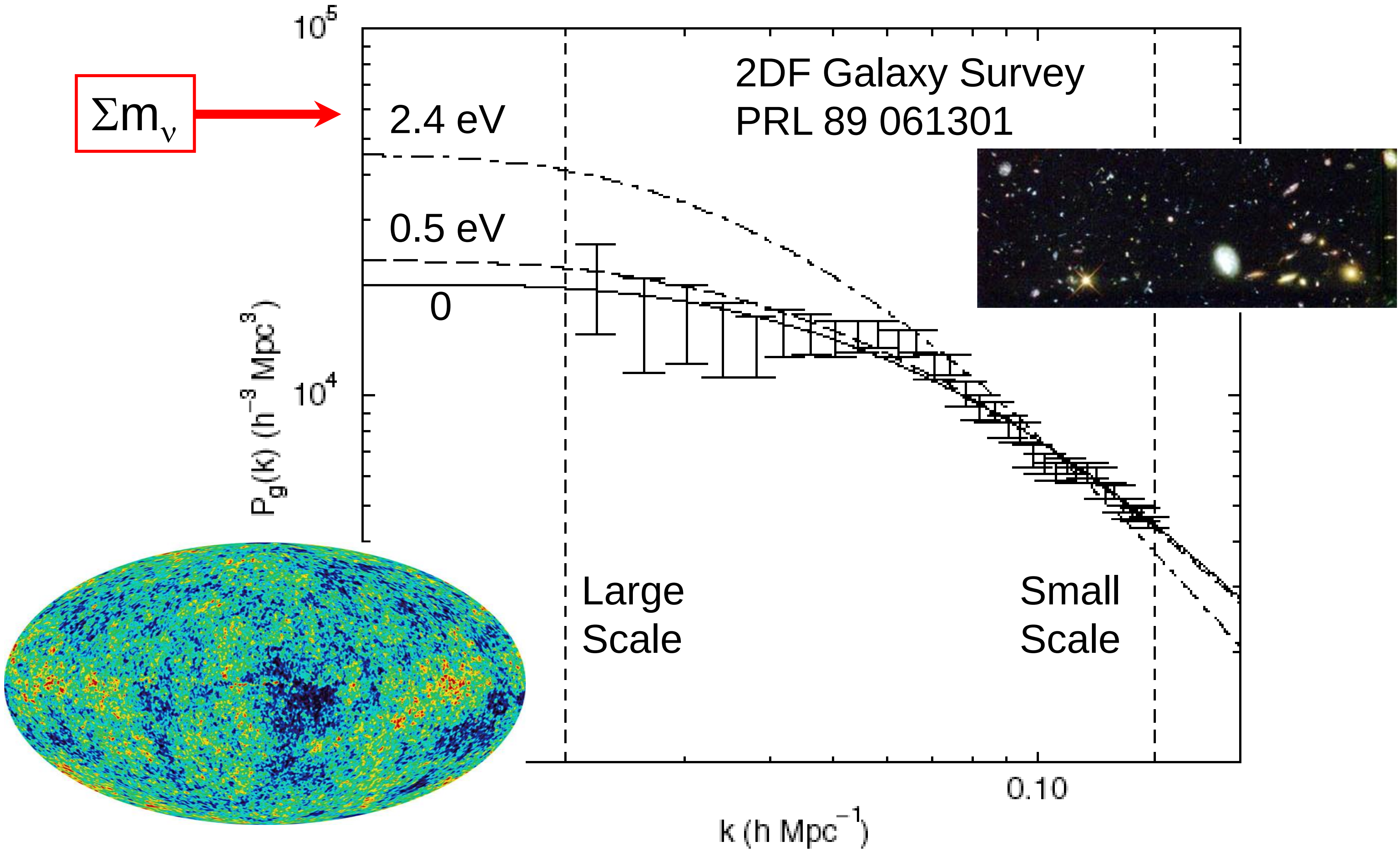
Experimental Determination of Neutrino Mass

- Beta Decay
  - Tritium
  - ^{187}Re
  - Other ideas?
- Neutrino Oscillations
- Supernova timing
- Double beta decay
- Cosmology
- Z-bursts

- **The mass is needed for**
  - Particle physics
  - Interpretation of supernova ν signal
  - Cosmology

Even small m_ν influences structure



Supernova Neutrino Time-of-flight

For a supernova at distance D (in 10 kpc) the time delay for a neutrino of mass m (eV) and energy E (MeV) is:

$$\Delta t(E) = 0.515 \left(\frac{m}{E}\right)^2 D$$

Beacom & Vogel
hep-ph/9802424

The delay must be ~ the duration of the neutrino signal to avoid model dependence at short times and not to be drowned in background at long times. For a **1 eV** result with 30-MeV neutrinos, **need D = 175 Mpc**. Scaling Kamiokande for the same rate as SN1987a, **detector mass must be 12 Gt**.

IceCube will be “only” 1 Gt, and not very sensitive at these low energies.

Z-bursts

Gelmini, Varieschi & Weiler, hep-ph/0404272

Hypothesis: the extreme-energy CR spectrum is produced by neutrinos from distant sources. The neutrinos can annihilate at the Z pole on relic neutrinos to produce the observable EE CR. (A GZK-style cutoff for neutrinos).

$$E_{\rm res} = \frac{M_Z^2}{2\,m_\nu} = 4\times 10^{21}\,{\rm eV}\left(\frac{\rm eV}{m_\nu}\right)$$

If cutoff is at 2 x 10^{20} eV, then m_ν > 20 eV, in disagreement with expt. EE CR thus likely not neutrino Z-burst debris.

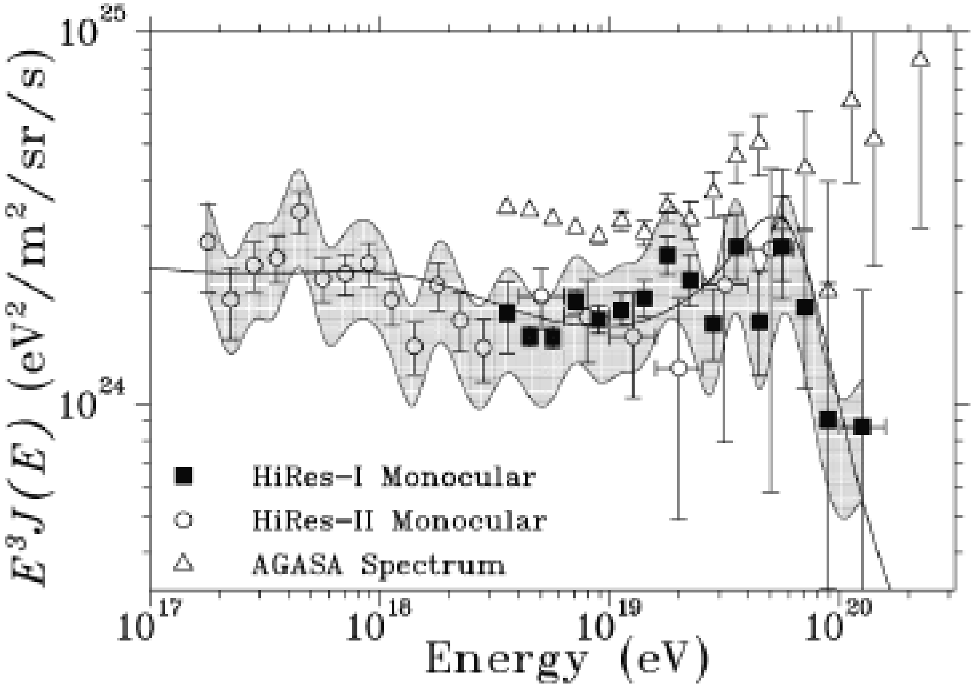
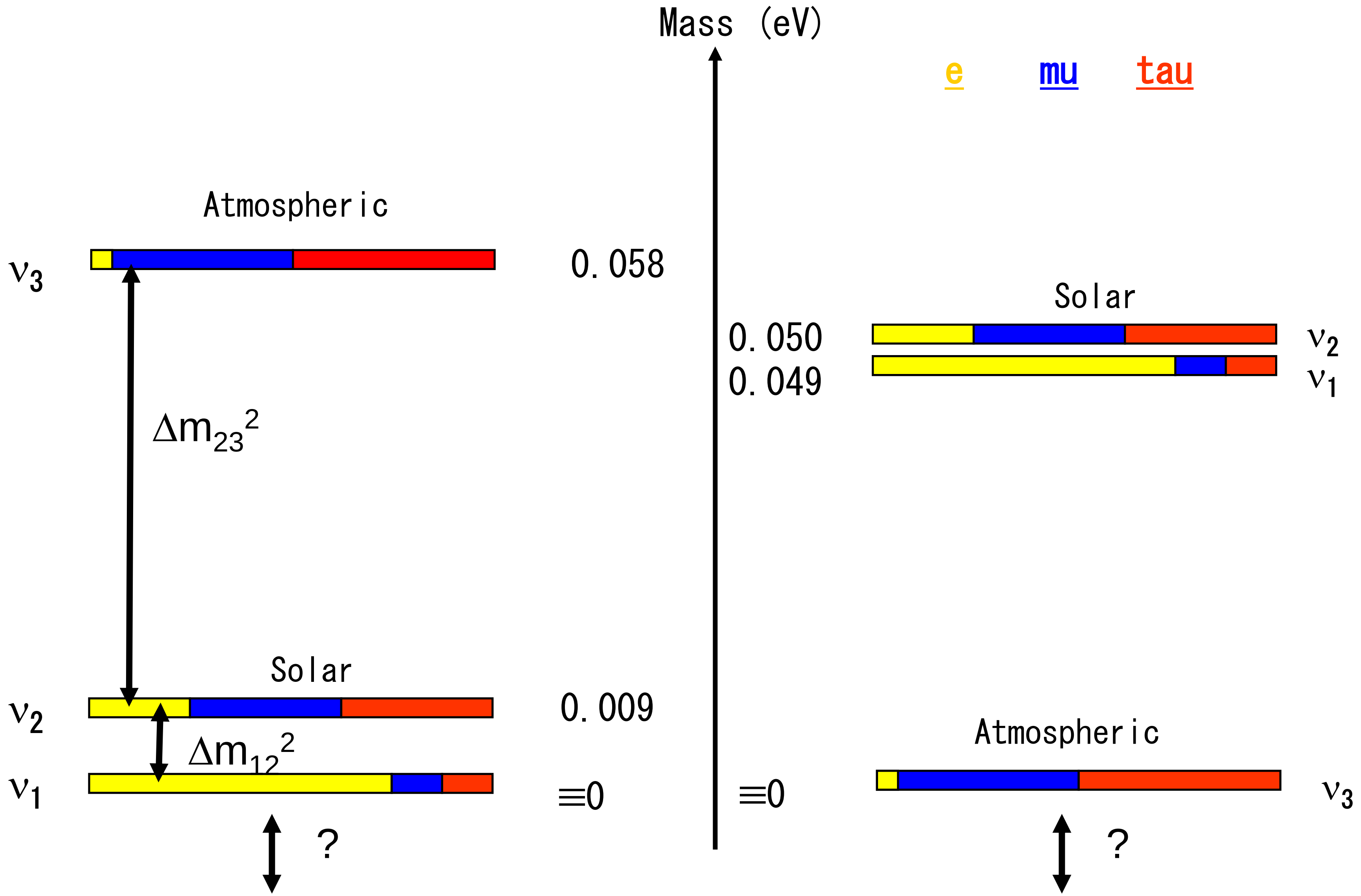


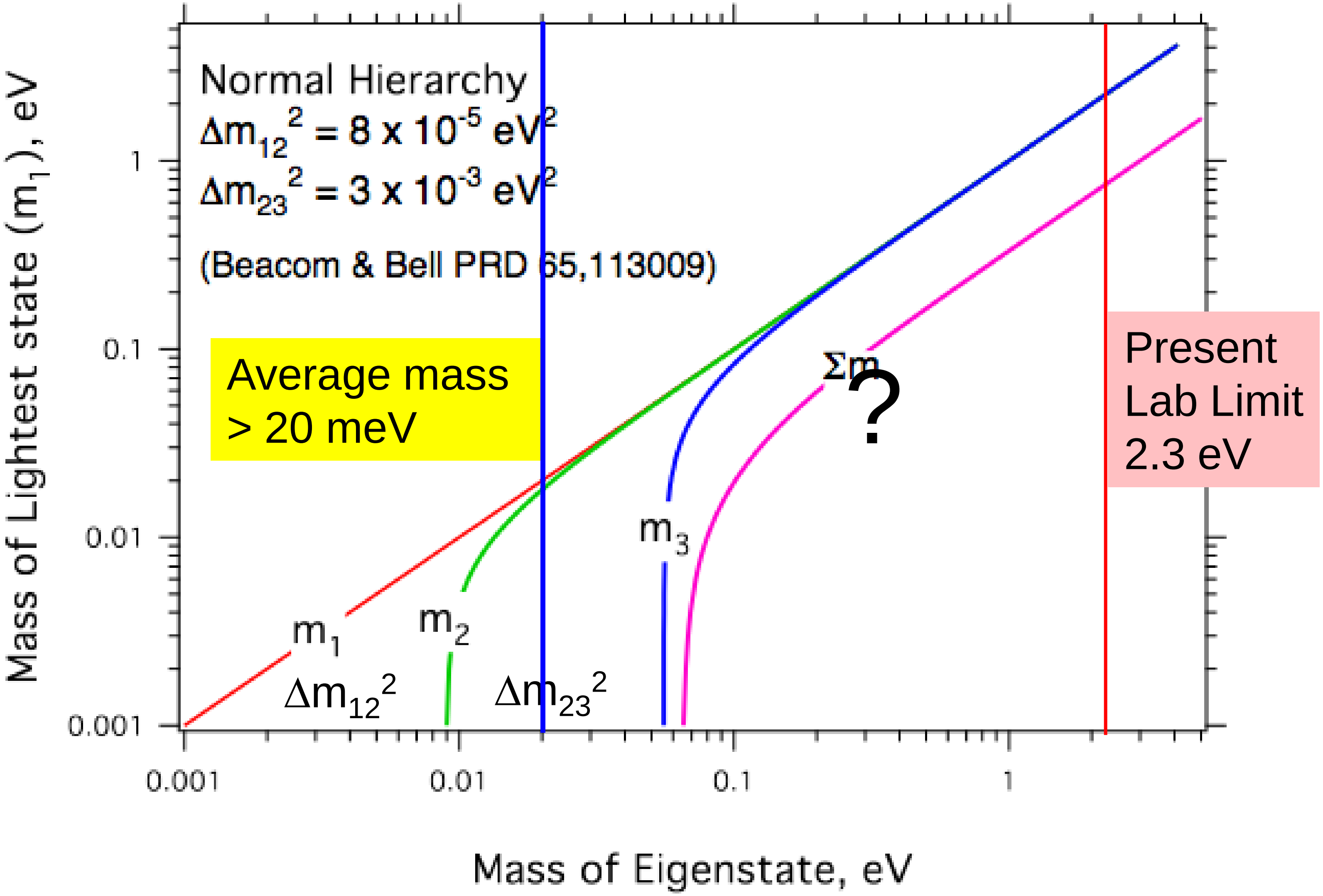
FIG. 4. Combined HiRes monocular spectrum. The squares and circles represent the HiRes-I and II differential flux $J(E)$, multiplied by E^3. The error bars are statistical only, and the systematic uncertainties are indicated by the shaded region. The line is a fit to the data of a model, described in the text, of galactic and extragalactic cosmic ray sources. The AGASA spectrum [15] is shown by triangles for comparison.

Abbasi et al., PRL 92, 151101

Minimum Neutrino Masses and Flavor Content



Masses linked by oscillations



Average mass
> 20 meV

Present
Lab Limit
2.3 eV

Ways to determine the neutrino mass scale

Methods	Present sensitivity	Future Sensitivity (5-15 years)
Cosmology (CMB + LSS)	0.7 eV ($\Sigma_i m_i$)	0.05 eV
0νββ Decay	0.5 eV	0.05 eV
Weak Decay Kinematics	2.2 eV	0.2 eV

Model Dependent

Direct measurement

Neutrinoless Double Beta Decay

Vogel hep-ph/0611243

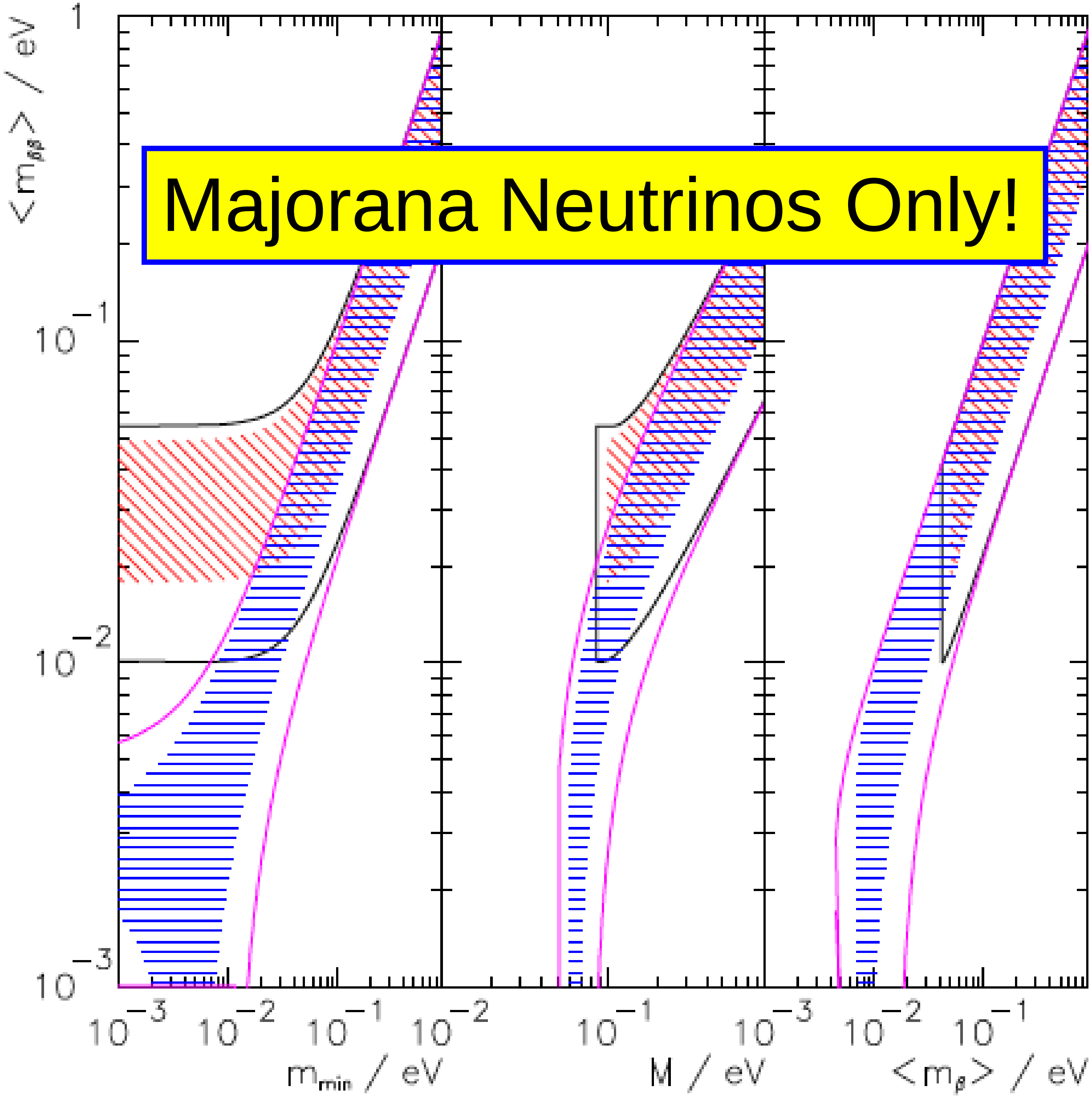
Red: inverted
Blue: normal

Banding: unknown Majorana phases

Lines: Osc. uncert.

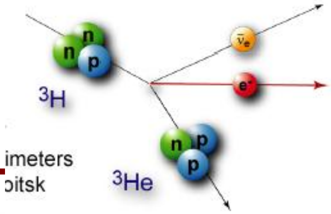
Nuclear matrix element uncertainty not shown

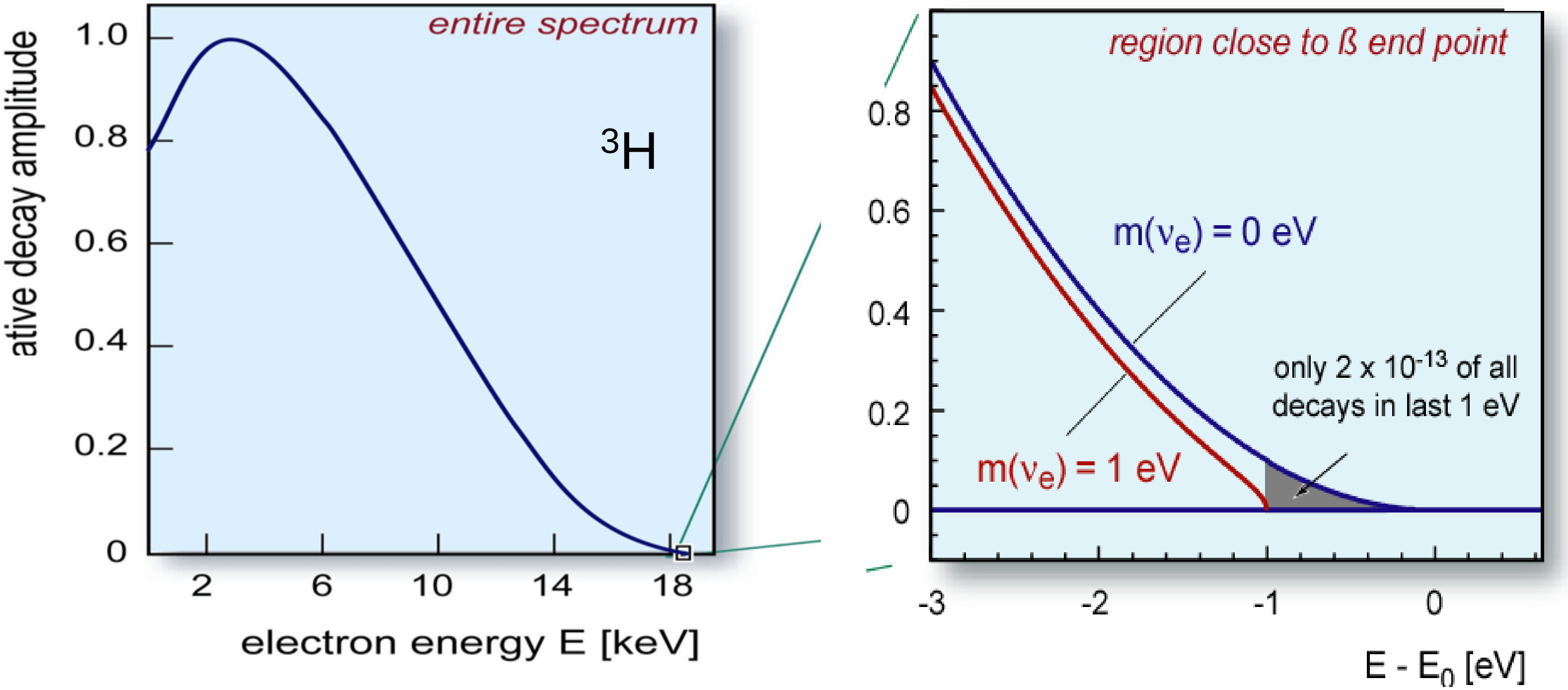
Left: vs. minimum mass eigenstate
Middle: vs. sum of masses M
Right: vs. kinematic electron-flavor mass



Majorana Neutrinos Only!

Beta decay and neutrino mass





Requirements:

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

Task:

Investigate ^{3}H or ^{187}Re endpoint with sub-eV precision

KATRIN Aim:

Improve m_ν sensitivity tenfold (2eV → 0.2eV)

What are we measuring in a Tritium experiment?

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

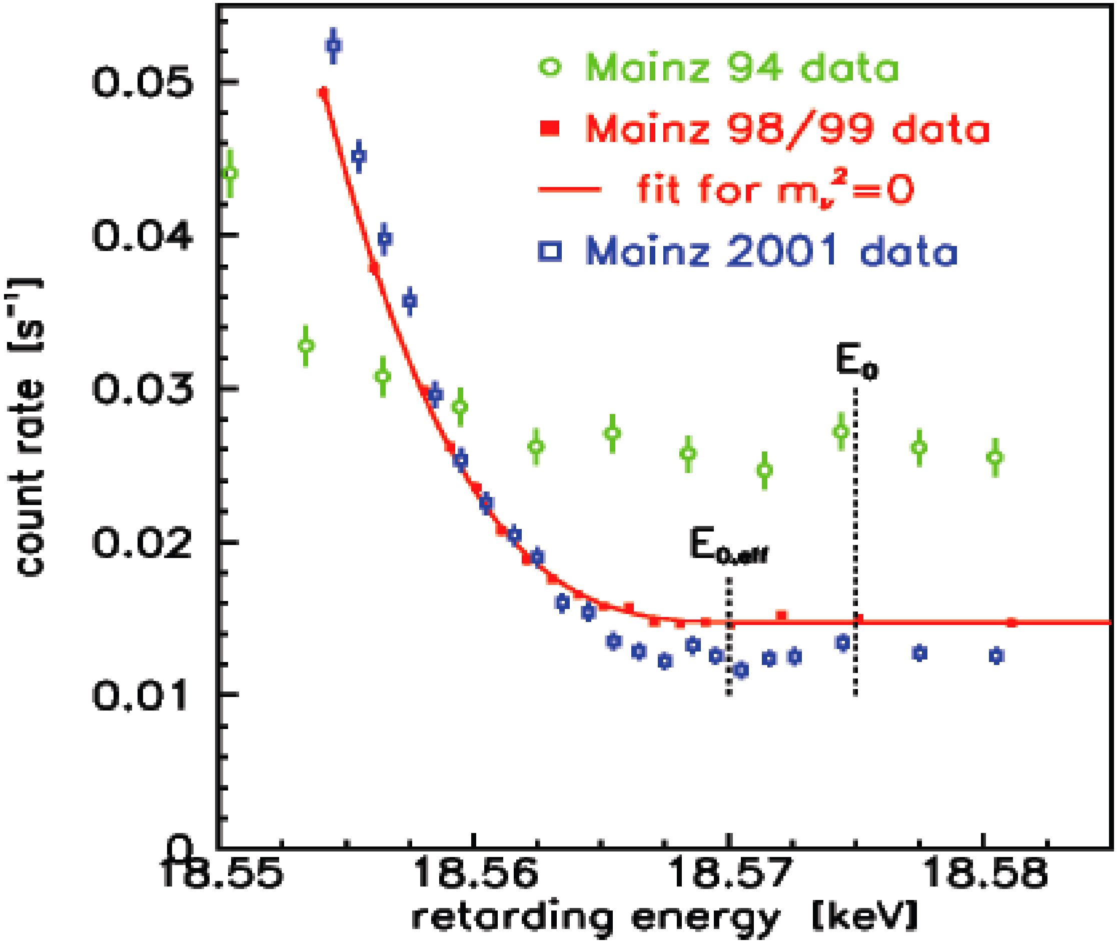
$$
\begin{aligned}
&= |\langle {}^3\mathrm{He}|\langle e|\langle \overline{\nu_e}|T|{}^3\mathrm{H}\rangle|^2 \\
&= |\sum_k U^*_{ek}\langle {}^3\mathrm{He}|\langle e|\langle \overline{\nu_k}|T|{}^3\mathrm{H}\rangle|^2 \\
&\sim pE(E-E_0)^2 \sum_k |U_{ek}|^2 \left(1 - \frac{m_k^2}{(E-E_0)^2}\right)^{1/2}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

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

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

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

Final Mainz Result Kraus et al. hep-ex/0412056



Improved S/N tenfold over 1994 data

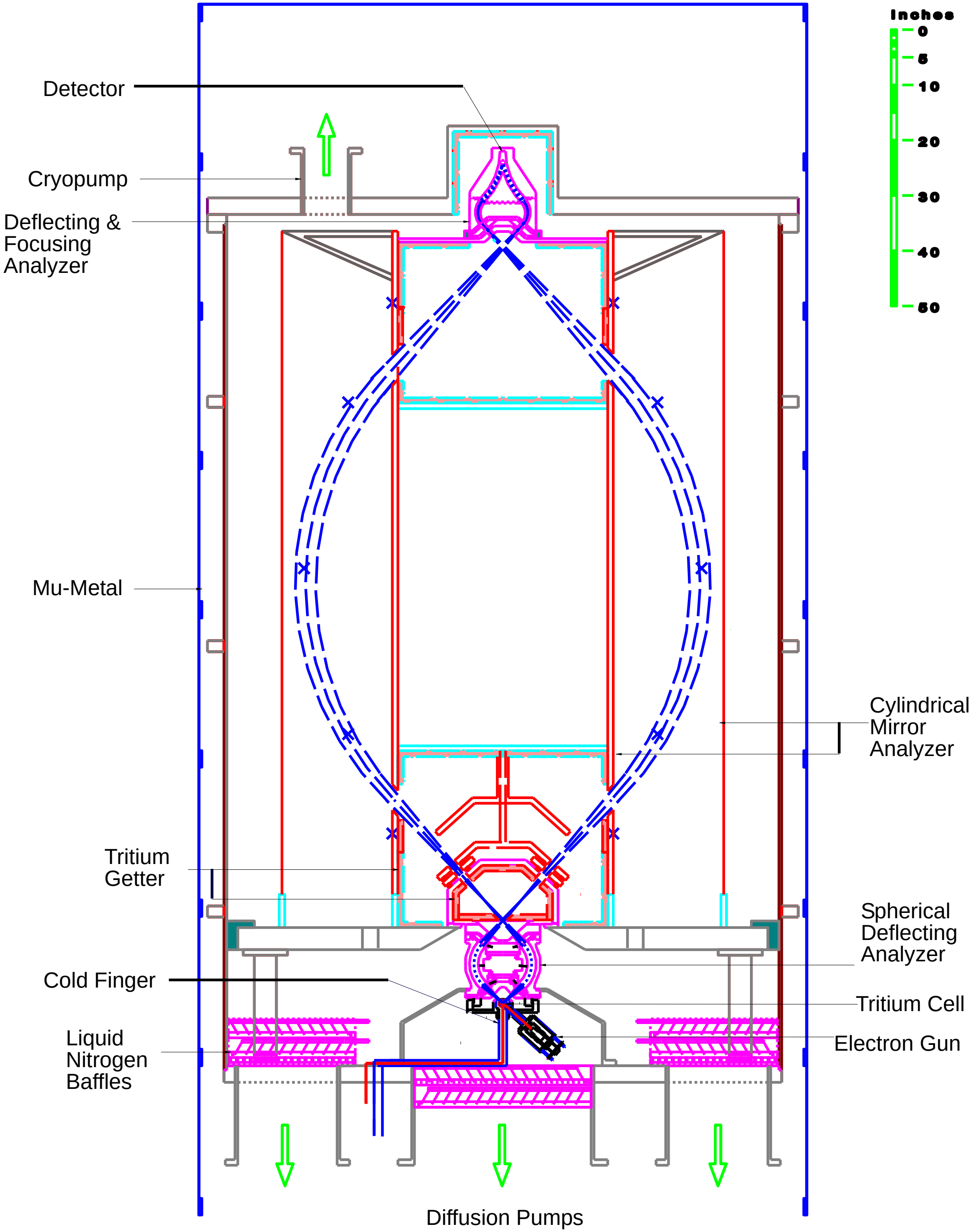
20 weeks of data in 1998, 1999, 2001

Stable background: pulsed RF clearing field applied at 20-s intervals

$$m^2(\nu_e) = (-0.6 \pm 2.2_{\mathrm{stat}} \pm 2.1_{\mathrm{syst}})\ \mathrm{eV}^2/\mathrm{c}^4$$

$$\chi^2/\mathrm{d.o.f.} = 208/194$$

$$\boxed{m(\nu_e) < 2.3\ \mathrm{eV}/\mathrm{c}^2 \quad (95\%\ \mathrm{C.L.})}$$



NEXTEX

U of Texas (1 M$)

Pure electrostatics

Possibility for electron diffr.

no magnetic fields <0.1 mG

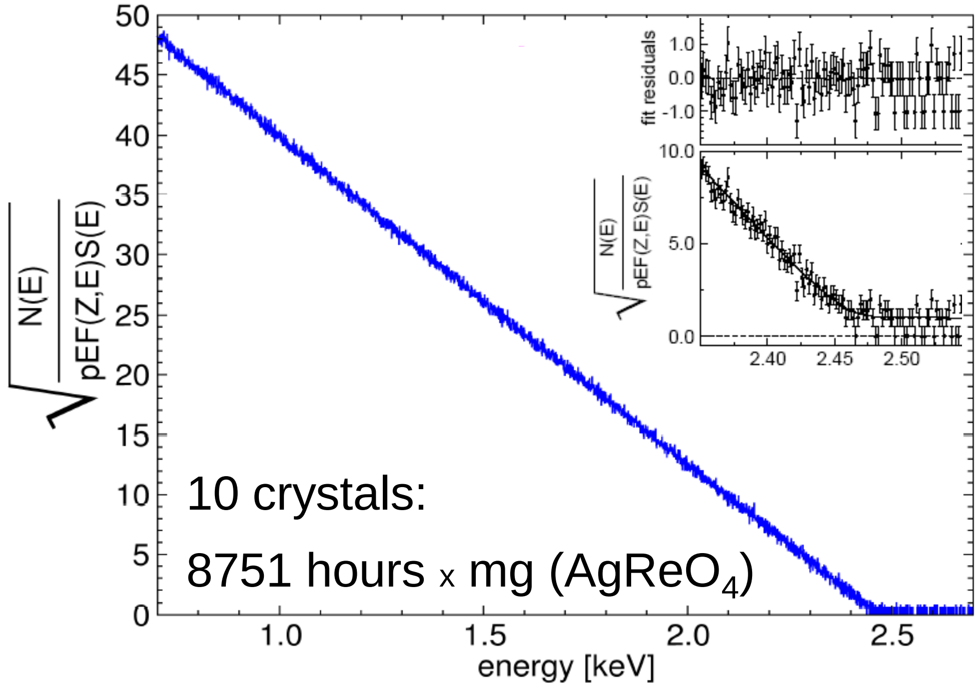
Sensitivity ~ 0.8 eV

Required funding 6.5M$

Not funded, it’s over

Microcalorimeters for ^{187}Re ß-decay

MIBETA: Kurie plot of 6.2 $\times 10^6$ ^{187}Re ß-decay events (E > 700 eV)



10 crystals:

8751 hours x mg ($AgReO_4$)

$E_0 = (2465.3 \pm 0.5_{stat} \pm 1.6_{syst})$ eV

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

MANU2 (Genoa)
metallic Rhenium
$m(\nu) < 26$ eV

Nucl. Phys. B (Proc.Suppl.) 91 (2001) 293

MIBETA (Milano)
$AgReO_4$
$m(\nu) < 15$ eV

Nucl. Instr. Meth. 125 (2004) 125

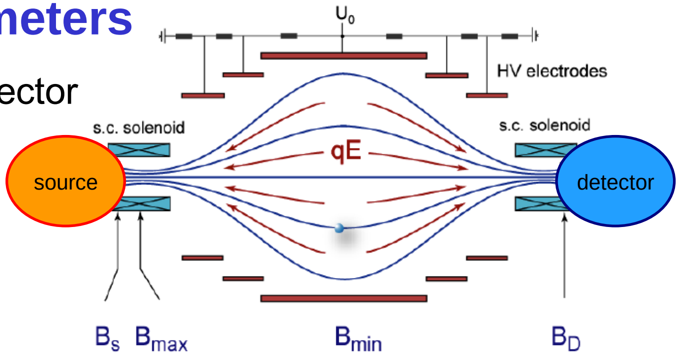
MARE (Milano, Como, Genoa, Trento, US, D)
Phase I : $m(\nu) < 2.5$ eV

hep-ex/0509038

β-decay - experimental techniques

Spectrometers

Source≠Detector



Advantages:

- Only examines region of interest
- Excellent energy resolution (~1eV)
- Very intense source (statistics)

Disadvantages:

- External source
  - -measure excited states
  - -Scattering, absorption

Choice of β-emitter: ^{3}H

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

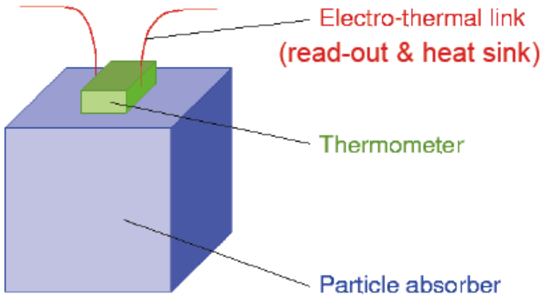
E_0 = 18.6 keV, $T_{1/2}$ = 12.3 years

Mainz & Troitsk→KATRIN

Bolometers

Source≡detector

(β-emitter=absorber)



Very low heat capacity at <100mK

Advantages:

- Detection of all released energy (including excited final states) except ν

Disadvantages:

- Pulse pile-up. Thermal integration time ~10^{-4} s→low count rate
- Records full spectrum - interesting region is small $\propto (m_\nu/E_0)^3$
- Many small detectors

Choice of β-emitter: ^{187}Re

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

E_0 = 2.46 keV (lowest β Q-value). $T_{1/2}$≈5×10^{10} years

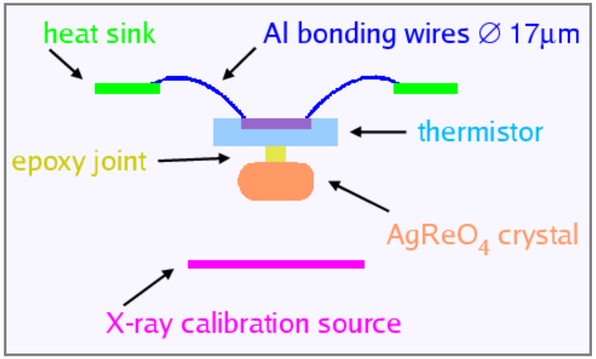
Manu & Mibeta→MARE

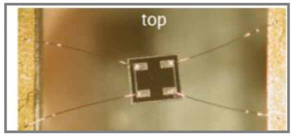
Complementary techniques - Different systematics

^{187}Re β–decay – cryogenic μ–calorimeters

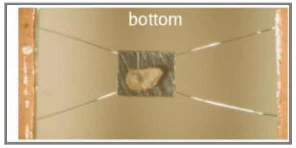
MIBETA experiment

(E. Fiorini et al. Milano, Como, Trento)

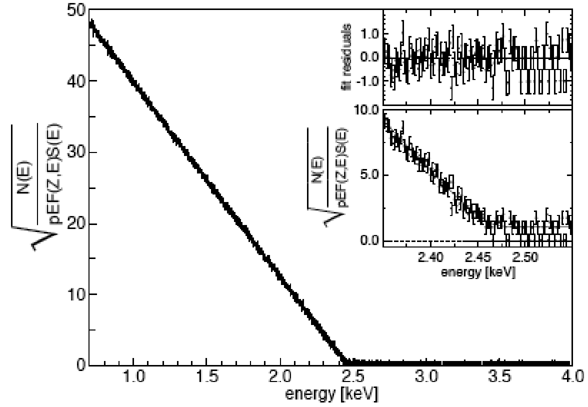




1 mm→| |←



- 10 detectors 250 →350 μg ≅ 2.5 mg
- AgReO$_4$ single crystals absorber
- Sensor - Si thermistors
- ΔE_{FWHM} 28.3 eV



MIBETA Kurie plot

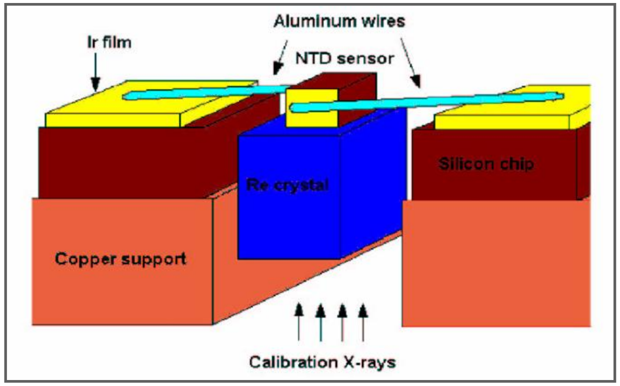
8 detectors

6.2 ^{187}Re decays > 700 eV

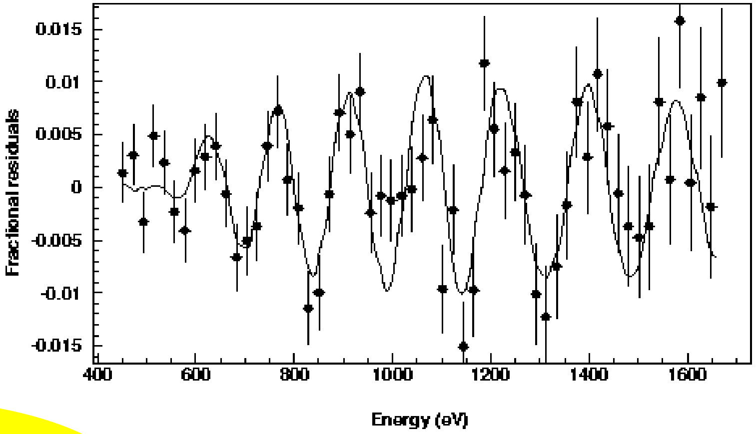
8751 hr. x mg

MANU experiment

(F.Gatti et al. Genoa)



- One detector, 1.5 mg
- Metallic Rhenium absorber
- Sensor - neutron transmutation doped (NTD) Ge therm.
- ΔE_{FWHM} = 96 eV



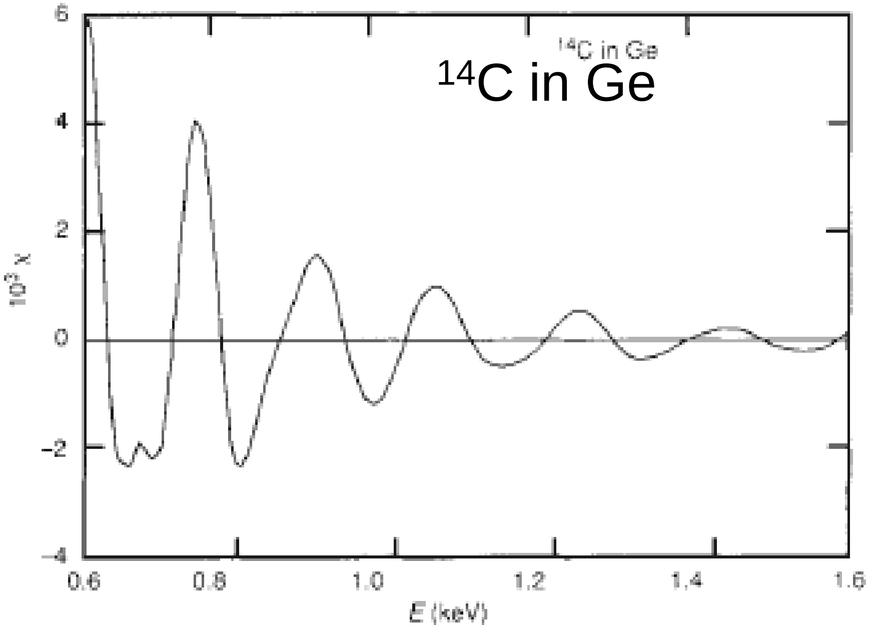
⟨M_β⟩ < 15 eV (90 % c.l.)

Current limit

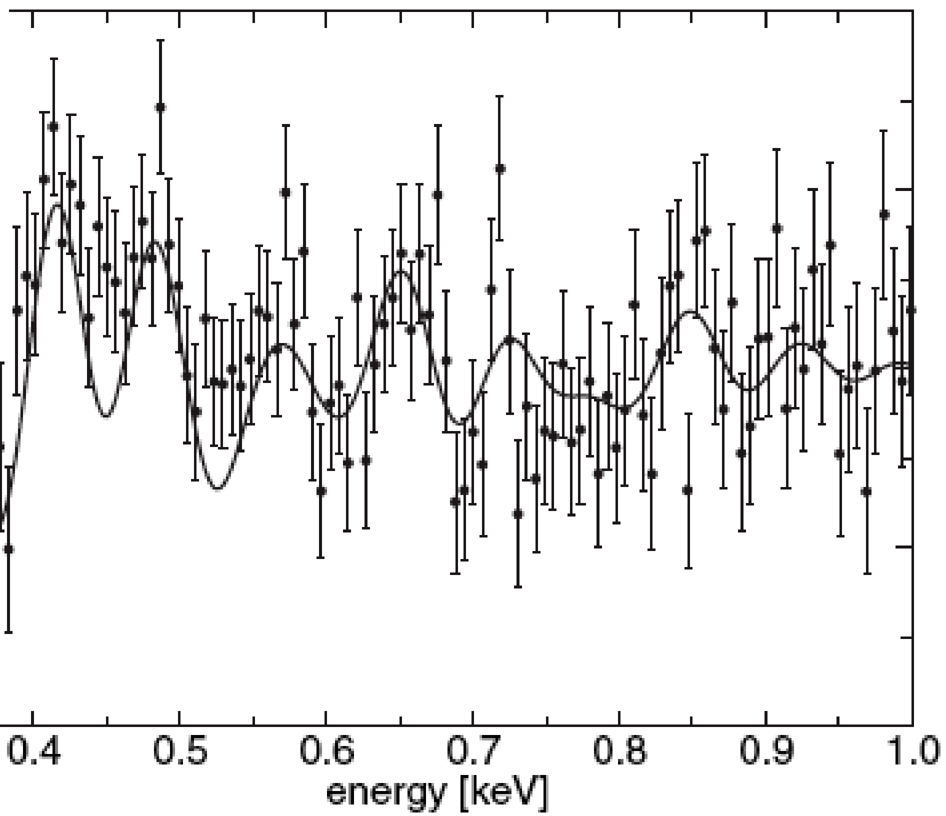
⟨M_β⟩<2.2 eV

⟨M_β⟩ < 19 eV (90 % c.l.)

BEFS predicted by Koonin (Nature 354, 468 [1991])



AgReO$_4$



Arnaboldi et al. PRL 96, 042503 [2006] measured electron p-wave intensity $F_p = 0.84(30)$ in this $5/2^+$ to $1/2^-$ transition

^{187}Re β–decay – future prospects

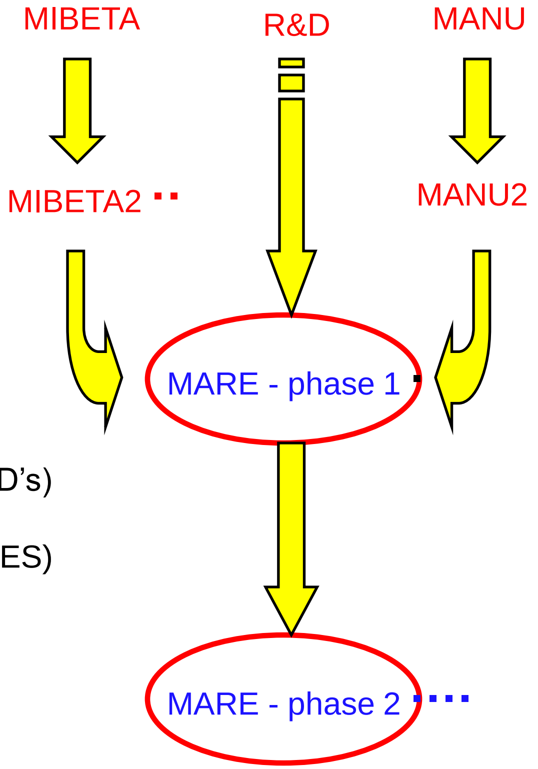
MARE - **M**icrocalorimeter **A**rrays for a **R**henium **E**xperiment

(10 institutes, Italy, Germany, USA)

Advances in:
- Micro-machining
- Large detector arrays
- Sensor technology
- Understanding systematic sources

Enables ~10^2 improvement in sensitivity
Independent test of spectrometer results
$m_\nu < 0.2$ eV…and beyond?

MIBETA2
288 $AgReO_4$ crystals, 450 μg each
Semiconductor thermistor sensors


MIBETA
R&D
MANU
MIBETA2
MANU2
MARE - phase 1
MARE - phase 2

MANU2
~300 metallic Re elements, 250 mg total
Transition edge sensors

R&D
3 new technologies

Metallic magnetic calorimeters (MMC's)
Improved energy resolution
Faster response time

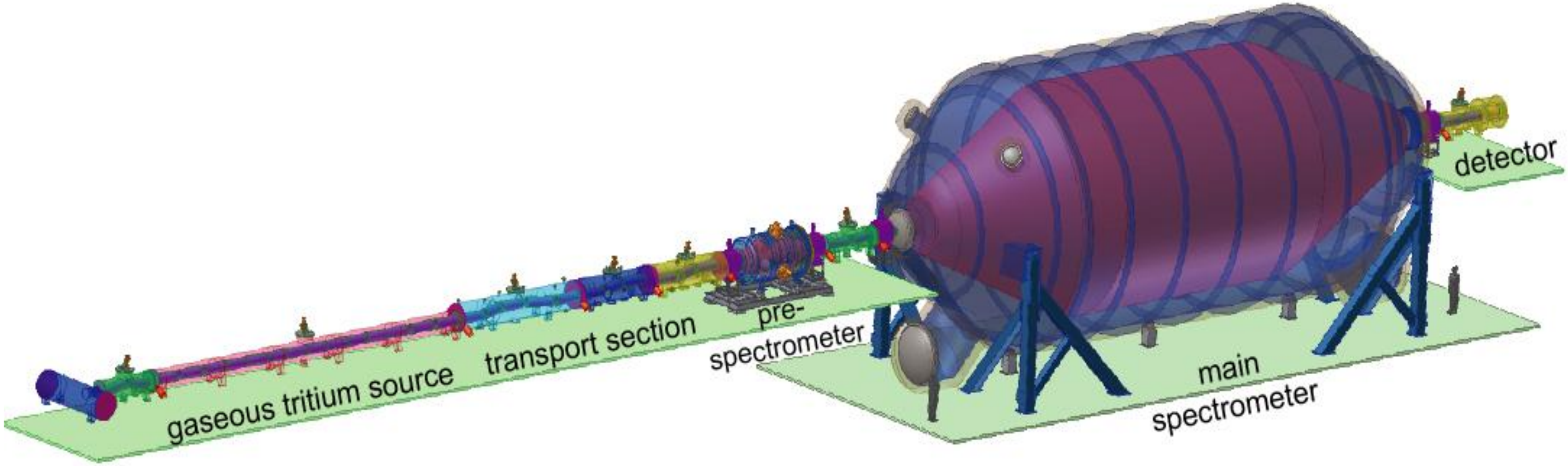
Multiplexed kinetic induction detectors (MKID's)
10^3-10^4 channels/amplifier

Superconducting transition edge sensors (TES)
(Baseline MARE-2)
60 x temperature sensitivity
100 x response time

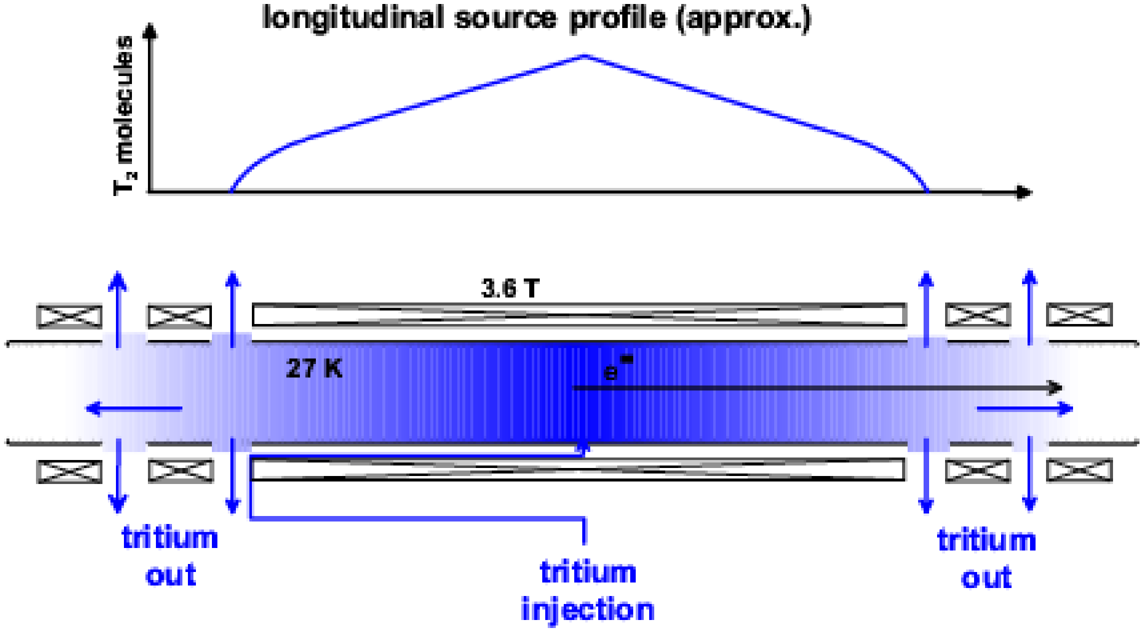
~300 elements
ΔE ~10 eV
Δt~ 100 μs
10^{10} decays in 4 years
$m_\nu < 2.5$ eV 90% CL by 2010

~5x10^4 elements (5 arrays)
ΔE ~5 eV
Δt ~1 μs
10^{14} decays in 3 years
$m_\nu < 0.2$ eV 90% CL

Direct Determination of Neutrino Mass with KATRIN



Los Alamos type Windowless Source



Principle of MAC-E Filter

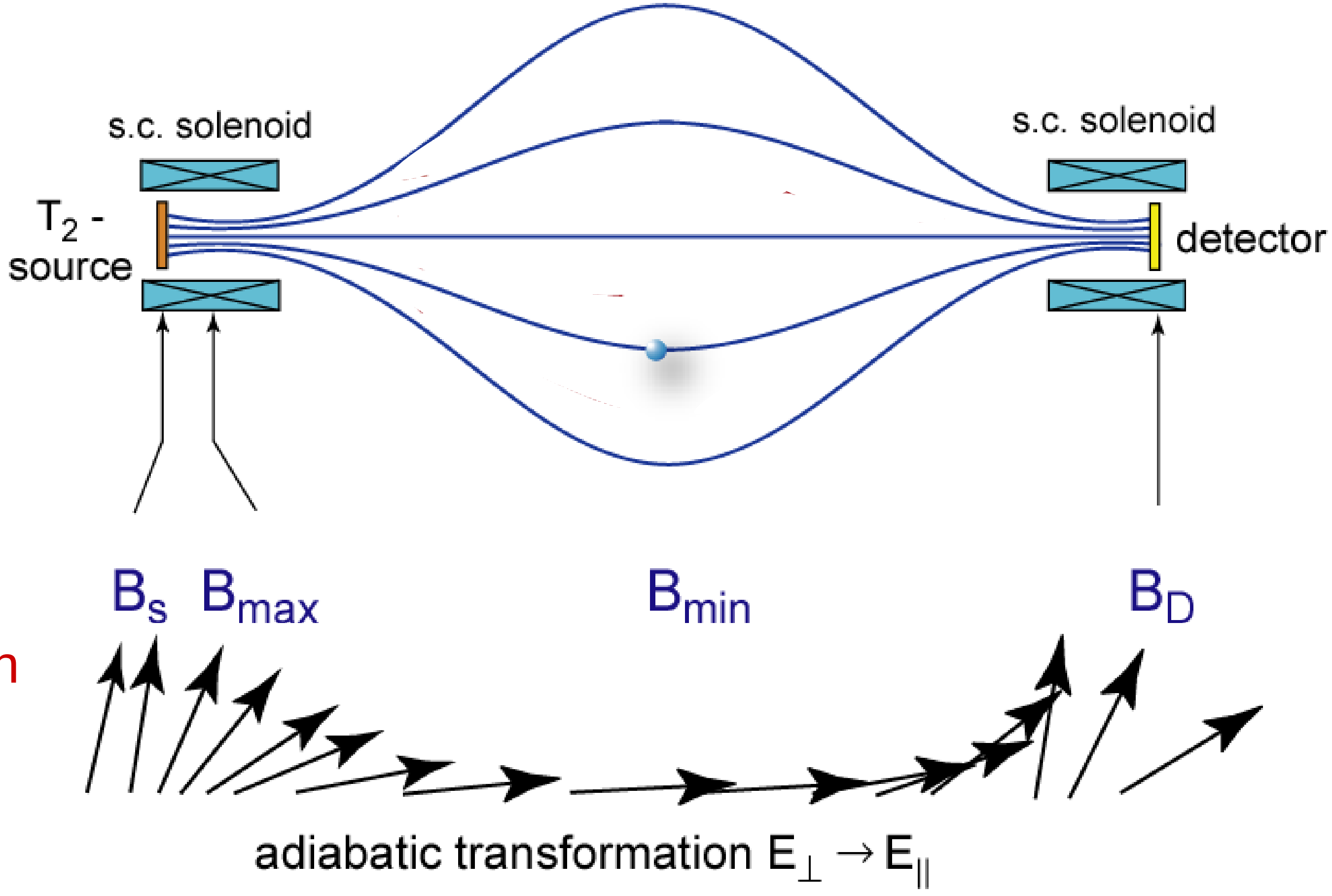
Adiabatic magnetic guiding of β´s along field lines in stray B-field of s.c. solenoids:

$B_{max} = 6$ T

$B_{min} = 3 \times 10^{-4}$ T

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

High pass filter with integral β transmission for E>qU



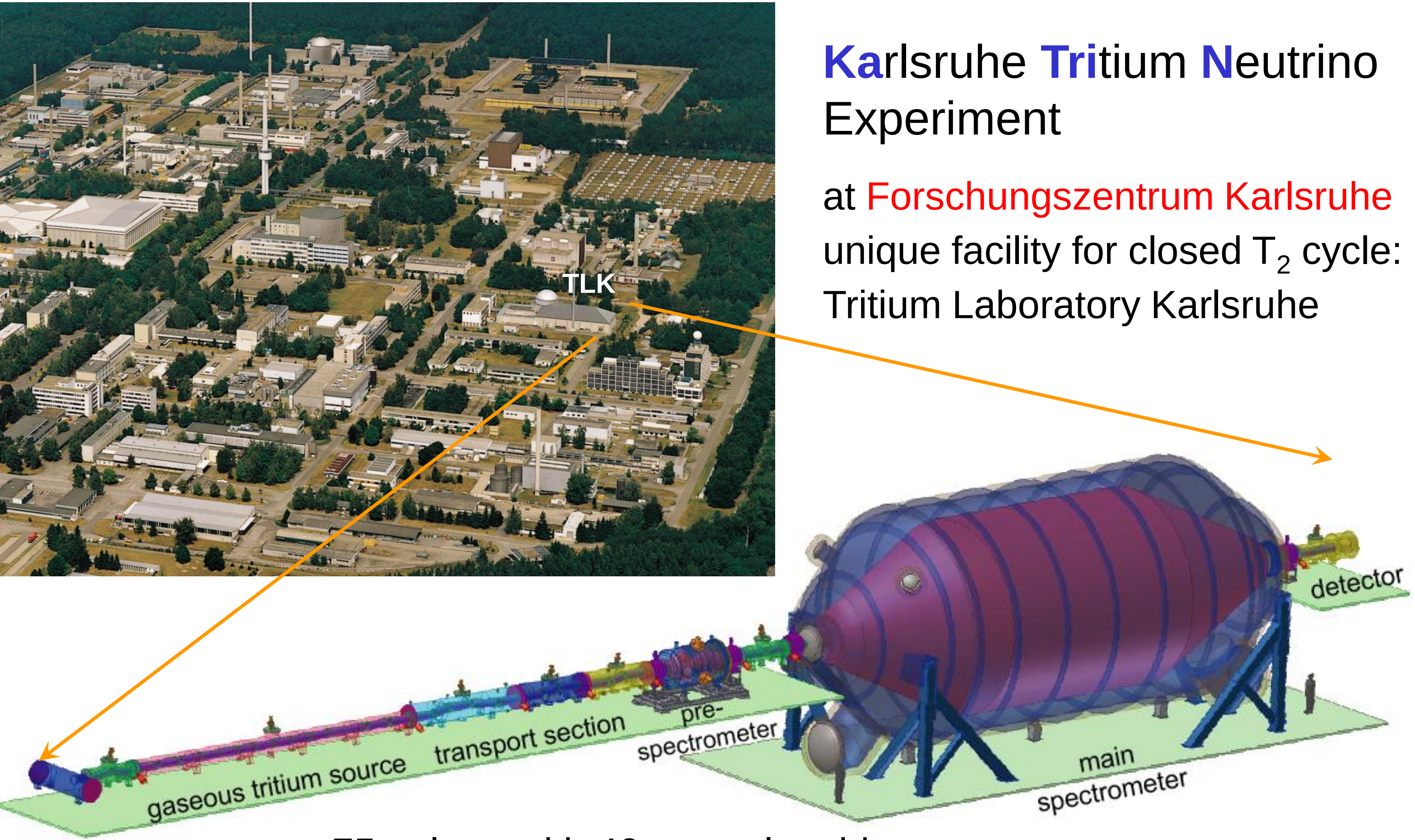
KATRIN experiment

Karlsruhe **Tri**tium **N**eutrino Experiment

at Forschungszentrum Karlsruhe

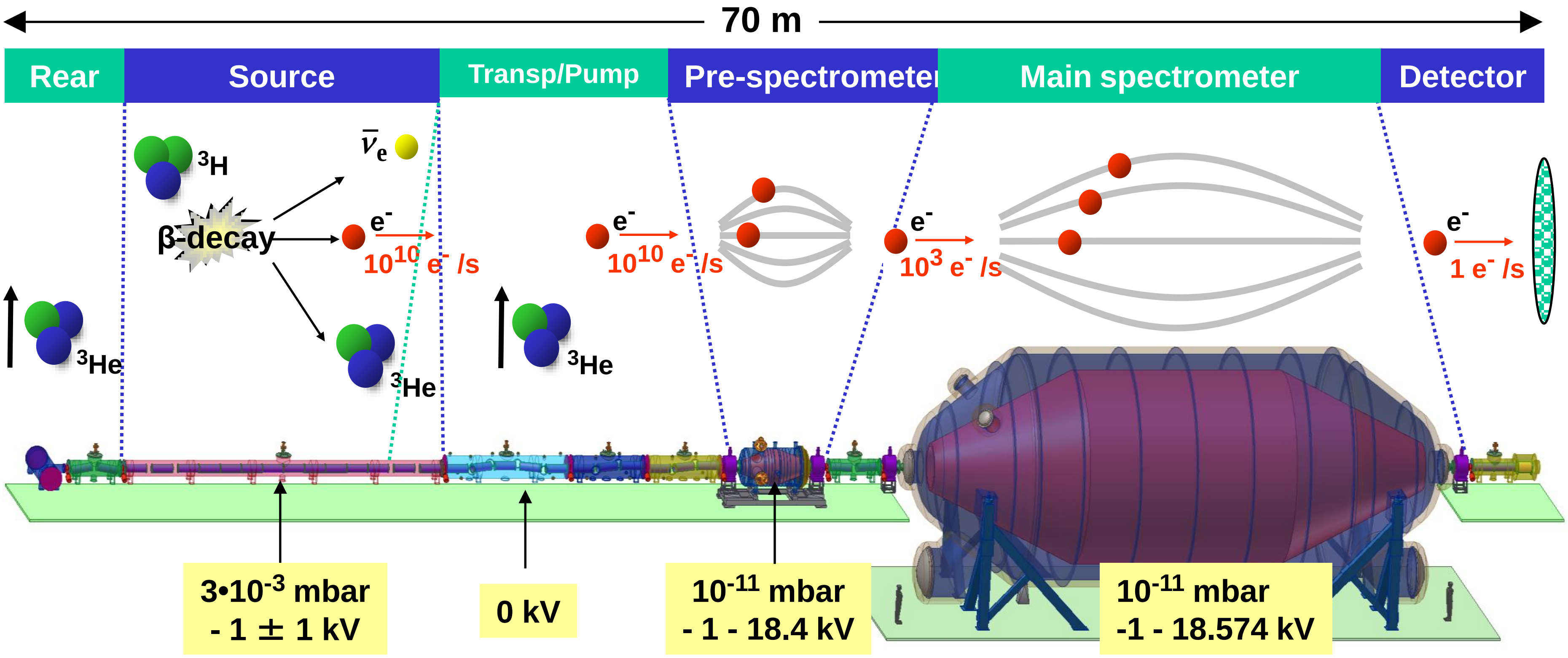
unique facility for closed T_2 cycle:

Tritium Laboratory Karlsruhe



~ 75 m long with 40 s.c. solenoids

Experimental Setup

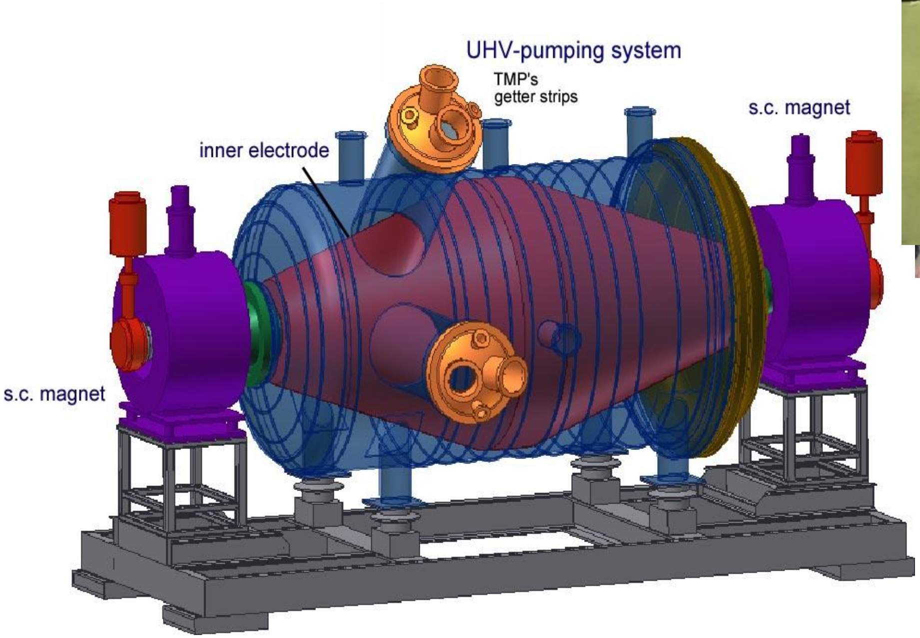


Rear System:	Source:	Transp. & Pump system:	Pre-spectrometer:	Main-spectrometer:	Detector:
Monitor source parameters	Provide the required tritium column density	Transport the electrons, adiabatically and reduce the tritium density significantly	Rejection of low-energy electrons and adiabatic guiding of electrons	Rejection of electrons below endpoint and adiabatic guiding of electrons	Count electrons and measure their energy

Pre-spectrometer

Parameters:

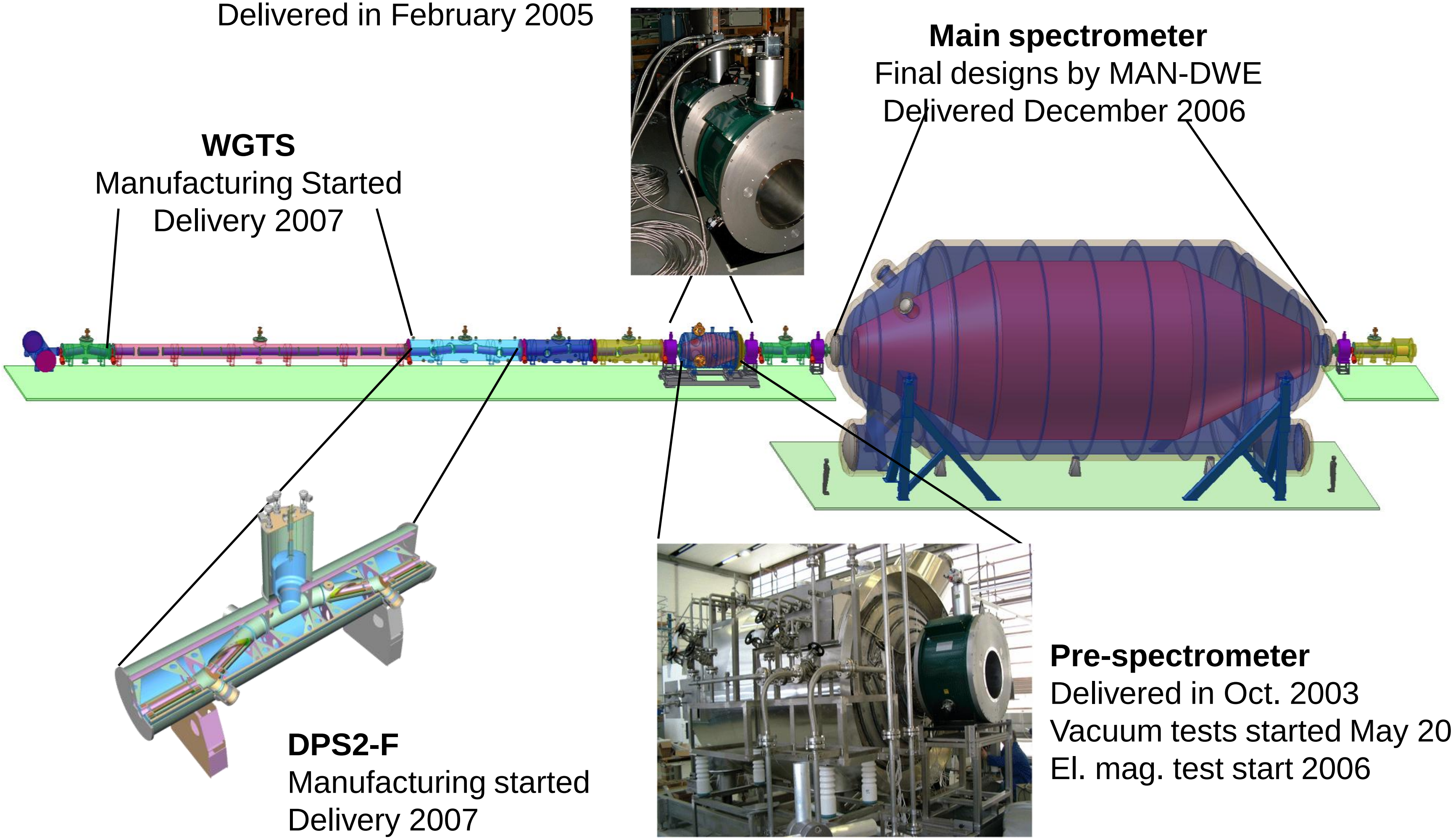
- Length: 3.4 m (flange to flange)
- Diameter:1.7 m
- Vacuum: < 10^{-11} mbar
- Material: Stainless steel
- Magnets: 4.5 T



Status:

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

Status of KATRIN Hardware Activities



Pre-spectrometer magnets
Delivered in February 2005

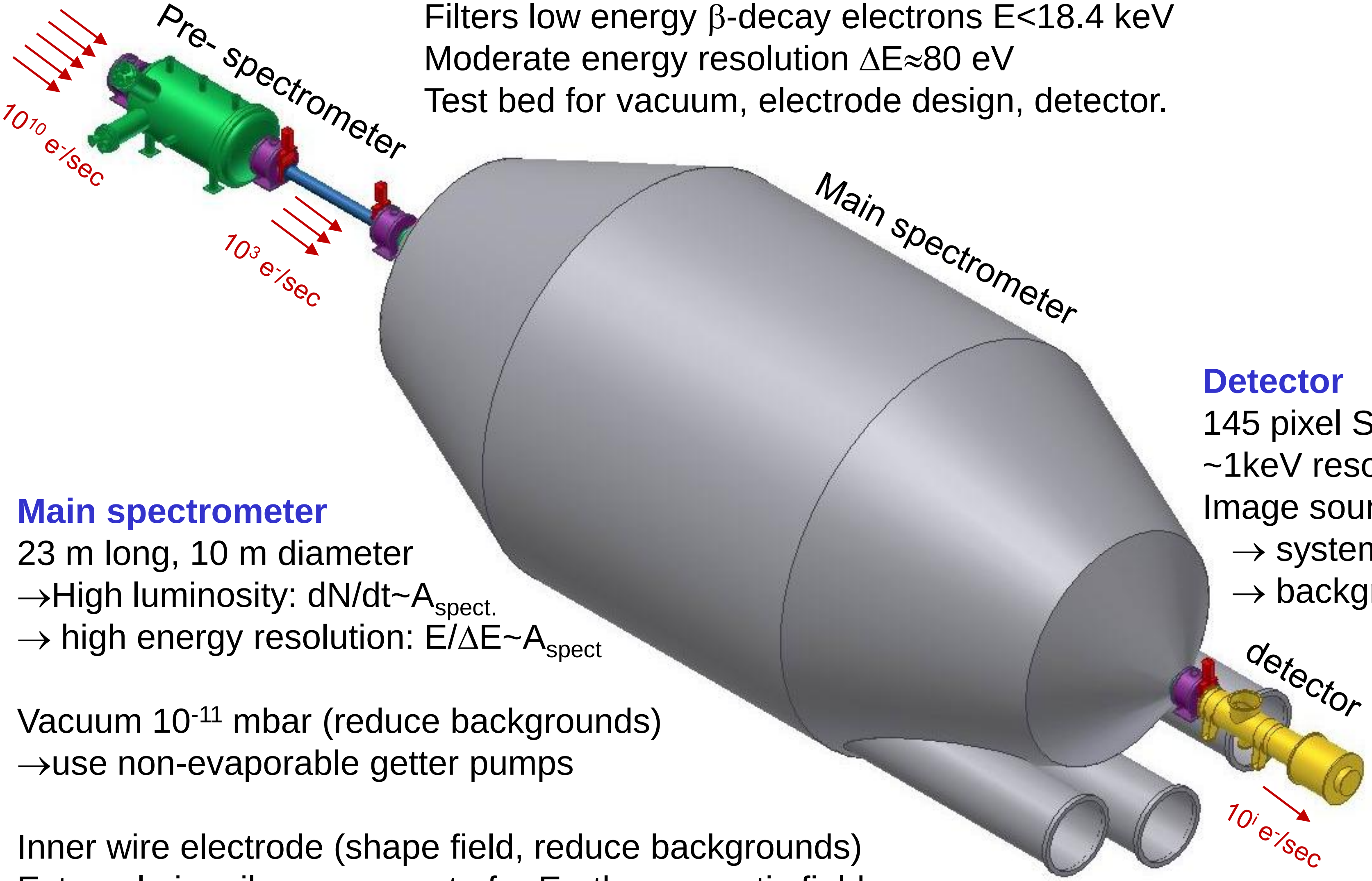
Main spectrometer
Final designs by MAN-DWE
Delivered December 2006

WGTS
Manufacturing Started
Delivery 2007

DPS2-F
Manufacturing started
Delivery 2007

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

Tandem design: -- Pre-filter, Energy analysis



Pre-spectrometer

Filters low energy β-decay electrons E<18.4 keV
Moderate energy resolution $\Delta E \approx 80$ eV
Test bed for vacuum, electrode design, detector.

Detector

145 pixel Si PIN diode
~1keV resolution
Image source
→ systematics
→ backgrounds

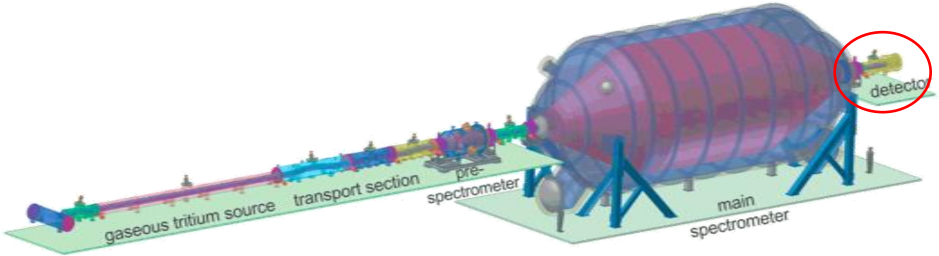
Main spectrometer

23 m long, 10 m diameter
→High luminosity: $dN/dt \sim A_{\text{spect.}}$
→ high energy resolution: $E/\Delta E \sim A_{\text{spect}}$

Vacuum 10^{-11} mbar (reduce backgrounds)
→use non-evaporable getter pumps

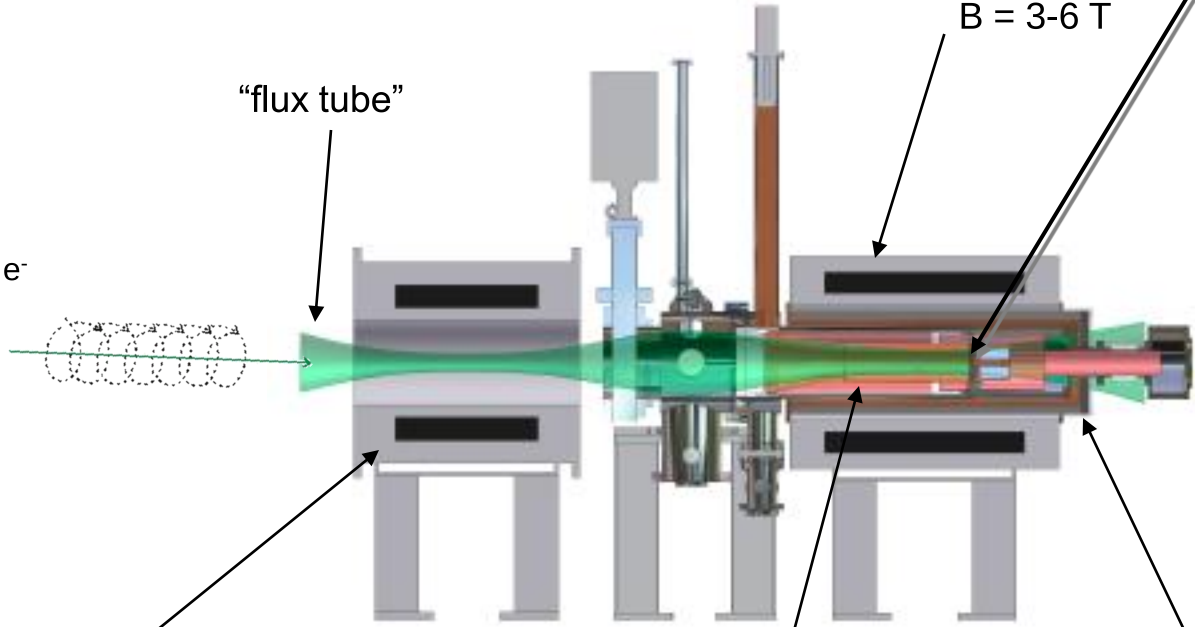
Inner wire electrode (shape field, reduce backgrounds)
External air coil - compensate for Earths magnetic field

Detector Section (Univ. of Washington, MIT)



Silicon PIN diode detector

- 9 cm active diameter



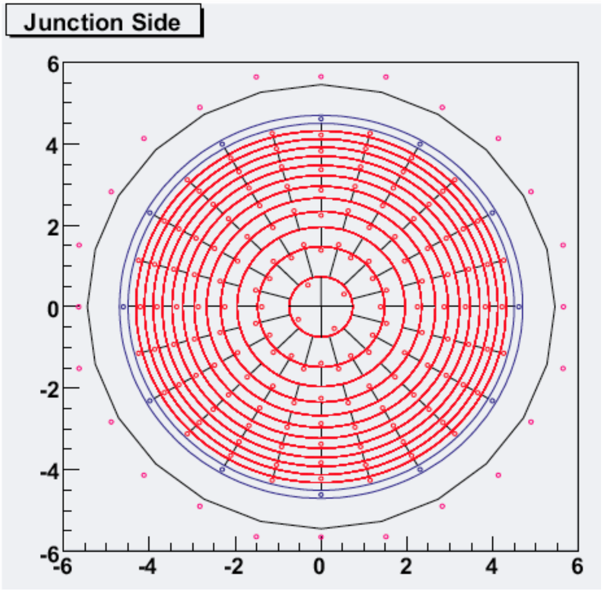
"flux tube"

detector magnet
B = 3-6 T

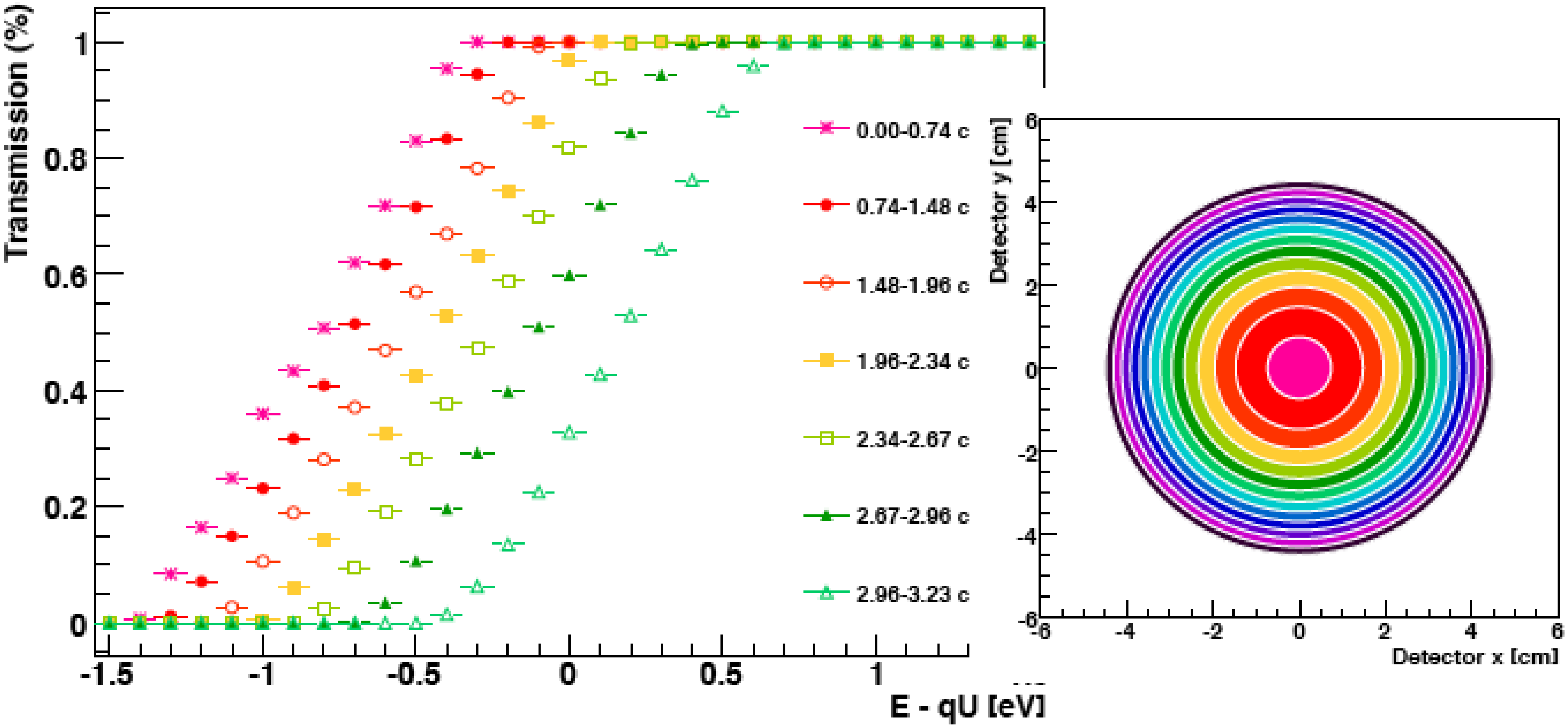
pinch magnet
B = 6 T

post-acceleration electrode

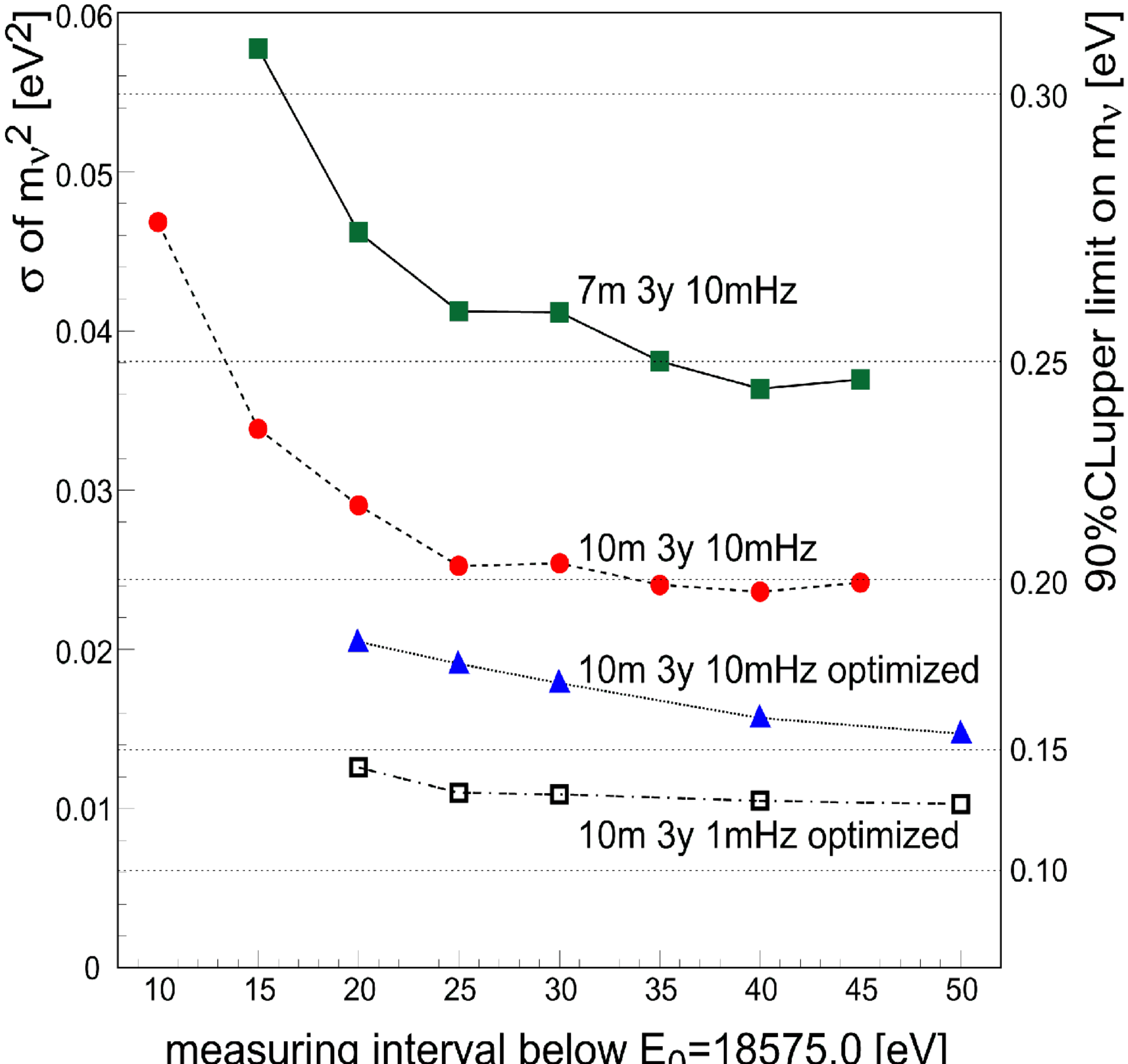
shielding & veto



Pixelized Detector Corrects Focal Plane Resolution

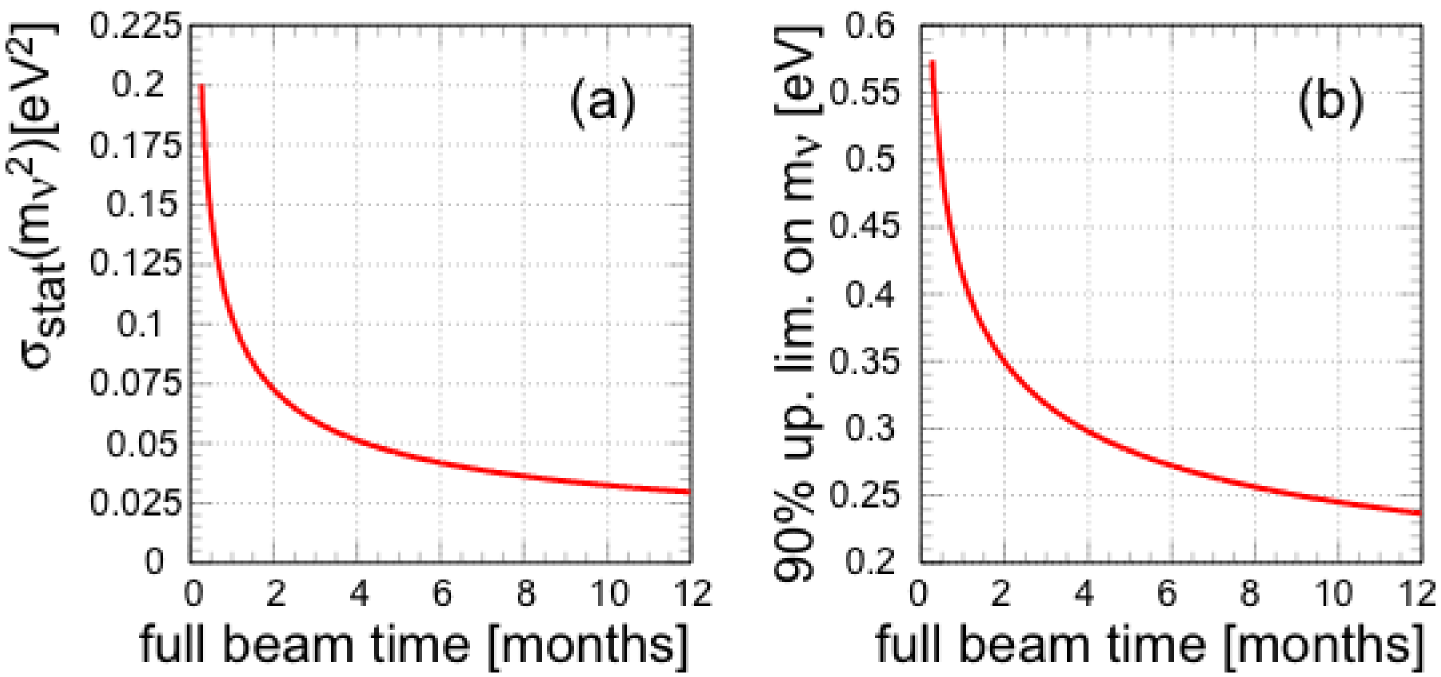


KATRIN Statistical Sensitivity



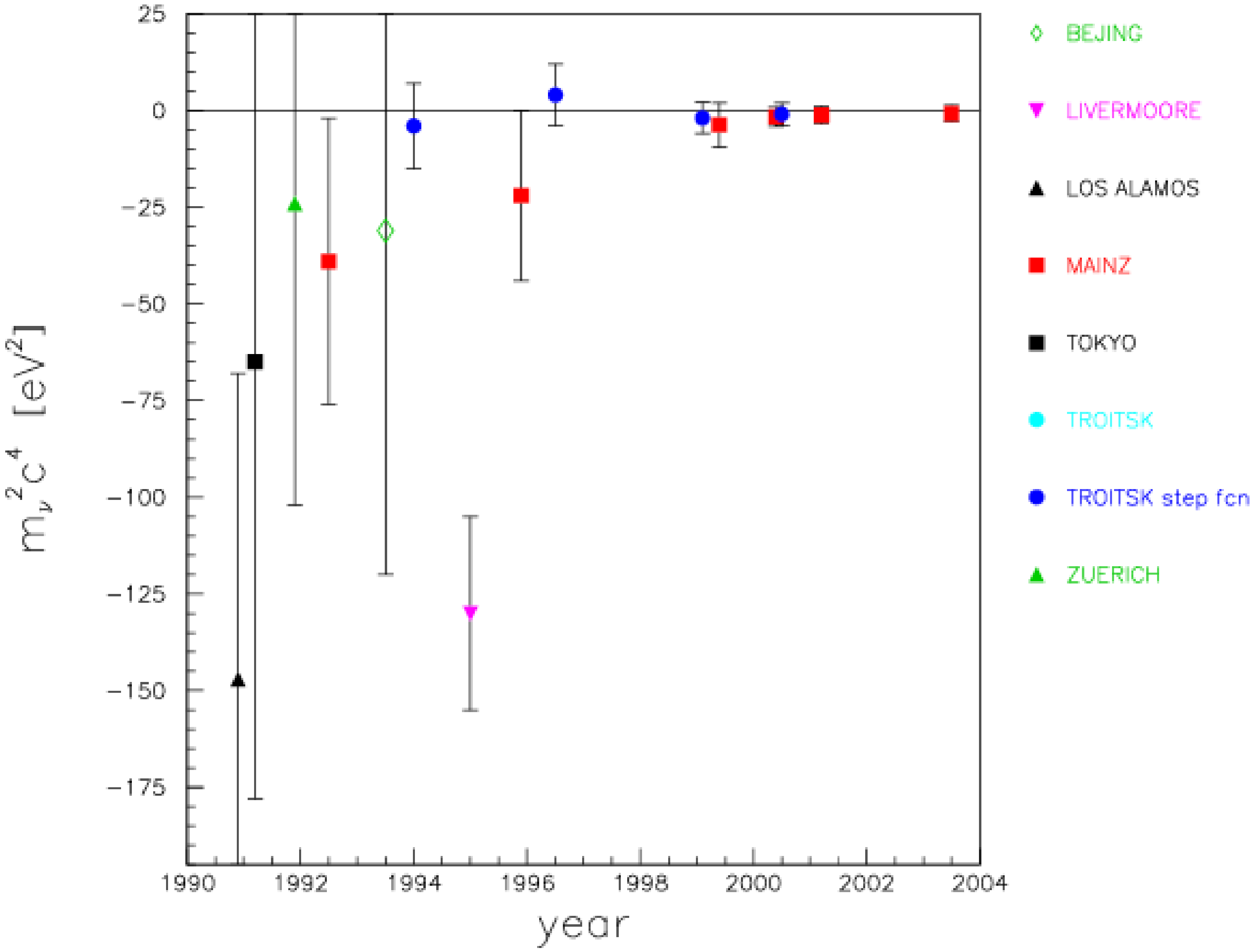
- Improved over original design (7 m diameter main spectrometer, source luminosity)
- Reduction in background
- Only shows statistical uncertainty

Sensitivity with run time



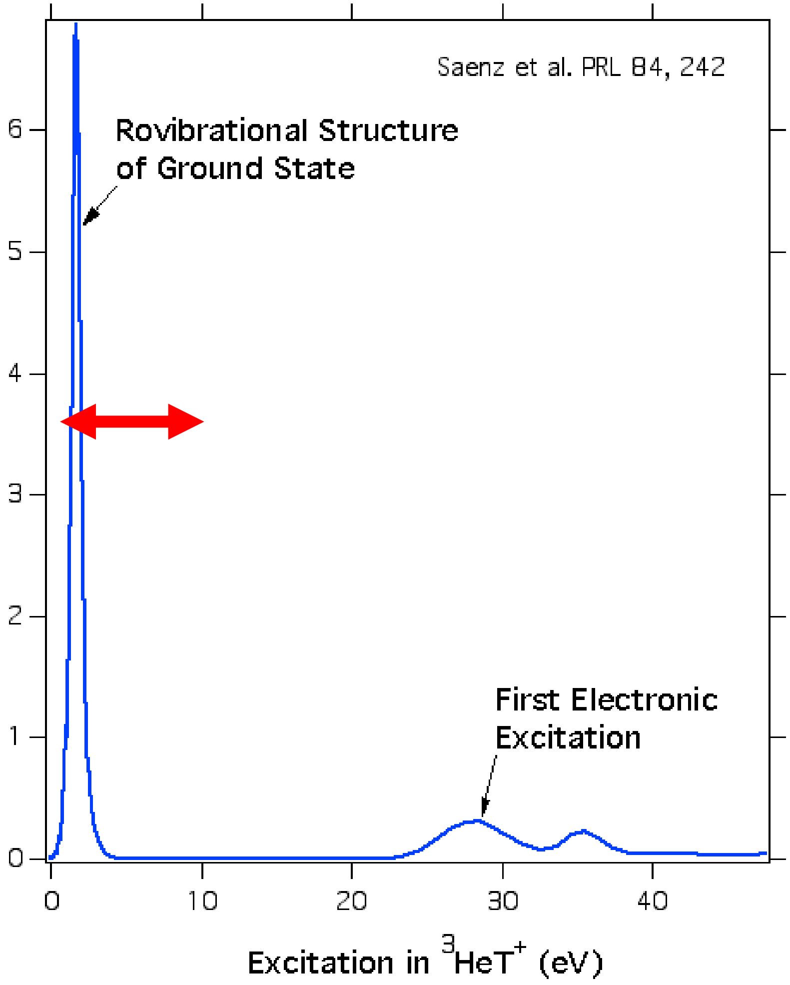
Voyage of the main spectrometer

Tritium Beta Decay History

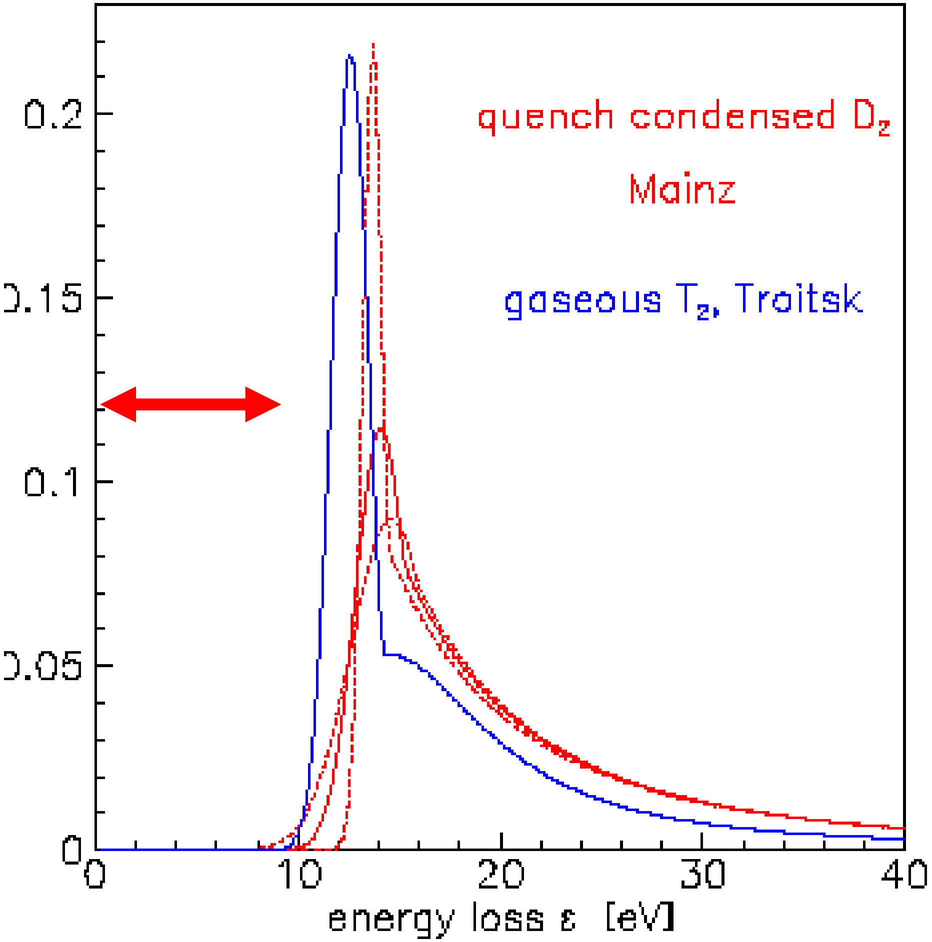


A window to work in

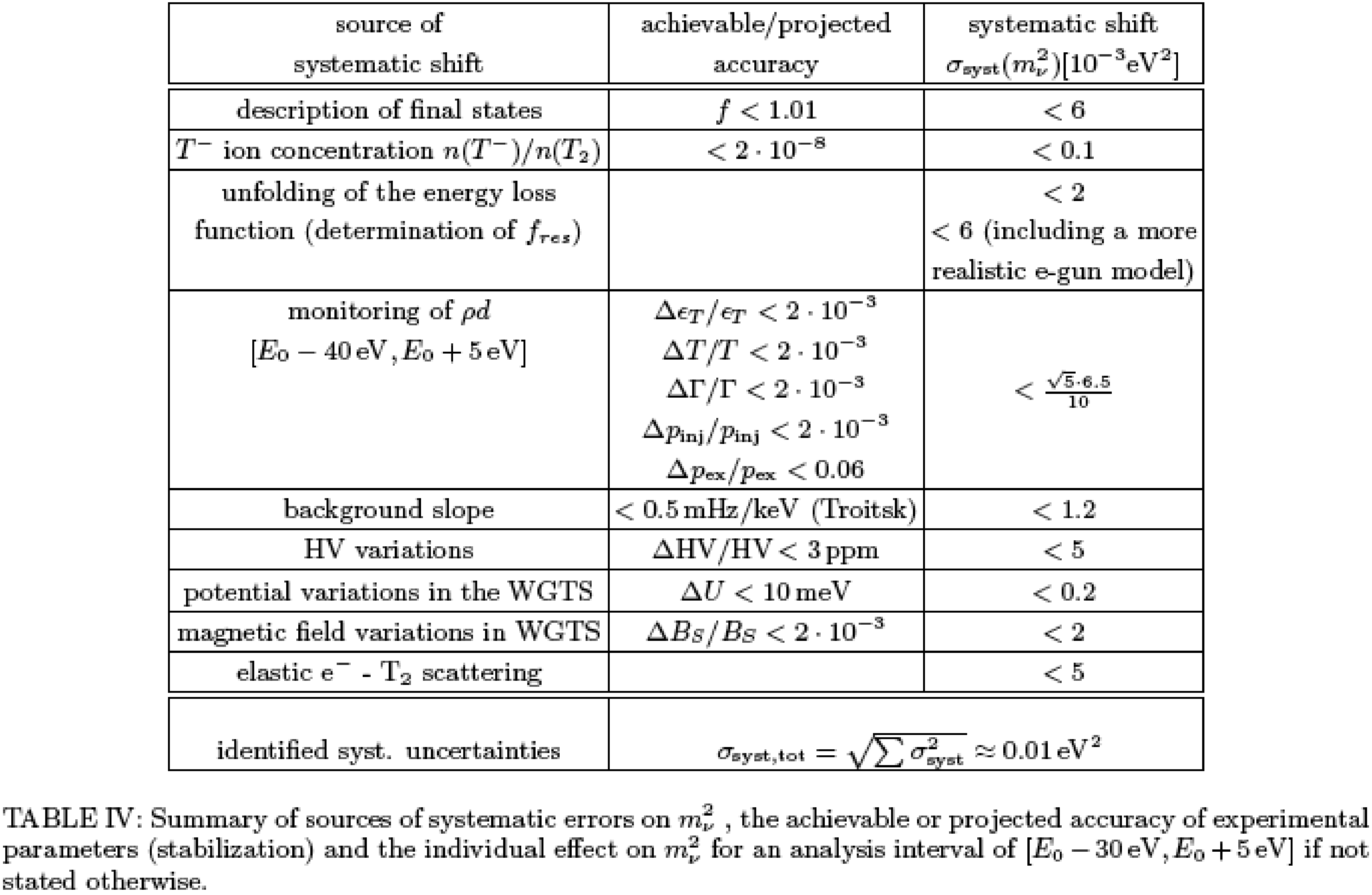
Molecular Excitations


Saenz et al. PRL 84, 242

Energy loss function



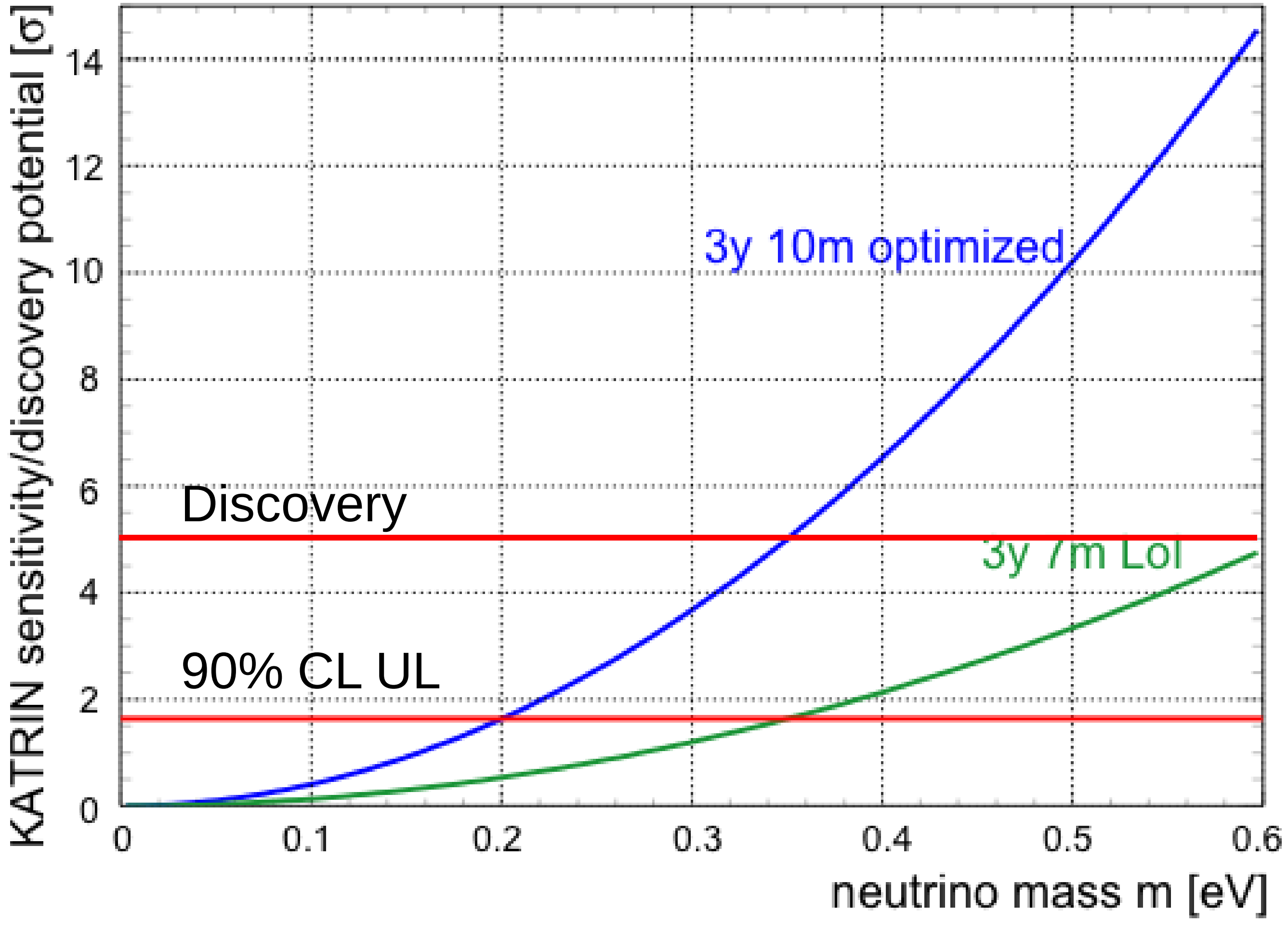
Systematic Uncertainties



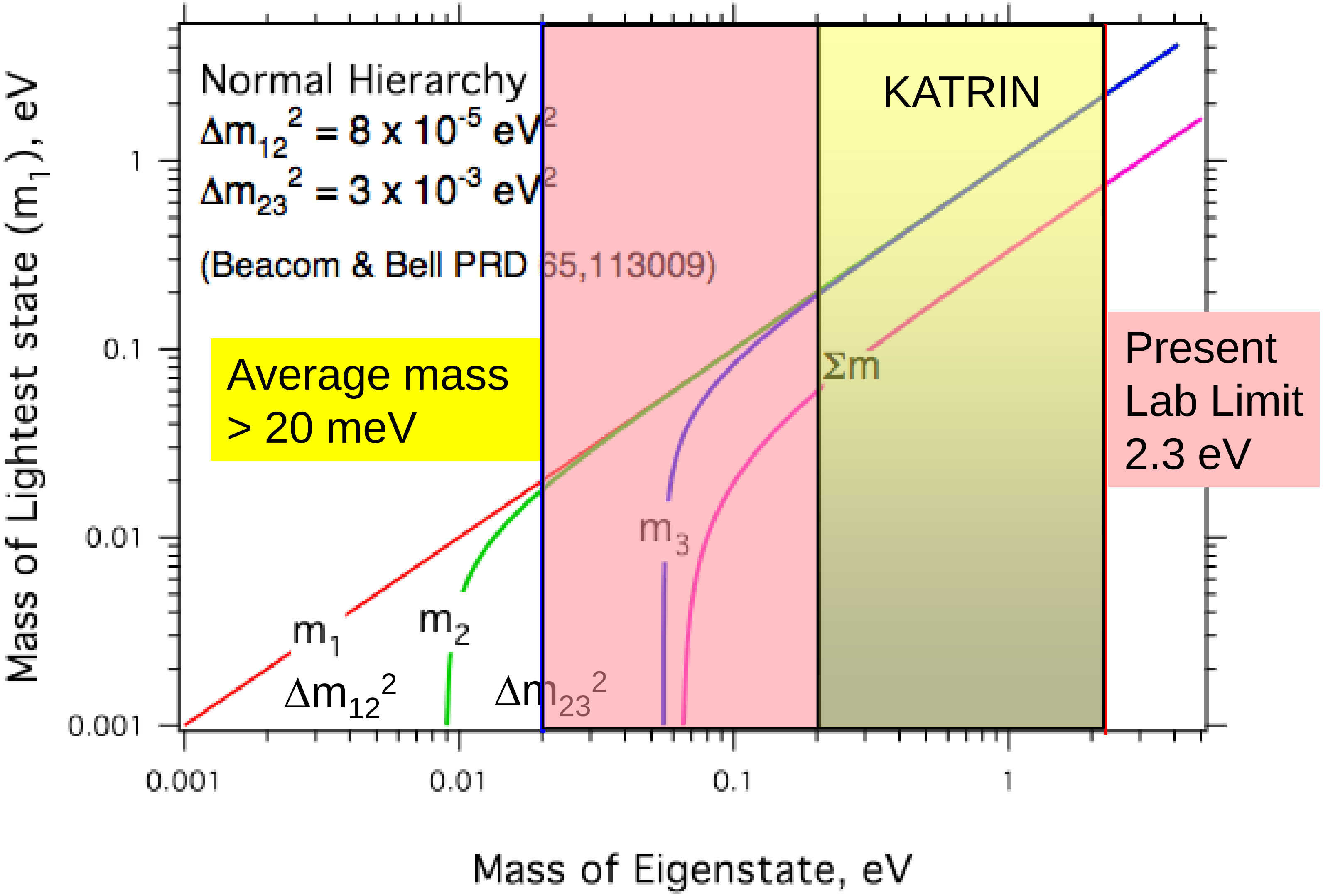
source of systematic shift	achievable/projected accuracy	systematic shift $\sigma_{syst}(m_\nu^2)[10^{-3}\mathrm{eV}^2]$
description of final states	$f < 1.01$	< 6
T^- ion concentration $n(T^-)/n(T_2)$	$< 2 \cdot 10^{-8}$	< 0.1
unfolding of the energy loss function (determination of f_{res})		< 2 < 6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

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

Improved sensitivity with larger system



Mass Range Accessible



Future tritium measurements?

- Ultimate sensitivity of spectrometers
  - require instrumental resolution of ~ E_e/m_ν
  - Linear size X of instrument scales with resolution:
    - Differential spectrometers $X \propto E_e/m_\nu$
    - Integral spectrometers $X \propto \sqrt{E_e/m_\nu}$
  - spectral fraction per decay in the last m_n of the spectrum is ~ $(m_\nu/E_o)^3$
  - source thickness is set by the inelastic scattering cross-section (3.4 x 10^{-18} cm^2), $\sigma n \leq 1$. Can't make it thicker, only wider.
  - If one wants ~1 event/day in last m_ν of the spectrum
    - for a 10 m magnetic spectrometer m_ν ~ 1.7 eV
    - for a 3 m dia. solenoid retarding field spectrometer m_ν ~ 0.3 eV

KATRIN is probably the end of the road for tritium beta decay

KATRIN outlook

- KATRIN can measure neutrino mass directly via kinematics of beta decay -- model independent
- Improvement of order of magnitude over previous best
- Challenging goal of $m_\nu < 0.2$ eV (90% C.L.) looks achievable
- German funding (33.5 M€) is in place
- US DOE funding ($2.5M) is in place
- Schedule for data collection beginning 3Q 2009.