The Standard Model and Beyond

(probing new physics with beta decay measurements)

Short Baseline

Neutrino Workshop

J.A. Formaggio

Massachusetts Institute of Technology

Status of neutrino masses

(Summary)

Beta decay measurements

(KATRIN)

Physics beyond the Standard Model

(sterile neutrinos and relic over-density)

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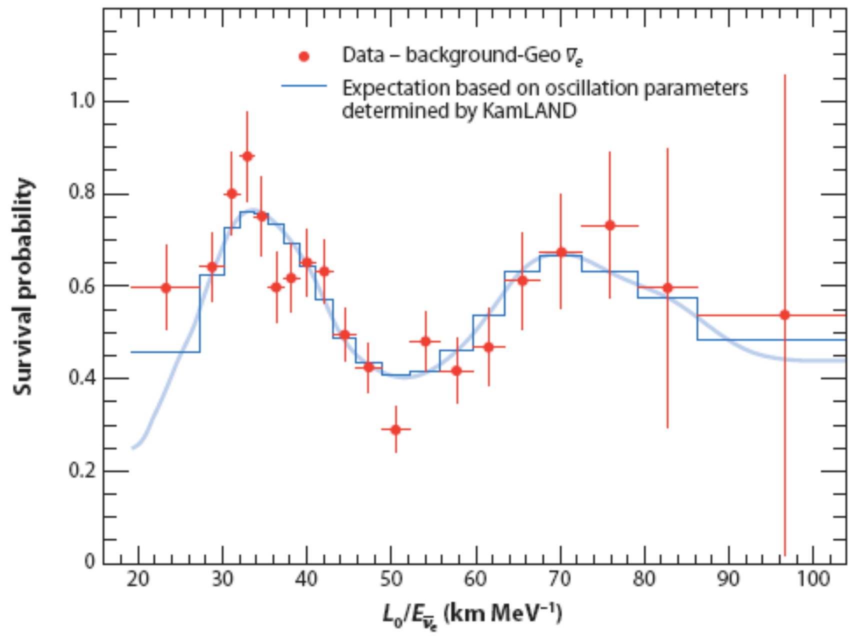
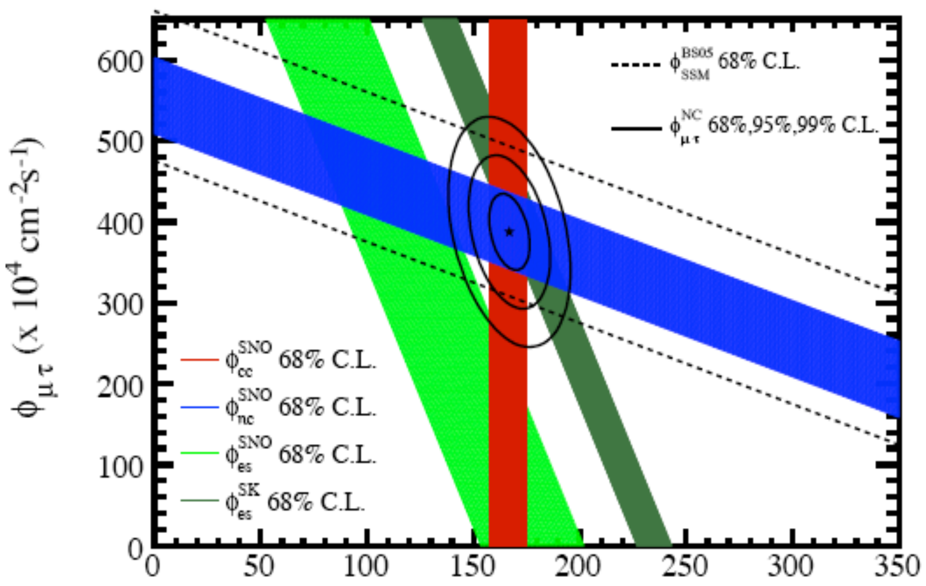
Body of Evidence



Reactor

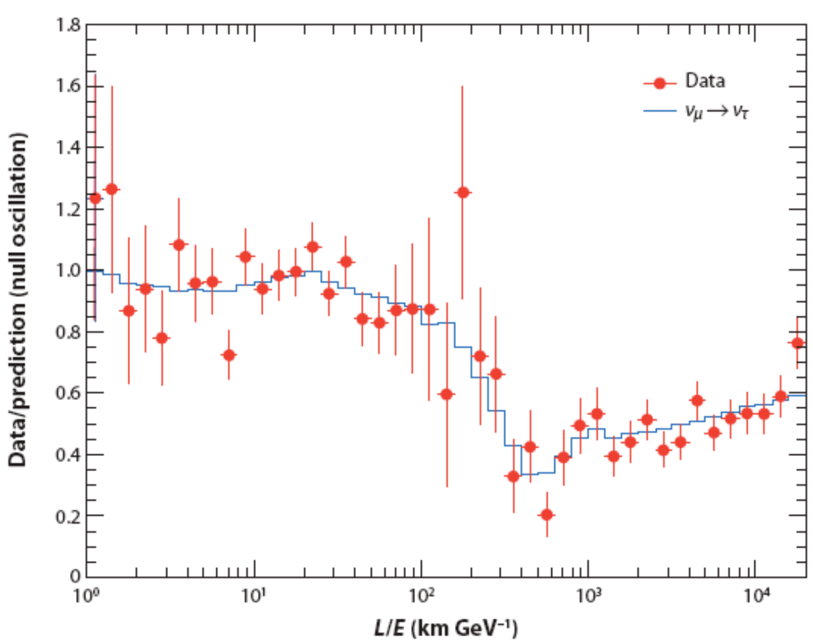
$$\sin^2(2\theta_{13}) < 0.19 \quad (90\%\ \text{C.L.})$$



Solar

$$\sin^2\theta_{12} = 0.304^{+0.022}_{-0.016}$$

$$\Delta m^2_{12} = 7.65^{+0.23}_{-0.20} \times 10^{-5}\ \text{eV}^2$$



Atmospheric

$$\sin^2\theta_{23} = 0.50^{+0.07}_{-0.06}$$

$$|\Delta m^2_{31}| = 2.40^{+0.12}_{-0.11} \times 10^{-3}\ \text{eV}^2$$

Camilieri, Lisi, Wilkerson Ann. Rev. 57 (2008).

The phenomena of neutrino oscillations is now firmly established.

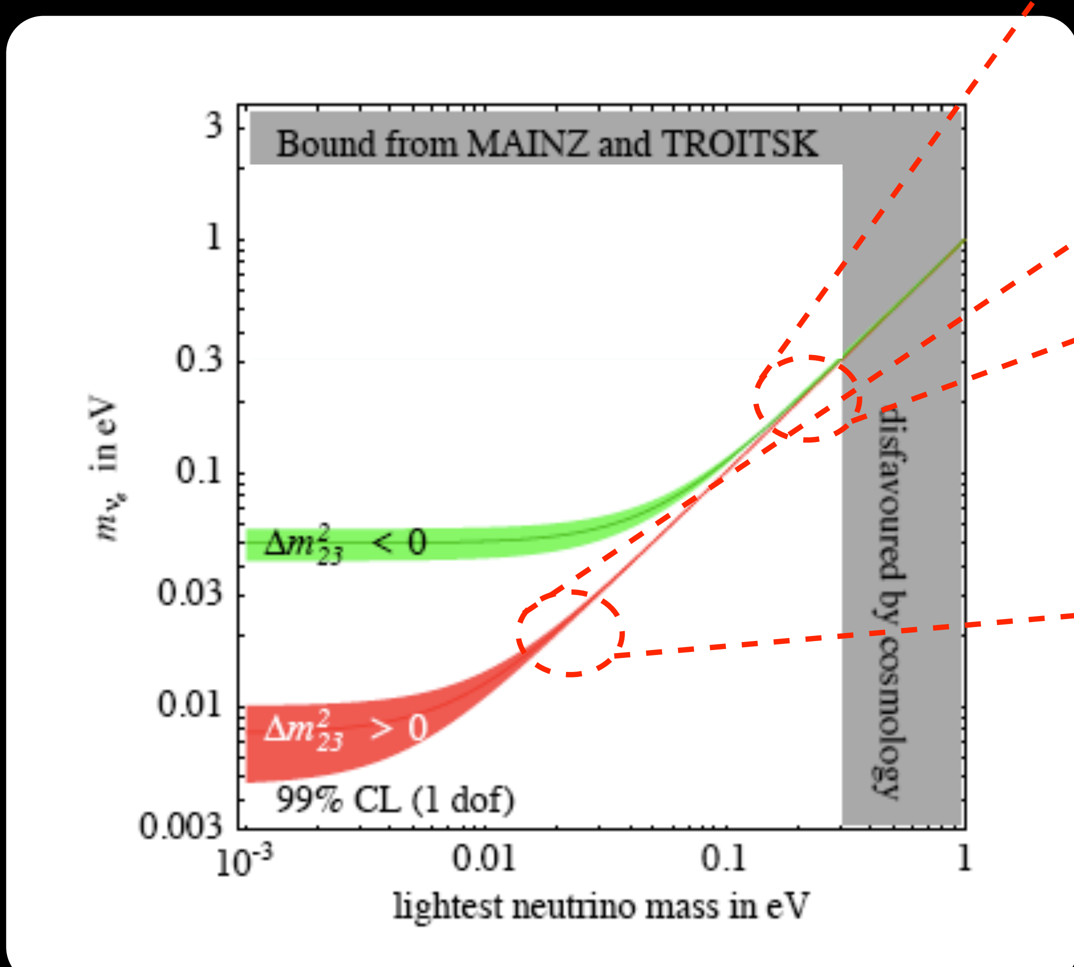
More Questions

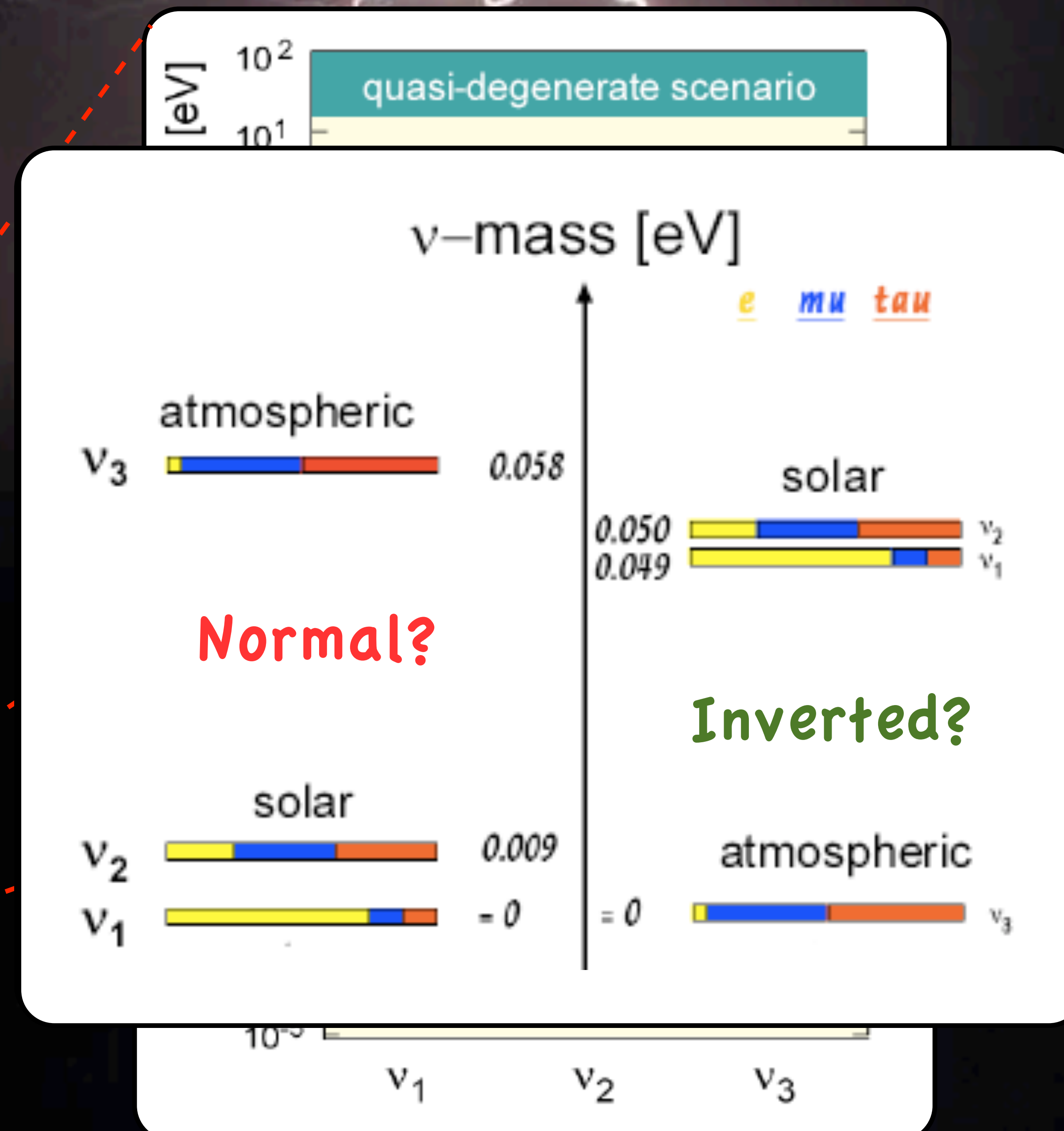
<u>What We Don't Know</u>

(1) What is the absolute scale of neutrinos?

(2) What is the mass hierarchy?

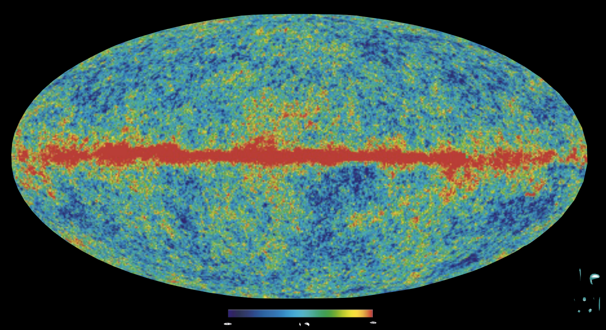
(3) What is the nature of neutrino mass?

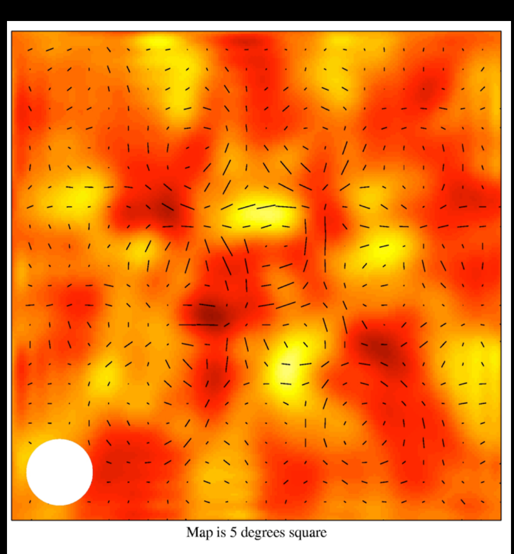




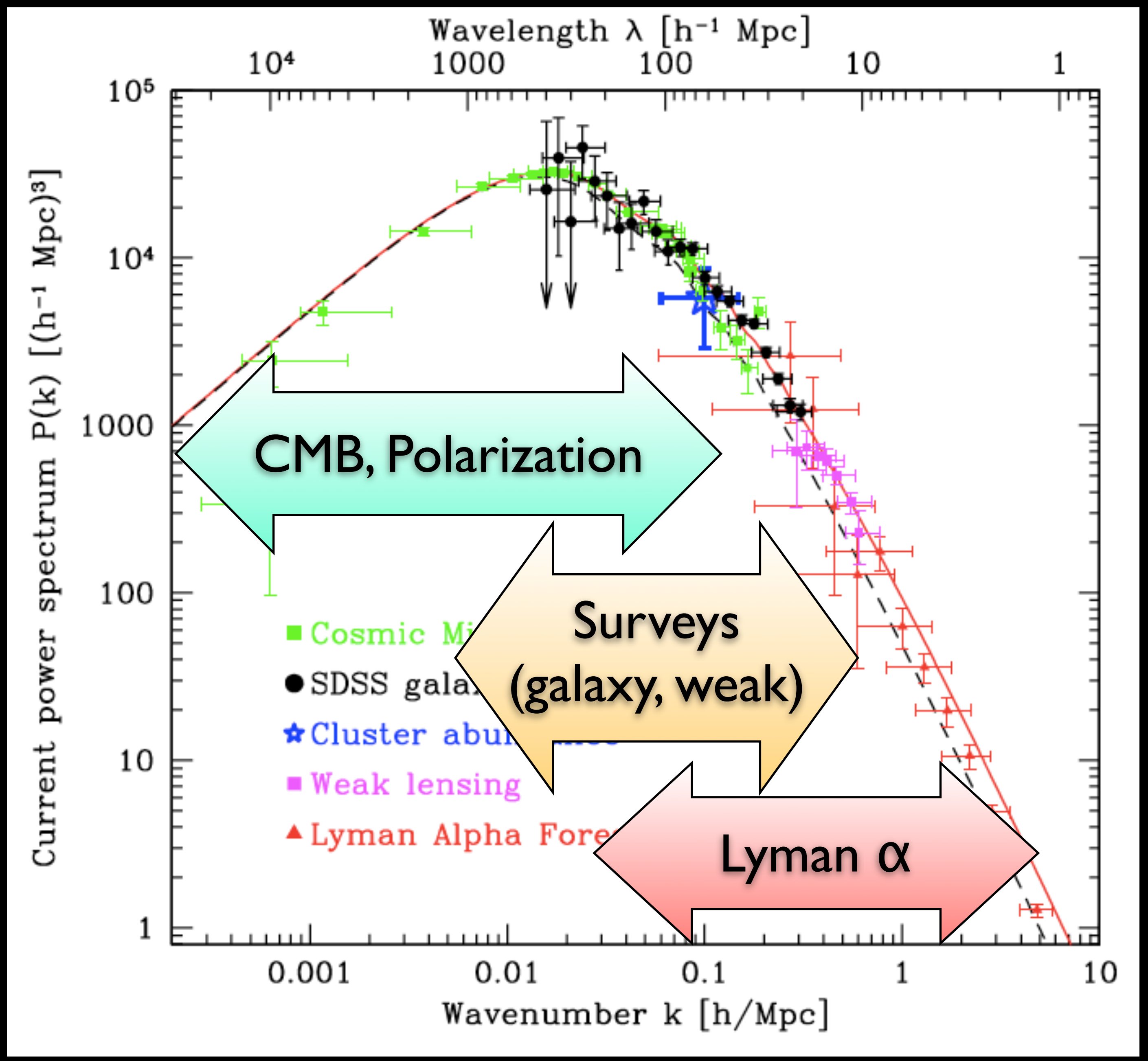
Cosmological Limits

WMAP Temperature Map



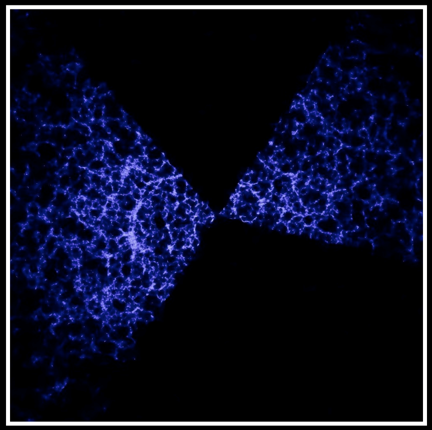


CMB Polarization

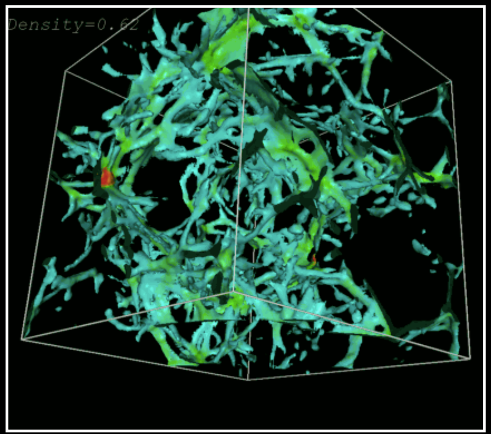


Max Tegmark, 2005

Galaxy Surveys



Weak lensing

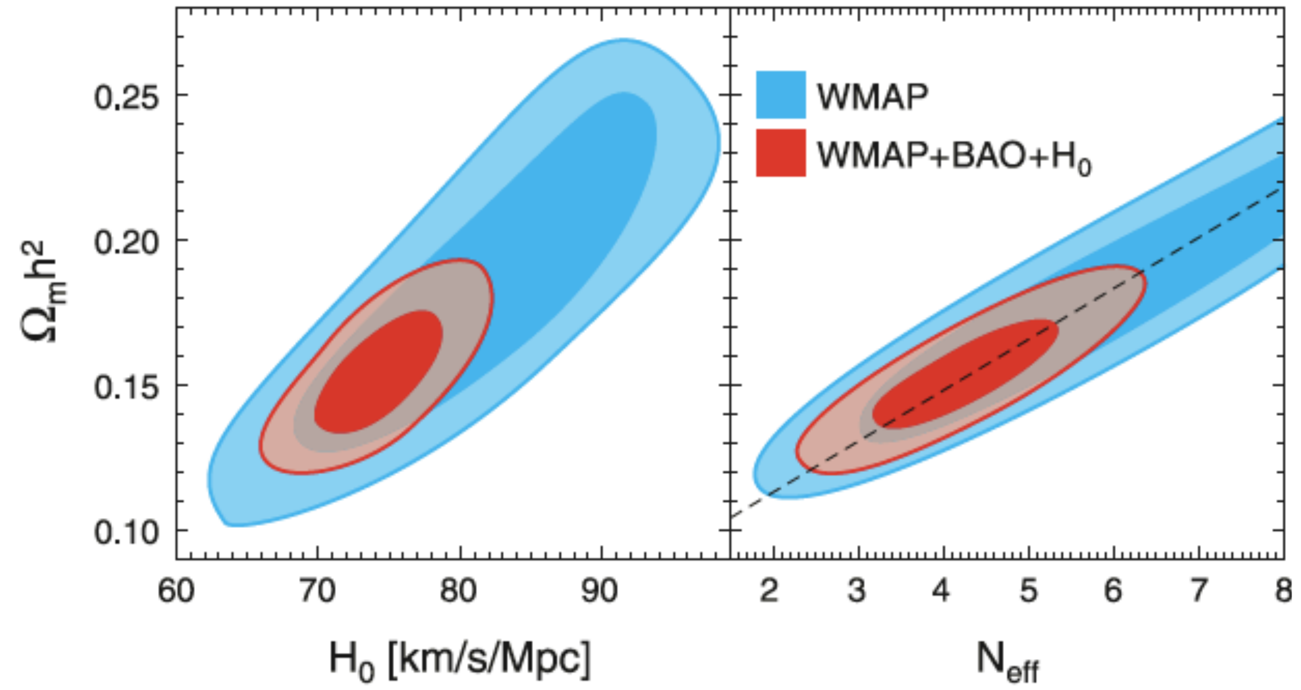


Lyman α

Current Limits

- Limits for neutrino masses depend in part on:
  - Which data is used, and...
  - ...what assumptions are made.

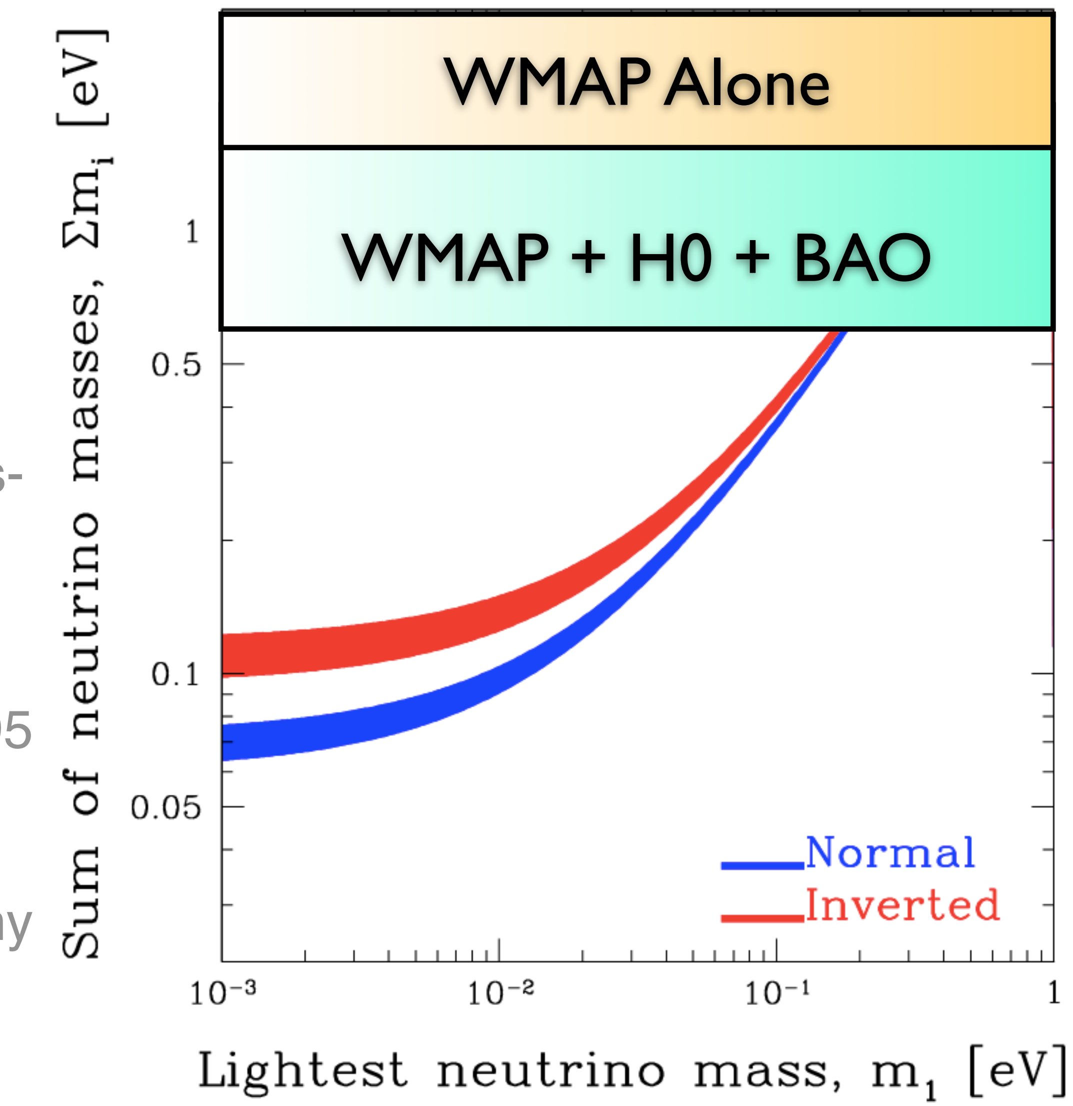
Set	$w = -1$	$w \neq -1$
WMAP 7 only	$\Sigma m_\nu < 1.3$ eV	$\Sigma m_\nu < 1.4$ eV
WMAP7 + BAO + H0	$\Sigma m_\nu < 0.58$ eV	$\Sigma m_\nu < 1.3$ eV
WMAP7 + BAO + SN	$\Sigma m_\nu < 0.7$ eV	$\Sigma m_\nu < 0.9$ eV



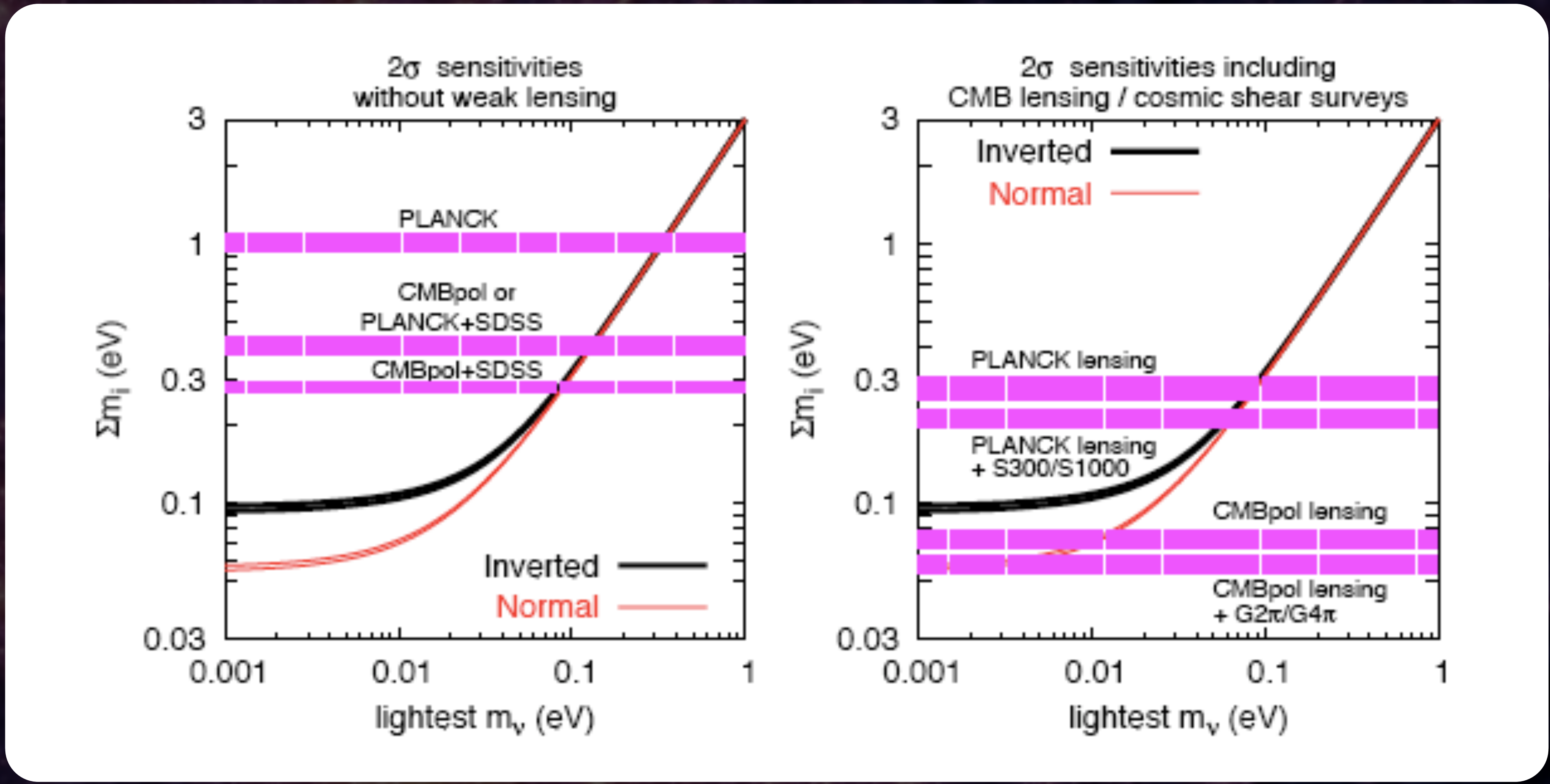
Gonzales-Garcia

arXiv: 1006.3795 v2

(and many others)



Upcoming Data



- Planck alone can push neutrino limits down 1 eV.
- Host of new experiments coming to the forefront.

Probe	Current	Mission	Reach
CMB	1.3 eV	CMBPol	0.6 eV
CMB Lensing	None	CMBPol	0.05 eV
Galaxy Distribution	0.6 eV	LSST	0.1 eV
21 cm	None	SKA	0.05 eV

Status of neutrino masses

(Summary)

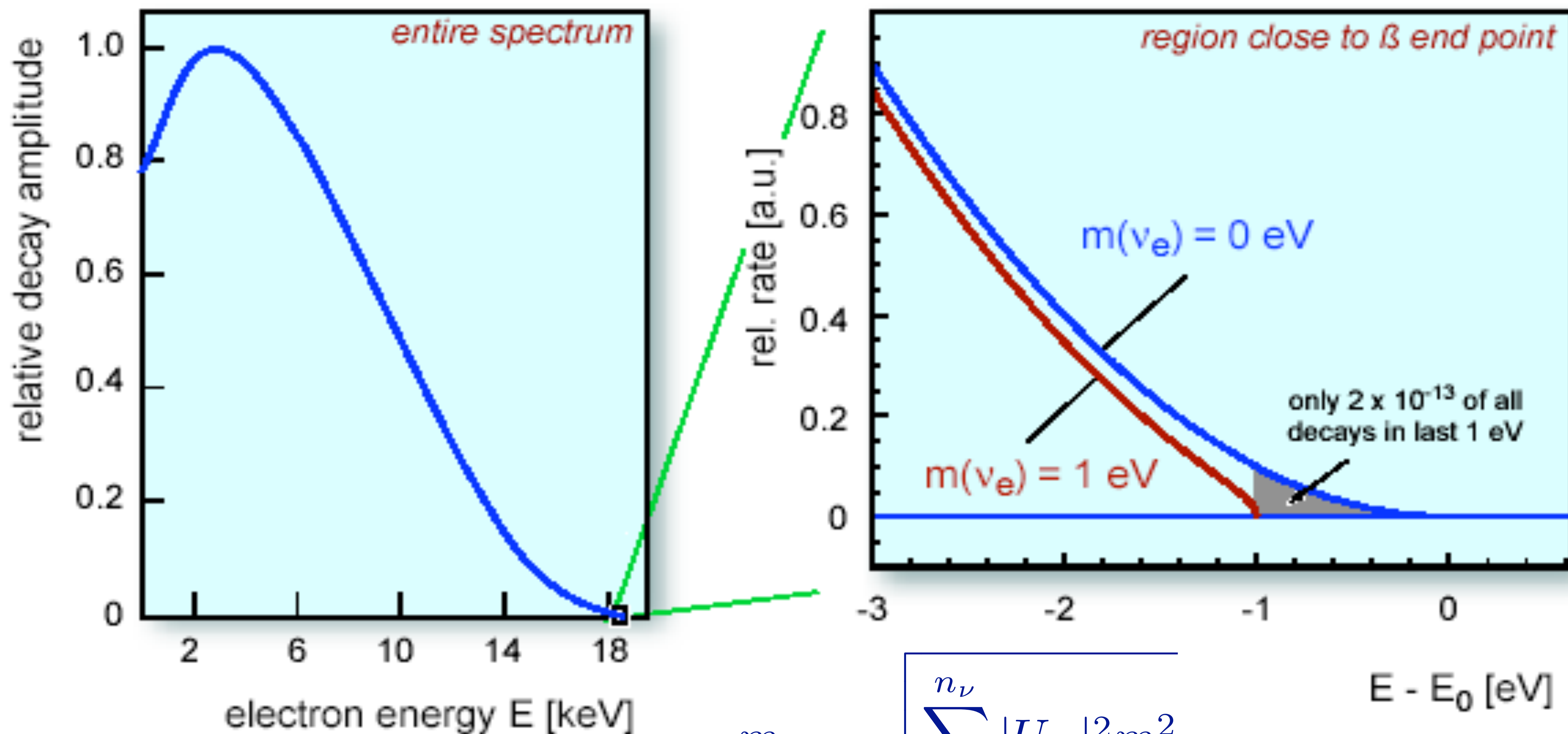
Beta decay measurements

(KATRIN)

Physics beyond the Standard Model

(sterile neutrinos and relic over-density)

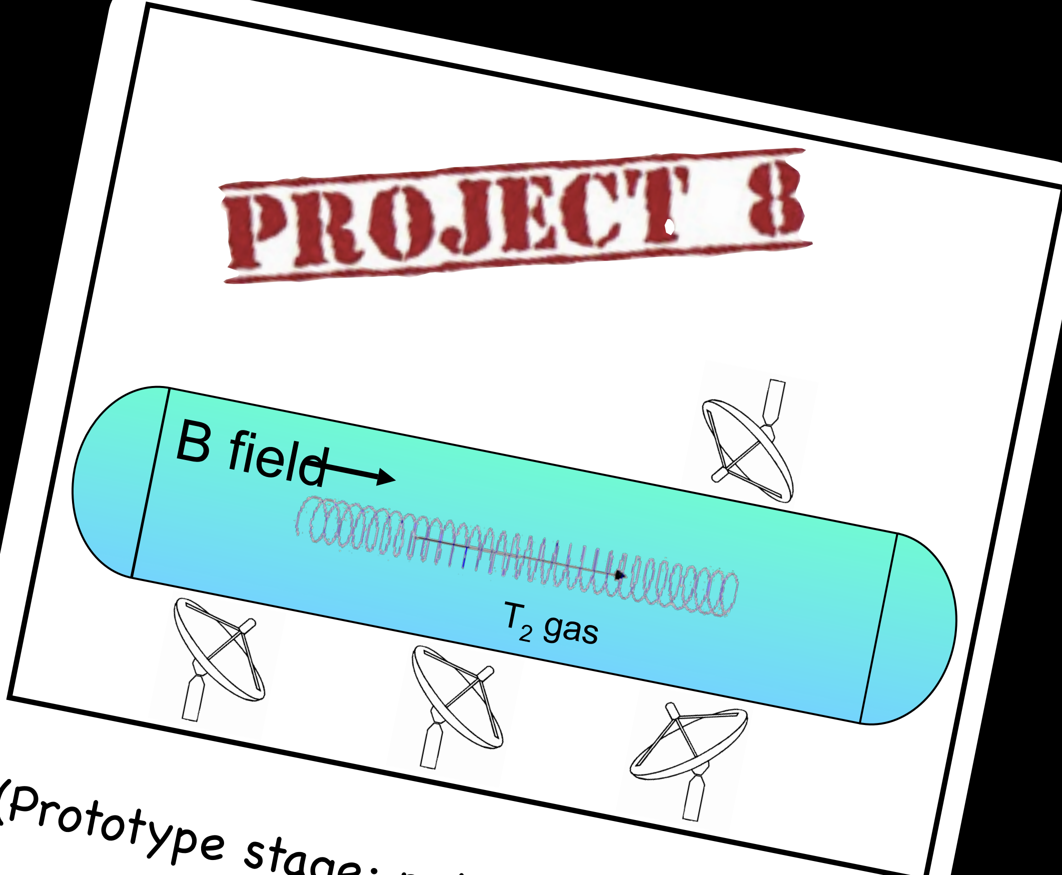
Direct Probes



$$m_\beta = \sqrt{\sum_{i=1}^{n_\nu} |U_{ei}|^2 m_i^2}$$

Beta decay allows a *kinematic* determination of the neutrino mass

No dependence on cosmological models or matrix elements



(Prototype stage; potentially scalable)


MARE
(Prototype stage)

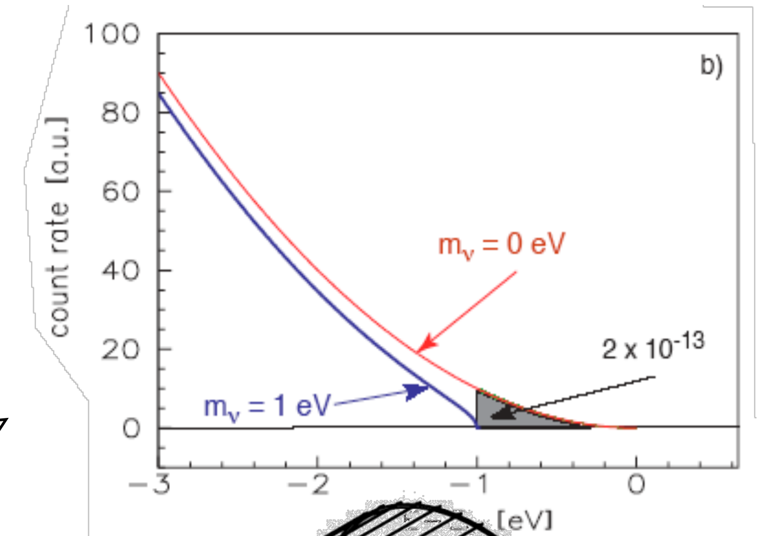

KATRIN
(State-of-the-art; on-going)

KATRIN is currently the prominent experiment for beta decay measurements.

New techniques being explored:

MARE and Project 8

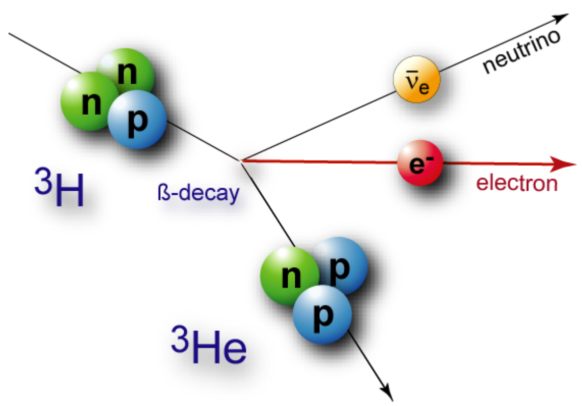
The KATRIN Experiment

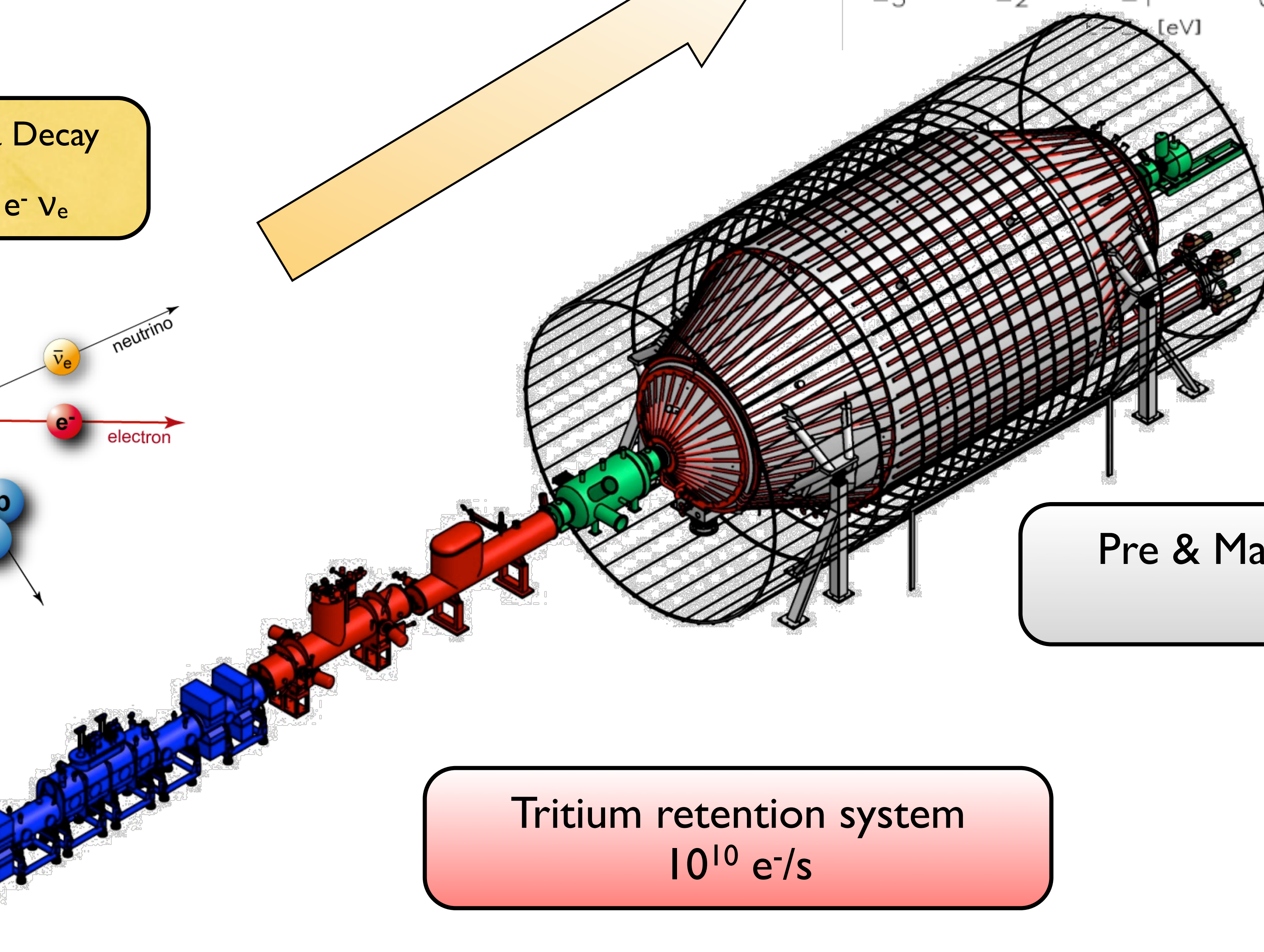


Electron Beta Decay Spectrum

Tritium Beta Decay

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





Detector
1 e⁻/s

Pre & Main spectrometers
10^3 e⁻/s

Tritium retention system
10^{10} e⁻/s

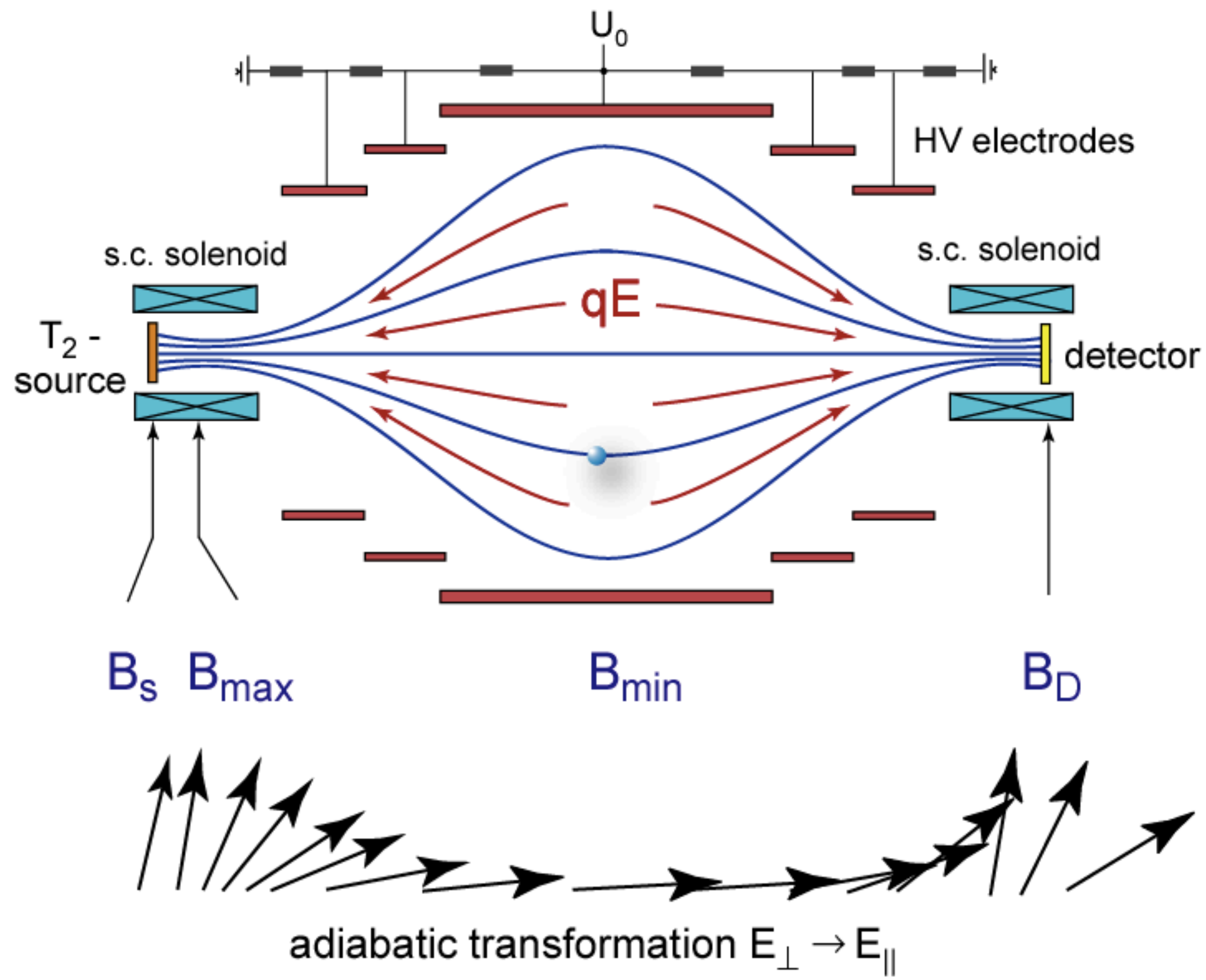
Windowless Gaseous Tritium Source
5×10^{19} T_2/s

MAC-E Filter Technique

KATRIN

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

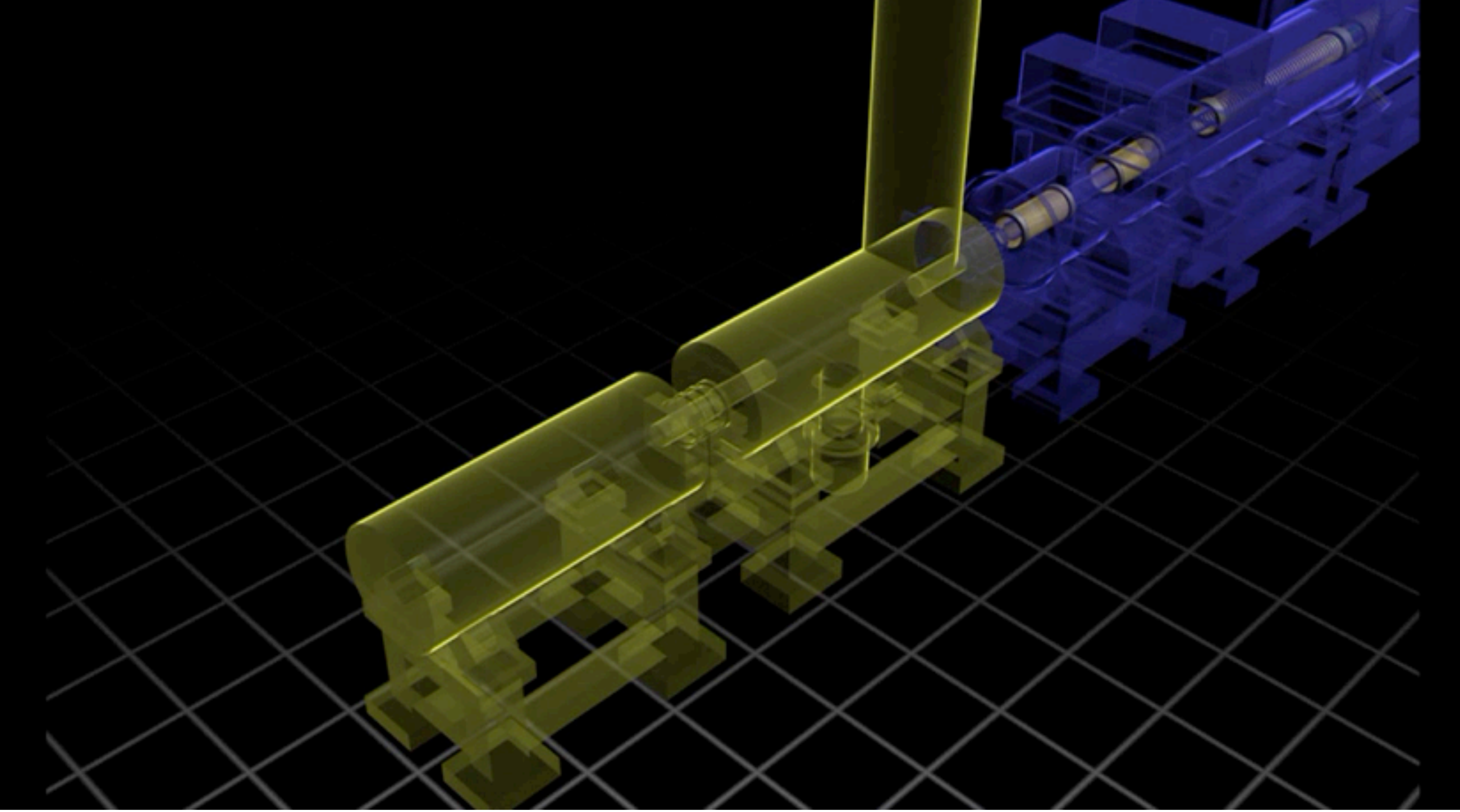
Spectroscopic: MAC-E Filter

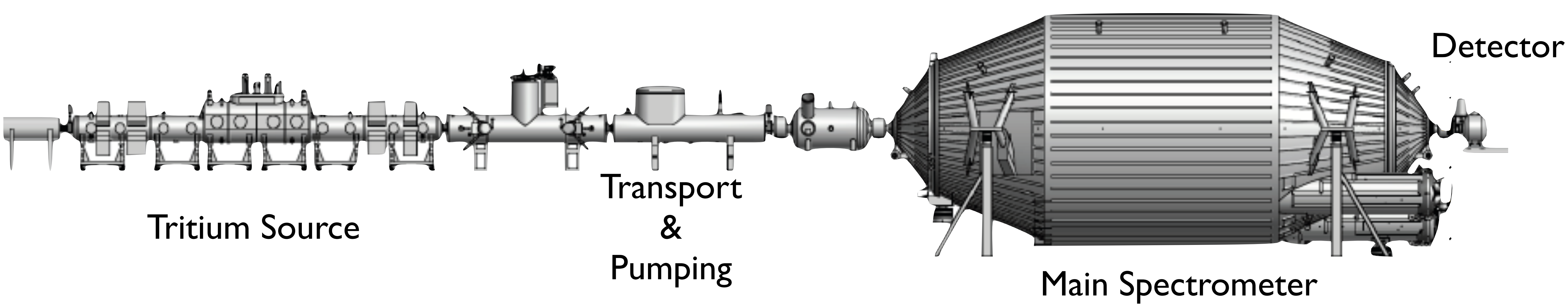


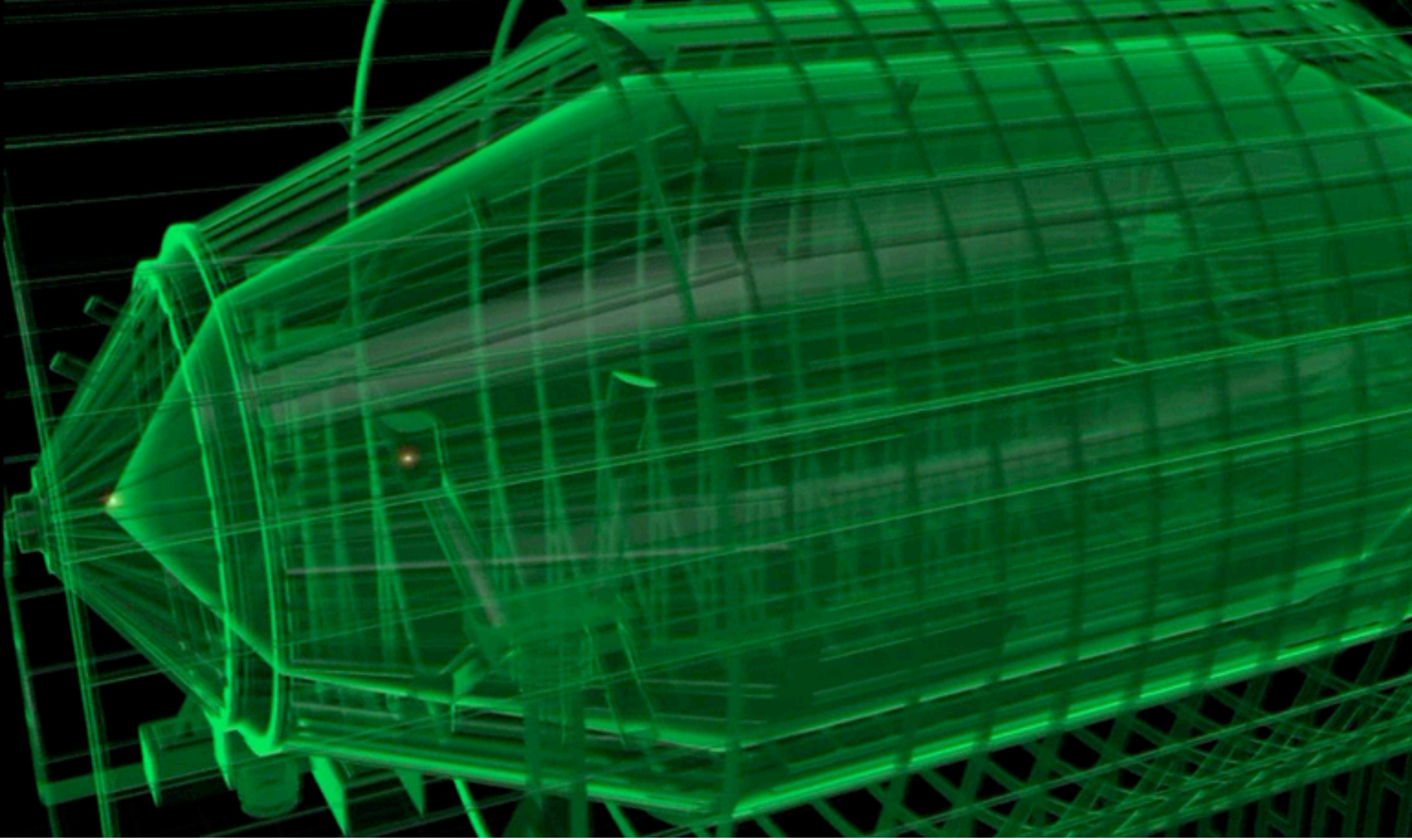
Inhomogeneous magnetic guiding field.

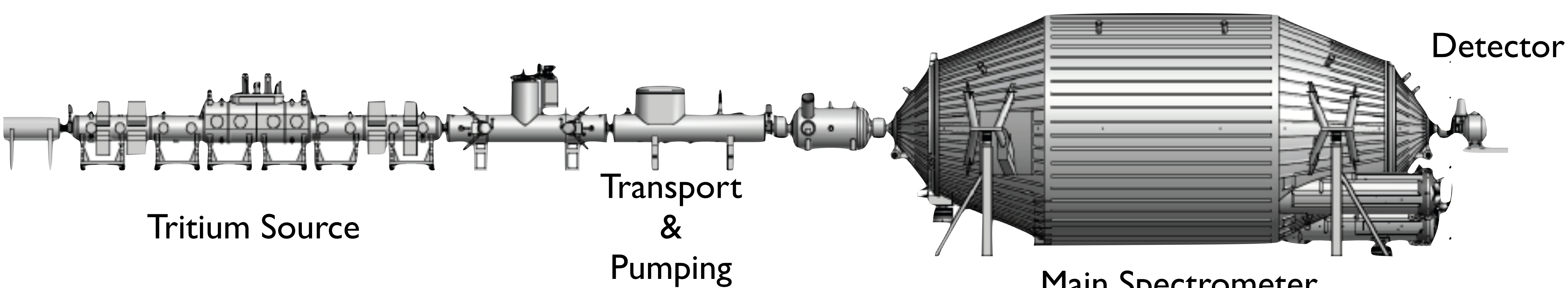
Retarding potential acts as high-pass filter

High energy resolution ($\Delta E/E = B_{min}/B_{max}$ = 0.93 eV)

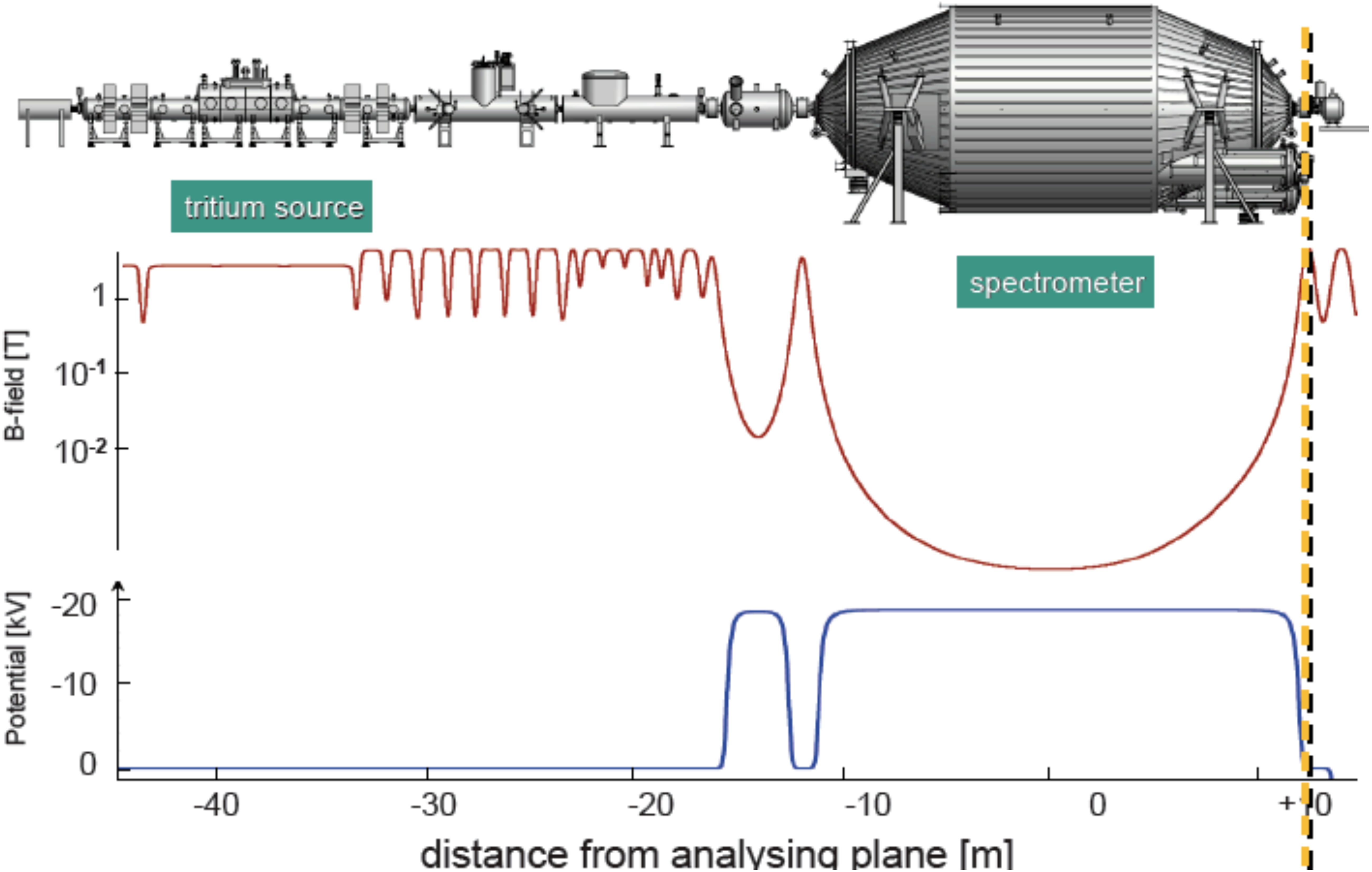



Detector
Transport
&
Pumping
Tritium Source
Main Spectrometer

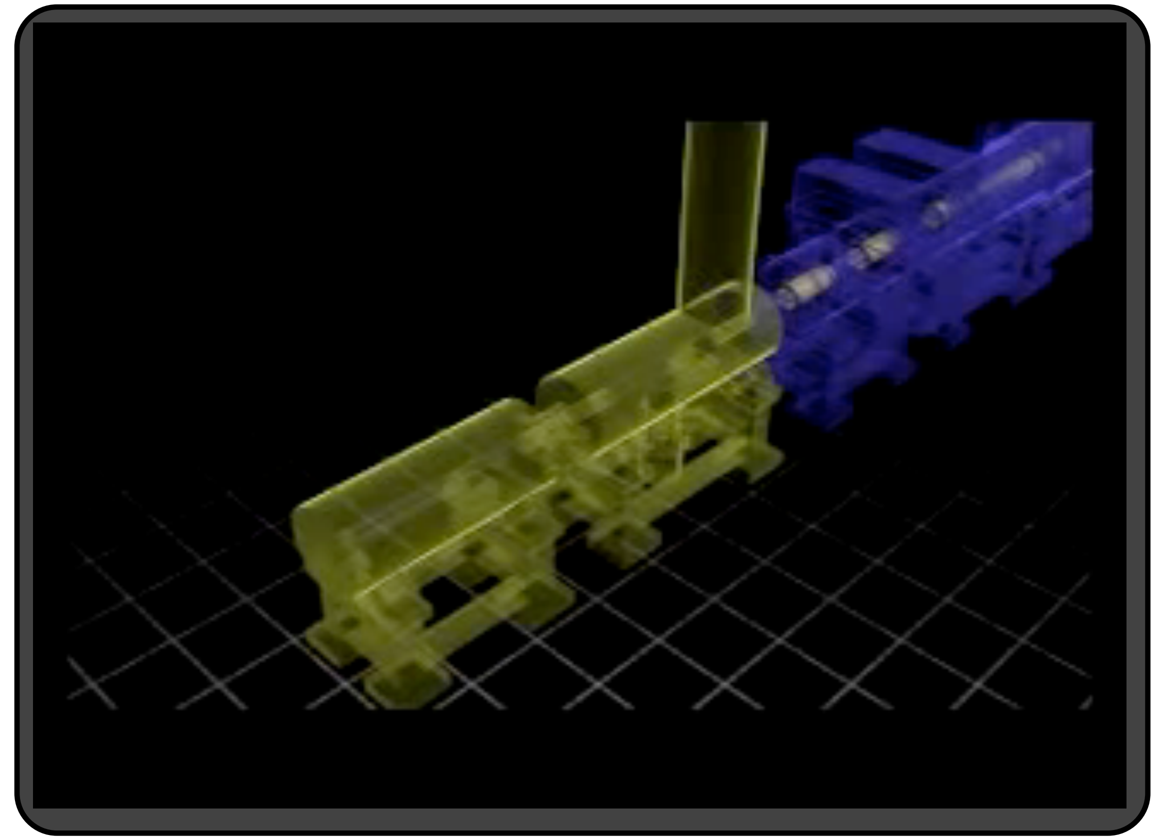



Detector
Transport
&
Pumping
Tritium Source
Main Spectrometer

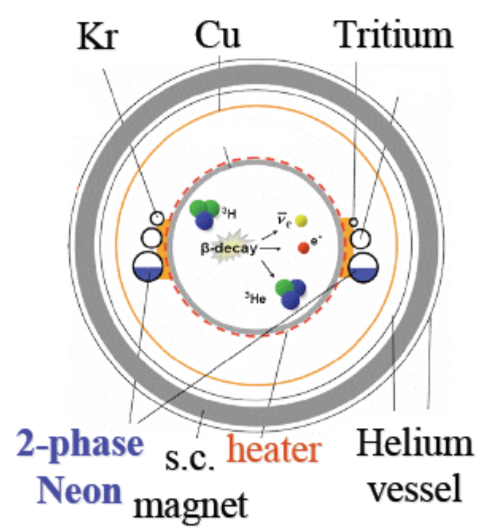
Electromagnetic Fields



The Windowless Gaseous Tritium Source (WGTS)

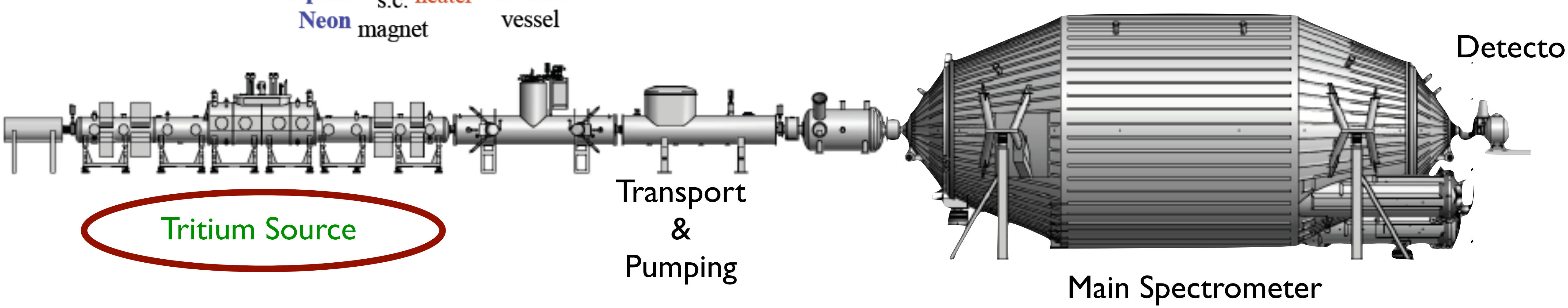


- Gaseous tritium source provides source of beta-decay electrons.
- Use of injection + differential pumping to provide well-controlled gas column density.
- In-situ monitoring of purity of gas via laser Raman spectroscopy.



T_2 Specifications

• Tritium activity:	1.7×10^{11} Bq
• Tritium throughput:	40 g T_2/day
• Temp. stability	$\pm$ 0.03 mK @ 27K
• Electron flux:	10^{11} β/s
• Column Density:	5×10^{17} cm^{-2}



Demonstrator

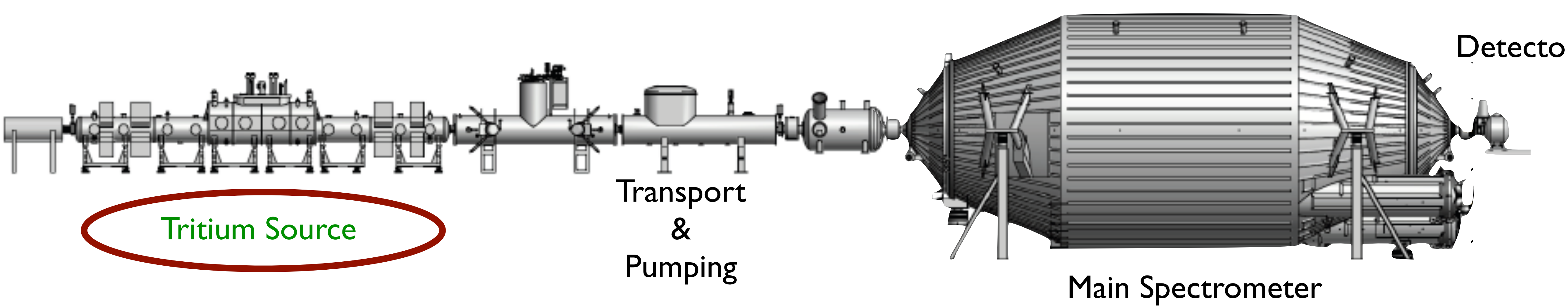
Solenoid testing

Recent milestone:

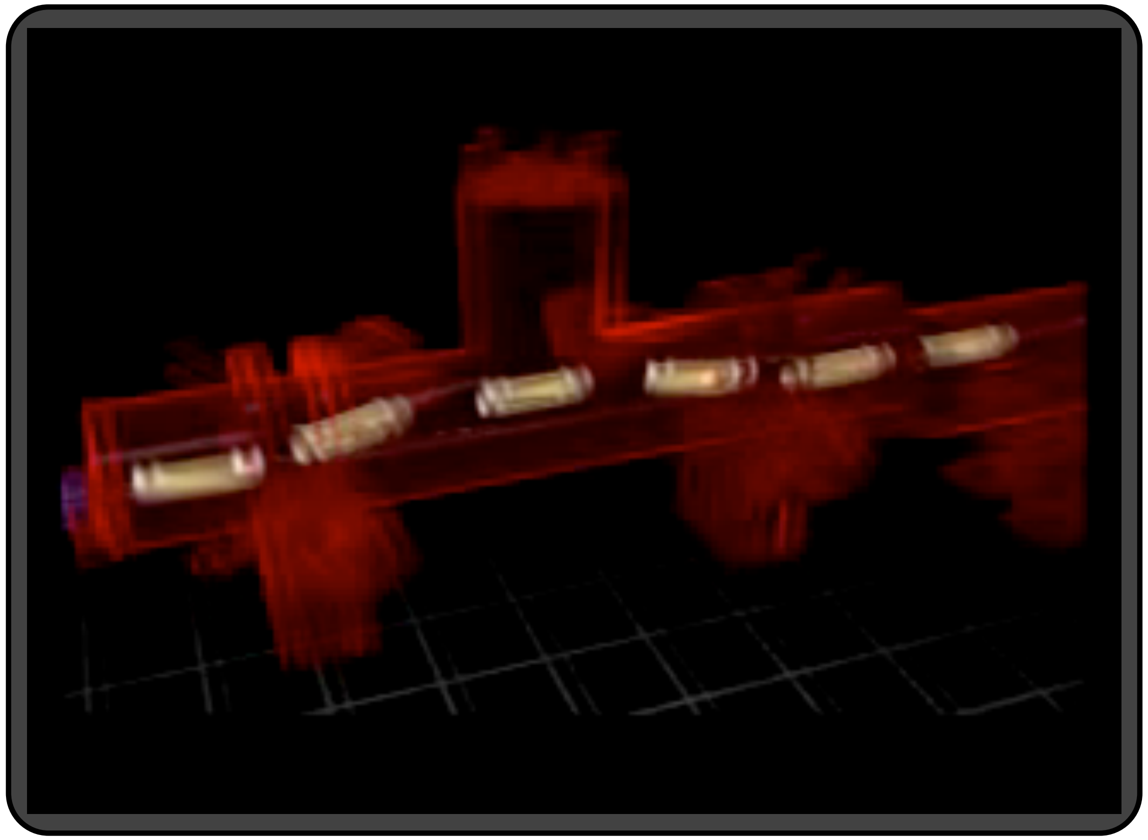
Demonstrator achieves

27 ± 0.03 K neon stability

Beam alignment (< 0.5 mm)



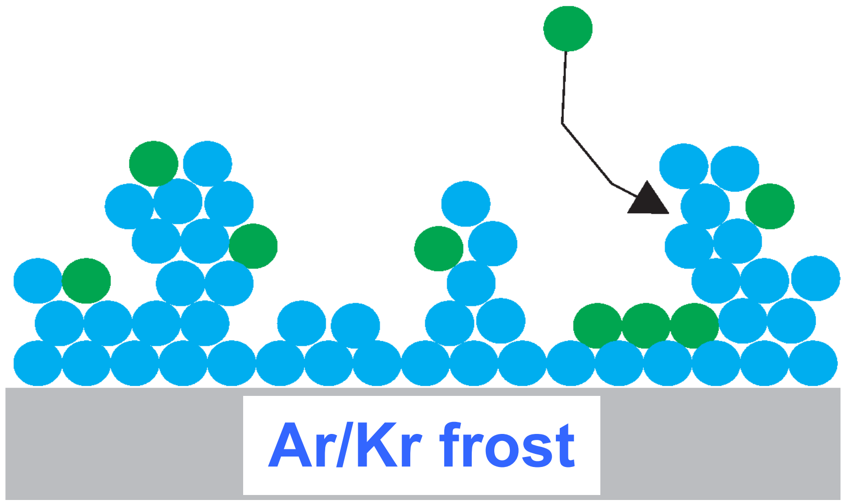
Tritium Retention Systems

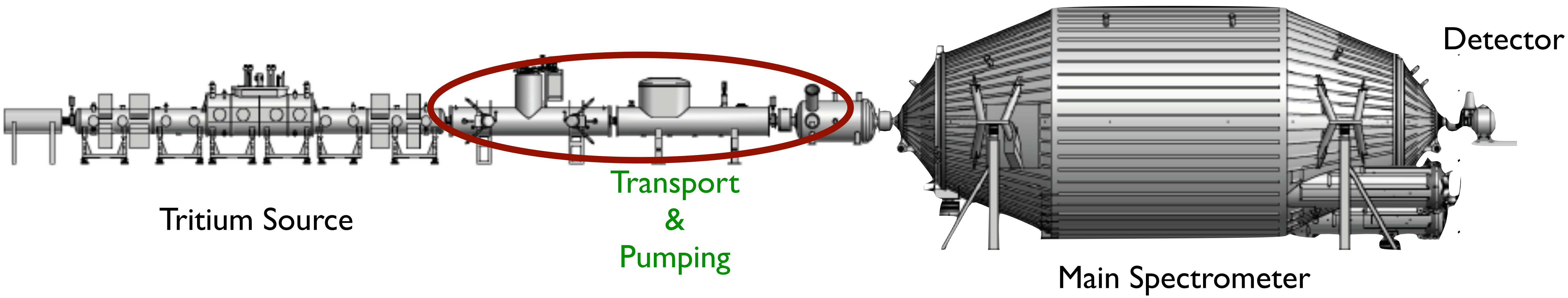


Includes both differential and cryo-absorption pumping systems.

The differential pumping system's goal is to reduce tritium flow to less than 10^{-14} mbar l/s (factor of 10^{7} reduction!)

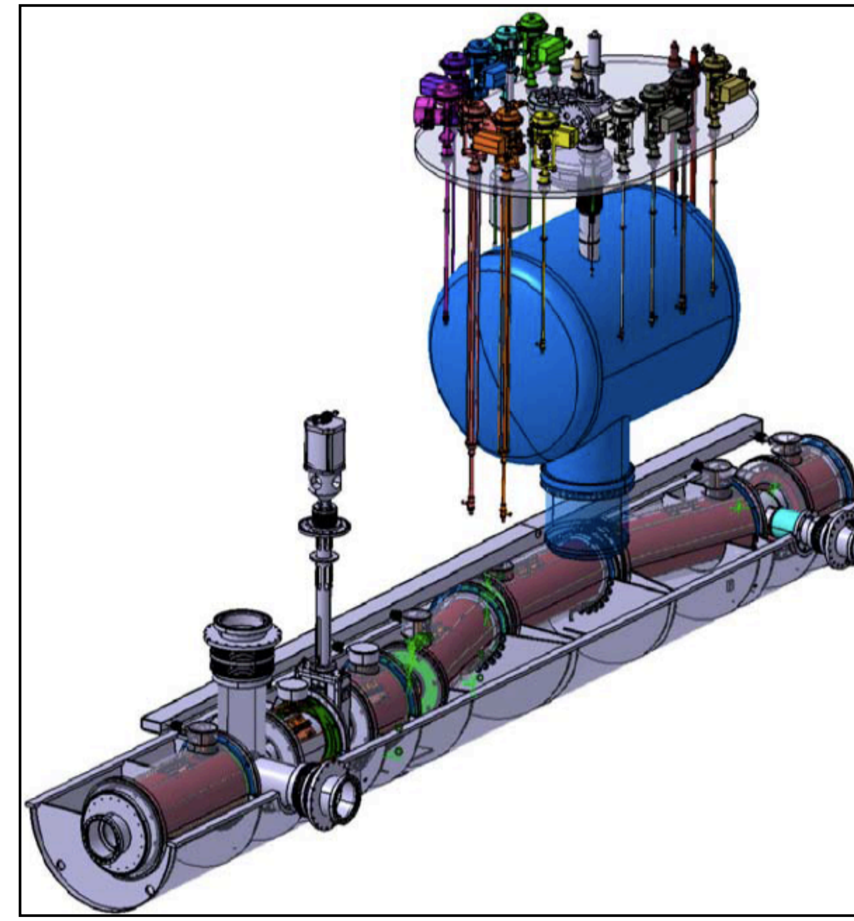
Cryo-pumping system makes use Ar/Kr frost at 3-4 K to trap residual tritium gas for further 10^{7} reduction.





DPS2-F System

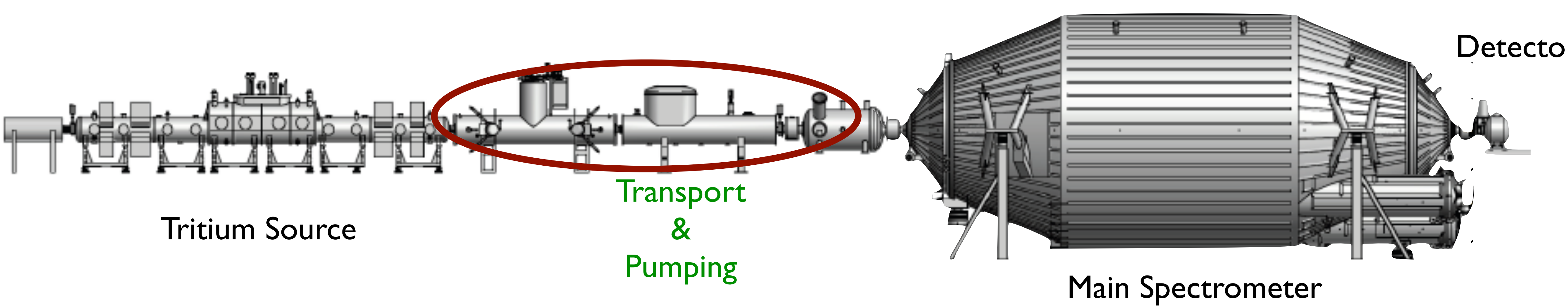
Transport tube



CPS design

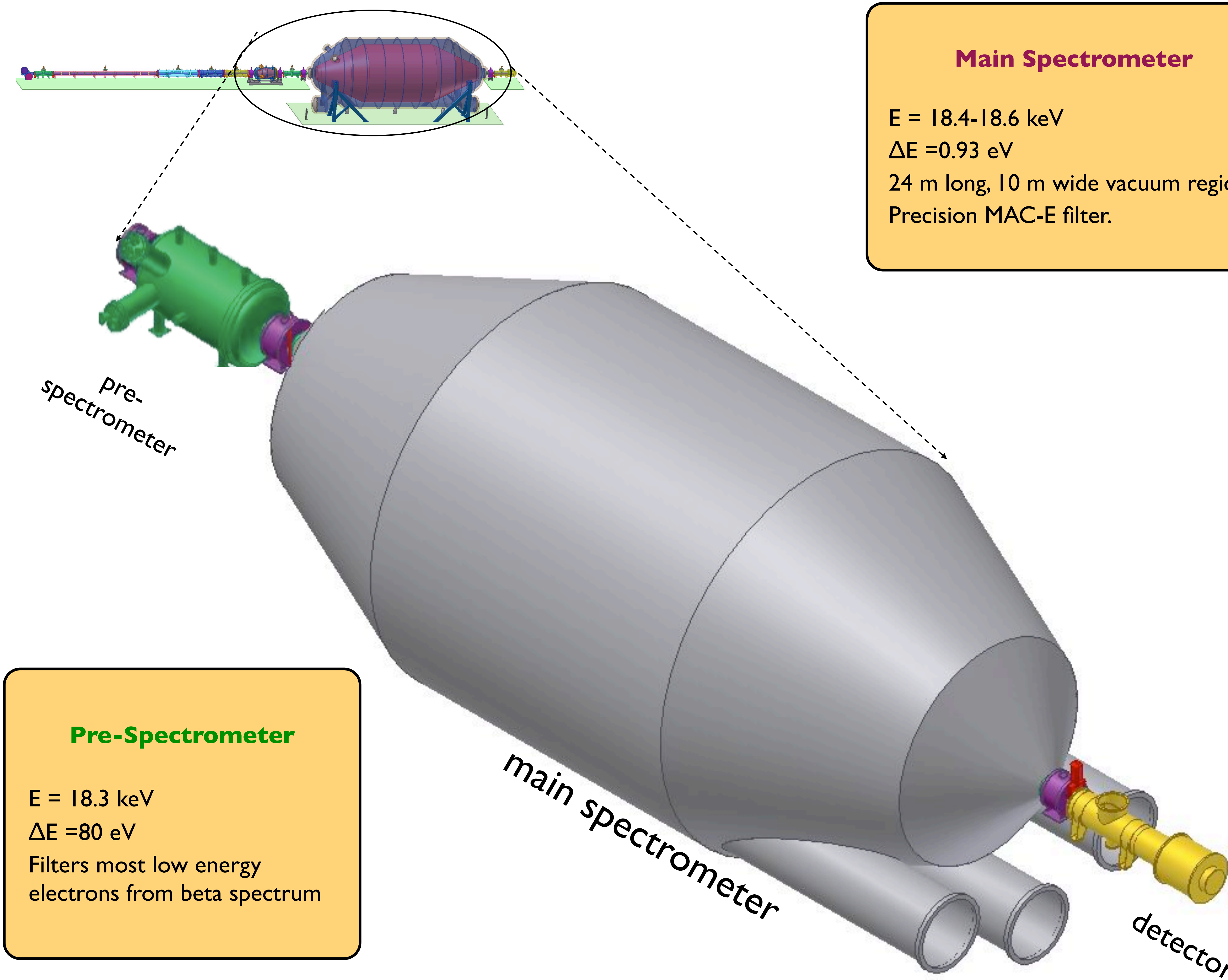
Recent milestones:

Differential pumping system commissioned.



Main Spectrometer

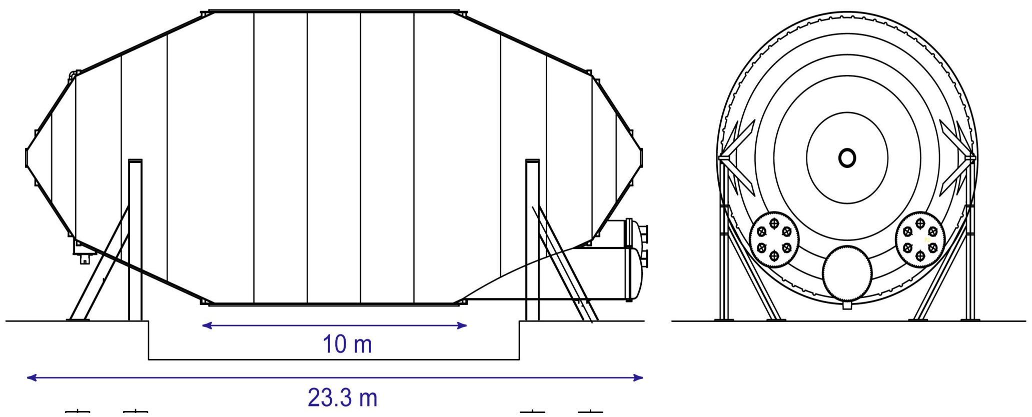
E = 18.4-18.6 keV
ΔE =0.93 eV
24 m long, 10 m wide vacuum region.
Precision MAC-E filter.

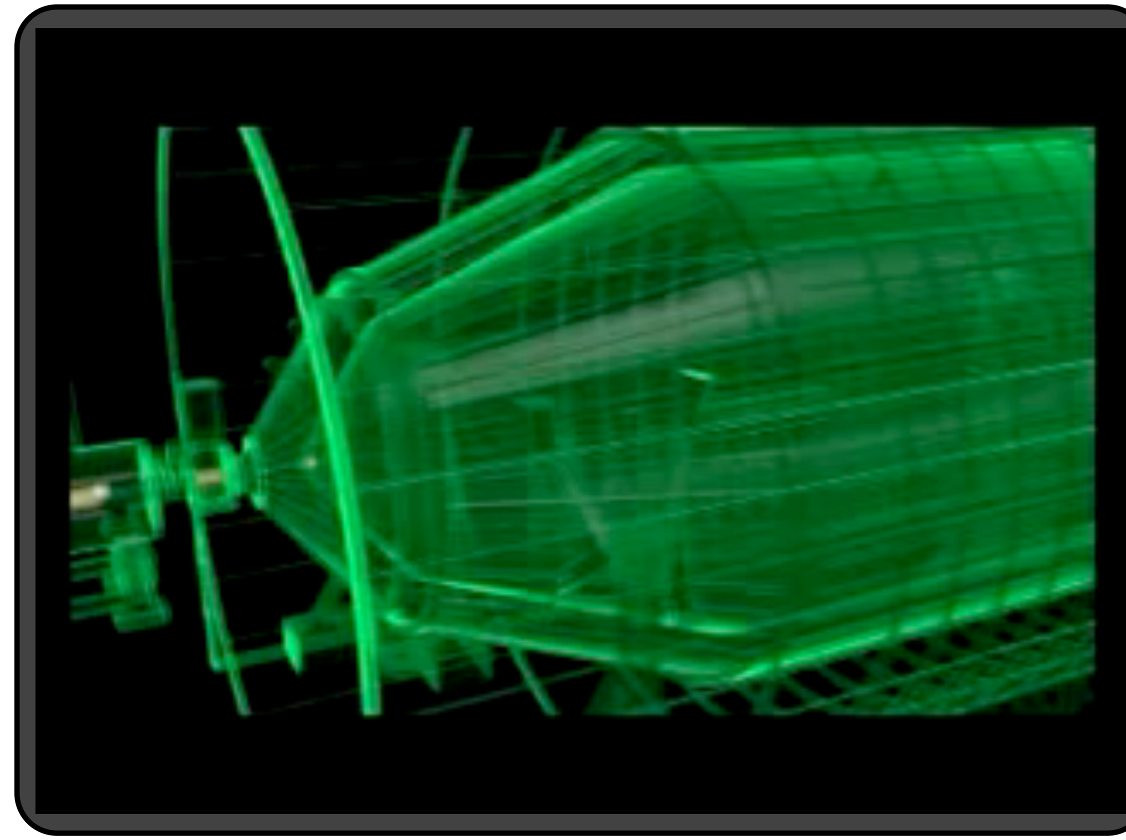


Pre-Spectrometer

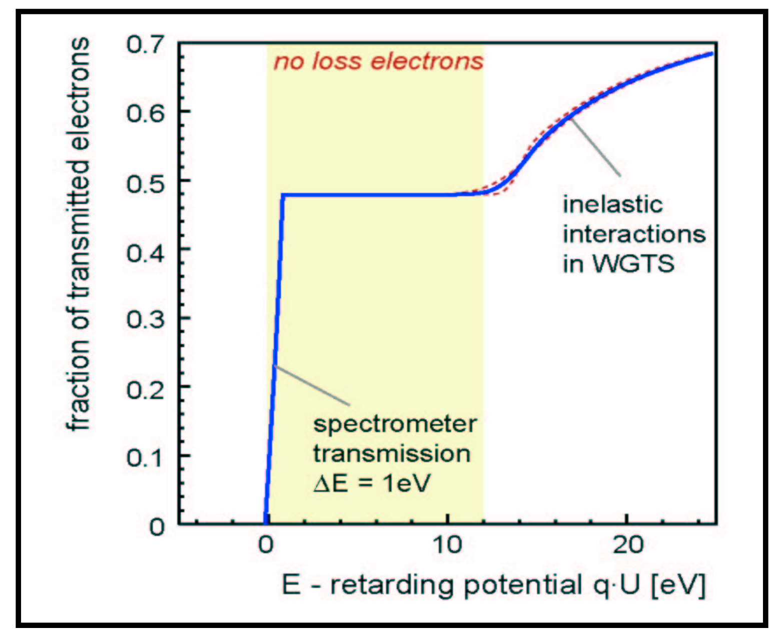
E = 18.3 keV
ΔE =80 eV
Filters most low energy electrons from beta spectrum

The Main Spectrometer



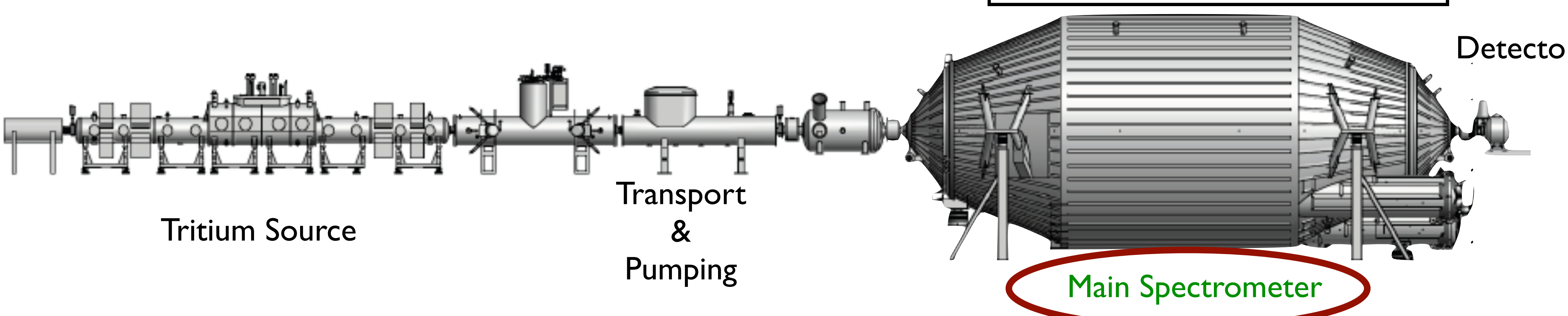


Inner wire electrodes installed for rejection of low energy particles produced from cosmic rays.

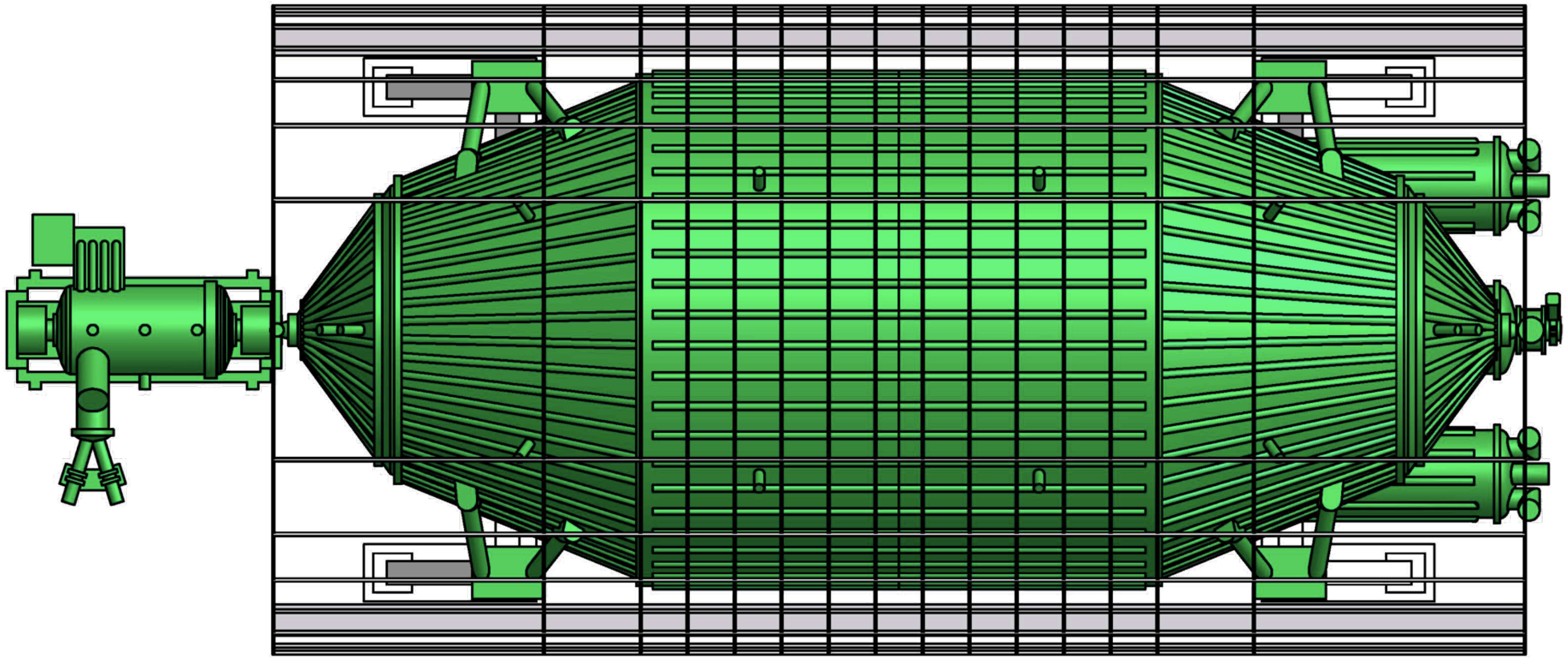


Combination of precision high voltage and low magnetic field with correction air coils.

Inherent resolution of $\Delta E = 0.93$ eV.



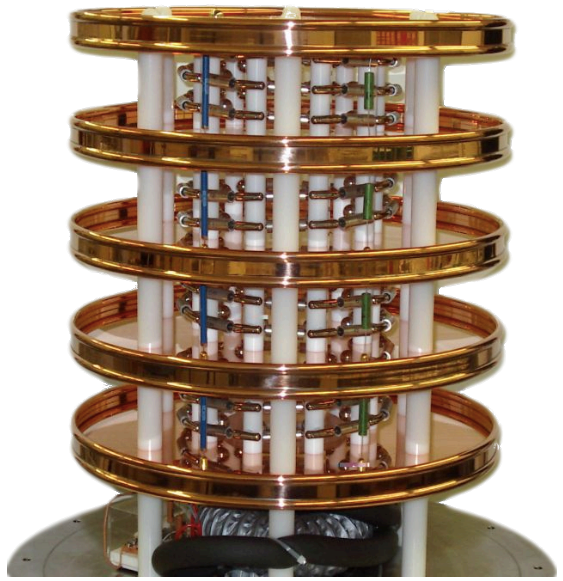
High Voltage Monitoring



KATRIN sensitivity goal requires 60 mV precision at 18.6 kV.

System monitored with high precision HV divider (10^{-6} stability).

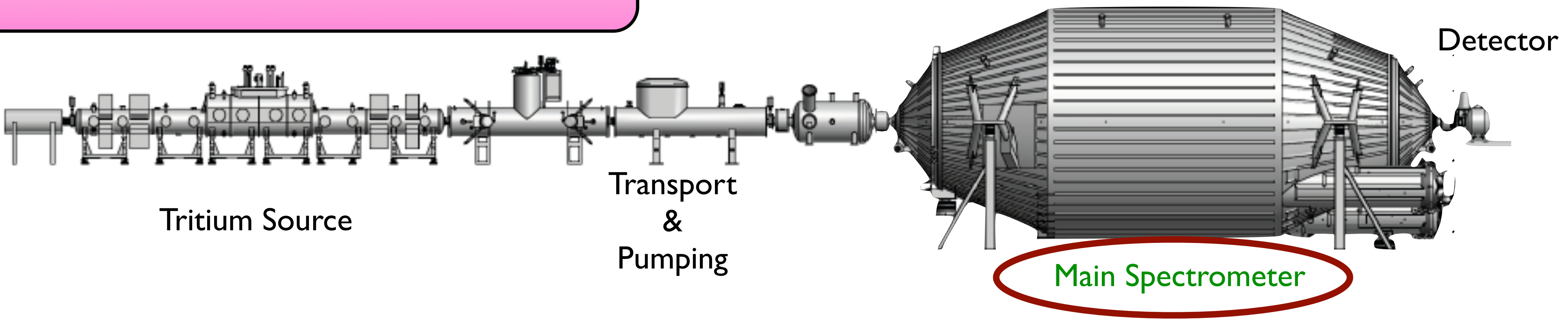
In-situ monitoring of ^{83m}Kr line using refurbished Mainz spectrometer.

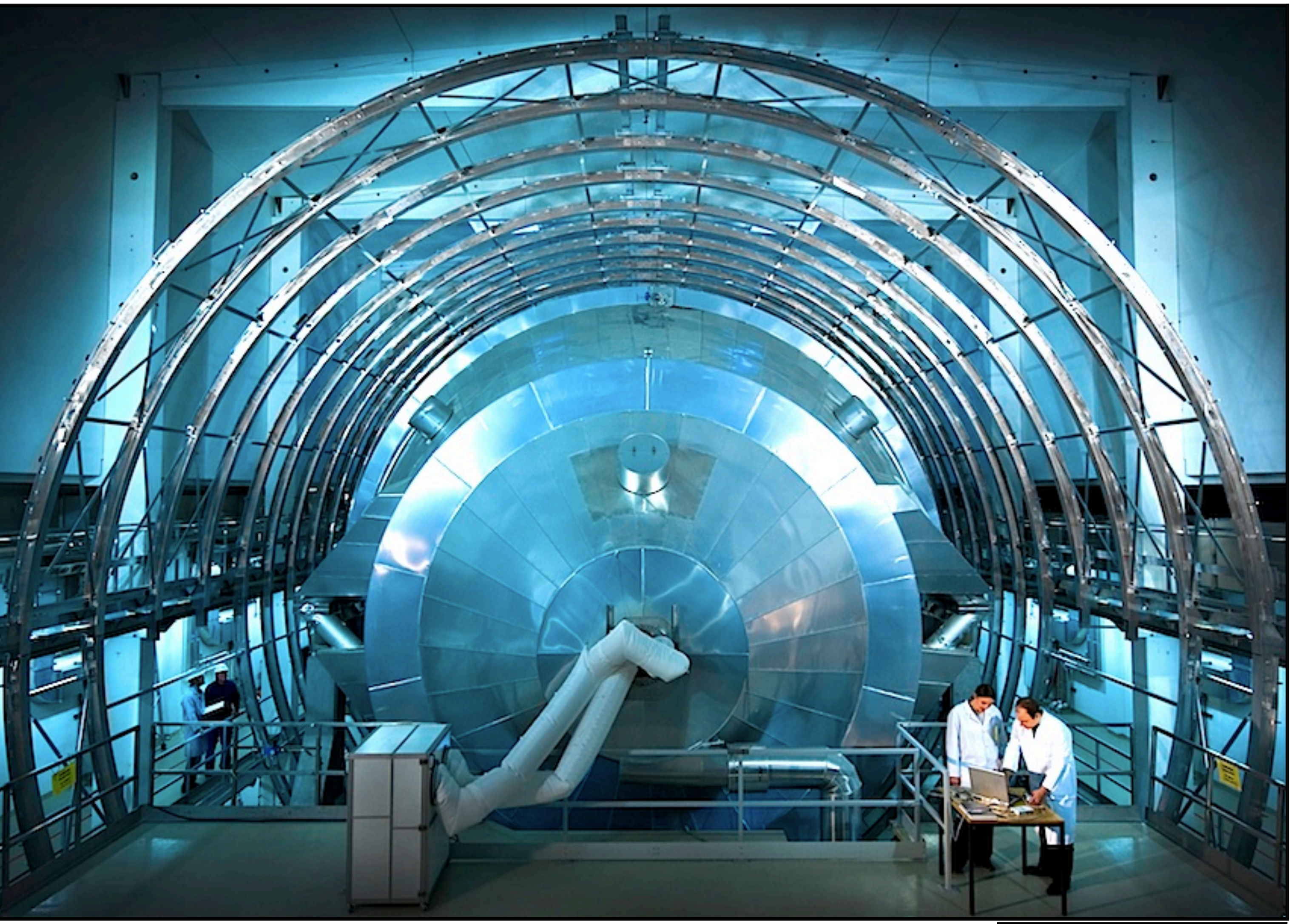


Recent milestones:

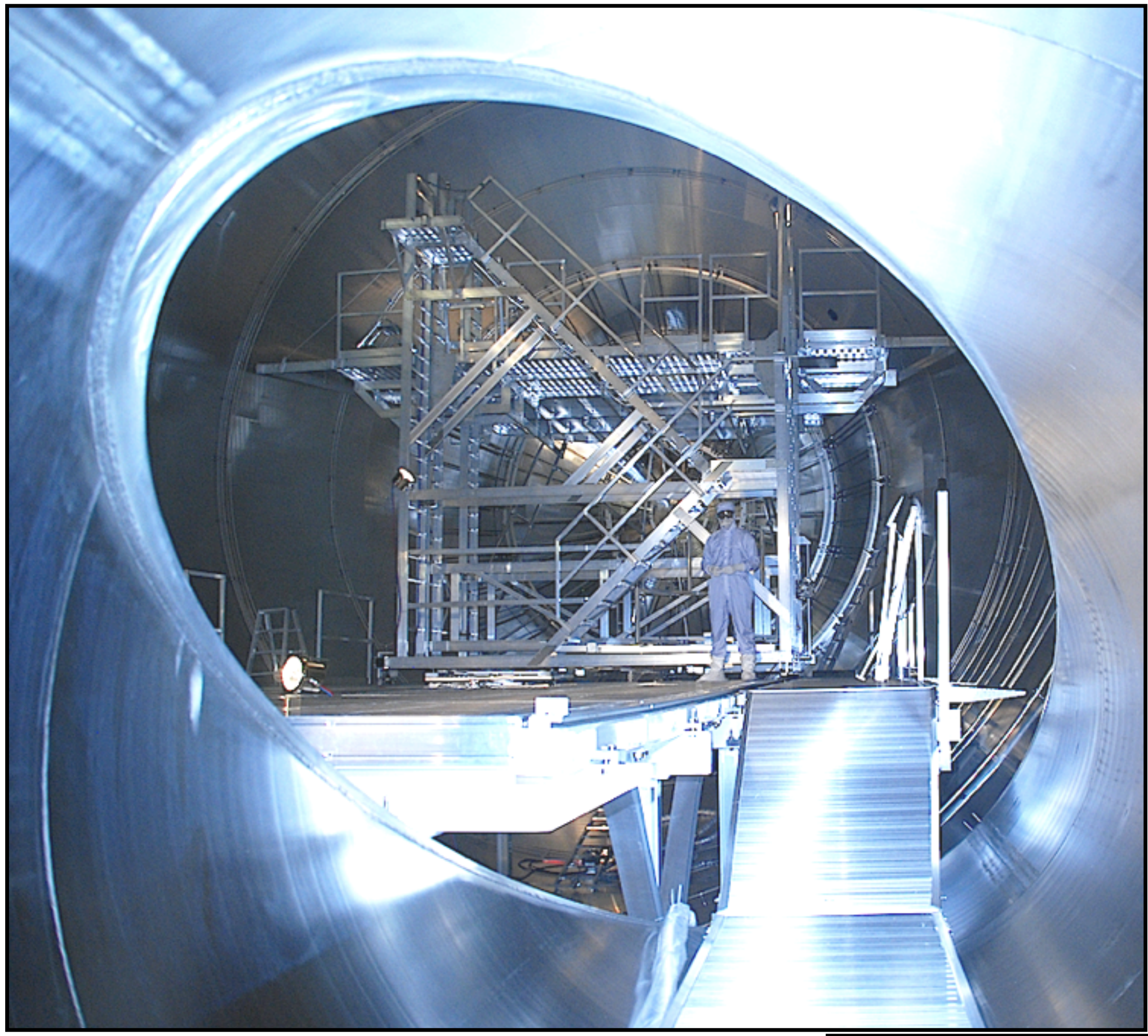
Monitor spectrometer installed.

HV stabilization ~x3 better than specification.





Air coil testing

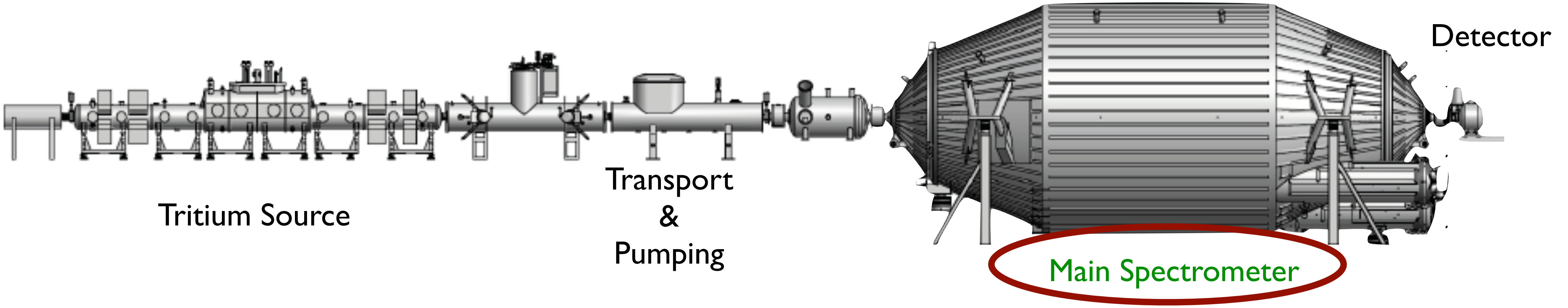


Vessel entrance

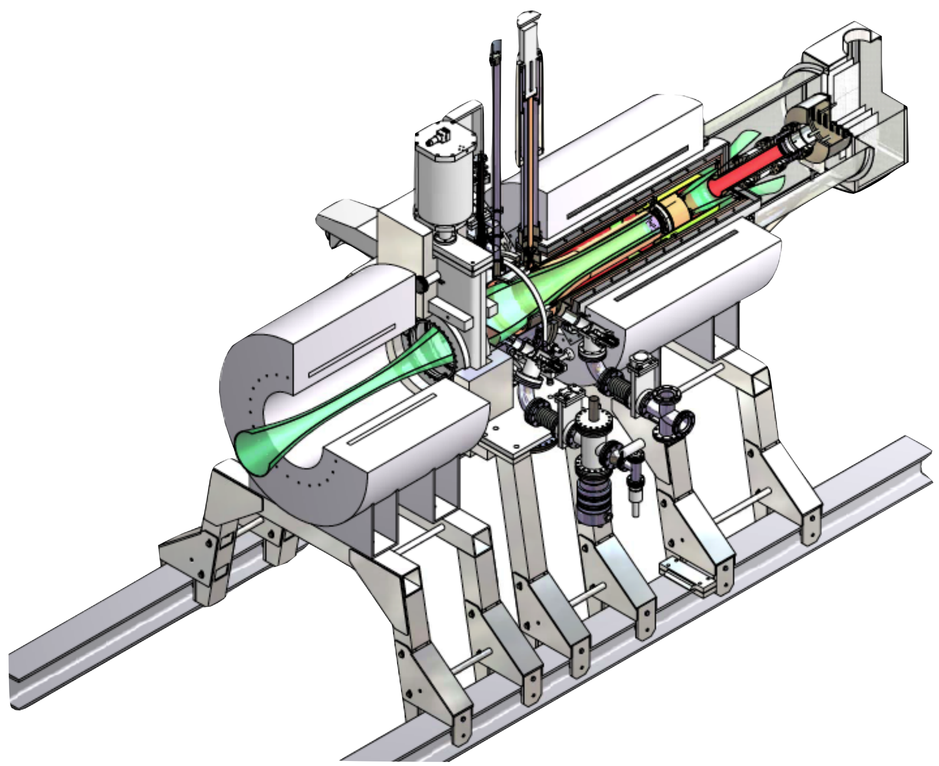
Recent milestones:

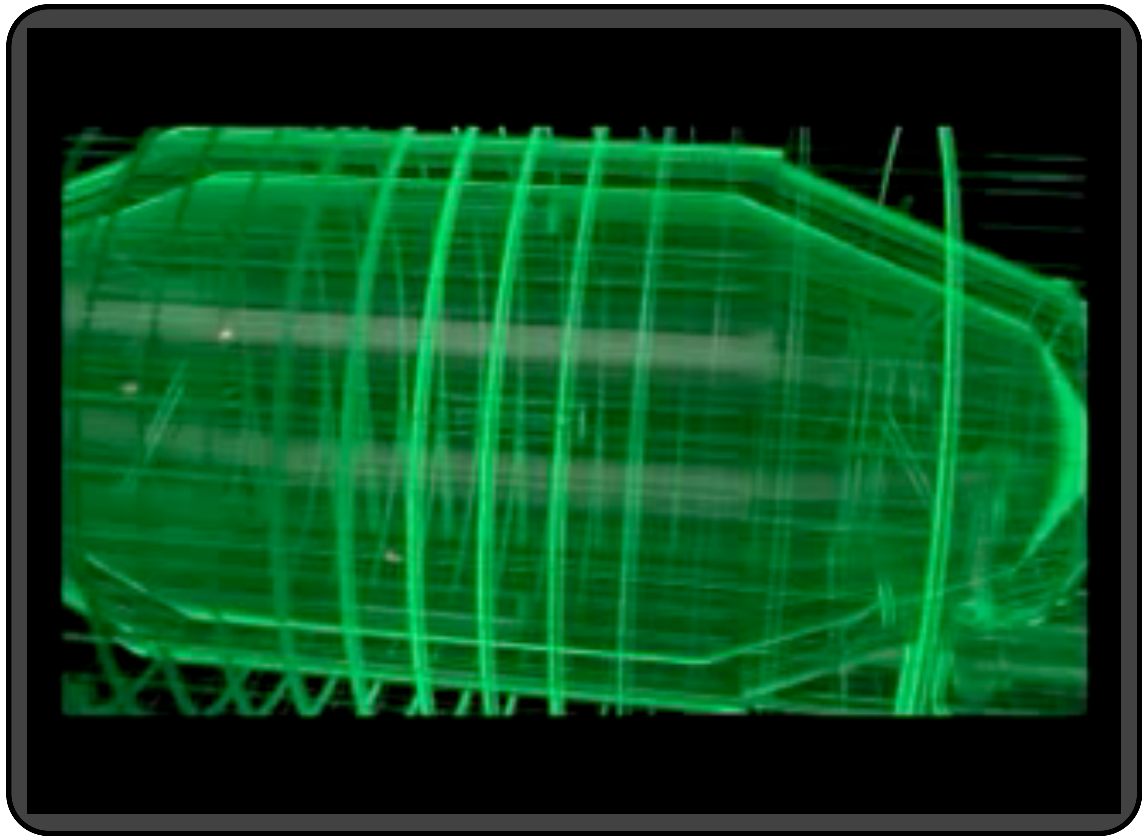
Air coils fully installed.

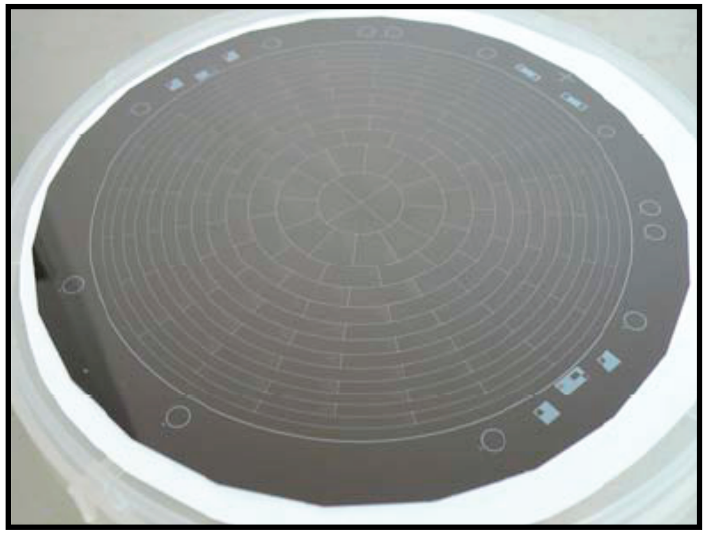
Wire mesh installed and vessel closed.



The Detector



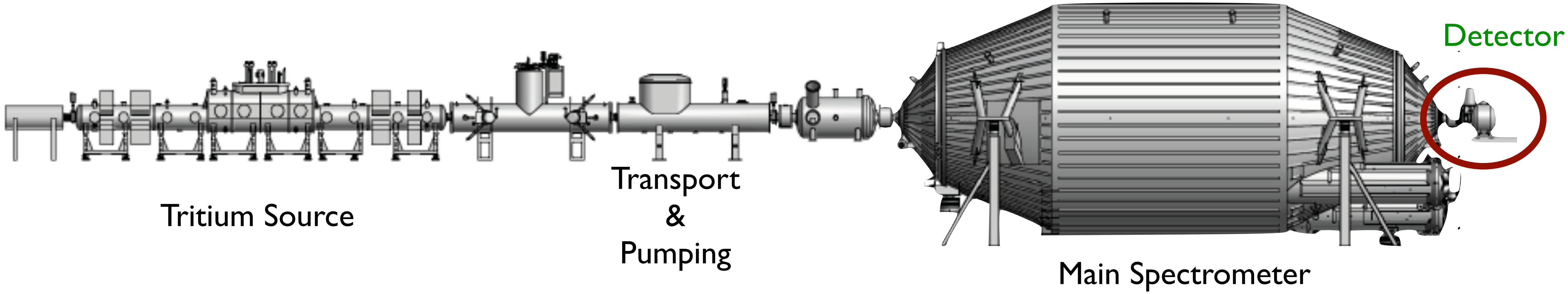


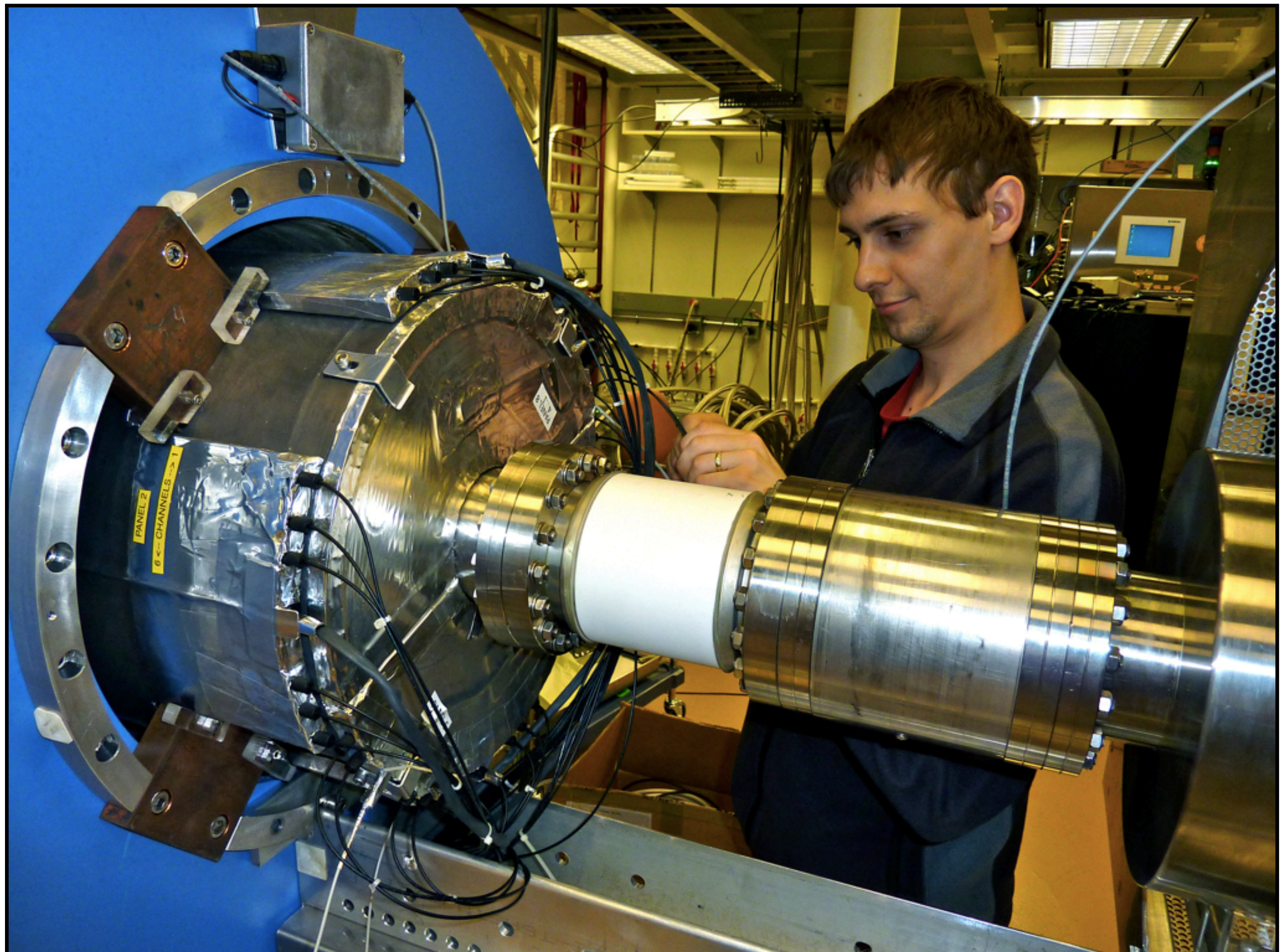


Final electron detection occurs on a segmented silicon detector (148 pixels for spatial resolution).

Two high-field magnets provide final focusing of tritium decay electrons onto detector.

Multiple background reduction techniques (veto, material selection, etc.) employed.





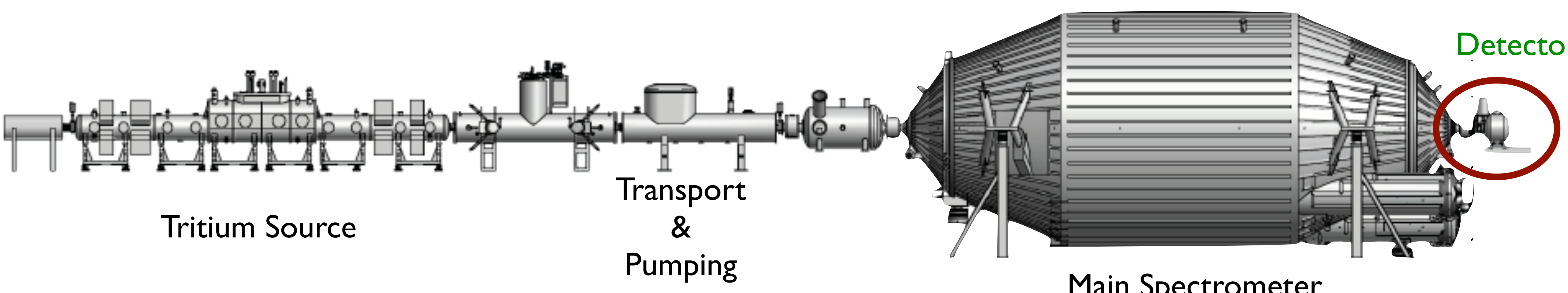
Veto installation

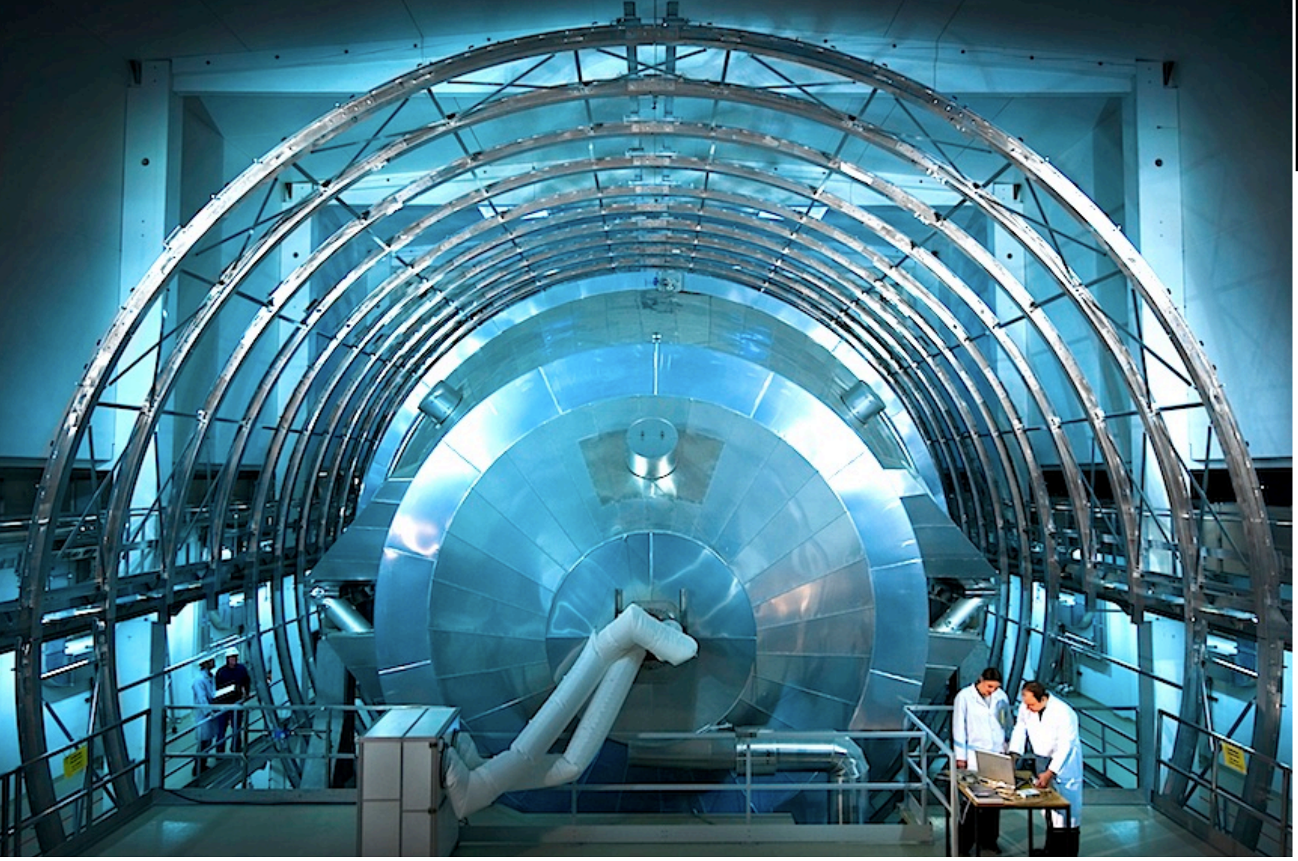
Focal plane magnets

Recent milestones:

Detector commissioned.

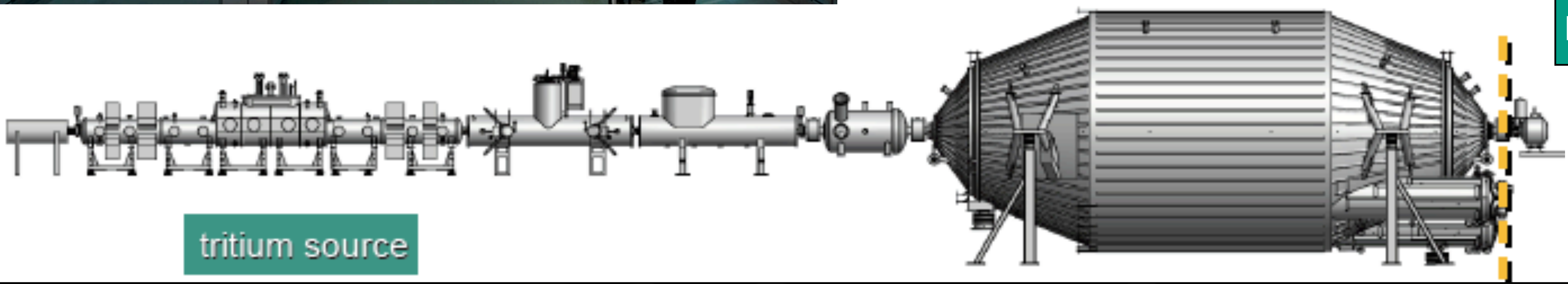
Being shipped to KIT for installation.





Spectrometer
and air coils

Detector

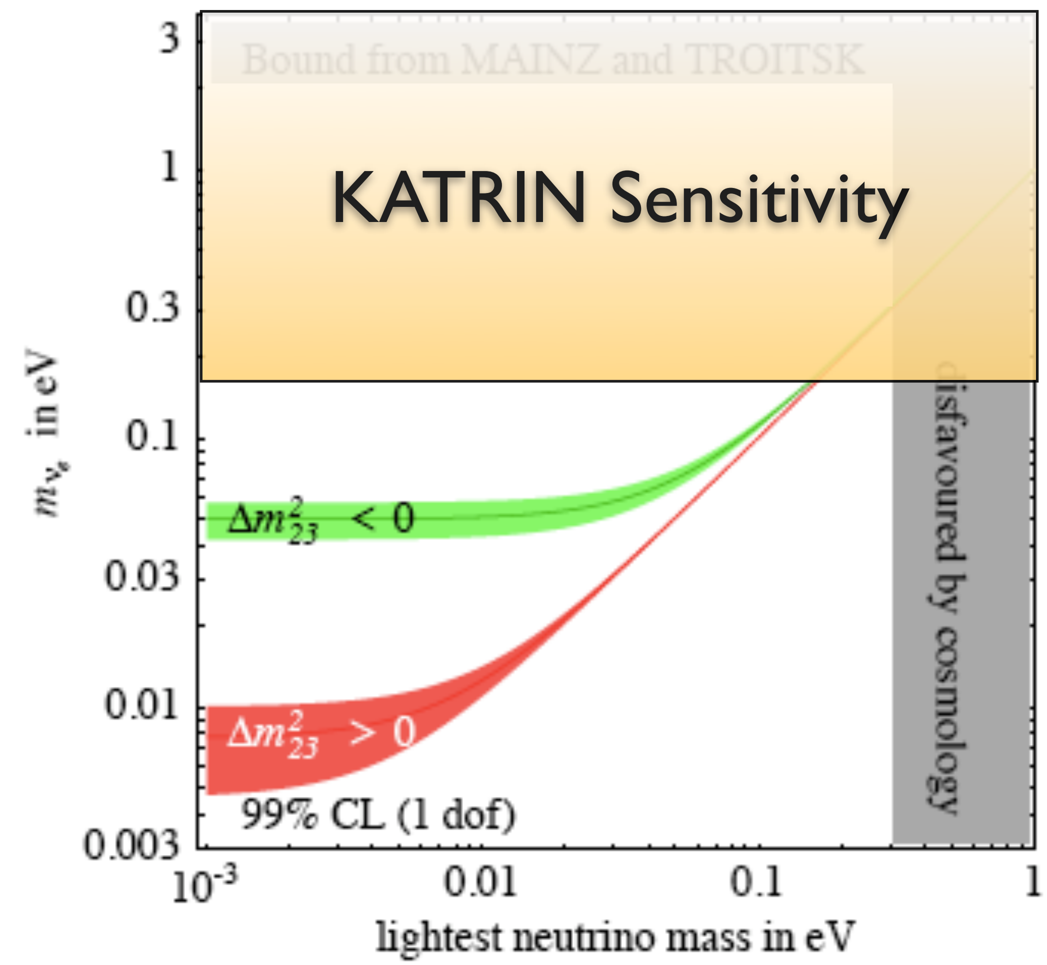


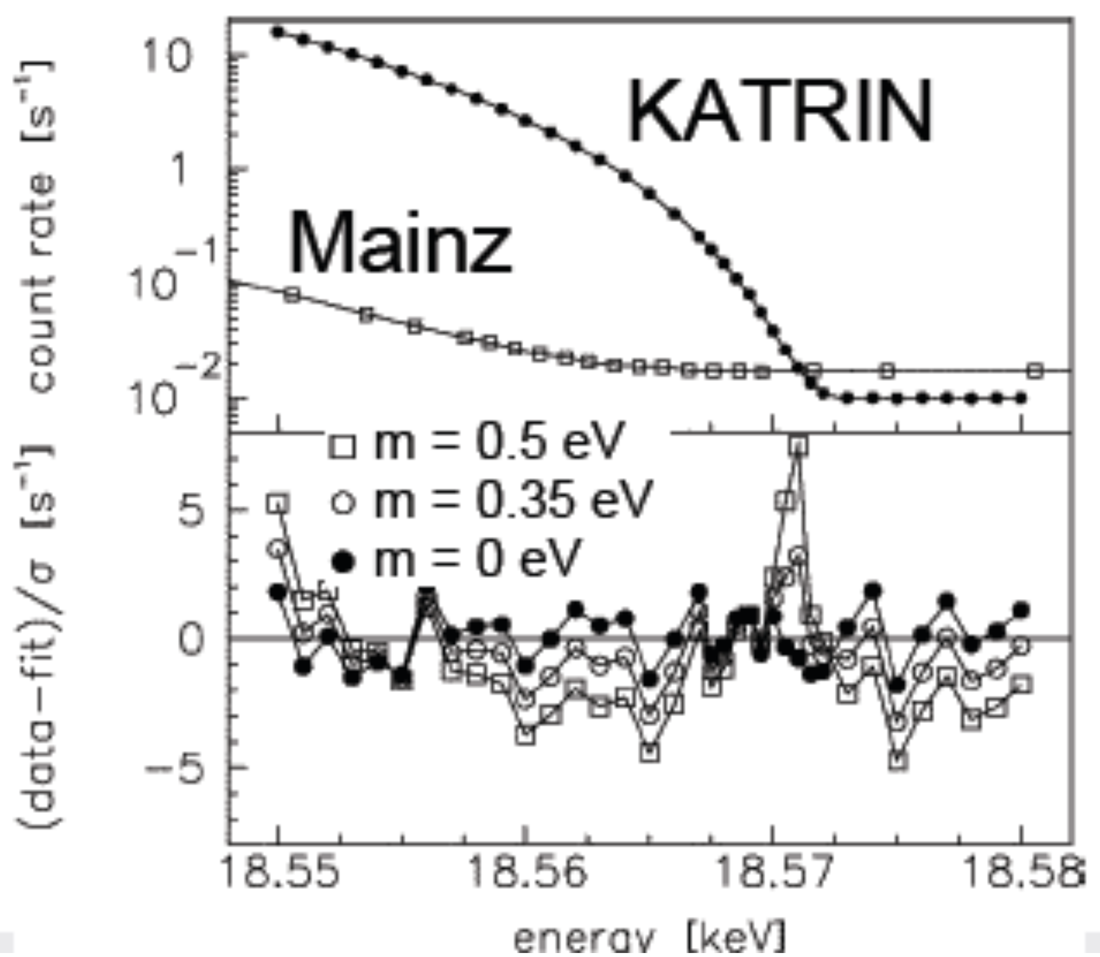
tritium source

Projected Sensitivity

$\Delta m_{\beta,stat}^2 = 0.018\ eV^2$ → Assumes 3 yr running

$\Delta m_{\beta,sys}^2 = 0.017\ eV^2$ → Major systematics include source purity, HV stability, source stability and T_2 final states





Neutrino Mass Goals

Discovery: 350 meV (at 5σ)

Sensitivity: 200 meV (at 90% C.L.)

Status of neutrino masses

(Summary)

Beta decay measurements

(KATRIN)

Physics beyond the Standard Model

(sterile neutrinos and relic over-density)

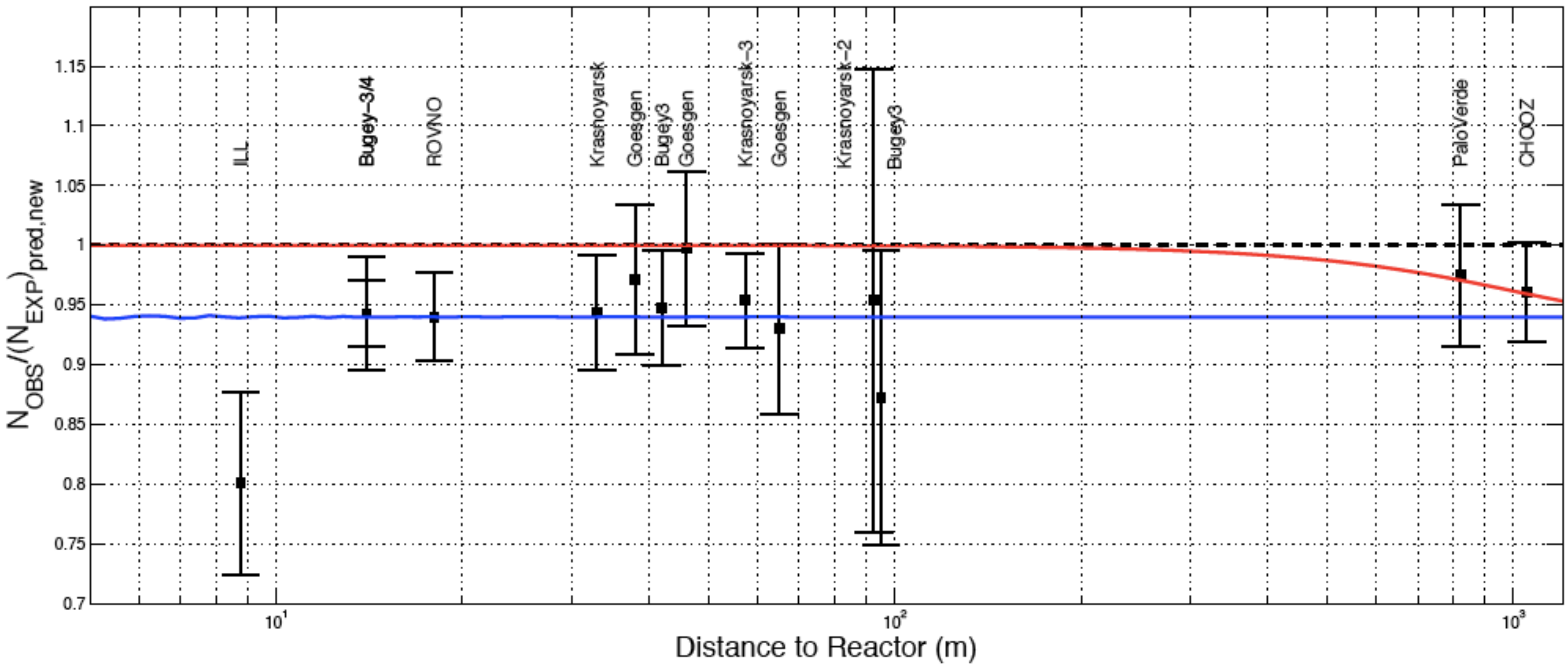
New Hints

New paper/analysis from Mention et al. shows a overall shift in reactor data. Shift appears consistent with possible sterile neutrino in the eV mass scale range.

Data also consistent with $^{51}Cr/^{37}Ar$ calibration data.

OK with MiniBooNE? Yes

Mention et al. (hep-ex:1101.2755)



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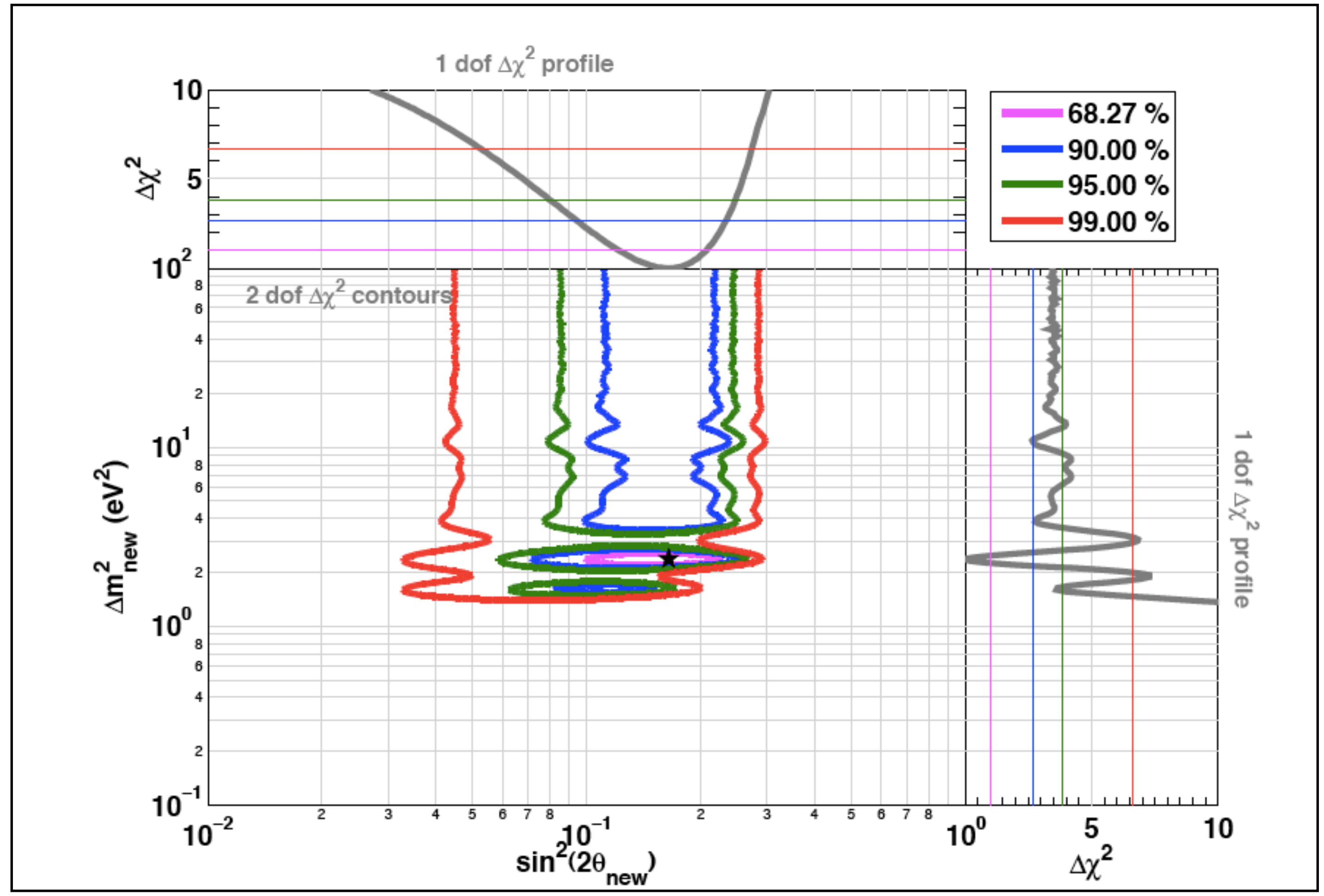
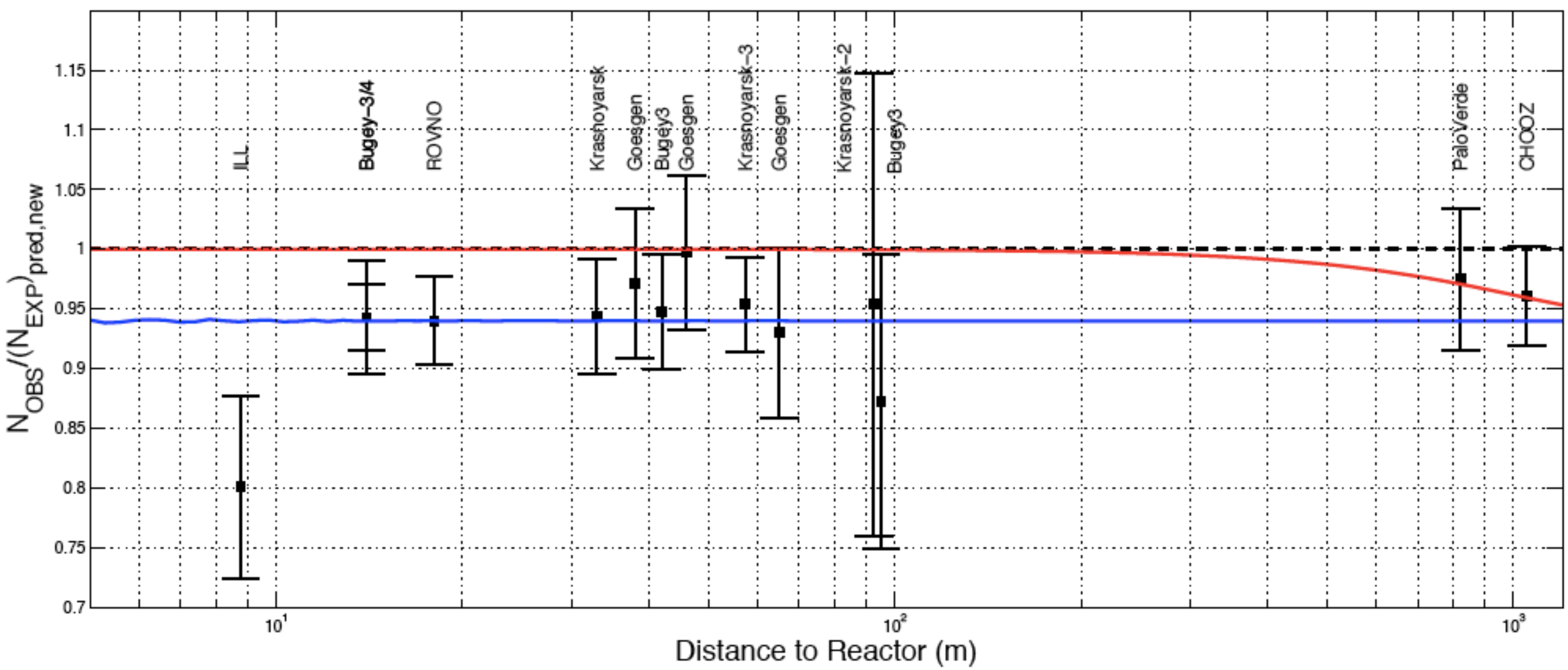


Mention et al. (hep-ex:1101.2755)



Kinks in the spectrum

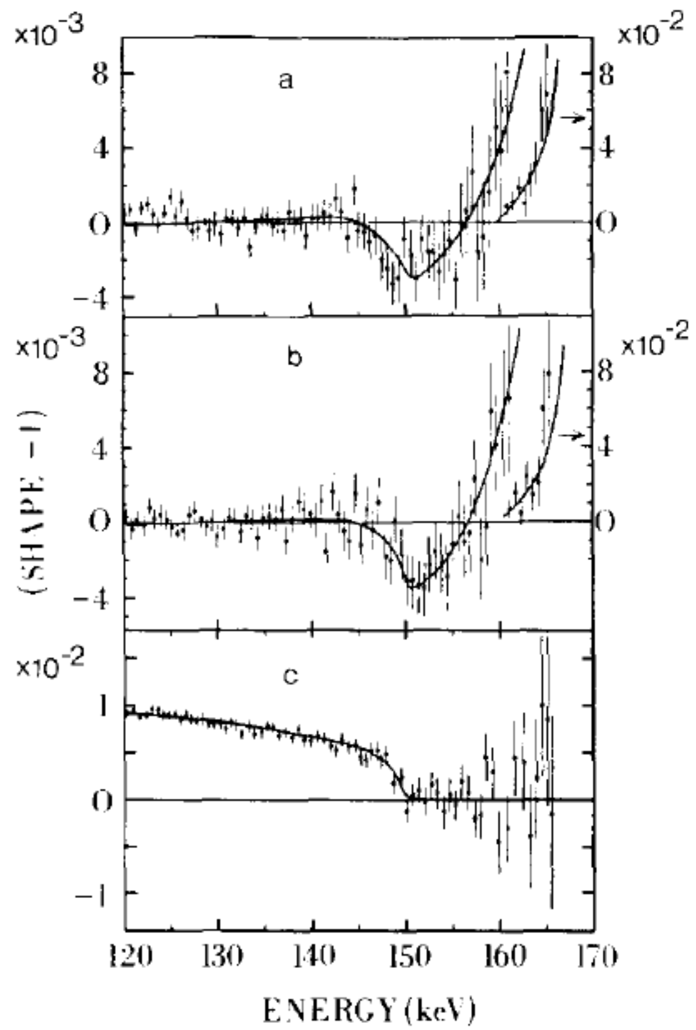
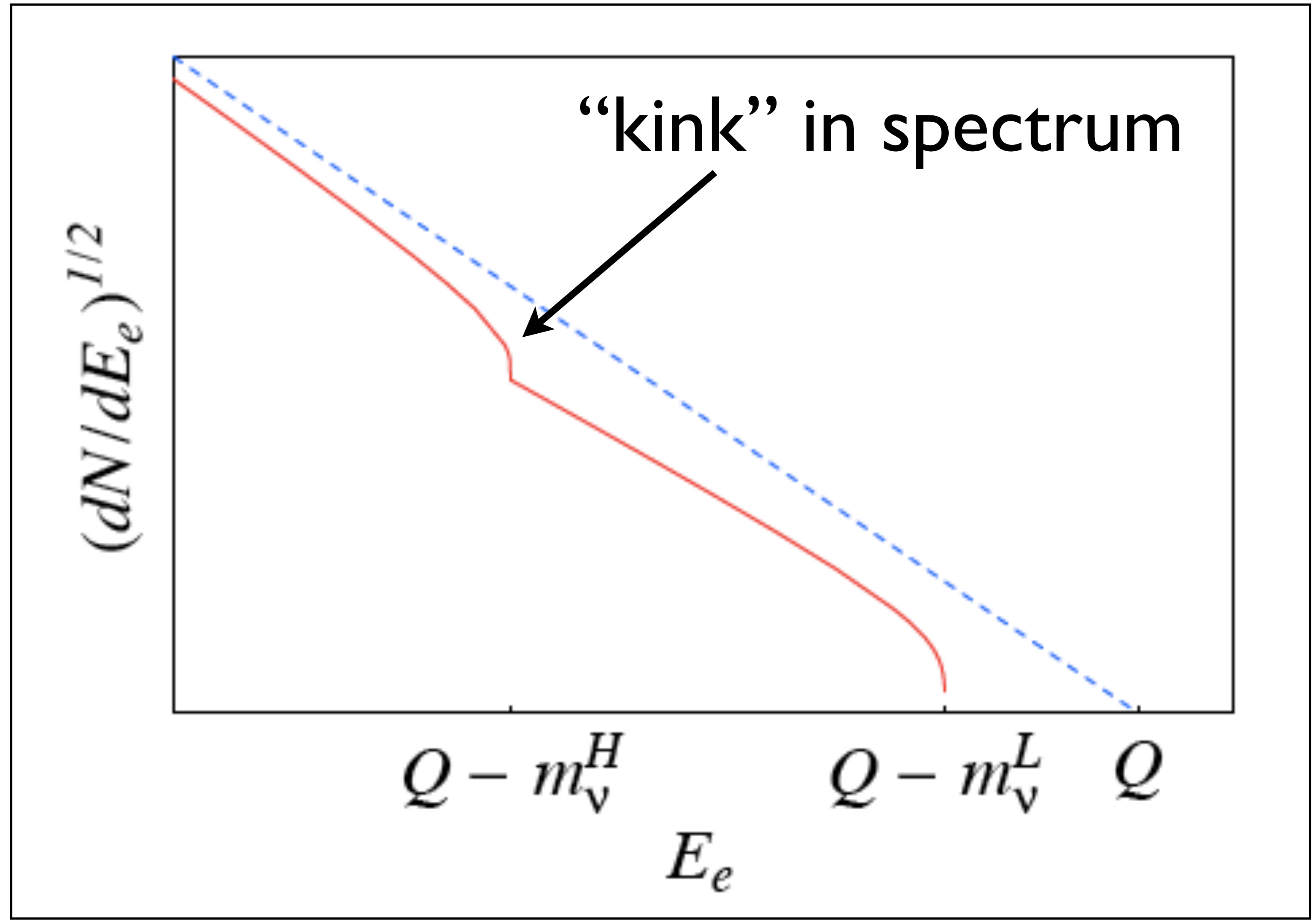


Fig. 4. Shape factors for (a) run #1 and (b) run #2 obtained by dividing the experimental spectra by the best least squares fit to the region 120–167 keV when no heavy neutrino mixing is allowed. The data plotted in (a) and (b) above 161 keV go off the scale set by the left ordinate and should be read using the scale indicated by the right ordinate. (c) Shape factor for combined data of runs #1 and #2 when normalizing a single component spectrum to the data over the region above 150 keV. The smooth curves in each case indicate the expected deviation for the emission of a 17 keV neutrino with $\sin^2\theta = 0.009$.



One can look for a partial suppression of the rate in the beta decay spectrum for a signature of sterile neutrinos.

However, proceed with caution...

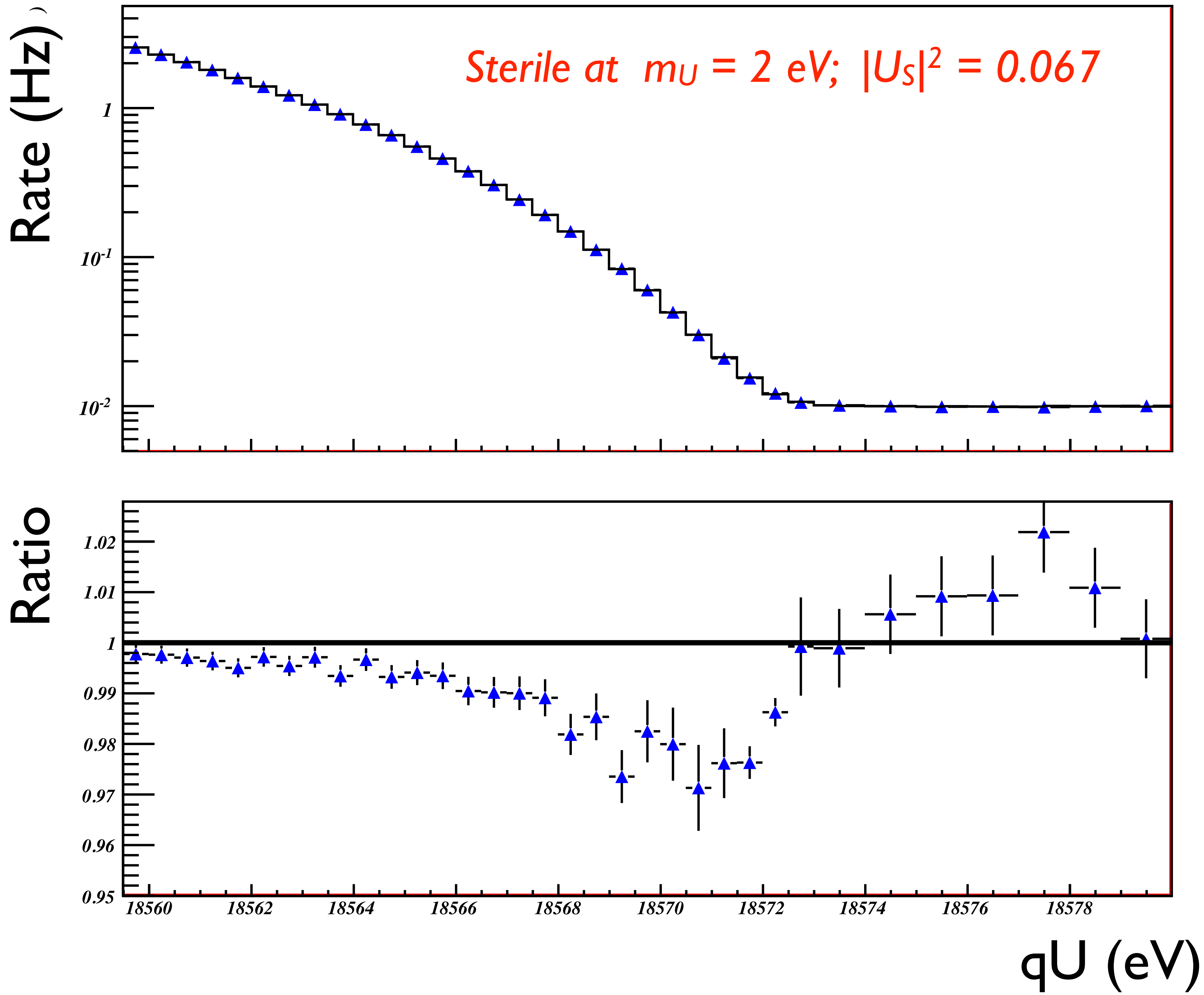
A. Hime and N. Jelley Phys. Lett. B 25 (1991)

Kinks in the spectrum

One can look for a partial suppression of the rate in the beta decay spectrum for a signature of sterile neutrinos.

Completely orthogonal to reactor or SBL methods.

Change in the available phase space for the decay.



Phase space term

$$\frac{dN}{dK_e} = N_{\rm decay} \cdot F(Z,K_e) \cdot p_e \cdot (K_e + m_e) \cdot z^2 \cdot \sum_{i=1,3} |U_{ei}|^2 \sqrt{1 - \frac{m_i^2}{z^2}} \cdot \Theta(E_0 - K_e - m_i)$$

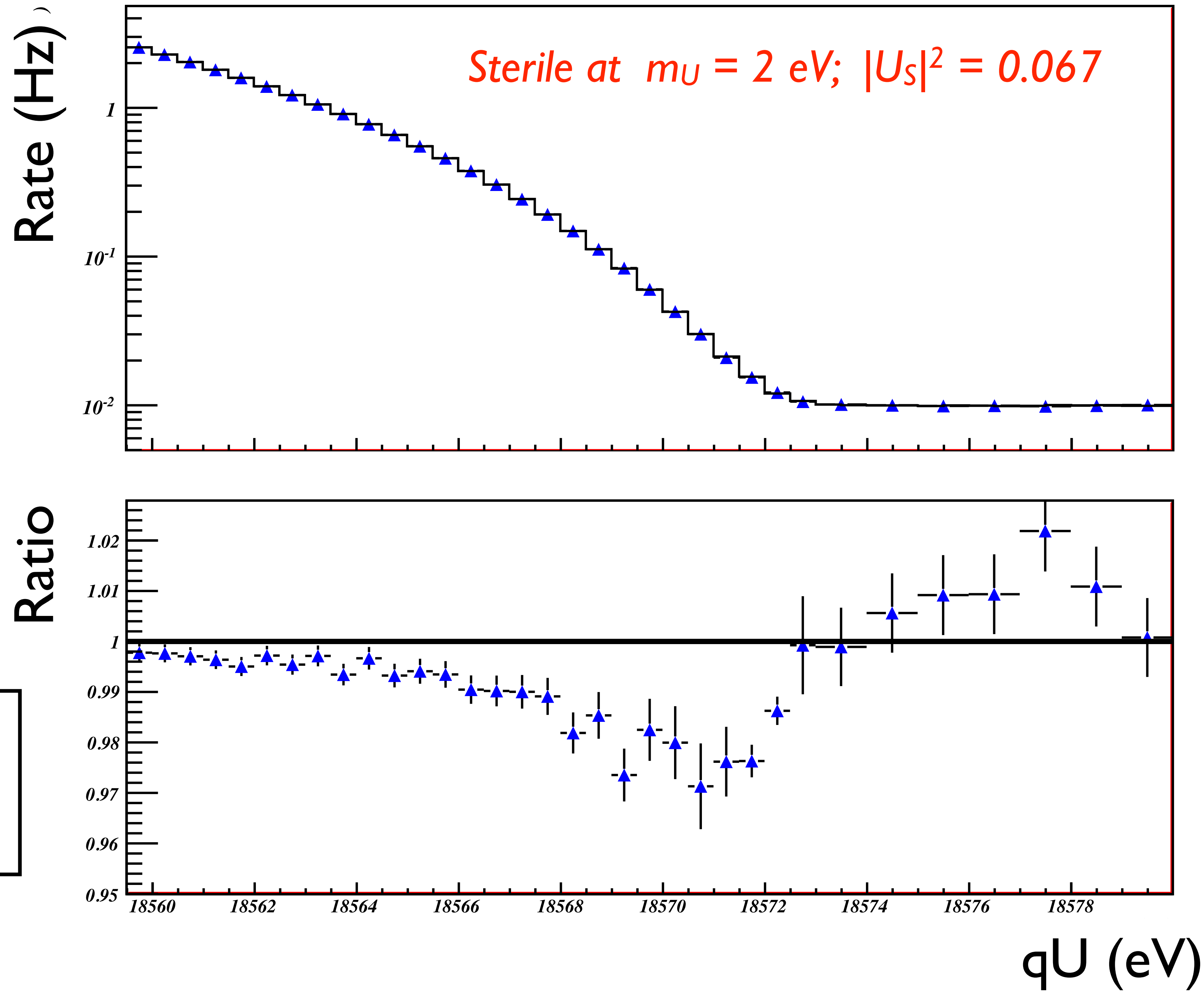
Kinks in the spectrum

Lower mass

$$\bar{m}_L^2 = \frac{\sum_{i=1}^{N_L} |U_{ei}|^2 m_i^2}{\sum_{i=1}^{N_L} |U_{ei}|^2}$$

Upper mass

$$\bar{m}_U^2 = \frac{\sum_{i=N_L+1}^{N} |U_{ei}|^2 m_i^2}{\sum_{i=N_L+1}^{N} |U_{ei}|^2}$$



Phase space term with steriles

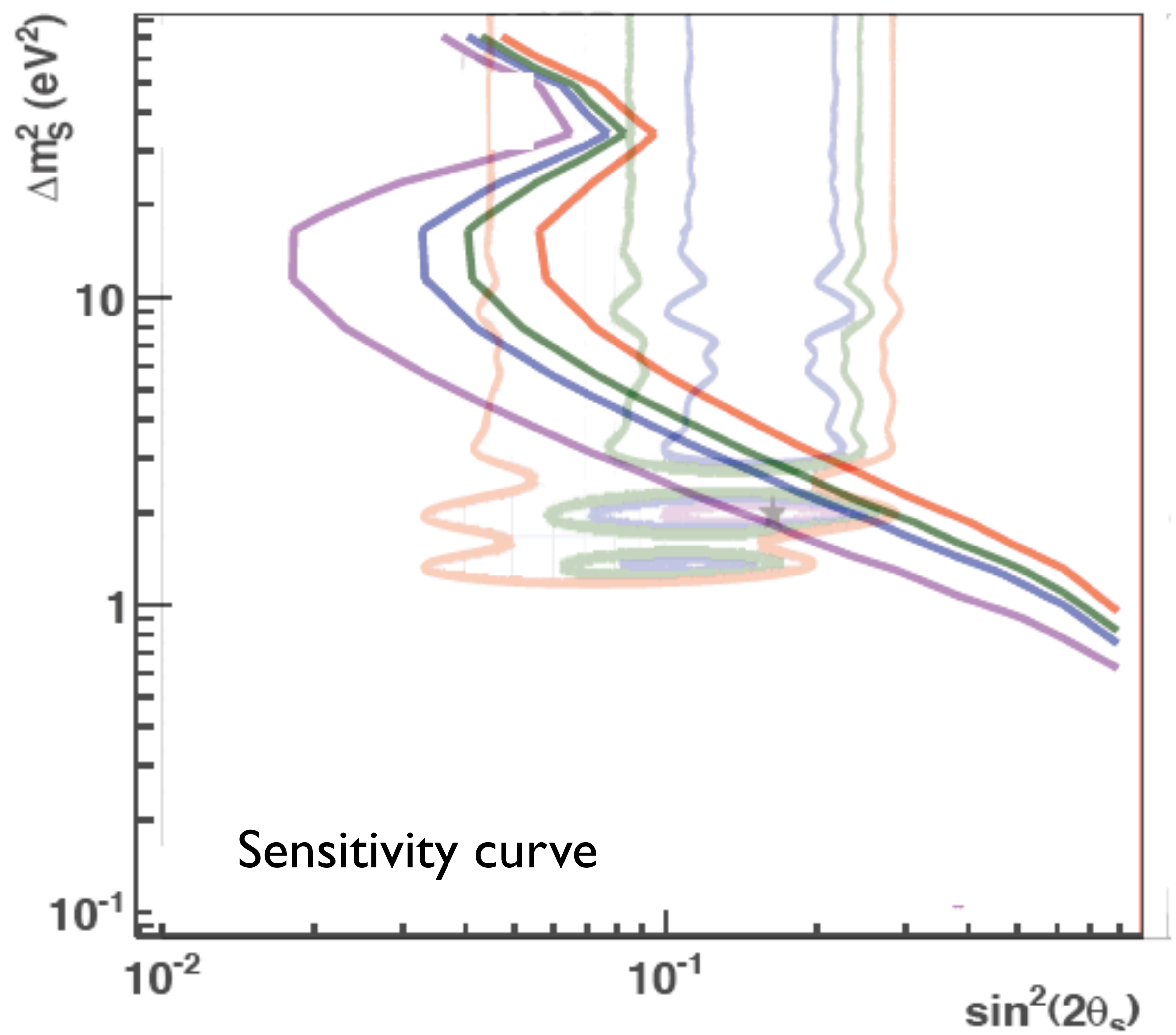
$$z^2 \left((1 - |U_S|^2) \sqrt{1 - \frac{\bar{m}_L^2}{z^2}} \cdot \Theta(z - \bar{m}_L) + |U_S|^2 \sqrt{1 - \frac{\bar{m}_U^2}{z^2}} \cdot \Theta(z - \bar{m}_U) \right)$$

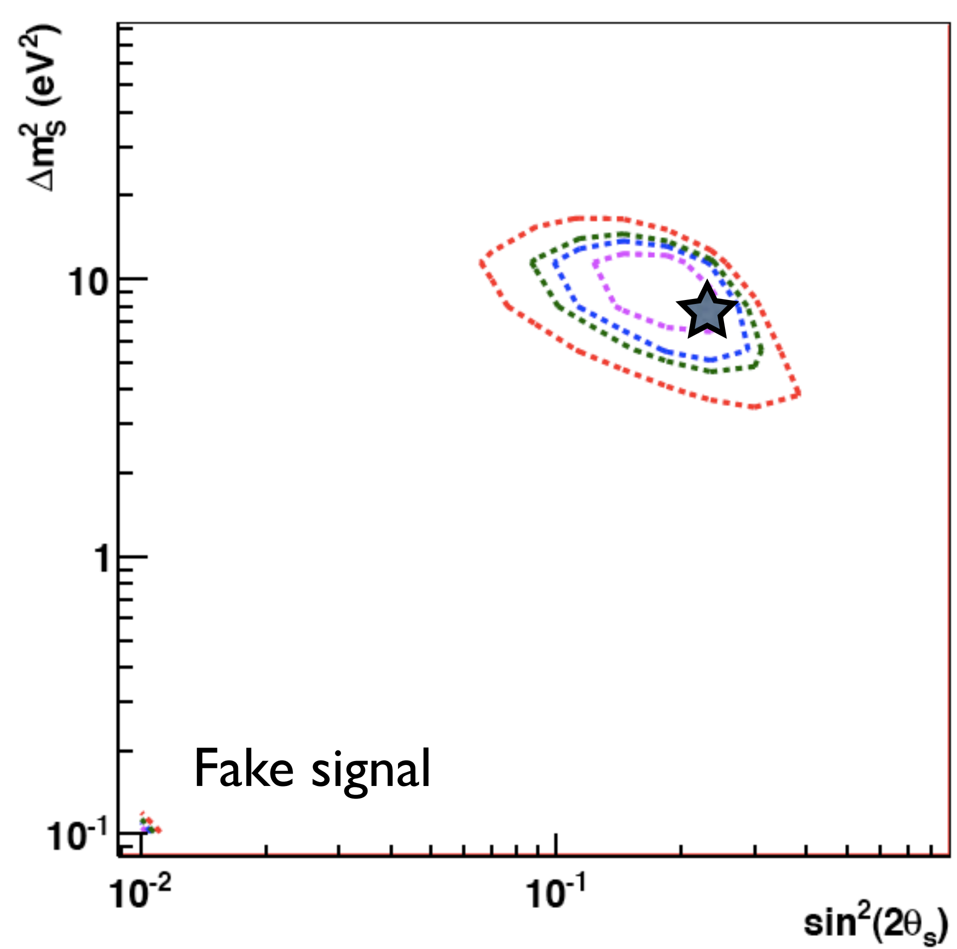
Methodology & Results

J.Formaggio and J. Barrett
http://arxiv.org/abs/1105.1222

- Simulation of KATRIN 3 year running program, fitting from -15 eV to +5 eV around the endpoint.
- Include statistical and systematic uncertainties.
- Likelihood fit (using both Minuit and Markov Chain Monte Carlo techniques)
    - Look at sensitivity by looking at goodness of fit to the presence of a mass splitting.

$$\Delta\mathcal{L} = \mathcal{L}(U_S^2, \bar{m}_U, \bar{m}_L) - \mathcal{L}(m_\beta)$$

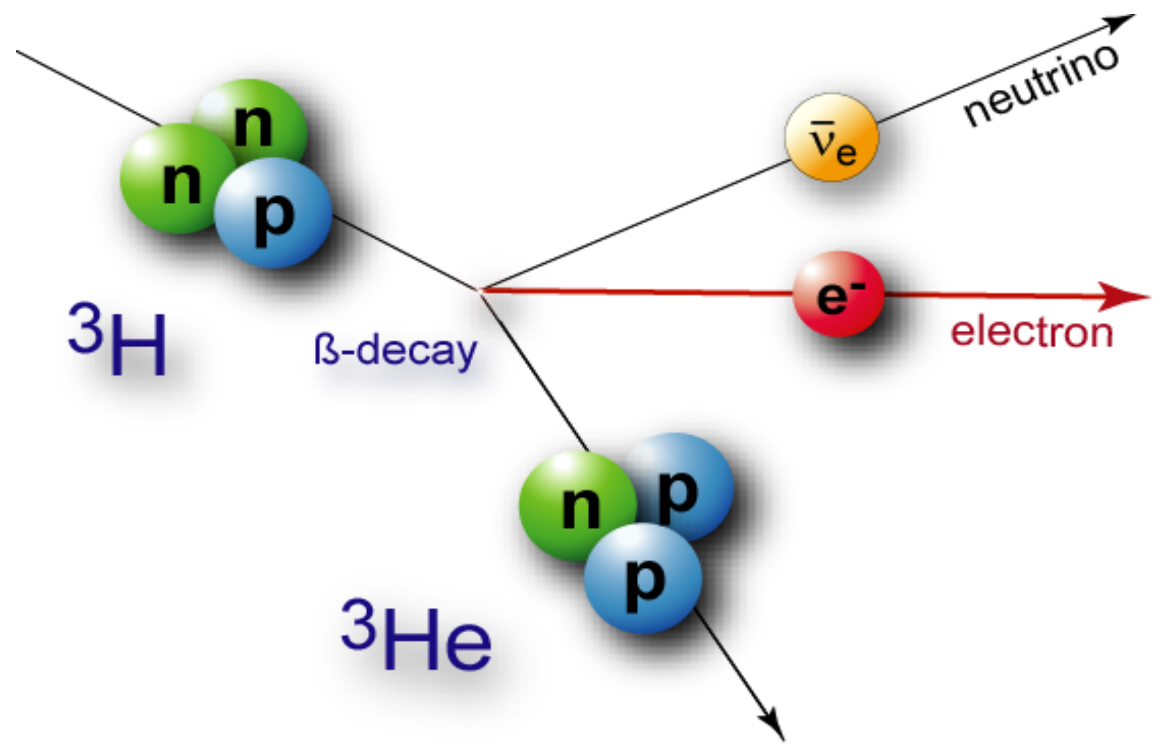




Neutrino Capture

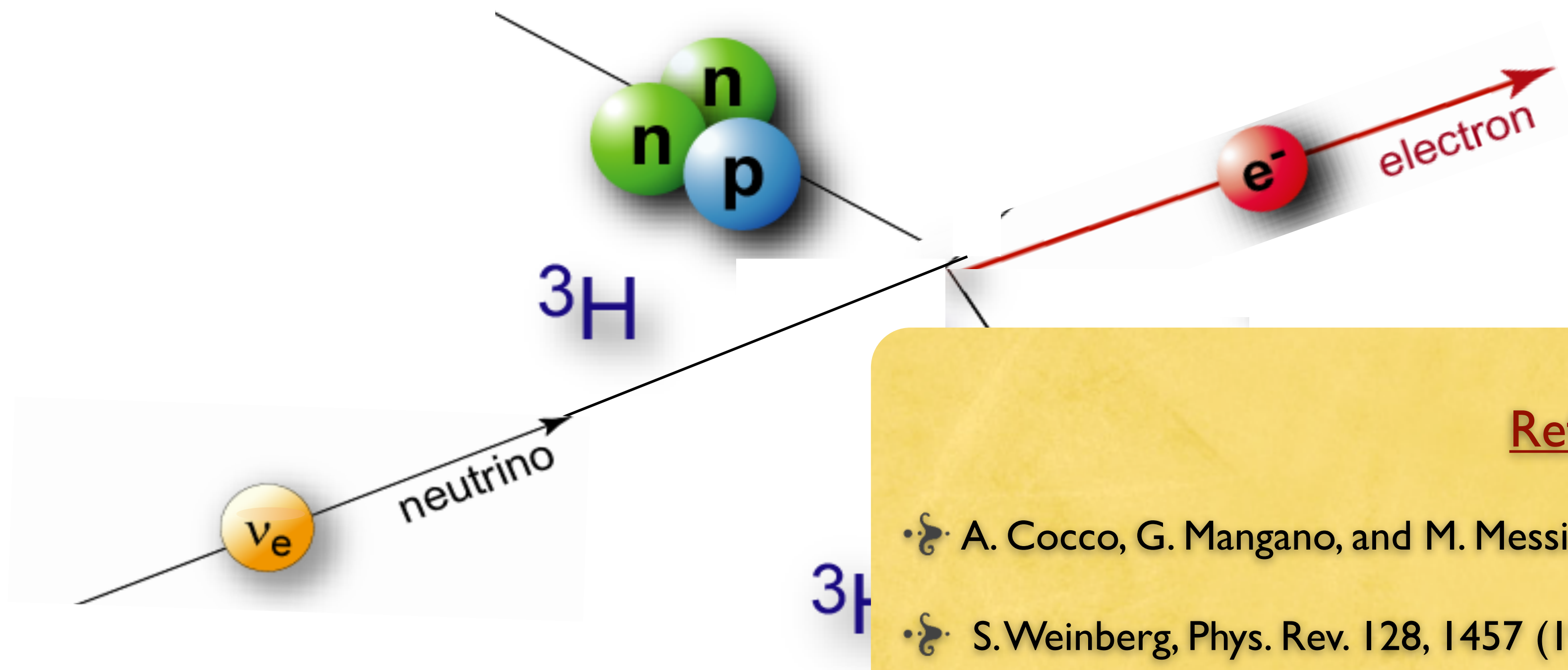
$^3H \rightarrow {}^3He^+ + e^- + \nu_e$

Instead of beta decay...



Neutrino Capture

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



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

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

Neutrino Capture Rate

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

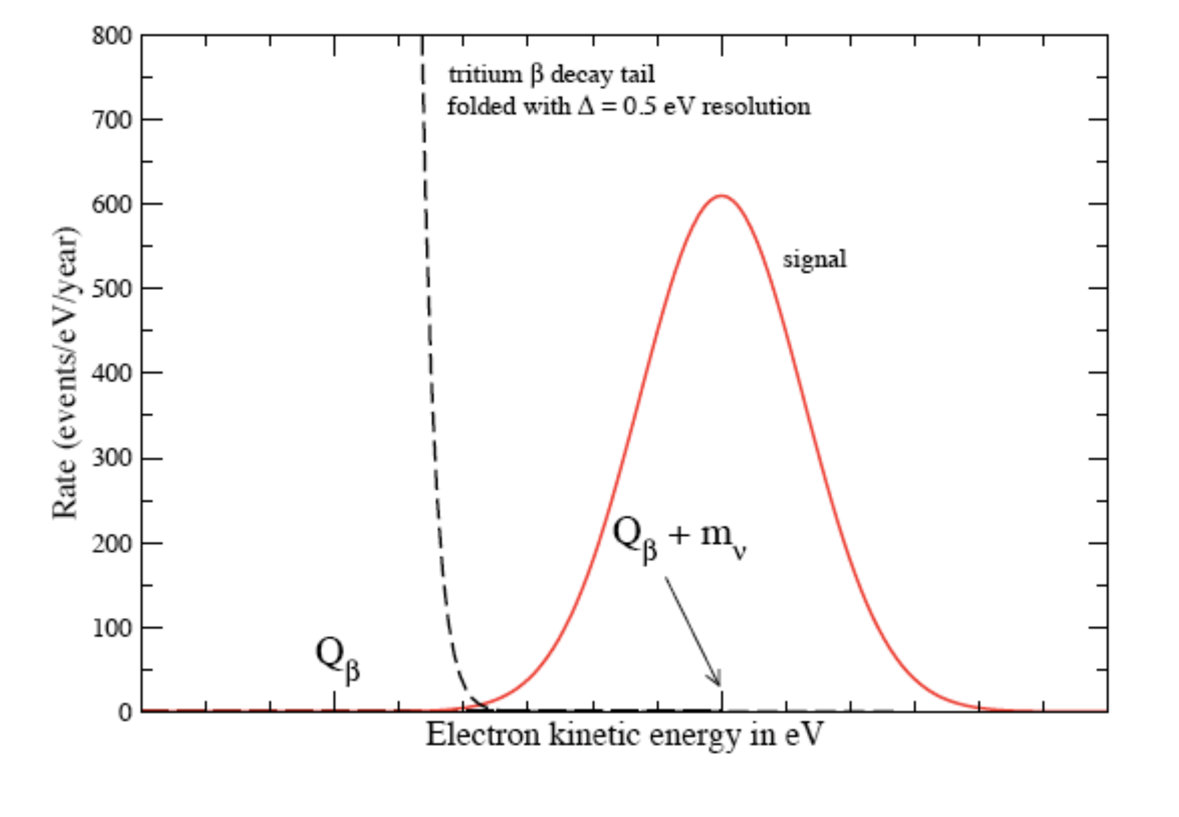
Tritium Cross-Section

- Has three main advantages:

  (i) The process is exothermic. There is enough energy for the decay to occur (because beta decay will happen anyway). Thus, it is threshold-less.

  (ii) Electron energy is almost mono-energetic, after the endpoint energy.

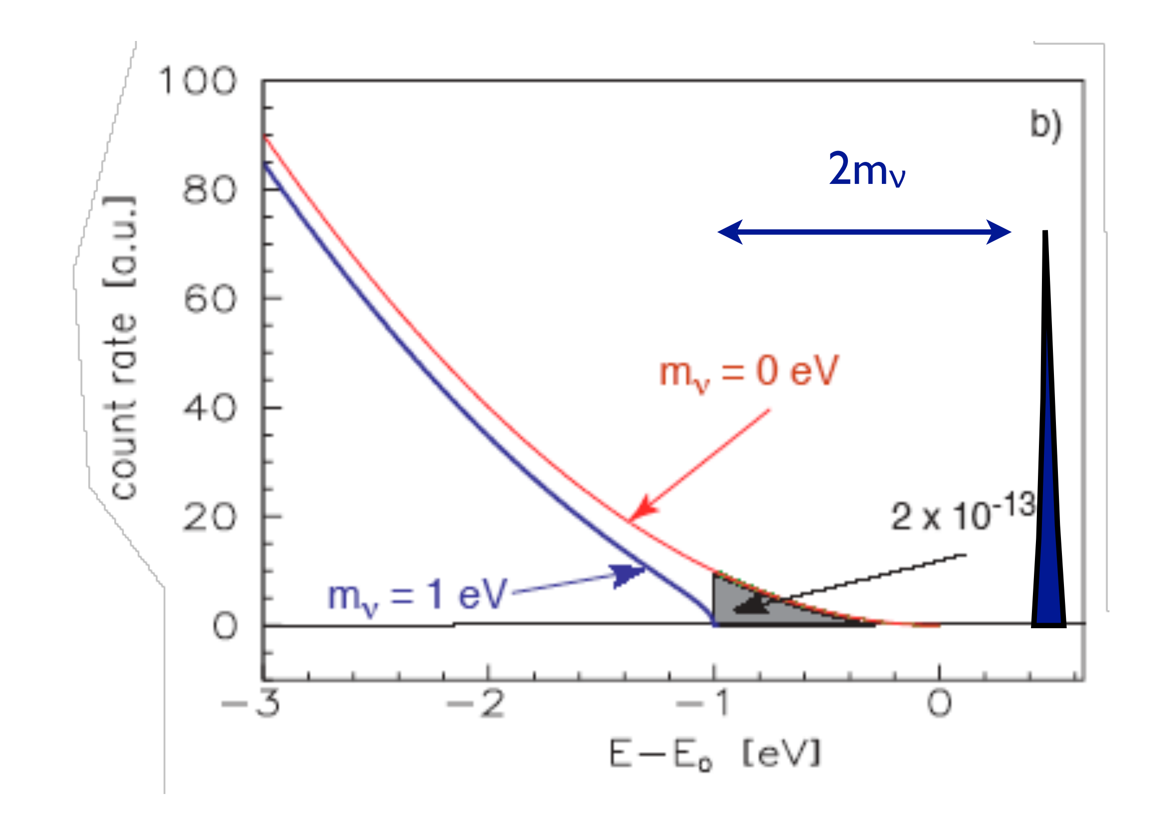
  (iii) For tritium, 100 g corresponds to 10 events/year.



The CνB and KATRIN

- Any beta-decay endpoint experiment can search for the CνB, including KATRIN.
- An analysis of KATRIN's sensitivity highlights its limitations: target mass, resolution, and backgrounds.

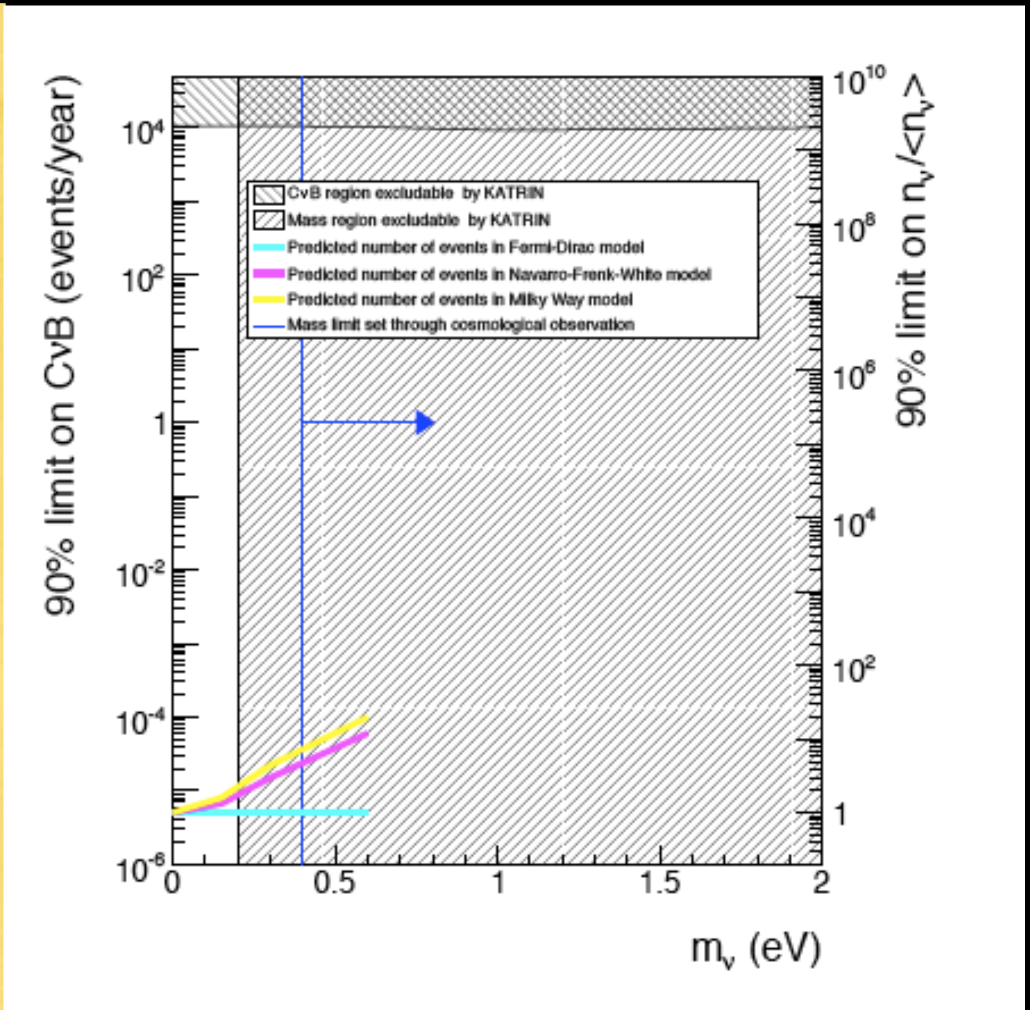
Sample neutrino capture signal with nominal beta decay background.

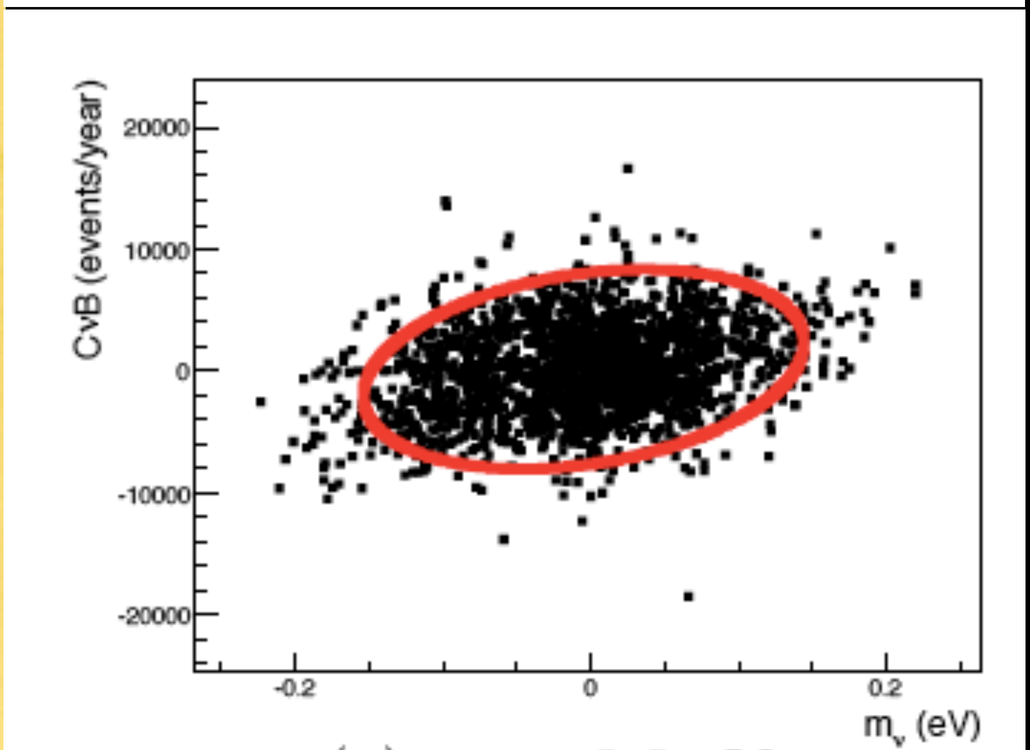


KATRIN's sensitivity to CνB.

A. Kaboth, J. Formaggio, and B. Monreal

Phys Rev. D 82 062001





(a) $m_\nu = 0.0$ eV

The next generation of beta decay experiments will provide greater sensitivity to the neutrino mass scale (down to the 200 meV).

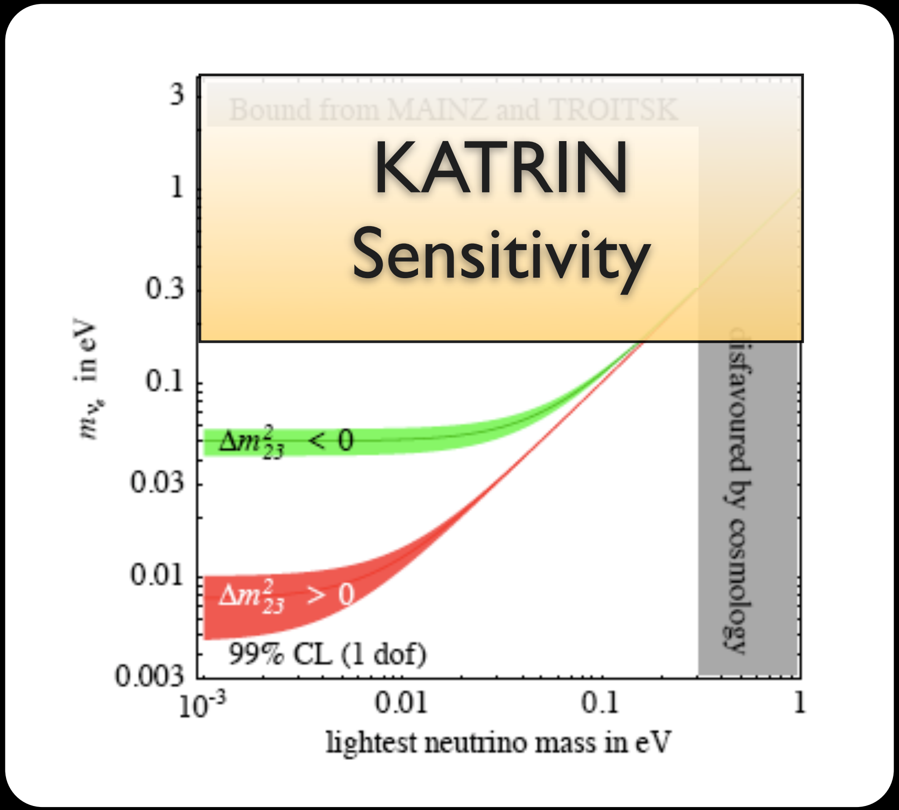
With such sensitivity, KATRIN can also search from new physics such as sterile neutrinos and relic over-abundance.

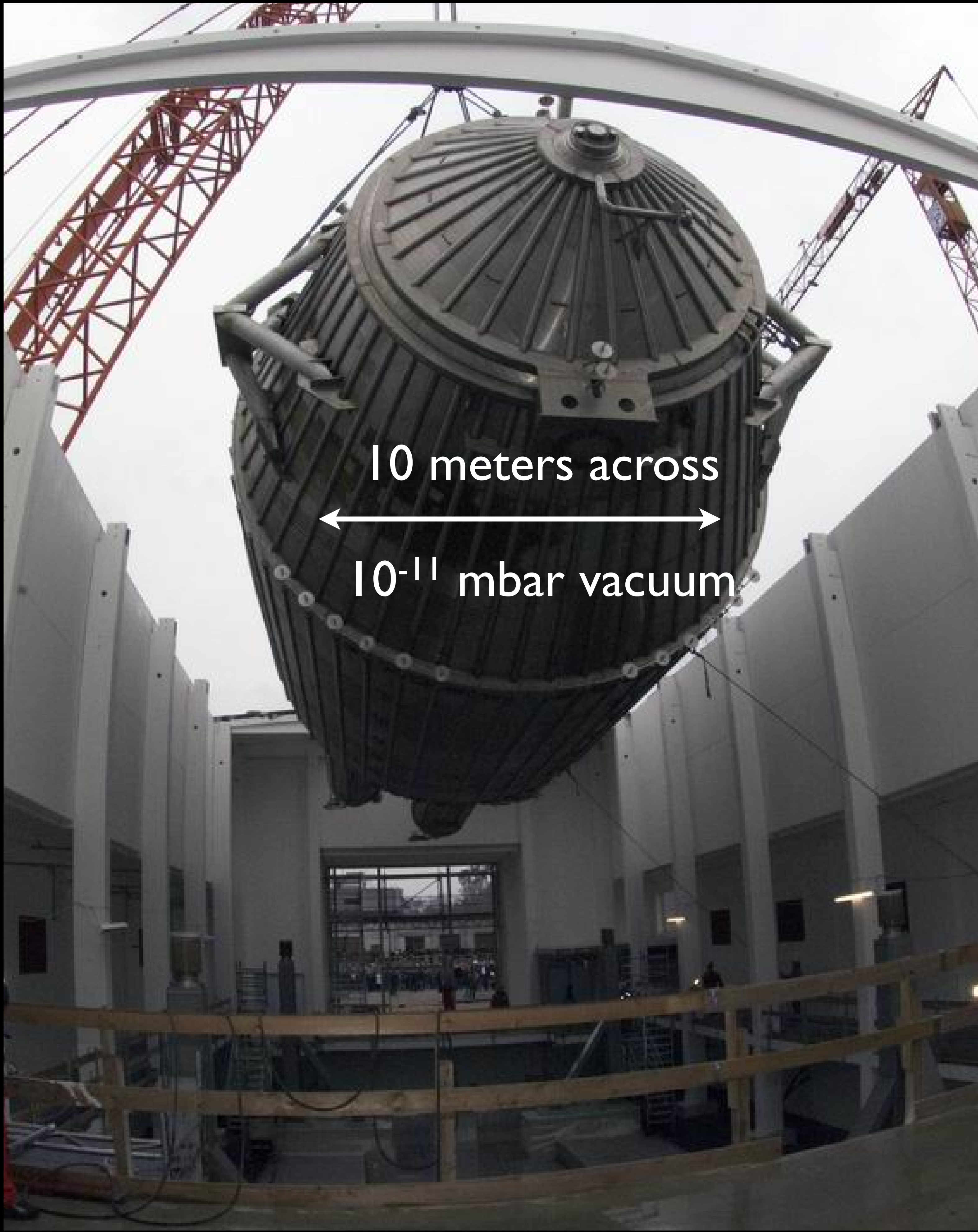
Competitive and orthogonal measurement of the reactor anomaly. A great deal of the allowed region can be eliminated or confirmed.

Thank you for your attention

Can we push further?

- KATRIN will achieve 200 meV scale. Can direct measurements push lower to the normal hierarchy scale?
- Any future experiment needs to be able to (a) have a better scaling law for increased target mass and (b) improve its energy resolution.

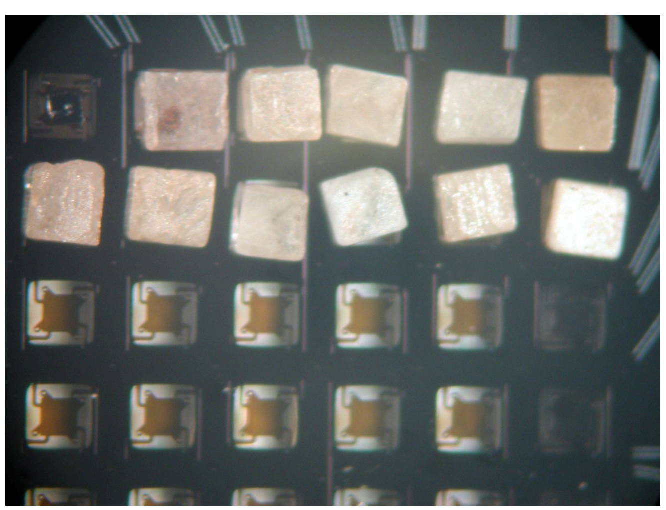




MARE

Bolometric:

MARE

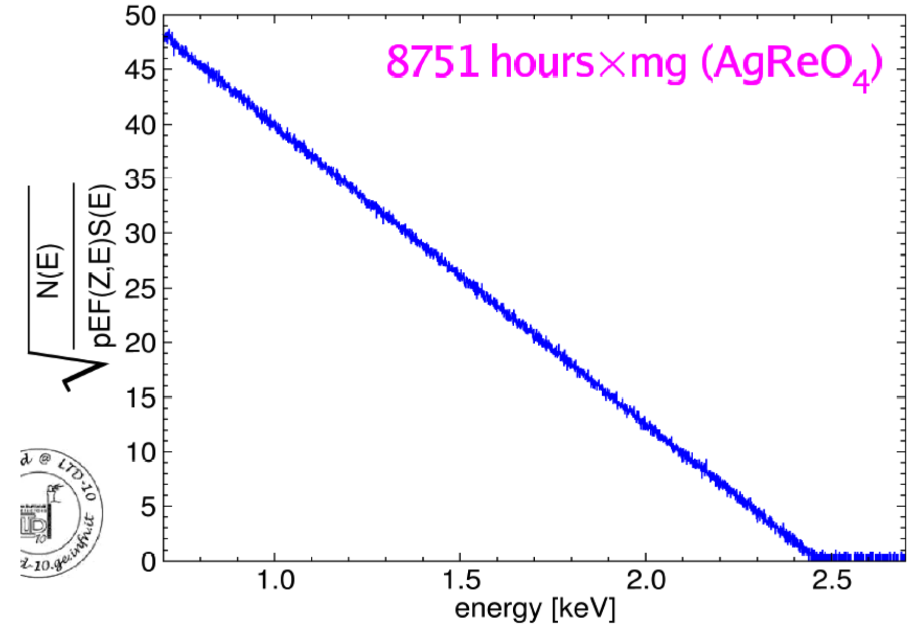


$$^{187}\mathrm{Re} \rightarrow {}^{187}\mathrm{Os} + e^- + \bar{\nu}_e$$

- Uses ^{187}Re as its beta source (one of the lowest endpoints, 2.3 keV)

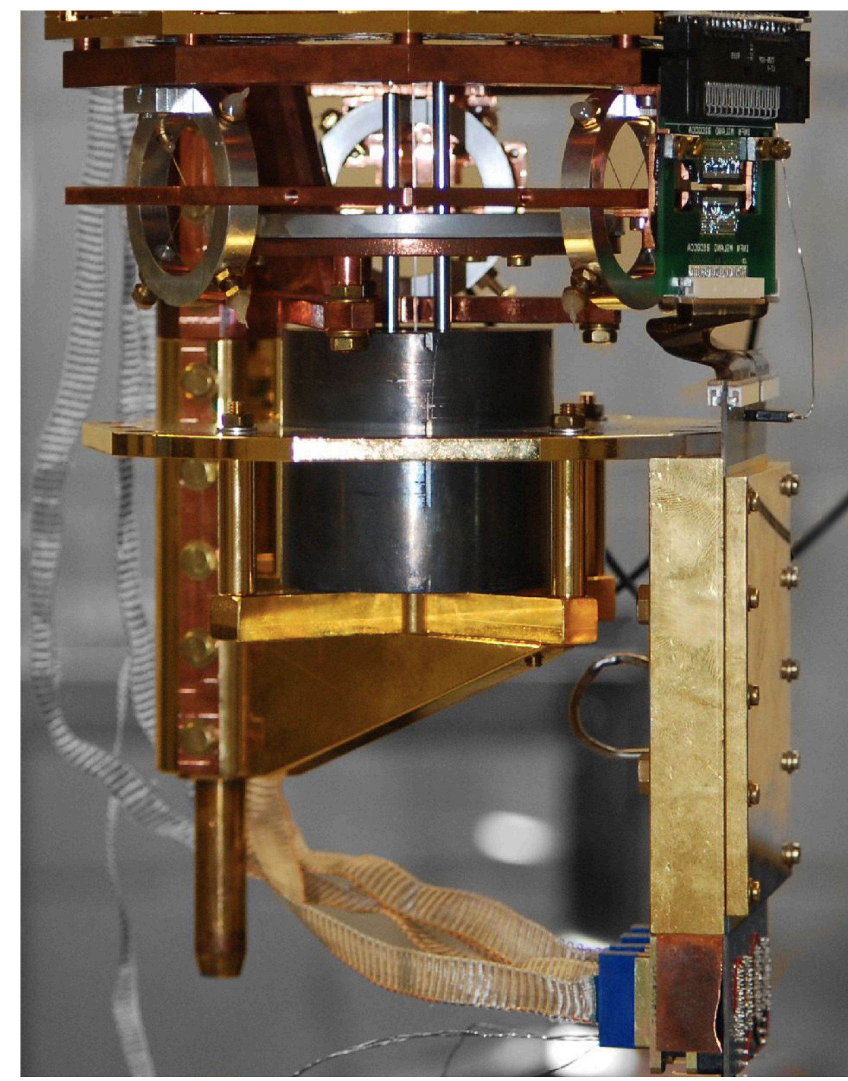
- Advantages:
  - No backscattering
  - No atomic or molecular final state effects.

- Disadvantages:
  - Extremely long half-life.
  - Pileup backgrounds.



$m_\nu^2 = (-112 \pm 207 \pm 90)\ \mathrm{eV}^2$

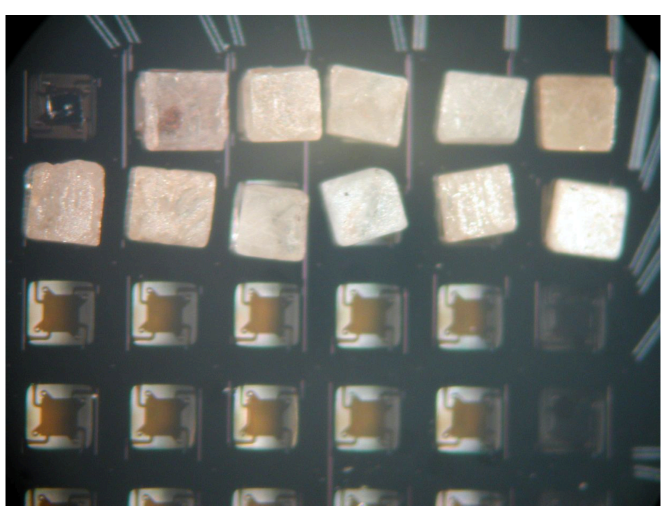
Cryogenic setup in Milan



MARE R&D

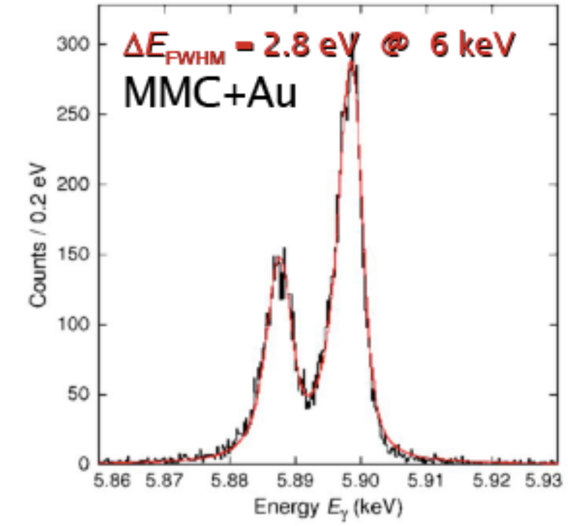
Bolometric:

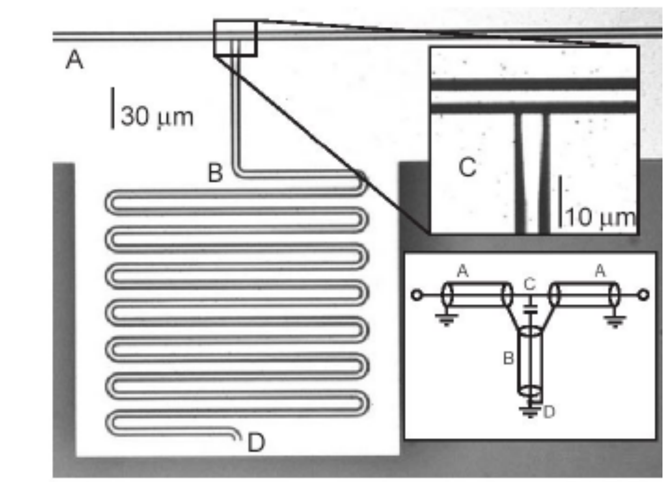
MARE



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

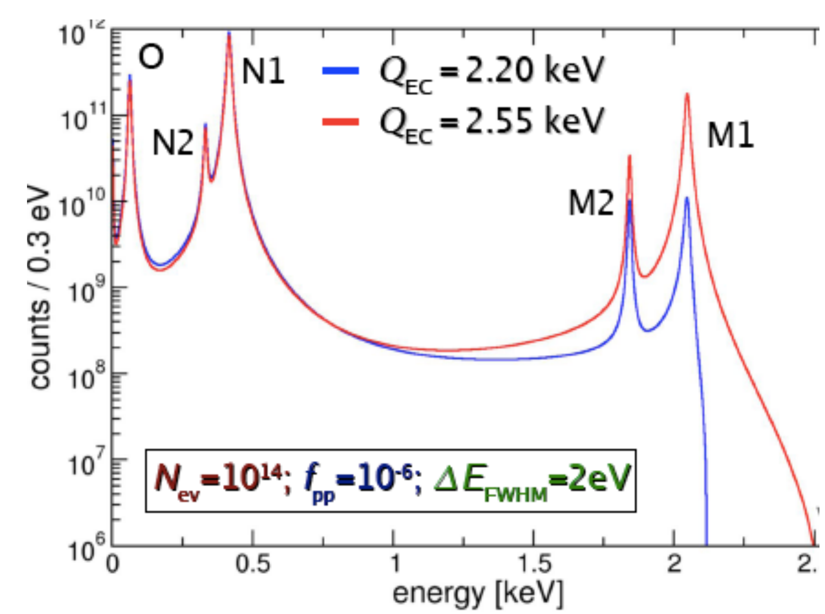
- New Technology:
  - Use of magnetic micro calorimeters. Minimize rise time and energy resolution.
  - MKID devices (1-10 GHz) resonating super-conductors.
  - Reduces pileup, increases pixelation and energy resolution





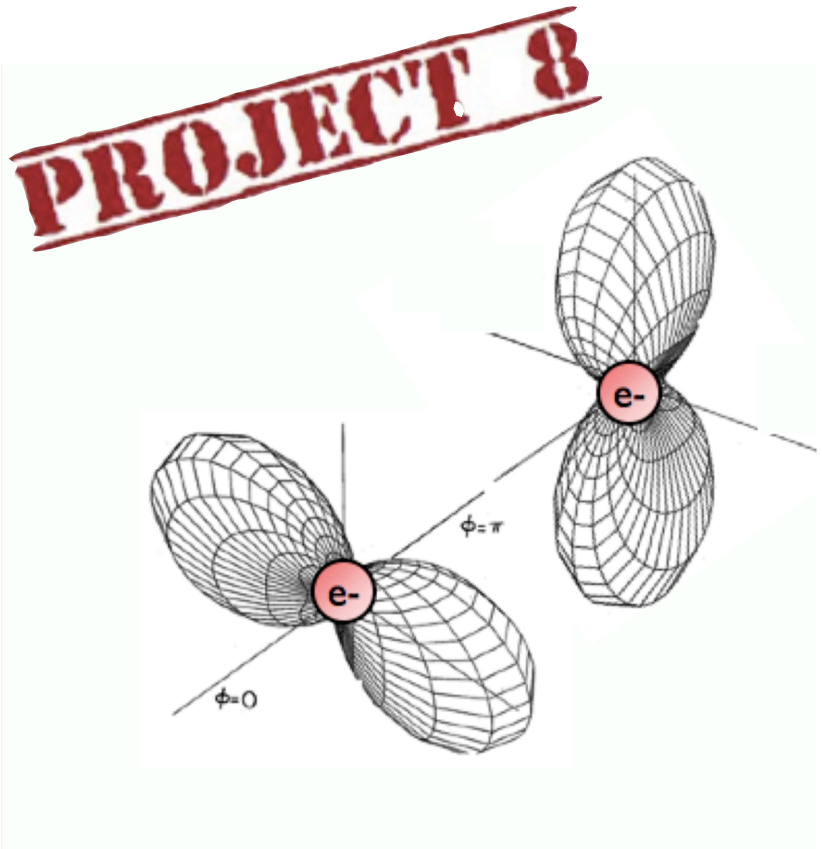
- New Isotopes:
  - Also exploring ^{183}Ho electron capture

$$^{183}Ho + e^{-} \rightarrow {}^{163}Dy* + \nu_e$$



R&D to lead to MARE 2 (eV sensitivity)

Project 8



Frequency

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

I. I. Rabi

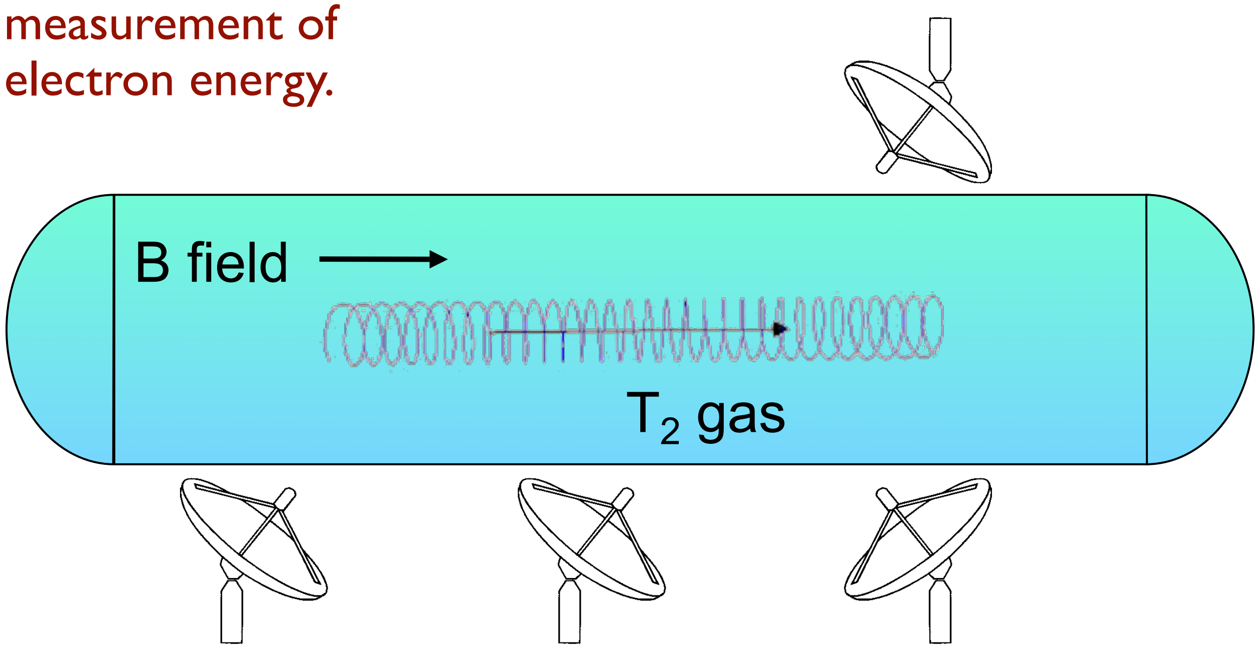
"Never measure anything but frequency."

A. L. Schawlow

- Use cyclotron frequency to extract electron energy.

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

- Non-destructive measurement of electron energy.



B. Monreal and J. Formaggio, Phys. Rev D80:051301

Advantages and Challenges

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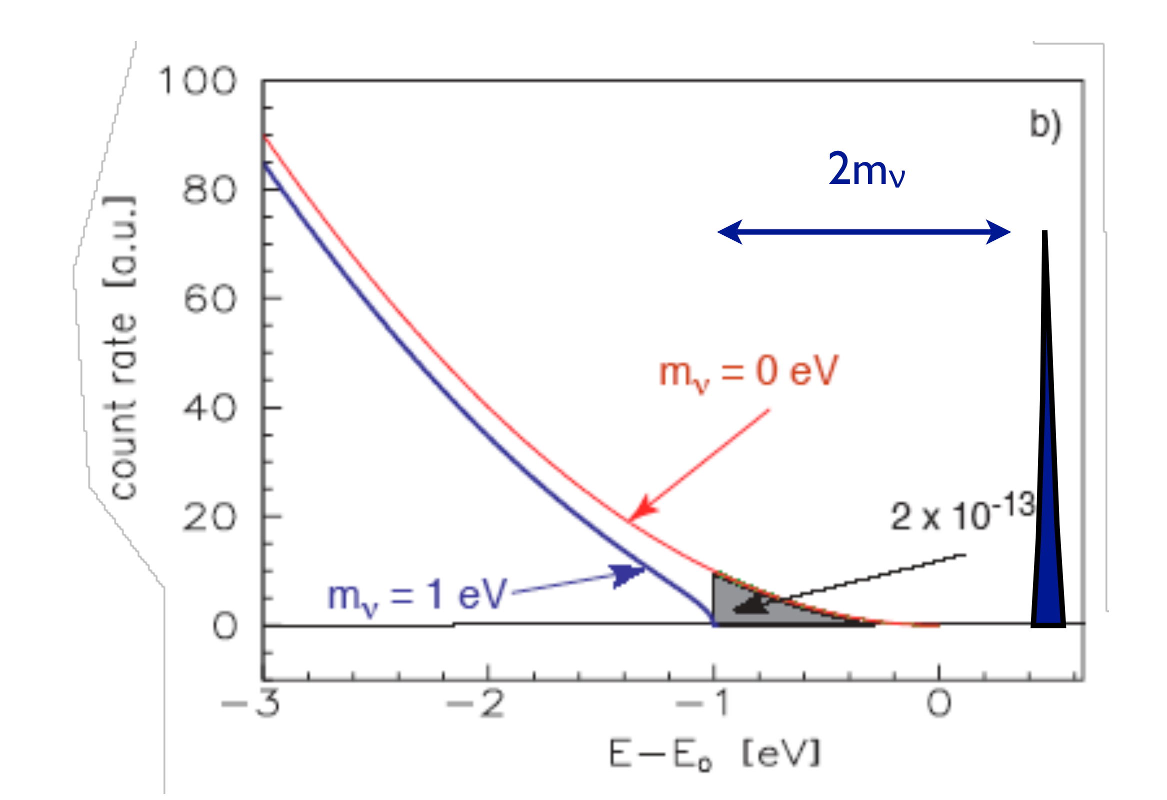

Target Mass:

Tritium provides the optimal target.

Good news: 100 grams yields 10 events/year

Bad news: High activity targets (~1 MCi) of tritium necessary.

Energy Resolution:

The signature places a signal after the beta end-point.

Good news: Initial searches need only 10x improvement.

Bad news: This is still very difficult.

Backgrounds:

Beta endpoint experiments have incredible signal-to-background separation.

Good news: Advantages with underground facilities.

Bad news: Given the necessary target mass, background rejection will be a serious challenge.