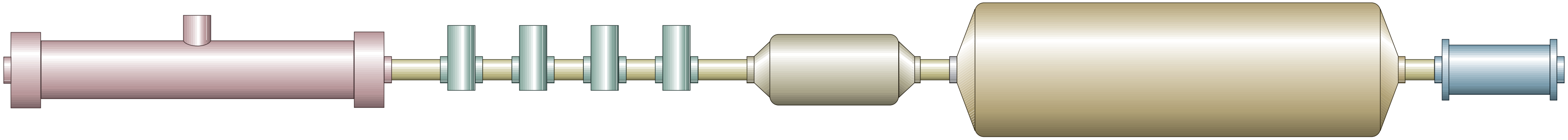
G. Drexlin, FZ Karlsruhe

Desy Seminar
November 20/21, 2001

KATRIN - neutrino masses in the sub-eV region

Status and perspectives of direct measurements of neutrino masses

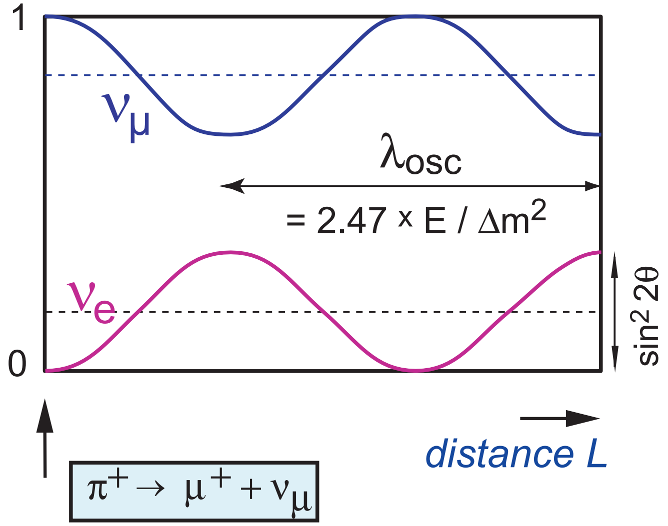


Introduction - massive ν's in cosmology and particle physics
tritium ß-decay experiments - the eV scale
KATRIN - the sub-eV scale
Conclusion

Neutrino Oscillations : 2 flavour mixing

Weak Eigenstates — *Mass Eigenstates*

$$\nu_\mu = \cos\theta\ \nu_1 + \sin\theta\ \nu_2$$
$$\nu_e = -\sin\theta\ \nu_1 + \cos\theta\ \nu_2$$



disappearance:

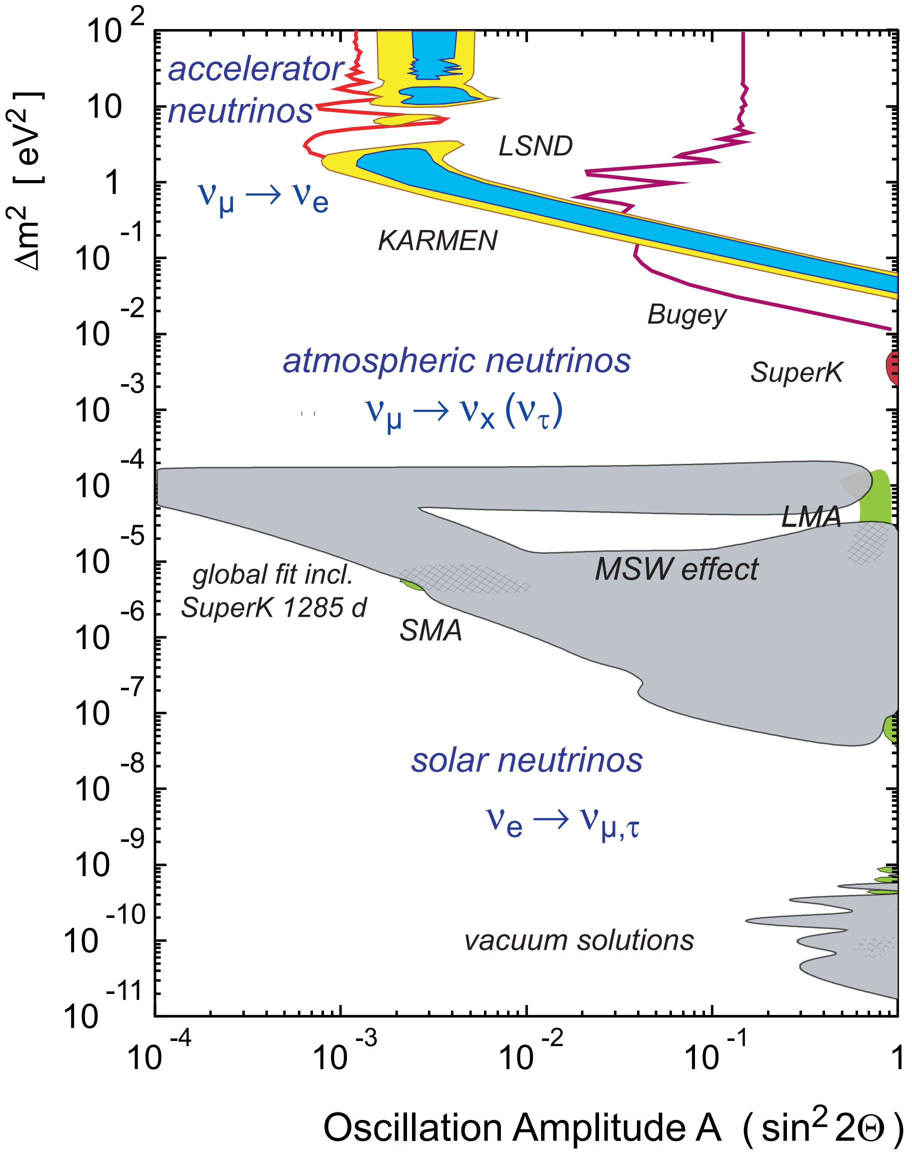
$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \times \sin^2(1.27\ \Delta m^2\ L / E)$$

$\Delta m^2 = |m_1^2 - m_2^2|$ *in eV²*

L = neutrino flight path (source-detector) *in m*

E = neutrino energy *in MeV*

Status of evidences for neutrino oscillations 2001



excluded parameter areas

Neutrino Oscillations : mixings & mass scale

flavour mixing : 3x3 unitary matrix U_{ij}
(Maki-Nakagawa-Sakata matrix)

differences of mass squares = rel. parameter

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

$$\Delta m^2_{12} = | m^2_1 - m^2_2 |$$
$$\Delta m^2_{23} = | m^2_2 - m^2_3 |$$
$$\Delta m^2_{13} = | m^2_1 - m^2_3 |$$

ν-oscillation experiments provide detailed informations on the mixing amplitudes U_{ij} and mass differences Δm^2_{ij}

...but oscillations only provide a *lower* limit on the ν-mass scale !

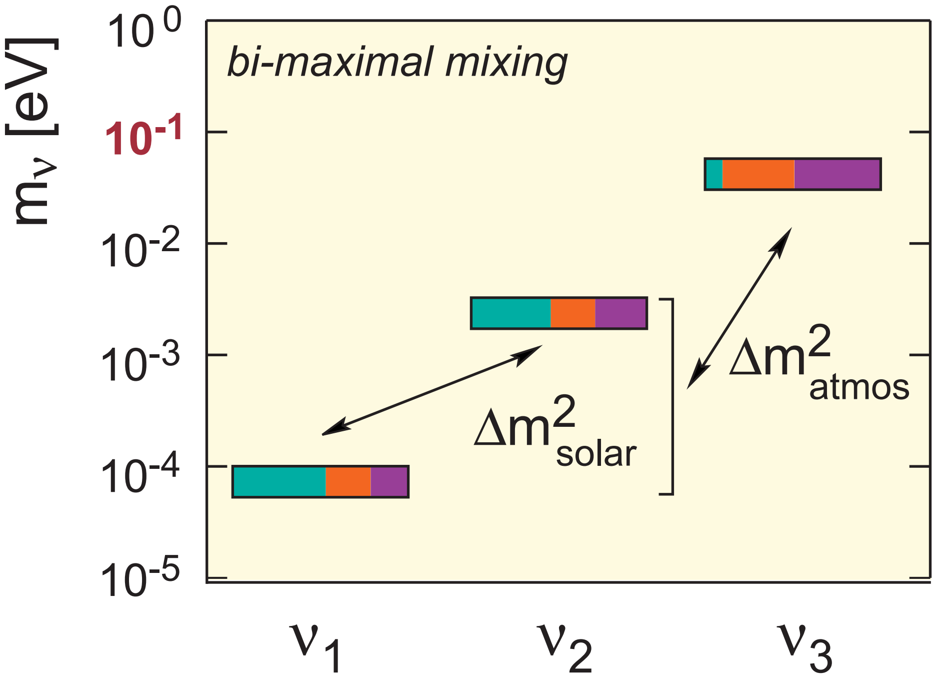
$$m_3 \geq \sqrt{\Delta m^2_{atmos}} = (0.04 - 0.07)\ \text{eV}$$

need determination of absolute mass scale

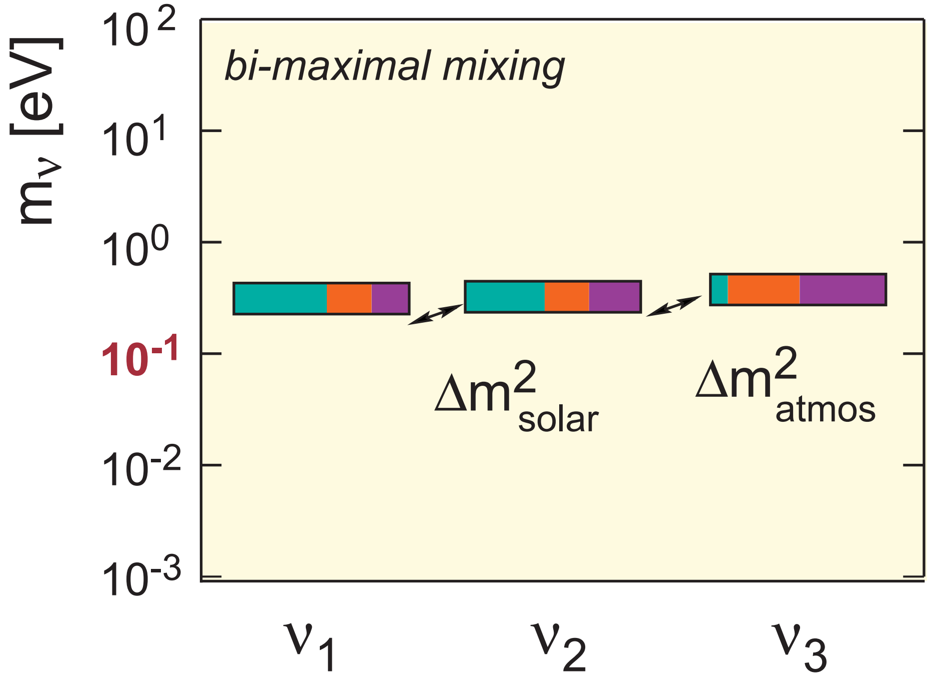
Neutrino Masses & Particle Physics

are neutrino masses hierarchical or degenerate ?

hierarchical scenarios



degenerate scenarios



Δm_{ij}^2 -values and mixings $\sin^2 2\theta_{ij}$ measured by ν-oscillation experiments

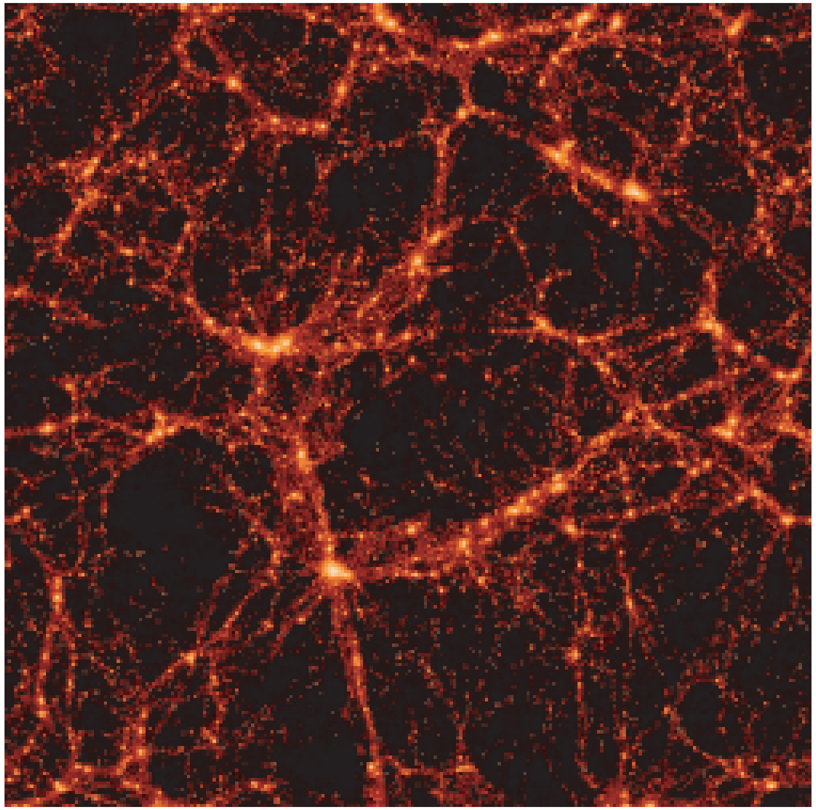
need absolute mass scale of neutrinos

neutrino masses in cosmology

primordial neutrinos as hot dark matter

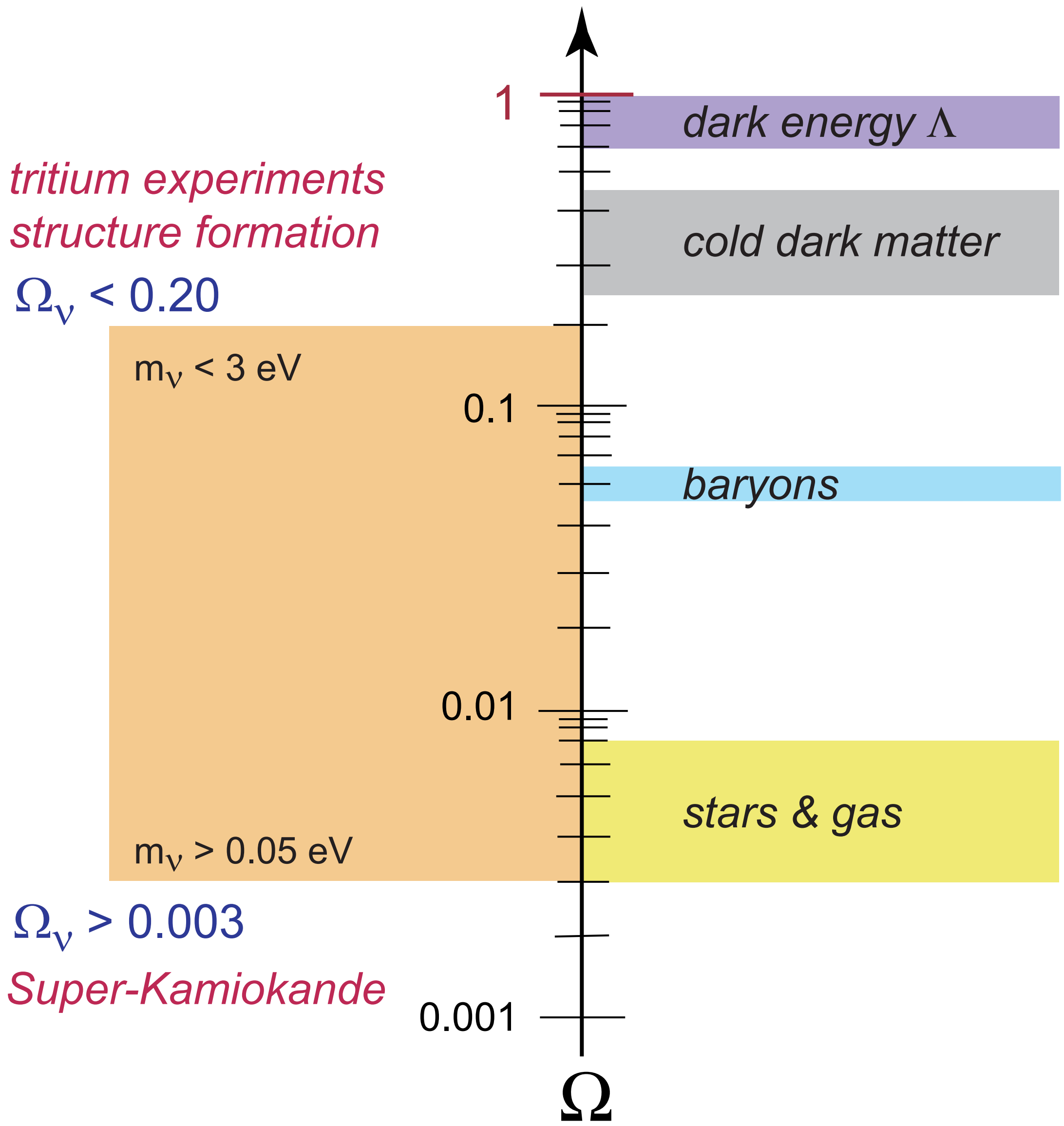
$$\Omega_\nu h^2 = \Sigma m_\nu / 92 \text{ eV}$$

Hubble parameter h= 0.65 (65 km/s/Mpc)



evolution of large scale structures

$\Omega = 1$ critical density & flat universe (inflation)



neutrino mass measurements - status and perspectives

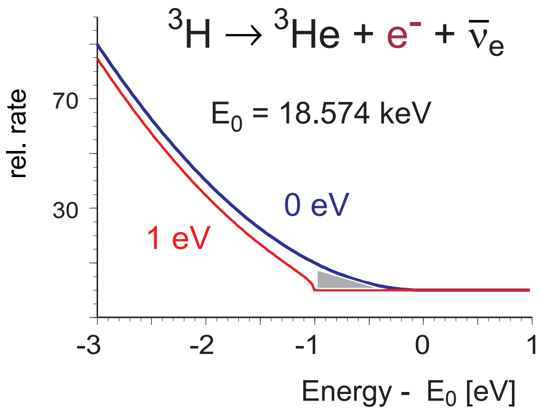
tritium-ß-decay : m_ν

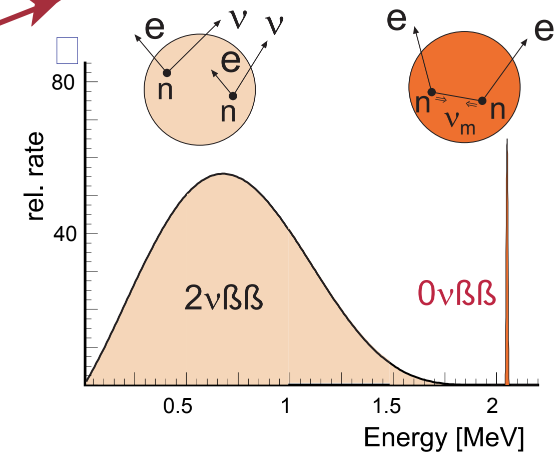
status 2001 : m_ν < 3 eV (95% CL.)
potential 2010 : m_ν < 300 meV (90% CL.)
exp. : KATRIN, μ-calorimeter(?)

0νßß-decay : $\langle m_\nu \rangle$

status 2001 : $\langle m_\nu \rangle$ < 0.5 eV (90% CL.)
potential 2010 : $\langle m_\nu \rangle$ < 20-50 meV (90% CL.)
exp. : ^{76}Ge (Genius, Majorana), ^{136}Xe (EXO), ^{100}Mo (MOON)

m_ν $\langle m_\nu \rangle$





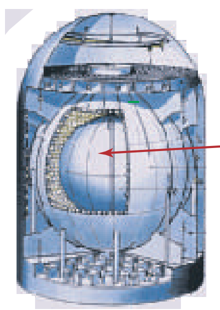
m_ν Σm_i

astrophysics : ν_e, ν_μ & ν_τ

status 2000 : m_ν < 23 eV
potential 2010 : m_ν < ~ 1 - 5 eV
exp. : Super-K, SNO, OMNIS

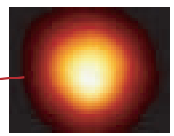
cosmology : Σm_i

status 2000 : Σm_i < 5 (30) eV } *model-dep.*
potential 2010 : Σm_i < ~ 1 - 3 eV
exp. : MAP, Planck, SDSS,

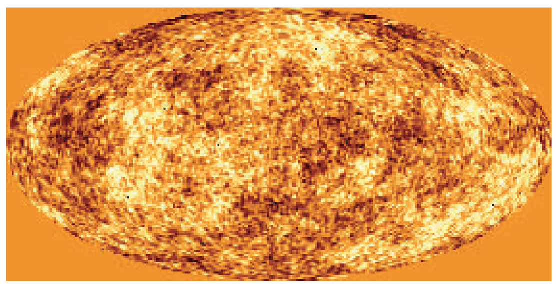


ν

SN200x(?)-ν-ToF



SN20xx



CMB (Planck)

microcalorimeters and ^{187}Re ß-decay

$^{187}_{85}Re \rightarrow ^{187}_{86}Os + e^- + \bar{\nu}_e$

Q= 2.6 keV (lowest Q-value!)

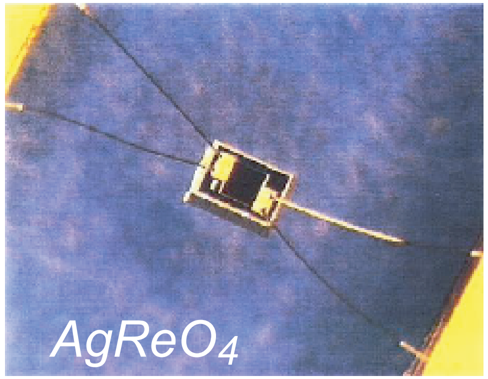
isotopic abundance 63%

Re crystals

ß-source = detector

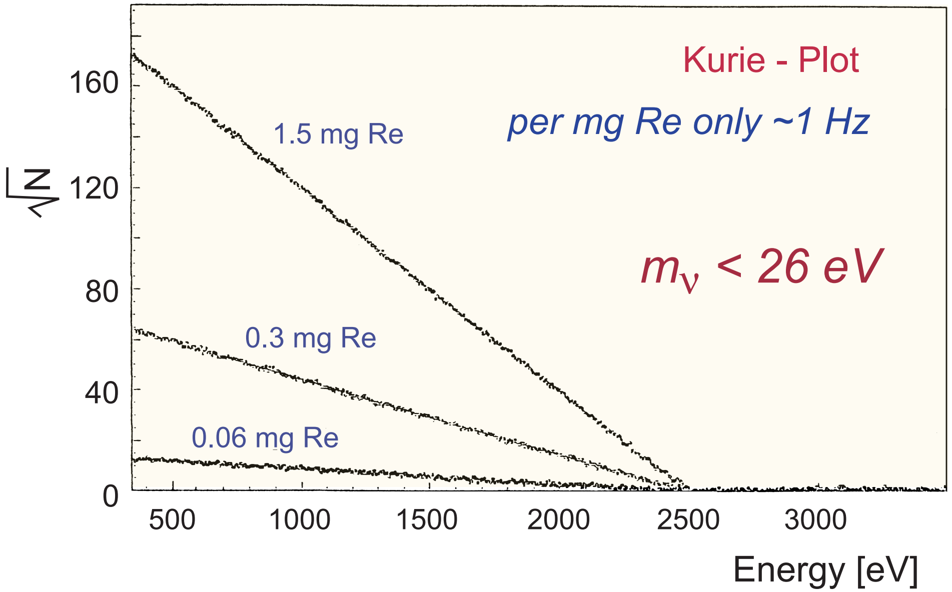
$5/2^+ \rightarrow 1/2^-$: unique first forbidden transition (shape factor calculation is required)

Re is metallic superconductor T_c = 1.69 K



lower Q improves sensitivity to ν-mass fraction close to E_0 (~E_0^3)

results of cryogenic μ-calorimeters



advantages : measure entire decay energy, less statistics required (~E_0^3)

problems : long term energy resolution, gain stability , energy leakage, ext. E_0 increase of ß-activity (pulse pile-up?)

experiments like MANU2 (30 mg Re) still in R&D phase (INFN Genova, INFN Milano)

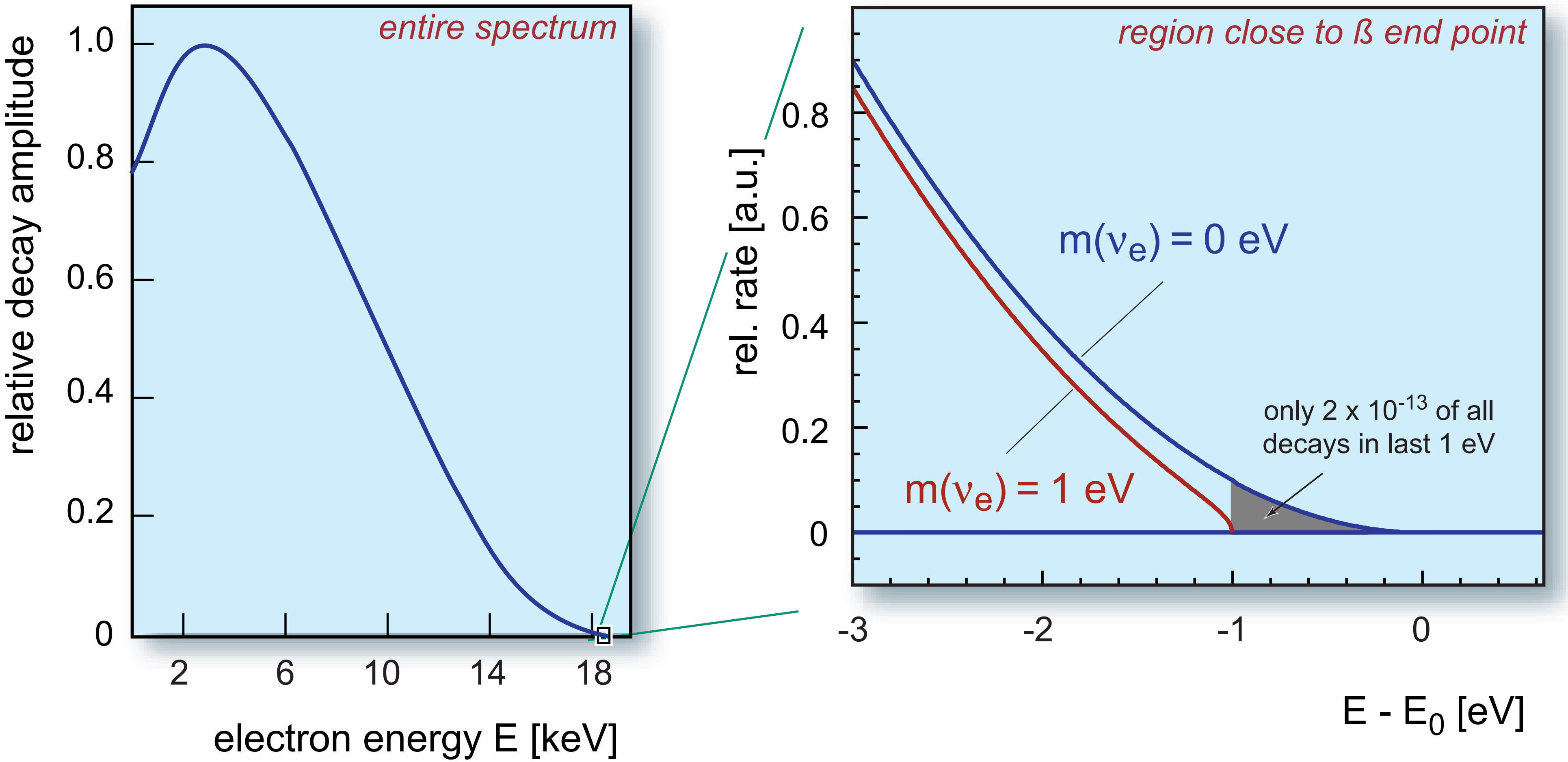
tritium ß-decay and the neutrino rest mass

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

superallowed

half life : $t_{1/2}$ = 12.32 a

ß end point energy : E_0 = 18.57 keV



Fermi theory : ß spectrum and ν rest mass

if recoil effects and excitations neglected: transition energy $E_0 = E_e + E_\nu$

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

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

experimental observable is m_ν^2

m_ν = 'mass' of the electron(anti-)neutrino $(\sum_i |U_{ei}|^2 m_i)$

$$K \sim \left[g_V^2 |M_F|^2 + g_A^2 |M_{GT}|^2 \right] \quad g_A / g_V = -1.26$$

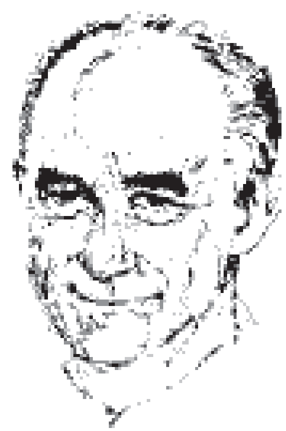
M_F (Fermi transition) : $\Delta J = 0$

M_{GT} (Gamov-Teller transition): $\Delta J = 0, \pm 1$

allowed transitions:

nuclear matrix elements M

not energy dependent



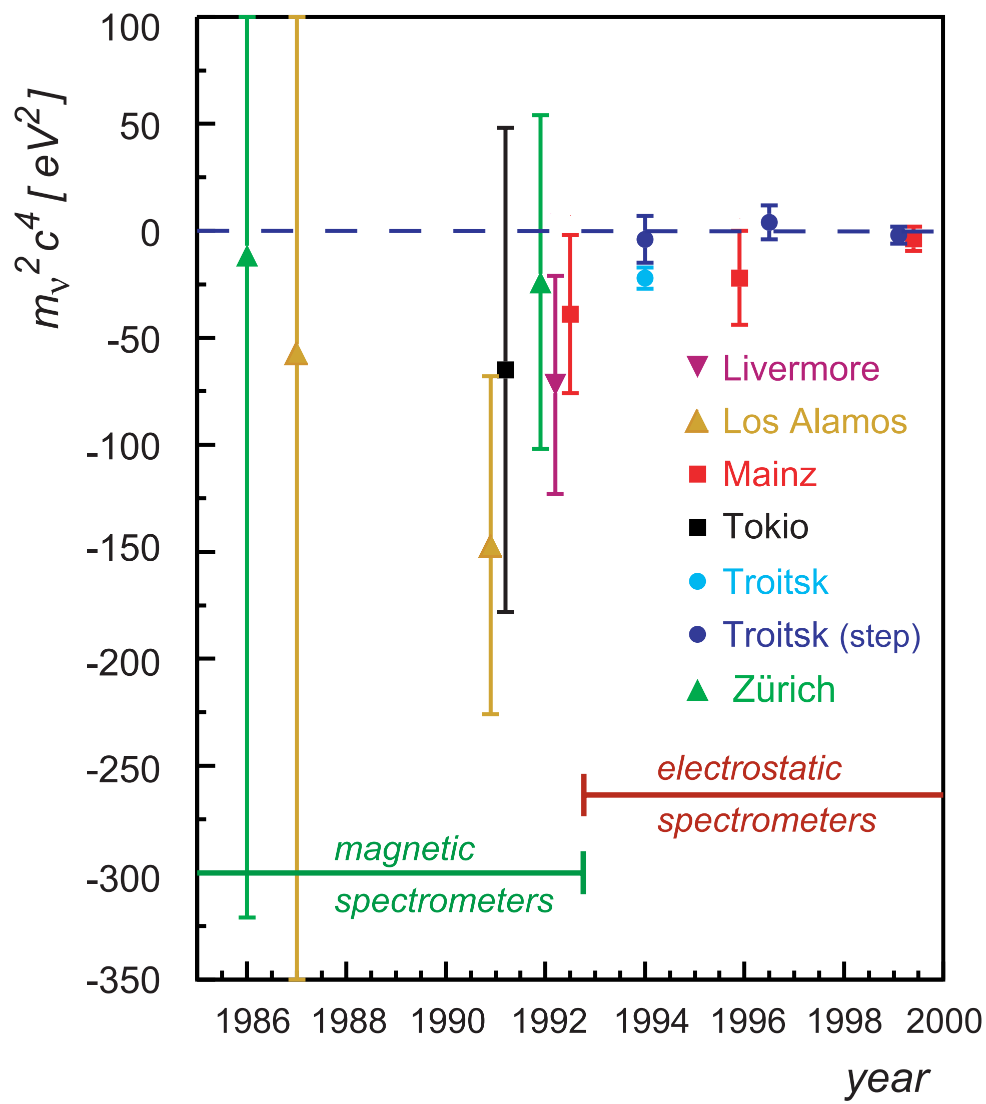
Fermi function $F(E,Z) = \frac{x}{1 - e^{-x}}$

with $x = 2\pi (Z+1) \alpha / ß$

Tritium ß-decay experiments

	m_ν
ITEP *T_2 in complex molecule* *magn. spectrometer (Tret'yakov)*	17-40 eV
Los Alamos *gaseous T_2 - source* *magn. spectrometer (Tret'yakov)*	< 9.3 eV
Tokio *T - source* *magn. spectrometer (Tret'yakov)*	< 13.1 eV
Livermore *gaseous T_2 - source* *magn. spectrometer (Tret'yakov)*	< 7.0 eV
Zürich *T_2 - source impl. on carrier* *magn. spectrometer (Tret'yakov)*	< 11.7 eV
Troitsk (1994-today) *gaseous T_2 - source* *electrostat. spectrometer*	< 2.5 eV
Mainz (1994-today) *frozen T_2 - source* *electrostat. spectrometer*	< 2.2 eV

experimental results



principles of an electrostatic spectrometer

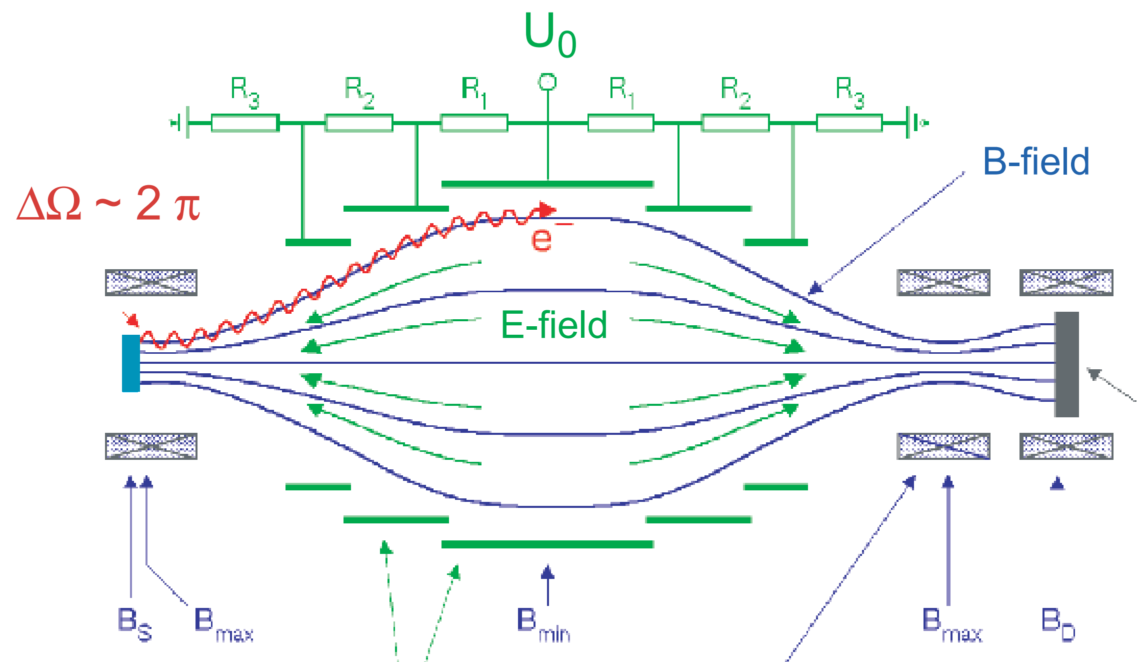
guiding by magnetic fields
(*magnetic adiabatic collimation*)
$\Delta\Omega \sim 2\pi$

electric (retarding-) field :
analysis of electron energies
(*electrostatic filter*)
integral transmission : $E > U_0$

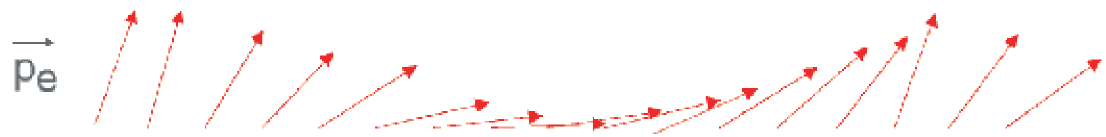
$$\vec{F} = (\vec{\mu} \cdot \vec{\nabla})\,\vec{B} + q\,\vec{E}$$

$$\mu = E_{\perp} / B = \text{const}$$

adiabatic motion



$E \,||\, B$

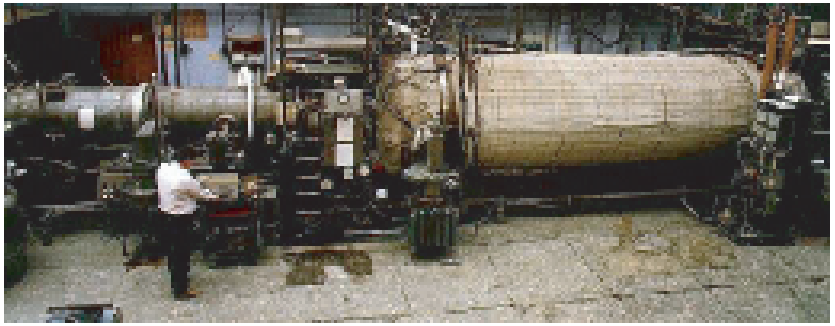


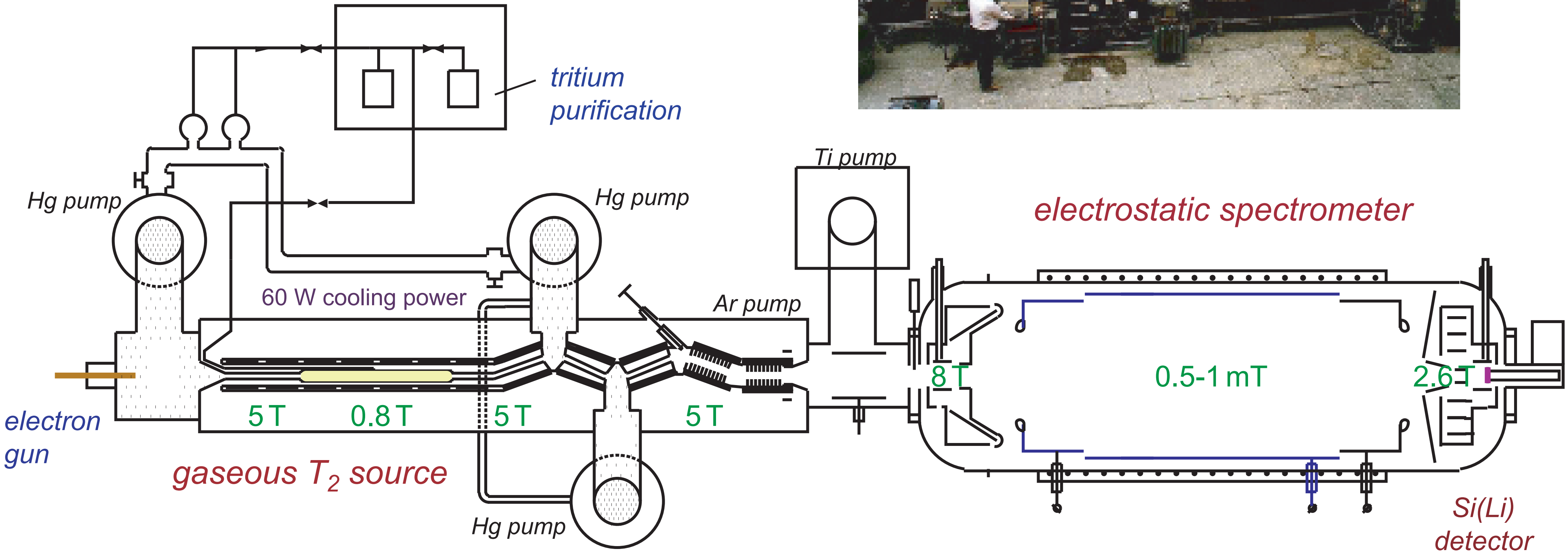
adiabatic transformation $E_{\perp} \rightarrow E_{||}$

Troitsk tritium-ß-decay experiment

gaseous tritium source and electrostatic spectrometer

~240 days of measurements from 1/1994 to 12/1999





0 1m 2m

3 m long tube
Ø = 50 mm
t = 26-28 K
T_2 : HT : H_2 = 6 : 8 : 2

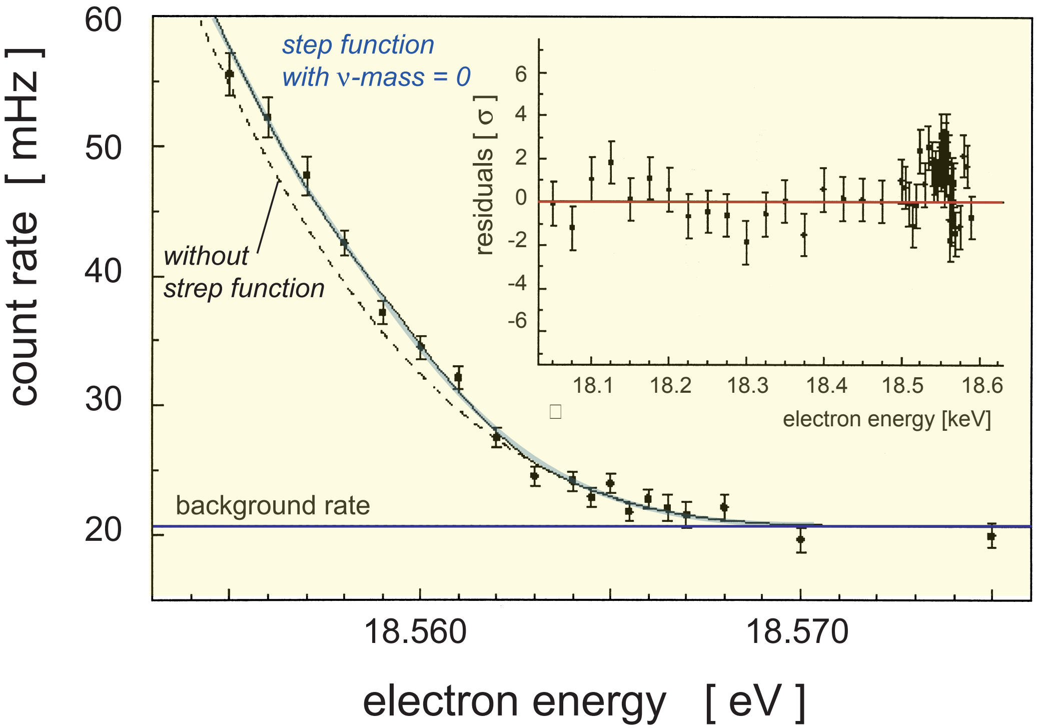
Ø = 1.2 m
l = 6 m
p = 10^{-9} mbar
ΔV = ± 0.2 V (short term)

Troitsk neutrino mass results

observation of a step like function close to end point

Intensity N_{step} ~ 6 x 10^{-11} of total T_2-decay rate *(on average)*

location : 5-15 eV below E_0 (run-specific !)
periodicity = 0.5 y ?



strong correlation between N_{step} and m_ν^2

requires phenomological fit to step function (taken into account for systematic error)

$$m_\nu^2 = -1.0 \pm 3.0 \pm 2.5 \text{ eV}^2$$
$$m_\nu \leq 2.5 \text{ eV} \ \ (95\% \text{ CL.})$$

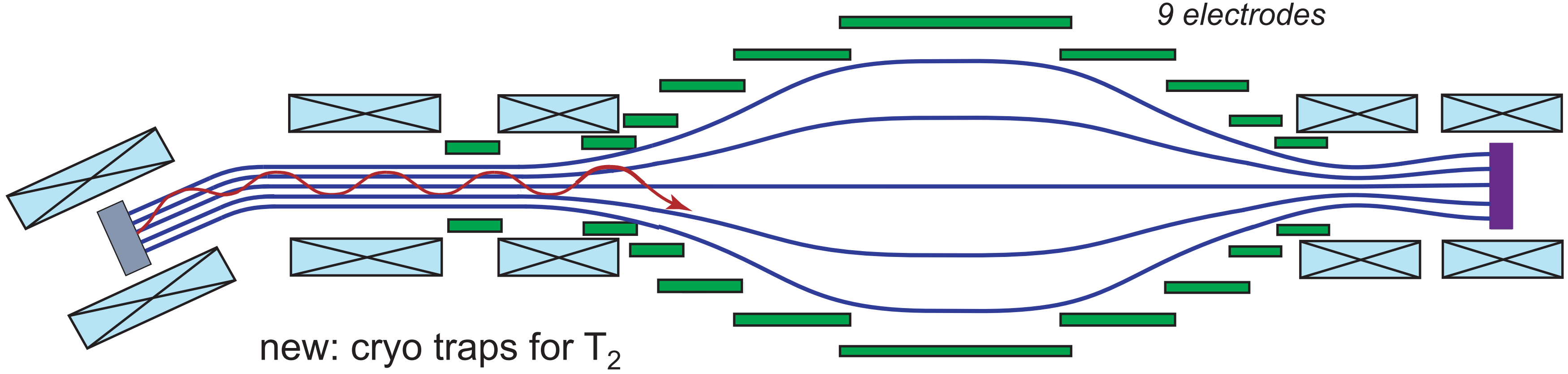
~ limit of the intrinsic sensitivity

V.M. Lobashev et al. , Phys. Lett. B 460 (1999) 227

Mainz neutrino mass experiment

quench condensed T_2 film and electrostatic retarding spectrometer

overall length source - detector ~6 m



$B_s = 1.1T$ B_{max} $B_{min} = 5 \times 10^{-4}$ T B_{max} B_D

molecular T_2 source

frozen T_2 film on HOP graphite
T = 1.7 K (stabilised)
A=2 cm² d=140 ML (480 Å)
20 mCi activity

spectrometer

ΔE ~ 3-4 eV resolution
$p < 5 \times 10^{-9}$ Pa
L = 2 m , d = 0.9 m

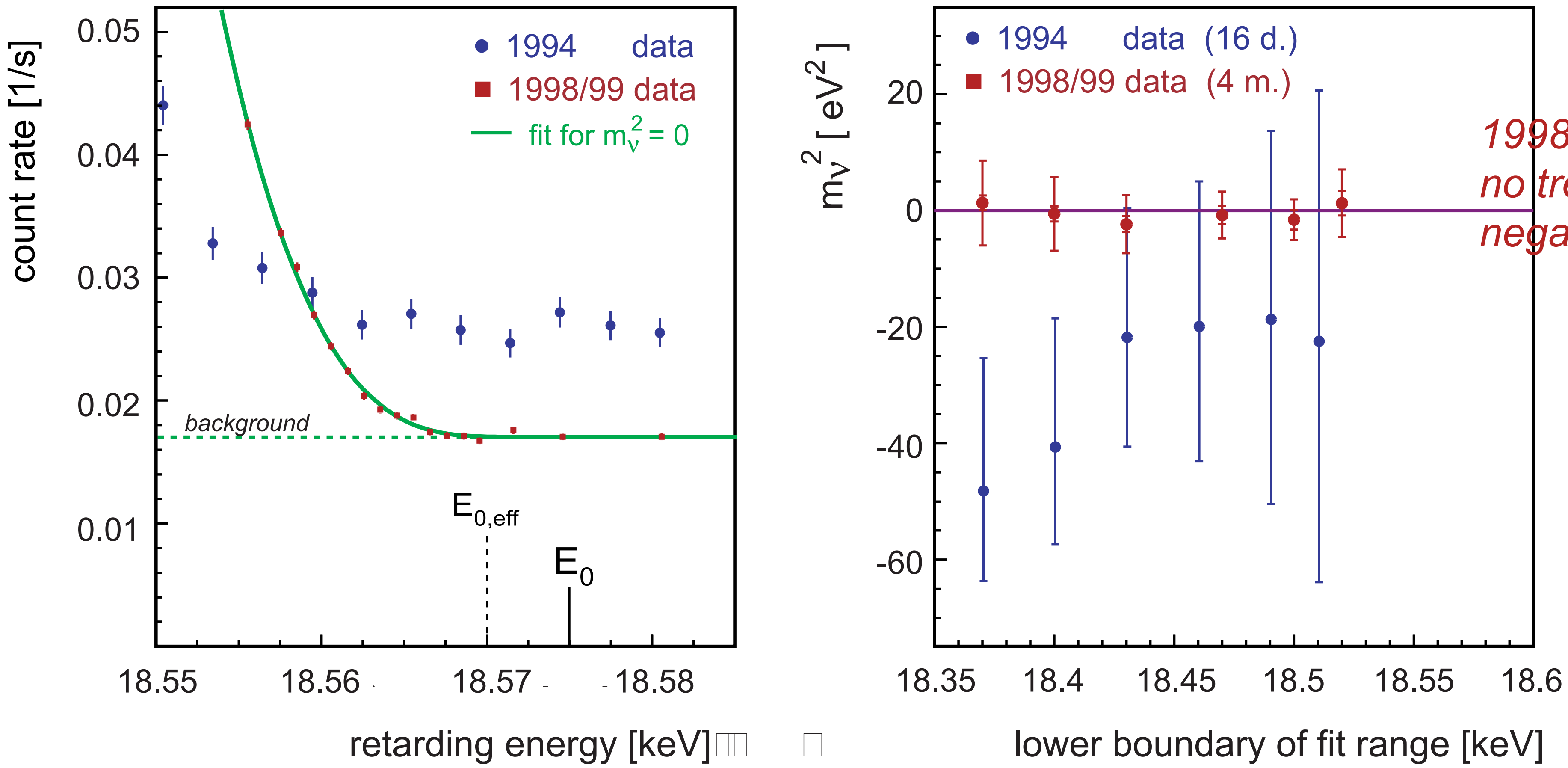
detector

segm. Si-detector

Mainz Experiment : Results 1994 - 99

new set-up since 1998 : signal/background ratio improved by factor 10

many systematic effects eliminated (film roughening, ...)



1998/99 data: no trend to negative m_ν^2

last 70 eV analysis :

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

$$m_\nu \leq \quad 2.2 \text{ eV} \quad (95\% \text{ CL.})$$

Nucl. Phys. B (Proc. Suppl.) 91 (2001) 273

intrinsic sensitivity limit of Mainz experiment

planning the next-generation direct ν mass experiment

experimental observable in ß-decay is m_ν^2

aim : improvement of m_ν by one order of magnitude (3 eV → 0.3 eV)

requires : improvement of m_ν^2 by two orders of magnitude (9 eV^2 → 0.09 eV^2)

improve statistics :

- stronger tritium source (factor 40) (& larger analysing plane)
- longer measuring period (~100 days → ~1000 days)

improve energy resolution :

- large electrostatic spectrometer with ΔE=1 eV (factor 4 improvement)

but : count rate close to ß-end point drops very fast (~δE^3)

last 10 eV : 2 x 10^{-10}
last 1 eV : 2 x 10^{-13}
of total ß-intensity

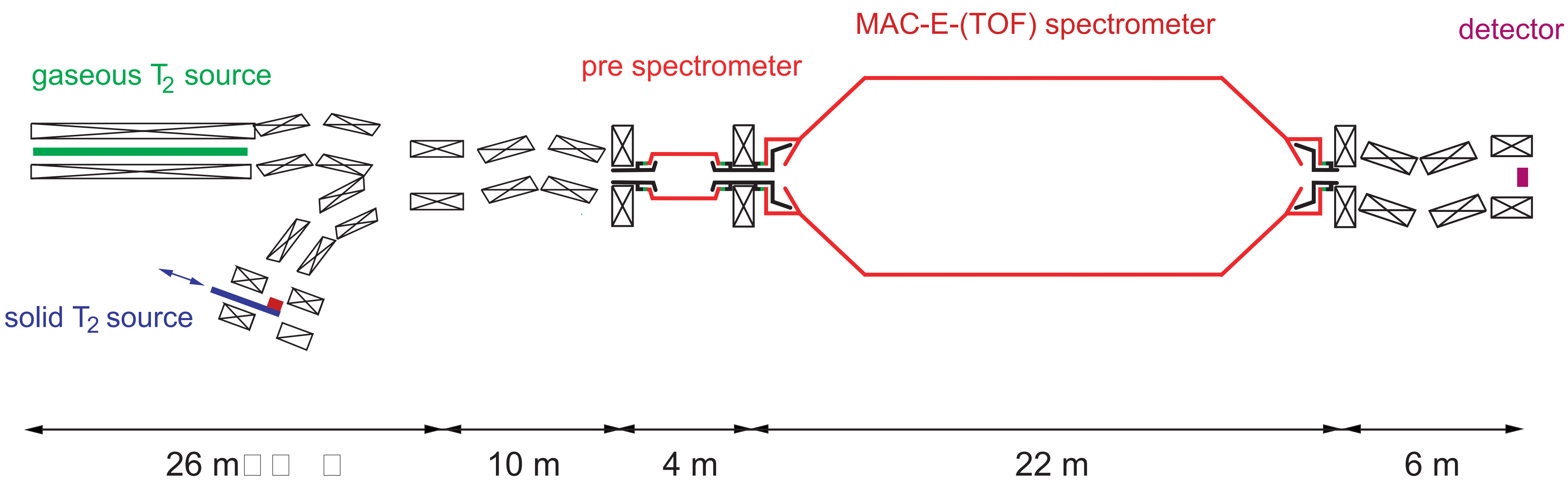
Karlsruhe Tritum Neutrino Experiment KATRIN

next-generation experiment with sub-eV neutrino mass sensitivity

FH Fulda - FZ & U Karlsruhe - U Mainz - INP Prague - U Seattle - INR Troitsk

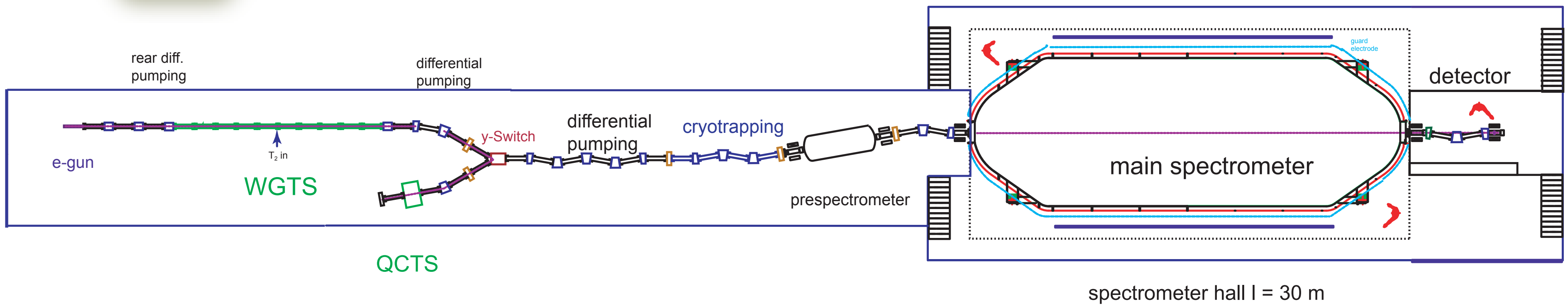
high luminosity | *background suppression* | *high energy resolution* | *control of systematics*

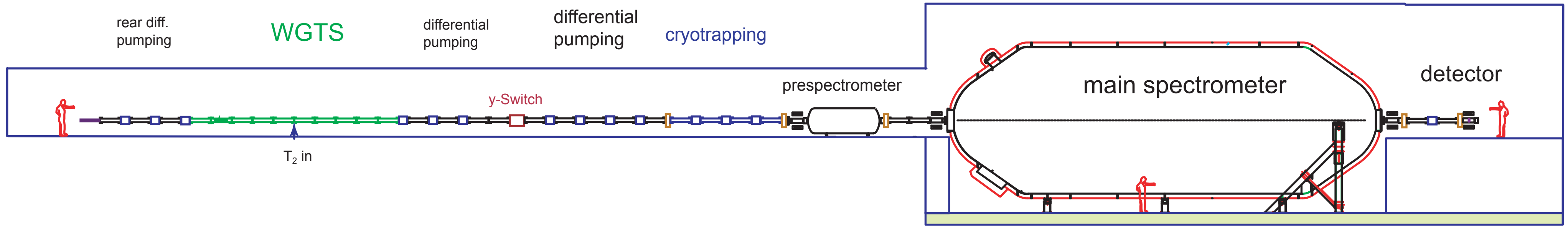
molecular tritium source | pumping | pre-filter | energy analysis | ß-electron counting



KATRIN experiment in linear configuration

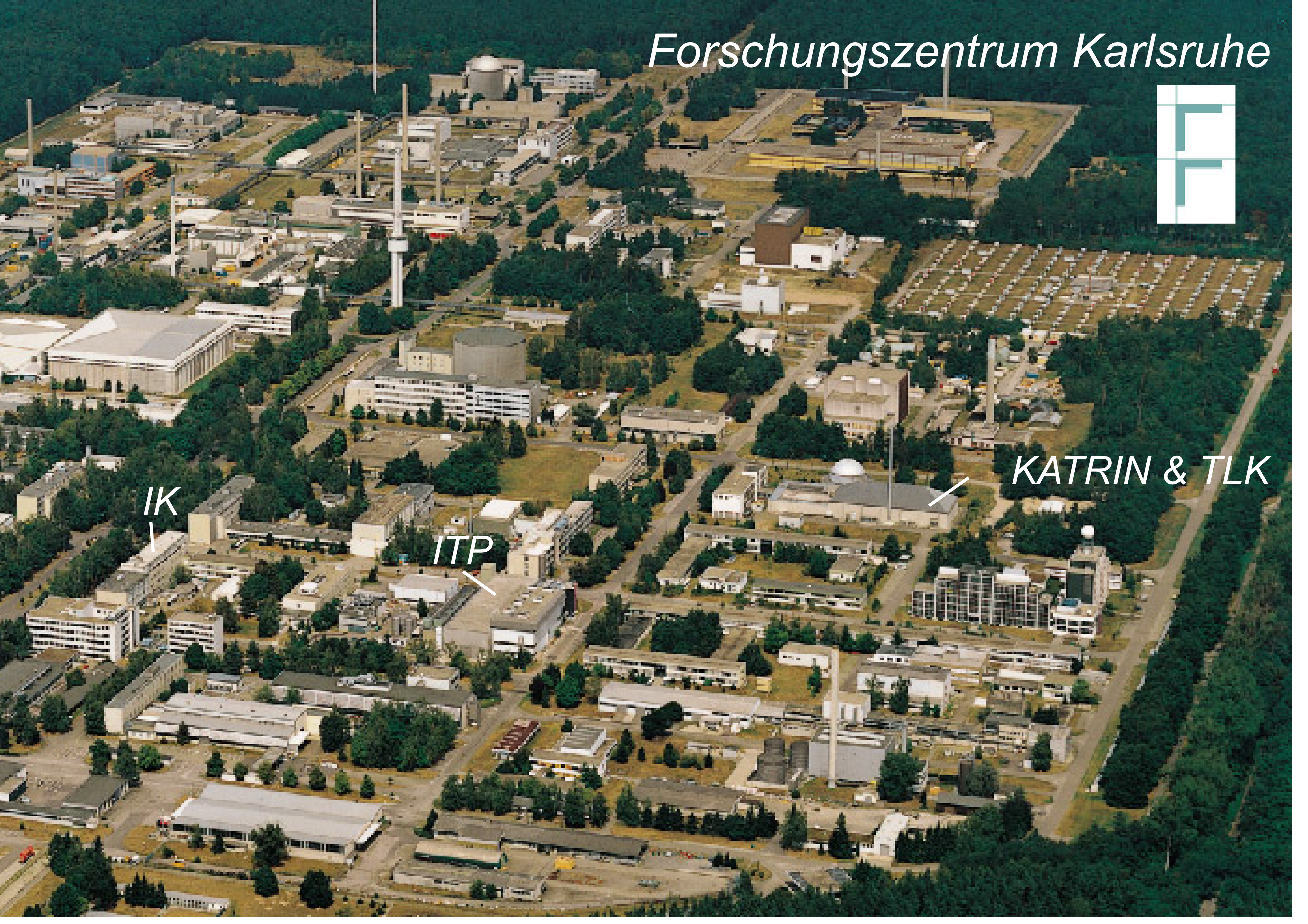
top view





side view

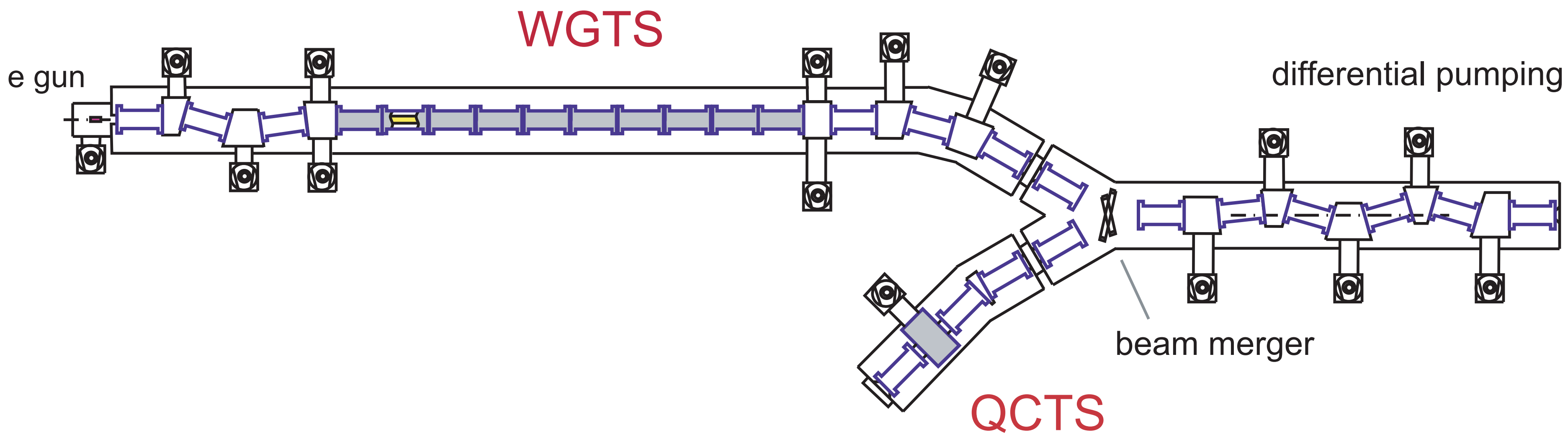
total length of KATRIN experimental hall
in linear set up ~ 70 m


Forschungszentrum Karlsruhe
KATRIN & TLK
IK
ITP

Molecular Tritium Sources : WGTS & QCTS

two sources : independent measurements with different systematic effects

Windowless Gaseous Tritium Source   Quench Condensed Tritium Source



WGTS

design parameters : length 10 m
diameter : 70 mm
temperature : 30 K

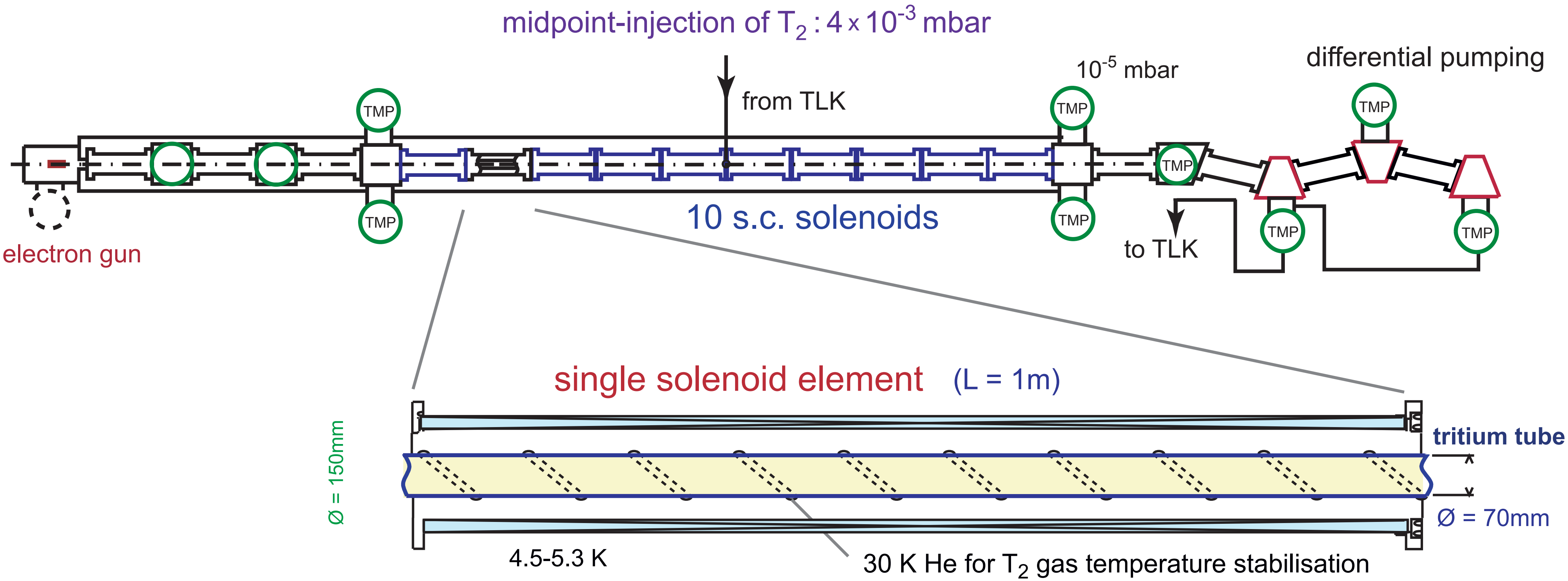
QCTS

design parameters : thickness ~35 nm
diameter : 70 mm
temperature : 1.6 K

WGTS - Windowless Gasous Tritium Source

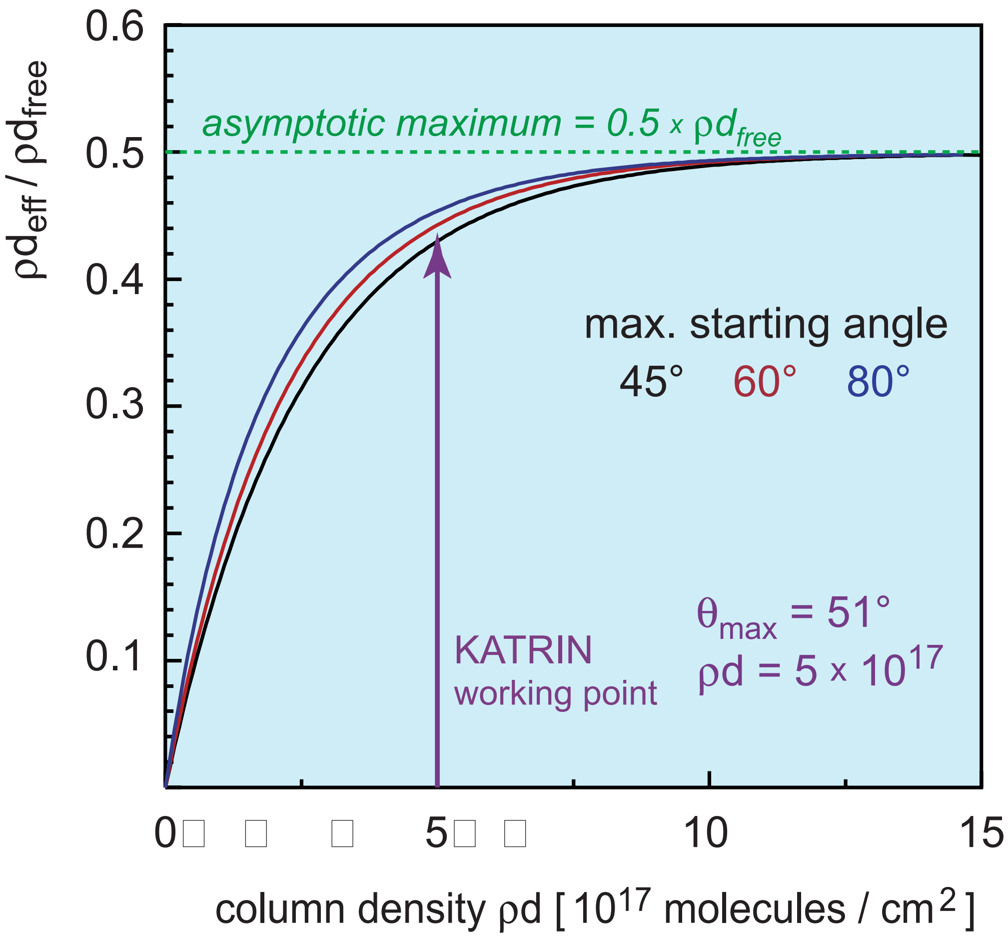
WGTS : maximum T_2 luminosity & smallest possible systematic errors
adiabatic electron transport in strong magnetic field & tritium diffusion

source parameters : L = 10 m, Ø = 70 mm, B_S = 6 T, gas purity > 99.5% T_2
T = 30 K (± 0.2°), column density ρd : 5×10^{17} T_2 / cm^2



WGTS parameters: column density ρd

choice of column density ρd and θ_{max} to maximise ß-count rate



Signal rate S close to ß-end point ('no loss' electrons : no inelastic scattering in WGTS)

$$S \sim (A_s \times \rho d) \cdot (1-\cos\theta_{max}) \cdot P_0(\rho d, \cos\theta_{max})$$

$N(T_2)$ $d\Omega$ no loss

$$S \sim A_A \cdot \Delta E/E \cdot \rho d_{eff}$$

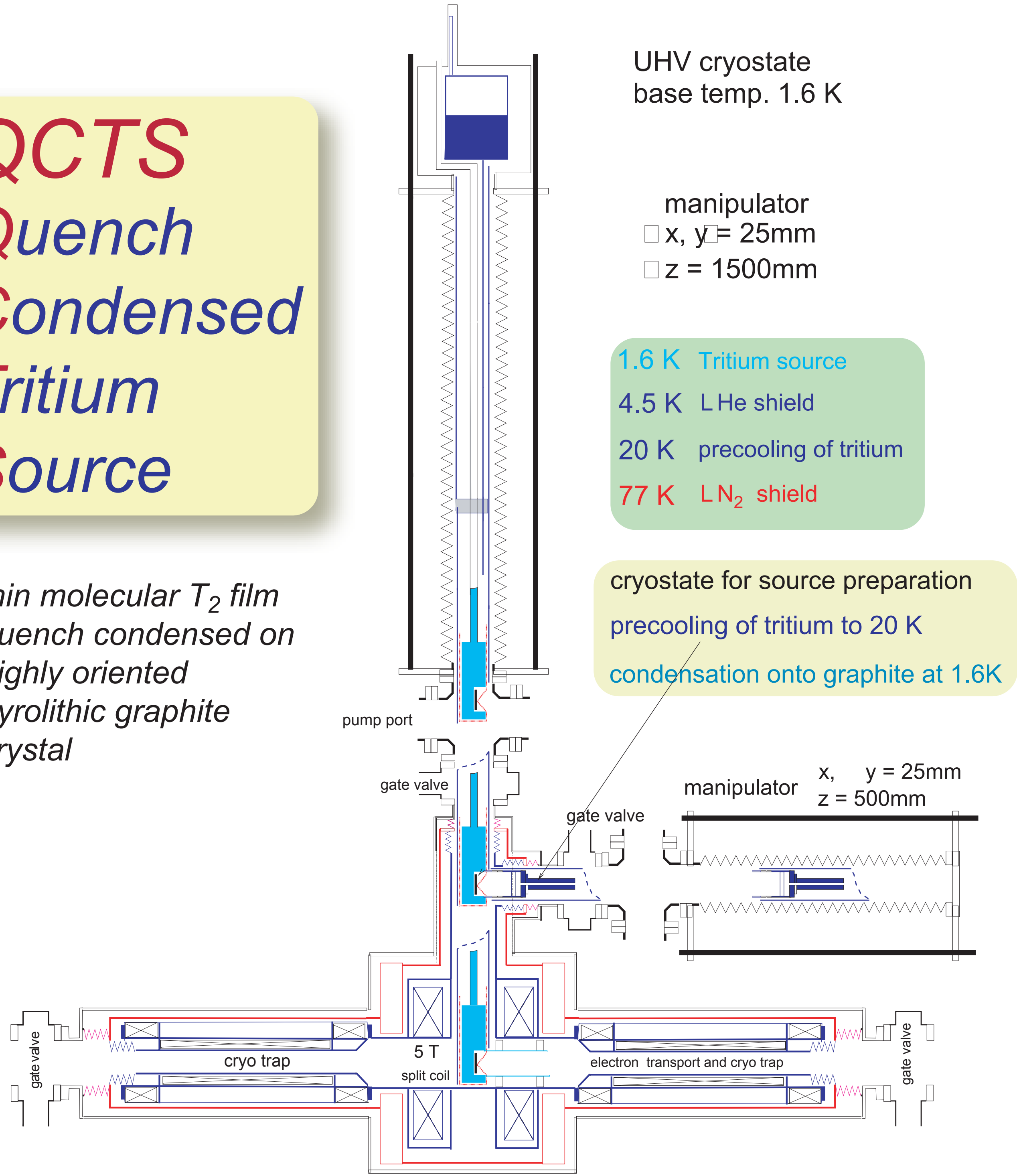
'effective' column density ρd_{eff}

virtual source of no loss ß-electrons at B_{max}

KATRIN WGTS delivers almost maximum count rate close to E_0

QCTS
Quench Condensed Tritium Source

thin molecular T_2 film quench condensed on highly oriented pyrolithic graphite crystal

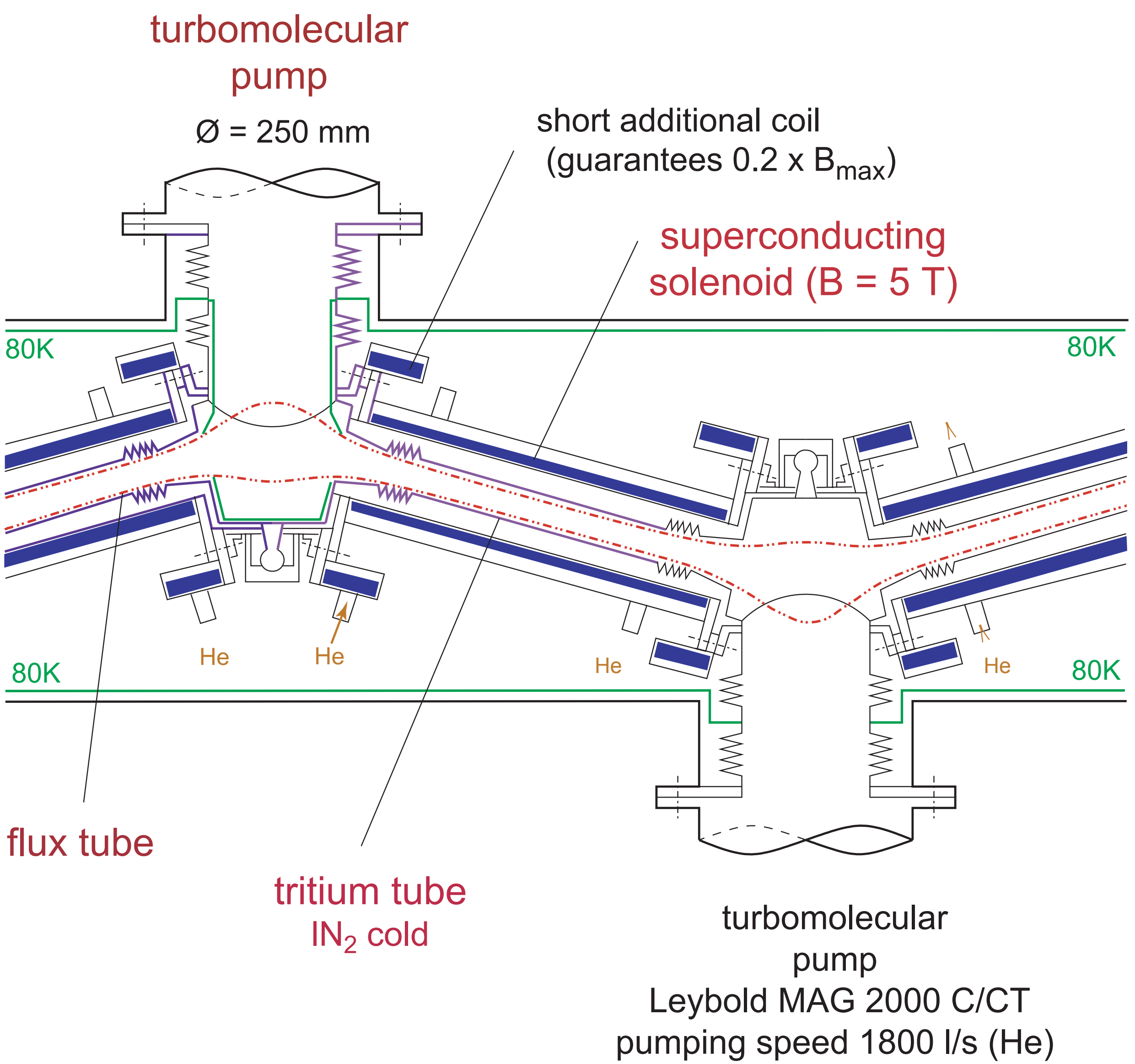


QCTS design parameters :

- thickness : 340 Å (100 monolayers)
- source diameter : 70 mm
- energy resolution : 2-3 eV
- temperature :1.6 K (avoid roughening transitions)
- effective lifetime : ~300 days (due to tritium evaporation)

The QCTS will provide results with independent systematic effects

layout of the differential pumping



differential pumping by
turbo molecular pumps

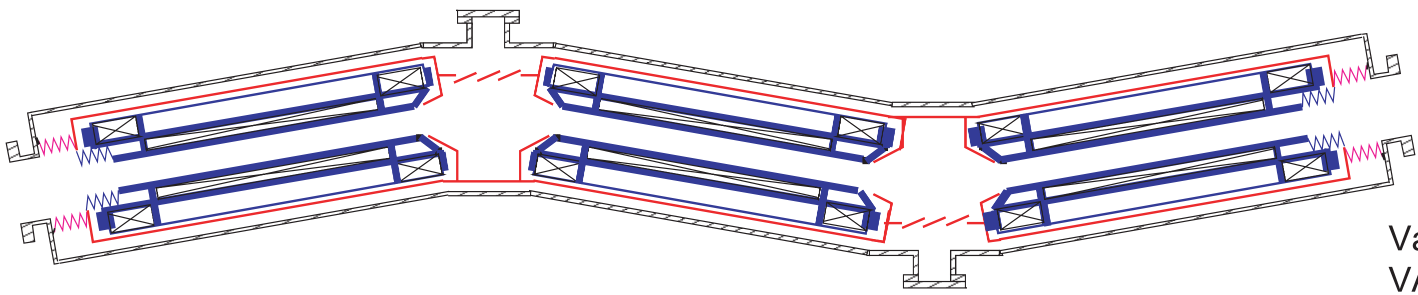
task :
tritium extinction by factor 10^9
transfer of used gas to TLK :
T_2 purification (>99.5%)

upstream :
tritium pressure < 10^{-7} mbar

tritium tubes and solenoids :
1 m long sections tilted by 20°

Electron transport and cryotrapping

tasks : transport of electrons to the spectrometer (B = 5 T)
inner tritium tube d = 90mm
cryotrapping of tritium & residual gases on lHe-cold bore



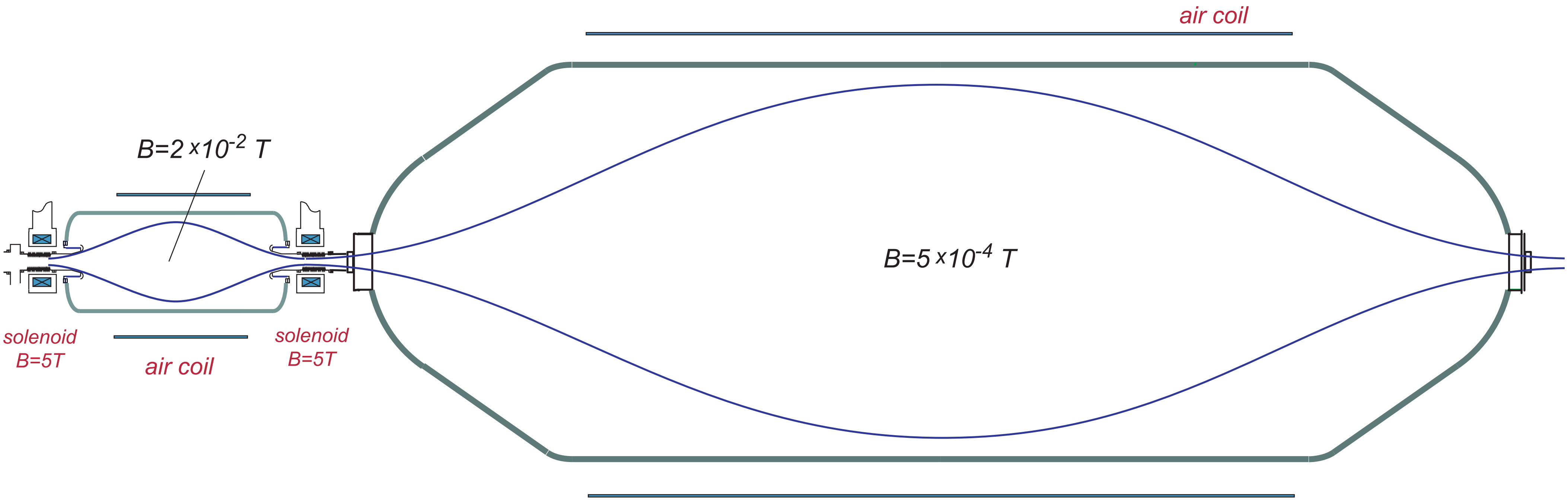
guided magnetic flux ~ 190 Tcm²
indvidual solenoids and pipes are tilted by 20° relative to each other
no direct line of sight !

cryptrapping part guarantees non-contamination of the spectrometer with tritium

electrostatic spectrometers - properties and geometry

electrostatic analysis of tritium ß-decay electrons (electrode system)

XUHV - conditions : $p < 10^{-11}$ mbar (degassing rate 10^{-13} mbar l / cm² s)



pre-spectrometer

fixed retarding potential 18.4 kV

Ø = 1.7 m / L = 4.0 m

ΔE = 80 eV

main spectrometer

variable retarding potential 18.5-18.6 kV

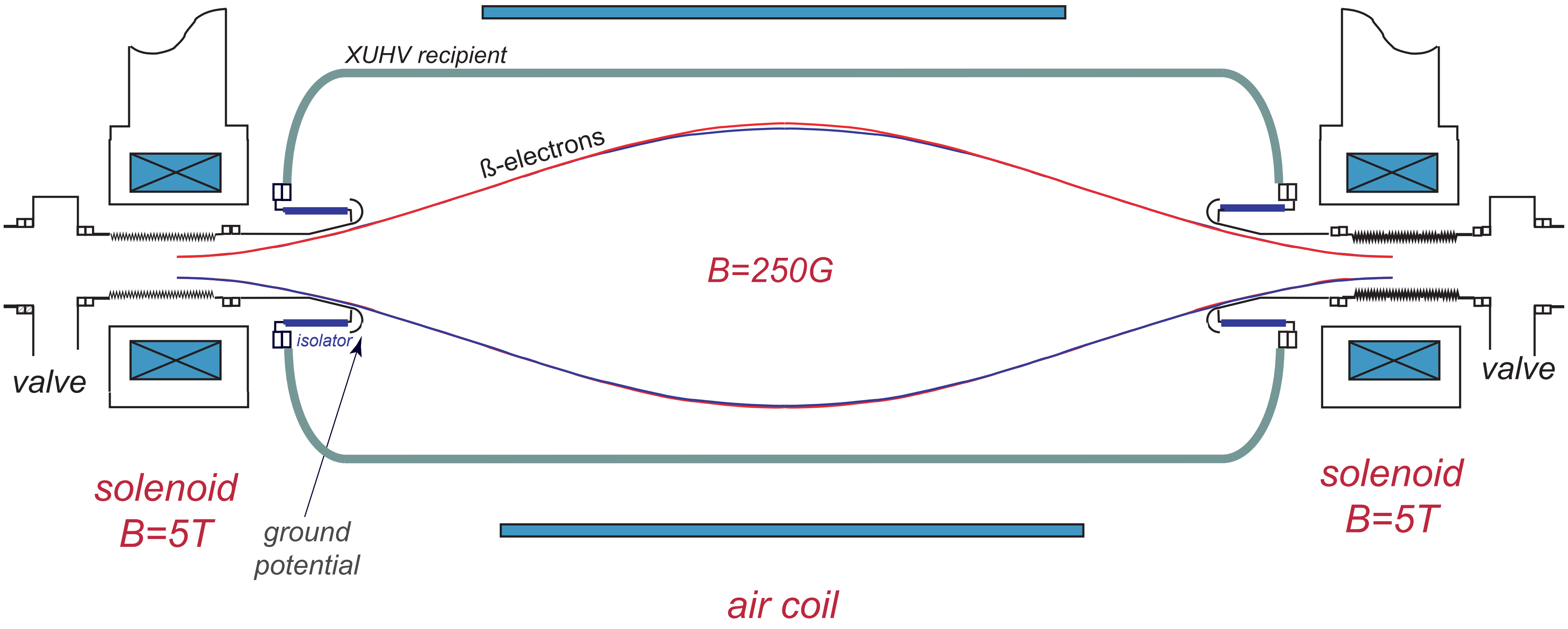
Ø = 7 m / L = 20 m

ΔE = 1 eV

KATRIN electrostatic pre-spectrometer

purpose : reject all ß-electrons with E<18.45 keV to suppress background in main spectrometer

□ □ □ □ □ ß-electron transmission factor : $\sim 10^{-7}$ with $\Delta E < 80$ eV

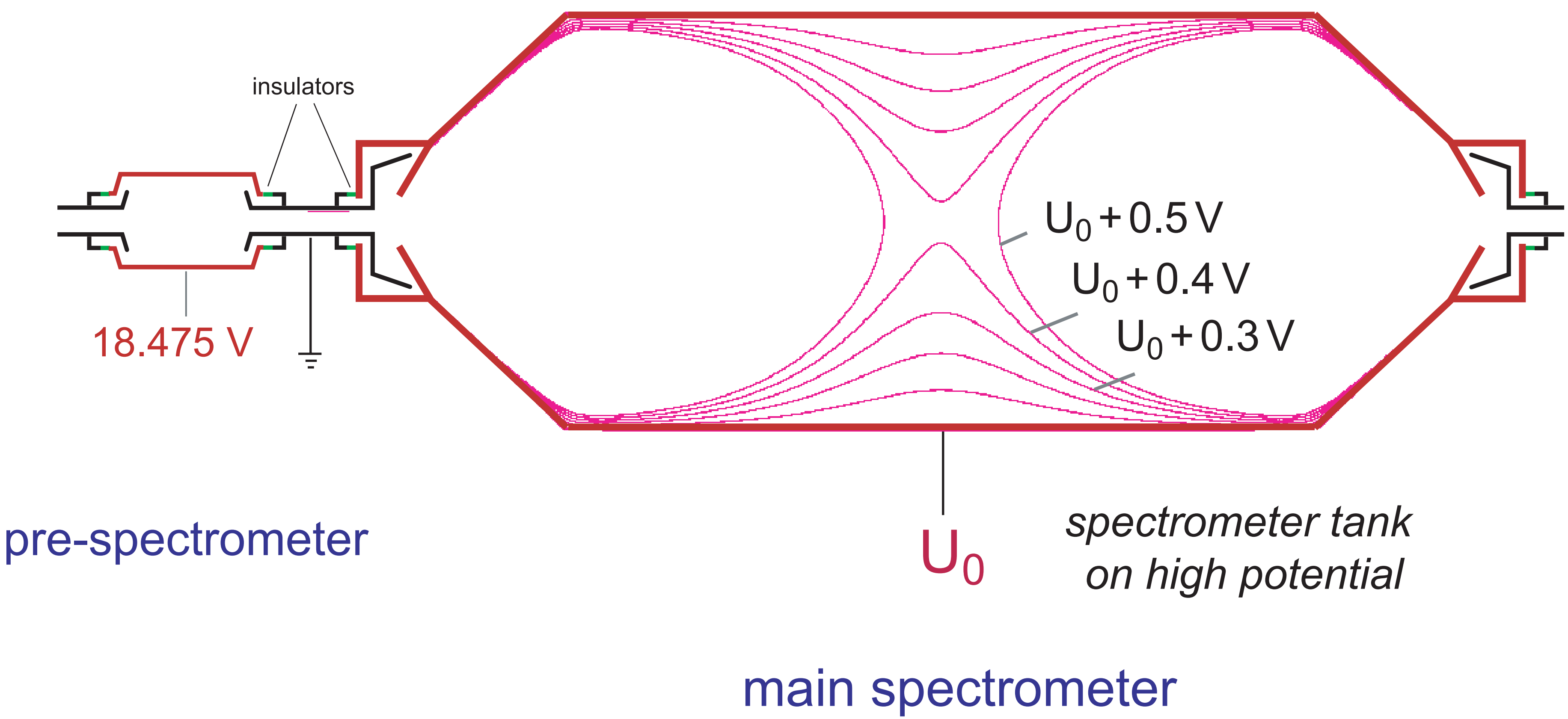


pre-spectrometer parameters: $l = 4.0$ m Ø = 1.7 m $p < 10^{-12}$ mbar

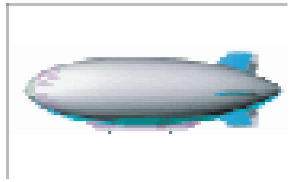
□ □ □ □ □ □ pumping by getters and TMPs

Optimization of the electrode design for the central spectrometer

symmetric drop of electrostatic potential in central plane
requirement: ΔU < 1 V is met !

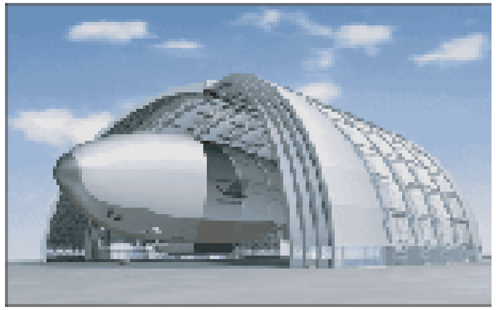


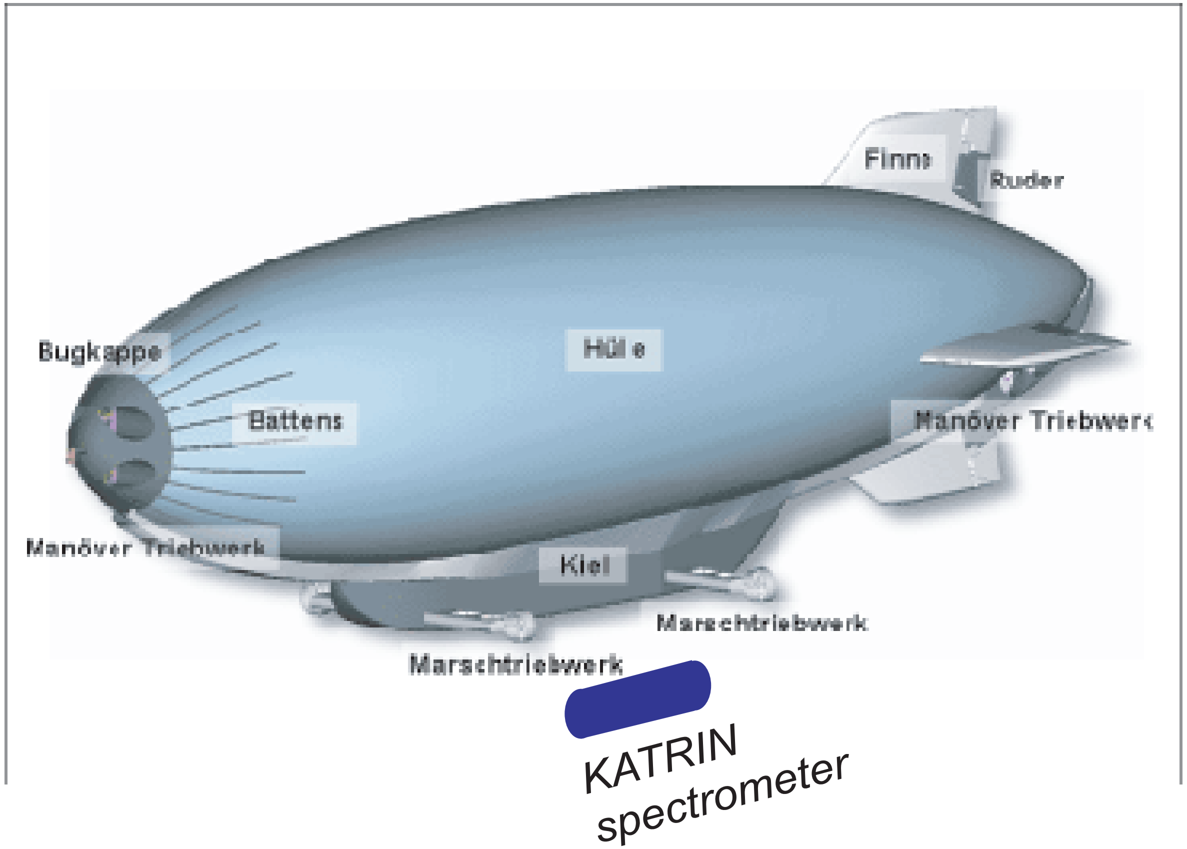
transport of the spectrometer to FZK



possible option : Cargolifter CL160

with 160 t transport capacity





Length 260 m , d = 65 m

cruising altitude :
maximum 2000 m

traveling speed :
80-100 km/h

costs : central european manufacturer to FZK
~60 kEuro

Detector Requirements

large sensitive area (Ø = 100 mm, i.e. ~10^4 mm^2)

high efficiency for <20 keV e^- (minimum dead layer)

good spatial resolution to measure source profile background studies ($\Delta x \times \Delta y$ ~ 5-10 mm²)

good time resolution for ToF mode (τ_{rise} < 0.1 μs)

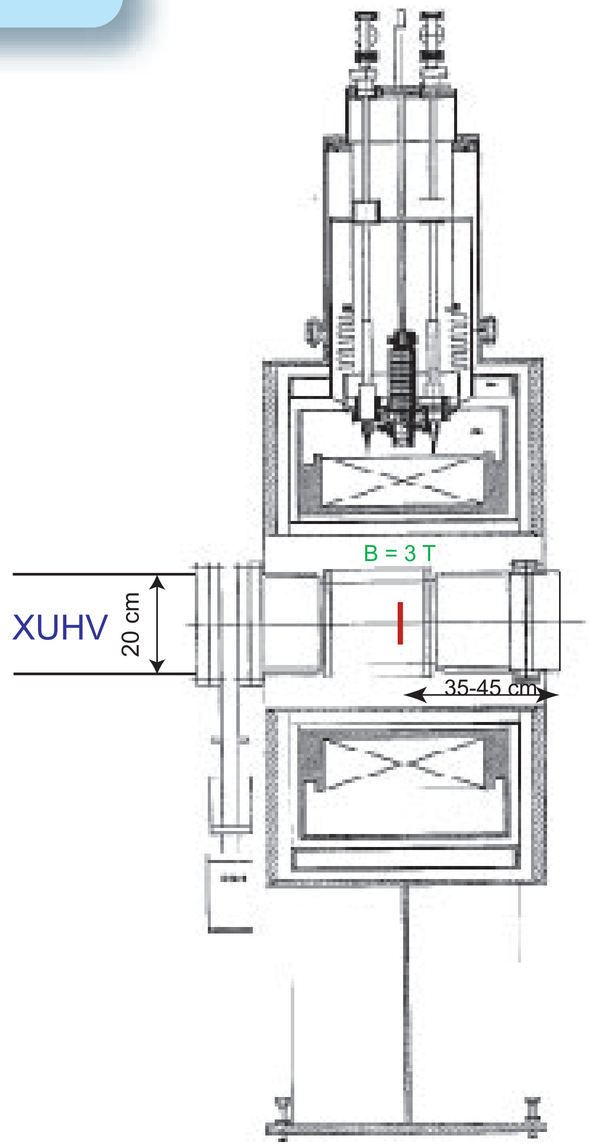
good energy res. / low el. noise (ΔE < 250-300 eV)

low γ-efficiency (thickness ≤ 300 μm)

small backscatter prob. for ß's (low Z, small angles)

low intrinsic background (bg rate ~ 1 mHz)

long-term operation a) strong B-fields (~ few T)
b) XUHV conditions

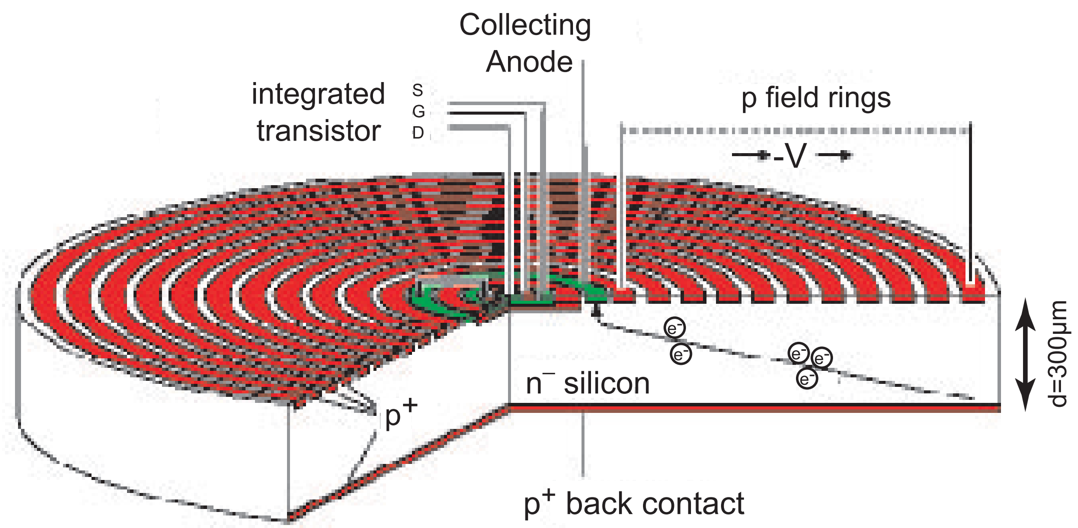


detector environment

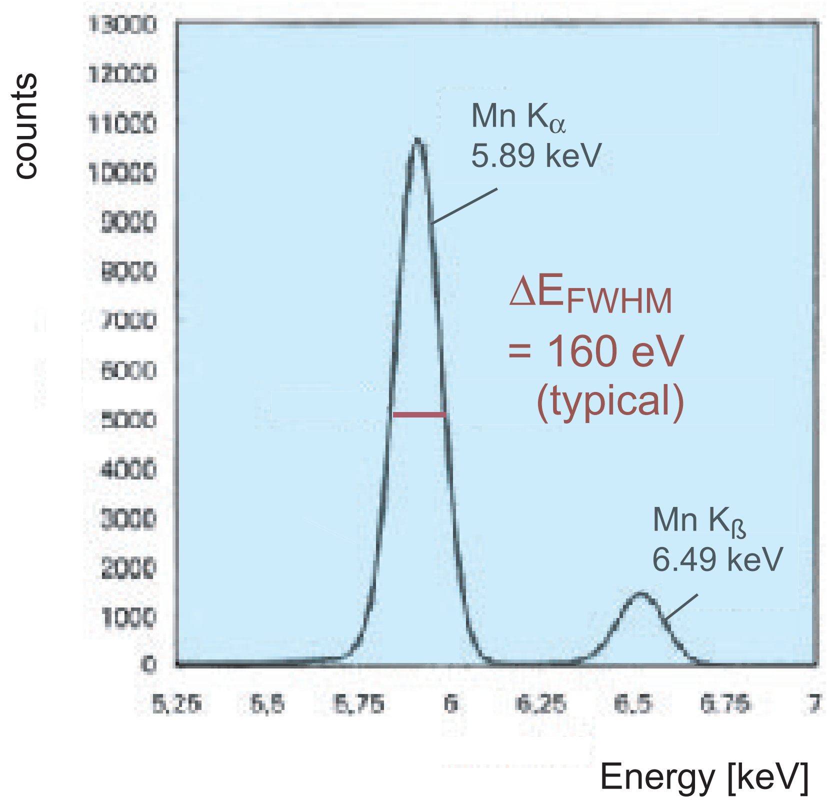
no LHC/Tesla radiation hardness required (rate ~ few mHz)

Silicon Drift Diodes for detection of keV ß-electrons

manufacturers : Halbleiterlabor Garching & KETEK, Canberra



energy resolution from Fe-55 source



layout : active area 5-10 mm^2
small collect. anode diameter 100-400 µm
segmented p^+ junctions

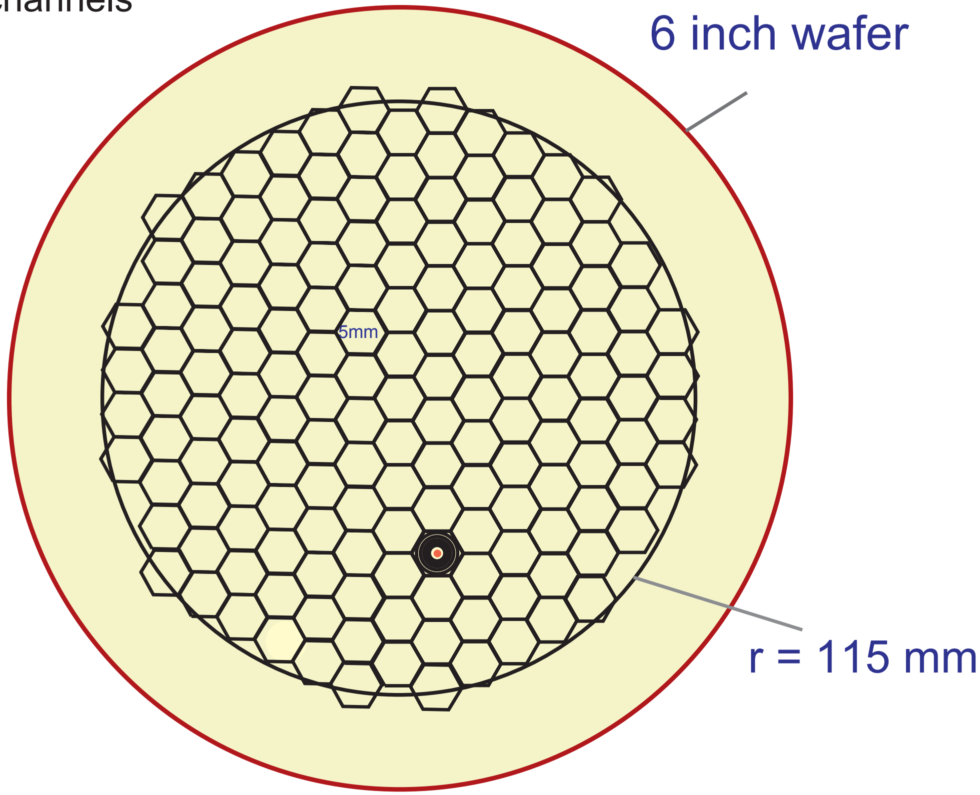
advantages : low capacitance ~ 0.1 pF
red. electronics noise (~90eV)
thin dead layer (30-50 nm)
integrated jFET
Peltier cooling sufficient

expected energy resolution @ 18.6 keV
ΔE (FWHM) = ~ 230 eV

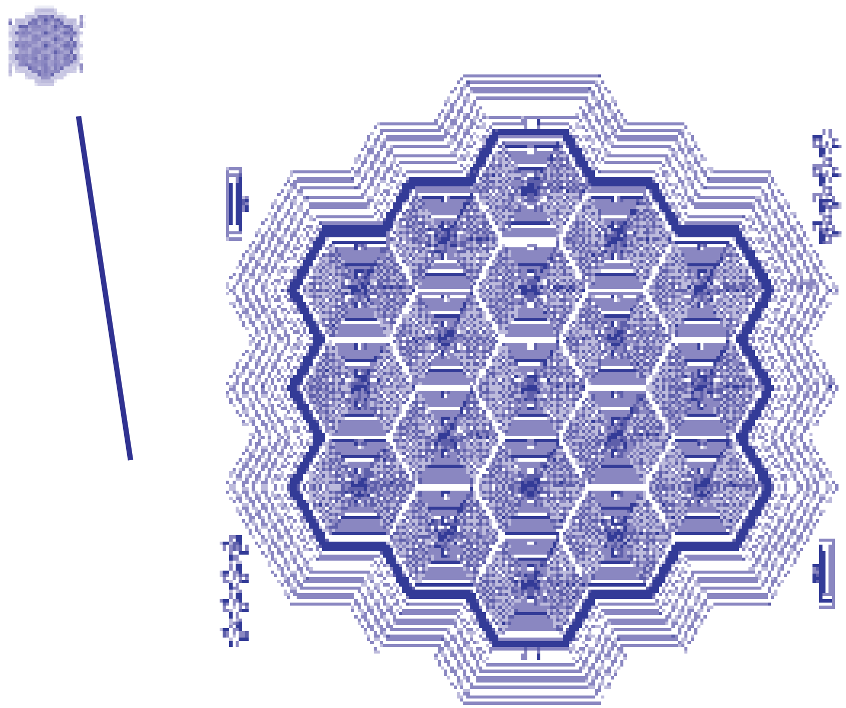
Multichannel Silicon Drift Diodes

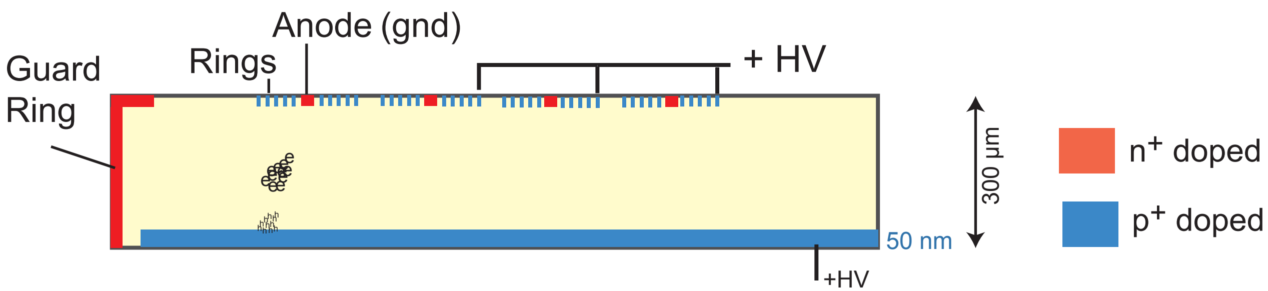
Monolithic Array *(very prelim.)*

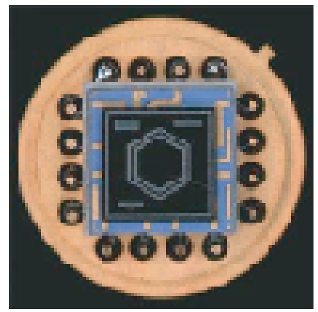
154 channels



current arrays of 19 SDDs (each 5 mm2)



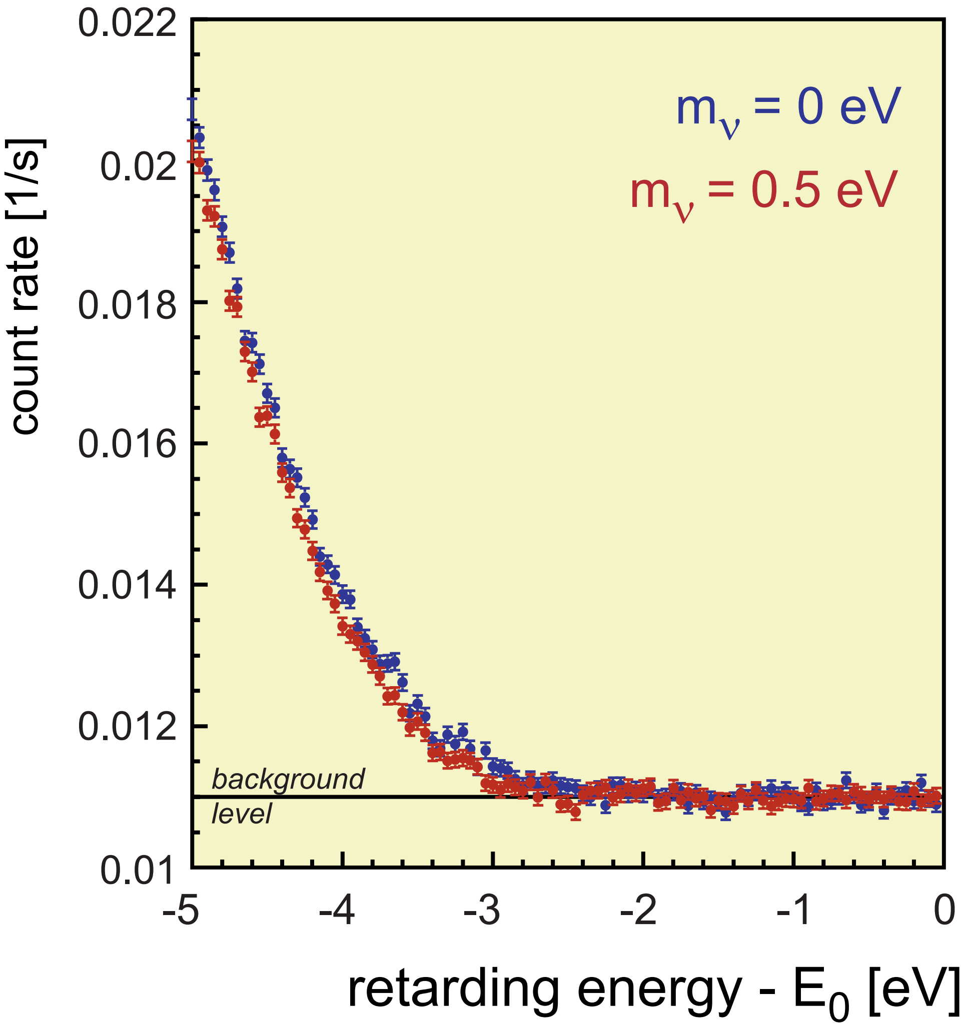




Estimated KATRIN sensitivity for neutrino masses

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

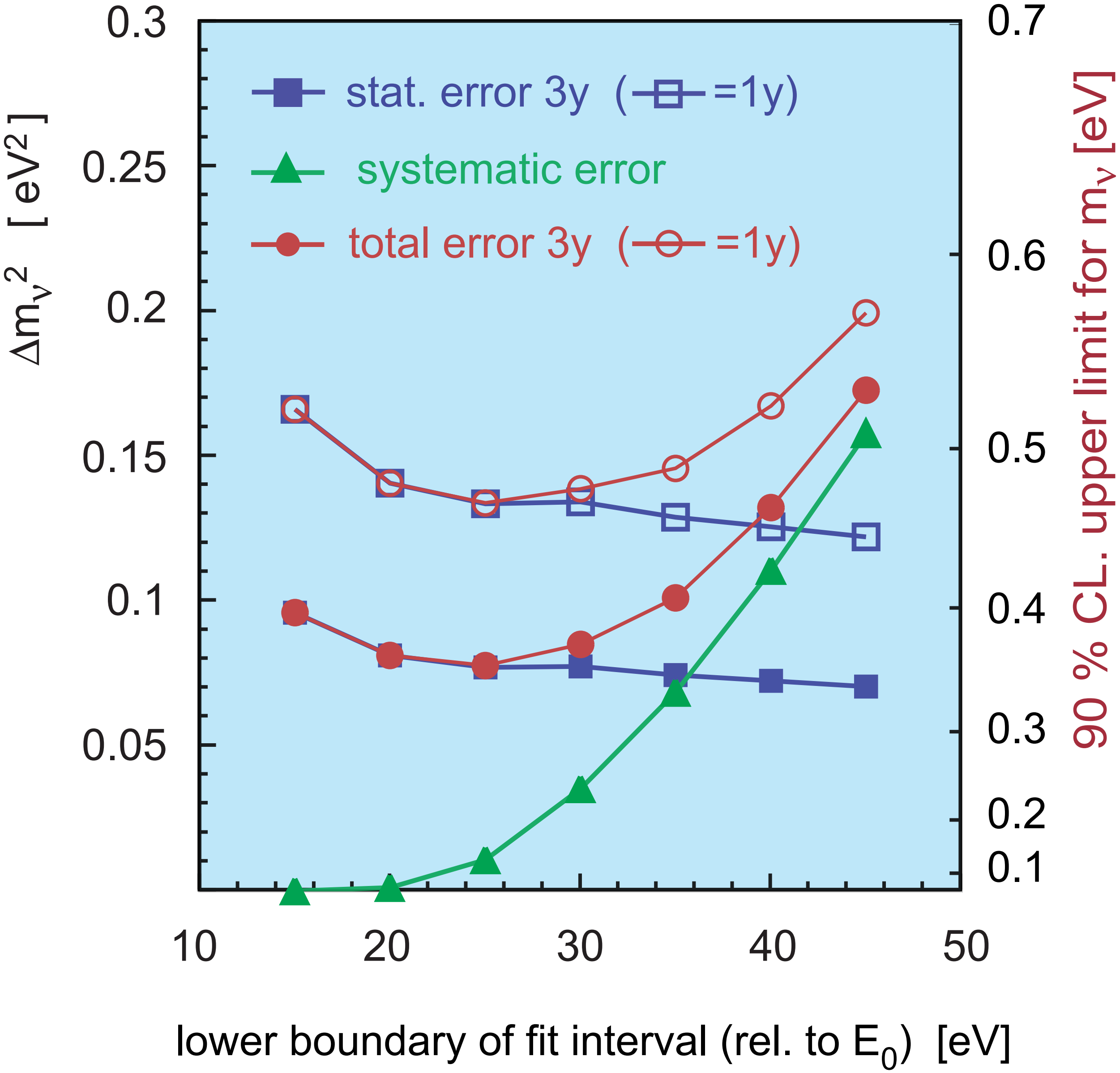
narrow interval close to ß end point (last 5 eV) from WGTS



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*

estimates of KATRIN sensitivity for m_ν



assumptions for simulation:

ΔE = 1 eV (spectrometer)

background rate = 11 mHz

WGTS : $\rho d = 5 \times 10^{17} / cm^2$

area = 29 cm^2

max. accepted angle 51°

systematic error :
2% energy loss in WGTS

m_ν < 0.35 eV (90% CL.)

Systematic Uncertainties

δE-interval = 15-20 eV

KATRIN focuses on very narrow region below E_0
(ΔE=1eV, high T_2 luminosity): many systematic uncertainties reduced

- *no contribution from excited electronic states of ^{3}He-T (δE > 25 eV)*
- *small contribution from inelastic scattering in source (for δE-Interval of 25 eV : 2% of signal from scattered electrons)*

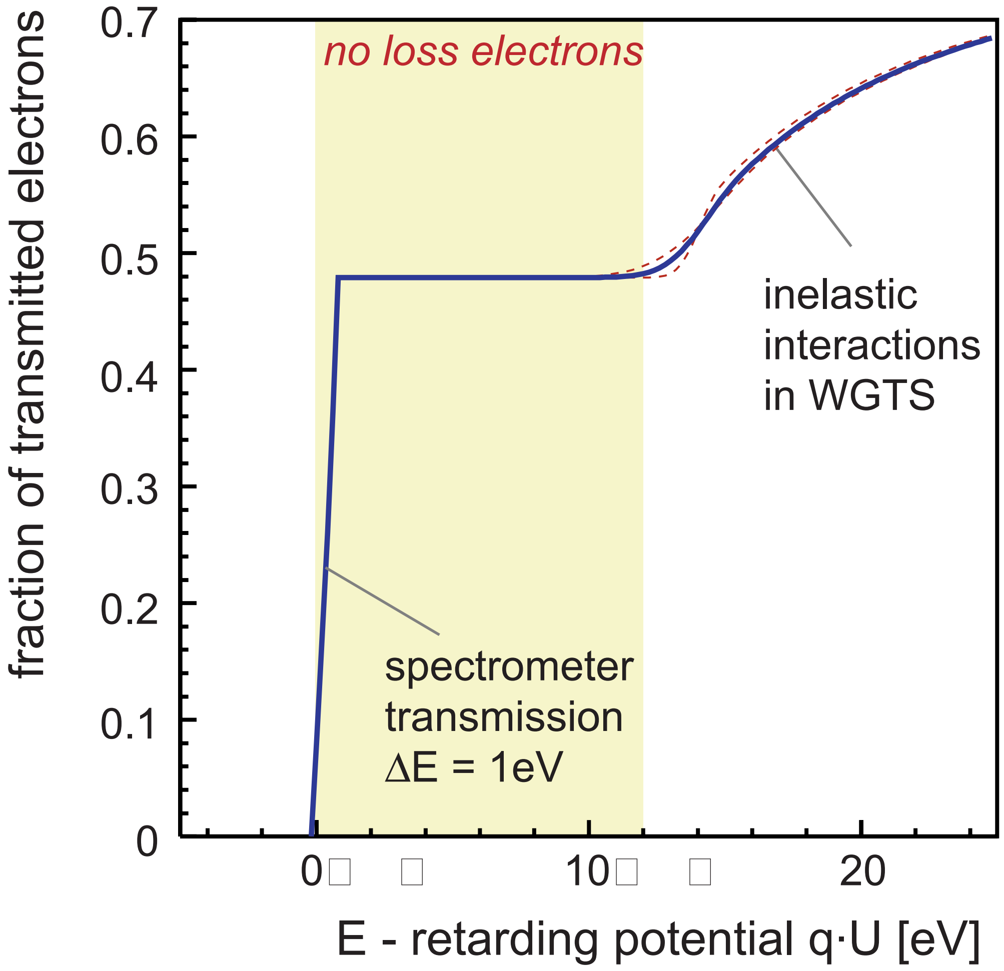
+ better vacuum & higher T_2 purity

remaining uncertainties :

- *calculations of rotational-vibrational excitations of ^{3}He-T ground state (0.2% theory uncertainty)*
- *inelastic scattering of ß-electrons in WGTS (2% uncertainty on σ_{tot}, can be improved)*
- *solid state effects (self-charging of film, neighbour excitations, ...) only QCTS*
- *stability of settings : HV calibration and stabilisation*
  □ □ □ □ □ WGTS activity and T_2 -purity

KATRIN response function

calculated response function for monoenergetic electrons (energy E)
emitted isotropically from WGTS close to tritium ß-endpoint at 18.6 keV



electrostatic spectrometer

analytical transmission function T :

depends only on B_S / B_A and B_A / B_{max}

no tails of resolution !!

molecular source WGTS

calculation of energy losses : $\sigma \times L(\theta)$

total cross section $\sigma = 3.4 \times 10^{-18}$ cm^2

parameters: $\rho d = 5 \times 10^{17}$ mol/cm^2

max. accepted angle 51°

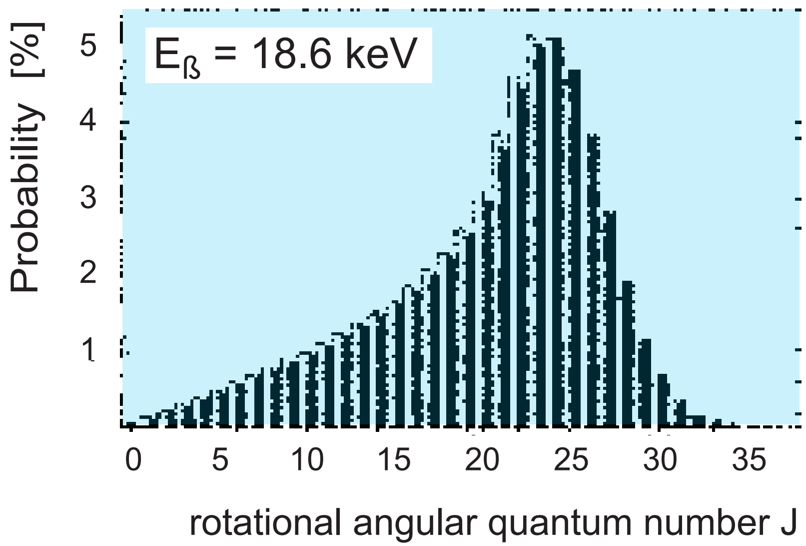
last 12 eV below E_0 :
only 'no loss' electrons !

Molecular Excitations of $^3HeT^+$

ß-decay of molecular T_2 : recoil energy, electronic & rotational-vibrational excitations

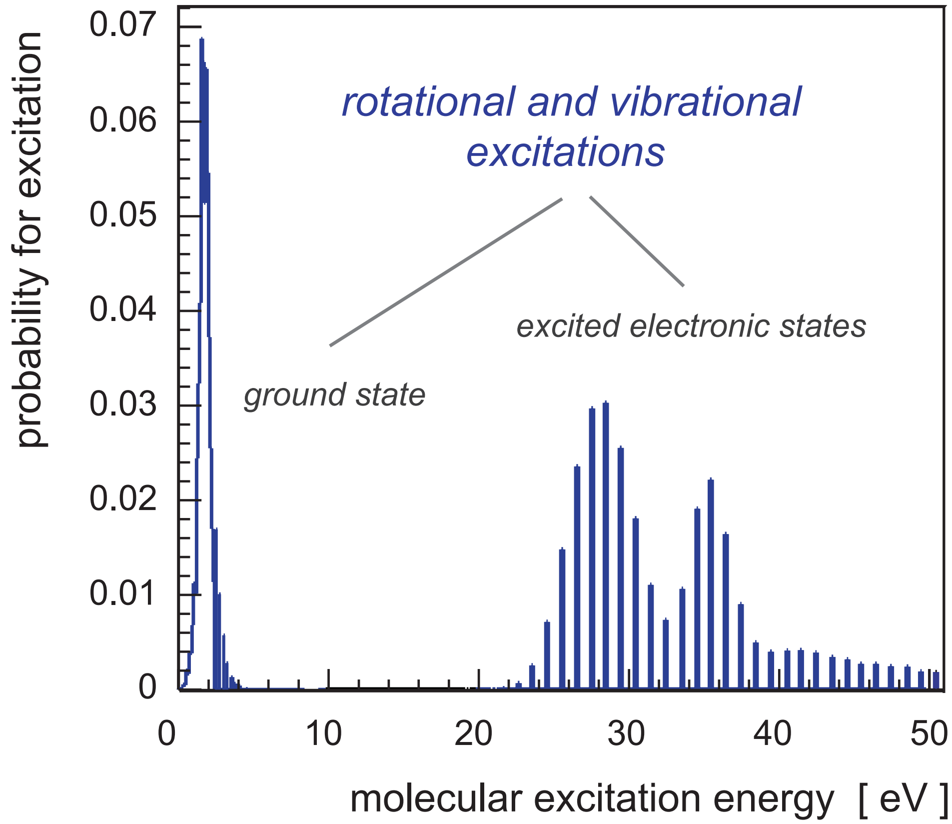
E_R = 1.72 eV @18.6 keV

final state probability	*electronic final state*
14 %	continuum
29 %	excited states
57 %	ground state



absolute accuracy of theory = 0.2 %

improved calculations of molecular final states



integration of spectrum yields 99.93% of total population probability

A. Saenz, S. Jonsell, P. Froelich, Phys. Rev. Lett. 84 (2000) 242

Implications of KATRIN result

cosmology

□ - measure or constrain ν–HDM : Ω_ν

- m_ν as input for analysis of high precision CMB data (MAP, Planck)

astrophysics

□ - m_ν as input for analysis of ν-ToF signal (black hole formation)

□ - test model of ν-origin of UHE-CRs above GZK cutoff (Z burst)

particle physics

□ - confirm or rule out most of the parameter space of models with degenerate neutrino masses, fix or constrain ν-mass scale

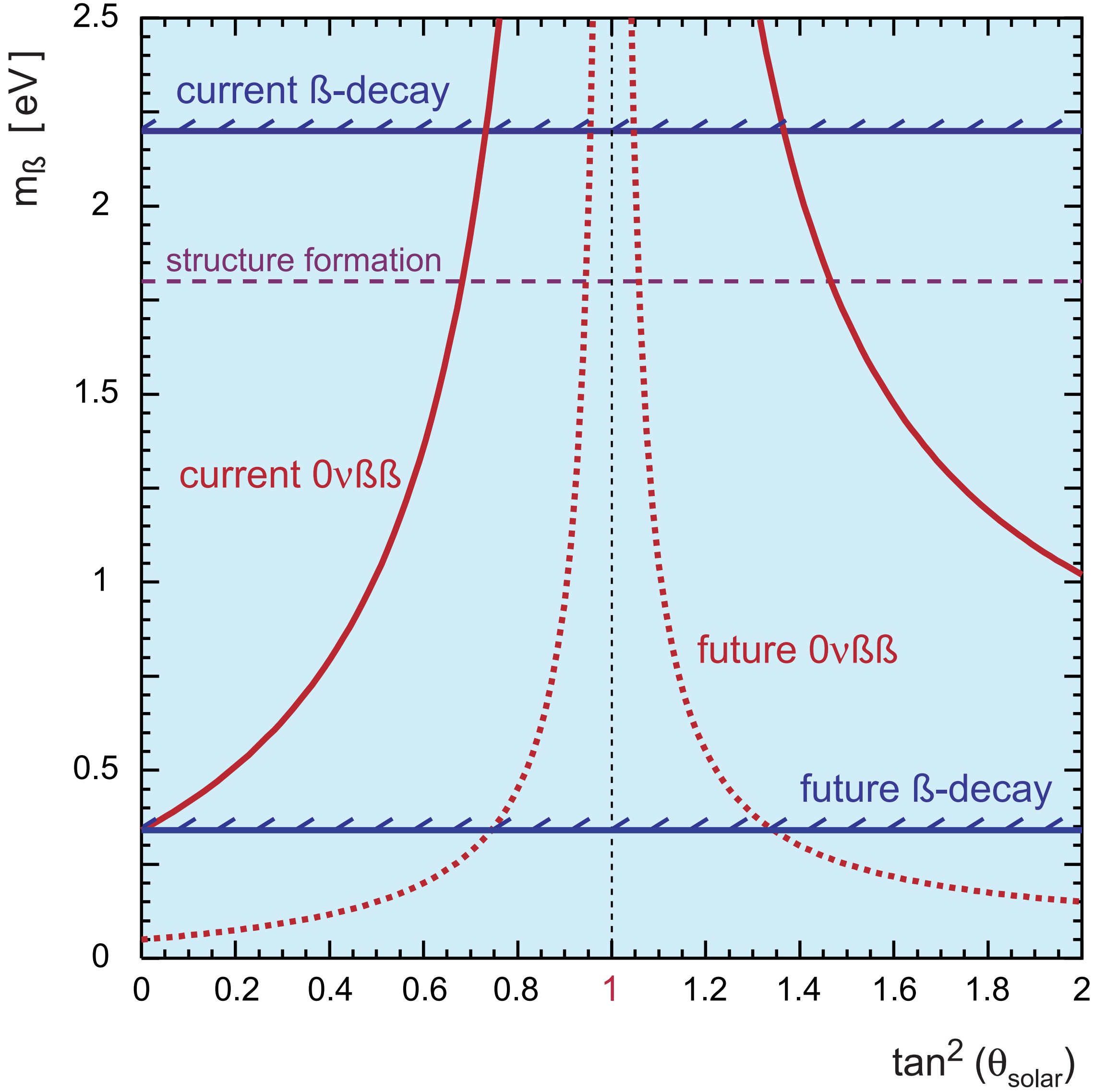
□ - possibility for indirect evidence for Majorana CP-phases from

□ combination with $0\nu\beta\beta$ results (for specific parameter range)

- non-SM physics

Bounds on effective ß-decay mass $m_ß$

Y. Farzan, O.L.G. Peres and A. Yu. Smirnov, Nucl.Phys. B612 (2001) 59-97



3 ν-scheme with mass degeneracy
$|U_{e3}^2 = 0|$

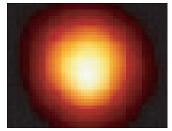
current 0νßß :
m_{ee} < 0.34 eV (Heidelberg-Moscow)

future 0νßß :
m_{ee} < 0.05 eV (CUORE, GENIUS, MOON,...)

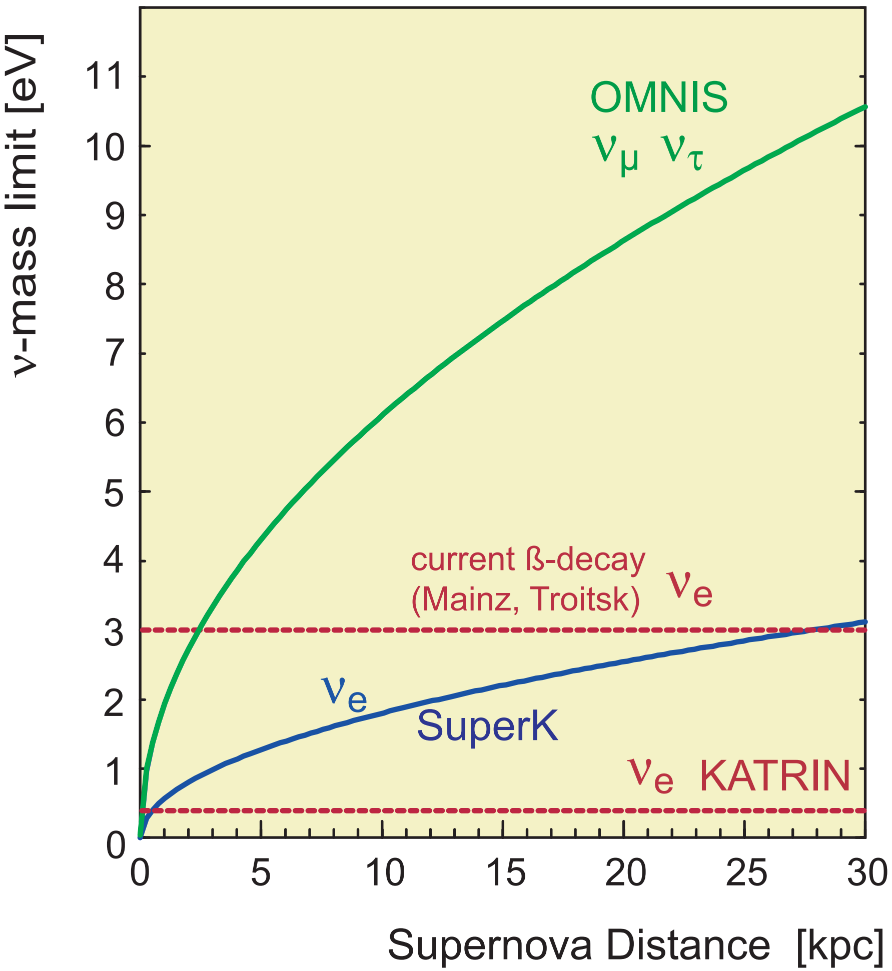
current ß-decay :
$m_ß$ < 2.2 eV (Mainz, Troitsk)

future ß-decay :
$m_ß$ < 0.35 eV (KATRIN)

ν–masses: sensitivity from a SN ν – signal


SN20xx

future m_ν limits expected from SN-ν
cutoff due to early black hole formation



'standard' method :
use time delay due to rest mass: f (E_ν, Δt_ν)

$$\Delta t_\nu \text{ [sec]} = 0.026 \cdot d \text{ [50 kpc]} \cdot m_\nu \text{ [1eV]} \cdot E_\nu^{-2} \text{ [10 MeV]}$$

limit from SN1987a :
11 ν's in Kamiokande and 9 ν's in IMB-3

$m(\nu_e) < 23$ eV

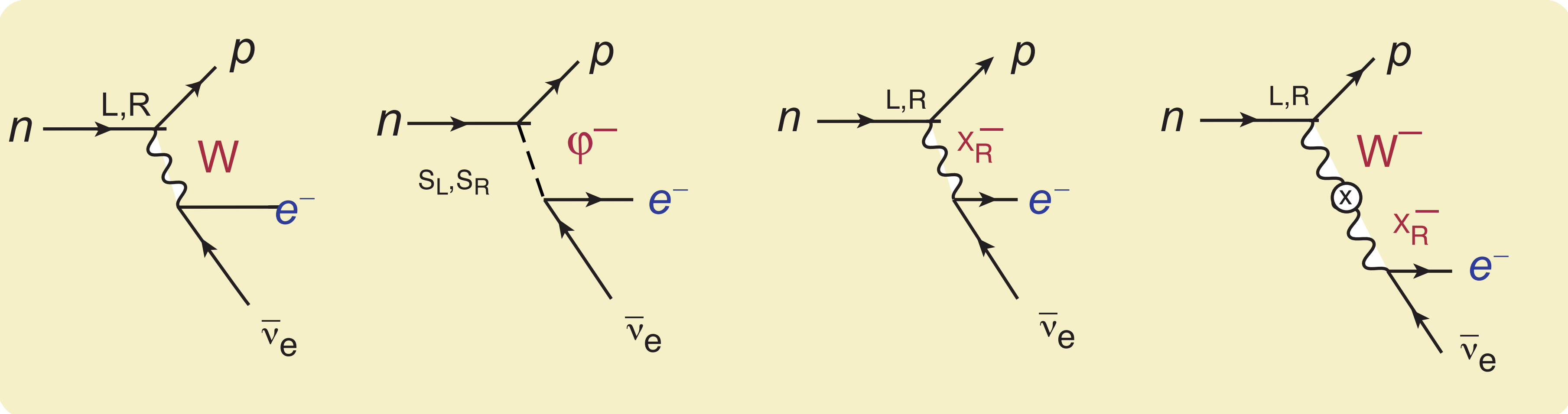
improved methods (SN - network) :

a) cutoff due to early black hole formation (problem : neutron star - black hole ratio uncertain)

b) correlation of ν-signal with gravitational waves (Virgo,Ligo)

‚non ν-mass' physics with KATRIN

- tritium ß-decay as test for non-SM interactions :



SM process | scalar exchange | direct RH current | mixing

G.J. Stephenson, T. Goldman, B.H.J. McKellar, Phys.Rev. D62 (2000) 093013

- tritium ß-decay as test of tachyonic neutrinos

J. Ciborowski, J. Rembielinski, Eur.Phys.J. C8 (1999) 157

Technological Challenges

electrostatic spectrometer

construction large vessel (Ø=7m, l=20m)

XHV ($p < 10^{-11}$ mbar)

HV control & stabilization

optimized electrode system

electron transport

> 30 superconducting solenoids

lHe and lN_2 supply (200W cooling power)

optimized particle tracking (l > 60 m)

reliable extinction of tritium (freeze out)

tritium sources

stable & safe tritium supply

high luminosity & reliability

control of syst. effects (TOF op., calib.)

solid state detector

excellent $\Delta E/E$ in high B-field (< 1keV)

good position resolution

mK operation of bolometer

experiment will be operational for several years

interdisciplinary solutions are required

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
7/2002	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
2007	commissioning and begin of data taking

KATRIN Collaboration

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University of Washington, Seattle

Conclusions & Outlook

KATRIN : a next generation tritium ß-decay experiment

with sensitivity to a sub-eV electron neutrino mass

motivations : cosmology (neutrino HDM)

particle physics (mass models)

many technological challenges

strong international collaboration has formed

2002 : pre-spectrometer running at Karlsruhe

more KATRIN information : www-ik1.fzk.de/tritium/