Laboratory Neutrino Mass Experiments

SSI 2000

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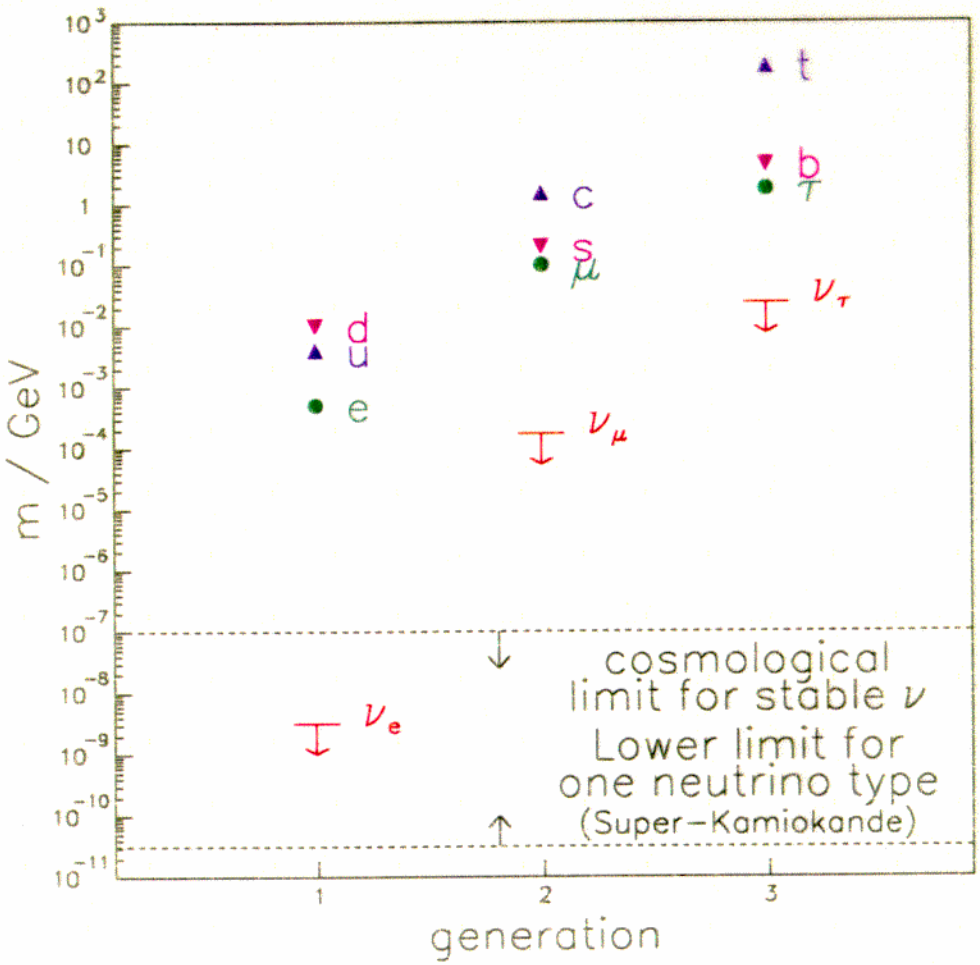
- Introduction
- Limits on the τ-neutrino mass
- Limits on the μ-neutrino mass
  - μ-momentum
  - π-mass
- Neutrinoless $\beta\beta$ decay
  - Principles
  - Present status
  - Proposal for new experiments
- Limit on the e-neutrino mass from nuclear β decay
  - Status of Re decay experiments
  - Status and perspectives of T_2 decay experiments

Fundamental fermions and their masses

Standard modell: $m_{\nu_e} = m_{\nu_\mu} = m_{\nu_\tau} = 0$)

LEPTONEN	$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}$	$\begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}$	$\begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}$
QUARKS	$\begin{pmatrix} u \\ d \end{pmatrix}$	$\begin{pmatrix} c \\ s \end{pmatrix}$	$\begin{pmatrix} t \\ b \end{pmatrix}$

Experimental masses or upper limits:



Massive neutrinos

Elementary particle physics:

- Possible understanding of fermion masses?
- Connection between fermion masses and mixing?
- Neutrino properties for $m(\nu) \neq 0$:

  → Neutrino mixing ($L_i \neq$ const.) → oscillations?

  (Solar und atmospheric ν problem, LSND ?)

  → Decays: $\nu \to \nu' \gamma$, $\nu \to \nu' e^- e^+$?

  → Particle type: dirac or majorana ($\nu \stackrel{?}{=} \bar{\nu}$)?

Cosmology:

Big bang theory:	"relic neutrinos": $N_\nu \approx 10^9 N_B$
Observation:	$\exists$ non-baryonic dark matter $\rho_{DM} \geq 0.3\rho_{crit}$
Density distribution:	"Mixed hot/cold dark matter" models:
	ν hot dark matter ($\rho_\nu \approx 0.2\rho_{crit}$):
	1 eV/c^2 $\leq m(\nu) \leq$ 2.5 eV/c^2
	(for 3 degenerated ν mass eigenstates)
Open question:	Are "relic neutrinos" the
	"hot dark matter" part of dark matter?
	→ neutrino masses of eV would be relevant

Limits on the Mass of ν_τ

Highest sensitivity

Collider experiments: $e^+e^- \to \tau^+\tau^-$

(*e.g.* Argus/DESY, Aleph/LEP)

Search for rare τ-decays:

$$\tau \to 5\pi\,(+\pi^o) + \nu_\tau \qquad (BR = 10^{-3})$$

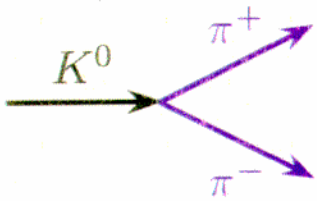
to set limits on E_ν ($0 < E_\nu < m_\tau - 5 \cdot m_\pi$)

$\to$ Decays with high muliplicity: ν_τ from spectral shape

Method: use the invariant mass of the "visible" 5(6) π's:

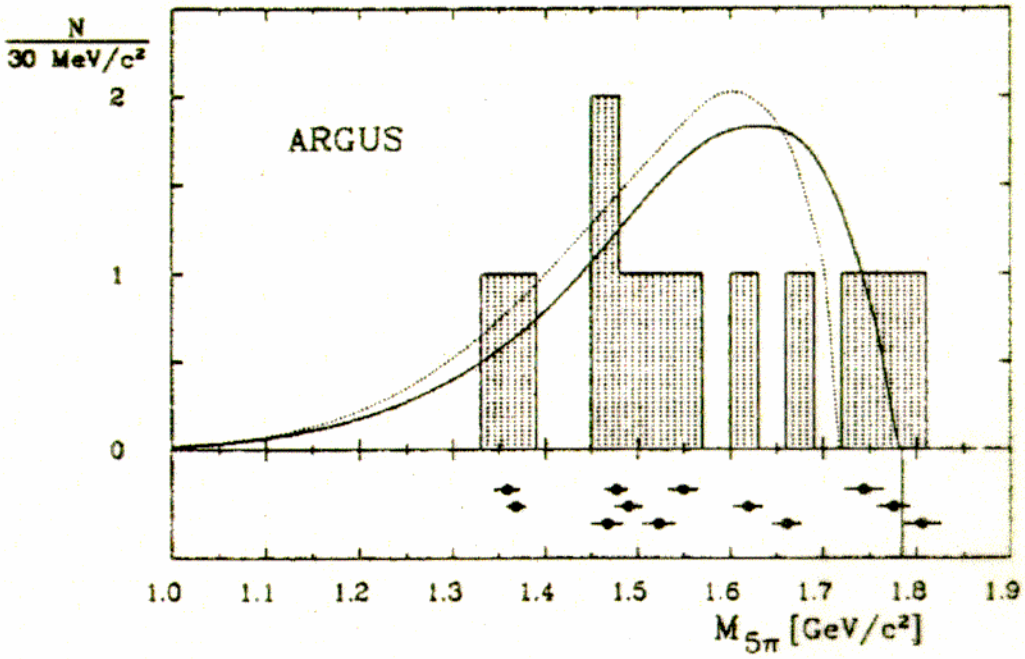
$$\begin{aligned} M_{5\pi}^2 &= \left(\sum E_i,\ \sum \vec{p}_i\right)^2 \\ &\leq (m_\tau - m_\nu)^2 \end{aligned}$$

Normal: Invariant Mass of all decay products, e.g. :



$$m^2(K^0) = \left(E(\pi^+) + E(\pi^-),\ \vec{p}(\pi^+) + \vec{p}(\pi^-)\right)^2$$

The Argus Experiment



$\rightarrow m_{\nu_\tau} < 35$ MeV

Albrecht *et al.*, Phys. Lett. B202 (1988) 149

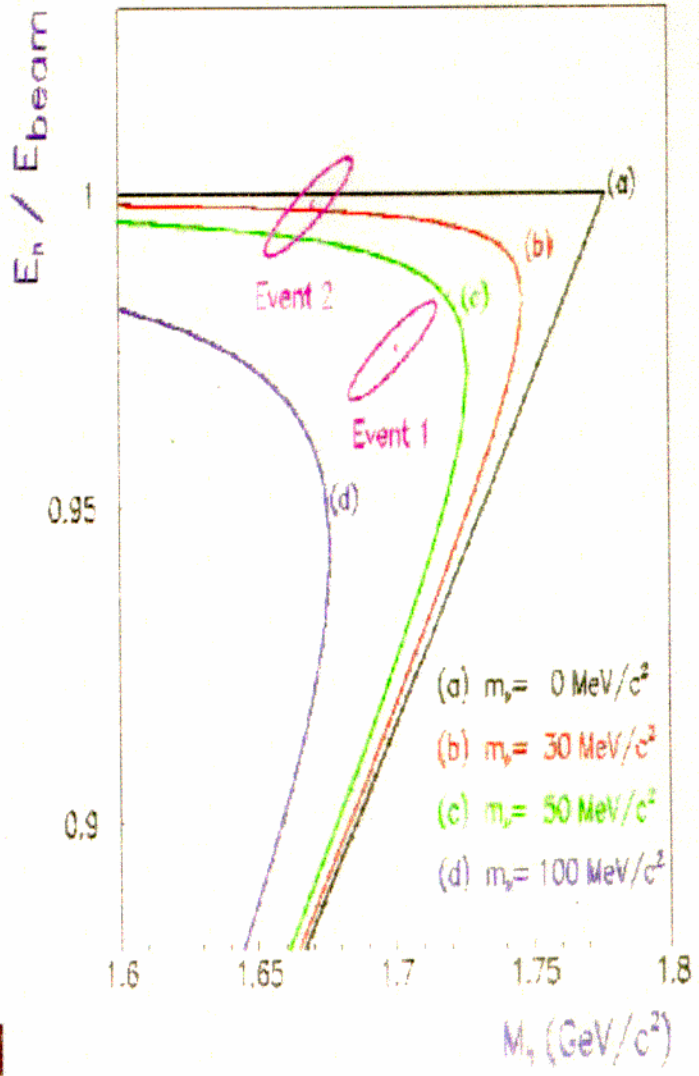
Measurement method

$$m_\nu^2 = (E_{beam} - E_h)^2 - (\vec{p}_\tau - \vec{p}_h)^2$$

$$= m_\tau^2 + M_h^2 - 2E_{beam}E_h + 2\sqrt{E_{beam}^2 - m_\tau^2}\sqrt{E_h^2 - M_h^2}\cos\theta_{h\tau}$$

For fixed m_ν kinematic limit at $\cos\theta_{h\tau} = \pm 1$

Analysis in E_h/E_{beam} vs M_h plane



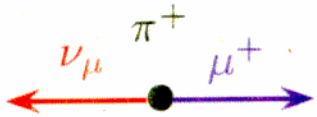
SUMMARY

- Direct limit: m_{ν_τ}<18.2MeV/c^2 @95%CL from ALEPH
- New limit from CLEO m_{ν_τ}<28MeV/c^2 with new higher statistics channel
- Some improvement in limit when likelihoods combined, but loophole remains
- Reasonable prospects for reaching 3MeV/c^2 at BABAR and BELLE

The mass of ν_μ

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$ (Two body decay)

Decay at rest:



$$|\vec{p}_\nu| = |\vec{p}_\mu|$$

$$m_\pi = E_\nu + E_\mu$$

$$\rightarrow \mathrm{m}_\nu^2 = \mathrm{m}_\pi^2 + \mathrm{m}_\mu^2 - 2 \cdot \mathrm{m}_\pi \cdot \sqrt{\mathrm{m}_\mu^2 + \mathrm{p}_\mu^2}$$

$$\Delta m_\nu^2 = 2\, p_\mu \sqrt{\Delta m_\pi^2 + 1.6 \Delta p_\mu^2 + 0.9 \Delta m_\mu^2}$$

3 different Experiments:

Values from PDG2000

Pionic atoms: $\mathrm{m}_\pi = 139.570180(350)$ MeV

Myonium: $\mathrm{m}_\mu = 105.658357(5)$ MeV

Magnetic spektrometer (PSI): $\mathrm{p}_\mu = 29.791998(110)$ MeV

$$\rightarrow \mathrm{m}(\nu_\mu) < 170\mathrm{keV}/\mathrm{c}^2 \quad (95\%\ \mathrm{c.l.})$$

K. Assamagan *et al.*, Phys. Rev. D53 (1996) 6065

Error dominated by Δm_π !

25 ppm

The PSI experiment (p_μ)

K. Assamagan *et al.*, Phys. Rev. D53 (1996) 6065

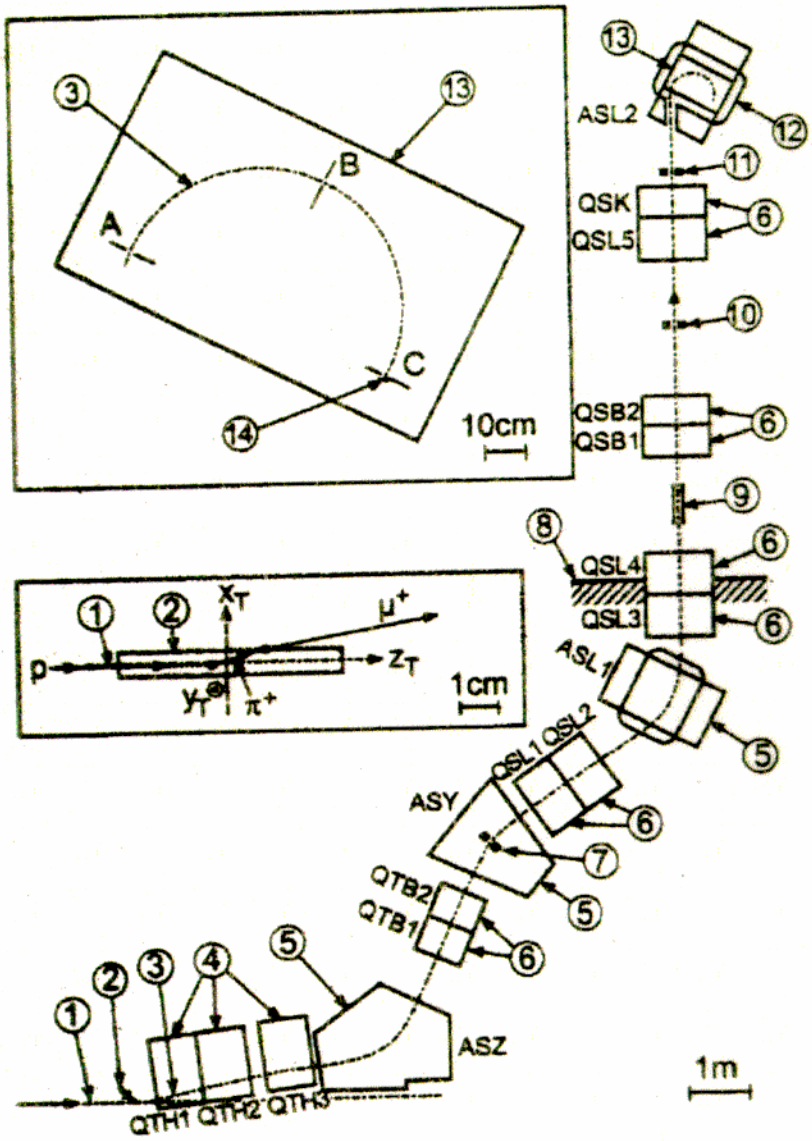


FIG. 1. Experimental setup. (1) Central trajectory of 590 MeV proton beam; (2) graphite target; (3) central trajectory of muon beam; (4) half-quadrupole magnets; (5) dipole magnets; (6) quadrupole magnets; (7) collimator defining the beam momentum acceptance; (8) concrete shielding of proton channel; (9) crossed-field particle separator; (10) lead collimator; (11) remotely movable collimator system (normally open); (12) magnetic spectrometer; (13) pole of spectrometer; (14) muon detectors (silicon microstrip and single surface-barrier detectors); A, B, C: copper collimators.

How to determine m_π to 1 ppm ?

Compare transitions in μ-atoms and π-atoms π^-, μ^-

π or μ - capture results in blow off of electronic shell

H – like atom with

$$\lambda = 1 / (R_\infty Z^2) * m_e / m_\pi * (1 + m_\pi / M) * L$$

R_∞ Rydberg ; M mass of the nucleus

L containing information on transition

Z nucl. charge ($Z_N = 7$; $Z_O = 8$)

inserting masses for and Z

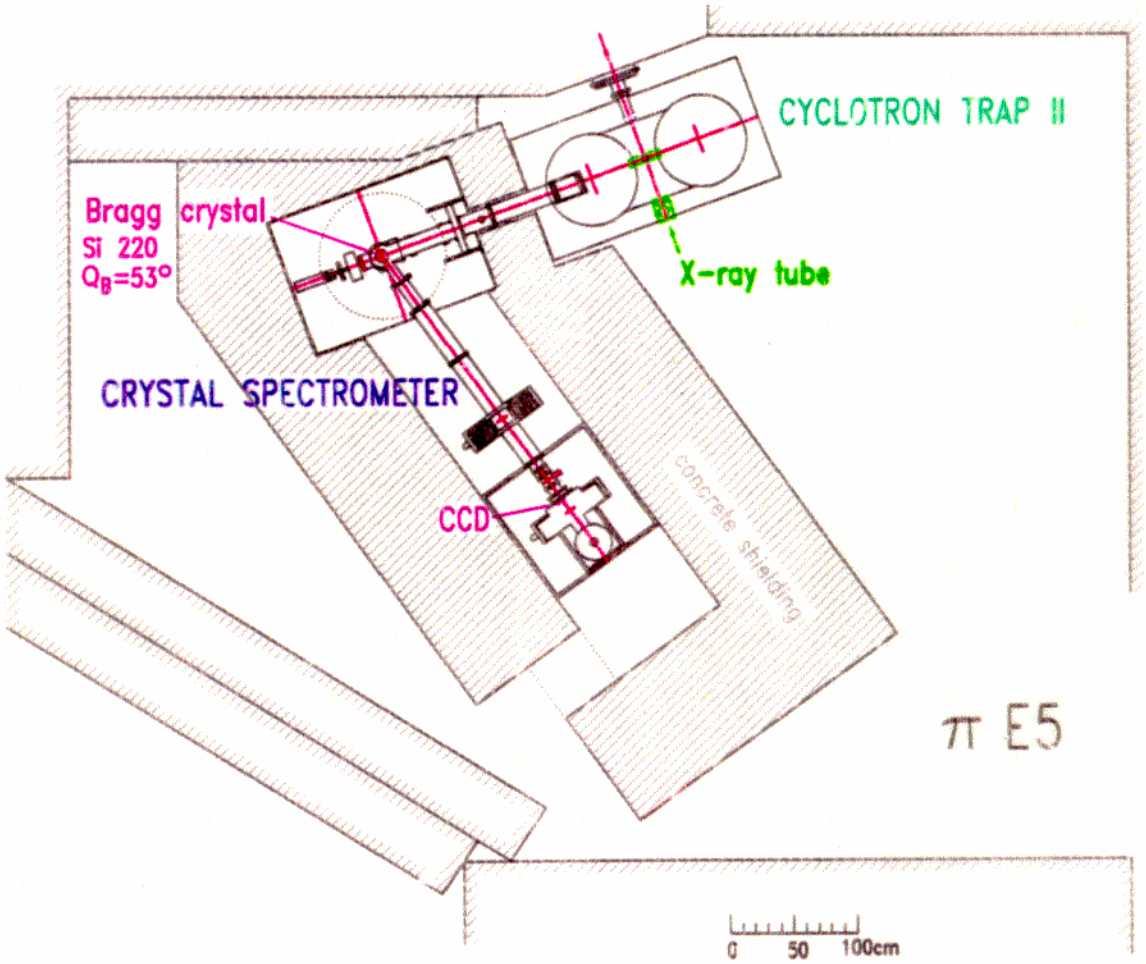
μ- oxigen and π - nitrogen yields

$\lambda(\mu\text{-O})/\lambda(\pi\text{-N}) = 1.0083....$

result:

- two very close lines
- identical quantumnumbers
- pion mass can be linked to muon mass
- working in gas avoids uncertainty due to K shell refilling
- pion decay in flight gives myons in the source
- gas mixture can be adjusted to equal countrate

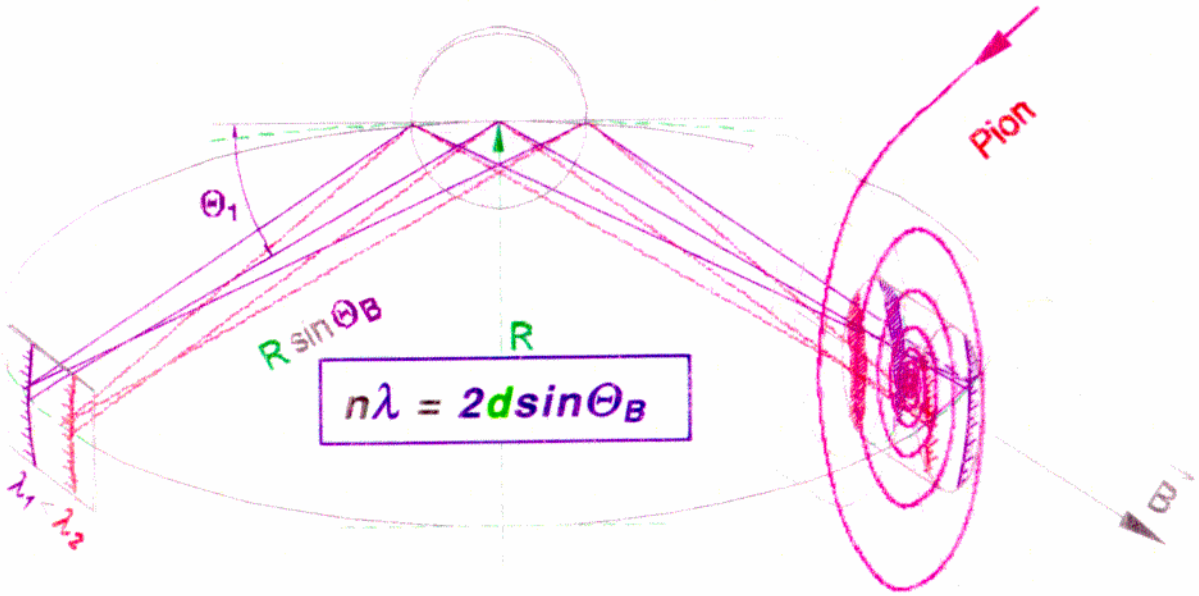
$m_\pi / m_\mu \approx \left(\frac{8}{7}\right)^2$


CYCLOTRON TRAP II
Bragg crystal
Si 220
Q_B=53°
X-ray tube
CRYSTAL SPECTROMETER
CCD
concrete shielding
π E5
0 50 100cm

EXPERIMENTAL METHOD

Focussing Bragg-Spectrometer
(Johann geometrie)

cylindrically or spherically bent crystals



two-dim. position-sensitive X-ray detector

Charge-Coupled Devices (CCDs)

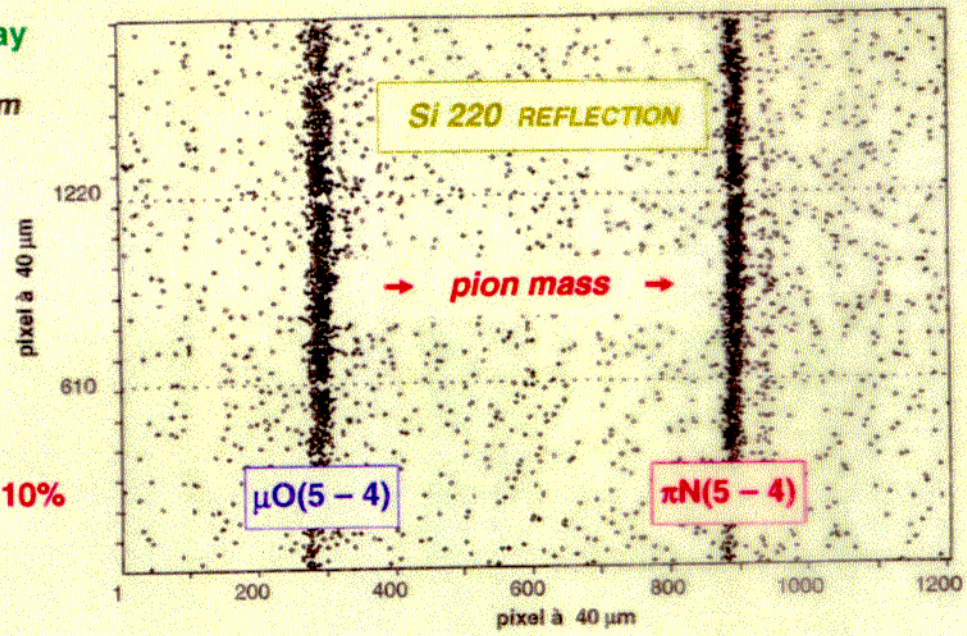
X-ray source

Cyclotron trap (gas cell)

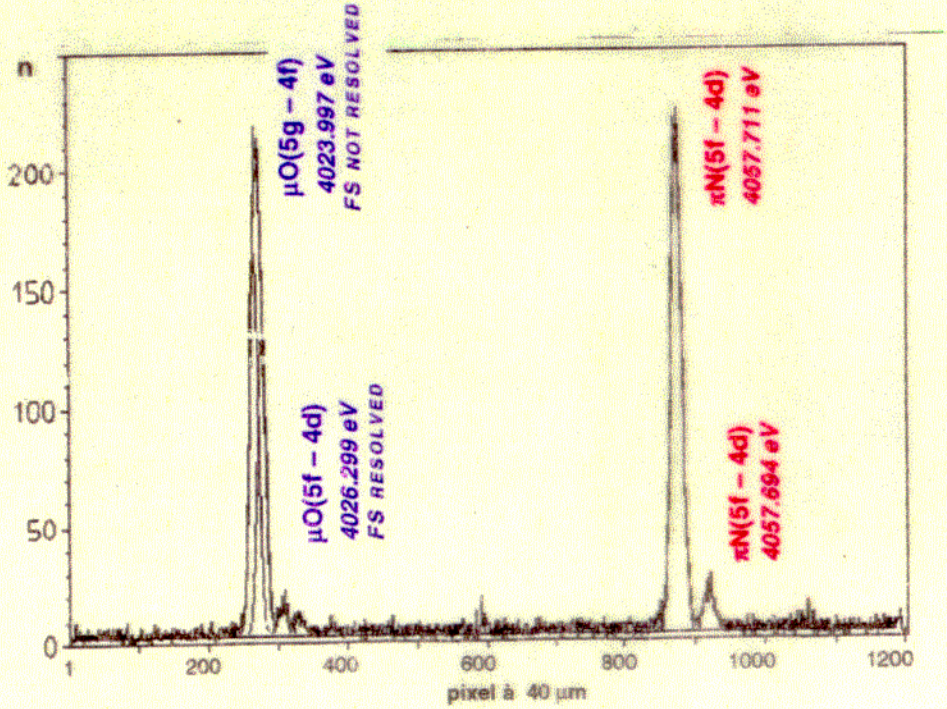
PSI 2000 SIMULTANEOUS MEASUREMENT

- 3 × 2 CCD array
- 50 mm × 75 mm

mixture O_2 / N_2 90% / 10%



1500 Cb (16 days)
≈ 40% of statistics

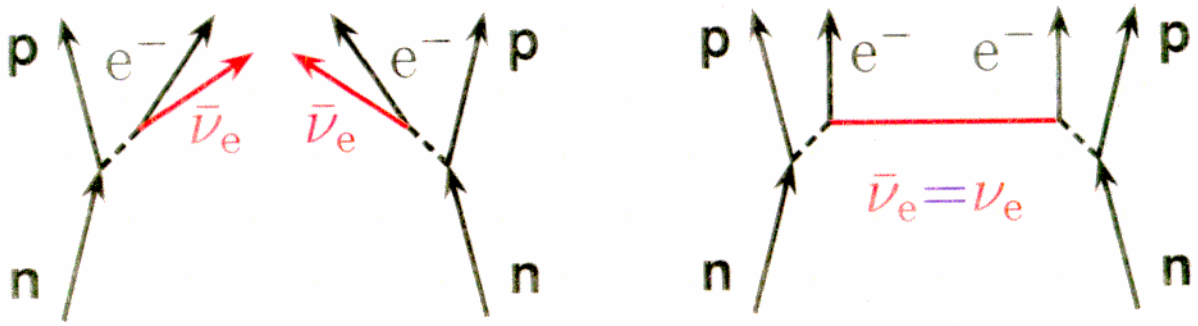


- 15 per hour and transition
- peak-to background ≈ 50

Double β Decay

$$(\mathrm{Z}, \mathrm{A}) \xrightarrow{\beta\beta} (\mathrm{Z}+2, \mathrm{A}) + 2\beta\,(+2\bar{\nu}_\mathrm{e})$$

$\beta\beta 2\nu$ $\qquad\qquad$ $\beta\beta 0\nu$

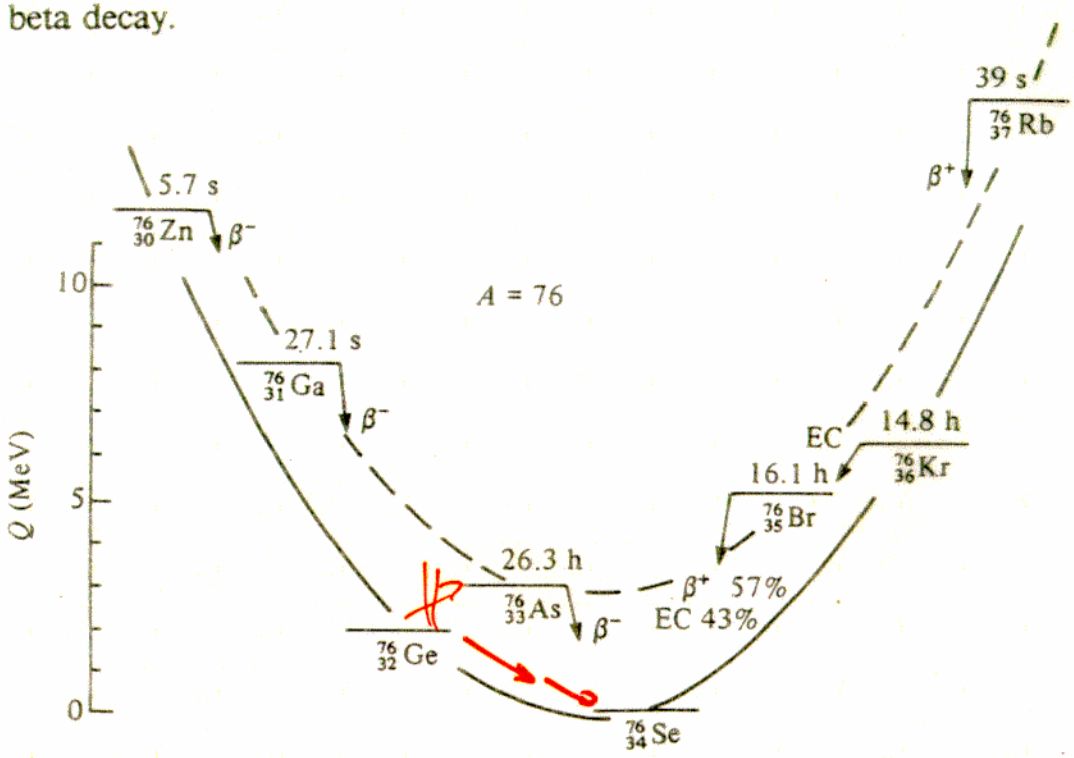


$\beta\beta 2\nu$: 2nd order process in weak interaction

$\beta\beta 0\nu$:

- works only if $\bar{\nu} = \nu$ (Majorana-Particle)
  $\rightarrow$ Violation of Lepton Number!
- righthanded emitted $\bar{\nu}$ must be absorbed as lefthanded ν.
  Amplitude $\rightarrow$ proportional m_ν (more exactly $\propto < \mathrm{m}_\nu >$)

Figure 6.1. Atomic masses of nuclei with $A = 76$. Parabolas connecting the even-even and odd-odd nuclear masses are indicated. ^{76}Ge and ^{76}Se are stable with respect to ordinary beta decay; ^{76}Ge, however, can decay by double beta decay.



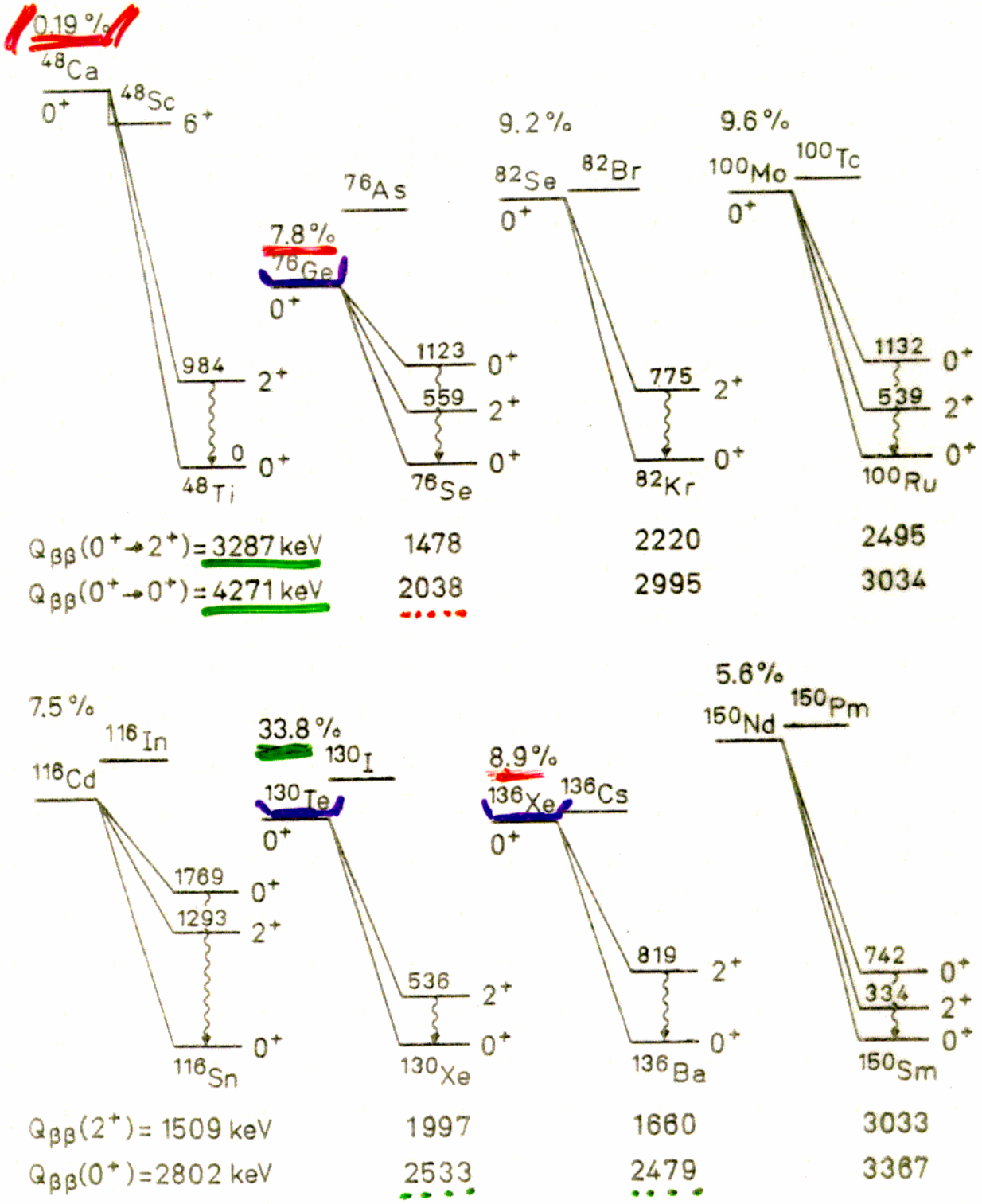
$$M_A(Z,A) = const + 2b_{sym}\frac{(A/2-Z)^2}{A^2} + b_{Coul}\frac{Z^2}{A^{1/3}} + m_e Z + \delta ,$$

the symmetry energy coefficient is b_{sym}~50 MeV

the Coulomb energy coefficient is b_{Coul}~0.7 MeV.

$\delta \sim \pm 12/A^{1/2}$ for odd N, odd Z, or even N, even Z, respectively

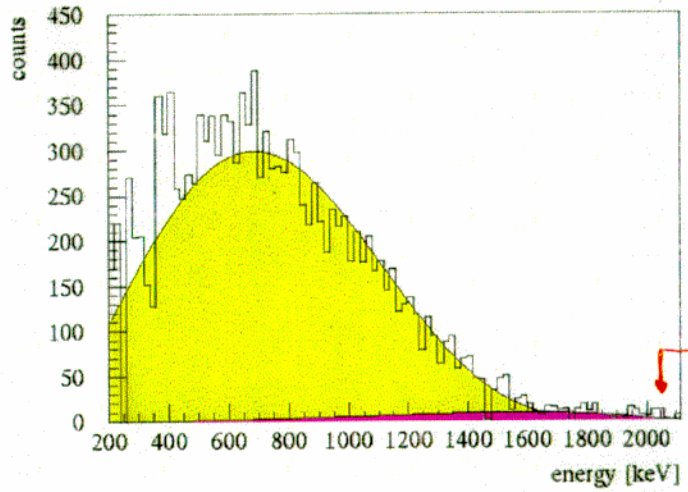
Level schemes of ββ -decay candidates



proposals

Energy Spektra of 2 e^-

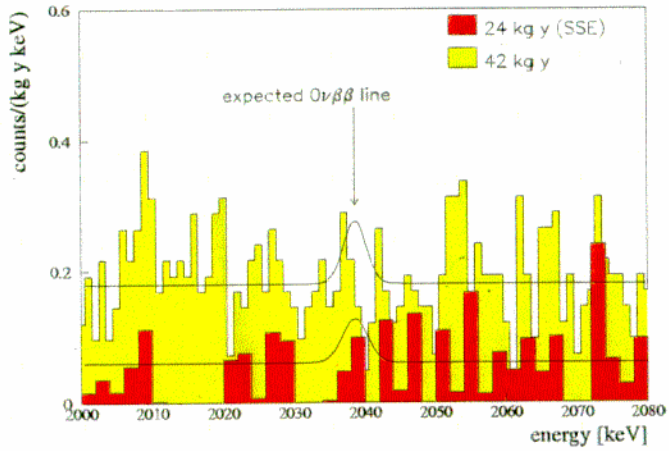
Heidelberg-Moscow ^{76}Ge Counter Experiment



$\beta\beta 2\nu$ observed

$\rightarrow T_{1/2} = 1.77 \pm 0.01^{+0.13}_{-0.11} \cdot 10^{21}$ y

(M. Günther *et al.*, Phys. Rev. D55 (1997) 54)



$\beta\beta 0\nu$ not observed, $T_{1/2} > 5.7 \cdot 10^{25}\ y$ (90 % C.L.)

Majorana ν $\rightarrow \langle m_\nu \rangle < 0.2\text{eV}$ (90 % C.L.)

(L. Baudis *et al.*, hep-ex/9902014)

uncertainty in nucl. matrix elements

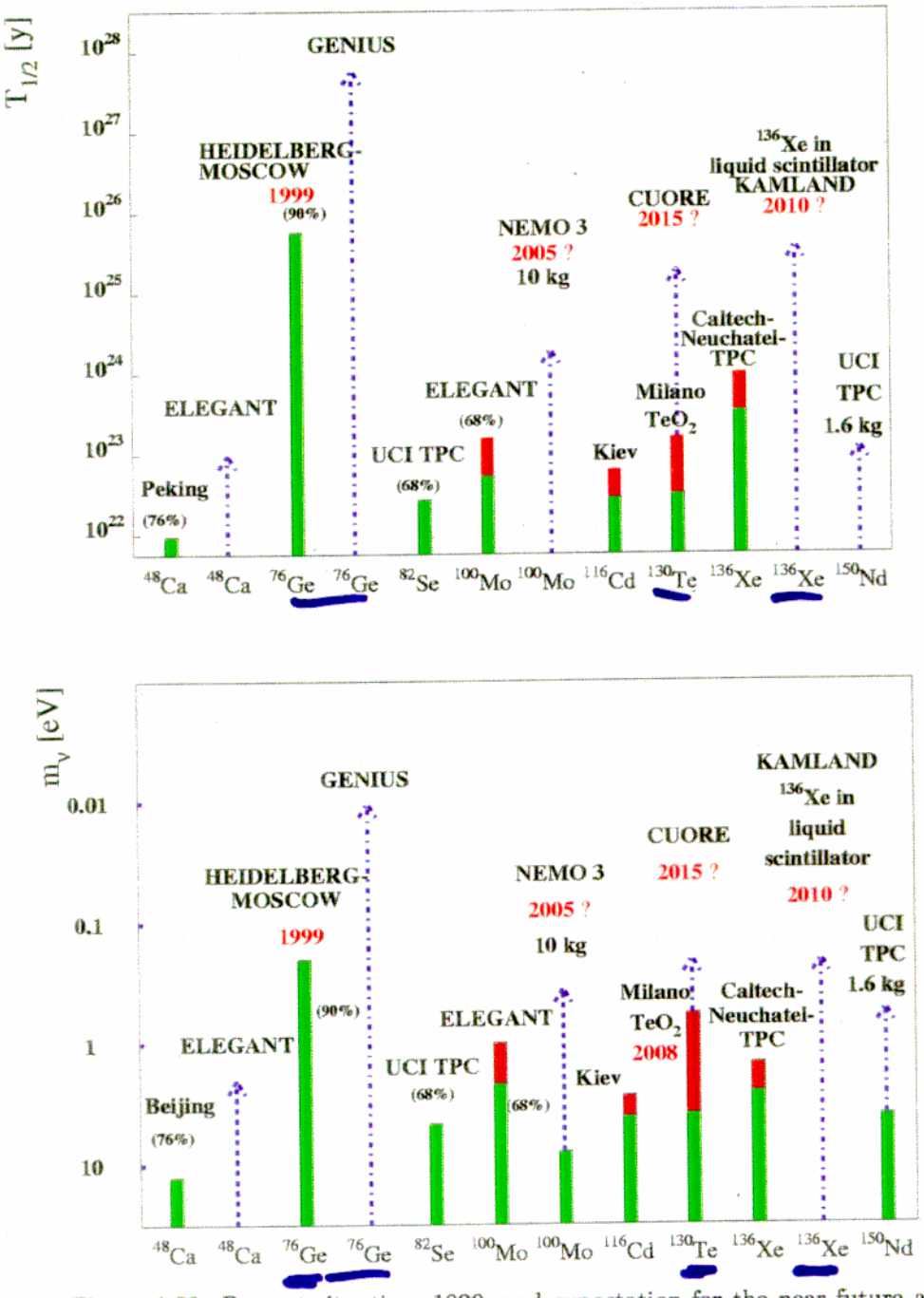


Figure 1.20: Present situation, 1999, and expectation for the near future and beyond, of the most promising $\beta\beta$-experiments concerning accessible half life (a) and neutrino mass limits (b). The light-shaded parts of the bars correspond to the present status, the dark parts of the bars to expectations for running experiments, dashed lines to experiments under construction and dash-dotted lines to proposed experiments.

Genius proposal

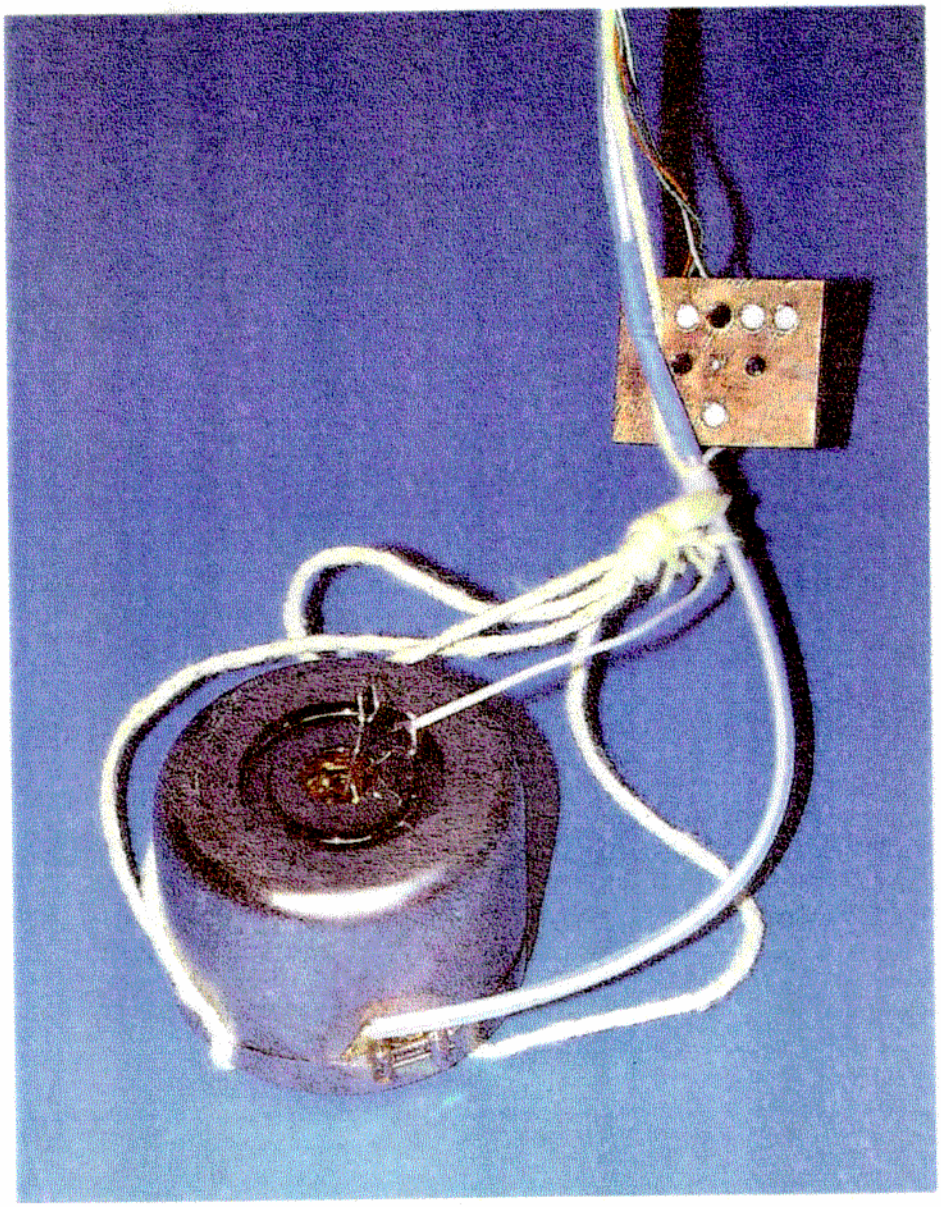


Figure 2.4: A naked Ge krystal suspended on kevlar wires. Only 3 g of material in total (kevlar and electrical contacts) were used.

Milano group, Cuore proposal

TeO_2 crystal for $\beta\beta0\nu$ experiment

CUORICINO

14 planes with 4 cryslals per plane

CUORE

17 towers, 15 planes per tower,

4 crystals per plane

CUORICINO set-up

The CUORICINO array is a set of

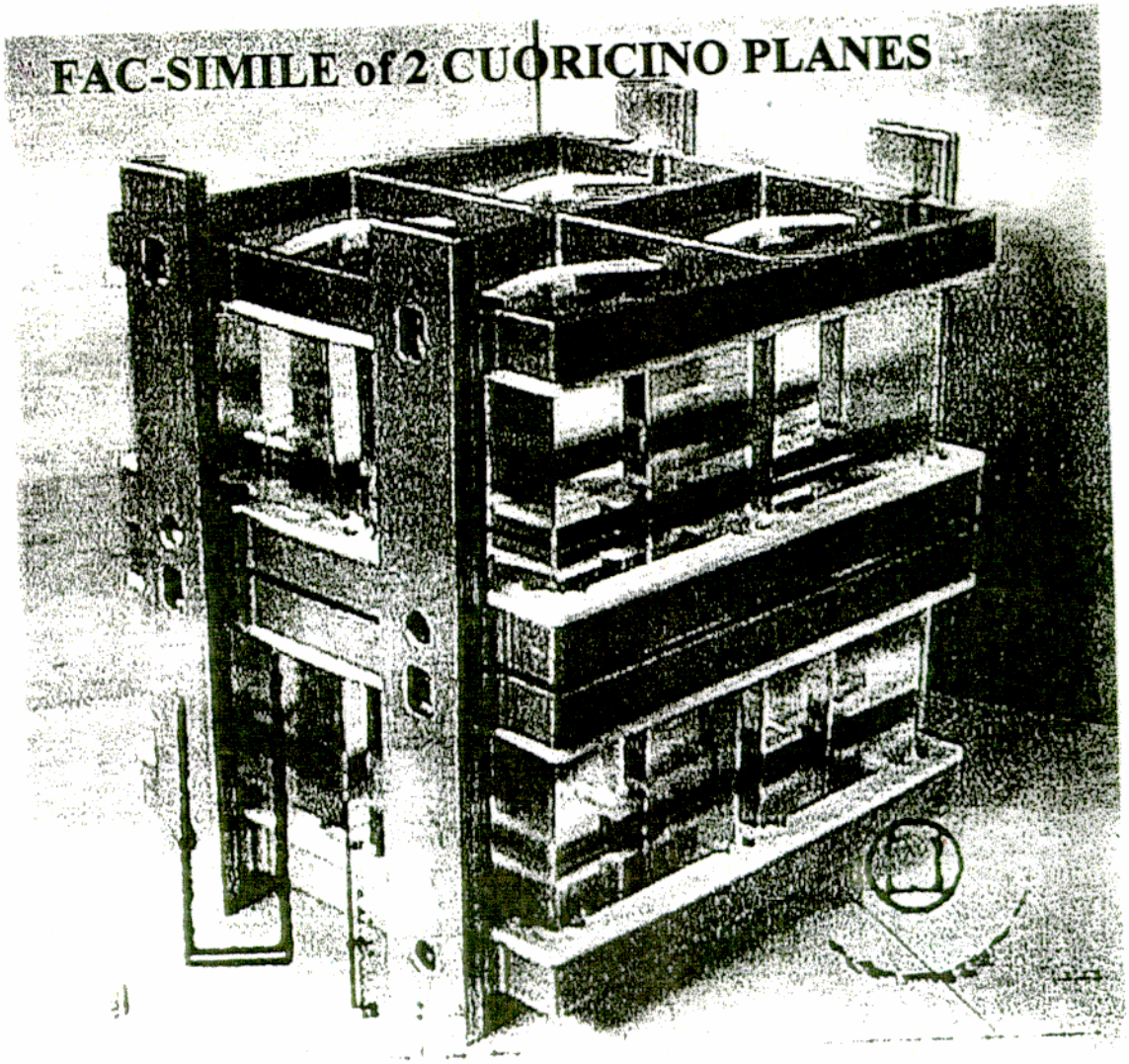
56 cubic TeO_2 crystals of and 760 g mass

arranged in a tower-like structure of

14 planes with 4 crystals per plane

The gap between the crystals is only 6 mm

compact structure which helps in study and reduction of background through coincidence analysis



CUORE (^{130}Te) vs. GENIUS (^{76}Ge)

GENIUS is a large expansion of the present Heidelberg-Moscow ^{76}Ge experiment

At the moment, the most sensitive $\beta\beta$ experiment with $<m_\nu>$ 0.5 eV

GENIUS simplified model: 288 enriched ^{76}Ge detectors x 3.6 Kg each, operated in a tank filled with LN_2 and shielded by it.

About 1 Ton of ^{76}Ge

COMPARISON OF THE PARAMETERS

	GENIUS	CUORE
Active Nuclide Number	$\approx 10^{28}$	$\approx 10^{27}$
Transition Energy	2040 keV	2528 keV
Relative Phase Space	1	≈ 3
Energy Resolution (1332 keV)	1.9 keV	3.5 keV
BKG level (1/100 present level)	$\approx 10^{-3}$ (kev kg y)$^{-1}$	$\approx 10^{-2}$ (kev kg y)$^{-1}$
BKG level (estimated)	$\approx 10^{-4}$ (kev kg y)$^{-1}$	Simulation in progress
Cost	$\approx$ 130 M$	$\approx$ 20 M$

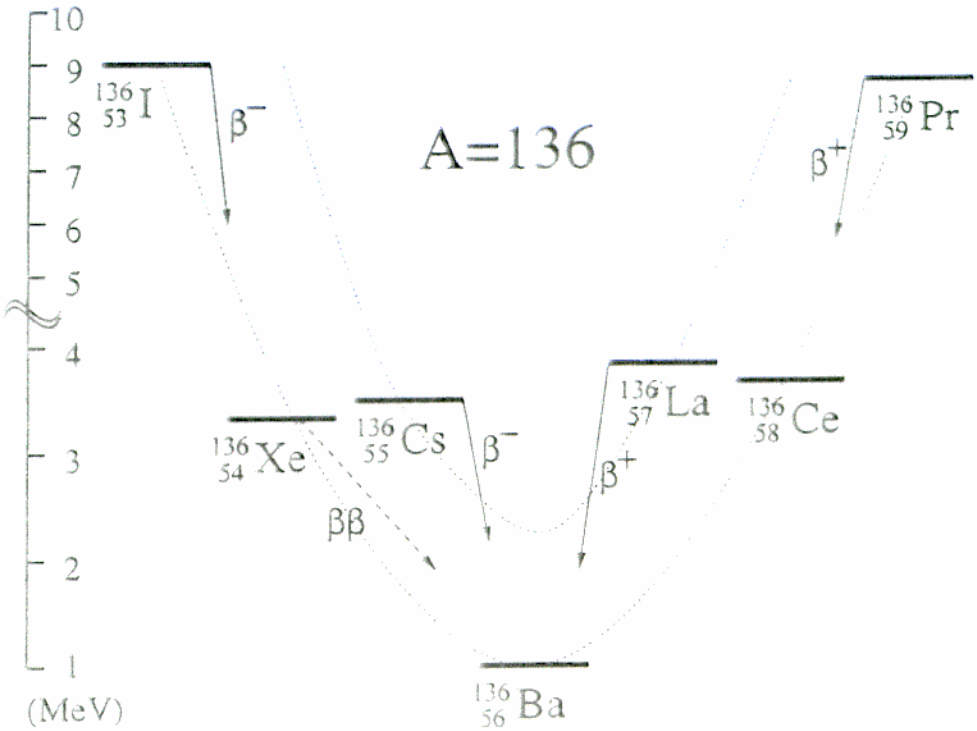
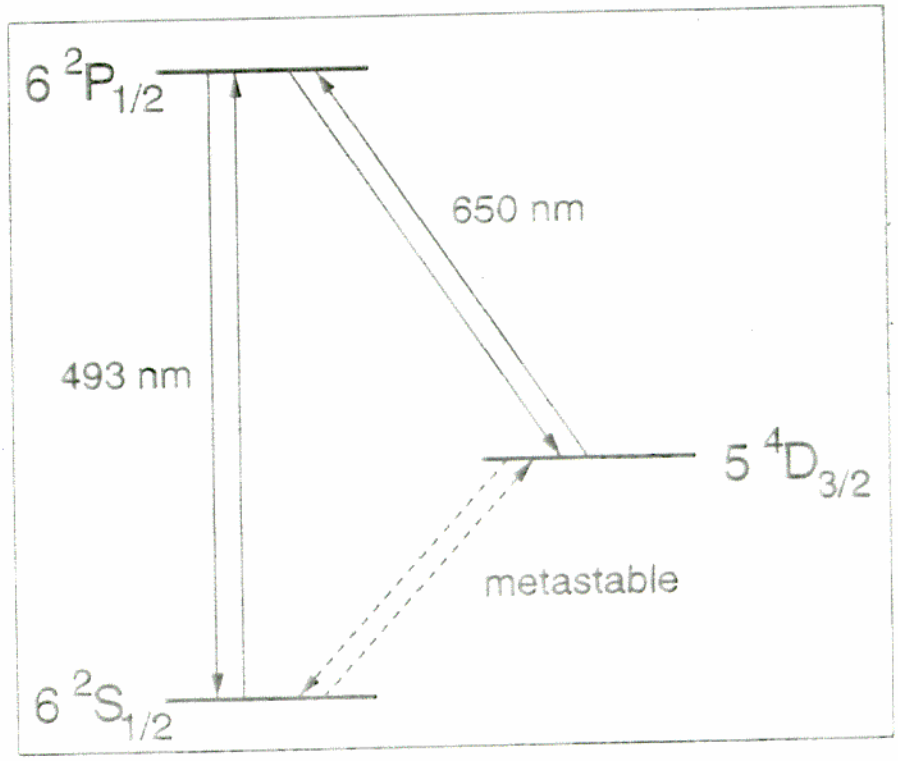


Figure 2: Simplified atomic mass scheme for nuclei with A=136. The parabolae connecting the odd-odd and even-even nuclei are shown. While ^{136}Xe is stable for ordinary β^- decay, it can decay into ^{136}Ba by a double-beta process.



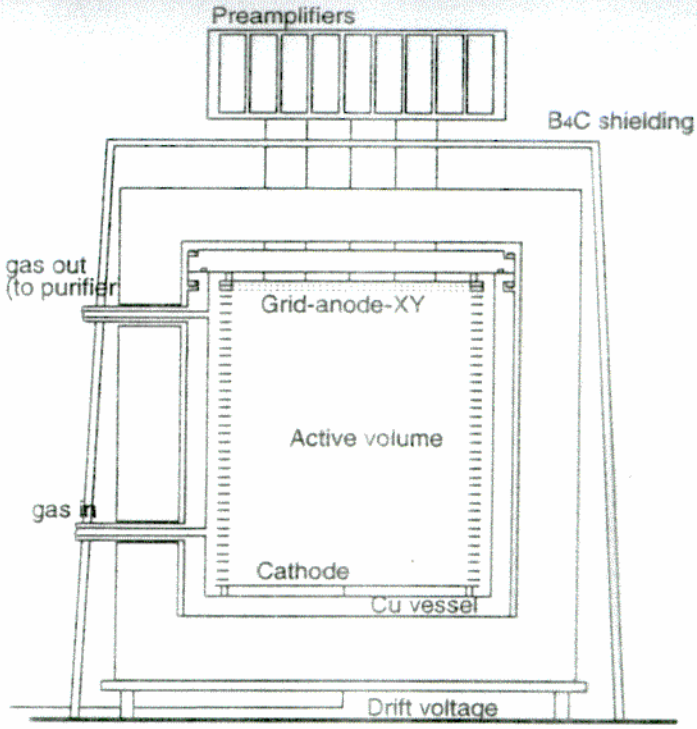


Figure 5: Scheme of the Gotthard TPC used in [22]. The total height of the active volume is 67.7 cm.

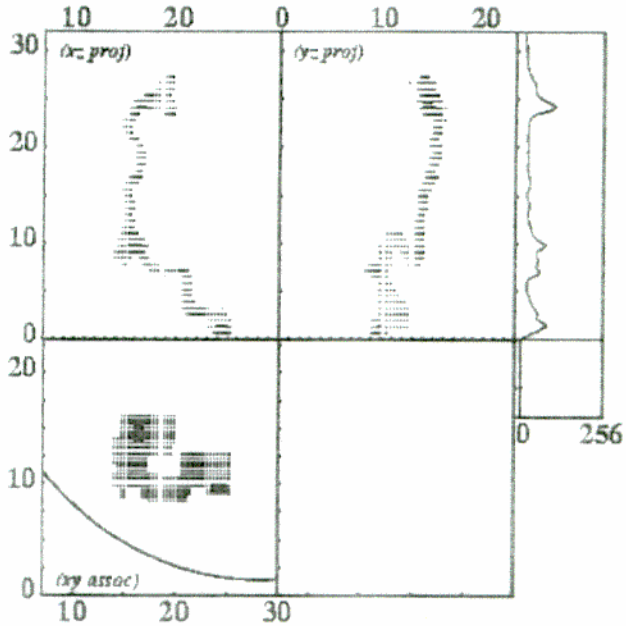


Figure 6: Electron tracks from a candidate double-beta decay event in xenon from [22]. The two main top panels show the xz and yz projections of the event, while the reconstructed xy view is given in the bottom part (dimensions are in cm). Pulse-height information is shown in the smaller panel on the right (in ADC counts). Note the higher ionization density at the end of the tracks. The circular sector in the bottom-left corner of the xy view represents the edge of the TPC.

PMTs
Wavelength shifter bars
HV Power Supply
Laser dump
Laser exit port (different azimuth)
TPC signals feedthrough
3.6 m
3.2 m
Pressurized buffer gas
micropattern readout plane
slow wide angle deflector
Laser detection region
cathode meshes
pressure equalizing membrane
650+493 nm laser system
fast ± 5° x-y deflector
Laser entrance port
pressure vessel
Lightguide feedthrough
^{136}Xe
5.0 m
(1 section)

Summary

- Assume that the TPC with Ba^+ tagging has no radioactivity background

- Use initially a) conservative Gotthard resolution $\sigma_E = 2.8\ \%$, b) $\sigma_E = 2.0\ \%$

Isotope	Total mass (kg)	Enrich. grade (%)	Det. eff. (%)	Meas. Time (yr)	Bkgd ($kg^{-1} yr^{-1} FWHM^{-1}$)	$T^{1/2}_{0\nu\beta\beta}$ (yr)	<m> (eV) QRPA	<m> (eV) NSM
^{76}Ge	11	86	75	2.2	0.3	$5.7\ 10^{25}$	0.2	0.6
^{136}Xe	3.3	63	22	1.5	2.5	$4.4\ 10^{23}$	2.2	5.2
^{130}Te	0.3	34				$5.6\ 10^{22}$	2.9	6.1
^{136}Xe a)	1000	65	70	5	0 + 1.8 evts	$8.3\ 10^{26}$	0.051	0.14
^{136}Xe b)	10000	65	70	10	0 + 5.5 evts	$1.3\ 10^{28}$	0.013	0.037

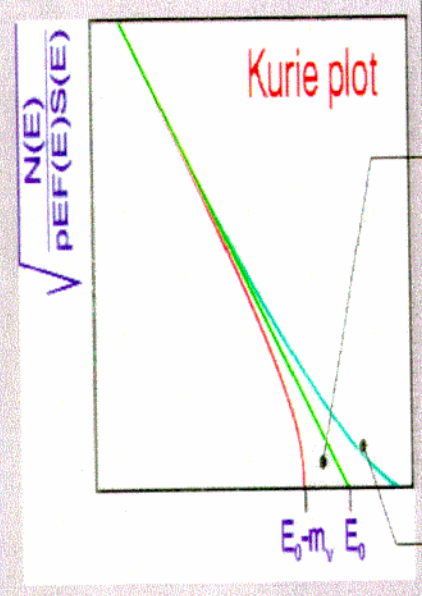
The meV region is within reach !

1-4 eV
0 - 100%

1. Physical Motivations

Kinematic measurement of neutrino mass

From nuclear β decay end-point:



relative rate at the end-point:

$$r \approx 2\left(\frac{m_\nu}{E_0}\right)^3$$

effect of:
- energy resolution
- background
- final state excitation

Spectrometers

- high energy resolution (1÷10 eV)
- high statistics at E_0
- many corrections
  - → spectrometer response
  - → atomic/molecular excited final states

Calorimeters

- measure all energy $E = E_0 - E_\nu$
  - → no source/excitation effects
- high energy resolution 10-30 eV Gaussian
- slow response ⇒ pile-up
  - → low β activity ⇒ low statistics
  - → array of many identical detectors

- ^{3}H: E_0 = 18.6 keV ⇒ $r \approx 3\times10^{-10}$ (m_ν=10 eV)
- ^{187}Re: E_0 = 2.5 keV ⇒ $r \approx 10^{-7}$ (m_ν=10 eV)

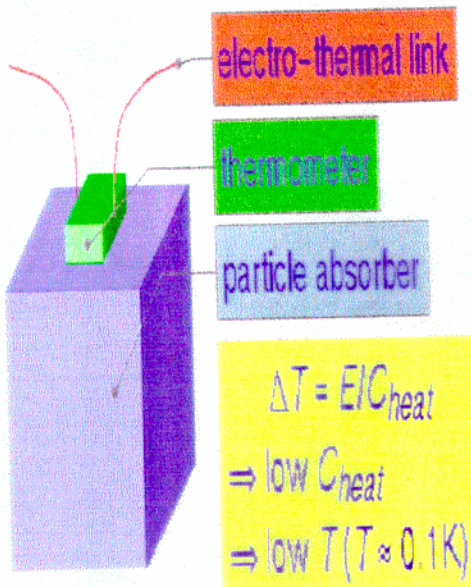
- Array of calorimeters to study the end-point of ^{187}Re β decay

$A_\beta = 6\cdot10^7$ Hz ^{3}H exp prop. $1.5\cdot10^9$ Hz

$A_\beta \sim 0.2$ Hz ^{187}Re

2. Thermal Microcalorimeters

Thermal detection

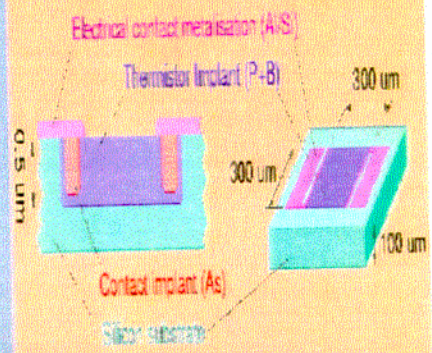


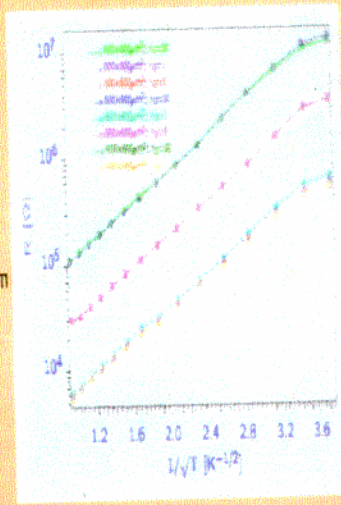
$\Delta T = E/C_{heat}$

$\Rightarrow$ low C_{heat}

$\Rightarrow$ low T ($T \approx 0.1$K)

Thermometer: silicon implanted thermistors



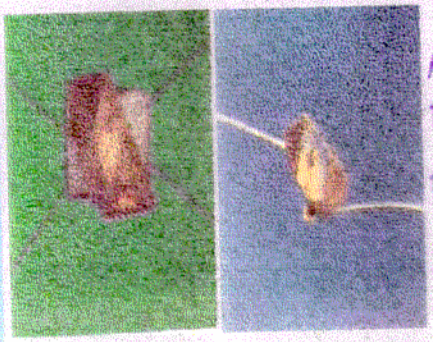


high reproducibility

$\Rightarrow$ arrays of detectors

Absorbers

$AgReO_4$ single crystals (250 ÷ 350 µg)



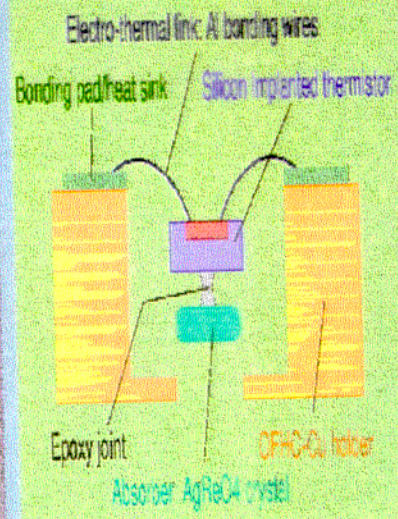
A = 358.1

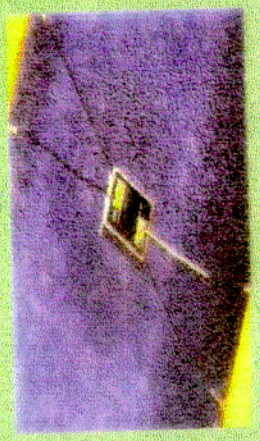
^{187}Re fraction ~0.32

$\tau_{1/2} \approx 4 \cdot 10^{10}$ y

$A_\beta \approx 5.4 \cdot 10^{-4}$ Hz/µg

Microcalorimeters

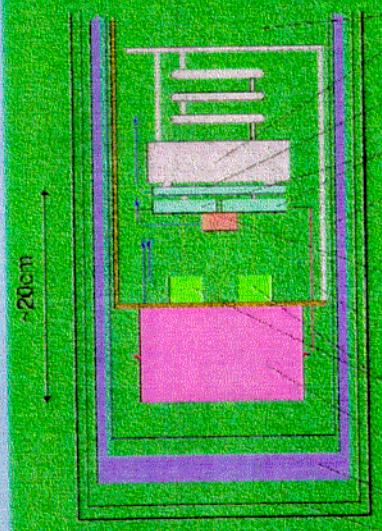




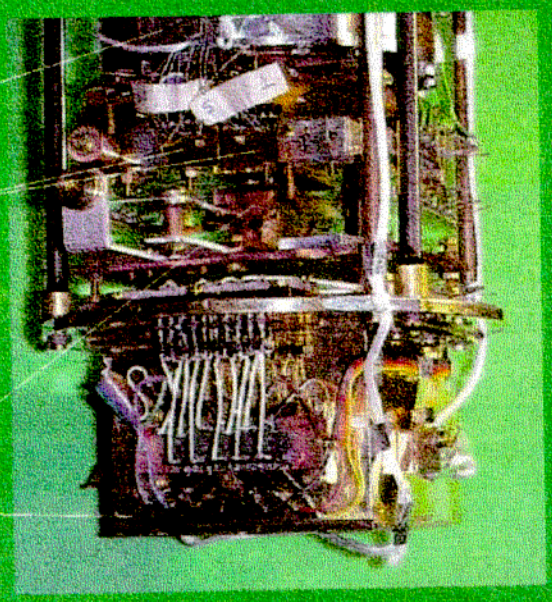
Si-micromachining under development

3. Experimental Set-Up

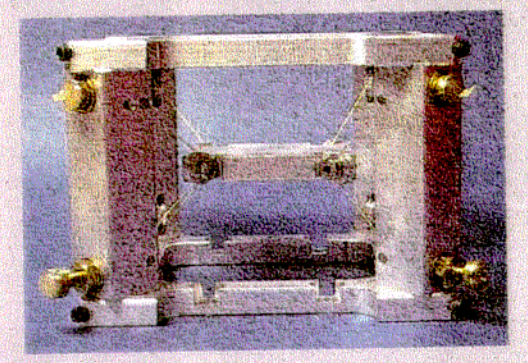
Dilution refrigerator



- Inner vacuum chamber
- Mixing chamber 12mK
- Low noise bias network 12mK
- Detector holders 25mK
- Cryoperm for magnetic shielding 600mK
- Thermometer and heater for temperature stabilization at 25mK
- Signal leads
- X-ray fluorescence sources with shutter 2K
- Preamp front-end 120K(inside) 2K(outside)
- Liquid He 4K
- Liquid N shield 77K

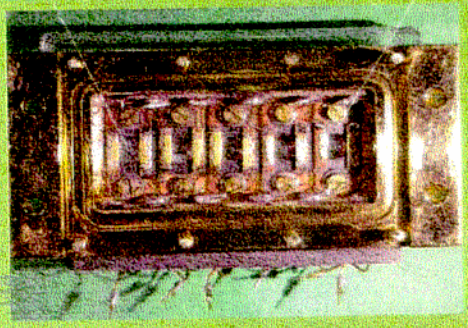


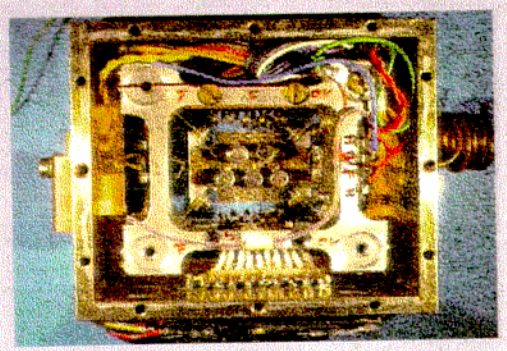
Cold read-out electronics



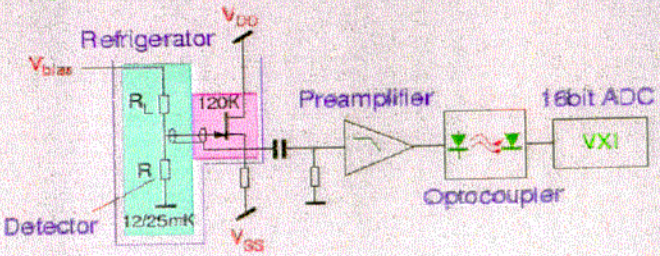
Detector holder

5 microcalorimeters and Roman Pb Shield





Cold JFET front-end with bootstrap and signal processing chain



5. Conclusions

The first long measurement with 8 $AgReO_4$ detectors is starting

Achievable sensitivity

Montecarlo simulation

A_0: single detector activity

pile-up fraction: $F \approx A_0 \tau_{rise}$

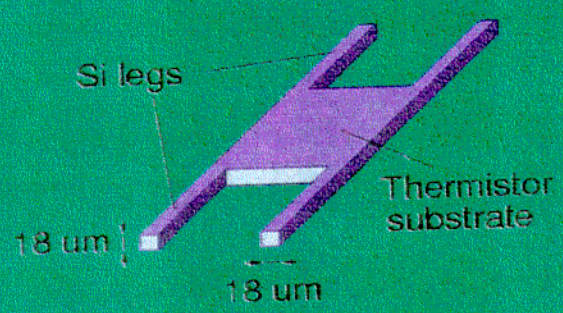
$\Sigma_{m\nu}$: 68% C.L. sensitivity on m_ν

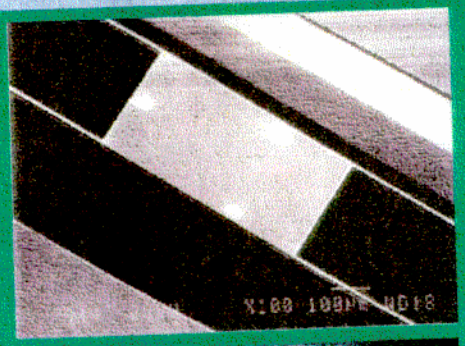
$N_{det} \times t_{meas}$ [y]	A_0 [Hz]	τ_{rise} [ms]	ΔE_{FWHM} [eV]	$\Sigma_{m\nu}$ [eV]
10	0.1	0.50	30	10.0
10	0.1	0.05	30	9.1
10	0.1	0.50	10	8.2
10	1.0	0.50	30	6.2
50	0.1	0.05	10	4.0

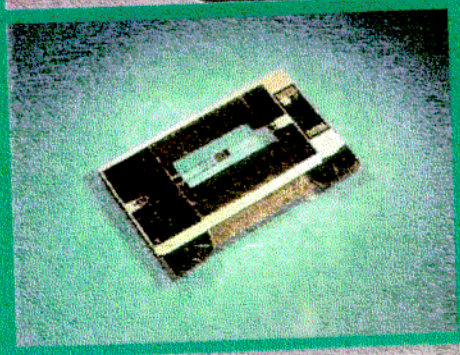
$m_\nu \approx 10$ eV possible in 1 year measurement

To increase the sensistivity:
- more detectors
- faster detectors and higher activities
- higher energy resolution

Future upgrade: Si-micromachining







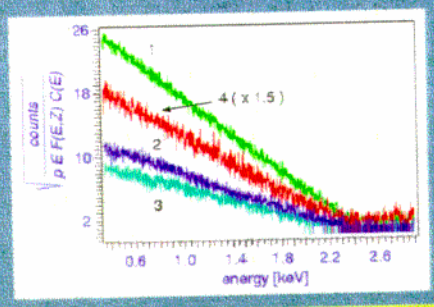
- better reproducibility
- easier handling
- larger arrays
- lower microphonic noise

4. Experimental Results

Detector development results

First measurements without shutter

	$AgReO_4$ mass [µg]	Operating Temperature [mK]	Measuring time [h]	Energy Resolution at 5.5 keV ΔE_{FWHM} [eV]	Time resolution τ_{rise} [ms]
1	~250	60.0	720.0	60.0	1.50
2	434±13	70.0	66.0	29.0	0.50
3	~250	60.0	135.0	25.0	1.00
4	284	60.0	144.0	62.0	4.00

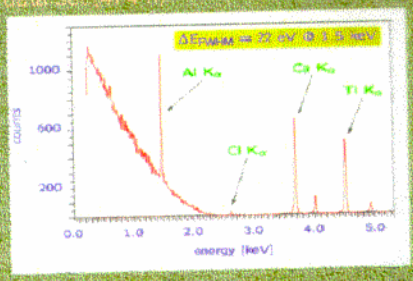


from detector #1 ⇒ $E_0 = 2460 \pm 5_{stat} \pm 10_{sys}$ eV

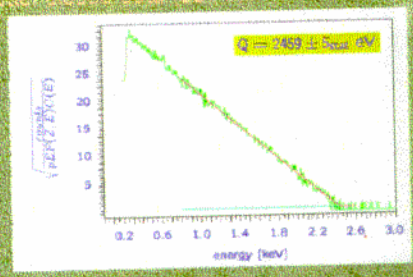
from detector #2 ⇒ $\tau_{1/2} = 43 \pm 4_{stat} \pm 3_{sys}$ Gyr

Fluorescence source with shutter
Detector with ~250µg $AgReO_4$ absorber

- full data set (474 h)



- shutter closed data (301 h)



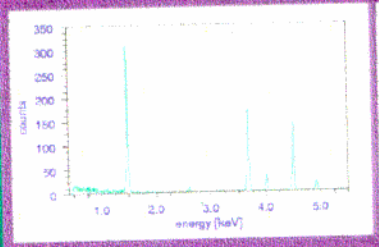
Present status

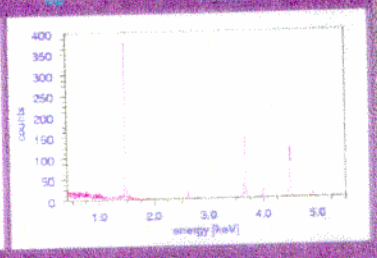
- Setting the optimal working point to start the experiment
- 8 running detectors: 2.3 mg $AgReO_4$ mass ⇒ β ^{187}Re activity A_β ~ 1.3 Hz
- Energy resolution: ΔE_{FWHM} = 20 ÷ 30 eV
- Time resolution: τ_{rise} = 0.7 ÷ 1.5 ms

	$AgReO_4$ mass [µg]	Operating Temperature [mK]	Baseline noise FWHM [eV]	Energy Resolution at 1.5 keV ΔE_{FWHM} [eV]	Time resolution τ_{rise} [ms]
1	259	52.1	17.1	22.7	0.92
		62.3	18.2	20.8	0.74
2	269	53.0	19.4	26.2	0.99
		63.2	20.3	31.4	0.82
3	286	52.0	16.7	22.2	1.10
		62.3	19.2	30.2	0.87
4	284	50.0	17.0	24.9	1.00
		59.4	20.4	29.7	0.69
5	323	51.2	20.7	23.9	1.16
		61.1	22.6	26.7	0.90
6	376	54.7	20.8	27.0	1.60
		65.9	23.6	25.6	1.20
7	272	56.4	18.4	22.5	1.30
		68.8	23.1	22.9	1.00
8	240	58.5	21.3	21.0	0.93
		70.5	21.8	25.7	0.77

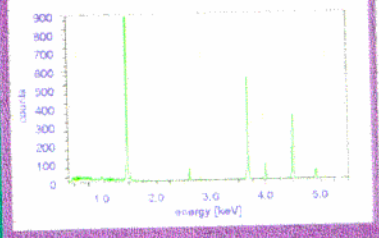
Sample calibration spectra

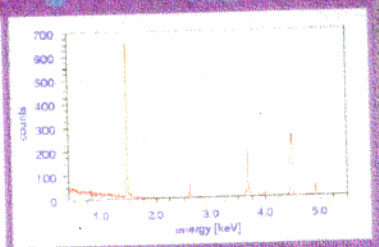
- Det. #2 (m = 269 µg) T_{op} = 53 mK, ΔE_{FWHM} = 26.2 eV
- Det. #4 (m = 284 µg) T_{op} = 50 mK, ΔE_{FWHM} = 24.9 eV





- Det. #7 (m = 272 µg) T_{op} = 56 mK, ΔE_{FWHM} = 22.5 eV
- Det. #8 (m = 240 µg) T_{op} = 70 mK, ΔE_{FWHM} = 25.7 eV





Neutrino Mass from Tritium β Decay
Present Limits and Perspectives

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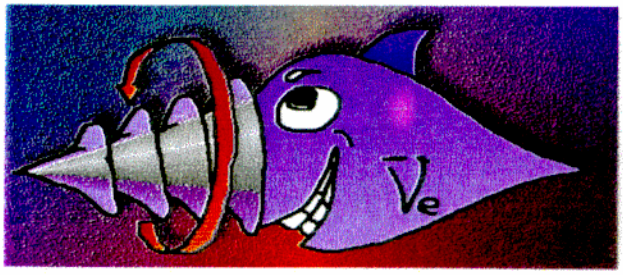
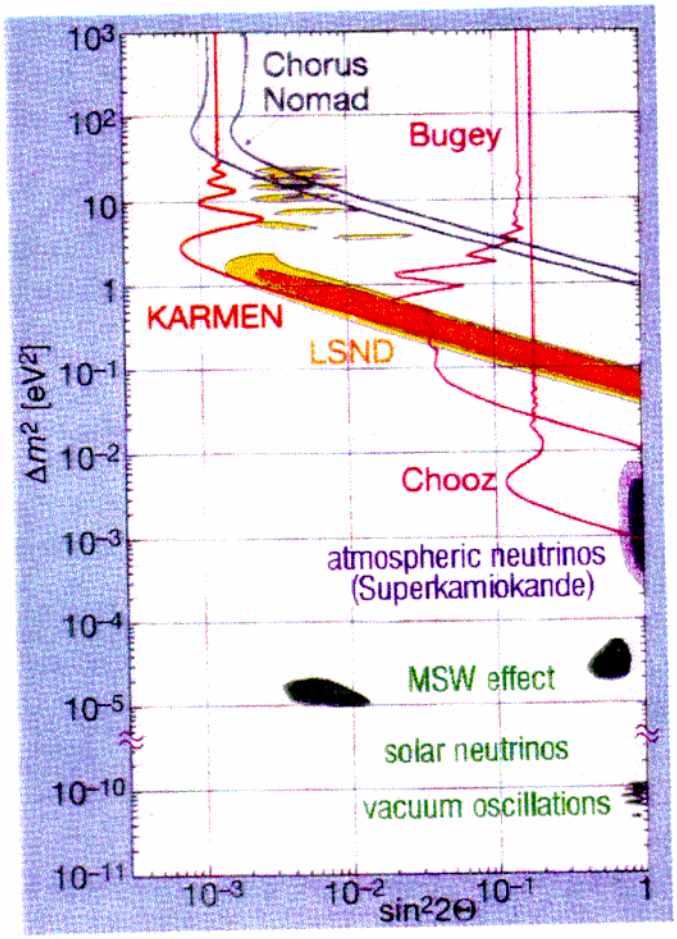
Guests: O.Kazachenko/Troitsk, A.Kovalik/Dubna+Prag



- Introduction
- The Mainz Neutrino Mass Experiment (and the Troitsk one)
- Outlook: a new large-scale tritium β decay experiment
- Summary

Motivation



Experiments with atmospheric and solar neutrinos:

$\Rightarrow$ **evidence for neutrino oscillations and masses !**

$\Delta m^2 \leq 5 \cdot 10^{-3}\ \mathrm{eV}^2$

no determination of ν masses !

Questions for direct neutrino mass determinations:

- Are the neutrino masses hierachical or degenerated?
  $\rightarrow$ required sensitivity on m_ν: ≤ 1 eV/c^2
- Do the neutrinos contribute to the missing Dark Matter in the universe significantly (HCDM: $\sum_i m_{\nu,i} \approx 5 - 7\ \mathrm{eV}/c^2$)
  $\rightarrow$ required sensitivity on m_ν: ≈ 1 eV/c^2

Possible scenarios

- Hierachical neutrino mass scenario (seesaw mechanism motivated):
  Δm^2 small $\rightarrow$ all neutrino masses are small,
- Degenerate neutrino mass scenario
  (oriented on results, phenomenological description):
  $\rightarrow$ all neutrinos have about the same mass
  Interesting mass range: 1 - 2.5 eV:
  neutrinos would be good candidates for missing hot dark matter
  $\rightarrow$ neutrino mass visible in tritium β decay

Dicision only by mass measurement with 1 eV sensitivity

Which way to go ?

- **Wait for next supernova:**
  - $\oplus$ In lucky case (SN in our galaxy)
    $\rightarrow$ down to $\approx$ 1 eV/c^2, limited by supernova time structure
  - $\ominus$ 1-3 supernovae per century in our galaxy
- **Other β decays and cryogenic bolometers:**
  - $\oplus$ Exciting new detector technology
  - $\oplus$ In principle scalable
  - $\ominus$ Mikrobolometers (^{187}Re) are still under development.
    $\rightarrow$ expected sensitivity for near future: 15 - 20 eV
- **Tritium β decay:**
  - $\oplus$ First MAC-E filters work successfully at Mainz and Troitsk
  - $\oplus$ Improvement by upscaling expected
  - $\ominus$ Would like to have non-integrating mode with also
    large luminosity and high energy resolution due to anomalies:
    Troitsk anomaly, tachyons, right-handed currents, ...
  - $\oplus$ $\rightarrow$ time-of-flight modus (MAC-E-TOF)

Direct determination of electron neutrino mass

No assumption about neutrino properties: except neutral, spin 1/2

(only use of $E^2 = p^2 + m^2 \Rightarrow m^2(\nu)$ is the observable, mostly)

if neutrinos do mix and neutrino masses are not resolved:

$$m^2(\nu_e) = \sum |U_{ei}^2| m^2(\nu_i)$$

$0 \leq |U_{ei}^2| \leq 1 \Rightarrow$ real average, no cancelations possible

$\Rightarrow$ complementary to $\beta\beta0\nu$:

$$\langle m_e \rangle = \sum U_{ei}^2 m(\nu_i)$$

($\beta\beta0\nu$: cancelations possible and requires Majorana neutrinos)

Direct method (β decay) is especially interesting in case of degenerated neutrino masses $m(\nu_1) \approx m(\nu_2) \approx m(\nu_3) \approx m$

β-decay: $m(\nu_e) \approx m$	$\beta\beta0\nu: \; 0 \leq \langle m_e \rangle \leq m$

In extreme case, *e. g.* bimaximal mixing and special choice of phases:

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

β-decay: $m(\nu_e) \approx m$	$\beta\beta0\nu: \; \langle m_e \rangle \approx 0$

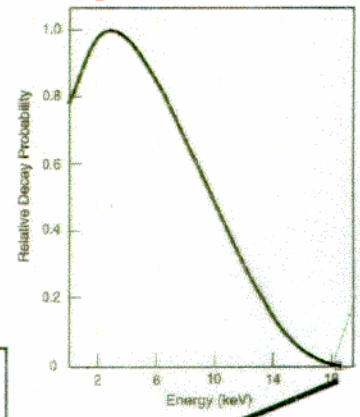
Direct measurement of m_{ν_e}

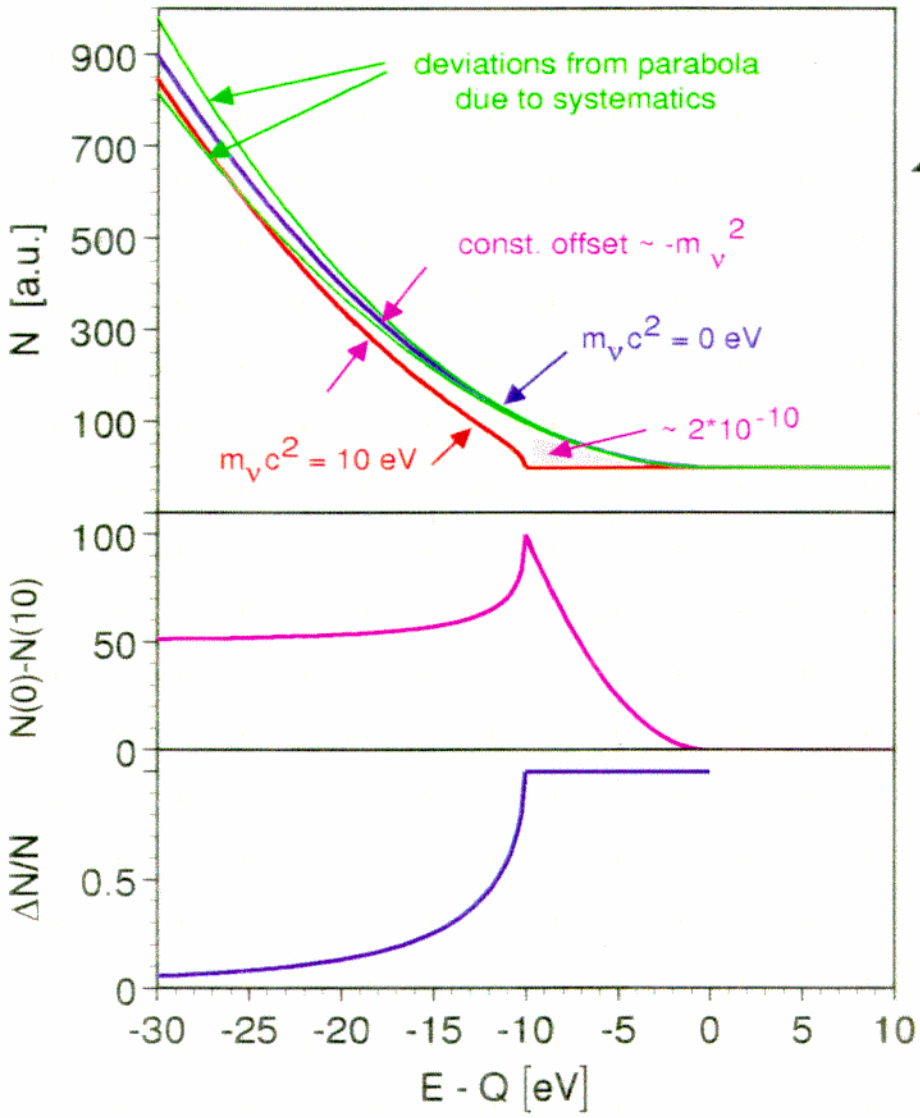
$^3H \longrightarrow {}^3He^+ + e^- + \bar{\nu}_e$:

superallowed

Q = 18.6 keV

$t_{1/2}$: 12.3 y





scattering
final states
resolution eff.

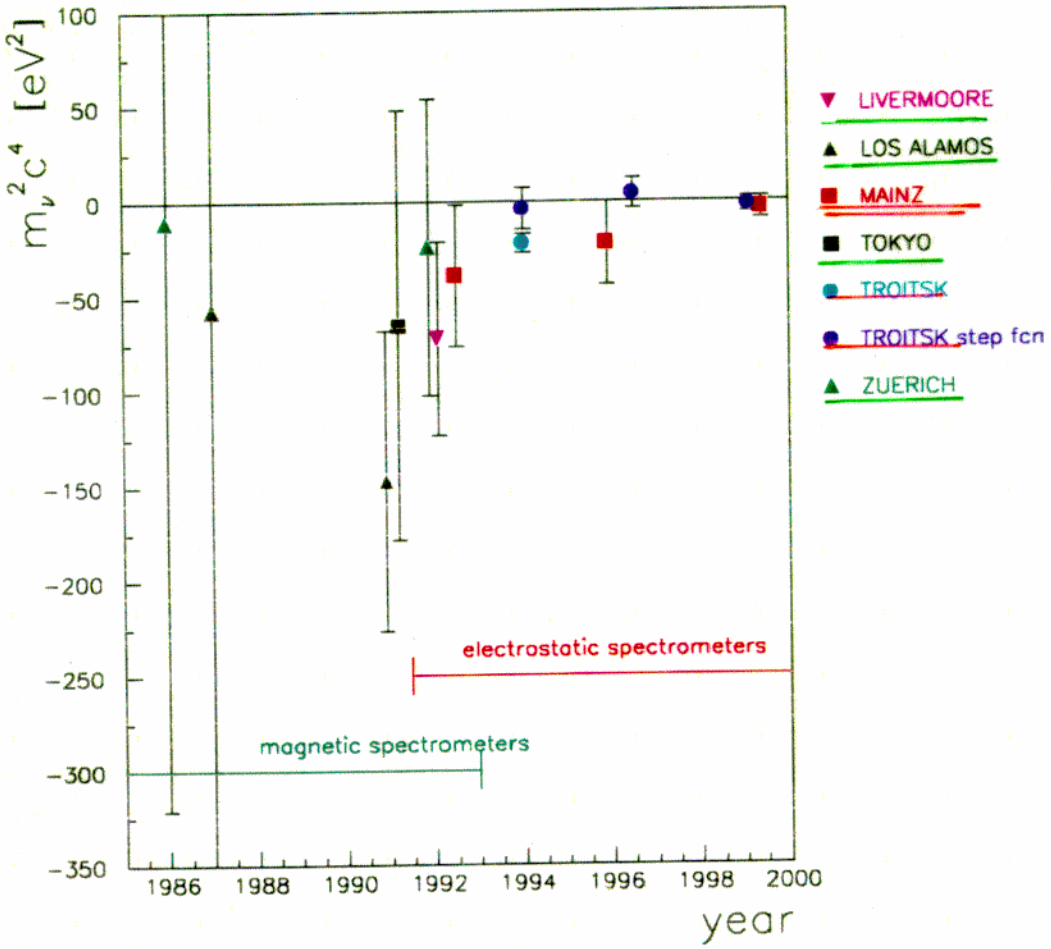
signature
for $m_\nu \neq 0$

rel. signature

if more than one eigenstate is contributing (not resolved):

$$\overline{m_\nu^2} := \sum_i |U_{ei}|^2 \cdot m_i^2$$

Tritium β decay experiments

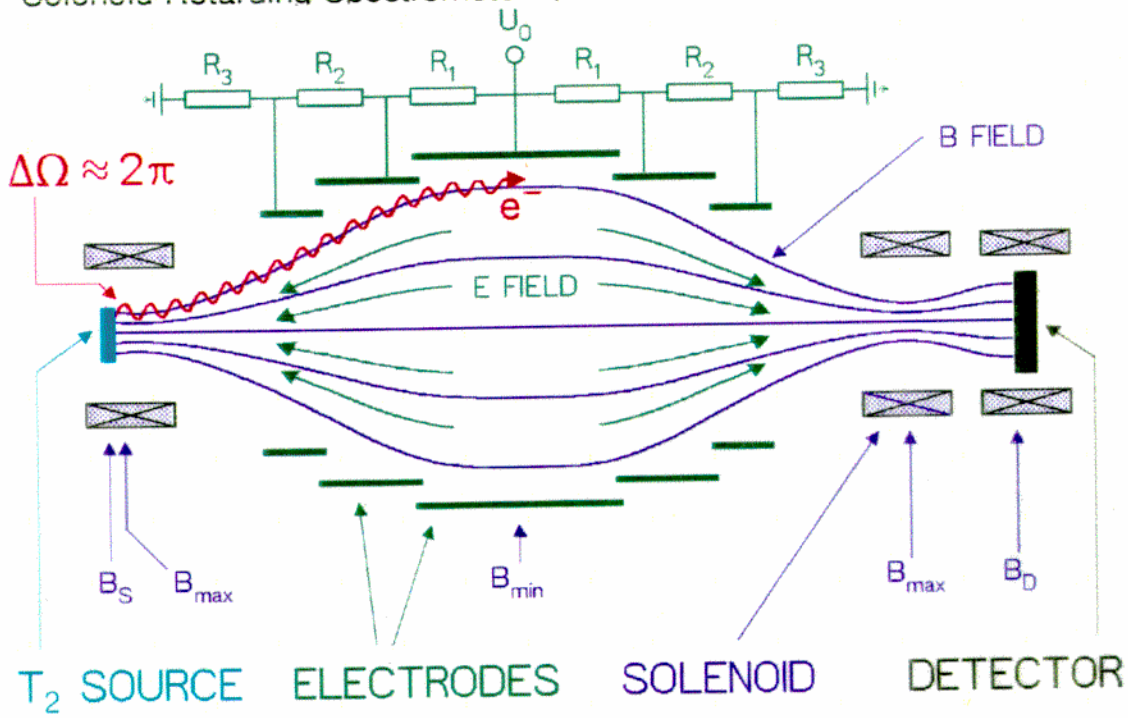


At present: 2 running experiments at Mainz and Troitsk

Magnetic Adiabatic Collimation

+ Electrostatic filter

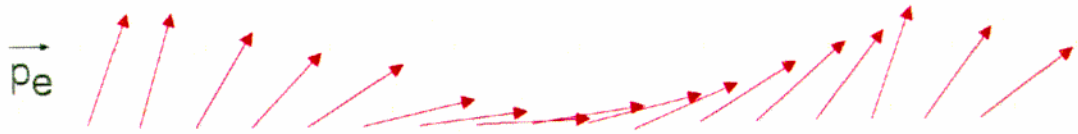
"Solenoid Retarding Spectrometer" (Nucl. Inst. Meth. B63 (1992) 345)



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

$$\mu = \frac{E_\perp}{B} = \text{constant}$$

WITHOUT E FIELD:



- magnetic guiding field

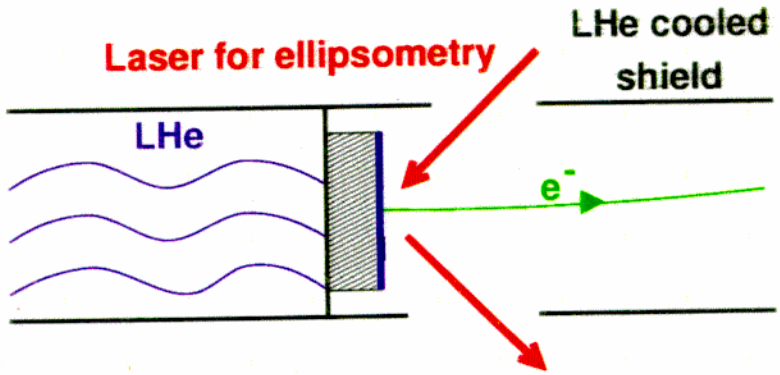
$$\rightarrow \quad \Delta\Omega \approx 2\pi$$

- adiabatic transf. $E_\perp \rightarrow E_{||}$ + electrostatic retardation

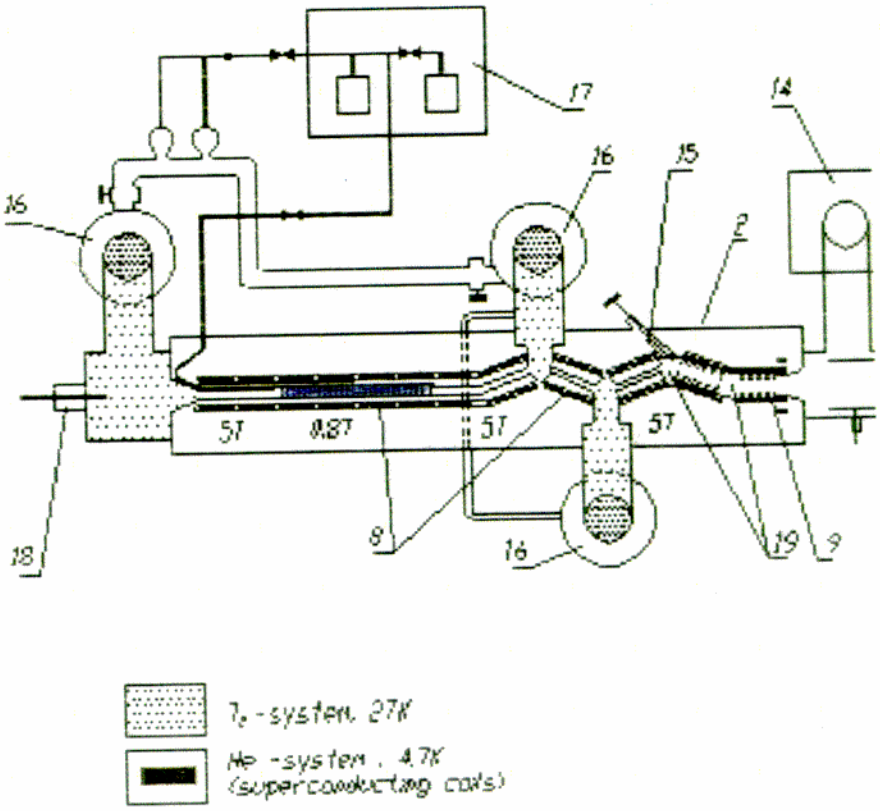
$$\rightarrow \Delta E \approx 4 - 6\,\text{eV}$$

Tritium sources in use

Solid state T_2 source (Mainz)

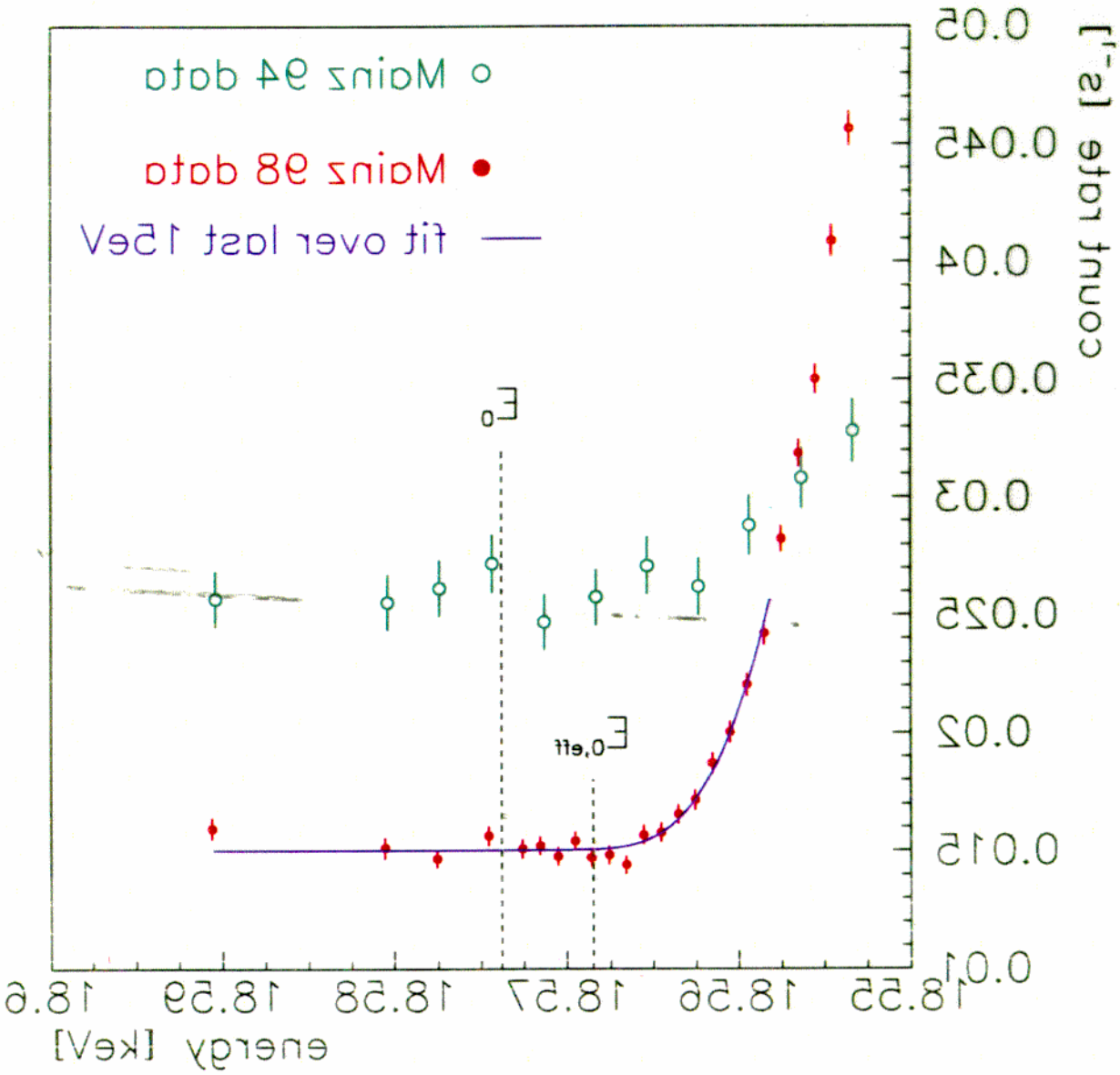


Gaseous T_2 source (Troitsk)

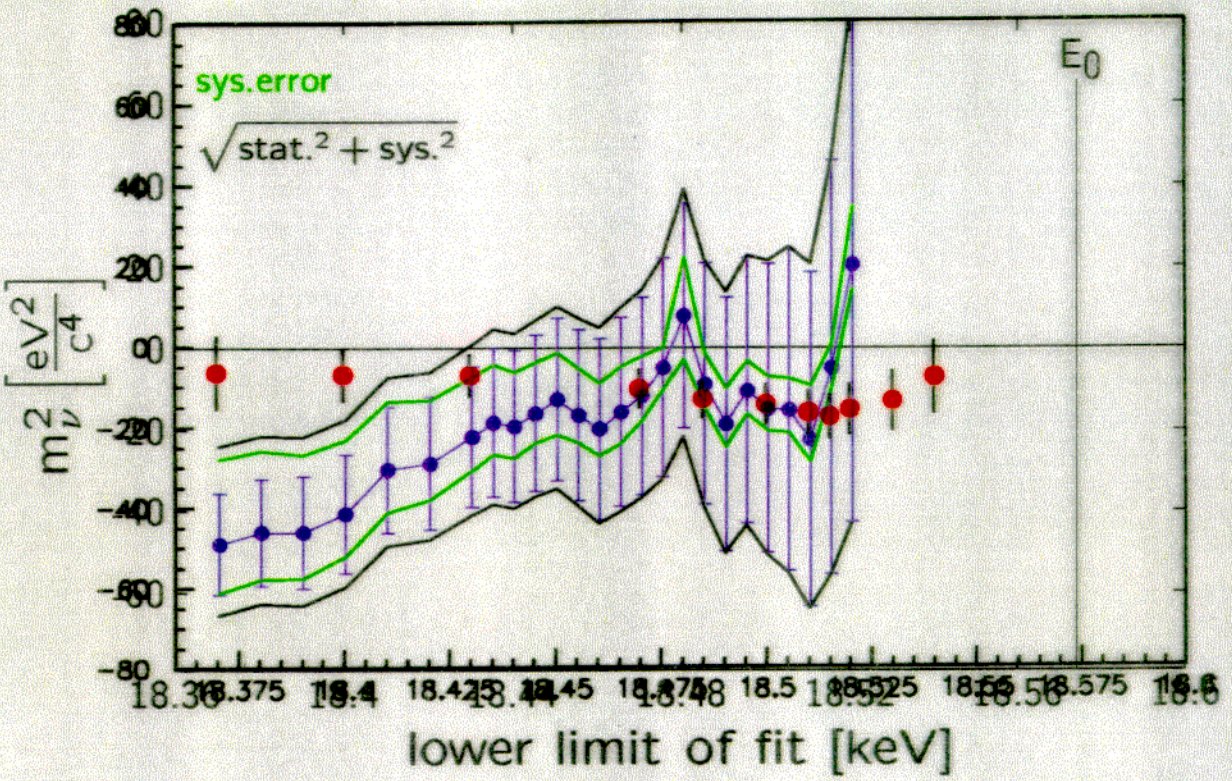


Summing up all 1998 data

Q3+Q4+Q5



Result 1994



→ fit abuses fit parameter m_ν^2

to compensate systematic discrepancies

between data and fit function

→ trend explainable by missing energy loss

Reasons for $m_\nu^2 < 0$ problem 1?

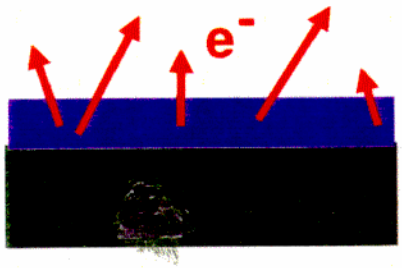
- Final state spectrum of $T_2 \rightarrow THe^+$?
  ("inner energy loss")
  $\rightarrow$ checked by theorists (incl. 2nd order): ok!

- Individual experimental errors?
  ("outer energy loss")

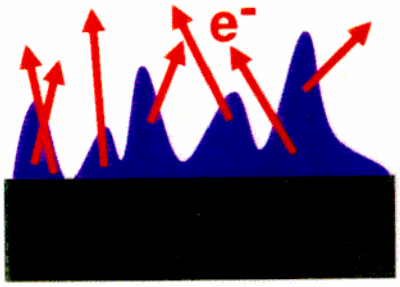
Search for sys. errors at Mainz:

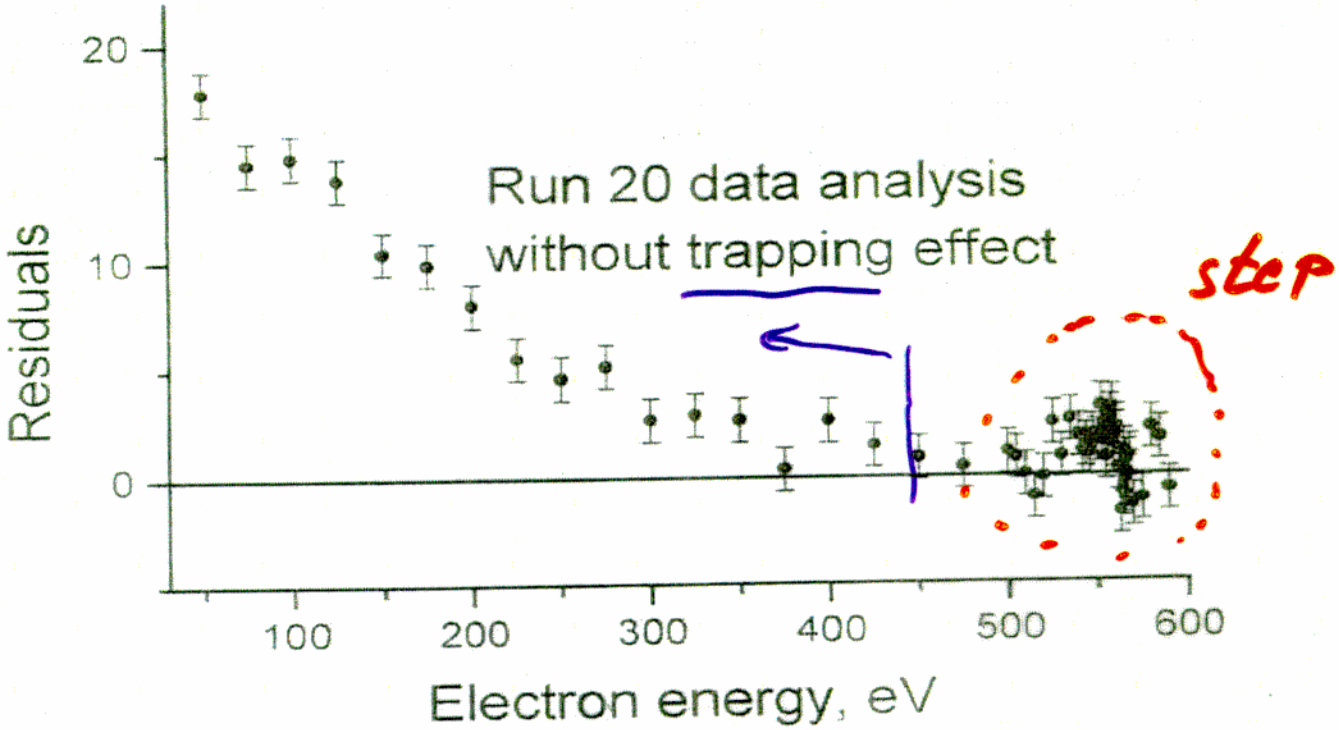
Many exp.checks of energy loss, backscatter and transmissions function

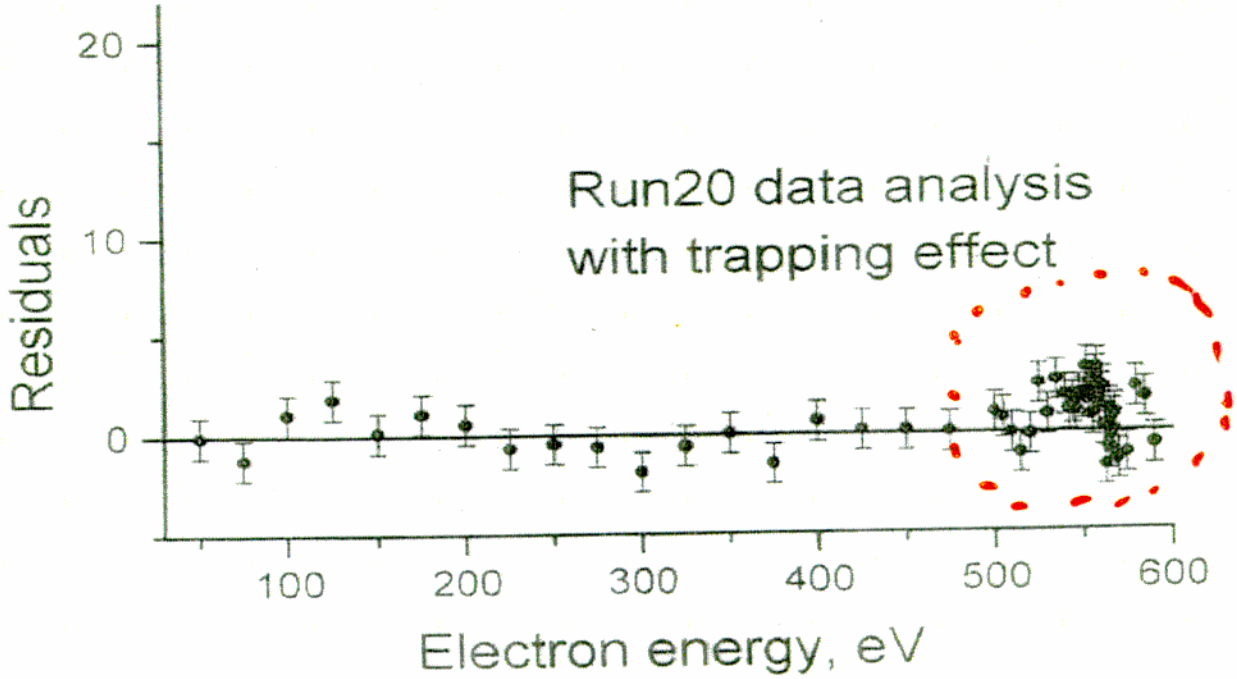
$\rightarrow$ all ok, but possibly:



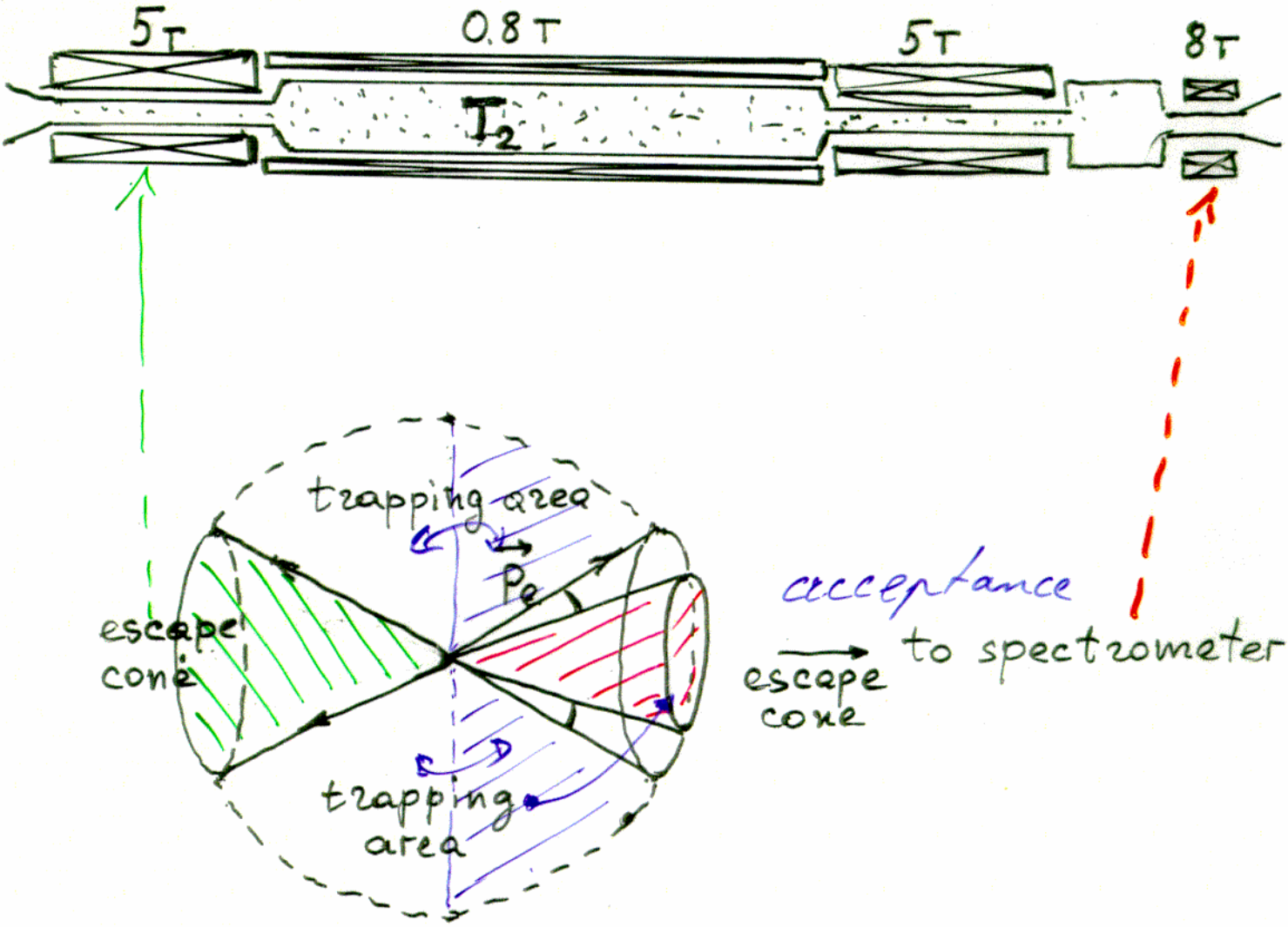
$\rightarrow$ roughening transition of T_2 film




Run 20 data analysis
without trapping effect
step
Residuals
20
10
0
100
200
300
400
500
600
Electron energy, eV


Run20 data analysis
with trapping effect
Residuals
20
10
0
100
200
300
400
500
600
Electron energy, eV

Trapping effect in the source.



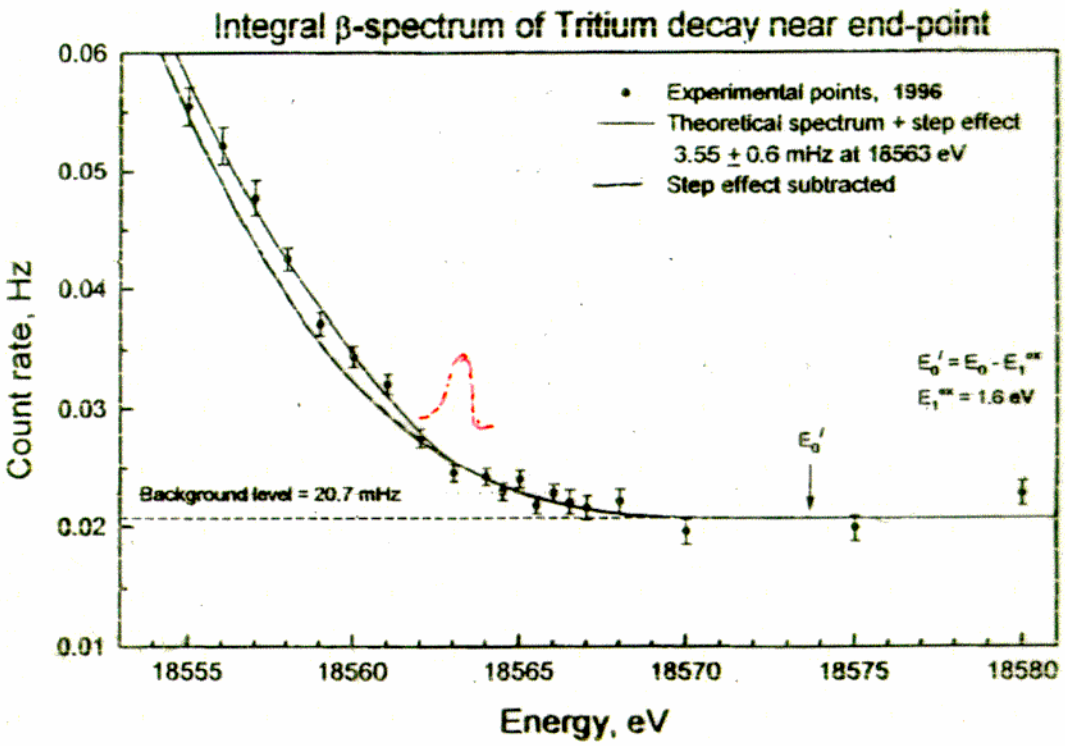
danger!
Scattering from the trapping area into the acceptance cone of the spectrometer

Troitsk Anomaly

Tritium β experiment at Troitsk/Russia:

Similar integrating spectrometer, but gaseous T_2 source

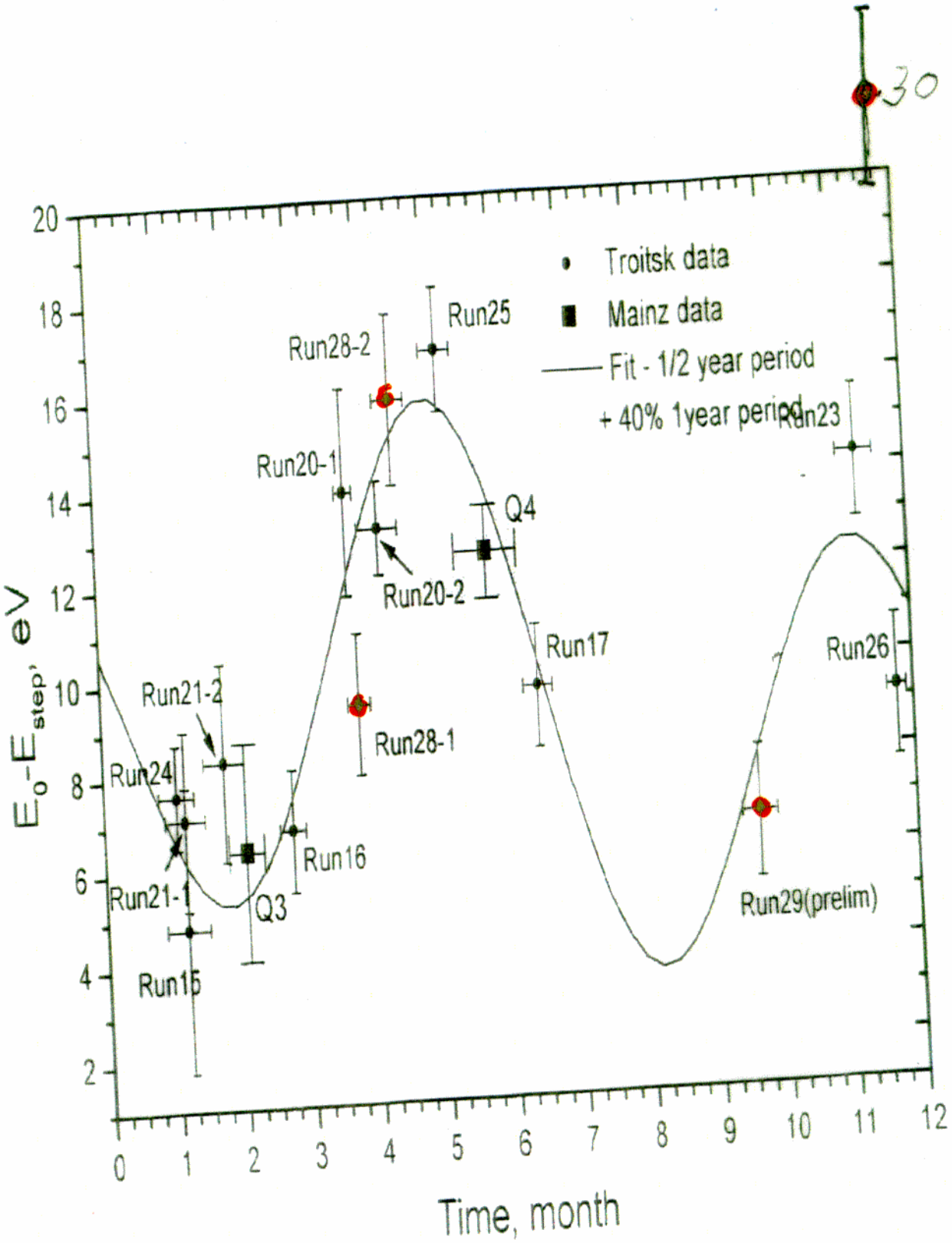
Observed anomalie:



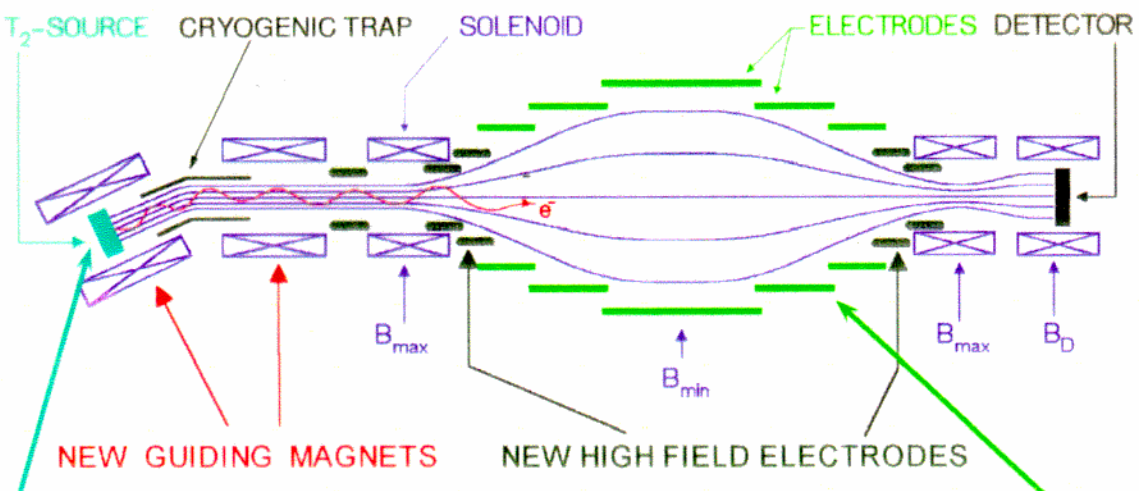
→ monoenergetic line in continous β spectrum?

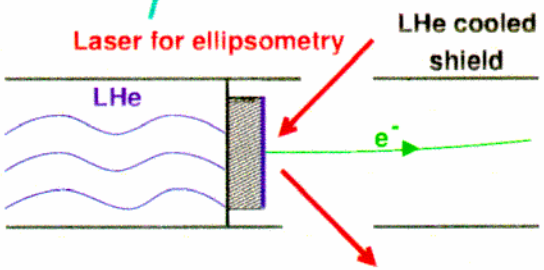
Reported by Troitsk (Neutrino 98, Phys. Lett. **B460** (1999) 227):

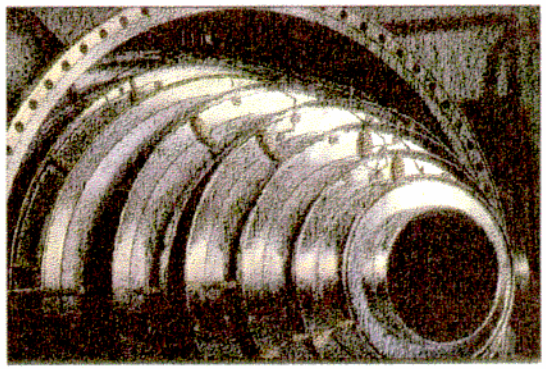
- anomaly: exist in 94 to 98 data
- amplitude: $\approx 10^{-10}$ of all decays, not constant
- position: oscillating between 5-15 eV below E_0 with 0.5 year period


30
Troitsk data
Mainz data
Fit - 1/2 year period
+ 40% 1year period
Run25
Run28-2
Run23
Run20-1
Q4
Run20-2
Run17
Run26
Run21-2
Run28-1
Run24
Run16
Run21-1
Q3
Run29(prelim)
Run15
E_0-E_{step}, eV
Time, month

The Mainz setup since 1997



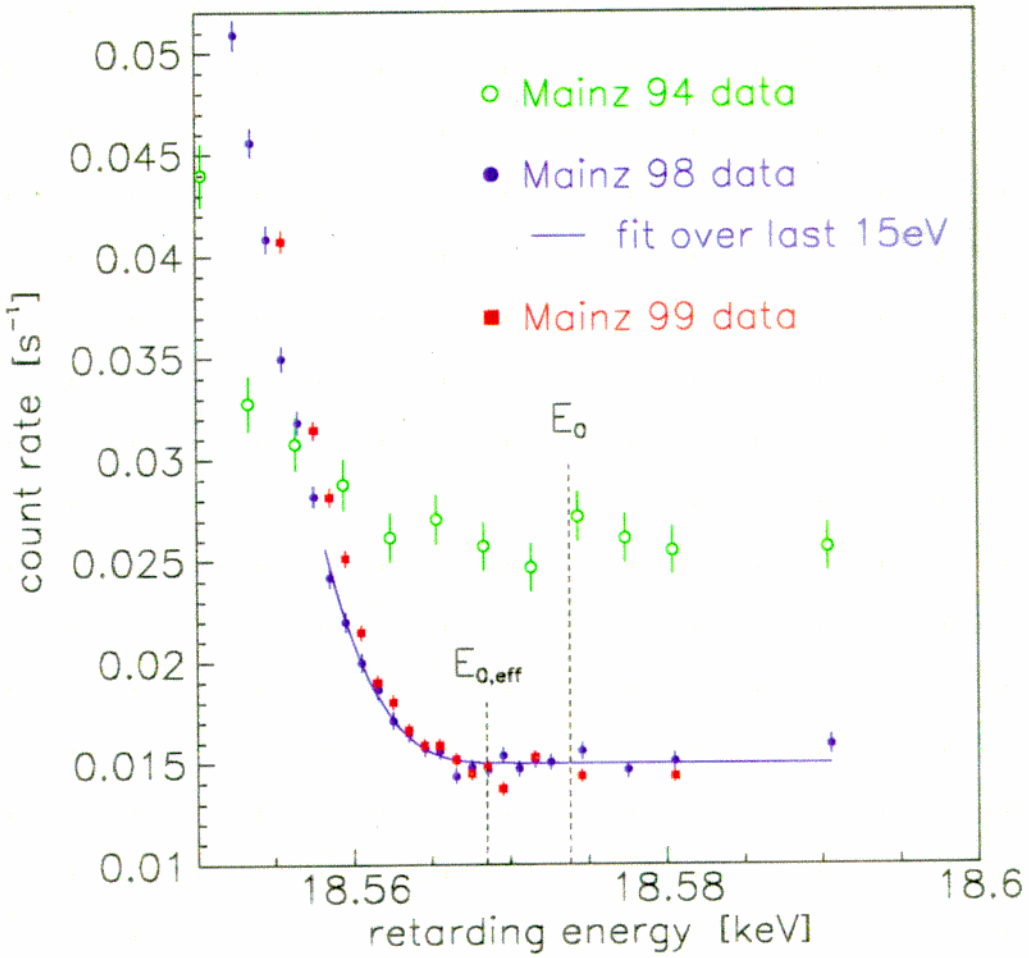




- T_2 film at 1.86 K
- quench condensed on HOPG
- $\approx$ 450 Å thick ($\approx$ 130 ML), area 2 cm^2
- thickness measurement by ellipsometry

Ch. Weinheimer

New Mainz 1999 measurements: Q6 – Q8



- 3 month measurement time in total
- More stable experimental parameters:
  Less failures, improved slow control
- More stable background:
  HF pulsing on electrodes inbetween measurements
- Optimized measurement point distribution
- Maximum starting angle accepted by spectrometer: 45° → 62°

Systematic uncertainties

- **Inelastic Scattering** — thickness measurement: $\Delta d = 3 - 9$ ML (37 %)

λ_{free} = 363 +/- 19 ML (Asseev et al., Eur. Phys. J. D10 (2000) 3!

shape of energy loss function

→ some differences to gaseous T_2

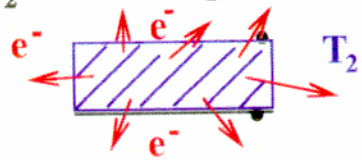
- **Final states** — (effects due to solid state) (35 %)

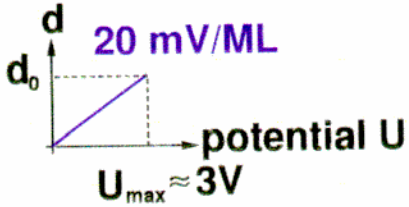
  spectator excitation

  changes of excited states energy levels

  (take full correction as systematic uncertainty into account)

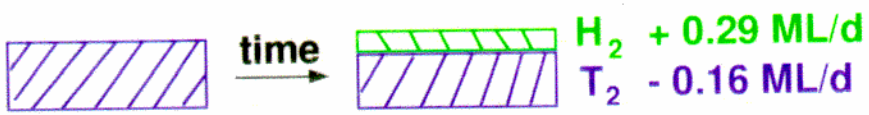
- **T_2 film charging up** (7 %)





(take 20% of effect as systematic uncertainty into account)

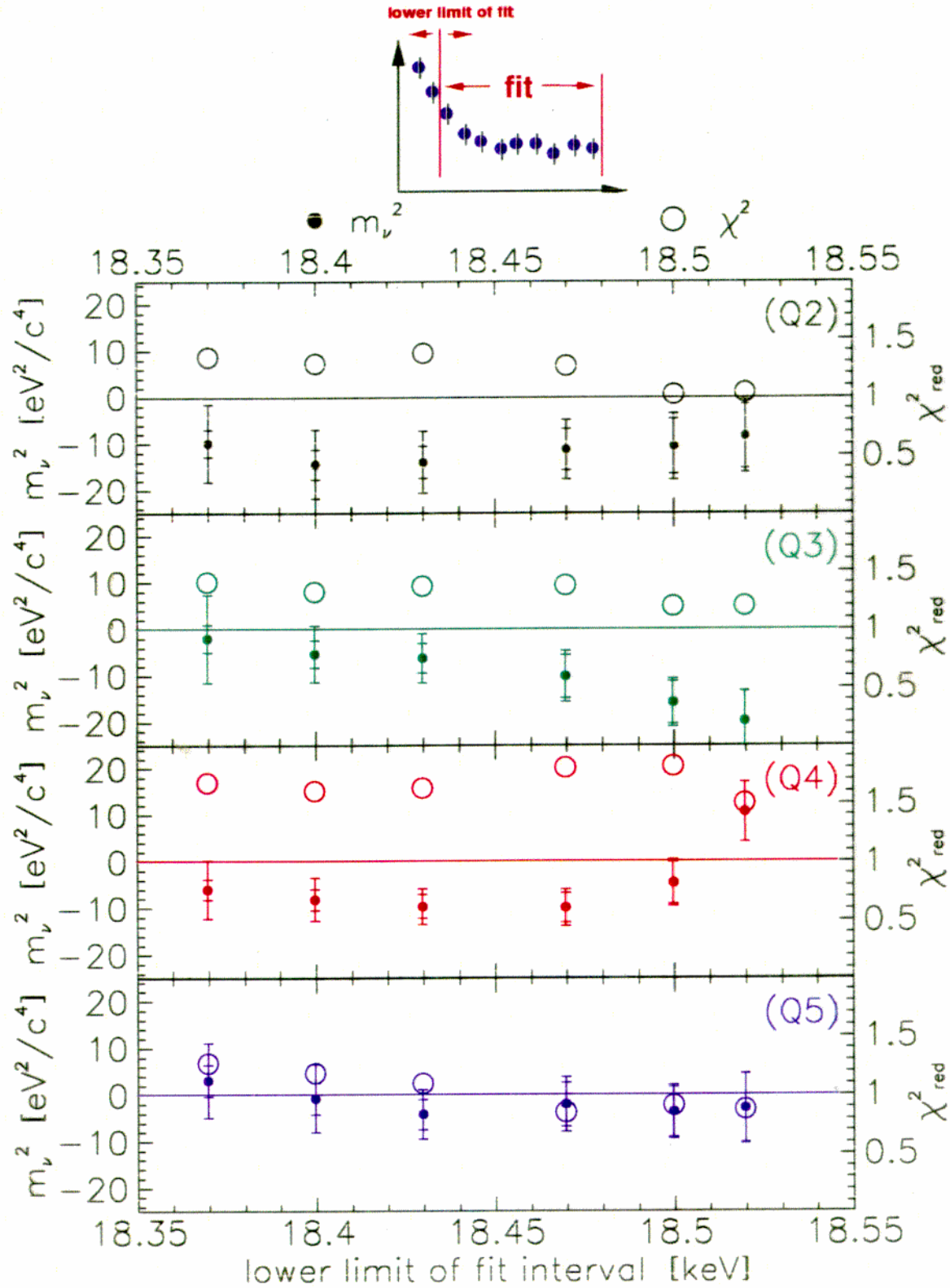
- **T_2 film loss, H_2 coverage** new (21 %)



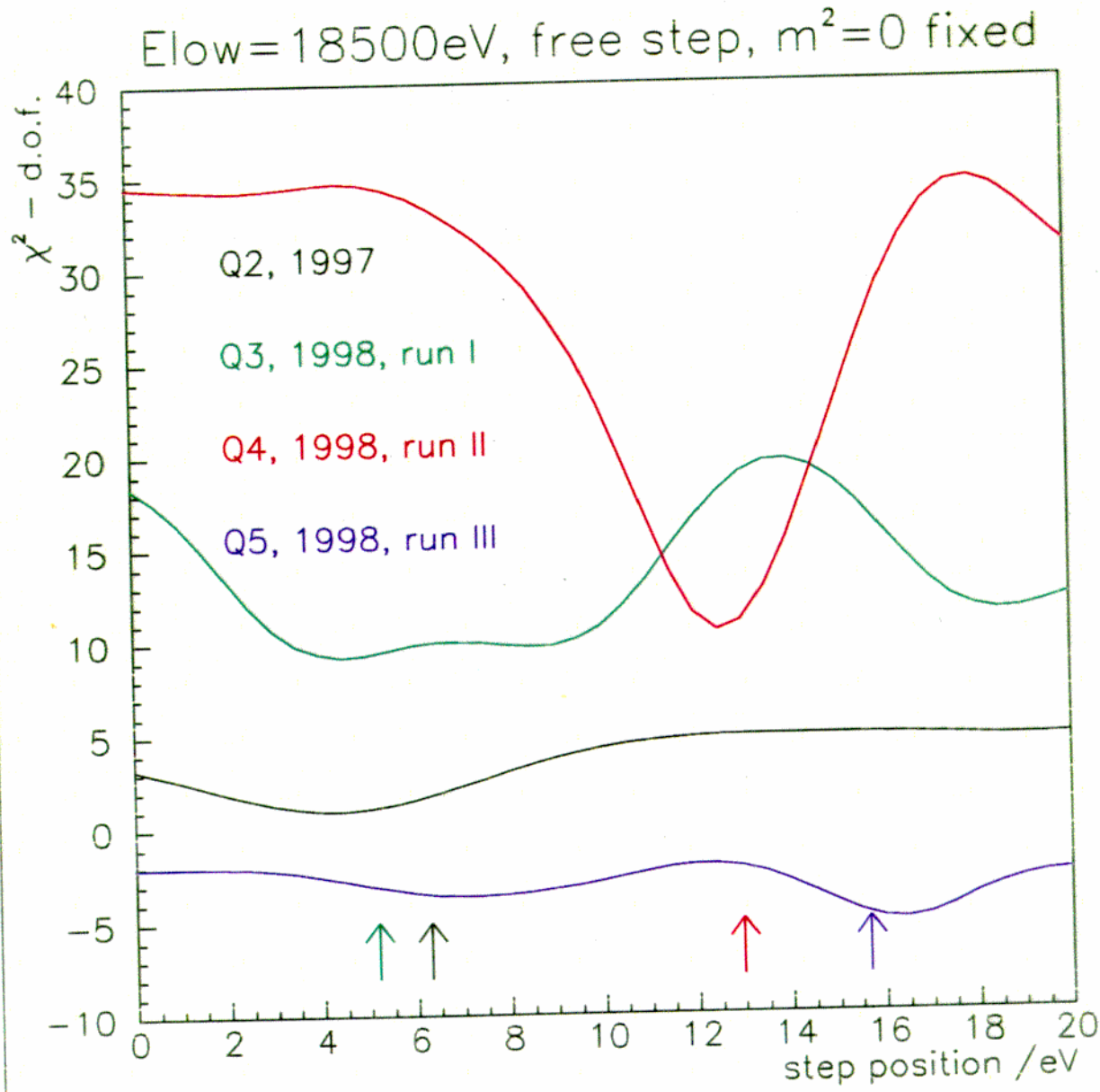
(take full correction as systematic uncertainty into account)

(contribution to systematic uncertainty for Q7, last 70 eV ↩)

m_ν^2 versus fit interval



Analysis for monoenerg. step ("Troitsk anomaly") for $m_\nu^2 = 0$ (Mainz data)

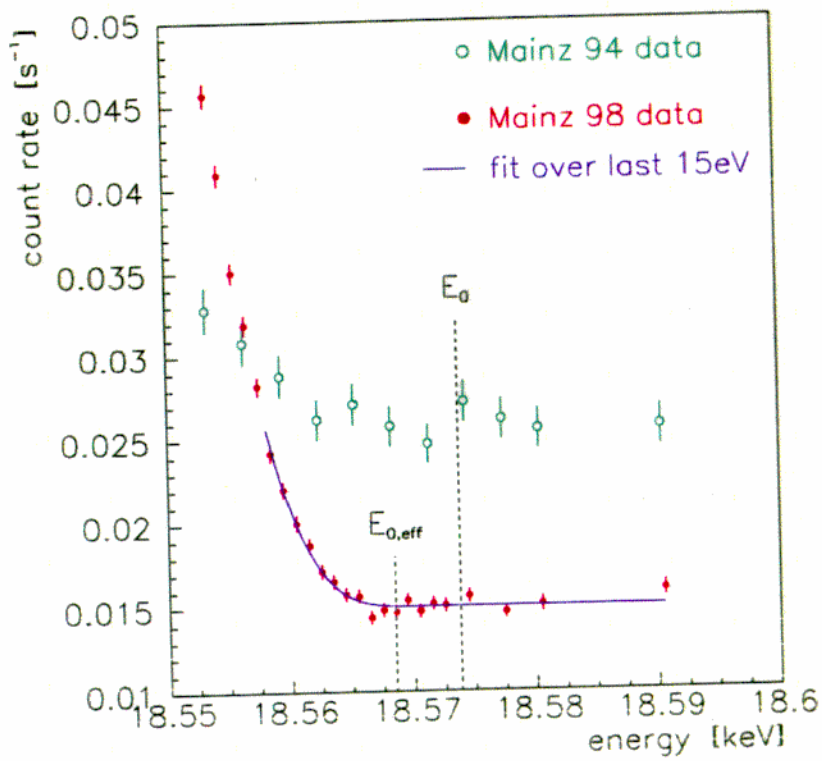


Upper limits from Mainz data 1

1.) Decorrelate m_ν^2 from systematics:

Sum of all 1998 data (Q3+Q4+Q5) (taken under same conditions)

- Take last 15 eV of β spectrum
  - $\rightarrow$ free of systematics (atomic phyiscs thresholds)
  - $\rightarrow$ no influence from "Troitsk-like" anomaly as observed in Q4
- Add two data points at 18470 eV and 18500 eV to decorrelate m_ν^2 from endpoint E_0 and amplitude
  - $\rightarrow$ minor influence of systematics
  - $\rightarrow$ minor influence from "Troitsk-like" anomalies



$$m_\nu^2 c^4 = -0.1 \pm 3.8 \pm 1.8 \mathrm{eV}^2$$

$\rightarrow m_\nu c^2 \leq 2.9$ eV (95%C.L., unified approach)

Upper limits from Mainz data 2

2.) If one believes in step as correct solution:

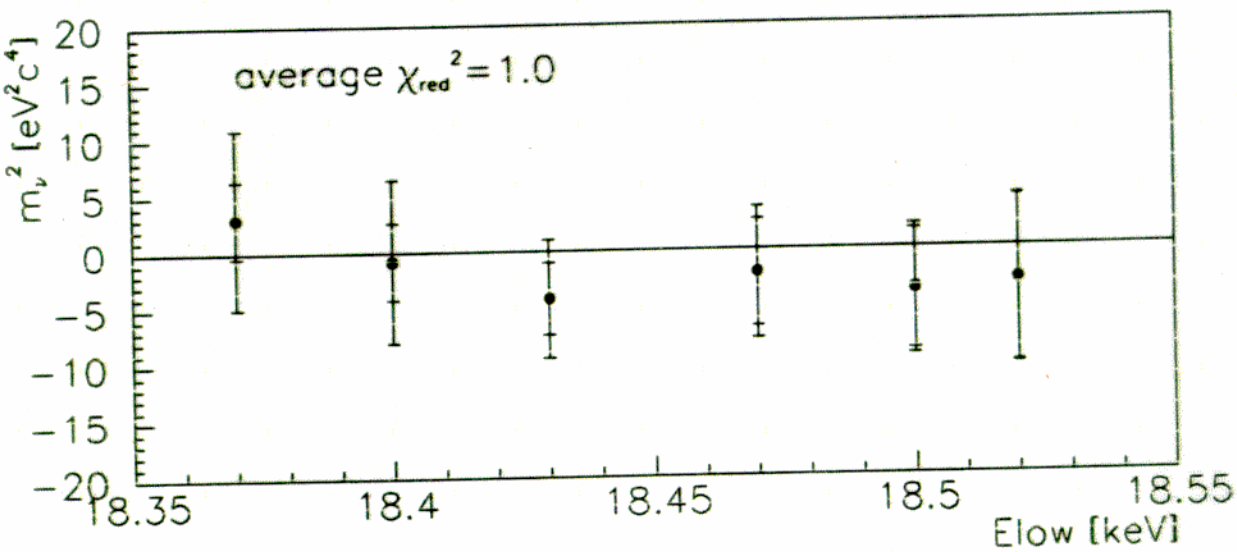
→ fit step and subtract it (only possible for Q4):

last 70 eV (Q4, 1998 run II):

$$m_\nu^2 c^4 = -1.8 \pm 5.1 \pm 2.0 \mathrm{eV}^2$$

$\rightarrow m_\nu c^2 \leq 3.0$ eV (95%C.L., unified approach)

3.) Considering Q5, 1998 run III alone:



→ Standardanalysis:

last 70 eV (Q5, 1998 run III):

$$m_\nu^2 c^4 = -3.7 \pm 5.3 \pm 2.1 \mathrm{eV}^2$$

$\rightarrow m_\nu c^2 \leq 2.8$ eV (95%C.L., unified approach)

(All results are published in Phys. Lett. **B460** (1999) 219)

Troitsk result

Subtracting line-like excess phenomenologically

by fitting β spectrum + line-like excess simulaneously

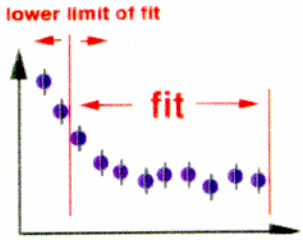
Combining results from 1994 - 1998 data:

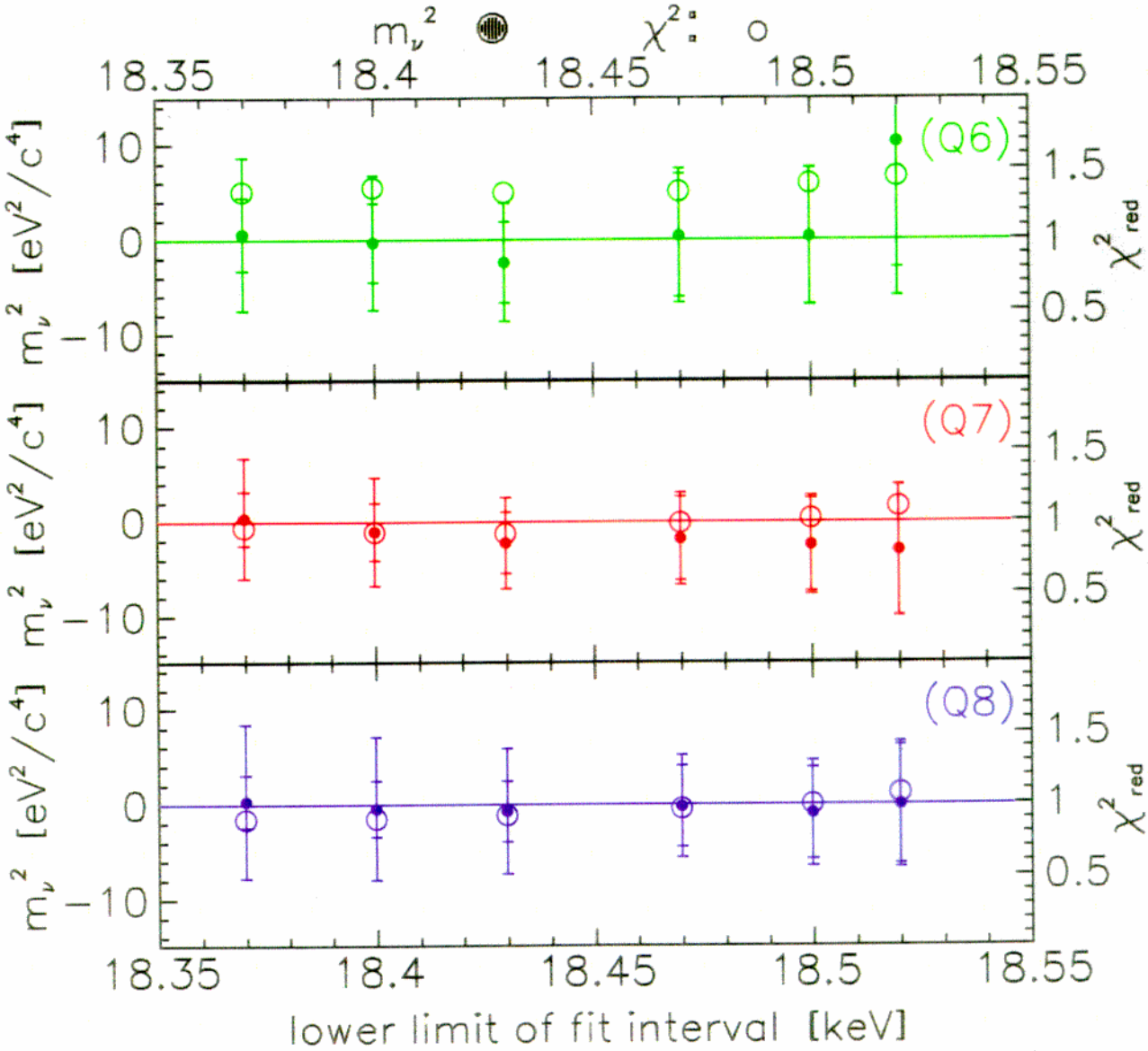
$$\rightarrow m_\nu^2 = -1.9 \pm 3.4_{\mathrm{stat}} \pm 2.2_{\mathrm{sys}} \ \mathrm{eV}^2/\mathrm{c}^4$$

$$\rightarrow m_\nu \leq 2.5 \ \mathrm{eV}/\mathrm{c}^2$$ (95% C.L, unified approach)

(Phys. Lett. **B460** (1999) 227)

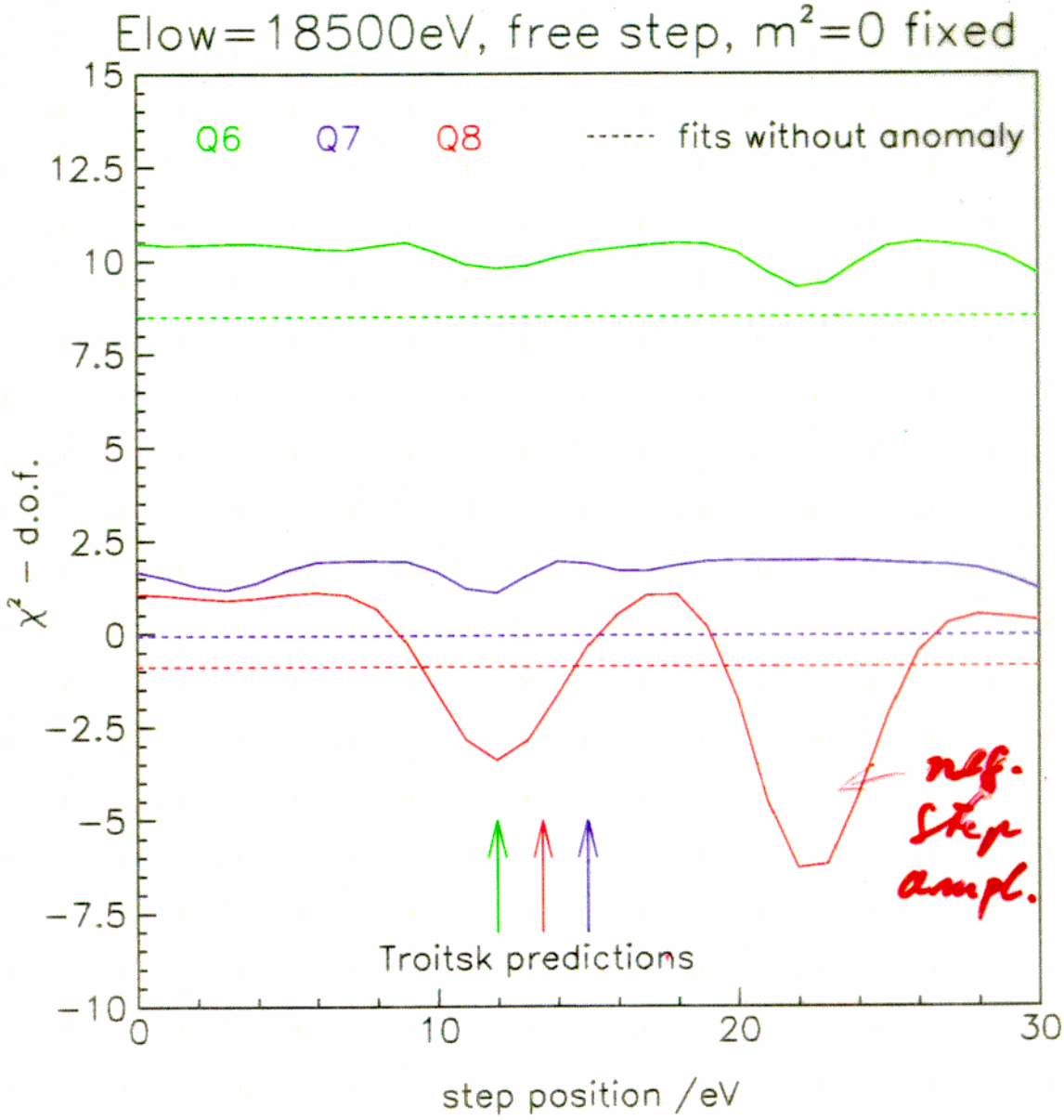
Fits of m_ν^2 for Mainz 1999 data





Ch.Weinheimer

"Troitsk-anomaly" in Mainz 1999 data?



→ No significant improvement of fit by introducing Troitsk anomaly

New results on m_ν for the Mainz data

- m_ν^2 behaviour:

  m_ν^2 is stable against variation of fit range

  m_ν^2 is compatible with phyisically allowed range

  $\rightarrow$ no indication for any residual problem in Mainz 1999 data!

- No indication for a non-zero neutrino mass:

  1. "last 15 eV"-analysis:

     take data points at 18.460 keV, 18.500 keV, $>$ 18.560 keV

     ($E_0 = 18.575$ keV)

     (result would not be affected by an eventual Troitsk-like anomaly at position as indicated by Q4)

1998	$m_\nu^2 c^4 = +0.1 \pm 3.9 \pm 2.1\ \mathrm{eV}^2$	$\chi^2/\mathrm{d.o.f.} = 16.1/20$
1999	$m_\nu^2 c^4 = +1.5 \pm 3.2 \pm 3.4\ \mathrm{eV}^2$	$\chi^2/\mathrm{d.o.f.} = 19.4/14$
1998+1999	$m_\nu^2 c^4 = +0.6 \pm 2.8 \pm 2.5\ \mathrm{eV}^2$	

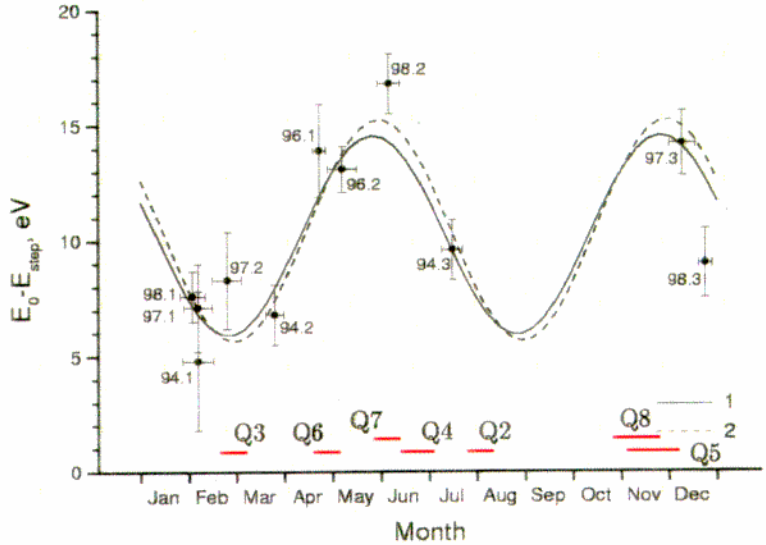
     $\rightarrow m_\nu c^2 \leq 2.8$ eV (95% C.L., unif. appr.)

  2. last 70 eV below endpoint (take data points $>$ 18.5 keV)

     Q5,Q6,Q7,Q8 $m_\nu^2 c^4 = -1.6 \pm 2.5 \pm 2.1\ \mathrm{eV}^2$ $\chi^2/\mathrm{d.o.f.} = 125/121$

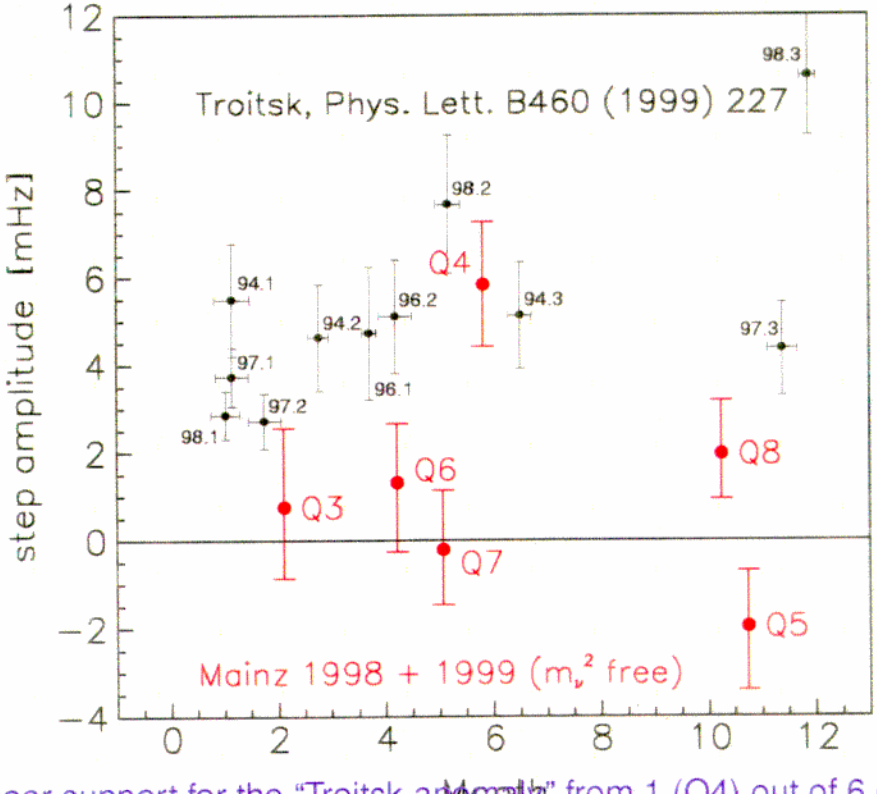
     $\rightarrow m_\nu c^2 \leq 2.2$ eV (95% C.L., unif. appr.)

"Troitsk-anomaly" in Mainz data?



(Phys. Lett. B460 (1999) 227)

dates of Mainz measurements



Mainz step amplitude at Troitsk prediction

- Clear support for the "Troitsk anomaly" from 1 (Q4) out of 6 data sets, is there something different for measurement Q4?
- But parameter space, favored by Troitsk, not fully excluded
- Clear contradiction to 0.5 y periodicity

Summary

- **Situation in neutrino physics:**
  - Neutrinos seem to oscillate $\rightarrow m_\nu \neq 0$
    Oscillation experiments: determination of Δm_ν^2, not of $m_{\nu,i}$
  - Models with degenerated neutrino masses: $0.5 < m_\nu < 2eV/c^2$
    $\rightarrow$ very interesting for particle physics and cosmology

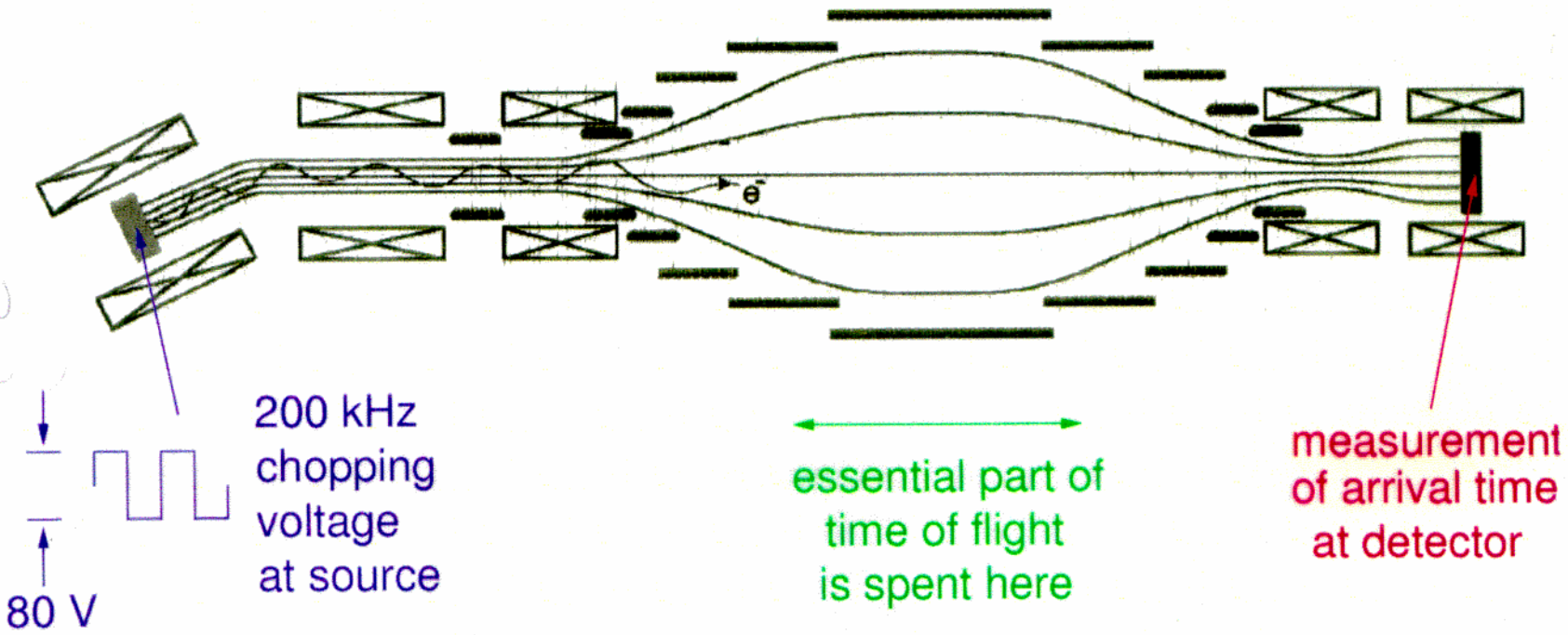
- **Mainz upgraded setup:**
  - Enables longterm automatic data taking with
    10 $\times$ better signal to background ratio than 1994
  - Old problem ($m^2 < 0$) understood and solved:
    no T_2 film roughening transition at 1.8 K
  - Much better understanding of systematics of T_2 films
    roughness, charging, energy loss of electrons
  - Troitsk anomaly: some support, but not for 1/2 year period
  - Synchronous measurements at Mainz and Troitsk in 1999
  - Current upper limit: $m_\nu < 2.8$ eV (1997 and 1998 data)
  - Reachable sensitivity: 2 eV

- **Perspectives:**
  - 2 eV sensitivity is not enough to decide between models,
    is not enough to check neutrino dark matter
  - $\rightarrow$ new large tritium β experiment with sub eV sensitivity
    Based on successful Mainz and Troitsk spectrometer types,
    additional non-integrating time-of-flight mode

Running the Mainz

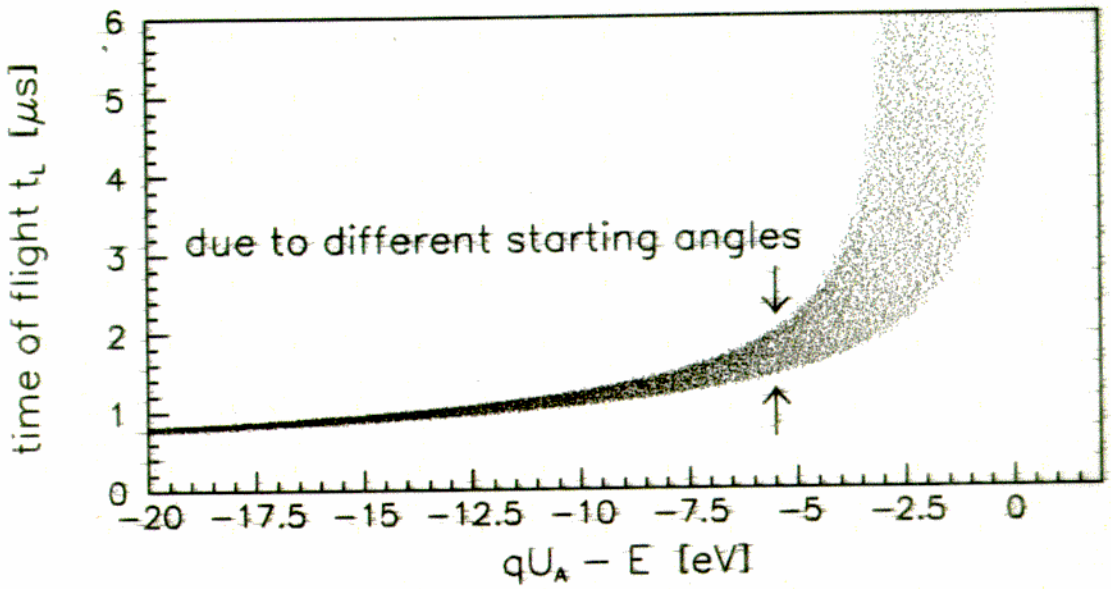
MagneticAdiabaticCollimation with Eelectrostatic Filter

in TimeOfFlight mode

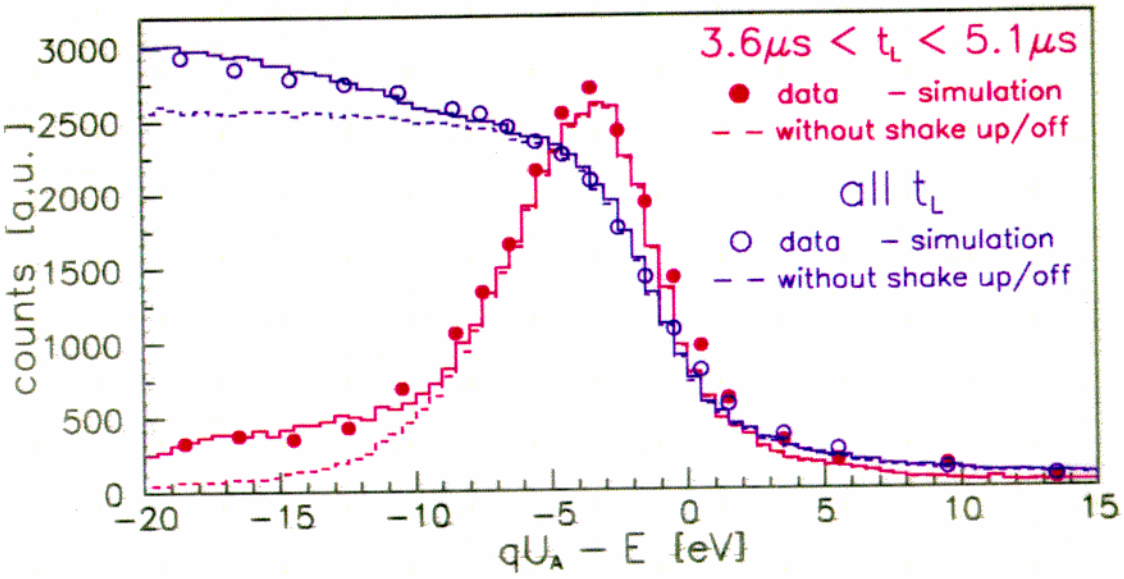


MAC-E-TOF mode

Principle:



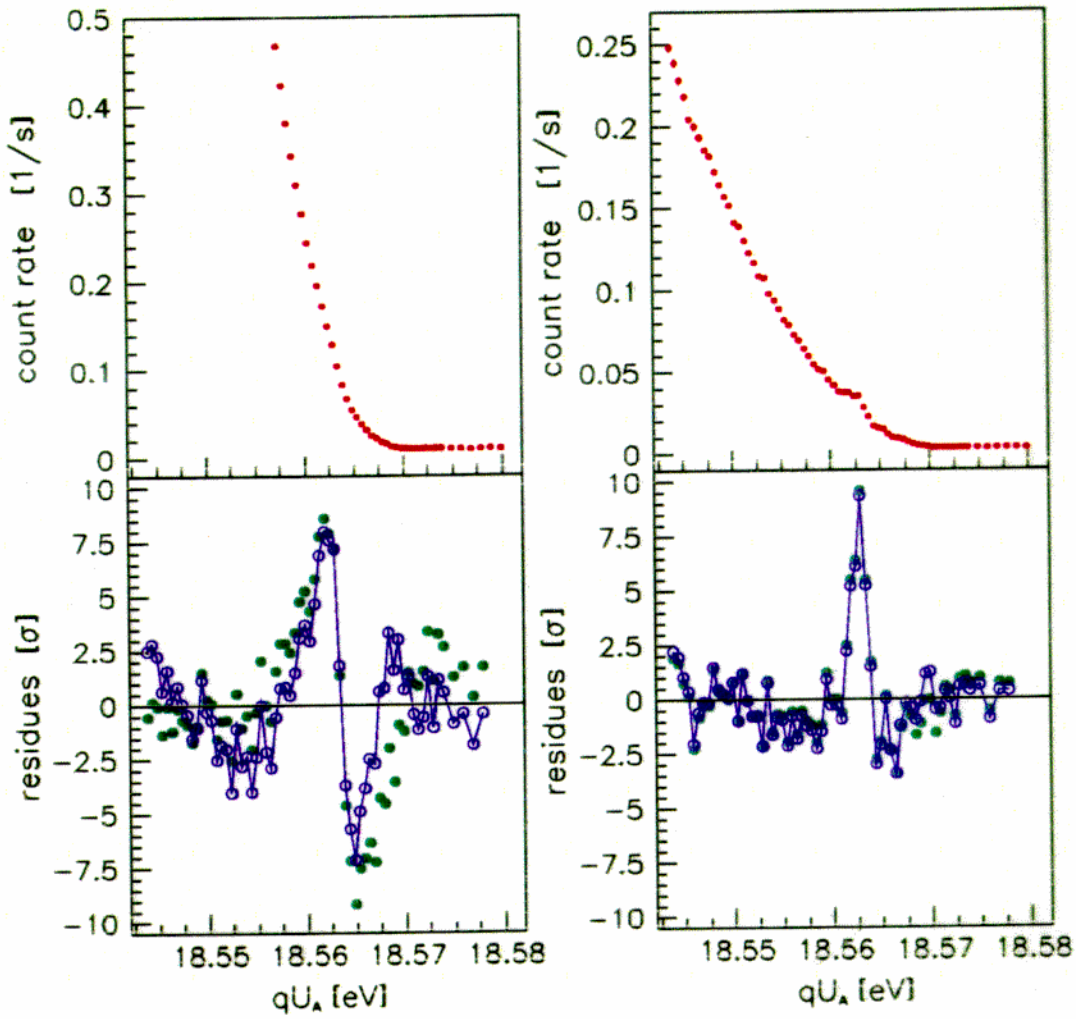
Measurement of ^{83m}Kr K conversion line:



(J. Bonn *et al.*, Nucl.Instr.Meth. **A421** (1999) 256)

Simulation with Troitsk Anomaly

Integral MAC-E mode MAC-E-TOF mode



- 2 month masurement time in total, 30 eV of β spectrum
- T_2 source, 200 monolayer equivalent thickness
- Troitsk Anomaly: position: 10 eV below endpoint E_0,
  amplitude: $6 \cdot 10^{-11}$
- Fit over full 30 eV for m_ν^2 free (filled circles), and
  for m_ν^2=0 (open circles)

Summary and outlook

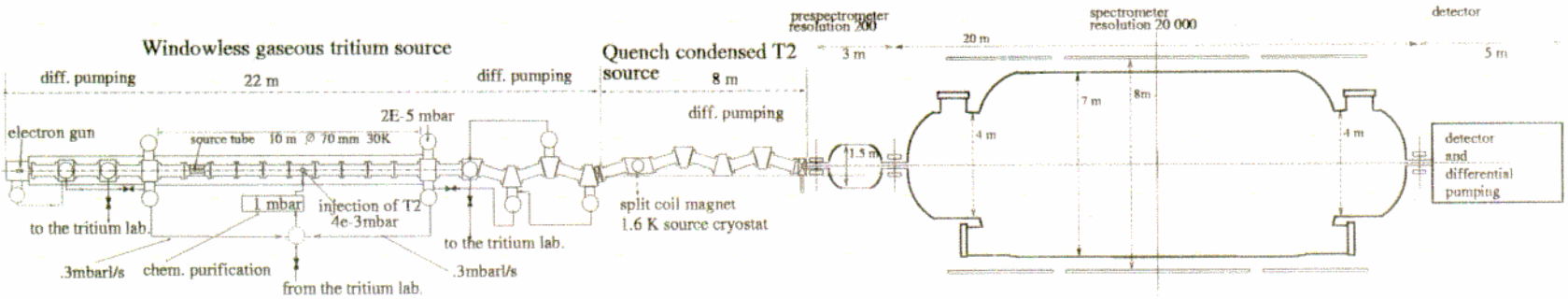
- Troitsk experiment: reporting "Troitsk anomaly"
- Mainz 1999 data:
  - Fully compatible with ordinary β spectrum at neutrino mass zero
  - 1998 + 1999 data: two upper limits ($\approx$ same sensitivity):

    "Last 15 eV" analysis: $m_\nu c^2 < 2.8\ eV$ (95 % C.L.)

    Last 70 eV analysis: $m_\nu c^2 < 2.2\ eV$ (95 % C.L.)
- "Troitsk anomaly" in Mainz data?

  Postulated half year period is at variance with Mainz data

  $\Rightarrow$ Synchronous measurements at Mainz and Troitsk scheduled to clarify "Troitsk anomaly"
- New Large Tritium β Experiment:
  - Design studies are under way

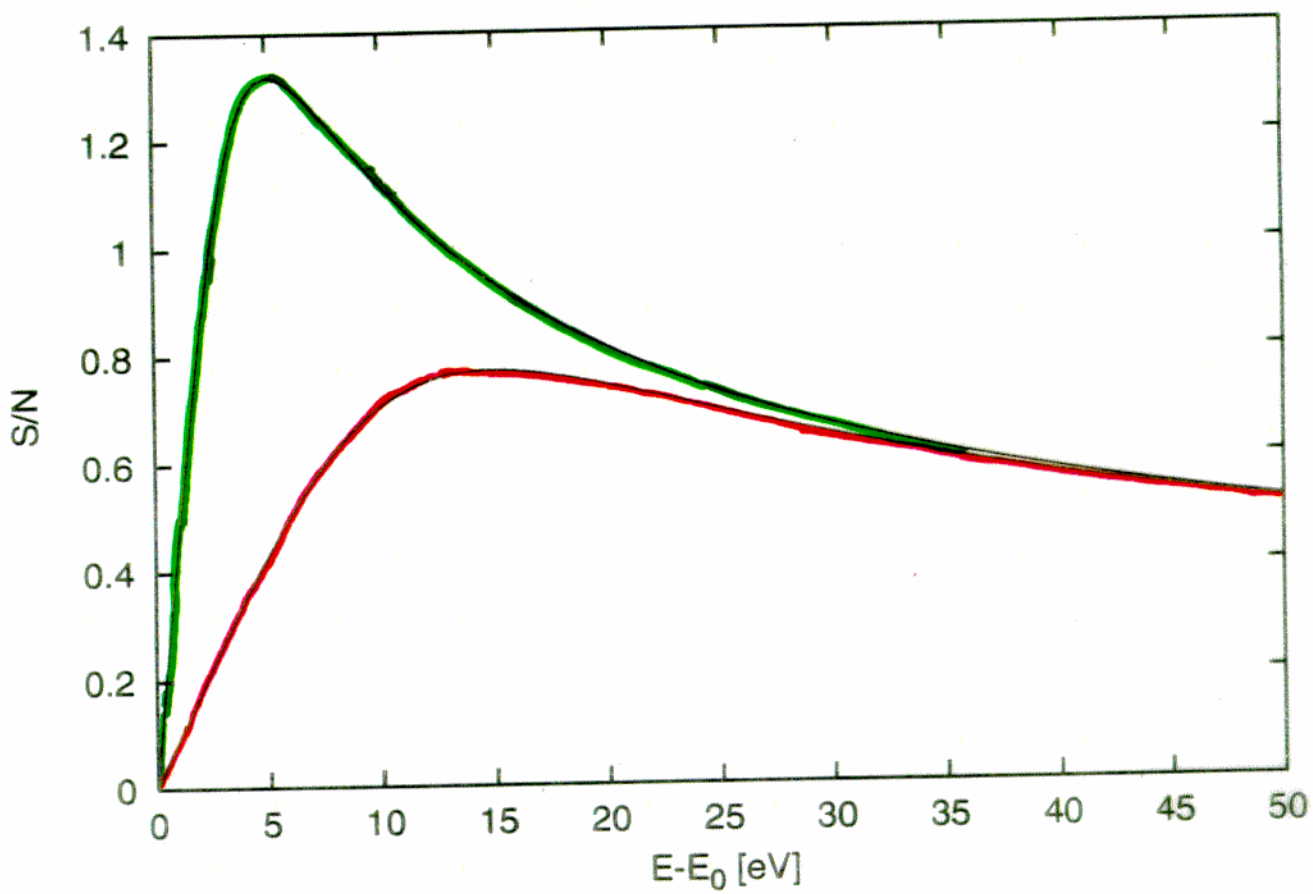


Signal to noise ratio

sensitivity to assumed m_ν

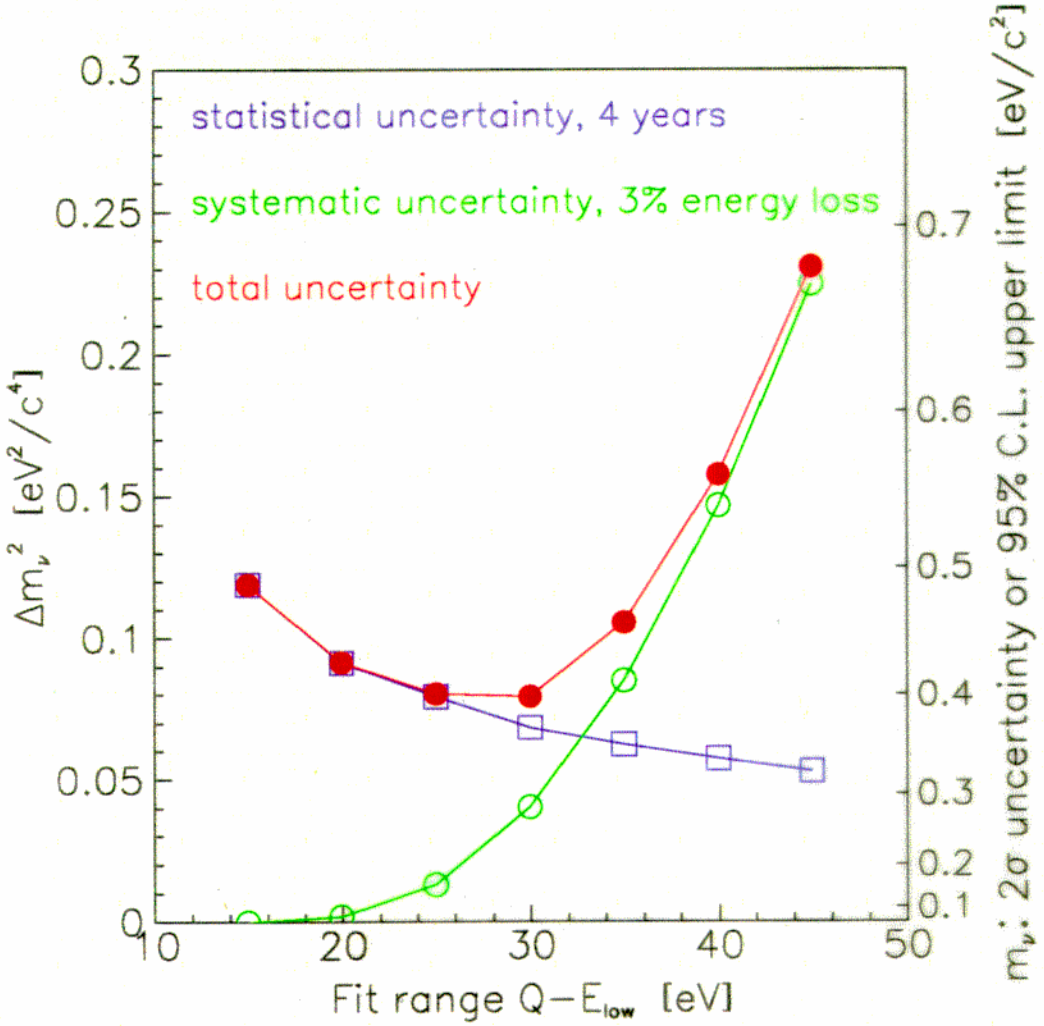
Parameter:

	present setup	proposed setup
• total amplitude:	$A = 6 * 10^7\ Bq$	$A = 1.5 * 10^9\ Bq$
• rel. amp. ($\Delta E^2 = m_\nu^2$):	$1.3 * 10^{-12}$	$2.6 * 10^{-14}$
• mass square:	$m_\nu^2 = 5\ eV^2$	$m_\nu^2 = 1\ eV^2$
• time of measurement: (for each datapoint)	$T = 10^5\ s$	$T = 10^5\ s$
• background:	$B = 2 * 10^{-2}\ s^{-1}$	$B = 2 * 10^{-2}\ s^{-1}$



Simulation of the sensitivity on m_ν

First simulation with conservative assumptions:



energy resolution: 1eV
source area: 20 cm^2
gaseous source effective thickness: 250 ML
max accepted starting angle: 70°
background rate: 11 mHz

$\Rightarrow$ Sensitivity on m_ν of < 0.5 eV/c^2