Karlsruhe Institute of Technology

Graduiertenkolleg 2149
Research Training Group

Measuring the neutrino mass with KATRIN

Annual Retreat of RTG 2149 *"Strong and Weak Interactions — From Hadrons to Dark Matter"*

WWU Münster / Telgte, 24-26 November 2015

Kathrin Valerius (KIT Center Elementary Particle and Astroparticle Physics, KCETA)

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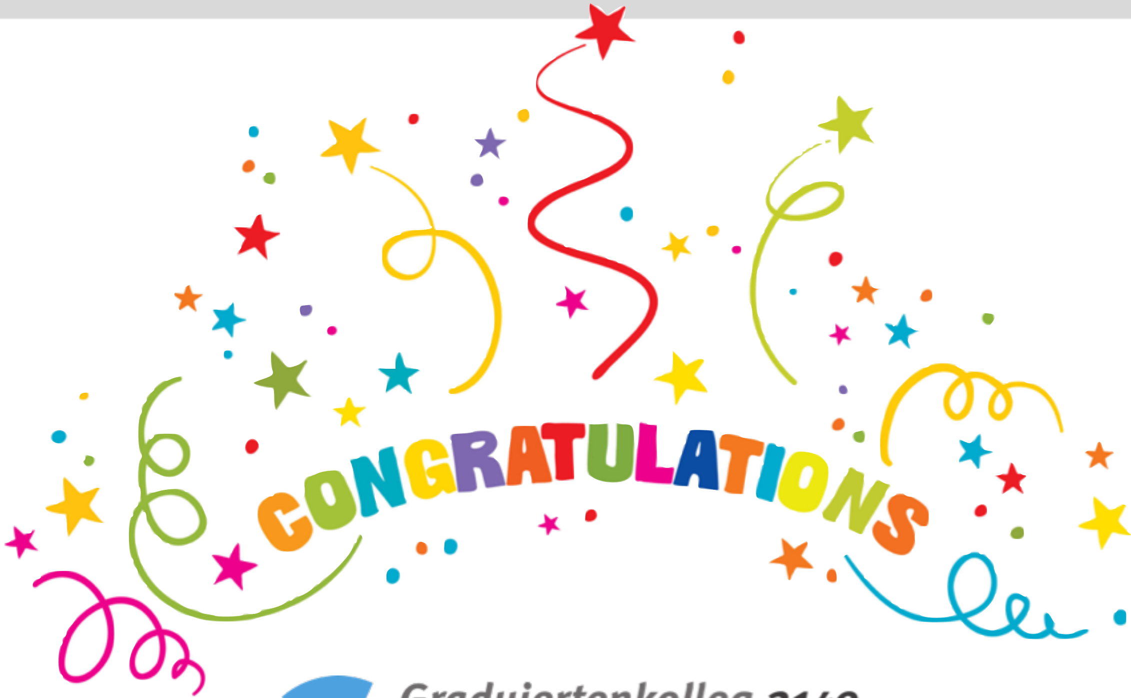

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Outline

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brief motivation

I. Why study massive neutrinos?

puzzling neutrinos

direct ν-mass measurement

II. How does neutrino mass measurement with KATRIN work?

elusive neutrinos

status & outlook

III. What are current steps to prepare the start of measurements with KATRIN?

challenging neutrinos

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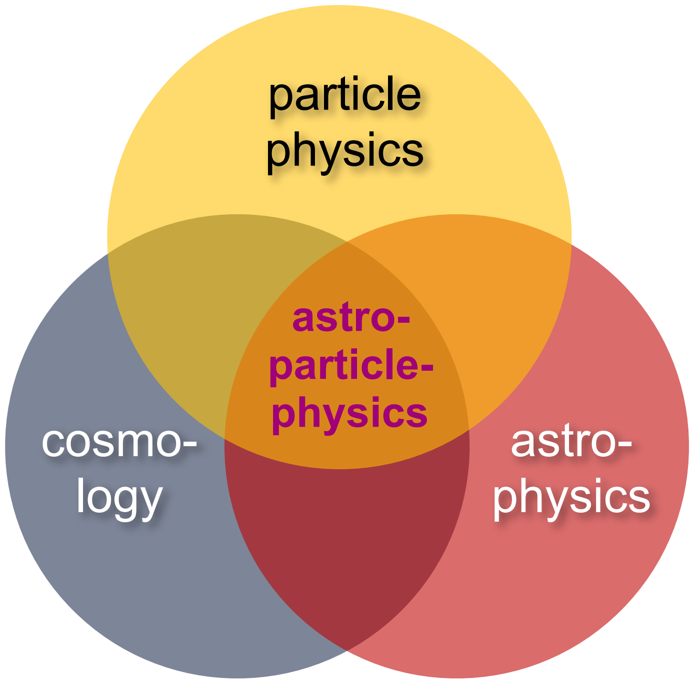
I. Motivation:

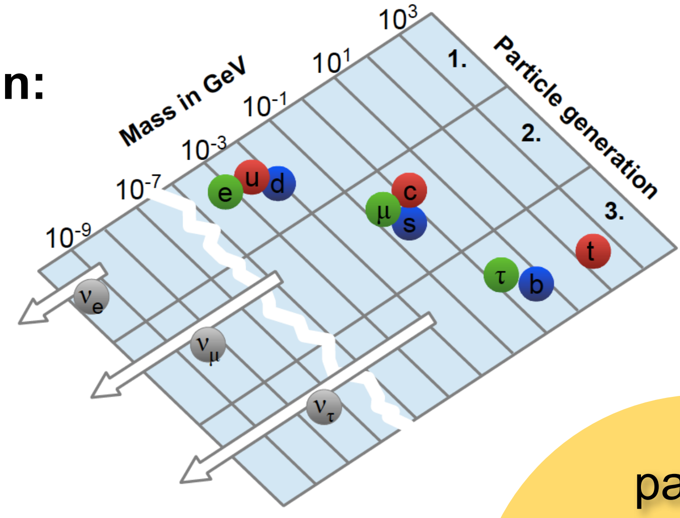
Massive neutrinos

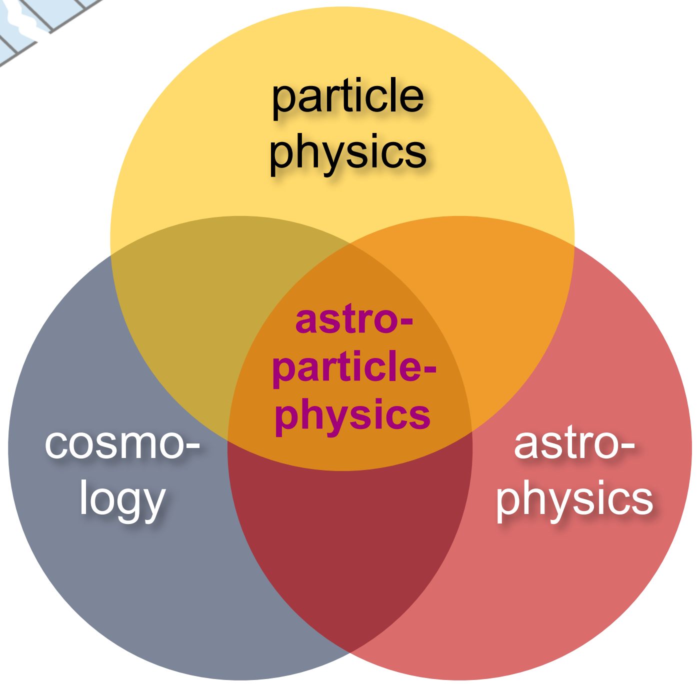
Massive neutrinos in astroparticle physics



Massive neutrinos in astroparticle physics

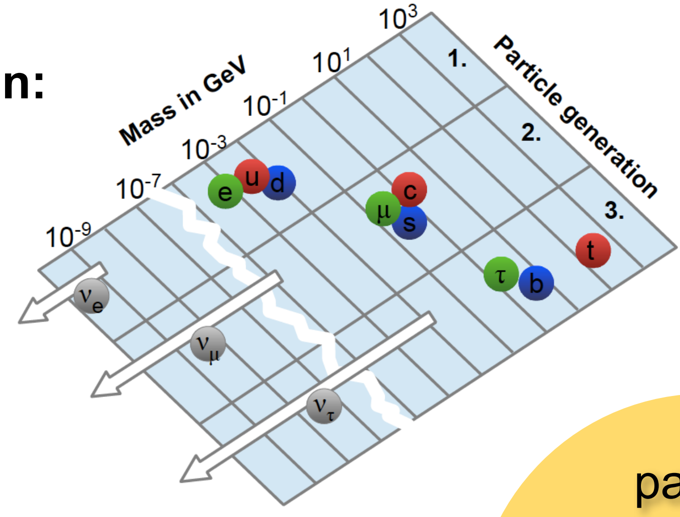
mass generation: new concepts

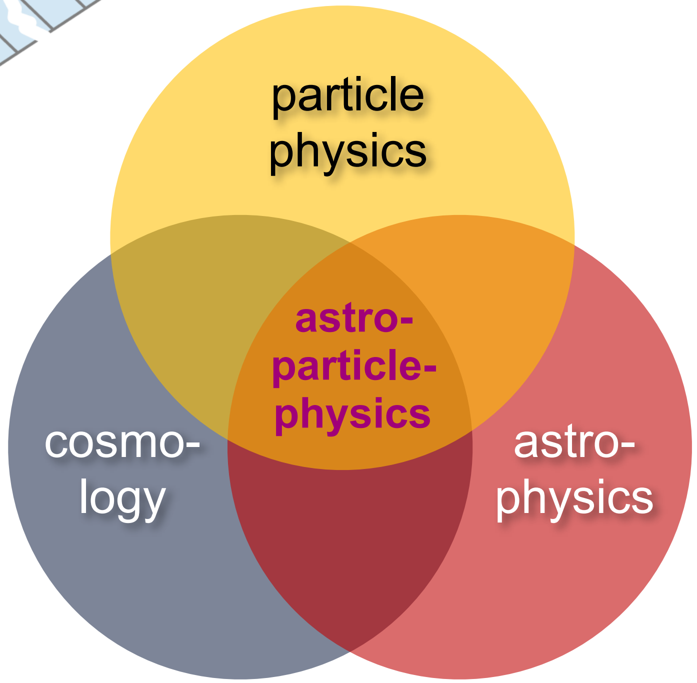




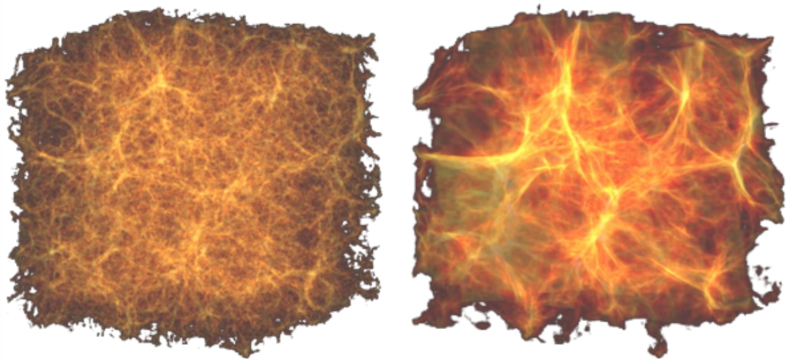
Massive neutrinos in astroparticle physics

mass generation: new concepts





massive neutrinos as “cosmic architects”



$\Sigma\, m_\nu$ = **0 eV** **6.9 eV**

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Massive neutrinos in astroparticle physics

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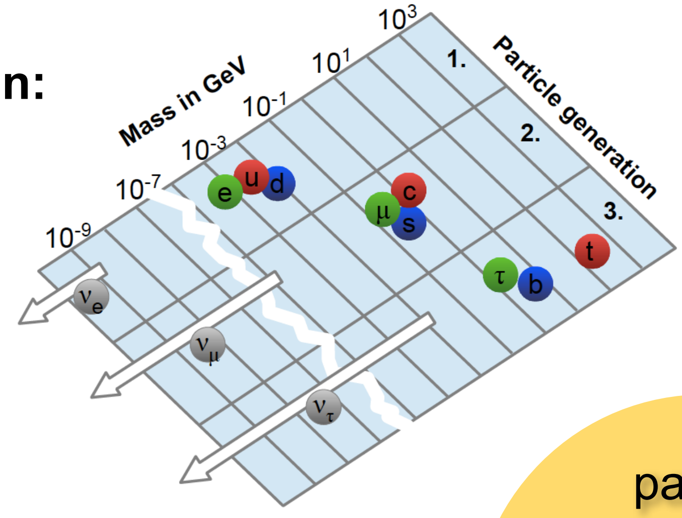
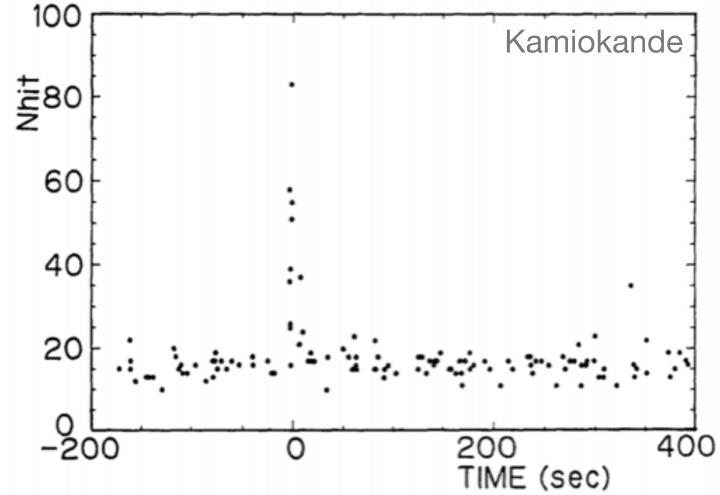
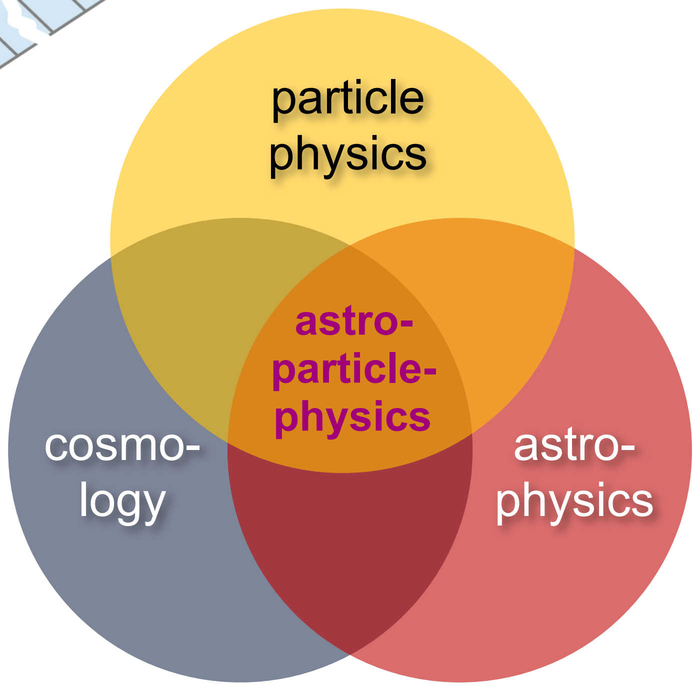
mass generation: new concepts



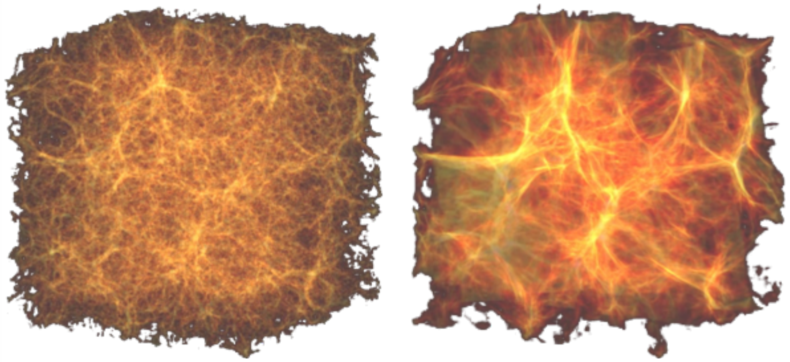
understanding astrophysical processes

Neutrino burst from SN 1987a





massive neutrinos as "cosmic architects"



Σm_ν = **0 eV** **6.9 eV**

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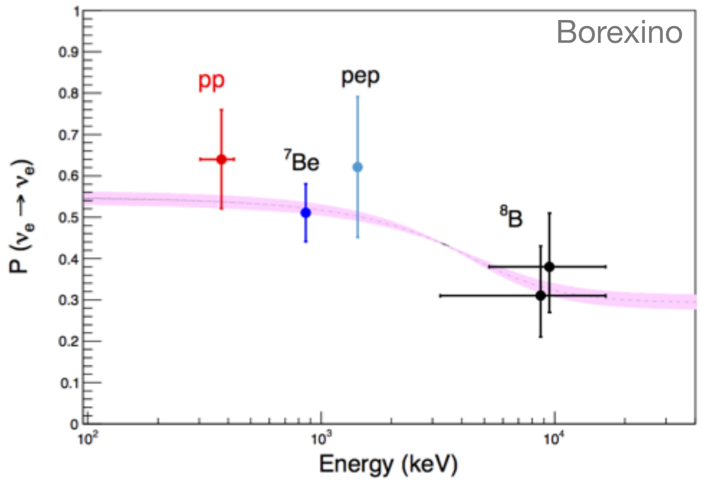
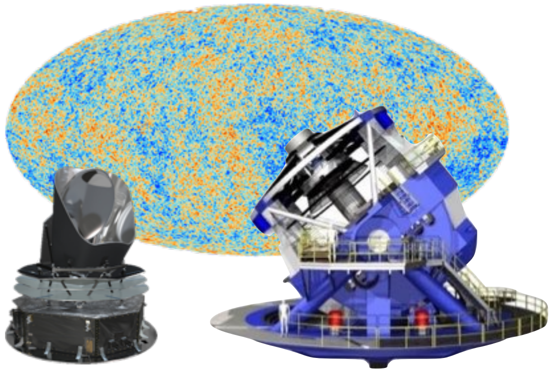
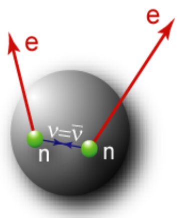
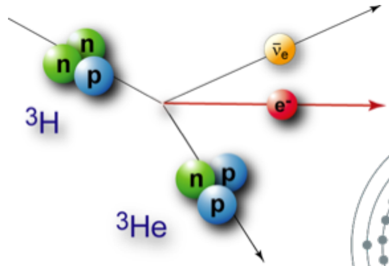
Matter effects in the sun

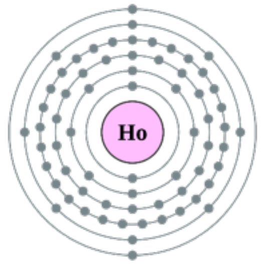


Complementary paths towards ν masses



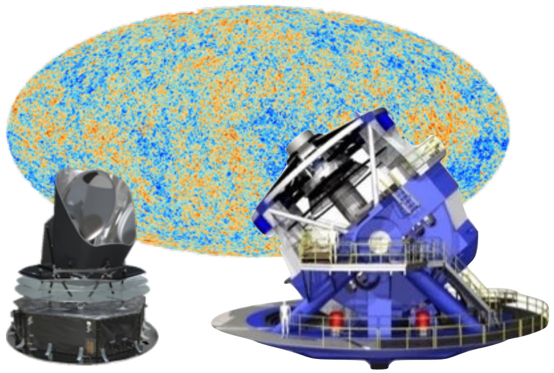


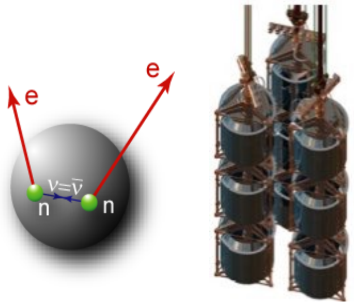


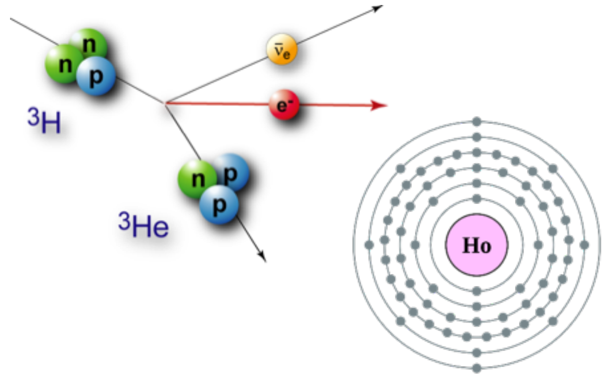


Tool	**Cosmology** CMB + LSS + ...	**Neutrinoless double β-decay**	**β-decay endpoint and EC**
Observable	$\sum m_\nu = \sum_{i=1}^{3} m_i$	$\langle m_{\beta\beta}\rangle = \left\lvert \sum_{j=1}^{3} \lvert U_{ej}\rvert^2 m_j e^{i\alpha_j} \right\rvert$	$m_\beta^2 = \sum_{i=1}^{3} \lvert U_{ei}^2 \rvert m_i^2$
Present upper limit	0.2 – 1 eV	0.2 – 0.4 eV	2 eV
Potential	20 – 50 meV	20 – 50 meV	200 meV
Model dependence	Multi-parameter cosmological model	- Majorana vs. Dirac - nucl. matrix elements	- **Direct,** only kinematics; - agnostic to Dirac/ Majorana nature

Complementary paths towards ν masses







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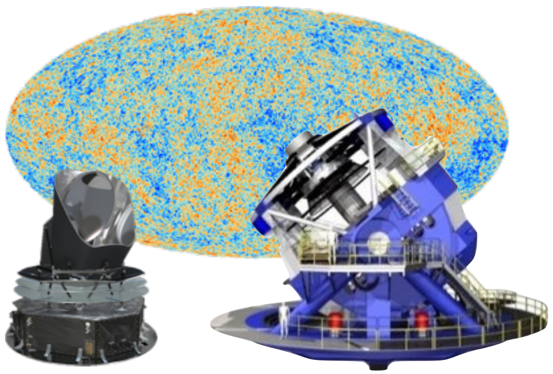
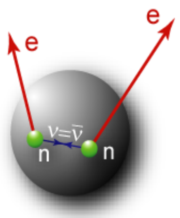
S. Hannestad

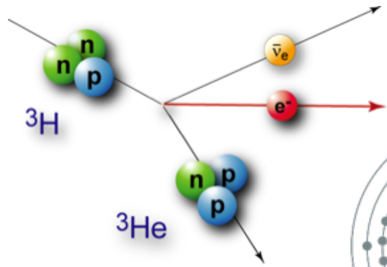
M. Lindner

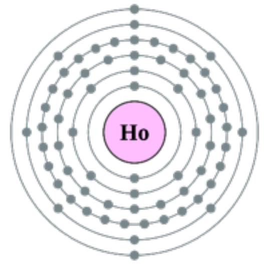
Complementary paths towards ν masses

Karlsruhe Institute of Technology









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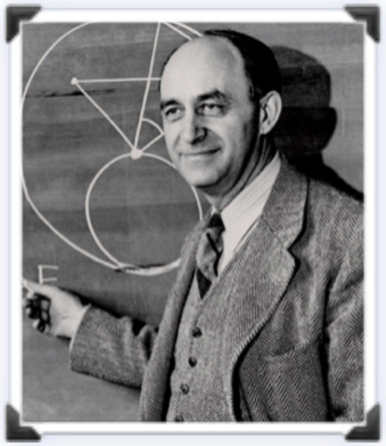
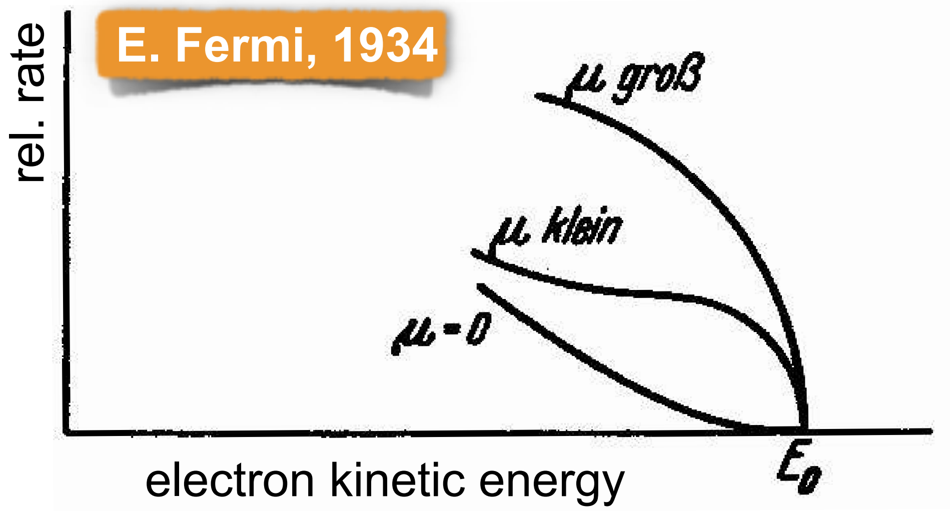
S. Hannestad

M. Lindner

II. Method:

Direct neutrino mass measurement in the laboratory





Direct neutrino mass measurement

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Imprint of m_ν on endpoint region of β spectrum (similar for EC):

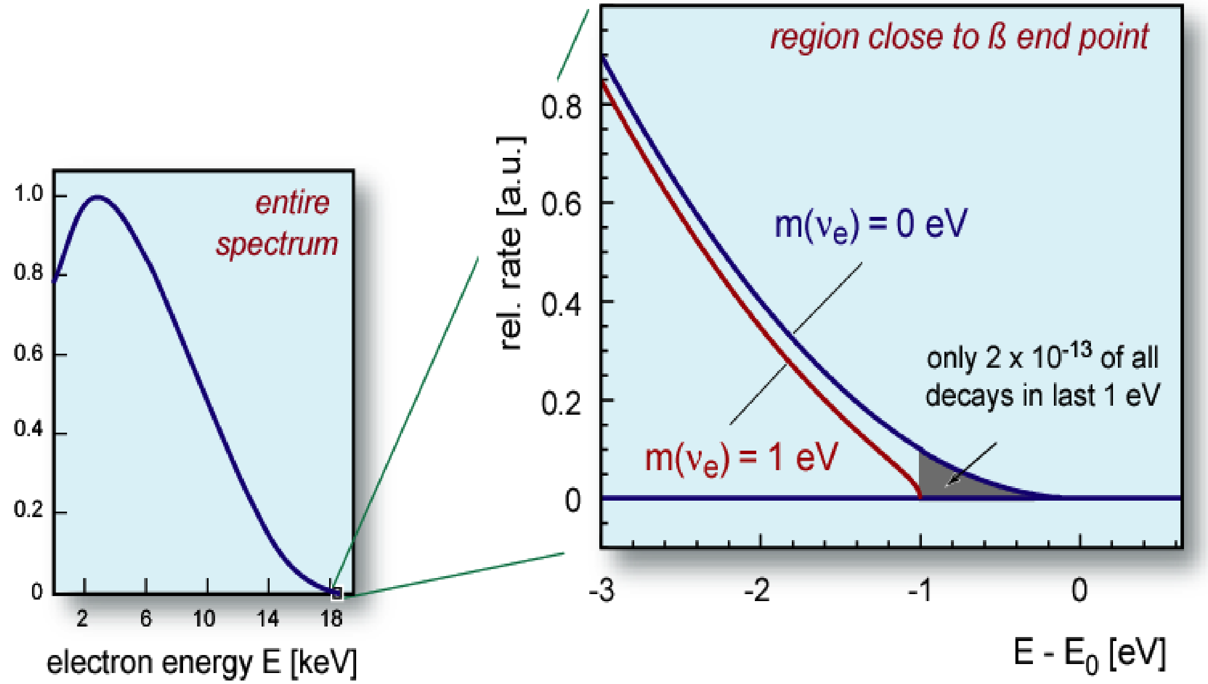
$$\frac{dN}{dE} = C \cdot F(Z,E) \cdot p \cdot (E+m_e) \cdot (E_0 - E) \cdot \sqrt{(E_0-E)^2 - m^2(\nu_e)}$$

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

observable: effective squared mass

Key requirements

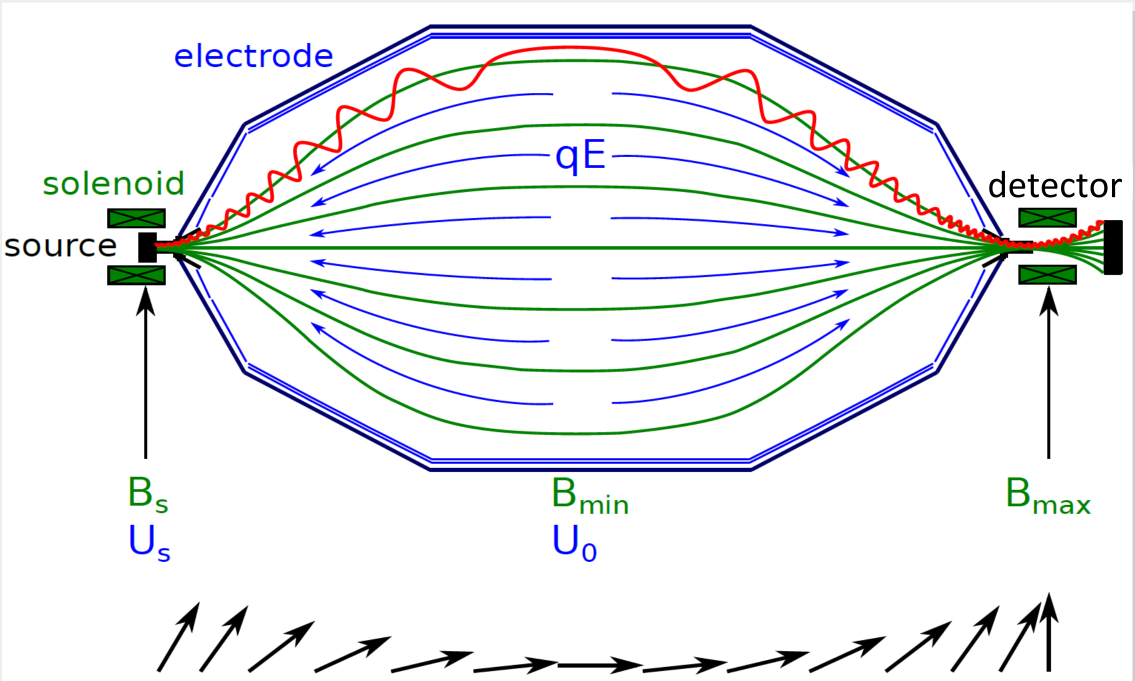
- Source isotope:
  - Low spectral endpoint Q
  - Large decay rate (short $T_{1/2}$)
- Instrument:
  - Excellent energy resolution
  - Very low background



Spectroscopic technique for β decay

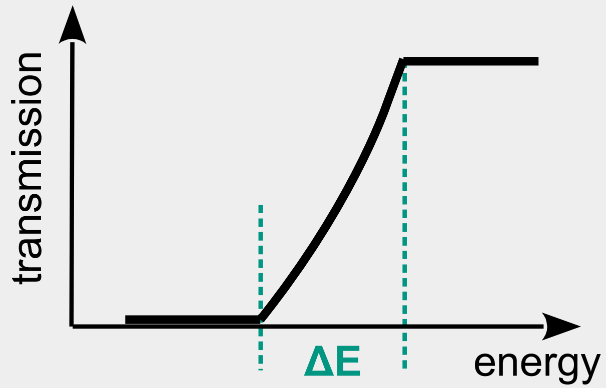
MAC-E filter technique

Magnetic Adiabatic Collimation with Electrostatic filter
Picard et al., NIM B63 (1992) 345



$$\mu = \frac{E_\perp}{B} = \text{const.}$$

Sharp high-pass filter:



Steps of filter potential
→ integrated β spectrum

Combination of high luminosity and high energy resolution:

$$\frac{\Delta E}{E} = \frac{B_{min}}{B_{max}} = \frac{1}{20000}$$

(at KATRIN)

PDG 2014

VALUE (eV)	CL%	DOCUMENT ID		
< 2 OUR EVALUATION				
< 2.05	95	[1] ASEEV	11	**Troitsk exp.**
< 2.3	95	[2] KRAUS	05	**Mainz exp.**

PDG 2014

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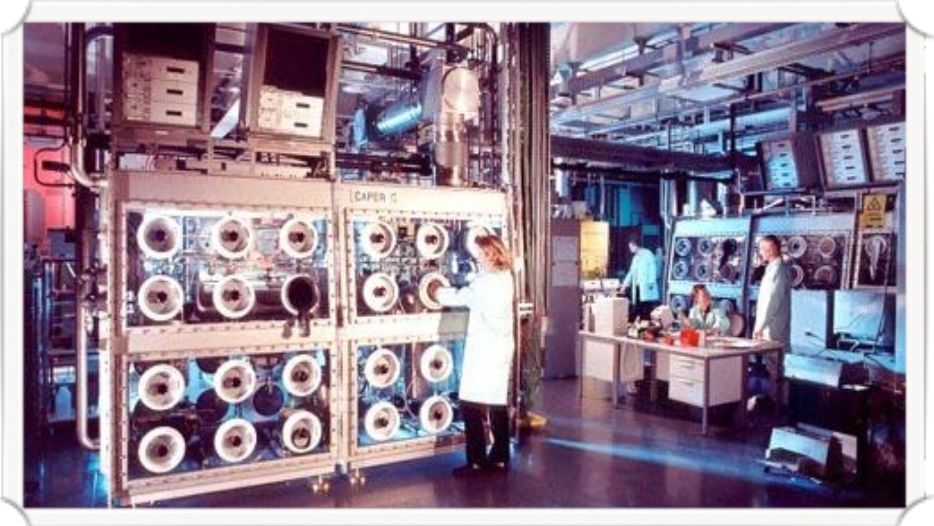
Sensitivity on m(ν_e):

2 eV ➜ **0.2 eV** (90% CL, 3 net years)

➜ Requires **x100** improvement on **m^2(ν_e)**

➜ Use expertise and infrastructure at KIT (Tritium Laboratory Karlsruhe, TLK)



KATRIN: A next generation tritium beta decay experiment with sub-eV sensitivity for the electron neutrino mass

KIT Karlsruhe Institute of Technology

PDG 2014

VALUE (eV)		CL%	DOCUMENT ID	
< 2	**OUR EVALUATION**			
< 2.05		95	[1] ASEEV	11
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Troitsk exp.
Mainz exp.

Sensitivity on $m(\nu_e)$:

2 eV ➜ **0.2 eV** (90% CL, 3 net years)

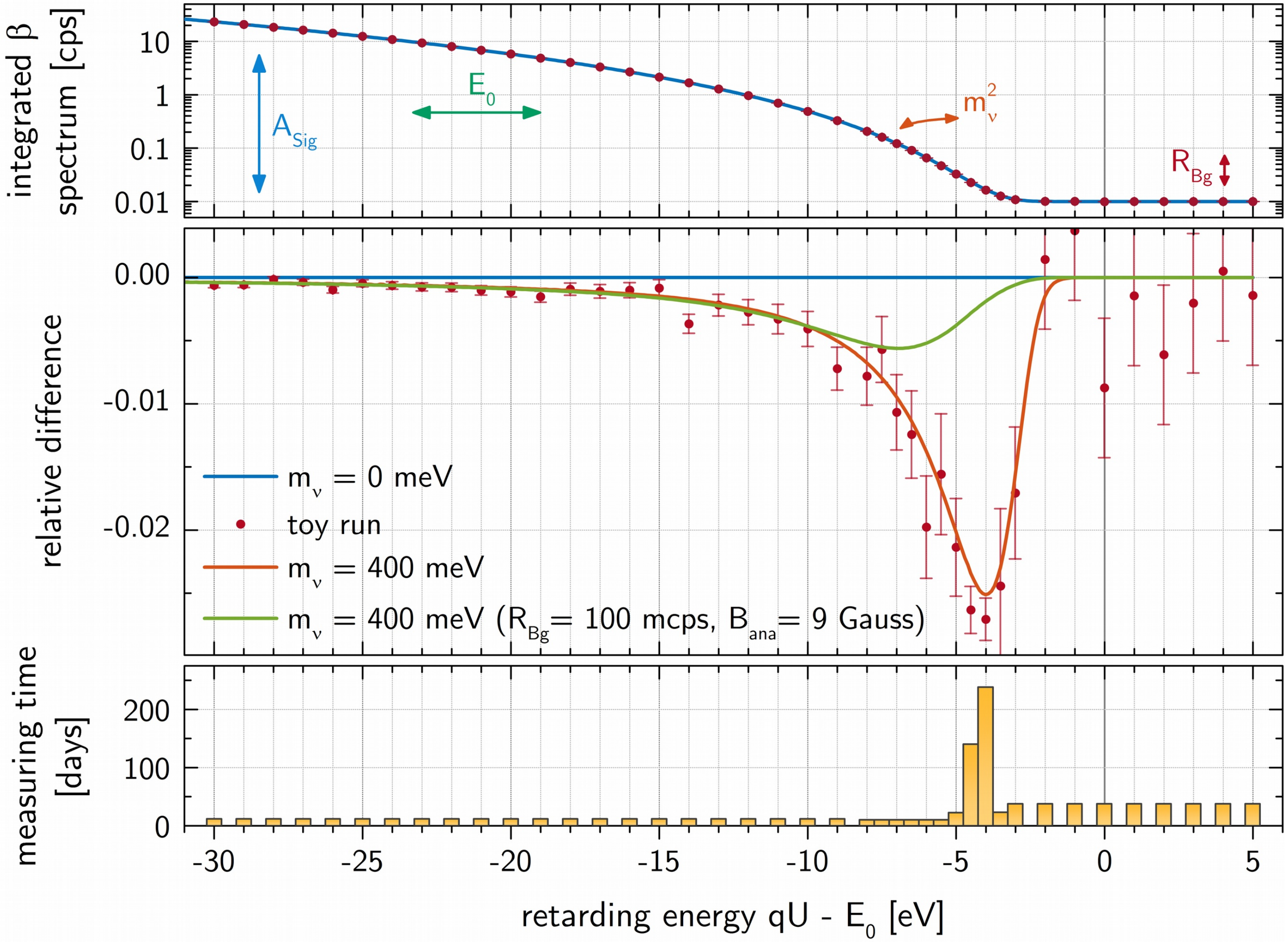
➜ Requires **x100** improvement on $\mathbf{m^2(\nu_e)}$

➜ Use expertise and infrastructure at KIT (Tritium Laboratory Karlsruhe, TLK)

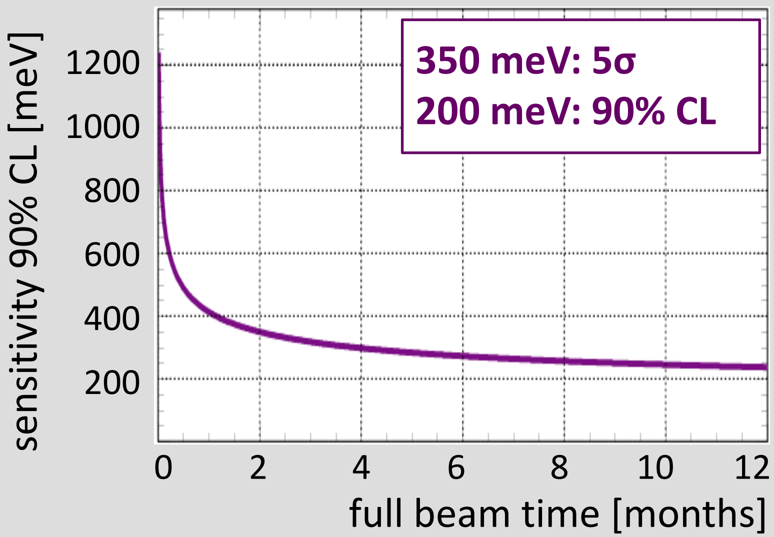
KATRIN collaboration:
~120 members
from 15 institutions in 5 countries

KATRIN: spectral fit & ν-mass sensitivity

Relative **shape** measurement of **integrated β spectrum:**

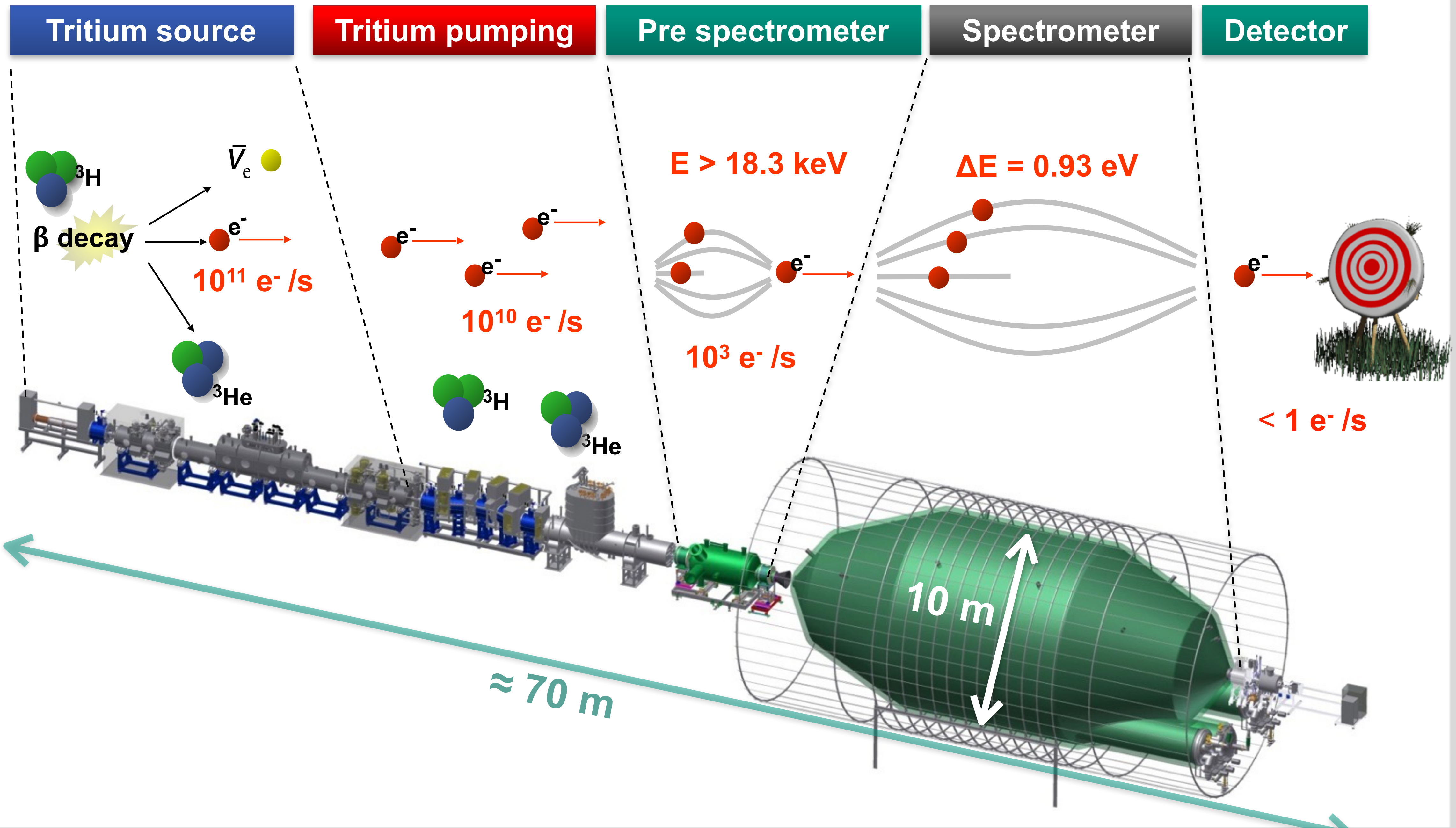


- 4 fit parameters:
  m_ν^2 , E_0 , A_S , R_{Bg}
- After **3 yrs** of data (~5 cal. yrs): balance of statistics and systematics



[figure c. M. Kleesiek]

KATRIN overview: 70 m beamline



Factor of 10 in sensitivity seems easy on paper, but …

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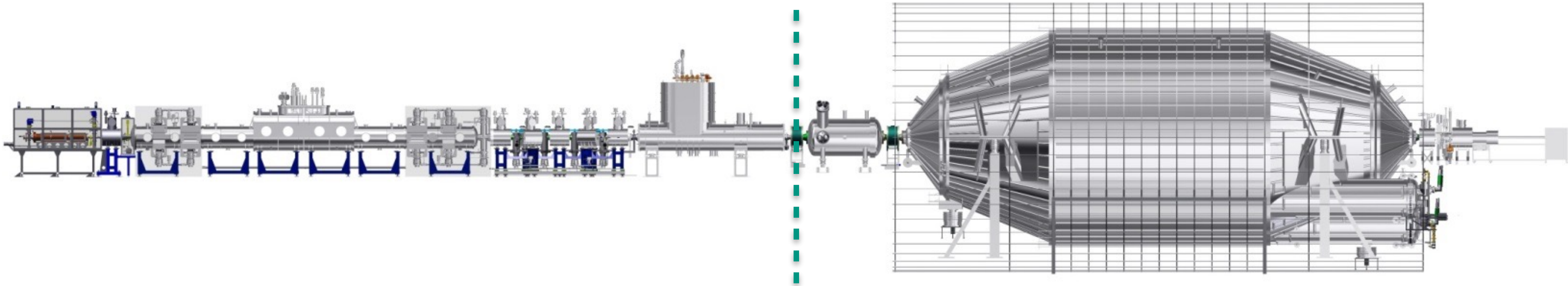
Factor of 10 in sensitivity seems easy on paper, but …

Eggenstein near Karlsruhe, Nov. 25, 2006

Experimental challenges



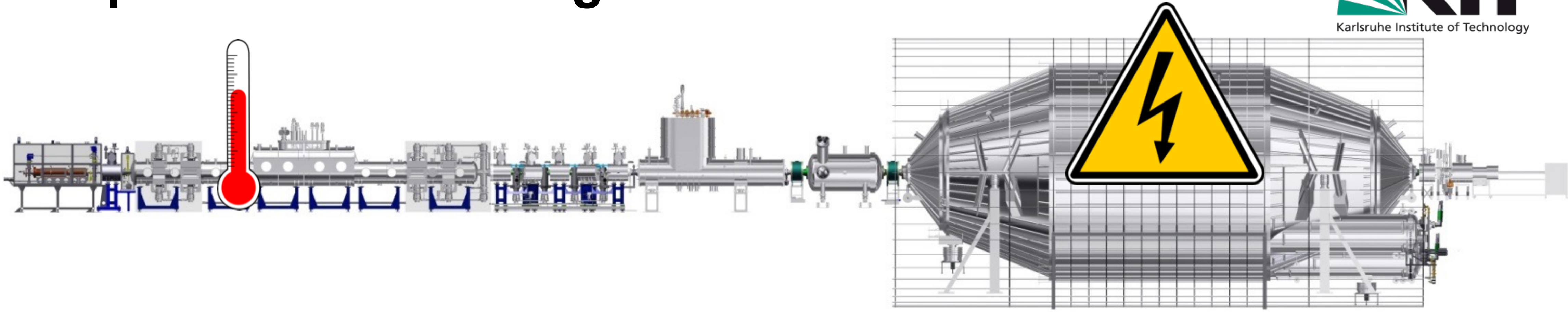
Source and Transport Section

- Windowless gaseous tritium source
  - Intensity (10^{11} decays/s)
  - Stability (10^{-3} h^{-1})
  - Isotopic purity (> 95%)
- Tritium retention (factor > 10^{14})
- Adiabatic transport of electrons

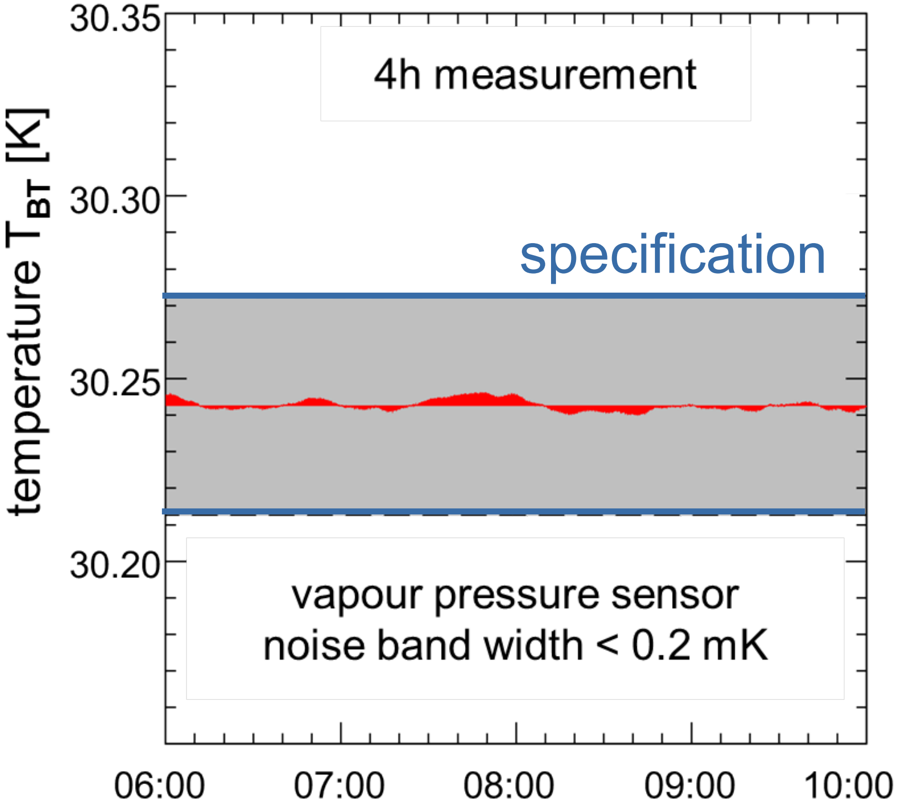
Spectrometer and Detector Section

- Spectrometer UHV ($p < 10^{-11}$ mbar)
- Energy resolution (<1 eV at 18.6 keV)
- High voltage stability (sub-ppm/month)
- High detection efficiency (10^{-3}-10^{3} cps)
- Low background rate (10^{-2} cps)

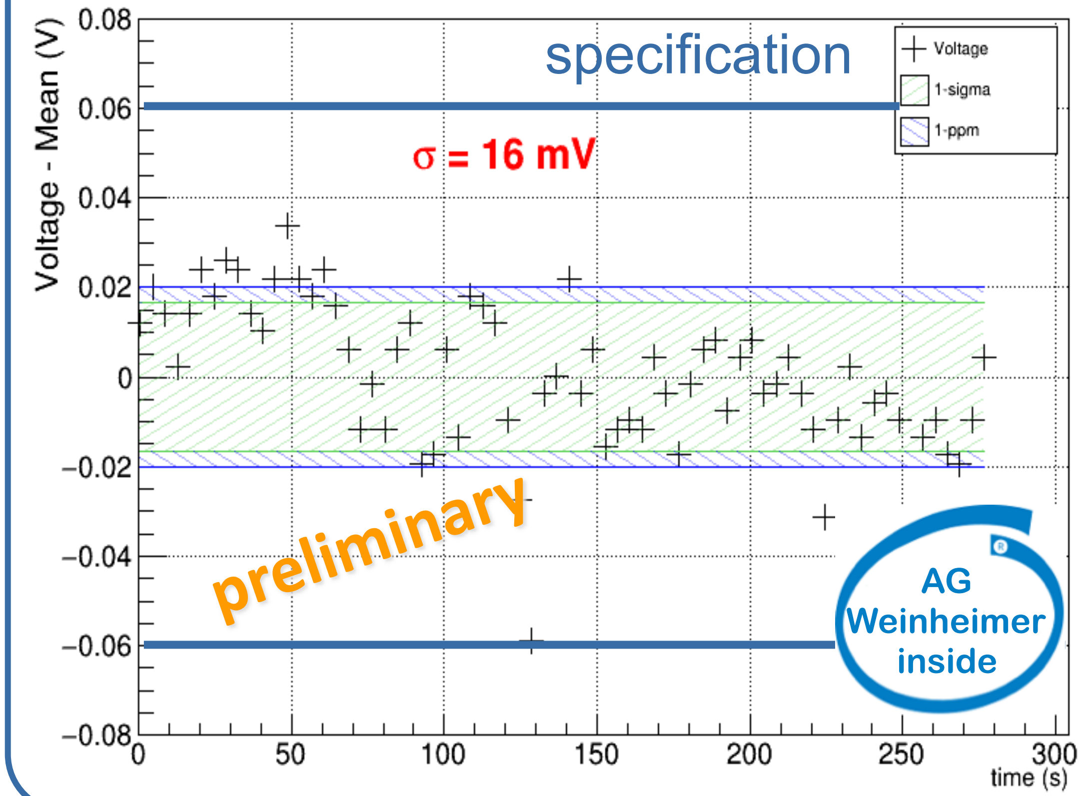
Experimental challenges … and solutions



Source demonstrator: ΔT/T ~ 10^{-4}



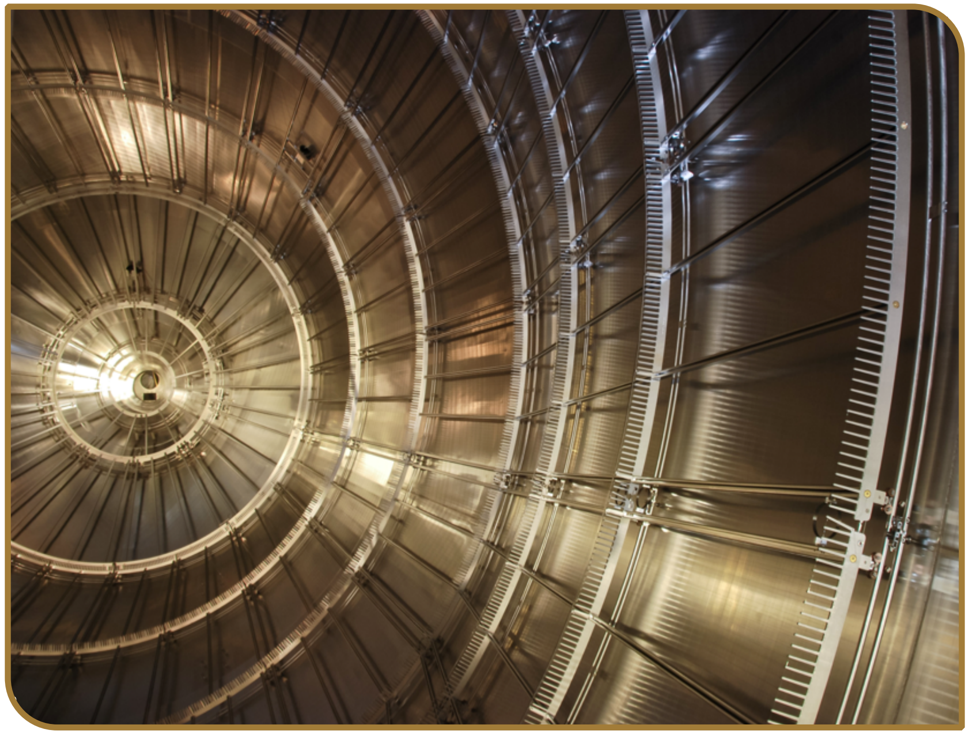
HV post-regulation: ΔU ~ 1 ppm



 [S. Grohmann et al., Cryogenics 55–56 (2013) 5]

III. Status of KATRIN

& route towards start of measurements



System integration and commissioning

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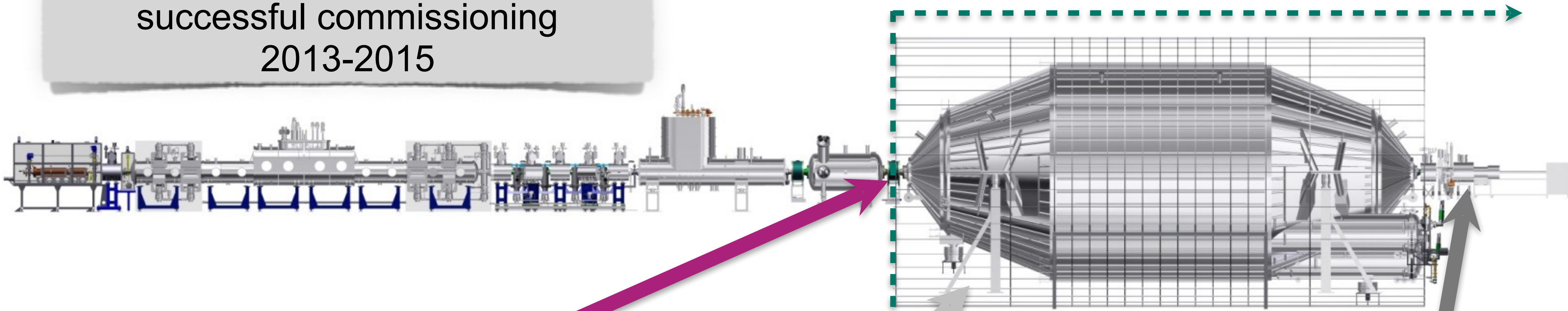
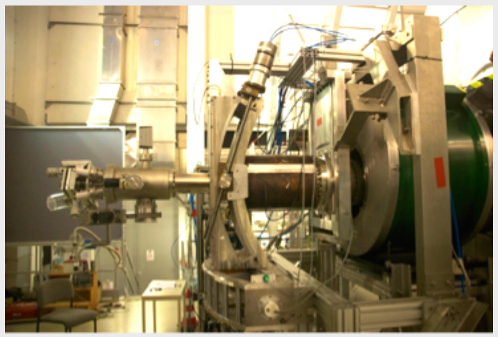
Spectrometer & detector:
successful commissioning
2013-2015



electron gun
well-defined
energy and angle

AG Weinheimer inside



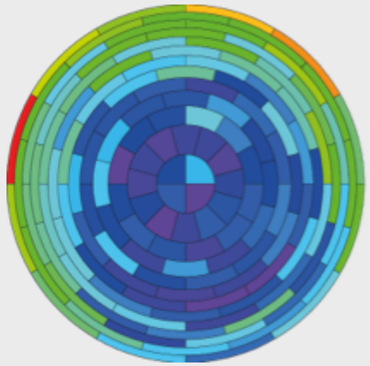
magnetic fields
- s.c. magnets
- field-shaping air coil systems

precision high voltage
vessel + wire electrodes

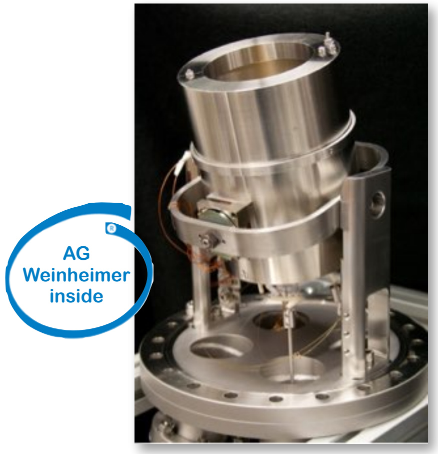
AG Weinheimer inside

vacuum system
- 1250 m^3 vacuum recipient
- TMPs + 3 km getter strips (+ LN_2-cooled baffles)

148-pix detector
spatial & timing info



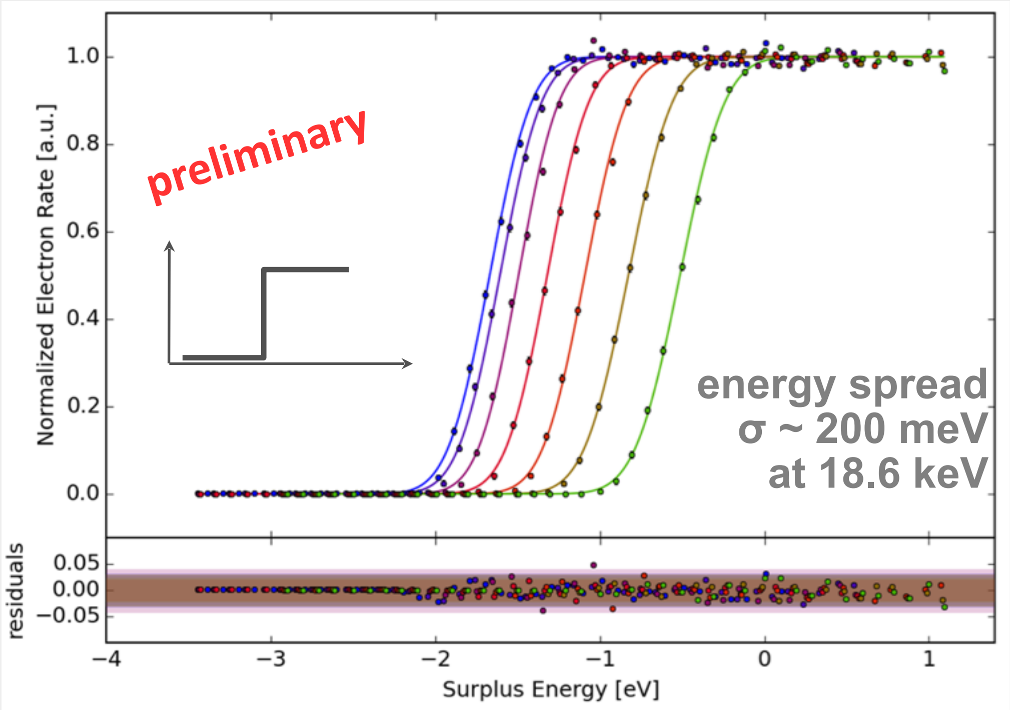
Spectrometer & detector commissioning



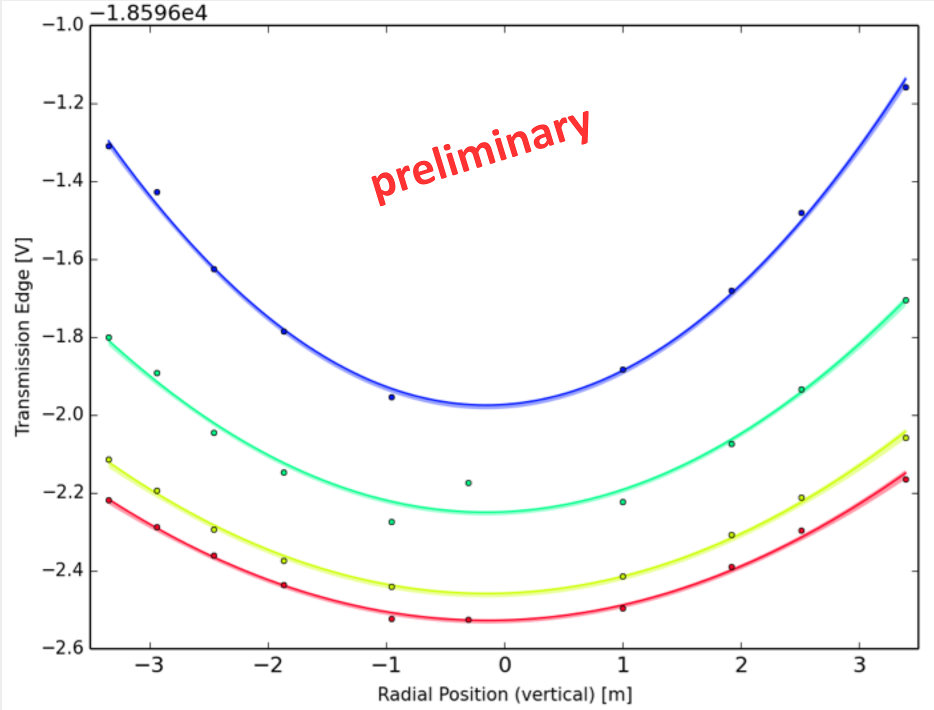
Characterisation of spectrometer transmission

using precision electron source:
energy- & angle-selective, point-like

Transmission characteristics of main spec. as expected (limited by e-gun systematics ...)



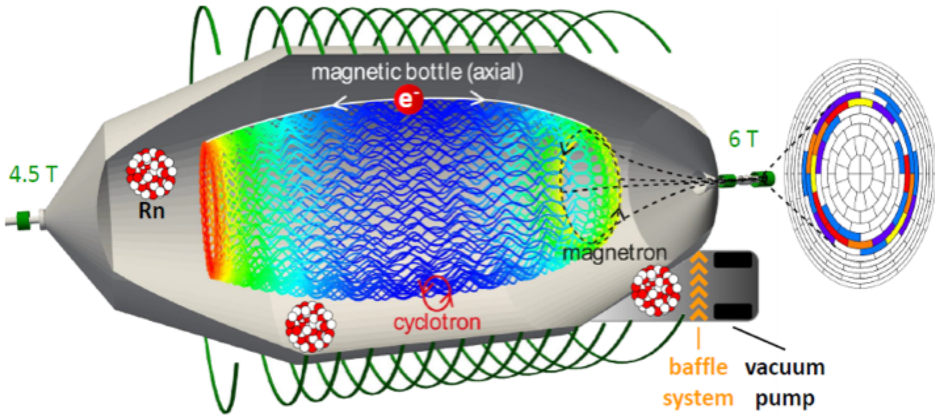
Radial dependence of retardation potential as expected (precision mapping by e-gun)



Spectrometer & detector commissioning

Characterisation of backgrounds

- Very efficient magnetic & electrostatic shielding, but only for charged particles (**e$^-$** and H$^-$)
- Neutral, unstable atoms ($^{219,\,220}$**Rn**, H*) can penetrate into inner flux tube
  → further measures required, e.g. passive shielding against Rn-induced secondaries



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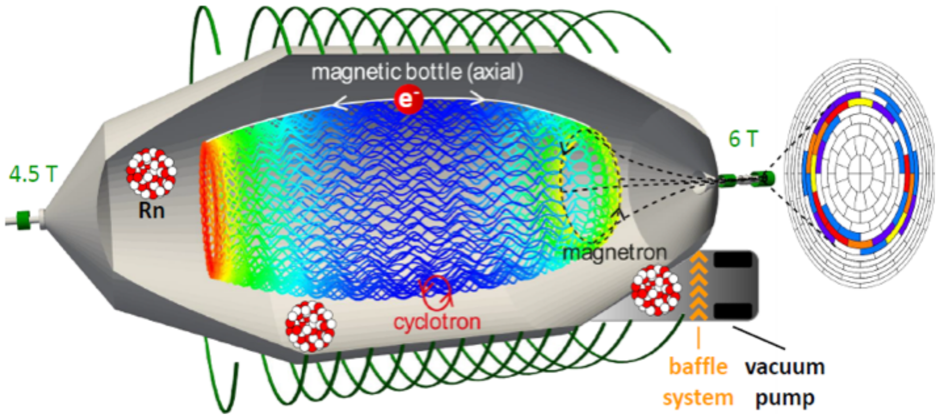
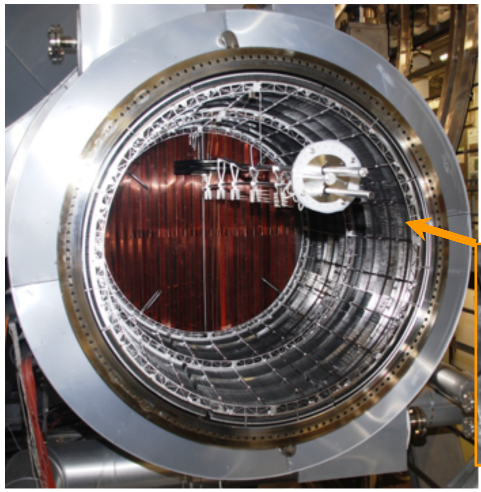
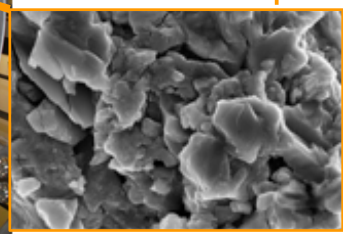


LN$_2$-cooled baffles



NEG strips



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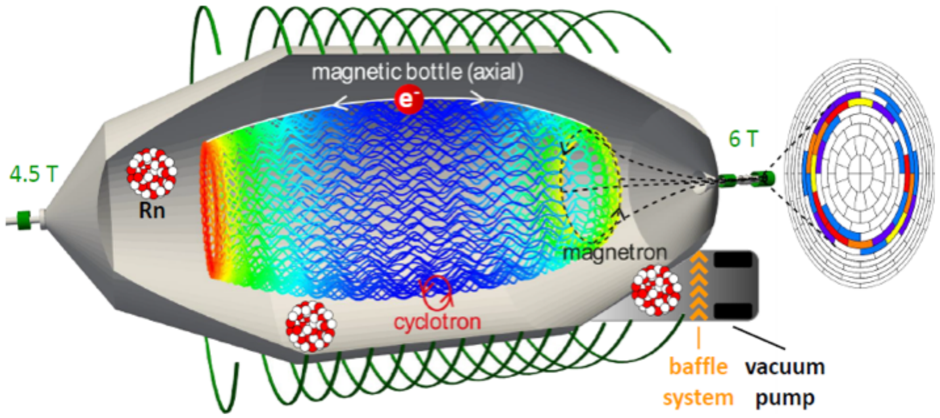

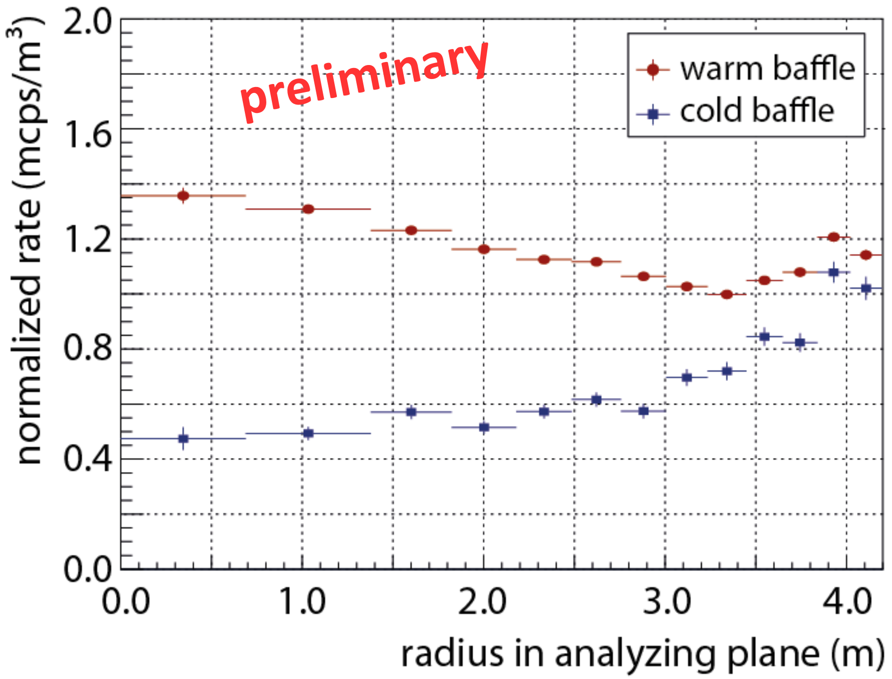

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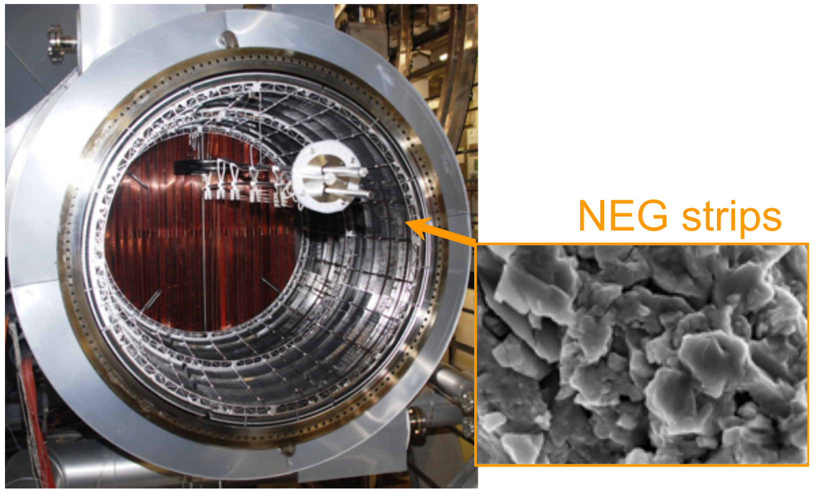
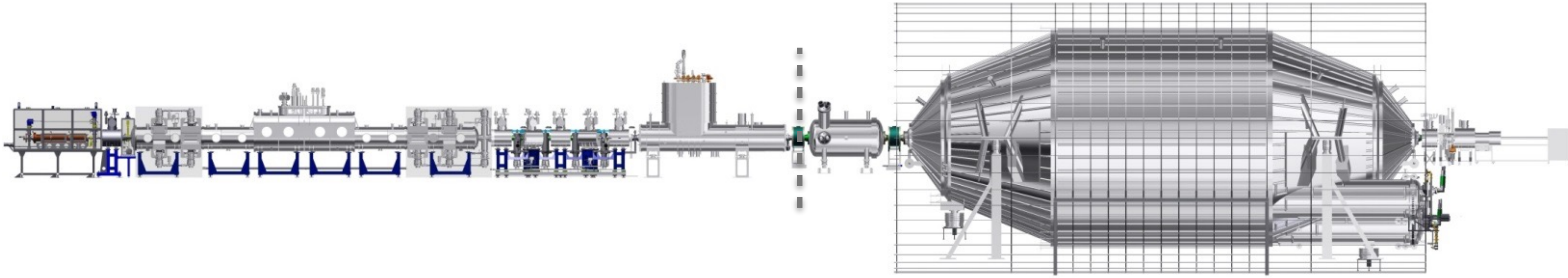


preliminary

477 ± 3 mcps background level achieved

System integration and commissioning



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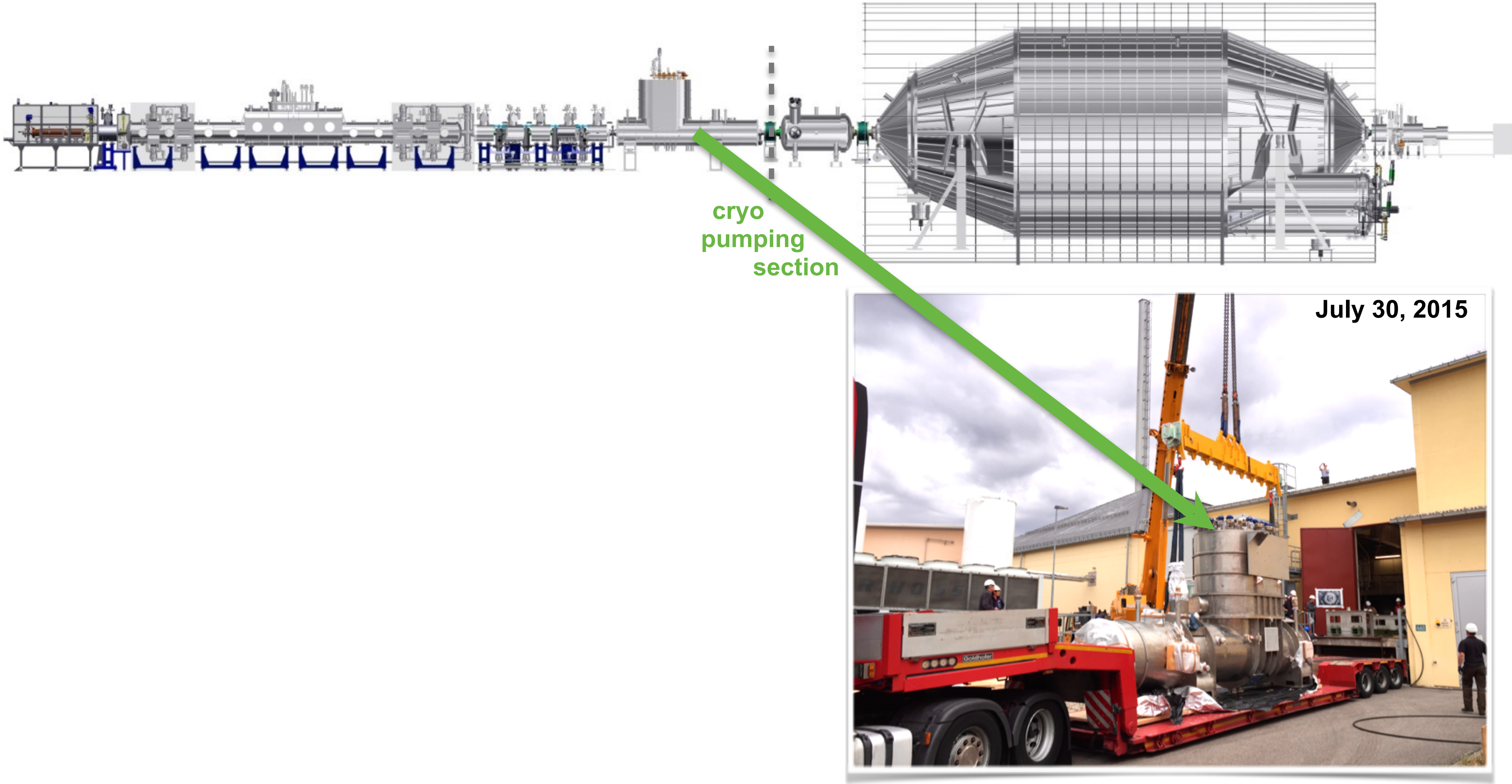

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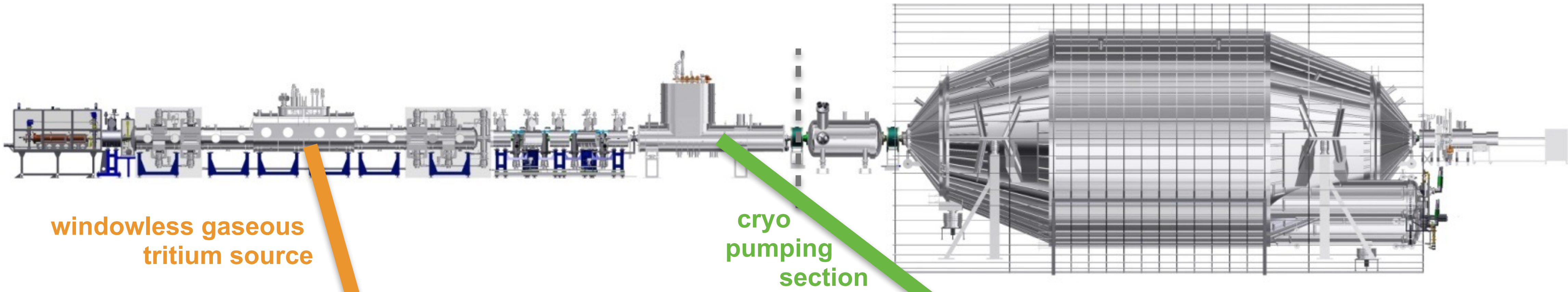
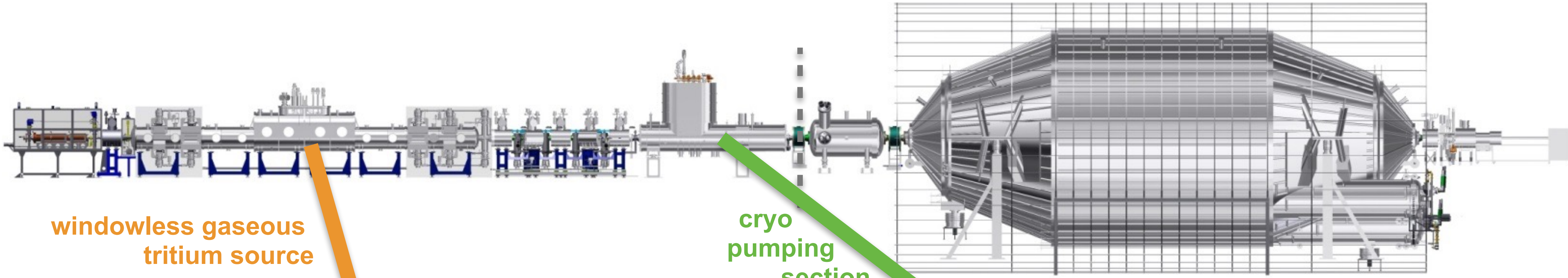


System integration and commissioning

Karlsruhe Institute of Technology

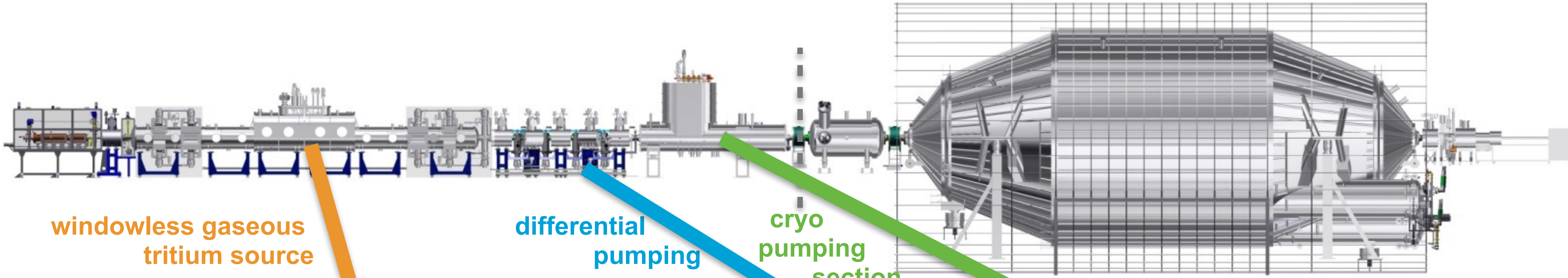


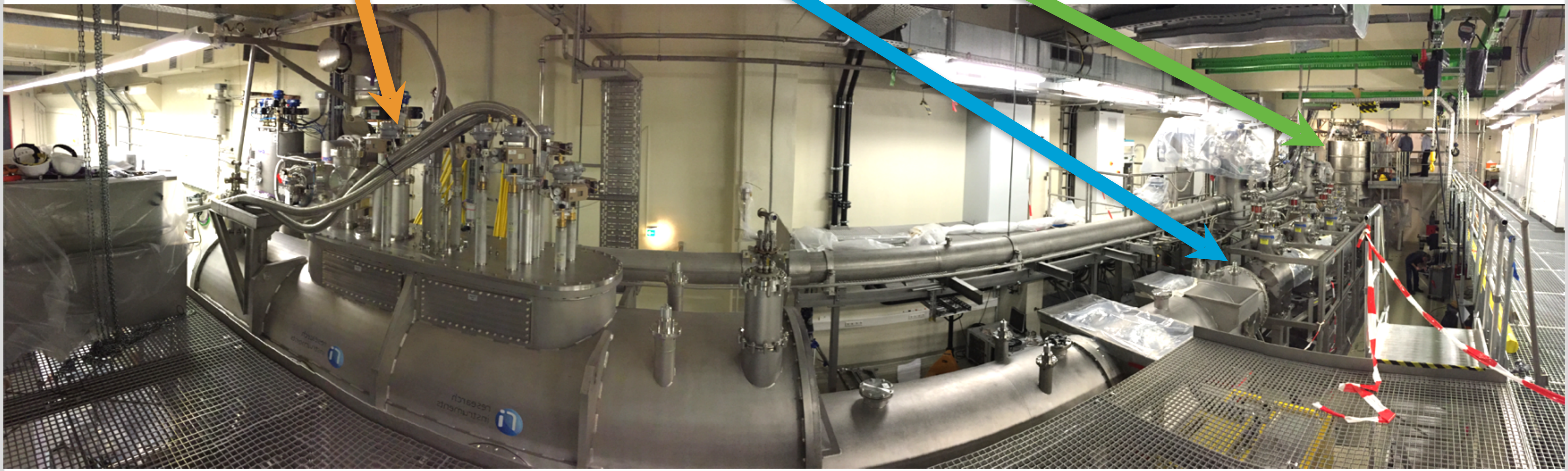
windowless gaseous tritium source

cryo pumping section

Summer 2015:
Arrival of last two major system components on site

System integration and commissioning

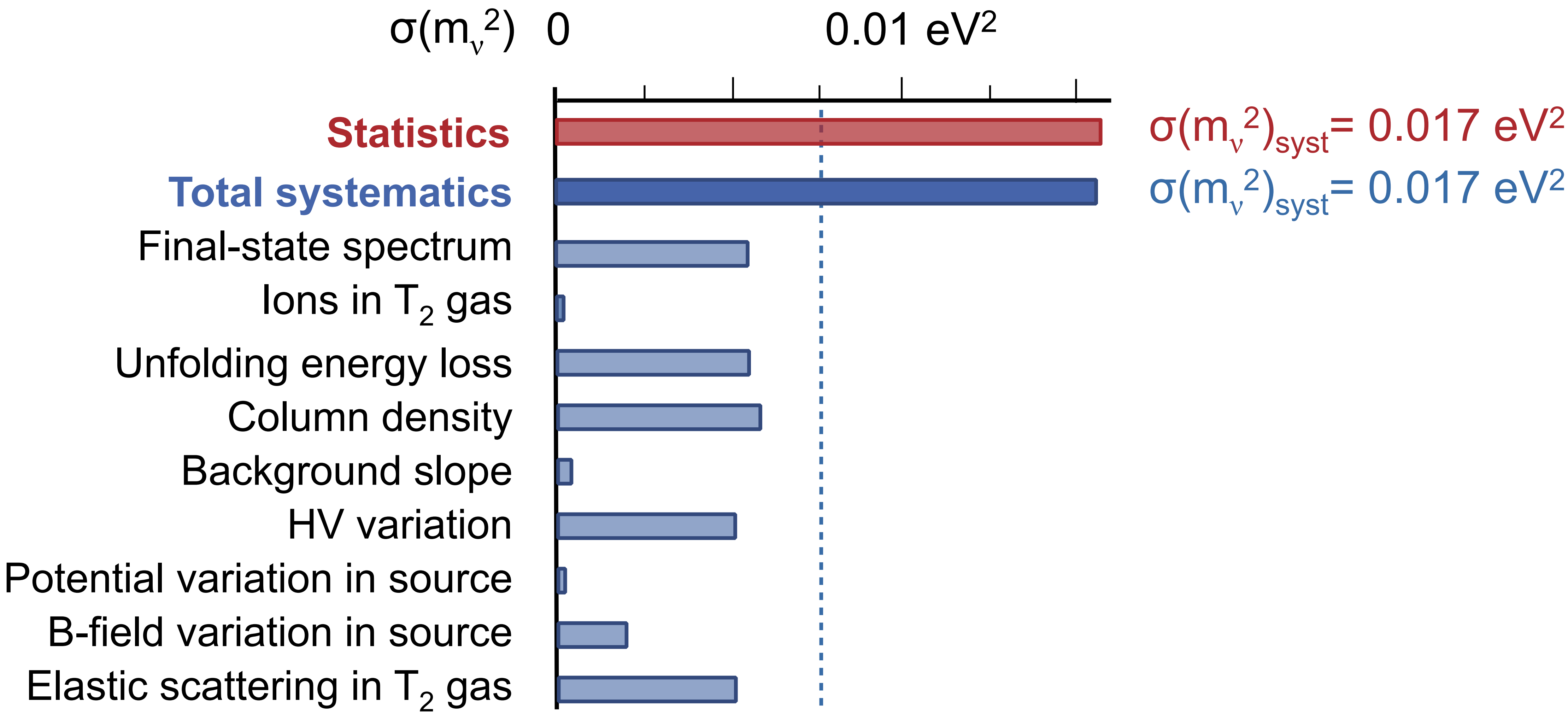




Sept. 2015: Major milestone achieved
full Source and Transport Section in place

KATRIN's systematic uncertainty "budget"

- Careful, conservative evaluation in KATRIN Design Report (2004)
- Dominant contributions by source-related effects



visualization courtesy R.G.H. Robertson

KATRIN's systematic uncertainty "budget"

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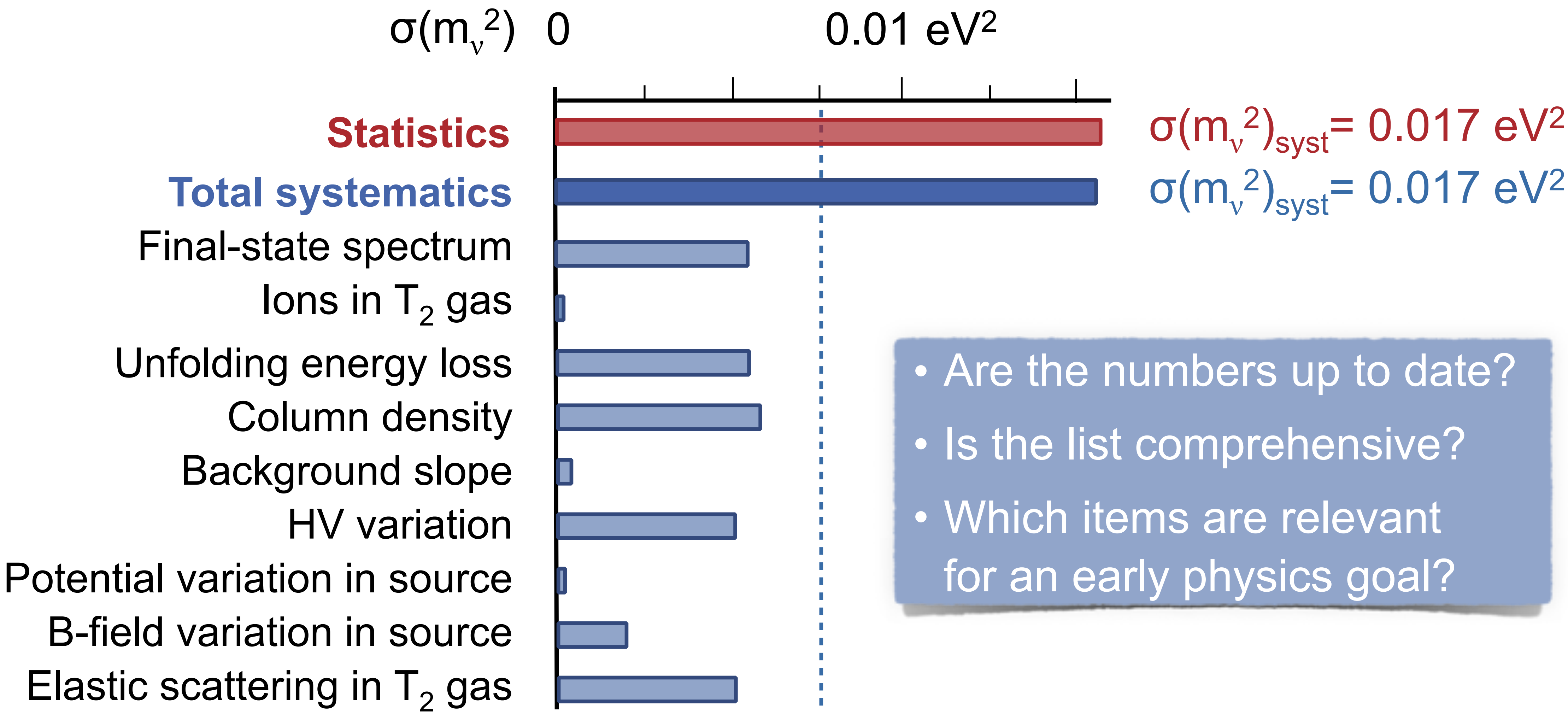


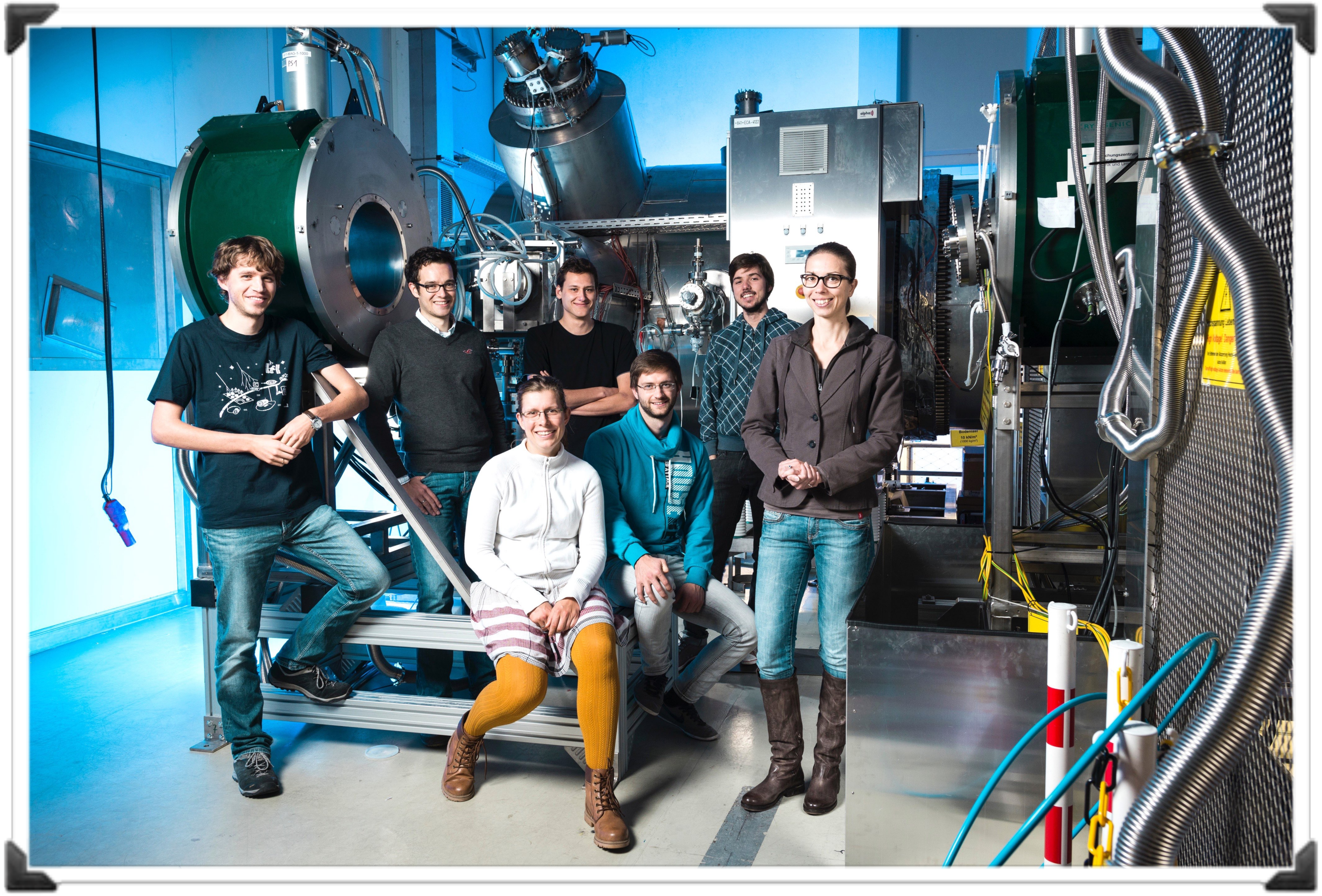
- Are the numbers up to date?
- Is the list comprehensive?
- Which items are relevant for an early physics goal?

Helmholtz-University Young Investigators Group (est. 2014):

"Analysis of KATRIN data to measure the neutrino mass and search for New Physics"

KIT Karlsruhe Institute of Technology

HELMHOLTZ | ASSOCIATION



Group members

- *K. Valerius*
  group leader
- *M. Kleesiek*
  postdoc
- *L. Kuckert*
  PhD student
- *H. Seitz-Moskaliuk*
  PhD student
- *F. Heizmann*
  PhD student
- *M. Klein*
  PhD student
- *M. Machatschek*
  Master's student

Former group members

- *M. Babutzka*
  postdoc
- *R. Combe*
  Master's student
- *J. Antoni*
  Diploma student

Example: Energy loss function

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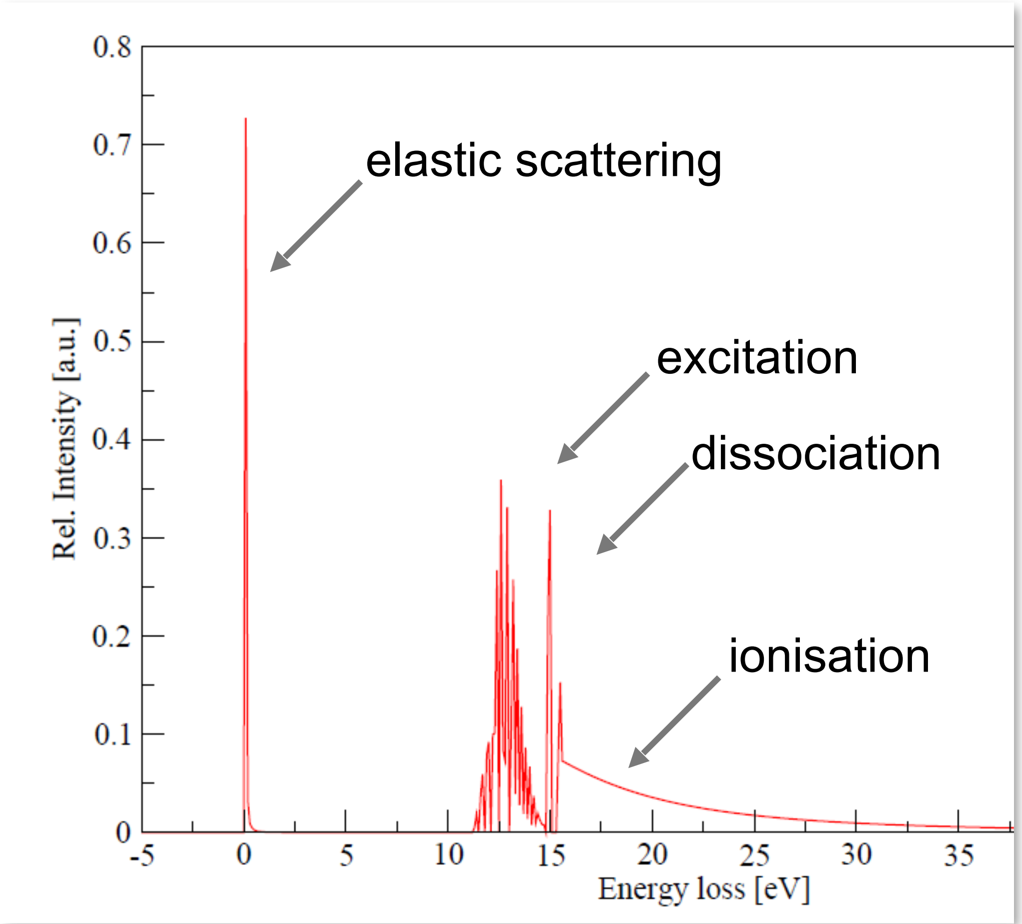
18.6 keV electrons undergo energy loss when scattering in gaseous T_2 source



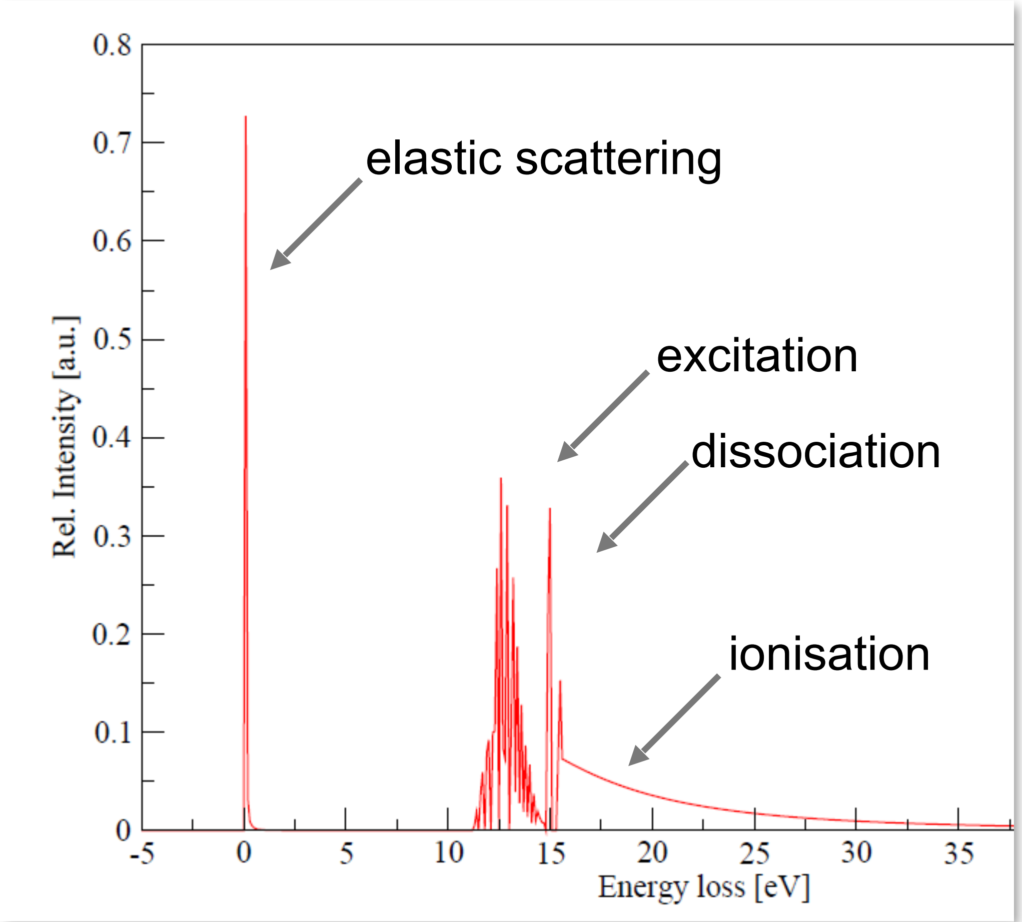
[C. Kranz, Dipl. thesis, Münster, 2011]

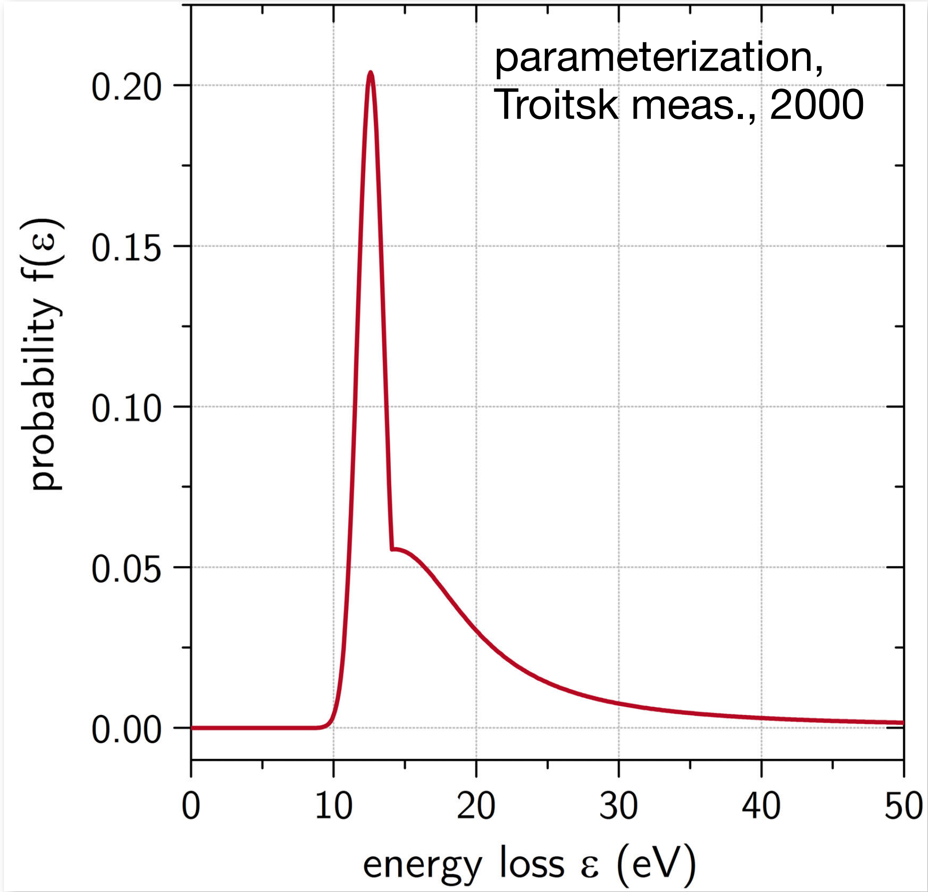
[Aseev++ 2000, figure from M. Kleesiek]

Example: Energy loss function

18.6 keV electrons undergo energy loss when scattering in gaseous T_2 source

model based on H_2/D_2 data
➜ *improved* measurement for T_2 necessary





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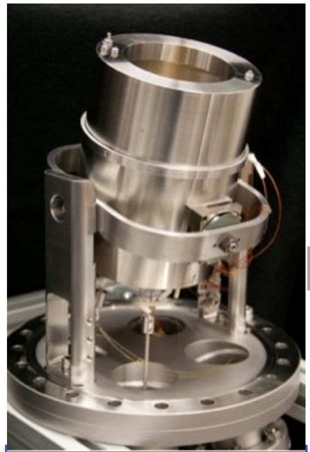
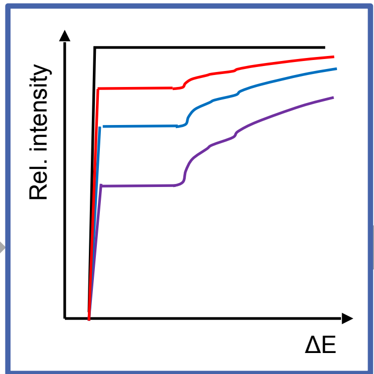
[Aseev++ 2000, figure from M. Kleesiek]

Energy loss function: measurement



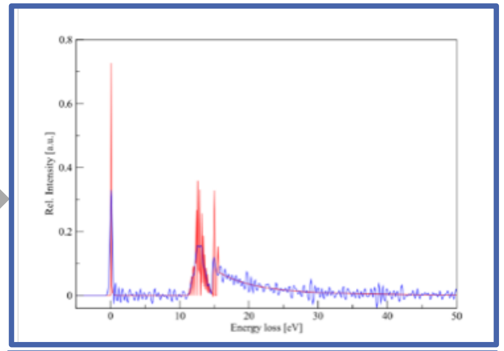
Egun



4 column densities:
[0, 0.5, 3.0, 6.0]
$*10^{17} cm^{-2}$

Keloss software package

[V. Hannen++, in prep.]

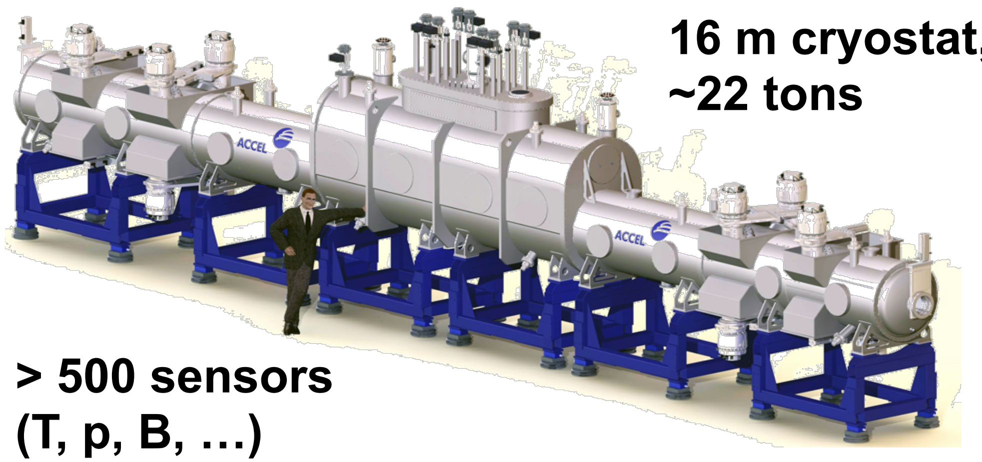


Energy loss function

C. Kranz, Diploma thesis 2011

- Work (with V. Hannen) on setting up detailed measurement proposal
- Deconvolution technique accurate enough for KATRIN
- Remaining uncertainties (e.g. column density setting) to be evaluated
- First test with D_2 suggested to train procedures

Example: Column density model



16 m cryostat, ~22 tons

> 500 sensors (T, p, B, …)

- Temperature, pressure, tritium purity to be stabilized at 10^{-3} level
- Small variations of op. parameters lead to fluctuations of column density ➜ syst. influence on $m^2(\nu)$

[L. Kuckert, F. Heizmann, M. Hötzel, KV++, *in prep.*] **[M. Kleesiek, L. Kuckert, KV++, *in prep.*]**

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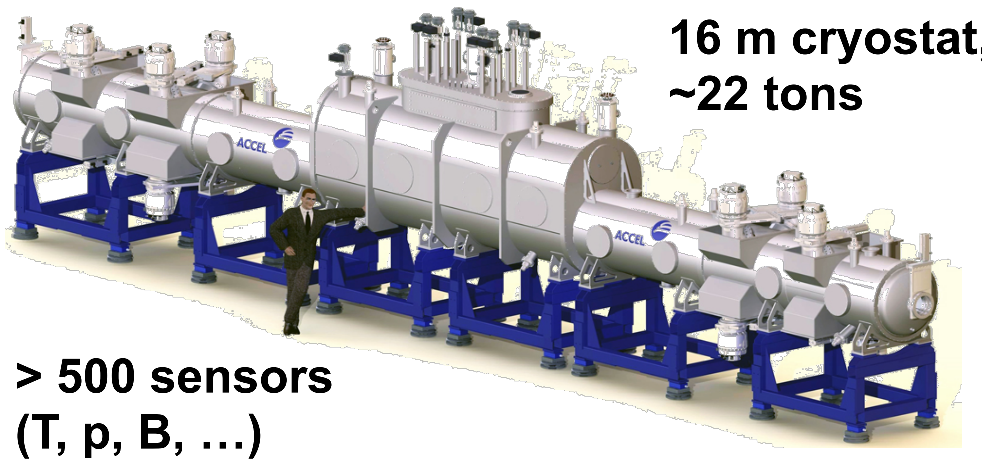

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Column density monitoring:

- Small detector in forward direction
- Regular control meas. with e-Gun

[L. Kuckert, F. Heizmann, M. Hötzel, KV++, *in prep.*] [M. Kleesiek, L. Kuckert, KV++, *in prep.*]

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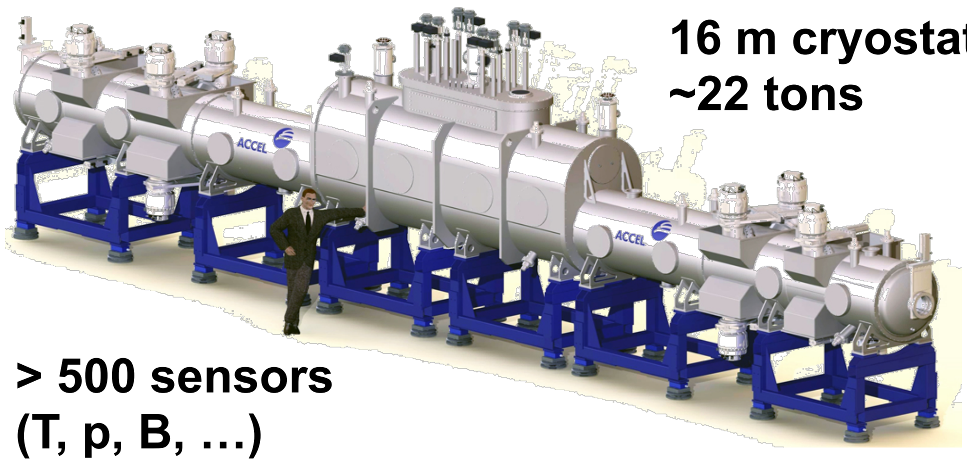

16 m cryostat, ~22 tons

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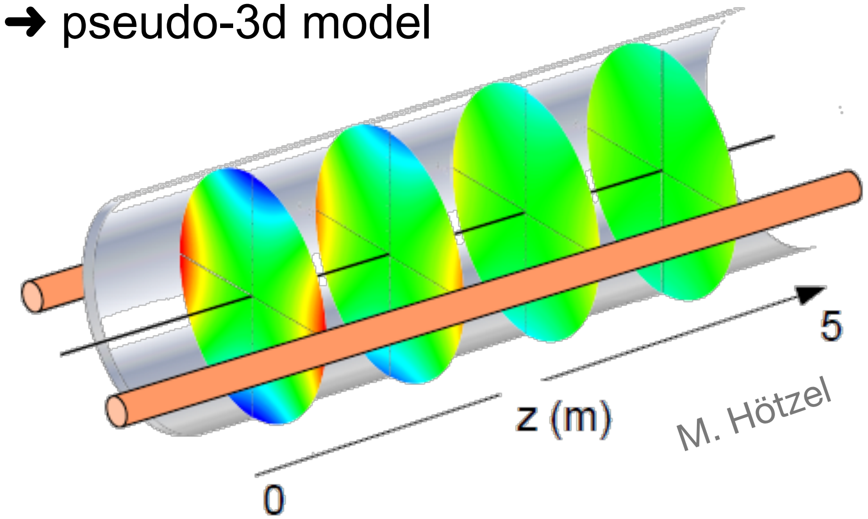
Gas dynamical model:
longitudinal profile + 2d slices
➜ pseudo-3d model



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- Small variations of op. parameters lead to fluctuations of column density ➜ syst. influence on $m^2(\nu)$

Column density monitoring:

- Small detector in forward direction
- Regular control meas. with e-Gun

+

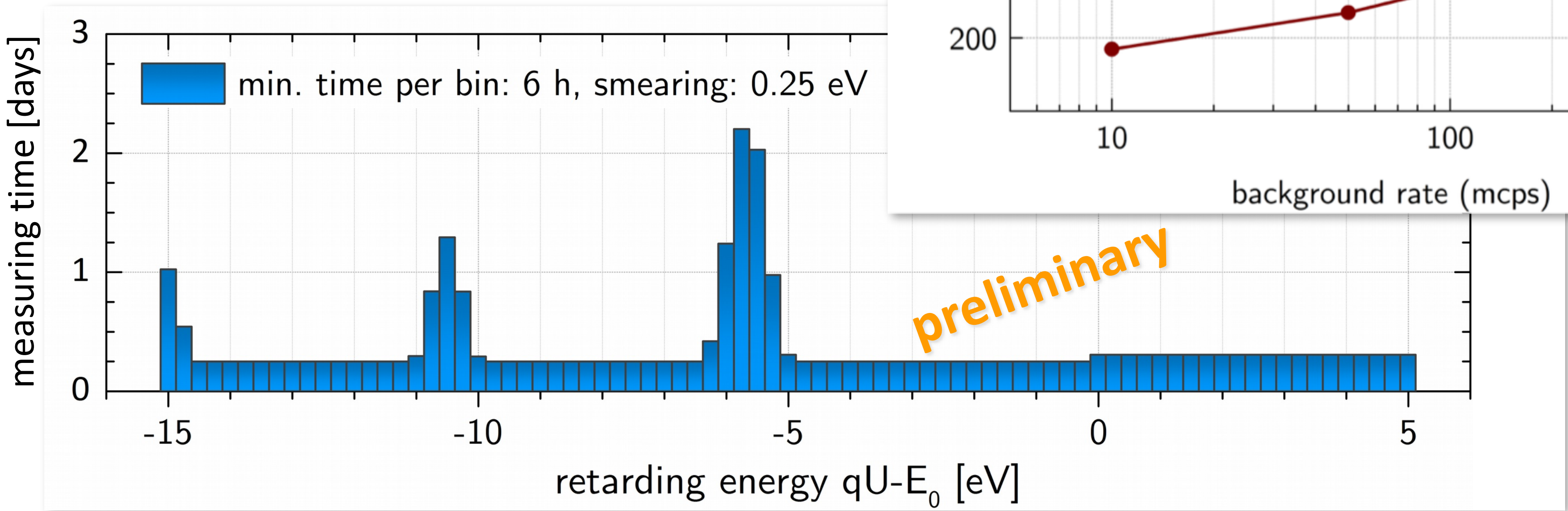
- Detailed modeling of **gas dynamics** and resulting spectrum
- Temporal and spatial variations of operational parameters ➜ **sensors**

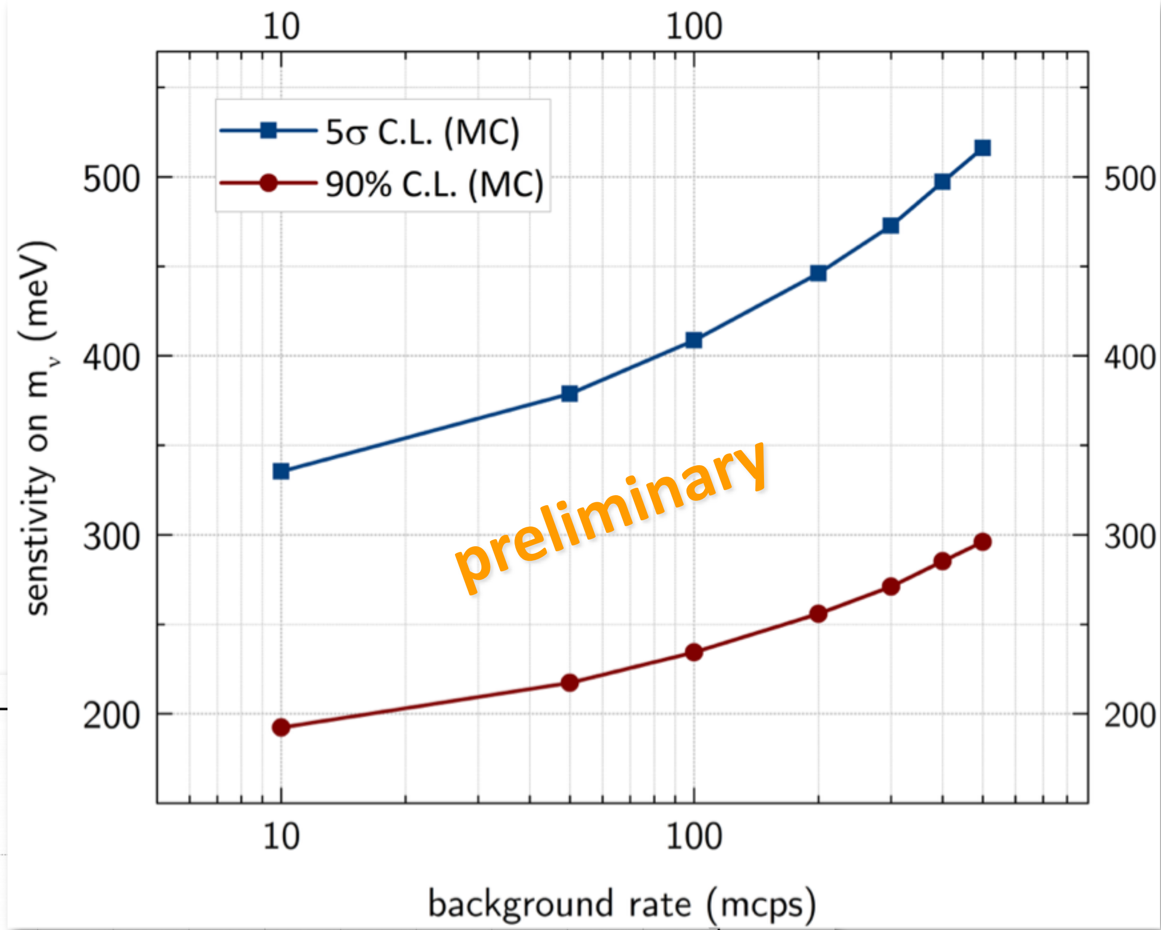
 [L. Kuckert, F. Heizmann, M. Hötzel, KV++, *in prep.*] [M. Kleesiek, L. Kuckert, KV++, *in prep.*]

Example: Sensitivity and background level

Development of MC-based tools for sensitivity estimates and meas. time optimization

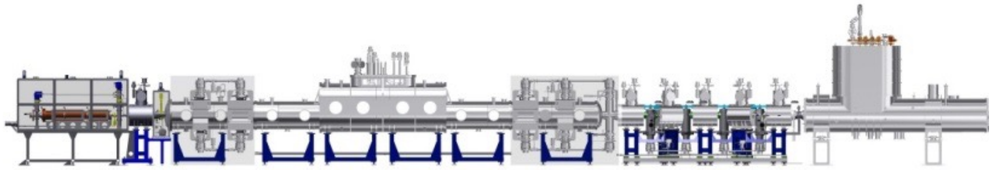
Illustration: proposal for **first month** of running KATRIN

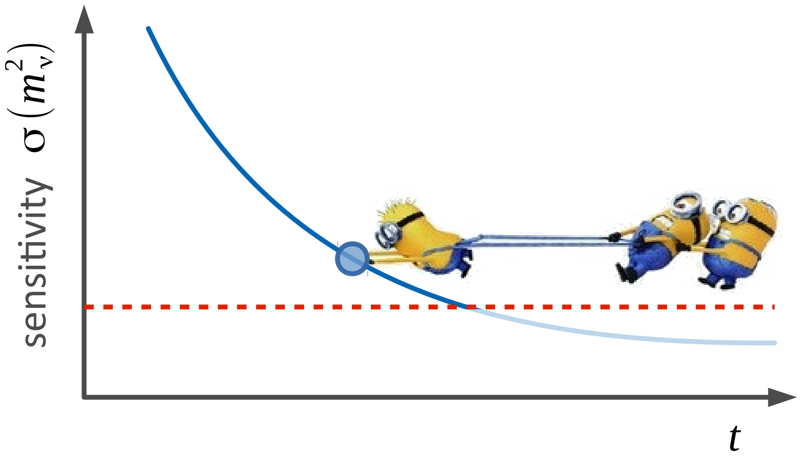




[M. Kleesiek, *in prep.*]

Further projects





Source-related systematics

- Descriptions of el. potential in source
- Plasma effects?
- Efficient retention of tritium ions?

Space charges and el. potential inhomogeneities probed by dispersing ^{83m}Kr in tritium gas

➜ simulation study ongoing

Technical/Analysis

- Development of high- and medium-level analysis tools
- Planning of commissioning tests during system integration
- … towards first physics runs with KATRIN!

Extra:

Exploring KATRIN's physics potential beyond neutrino masses

KATRIN: ν-mass sensitivity … and more:

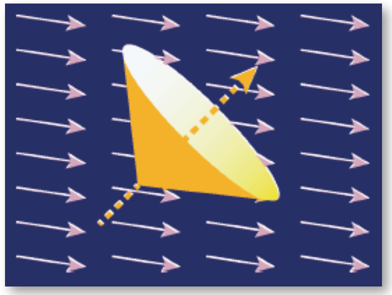
Explore physics potential

standard operation mode for KATRIN

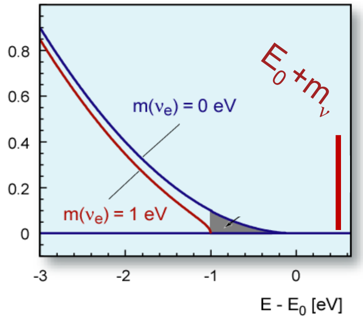
- **close to the spectral endpoint E_0:**

RH currents
Bonn et al. (2011),
Barry, Heek, Rodejohann (2014)

Violation of Lorentz symmetry
e.g. Diaz, Kostelecky & Lehnert (2013)

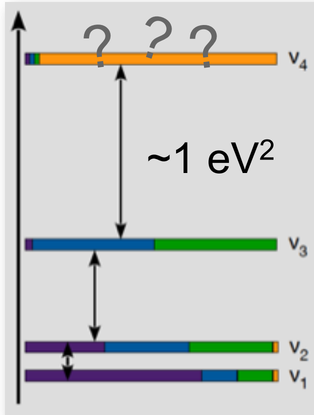


Constraining local CνB
e.g. Kaboth & Formaggio (2010),
Fässler et al. (2013)



capture of relic ν on β-instable nuclei

Search for eV-scale sterile ν
e.g. Formaggio & Barrett (2011)



- **and further away from E_0:**
  search for keV-mass scale sterile ν as WDM candidates
  Mertens et al. (2015); Steinbrink et al. (2014)

non-standard operation, novel detector concepts

Imprint of sterile neutrinos on β spectrum

Shape modification below E_0 by active $(m_a)^2$ and sterile $(m_s)^2$ neutrinos:

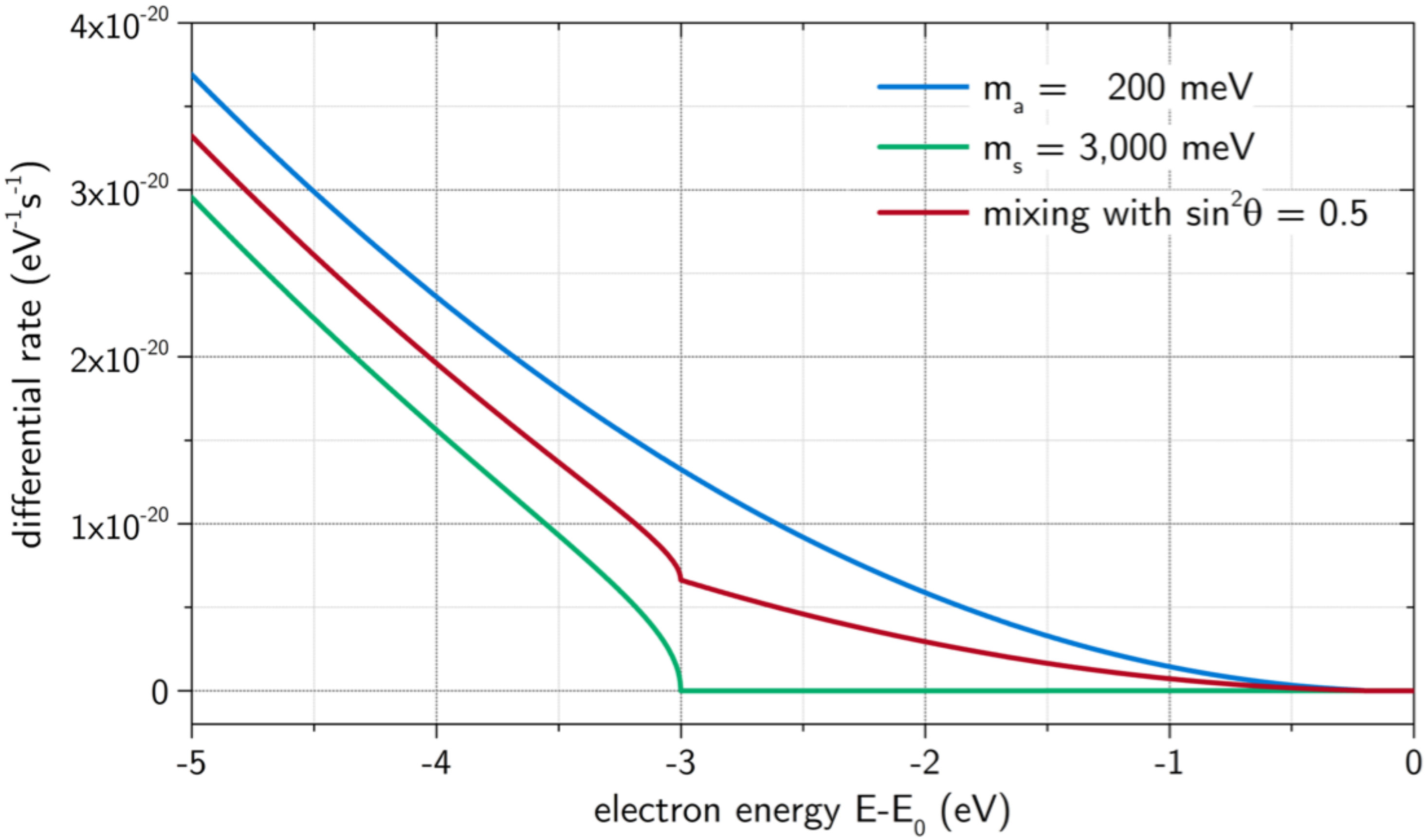
$$\frac{dN}{dE} = \cos^2\theta_s \frac{dN}{dE}(m_a^2) + \sin^2\theta_s \frac{dN}{dE}(m_s^2)$$

⇒ additional kink in β spectrum at $E = E_0 - m_s$

example:

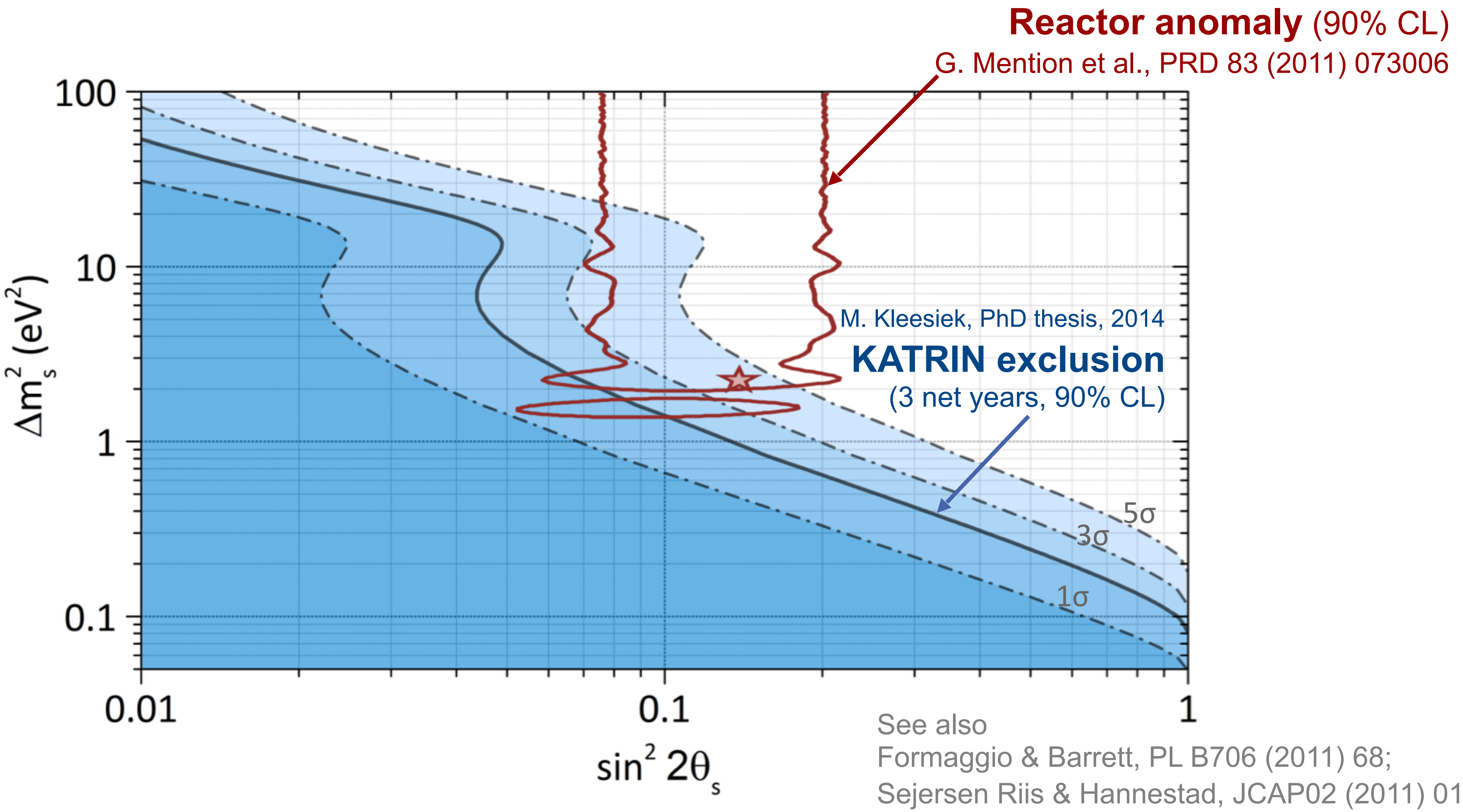
light sterile ν

$m_s = 3$ eV



Search for eV-scale sterile ν with KATRIN

- "Reactor antineutrino anomaly": $|\Delta m_s^2| > 1.5\ \mathrm{eV}^2, \quad \sin^2(2\theta_s) = 0.14 \pm 0.08 \quad (95\%\,\mathrm{CL})$
- Favoured parameter space can be probed by KATRIN:



See also
Formaggio & Barrett, PL B706 (2011) 68;
Sejersen Riis & Hannestad, JCAP02 (2011) 011;
Esmaili & Peres, PR D85 (2012) 117301

Summary & Outlook

Karlsruhe Institute of Technology

- KATRIN sensitivity on m(ν_e): **200 meV** (90% CL, 3 yrs of data)
  - ultimate MAC-E type experiment with molecular T_2
  - will cover degenerate ν mass regime
- Rich physics potential in addition to light neutrino mass
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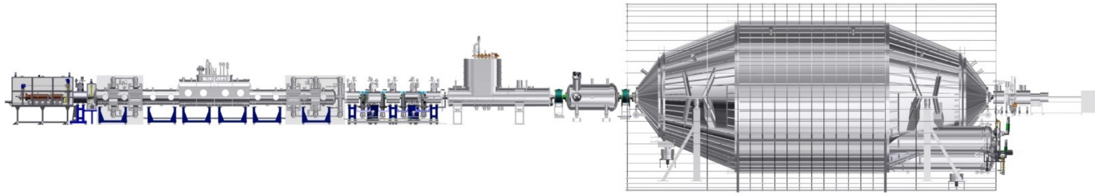

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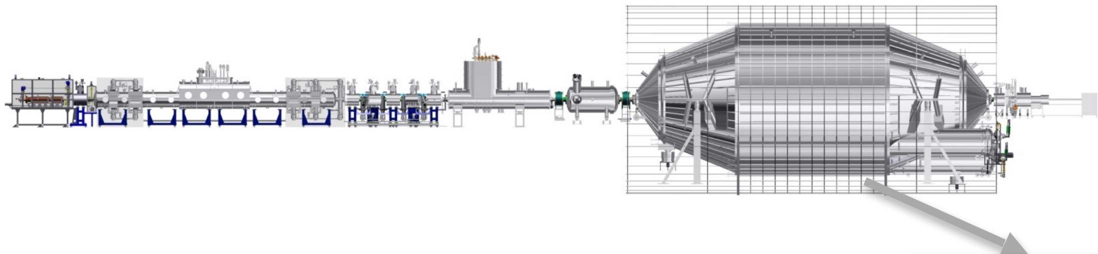

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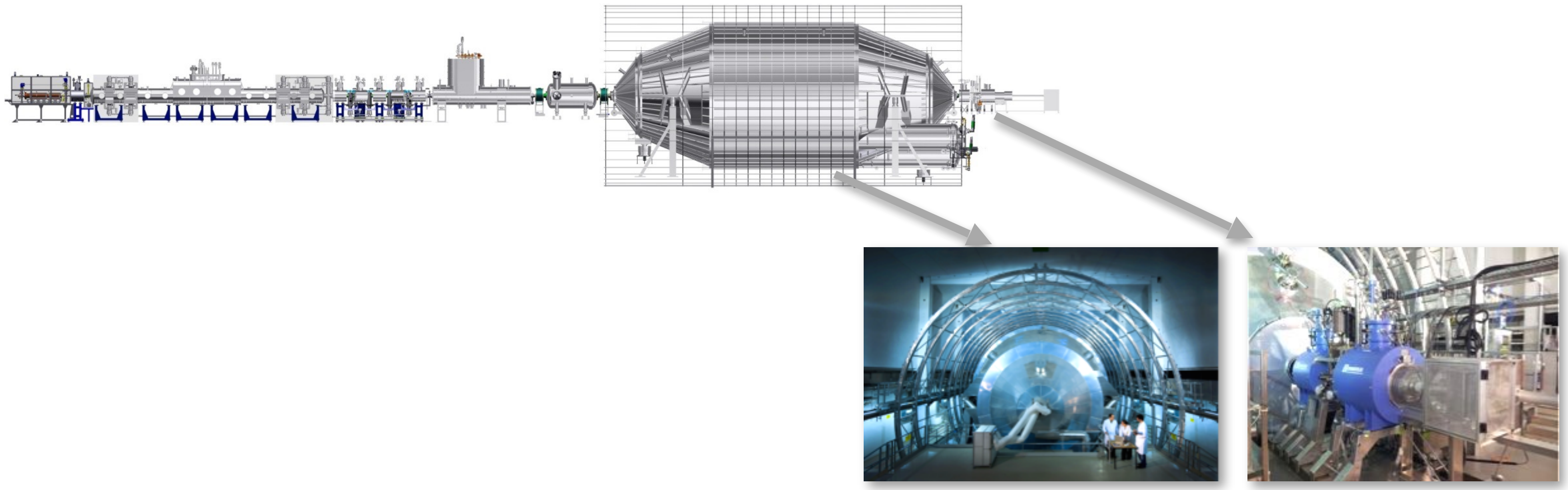

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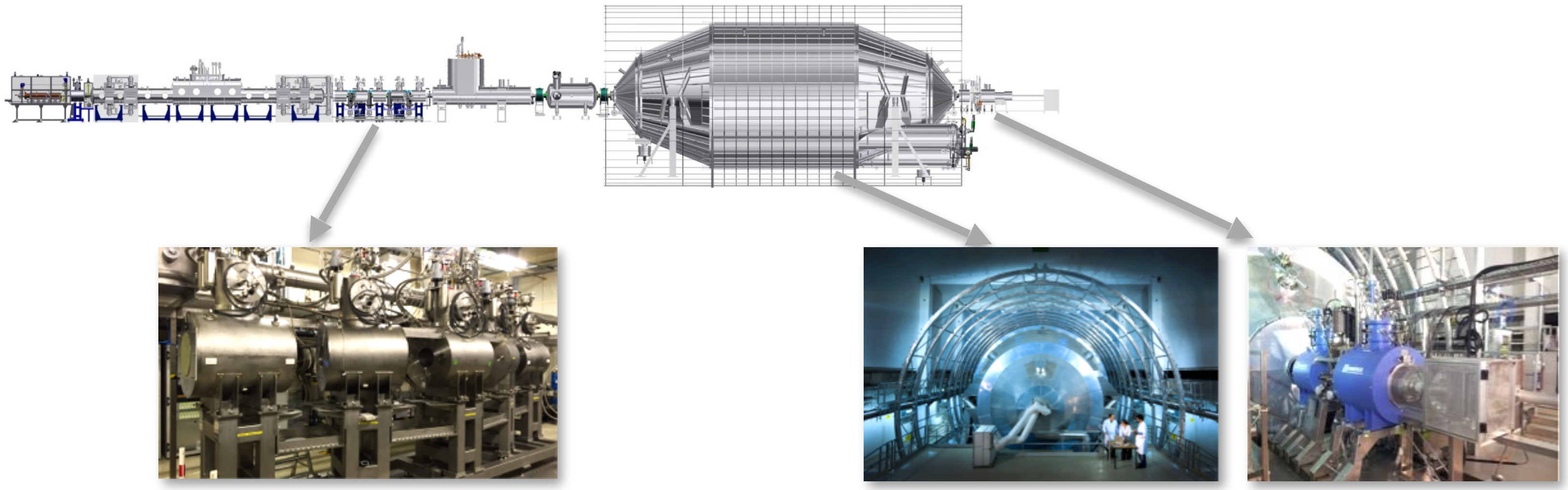

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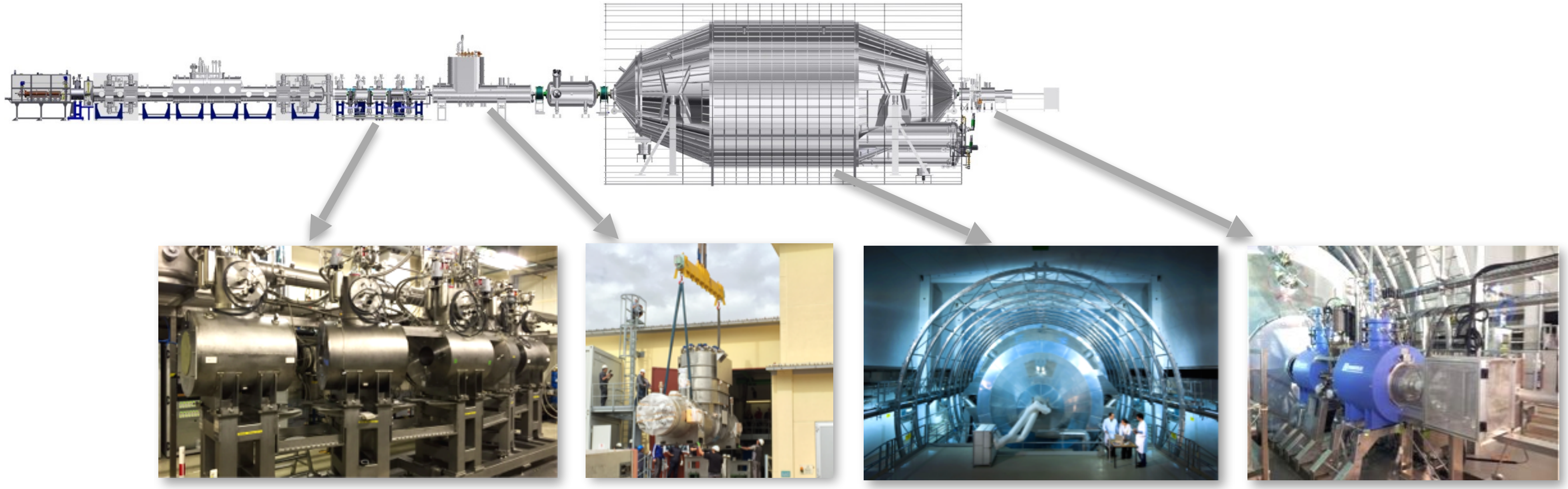

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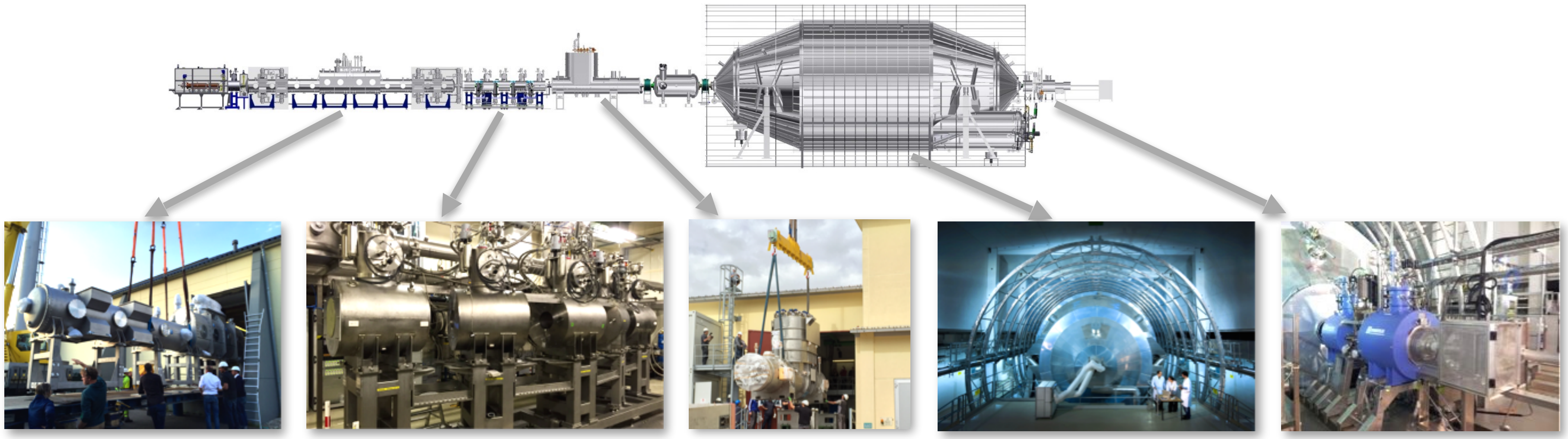

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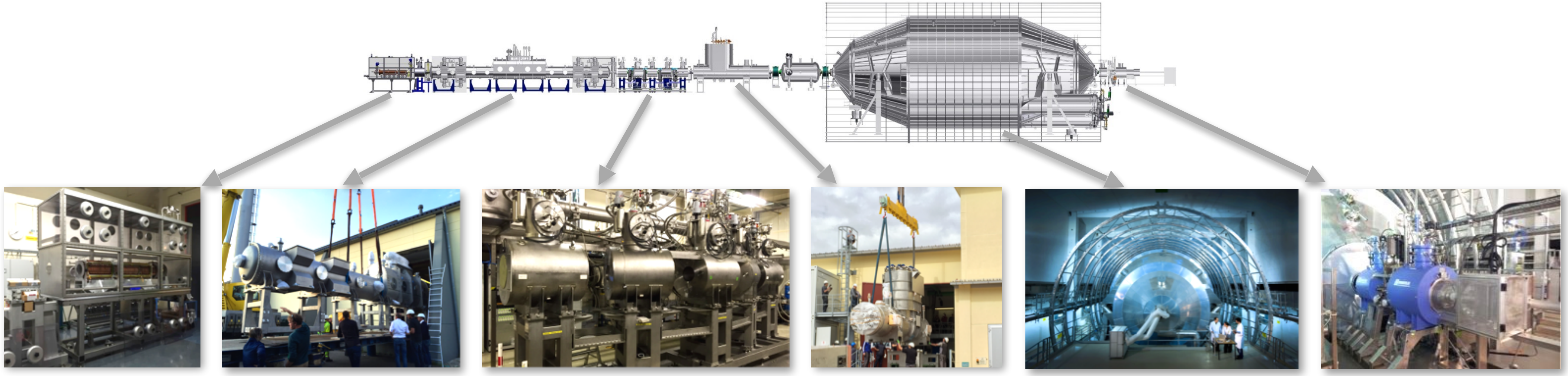


Thank you!

Thank you!

Karlsruhe Institute of Technology

Supplementing slides

Effect of RH current contributions

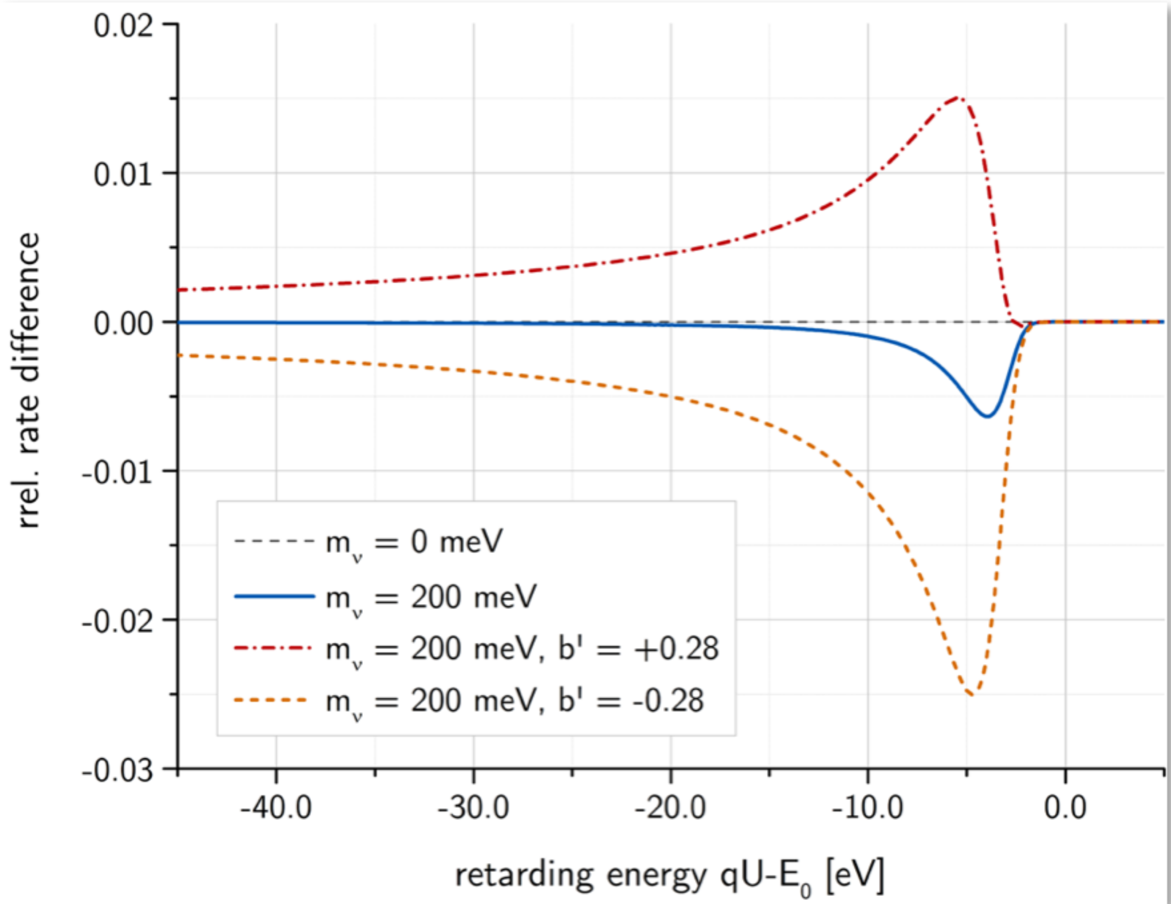
Karlsruhe Institute of Technology

$$\frac{d\Gamma}{dE\,dt} \propto E_\nu \sqrt{E_\nu^2 - m_\nu^2}\left(1 + b'\frac{m_\nu}{E_\nu}\right)$$

[J. Bonn et al., *Phys. Lett. B* 703 (2011) 310]

Fierz-like parameter *b'* enters differential rate

$$b' \approx -2\,\frac{\mathfrak{Re}(L_V R_V^* + L_V R_S^*)|\mathcal{M}_F|^2 + \mathfrak{Re}(L_A R_A^* + L_A R_T^*)|\mathcal{M}_{GT}|^2}{|L_V|^2|\mathcal{M}_F|^2 + |L_A|^2|\mathcal{M}_{GT}|^2}$$



Imprint on integrated spectrum:

- Only small sensitivity on *b'* if endpoint E_0 left free in fit
  ➜ good for determination of $m^2(\nu_e)$
- Improvement of present bounds on *b'* with KATRIN for small $m(\nu_e)$ if
  - external E_0 value with accuracy < 50 meV as input*
  - absolute energy scale in KATRIN U_{spec} - U_{source} known to same accuracy of < 50 meV

Figure: M. Kleesiek

*) 70 meV accuracy:
E. G. Myers et al., *PRL* 114 (2015) 013003

Probing Lorentz invariance in β decay

[Kostelecky & Mewes (2004, 2009)]

Standard Model Extension (SME) framework:

Neutrinos satisfy Dirac-like equation

$$(i\mathbf{\Gamma}^\alpha \partial_\alpha - \mathbf{M})\,\psi = 0$$

with $\mathbf{\Gamma}$, $\mathbf{M}$ including momentum-dependent coefficients

[review: Diaz (2014)]

Experimental searches:
- Neutrino oscillations
- Neutrino velocity (ToF)
- Weak decays

probe oscillation-free parameters

Probing Lorentz invariance in β decay

Karlsruhe Institute of Technology

[Kostelecky & Mewes (2004, 2009)]

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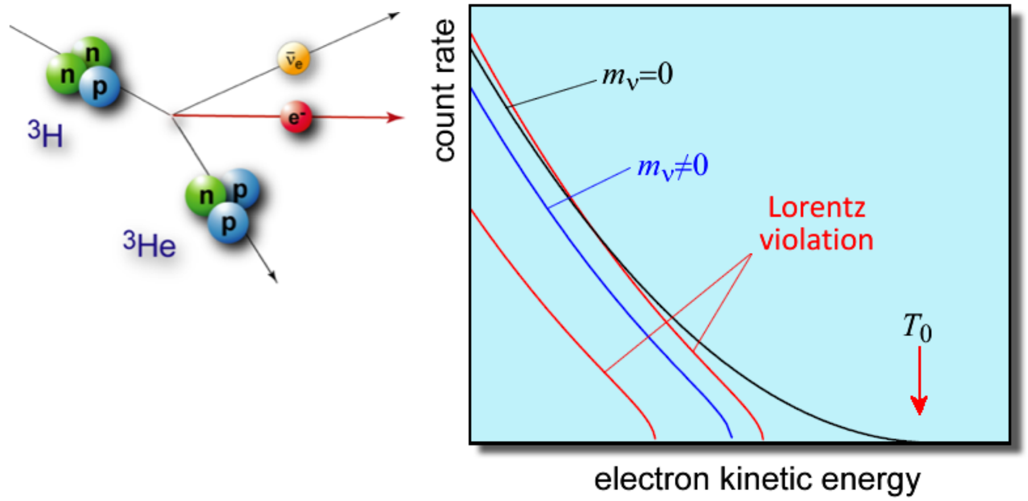
Tritium β decay:



[Diaz, Kostelecky, & Lehnert (2013)]

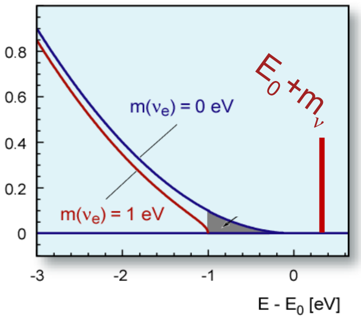
- Modified energy dependence of decay rate
- Spectral shape dependent on sidereal time and experiment orientation
- Effective dim-3 coefficient: osc. shift of endpoint $T_{0,\mathrm{eff}}$ with $\omega_{\mathrm{sidereal}}$
- Effective dim-2 coefficient: osc. of m^2 parameter (can mimic tachyonic ν)

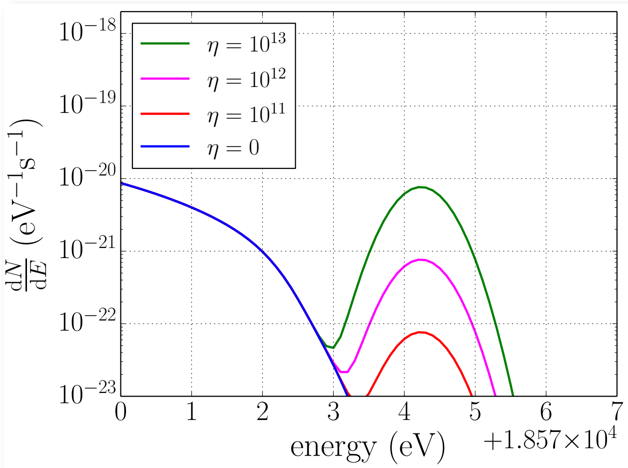
Constraining local CνB density with KATRIN

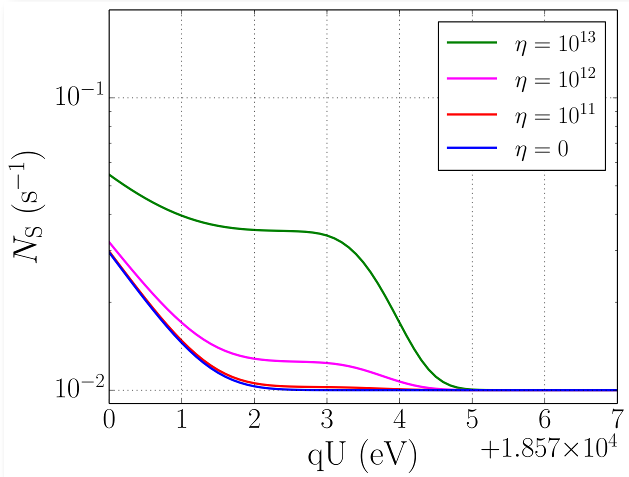
About every neutrino physicist goes through a phase in his or her career and asks ‘There’s got to be a way to measure the relic neutrino background’ — Peter Fisher

ν capture on β-instable nuclei:

$${}^{A}_{Z}N + \nu_e \rightarrow {}^{A}_{Z+1}N' + e^-$$



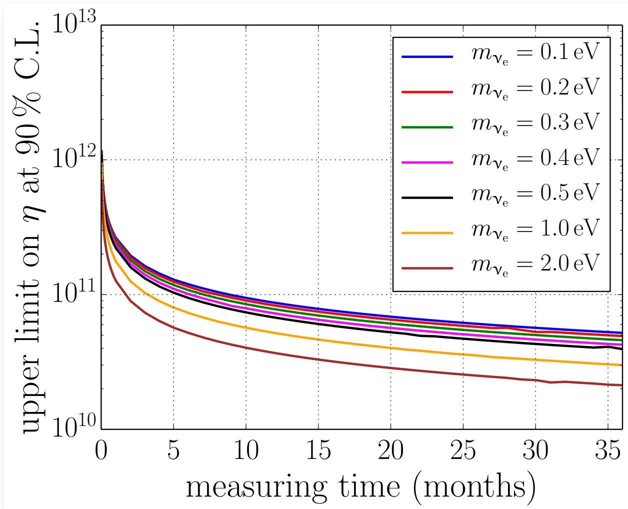


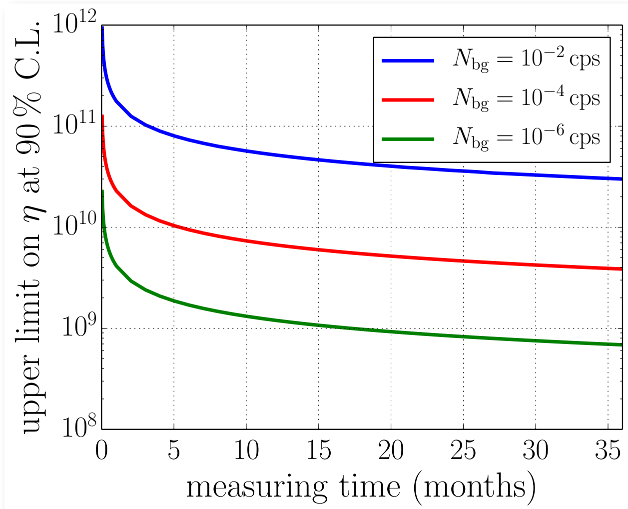


Threshold-free, but tiny cross section $\mathcal{O}(10^{-45}\ \mathrm{cm}^2)$

KATRIN reference setup only sensitive to local overdensity:

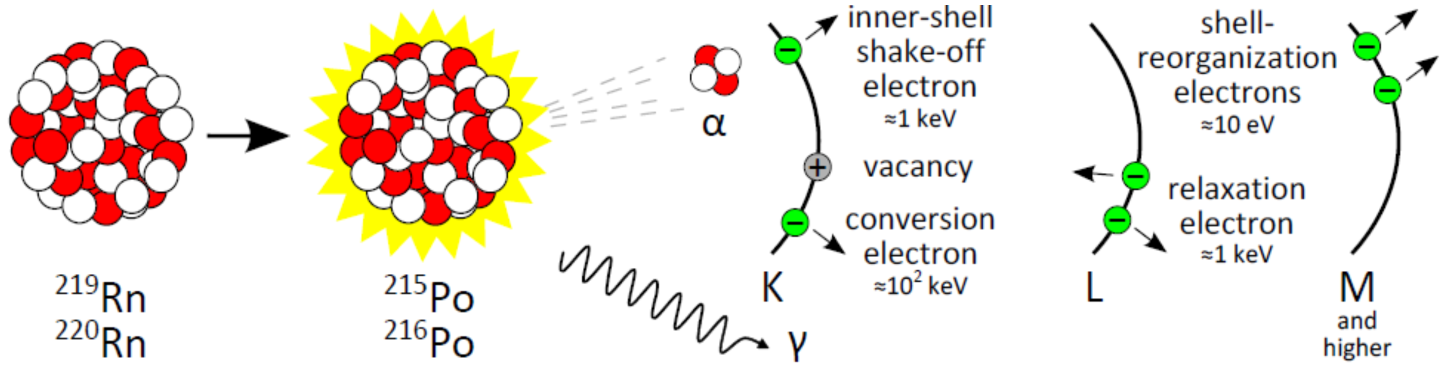
$$\eta = \frac{n_\nu}{\langle n_\nu \rangle}$$





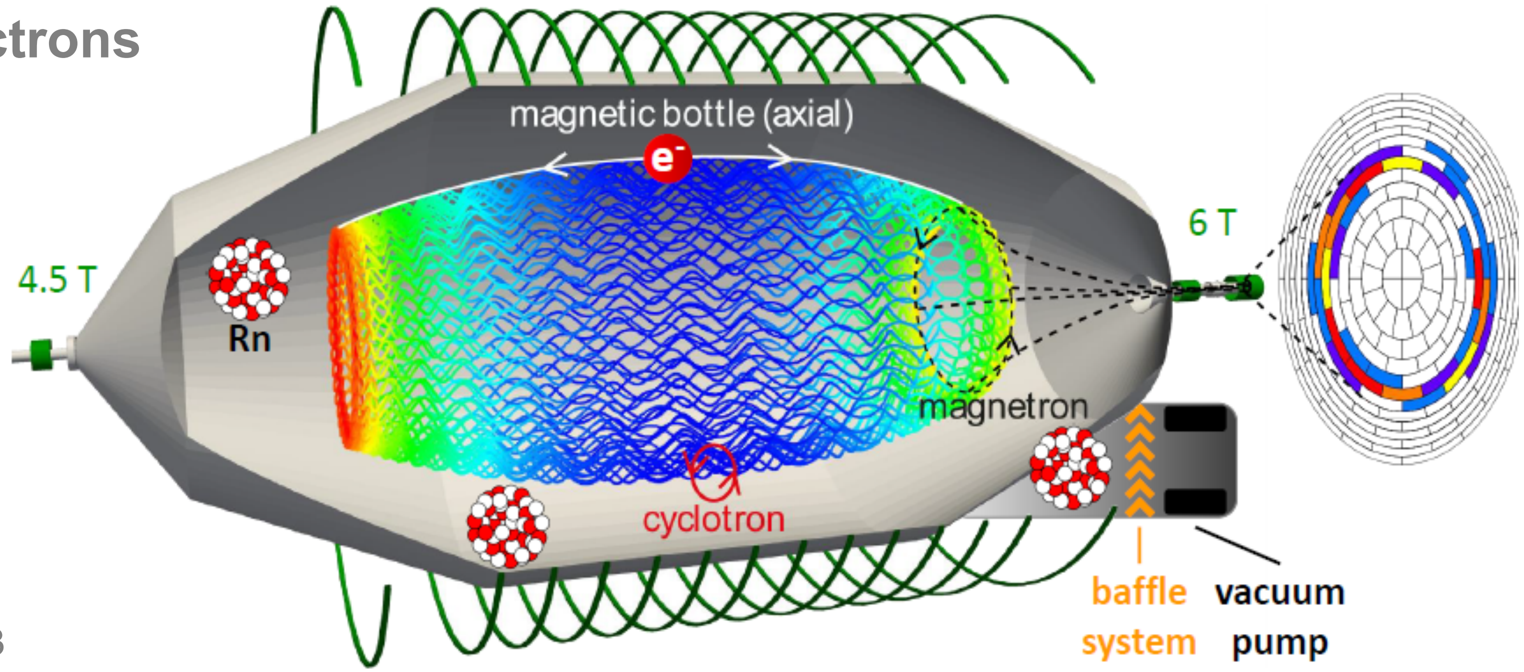
[F. Heizmann, Master’s thesis (2015); see also: Kaboth & Formaggio (2010), Fässler et al. (2013)]

Radon-induced background



Electron emission

Trapping of electrons & production of secondaries



Fränkle et al. 2011
Mertens et al. 2012
Wandkowsky et al. 2013

Background characterization

2015:
2nd phase of commissioning measurements completed

> Spectrometer works as MAC-E filter

> LN2-cooled baffles eliminate Radon-induced background with efficiency of (97 ± 2)%

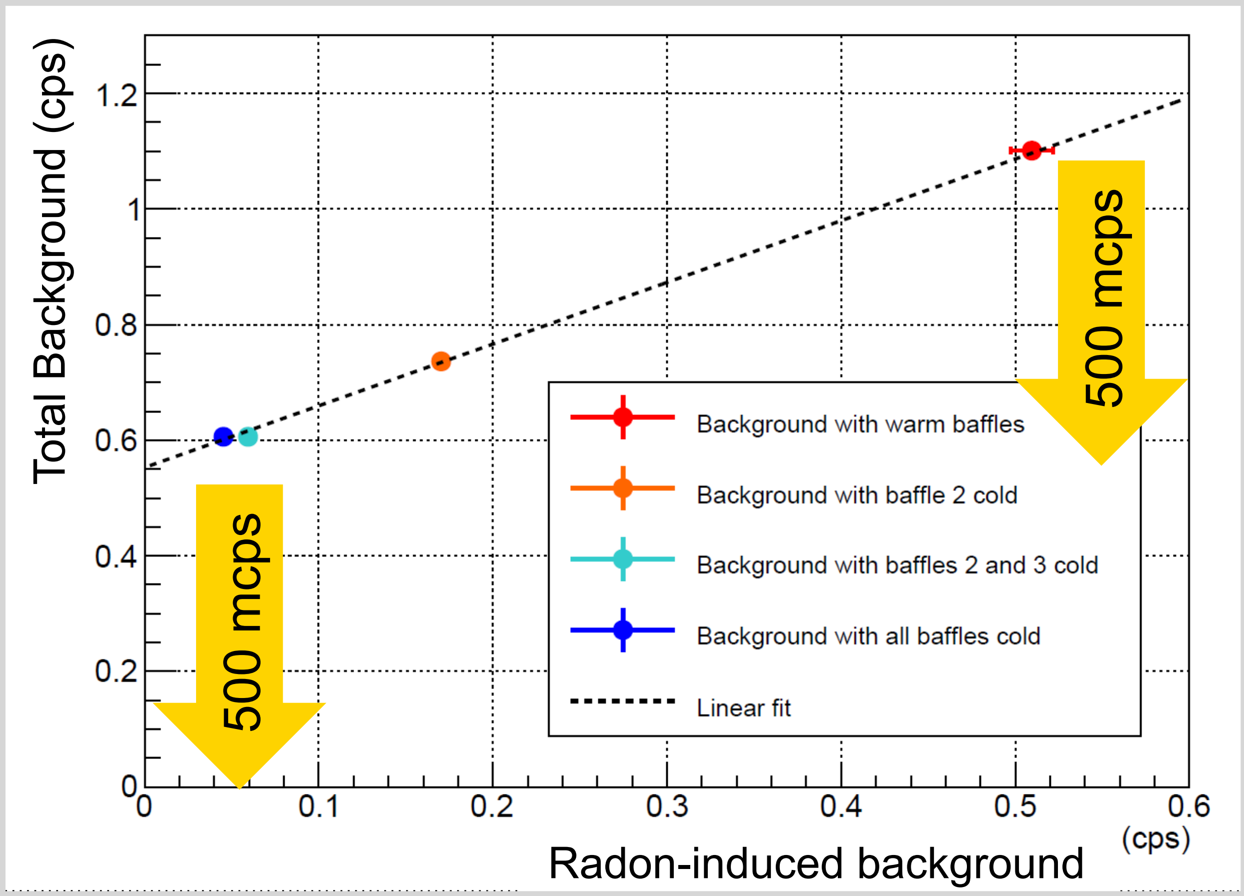
> Remaining background still under investigation

$$B_{total} = S_{Rn} + C_{Rn} + R$$

$$S_{Rn} = \alpha \cdot C_{Rn}$$

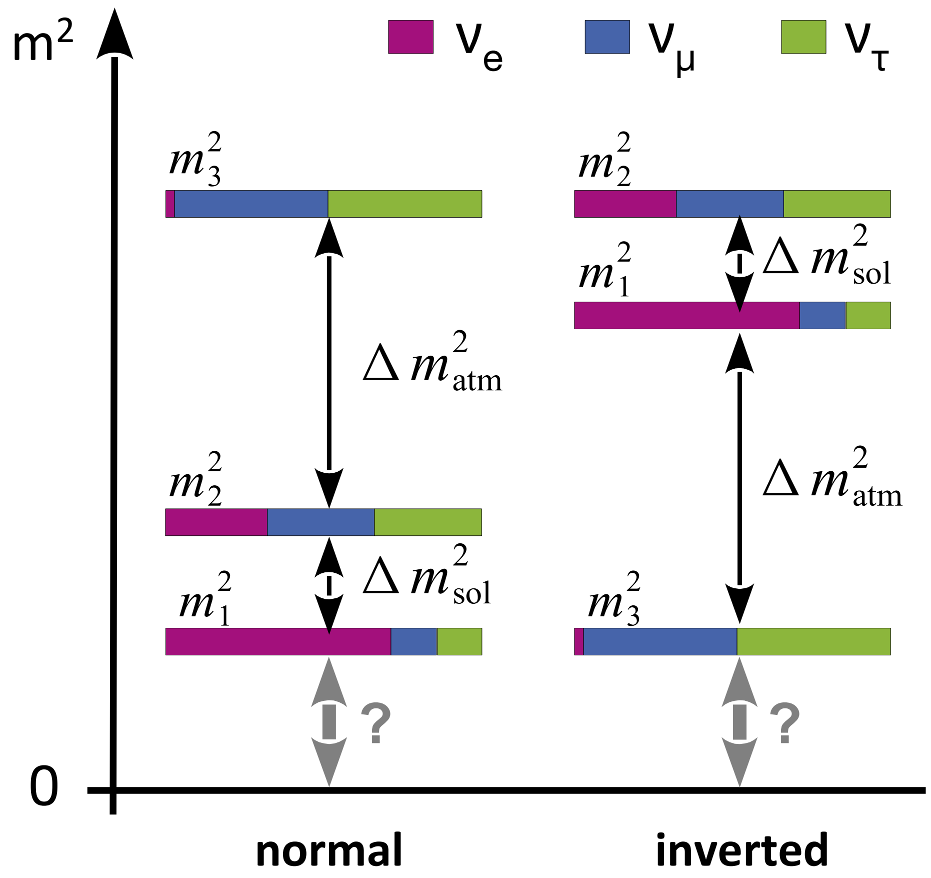
$$B_{total} = (\alpha+1) \cdot C_{Rn} + R$$

B_{total} : Total background rate
S_{Rn} : Radon-induced single event rate
C_{Rn} : Event rate in Radon-induced clusters
R : Non-Radon-induced bg rate



Neutrino mixing and mass scheme

Wealth of ν oscillation data:



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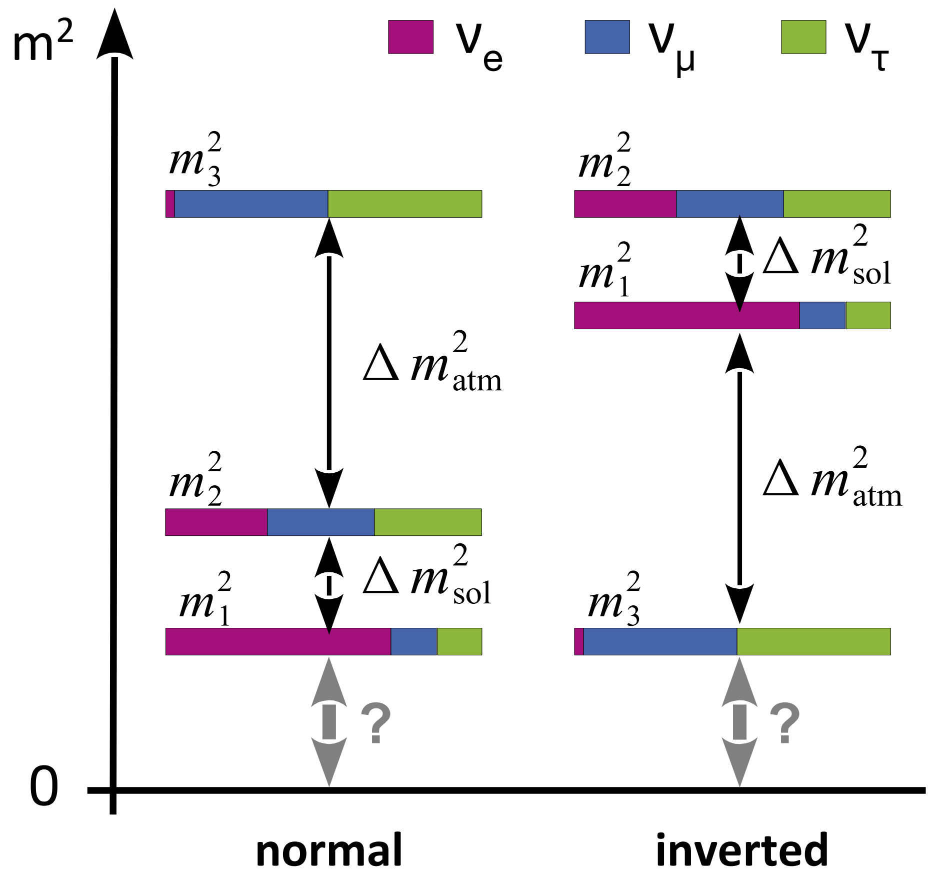
Wealth of ν oscillation data:

- Large neutrino mixing and tiny neutrino masses $m(\nu_i) \neq 0$ established



Neutrino mixing and mass scheme

Karlsruhe Institute of Technology

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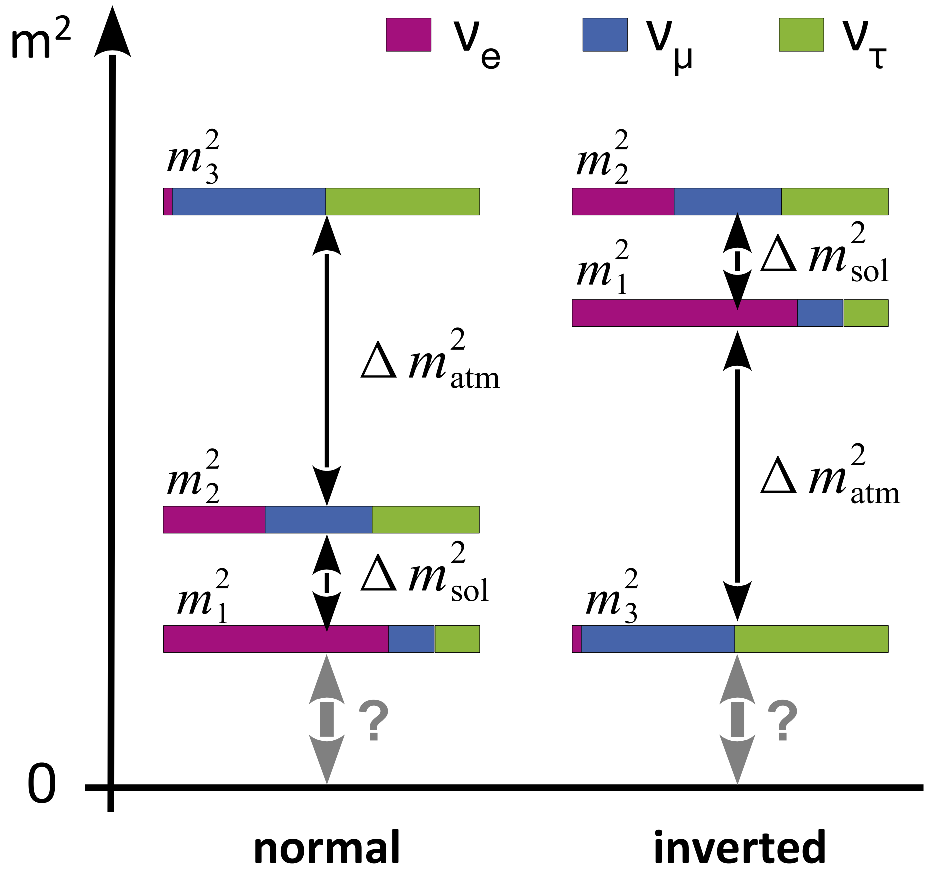
BSM physics!



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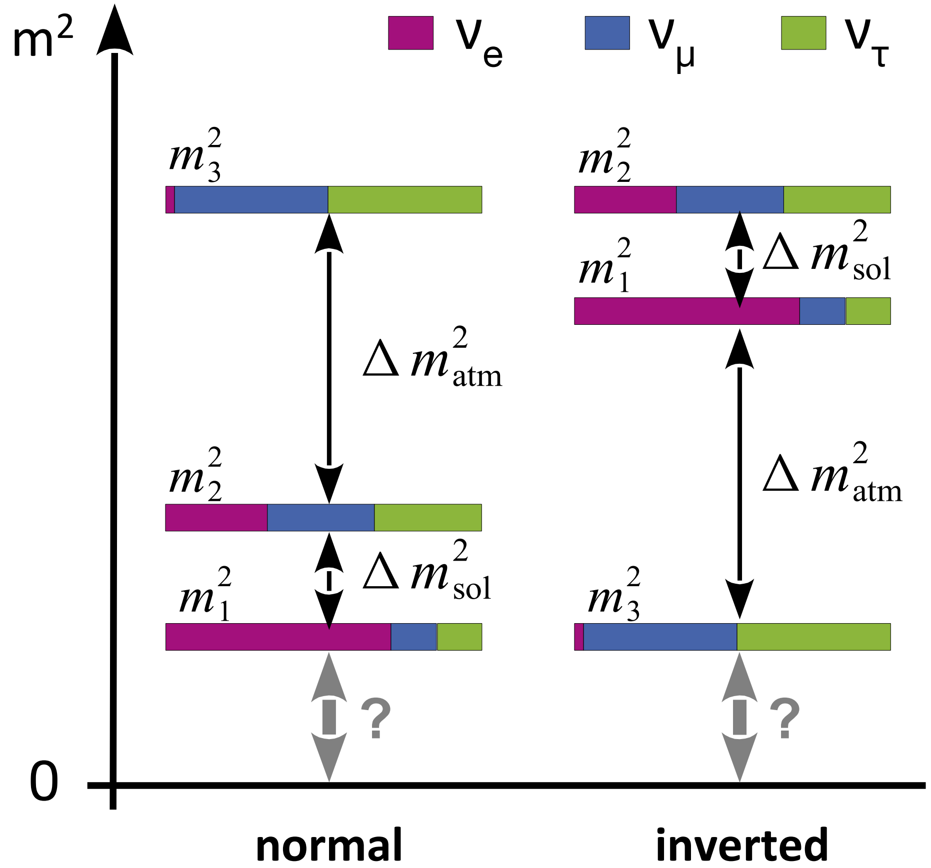

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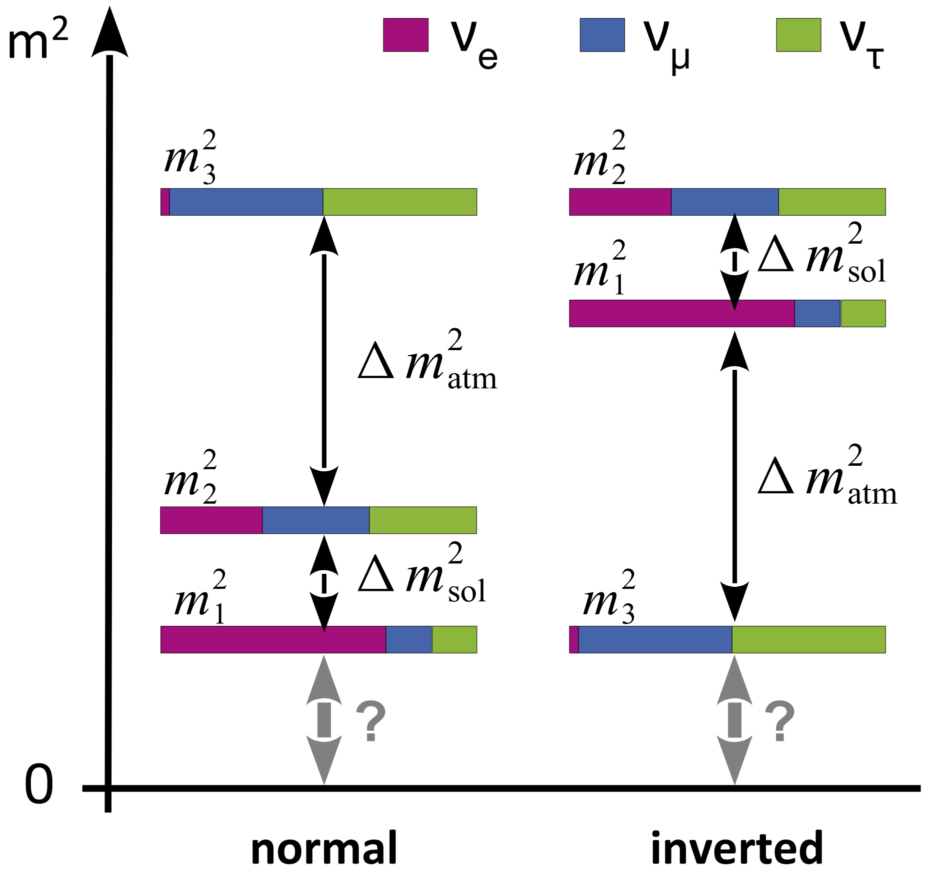

Neutrino mixing and mass scheme

Karlsruhe Institute of Technology

Wealth of ν oscillation data:

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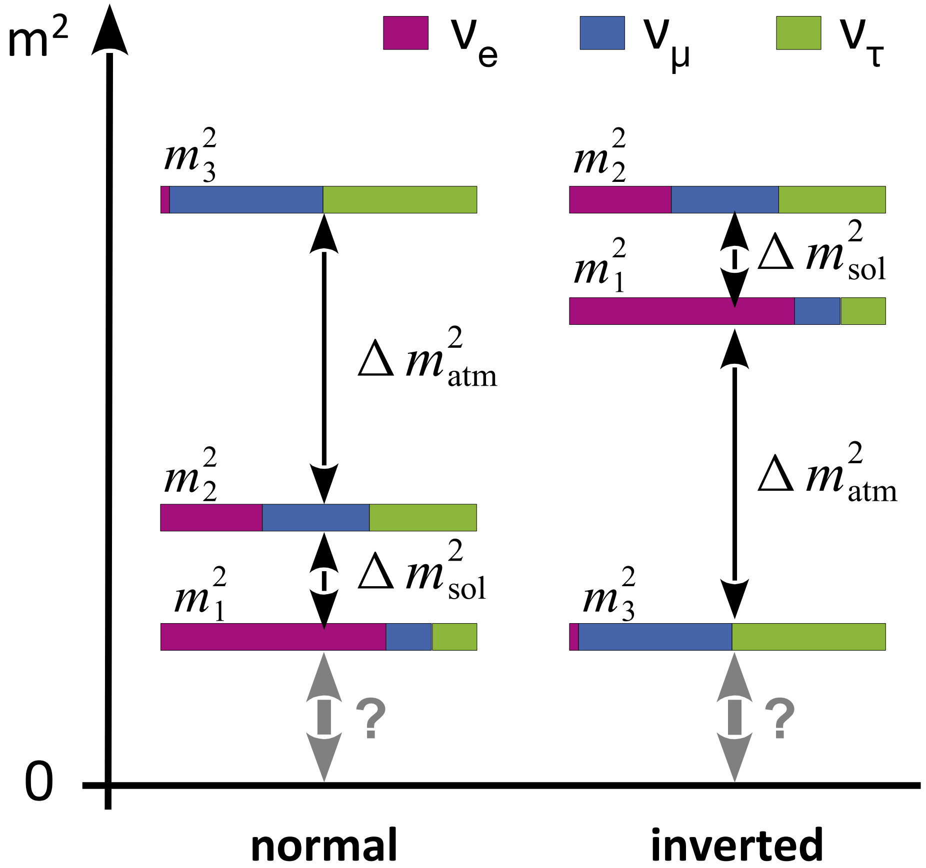
- ***What is the absolute ν mass scale?***



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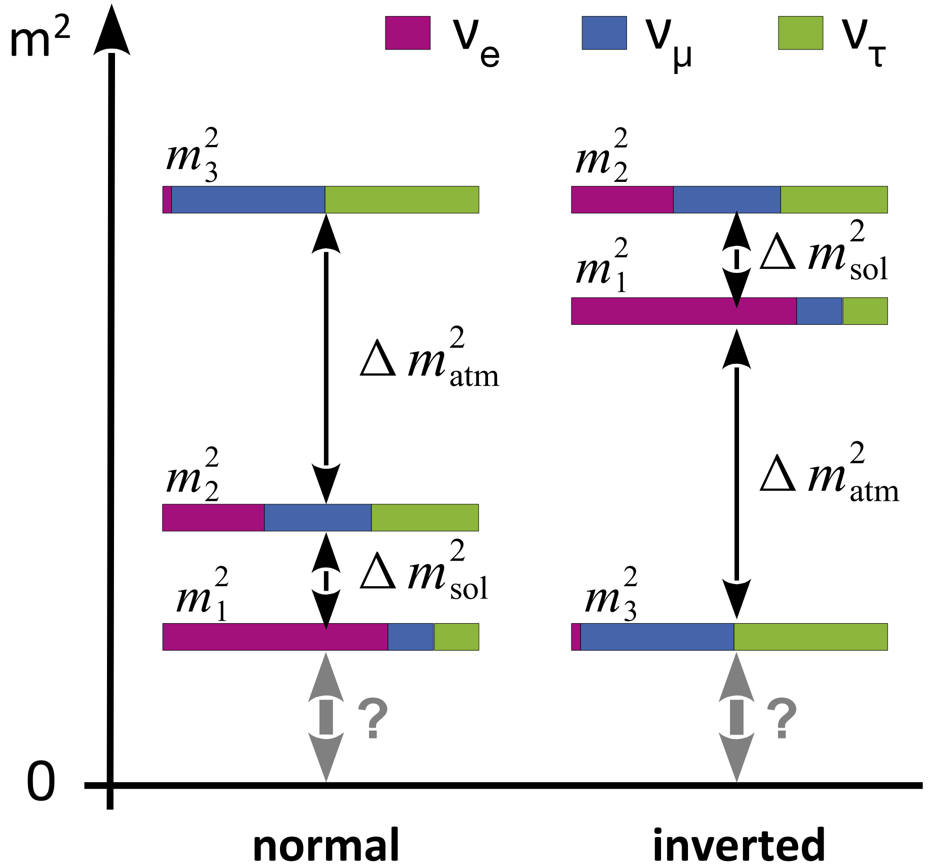
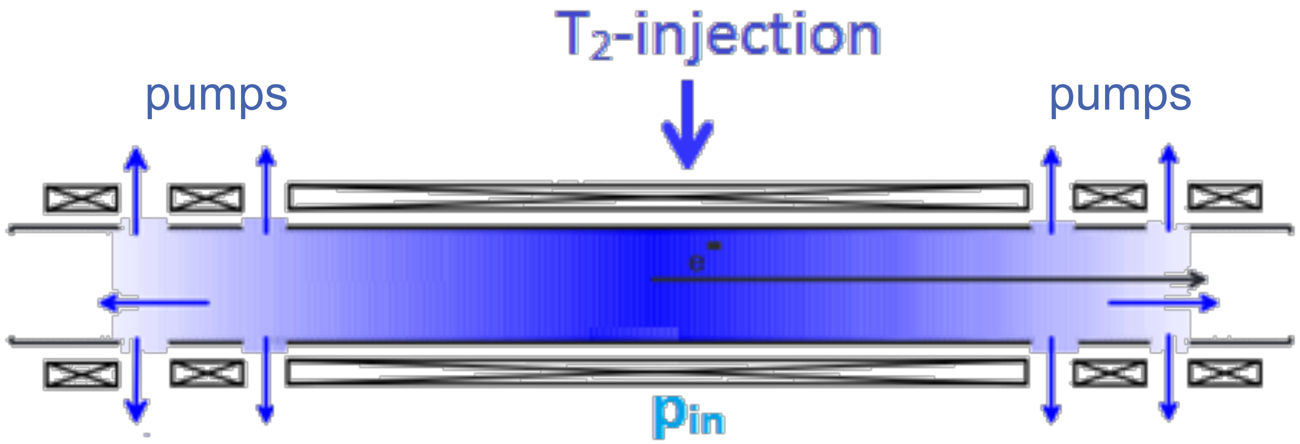


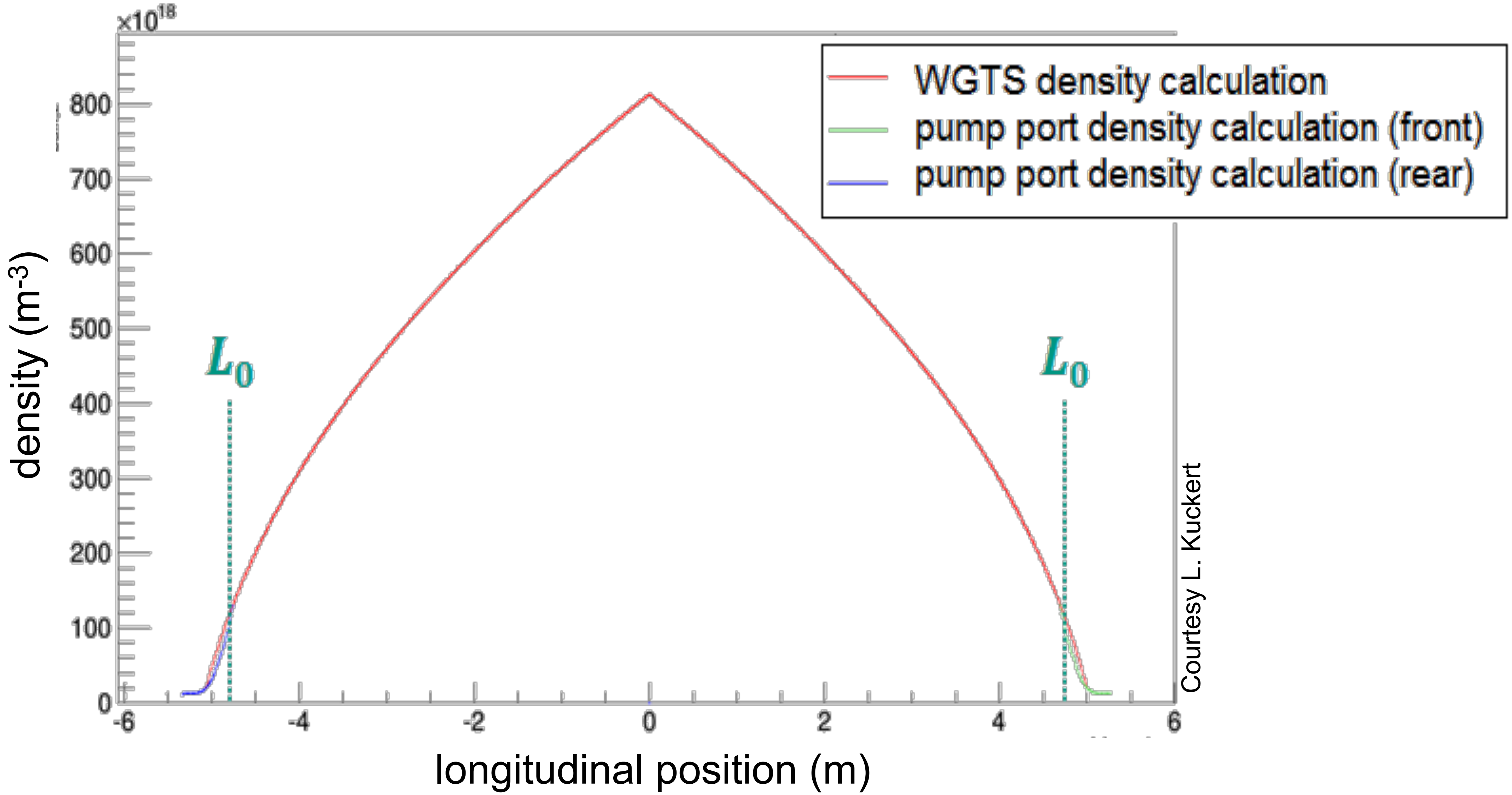
So far: only **upper** (< 2 eV) and **lower bounds** (>0.01 resp. >0.05 eV)

WGTS gas flow regimes

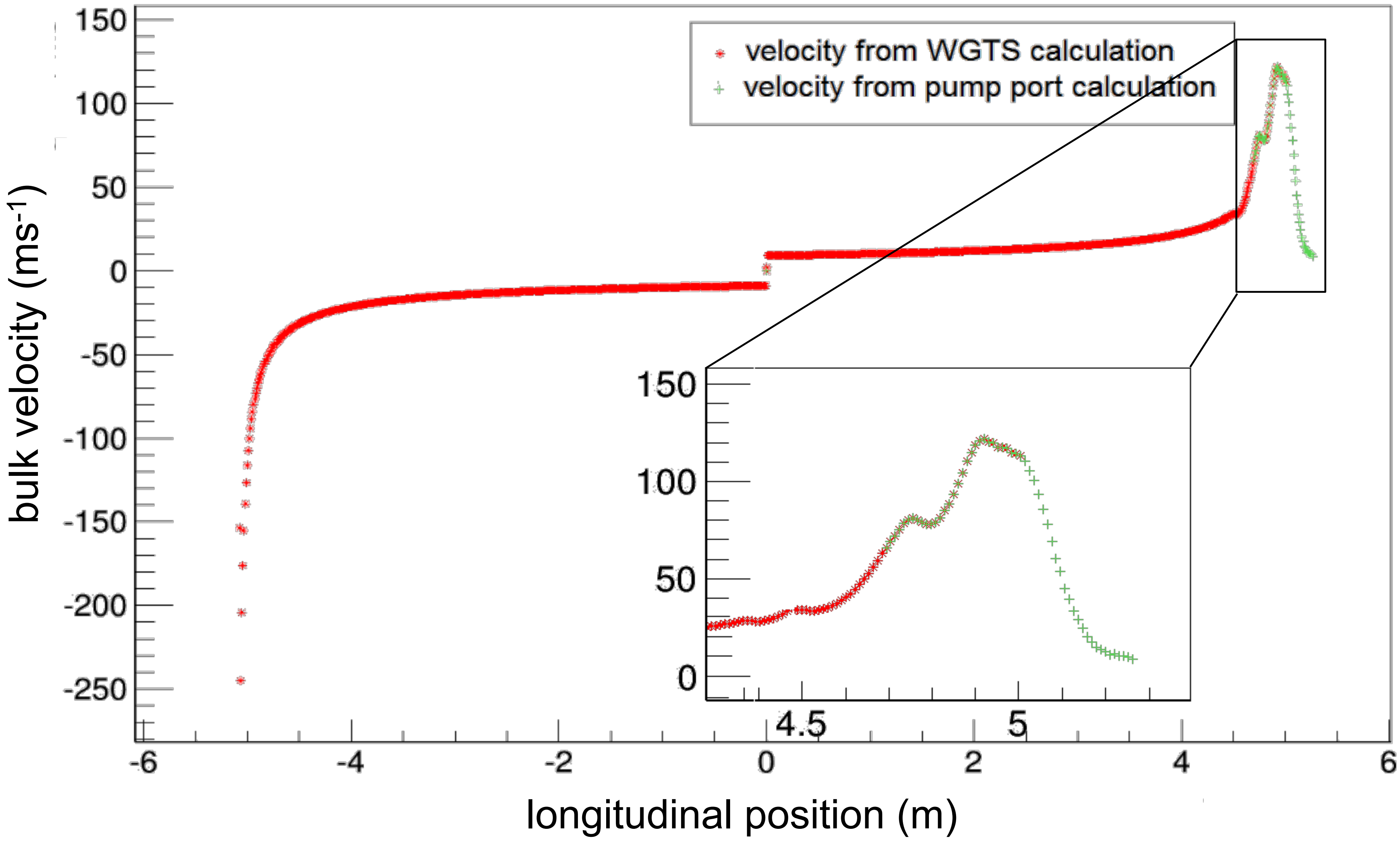


Pressure	$0.02P_{in}$	0.34Pa	$0.02P_{in}$	p
	0.46	23	0.46	δ
Flow Regime	**Transition flow**	**Continuum**	**Transition flow**	**Molecular flow**
Model equation		Navier Stokes equation	Boltzmann equation	Monte Carlo

1D tritium density profile

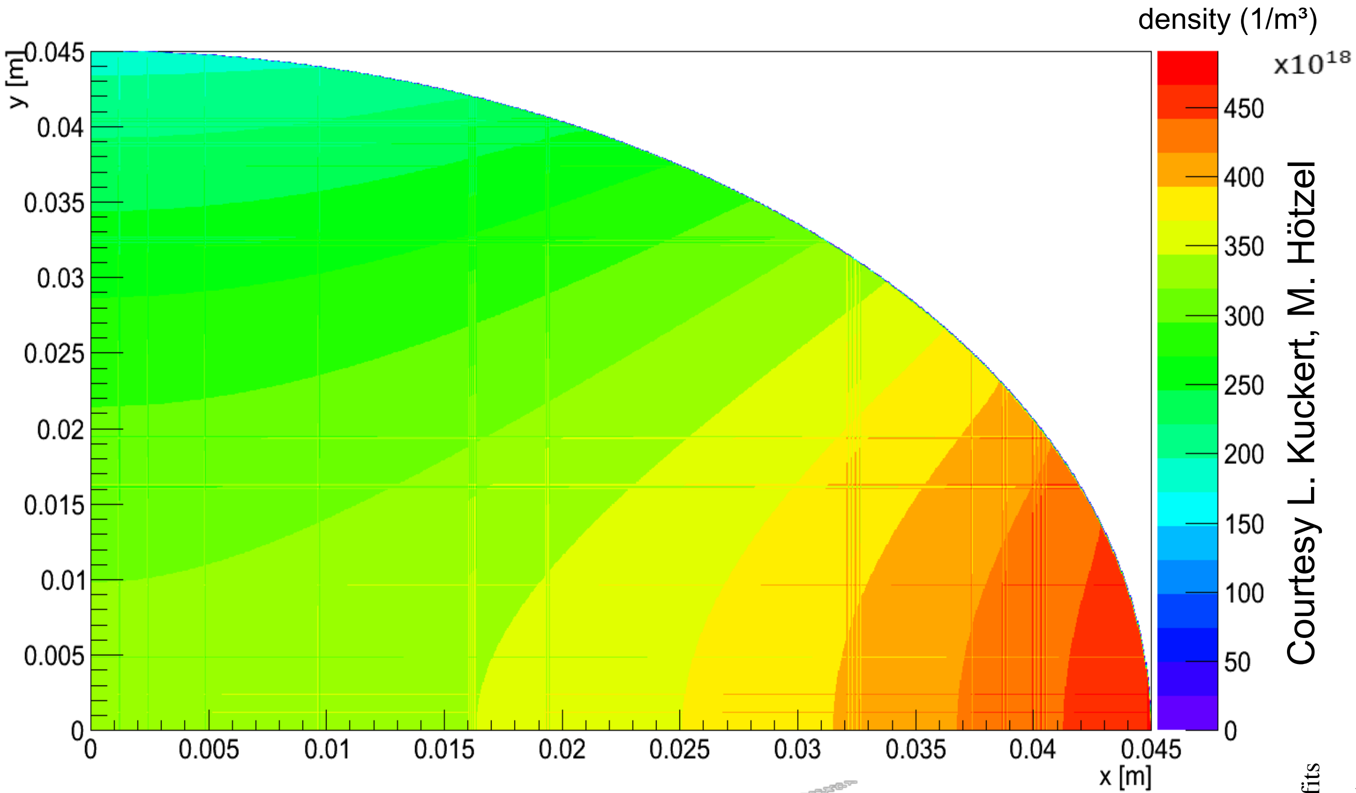


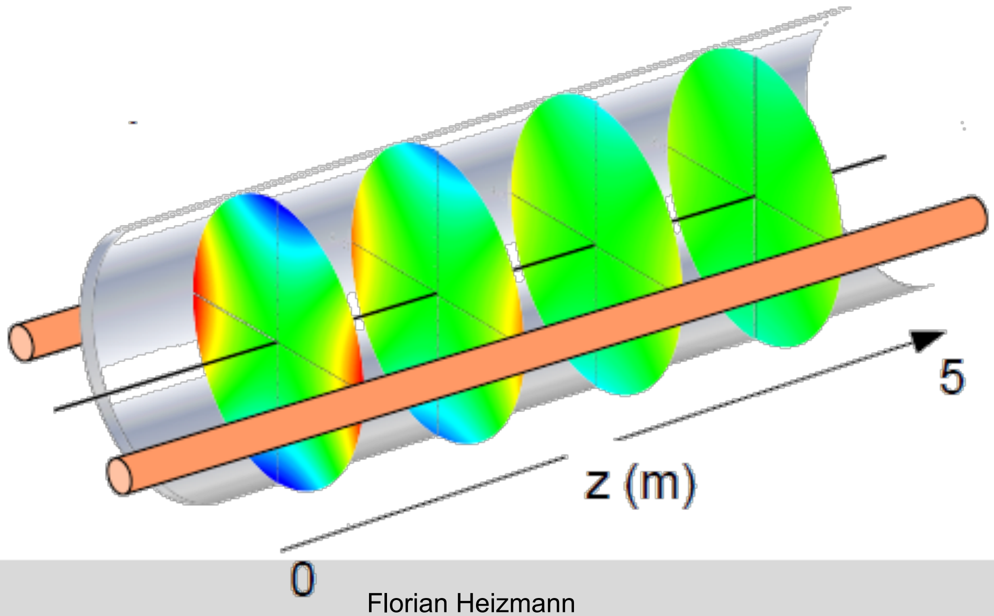
1D velocity profile

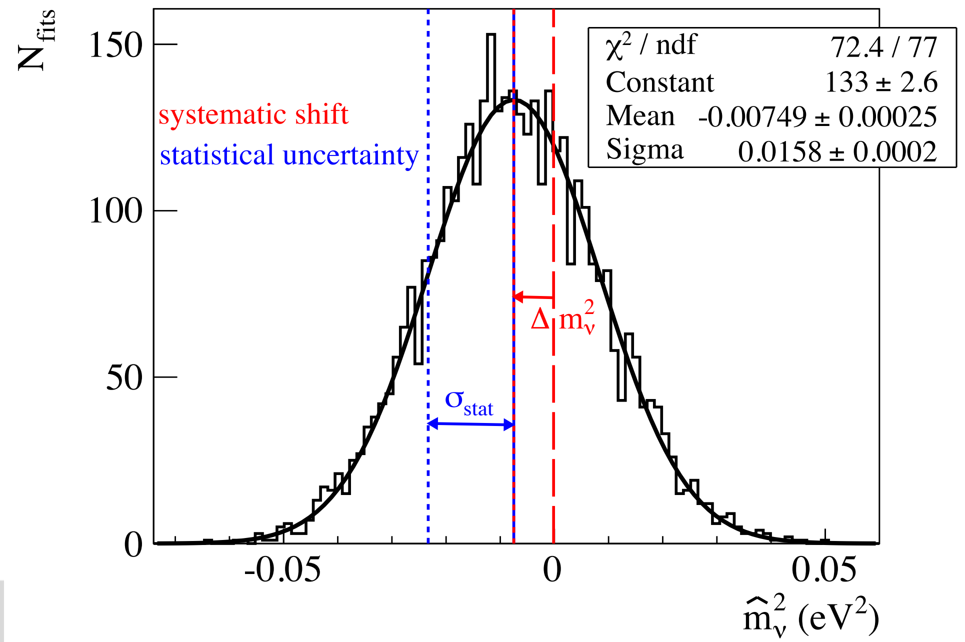


Courtesy L. Kuckert

Pseudo 3D density profile

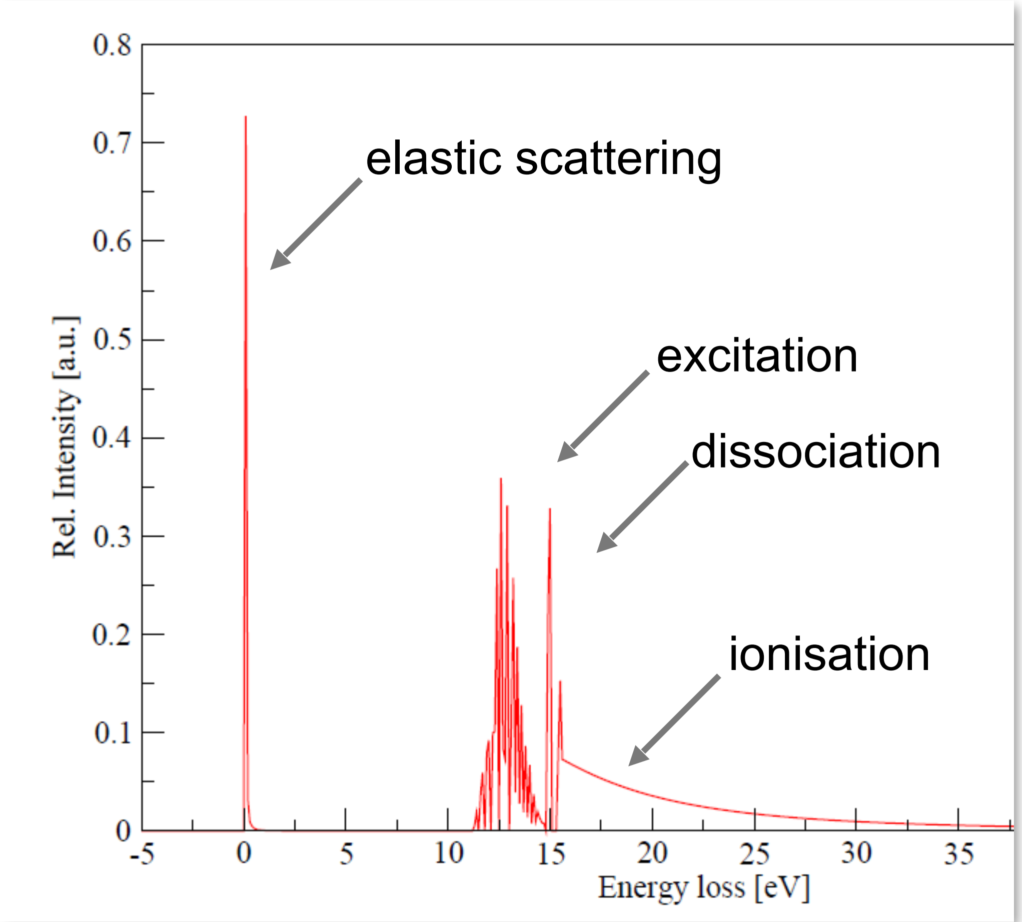


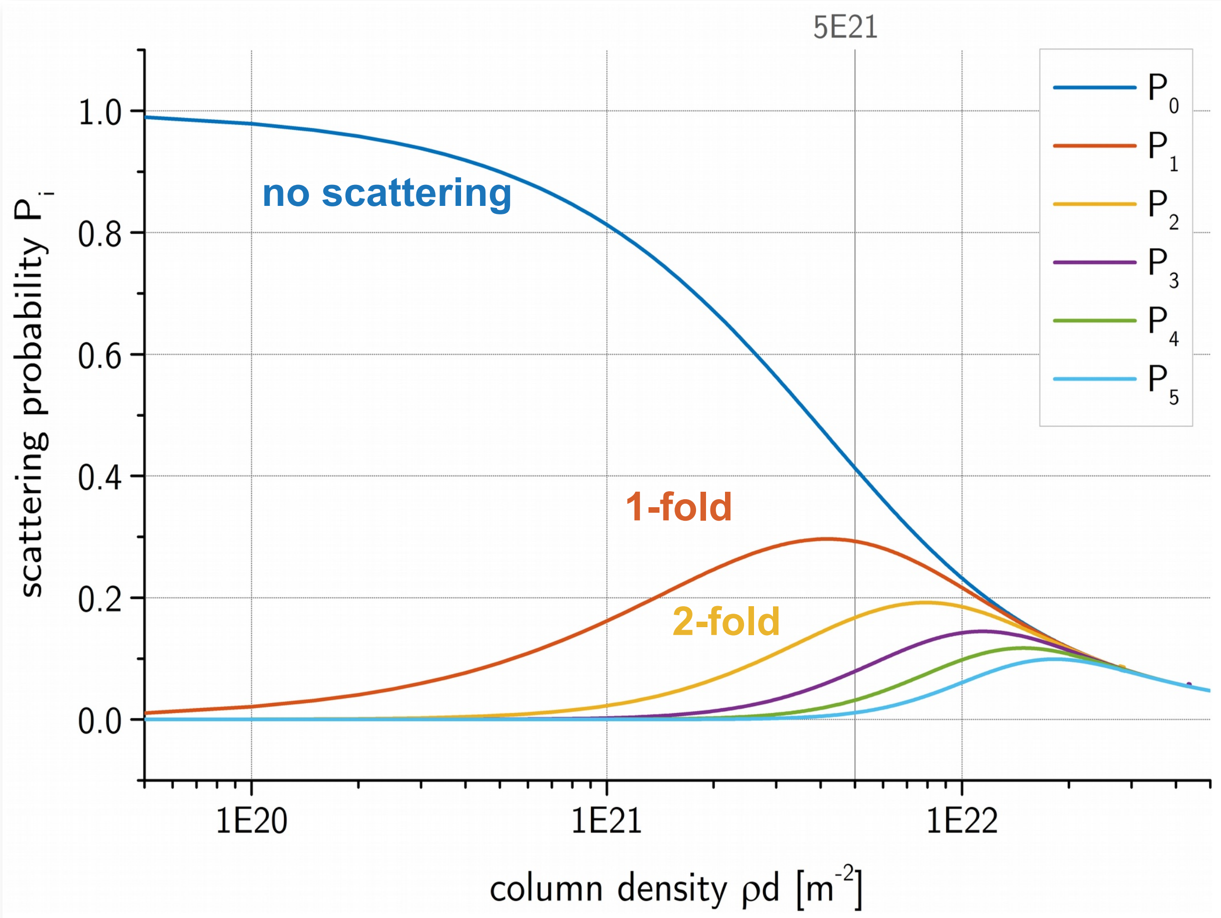




Example: Energy loss function

18.6 keV electrons undergo scattering & energy loss when traversing the gaseous T_2 source:





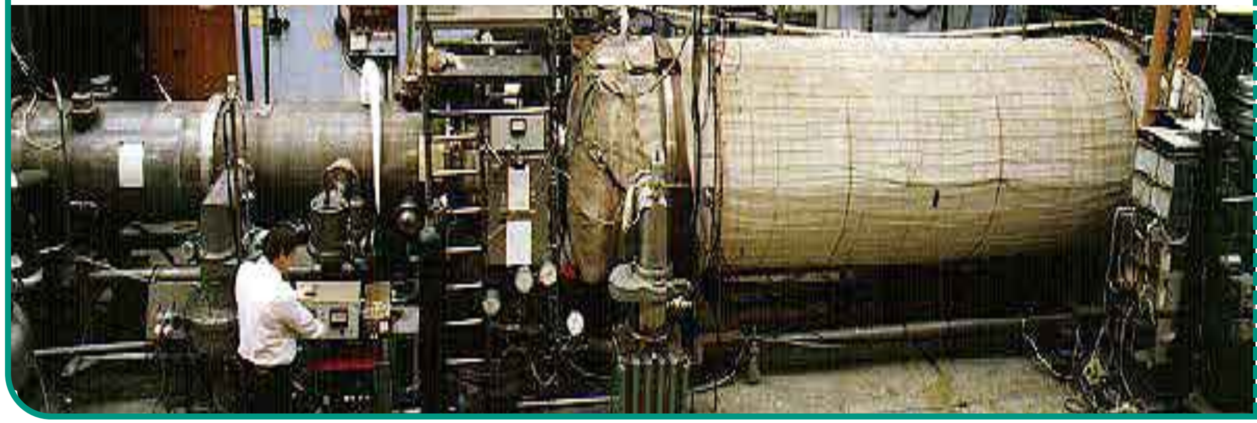
[C. Kranz, Dipl. thesis, Münster, 2011]

[M. Kleesiek]

Troitsk & Mainz experiments

Troitsk experiment

- windowless gaseous tritium source



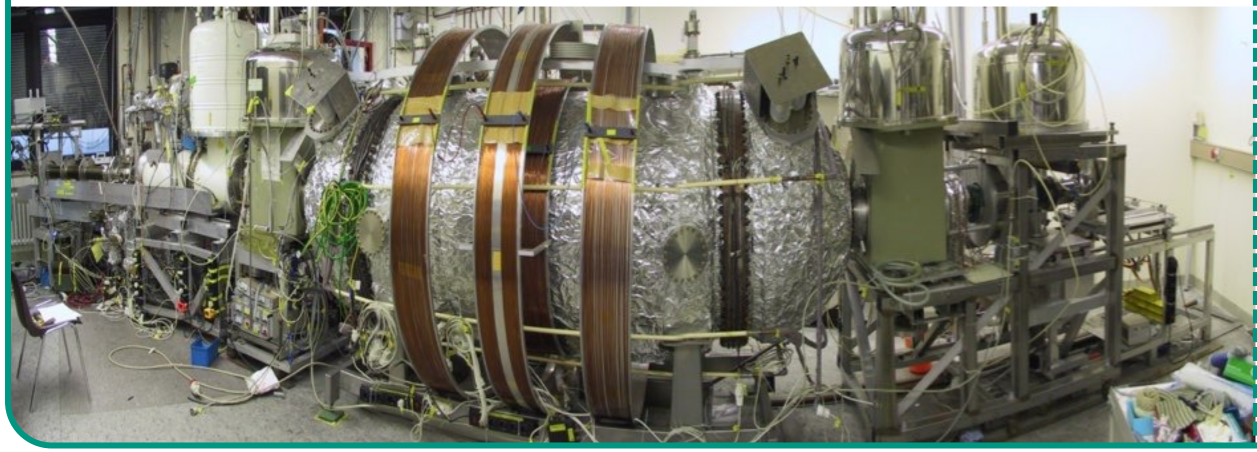
$$m^2(\nu_e) = (-0.67 \pm 1.89 \pm 1.68)\ eV^2$$

$$m(\nu_e) < 2.05\ eV$$

V.N. Aseev et al., Phys. Rev. D 84 (2011) 112003

Mainz experiment

- quench condensed tritium source

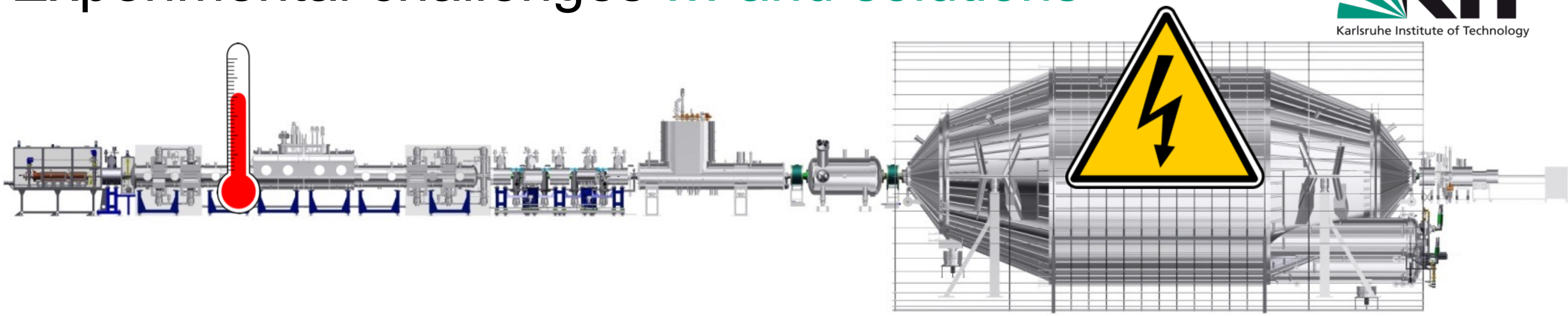


$$m^2(\nu_e) = (-0.6 \pm 2.2 \pm 2.1)\ eV^2$$

$$m(\nu_e) < 2.3\ eV$$

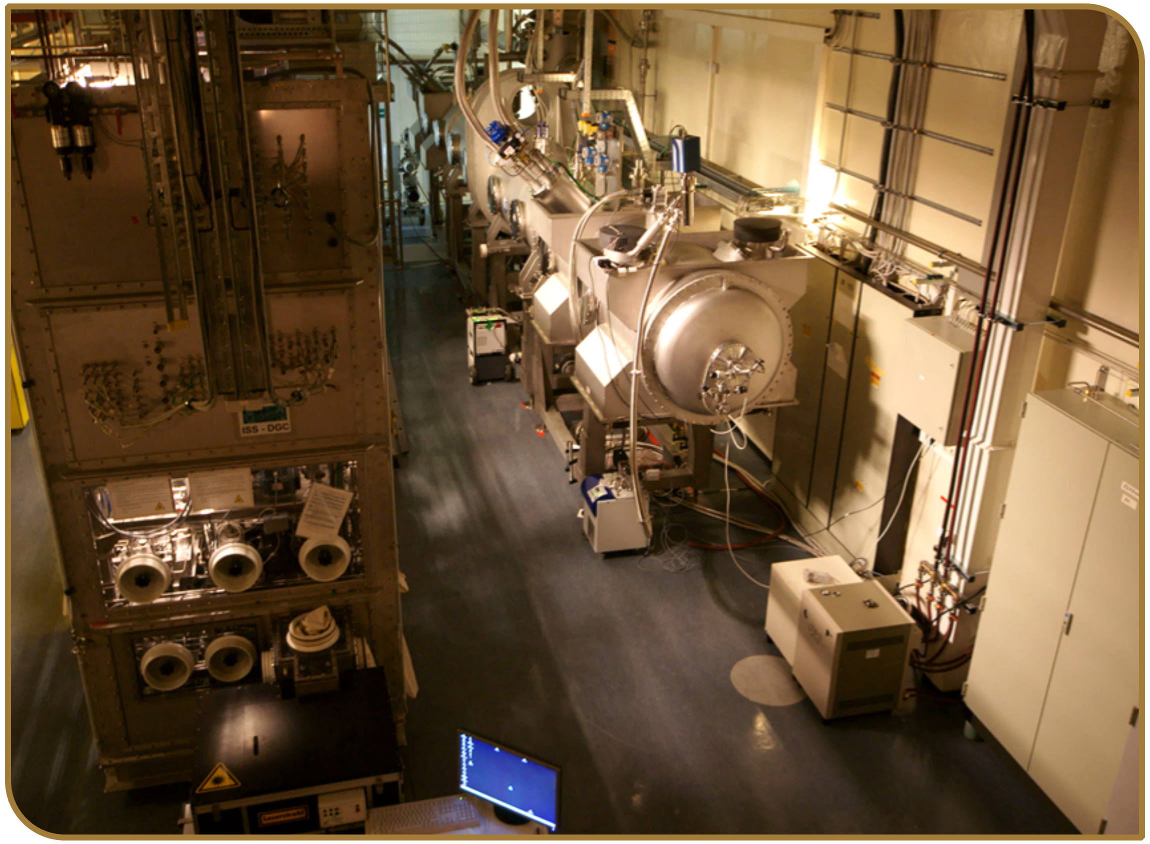
C. Kraus et al., Eur. Phys. J. C 40 (2005) 447

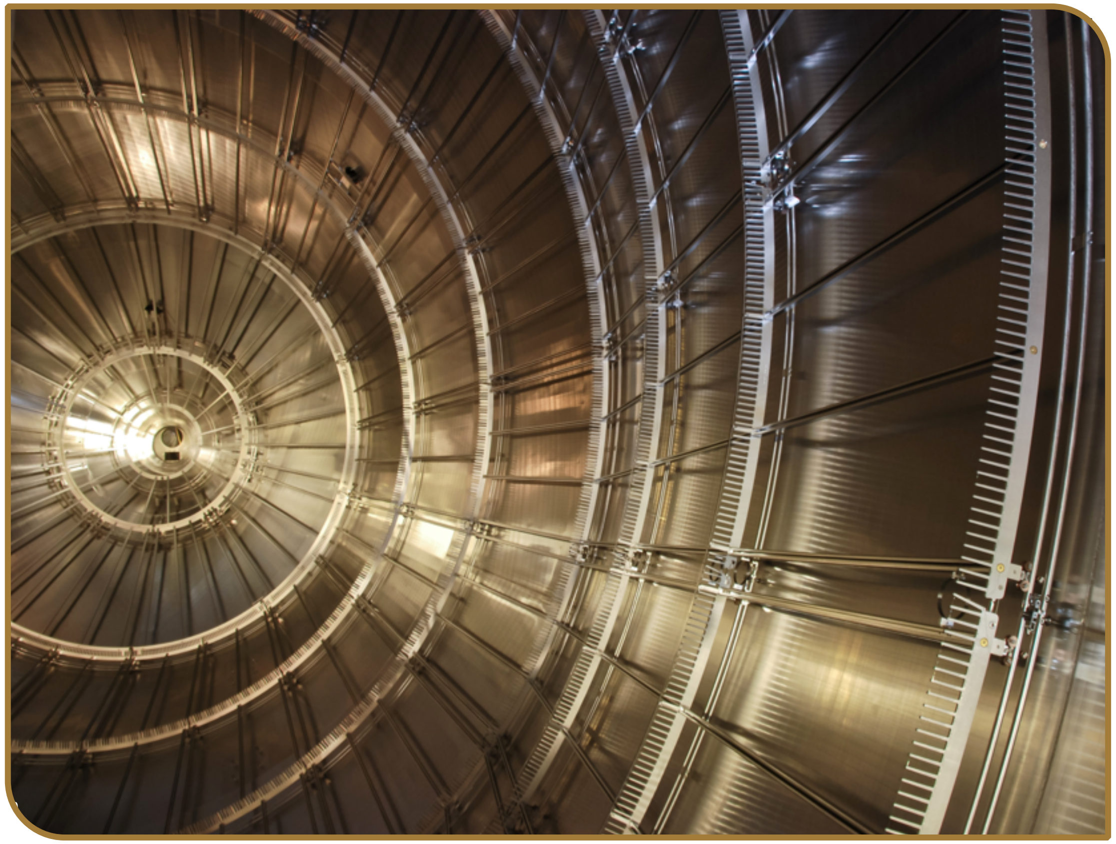
Experimental challenges … and solutions



required: source fluctuation: $\Delta T/T < 10^{-3}$

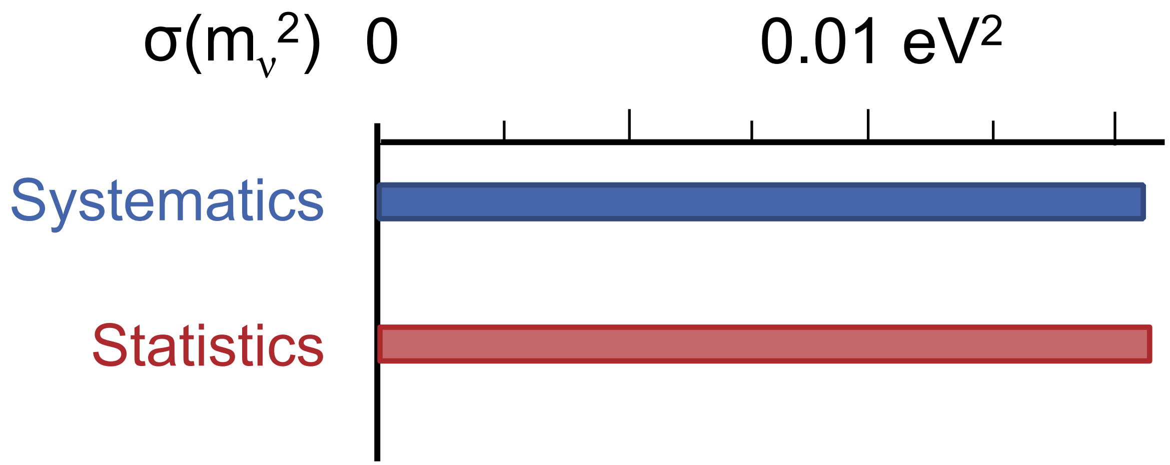
required: HV-fluctuations: ΔU < 60 mV





KATRIN sensitivity in a nutshell

A simple sensitivity estimate from combining (conservative) **systematics** budget with **statistical** uncertainty (3 net years of data):



$\sigma(m_\nu^2)_{syst} = 0.017\ eV^2$

$\sigma(m_\nu^2)_{stat} = 0.018\ eV^2$

adding in quadrature

$\sigma(m_\nu^2)_{total} = 0.025\ eV^2$

unified approach
Feldman & Cousins, 1998

$L(90\%\ CL) = \sqrt{1.64 * \sigma(m_\nu^2)_{total}}$

$\mathbf{m_\nu < 200\ meV\ (90\%\ CL)}$

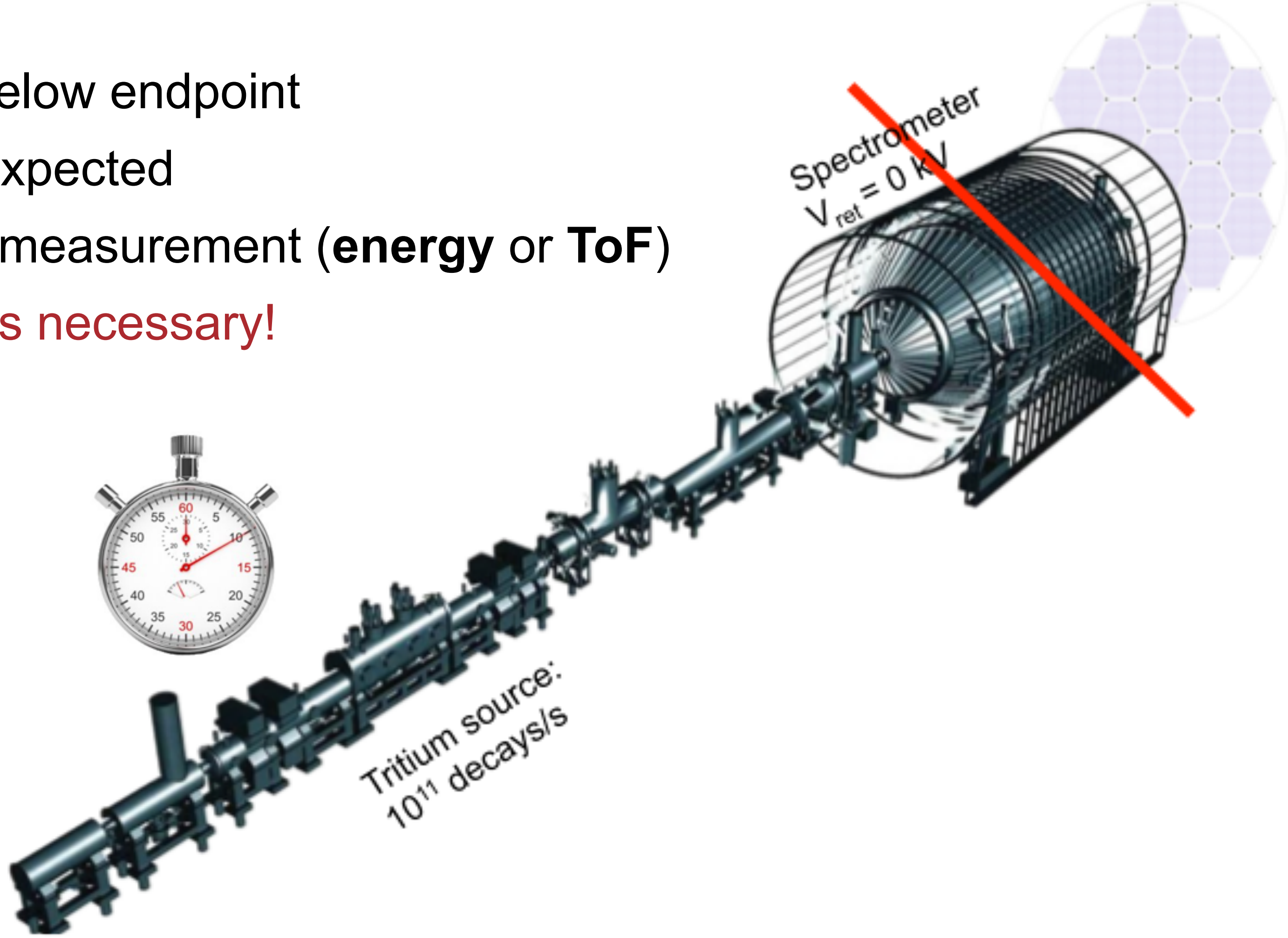
visualization courtesy R.G.H. Robertson

Search for keV-scale sterile ν with KATRIN

The challenge:

- High count rates at ~few keV below endpoint
- Tiny sterile admixture $\sin^2(\theta_s)$ expected
- Best sensitivity for **differential** measurement (**energy** or **ToF**)

➡ Development of new techniques necessary!



*) **TR**itium beta decay **I**nvestigation on **S**terile **T**o **A**ctive **N**eutrino mixing

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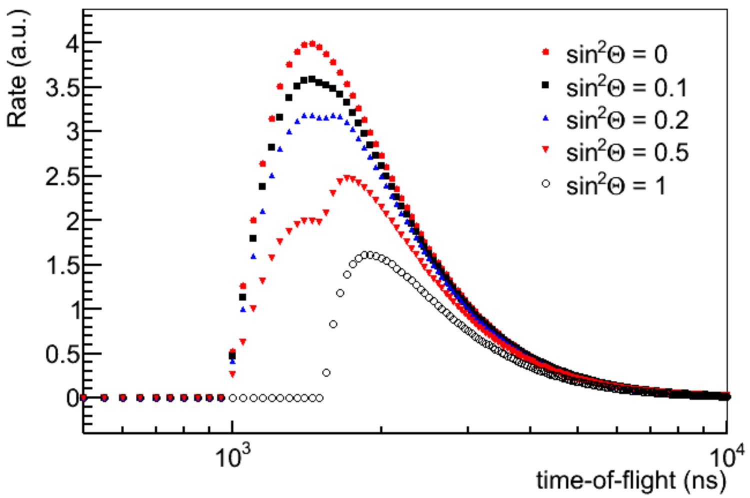
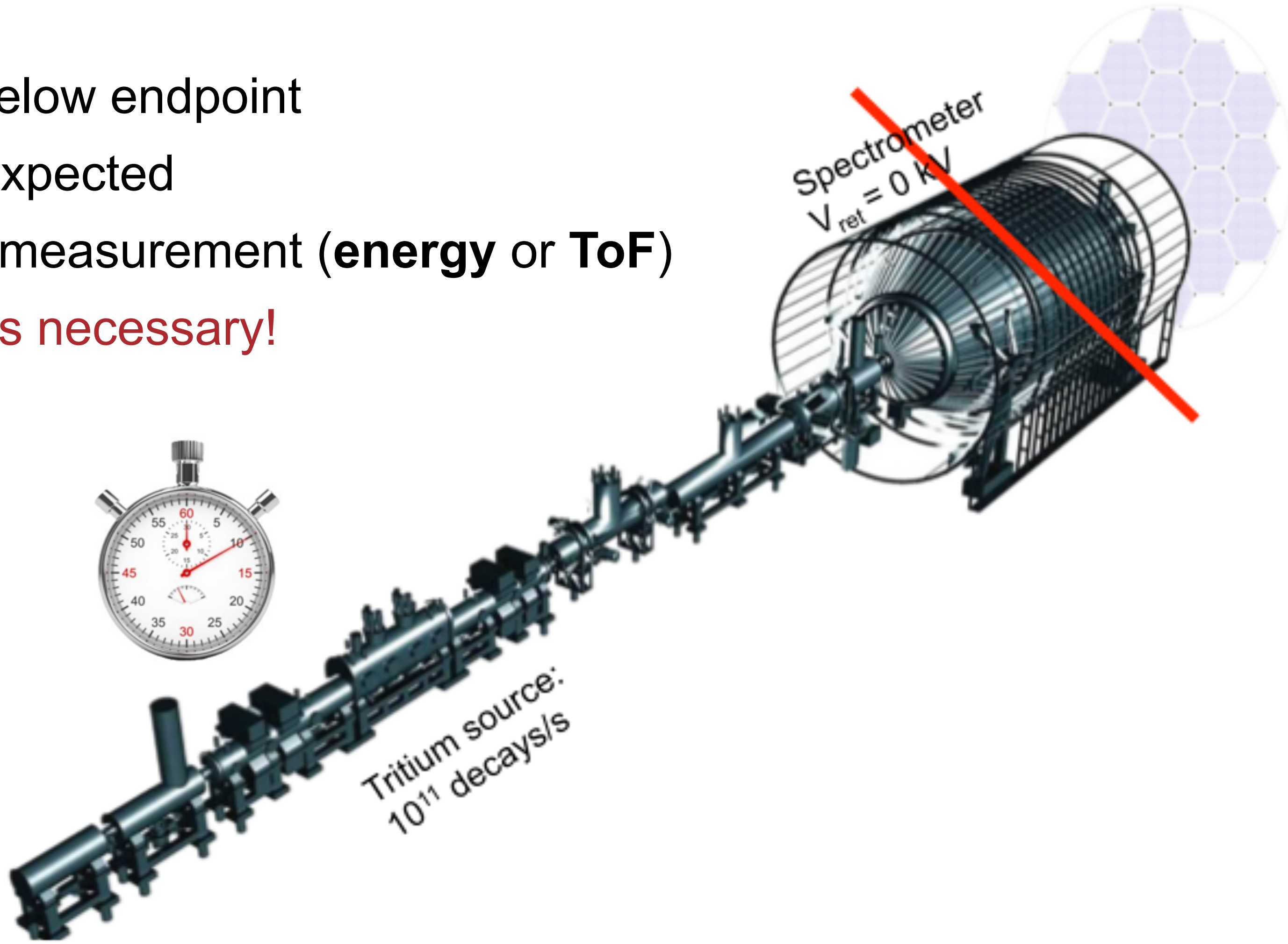
ToF option:
electron tagger required





[Steinbrink et al. (2013), Robertson et al. (in prep.)]

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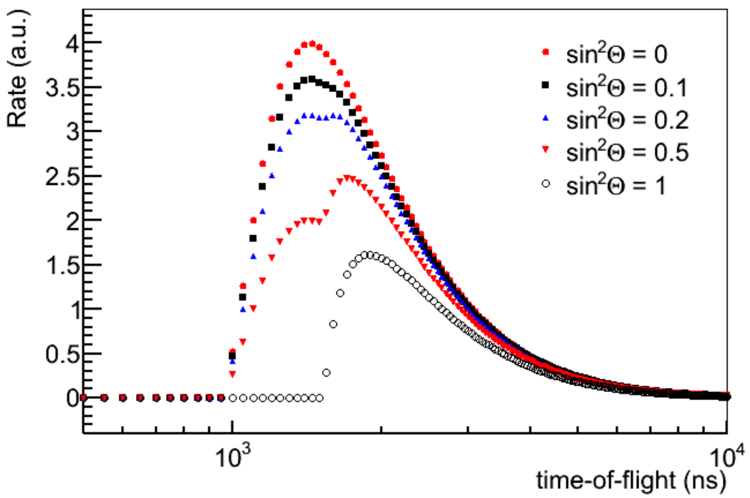

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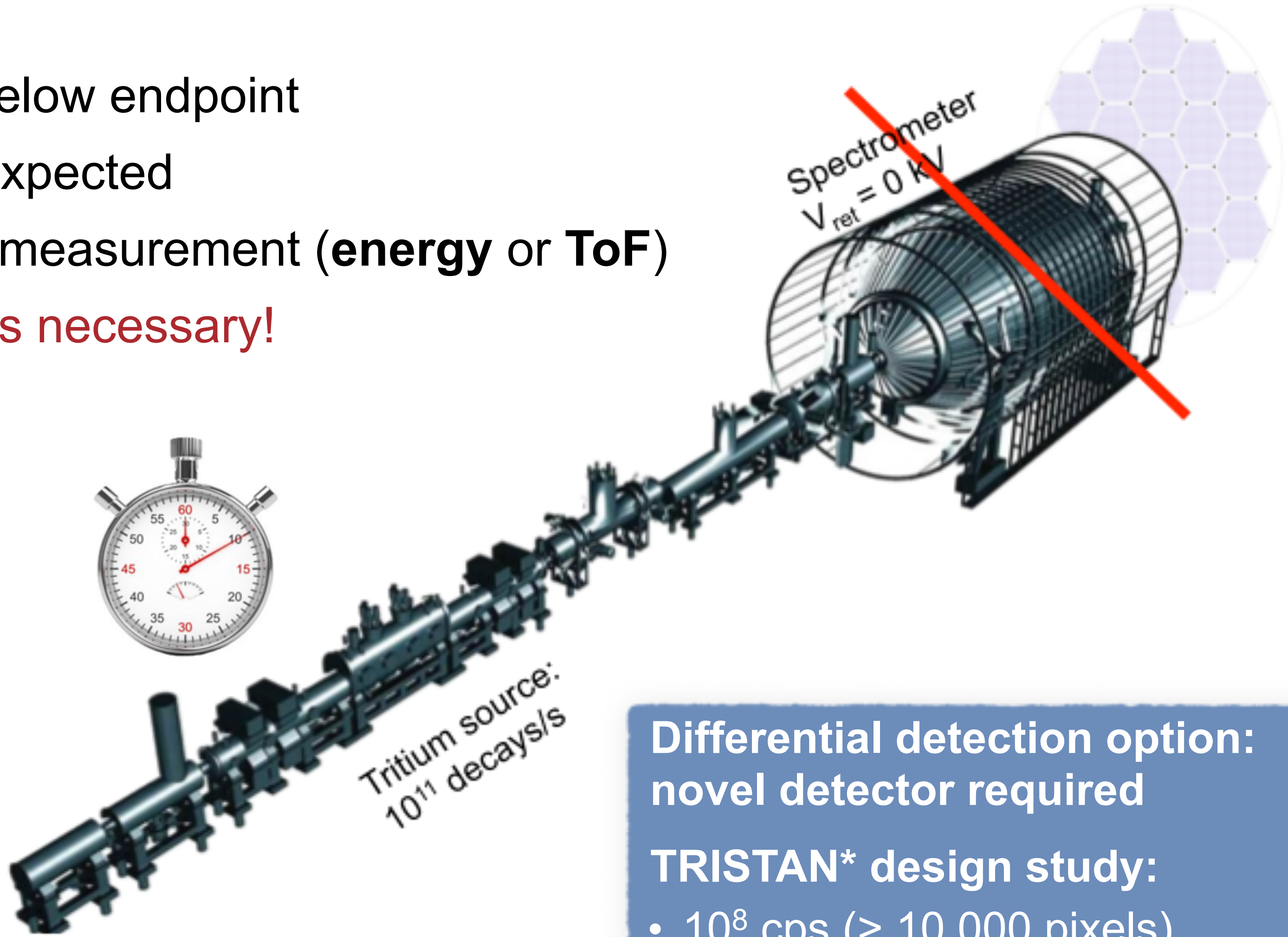

Differential detection option:
novel detector required

TRISTAN* design study:

- 10^8 cps (> 10 000 pixels)
- FWHM 300 eV @ 20 keV
- > 20 cm diameter

[Mertens et al. (2015)]

*) **TR**itium beta decay **I**nvestigation on **S**terile **T**o **A**ctive **N**eutrino mixing

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TRISTAN prototype (10/2015):
characterize pile-up, backscattering,
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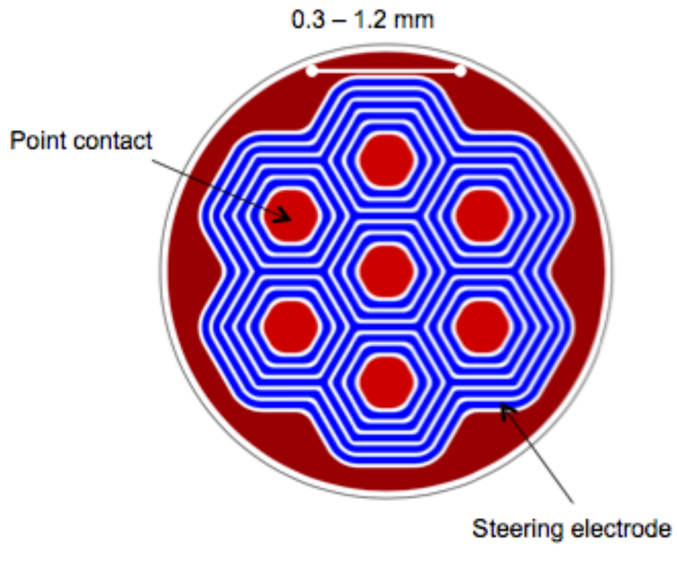

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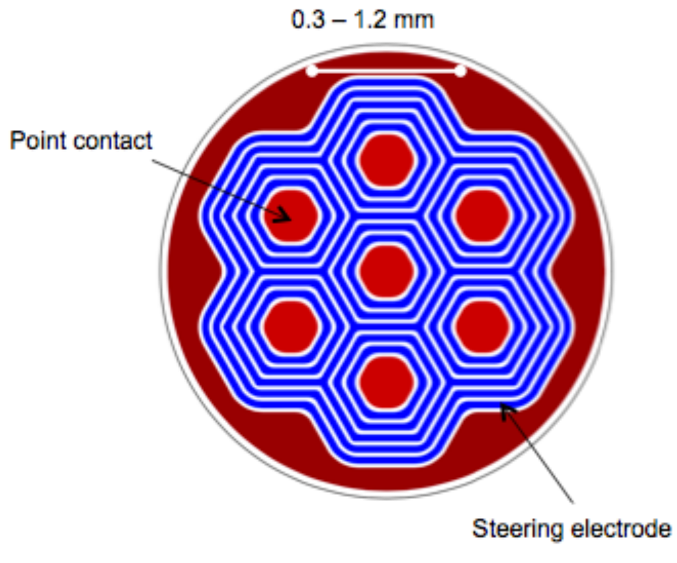

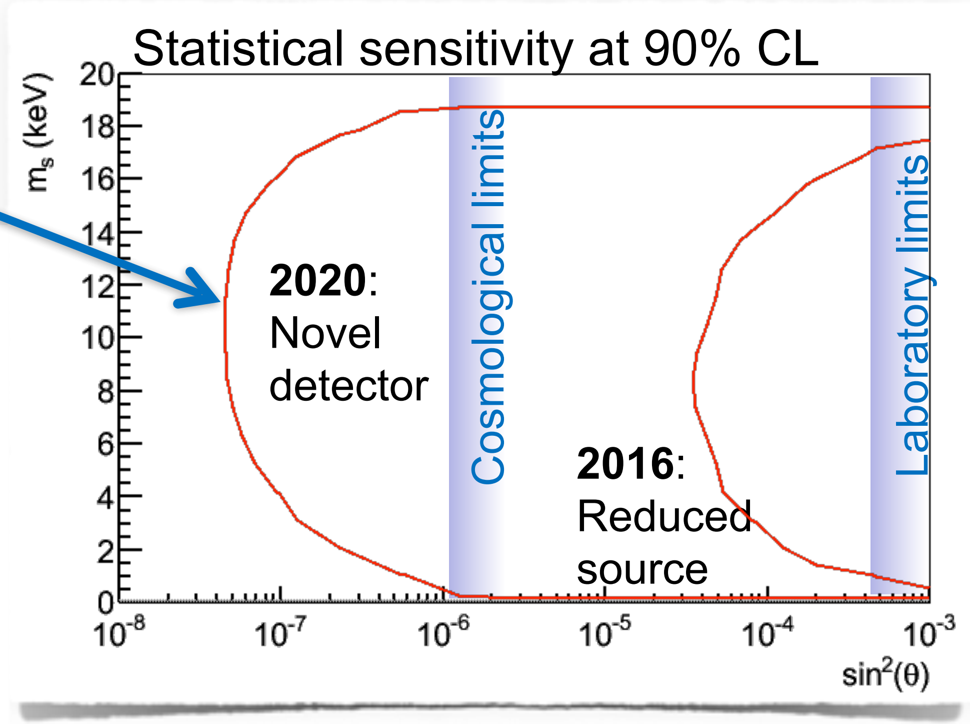

courtesy S. Mertens

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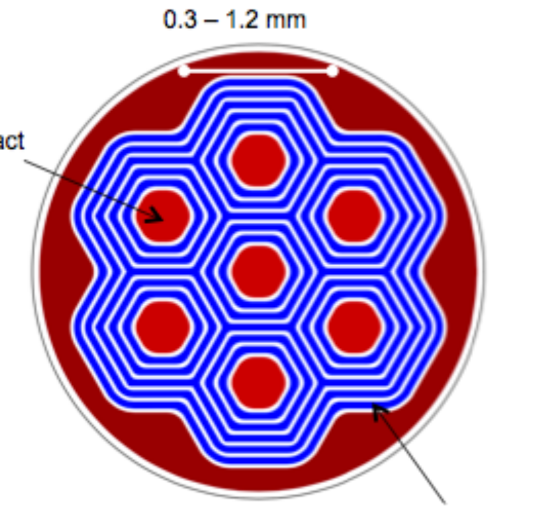
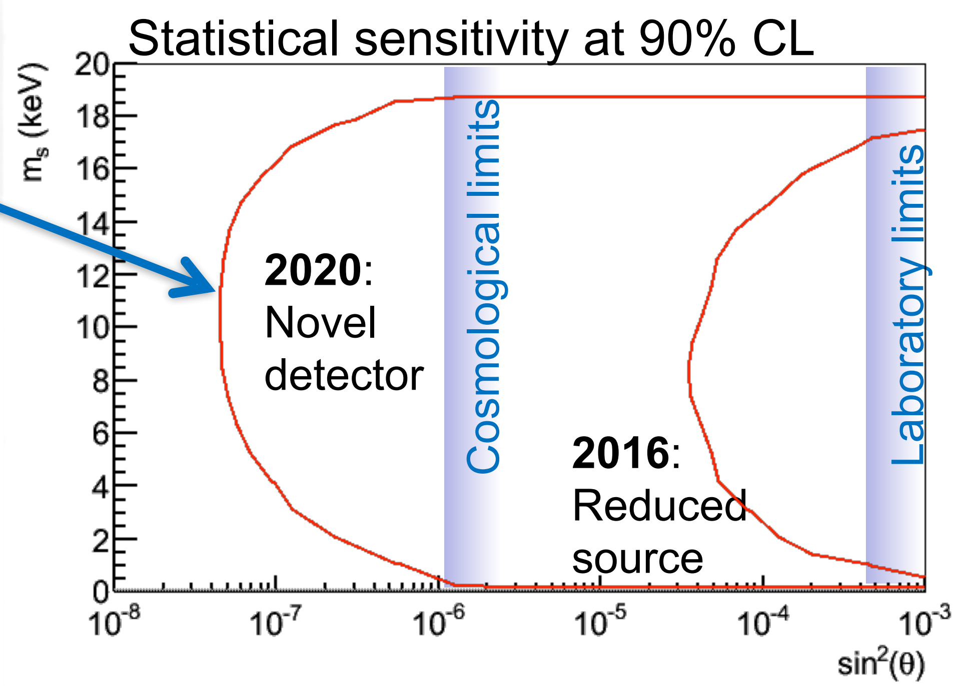


Collaboration with HLL Munich and LBNL



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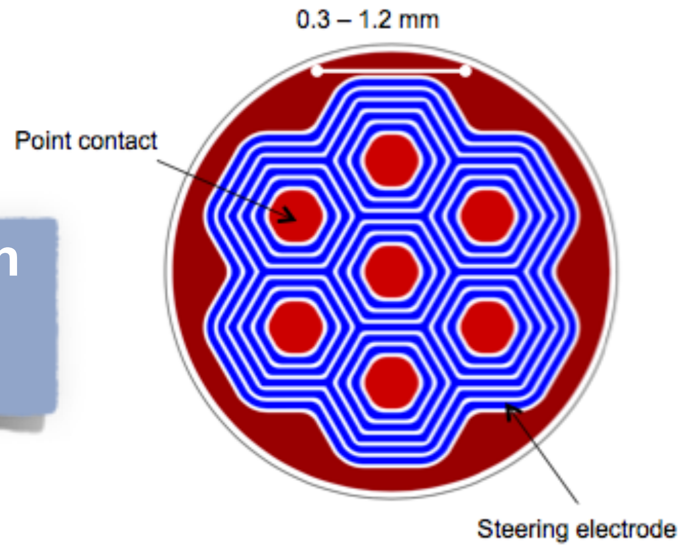

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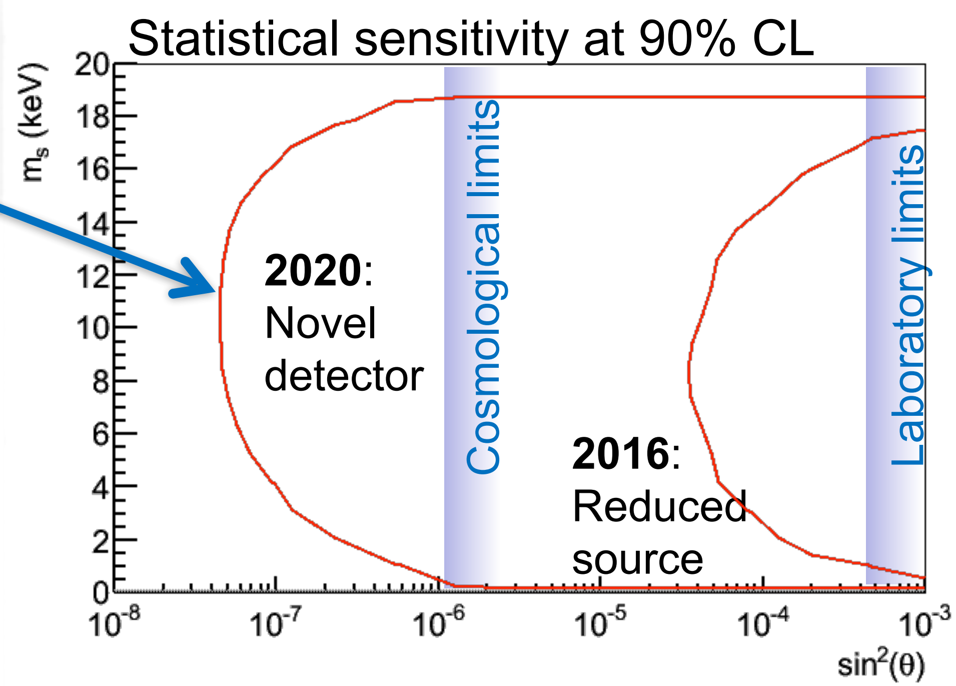


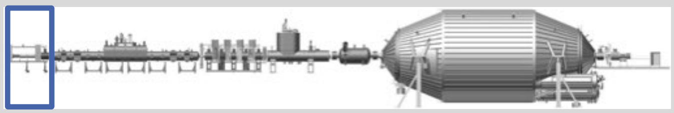
courtesy S. Mertens

➜ High-sensitivity keV sterile ν search probing cosmologically allowed parameter space after the ν-mass measurement with KATRIN

Rear Section – design and assembly

Major importance for systematics:

- **Precision e^- source:**
  column density monitoring
  and determination of energy loss
  function (scattering)



Rear Section – design and assembly

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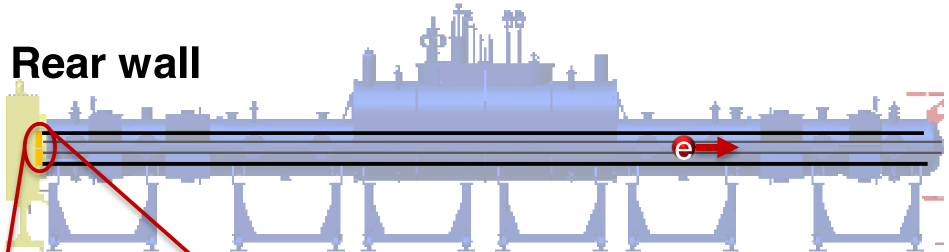
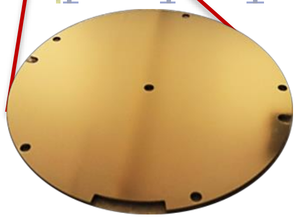
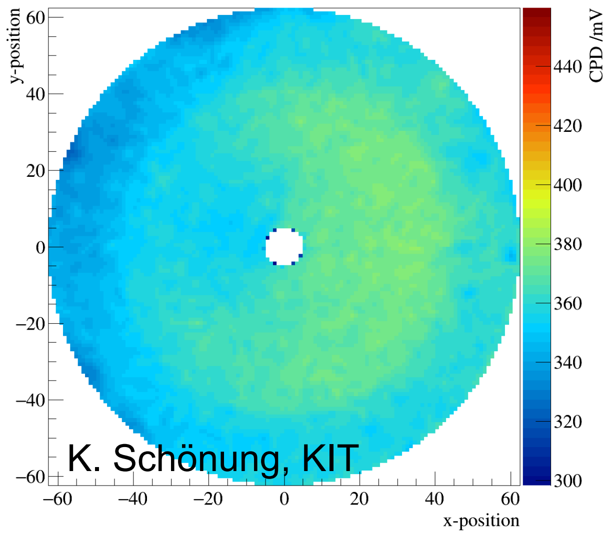
- **Rear Wall:**
  stable and homogeneous
  electrostatic potential in the
  source plasma

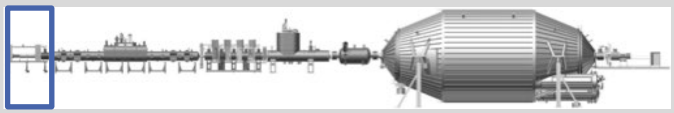




⌀15 cm gold surface
for homogeneity

work function test
of smaller sample

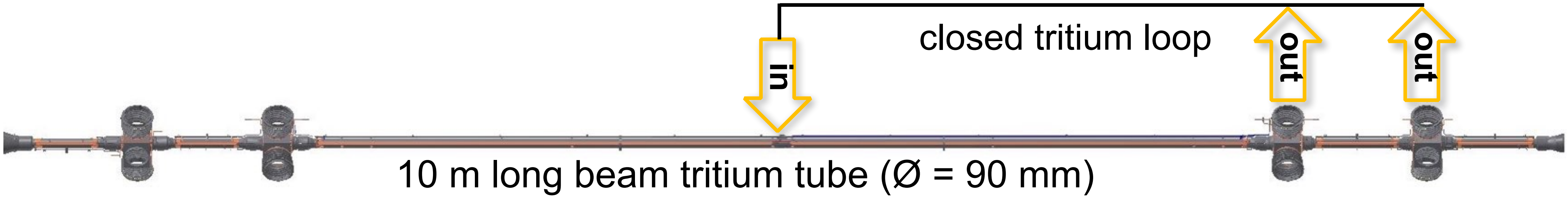


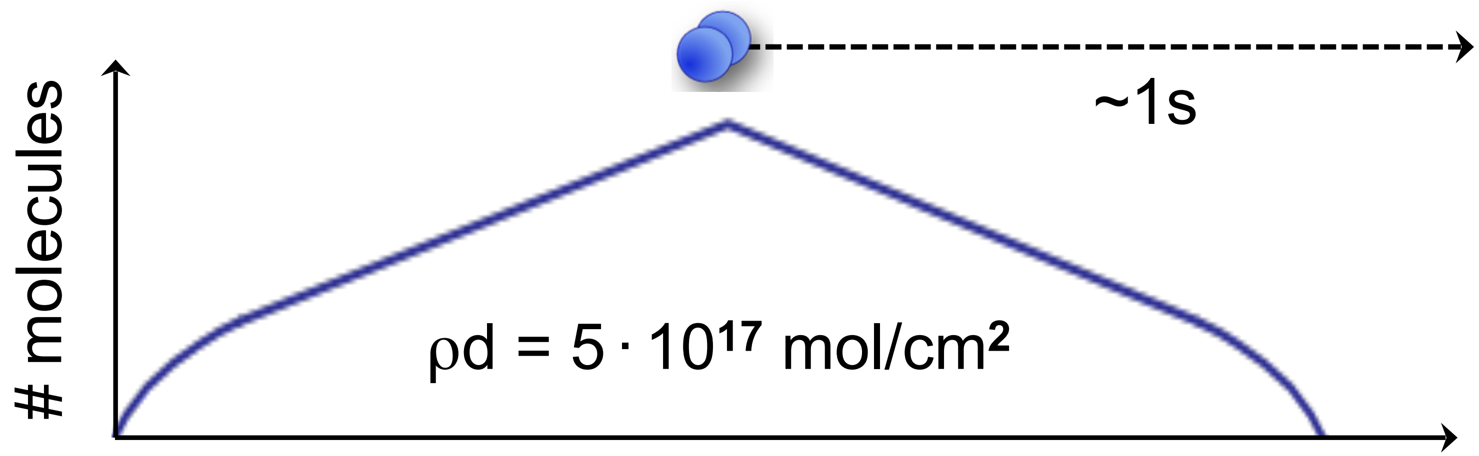


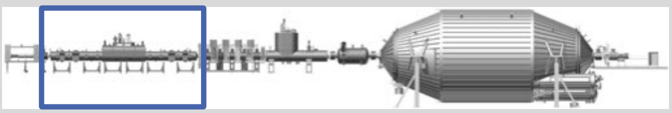
WGTS – windowless gaseous source

Closed-loop processing of molecular T_2:

- isotopic purity > 90%
- 10^{11} β decays / s
- 40% no-loss electrons
- stability at level 10^{-3}
- extensive control of systematics







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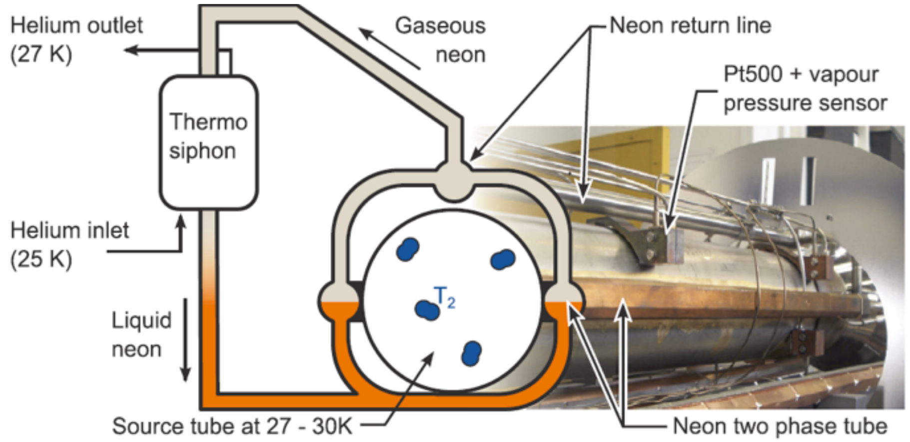
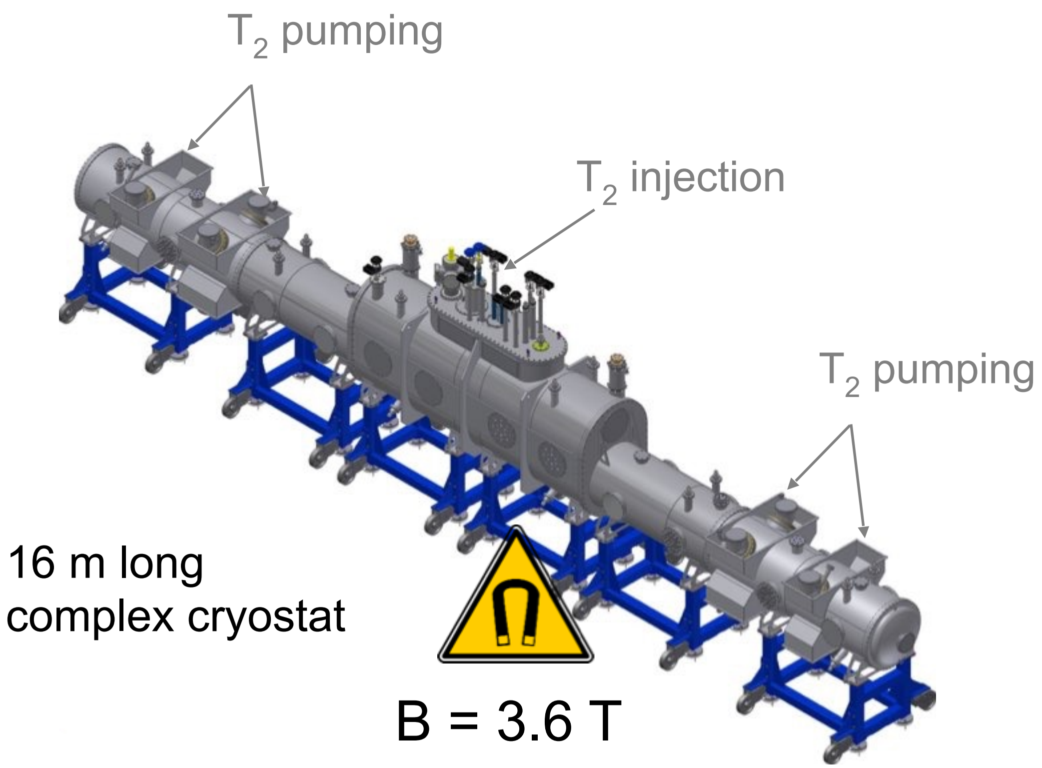
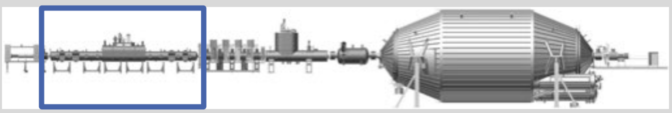
novel 2-phase neon cooling concept



[S. Grohmann et al., Cryogenics 55–56 (2013) 5]





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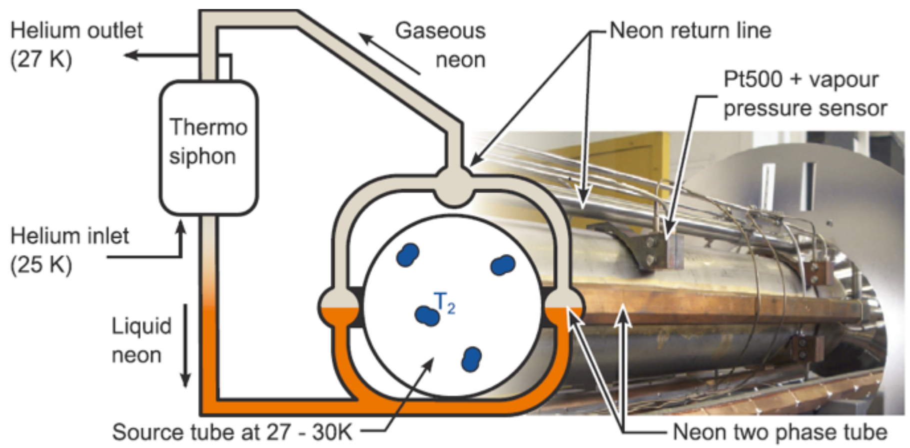

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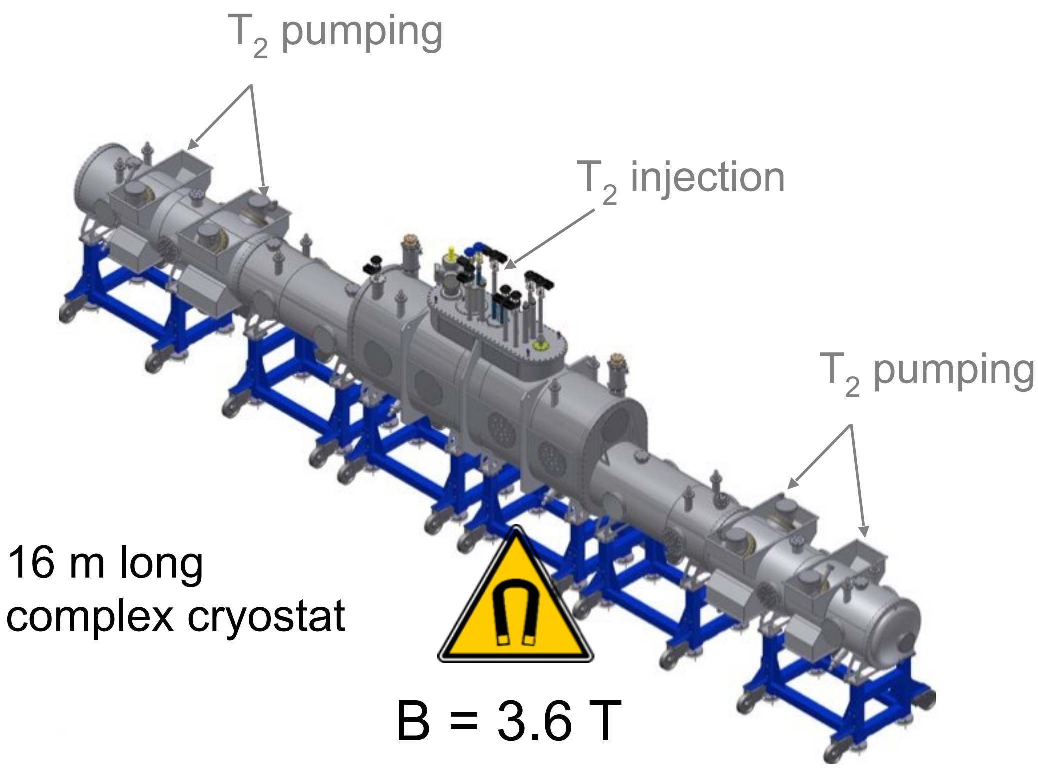
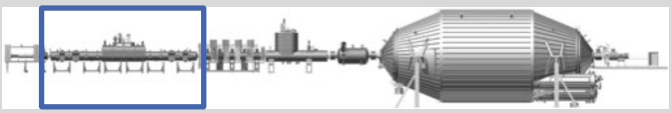
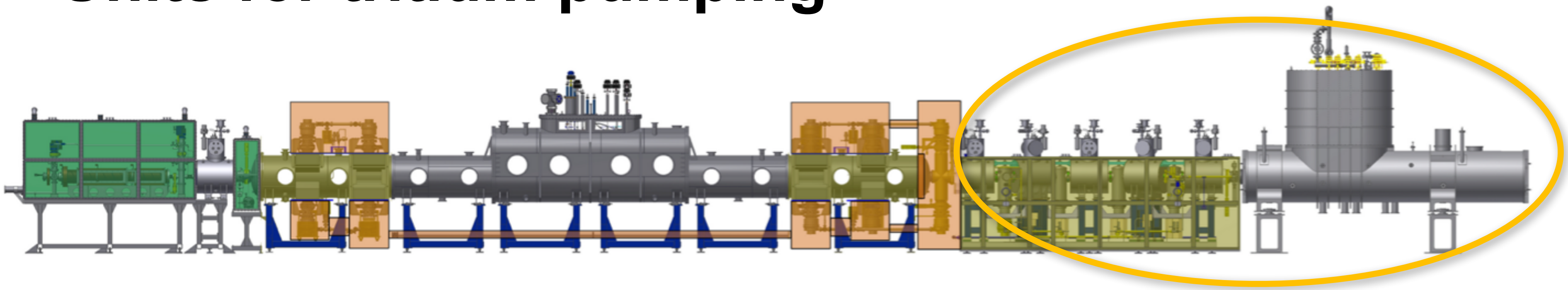




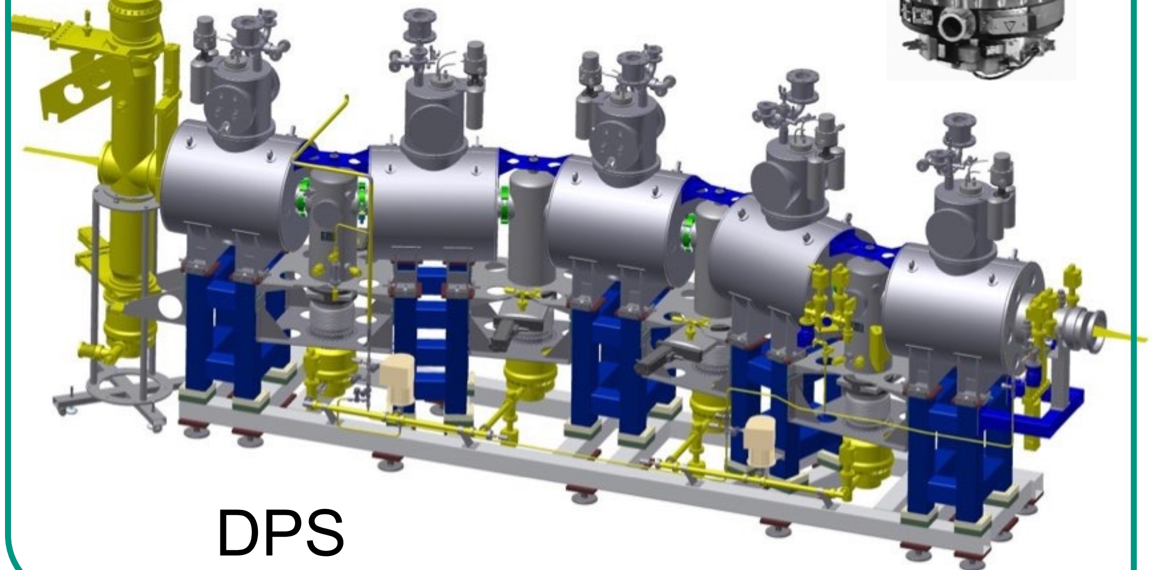
Units for tritium pumping



tritium free

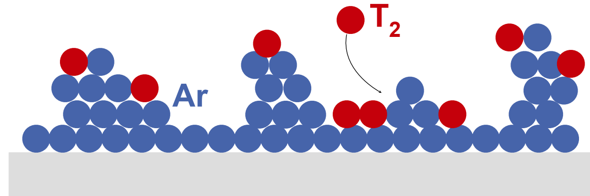
Two large cryostat systems for overall tritium retention **factor > 10^{14}**

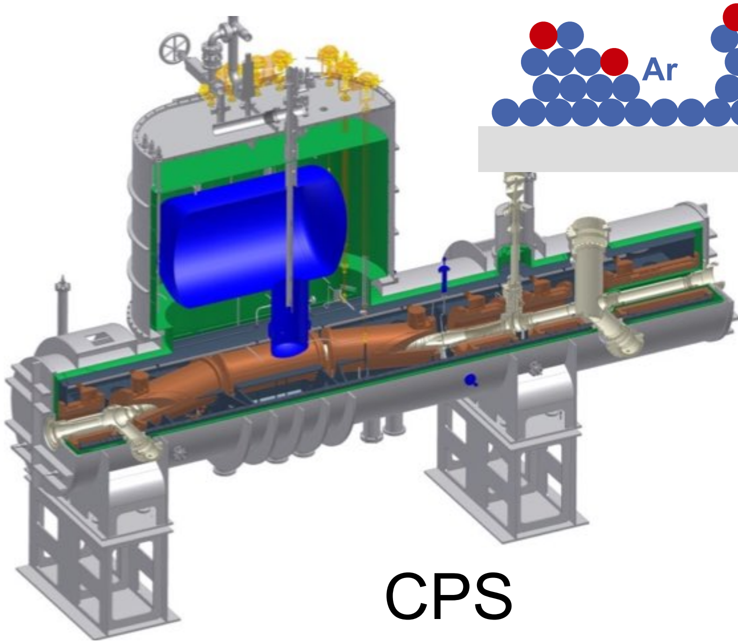
- **Differential Pumping Section DPS**
  active pumping by TMPs



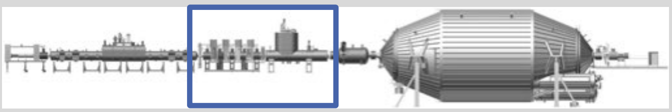
DPS

- **Cryogenic Pumping Section CPS**
  cryosorption on Ar-frost at 3-4 K





CPS



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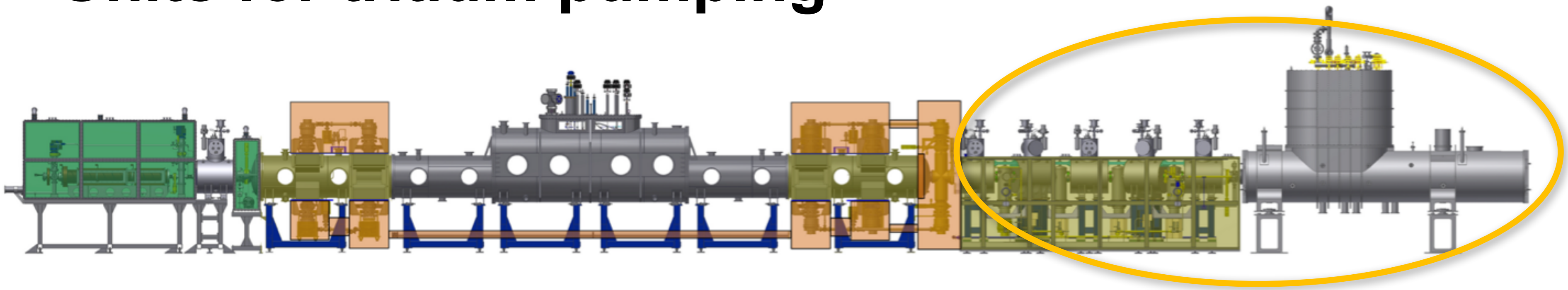

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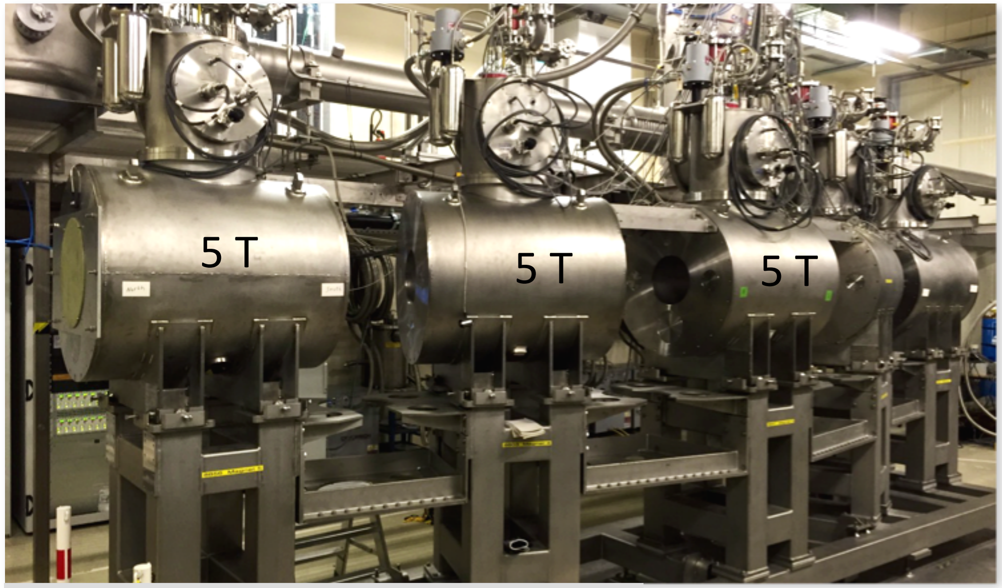
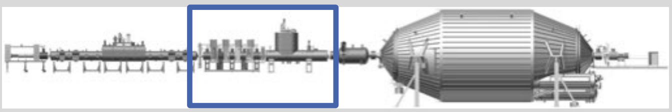
▪ Differential Pumping Section DPS

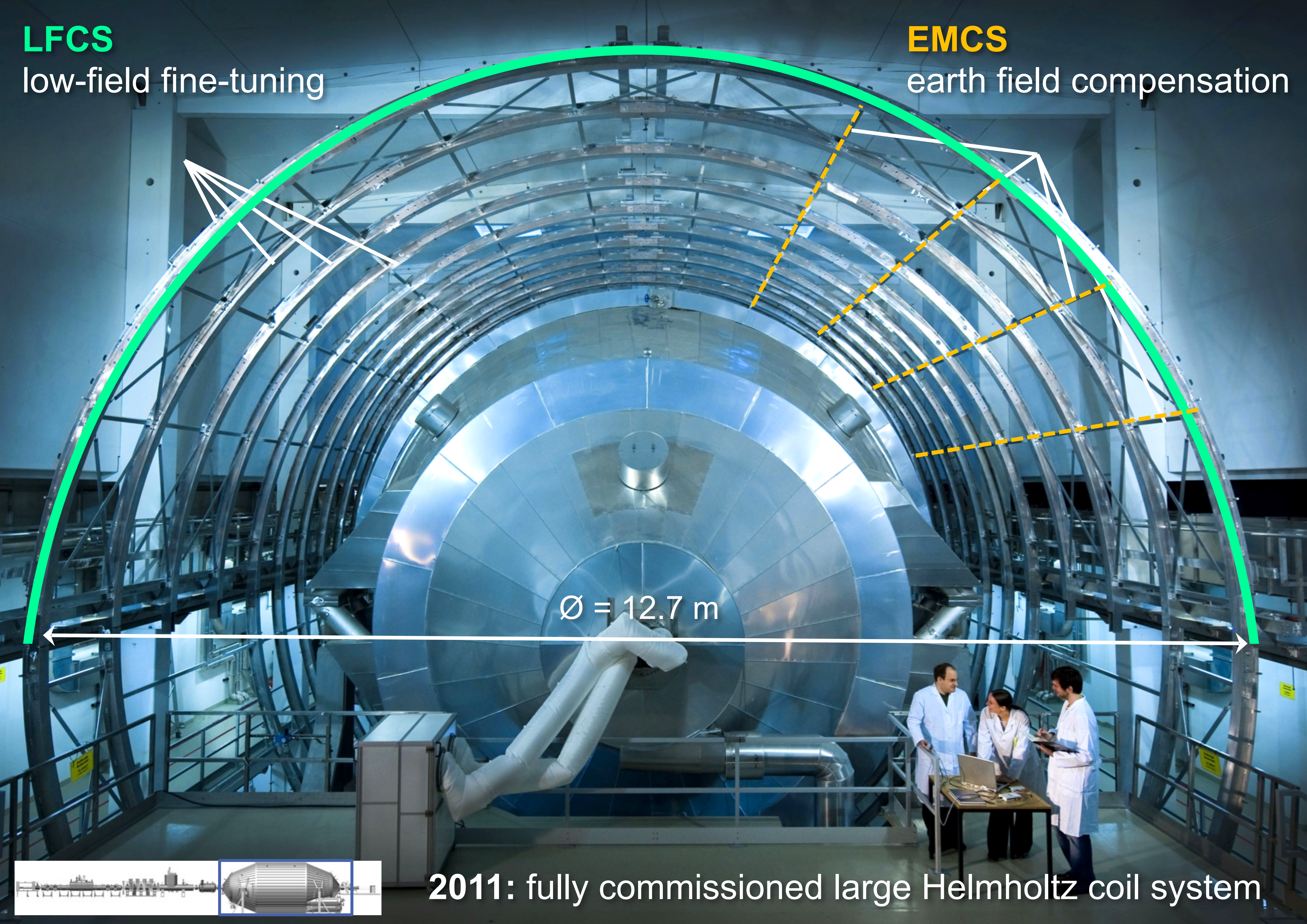


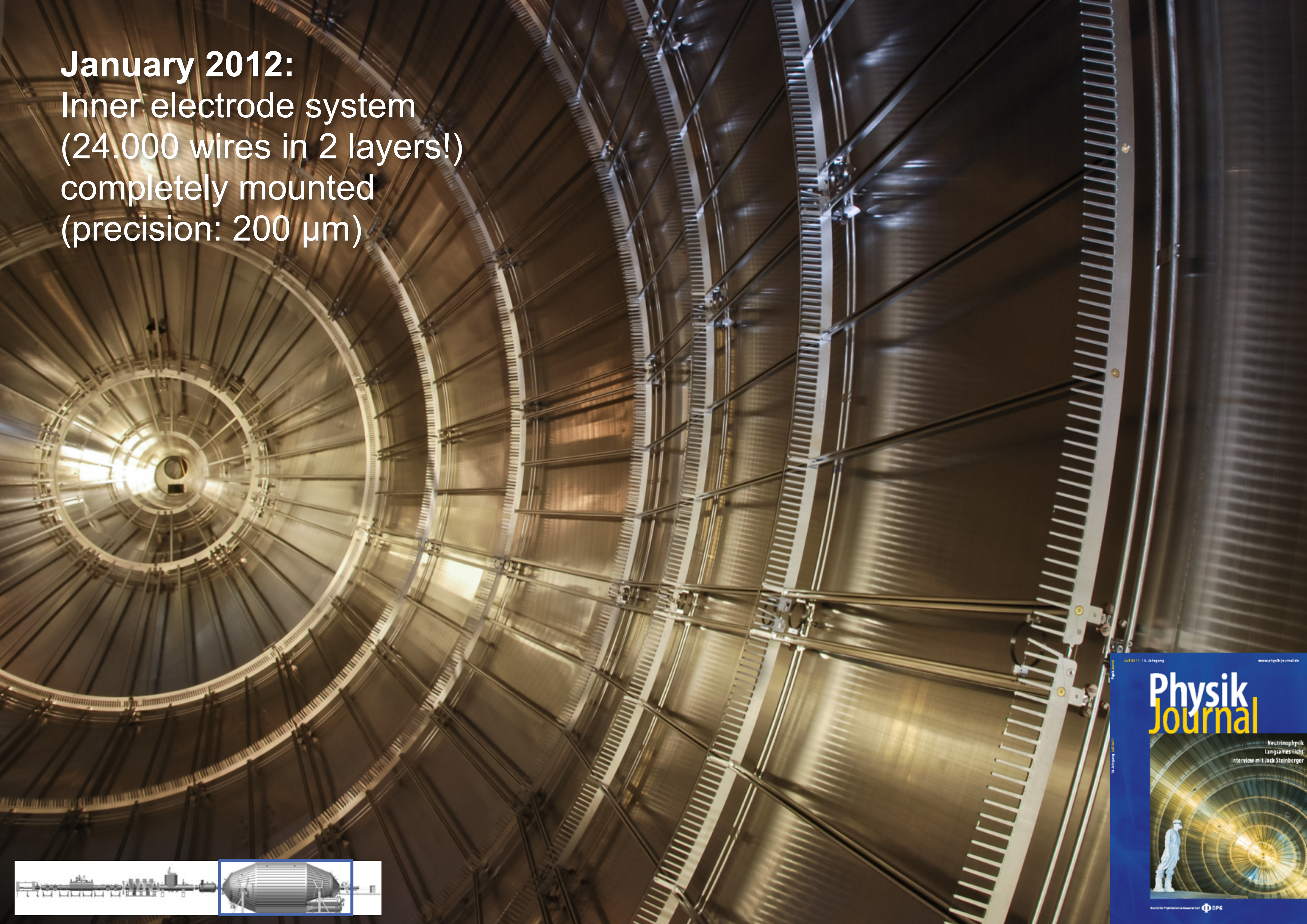
DPS site acceptance tests at KIT almost completed

▪ Cryogenic Pumping Section CPS

Delivered to KIT 07/2015
Installation started




LFCS
low-field fine-tuning
EMCS
earth field compensation
Ø = 12.7 m
2011: fully commissioned large Helmholtz coil system


January 2012:
Inner electrode system
(24.000 wires in 2 layers!)
completely mounted
(precision: 200 µm)
Physik Journal
Neutrinophysik
Langsames Licht
Interview mit Jack Steinberger

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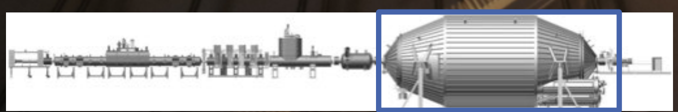
Bake-out at 300 (200)°C
to achieve UHV conditions
p < 10^{-11} mbar



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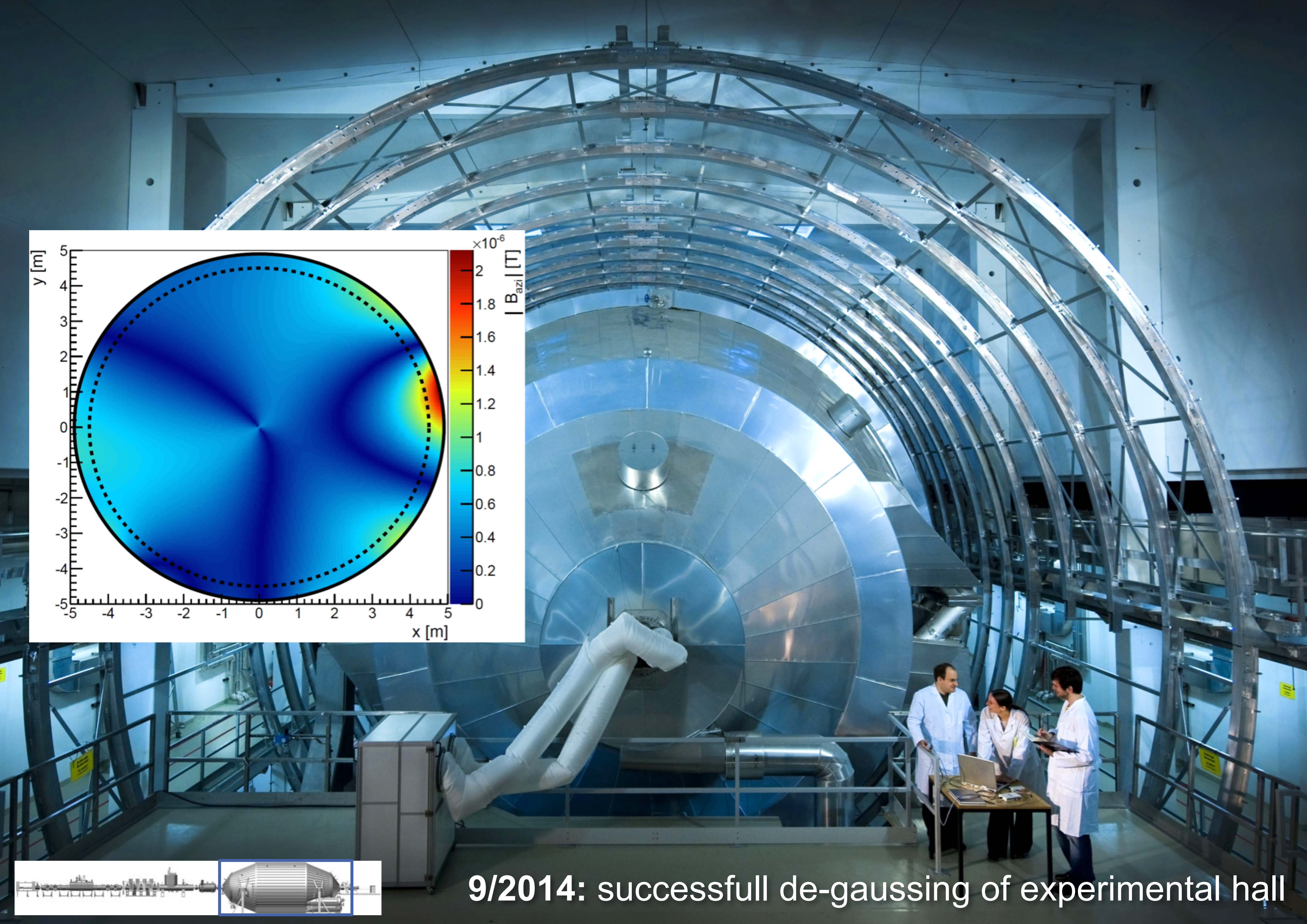
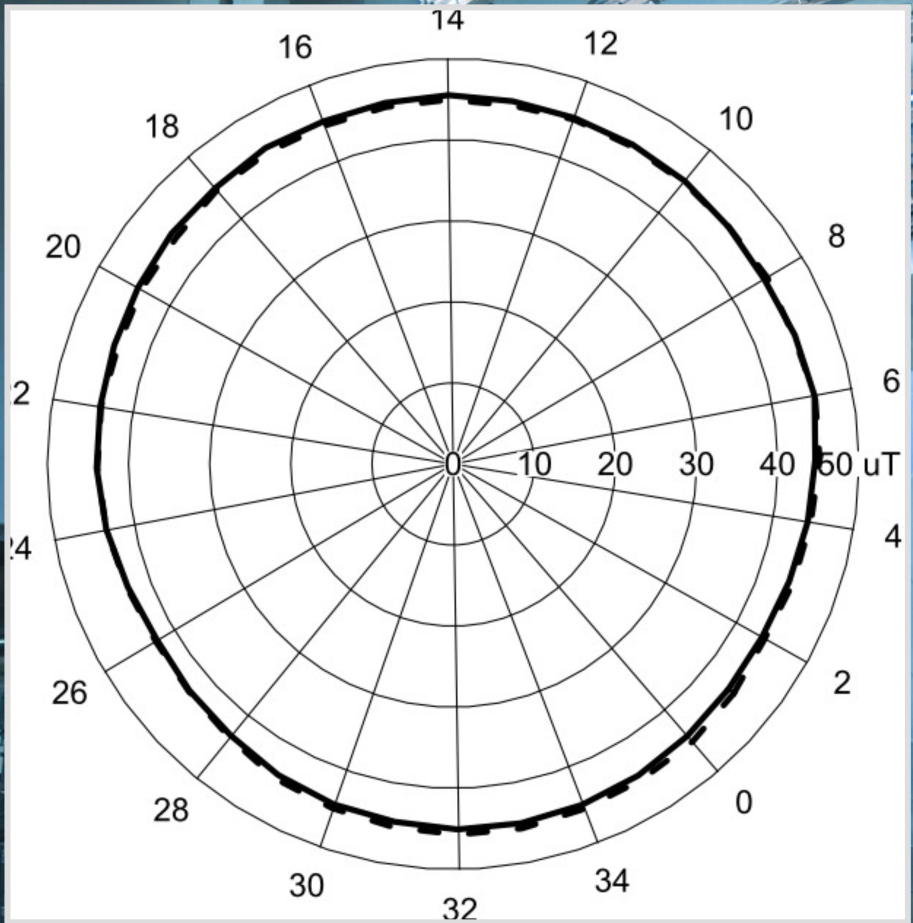
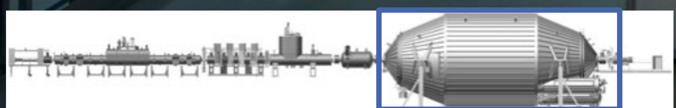
Trivia question:
UHV recipient — LHC vs. KATRIN?



9/2014: successfull de-gaussing of experimental hall



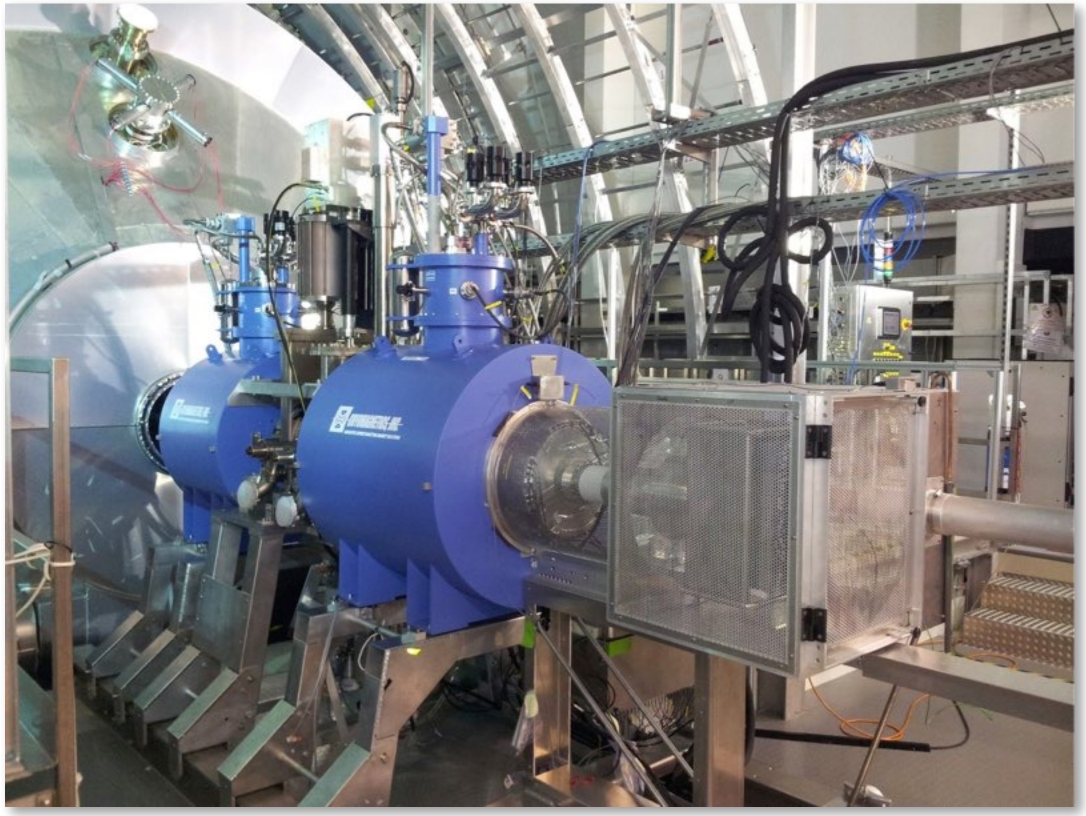


9/2014: successfull de-gaussing of experimental hall

Detector system

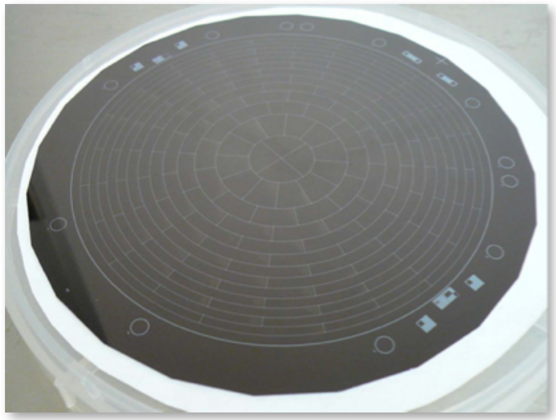
Requirements:

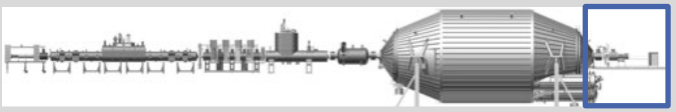
- detection of β-electrons (mHz to kHz)
- high efficiency (> 90%)
- low background (< 1 mHz)
  ➜ passive and active shielding
  ➜ post-acceleration (10-30 kV)
- good energy resolution (~1 keV)



Characteristics:

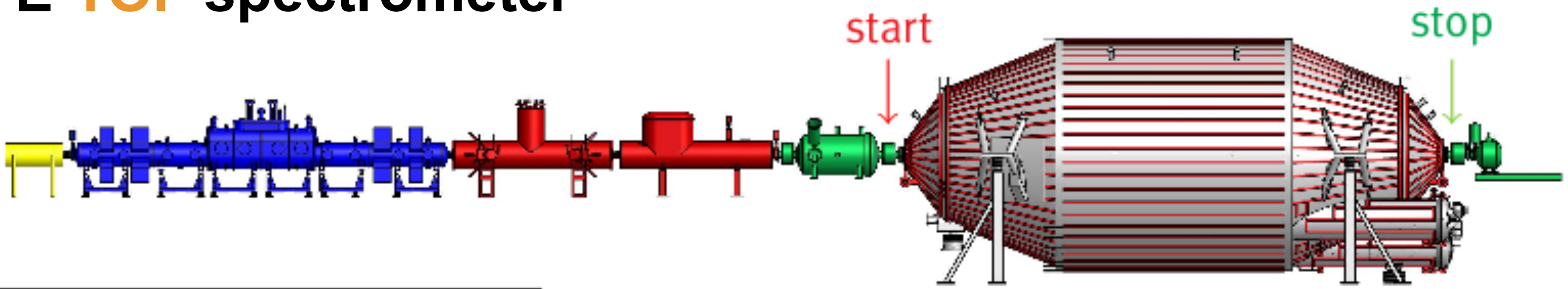
- 90 mm Ø Si PIN diode
- thin entry window (50 nm)
- segmented wafer (148 pixels)
  ➜ compensate field inhomogeneities
  ➜ radial-dependent background
  ➜ investigate systematic effects
- detector magnet 3 - 6 T

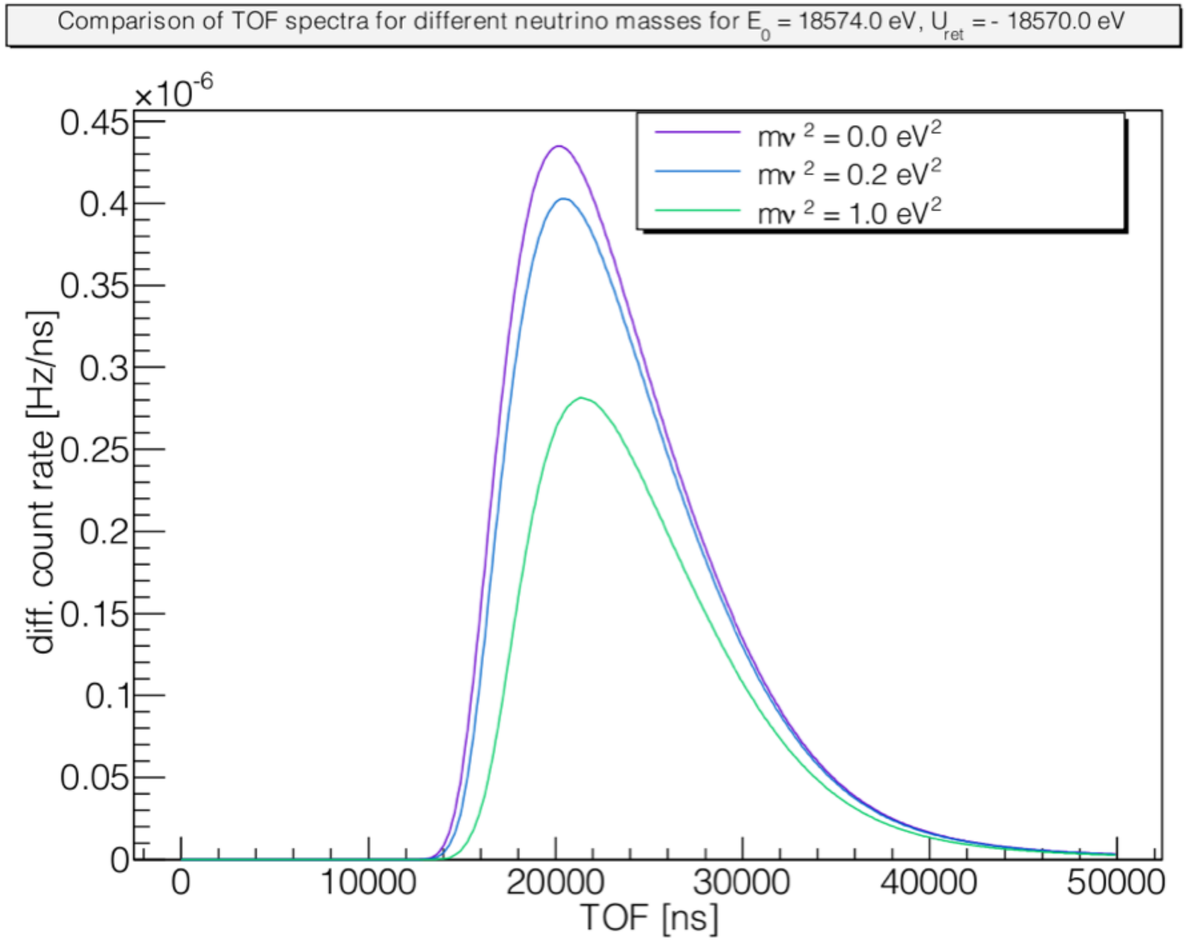




1st avenue: exploit differential β spectrum

Idea: Upgrade to MAC-E-TOF spectrometer





Spectrometer as 24 m long “delay line”
➜ very sensitive to small differences in surplus energy

TOF spectrum records full β spectrum
➜ save meas. time by using only few voltage settings of MAC-E filter

Coincidence requirement
➜ add. background suppression

Technical realization?
(a) pre-spectrometer as gated filter
(b) radio frequency tagger

[Bonn et al. (1999), Steinbrink et al. (2013), Robertson et al. (in prep.)]

2^{nd} avenue: alternative spectroscopic technique

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Idea: Cyclotron Radiation Emission Spectroscopy (CRES)

[Formaggio & Monreal, PRD 80 (2009) 051301(R)]

$$\omega(\gamma) = \frac{\omega_c}{\gamma} = \frac{eB}{E_{\mathrm{kin}} + m_e}$$

Energy measured via **cyclotron frequency** of single electrons in B field

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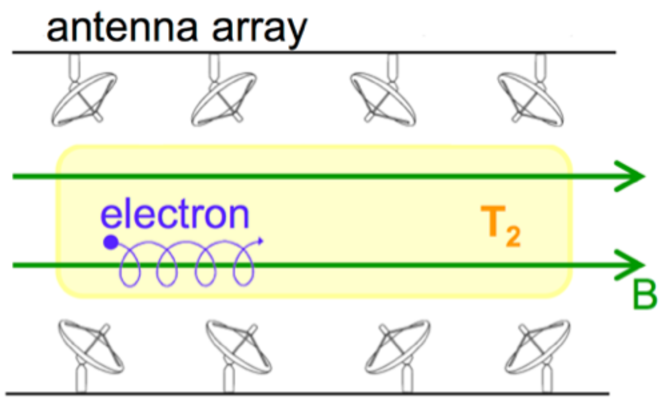

B ~1 T,
E ~18.6 keV
➜ ω ~27 GHz

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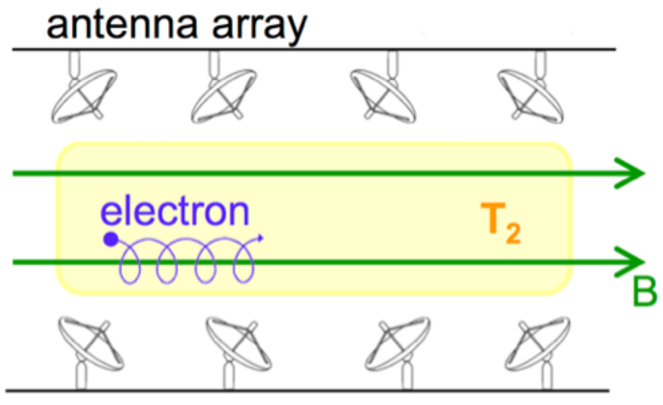

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"KATRIN"-like gaseous source:
uniform B-field and low-pressure T_2 gas

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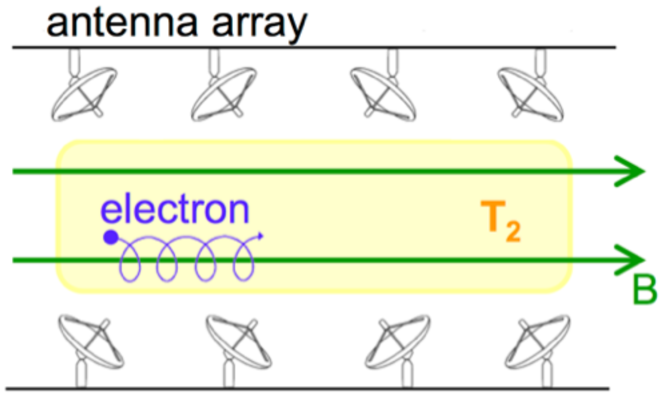

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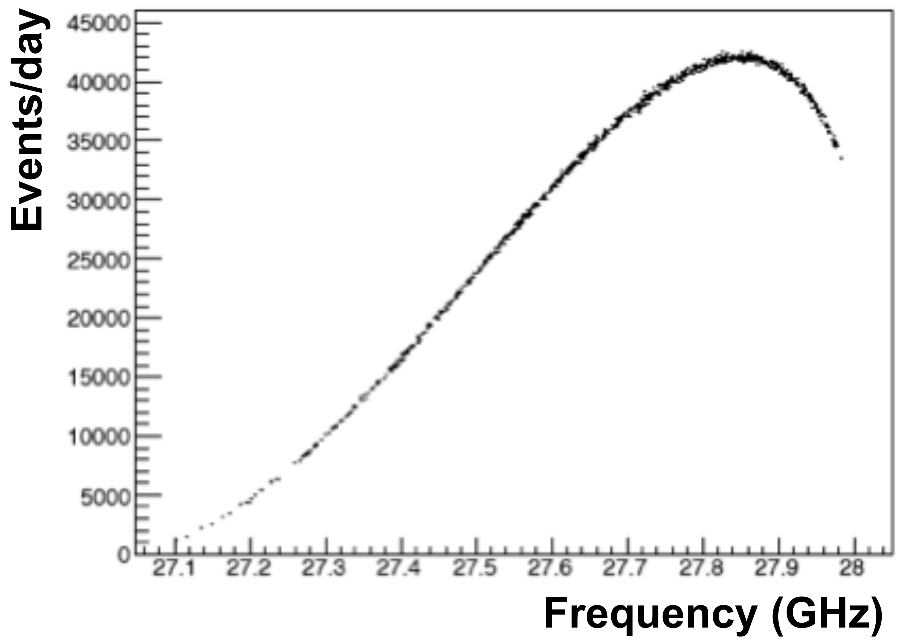

"KATRIN"-like gaseous source:
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Why sterile neutrinos?

Hints of eV-scale sterile neutrinos?

Hints of keV-scale sterile neutrinos?

Why sterile neutrinos?

Karlsruhe Institute of Technology

Hints of eV-scale sterile neutrinos?

May explain anomalous oscillation results from
- Short baseline accelerator experiments
- Gallium experiments
- Reactor experiments

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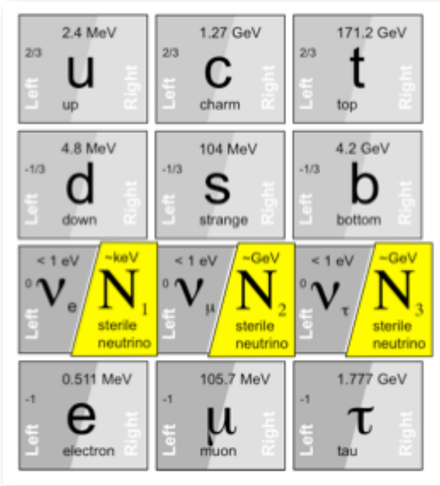

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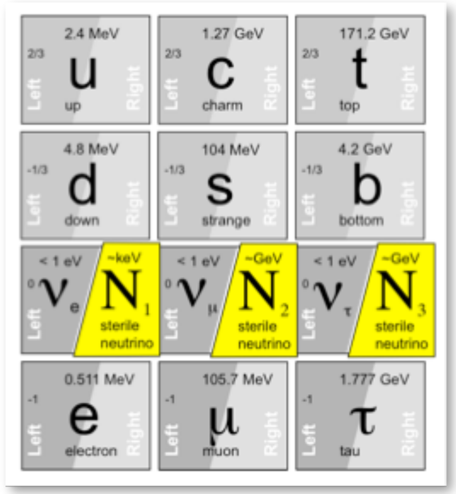

In agreement with cosmological observations from small to large scales [e.g., Shi & Fuller (1999)]

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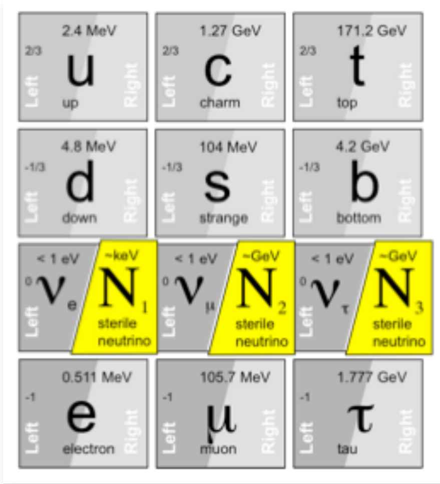

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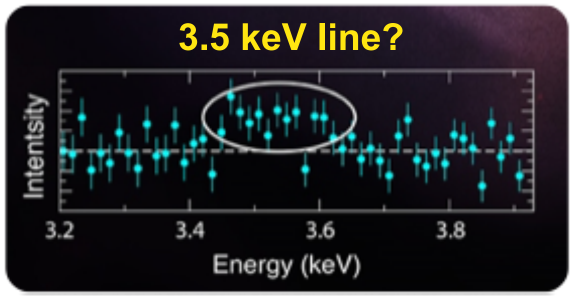

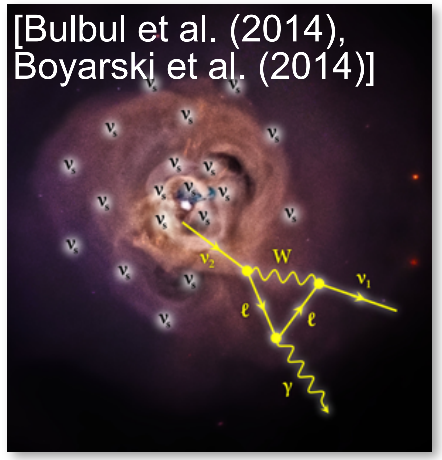

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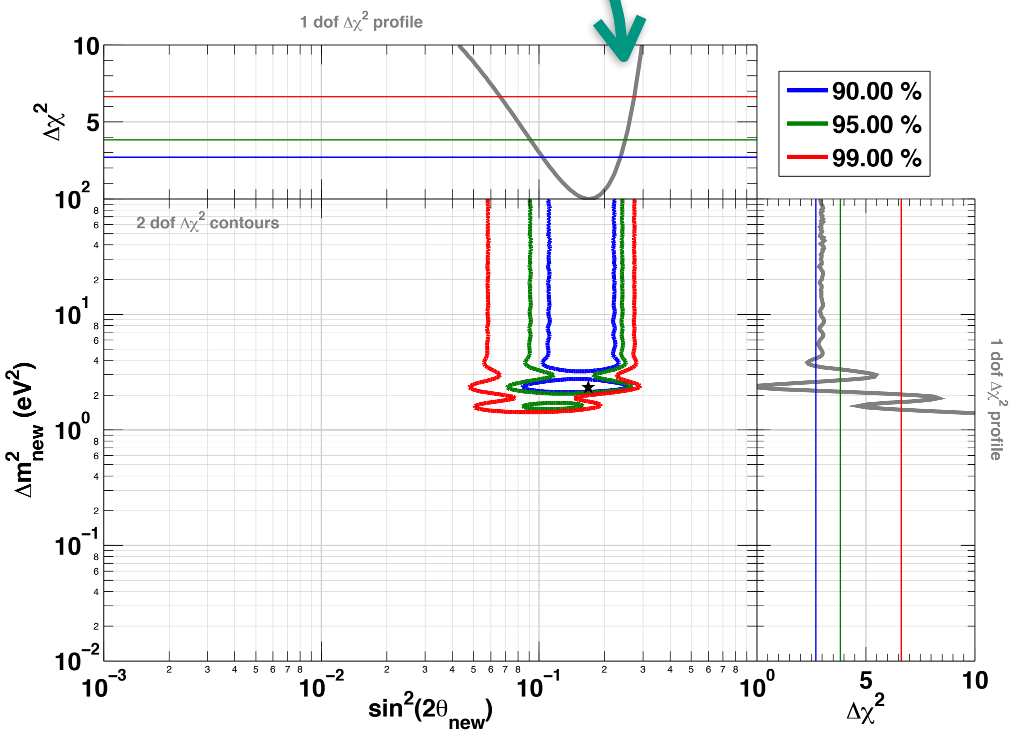

[G. Mention et al. (2011), updated in White Paper (2014)]

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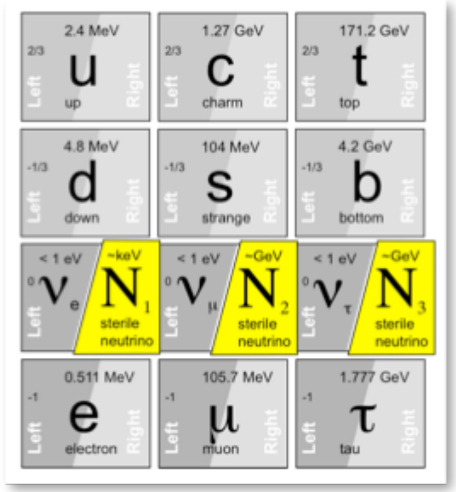

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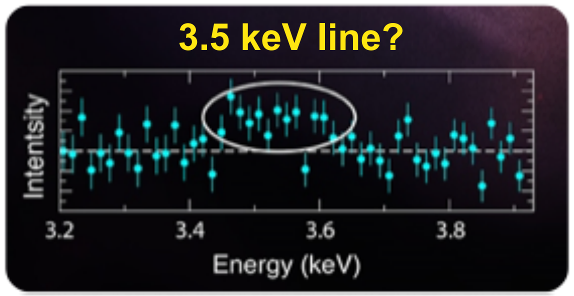

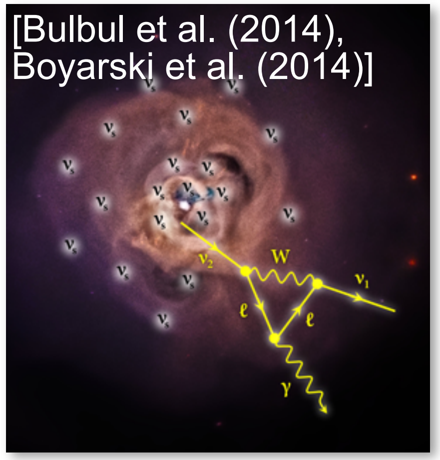

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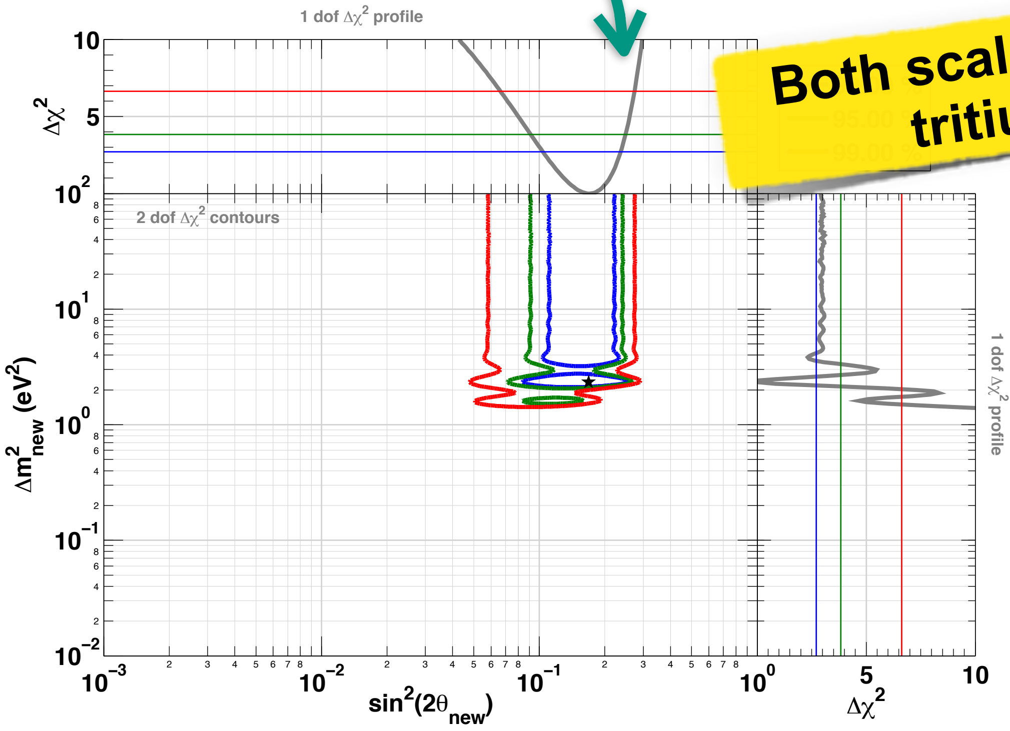

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Both scales accessible in tritium β decay

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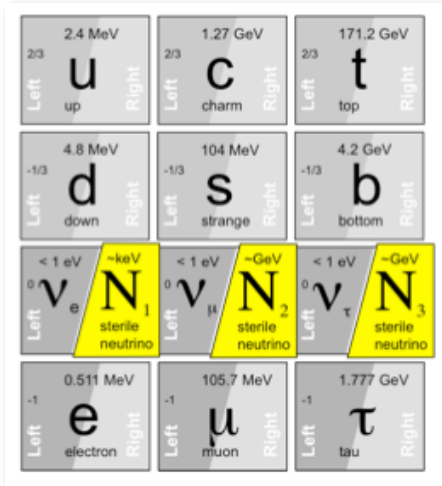

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