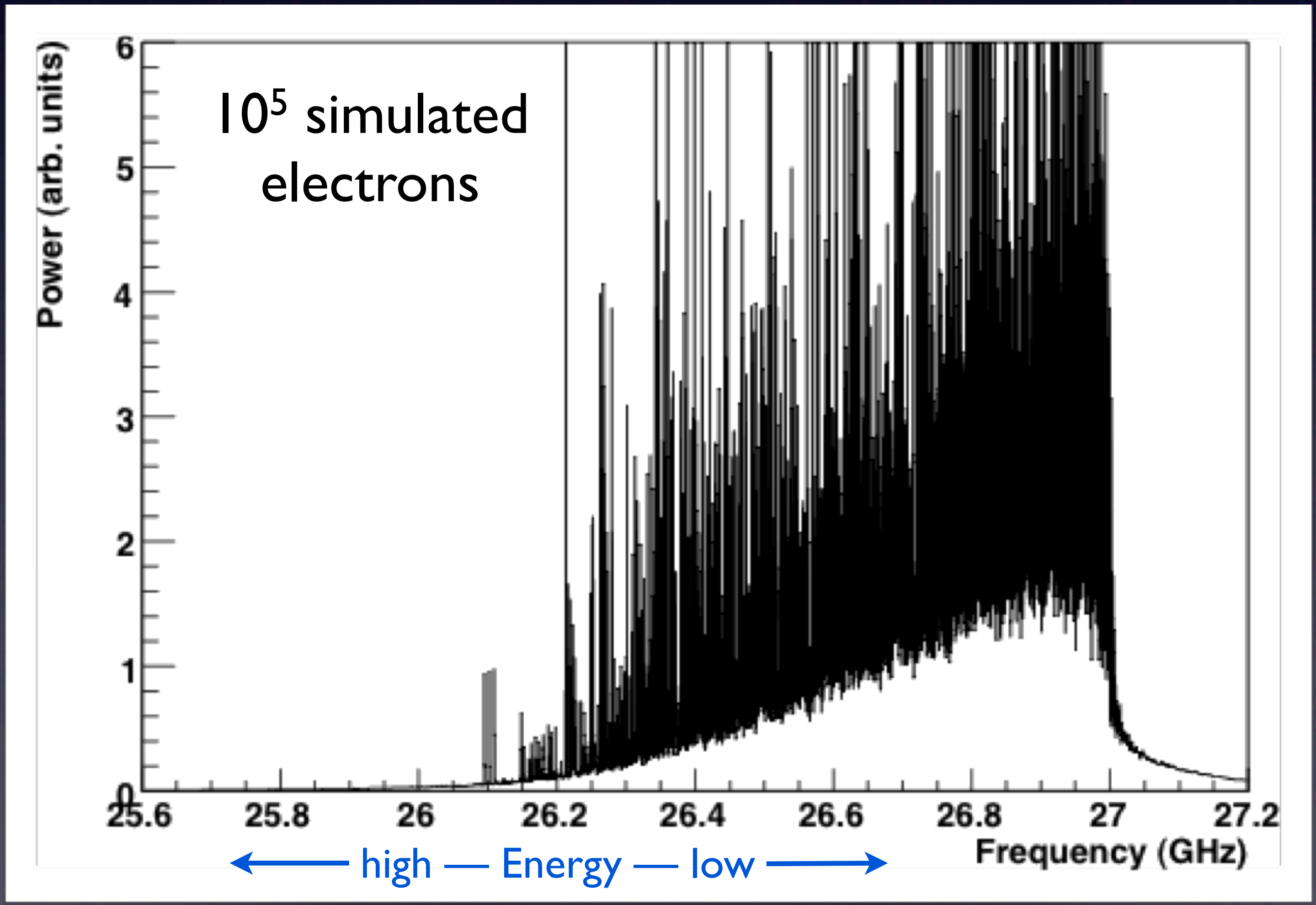
A Simulated Experiment



From B. Monreal and J. Formaggio, Phys. Rev. D80 051301 (2008)

Simulated Results

- Low energy electrons dominate at higher frequencies
- Rare, high energy electrons give a clean signature at the endpoint



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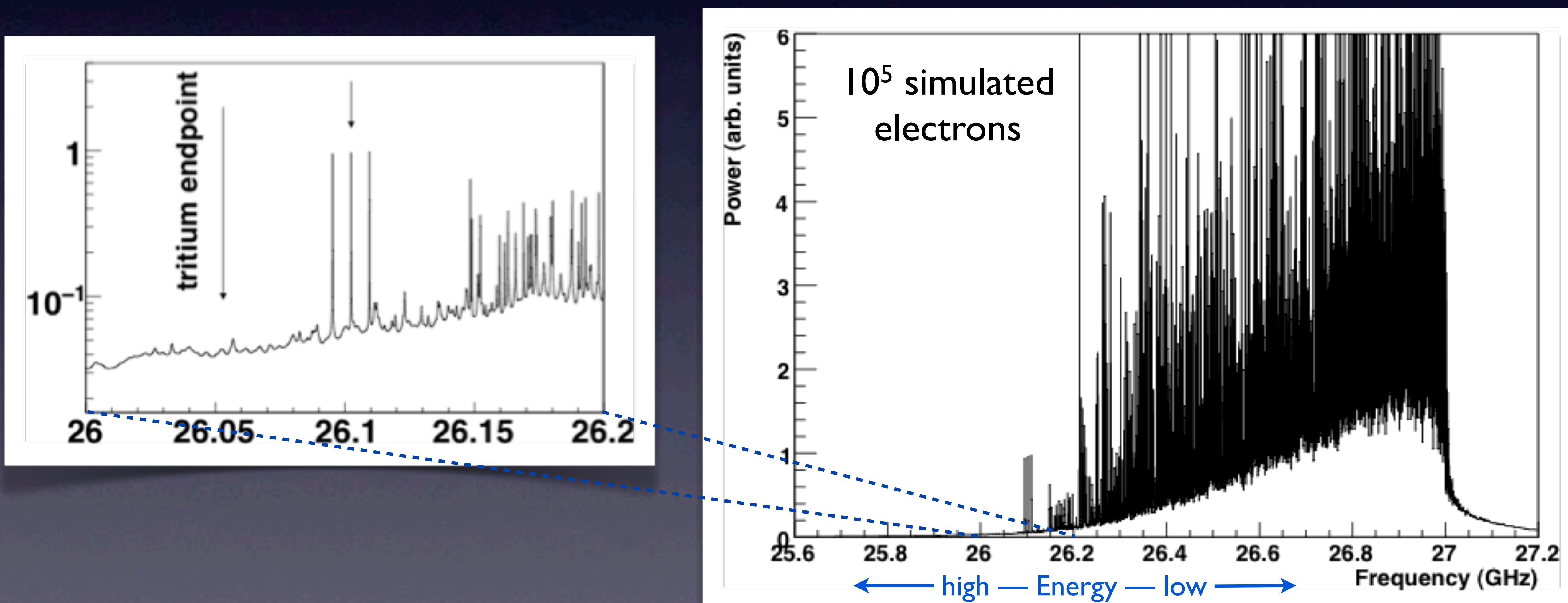
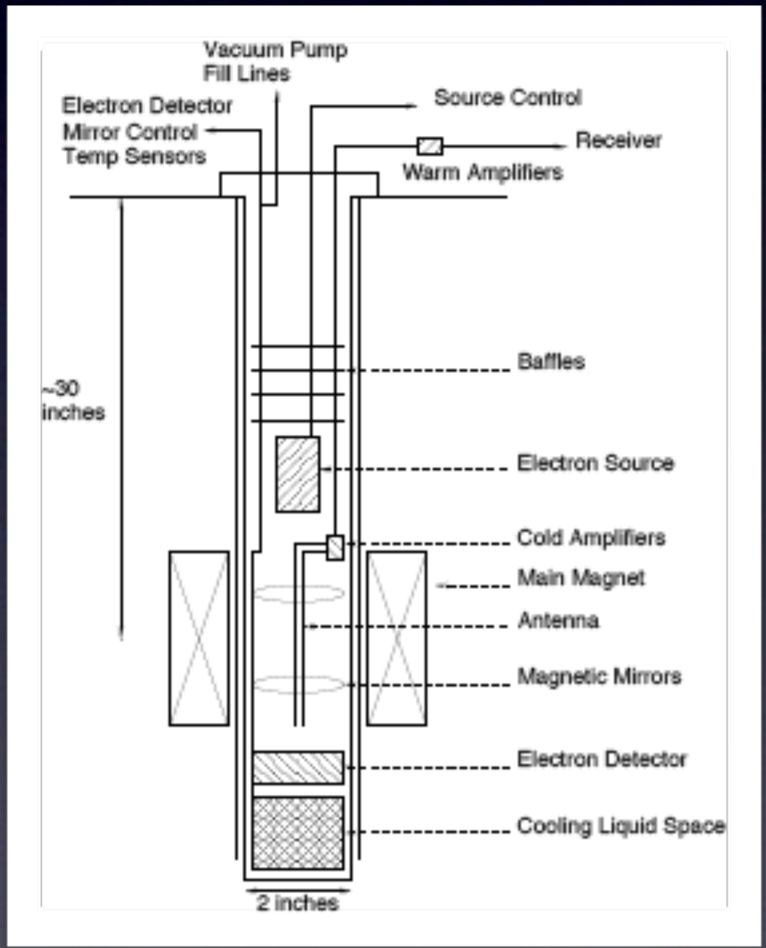


A Few Comments

- Some of the difficulties of a spectrometer-type measurement are avoided
  - Source size scales with the volume
  - The full differential spectrum is available
- New uncertainties will be thoroughly investigated
  - A low gas density is needed to reduce scattering
  - Magnetic homogeneity can be studied with calibrations and direct measurements

Demonstrating the Technique

- The technique appears to be feasible, but many aspects need to be demonstrated
- A prototype is being built at UW
- There are several questions to answer
  1. Can we detect the signal?
  2. What is the resolution of the technique?
  3. Can we measure the ^{83m}Kr spectrum?



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Summary and Outlook

- Tritium beta decay provides a model-independent way to study the neutrino mass scale
- KATRIN will achieve a sensitivity of m_ν < 200 meV
- KATRIN commissioning is ongoing and the system will be fully integrated by 2012
- Project 8 aims to use cyclotron radiation to non-destructively measure the electron energy
- A prototype is under construction to investigate the feasibility of this technique
- With KATRIN, MARE, and Project 8, there will definitely be exciting results for the study of the neutrino mass scale in the near future