Karlsruhe Institute of Technology

11th International Neutrino Summer School

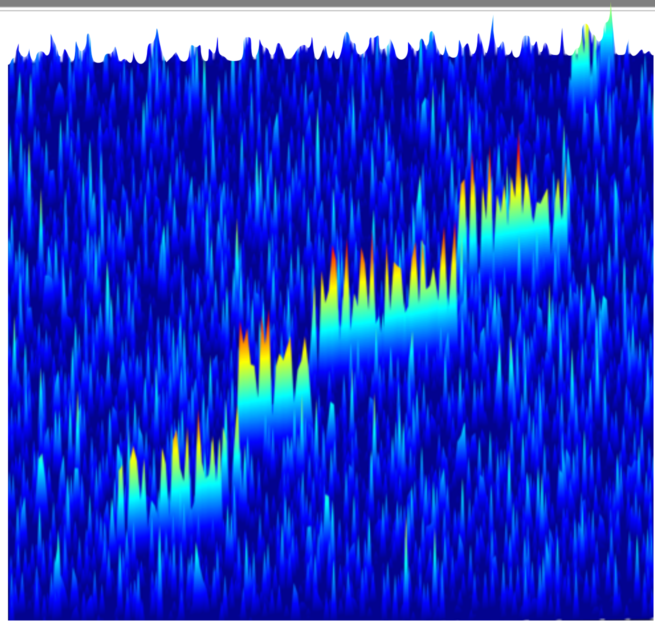
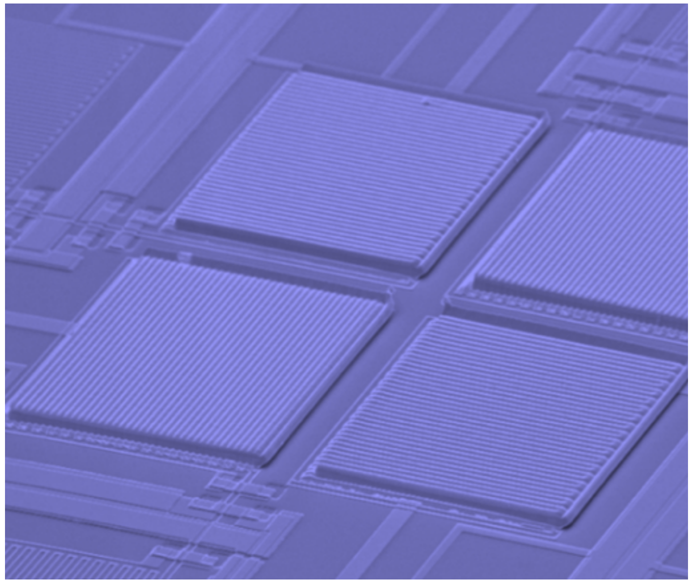
Waldthausen/Mainz

May 21 - June 1, 2018

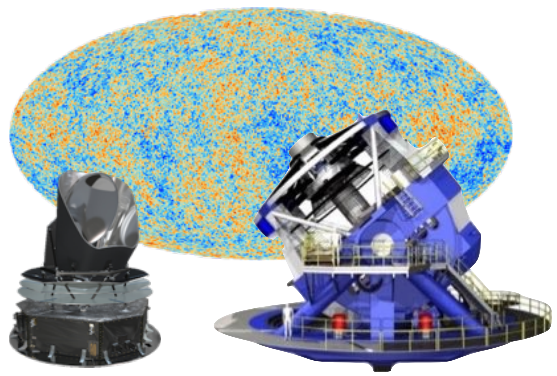
Direct probes of neutrino mass

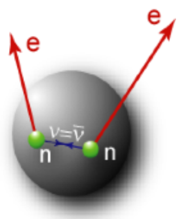
Tritium β-decay and EC of ^{163}Ho

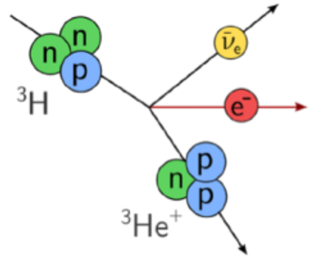
KATHRIN VALERIUS | KIT-IKP (Institute for Nuclear Physics)

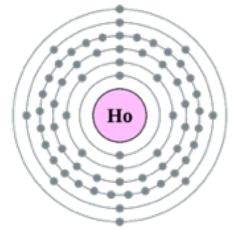




Complementary paths to the ν mass scale









	Cosmology	Search for 0νββ	β-decay & electron capture
Observable	$M_\nu = \sum_i m_i$	$m_{\beta\beta}^2 = \left\lvert \sum_i U_{ei}^2 m_i \right\rvert^2$	$m_\beta^2 = \sum_i \lvert U_{ei} \rvert^2 m_i^2$
Present upper limit	~0.15 – 0.6 eV	~0.1 – 0.4 eV	2 eV
Potential: near-term (long-term)	60 meV (15 meV)	50 – 200 meV (20 – 40 meV)	200 meV (40 – 100 meV)
Model dependence	Multi-parameter cosmological model	- Majorana nature of ν, lepton number violation - BSM contributions other than m(ν)? - Nuclear matrix elements	**Direct,** only kinematics; no cancellations in incoherent sum

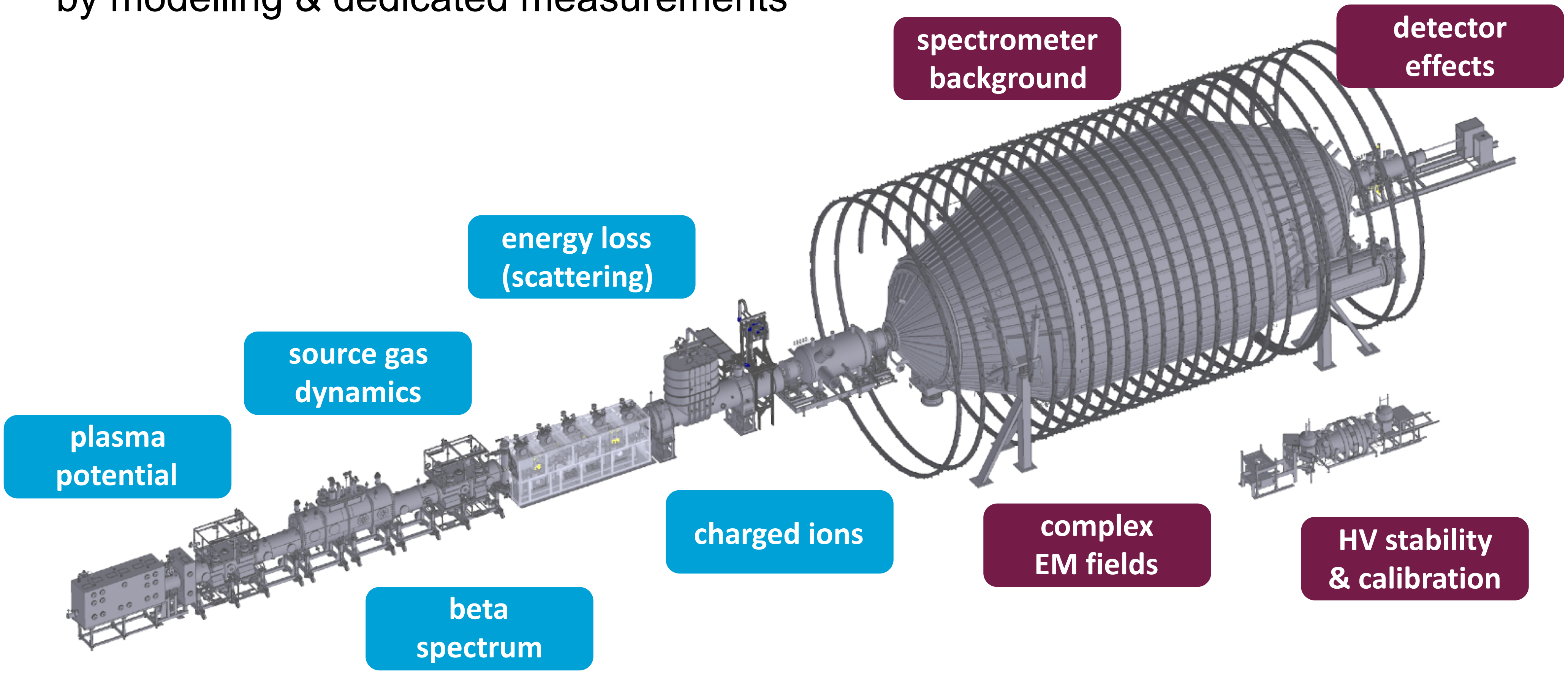
➜ Y. Wong | ➜ S. Schönert | ➜ this lecture

A detailed look at how direct neutrino mass experiment works (continued)

- Background sources
- Systematic uncertainties

Systematic uncertainties

Complex beamline setup with many sub-components
➜ many sources of systematics need to be considered
by modelling & dedicated measurements



Ongoing: evaluation of systematics with commissioning data

Statistical & systematic uncertainties

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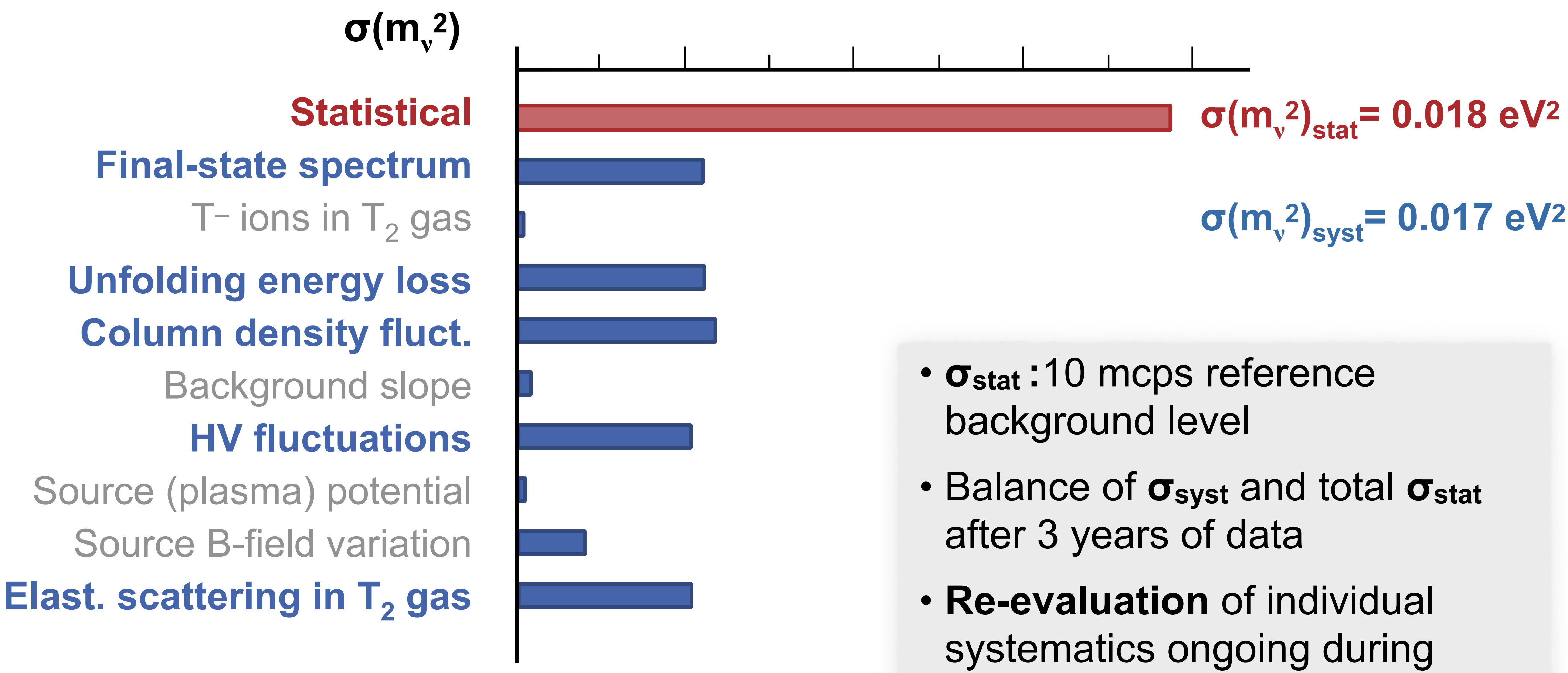
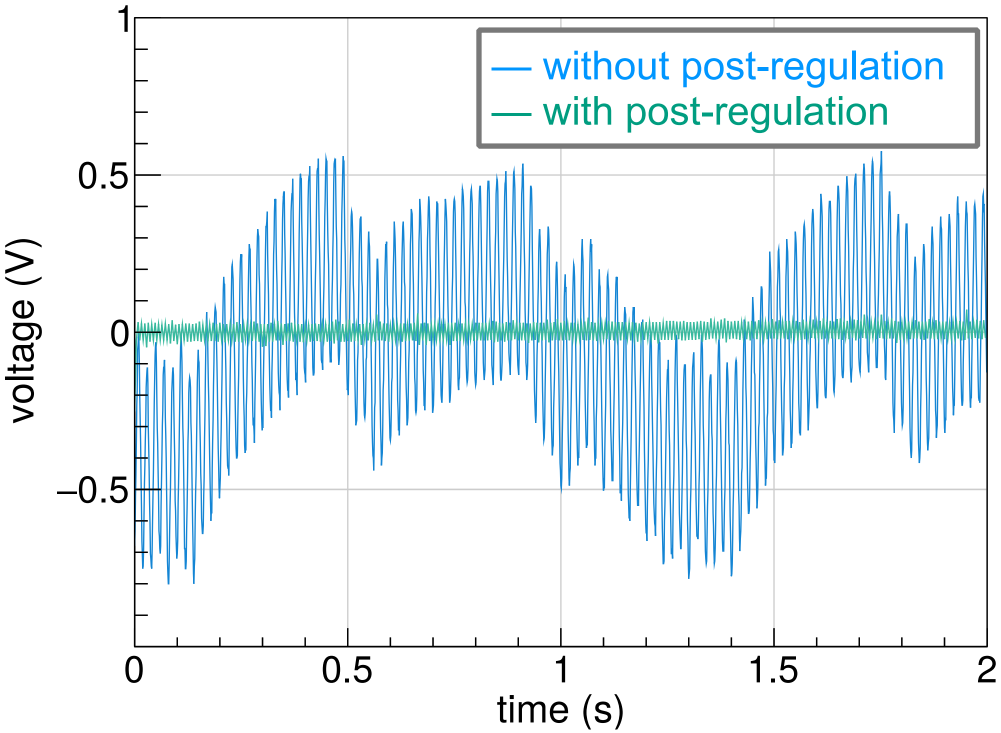
KATRIN's uncertainty budget (design sensitivity, ~2004):



- σ_{stat} : 10 mcps reference background level
- Balance of σ_{syst} and total σ_{stat} after 3 years of data
- **Re-evaluation** of individual systematics ongoing during system characterisation

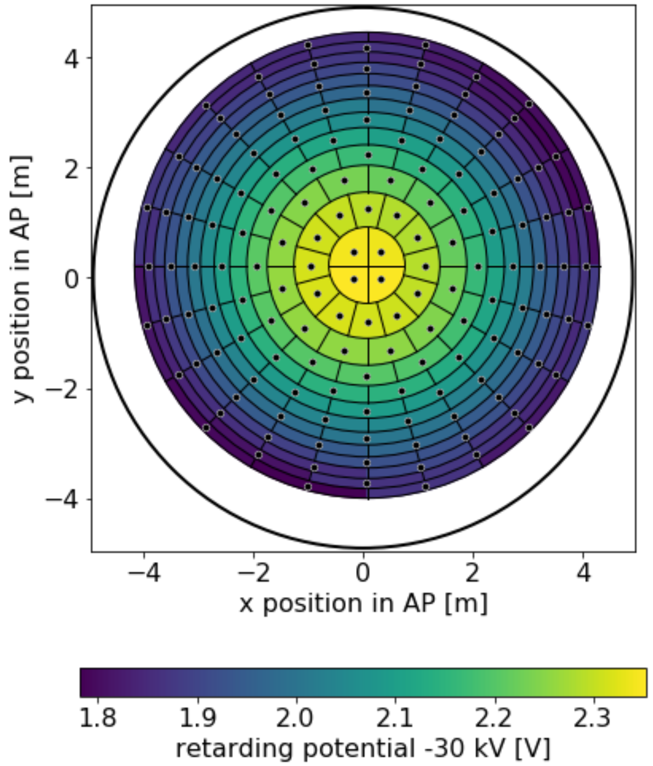
Example 1: High voltage and magnetic fields

Precision high-voltage monitoring and active regulation



- ➜ DC component: sub-ppm long-term stability monitored with precision HV divider
- ➜ AC component: active compensation reduces 500 mV_{pp} noise to $\sigma < 20$ mV (~1 ppm)

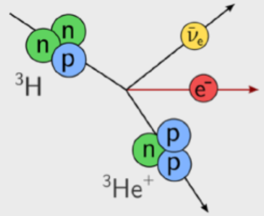
Field homogeneity across ⌀10 m analysing plane



- ➜ Sophisticated numerical model KEMField code, New J. Phys. **19** (2017) 053012
- ➜ Measurements with precision electron source (e-gun)

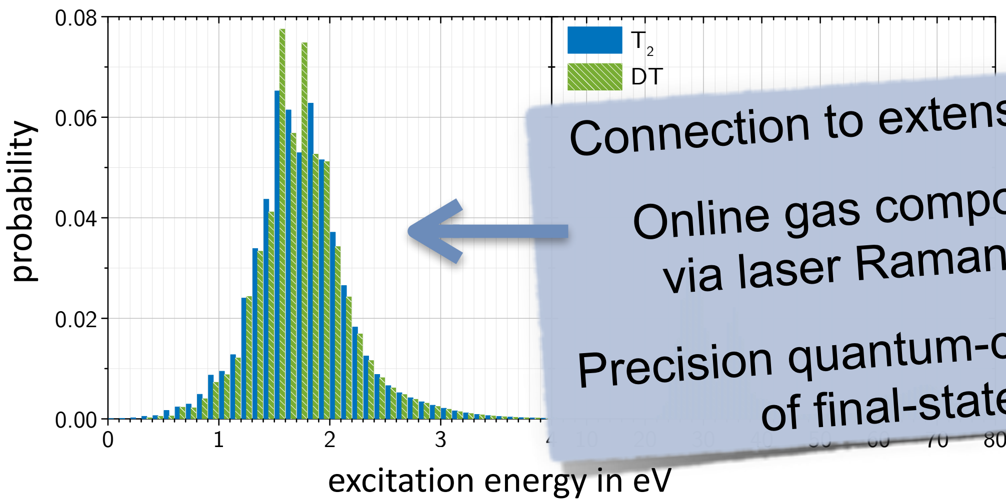
Example 2: Beta-spectrum model

Reference spectrum generator



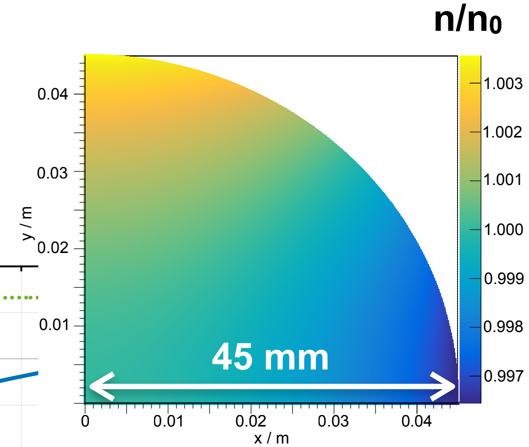
State-of-the-art nuclear & molecular theory

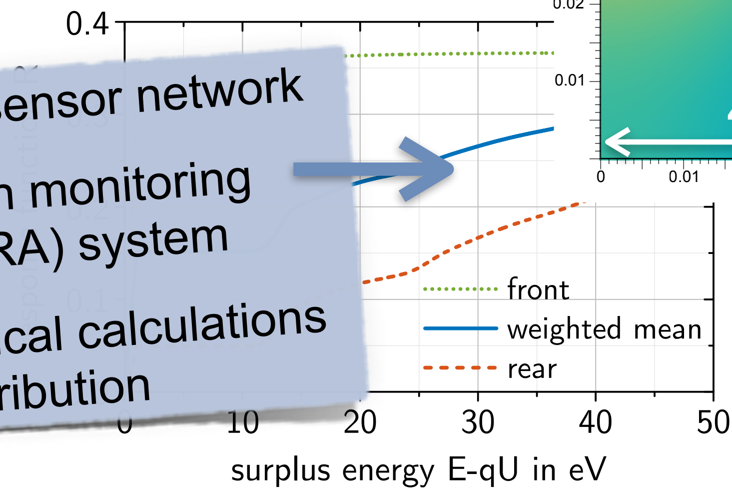
- electronic & ro-vib. excitations, radiative corrections, Doppler effect
- minor: relativistic Fermi function & recoil, screening, finite nuclear extension, …



3d gas-dynamics modelling

- longitudinal and radial pressure, density, temperature profiles
- plasma potential
- magnetic field model



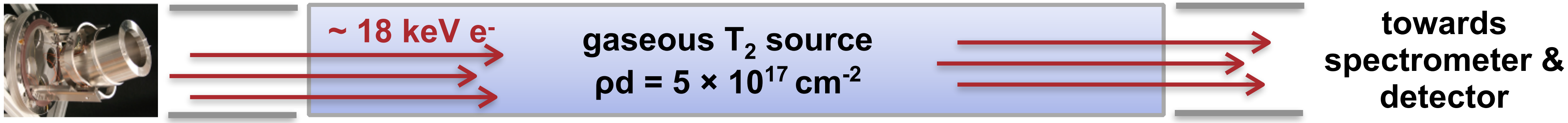


Connection to extensive sensor network

Online gas composition monitoring via laser Raman (LARA) system

Precision quantum-chemical calculations of final-state distribution

Example 3: Energy loss function

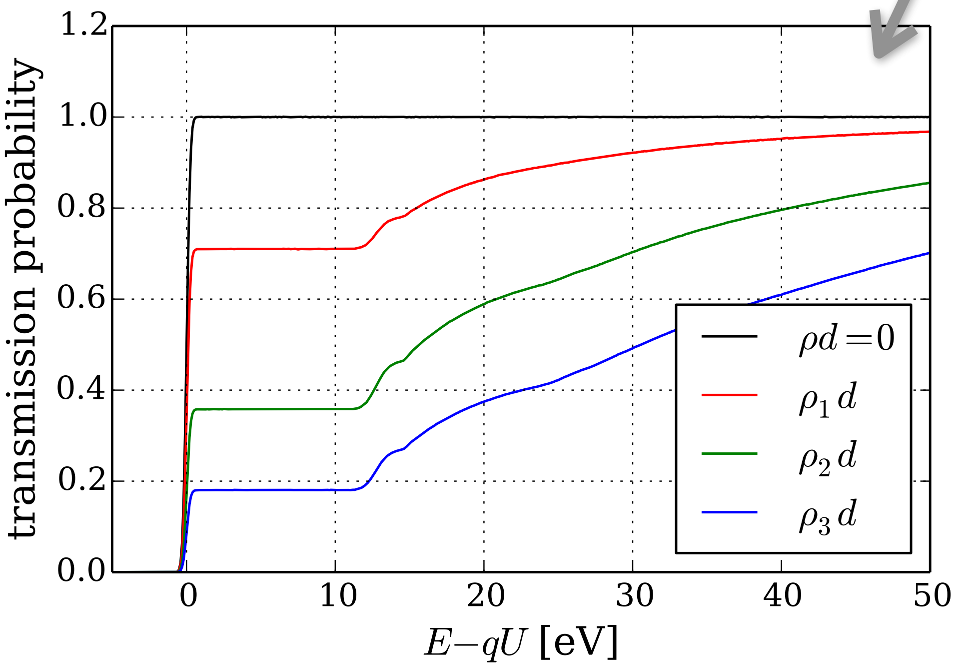


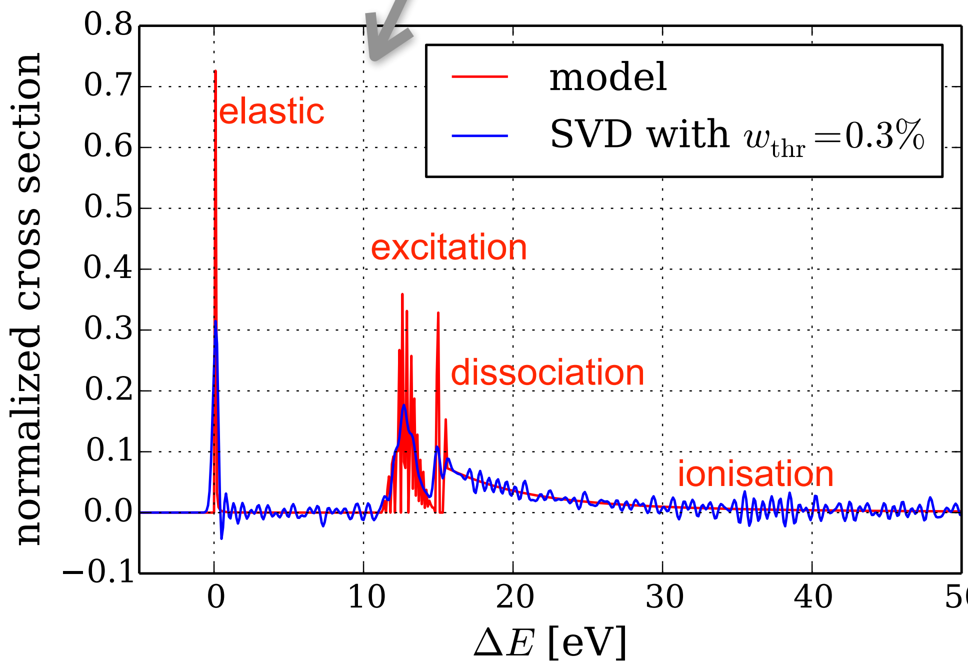
precision electron source
- pulsed
- narrow-band (< 200 meV)
- angular selectivity

(1) measurement of electron transmission at different gas column densities *ρd*

(2) determine energy loss function through deconvolution

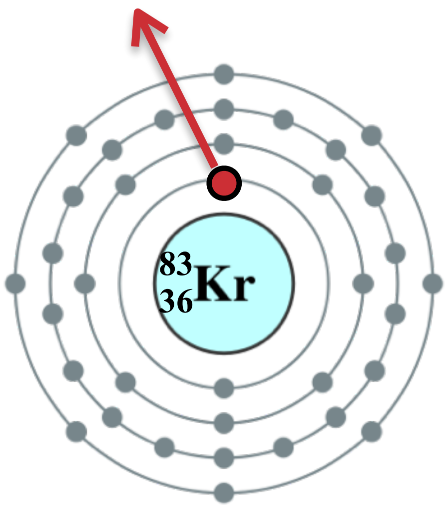
(here: singular value decomposition, SVD)

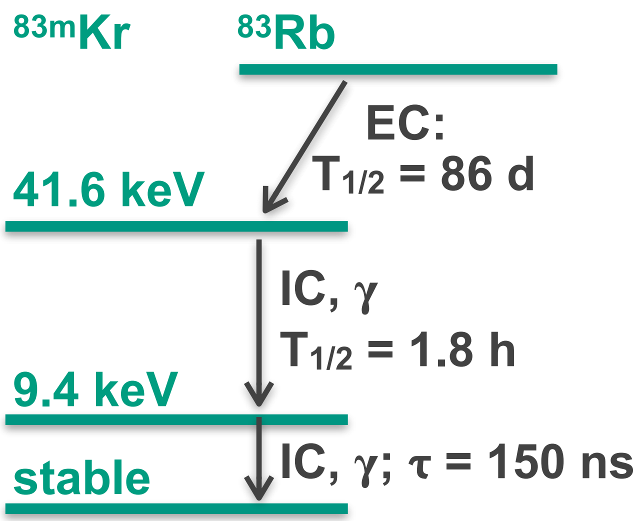


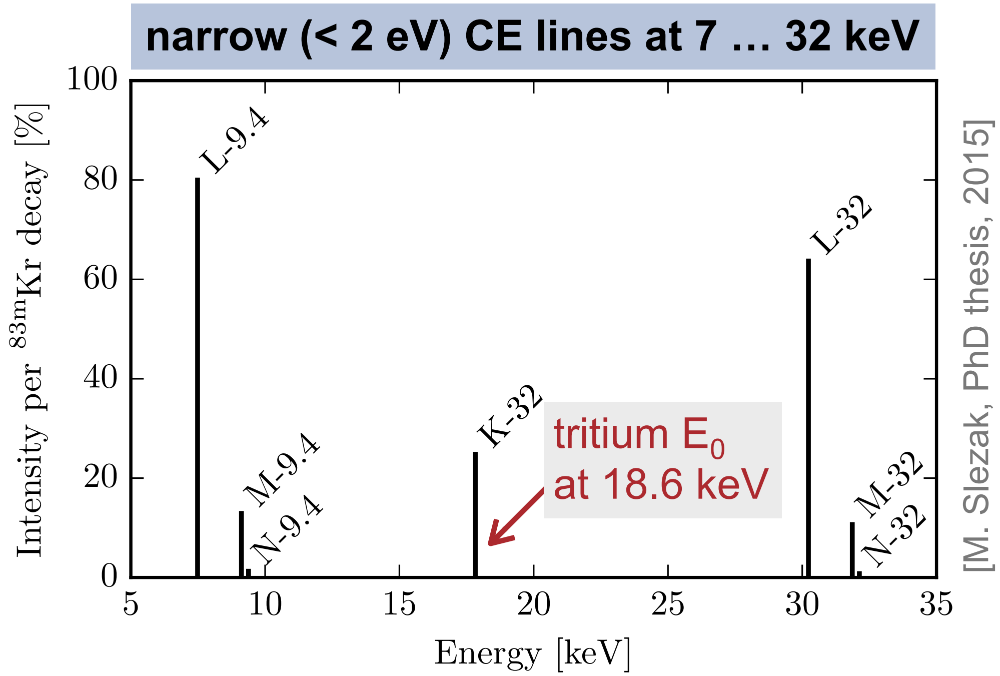


[V. Hannen *et al.*, Astropart. Phys. 89 (2017) 30]

KATRIN milestone: gearing up for tritium with ^{83m}Kr







➜ **A versatile calibration tool, widely used in neutrino & DM experiments!**

Two-week KATRIN krypton campaign (July 2017):

Hardware readiness from source to detector with ^{83m}Kr as short-lived "tracer"

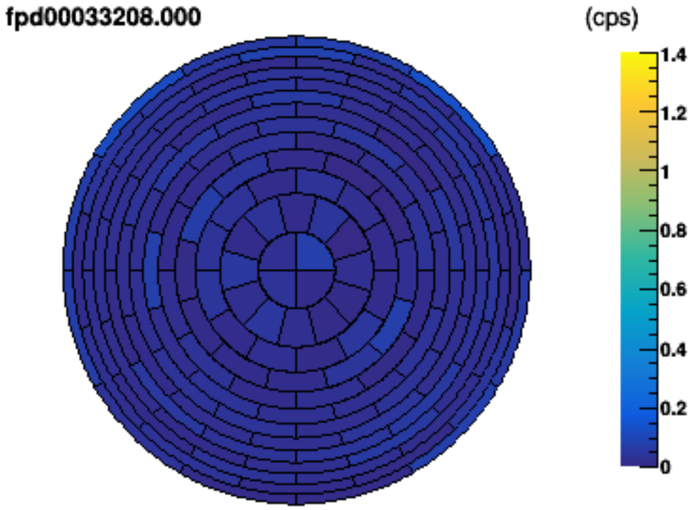
➜

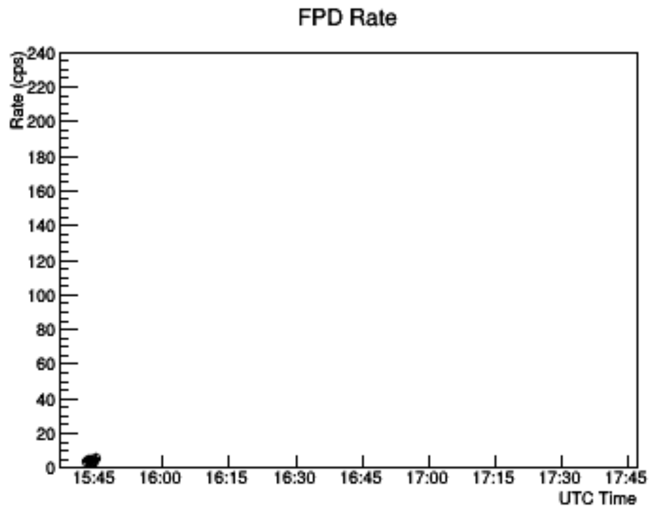
Data chain from raw data & slow control to high-level analysis tools

➜

System characterization: sharp transmission of MAC-E filter, detector properties, system alignment, absolute energy scale calibration, …

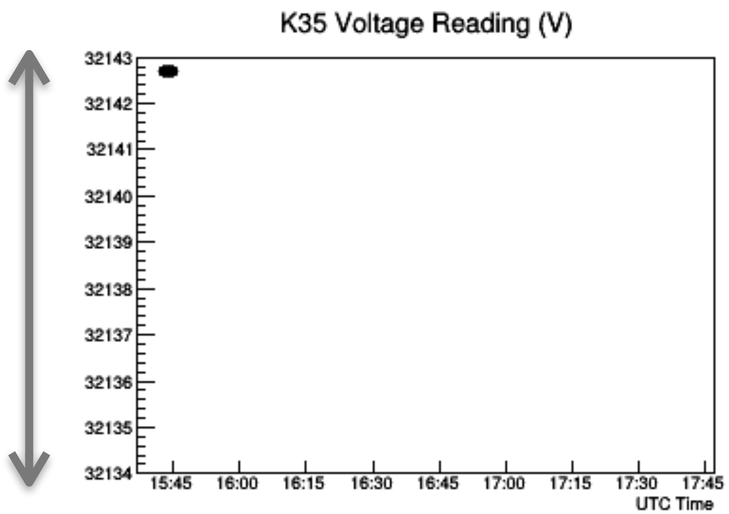
A krypton line scan with the integrating spectrometer: real data





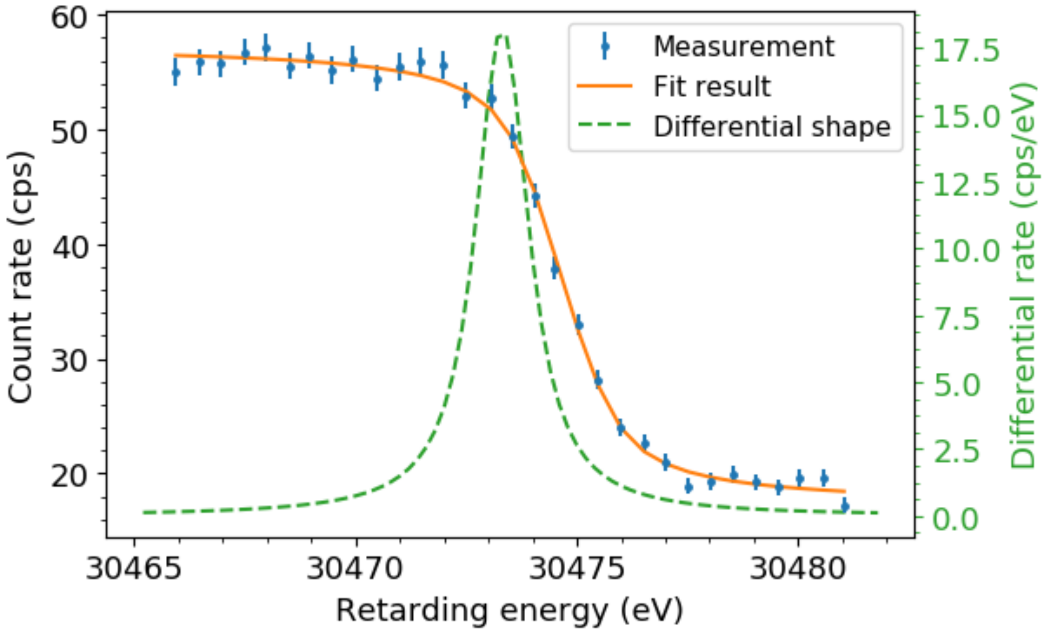
scan duration ~2 hrs
(low intensity of N-32 lines)

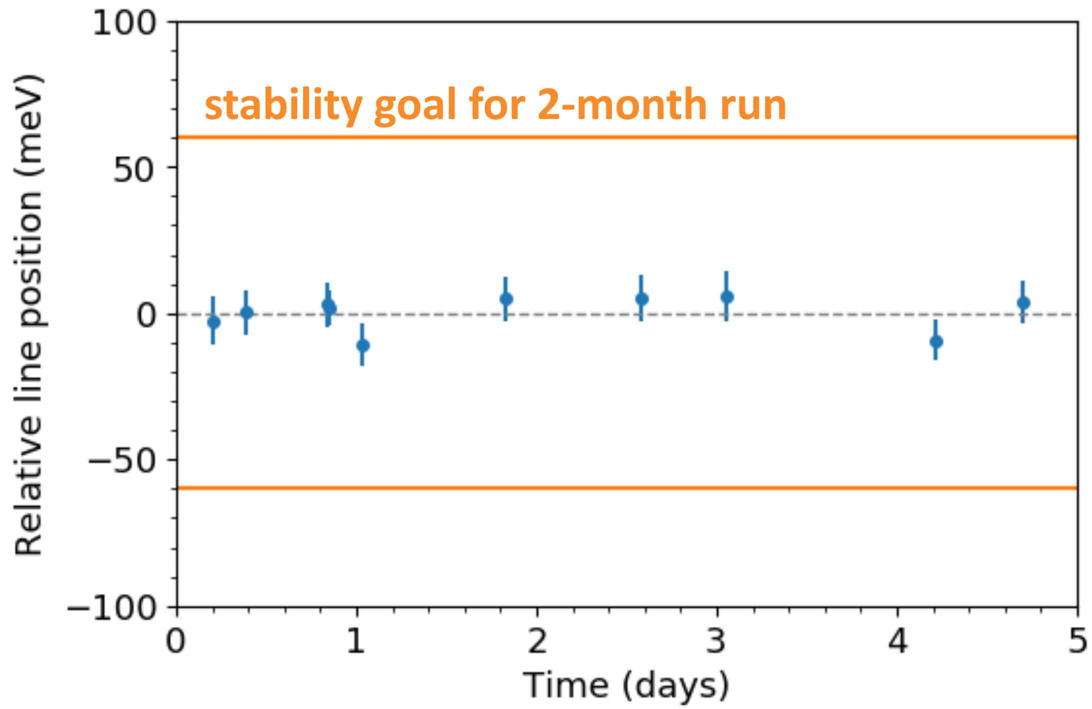
9 eV window
around
32140 eV line



Krypton demonstrates performance of overall KATRIN system

Example: **L_3-32** line (30.5 keV, Γ ~1.4 eV)





- ✓ Sharp resolution (~2 eV at 30 keV) and excellent linearity of energy scale
- ✓ New calibration method of HV meas. (< 5 ppm) based on relative line positions
- ✓ Highly stable overall system from source to detector

Arenz et al. (KATRIN Collab.), JINST **13** (2018) P04020 and EPJ **C78** (2018) 368

May 2018: KATRIN's very first tritium!

First tritium circulation on May 18th

First spectrum scans recorded on May 19th

- Nominal gas column in the source beam tube, but D_2 instead of T_2 for now
- Starting with mixing in only small amount of tritium (~ 1% of nominal activity)
- Stay tuned for NEUTRINO 2018!

Operation and analysis crew in the control room

- Looking forward to the KATRIN inauguration on June 11, 2018

Next steps for KATRIN

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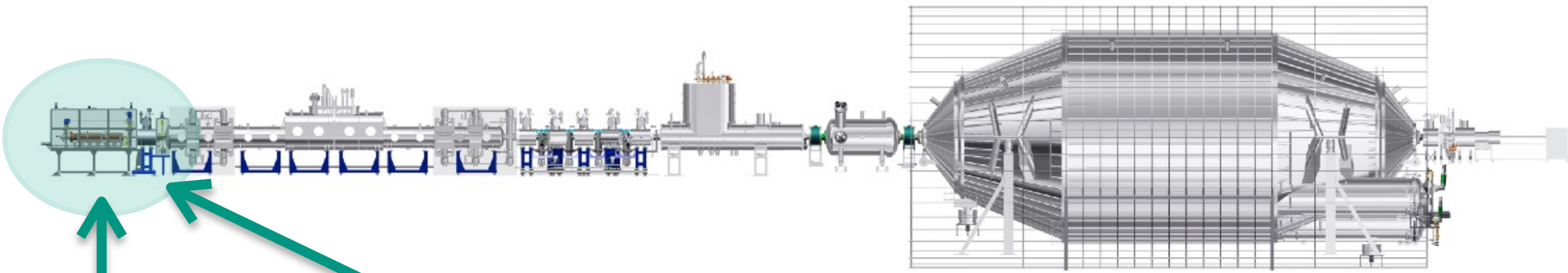
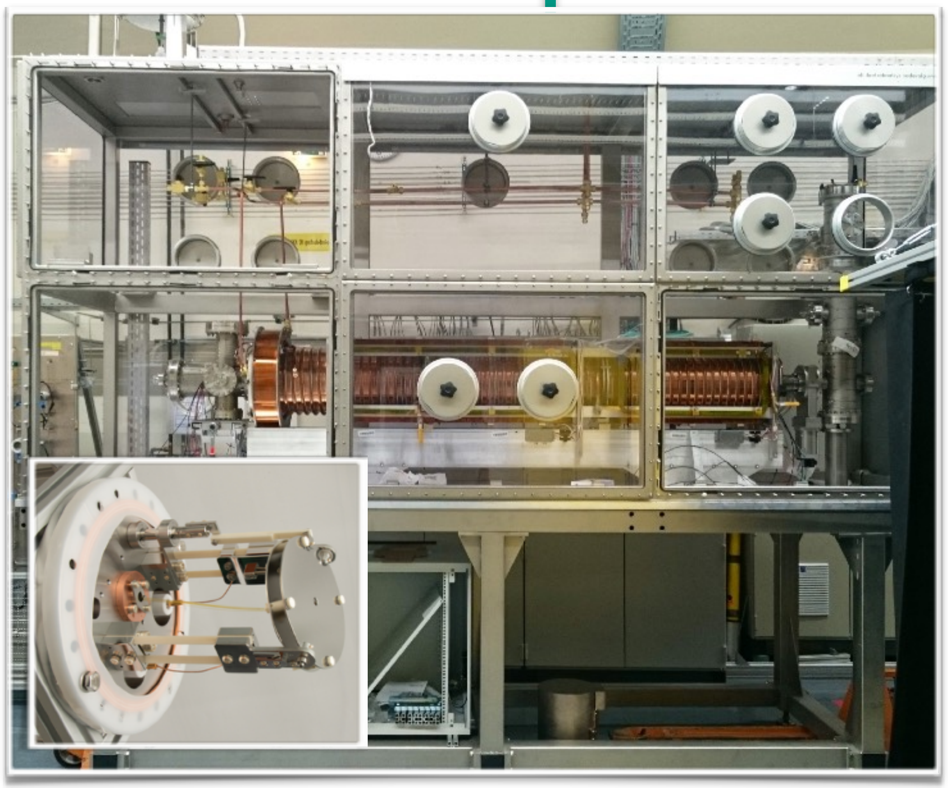
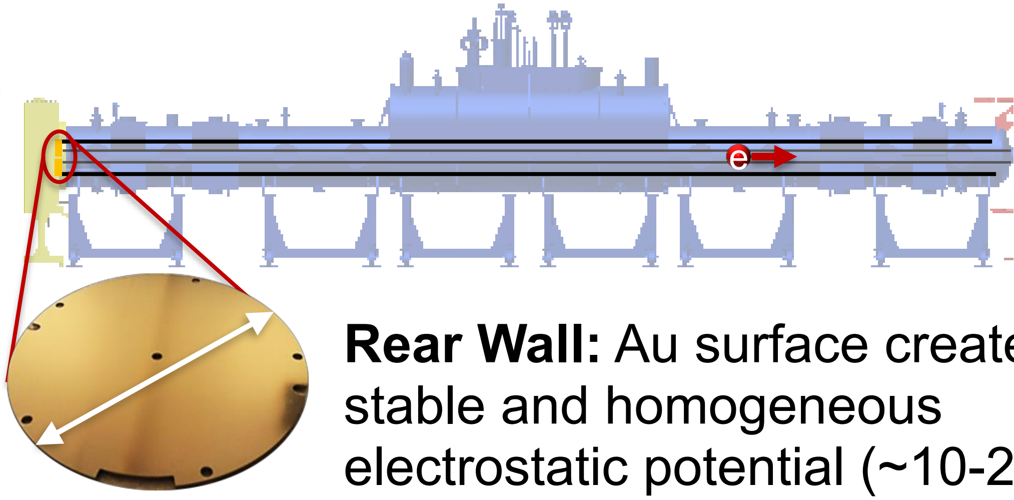
Calibration & monitoring systems: major importance for systematics control

“Rear Section”: under construction





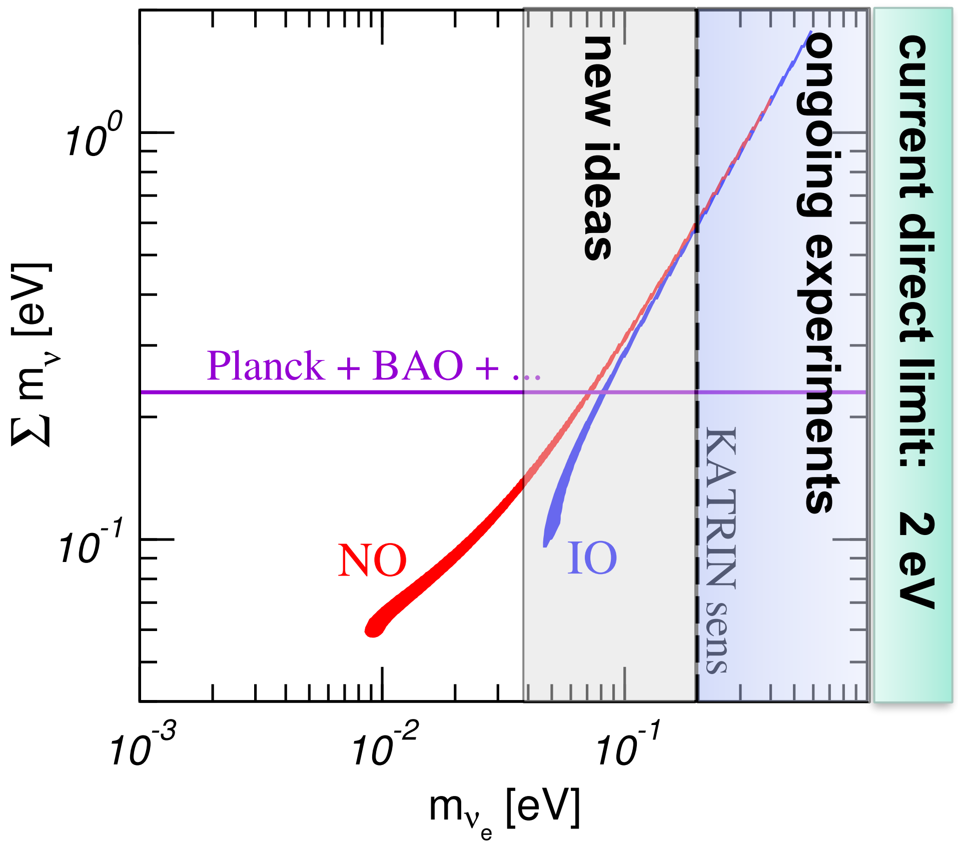


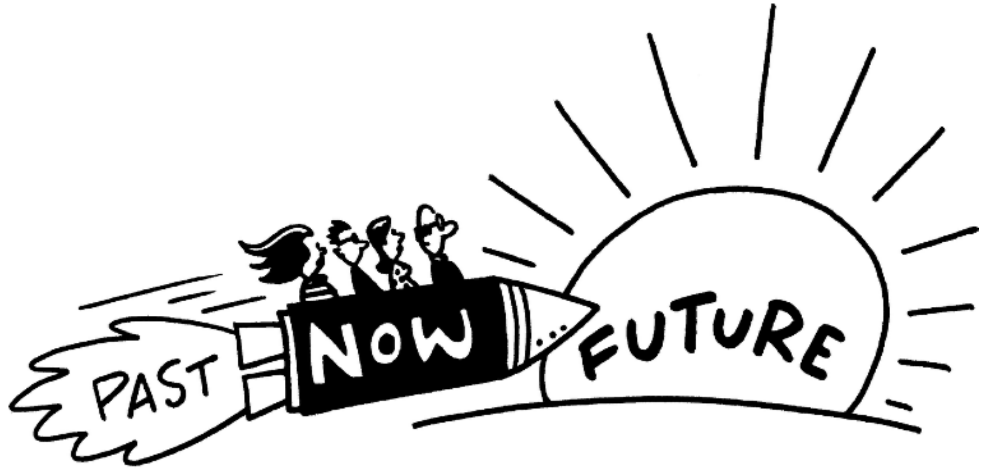
⌀ 150 mm

Rear Wall: Au surface creates stable and homogeneous electrostatic potential (~10-20 mV) in the source plasma

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

IV. Novel approaches





How to further improve ν-mass sensitivity?

Problems:

MAC-E technique does not scale further

- energy resolution
- source luminosity

∅100 m spectrometer ???

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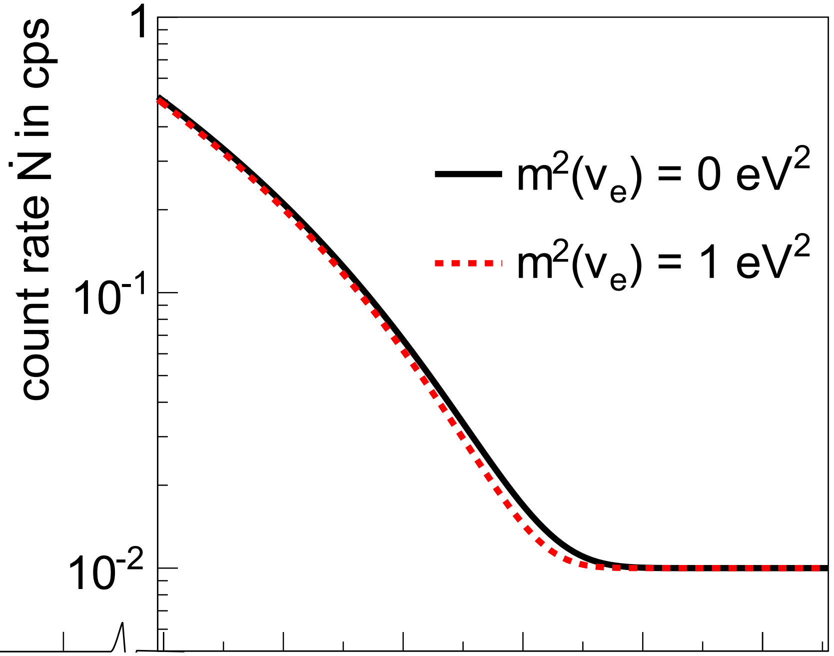


Integrated β spectrum: loss of information

How to further improve ν-mass sensitivity?

Problems:

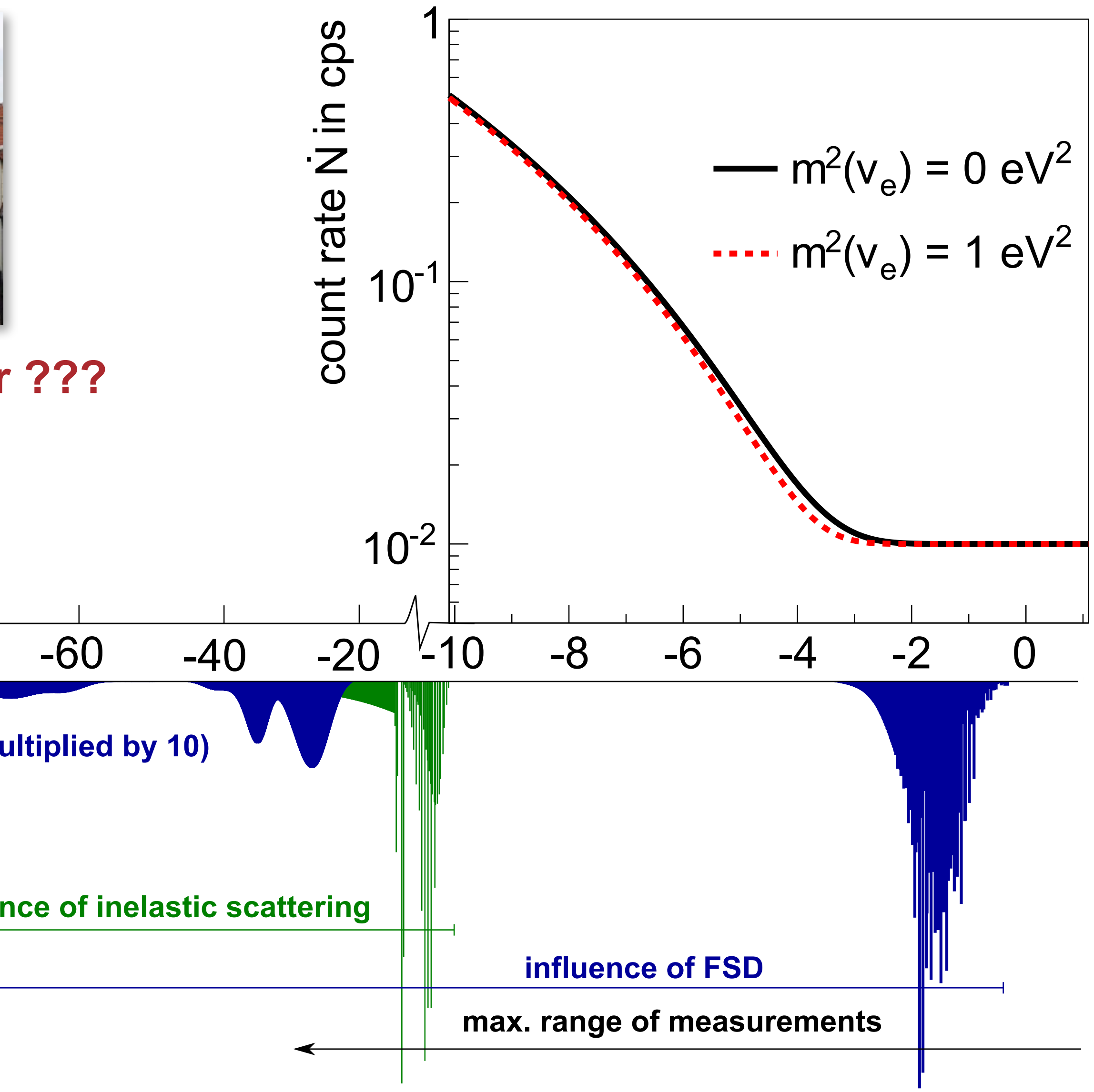
MAC-E technique does not scale further

- energy resolution
- source luminosity

∅100 m spectrometer ???

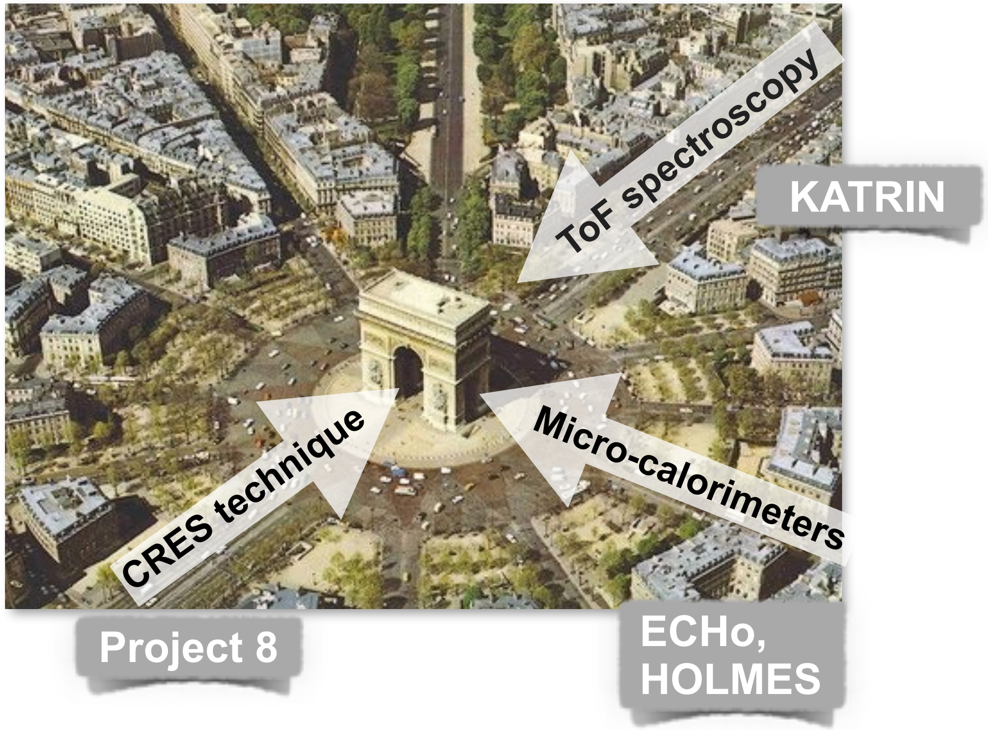
Integrated β spectrum: loss of information

Final state uncertainty in molecular T_2



Novel developments

Several avenues towards improvement:



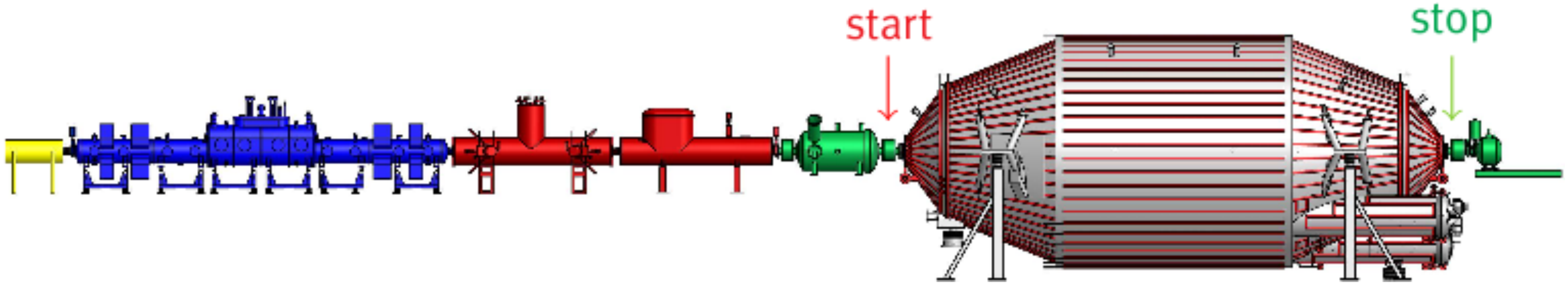
1st avenue

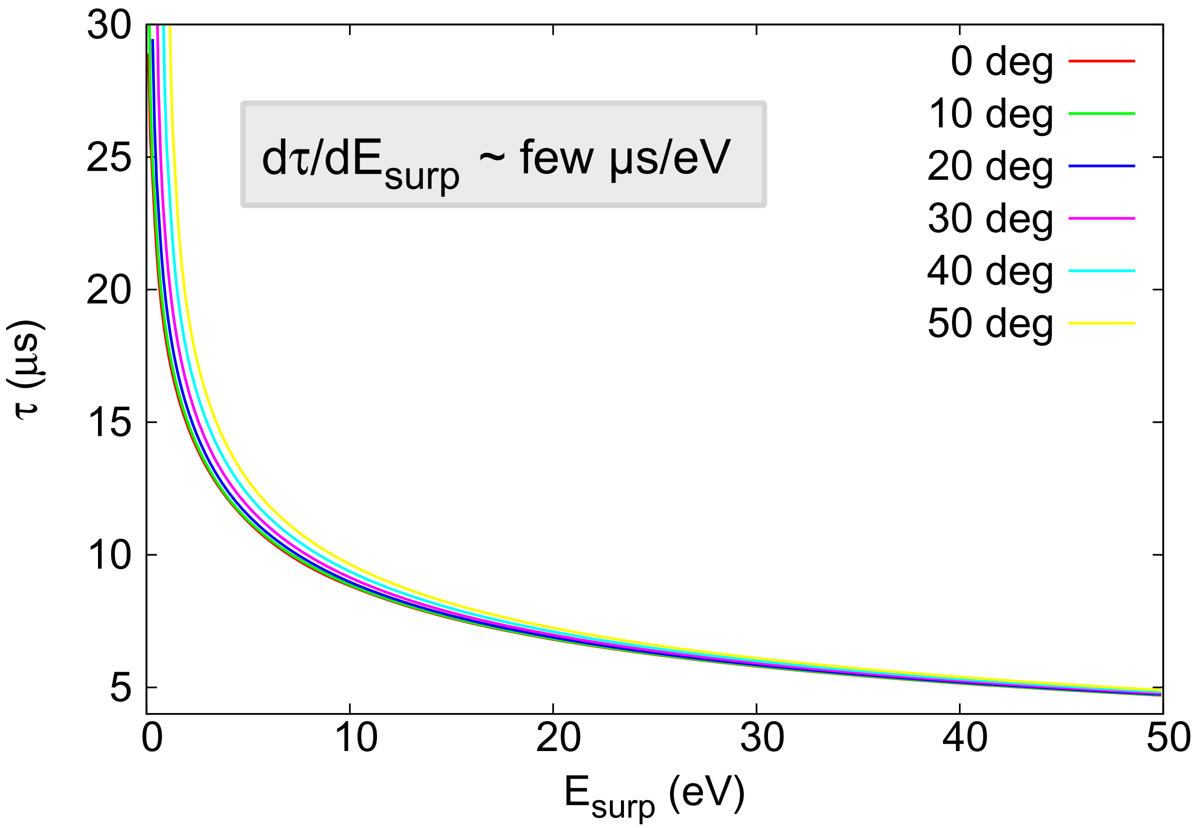
Time-of-flight spectroscopy

[credit: Nicho Steinbrink]

Measuring a differential β spectrum

Idea: Upgrade to MAC-E-TOF spectrometer

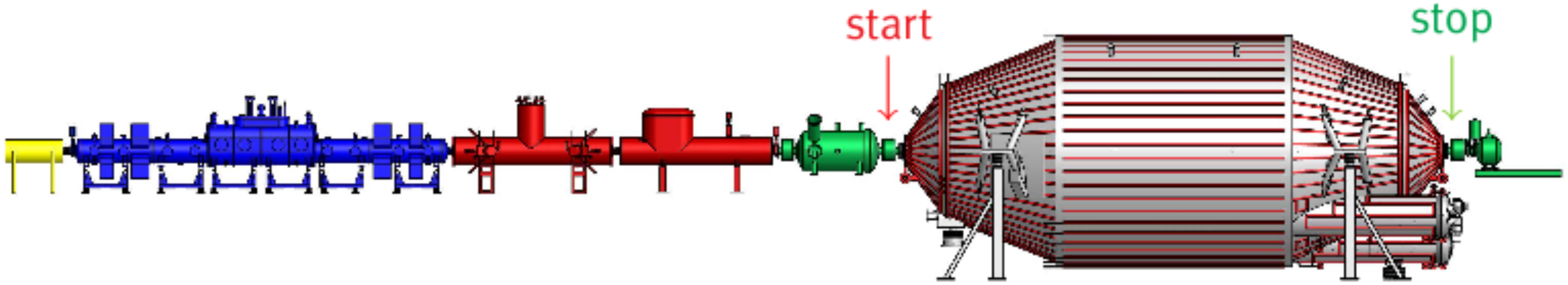


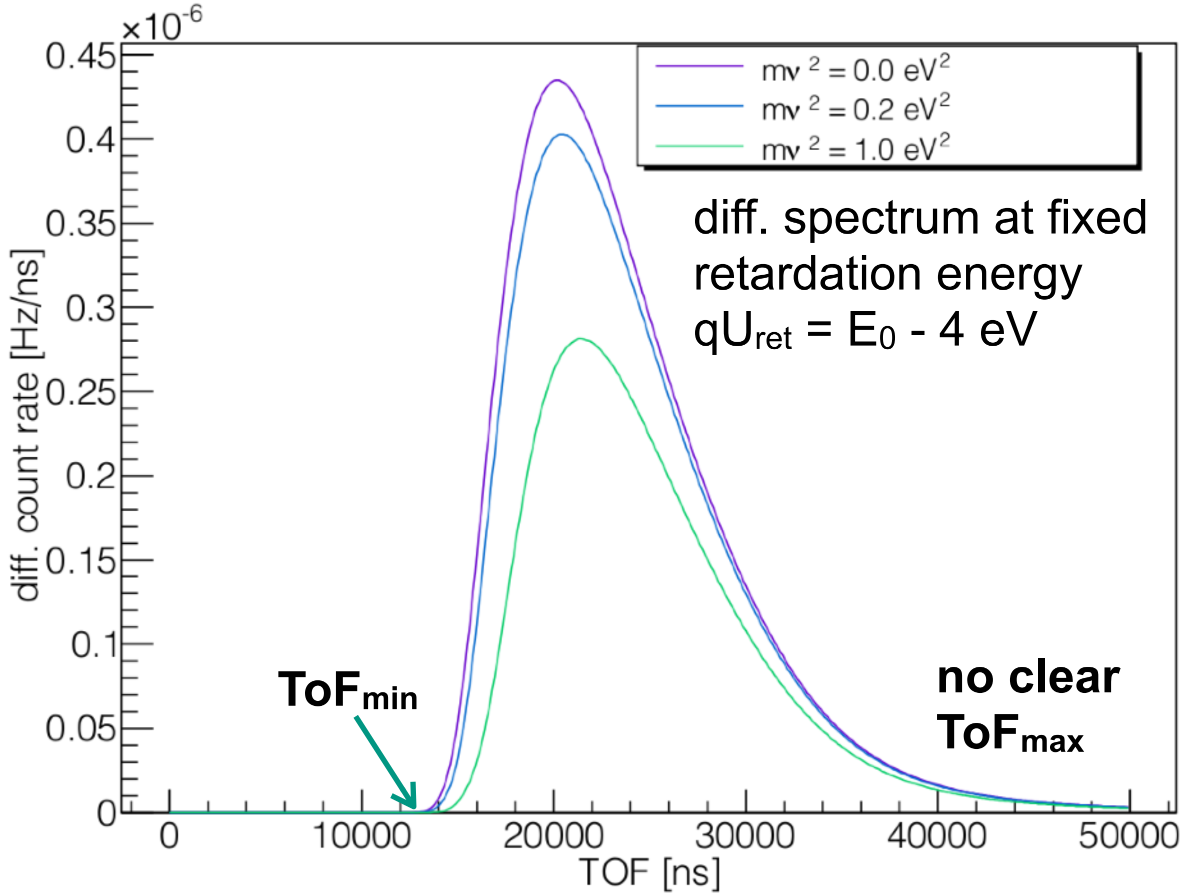


Spectrometer as 24 m long "delay line"
➜ very sensitive to small differences in surplus energy
(especially at low surplus energies above the retardation potential)

Measuring a differential β spectrum

Idea: Upgrade to MAC-E-TOF spectrometer





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

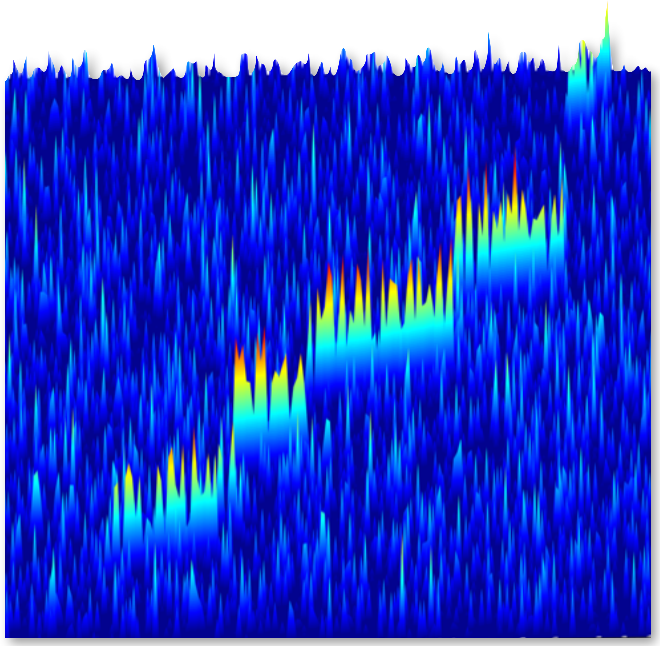
Coincidence requirement
➜ background suppression

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

[Bonn *et al.* 1999, Steinbrink *et al.* 2013 & 2018]

2nd avenue

Frequency-based approach



"Never measure anything but frequency." — Arthur L. Schawlow

Cyclotron Radiation Emission Spectroscopy (CRES)

PROJECT 8

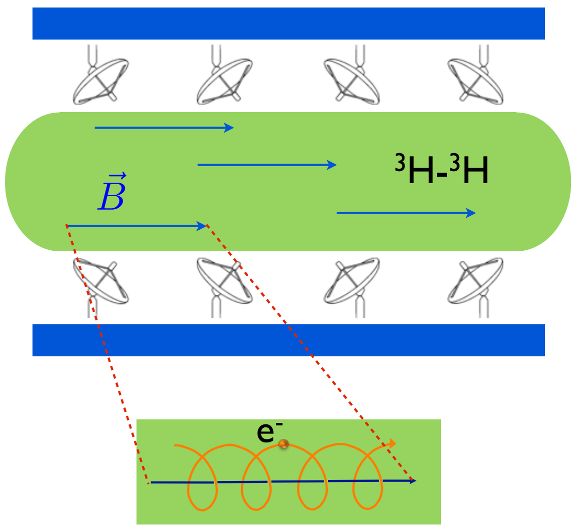
UW Seattle, MIT, UCSB,
Pacific NW, CfA, Yale,
Livermore, KIT, U Mainz

Non-destructive measurement of electron **energy** via **cyclotron frequency:**

$$f(\gamma) = \frac{1}{2\pi}\frac{f_c}{\gamma} = \frac{eB}{m_e + E_{kin}}$$

The challenge:

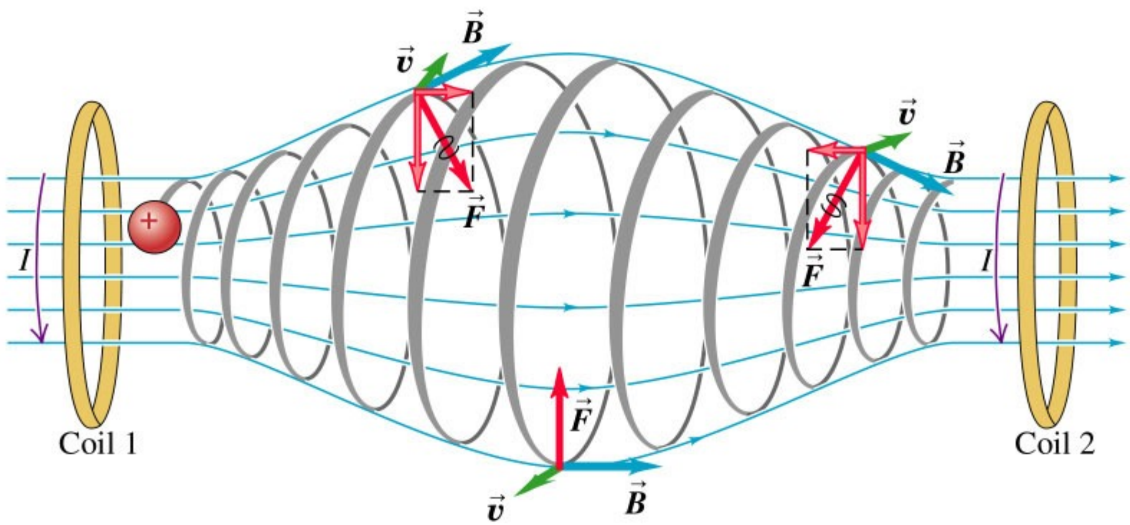
- Energy resolution:
  ΔE/E ~ Δf/f ~ ppm
- Frequency resolution:
  Δf ~ 1/Δt
  Δt ~20 μs → 1400 m at 18 keV
  need multiple passes in a trap



uniform B-field, magnetic trap

low-pressure gas cell

antenna array



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

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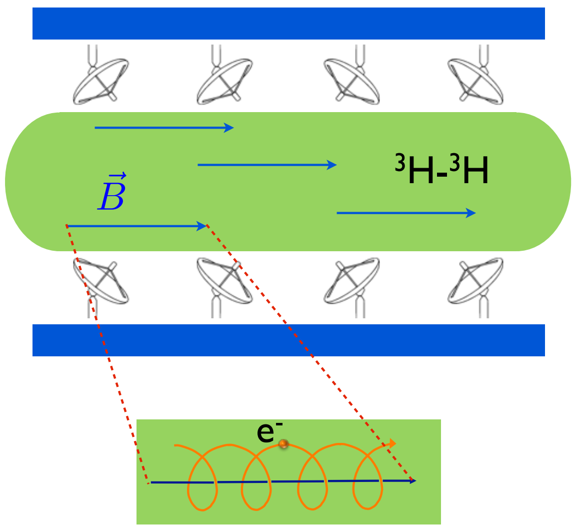
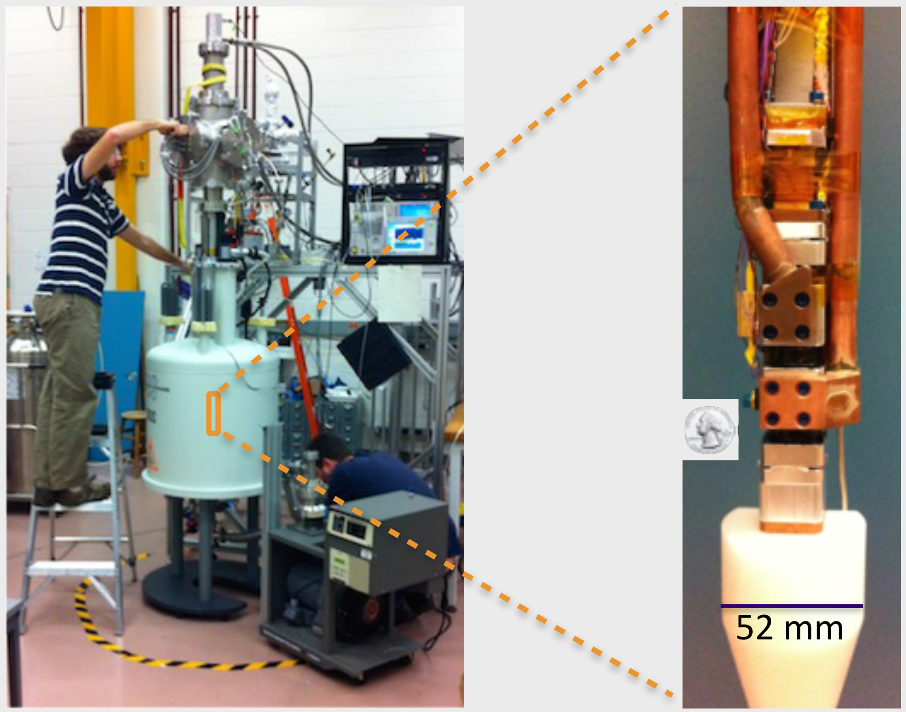


uniform B-field, magnetic trap

low-pressure gas cell

antenna array

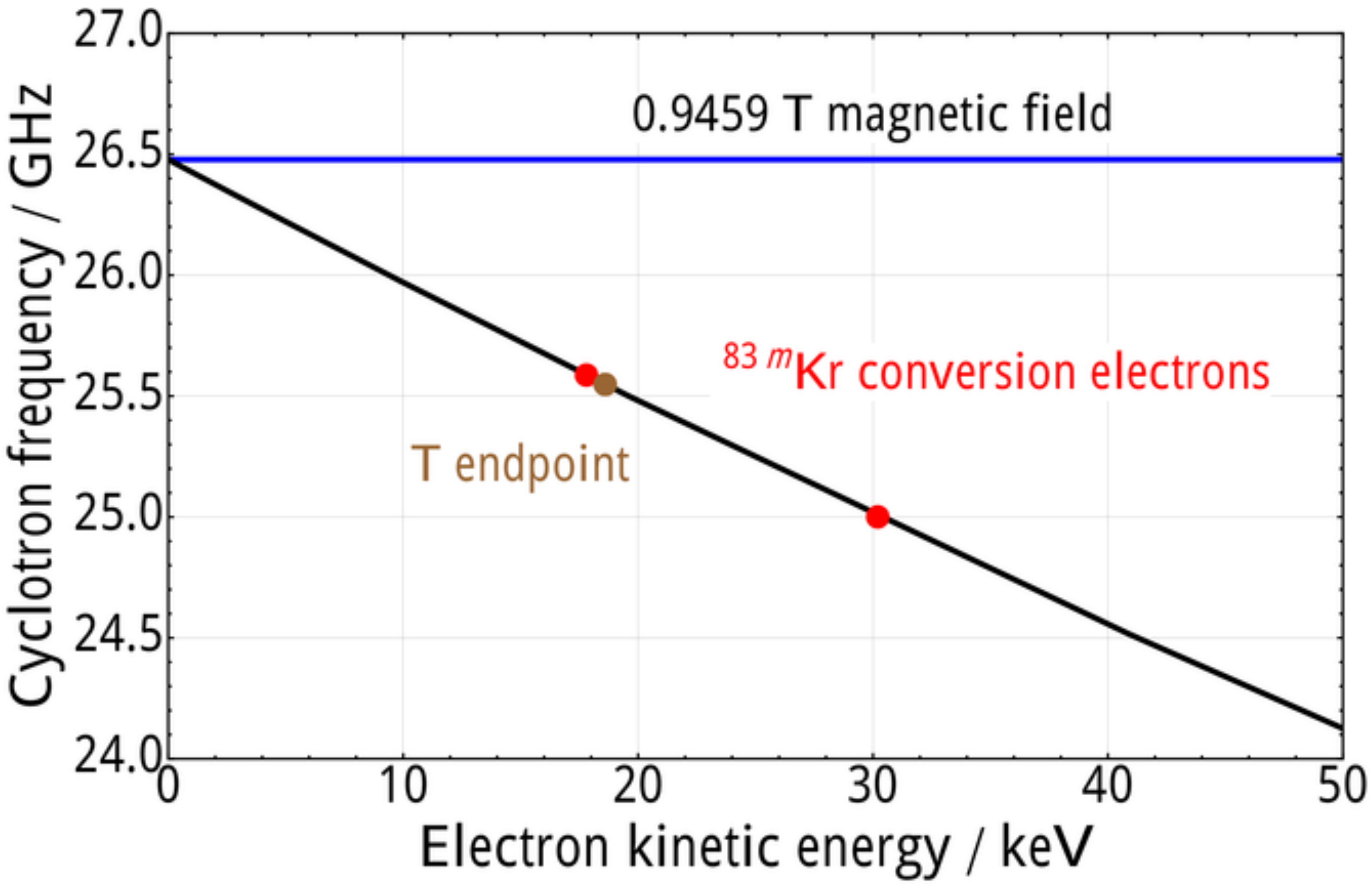
From theoretical idea to experimental reality within 5 years



➜ Proof of principle of CRES technique

Towards tritium β spectroscopy with CRES

Some practical points: frequency range



~ 1 T magnetic field:
cyclotron frequency
in K band (IEEE)

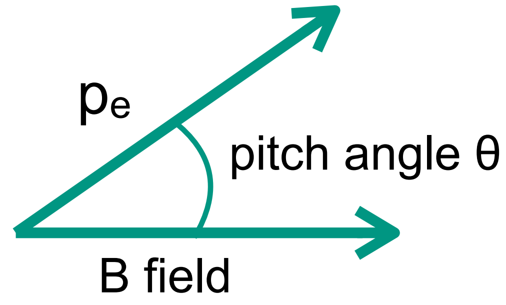
^{83m}Krypton has
monoenergetic
conversion electrons
close to tritium endpoint

Towards tritium β spectroscopy with CRES

Some practical points: radiated power

Larmor formula

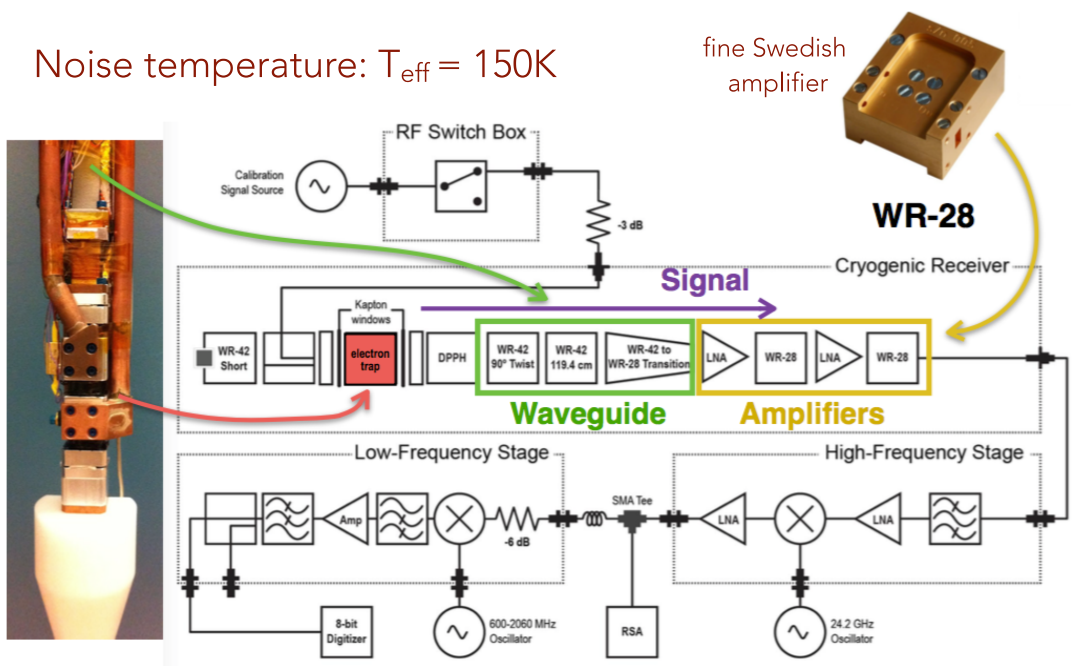
$$P(\gamma,\theta) = \frac{1}{4\pi\varepsilon_0}\,\frac{2}{3}\,\frac{q^4 B^2}{m_\mathrm{e}^2}\,(\gamma^2 - 1)\sin^2\theta$$



Emitted power:

- **1.7 fW** for 30.4 keV at θ = 90°
- **1.1 fW** for 18 keV at θ = 90°

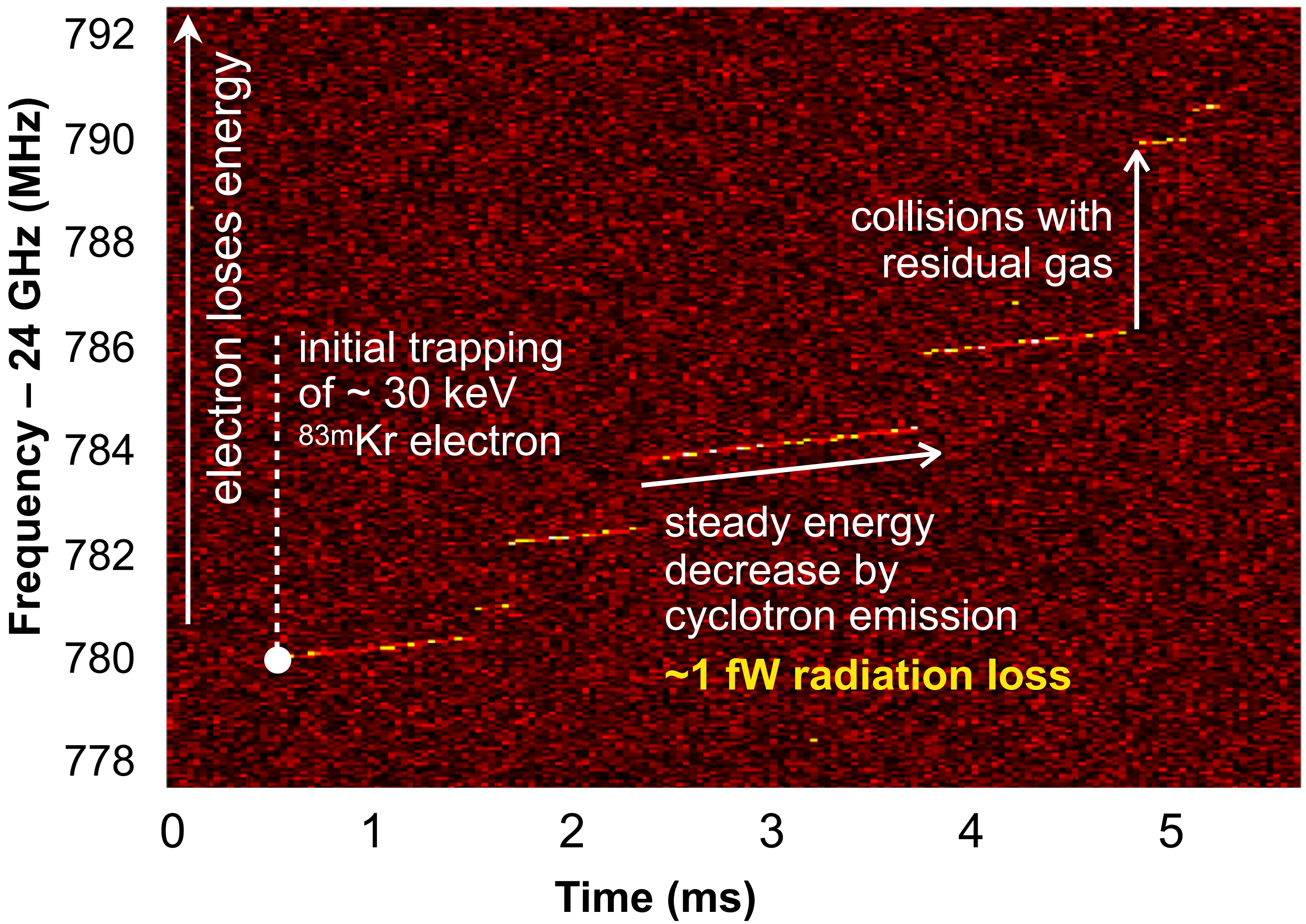
➜ Need low-noise cryogenic RF system



from S. Böser

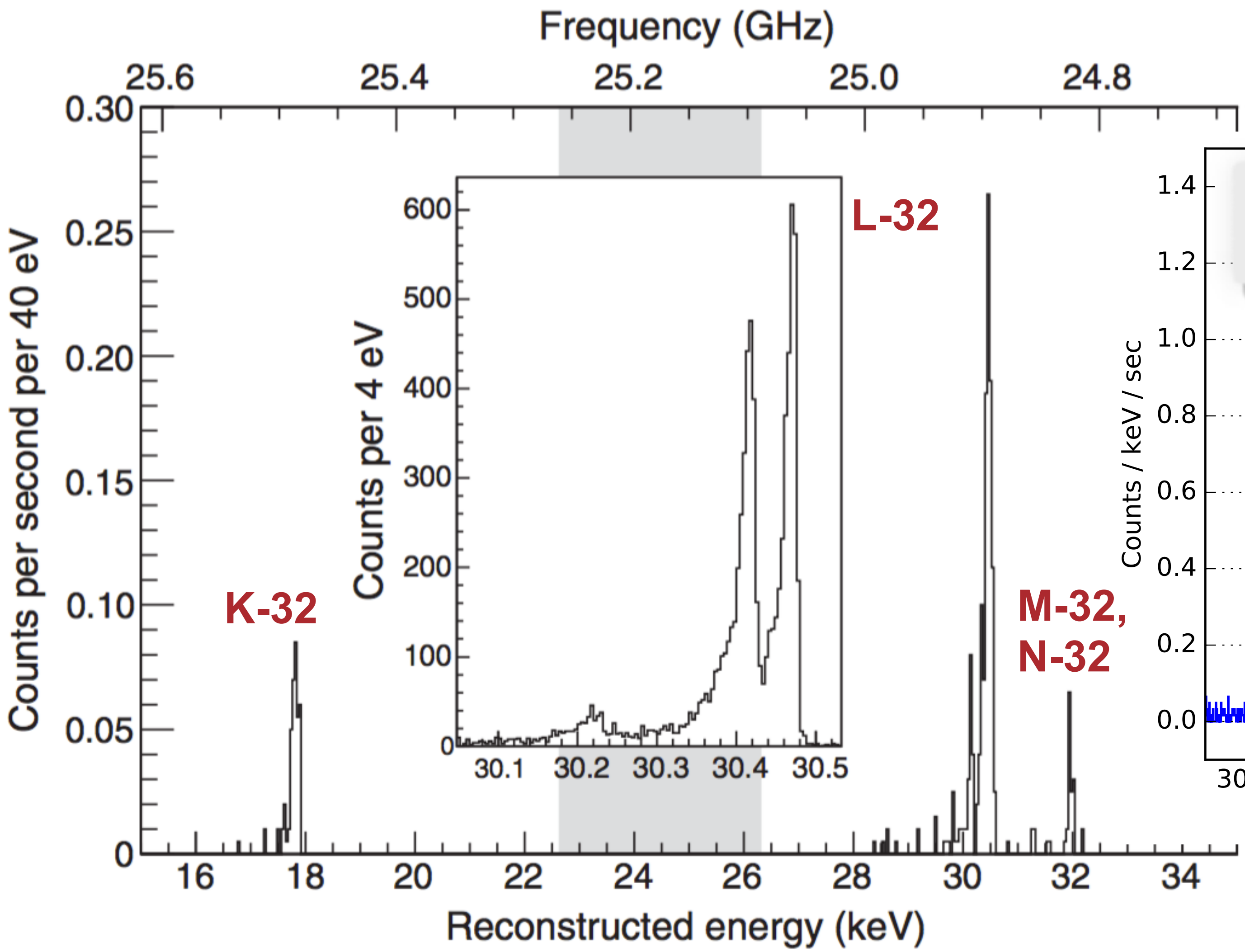
Project 8: phase I results

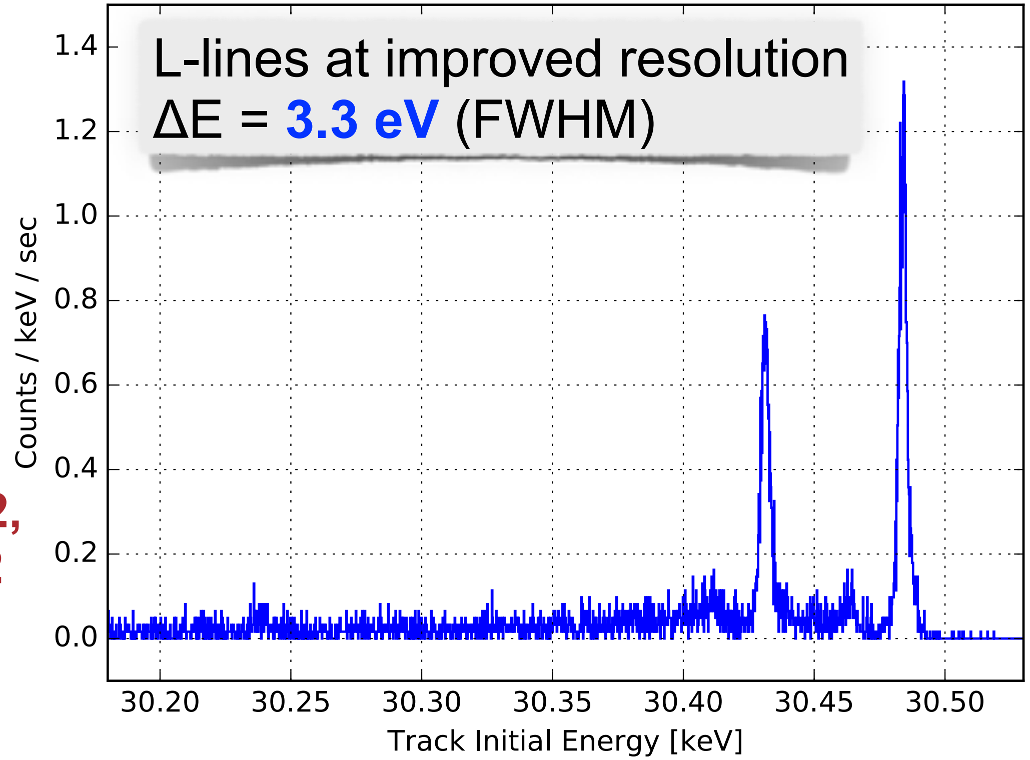
First spectrogram of cyclotron radiation from single keV electrons (^{83m}Kr)



Project 8: phase I results

^{83m}Kr lines at 17.8, 30.4, 32 keV clearly seen at ΔE = 140 eV (FWHM)

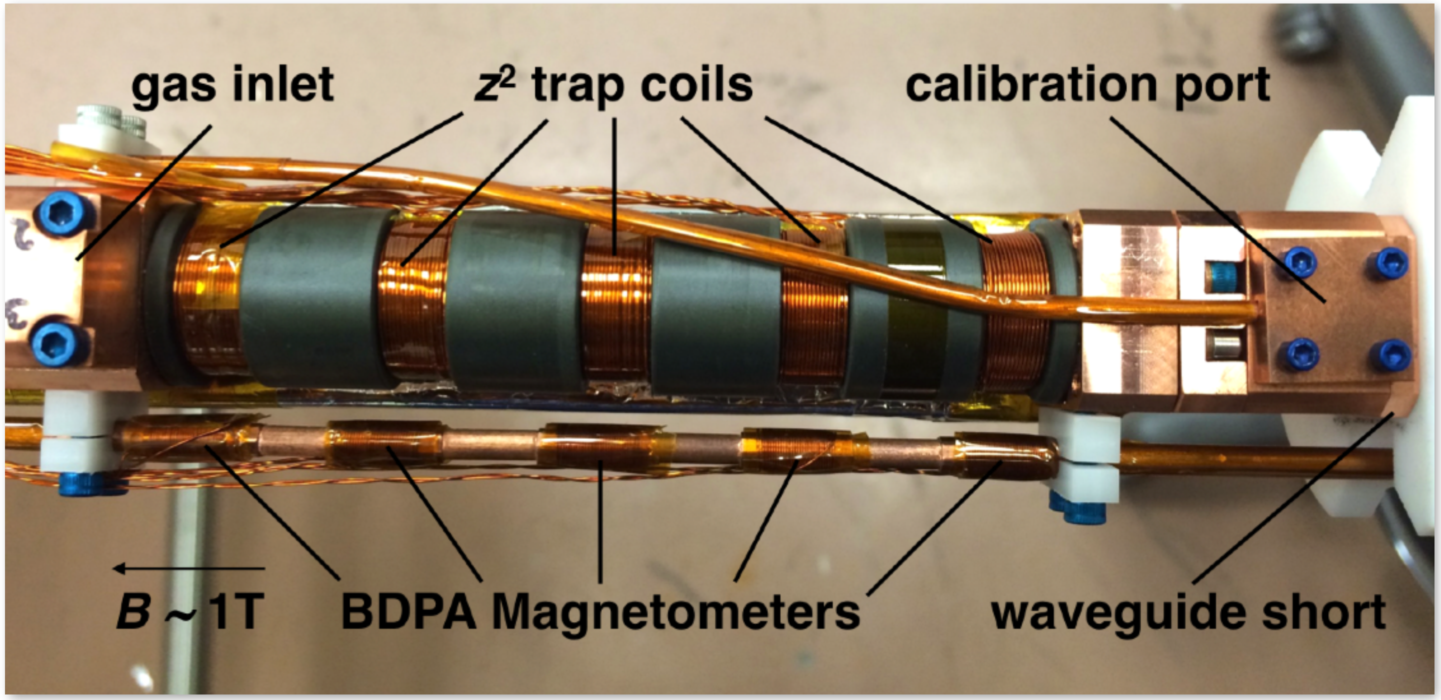




[Asner *et al.*, PRL 114 (2015) 162501; Ashtari E. *et al.*, J. Phys. G 44 (2017) 054004]

Project 8: phased approach

- **Phase I (2010-2016): proof of principle**
  Single-electron CRES demonstrated with conversion electron lines from ^{83m}Kr
- **Phase II (2015-2018): tritium demonstrator**
  - Improved waveguide, read-out, energy resolution, systematics studies
  - Continuous T_2 β-spectrum, $m(\nu_e) \sim 100 \ldots 10$ eV

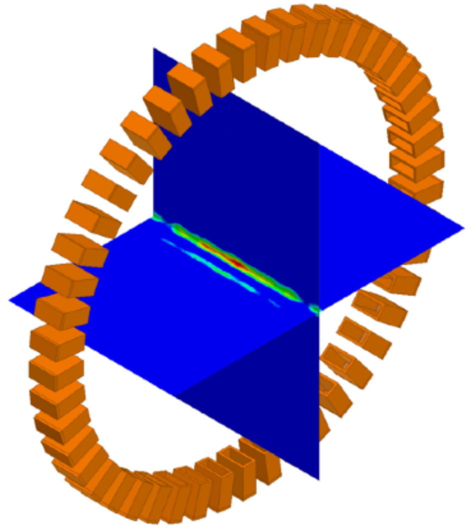


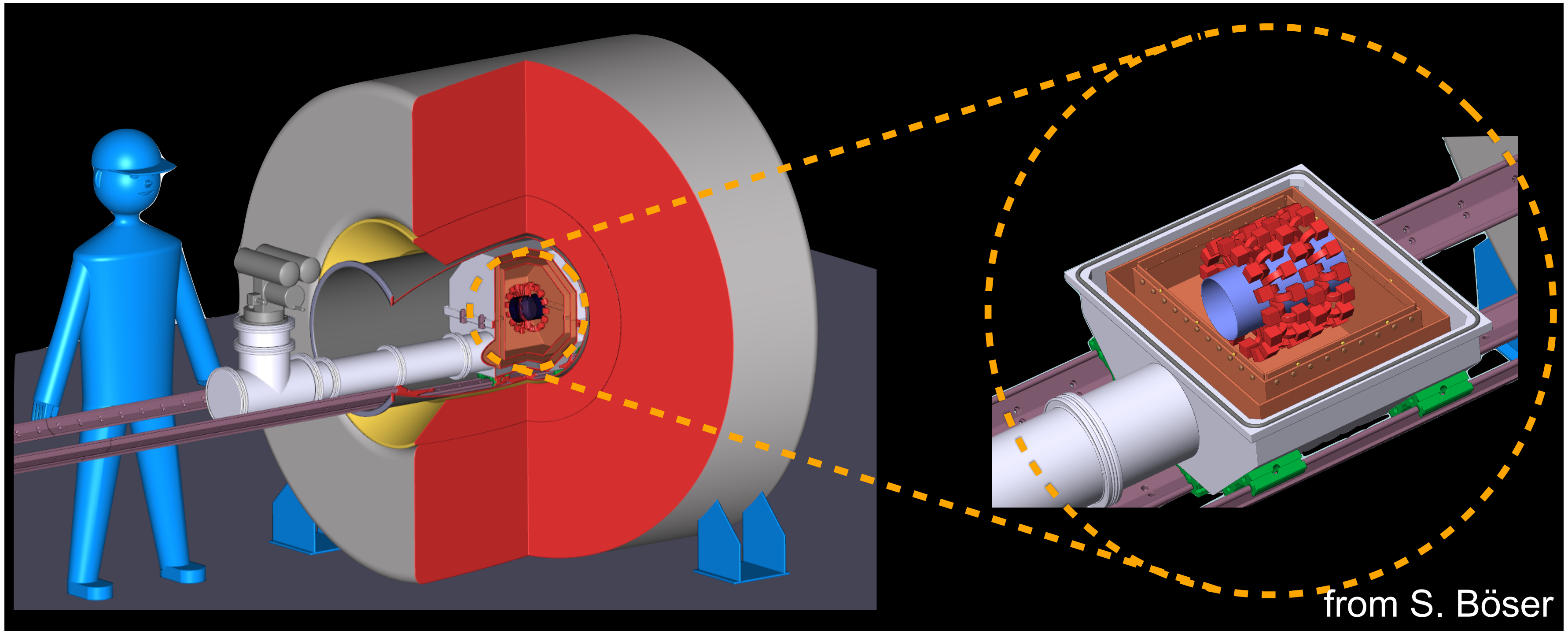
Phase II set-up

T_2 data coming up soon!

Project 8: phased approach

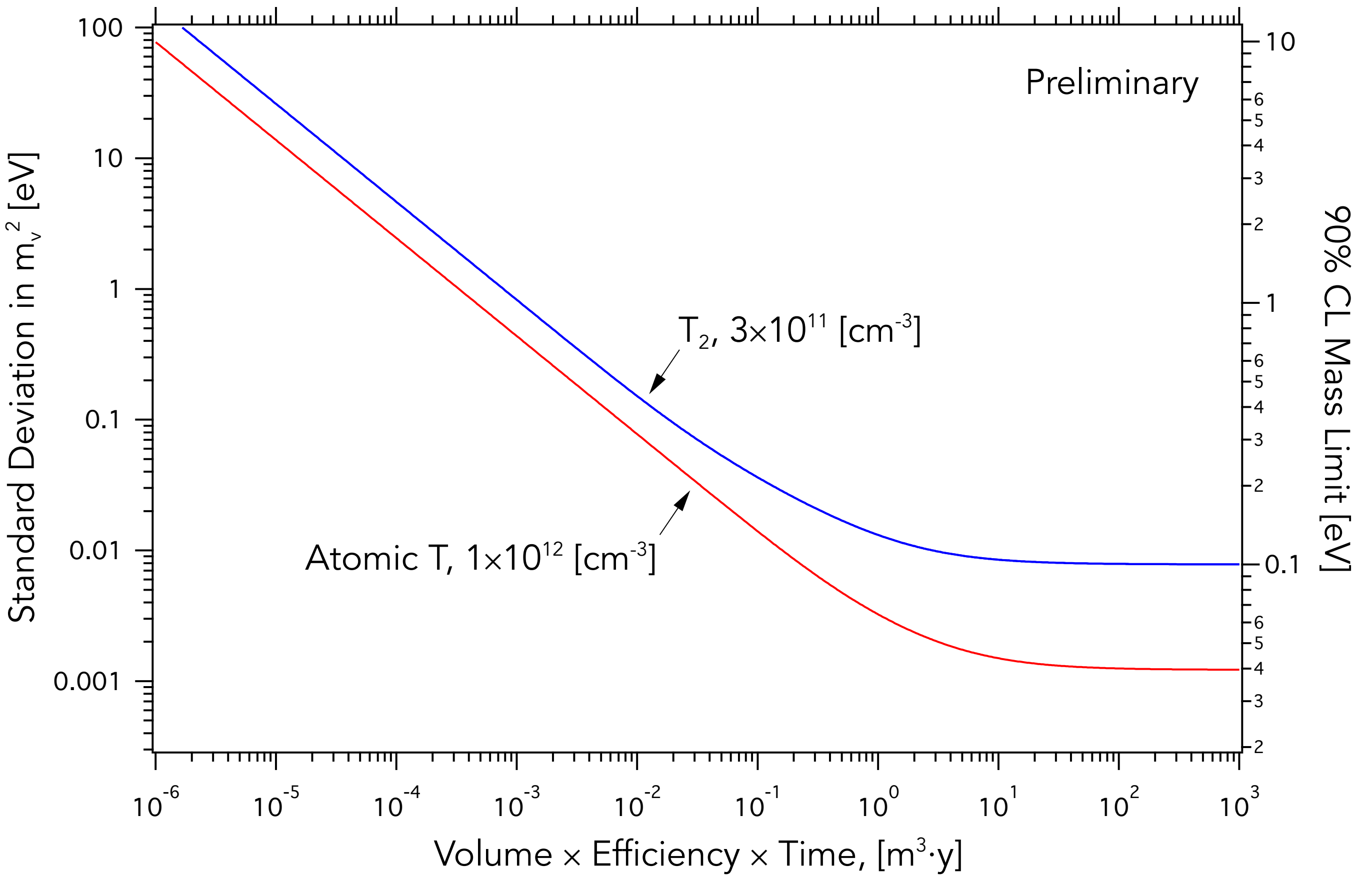
- **Phase III (2016-2020): large volume demonstrator**
  - Open-bore MRI magnet: cryostat moved in on rails
  - Phased-array read-out, digital beam-forming
  - 10^5 Bq in 200 cm^3 volume (10-20 cm^3 effective)
  - Tritium data competitive with $m(\nu_e) \sim 2$ eV (1 yr)
  - Ongoing design for trap, cryo-system, antenna array

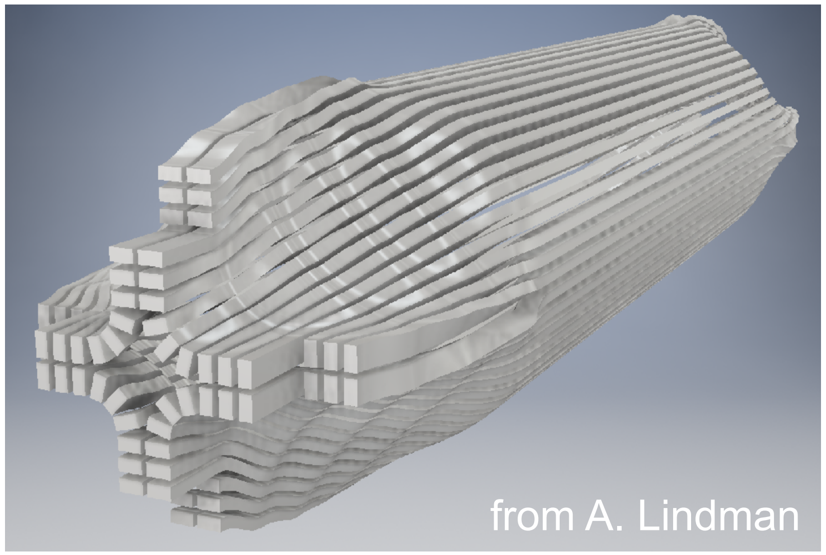




Project 8: phased approach

- **Phase IV (2017+): atomic tritium source**
  - goal: sub-eV sensitivity at inverted hierarchy scale
  - R&D for large-volume magnetic trap for atomic tritium (< 50 mK)
  - 10^{18} atoms (~10^9 Bq activity) in fiducial volume of 10+ m^3

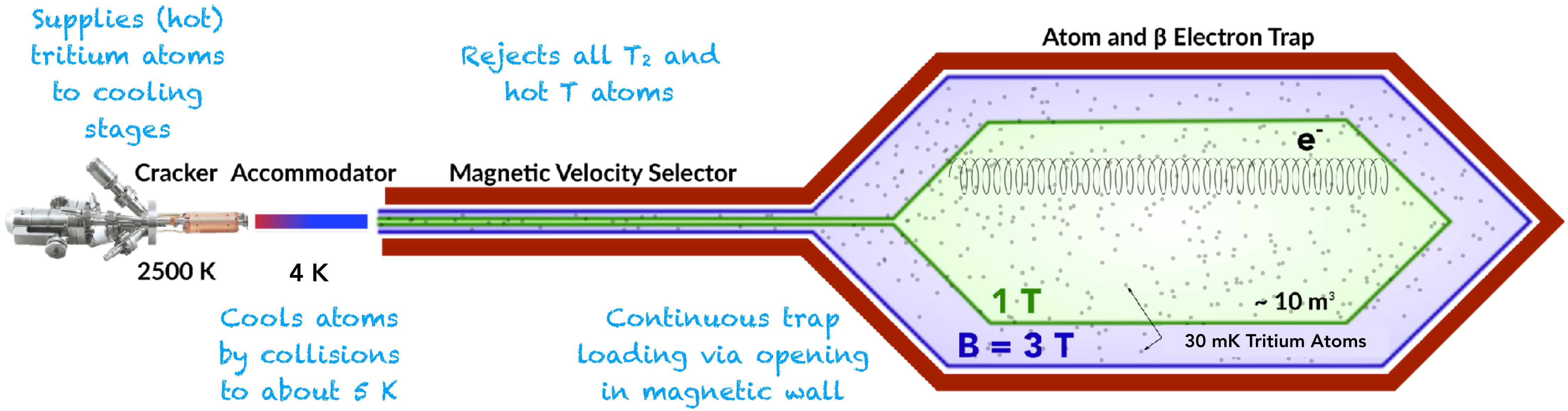




Multipole trap based on Ioffe-Pritchard concept (cf. ALPHA antihydrogen trap)

Project 8: phased approach

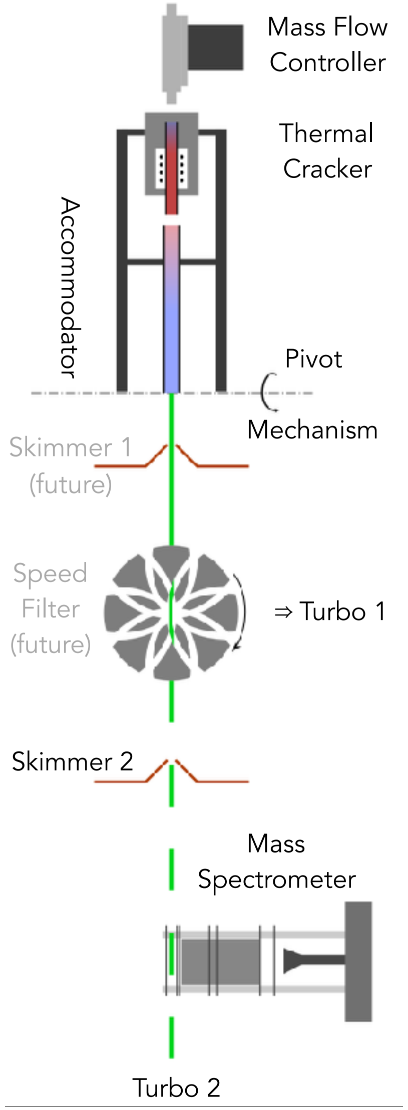
- **Phase IV (2017+): atomic tritium source**
  - goal: sub-eV sensitivity at inverted hierarchy scale
  - 10^{18} atoms in fiducial volume (~10^9 Bq activity)
  - R&D for large-volume (> 10 m^3) atomic tritium trap (< 1 K)

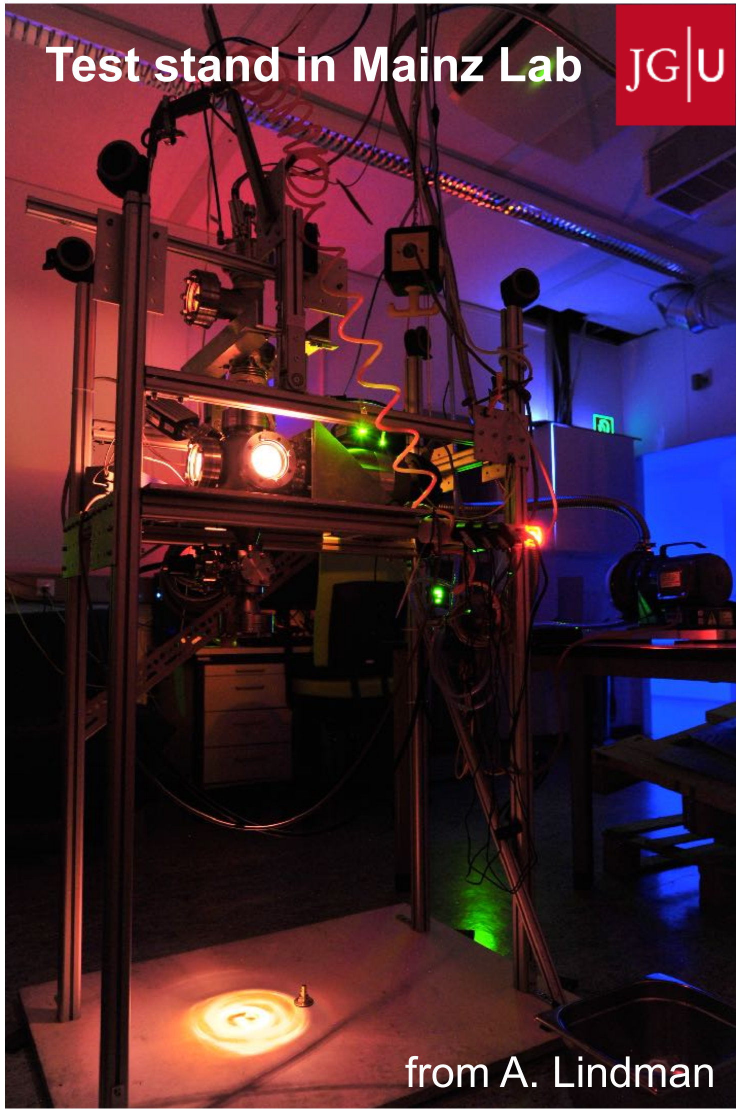


from A. Lindman

Project 8: phased approach

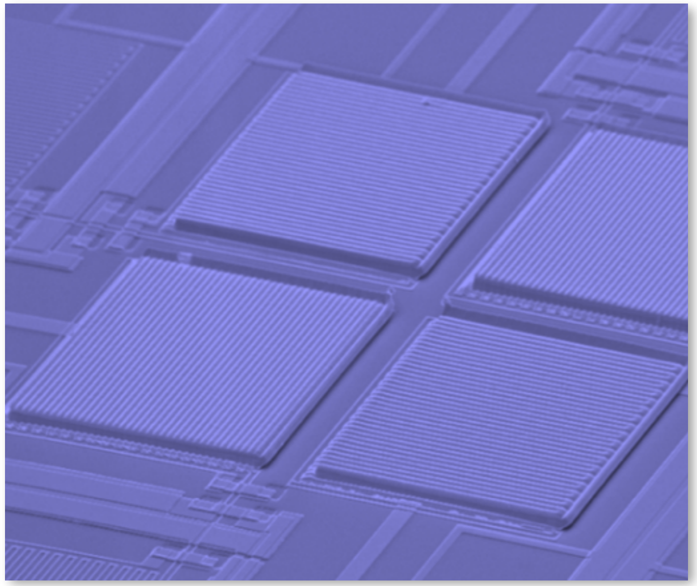
- **Phase IV (2017+): atomic tritium source**





3rd avenue

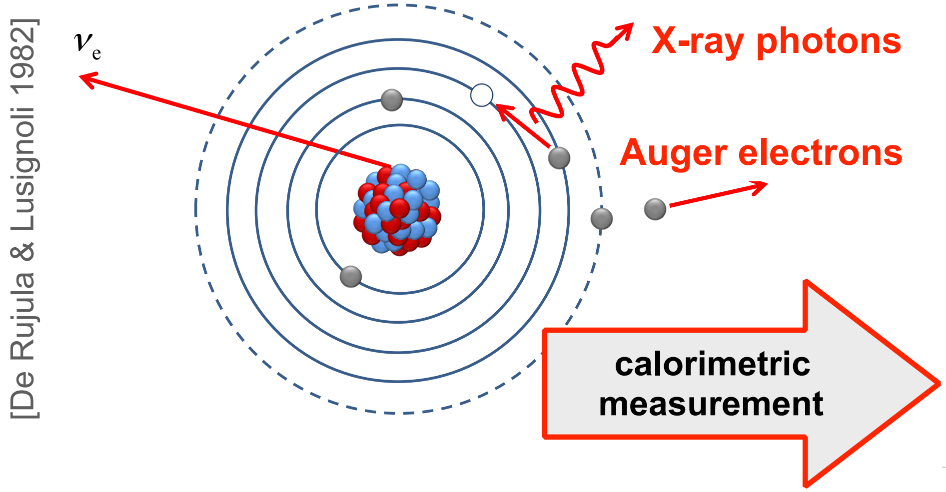
Calorimetric approach using ^{163}Ho



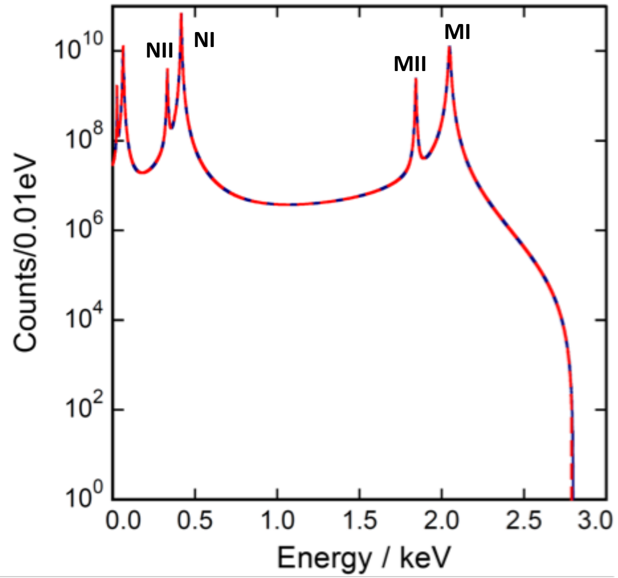
ν-mass from ^{163}Ho electron capture

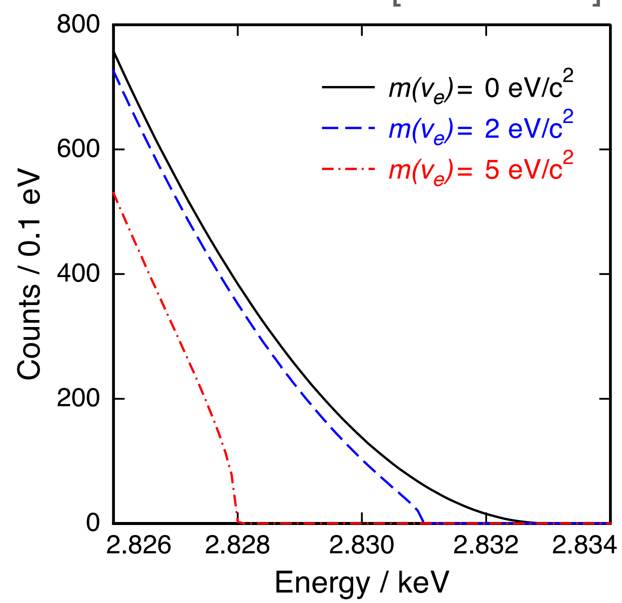
$^{163}Ho \longrightarrow {}^{163}Dy^{*} + \nu_e$

Low Q_{EC} ~2.8 keV and $T_{1/2}$ ~ 4570 years



[L. Gastaldo]





$$\frac{dW}{dE_C} = A(Q_{EC} - E_C)^2 \sqrt{1 - \frac{m_\nu^{\ 2}}{(Q_{EC} - E_C)^2}} \sum_H B_H \varphi_H^{\ 2}(0) \frac{\frac{\Gamma_H}{2\pi}}{(E_C - E_H)^2 + \frac{\Gamma_H^{\ 2}}{4}}$$

ν-mass from ^{163}Ho electron capture

Challenges (experiment):

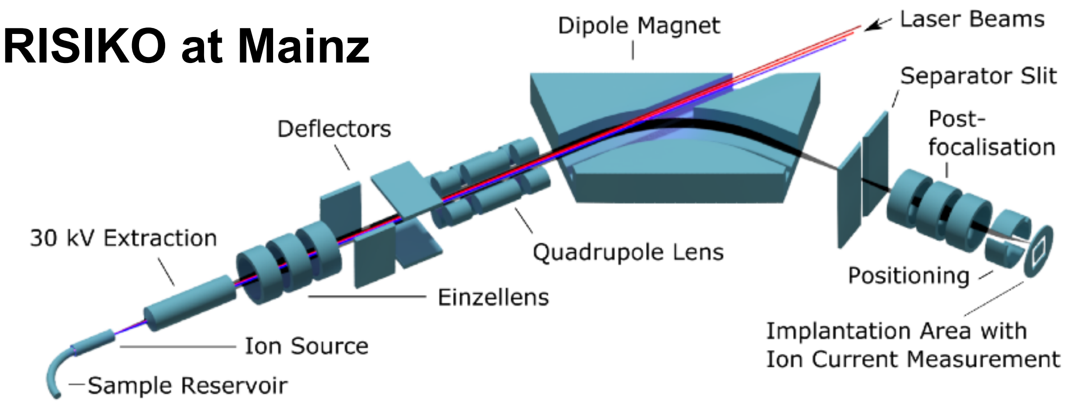
- Production & purification of isotope ^{163}Ho
- Incorporation of ^{163}Ho into high-resolution detectors ($2 \cdot 10^{11}$ atoms for 1 Bq)
- Operation & readout of large arrays

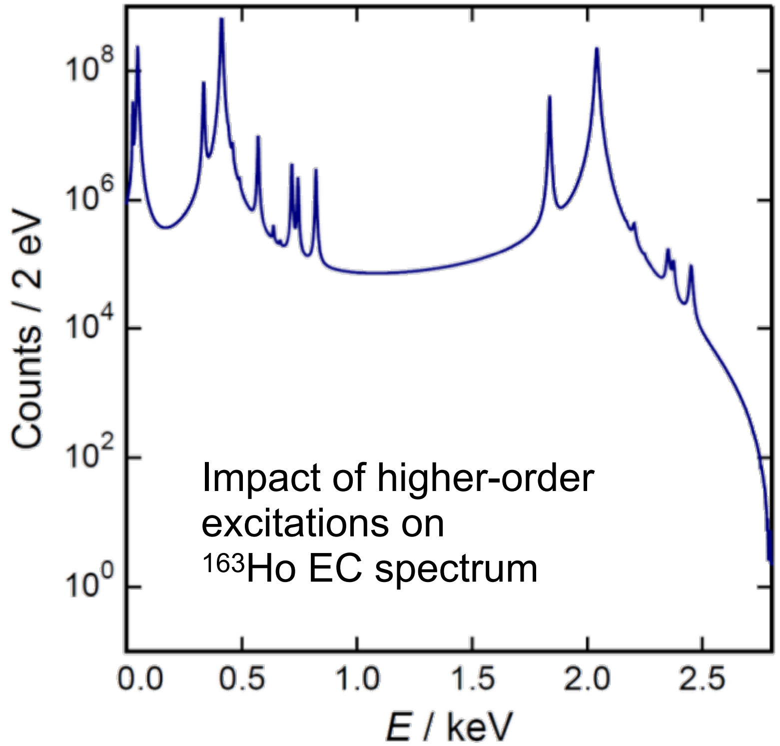
Challenges (theory & spectral shape):

- Understanding of calorimetric spectrum (nuclear & atomic physics + detector response)
- Independent determination of Q_{EC} by Penning-trap mass spectrometry

Er161 3.21 h 3/2- EC	Er162 0+ 0.14	Er163 75.0 m 5/2- EC	Er164 0+ 1.61	Er165 10.36 h 5/2- EC	Er166 0+ 33.6
Ho160 25.6 m 5+ * EC	Ho161 2.48 h 7/2- * EC	Ho162 15.0 m 1+ * EC	Ho163 4570 y 7/2- * EC	Ho164 29 m 1+ * EC,β-	Ho165 7/2- 100

RISIKO at Mainz

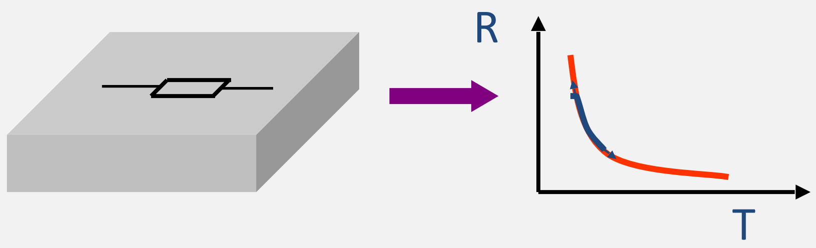




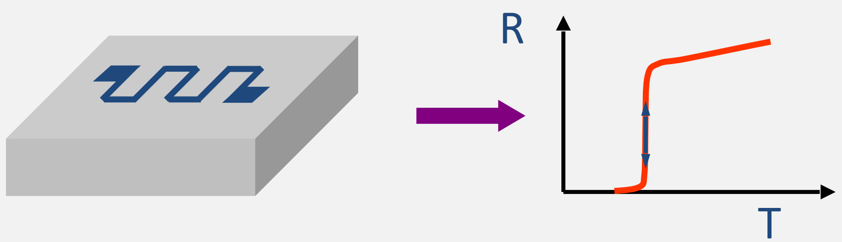
[A. Faessler et al., PRC 91 (2015) 045505, 064302]

Temperature sensors — technologies

Resistance of highly doped semiconductors



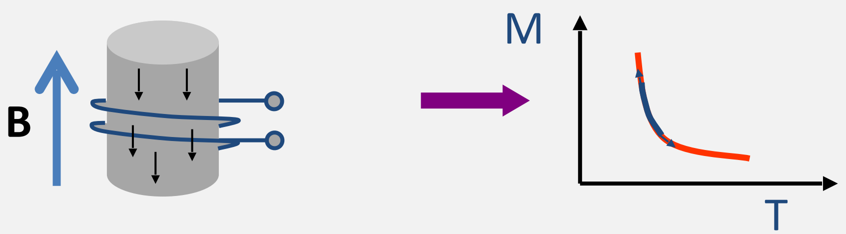
Resistance at superconducting transition, TES



HOLMES

NuMECS

Magnetization of paramagnetic material, MMC

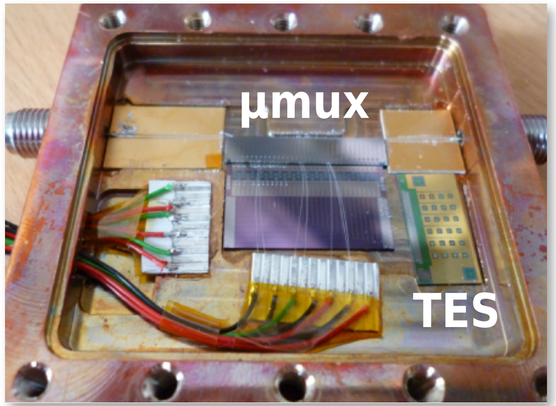


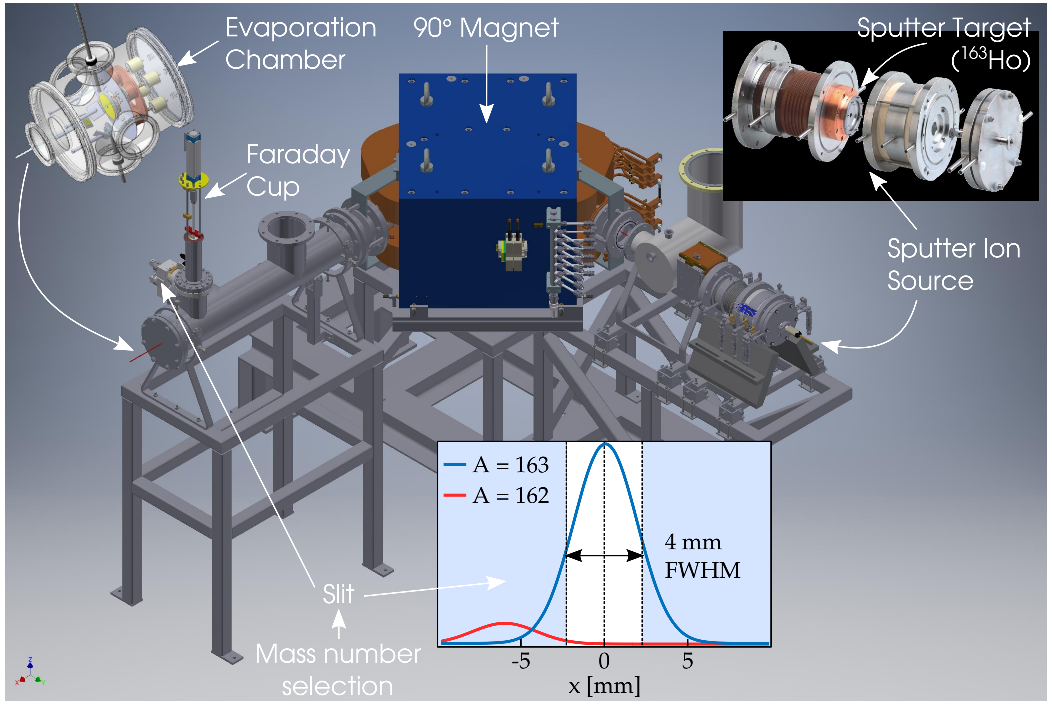
ECHo

CERN
India Slovakia
Hungary Russia

 [Cryogenic Particle Detection, (ed. C. Enss), Topics Appl. Phys. 99 (Springer, 2005)]

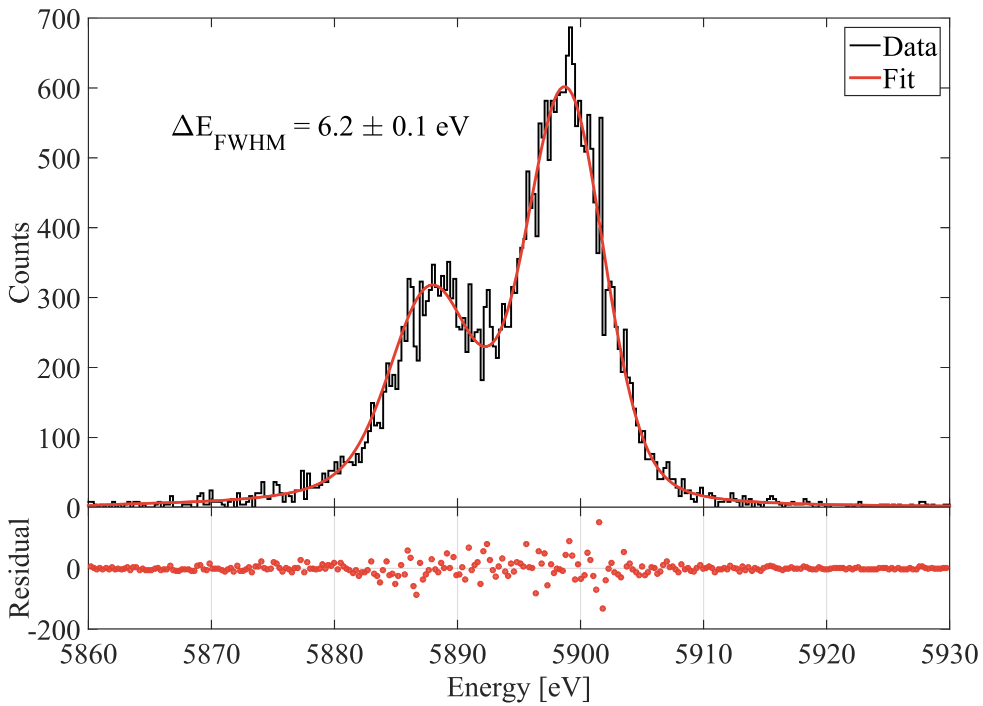
TES technology: HOLMES





Custom mass-separator ion implanter at Genova

Mn K$\alpha_{1,2}$ lines at ~5 eV resolution, τ_{rise}~ few µs



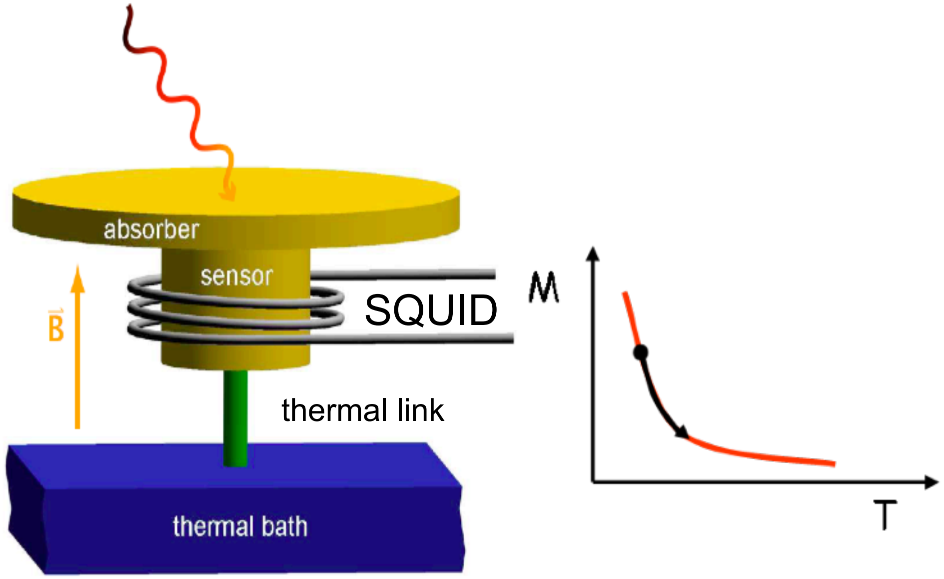
HOLMES design & timeline:

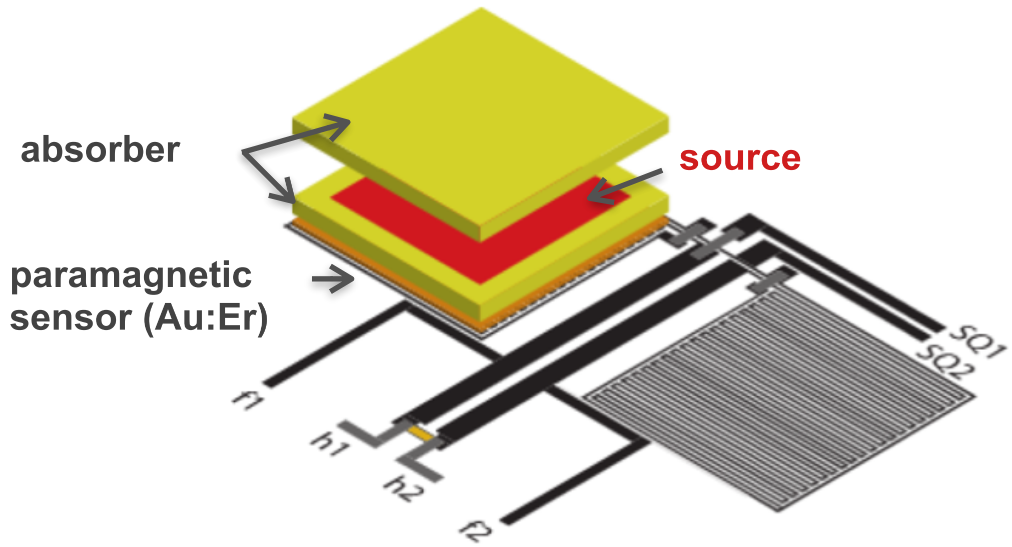
- 6.5 x 10^{13} nuclei ^{163}Ho (~300 Bq) per pixel
- ΔE ~ 1 eV, τ_{rise}~ 1 µs;
  1000-pix array (**1 eV goal**) expected for 2018
- TES array + DAQ ready, first implant. coming up
- Spectrum measurements in preparation
- **32 pixels for 1 month → m_ν sensitivity ~10 eV**

[A. Giachero et al., JINST 12 (2017) C02046] [M. de Gerone, TAUP 2017]

MMC technology: ECHo

Metallic **M**agnetic **C**alorimeters (**MMC**) with paramagnetic Au:Er sensor read out by SQUID





δT in absorber from EC-decay

⇨ change in magnetization M of sensor

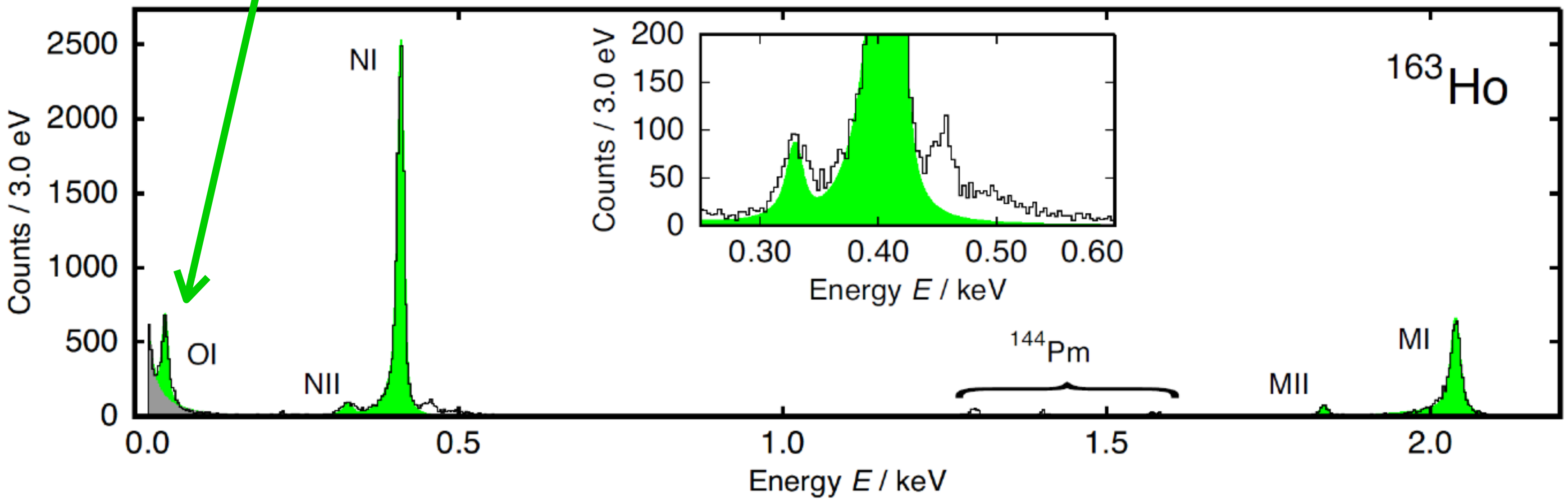
signal: $$\delta\Phi_S \sim \frac{\partial M}{\partial T}\cdot\Delta T \sim \frac{\partial M}{\partial T}\cdot\frac{1}{C_{tot}}\cdot\delta E$$

- Fast rise time (~130 ns) and excellent linearity & resolution (ΔE_{FWHM} < 5 eV)
- Multiplexed readout of MMC arrays

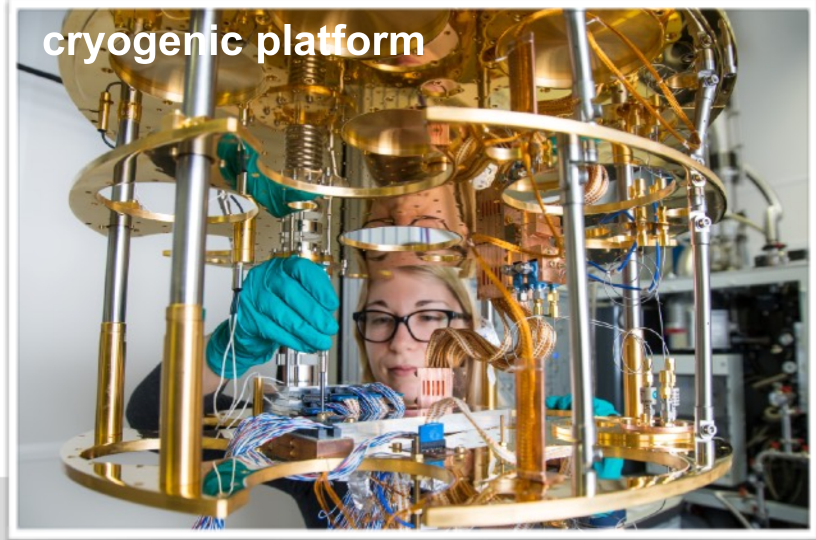
 [A. Fleischmann et al., *AIP Conf. Proc.* 1185, 571, (2009)] [Gastaldo *et al.* (2014)]

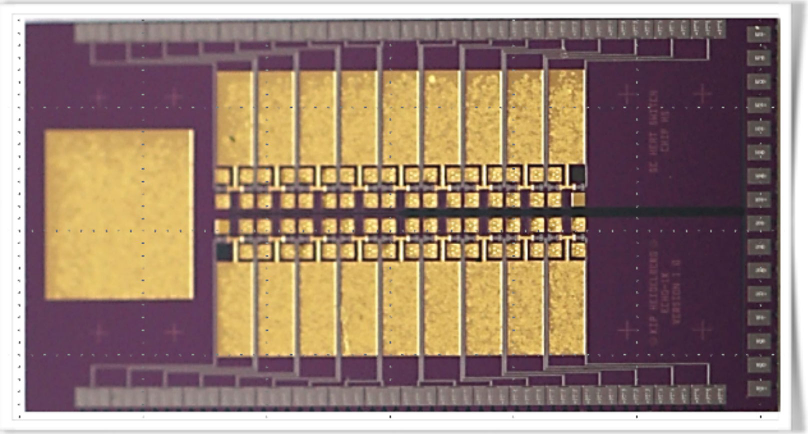
MMC technology: ECHo

Precision ^{163}Ho spectrum
first calorimetric measurement of OI-line



Ranitzsch *et al.*, PRL 119 (2017) 122501





64-pix detectors optimized for implantation

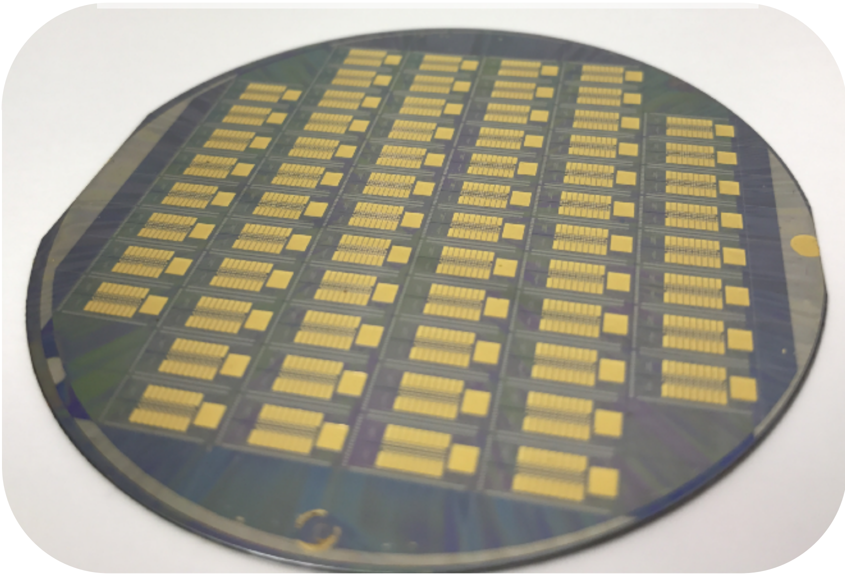
microwave SQUID multiplexing readout

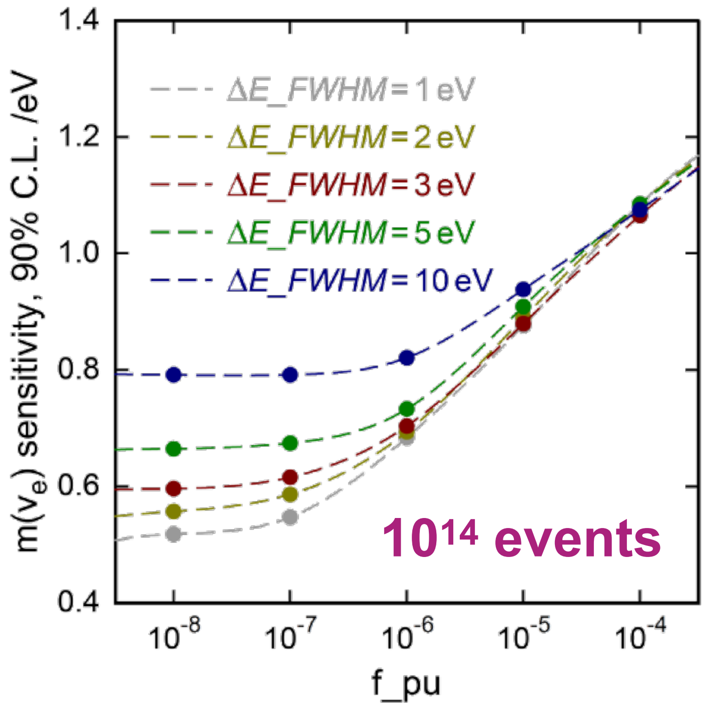
ECHo line

- **ECHo-1k** (2015-2018, taking data now)
  - prove scalability with medium-sized array: 100 detectors x 10 Bq
  - 1 yr meas. time for $N_{event} \sim 10^{10}$:
    ➜ $m(\nu_e) < 10$ eV

- Next step: **ECHo-1M**
  - large-scale experiment for sub-eV sensitivity
    100 arrays of 1000 detectors, at 10 Bq each

3" wafer with 64 ECHo-1k chips





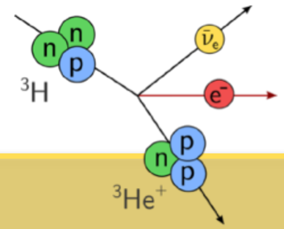
[courtesy L. Gastaldo]

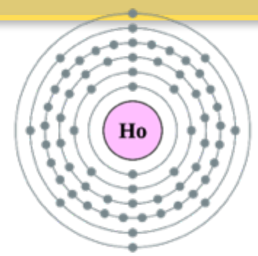
[The ECHo Collaboration, EPJ-ST 226 8 (2017) 1623]

Direct ν-mass determination: status and outlook

Karlsruhe Institute of Technology

current achievements		next goals
Start of T_2 data in 2018 after extensive commissioning program	**KATRIN**	Long-term data-taking (5 yrs) for full sensitivity **(0.2 eV)**
CRES proof of principle with ^{83m}Kr, testing new cell for T_2	**Project 8**	Develop CRES for **10 → 2 eV,** and towards IH (atomic source)
R&D for atomic source concept, MAC-E + calorimeter	**PTOLEMY**	Devise large-scale experiment to tackle m(ν) and CνB





ECHo
HOLMES

Current achievements:

- Advanced detector development (MMC and TES technologies)
- Test of scalable arrays, readout
- High-purity ^{163}Ho production and implantation

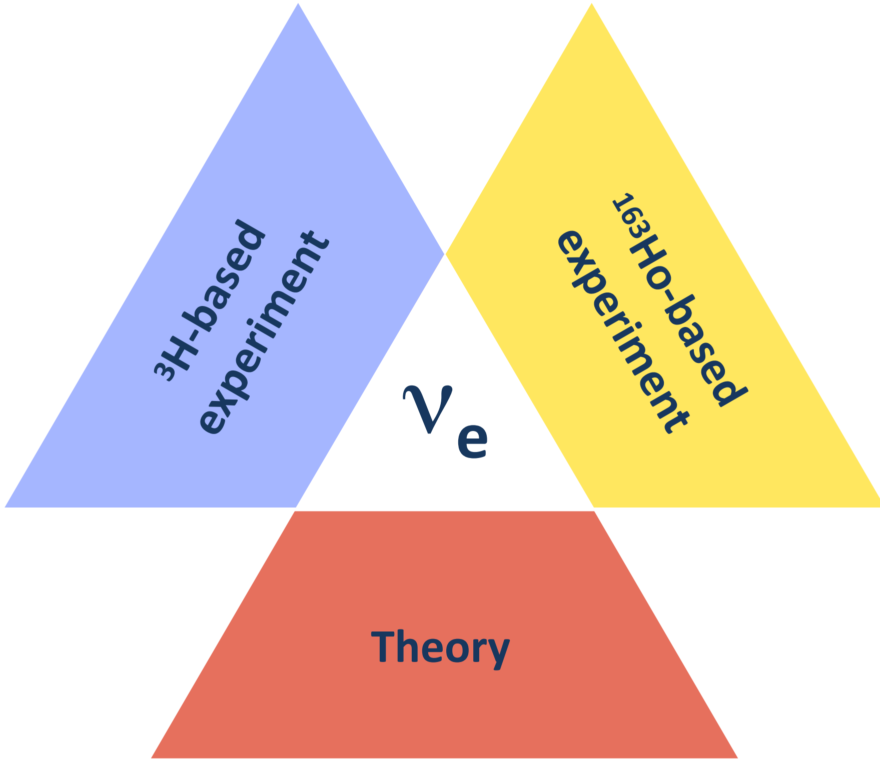
Next goals:

- Operate medium-size arrays (~10^{10} counts) for **10 eV** sens.
- Prepare large arrays (~10^{14} counts) for **sub-eV** sens.

Direct ν-mass determination: strong activities in experiment and theory!

Karlsruhe Institute of Technology

Workshop at ECT*, Trento, March 2018

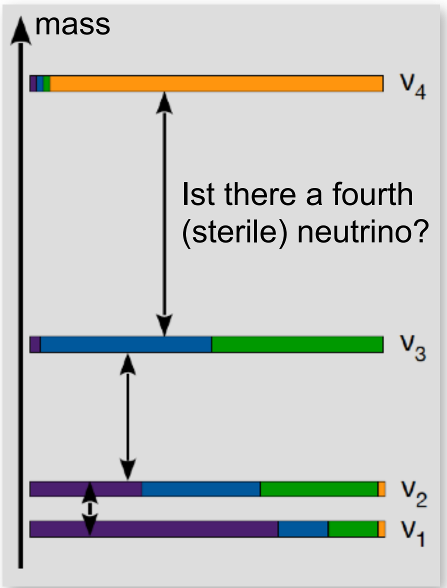


Summary / Take-away

More physics questions for direct kinematic experiments

Examples:

- How many neutrino states are there?



- Do neutrinos participate in novel (exotic) forms of interaction?

left-right symmetric model

right-handed charged currents

non- V—A interactions

Imprint of sterile neutrinos on β spectrum

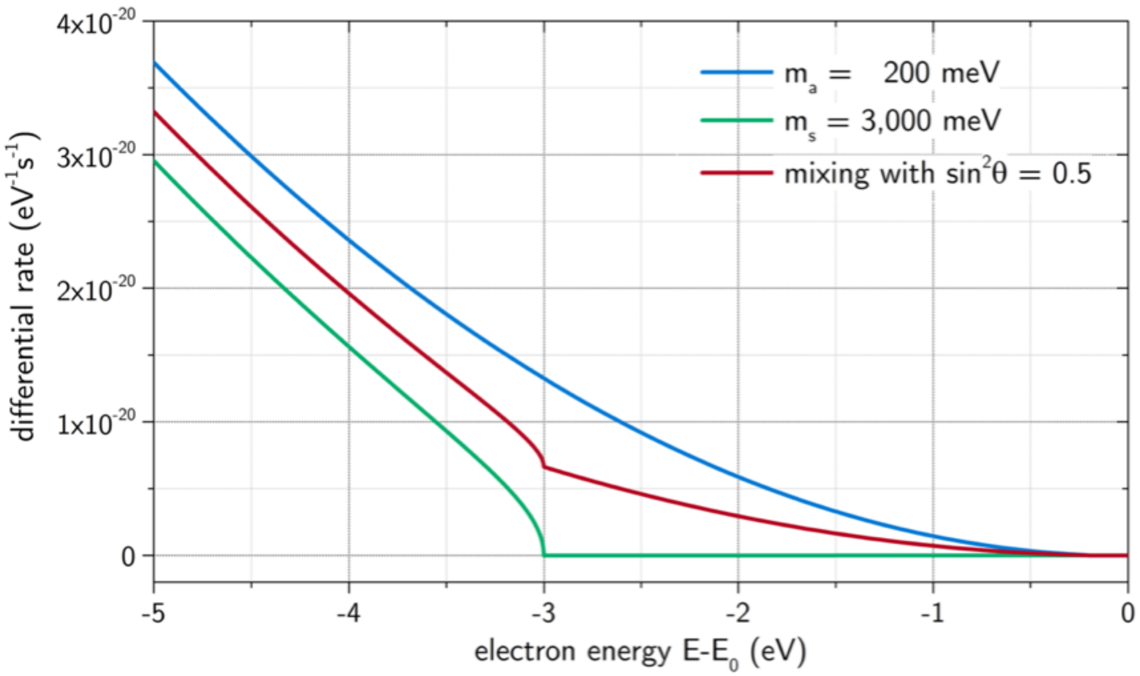
Karlsruhe Institute of Technology

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

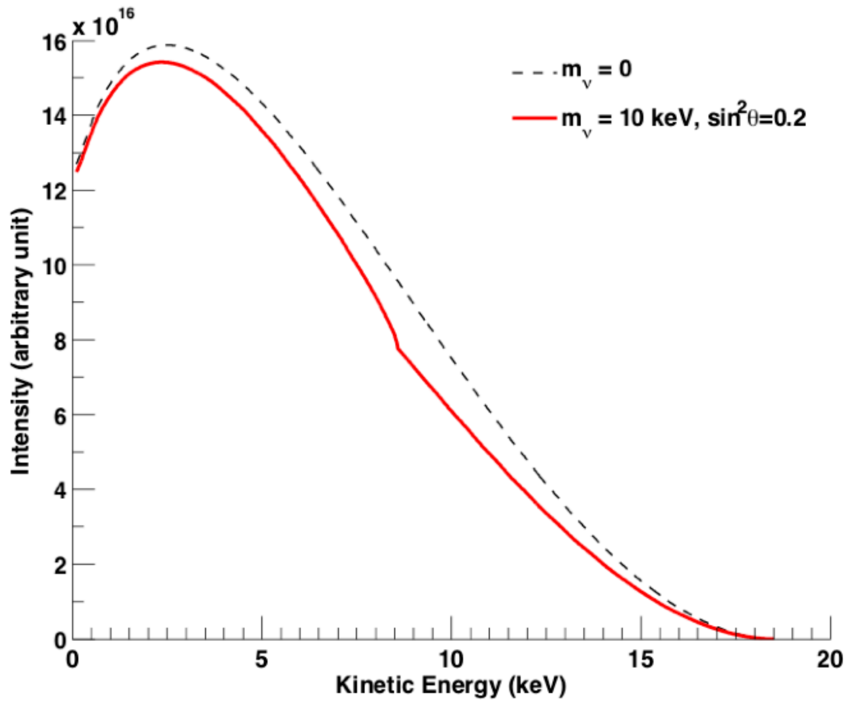
$$\frac{\mathrm{d}N}{\mathrm{d}E} = \boxed{\cos^2\theta_s \frac{\mathrm{d}N}{\mathrm{d}E}(m_a^2)} + \boxed{\sin^2\theta_s \frac{\mathrm{d}N}{\mathrm{d}E}(m_s^2)}$$

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

light sterile ν, m_s = 3 eV



keV sterile ν, m_s = 10 keV



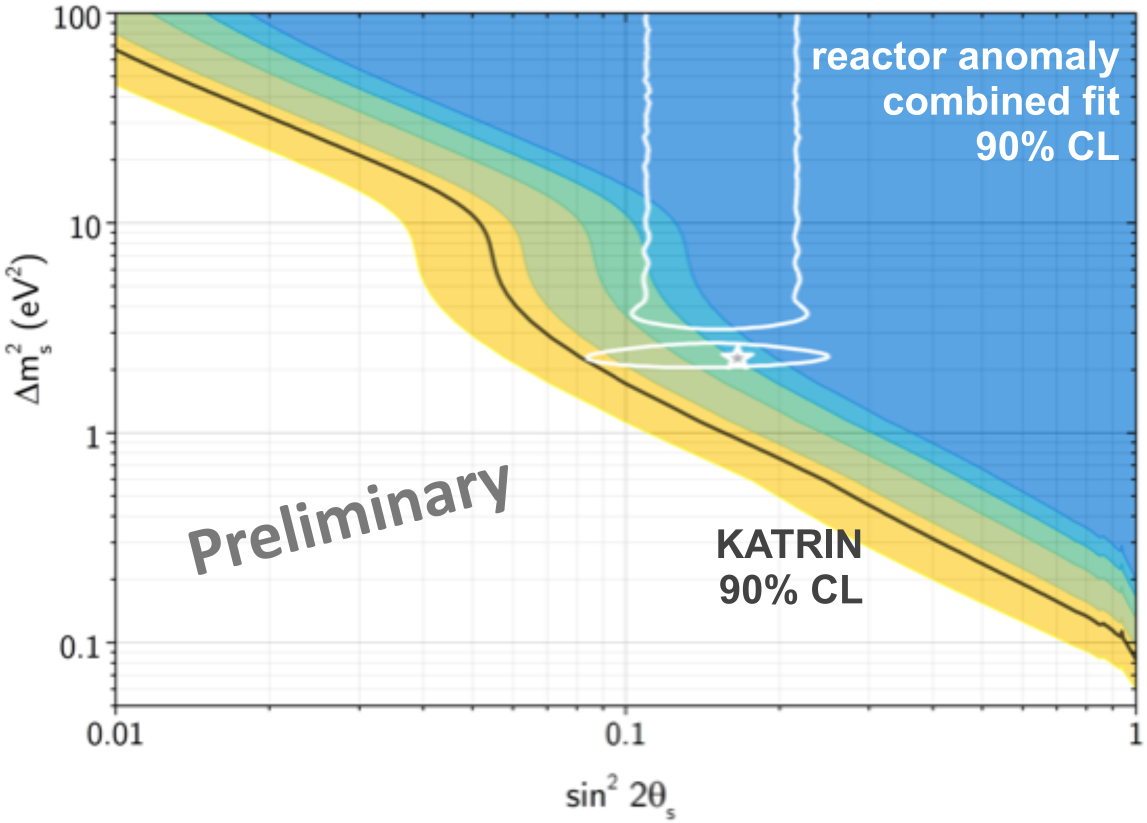
Can we detect heavy neutrino states in a direct mass measurement?

Karlsruhe Institute of Technology

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

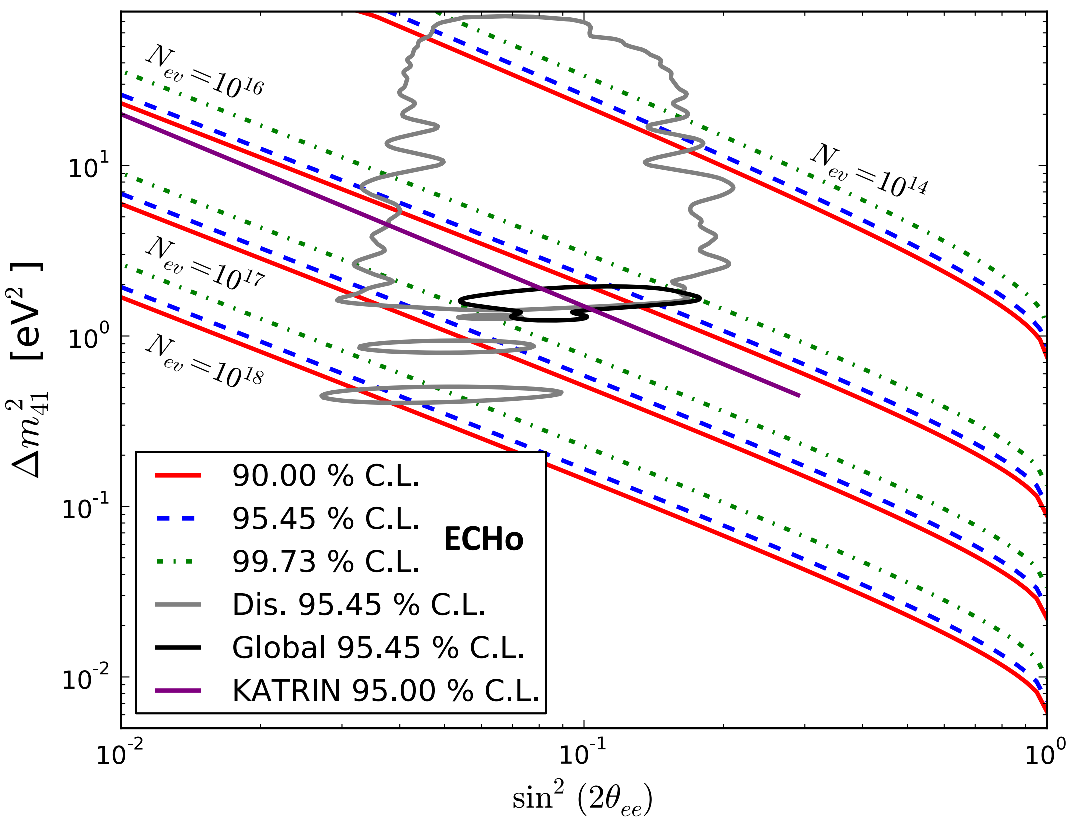
light sterile neutrinos

Tritium: KATRIN



[M. Kleesiek, PhD thesis, KIT, 2014]

Holmium: ECHo

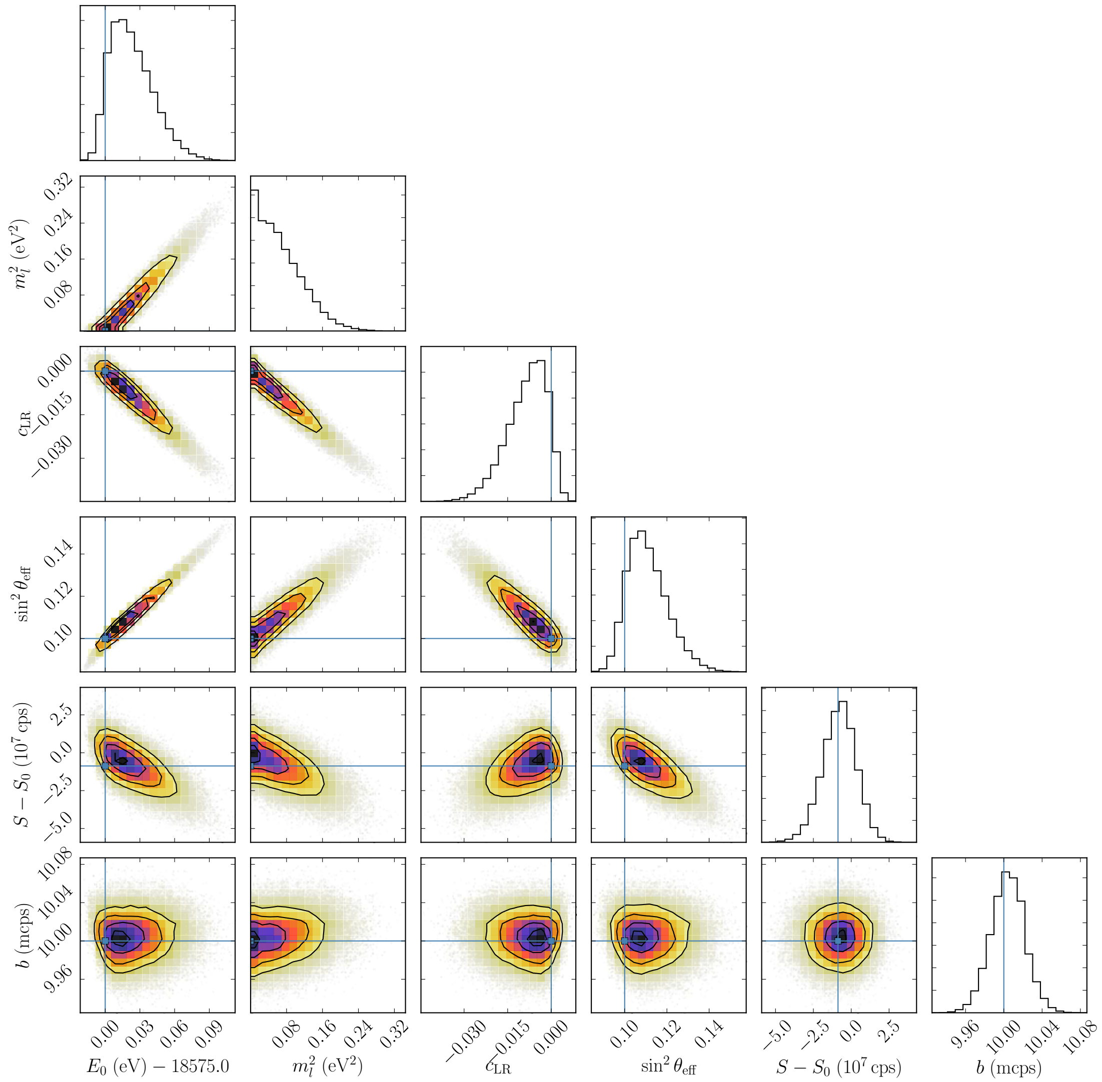


[L. Gastaldo *et al.*, JHEP 06 (2016) 061]

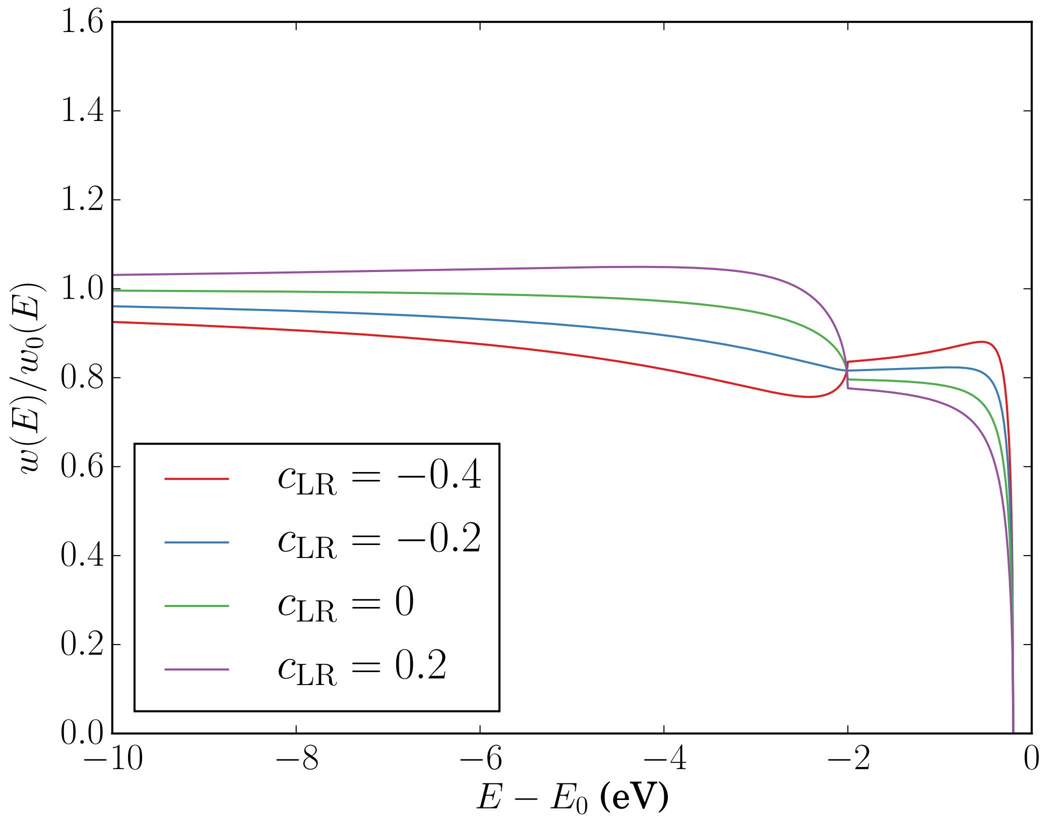
Can we detect heavy neutrino states in a direct mass measurement?

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

light sterile neutrinos
+ novel interactions



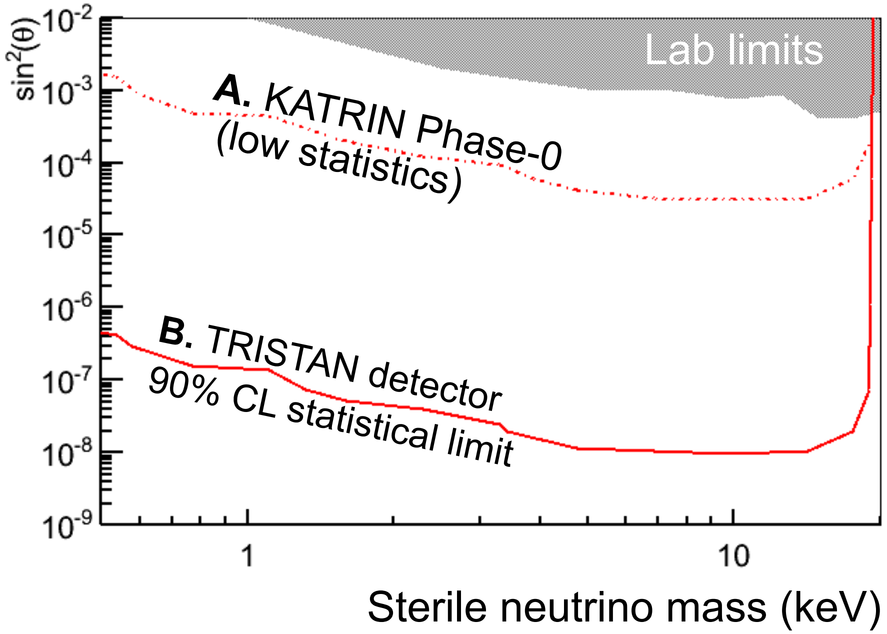
Spectral shape distortion close to E_0 due to interference term in left-right symmetric model



[Steinbrink *et al.*, **JCAP 06 (2017) 015**]

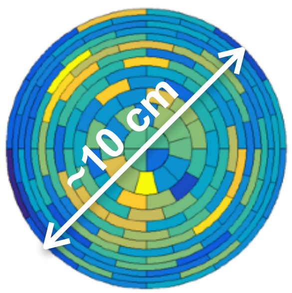
Search for keV-scale sterile ν with TRISTAN at KATRIN

- High count rates at ~few keV below endpoint
- Tiny sterile admixture $\sin^2(\theta_s)$ expected
- Best sensitivity for differential measurement at resolution ~300 eV



A. KATRIN Phase-0

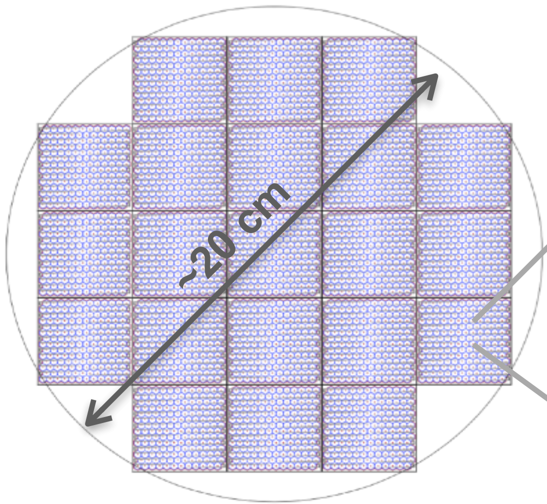
initial ramp-up phase of KATRIN at reduced source strength



148 pixels
KATRIN 2018

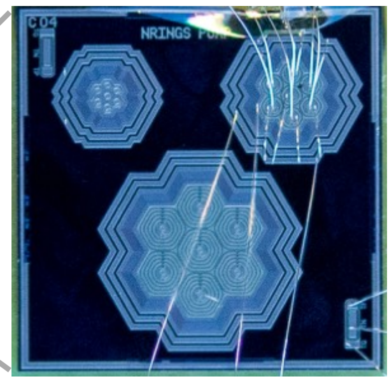
B. TRISTAN project

detector upgrade after completion of 5-year KATRIN running



~ 3500 pixels
KATRIN ca. 2024

7-pixel SDD prototype
(MPP/HLL Munich)

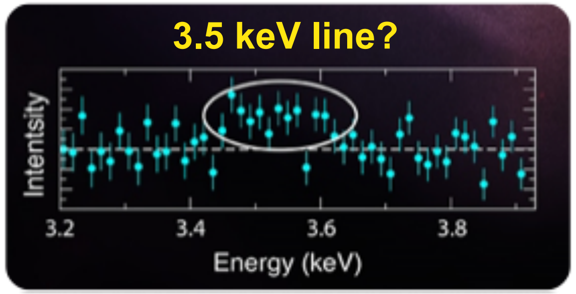


test run at Troitsk
summer 2017

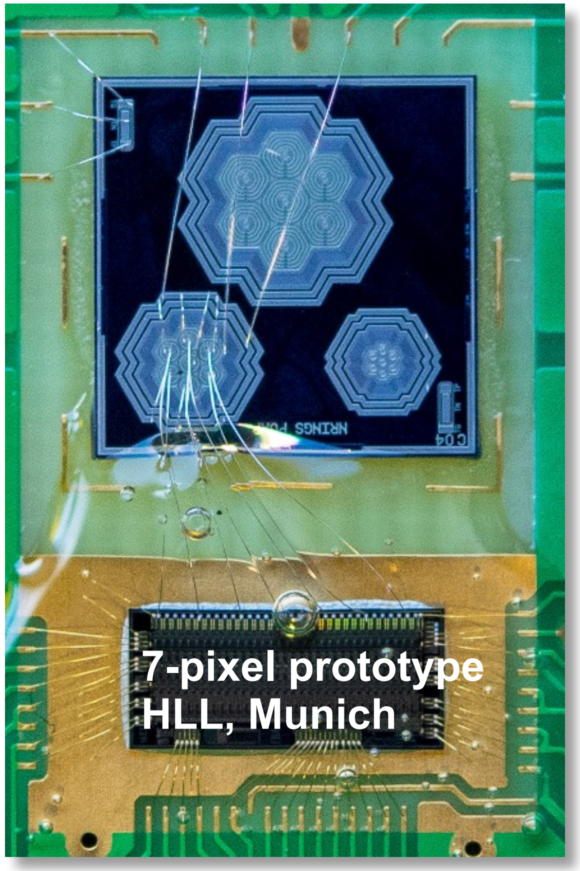
+ further technology options developed at KIT-IPE

Can we detect heavy neutrino states in a direct mass measurement?

Karlsruhe Institute of Technology

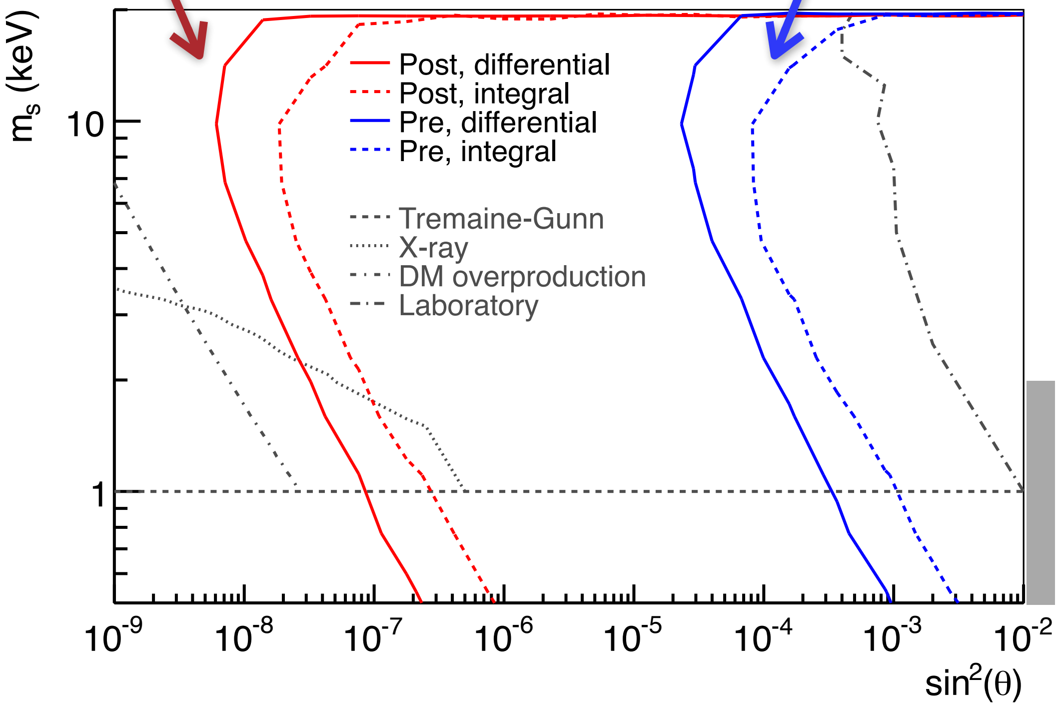


- … **further away from E_0:**
  search for keV-scale sterile ν as WDM candidates



novel concepts required

first tritium data at reduced source strength of KATRIN



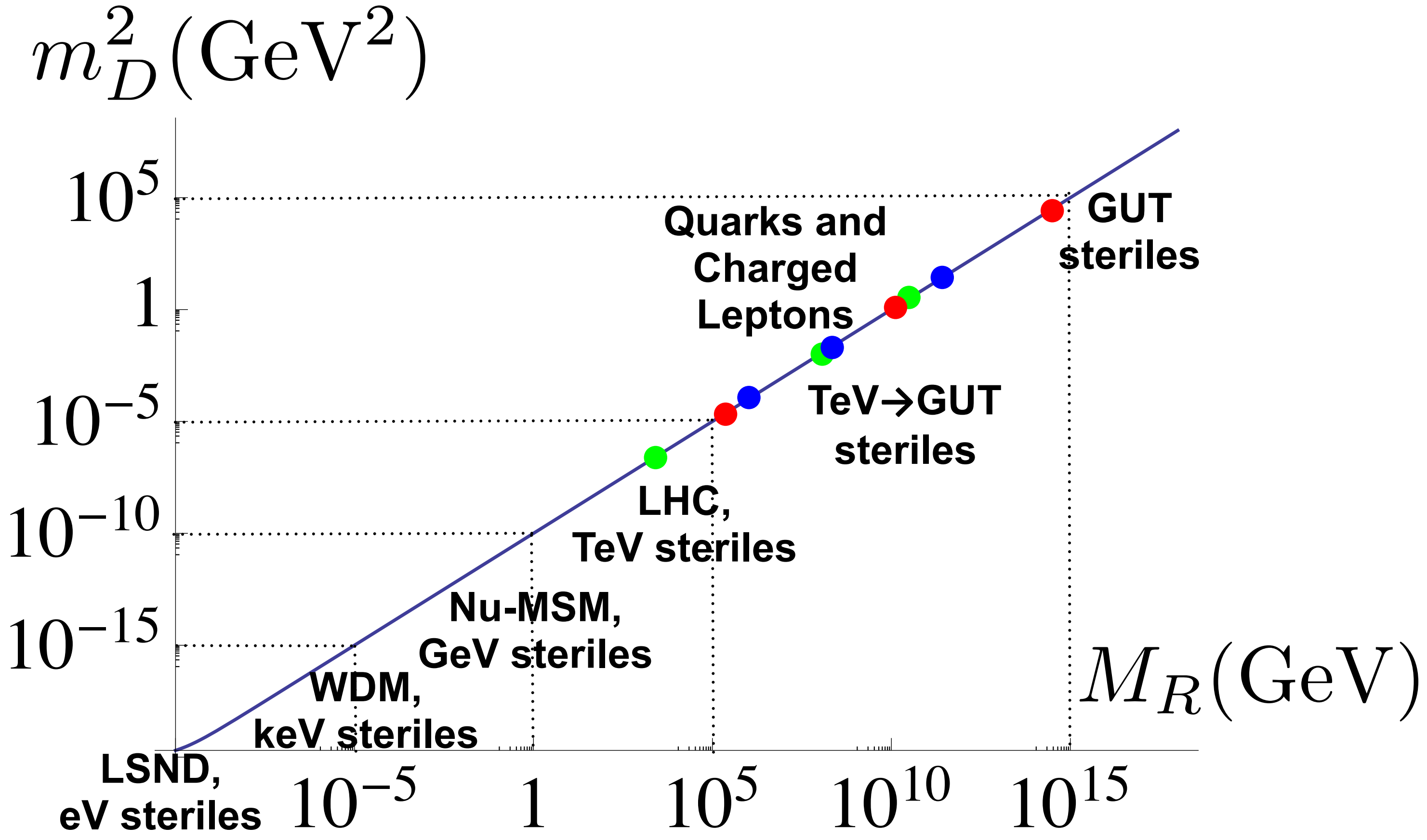
see: recent result of Troitsk nu-mass exp. [Abdurashitov *et al.*, JETP Lett. 105 (2017) 753]

KeV sterile neutrino white paper [Adhikari *et al.*, JCAP 01 (2017) 025]

Right-handed heavy neutrino states

Required values of m_D^2 to obtain small neutrino masses m_ν ~ 10^{-10} GeV via seesaw mechanism:

$$m_\nu \approx \frac{m_D^2}{M_R}$$



Well motivated extension of SM