- astroparticle physics motivation
- direct $\nu$–mass experiments
- KATRIN components: source & spectrometers
- sensitivity & outlook
neutrino masses in cosmology, astrophysics & particle physics

neutrino mass and hot dark matter

mass hierarchy

\[ \sum_{i=1}^{3} m_i \]

\[ m_{1,2,3} \]

\[ m_3 \]

\[ m_2 \]

\[ m_1 \]

\[ \Delta m_{23}^2 \]

\[ \nu_{atm} \]

\[ \Delta m_{12}^2 \]

\[ \nu_{solar} \]

\[ LMA \]

\[ \Omega_{\nu} h^2 = \sum m_\nu / 93.5 \text{ eV} \]

\[ \Omega_{\text{tot}} = 1.02 \pm 0.02 \]

flat universe

dark energy \( \Lambda \)

dark matter

structure formation

tritium experiments

baryons

stars & gas

KATRIN

Super-Kamiokande

\[ \Sigma m_i < 6.6 \text{ eV} (3\nu) \]

\[ \Sigma m_i < 2.2 \text{ eV} (3\nu) \]

\[ \Sigma m_i < 0.6 \text{ eV} (3\nu) \]

\[ \Sigma m_i > 0.05 \text{ eV} (1\nu) \]

\[ \Omega_{\nu} < 0.14 \ (3\nu) \]

\[ \Omega_{\nu} > 0.001 \ (1\nu) \]
three roads to neutrino masses

**β-decay**: absolute $\nu$-mass
- model independent, kinematics
- status: $m_\nu < 2.3$ eV
- potential: $m_\nu < 200$ meV
- EU&US: KATRIN

**$0\nu\beta\beta$-decay**: eff. Majorana mass
- $\nu$-nature (CP), peak at $E_0$
- status: $m_\nu < 0.35$ eV
- potential: $m_\nu < 30$ meV
- US: Majorana, EXO, EU: Cuore, Gerda

**laboratory**

**neutrino mass measurements**
- status 2004 & potential 2014

**cosmology**: $\nu$ hot dark matter $\Omega_\nu$
- model dependent, analysis of LSS data
- status: $m_\nu < 0.7$ eV
- potential: $m_\nu < 70$ meV
- US: WMAP, SDSS, LSST, EU: Planck

SN20xx

CMBR
cosmological studies

CMBR

WMAP

Powerspectrum of CMBR

220,000 galaxies with \( <z> = 0.11 \)

Powerspectrum of CMBR

best fit \( \Lambda \)CDM model

\[ P(k) \propto \frac{1}{k^2} \]

combined result

\[ m_\nu < 0.24 \text{ eV} \]

(95\%CL.)

+ Ly \( \alpha \) data

2dF powerspectrum of matter fluctuations

massive \( \nu \)'s: loss of power at small scales

analysis: \( 0.02 < k < 0.15 \)
cosmological studies

CMBR

WMAP

Powerspectrum of CMBR

220,000 galaxies with $<z>=0.11$

+ XLF data

combined result

$m_\nu = 0.24$ eV

(central value)

2dF powerspectrum of matter fluctuations

massive $\nu$'s: loss of power at small scales

analysis: $0.02 < k < 0.15$
model independent neutrino mass from $\beta$-decay kinematics

$$\frac{d\Gamma_i}{dE} = C p \left( E + m_e \right) \left( E_0 - E \right) \sqrt{(E_0 - E)^2 - m_i^2} F(E) \theta(E_0 - E - m_i)$$

$$C = G_F^2 \frac{m_e^5}{2 \pi^3} \cos^2 \theta_C |M|^2$$

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

$\beta$-source requirements:
- high $\beta$-decay rate (short $t_{1/2}$)
- low $\beta$-endpoint energy $E_0$
- superallowed $\beta$-transition
- few inelastic scatters of $\beta$'s

$\beta$-detection requirements:
- high resolution ($\Delta E < \text{few eV}$)
- large solid angle ($\Delta \Omega \sim 2\pi$)
- low background

Experimental observable is $m_\nu^2$
The history of tritium $\beta$-decay results includes:

- **ITEP**
  - $T_2$ in complex molecule
  - magn. spectrometer (Tret'yakov)
  - $m_\nu$: 17-40 eV

- **Los Alamos**
  - gaseous $T_2$ - source
  - magn. spectrometer (Tret'yakov)
  - $< 9.3$ eV

- **Tokio**
  - $T$ - source
  - magn. spectrometer (Tret'yakov)
  - $< 13.1$ eV

- **Livermore**
  - gaseous $T_2$ - source
  - magn. spectrometer (Tret'yakov)
  - $< 7.0$ eV

- **Zürich**
  - $T_2$ - source impl. on carrier
  - magn. spectrometer (Tret'yakov)
  - $< 11.7$ eV

- **Troitsk (1994-today)**
  - gaseous $T_2$ - source
  - electrostat. spectrometer
  - $< 2.05$ eV

- **Mainz (1994-today)**
  - frozen $T_2$ - source
  - electrostat. spectrometer
  - $< 2.3$ eV
**E-technique**

energy analysis by electrostatic retardation field (electrodes)

variable E-field:

$U_0 < 30 \text{ kV}$

integral particle transmission $E > U_0$

high pass filter!

\[ \vec{F} = (\mu \cdot \vec{v}) \vec{B} + q \vec{E} \]

$\mu = E_{\perp} / B = \text{const}$
Status of previous tritium experiments

Mainz & Troitsk have reached their intrinsic limit of sensitivity

Troitsk
windowless gaseous T₂ source
analysis 1994 to 1999, 2001
\[ m_\nu^2 = -2.3 \pm 2.5 \pm 2.0 \text{ eV}^2 \]
\[ m_\nu \leq 2.2 \text{ eV (95\% CL.)} \]

Mainz
quench condensed solid T₂ source
analysis 1998/99, 2001/02
\[ m_\nu^2 = -1.2 \pm 2.2 \pm 2.1 \text{ eV}^2 \]
\[ m_\nu \leq 2.2 \text{ eV (95\% CL.)} \]

Both experiments now used for systematic investigations
Karlsruhe Tritium Neutrino Experiment

at Forschungszentrum Karlsruhe
unique facility for closed $T_2$ cycle:
Tritium Laboratory Karlsruhe

~ 75 m linear setup with 40 s.c. solenoids
Experimental observable in $\beta$-decay is $m_{\nu}^2$.

**Aim:** improve $m_{\nu}$ by one order of magnitude (2 eV → 0.2 eV)

**Requires:** improve $m_{\nu}^2$ by two orders of magnitude (4 eV$^2$ → 0.04 eV$^2$)

**Problem:** count rate close to $\beta$-end point drops very fast ($\sim \delta E^3$)

Designing a next-generation experiment
tritium bearing components - overview

T=77 K  T=27 K  T=77 K  T=5 K

R=10^7  R=10^7

cryo-trapping

active pumping

tritium source

active pumping

T2 injection

inner Loop

T2 retention system, batch mode, 60 days (<1 Ci)

1%

isotope separ.

5%

Outer Loop

95%

R=10^7

DPS1-R

WGTS

DPS1-F

CPS1-F

CPS2-F

DPS2-F

DPS2-R

control system
windowless tritium source - design

molecular gaseous $\beta$-decay source, maximum luminosity ($10^{11} \beta/s$)

- integral design criterium: column density $\rho_d = 5 \times 10^{17}$ molecules / cm$^2$

precision: $\pm 0.1\%$

single design criteria:

- magnetic field $B = 3.6$ T (±2%)
- tritium injection $5 \times 10^{19}$ mol/s = $4.7$ Ci/s = $1.7 \times 10^{11}$ Bq/s = $40$ g tritium / day
- temperature $T = 27-30$K $\Delta T \leq 30$ mK
- pumping speed $12,000 \ell / s$
WGTS – tritium pressure

injection

conductance > 2000 ℓ/s
gas dynamics calculations
MC calculations

absolute pressure [µbar]
distance from WGTS centre [m]
WGTS – magnetic field

3.3m 3.3m 3.3m

6 T 5.6 T

5 T

3.6 T

4 T

3 T

2 T

1 T

-6m -4m -2m 0 2m 4m 6m 8m
WGTS – cooling concept

- **Operating temperature:** 27–28 K
  - **Spatial (homogeneity):** ± 0.1%
  - **Time (stability/hour):** ± 0.1%

**Conceptual design:**
2-phase Neon (boiling liquid)

![Diagram showing a 2-phase Neon beam pipe with tritium and helium vessels, and a graph showing liquid level vs. pipe length with upper and lower stability limits.]

- 2 separate cooling pipes Ø=16mm
  - (2 wall barrier concept for T₂)
closed tritium cycle

test experiment TILO  
design tritium cycle at TLK

experimental aims: test of
• molecular-kinetetic models
• measurement- & control system

measurements since June 2005

inner Loop  – stable WGTS parameters
outer Loop  – high tritium purity
task: active pumping of $T_2$ molecules

- flux reduction by factor $2 \times 10^8$

method: serial TMP pumpports (2000 l/s)

- 5 solenoids with $B=5.6T$
  (LHe bath cooling)
- 4 pumping ports ($T=77K$)
cryogenic pumping section

**objective:** retention of remaining tritium flux

tritium partial pressure spectrometer $p < 10^{-20}$ mbar

**method:** cryo-sorption on condensing Ar-frost

**rate:** $<1$ Ci $T_2$ in 60 days *(regeneration with warm He-gas)*
objective: retention of remaining tritium flux

tritium partial pressure spectrometer $p < 10^{-20}$ mbar

method: cryo-sorption on condensing Ar-frost

rate: $< 1$ Ci T$_2$ in 60 days (regeneration with warm He-gas)
electrostatic spectrometers

tandem design: pre-filter & energy analysis

**pre-filter**
fixed retarding potential
U=18.3 keV
\( \Delta E \approx 100 \text{ eV} \)

**precision filter**
variable retarding potential for scanning
U=18.4-18.6 keV
\( \Delta E = 0.93 \text{ eV} \)
electrostatic spectrometers

pre-spectrometer

tandem design: pre-filter & energy analysis

10^{10} e-/s

10^3 e-/s

10^{-2} e-/s

Reduction of background from ionising collisions

main spectrometer

detector
pre-spectrometer

Task: pre-filter for low-energy β-decay electrons (E < 18.4 keV)

~5 x 10^{10} \, \beta^-/s from WGTS

length: 3.42 m (flange-flange)
diameter: 1.70 m, stainless steel 1.4429
assembly works at French manufacturer SDMS

electropolished inner surface

assembly finished:
leak test at SDMS
pre-spectrometer

assembly works at Karlsruhe

heating / cooling system, s.c. magnets, vacuum instrumentation,

dry air compartment & HV safety interlock
pre-spectrometer: vacuum tests

UHV concept: TMP`s & NEG-getters

1. **outgassing rate @ -20°C**
   - specified: $1 \times 10^{-12}$ mbar l / cm$^2$ s
   - measured: $7 \times 10^{-14}$ mbar l / cm$^2$ s
   - gas charge: ~50% vessel, ~50% TMP&QMS

2. **final pressure**
   - specified: $p < 10^{-11}$ mbar @ -20°C
   - measured: $p < 10^{-11}$ mbar @ RT

important radioactivity tests of NEG getters @MPIK ⇒ low level getters
task: verification of electromagn. concept

8x8 Si-PIN Array

pre-spectrometer: elmagn. tests

wire electrode

s.c.-magnets

electron gun
main spectrometer – design

design parameters:

- volume: 1258 m$^3$
- surface: 605 m$^2$
- thickness: 32 mm
- material: 1.4429
- weight: 192 t

pumping port for getters
main spectrometer – manufacture

2 conical end pieces

1 cylindrical centre piece
main spectrometer – manufacture

- 2 conical end pieces
- 1 cylindrical centre piece

- Plasma cutting under water
- Stainless steel plates
main spectrometer – manufacture

2 conical end pieces

1 cylindrical centre piece

Deggendorf, January 31 2006
main spectrometer – manufacture

2 conical end pieces

1 cylindrical centre piece

electro-polishing
main spectrometer – transport logistics

Delivery to FZK:
September, 21 2006
tasks of inner wire-based electrode system:

- background reduction
  - screening of low-energy electrons
  - removal of trapped particles
- fine forming of retarding potential

main spectrometer – inner electrode
**inner wire-based electrode system**

**two-layer system**

1. wire plane
   parallel/equidistant to spectrometer wall
   const. wire spacing
   const. $U_1 = U_{sp} + \Delta U_1$

2. wire plane
   non-equidistant
   var. wire spacing
   var. $U_2 = U_{sp} + \Delta U_2$

wire sag: sub-mm!
Mounting system for electrode system

Conceptual design for a UHV compatible mounting system in main spectrometer inner volume
precision HV supply

measurements require HV-stabilisation/monitoring/calibration on ppm level (wideband: DC up to MHz)

0 - 35 kV voltage divider 0 - 10 V
1:1972

precision-HV power supply
< ± 5 ppm stability

precision-digital-Voltmeter
0.5ppm/h (4ppm/1y)

test at PTB: sub-ppm level reached!!
 ppm-voltage divider ✅
transported magnetic flux 191 T cm²

emotional transmission:
1. magnetic conversion
2. electrostatic retardation

detector

E=18.6 keV

γ (start) = 30 min
elv (start) = 51 deg
azm (start) = 10 deg

energy analysis

center of entrance solenoid
analysing plane

β-decay electrons from WGTS
Air coil system

electromagnetic layout based on additional air coil system:
- Compensation earth magnetic field (EMC) axially
- Homogeneity B-field analysing plane (LFC) radially

EMC units
(cos-arrangement)
Length = 24m

Mounting test of first air coil
task: detection of transmitted β-decay electrons with high energy resolution ($\Delta E = 1$ keV)
record radial profile of flux tube
aim: background minimisation, systematic effects

design: radially segmented Si-PIN diode array
~400 pixels with $A=100$ cm$^2$
KATRIN design optimisation

Improvement of experimental sensitivity (2001-04)

- Enlargement of WGTS diameter ($\times 2$)
- Enlargement of main spectrometer dimensions ($\varnothing = 7 \text{ m} \rightarrow 10 \text{ m}, L = 20 \text{ m} \rightarrow 23 \text{ m}$) for $\Delta E = 0.93 \text{ eV}$
- Improved tritium infrastructure ($T_2$ purity 70% $\rightarrow$ 95%)
- Inner wire electrode system (pre- & main spectrometer)
- Active trap clearing (dipole fields, FT-ICR)
- Extreme UHV with $p < 10^{-11} \text{ mbar}$
- Monitor spectrometer (reference for HV)
- System for measuring inelastic $\beta$-scatterings in WGTS
- Stabilisation of WGTS-parameters to 0.1% ($T, p_{\text{inj}}, \ldots$)
- Optimisation & enlargement of tritium pumping section
MC spectra for 1 full measuring year KATRIN

- source column density: \( \rho_d = 5 \times 10^{17} \text{ cm}^{-2} \)
- magnetic field strengths: \( B_S, B_{\text{pinch}}, B_A = 3.6, 6, 3 \times 10^{-4} \text{ T} \)
- energy resolution: \( \Delta E/E = 1/20000 = 0.93/18600 \)
- effective analysing area: \( A_{\text{eff}} = \pi \times (450 \text{ cm})^2 \)
- imaged source area (deduced): \( A_S = \pi \times (4.11 \text{ cm})^2 \)
- Tritium source purity: \( \varepsilon_{\text{Tritium}} = 0.95 \)
- detector efficiency: \( \varepsilon_{\text{Detector}} = 0.9 \)
- \( \beta \) endpoint energy: \( E_0 = 18575.0 \text{ eV} \)
- background rate per \( U_0 \): \( \Gamma = 10 \text{ mHz (1 mHz)} \)

scanning procedure: time per \( U_0 \)
- 2× stronger gaseous source (Ø=75mm → Ø=90mm) required Ø=10m spectrometer
- optimised measuring point distribution (~5 eV below $E_0$)
- active background reduction by inner electrode system, low background detector (needs further detailed tests)
background – sources & suppression

total background rate at Mainz/Troitsk: \(\sim 10\ \text{mHz}\), aim for same rate at KATRIN

- **detector:** aim for bg-rate in few mHz range, environmental \(\gamma\)'s / X-rays & cosmics, larger area: better energy resolution & better shielding, thinner detector, material selection
develop background model on GEANT4.4 simulations

- **spectrometer:** aim for bg-rate in few mHz range
  a) low energy shake off electrons from tritium \(\beta\)-decays
  \[1\text{mHz bg-rate from } \sim 10^{-20}\ \text{mbar tritium partial pressure} \text{ (cryotrapping section)}\]
  b) \(\beta\)-decay electrons in keV-range that get trapped (\(\rightarrow\) ionising collisions)
      stringent XHV conditions \(< 10^{-11}\ \text{mbar}\) & active removal of trapped particles
  c) cosmic ray induced \(\delta\)-electrons (muons, elmag. showers, hadronic component)
      can create ions, \(\rightarrow\) tertiary reactions: electrons & \(H^-\) ions,
      stringent XHV conditions \(< 10^{-11}\ \text{mbar}\) & active removal of trapped particles
  d) trapped \(\beta\)-electrons (from 'normal' tritium decays in WGTS)
      stringent XHV conditions \(< 10^{-11}\ \text{mbar}\) & active removal of trapped particles

- **sources:**
  a) \(\beta\)-electrons from tritium decays in areas with different source potential
  b) \(\beta\)-electrons from \(T^-\) ions (higher end-point) careful electromag. design
1. inelastic scatterings of β´s inside WGTS (major uncertainty in KATRIN)
   - requires dedicated e-gun measurements, unfolding techniques for response fct.
2. HV stability of retarding potential on ~1ppm level required
   - precision HV divider (PTB), monitor spectrometer beamline
3. fluctuations of WGTS column density (required < 0.1%)
   - e-gun measurements, rear detector, rear plate,
     Laser-Raman spectroscopy, stabilisation of T=27K beam tube, injection pressure
4. WGTS charging due to remaining ions (MC: \( \phi < 20\text{mV} \))
   - inject low energy meV electrons from rear side, diagnostic tools available
5. final state distribution
   - very reliable quantum-chem. calculations exist, new calc. by J Tennyson (UCL)
molecular excitations

$\beta$-decay of molecular $T_2$: recoil energy, electronic & rotational-vibrational excitations

$E_R = 1.72 \text{ eV} @ 18.6 \text{ keV}$

<table>
<thead>
<tr>
<th>final state probability</th>
<th>electronic final state</th>
</tr>
</thead>
<tbody>
<tr>
<td>14%</td>
<td>continuum</td>
</tr>
<tr>
<td>29%</td>
<td>excited states</td>
</tr>
<tr>
<td>57%</td>
<td>ground state</td>
</tr>
</tbody>
</table>

$E_\beta = 18.6 \text{ keV}$

probability for excitation

rotational and vibrational excitations

excited electronic states

ground state

integration of spectrum yields 99.93% of total population probability

absolute accuracy of theory = 0.2 %

calibration & long-term monitoring

absolute calibration of energy

K-32 conversion e\(^{-}\) line of gaseous \(^{83m}\)Kr

\[ E = \left[ (17824.35 \pm 0.75) - (\phi_{\text{spec}} - \phi_{\text{spec}}) \right] \text{ eV} \]

difference in work functions

based on

\[ E_\gamma \text{ (gamma energy)} = (32151.55 \pm 0.75) \text{ eV} \]
\[ E_b \text{ (bind. energy of K-elec.)} = (14327.09 \pm 0.39) \text{ eV} \]
& atomic recoil energy corrections

precision for \( E \) can be further improved!

long-term monitoring of retarding energy

use separate monitor source & separate monitor spectrometer

QCMS: *quench condensed* monitor source of \(^{83m}\)Kr
either \(^{83}\)Rb / \(^{83}\)Kr source or repeated condensation of \(^{83}\)Kr

monitor spectrometer:

transfer Mainz spectrometer to KATRIN experimental hall
fed by *same HV as spectrometer*

*need to accelerate electrons from \(^{83m}\)Kr (~800 V, high prec. )*
**KATRIN sensitivity**


- improved statistics: source luminosity, scanning
- reduced systematics: β-energy losses in source

**sensitivity (90% CL)**

\[ m(\nu) < 0.2 \text{ eV} \]

**discovery potential**

\[ m(\nu) = 0.35 \text{ eV (5}\sigma) \]

- improved statistics: source luminosity, scanning
- reduced systematics: $\beta$-energy losses in source

KATRIN sensitivity

improved sensitivity & $\beta\beta_0$\nu

$E_0=2039$ keV

claim for $m_{ee}=0.44$ eV (4.2$\sigma$) [0.1-0.9eV]

sensitivity optimisation: LoI (2001) \rightarrow \text{reference design (2004)}

- improved statistics: source luminosity, scanning
- reduced systematics: $\beta$-energy losses in source

\[
\begin{align*}
\end{align*}
\]

claim for $m_{ee}=0.44 \text{ eV (4.2\sigma)} \ [0.1-0.9\text{eV}]$

KATRIN sensitivity
KATRIN Collaboration

at present > 105 members
D-USA-UK-RU-CZ-BR
18 institutes
new in 2005: MIT, UCL

K. Maier, R. Vianden
Universität Bonn, Helmholtz - Institut für Strahlen- und Kernphysik (D)

J. Herbert, O. Malyshnev, R. Reid
ASTeC*, CCLRC- Daresbury Laboratory, Daresbury (UK) (*Expertengruppe)

I.N. Meshkov, Y. Syresin
JINR*, Dubna (RU) (*assoz. Mitglied)

A. Ospowicz
Fachhochschule Fulda, FB Elektrotechnik (D)

T. Armbrust, L. Bornschein, G. Drexin, F. Eichelthardt, F. Habermehl, F. Schwamm, J. Wolf
Universität Karlsruhe, Institut für Experimentelle Kernphysik (D)

Forschungszentrum Karlsruhe, Institut für Kernphysik (D)

A. Beglarian, H. Gemmeke, S. Wustling
Forschungszentrum Karlsruhe, Institut für Prozeßdatenverarbeitung und Elektronik (D)

Forschungszentrum Karlsruhe, Institut für Technische Physik (D)

U. Besserer, B. Bornschein, L. Dörr, M. Glugla, G. Hellriegel, O. Kazachenko, P. Schäfer, J. Wendel
Forschungszentrum Karlsruhe, Tritium Labor Karlsruhe (D)

M. Keilhauer, M. Neuberger, A. Weis
Forschungszentrum Karlsruhe, S-Bereich: Kfm. Projektabwicklung/Aufträge (D)

J. Angnik, J. Bonn, R. Carr, K. Essig, B. Flatt, C. Kraus, E.W. Olten, P. Schwinzer, D. Sevilla Sanchez
Universität Mainz, Institut für Physik (D)

H.W. Ortjohann, B. Ostrick, M. Prall, T. Thummler, N.A. Titov, K. Valerius, C. Weinheimer
Universität Münster, Institut für Kernphysik (D)

G.R. Myreni
Jefferson Laboratory/Old Dominion*, Newport News (USA) (*Expertengruppe)

F. Sharipov
Universidade Federal do Parana*, (Brasilien) (*Expertengruppe)

E.V. Geraskin, O.V. Ivanov, V.M. Lobashev, S. Ospov, A. Skasyrskaya, V. Usanov, S.A. Zadorozhny
Academy of Sciences of Russia, INR Troitsk (RU)

O. Dragoun, J. Kašpar, A. Kovalík, M. Ryšavý, A. Špalek, D. Věrová, M. Zbořil
Czech Academy of Sciences, NPI, Rež / Prague (CZ)

University of Washington, Seattle (USA)

M. Charlton, A.J. Davies, R. Lewis, H.H. Telle
University of Wales, Swansea (UK)
<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001</td>
<td>first presentation, founding of KATRIN collaboration, LoI: hep-ex/0109033 BMBF funding 'Astroteilchenphysik'</td>
</tr>
<tr>
<td>since 2002</td>
<td>background studies, R&amp;D works, design optimisation</td>
</tr>
<tr>
<td>2003</td>
<td>pre-spectrometer manufacture, order for first large magnet group</td>
</tr>
<tr>
<td>2004</td>
<td>evaluation by HGF programme, Design Report 2004, orders for main spectrometer, WGTS &amp; He-liquefier,…</td>
</tr>
<tr>
<td>2005</td>
<td>vacuum tests pre-spectrometer</td>
</tr>
<tr>
<td>2006</td>
<td>electromagn. tests pre-spectrometer, main spectrometer on site</td>
</tr>
<tr>
<td>2007</td>
<td>source demonstrator, inner electrode mounting</td>
</tr>
<tr>
<td>2008</td>
<td>commissioning of WGTS, tritium loops, em. test of spectrometers</td>
</tr>
<tr>
<td>2009</td>
<td>system integration &amp; first tritium runs</td>
</tr>
<tr>
<td></td>
<td>regular data taking for 5-6 years (3fb years)</td>
</tr>
</tbody>
</table>
the growing excitement of neutrino physics

Summary

measure absolute neutrino masses

KATRIN only model-independent approach with sub-eV sensitivity