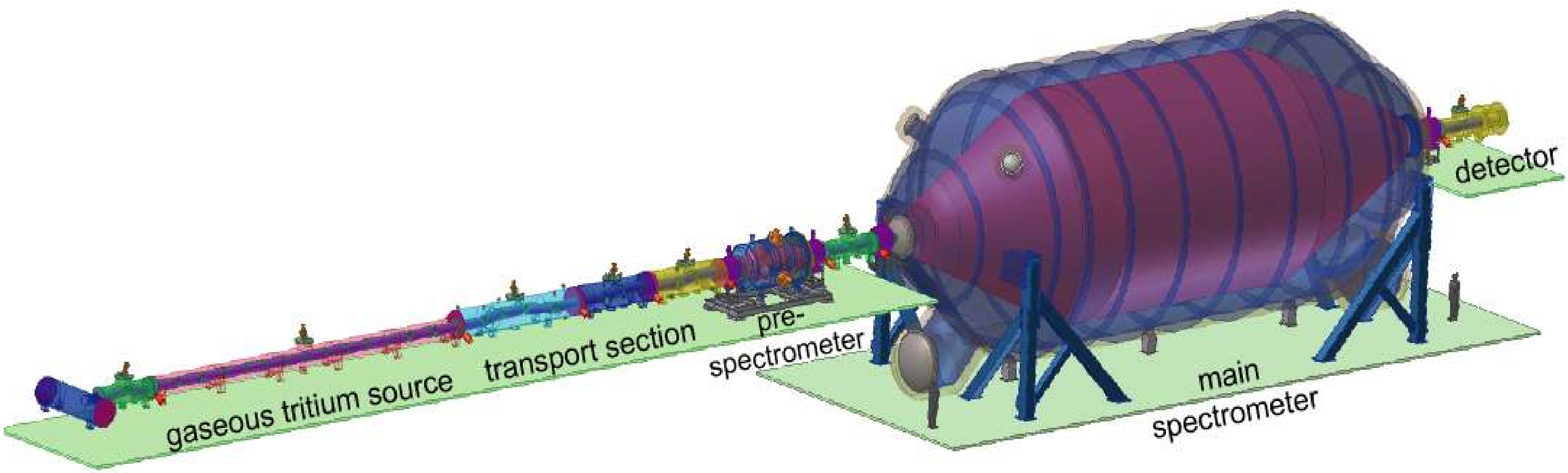
Direct Determination of Neutrino Mass with KATRIN



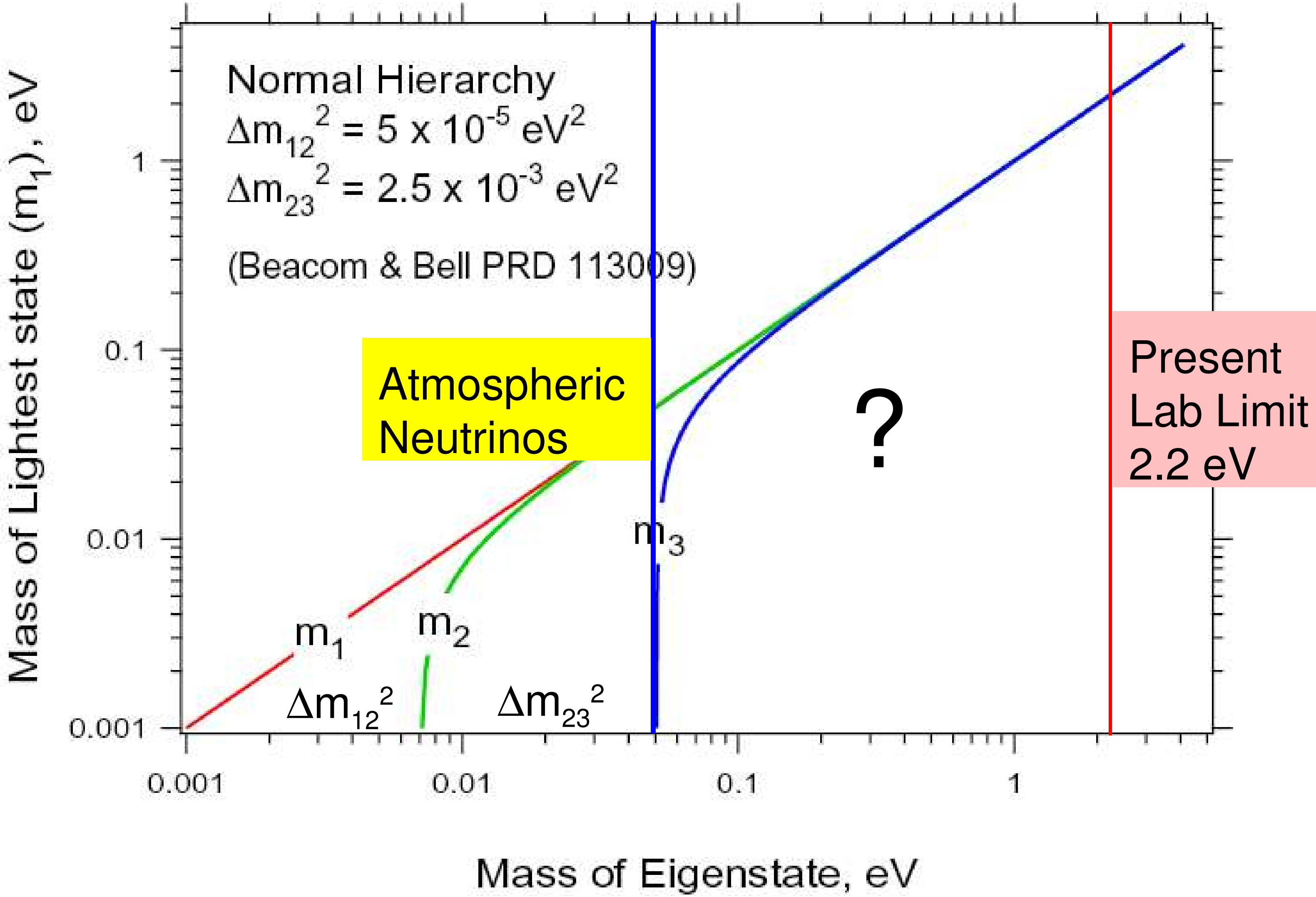
Hamish Robertson

(University of Washington)

for the KATRIN Collaboration,

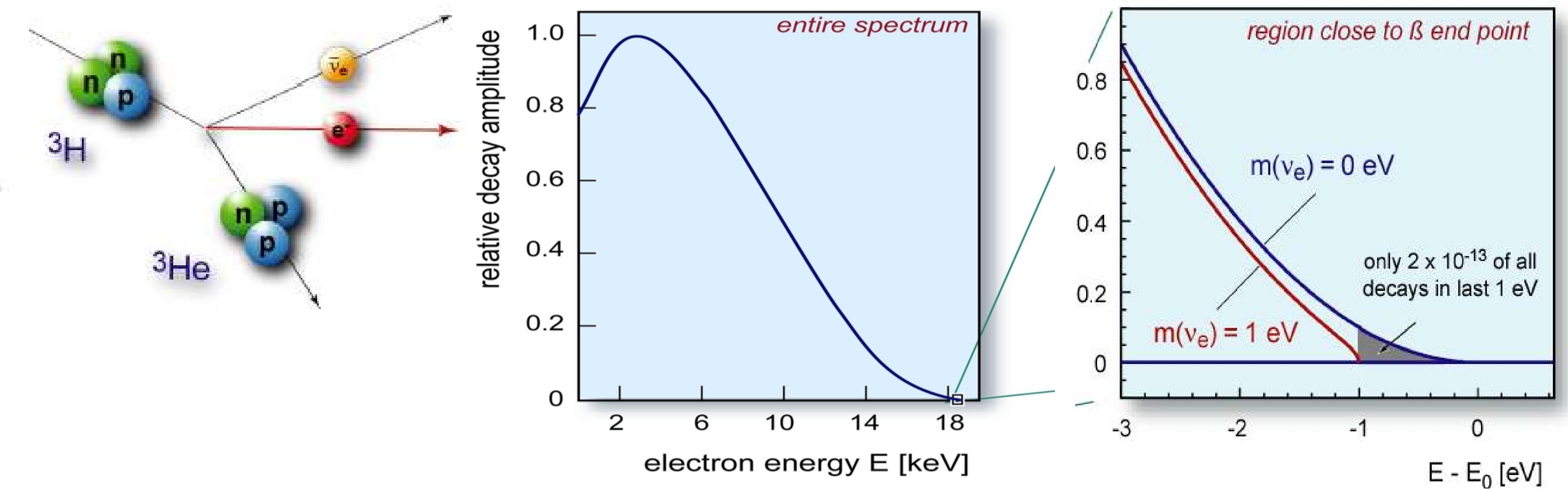
- The mass is needed for
  - Particle physics
  - Interpretation of supernova ν signal
  - Cosmology
- Oscillations link all the masses together

All masses linked to lightest by oscillations



H. Robertson

Tritium beta decay and neutrino mass



Requirements:

- Strong source
- Excellent energy resolution
- Small endpoint energy E_0
- Long term stability
- Low background rate

KATRIN Task:
Investigate Tritium endpoint with sub-eV precision

KATRIN Aim:
Improve m_ν sensitivity 10 x (2eV → 0.2eV)

What are we measuring in a Tritium experiment?

Decay rate $= |\langle f|T|i\rangle|^2$

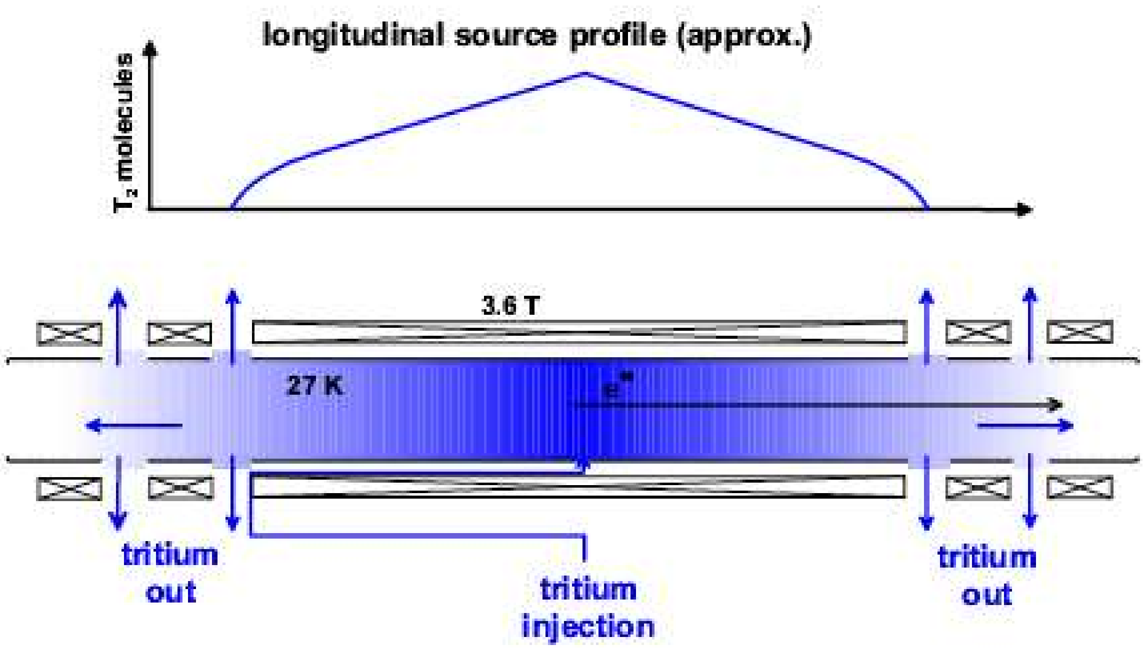
$$
\begin{aligned}
&= |\langle {}^3\mathrm{He}|\langle e|\langle\overline{\nu_e}|T|{}^3\mathrm{H}\rangle|^2 \\
&= |\sum_k U^*_{ek}\langle {}^3\mathrm{He}|\langle e|\langle\overline{\nu_k}|T|{}^3\mathrm{H}\rangle|^2 \\
&\sim pE(E-E_0)^2\sum_k |U_{ek}|^2\left(1-\frac{m_k^2}{(E-E_0)^2}\right)^{1/2}
\end{aligned}
$$

We see a sum of beta spectra weighted by $|U_{ek}|^2$.

When $m_1 \simeq m_2 \simeq m_3 = m_\nu$, **reduces to** m_ν^2 **formula, as in the old days:**

$$
\sim pE(E-E_0)^2\left(1-\frac{m_\nu^2}{(E-E_0)^2}\right)^{1/2}
$$

Los Alamos type Windowless Source

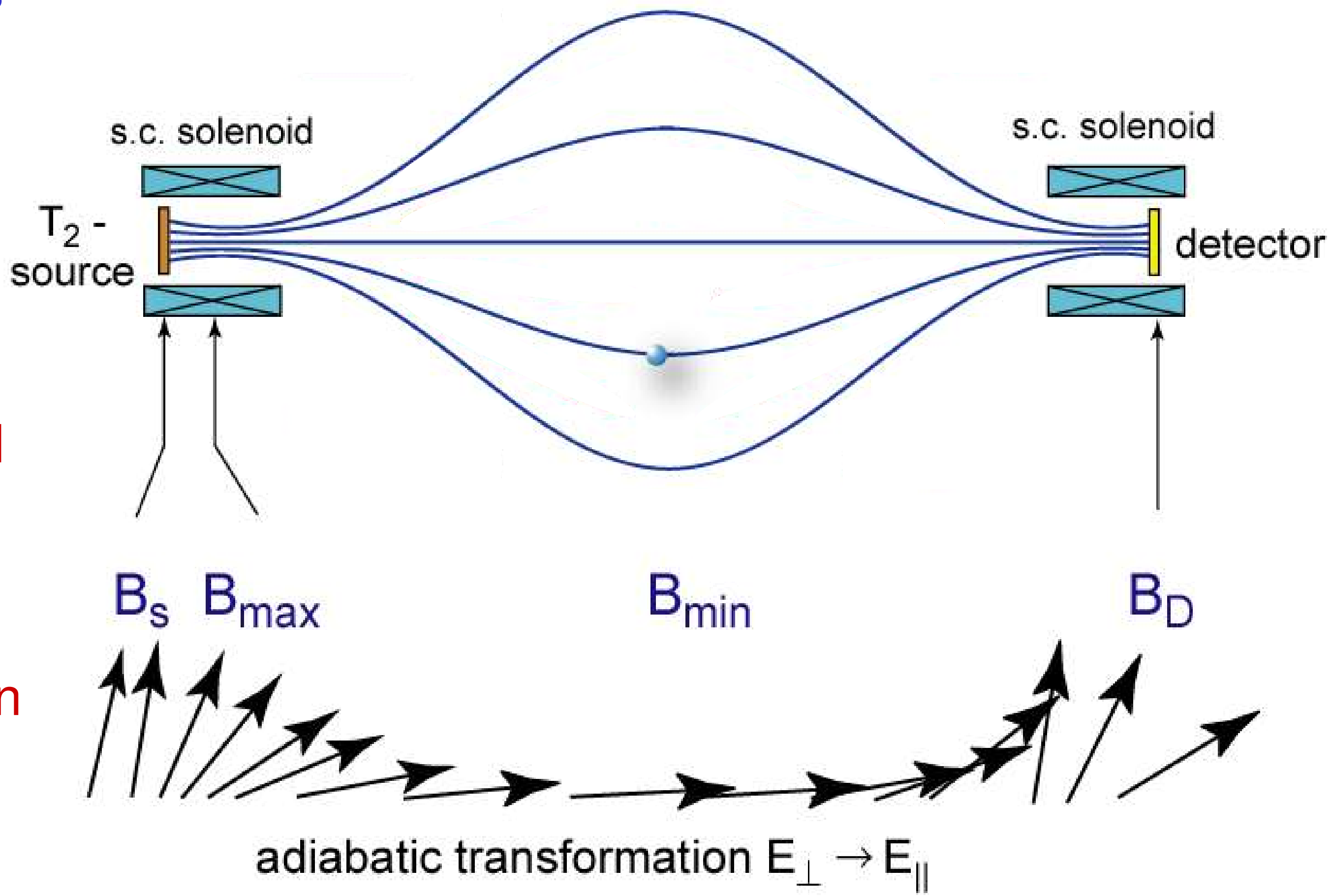


Principle of MAC-E Filter

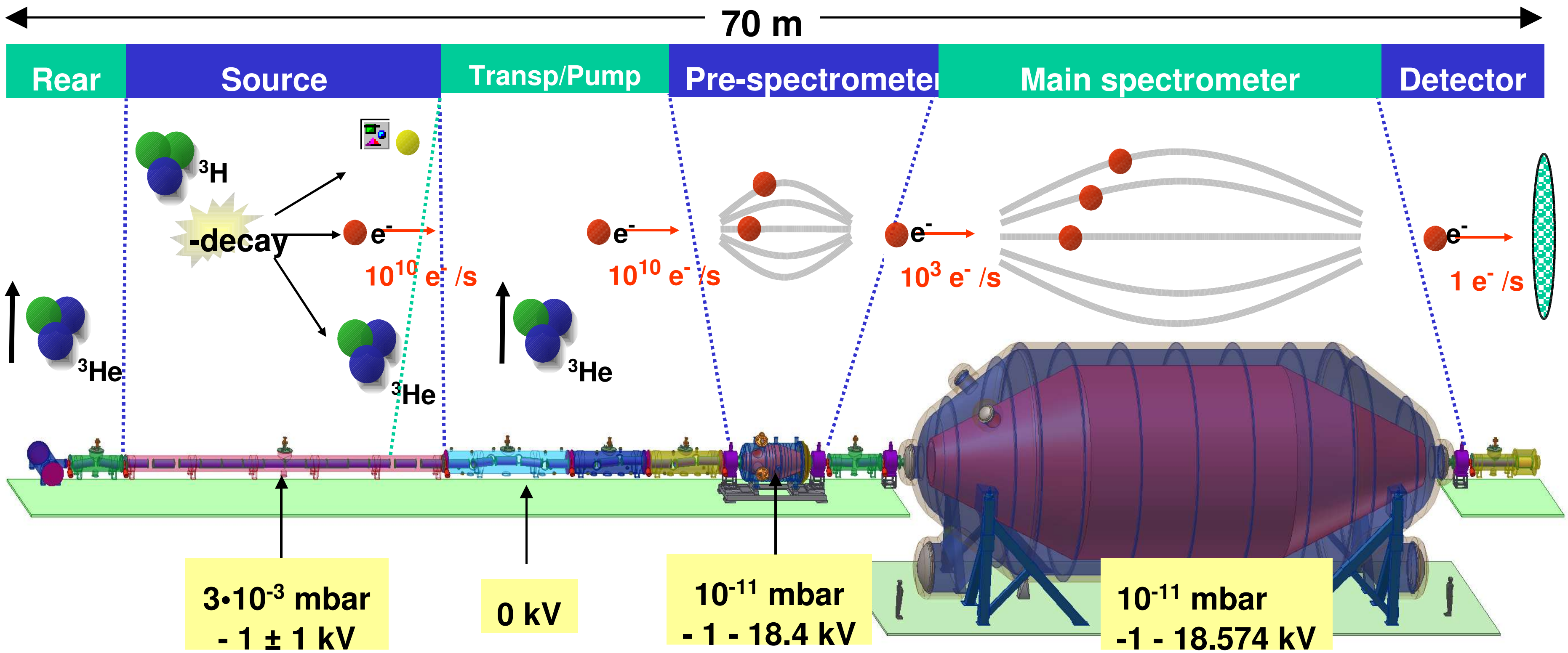
Adiabatic magnetic guiding of β´s along field lines in stray B-field of s.c. solenoids:
B_{max} = 6 T
B_{min} = 3×10^{-4} T

Energy analysis by static retarding E-field with varying strength:

High pass filter with integral β transmission for E>qU



Experimental Setup



Rear System:
Monitor source parameters

Source:
Provide the required tritium column density

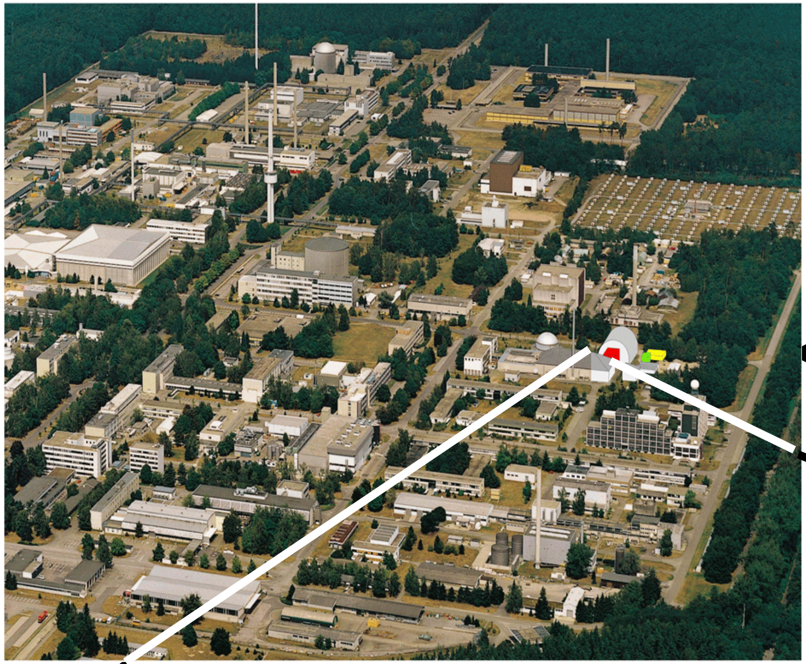
Transp. & Pump system:
Transport the electrons, adiabatically and reduce the tritium density significantly

Pre-spectrometer:
Rejection of low-energy electrons and adiabatic guiding of electrons

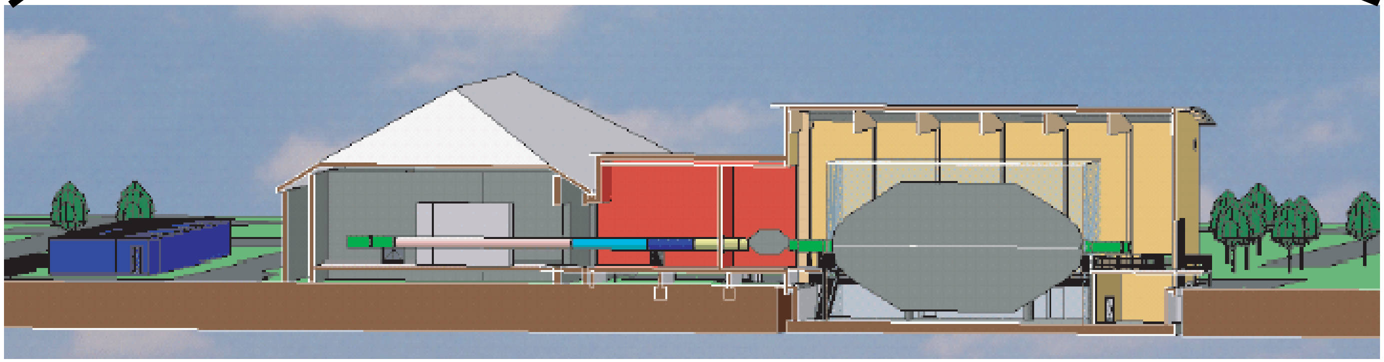
Main-spectrometer:
Rejection of electrons below endpoint and adiabatic guiding of electrons

Detector:
Count electrons and measure their energy

KATRIN at Forschungszentrum Karlsruhe (FZK)



- TLK (part of FZK) is the only lab worldwide with a closed tritium cycle
- Built to demonstrate the fuel cycle for fusion (ITER)
- Provides all the necessary infrastructure for processing
- Licensed amount of 40 g, current inventory 25 g

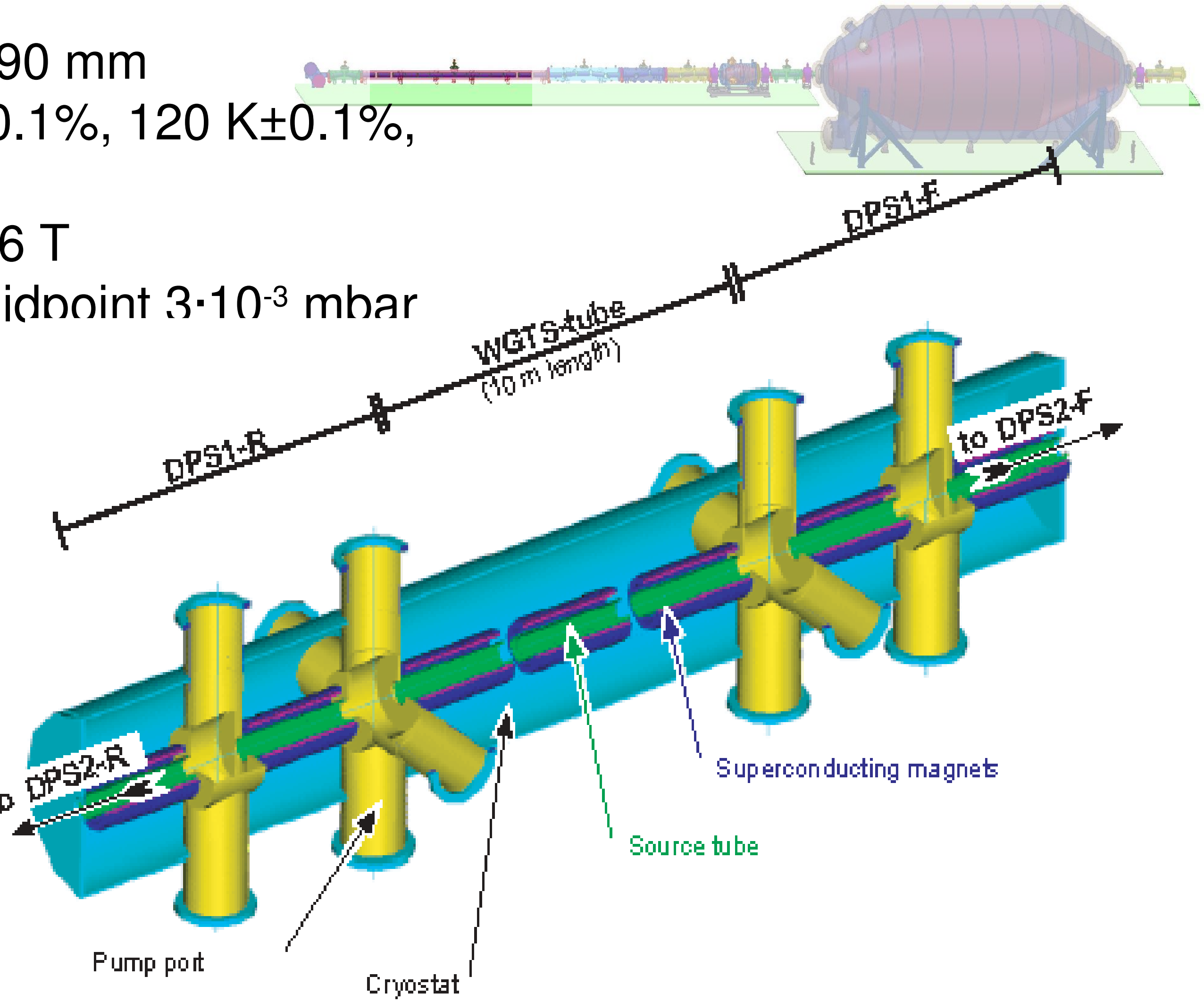


Windowless Gaseous Tritium Source WGTS

Source parameters:

- Beam tube, L= 10 m, d=90 mm
- Beam tube temp. 27 K±0.1%, 120 K±0.1%, 550 K
- Central magnetic field 3.6 T
- Tritium injection at the midpoint $3 \cdot 10^{-3}$ mbar
- Source column density:

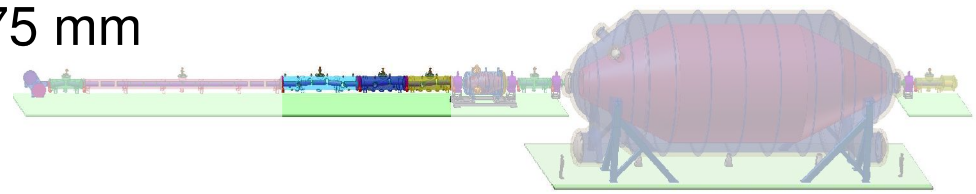
  $5 \cdot 10^{17}$ mol/cm^2

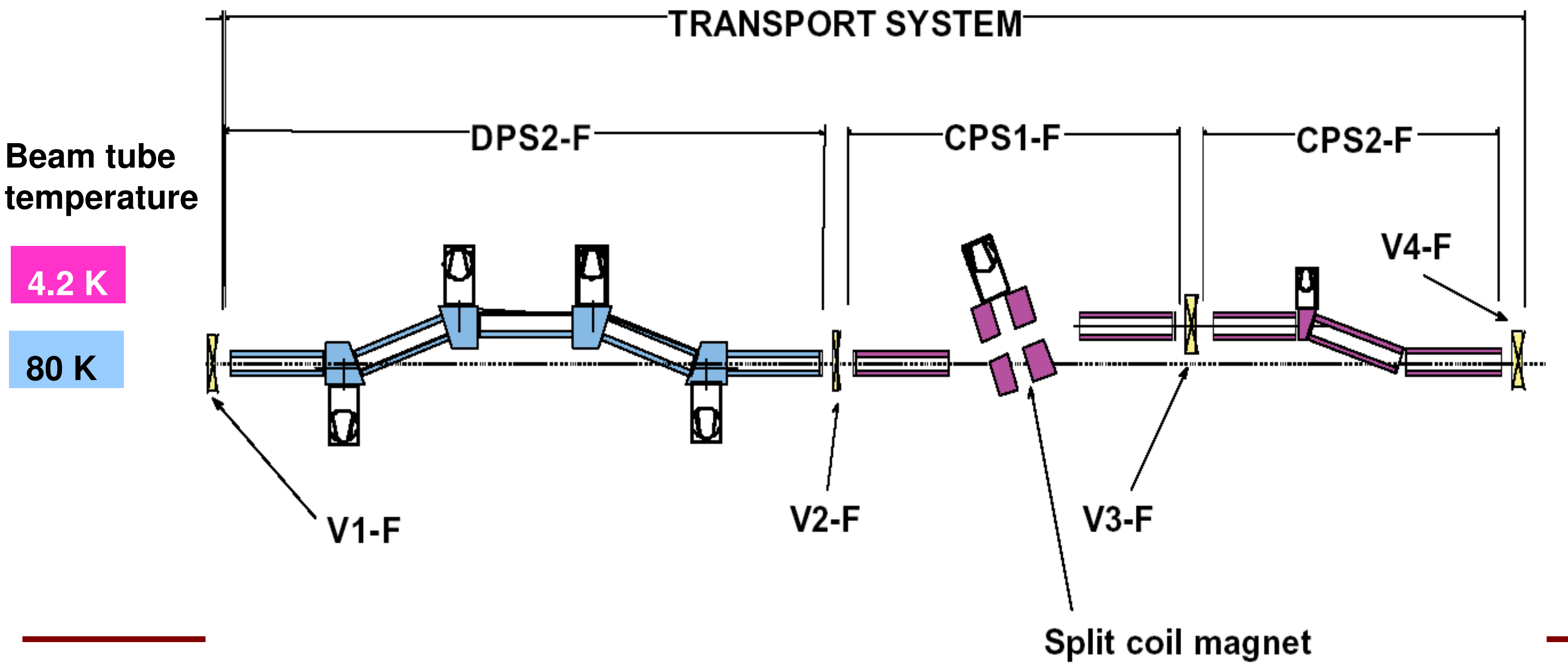


Transport Section

Transport section parameters:

- Beam tube sections, L= 1 m, d=75 mm
- Central magnetic field 5.6 T
- Total reduction factor of 10^{11}
- Differential pumping by TMPs
- Cryotrapping at 4.2 K by Argon frost

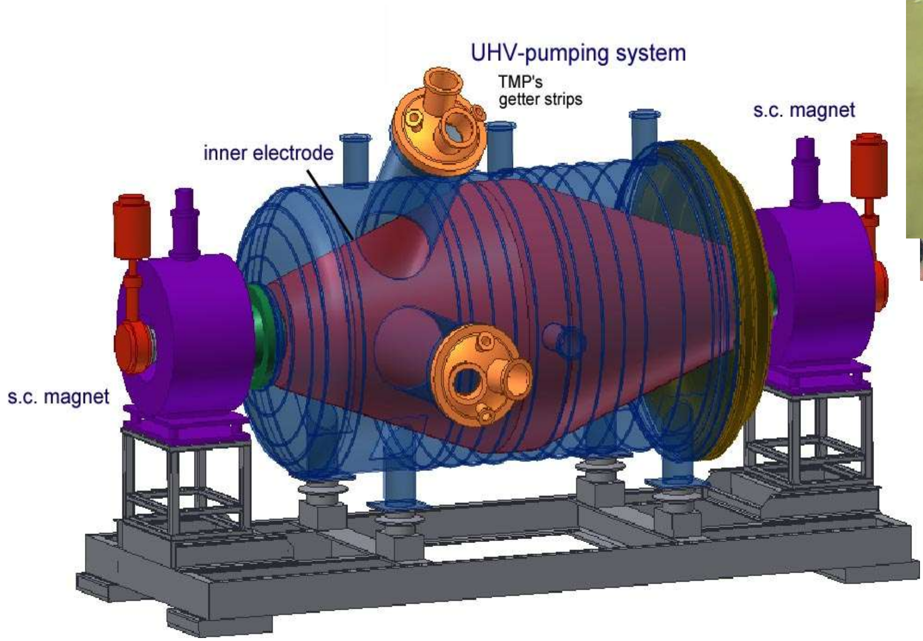




Pre-spectrometer

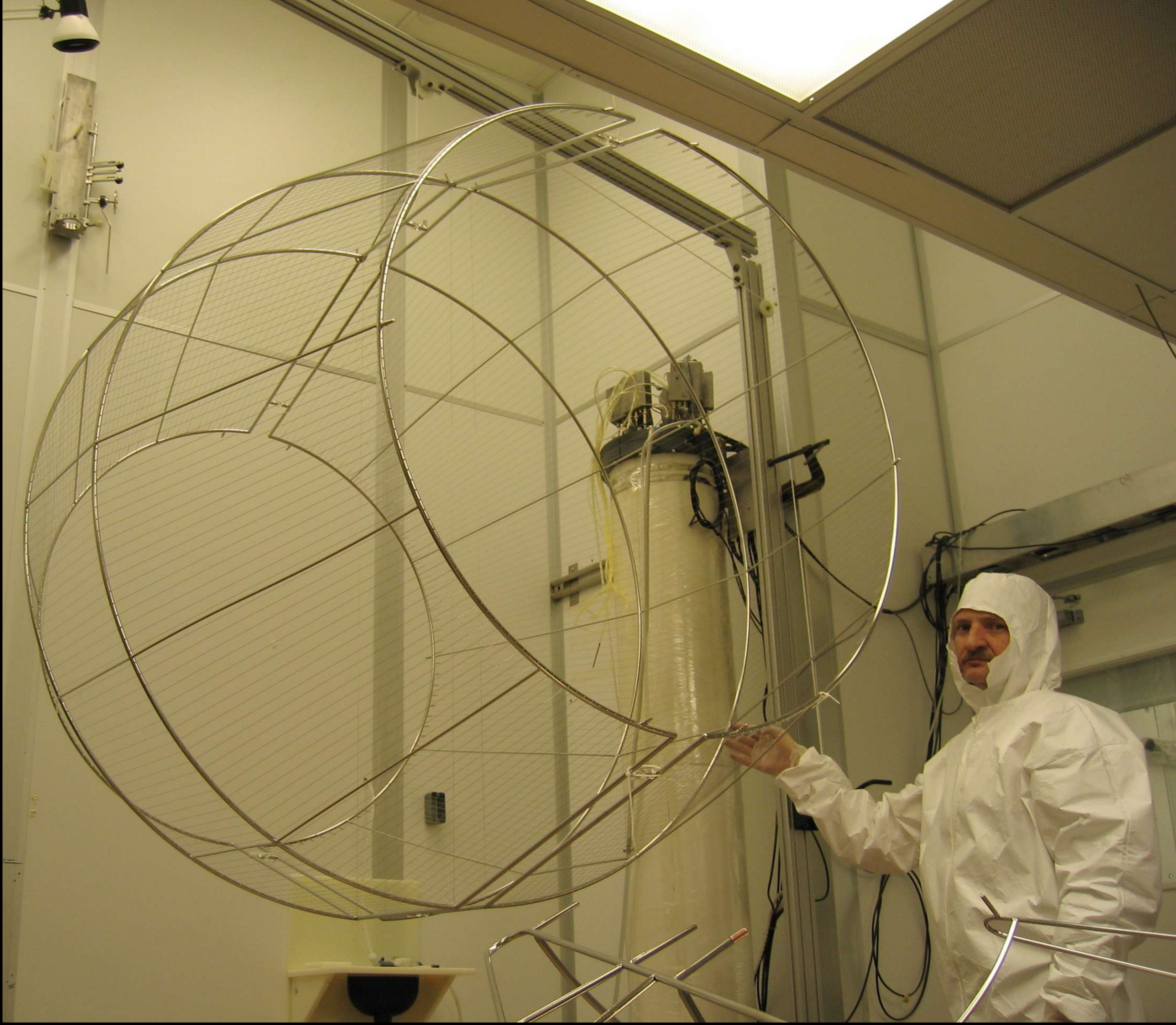
Parameters:

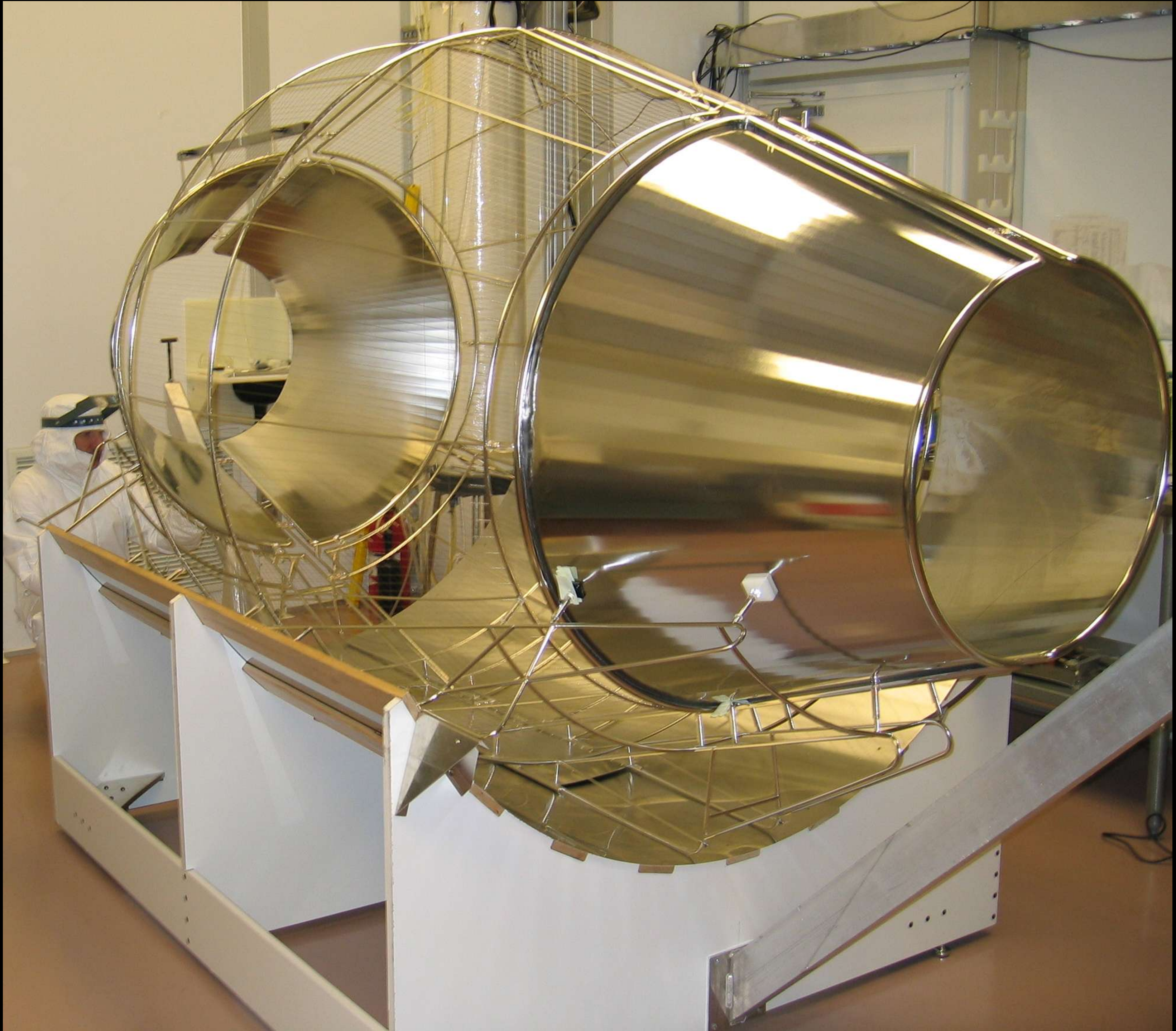
•Length: 3.4 m (flange to flange)
•Diameter:1.7 m
•Vacuum: < 10^{-11} mbar
•Material: Stainless steel
•Magnets: 4.5 T



Status:

•Vacuum $7 \cdot 10^{-11}$ mbar (without getter)
•Outgassing $7 \cdot 10^{-14}$ mbar l/ s cm^2
•Measurements scheduled for 2005



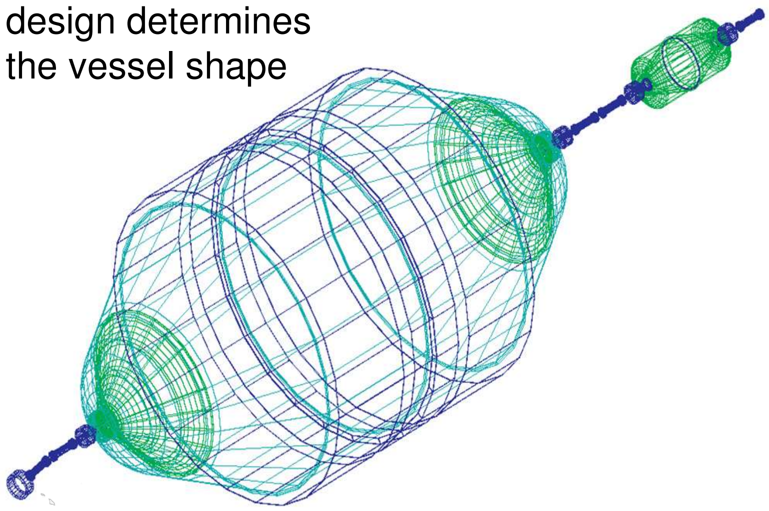


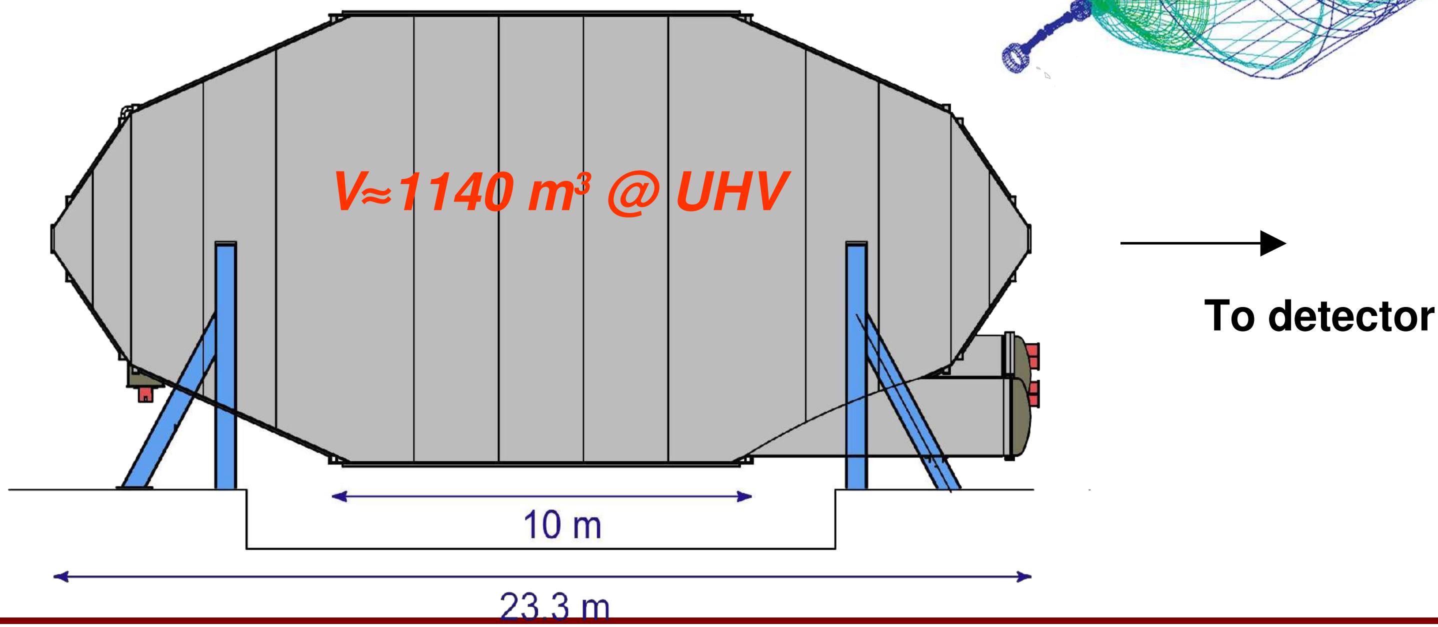
Main Spectrometer

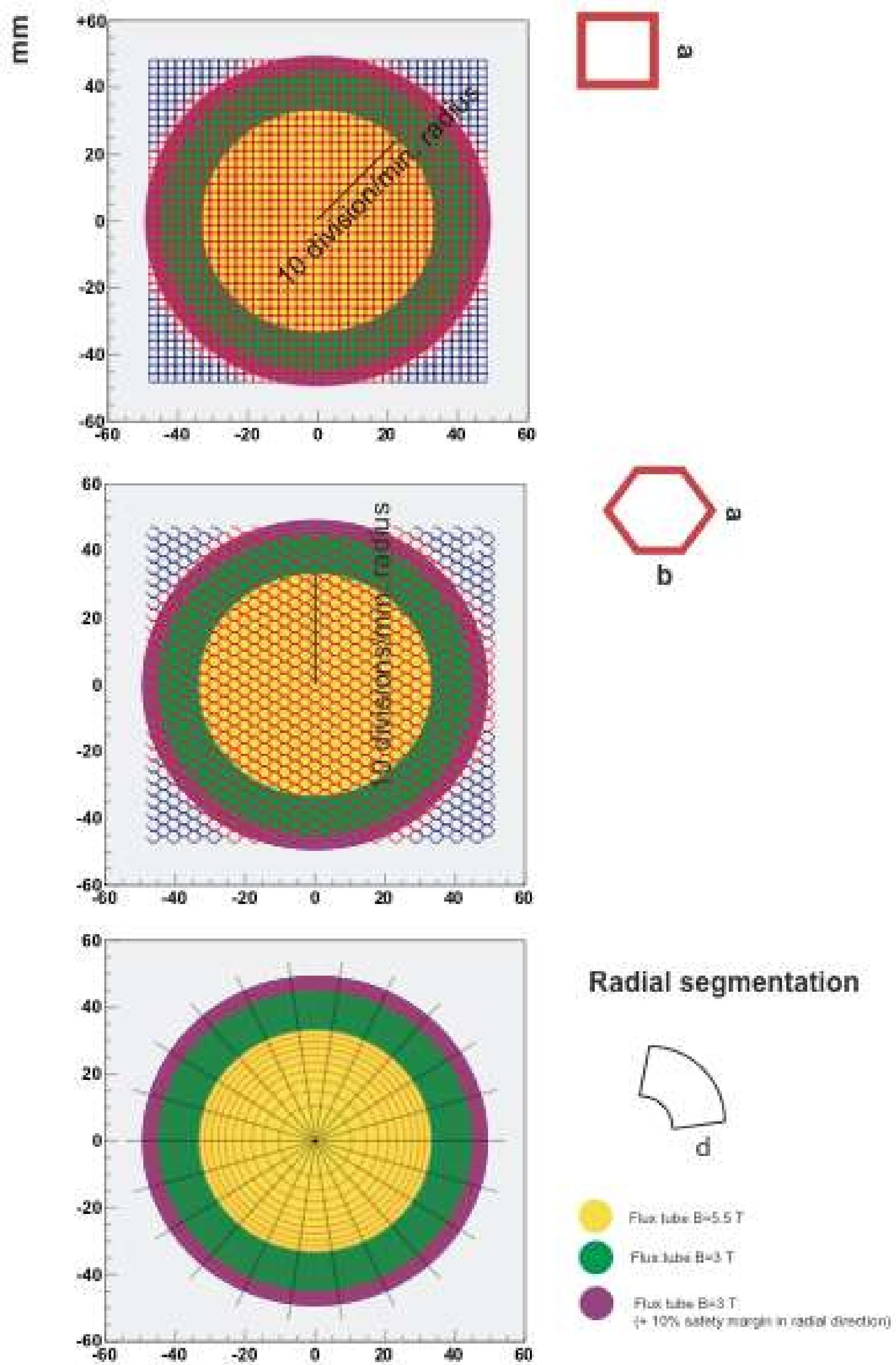
Main spectrometer parameters:

- Length (from flange to flange): about 24 m.
- Inner Diameter (cylindrical part): 9.80 m.
- Wall outgassing rate < 10^{-12} (mbar·l/s·cm^2).
- Ultimate pressure < 10^{-11} mbar .
- Temperatures between –20 °C and 350 °C.
- Voltage of 18.6 kV with 1 ppm accuracy

Electromagnetic design determines the vessel shape







Detector

Requirements for detector:

- Background: < 1 mHz
- Post acceleration option
- Segmented detection
- Sensitive to e^- < 100 keV
- Energy res. < 600 eV

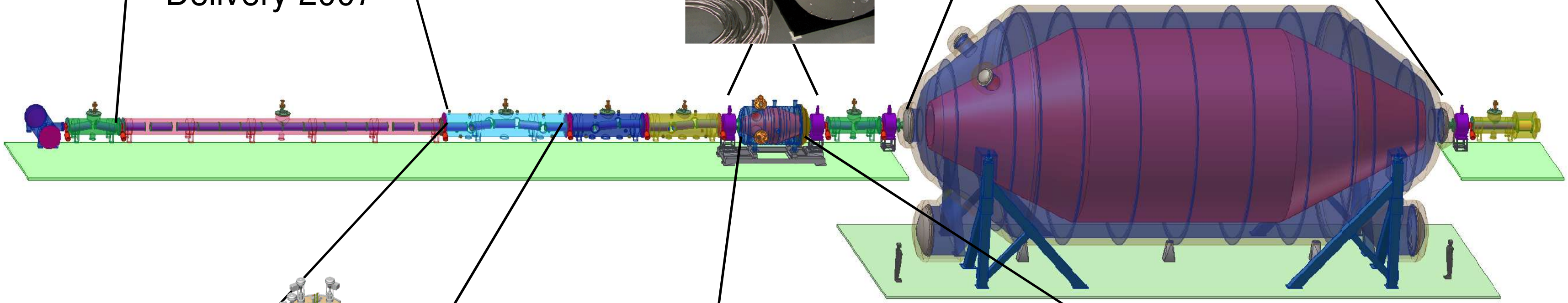
Prespectrometer detector

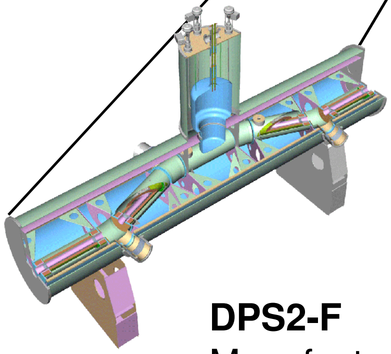
Status of KATRIN Hardware Activities

Pre-spectrometer magnets
Delivered in February 2005

Main spectrometer
Final designs by MAN-DWE
Delivery early 2007

WGTS
Manufacturing Started
Delivery 2007

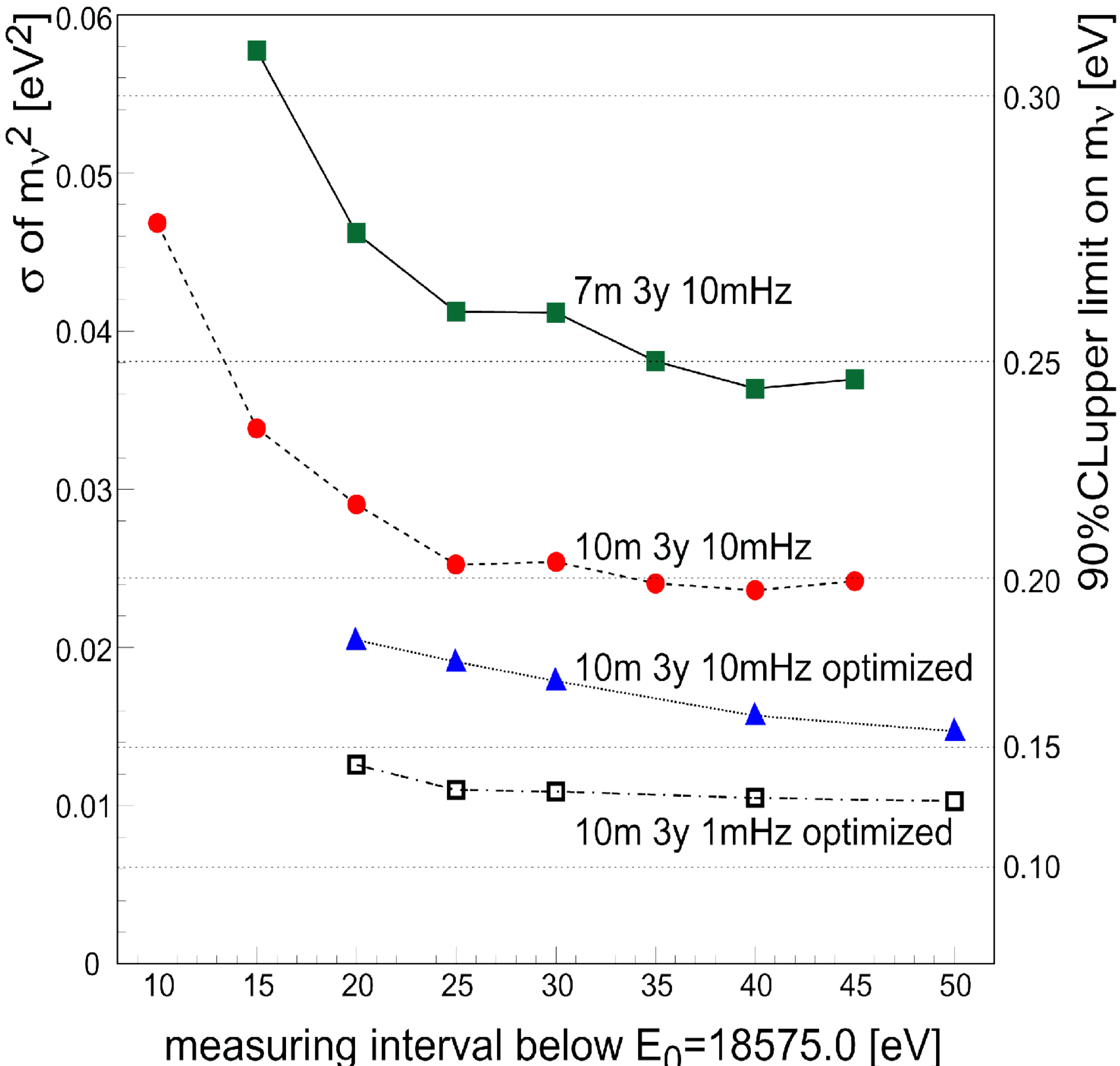




DPS2-F
Manufacturing started
Delivery 2006

Pre-spectrometer
Delivered in Oct. 2003
Vacuum tests started May 2004
El. mag. test start 2006

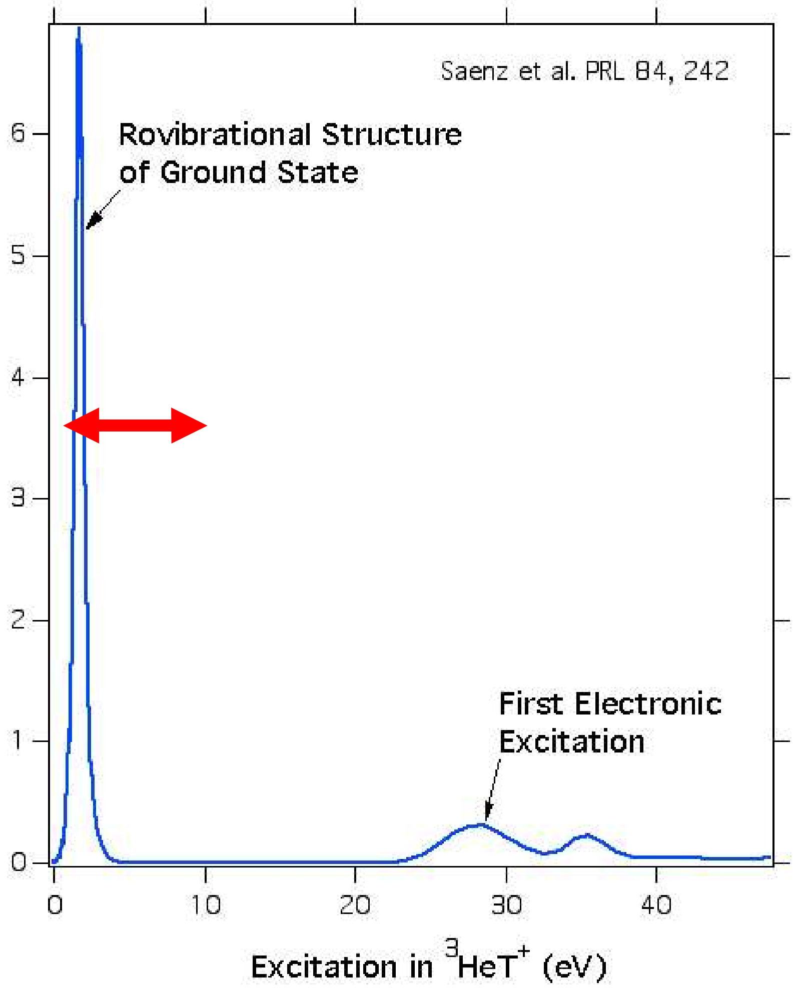
KATRIN Sensitivity



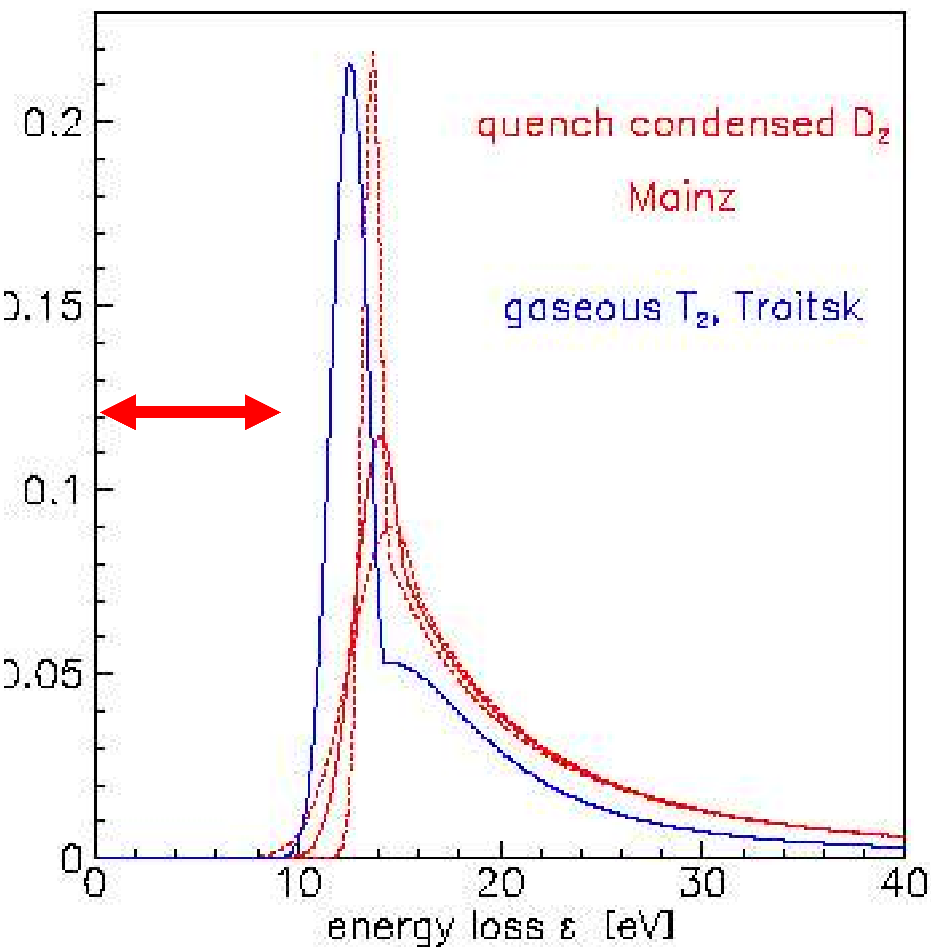
- Improved over original design (7 m diameter main spectrometer, source luminosity)
- Reduction in background
- Only shows statistical uncertainty

A window to work in

Molecular Excitations



Energy loss function

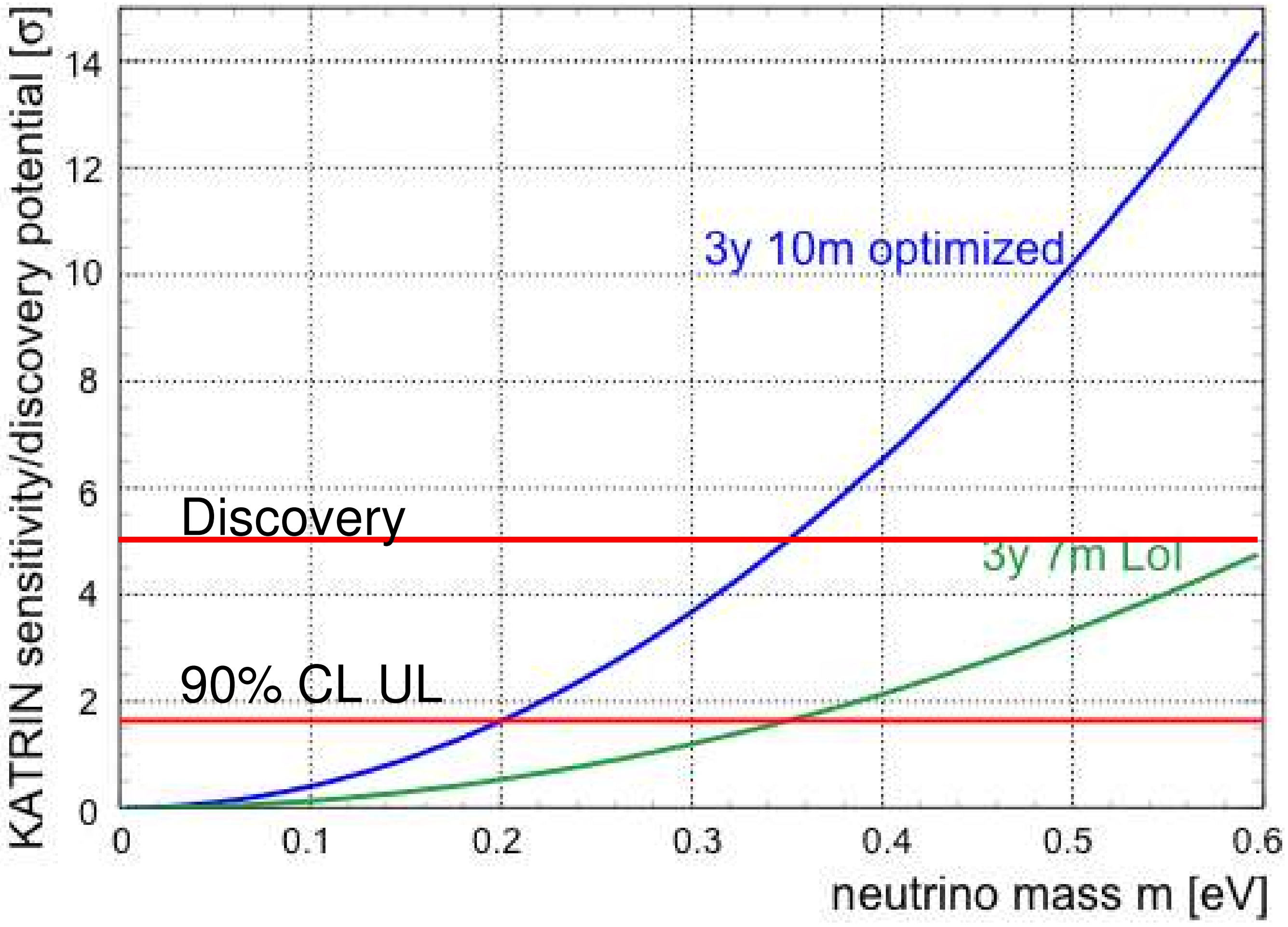


Systematic Uncertainties

source of systematic shift	achievable/projected accuracy	systematic shift $\sigma_{syst}(m_\nu^2)[10^{-3}\mathrm{eV}^2]$
description of final states	$f < 1.01$	< 6
T^- ion concentration $n(T^-)/n(T_2)$	$< 2 \cdot 10^{-8}$	< 0.1
unfolding of the energy loss function (determination of f_{res})		< 2 < 6 (including a more realistic e-gun model)
monitoring of ρd $[E_0 - 40\,\mathrm{eV}, E_0 + 5\,\mathrm{eV}]$	$\Delta\epsilon_T/\epsilon_T < 2 \cdot 10^{-3}$ $\Delta T/T < 2 \cdot 10^{-3}$ $\Delta\Gamma/\Gamma < 2 \cdot 10^{-3}$ $\Delta p_{inj}/p_{inj} < 2 \cdot 10^{-3}$ $\Delta p_{ex}/p_{ex} < 0.06$	$< \frac{\sqrt{5} \cdot 6.5}{10}$
background slope	$< 0.5\,\mathrm{mHz/keV}$ (Troitsk)	< 1.2
HV variations	$\Delta HV/HV < 3\,\mathrm{ppm}$	< 5
potential variations in the WGTS	$\Delta U < 10\,\mathrm{meV}$	< 0.2
magnetic field variations in WGTS	$\Delta B_S/B_S < 2 \cdot 10^{-3}$	< 2
elastic e^- - T_2 scattering		< 5
identified syst. uncertainties	$\sigma_{syst,tot} = \sqrt{\sum \sigma_{syst}^2} \simeq 0.01\,\mathrm{eV}^2$	

TABLE IV: Summary of sources of systematic errors on m_ν^2 , the achievable or projected accuracy of experimental parameters (stabilization) and the individual effect on m_ν^2 for an analysis interval of $[E_0 - 30\,\mathrm{eV}, E_0 + 5\,\mathrm{eV}]$ if not stated otherwise.

Improved sensitivity with larger system



Conclusions

- KATRIN can measure neutrino mass directly via kinematics of beta decay -- model independent
- Improvement of order of magnitude over previous best
- Challenging goal of $m_\nu < 0.2$ eV (90% C.L.) looks achievable
- German funding (33.5 M€) is in place
- US DOE funding requested (~$2M)
- On schedule for data collection beginning 3Q 2009

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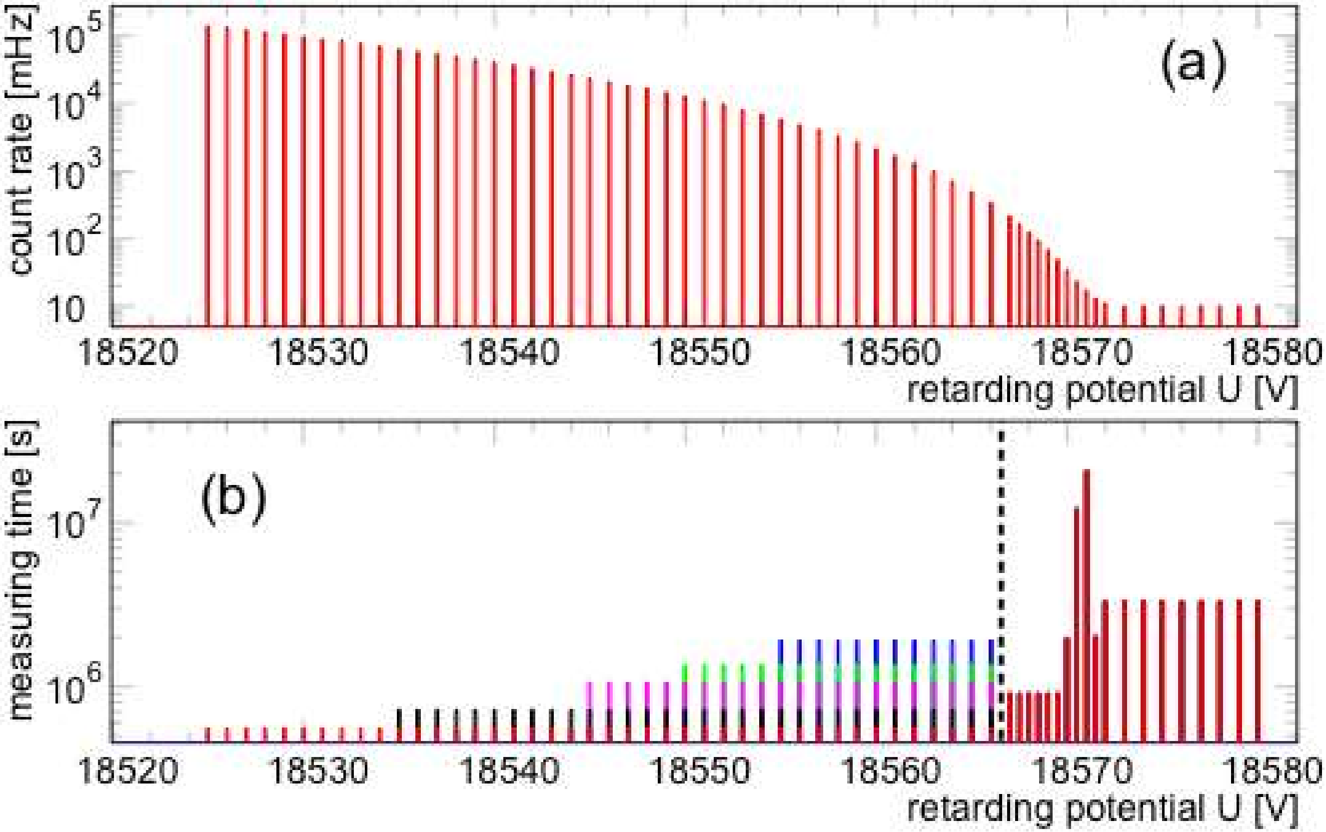
UW is recruiting faculty and postdocs in neutrino physics!
http://www.phys.washington.edu/

Optimized run time at each energy



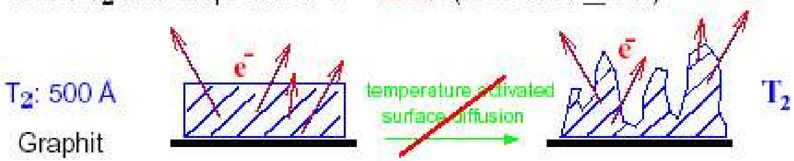
Challenges

- Vacuum of 10^{-11} mbar in the main spectrometer of over 1000 m^3
- Controlling tritium density to 0.1% precision
- Maintaining tritium gradient of 10^{11} from WGTS to main spectrometer to avoid contamination
- Detector background of < 1 mHz
- Heating and cooling the set-up safely to reach vacuum

Data taking in 1998 and 1999

6 Runs (labelled Q3–Q8),
7 months measurement time in total:
(possible due to automation of apparatus)

- Increasing of signal by a factor of 5
  Decreasing of background by a factor of 2
  $\rightarrow 10\times$ better signal/background
- Lower T_2 film temperature: T = 1.86 K (instead of $\geq$ 3 K)

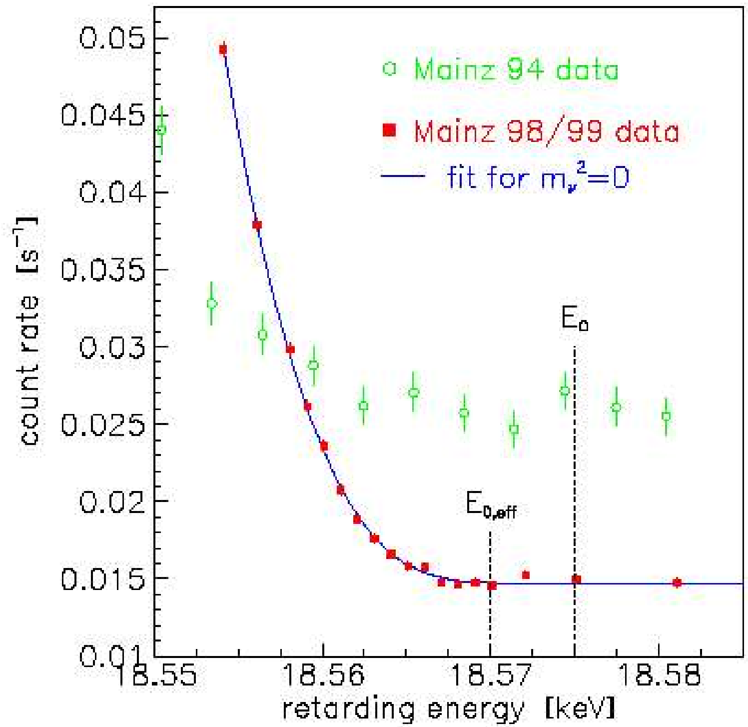


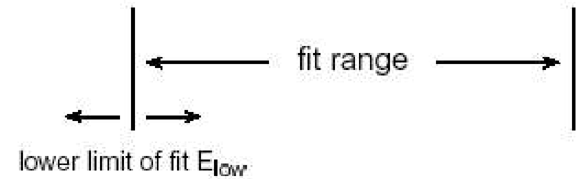
(larger energy losses)
(problems of 1991 and 1994)
($\rightarrow$ negative m_ν^2 value problem)

L. Fleischmann *et al.*, J. Low Temp Phys. **119** (2000) 615,
L. Fleischmann *et al.*, Eur. Phys. J. **B16** (2000) 521

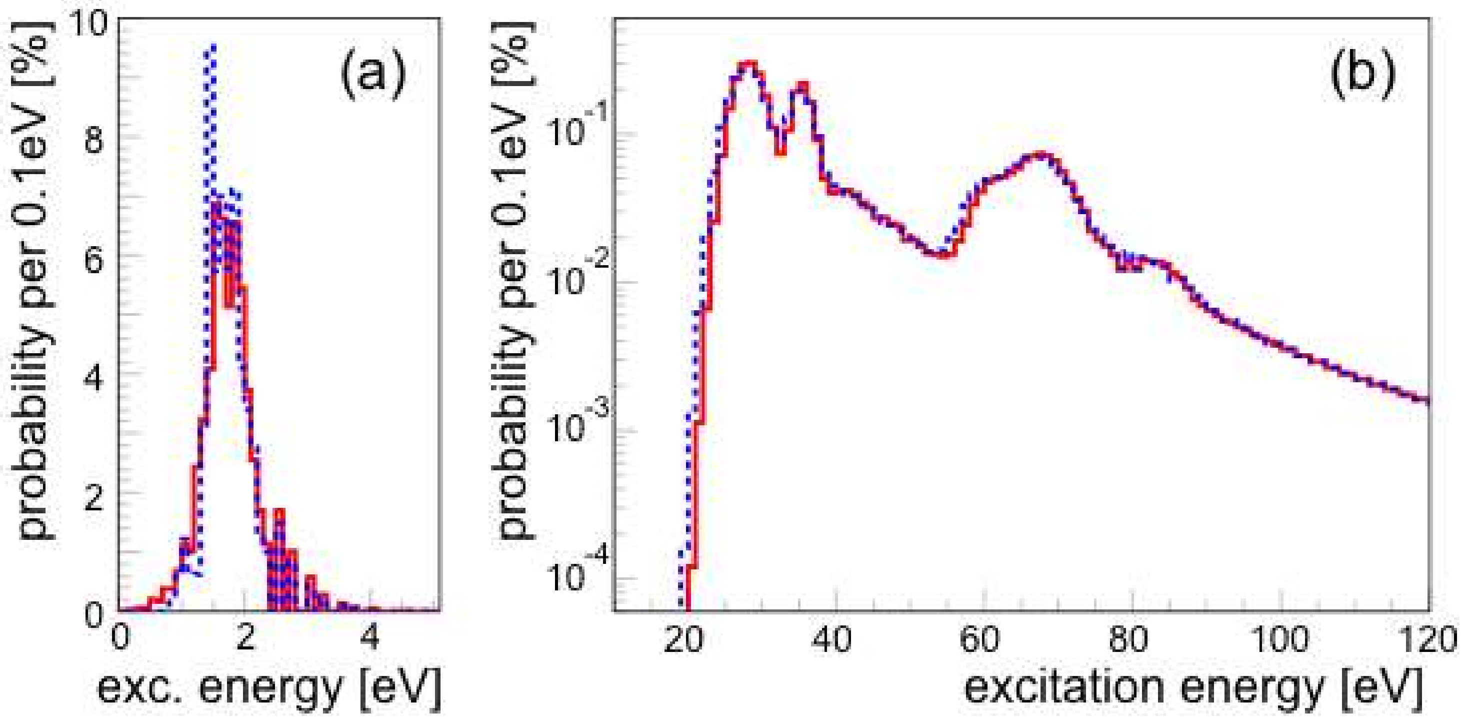
- Better spectrometer resolution: ΔE = 4.8 eV
  (instead of 6.5 eV)
- More stable background:
  HF pulsing on electrodes inbetween measurements from Q5 on

Mainz 1998 + 1999 measurements: Q3 – Q8





Final States

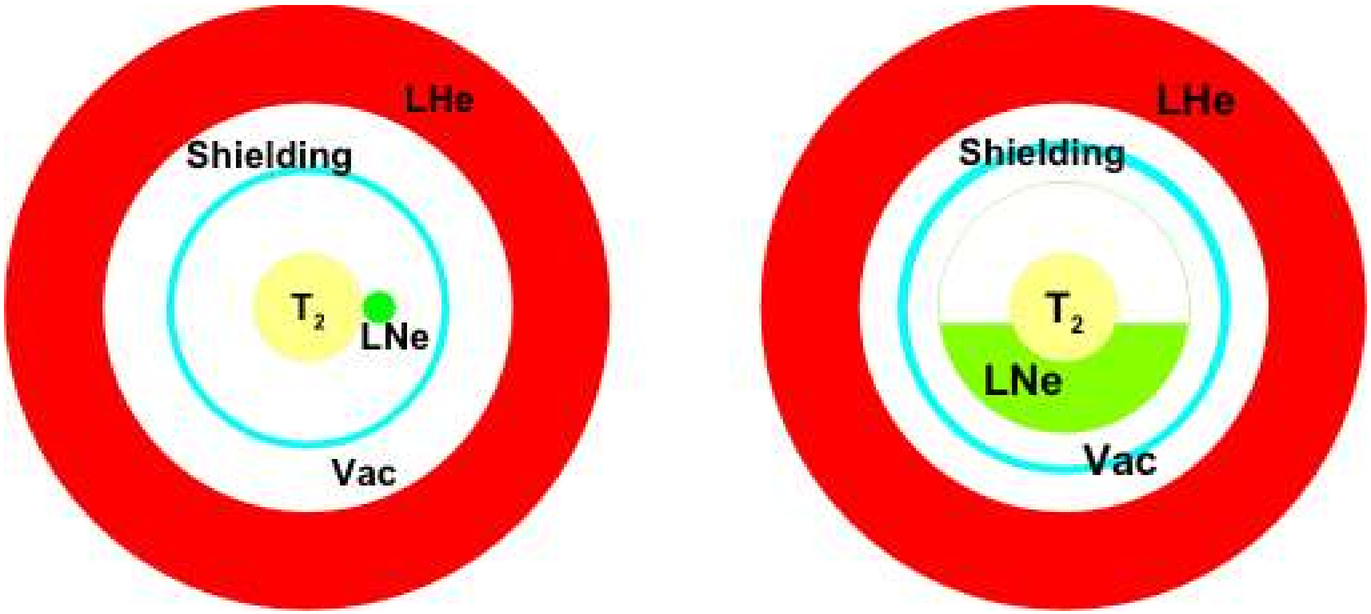


Red: $^3HeT^+$

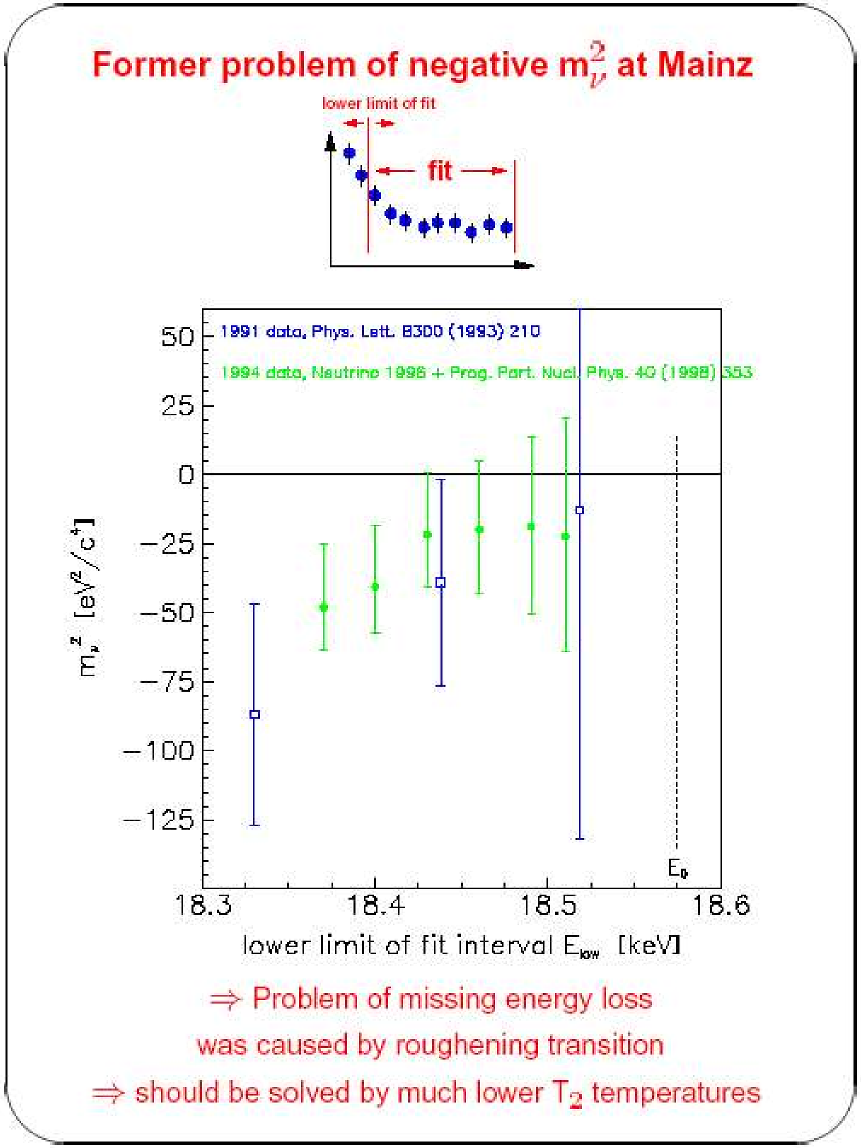
Blue: $^3HeH^+$

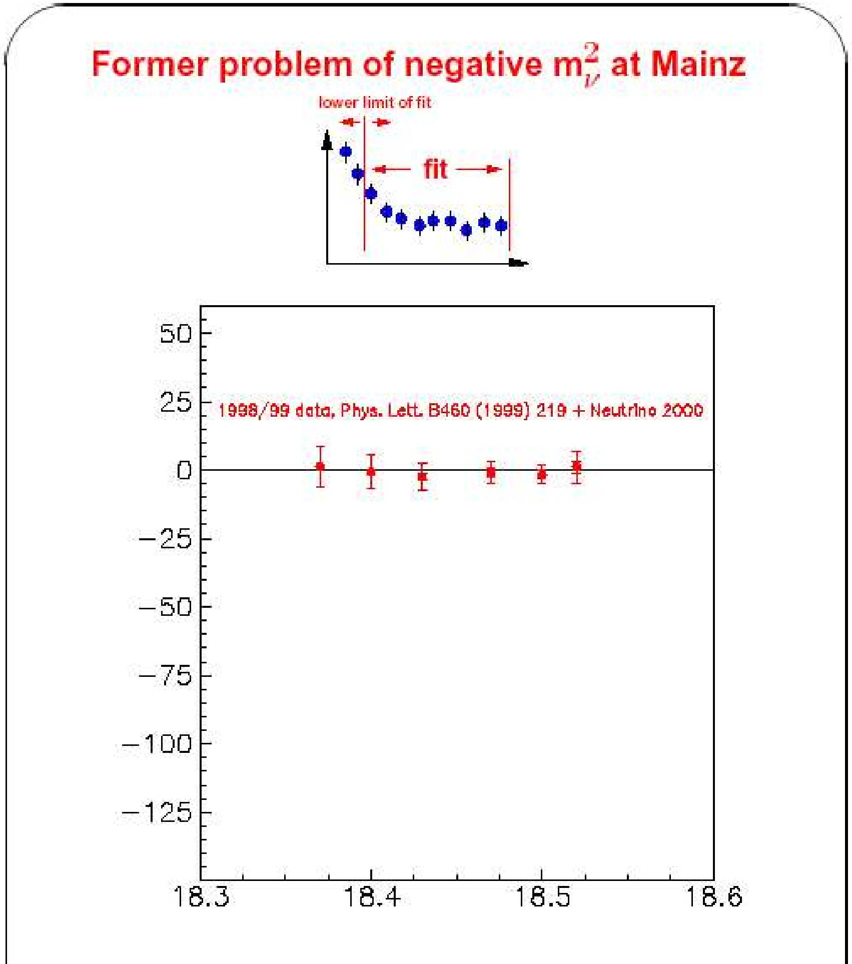
1% uncertainty in rovib spectrum → $\Delta m^2 = 6 \times 10^{-3}\ eV^2$

Source cooled with LNe at 27-30K



Mainz Systematics Resolved

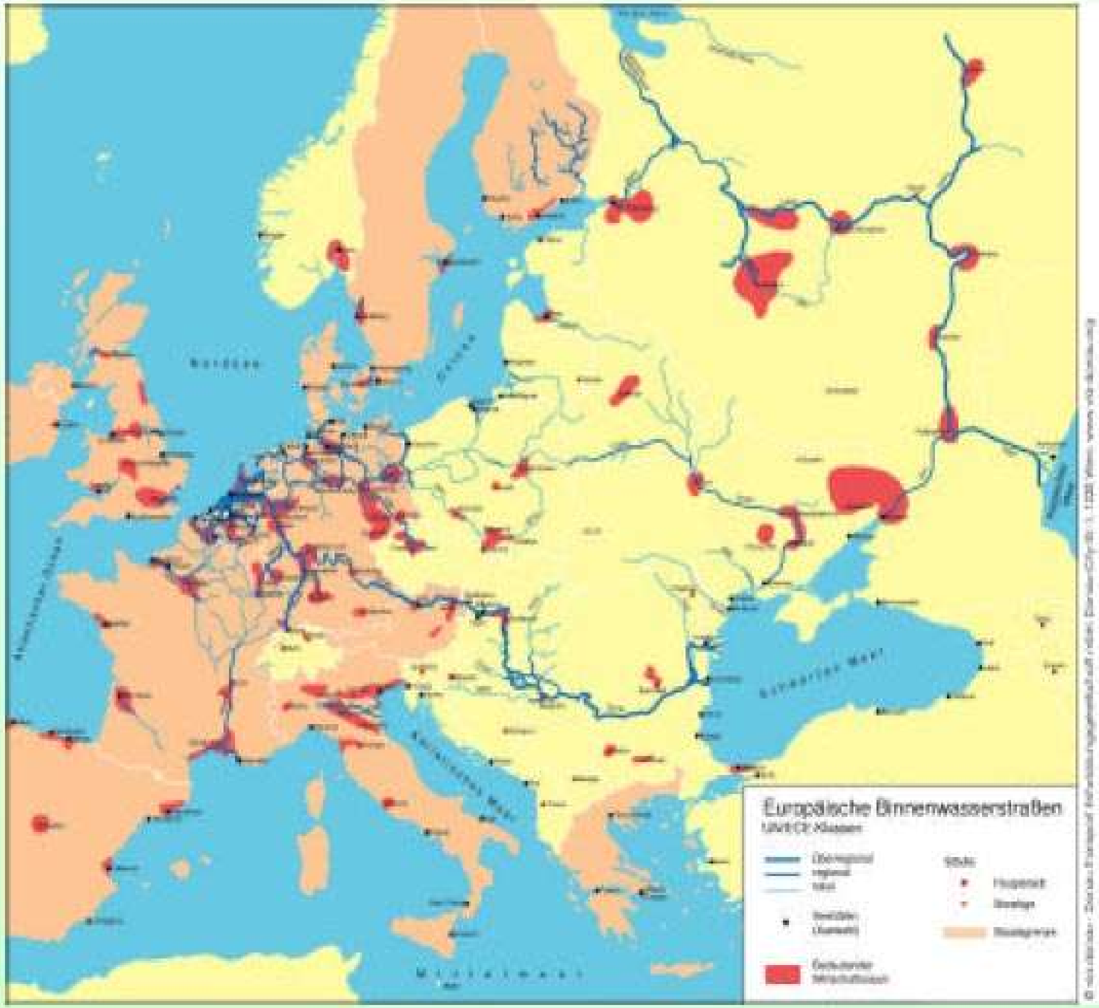




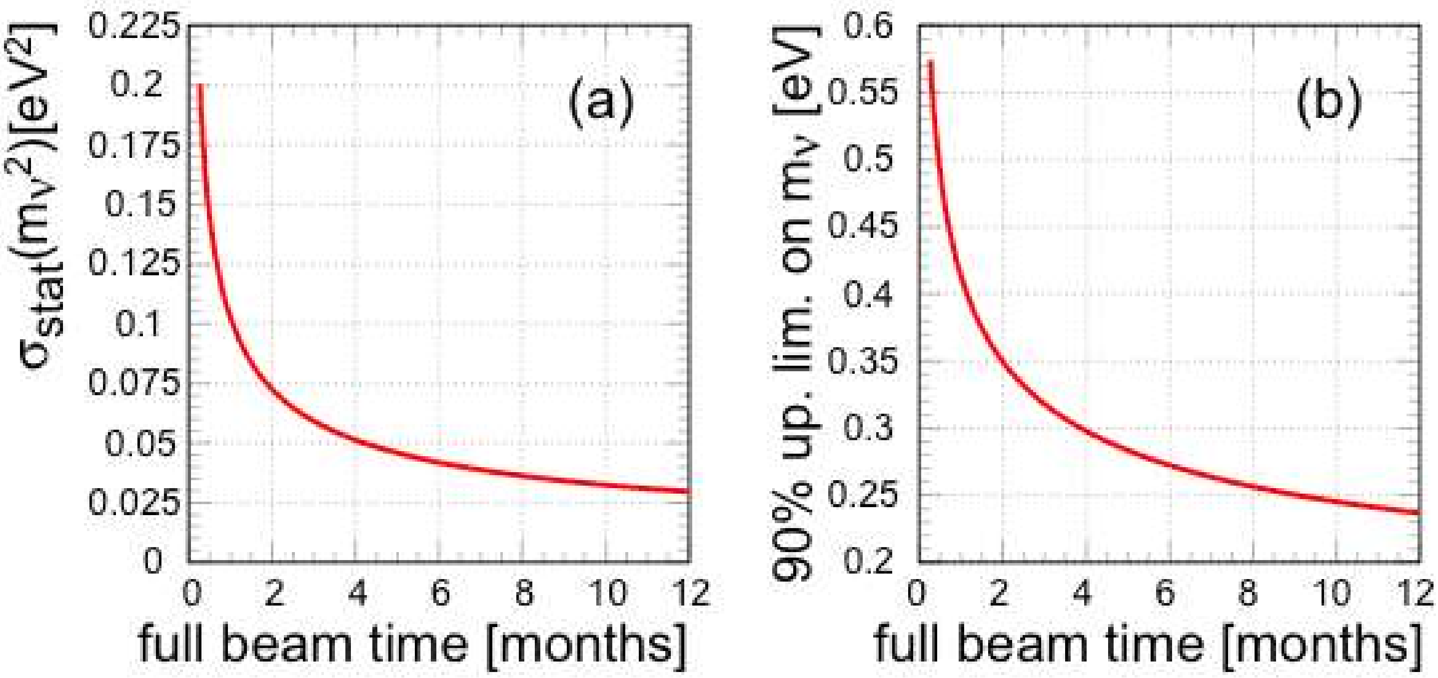
T_{source} = 1.8 K

Trap pulsing on

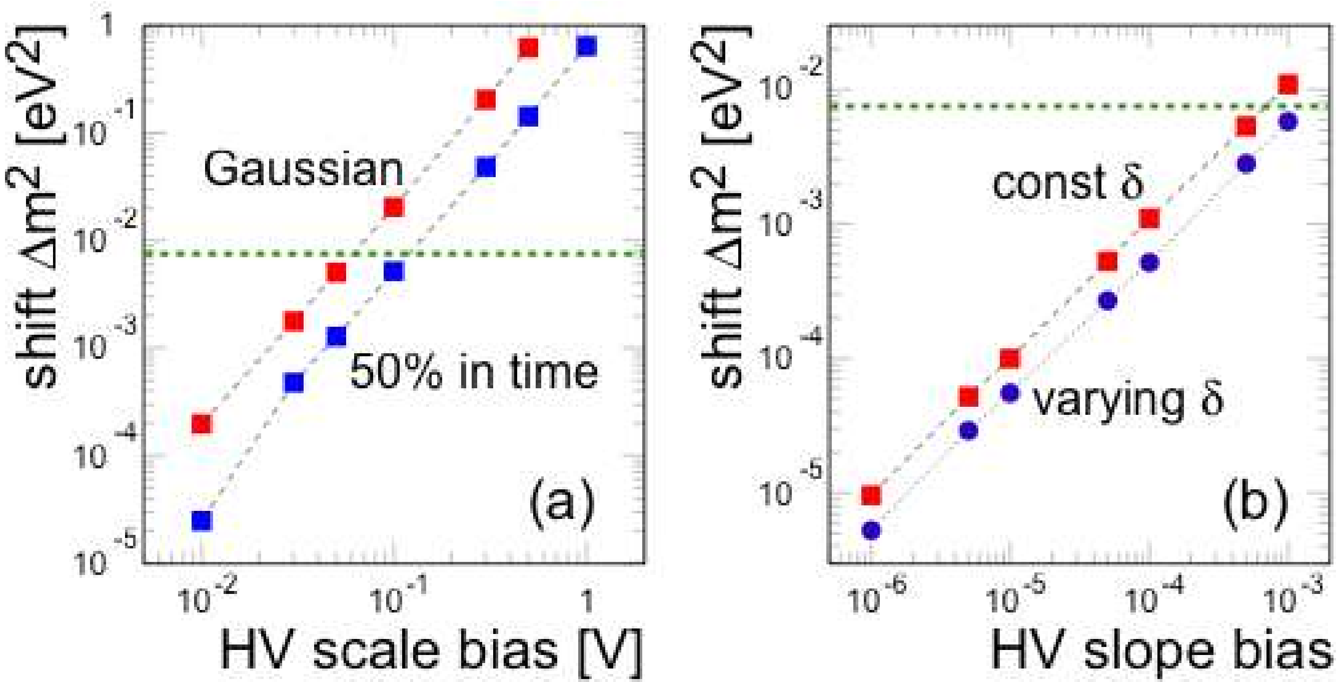
Main Spectrometer Path



Sensitivity with run time



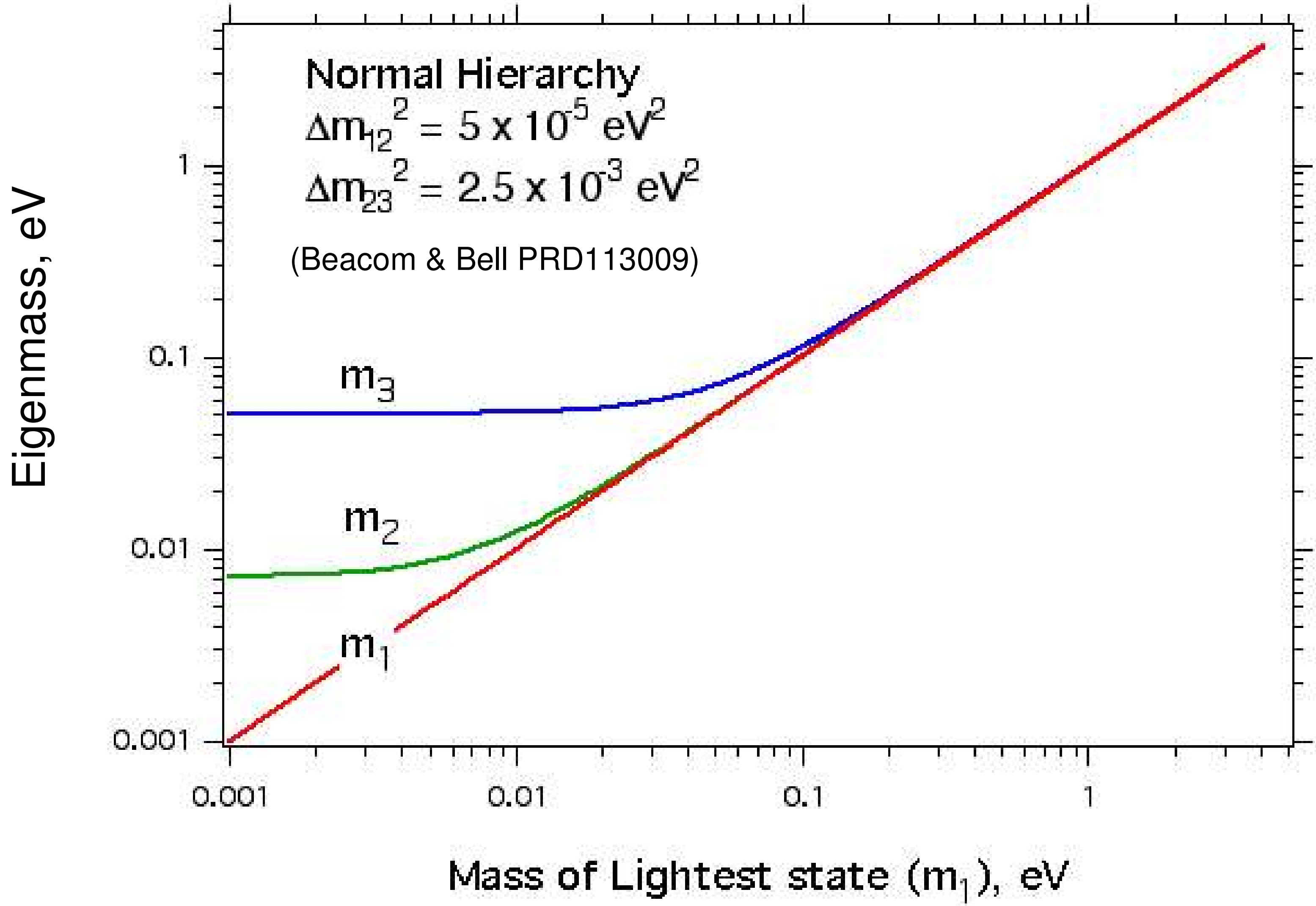
HV must be stable to 3 ppm



Gaussian or binary variations

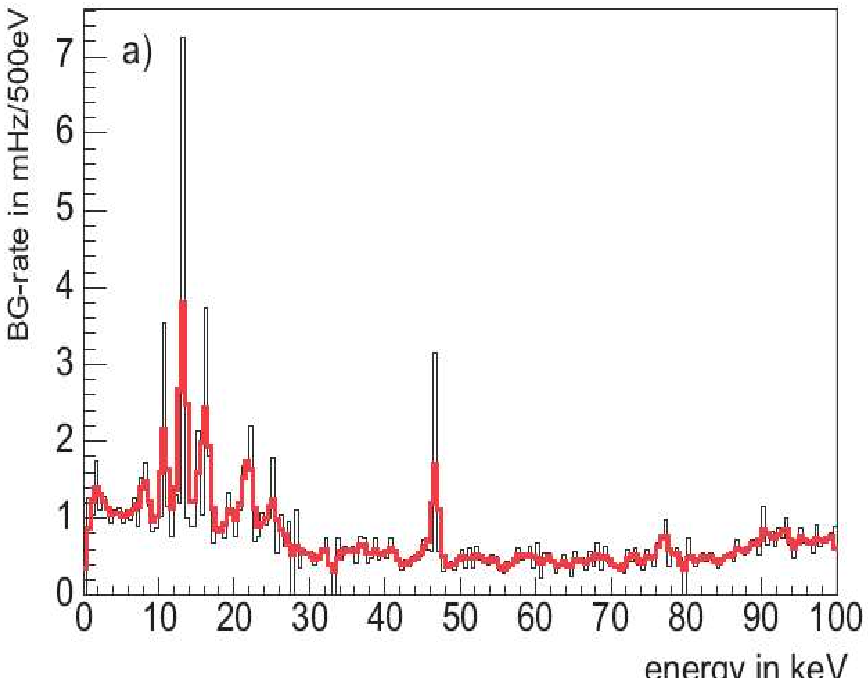
Slope errors

All masses linked to lightest by oscillations



Backgrounds

- Backgrounds near detector from natural radioactivity, muons, neutrons
- Minimize by material selection and active/passive shielding
- Post acceleration
- Background from spectrometer -- position resolution of detector



Monte Carlo of detector backgrounds

Experimental Approaches

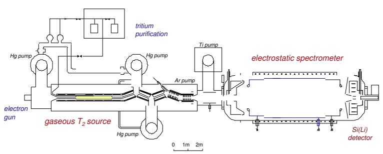
- ***Tritium beta decay -***
  - Mainz (to KATRIN)
  - Troitsk (to KATRIN)
  - U Texas, Austin (Cylindrical Mirror R&D)
  - KATRIN
- ***^{187}Re Calorimetry***
- ***Supernova***
  - Standard core collapse: $m_\nu \geq 20$ eV
  - Breakout burst: $m_\nu \geq 2$ eV

    (Megaton detector required)
  - Collapse to Black Hole: $m_\nu \geq 1.8$ eV

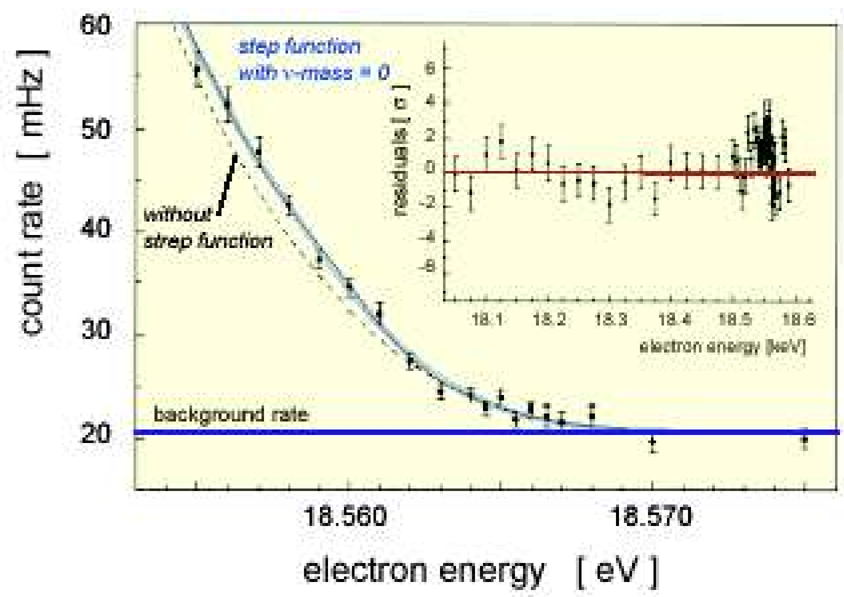
    (Rotation neglected)

    Beacom, Boyd, Mezzacappa PRD63 073011

Troitsk tritium β-decay experiment



200 days of data since 1994



Solenoid retarding spectrometer

The Standard Model Cast of Particles:

$$\begin{pmatrix} u \\ d' \end{pmatrix}_L \quad \begin{pmatrix} c \\ s' \end{pmatrix}_L \quad \begin{pmatrix} t \\ b' \end{pmatrix}_L$$

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$$

$$(\, u \,)_R \quad (\, c \,)_R \quad (\, t \,)_R$$

$$(\, d' \,)_R \quad (\, s' \,)_R \quad (\, b' \,)_R$$

$$(\, e \,)_R \quad (\, \mu \,)_R \quad (\, \tau \,)_R$$

No ν_R ! $\rightarrow$

Hence no ν mass in the S.M.

R.H. fields can be found in the $\overline{\nu}$ to make massive Majorana neutrinos. But must enlarge Higgs sector.

When neutrinos are mixed…

ν mass from
beta decay

ν mass
from ββ
ε = ±1, CP cons.

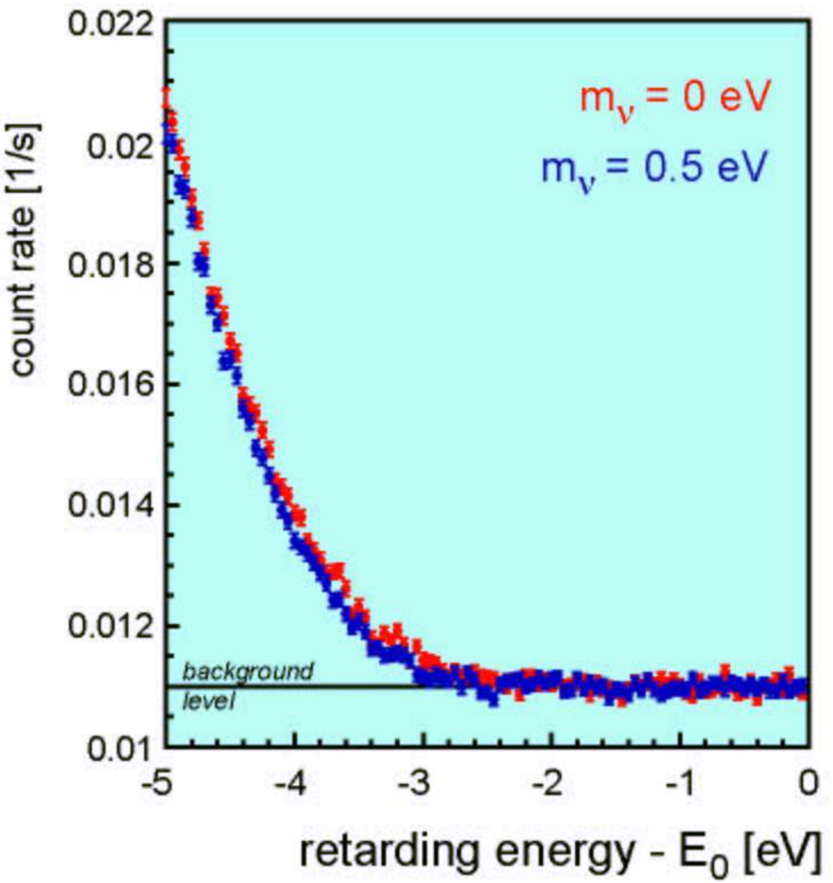
KATRIN - time schedule

1/2001	first presentation at international workshop at Bad Liebenzell
6/2001	formal founding of KATRIN collaboration
9/2001	Letter of Interest (LoI) submitted hep-ex/0109033 BMBF funding 'astroparticle physics' for german universities
5/2002	Complete successful FZK International Panel Review
12/2002	Submission of proposal
2002-03	sytematic studies of background processes and design optimisation funding requests (HGF, DOE, ...) and reviews pre-spectrometer measurements and R&D studies
2004-06	set up of spectrometer, solenoid system, transport system, detector and tritium sources, hall construction, cryo supply
2006	commissioning and begin of data taking

Estimated KATRIN sensitivity for neutrino masses

realistic MC simulation of sub-eV ν-mass signal close to sensitivity limit

narrow interval close to ß end point (last 5 eV) from WGTS

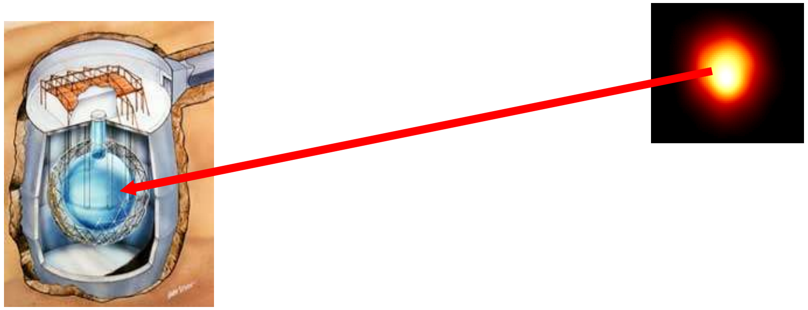


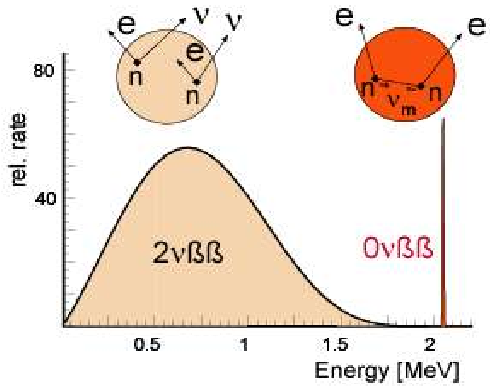
input paramters for simulation :

- *measuring time : 3 years*
- *ΔE = 1 eV (spectrometer)*
- *background rate = 11 mHz*
- *WGTS :*
  column density 5 x 10^{17} / cm^2
- *max. accepted angle 51°*
- *molecular excitations included*

Measurement Methods

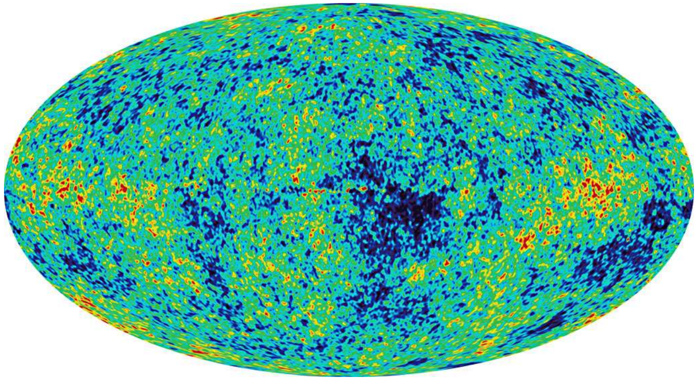
<u>Flavor change/oscillation</u>:
- Solar, atmospheric, reactor, supernova ν's
- SNO, SuperK, KamLAND





<u>0νββ-decay</u> → $\langle m_\nu \rangle$:
- ex. Heidelberg-Moscow, Cuoricino
- Majorana particle

<u>Cosmology</u> → Σm_ν:
- CMBR + LSS
- Model dependent
- ex. WMAP, 2dF, SDSS



Neutrinos from the Big Bang

Neutrino density related to closure density $\Omega_\nu h^2 = \frac{\sum_i m_i}{93.5\text{eV}}$.

Hubble now quite accurately known:

Hubble Key Project: $h = 0.72 \pm 0.03 \pm 0.07$

WMAP: $h = 0.72 \pm 0.05$

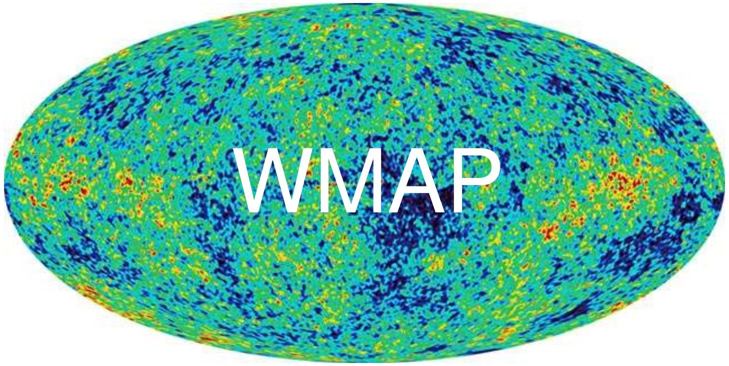
(h = 1 is 100 km s^{-1} Mpc^{-1}, or 10^{-8} per year)

So neutrinos close the universe when

$(m_1 + m_2 + m_3) = 49$ eV

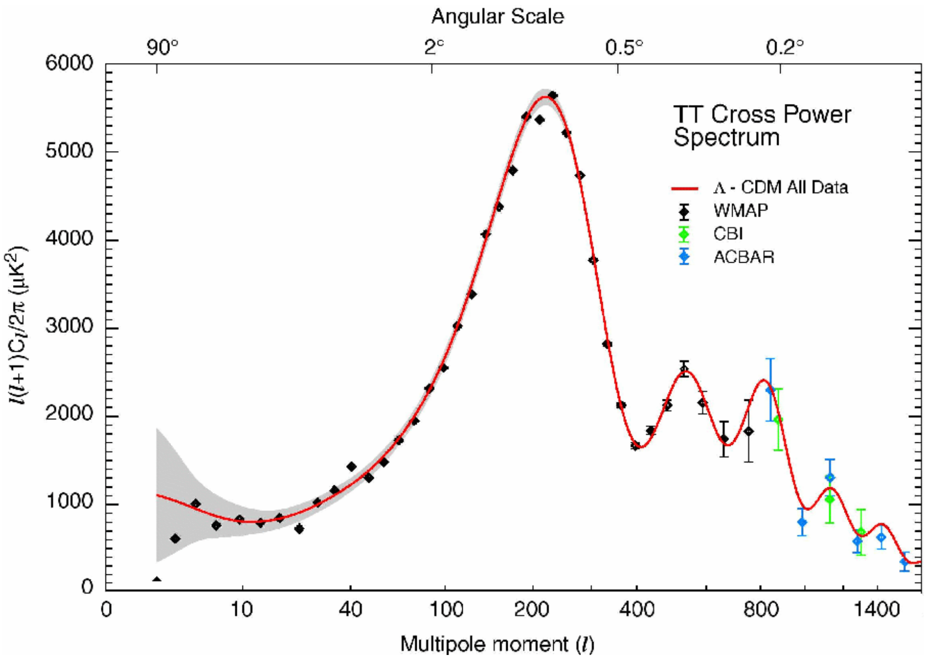
Spergel et al. *astro-ph*/0302209 v2

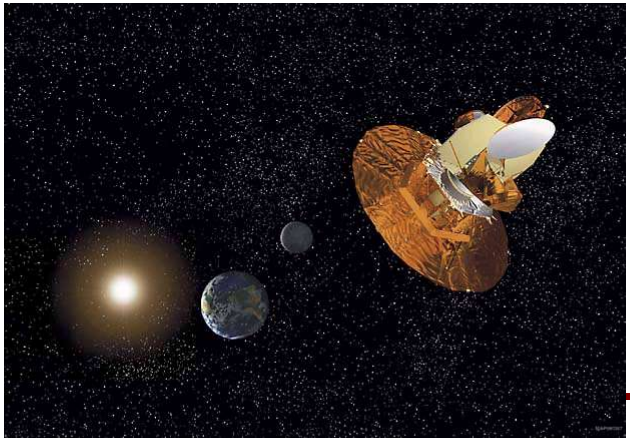
Neutrino mass from cosmology



measurement of CMBR

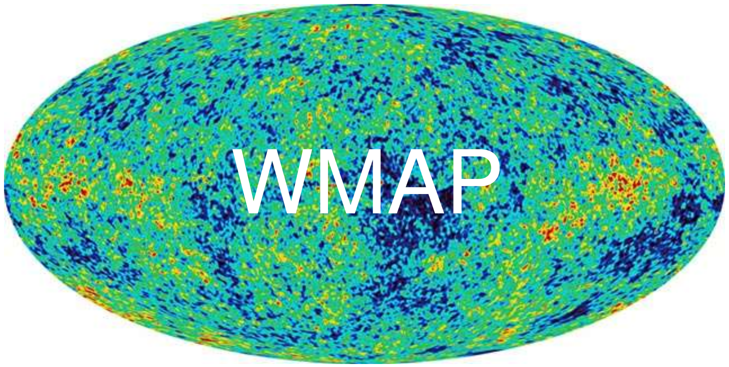
(Cosmic Microwave Background Radiation)





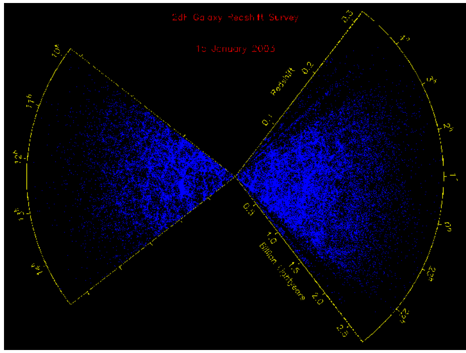
D.N. Spergel et al., astro-ph/0302209

Neutrino mass from cosmology



measurement of CMBR

(Cosmic Microwave Background Radiation)



measurement of matter density distribution

LSS (Large Scale Structure)

2dF, SDSS, ...

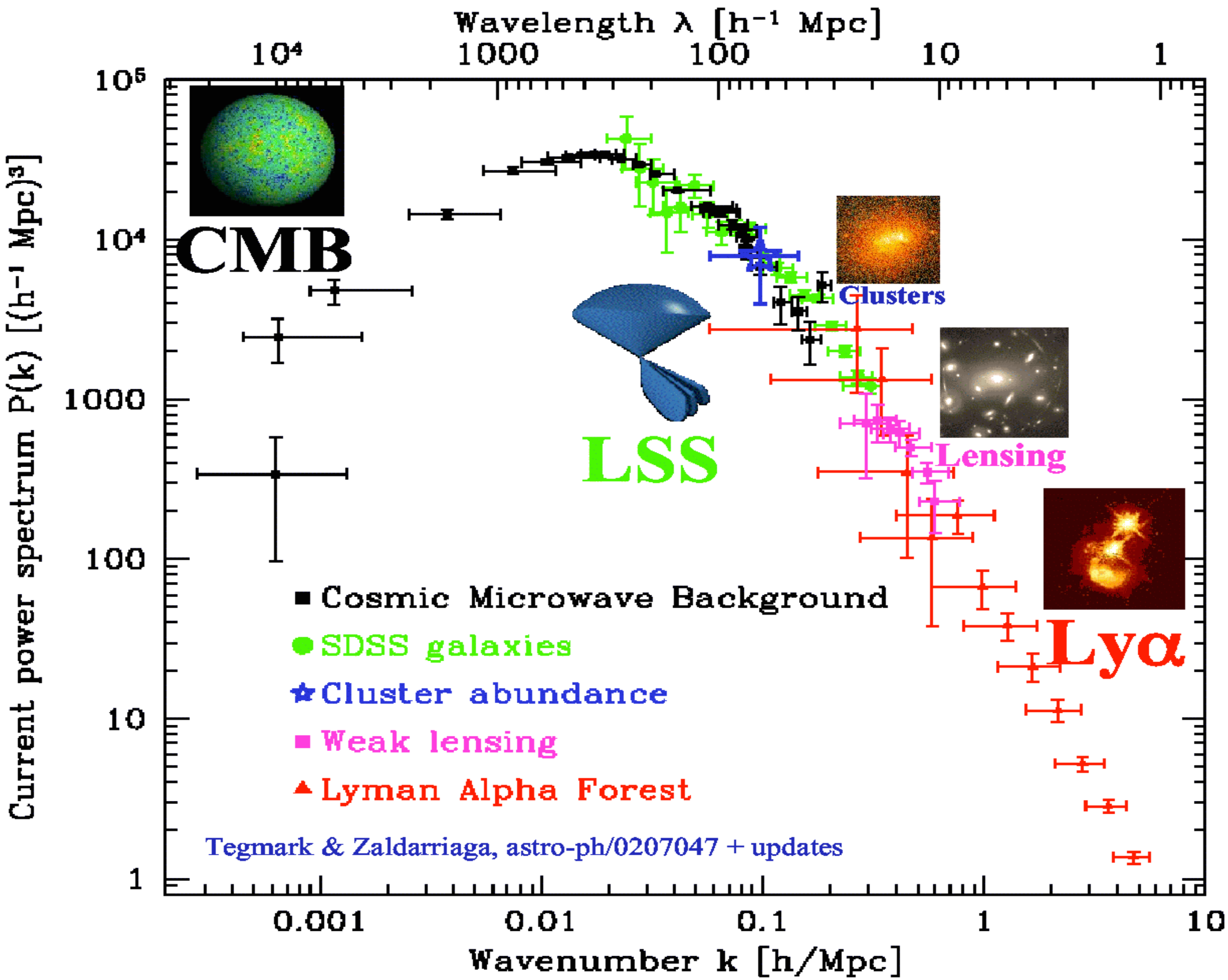
big bang theory:

neutrino density in universe

$n_\nu = 336 / cm^3$

model development (NCSA Simulation)

Neutrino mass from cosmology

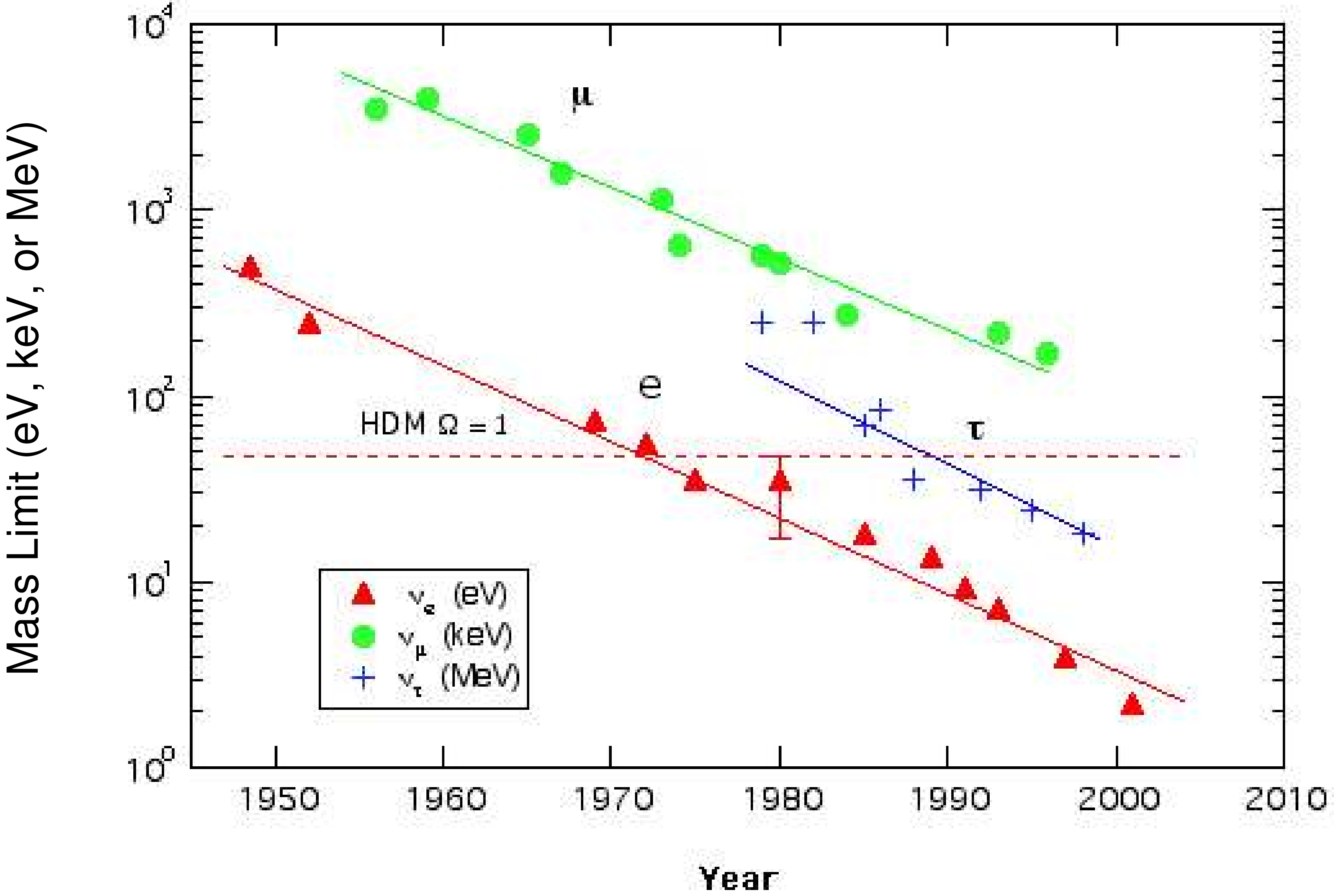


3 Different Neutrinos

Towards the end of the twentieth century …

ν_e	< 2.2 eV
e	510998.02 eV
ν_μ	< 0.19 MeV
μ	105.6583568 MeV
ν_τ	<18.3 MeV
τ	1777.03 MeV

Direct Mass Limits: the History



But ν_e, ν_μ, ν_τ do not exist…

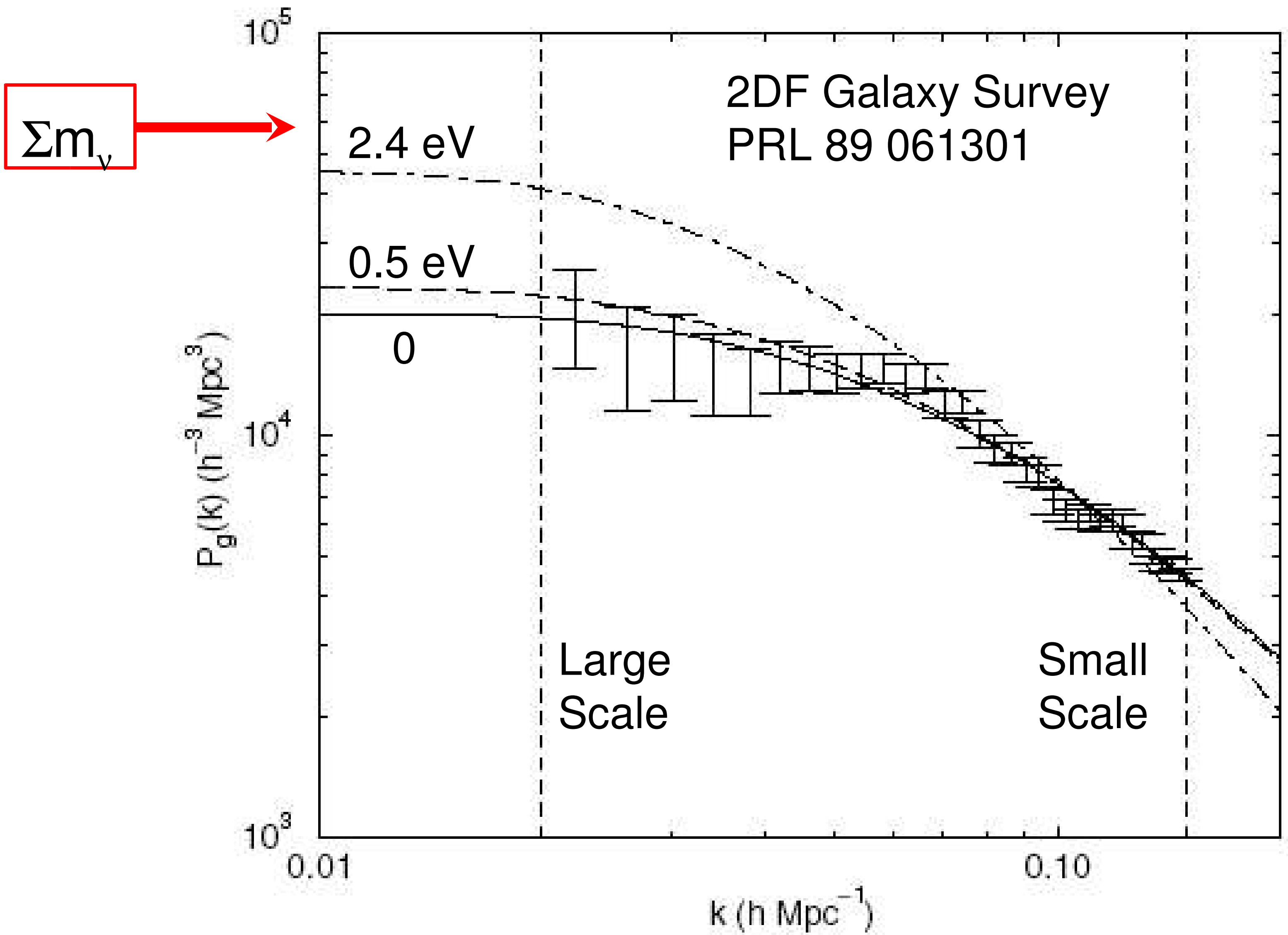
Mixing:

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

$$\nu_e = U_{e1}\nu_1 + U_{e2}\nu_2 + U_{e3}\nu_3$$

etc.

Even small m_ν influences structure



Best bet for MNSP Matrix:

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

Atmospheric

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1/\sqrt{2} & 1/\sqrt{2} \\ 0 & -1/\sqrt{2} & 1/\sqrt{2} \end{pmatrix} \times$$

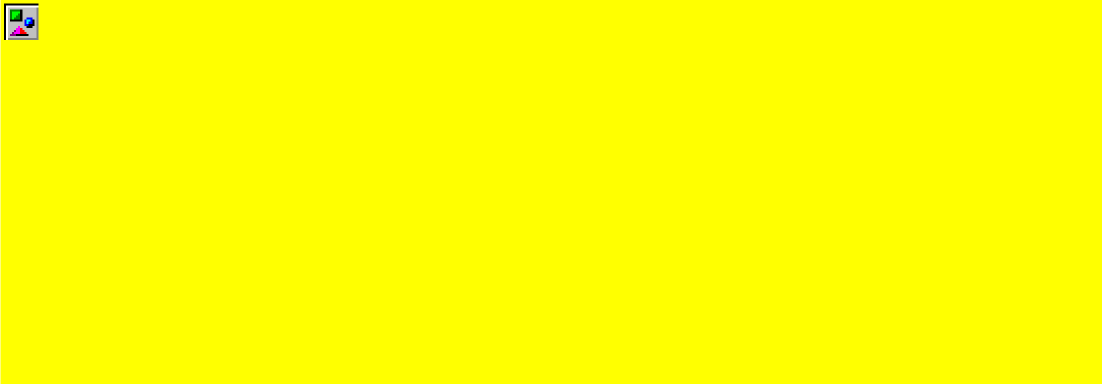
Chooz

$$\times \begin{pmatrix} \sim 1 & 0 & e^{-i\delta_{CP}} \sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}} \sin\theta_{13} & 0 & \sim 1 \end{pmatrix} \times$$

LMA

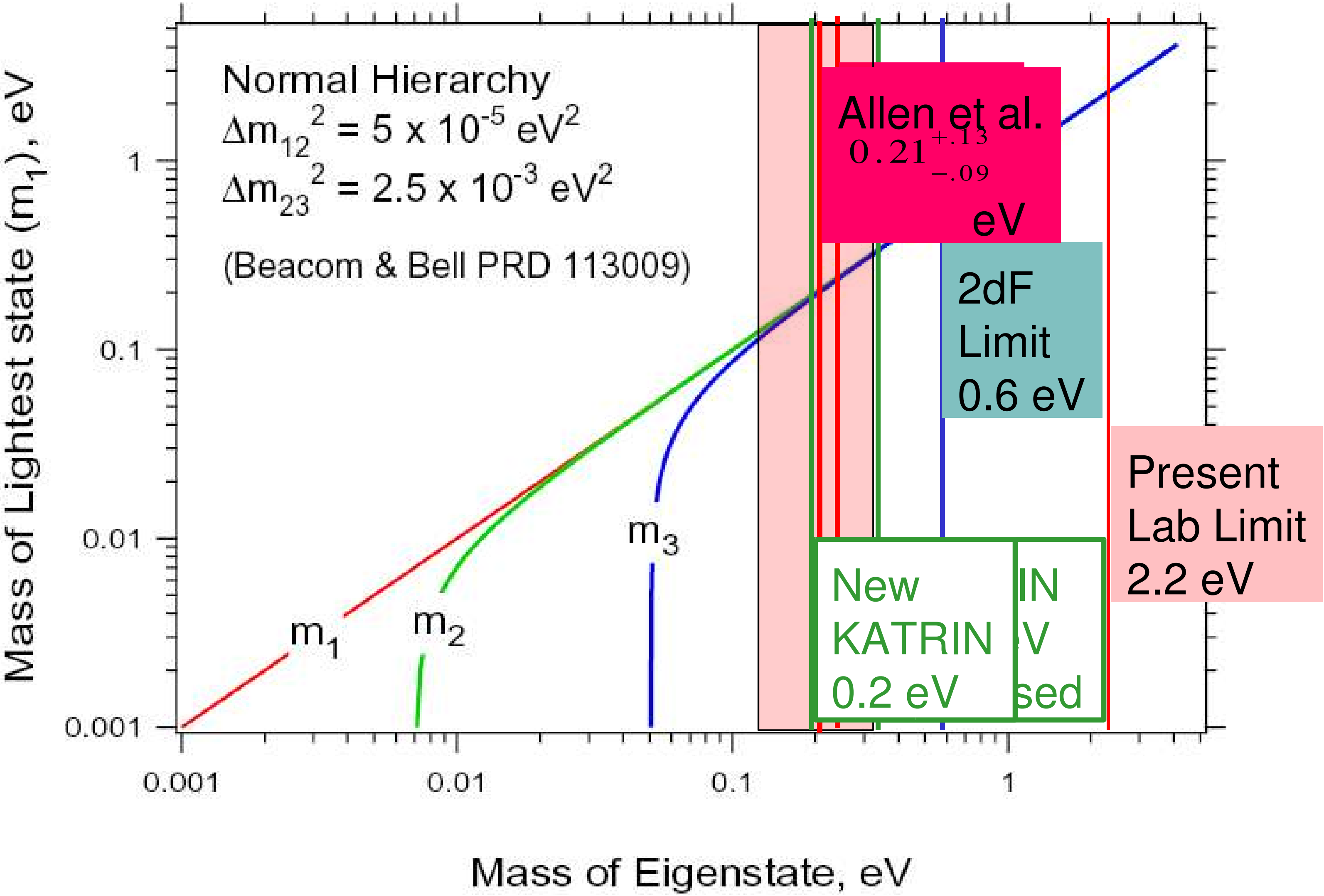
$$\times \begin{pmatrix} 0.85 & 0.51 & 0 \\ -0.51 & 0.85 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Mass eigenstate expansion



There is no "mass of the electron neutrino", etc. The electron neutrino is a linear combination of (at least) 2 states with different masses.

All masses linked to lightest by oscillations

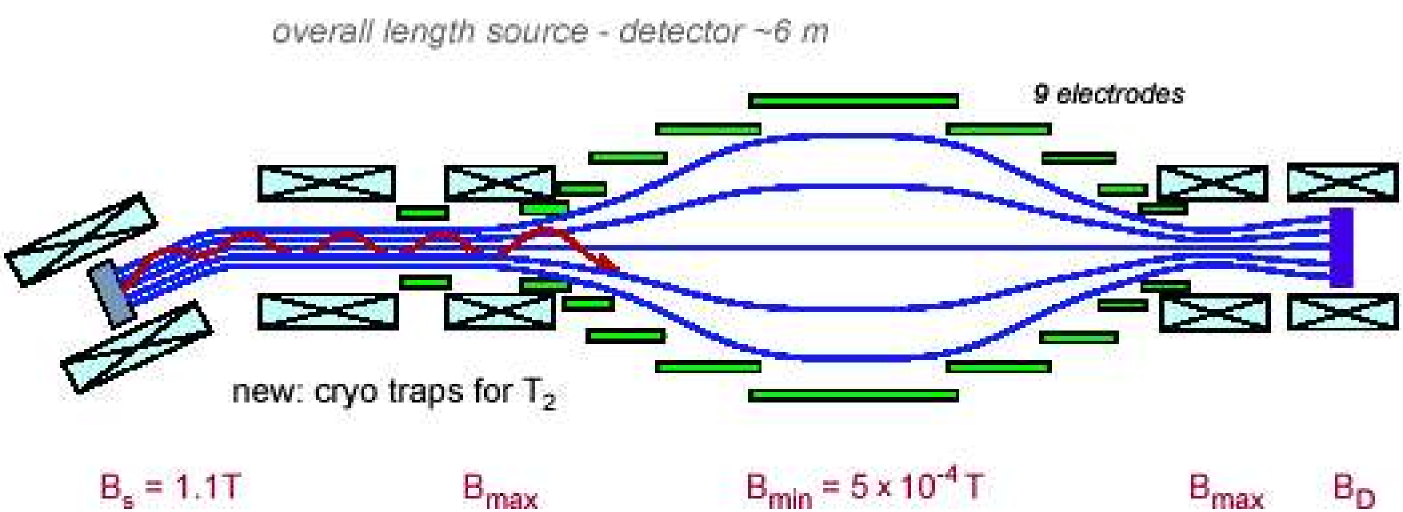


Mainz Neutrino Mass Experiment

Quench condensed solid T_2 source

Early results (94) showed systematic effects, traced to source film roughening transition. (fixed by lowering temperature)

95-97 significant background reduction, signal improvement

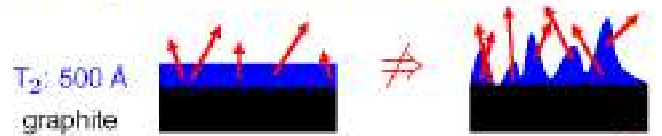


Mainz: (final) neutrino mass results 1998-2001

detailed investigations of systematic effects

- roughening transition of T_2 film

  avoided by keeping film T < 2K

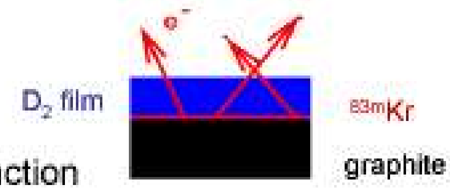


1991-94: higher energy losses _ negative $m^2(\nu)$

L. Fleischmann et al., J. Low Temp. Phys. **119** (2000) 615
L. Fleischmann et al., Eur. Phys. J. **B16** (2000) 521

- inelastic scattering in T_2 film

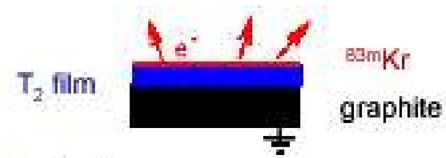
  determination of cross section and energy loss function



V. Aseev et al., Europ. Phys. J. **D10** (2000) 39

- self charging of T_2 film

  determination of critical field



B. Bornschein et al., J. Low Temp. Phys. **D10** (2000) 39

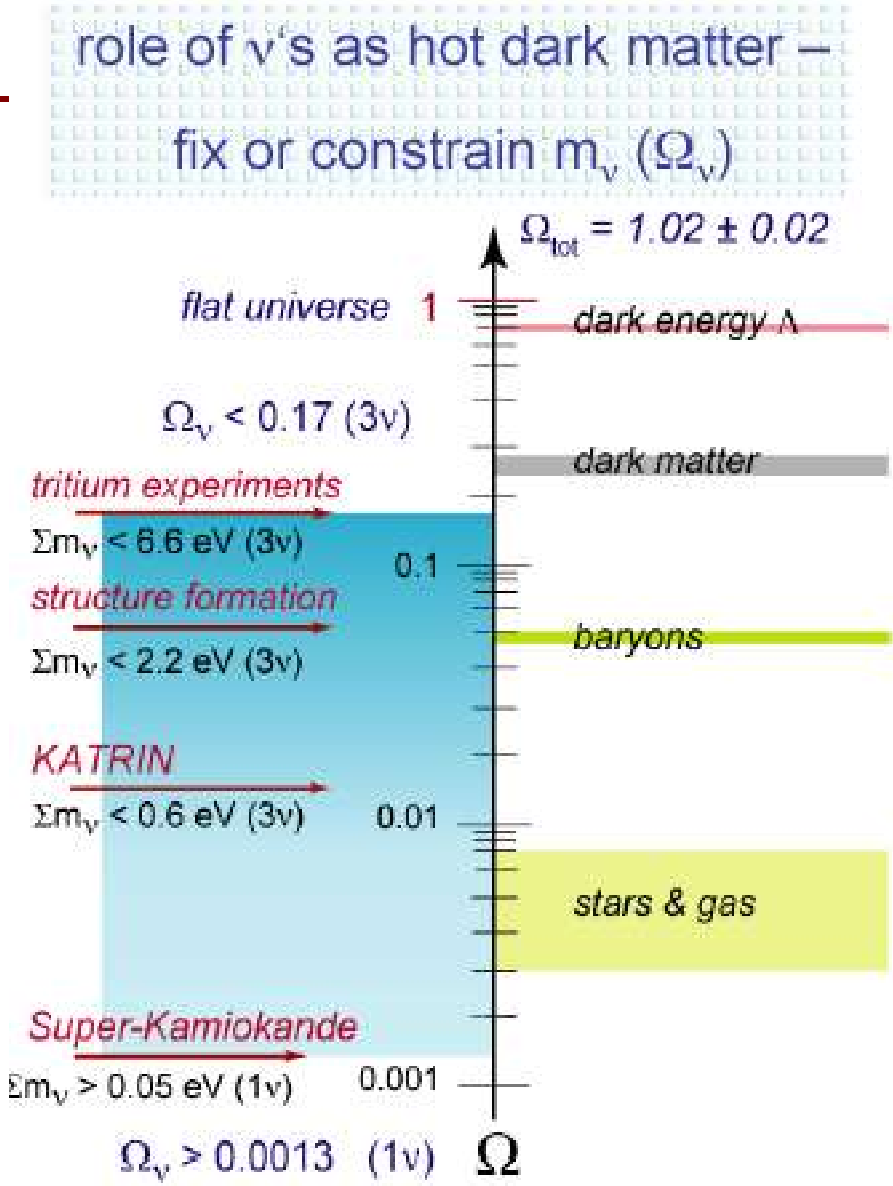
- new: neighbour excitation amplitude fitted with data

  agrees with calculations

Neutrinos in the Universe

Oscillations:
Neutrino mass (summed over all flavors) is **at least 0.05 eV**, as much as luminous stars.

Tritium Beta Decay:
But from tritium beta decay and neutrino oscillations, it is **not greater than 6.6 eV.**



Mainz Results

J. Bonn et al. Nucl. Phys. B (Proc. Suppl.) 91 (2001) 273

1. Last 70 eV below endpoint (data > 18.5 keV)

   Runs Q5, Q6, Q7, Q8

   $m_\nu^2 = -1.6 \pm 2.5 \pm 2.1\ eV^2$ χ^2/d.o.f. = 125/121

   $m_\nu^2 \leq 2.2$ eV (95% CL, Feldman-Cousins)

2. "Last 15 eV" analysis (data 18460, 18500, >18560 keV)

   (E_0 = 18.575 keV)

   Result would not be affected by Troitsk-like anomaly

   1998: $m_\nu^2 = +0.1 \pm 3.9 \pm 2.1$

   1999: $m_\nu^2 = +1.5 \pm 3.2 \pm 3.4$

   1998 + 1999: $m_\nu^2 = +0.6 \pm 2.8 \pm 2.5$

   $m_\nu^2 \leq 2.8$ eV (95% CL, Feldman-Cousins)

3. More data being analyzed

Cosmological Implications

Atmospheric neutrinos: $\Delta\, m_{23}^2 \approx 2.5 \times 10^{-3}\ eV^2$

$\therefore$ One neutrino mass > 0.05 eV

SNO + KamLAND: $\Delta\, m_{12}^2 \approx 8.0\ x\ 10^{-5}\ eV^2$

$\therefore$ One neutrino mass > 0.009 eV

Limits on "ν_e mass" give: $m(\nu_{1,2,3}) < 2.2$ eV

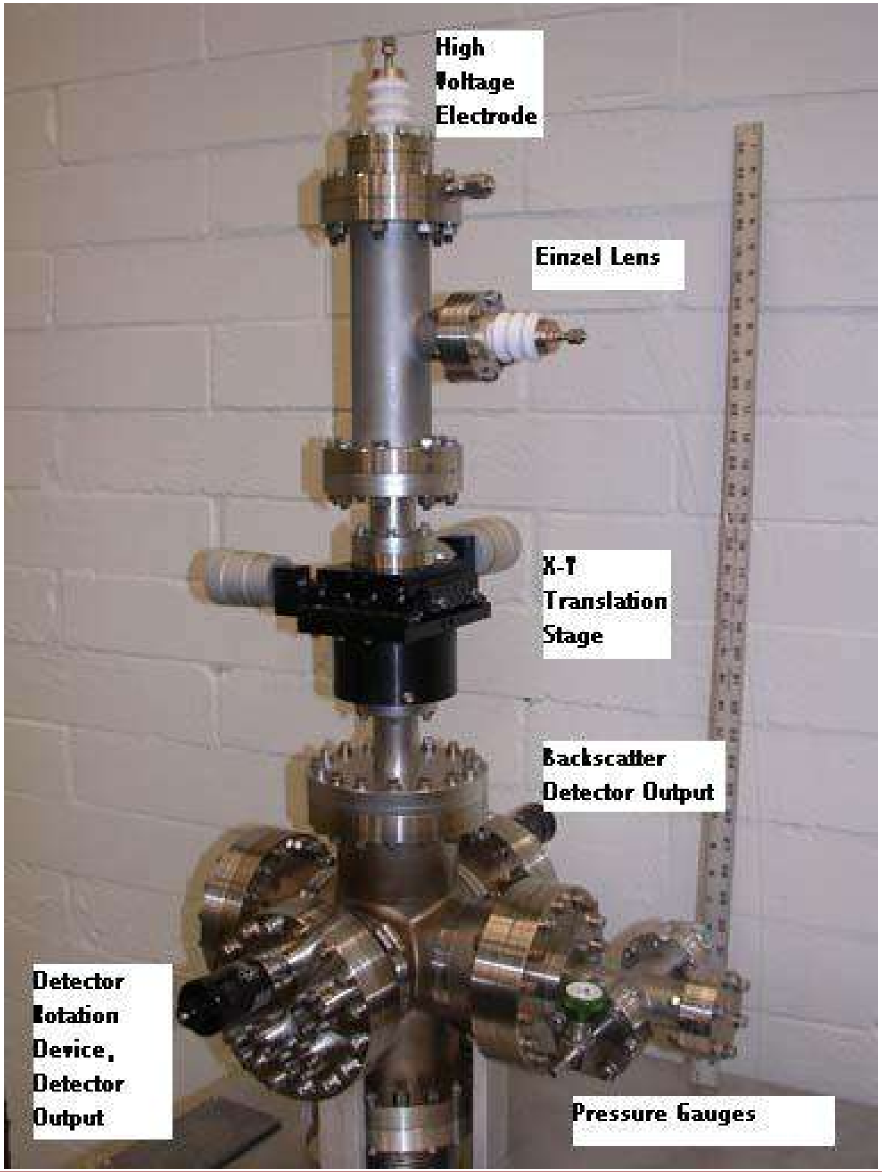
Σ neutrino masses: $0.059 < m_1 + m_2 + m_3 < 6.6$ eV

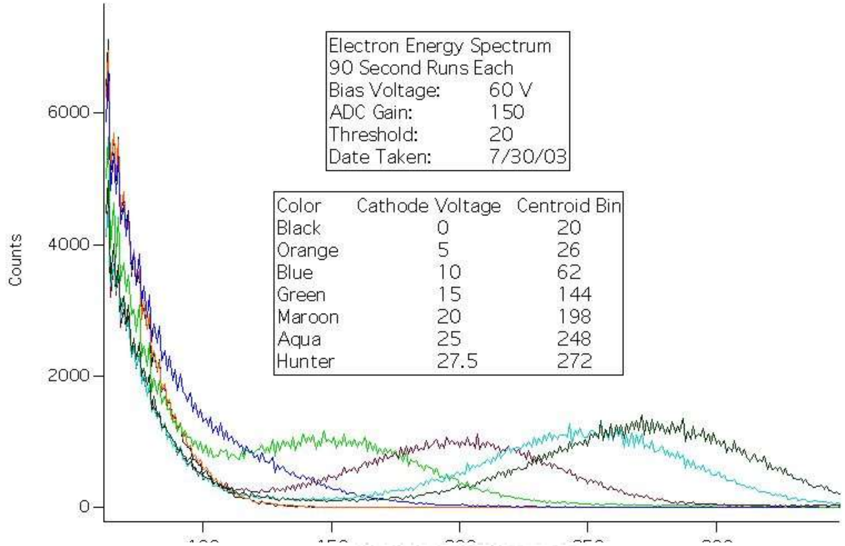
↳ limit on ν fraction of universe closure density: $0.001 < \Omega_\nu < 0.13$

Keys to β-decay shape measurements

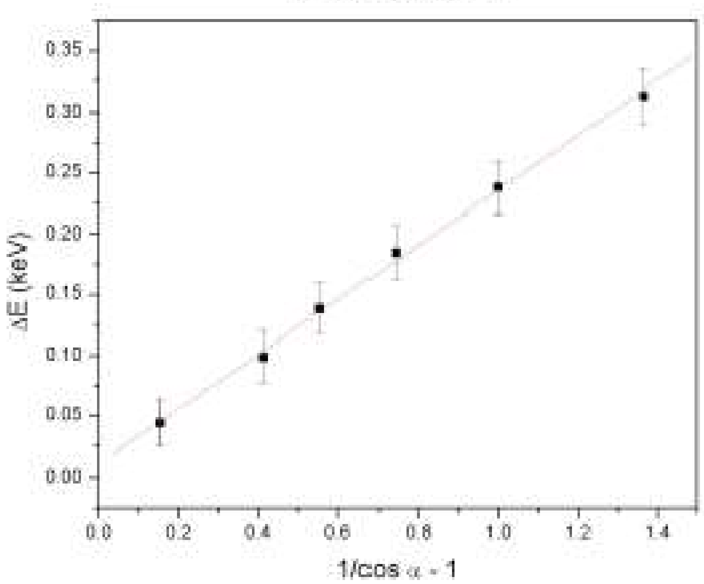
- **Statistics and uncertainty budget**
  - Only 2 x 10^{-13} decays in last 1 eV below endpoint.
  - For 10 eV sensitivity, 100 eV^2, for 1 eV sensitivity, 1 eV^2
  - Must reduce backgrounds (~mHz) and ensure that they are very stable with time.
- **Eliminate or characterize all possible shape effects**
  - atomic final state effects
    - use atomic or molecular tritium source ($^3H \Rightarrow {}^3He + e^- + \bar{\nu}_e$)
    - utilize spectrum above atomic states (last 20 eV below endpoint)
  - energy loss shape effects
    - directly measure
    - use only no-loss portion of spectrum (last 10 eV below endpoint)
  - instrumental shape effects
    - direct measurements, using $^{83}Kr^m$
    - use integral spectrometers with very good resolution (~ eV)

UW Electron Gun for Detector Tests

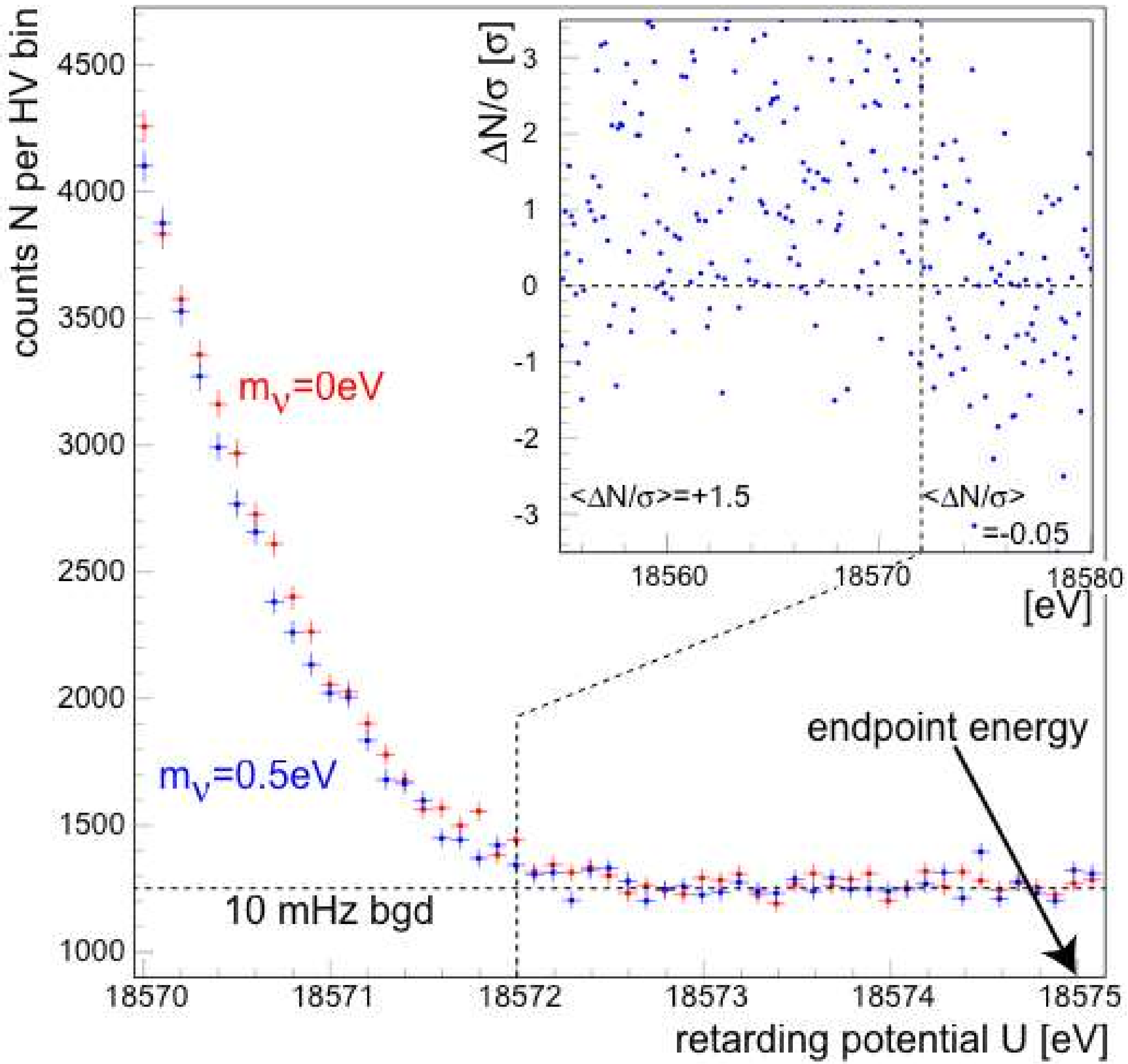




ΔE vs. 1/cos α - 1

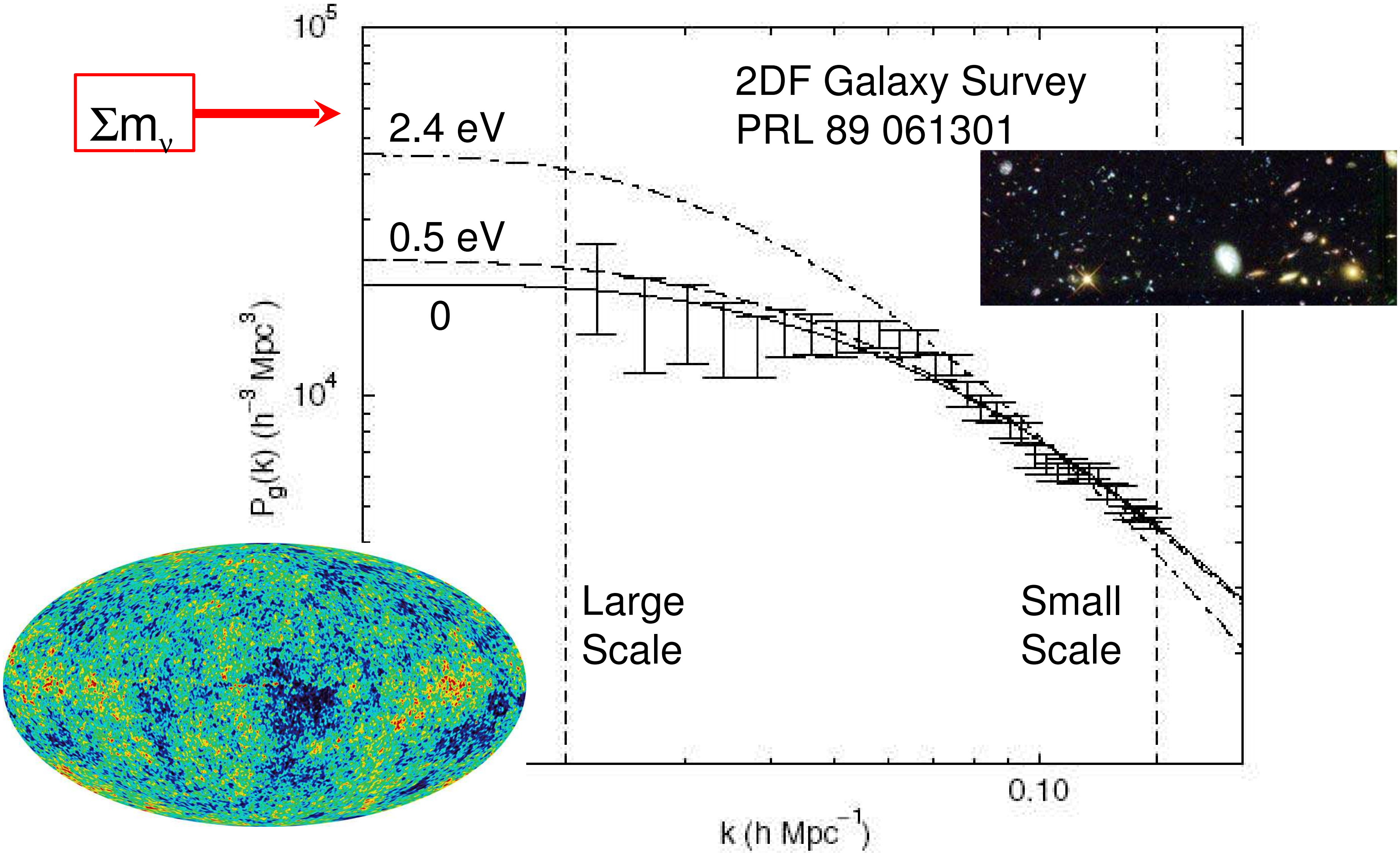


Spectrum



counts N per HV bin
4500
4000
3500
3000
2500
2000
1500
1000
18570
18571
18572
18573
18574
18575
retarding potential U [eV]
m$_\nu$=0eV
m$_\nu$=0.5eV
10 mHz bgd
endpoint energy
ΔN/σ [σ]
3
2
1
0
-1
-2
-3
<ΔN/σ>=+1.5
<ΔN/σ>
=-0.05
18560
18570
18580
[eV]

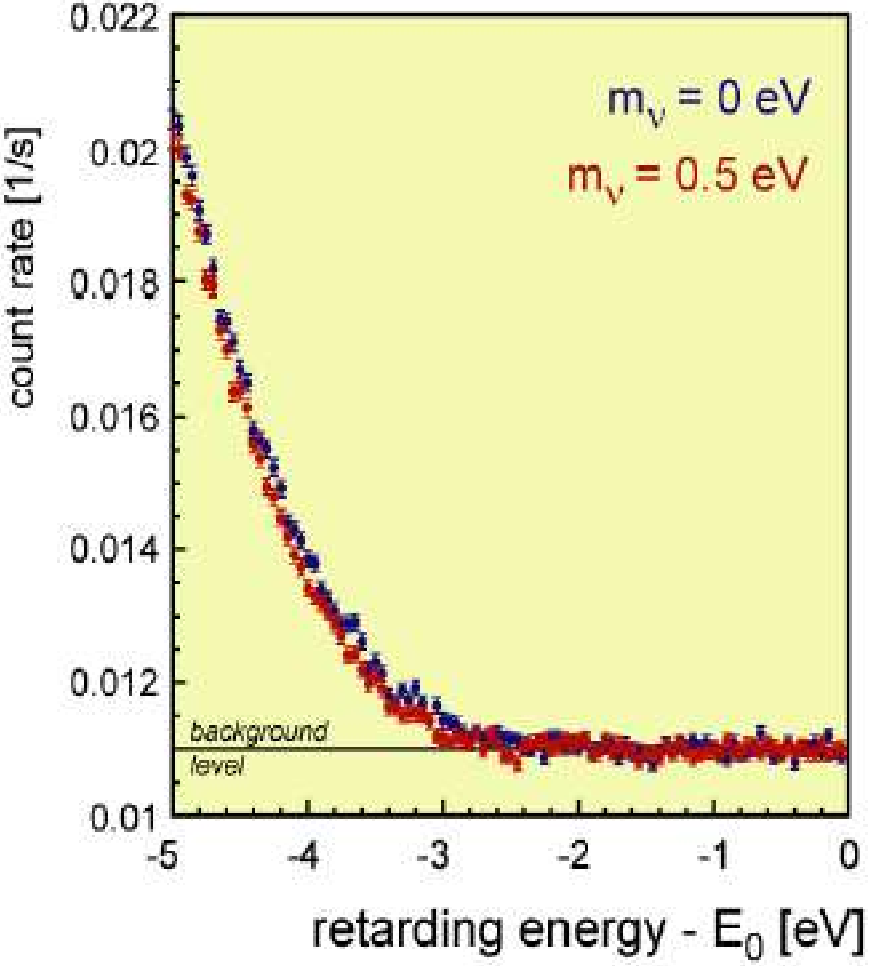
Even small m_ν influences structure



KATRIN Sensitivity

MC spectra for 3 years

with Γ(bg) = 10 mHz:



statistical & syststematic errors contribute ~equally

no ν-mass signal –

KATRIN sensitivity :

$m(\nu) < 0.2$ eV (90% CL)

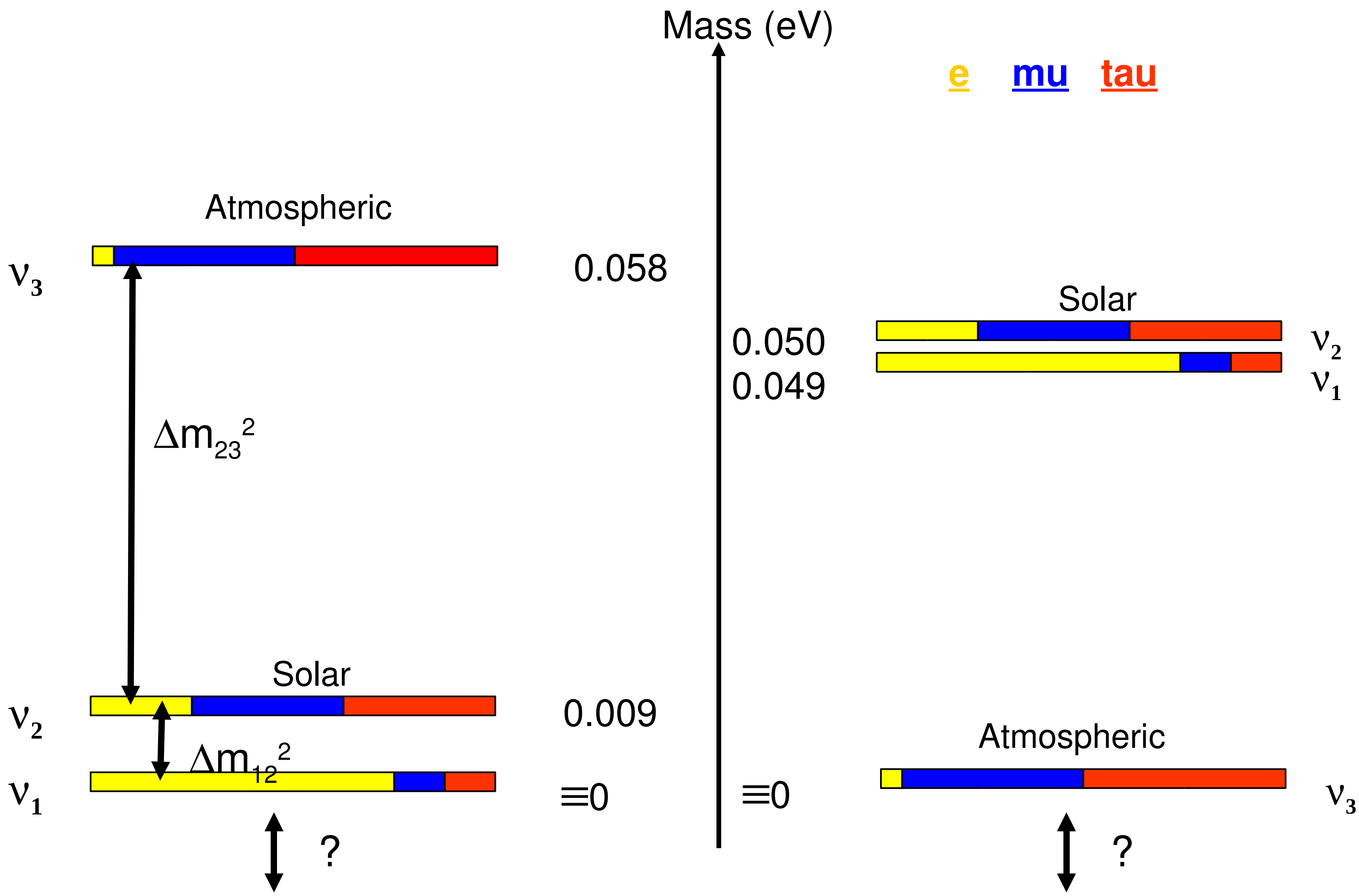
evidence for ν-mass signal –

KATRIN discovery potential :

$m(\nu) = 0.35$ eV (5σ)

$m(\nu) = 0.30$ eV (3σ)

Neutrino Masses and Flavor Content



Tritium Beta Decay Results