Direct Measurements of Neutrino Mass

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Direct Measurements of m_ν

- Review of current results
  - Kinematics, Calorimetry and not only...
    - ν_τ from τ decay
    - ν_μ from π decay
    - ν_e from nuclear β decay
  - $\beta\beta$ Decay Experiments
- Far fetched, exotic (im)possibilities proposed...
- Serious (one order of magnitude), planned improvements
  - ν_e, ν_μ, $\beta\beta$
- Does it (still) make sense in view of oscillation results?
- Conclusions

$m_\nu \neq 0$

- **A belief supported by oscillation results. These also indicate that Δm^2 is small. Yet**
  - **Absolute scale of m_ν is still unknown**
  - **Dirac or Majorana mass?**
- **Mechanisms to generate neutrino masses do not have a lot of predictive power**
- **There exist *indirect* limits based upon Cosmology, Big Bang Nucleosynthesis etc.. ($\Sigma m_{\nu_i} \leq 92\Omega_\nu h^2 eV$)**
  - **Tend to be much smaller (for ν_μ and ν_τ) than *laboratory* limits**
  - **Rely upon a number of theoretical assumptions**
- **The issue is experimental ⇒ Measure it!**

ν_τ

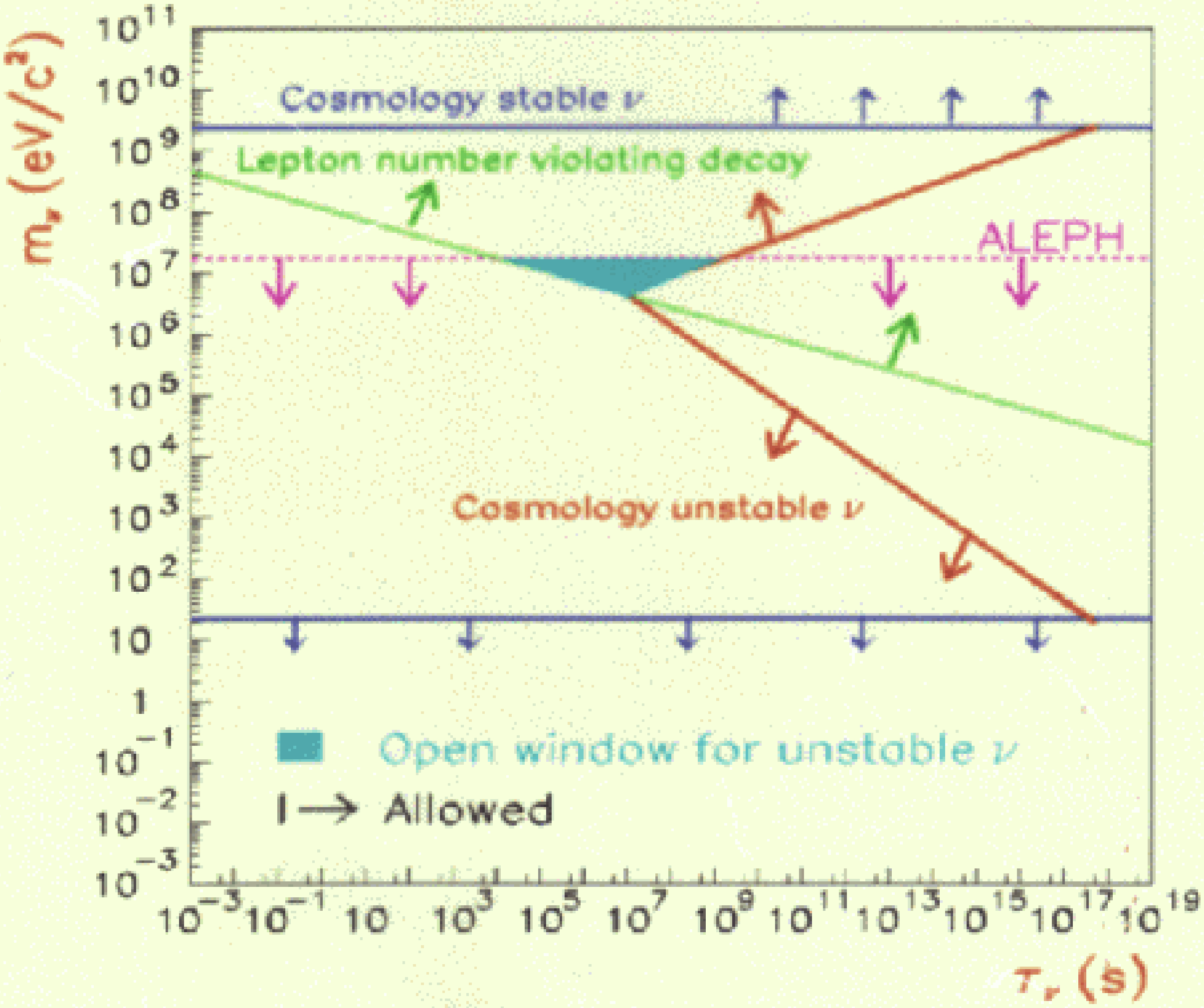
- The heaviest - in "natural" mass schemes - but also the flavour with the least stringent limits ⇒ free to speculate (e.g. could it be unstable?)

- Effects of mixing neglected (assume ν_3 dominates)

- Limits come from decays of τ leptons produced at e^+e^- colliders through
  - Comparison between predicted and observed branching ratios
    - massive neutrinos would limit phase space and reduce decay rates.
    - limited by knowledge of τ mass and lifetime
  - Analysis of hadronic decays $\tau \to (n\pi)\nu_\tau$ with $n = 3, 5, 6$ (ALEPH and other LEP experiments) and $n = 4$ (CLEO).

(18.2 MeV) (22 MeV)

Limits relative to ν_τ



(from R. Barate et al., ALEPH Collaboration, European Physical Journal C 2 (1998) 3, 395)

Method

- The decay is described as a two-body decay

  $$\tau(E_\tau, \vec{P}_\tau) \rightarrow hadrons(E_h, \vec{P}_h)\ \ \nu_\tau(E_\nu, \vec{P}_\nu)$$

- E_τ is known (beam energy); the τ-direction of flight is not

- The momenta $\vec{P}_h$ are measured: this would allow to estimate E_h and m_h which are therefore correlated ($\rho \sim 0.5 - 0.7$)

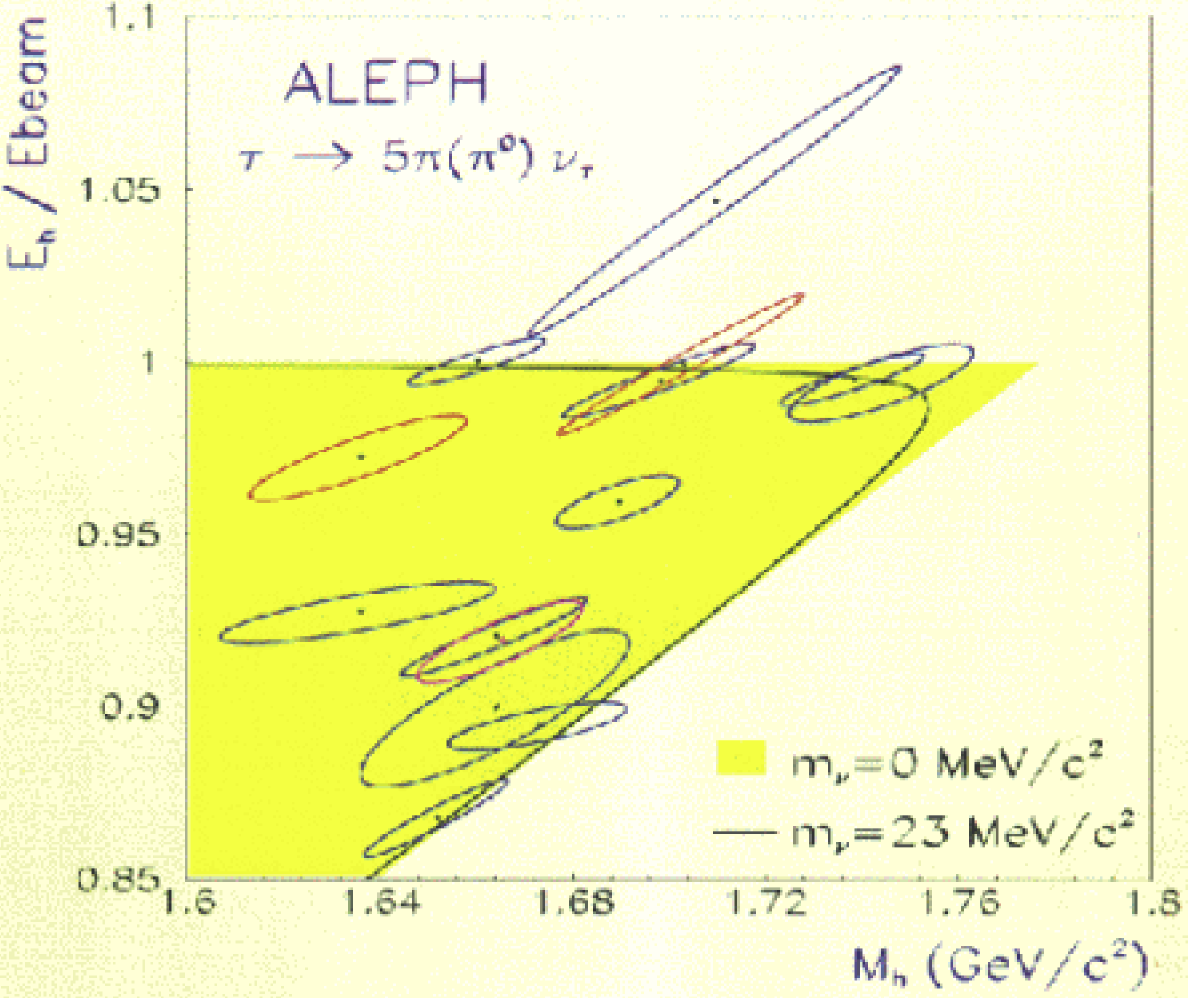
- E_h is constrained to be in the interval $\gamma(E_h^* \pm \beta P_h^*)$

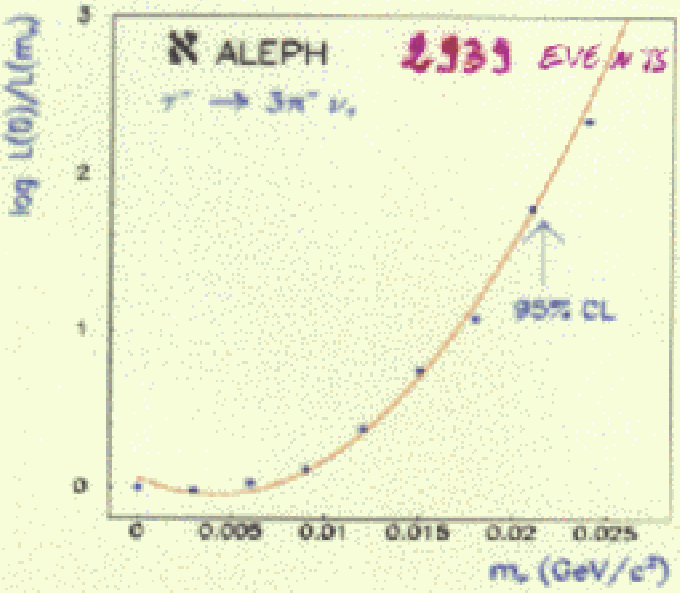
- Likelihood fit to the density of events in the (m_h, E_h) plane (determined by $d\Gamma/dm_h$).

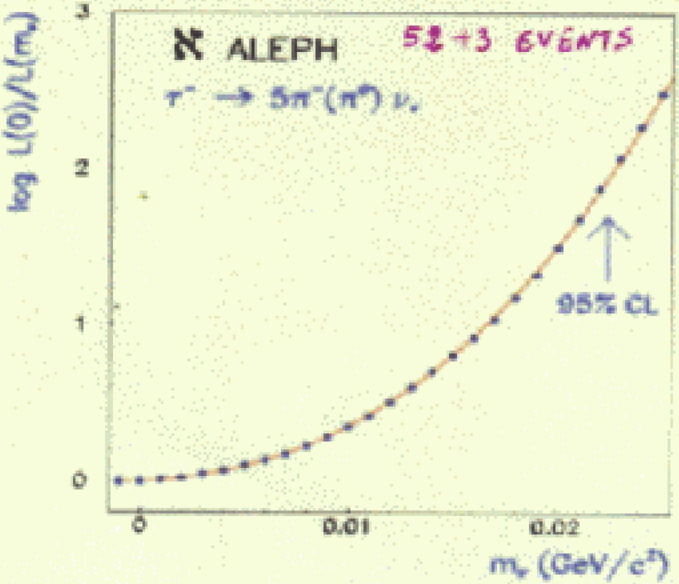
  $$\frac{1}{\Gamma} \cdot \frac{d^2\Gamma}{dm_h dE_h} \propto |M|^2(m_\tau^2, m_h^2, m_\nu^2) \cdot \lambda^{1/2}(m_\tau^2, m_h^2, m_\nu^2)$$

- Best with multi-hadron final states

- Need $v(q^2)$ and $a(q^2)$, vector and axial-vector spectral functions


ALEPH
$\tau \rightarrow 5\pi(\pi^0)\,\nu_\tau$
E_h / Ebeam
1.1
1.05
1
0.95
0.9
0.85
1.6
1.64
1.68
1.72
1.76
1.8
M_h (GeV/c^2)
m_ν=0 MeV/c^2
m_ν=23 MeV/c^2





Combined: $m_\nu < 18.2\ MeV$ **at 95% C.L.**

ν_μ

From kinematics of decay $\pi^+ \rightarrow \mu^+ \nu_\mu$

at rest...

$$\boxed{m^2_{\nu_\mu} = m^2_\pi + m^2_\mu - 2 m_\pi E_\mu}$$

- Necessary ingredients:
  - Measure μ^+ momentum
  - Masses of π^+ and μ^+ are *known*
    - Assume (CPT): $m_{\pi^+} = m_{\pi^-}$
    - m_{π^-} and m_{μ^+} measured in other experiments
- Experimental uncertainty $\Delta(m^2_\nu)$:

$2(m_\pi - E_\mu)\ \ \Delta m_\pi$	59.6 *MeV*
$2m_\mu\,[1 - (m_\pi/E_\mu)]\ \ \Delta m_\mu$	−57.3 *MeV*
$-2m_\pi\ p_\mu/E_\mu\ \ \Delta p_\mu$	−75.8 *MeV*

to be added in quadrature

....and in flight

$$\boxed{\text{For } \theta = 0,\ P_\nu = P_\mu - P_\pi}$$

- Necessary ingredients:
  - Measure P_π, P_μ and θ
  - Calculate $P^\circ_\nu = P^\circ_\mu - P_\pi$ (P° are quantities evaluated assuming $m_\nu = 0$)
    - $P_\nu - P^\circ_\nu$ measures the effect of a massive neutrino!
- Experimental uncertainty
  - Accuracy on pion and muon masses less important
  - Largest contribution to the error on P°_ν, the *calculated* neutrino momentum, from angular accuracy ($\sim P^3_\pi \cdot \bar{\theta} \cdot \Delta\bar{\theta}$)
  - Systematic errors would affect P_ν, the *measured* neutrino momentum ⇒ Measure P_μ and P_π event-by-event in the same spectrometer.

π-Decay	Year	$m^2_{\nu_\mu}$ $(MeV/c^2)^2$	Limit (MeV/c^2)
At rest	**1979**	0.13 ± 0.14	0.57
In Flight	**1982**	-0.14 ± 0.20	0.50
At rest	**1984**	-0.163 ± 0.08	0.25
At rest	**1994**	-0.148 ± 0.024	
		-0.022 ± 0.023	0.17
At rest	**1996**	-0.016 ± 0.023	0.17
PDG	**2000**	**Average** m_π	0.19

Two possible solutions for the π mass (from analysis of x-rays in $4f \rightarrow 3d$ transitions of pionic ^{24}Mg, depending on the assumption of one or two K-shell electrons).

Best experiment measures
$P_\mu = (29.79200 \pm 0.00011)\ MeV/c$ (B = 0.276 T)

$\bar{\nu}_e$

- The quantity determined - from the shape of the β spectrum of Tritium - is

$$m^2(\nu_e) = \Sigma |U_{ei}|^2 \; m_i^2$$

(cfr. $0\nu\beta\beta$ decay)

- The shape has the "simple" form

$$A \cdot F(E,Z) \cdot \underbrace{E \cdot p}_{e} \cdot \Sigma \underset{\uparrow\,\text{PROB}}{W_i}(\underset{\llcorner\,\text{END-POINT ENERGY OF FINAL STATE } i}{E_{0i}} - E)\sqrt{(E_{0i} - E)^2 - m_\nu^2}$$

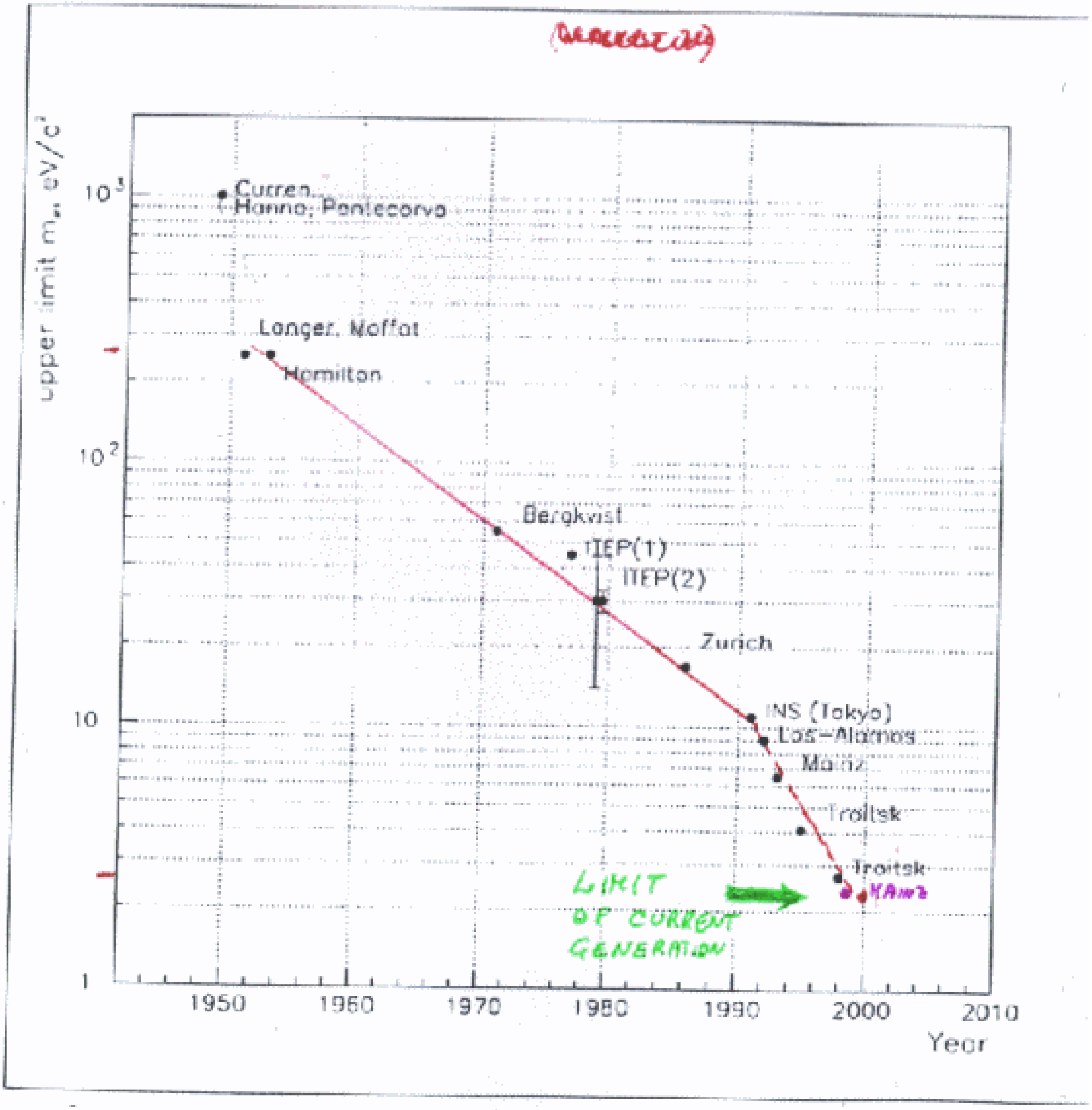
(18.6 KEV)

- Long history of progress, although approaching the ultimate limit of current generation of experiments
  - Magnetic Adiabatic Collimation and Eletrostatic Filters (Troitsk and Mainz) TRITIUM
    (GASEOUS VS CONDENSED SOURCE)
  - Bolometric measurements of ^{187}Re β-decay (Milano, Genova). Complementary technique but still in R&D phase. (Res ~10 eV)

30 YEARS

2 ORDERS OF MAGNITUDE

([illegible])



TROITSK EXPERIMENTAL SETUP

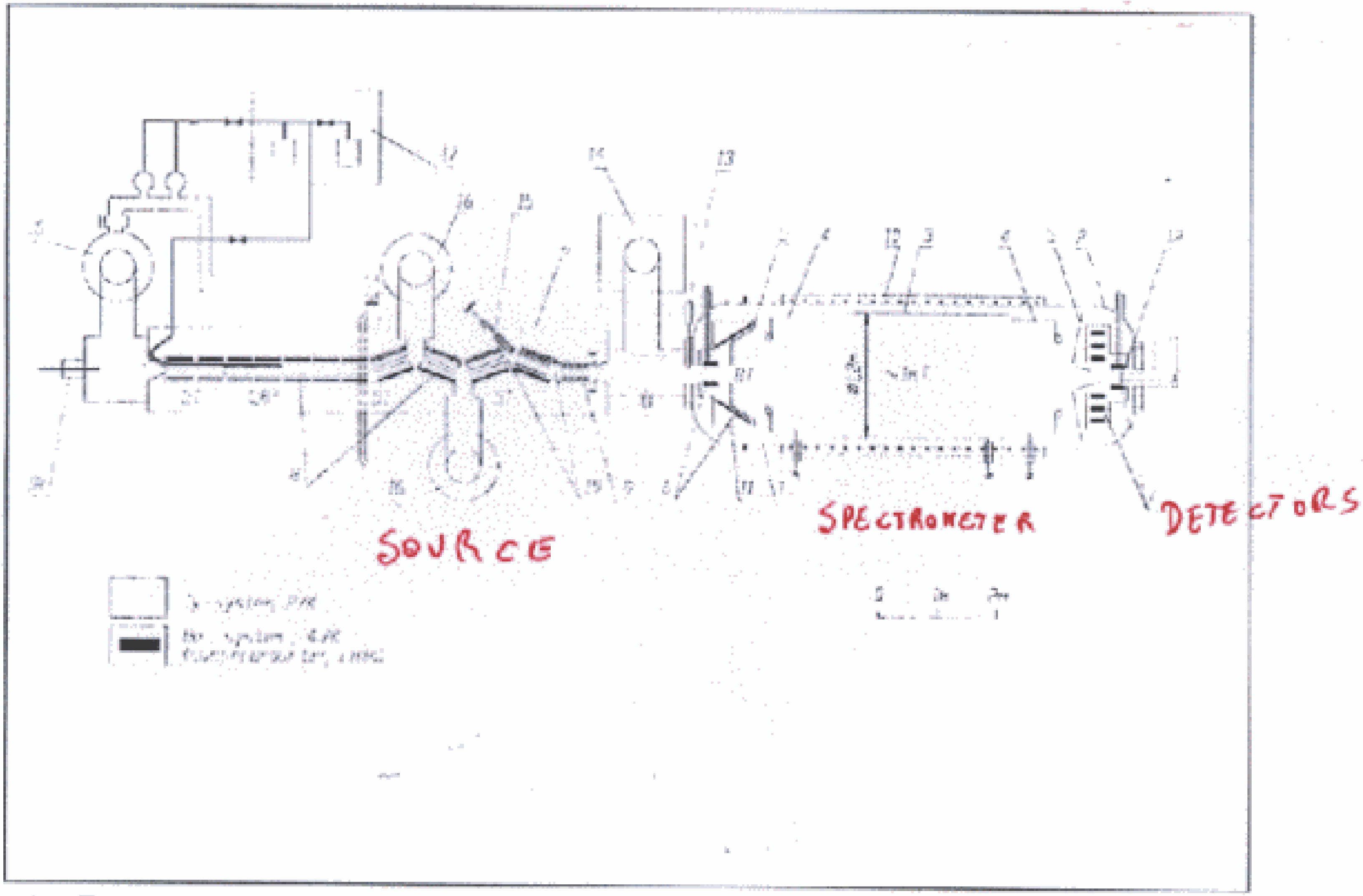


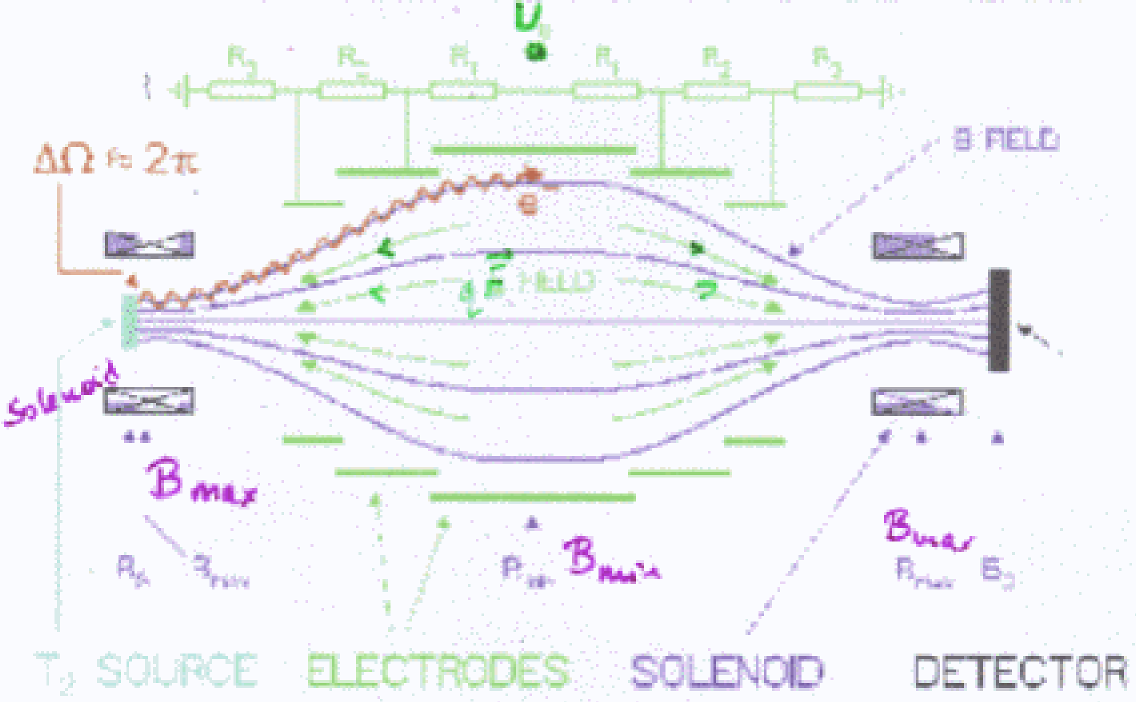
Fig. 2. Experimental set-up. (1),(2) vacuum tank; (3),(4) electrostatic analyzer; (5) grounded electrode; (6),(7),(8),(9) superconducting coils; (10) warm coil; (11)LN_2 jacket; (12) Si(Li) detector; (13) fast shutter;(14) Ti-pump ; (15) cold valve; (16) Hg diffusion pump; (17)T_2 purification system; (18) electron gun;(19) argon pump.

Courtesy of Ch. Weinheimer

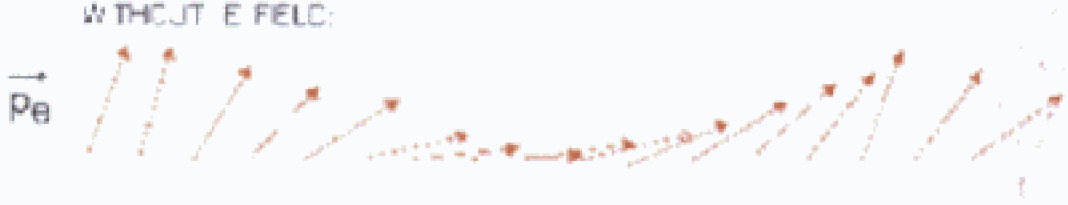
Magnetic Adiabatic Collimation

+ Electrostatic filter

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



$$\vec{F} = (\vec{\mu}\vec{\nabla})\vec{B} + q\vec{E} \qquad \mu = \frac{E_\perp}{B} = \text{constant}$$



- magnetic guiding field

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

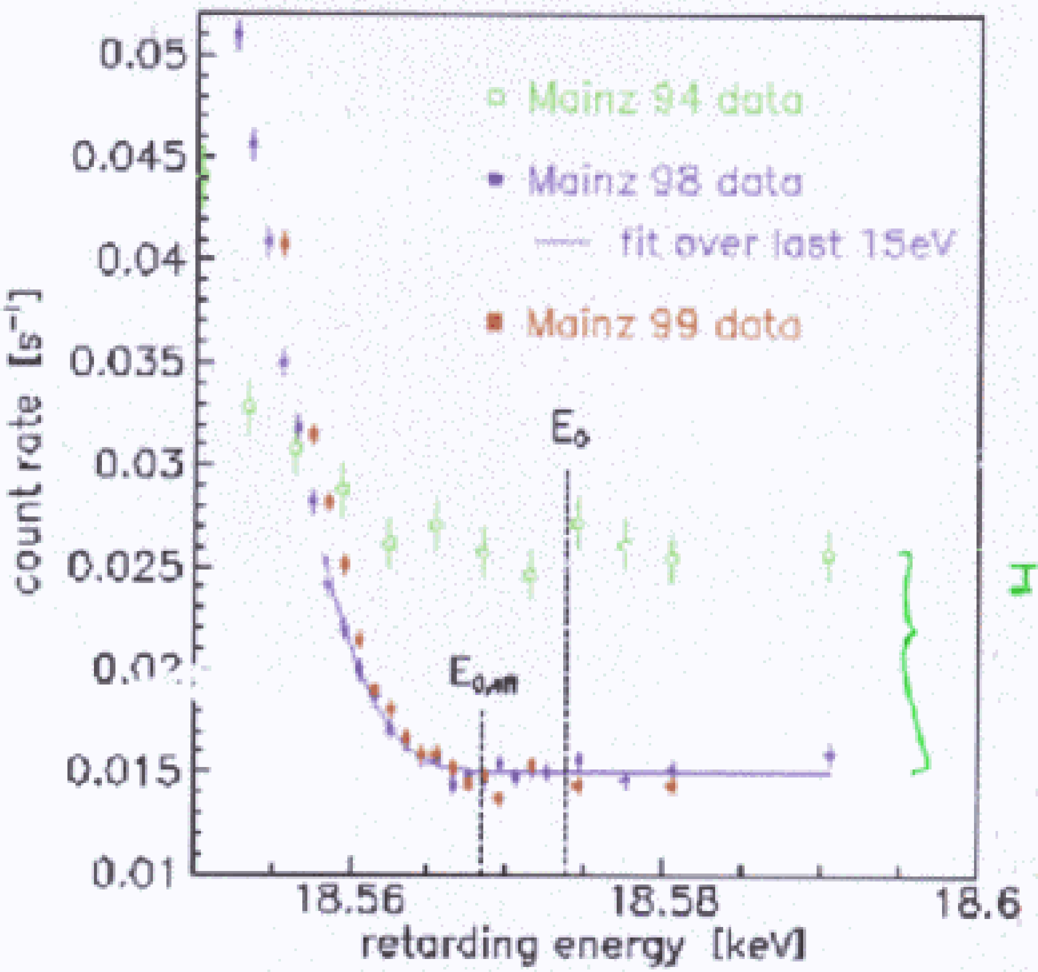
- adiabatic transf. $E_\perp \rightarrow E_\parallel$ + electrostatic retardation

$$\rightarrow \Delta E = E \cdot B_{min}/B_{max} \approx 4-6\text{eV}$$

ISOTROPICALLY EMITTED ELECTRONS ⇒ BROAD BEAM
ALMOST PARALLEL TO B-FIELD LINES

• IF $E >$ RETARDING POTENTIAL
↳ ACCELARATED TOWARDS DETECTOR

New Mainz 1999 measurements: Q6 – Q8



Improvements IN SPECTROM.

Systematic Uncertainties and Anomalies

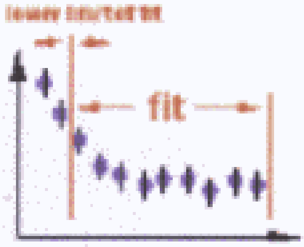
- **Inelastic Scattering** (37%)
  - Estimated measuring energy loss of 17.8 *keV* electrons in D_2 films. The uncertainty on the source thickness contributes as well
- **Final states** (35%)
  - Excitation of neighbour molecules.
  - Change in the energy levels of excited states
- **"Thinning" of T_2 film and H_2 deposit** (21%)
  - Confirmed by time measurements of film thickness
- **Charging of T_2 film** (7%)
  - Determined by measuring the energy shift of the $K-32$ line of Kr source at different depths

((POTENTIAL VARIES LINEARLY WITH DISTANCE
3V for 1998 - 1999 DATA)

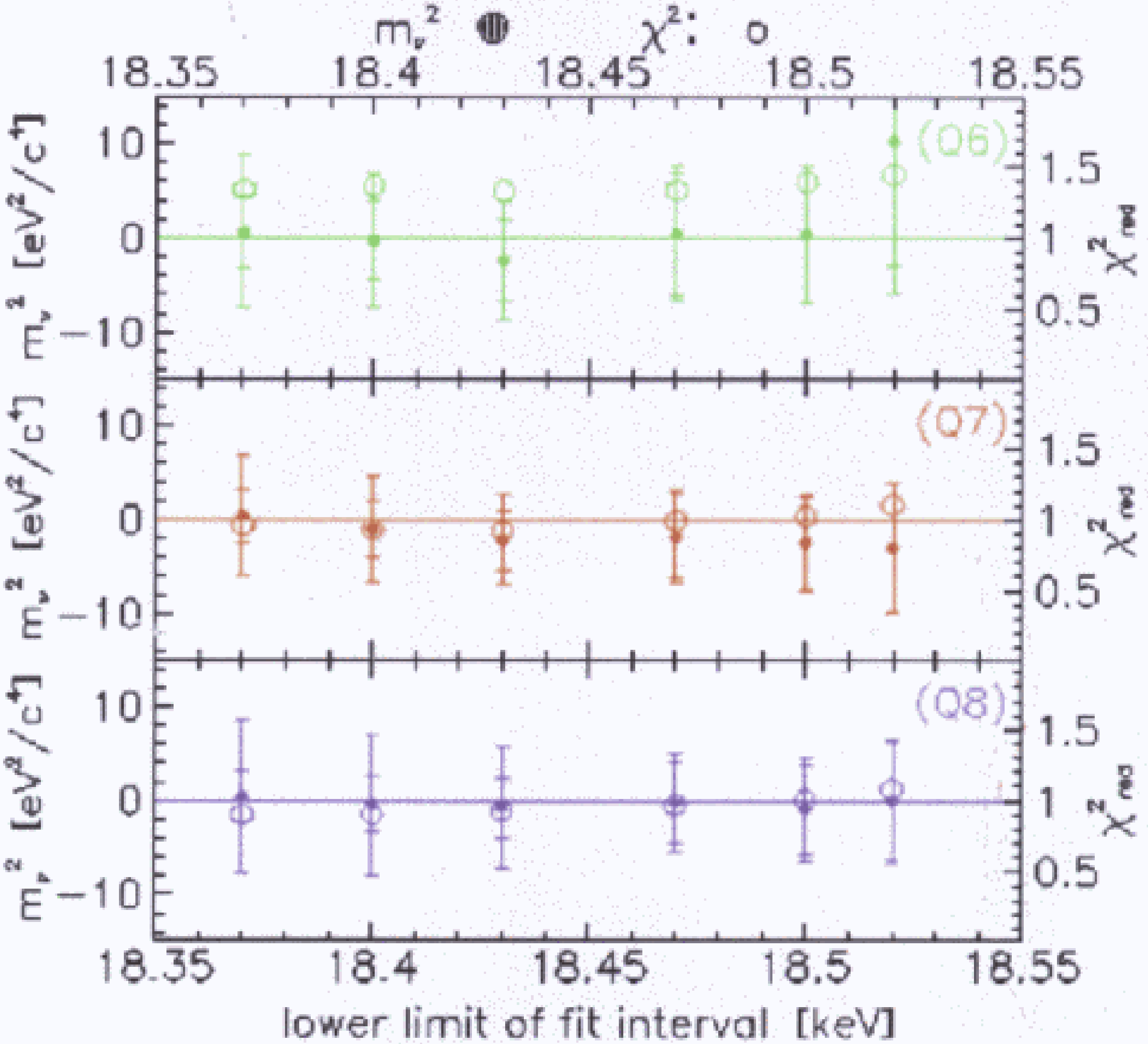
- Are monoenergetic lines present in the spectrum near the end point? Is there a periodicity?

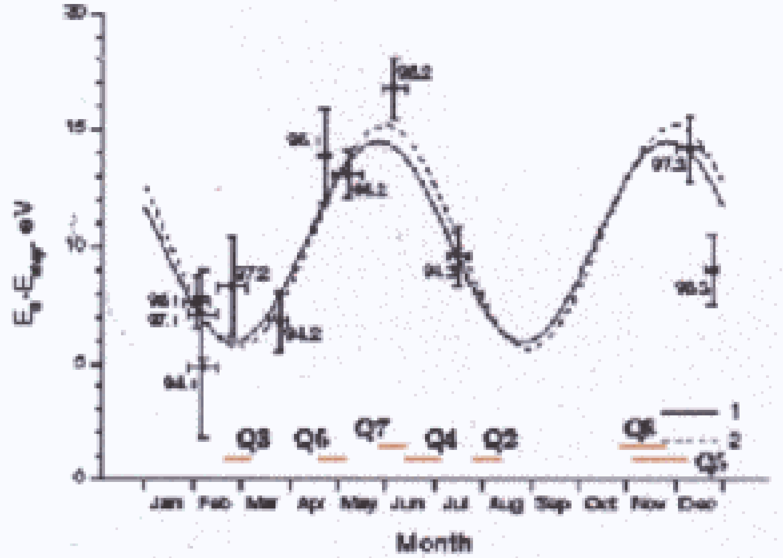
- NO DEPENDENCE ON FIT INTERVAL (lower Edge)

Fits of m_ν^2 for Mainz 1999 data



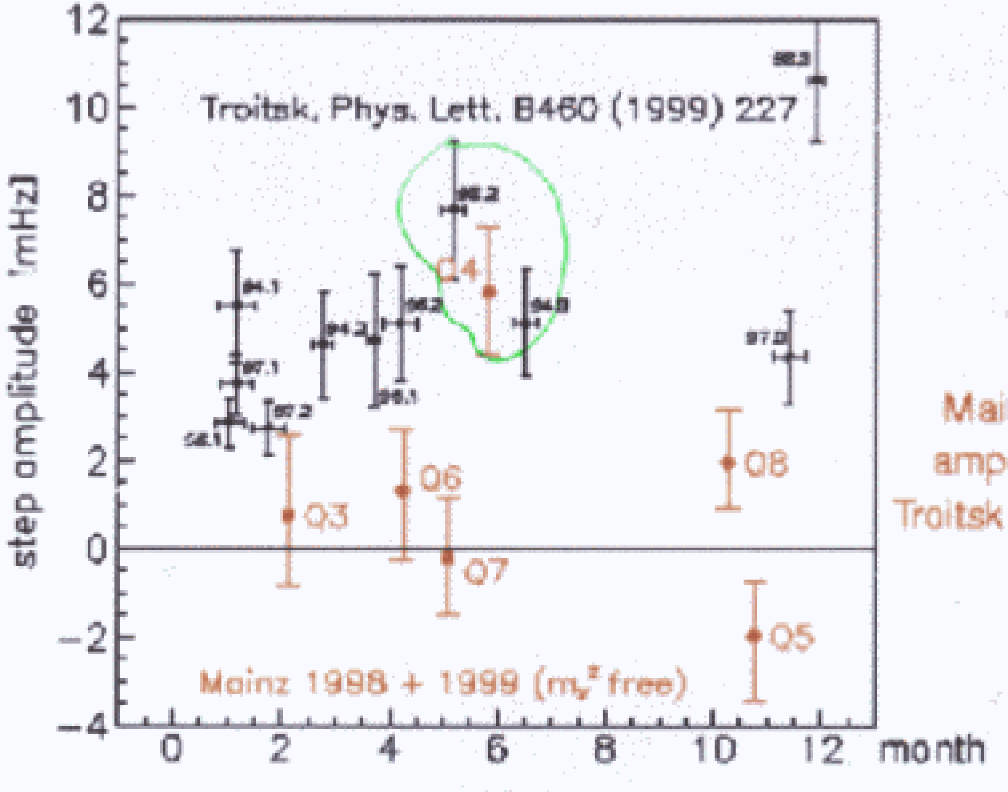
↑18.66 keV





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

dates of Mainz
measurements



Mainz step
amplitude at
Troitsk prediction

Q4 "SUPPORTS" THE ANOMALY

NO INDICATION THAT $m_{\nu_e} \neq 0$

Group	Year	$m^2_{\bar{\nu}_e}$ $(eV/c^2)^2$	Comments
Troitsk	1994	$-2.7 \pm 10.1 \pm 4.9$	
Troitsk	1996	$0.5 \pm 7.1 \pm 2.5$	
Troitsk	1997-1	$-8.6 \pm 7.6 \pm 2.5$	
Troitsk	1997-2	$-3.2 \pm 4.8 \pm 1.5$	
Troitsk	1998-2	$-0.6 \pm 8.1 \pm 2.0$	
Troitsk	Combined	$-2.0 \pm 3.5 \pm 2.1$	
Mainz	1998	$0.1 \pm 3.9 \pm 2.1$	"last" 15 eV
Mainz	1999	$1.5 \pm 3.2 \pm 3.4$	
Mainz	1998+1999	$+0.6 \pm 2.8 \pm 2.5$	
Mainz	1998+1999	$-1.6 \pm 2.8 \pm 2.5$	"last" 70 eV

$m_{\bar{\nu}_e} < 2.5\ eV/c^2$ at $95\%CL(Bayessian)$ (Troitsk)

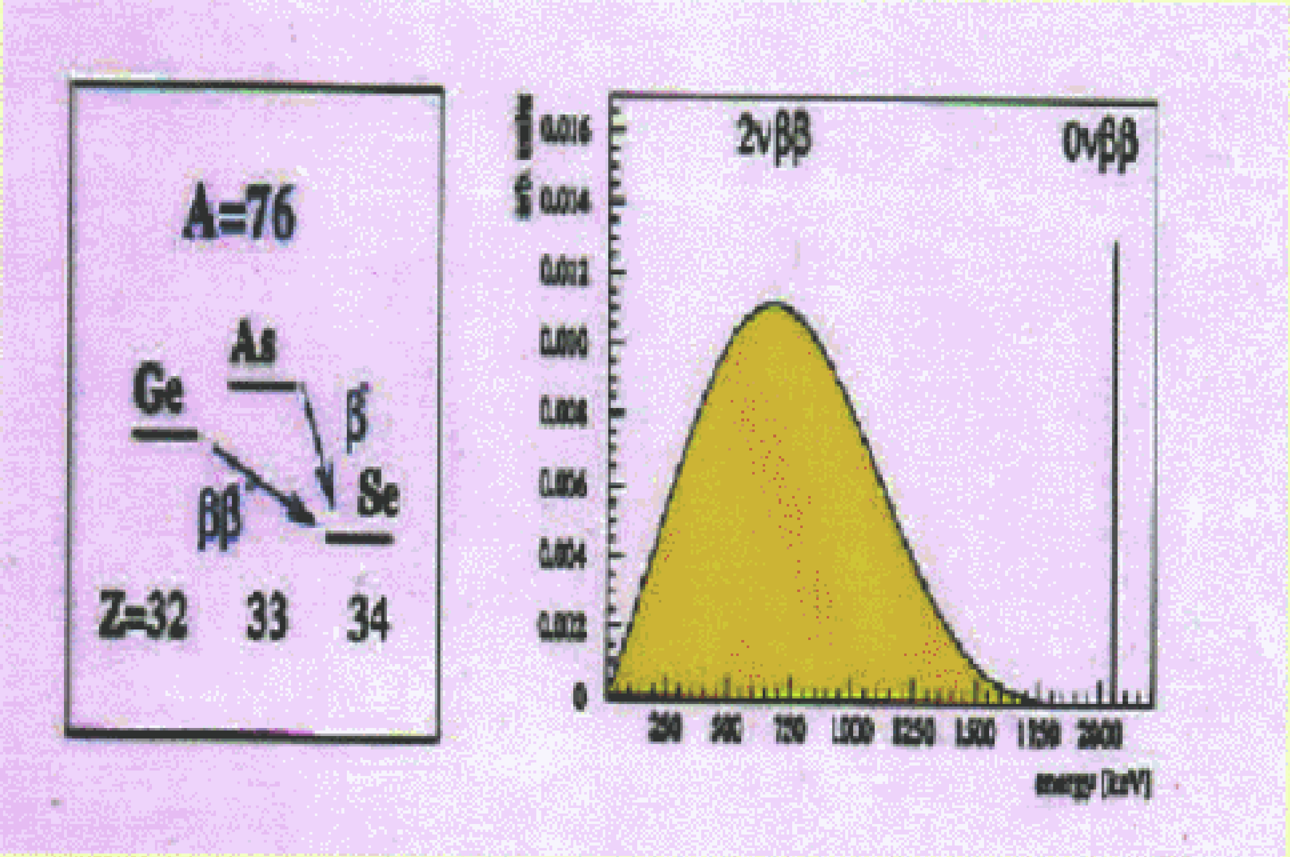
$m_{\bar{\nu}_e} < 2.8\ eV/c^2$ at $95\%CL(unified)$ (Mainz 15 eV)

$m_{\bar{\nu}_e} < 2.2\ eV/c^2$ at $95\%CL(unified)$ (Mainz 70 eV)

Double β Decay

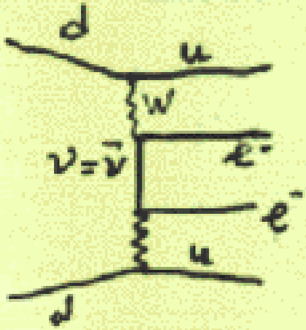
Killing two β-irds with oν-e stone!

- Process $(A, Z) \rightarrow (A, Z+2) + 2e^- + (2 \ or \ 0)\overline{\nu}$



- 2ν: Allowed and observed in several nuclei with $T_{1/2} \sim 10^{19} - 10^{24}$ y

- 0ν
  - Sensitive to effective neutrino Majorana mass, that is a combination of physical masses



$$\nu_e = \sum_i U_{ei} \nu_i$$

$$|m_{ee}| = \left| \sum_j |U_{ej}|^2 e^{i\phi_j} m_j \right|$$

- PHASES ⇒ A DIFFERENT INGREDIENT
- m_{ee} FROM DATA ⇒ LOWER BOUND ON PHYSICAL MASSES

  - It could give insights on many aspects of physics beyond SM
  - To date it has never been observed

- Essentially two types of detectors, with obvious requirements
  - Detector = Source (Heidelberg-Moscow) (GRAN SASSO)
  - Detector ≠ Source (NEMO) (FREJUS)

- ENERGY RESOLUTION
- LOW BACKGROUND COUNTS (STAY DEEP UNDERGROUND)

HEIDELBERG - MOSCOW

- ${}^{76}Ge \to {}^{76}Se$

$T_0 = 2038.6$ keV

NATURAL ABUNDANCE 7.7% ⇒ ENRICHED (86%) $\boxed{11.5\,kg}$

$$\boxed{T_{1/2} \sim a\sqrt{\frac{M t}{\Delta E\, B}}\;\varepsilon}$$

M = ACTIVE MASS

t = MEASURING TIME

ΔE = ENERGY RESOL

B = BKGD COUNTING RATE

Q = ISOTOPICAL ABUNDANCE

ε = EFFICIENCY

- IN ITS FINAL, RUNNING FORM SINCE 1996

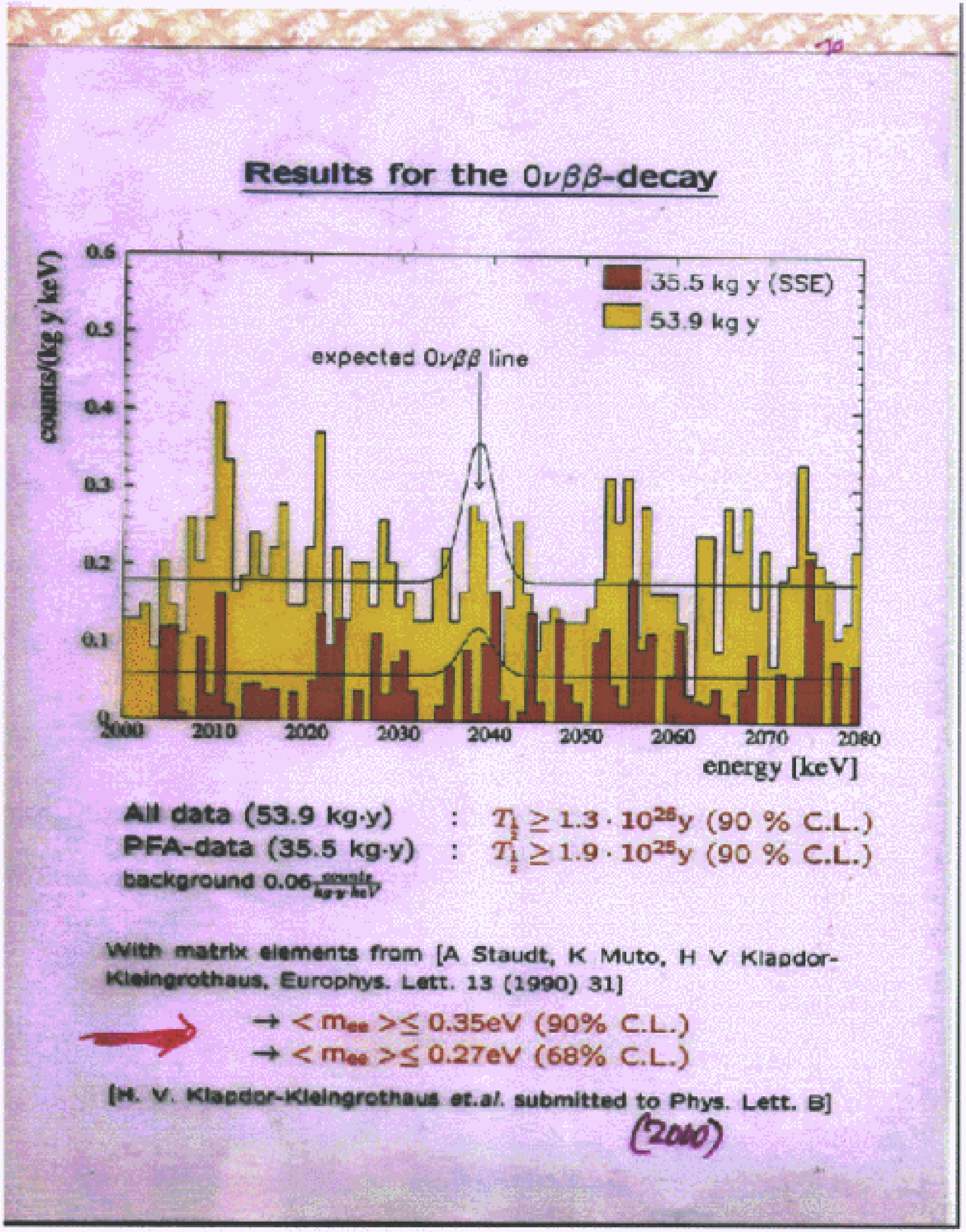
$\langle m_{ee} \rangle < 0.35$ eV (90% CL)

< 0.27 eV (68% CL)

FROM

HEIDELBERG-MOSCOW EXPERIMENT

ΔE = 0.2%



Results for the $0\nu\beta\beta$-decay

All data (53.9 kg·y) : $T_{\frac{1}{2}} \geq 1.3 \cdot 10^{25}$y (90 % C.L.)

PFA-data (35.5 kg·y) : $T_{\frac{1}{2}} \geq 1.9 \cdot 10^{25}$y (90 % C.L.)

background $0.06 \frac{\text{counts}}{\text{kg·y·keV}}$

With matrix elements from [A Staudt, K Muto, H V Klapdor-Kleingrothaus, Europhys. Lett. 13 (1990) 31]

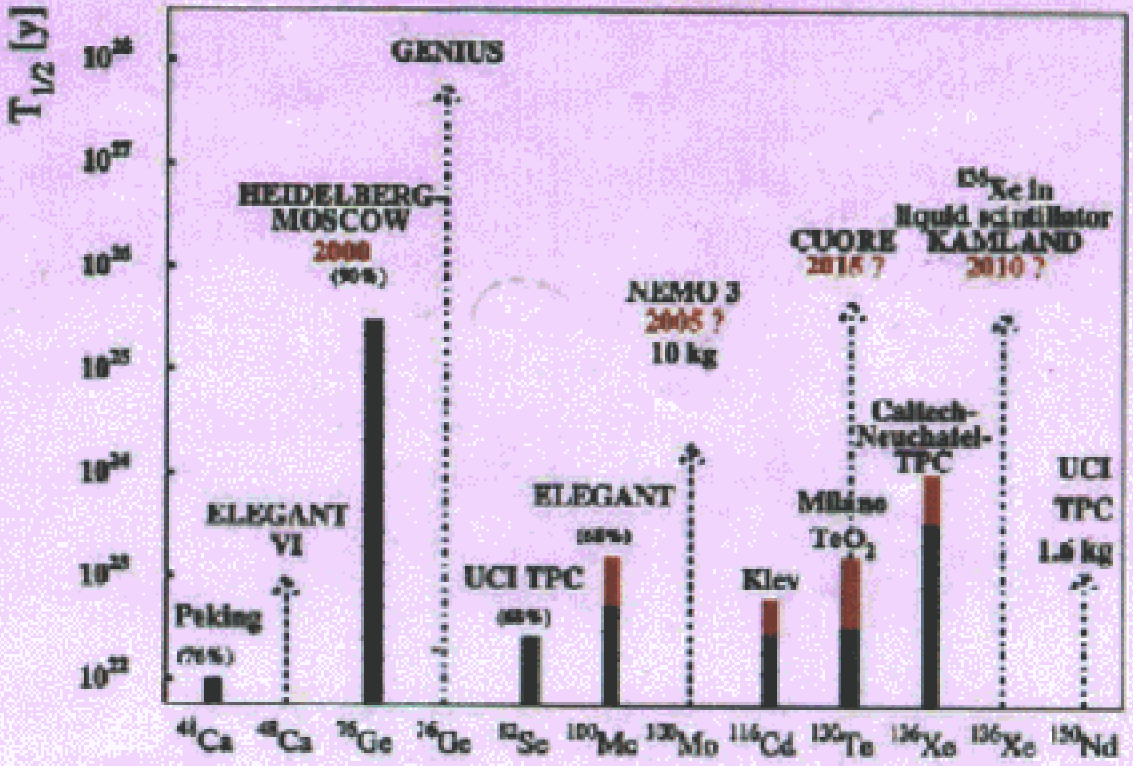
→ $< m_{ee} > \leq 0.35$eV (90% C.L.)

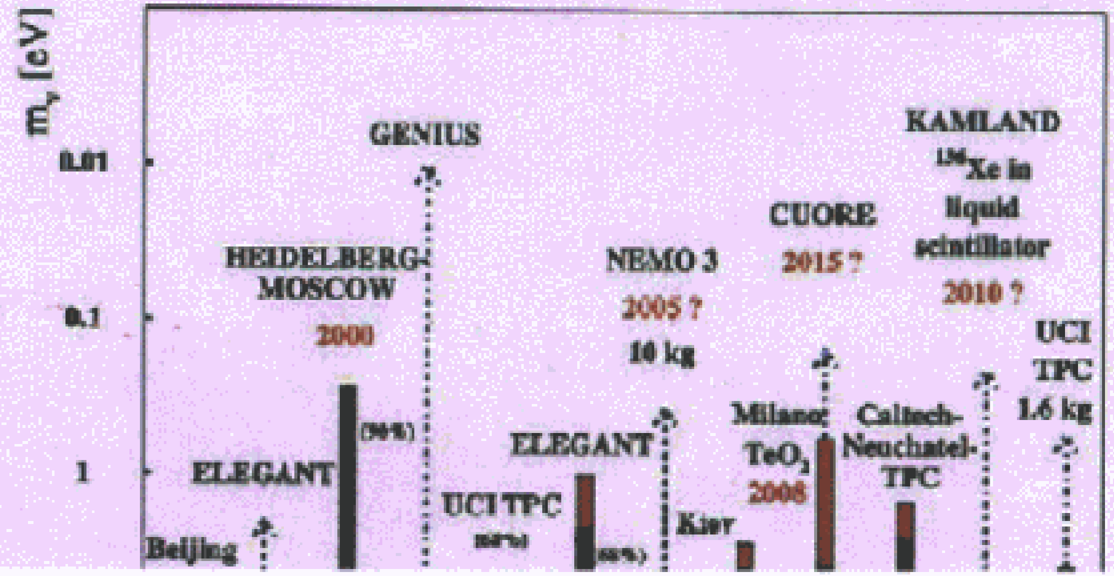
→ $< m_{ee} > \leq 0.27$eV (68% C.L.)

[H. V. Klapdor-Kleingrothaus *et.al.* submitted to Phys. Lett. B]

(2000)

Present limits of $0\nu\beta\beta$-experiments





(Im)Possibilities

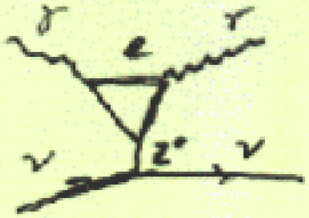
- **Return to the past?**
  - Many suggestions made to use different processes to measure m_ν
  - Impossible then ⇒ Possible now? (detection and/or beam intensities
- **For instance: Pion radiative decay** $\pi \rightarrow \mu\gamma\nu_\mu$
  - Simple to detect
  - The end point energy of the photon depends linearly on m_ν

$$E_\gamma^{max} = \frac{m_\pi}{2}\left[1-\left(\frac{m_\mu}{m_\pi}\right)^2\left(1+\frac{m_\nu}{m_\mu}\right)^2\right]$$

  - The shift is $\Delta E_\gamma^{max} \sim \frac{m_\mu}{m_\pi} m_\nu$
  - To improve by a factor of 10 need $\frac{\Delta E_\gamma^{max}}{E_\gamma^{max}} \sim 5 \cdot 10^{-4}$ at $30 MeV$

- **For instance 2: Can we do without the pion?**
  - In $\nu_\mu\ e \to \nu_\mu\ e$ scattering, T_{max} of the electron is sensitive to m_ν (the cross section too, but too small an effect)
  - Resolution needed: a detector with the energy resolution of Borexino would set $\sim 3\ MeV$ limit (if ν from π decay). Not exciting for ν_μ!

- **Or back to the future?**
  - Could one measure m_ν using the process $\gamma\nu \to \gamma\nu$?



  - Detection of a high energy backward photon
  - Cross section, although enhanced relative to massless neutrinos, *discouragingly* small

D_s^* Decays

- **Diffractively produced D_s^* in $\bar{\nu}_\mu$ interactions at neutrino factories**
  - Measure BR($D_s \to l\nu$) and f_D (G. De Lellis et al.)
  - $\sim 50k$ events expected
- Consider

$$D_s^* \to \gamma D_s$$
$$\hookrightarrow \nu_\tau \tau$$
$$\left.\begin{array}{l} \to \pi\nu_\tau \\ \to \pi\pi\pi\nu_\tau \end{array}\right\} \sim 20\%$$

- Measure
  - $\vec{P}_\gamma$ from decay $D_s^* \to \gamma D_s$
  - Direction of D_s
  - Direction of τ (Not measured at colliders)
  - $\vec{P}_\pi$ of all charged decay products of τ
- Then each event yields a measurement of $m(\nu_\tau)$

NuMass (E952) (R.M. Carey et al.)

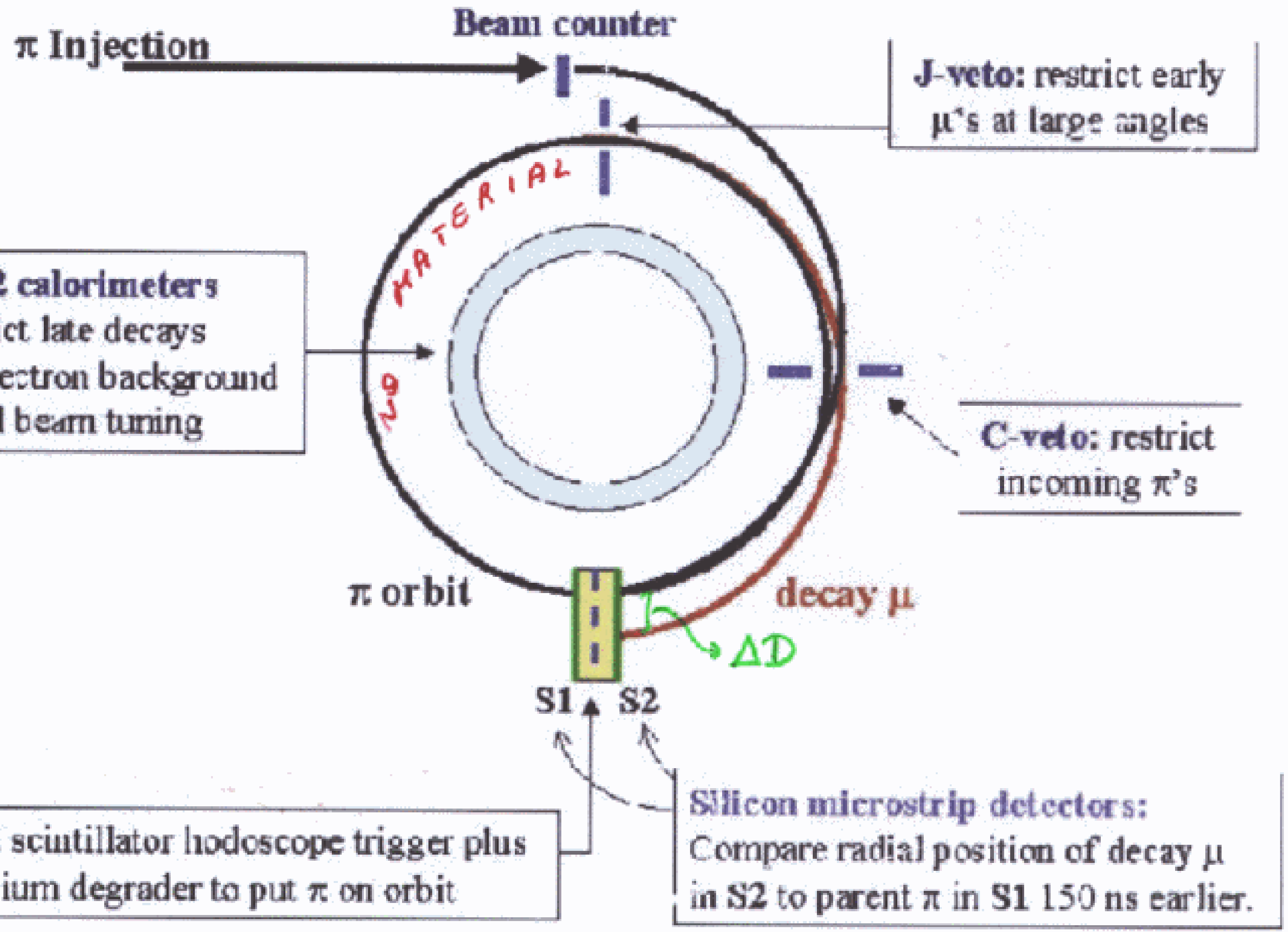
An elegant proposal "targetting" $m(\nu_\mu)$

- It uses decay in flight of pions and the g-2 magnet at BNL
- It aims at an improvement of a factor of 20
  - Measures $\Delta p = p_\mu - p_\pi$ with a resolution of $\Delta p/p_\mu \sim 6 \cdot 10^{-9}$ which would yield $m(\nu_\mu) < 8\ keV$
  - Precision achievable if multiple scattering can be avoided
  - Momentum ⇒ Position measurements (silicon microstrips with $1.4\mu m$ resolution)
  - Uncertainty on pion mass less important since decay in flight $(p_\pi \sim 3 GeV)$

E952 BNL

NUMASS

P. Cushman et



J-veto: restrict early μ's at large angles

C-veto: restrict incoming π's

24 g-2 calorimeters
Restrict late decays
Identify electron background
Initial beam tuning

Embedded scintillator hodoscope trigger plus beryllium degrader to put π on orbit

Silicon microstrip detectors:
Compare radial position of decay μ in S2 to parent π in S1 150 ns earlier.

$\frac{X}{X_0} \approx 15\%$ $\theta_{rms} = 1.56$ mrad

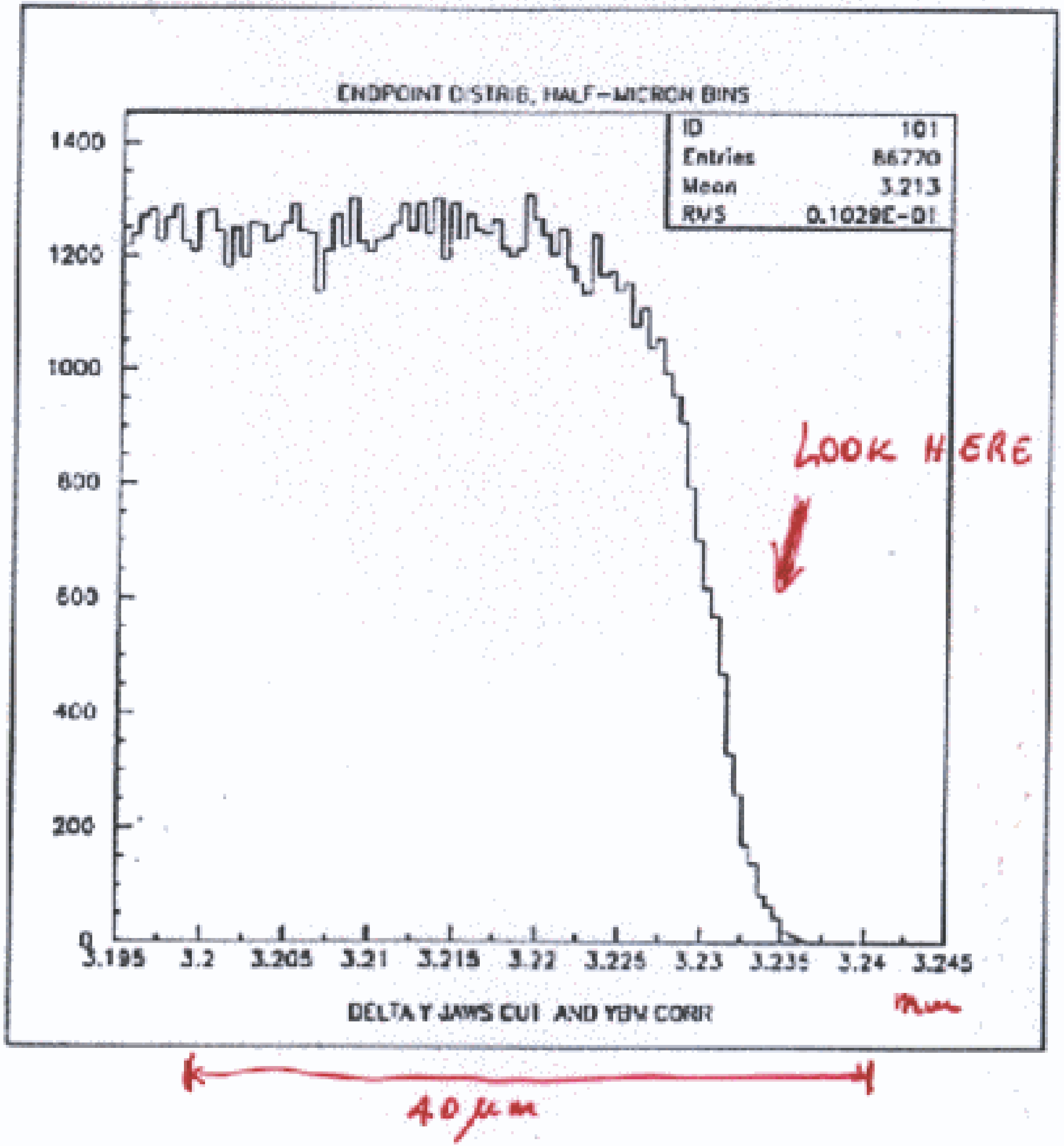
- The trajectory of muons from π that decay in the forward direction will be a circumference of diameter larger than the parent pion
- Neutrino mass would reduce this diameter

$$\frac{\delta D}{D} = \frac{-m_\nu^2}{2 p_0 m_\pi}$$

- The radial distribution of decay muons is measured (especially the edge).
- Slow injection (1 PARTICLE EVERY TWO CYCLES)
- **Could run in parasitic mode**
- Results expected after $800h$ running time

E952

RADIAL DISTRIBUTION OF μ'S TOWARDS END POINT (REFERENCED TO PION IMPACT POINT)



KATRIN

Next generation experiment

- What is needed to be able to access sub eV region?
  - Energy resolution: $\frac{\Delta E}{E} = \frac{B_{min}}{B_{max}}$ ↑
  - Luminosity of the source. It depends on surface and maximum angle of acceptance $\uparrow_{100}$ $(\propto m_\nu^2)$

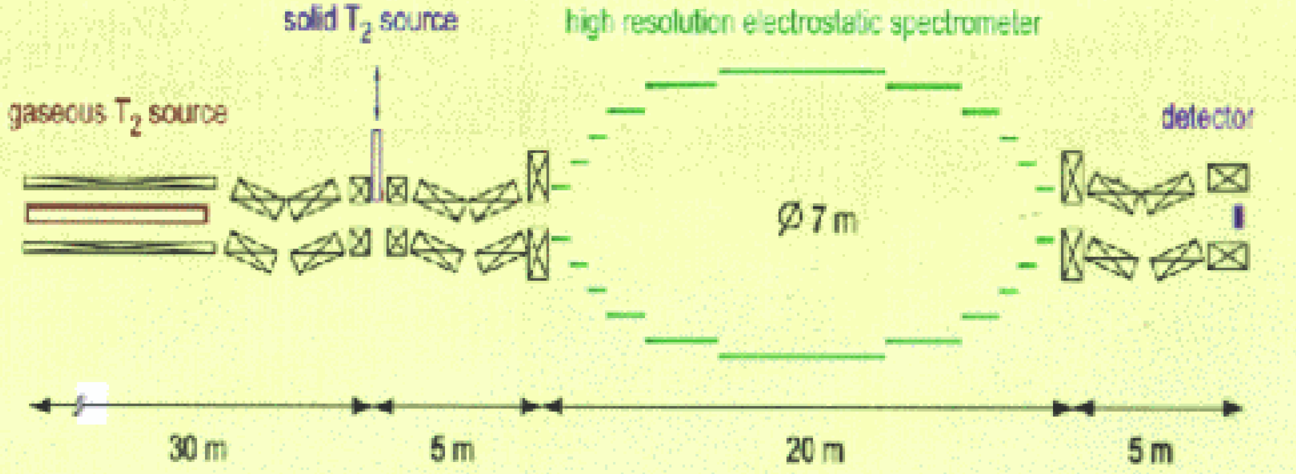
Translated into a quality factor

$$Q = \frac{A_A}{2(1+\cos\theta_{max})}$$

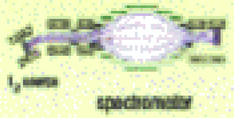
A_A area of the analysing plane in the spectrometer

- $\Delta E = 1\ eV$ implies $\frac{B_{min}}{B_{max}} \sim 5 \cdot 10^{-5}$ a factor four better than currently used

- Features
  - Spectrometer 7 m diameter 20 m length (LARGER THAN CURRENT)
  - Usage of both Gaseus an Condensed tritium source for systematic check and comparisons
  - Usage of time of flight mode to disentangle anomalies (not integrating) ("tested" by MAINZ GROUP) NIM A421, 256



Present Mainz Setup :



KATRIN PROPOSED SETUP

Courtesy of Ch. Weinheimer

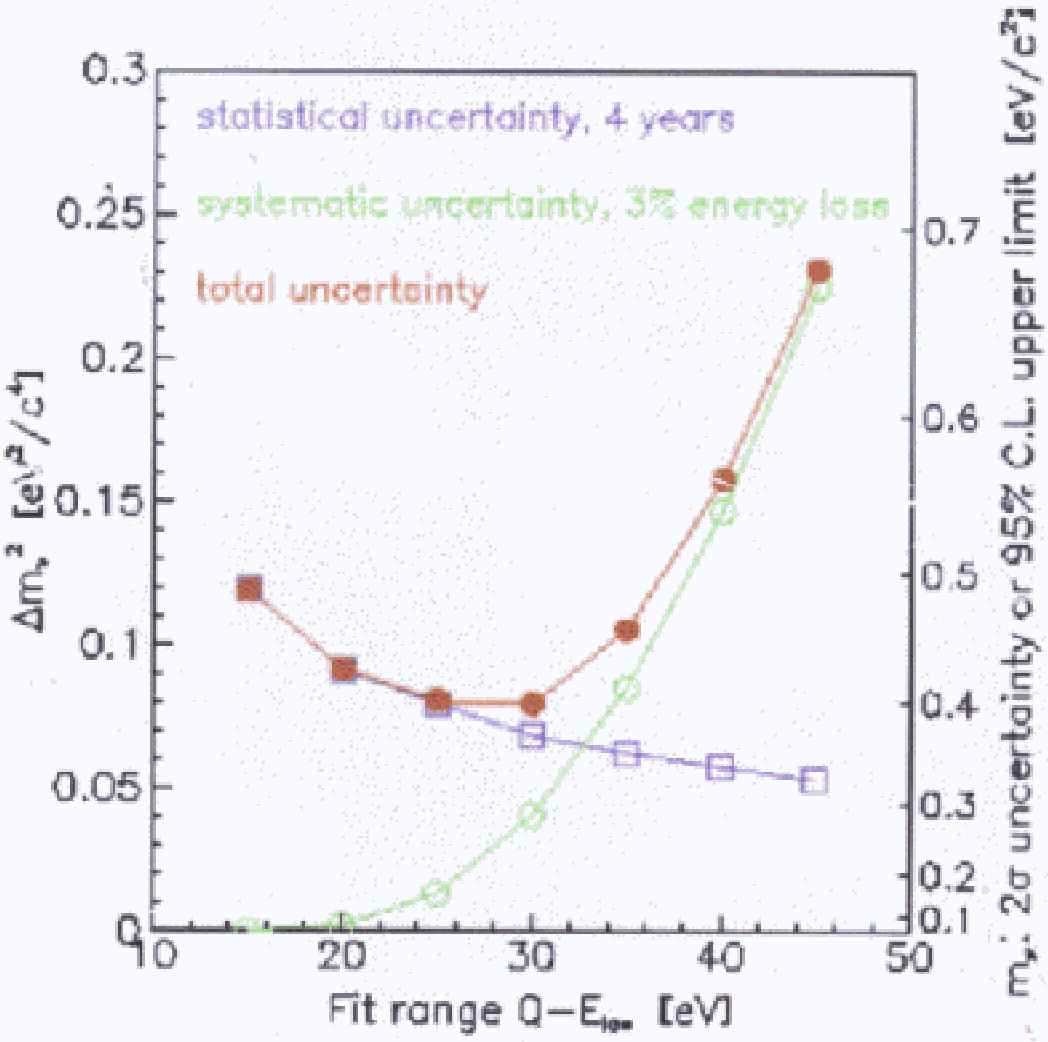
SOURCE AREA 29 cm^2

$\Delta E = 1\,eV$

$\theta_{max} = 51°$

Simulation of the sensitivity on m$_\nu$

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$_\nu$ of < 0.5 eV/c^2

0.35 90%

GENIUS

- OPERATE A LARGE AMOUNT OF Ge CRYSTALS IN LIQUID NITROGEN (1 ton OF ENRICHED Ge
  SUSPENDED IN A TANK
  12 m ⌀ AND 12m LENGTH

- REAL QUESTION: CAN THE BACKGROUND BE REDUCED?
  0.3 EVENTS/(t y keV) (3 ORDERS OF
  MAGNITUDE LOWER
  THAN CURRENT

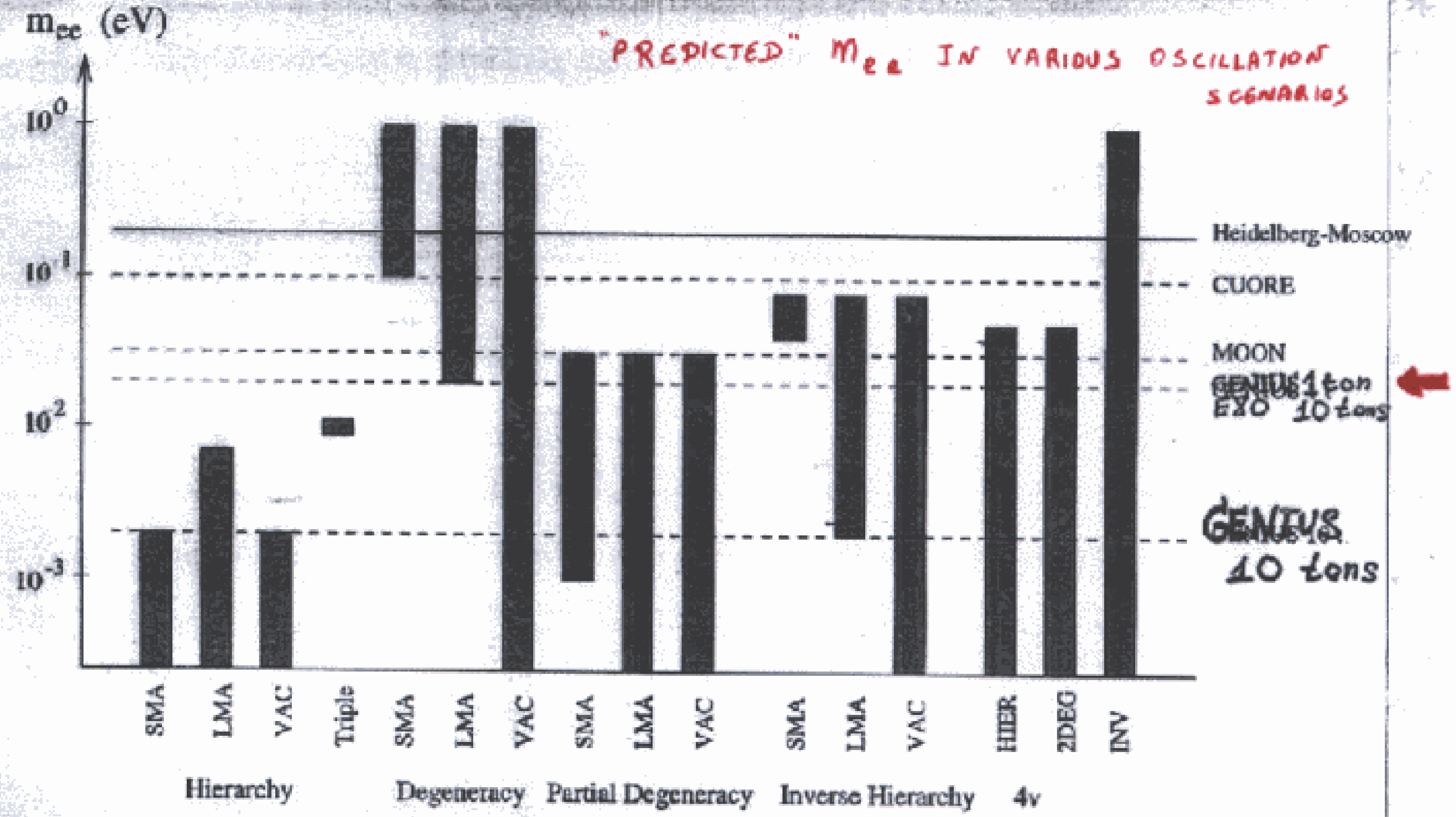
- REMOVING ALMOST ALL MATERIAL AROUND Ge DETECTORS HELPS

- DETAILED SIMULATIONS OF INTERNAL AND EXTERNAL SOURCES
  - NITROGEN SHIELDING
  - PHOTONS AND NEUTRONS FROM ROCK
  - MUON INTERACTIONS AND INDUCED ACTIVITY
  - IMPURITIES
  - STEEL VESSEL AND CRYSTAL HOLDER
  - Ge CRYSTALS

- TEST FACILITY ("SMALL" 40 kg PROTOTYPE) THAT SHOULD PROVE POSSIBLE REDUCTION BY A FACTOR OF 10

- ULTIMATE SENSITIVITY
  - 0.02 eV 1 ton 1 YEAR
  - 0.006 eV 1 ton 10 YEARS
  - 0.002 eV 10 ton 10 YEARS

"PREDICTED" m_{ee} IN VARIOUS OSCILLATION SCENARIOS



[H.V. Klapdor - Klein grothaus, H. Päs, A. Smirnov hep-ph/0003219]

Conclusions

- The current limits on neutrino mass from experiments that could measure it directly are:
  - $< 2.2\ eV$ for $\bar{\nu}_e$
  - $< 170\ keV (190\ keV PDG)$ for ν_μ
  - $< 18.2\ MeV$ for ν_τ
  - $< m_{ee} >< 0.27\ eV$ for neutrinoless $\beta\beta$ decay
- Current experiments appear also to have reached their limit
- Many think that it is justified to embark in new experiments even in view of (or because of) <u>current</u> results from oscillations

. Reasons

- Because to improve $m(\nu_\mu)$ limit by a factor of 20 has great merit
- Because $\beta\beta$ - with theoretical guidance - could help disentangle a complicated situation
- Because ν_e is so tantalising close to interesting values!

- While we wait for a supernova to set order of eV limits on $m(\nu_\mu)$ and $m(\nu_\tau)$, an analogy....