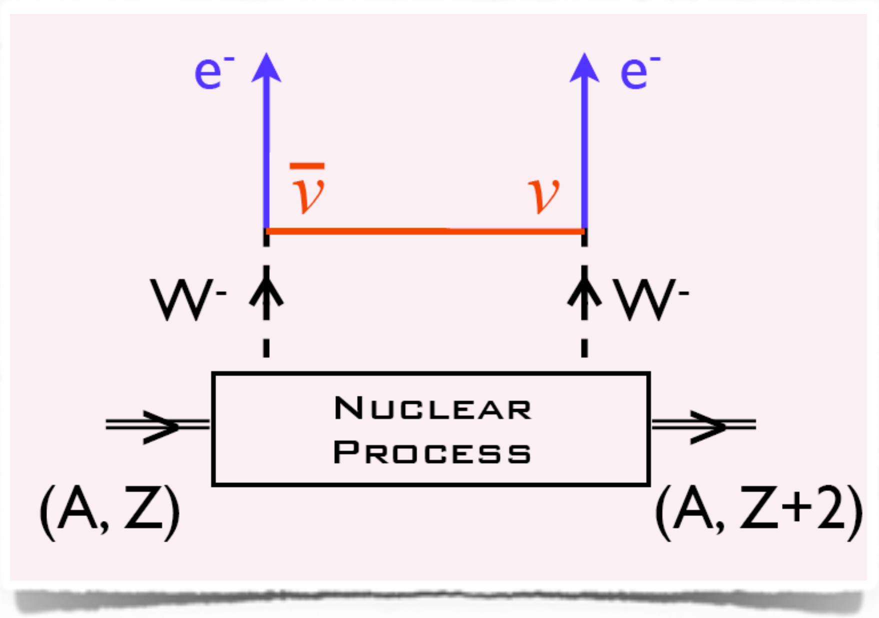
Probing ν mass with lab experiments:

Search for neutrinoless double beta decay



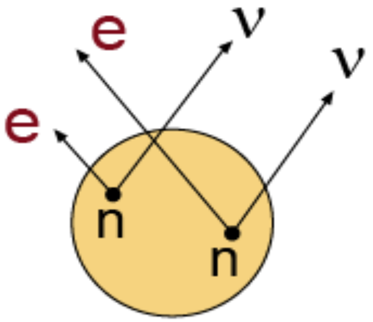
Double β-decay: 2νββ & 0νββ modes

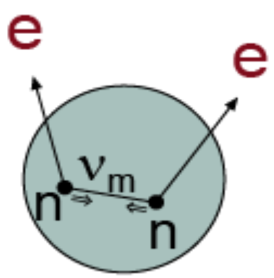
2nd-order weak interaction processes:

- extremely long half-lives: $T_{1/2} \sim 10^{18 \dots 21}$ years for 2νββ, > 10^{25} years for 0νββ
- 2νββ observed in 13 isotopes (first: $\beta^-\beta^-$ in ^{82}Se; recent: double EC in ^{130}Ba, ^{87}Kr)
- 0νββ **not** observed so far

2νββ

$$(Z,A) \rightarrow (Z+2,A) + e_1^- + e_2^- + \bar{\nu}_{e,1} + \bar{\nu}_{e,2}$$



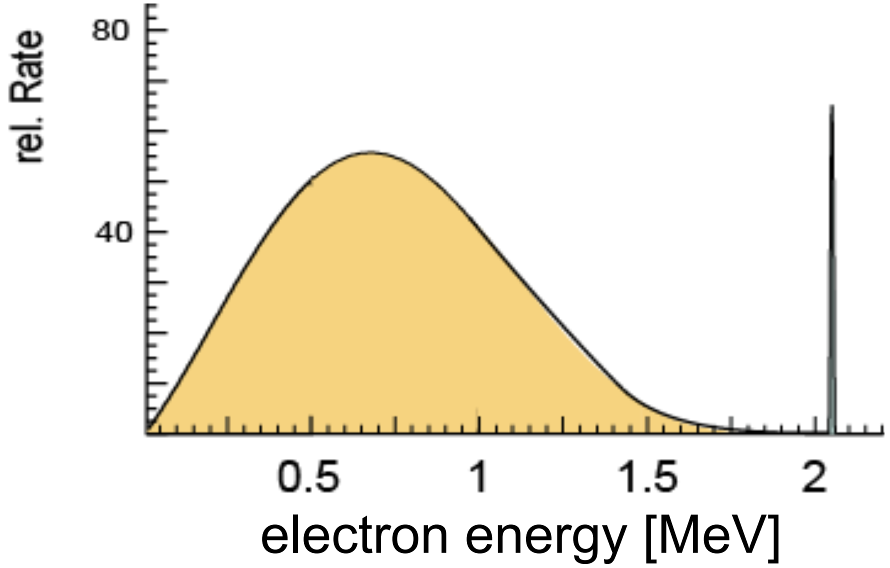


0νββ

$$(Z,A) \rightarrow (Z+2,A) + e_1^- + e_2^-$$

first description:

M. Goeppert-Mayer (1935)



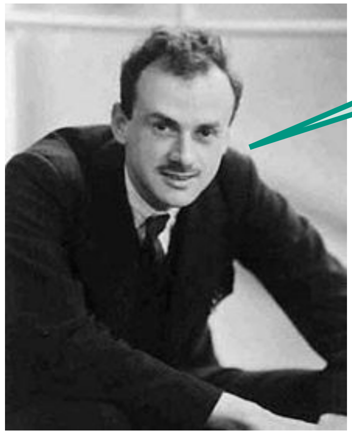
first description:

G. Racah (1937) E. Majorana

Why study $0\nu\beta\beta$? — If observed, …

- … lepton number violation ($\Delta L = 2$) offers promising scenarios for baryogenesis.
  ➜ *Independent of underlying physics: "Matter-creating" process in the lab.*
- … the neutrino nature will be determined as Majorana type.
  ➜ *Seesaw mechanisms can explain the smallness of neutrino masses.*
- … we can learn about the neutrino mass scale from the observed half-life
  ➜ *"Black-box" theorem: Regardless of decay operator, always get a Majorana ν mass.*

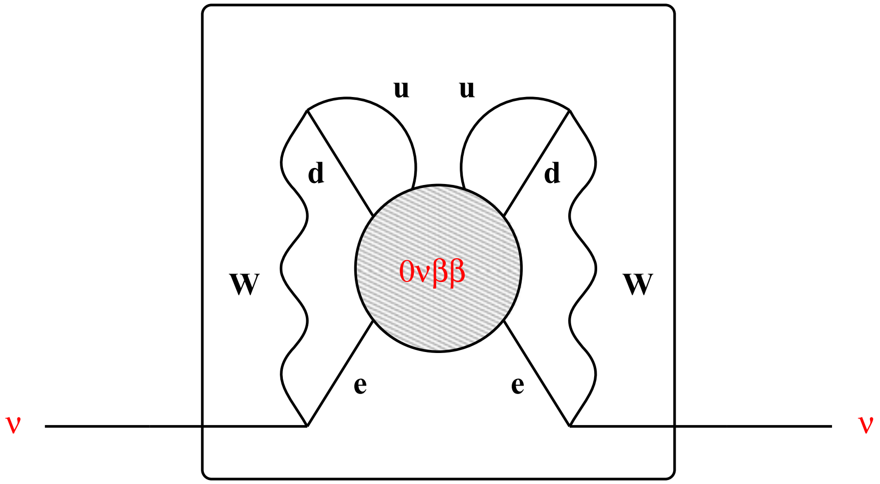
Particle and antiparticle are fundamentally different!



Paul A. M. Dirac

Particle and antiparticle in essence are the same!

Ettore Majorana



0νββ & Majorana mass $m_{\beta\beta}$

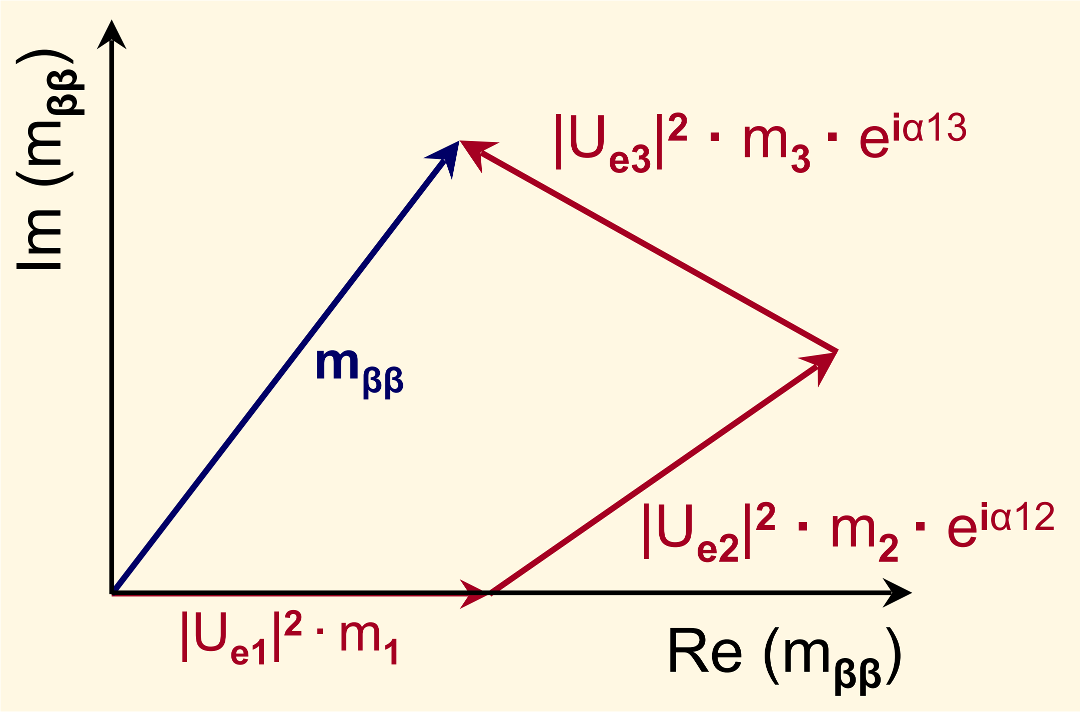
$m_{\beta\beta}$ is the **coherent** sum over mass eigenstates m_1, m_2, m_3:

$$\langle m_{\beta\beta}\rangle = \left|\sum_{j=1}^{3} |U_{ej}|^2\, m_j\, e^{i\alpha_j}\right|$$

2 independent Majorana CP-phases α_i

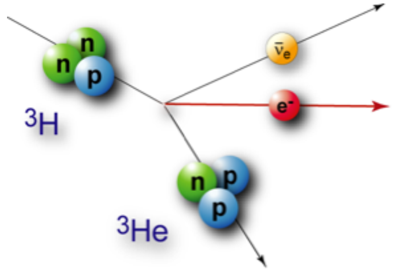
↳ cancellations are possible

if $\alpha_i \neq n \cdot \pi$ ➜ CP violation



by contrast: **m_β** in single β decay is formed by **incoherent** sum (no cancellations):

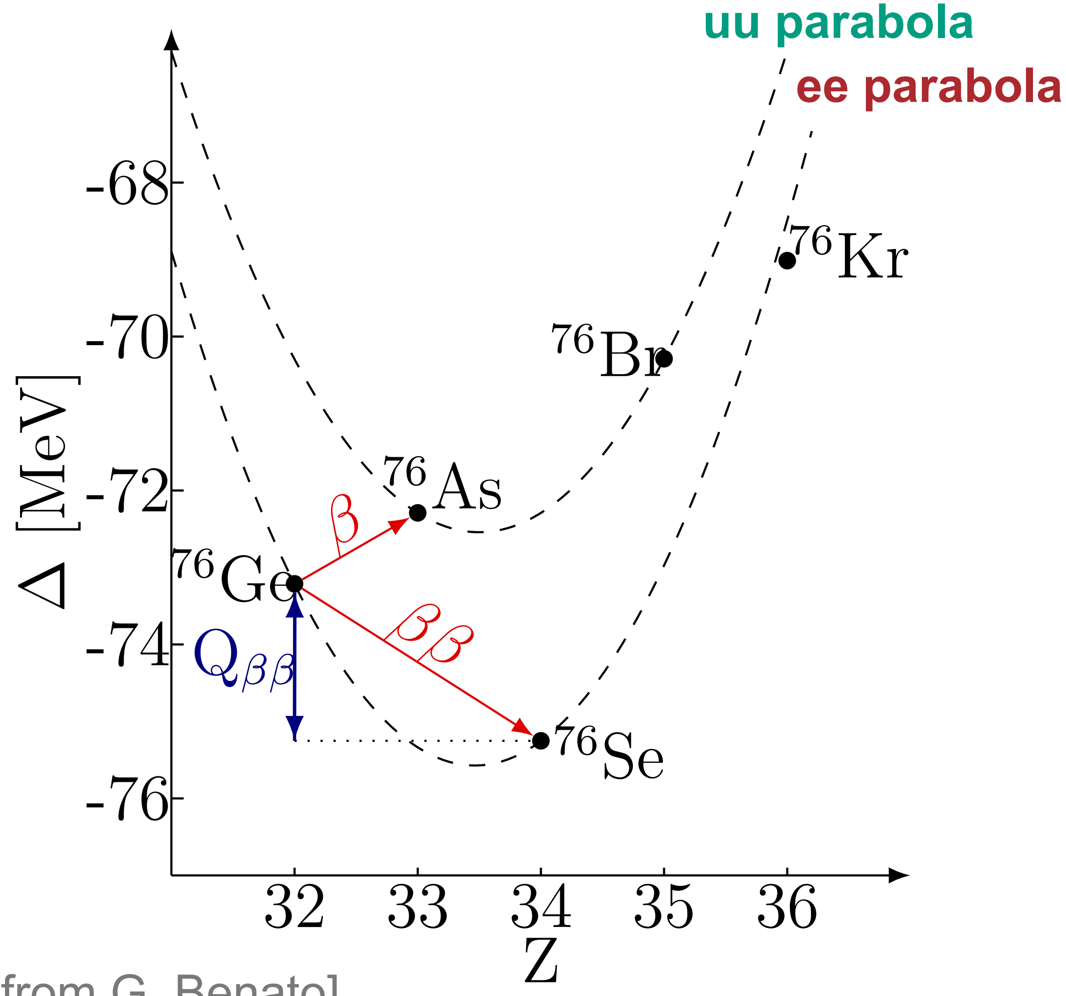
$$m_\beta = \sqrt{\sum_{i=1}^{3} |U_{ei}^2|\, m_i^2}$$



Double beta decay: candidate nuclides

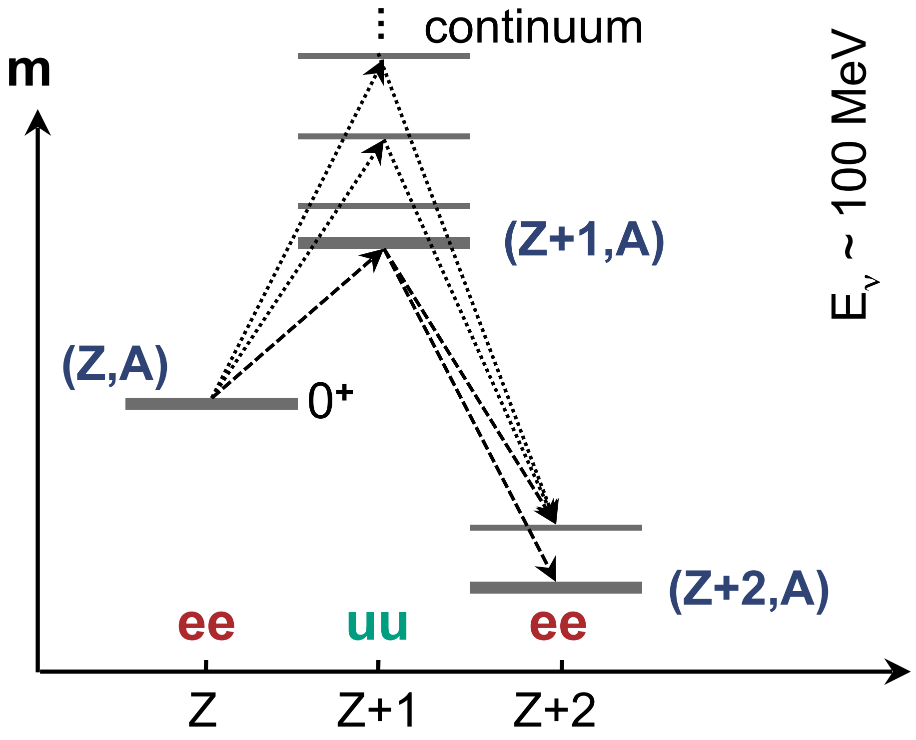
Bethe-Weizsäcker mass formula: pairing term difference in isobars with even mass

mass parabolas for A=76 isobars:



[from G. Benato]

virtual intermediate states (Z+1,A)



Double beta decay: candidate nuclides

- 35 naturally occurring nuclides capable of undergoing double beta decay
- Decay rate for $0\nu\beta\beta$ scales as **~Q^5** ; also: copious **backgrounds** below ~2.6 MeV

11 nuclei for $2\nu\beta^-\beta^-$ at Q > 2 MeV:

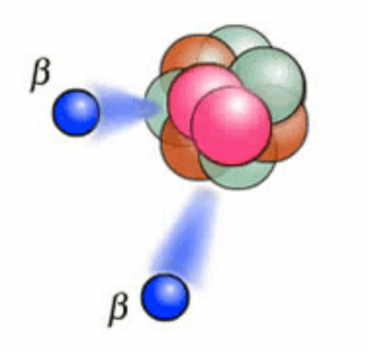
$\beta^-\beta^-$ decay	Q [MeV]	nat. [%]
$^{48}\mathrm{Ca} \rightarrow {}^{48}\mathrm{Ti}$	4,274	0,187
$^{76}\mathrm{Ge} \rightarrow {}^{76}\mathrm{Se}$	2,039	7,8
$^{82}\mathrm{Se} \rightarrow {}^{82}\mathrm{Kr}$	2,995	9,2
$^{96}\mathrm{Zr} \rightarrow {}^{96}\mathrm{Mo}$	3,348	2,8
$^{100}\mathrm{Mo} \rightarrow {}^{100}\mathrm{Ru}$	3,034	9,6
$^{110}\mathrm{Pd} \rightarrow {}^{110}\mathrm{Cd}$	2,004	11,8
$^{116}\mathrm{Cd} \rightarrow {}^{116}\mathrm{Sn}$	2,809	7,5
$^{124}\mathrm{Sn} \rightarrow {}^{124}\mathrm{Te}$	2,288	5,64
$^{130}\mathrm{Te} \rightarrow {}^{130}\mathrm{Xe}$	2,527	34,5
$^{136}\mathrm{Xe} \rightarrow {}^{136}\mathrm{Ba}$	2,458	8,9
$^{150}\mathrm{Nd} \rightarrow {}^{150}\mathrm{Sm}$	3,368	5,6

6 nuclei for $2\nu\beta^+\beta^+$/EC at lower Q:

$\beta^+\beta^+$ decay	Q [MeV]	nat. [%]
$^{78}\mathrm{Kr} \rightarrow {}^{78}\mathrm{Se}$	***0,838***	0,35
$^{96}\mathrm{Ru} \rightarrow {}^{96}\mathrm{Mo}$	***0,676***	5,5
$^{106}\mathrm{Cd} \rightarrow {}^{106}\mathrm{Pd}$	***0,738***	1,25
$^{124}\mathrm{Xe} \rightarrow {}^{124}\mathrm{Te}$	***0,822***	0,10
$^{130}\mathrm{Ba} \rightarrow {}^{130}\mathrm{Xe}$	***0,534***	0,11
$^{136}\mathrm{Ce} \rightarrow {}^{136}\mathrm{Ba}$	***0,362***	0,19

➜ even longer expected $T_{1/2}$

Double β-decay & Majorana mass $m_{\beta\beta}$



$$\boxed{\left\langle m_{\beta\beta}\right\rangle^2 = \left(T_{1/2}^{0\nu\beta\beta}\cdot G^{0\nu\beta\beta}(E_0,Z)\cdot\left| M_{GT}^{0\nu\beta\beta} - \frac{g_V^2}{g_A^2} M_F^{0\nu\beta\beta}\right|^2\right)^{-1}}$$

experimental value of 0νββ **half-life**

phase space factor

Gamov-Teller and Fermi **nuclear matrix elements**

- **experimental observable: $T_{½}$**
  ⇳ 0νββ event number depending on measuring time, number of target nuclei, experimental efficiency, background
- **weak interaction (phase space factor): $G^{0\nu\beta\beta}$**
  ⇳ determined by ββ-endpoint energy; strong dependence $\sim Q^5$
- **nuclear physics (matrix elements): $M^{0\nu\beta\beta}$**
  ⇳ shell model calculations, difficult to reduce large uncertainties

Sensitivity drivers

$$T^{0\nu}_{1/2}(\mathrm{FOM}) \propto a \cdot \epsilon \cdot \sqrt{\frac{M \cdot t}{b \cdot \Delta E}}$$

Requirements:

- Large isotopical abundance (***a***)
- High efficiency (***ϵ***)
- Large Mass (***M***)
- Long counting time (***t***)
- Low background (***b***)
- Good energy resolution (***ΔE***)

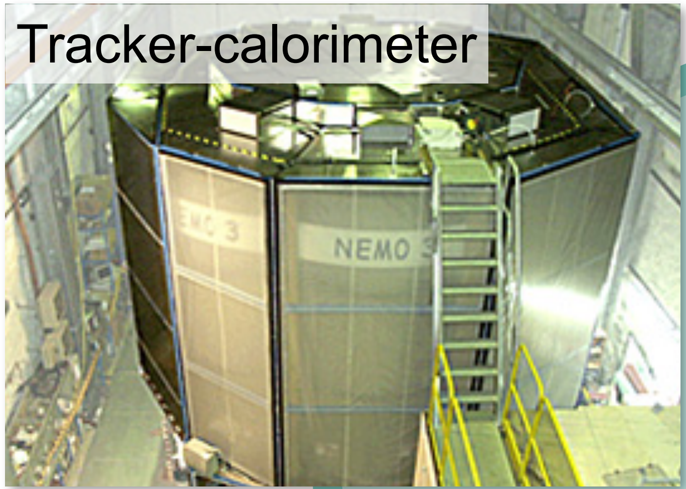
➜ Many suitable combinations for isotope + detector technology

➜ If ROI is background free: linear scaling with ***M*** and ***t*** !

$$T^{0\nu}_{1/2}(\mathrm{FOM}) \propto a \cdot \epsilon \cdot M \cdot t$$

Experimental techniques

Tracker-calorimeter

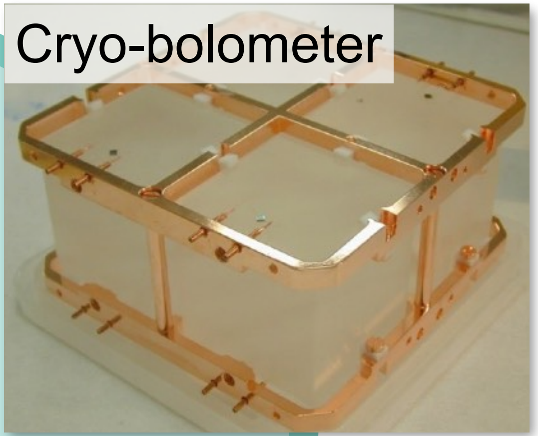


NEMO-3 -> Super-NEMO

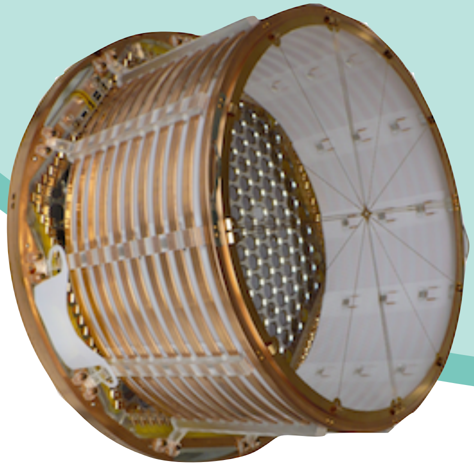
Ge diodes

GERDA, MAJORANA
-> LEGEND

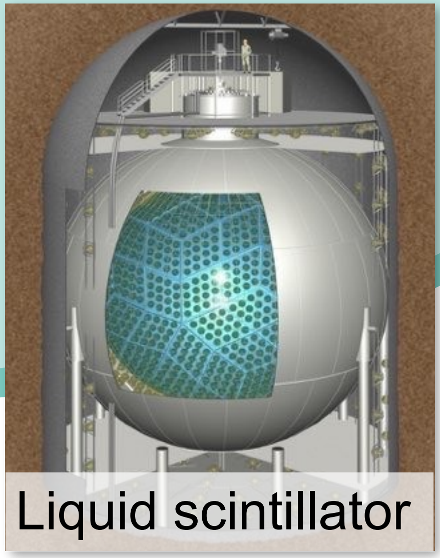
Cryo-bolometer



CUORE -> CUPID



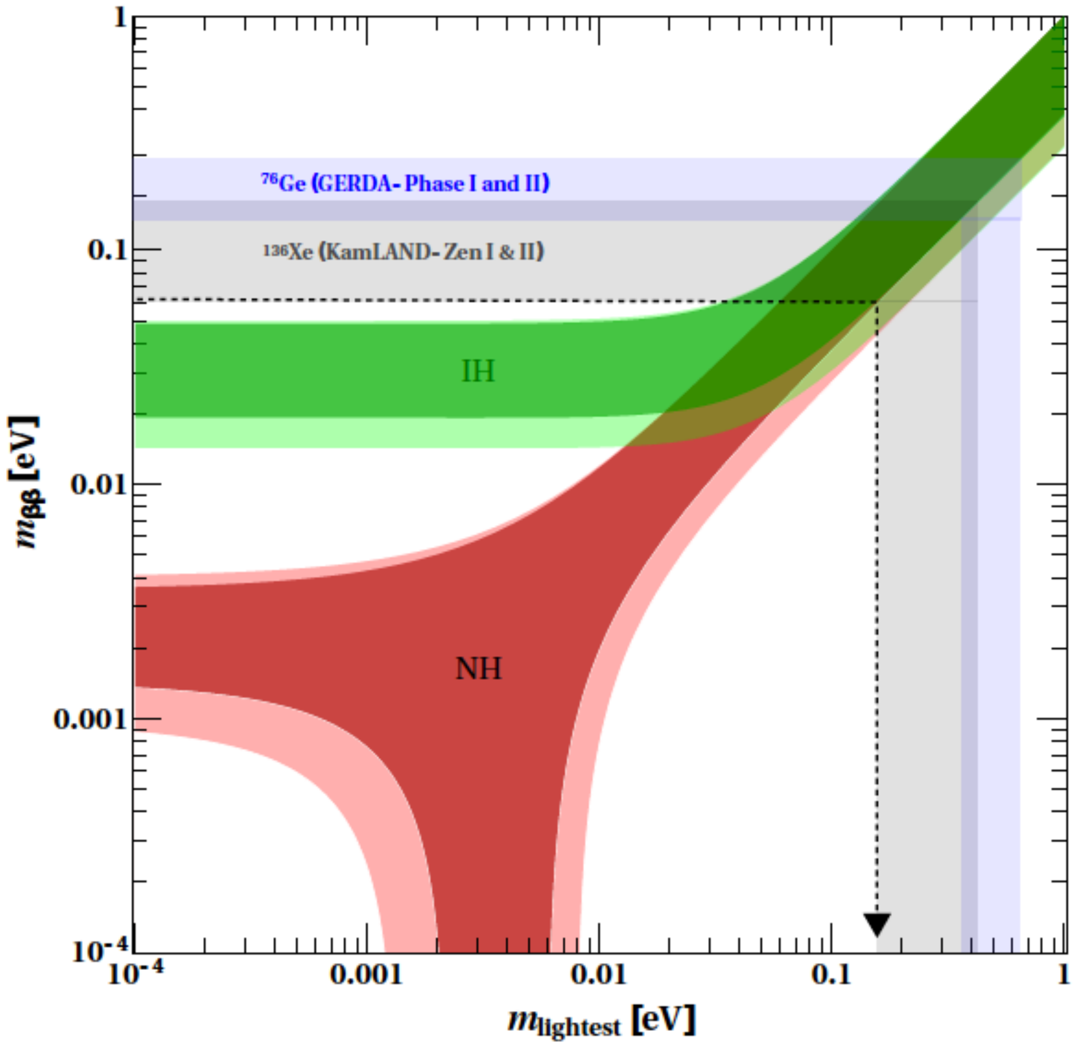
Noble element TPC
(liquid:) EXO-200 -> nEXO
(gas:) NEXT/ PANDA-X III



Liquid scintillator

KamLAND-Zen, SNO+

Current constraints



Most stringent bounds now approaching inverted hierarchy

Next generation has good discovery potential, even for normal hierarchy:

see

- Agostini, Benato, Detwiler, *PRD* 2017
- Caldwell, Merle, Schulz, Totzauer, *arXiv:1705.01945*
- Ge, Rodejohann, Zuber, *arXiv:1707.07904*

[from M. Agostini, Erice 2017; adapted from Dell'Oro *et al,* Adv. H. Energy Phys. 2016]

Germanium diodes: MAJORANA and GERDA

MAJORANA

Conventional design:

Vacuum cryostats in a *passive graded shield* with *ultra-clean materials*

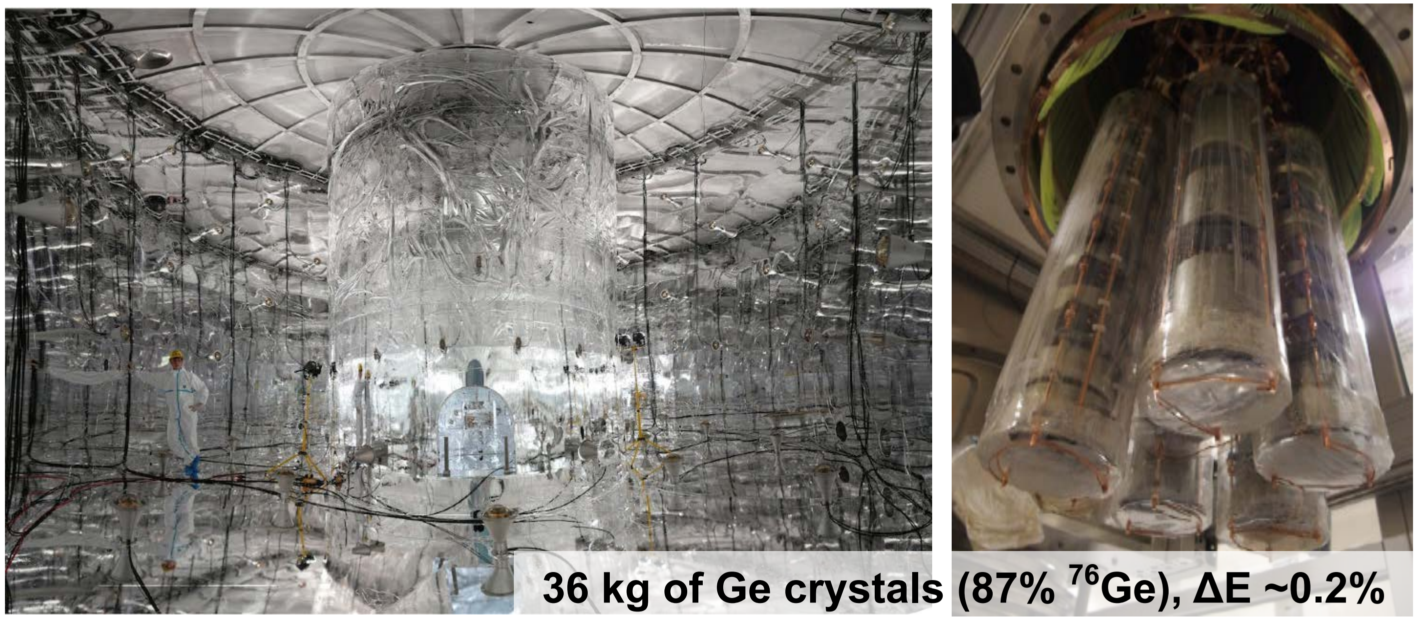
44 kg of Ge crystals (88% ^{76}Ge), ΔE ~0.1%

SURF (South Dakota, USA)

GERDA

Novel design:

Direct immersion in *active LAr shield*

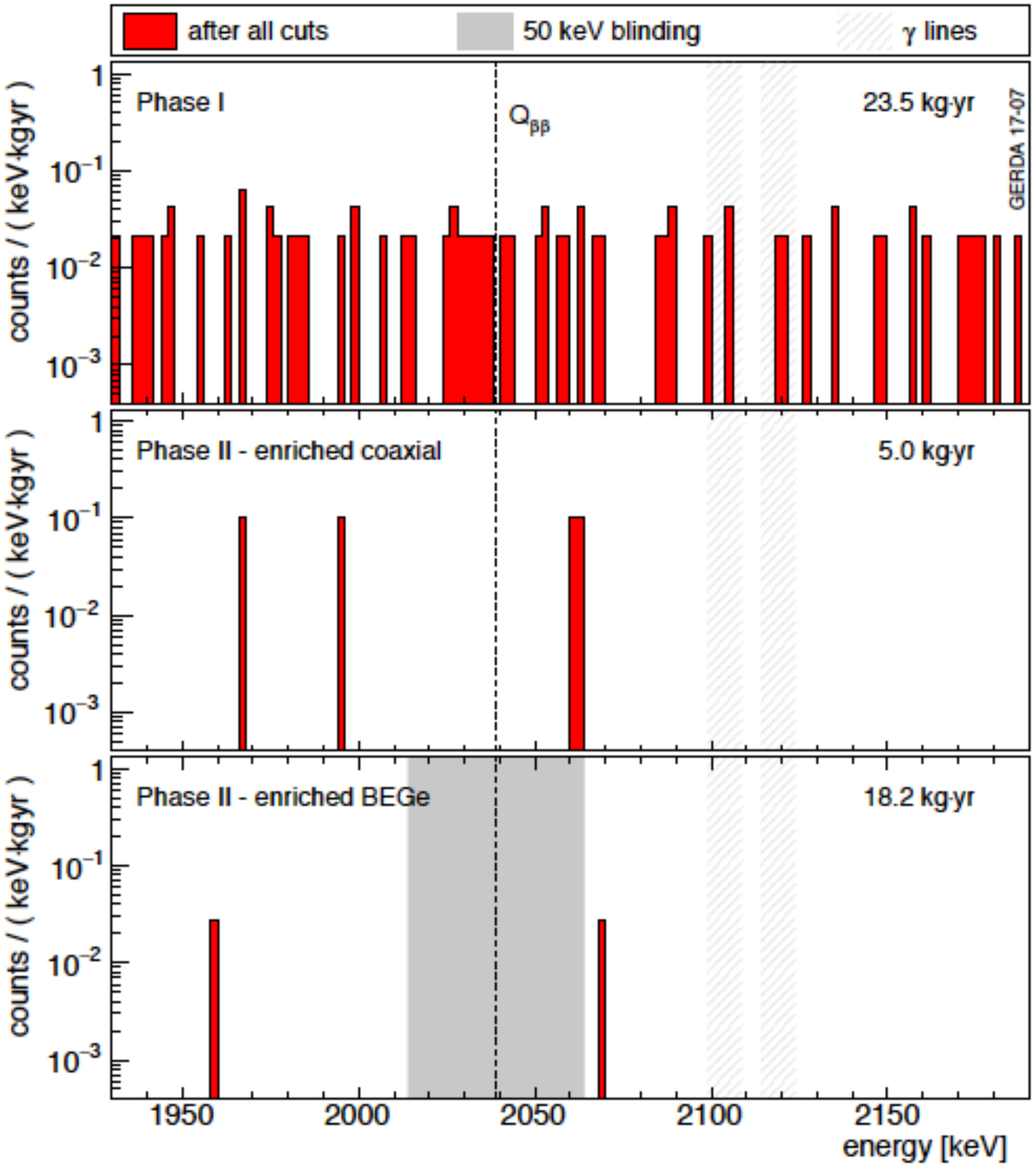


36 kg of Ge crystals (87% ^{76}Ge), ΔE ~0.2%

Gran Sasso (Italy)

Alan Poon (LBNL), Erice 2017

Germanium diodes: results



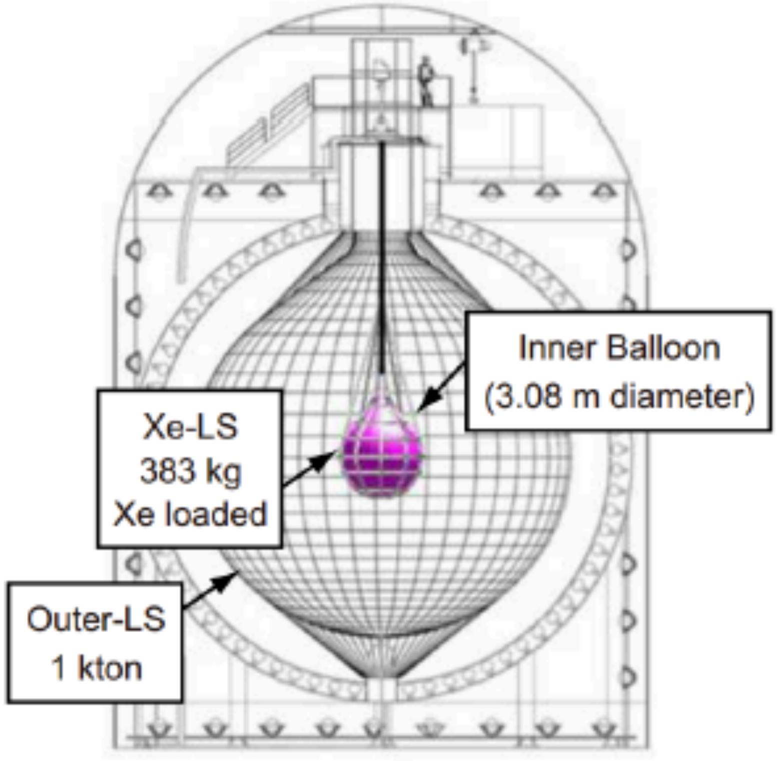
- Combined analysis **GERDA phase I + II**
- "Background-free" running in phase II
  - Two counts after unblinding
  - No count at $Q_{\beta\beta}$
- $T_{1/2} > 8.0 \times 10^{25}$ yr (90% CL)

- Next-generation project: LEGEND "Large Enriched Germanium Experiment for Neutrinoless ββ Decay"
- Staged approach, starting with ~200 kg in existing GERDA cryostat
- Final goal: 1000 kg-scale detector for sensitivity $>10^{27}$ yr
- Background improvement required: x30 (x5 for LEGEND-200)

[Nature 544 (2017) 47 + new data unblinded in August 2017]

Liquid Scintillator: KamLAND-Zen

Isotope:	^{136}Xe ($Q_{\beta\beta}$=2458 keV)
Resolution:	240-270 keV FWHM
Mass:	350 kg
Technology:	Xe-loaded liquid scintillator
Status:	completed/upgrading



Inner Balloon (3.08 m diameter)

Xe-LS
383 kg
Xe loaded

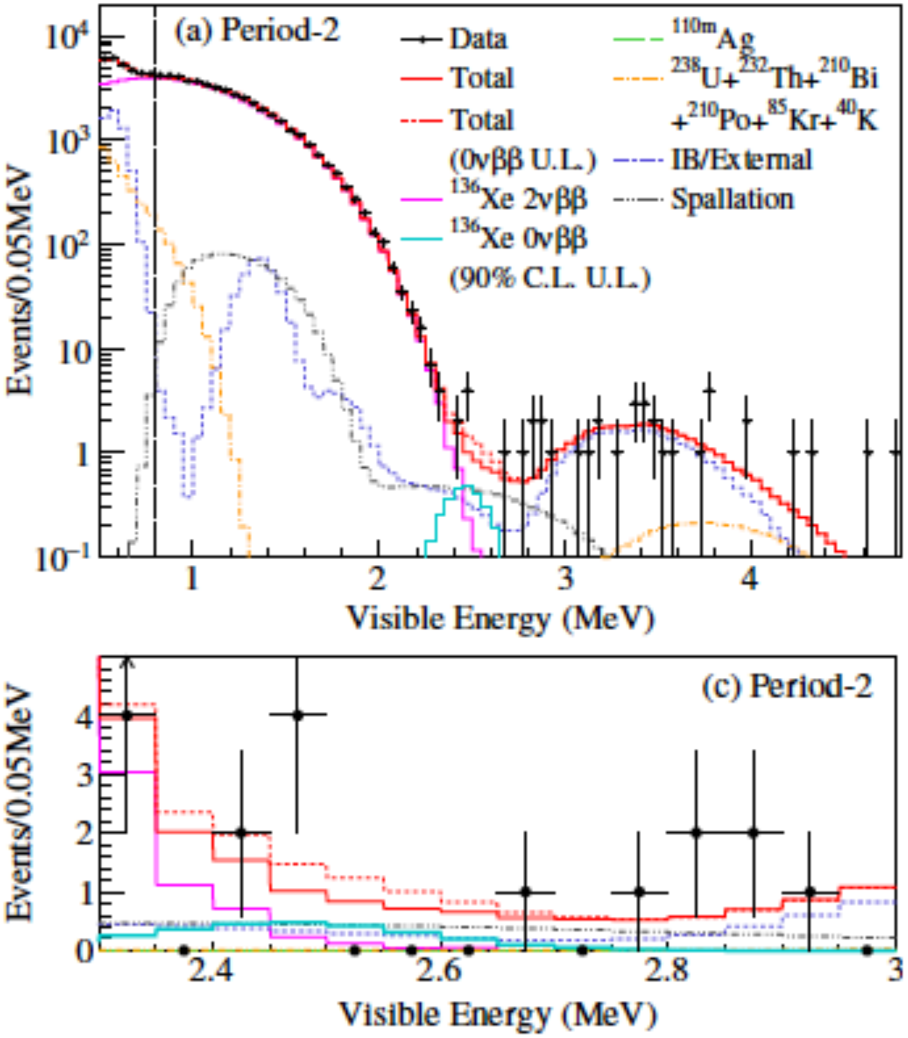
Outer-LS
1 kton

[Phys.Rev.Lett. 117 (2016) no.10, 109903]

Latest result with 504 kg·yr + old data:

$$T^{0\nu}_{1/2} > 10.7 \cdot 10^{25}\,\text{yr (90\% C.L.)}$$

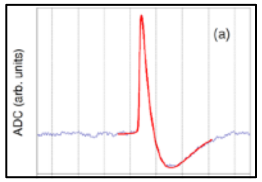
$$T^{0\nu}_{1/2} > 5.6 \cdot 10^{25}\,\text{yr (sensitivity)}$$



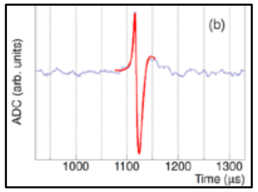
[from M. Agostini, Erice 2017]

Liquid Xenon TPC: EXO-200

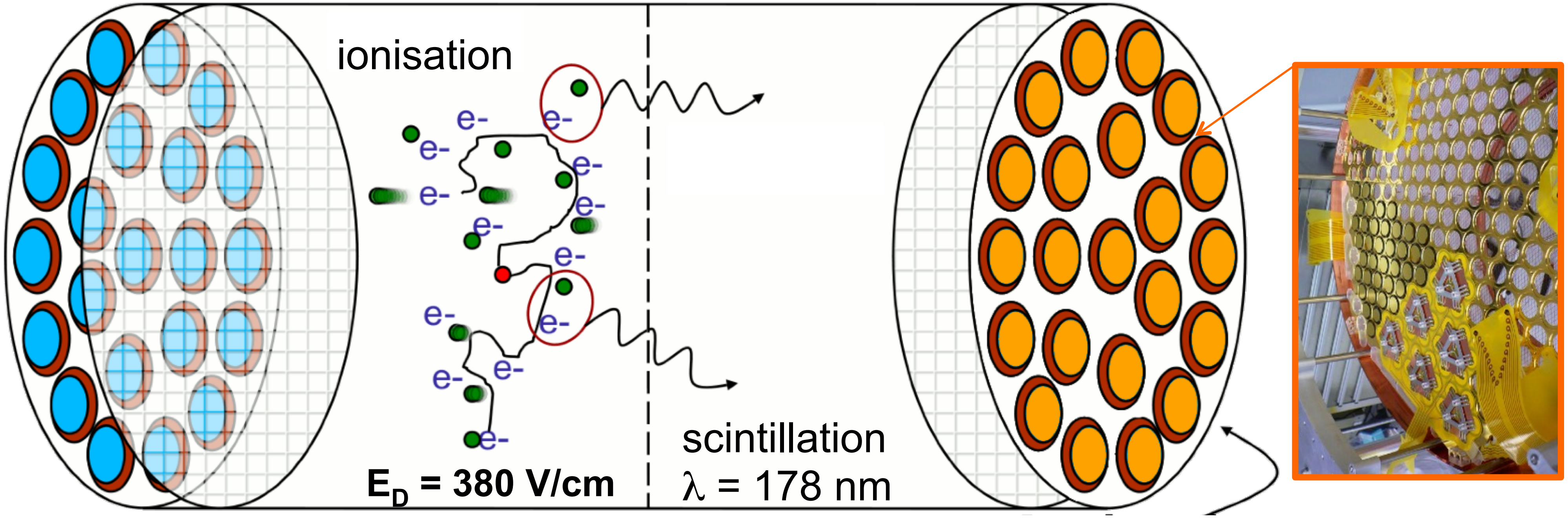
- Enriched Xenon Observatory at WIPP/New Mex., running **~175 kg of LXe** (80.6% ^{136}Xe)
- More than a calorimeter: spatial resolution (x,y,z) and PID allows discrimination of multi-site (bg-like) vs. single-site (0νββ-like) events
- Anticorrelation of charge and light signals (compare DM detectors), tags α events
- Now preparing **nEXO**: 5-ton monolithic detector (~1 t fiducial), 1.3 m electron drift length, ~4 m^2 of SiPM photosensors, option of ^{136}Ba tagging



Collection



Induction

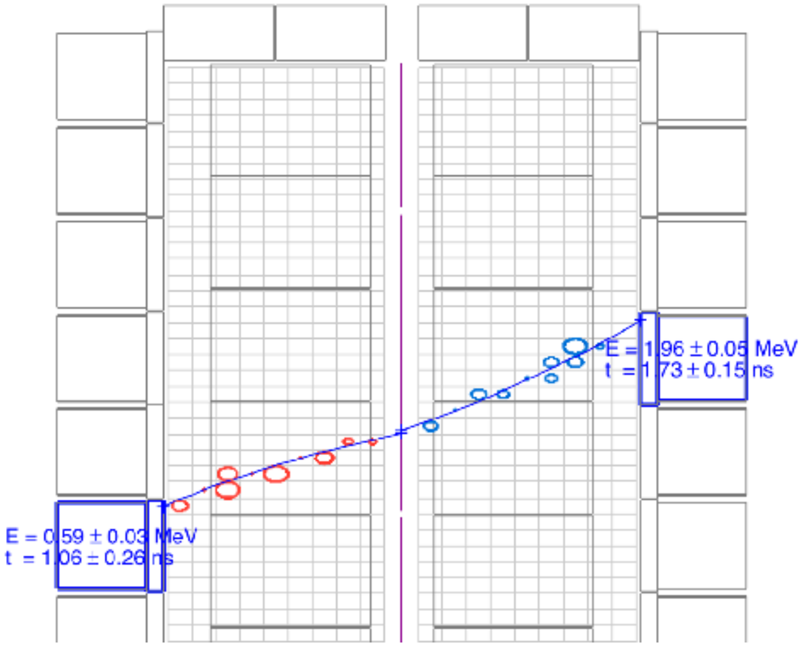


ground pot. cathode photodiodes

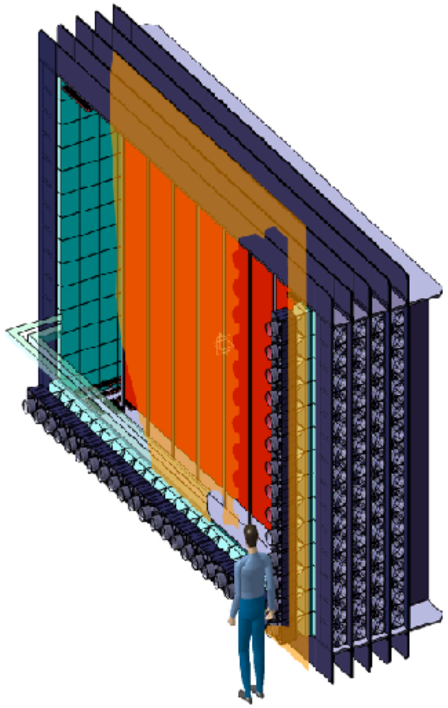
Tracking-Calorimeter: SuperNEMO

- Successor of NEMO-3 at Laboratoire Souterrain de Modane (LSM)
- Baseline isotope: ^{82}Se, foils can be exchanged (high Q-values: ^{150}Nd, ^{48}Ca)
- Unique feature: tracking allows to detect ββ-signature (vertex)
- Demonstrator (= 1st module) currently in commissioning, first data end of 2017
- Design sensitivity: $T_{1/2} > 10^{26}$ a, $m_{\beta\beta}$ ~50-100 meV

$\beta^-\beta^-$ reconstruction

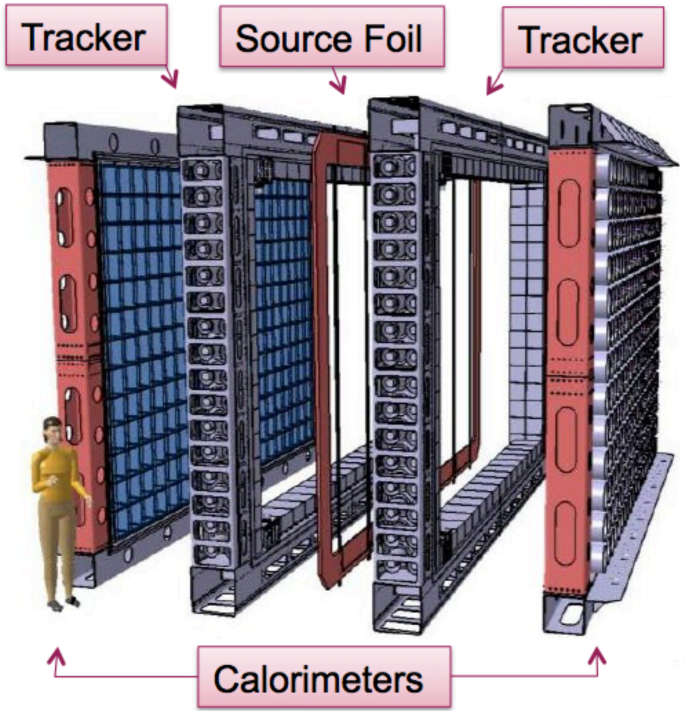


demonstrator module



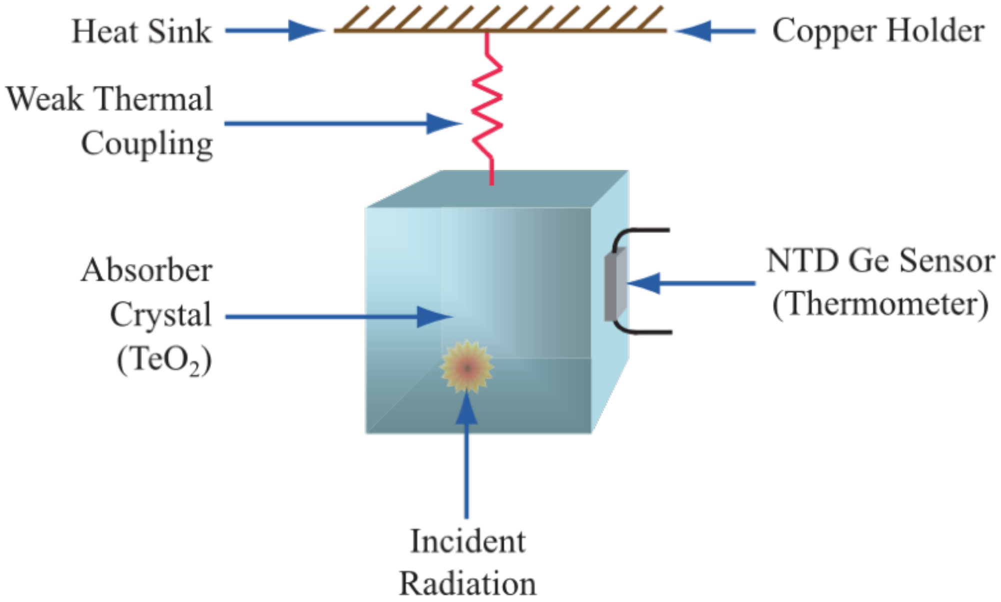
B ~2.5 mT + TOF

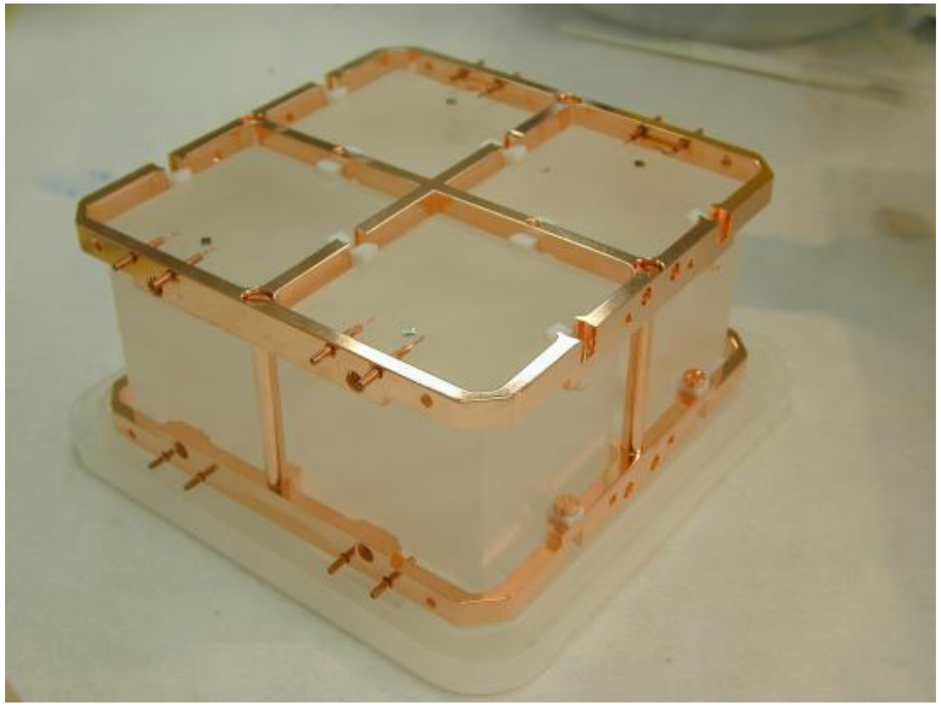
5-7 kg enriched source material



Cryogenic bolometer technique

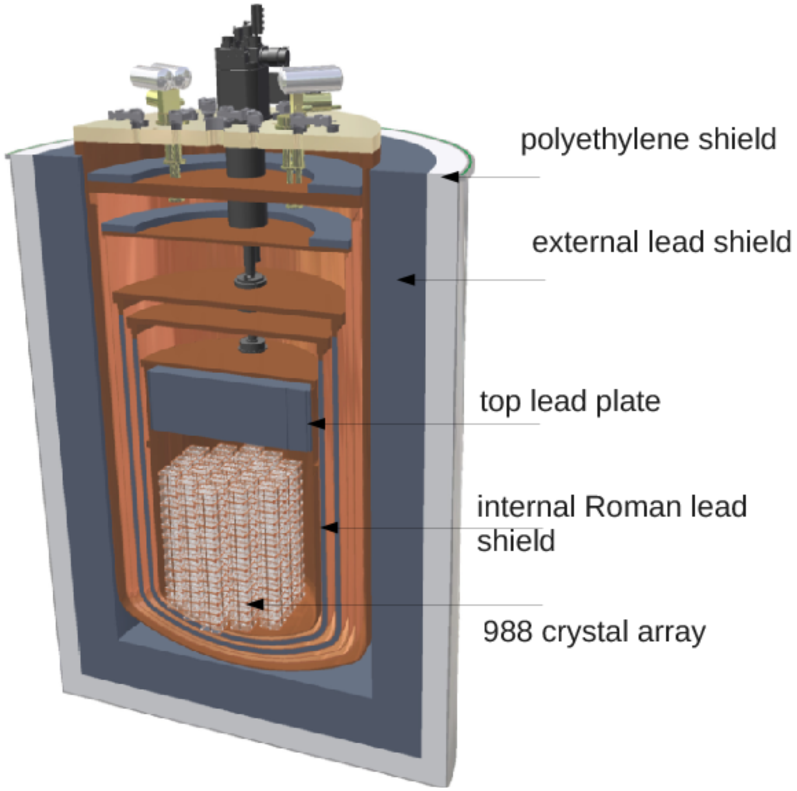
- Electrons create phonons/heat in absorber (e.g., TeO_2 crystal)
- Heat capacity: ~$(T/T_D)^3$ (Debye Law)
- Example:
  - Operating temperature: 10 mK
  - Temperature change per energy: 10 – 20 μK/MeV
- At $Q_{\beta\beta} = 2.5$ MeV → $\Delta T < 50\ \mu K$



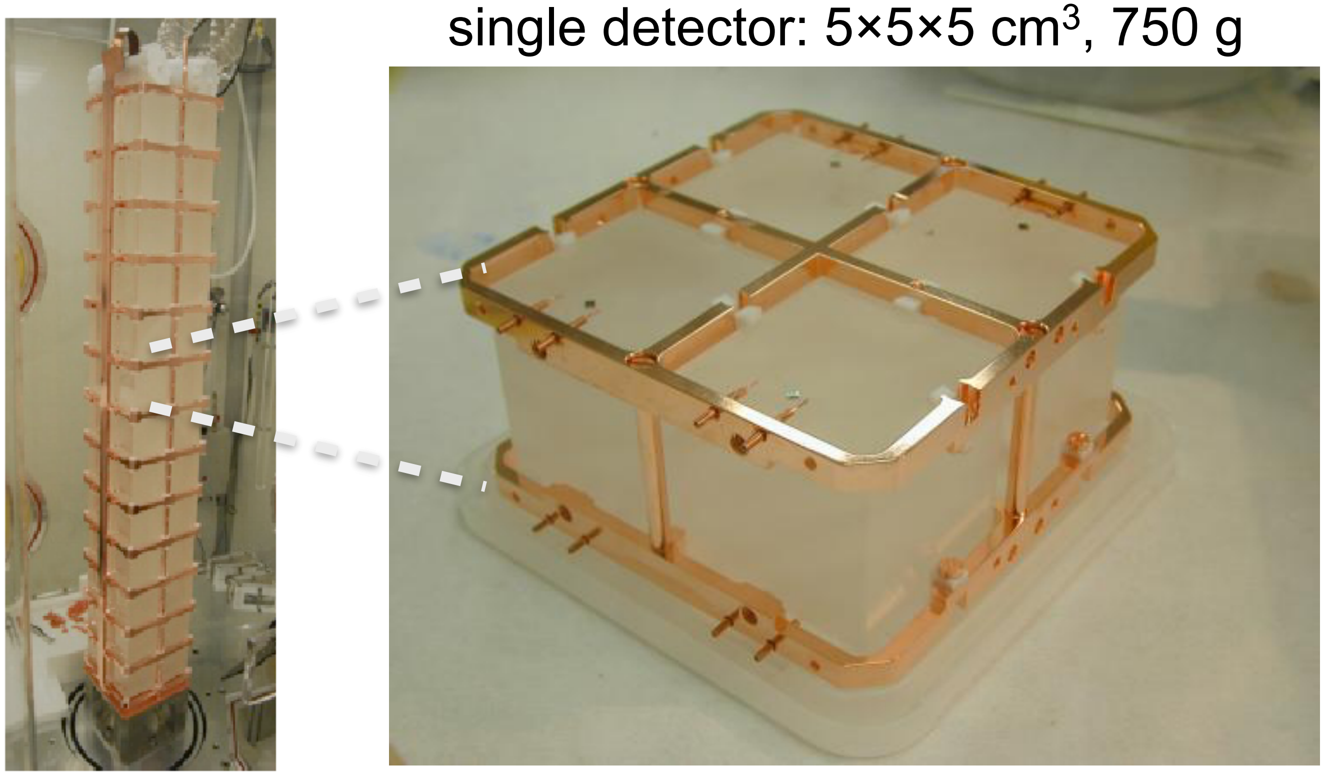


Cryogenic bolometer: CUORE

- First ton-scale $0\nu\beta\beta$ exp. with thermal detectors; at Gran Sasso underground laboratory
- TeO_2 detectors & cryo-technology piloted by Cuoricino & CUORE-0 (~40 kg)
- Since Feb. 2017: operation of **988 detectors** at **T ~7 mK**
- Total mass: 742 kg of TeO_2 ➜ **206 kg of ^{130}Te**



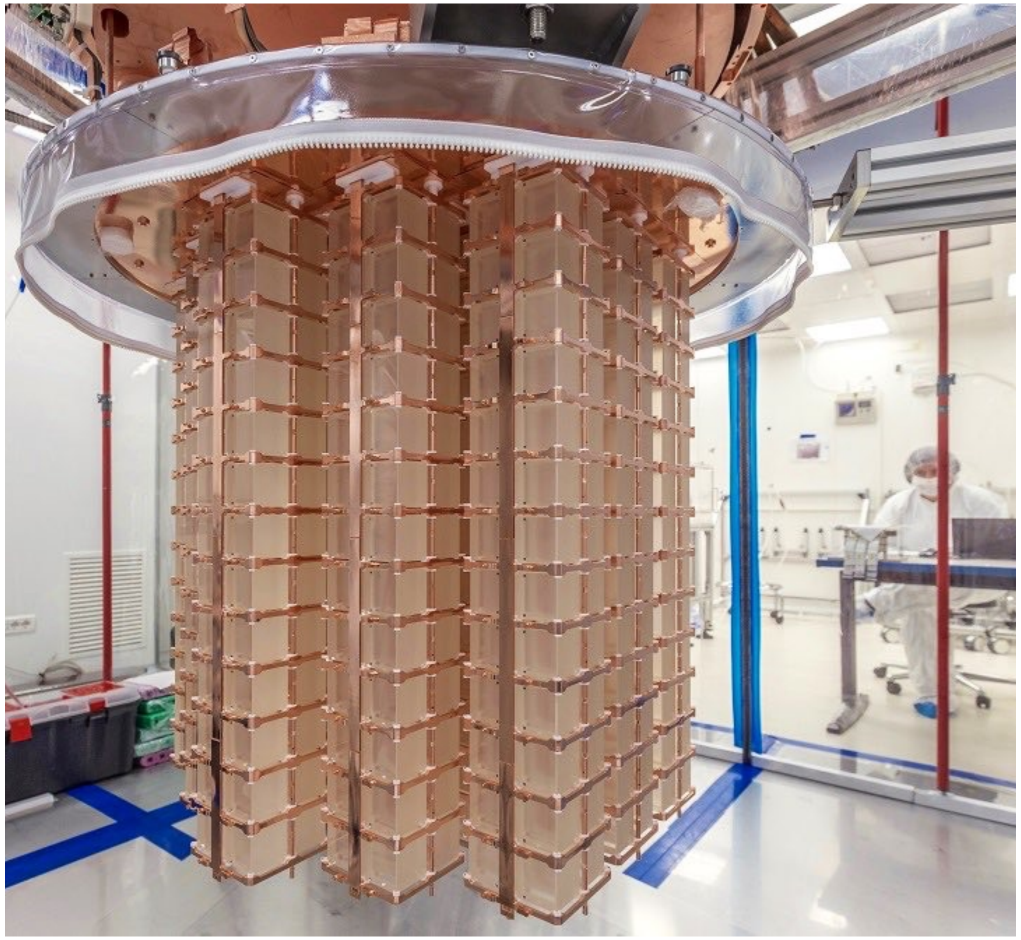
single detector: 5×5×5 cm^3, 750 g



19 towers x 13 planes x 4 crystals = 988 crystals

Cryogenic bolometer: CUORE

The coldest cubic meter in the Universe!
CUORE: at ~10 mK
Cosmic microwave background: 2.7 K



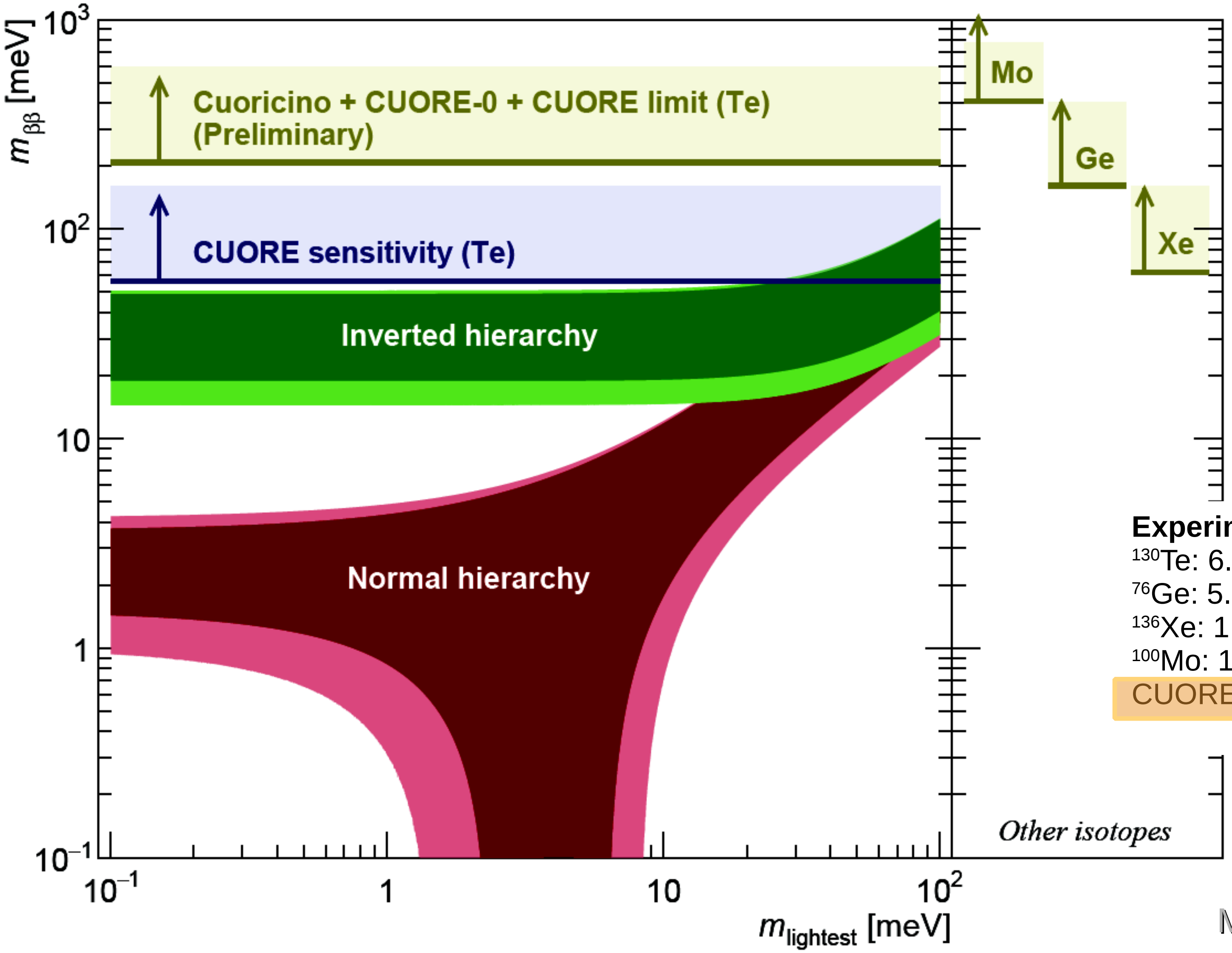
19 towers x 13 planes x 4 crystals = 988 crystals

cryogenic platform with helium dilution cryostat

Cryogenic bolometer: CUORE

First CUORE science run, combined with Cuoricino + CUORE-0:

$\tau_{1/2}^{0\nu} > 6.6 \times 10^{24}$ y (90%C.L.) ⟷ $m_{\beta\beta} < 210 - 590$ meV



NME
Phys. Rev. C 91, 034304 (2015)
Phys. Rev. C 87, 045501 (2013)
Phys. Rev. C 91, 024613 (2015)
Nucl. Phys. A 818, 139 (2009)
Phys. Rev. Lett. 105, 252503 (2010)

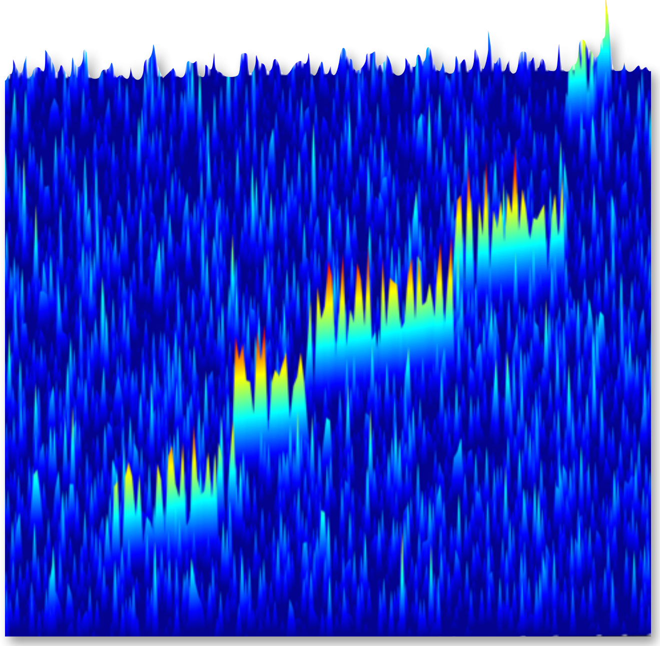
Experiments
^{130}Te: 6.6×10^{24} yr from this analysis
^{76}Ge: 5.3×10^{25} yr from Nature 544, 47–52 (2017)
^{136}Xe: 1.1×10^{26} yr from Phys. Rev. Lett. 117, 082503 (2016)
^{100}Mo: 1.1×10^{24} yr from Phys. Rev. D 89, 111101 (2014)
CUORE sensitivity: 9.0×10^{25} yr

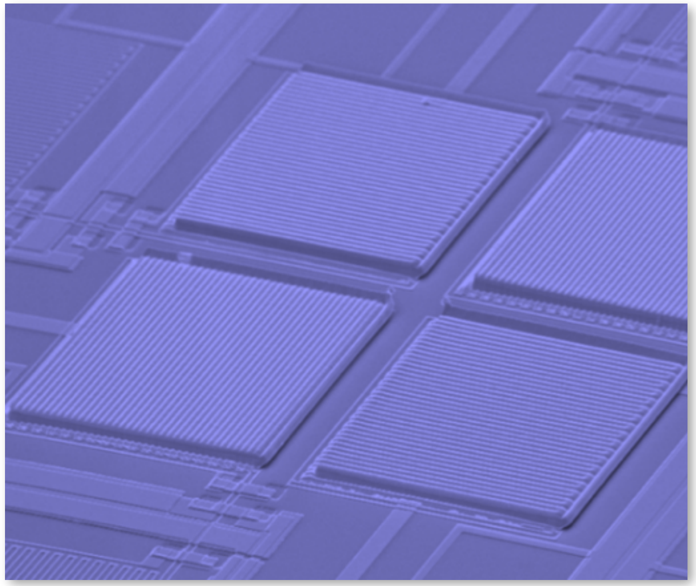
for 5 years of data

Monica Sisti – Erice, September 18, 2017

Probing ν mass with lab experiments:

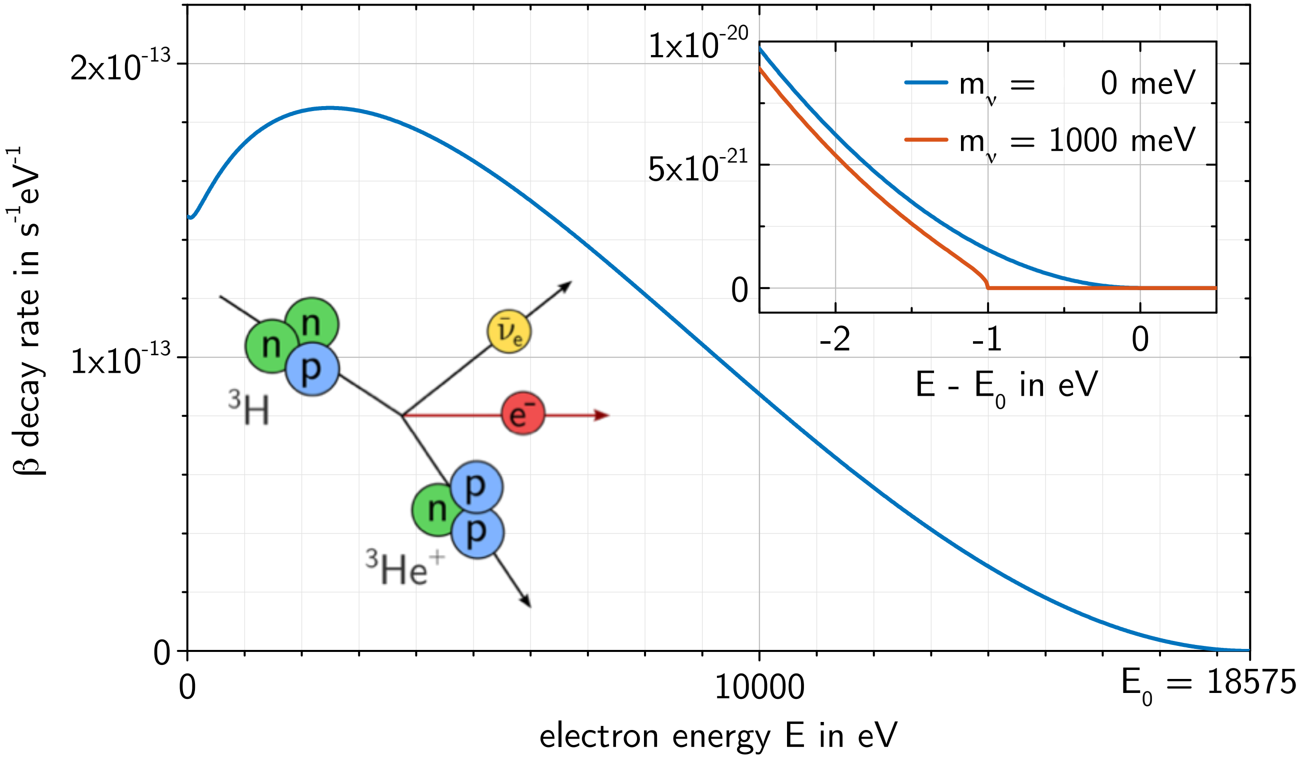
Direct kinematical measurements of weak decays





Direct kinematic determination of m(ν_e)

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E} = C\,F(Z,E)\,p\,(E+m_\mathrm{e})\,(E_0-E)\,\sum_i |U_{\mathrm{e}i}|^2 \sqrt{(E_0-E)^2 - m^2(\nu_i)}$$



Key requirements:

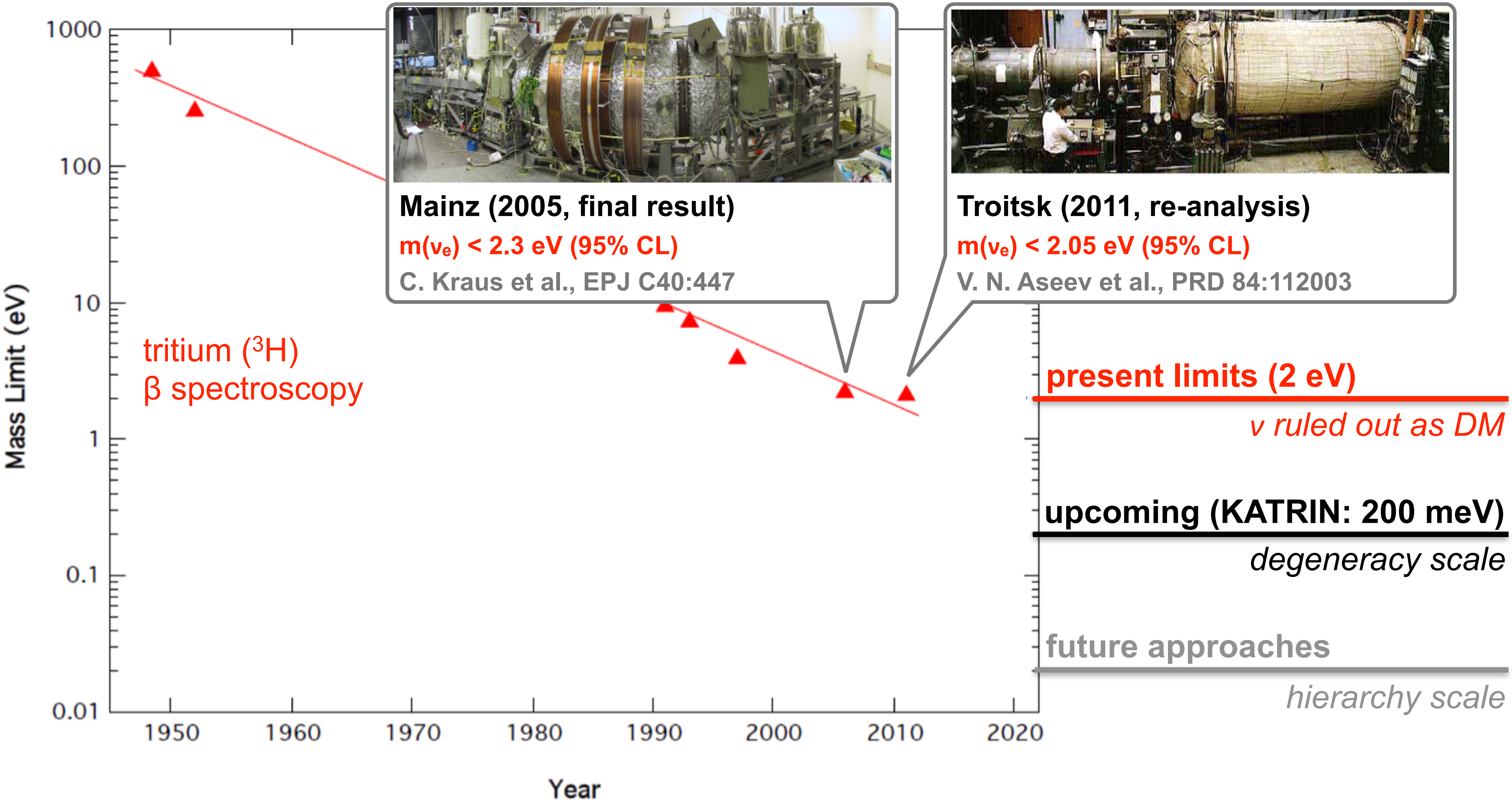
- Low-endpoint β/EC nuclide:
  E_0 = 18.6 keV for **^{3}H**,
  2.8 keV for **^{163}Ho**
- High-activity source:
  $T_{1/2}$ = 12.3 yr for **^{3}H,**
  4.5 kyr for **^{163}Ho**
- Excellent energy resolution (MAC-E filter or calorimeter)

Kinematic measurement can probe for **heavier neutrino states**
➜ eV-scale and keV-scale sterile ν

Spectral distortion measures **“effective” mass square:**

$$m^2(\nu_\mathrm{e}) := \sum_i |U_{\mathrm{e}i}|^2\, m_i^2$$

Moore's Law of direct neutrino mass searches



Mainz (2005, final result)

$m(\nu_e) < 2.3$ eV (95% CL)

C. Kraus et al., EPJ C40:447

Troitsk (2011, re-analysis)

$m(\nu_e) < 2.05$ eV (95% CL)

V. N. Aseev et al., PRD 84:112003

present limits (2 eV)

ν ruled out as DM

upcoming (KATRIN: 200 meV)

degeneracy scale

future approaches

hierarchy scale

Courtesy J.F. Wilkerson/R.G.H. Robertson

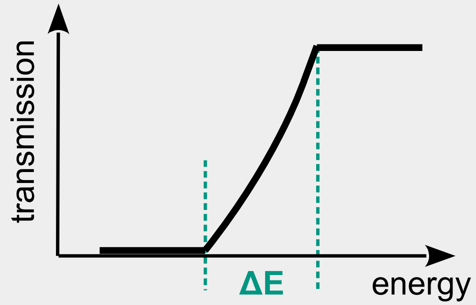
High-resolution β spectrometer

Magnetic Adiabatic Collimation & Electrostatic Filter

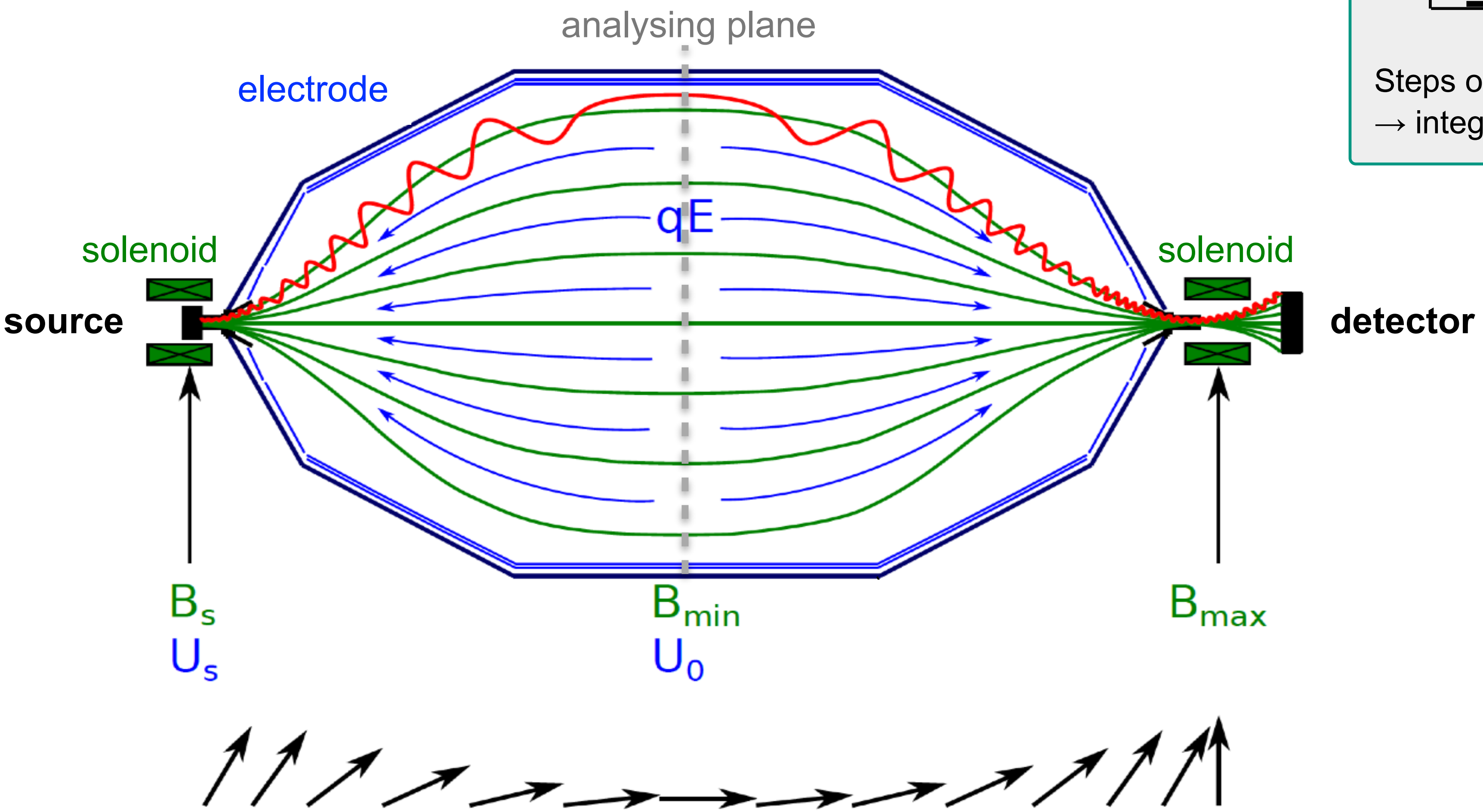
- ➜ integrating electrostatic filter ($E_{kin} > eU_0$)
- ➜ “clean” (analytic) response function
- ➜ ΔE < 1 eV at 18.6 keV

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

Sharp high-pass filter:



Steps of filter potential
→ integrated β spectrum

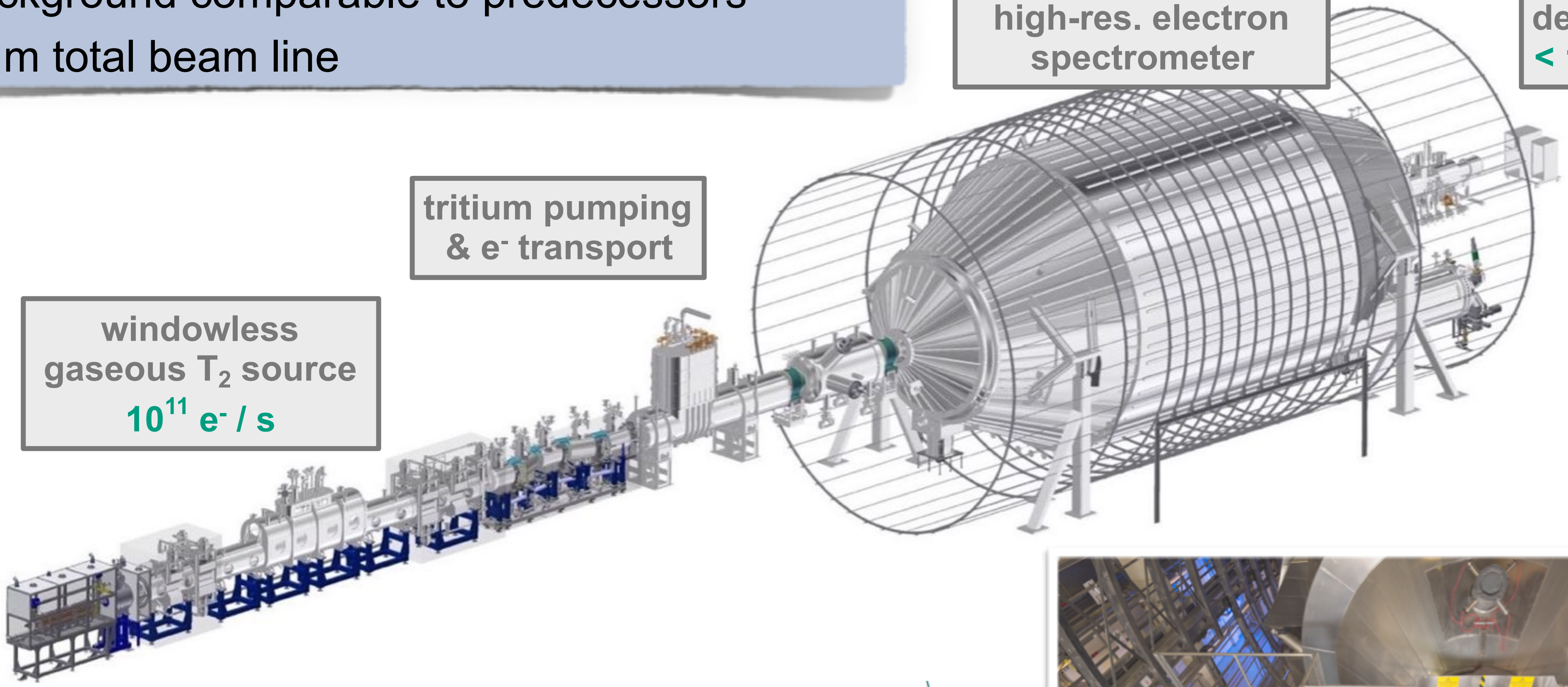


[Beamson et al. 1980; Kruit & Read 1983; **Lobashev 1985; Picard et al. 1992**]

The Karlsruhe Tritium Neutrino Experiment

Sensitivity: 2 eV ➜ 0.2 eV

- Improvement x100 in statistics and systematics
- Background comparable to predecessors
- 70 m total beam line

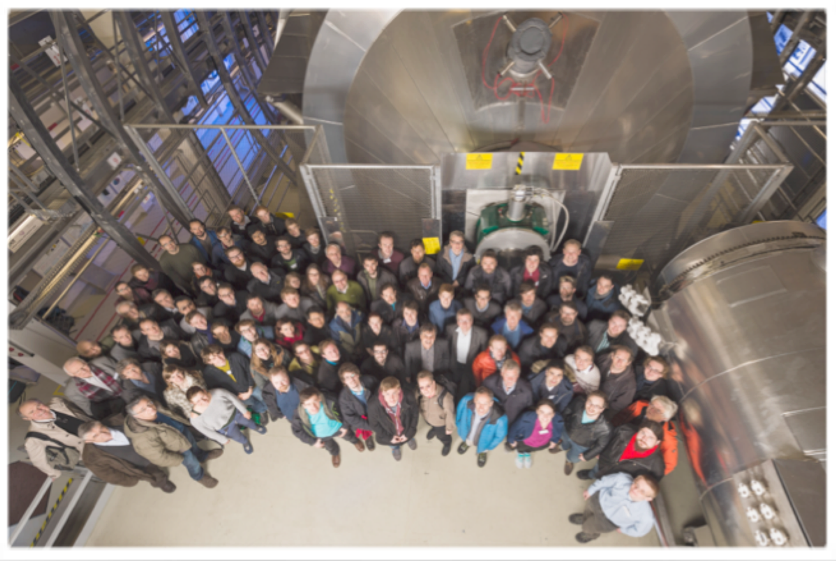


windowless gaseous T_2 source
10^{11} e^- / s

tritium pumping & e^- transport

high-res. electron spectrometer

electron detector
< 1 e^- / s

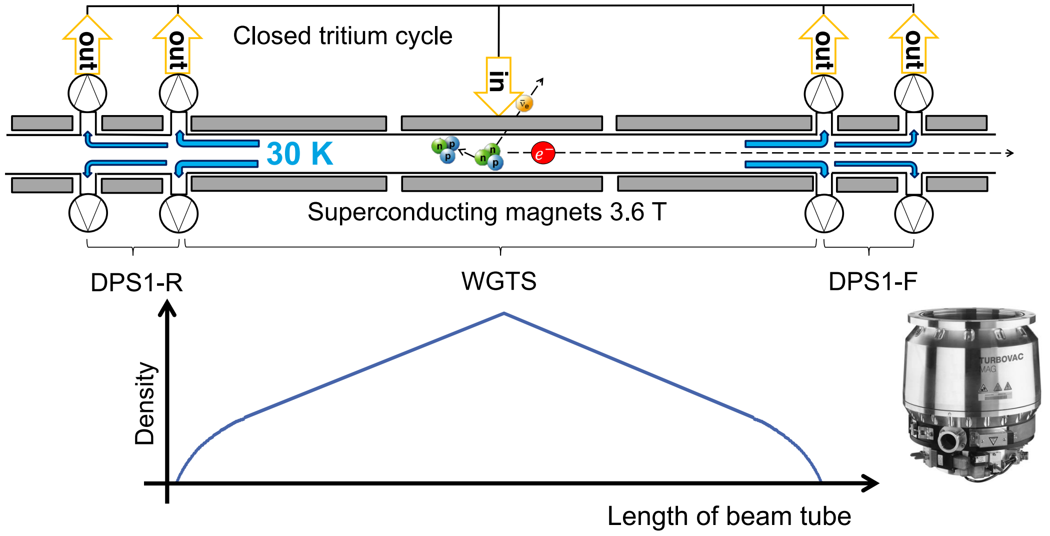


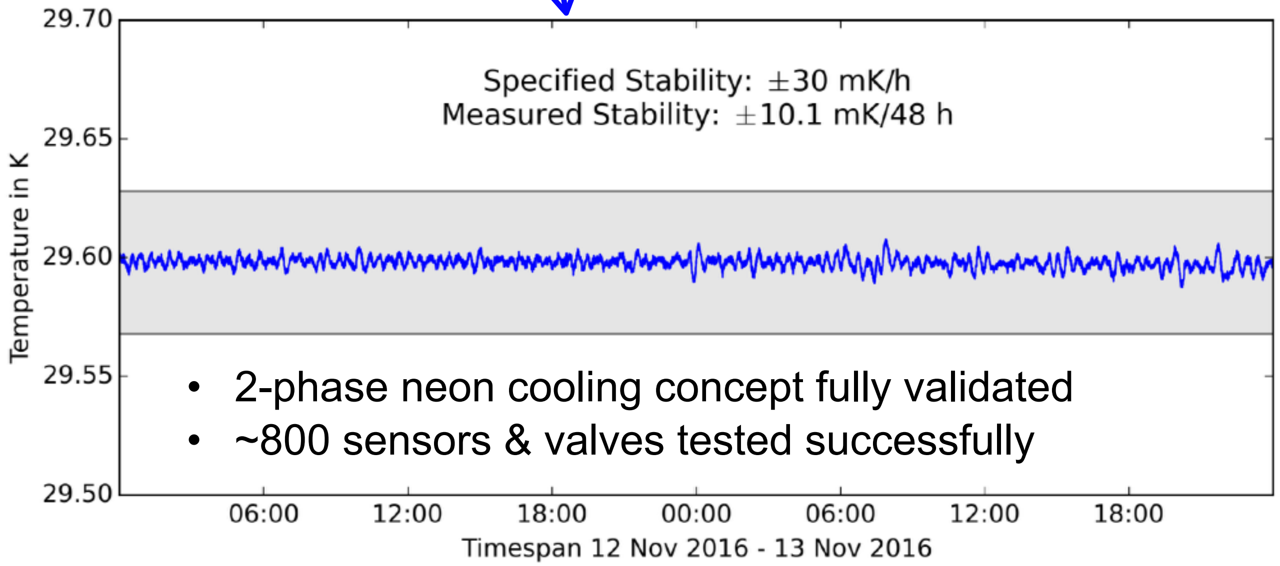
Hochschule Fulda
University of Applied Sciences
The University of North Carolina at Chapel Hill
Max-Planck-Institut für Physik
KIT Karlsruher Institut für Technologie
Max-Planck-Institut für Kernphysik
Berkeley Lab
Universidad Complutense Madrid
JGU Johannes Gutenberg Universität Mainz
TUM
Westfälische Wilhelms-Universität Münster
universitätbonn
Case Western Reserve University
University of Washington
Carnegie Mellon University
Bergische Universität Wuppertal
cea

Status of the KATRIN source

Gaseous molecular tritium source of

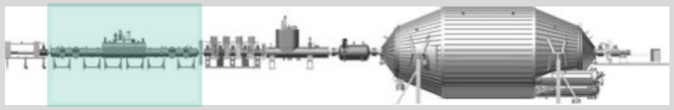
- high activity (~170 GBq)
- high isotopic purity ($\varepsilon_T > 95\%$)
- high stability (0.1%)





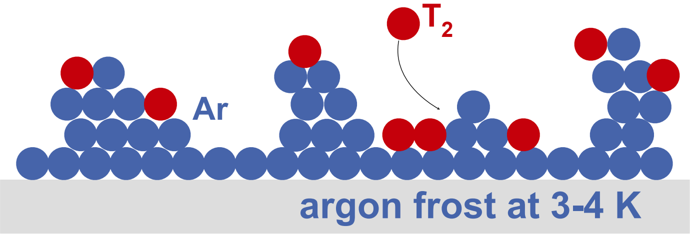
- 2-phase neon cooling concept fully validated
- ~800 sensors & valves tested successfully

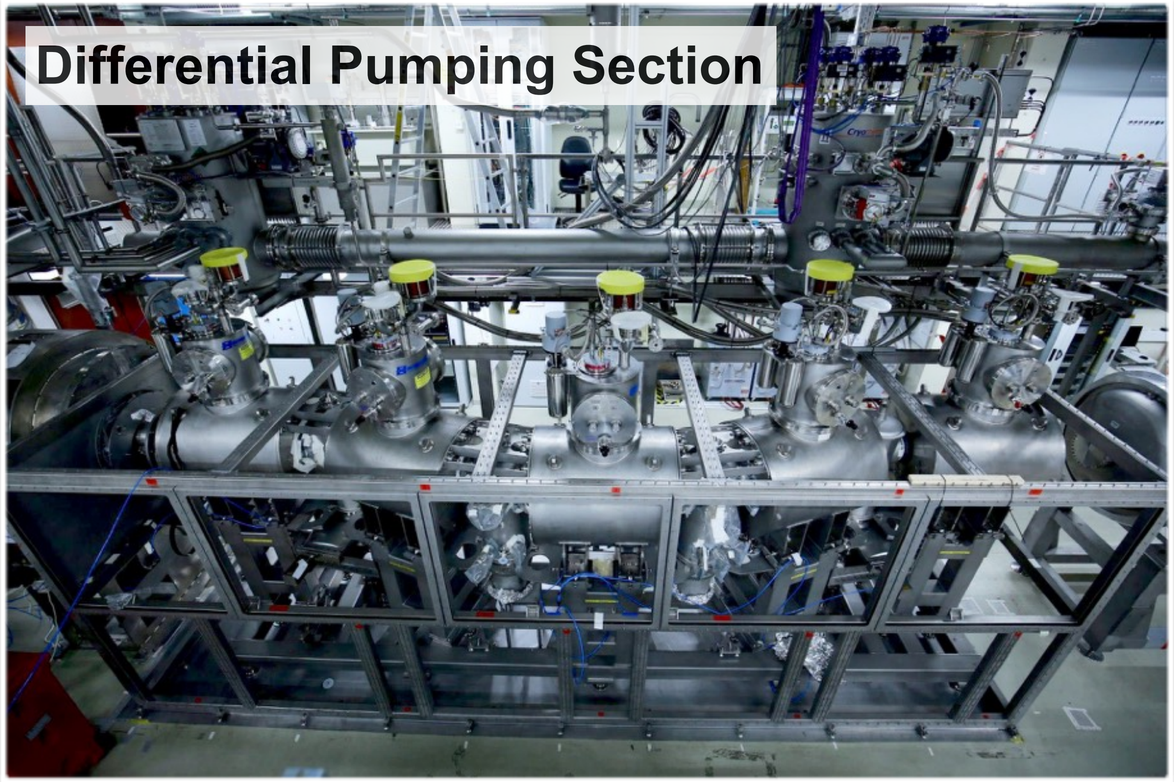

Sept. 2015



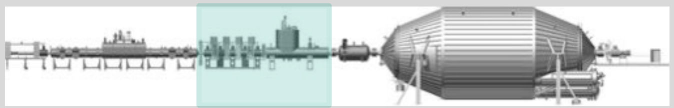
Transport & pumping sections

- Fully adiabatic, **lossless electron transport** in 5.6 T magnetic field
- **Reduction of T_2 flow rate** to spectrometers by factor **$>10^{14}$**: magnetic chicane with **differential** and **cryo-pumping**
- Ion diagnostics & **ion flux blocking** by electrostatic barrier



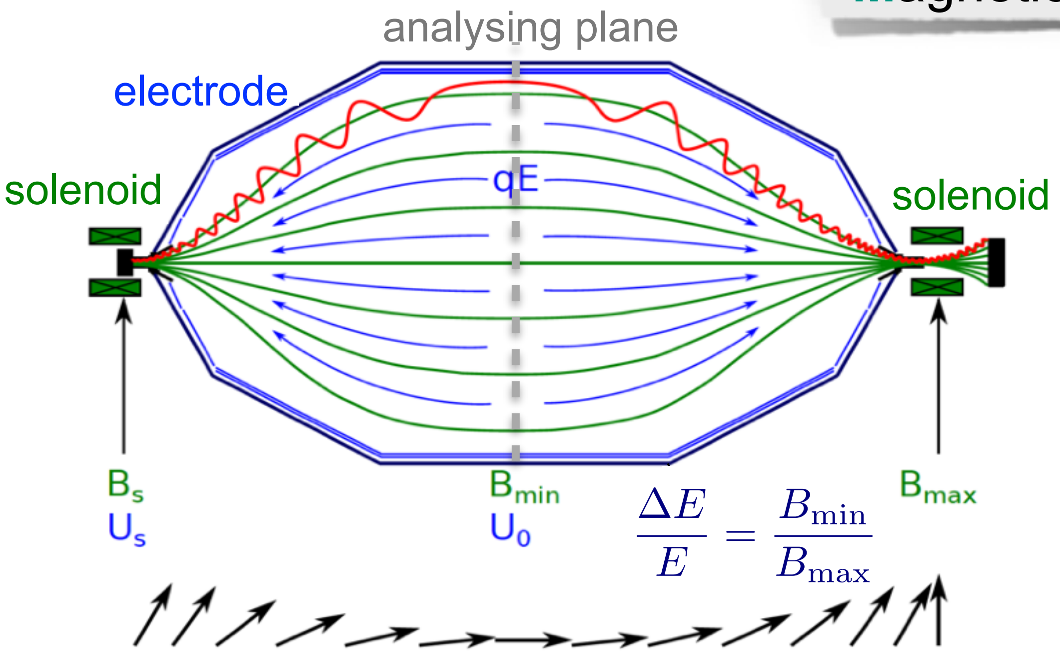


July 2015

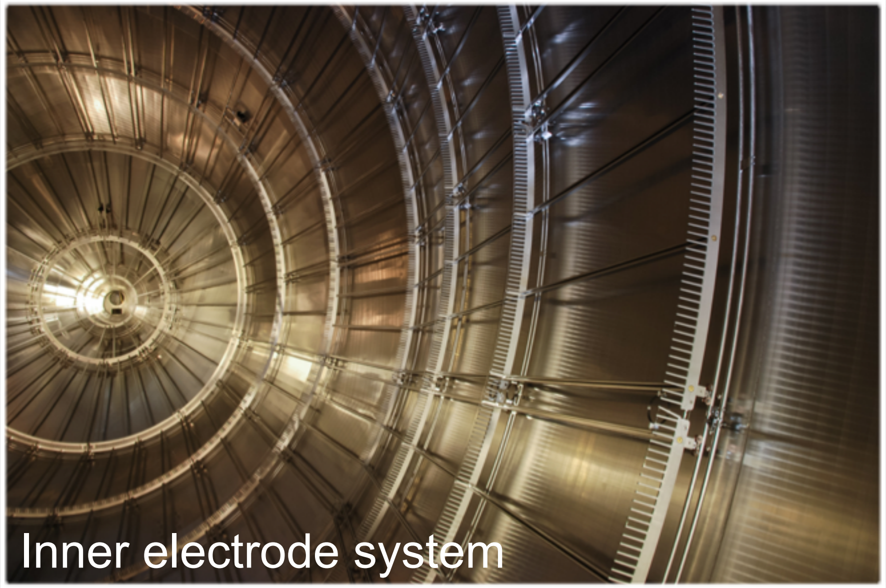


KATRIN main spectrometer

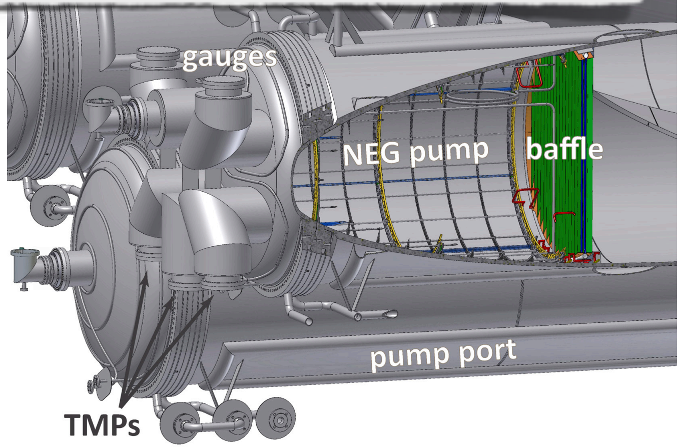
Magnetic Adiabatic Collimation and Electrostatic Filter



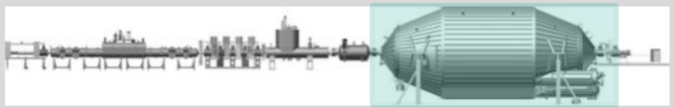
$$\frac{\Delta E}{E} = \frac{B_{\min}}{B_{\max}}$$


Inner electrode system

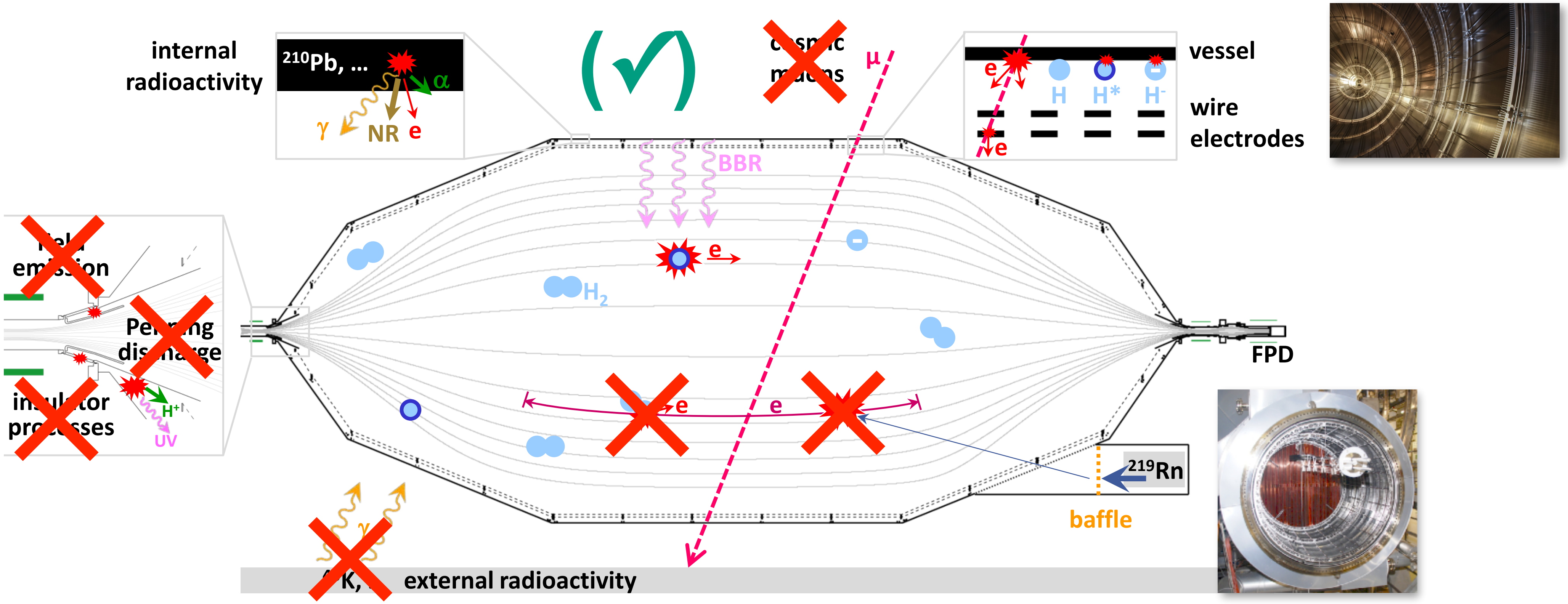
UHV system for ~1250 m³ spectrometer




Large Helmholtz coil system

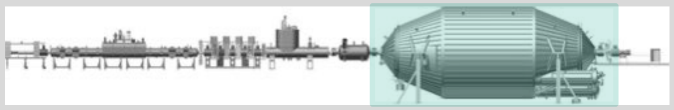


Spectrometer-related backgrounds

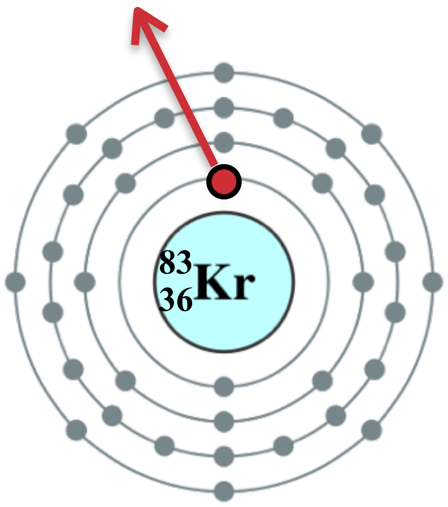


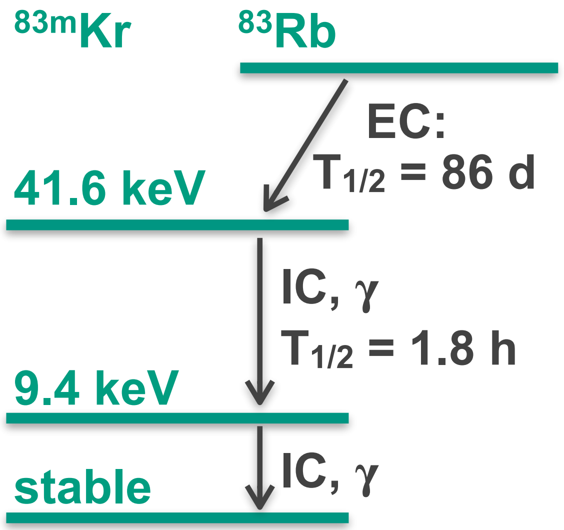
- **8 sources of background investigated and understood**
- **7 out of 8 avoided or actively eliminated by**
  - fine-shaping of special electrodes
  - inner electrode (wire grids on neg. potential)
  - symmetric magnetic fields
  - cold traps (LN$_2$-cooled baffles to remove ^{219}Rn)

- **1 out of 8 remaining:**
  ^{210}Pb on spectrometer walls
  (thermal ionisation of neutral H* atoms)
- Countermeasures:
  - extensive bake-out (done)
  - irradiation by strong UV source (ongoing investigation)



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





^{83m}Kr

^{83}Rb

EC:
$T_{1/2} = 86$ d

41.6 keV

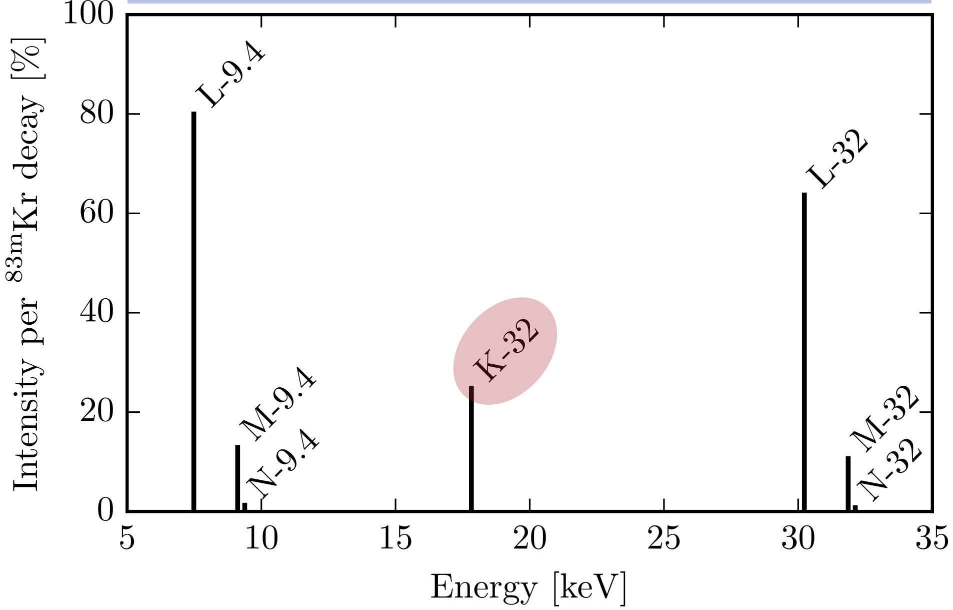
IC, γ
$T_{1/2} = 1.8$ h

9.4 keV

stable

IC, γ

narrow (< 2 eV) CE lines at 7 … 32 keV



[M. Slezak, PhD thesis, 2015]

KATRIN krypton campaign: 3-19 July 2017

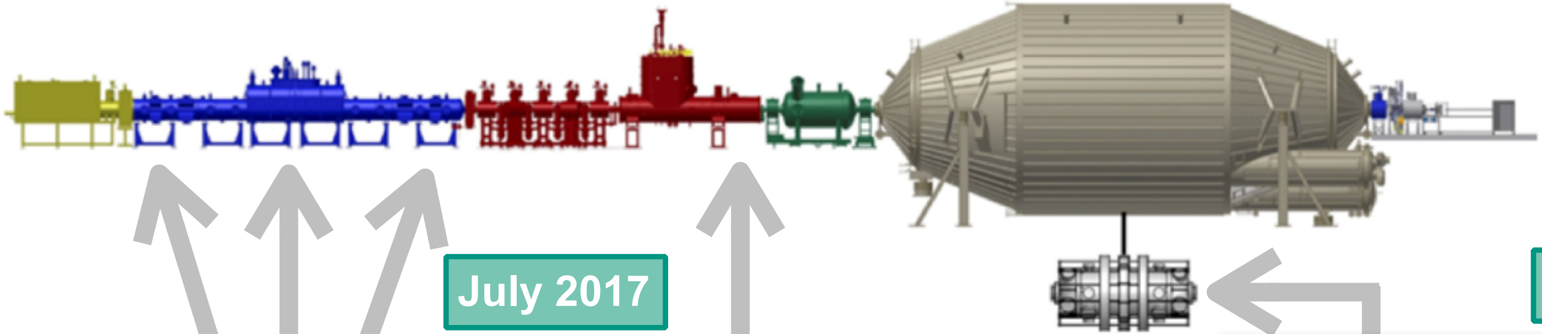
Hardware readiness from source to detector with ^{83m}Kr as short-lived “tracer”

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

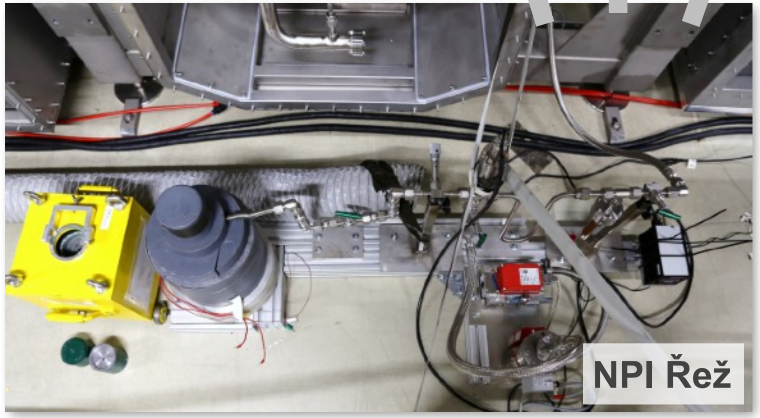
System characterization with mono-energetic & isotropic CE:

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

Three complementary krypton sources at KATRIN



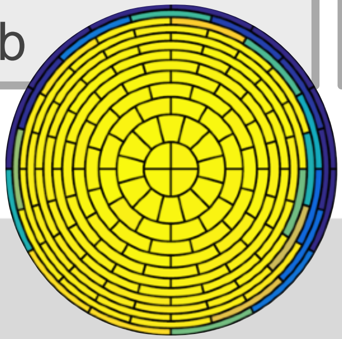
July 2017



NPI Řež

1. Gaseous ^{83m}Kr source

- Krypton decays inside WGTS beam tube (100 K)
- Homog. spatial distribution
- Ca. 1 GBq ^{83}Rb

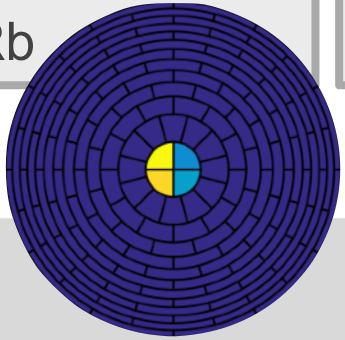


July 2017

U Münster

2. Condensed ^{83m}Kr source

- Thin film on cold substrate
- Spot-like source, can be moved across flux tube
- Ca. 1 MBq ^{83}Rb



since 2012

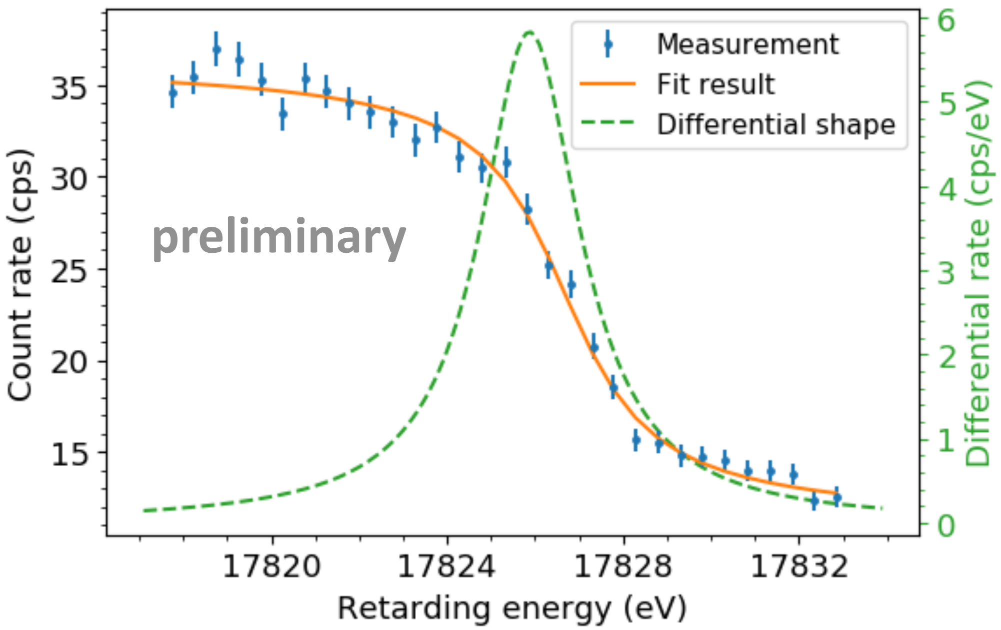
U Bonn & NPI Řež

3. Implanted ^{83m}Kr source

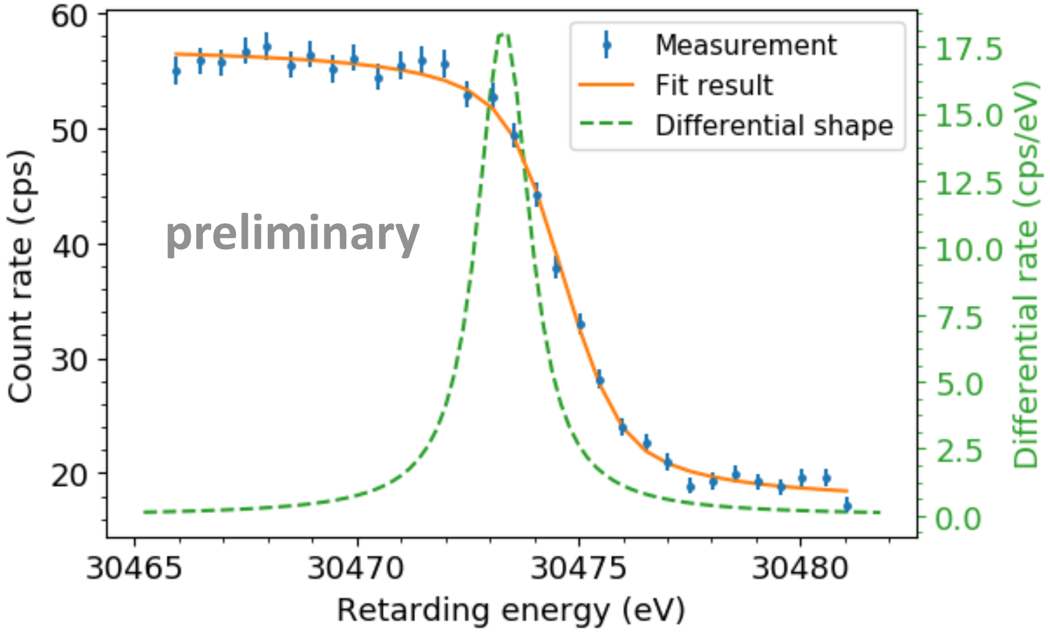
- Parallel measurement at Monitor Spectrometer
- Excellent stability proven over several years

Line stability & absolute calibration (gaseous Kr source)

K-32 line (17.8 keV, Γ ~2.8 eV)



L_3-32 line (30.47 keV, Γ ~1.4 eV)



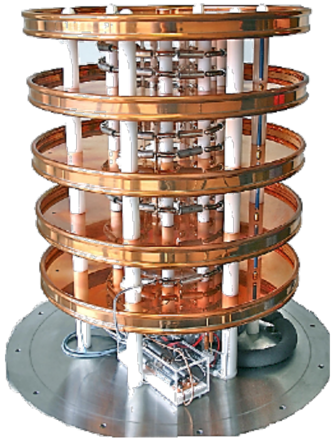
- Example runs (two out of many line scans)
- Only central detector ring shown (x30 more statistics available)
- High-resolution scans of narrow $N_{2,3}$-32 doublet (670 meV hyperfine splitting, sub-eV natural widths, background-free at 32 keV) currently being analyzed

Line stability & absolute calibration (gaseous Kr source)

- Line position stability (L3-32) well within KATRIN goal of ± 60 meV

➡ Excellent stability of Krypton source and HV system

TAUP Conference, July 2017

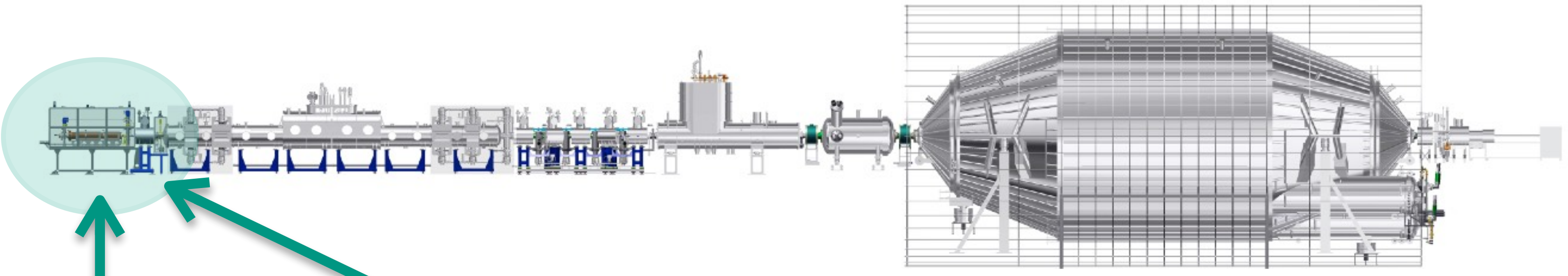


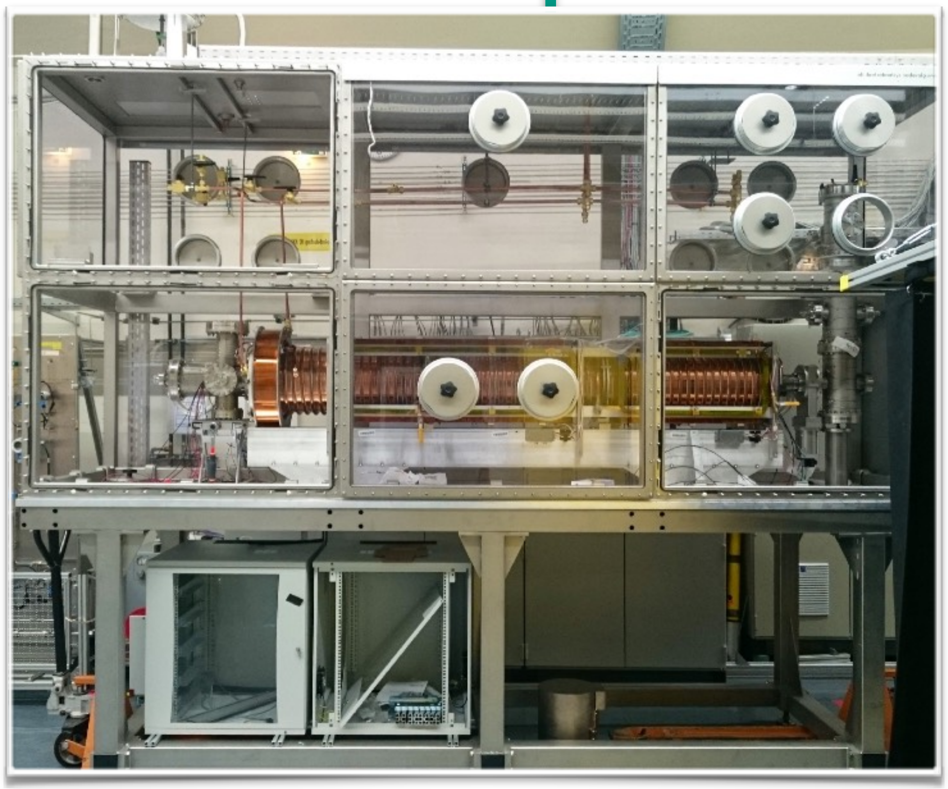
In cooperation with
German national
metrology institute
PTB

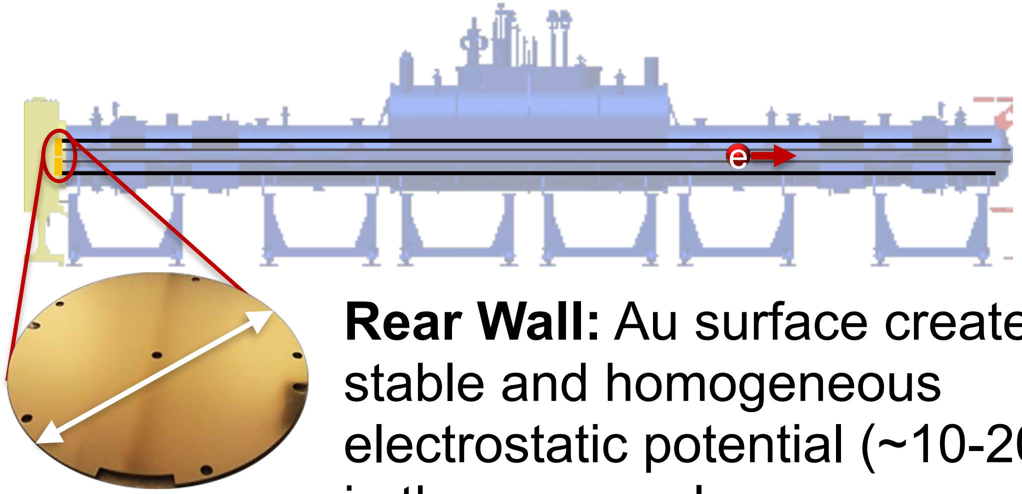
- Absolute calibration of HV divider with nuclear standard
- Line position difference L3-32 — K-32
  → source-related systematics cancel
  → ~5 ppm preliminary uncertainty on energy scale
  (very good agreement with 2013 PTB calibration value!)

Integration of Calibration and Monitoring System

“Rear Section”: major importance for systematics control







⌀ 150 mm

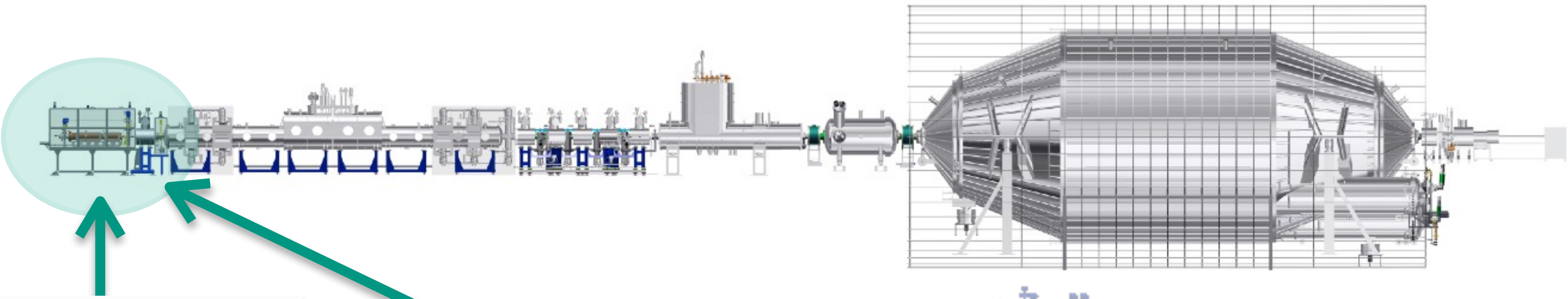
Rear Wall: Au surface creates stable and homogeneous electrostatic potential (~10-20 mV) in the source plasma

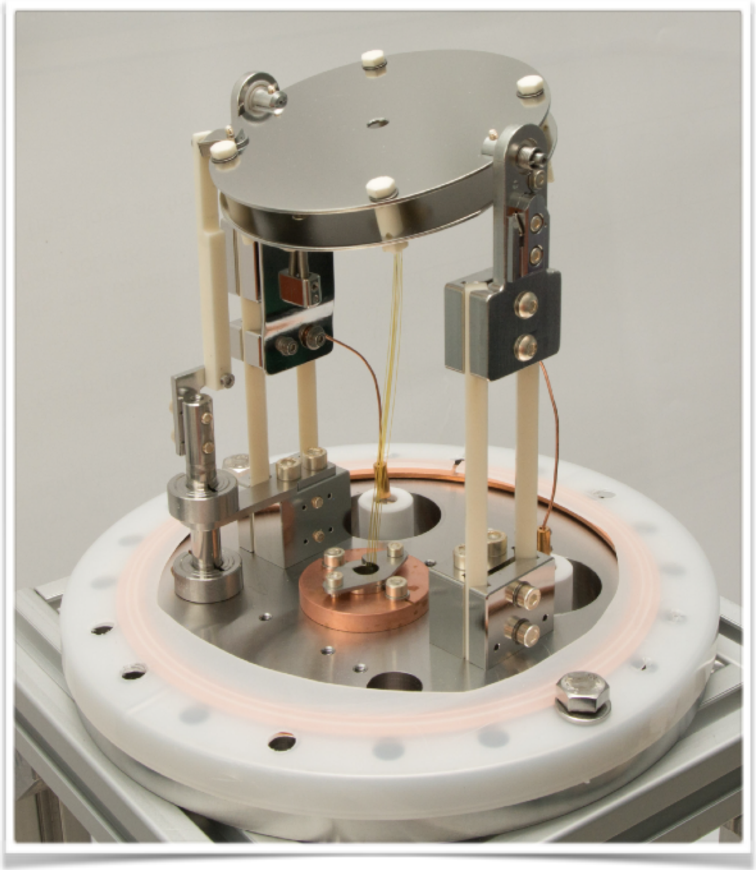
under construction

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

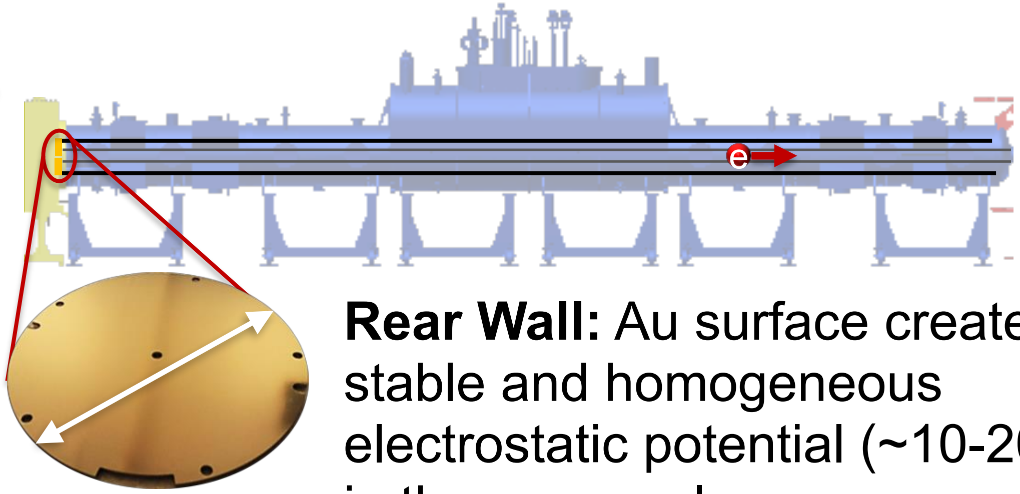
Integration of Calibration and Monitoring System

“Rear Section”: major importance for systematics control





c. Philipp Ranitzsch



⌀ 150 mm

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

under construction

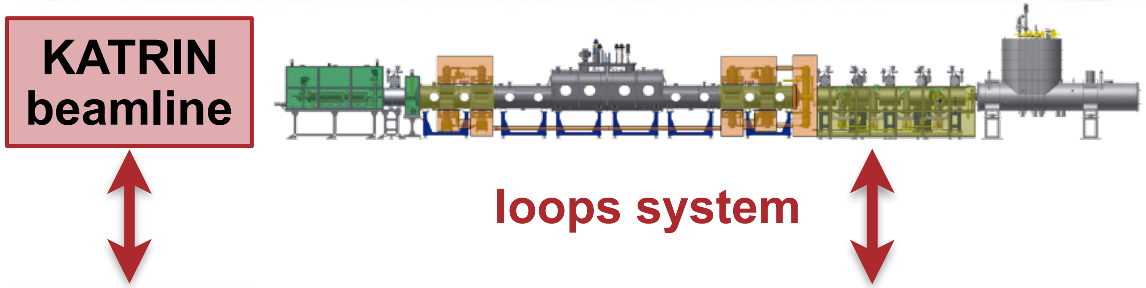
Precision e^- source:
regular column density monitoring
+ determination of energy loss function (scattering)

[see Behrens *et al.*, EPJ **C**77 (2017) 410;
PhD theses Behrens, Erhardt, Barrett, Wierman, Kraus]

Towards tritium data-taking with KATRIN

[B. Bornschein *et al.*, Fusion Sci. Technol. (2017)]

System complete
(except tritium loops, calibration system)

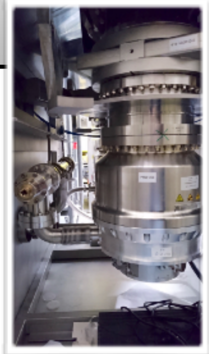


KATRIN beamline

loops system

TLK infra-structure

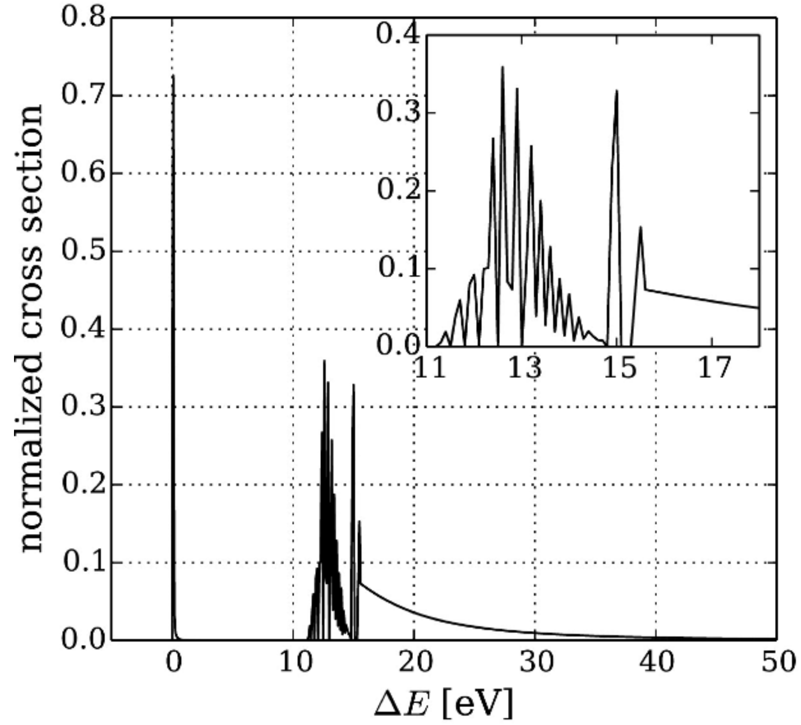
Central Tritium Retention System & isotope separation



Tests with inactive D_2
➜ with traces of T_2

Physics commissioning

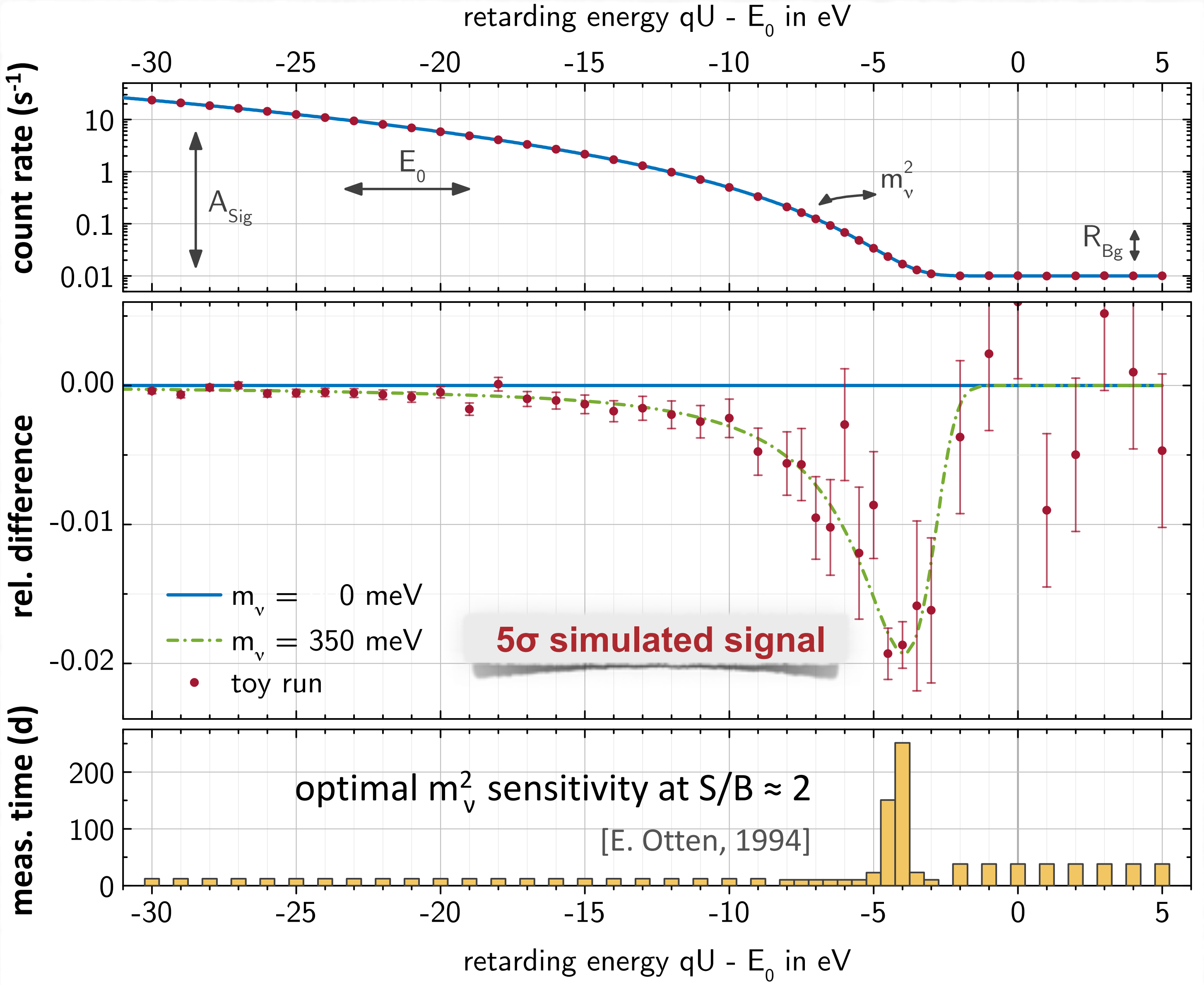
e.g. energy loss measurement



[V. Hannen *et al.*, Astropart. Ph. (2017)]

Tritium data-taking: start in 2018
KATRIN inauguration ceremony: June 11, 2018 (after NEUTRINO'18 at Heidelberg)

KATRIN: neutrino mass analysis & sensitivity



5σ simulated signal

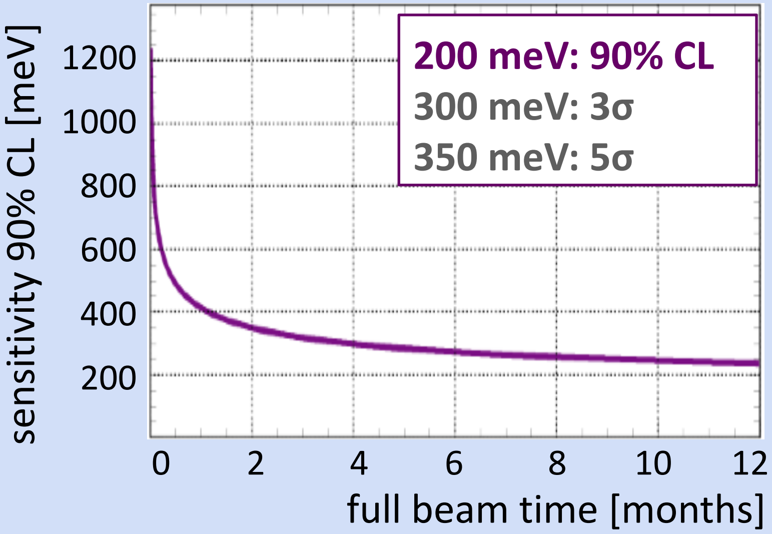
optimal m_ν^2 sensitivity at S/B ≈ 2

[E. Otten, 1994]

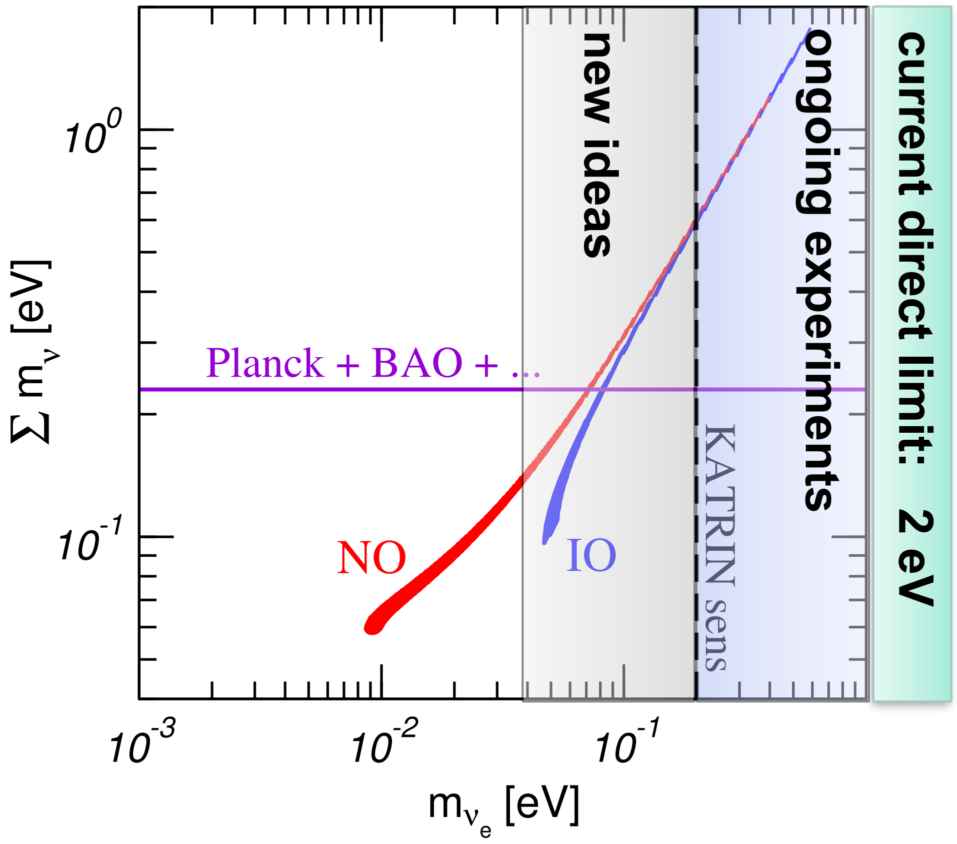
- Relative **shape** measurement of **integrated β spectrum**
- 4 fit parameters: m_ν^2 , E_0 , A_S , R_{Bg}

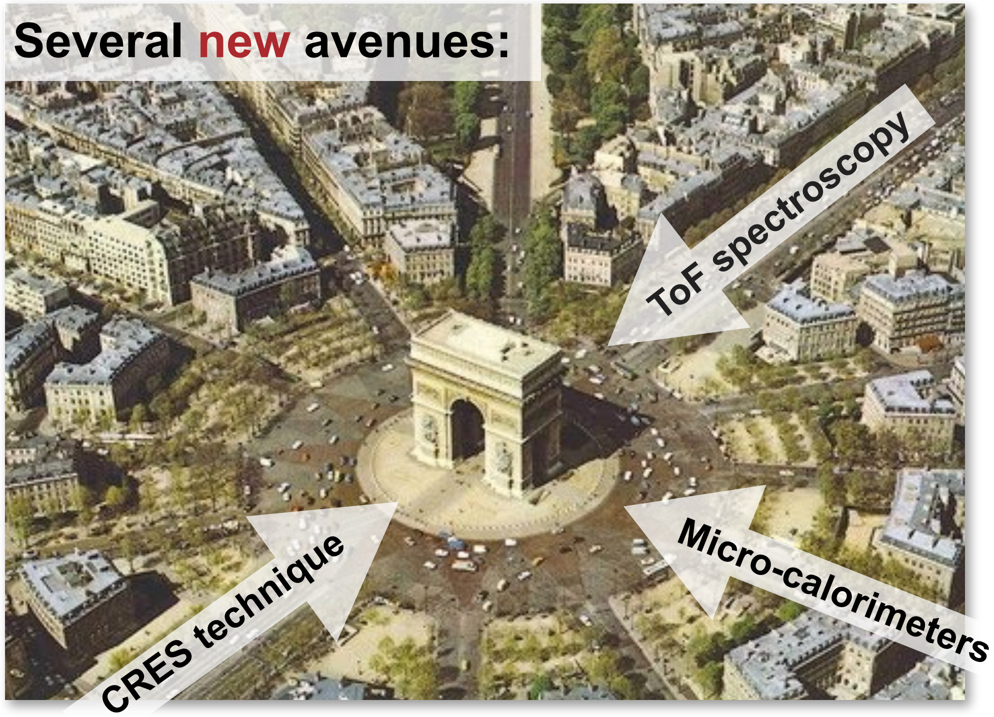
3 yrs (5 cal. yrs) to balance statistics and systematics

at design parameters:



Future prospects in direct neutrino mass search

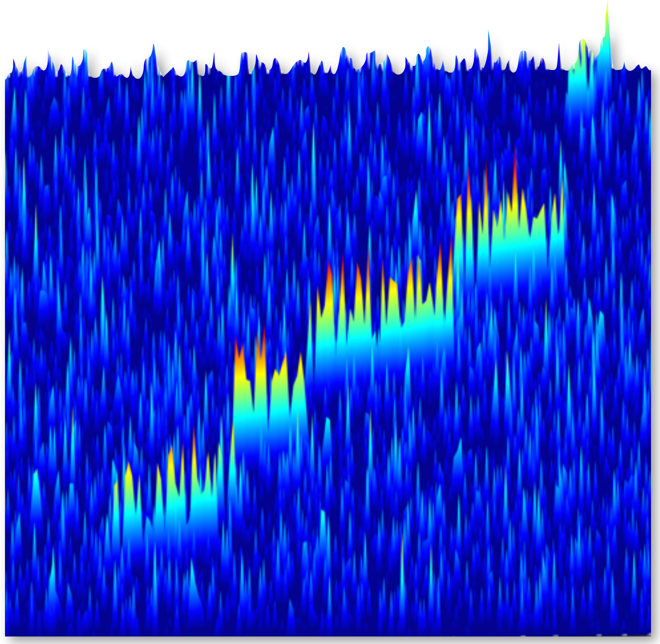




Challenges for further improvement:

- Opacity of gaseous T_2 source (already optimised for KATRIN, ~40% no-loss e^-)
- MAC-E filter measures *integral* beta spectrum
- Molecular final state excitations (vib: ~100 meV) as ultimate limitation for T_2

Frequency-based approach

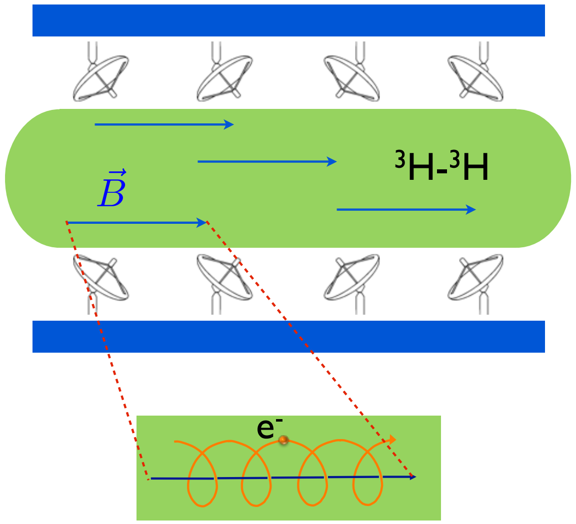


Cyclotron Radiation Emission Spectroscopy (CRES)

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

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

$$\omega(\gamma) = \frac{\omega_\mathrm{c}}{\gamma} = \frac{eB}{E_\mathrm{kin} + m_\mathrm{e}}$$

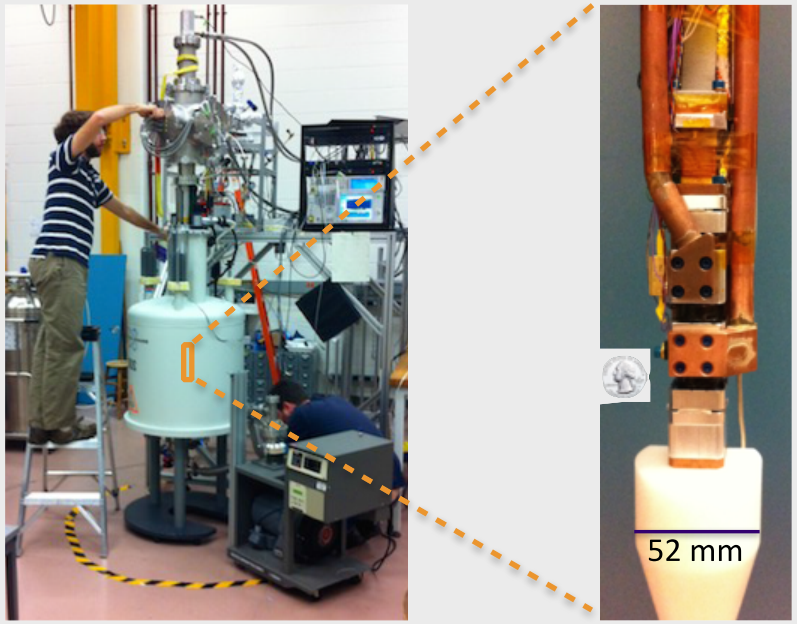


uniform B-field, magnetic trap

low-pressure gas cell

antenna array

Phase I system

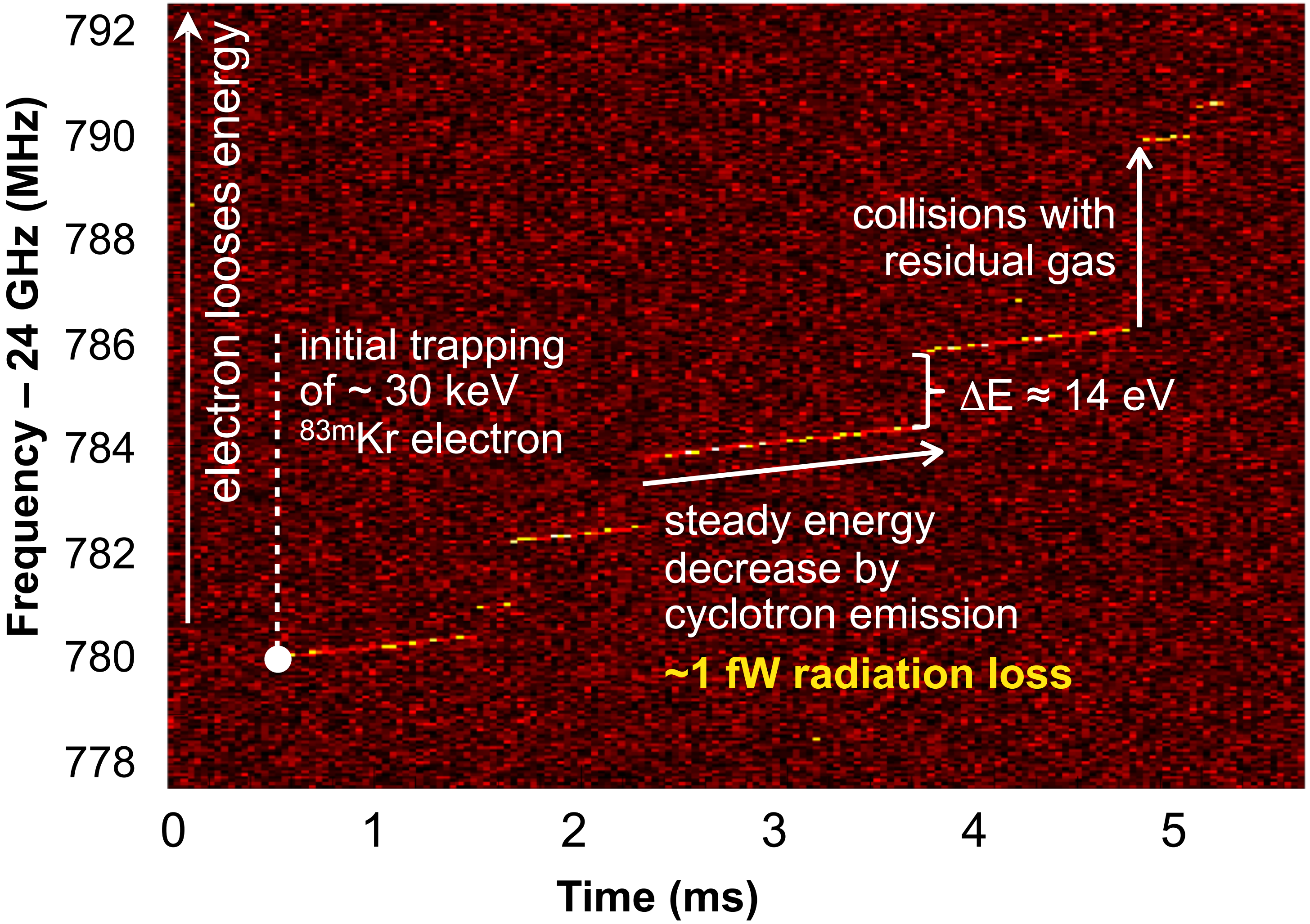


➜ Proof of principle of CRES technique

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

Project 8: phase I results

First observation of cyclotron radiation from single keV electrons



electron looses energy

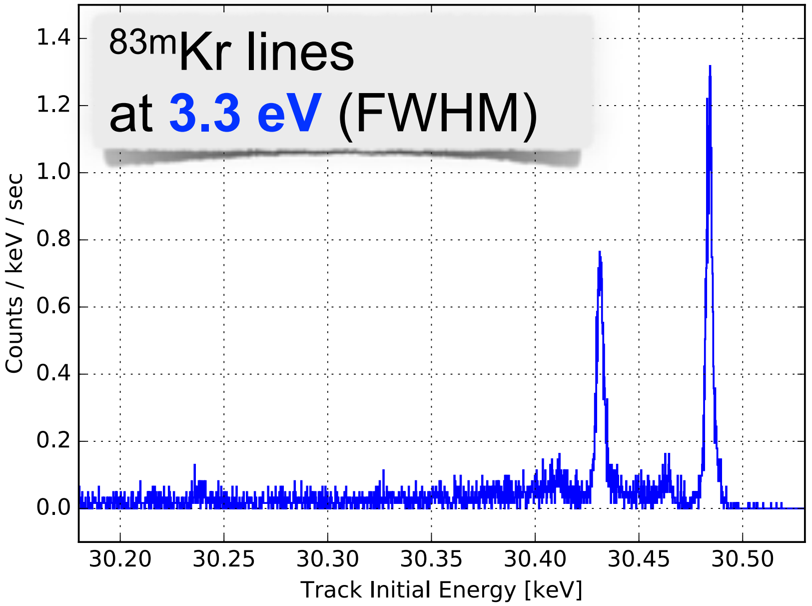
initial trapping of ~ 30 keV ^{83m}Kr electron

collisions with residual gas

ΔE ≈ 14 eV

steady energy decrease by cyclotron emission

~1 fW radiation loss



^{83m}Kr lines at **3.3 eV** (FWHM)

[Asner *et al.*, PRL 114 (2015) 162501; La Roque et al., NEUTRINO 2016]

Project 8: staged approach

- **Phase I (2010-2016): proof of principle**

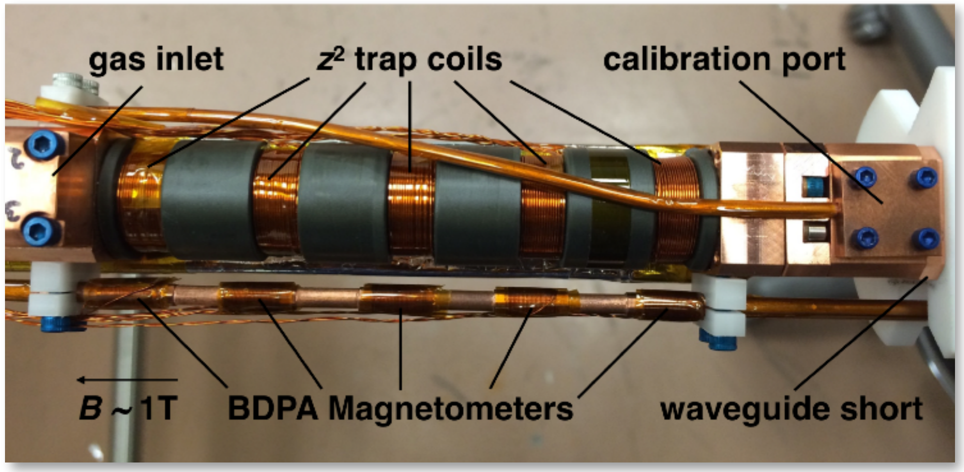
  Single-electron CRES demonstrated
  with conversion electron lines from ^{83m}Kr

- **Phase II (2015-2017): tritium demonstrator**
  - Improved waveguide, read-out, energy resolution, systematics study
  - Continuous T_2 β-spectrum, $m(\nu_e) \sim 100 \ldots 10$ eV

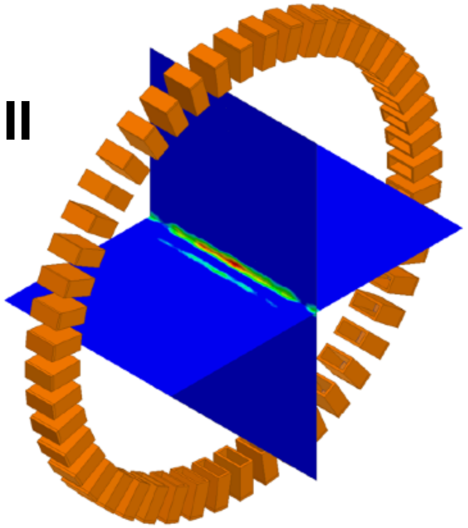
- **Phase III (2016-2020): large volume demonstrator**
  - Conceptual design for “open” receiver array, MRI magnet
  - 10^5 Bq in 200 cm^3 volume (10 cm^3 effective)
  - Tritium data competitive with $m(\nu_e) \sim 2$ eV (1 yr)

- **Phase IV (2017+): atomic tritium source**
  - R&D for large-volume (200 m^3) atomic tritium source (< 1 K), magnetic confinement
  - goal: sub-eV sensitivity at inverted hierarchy scale

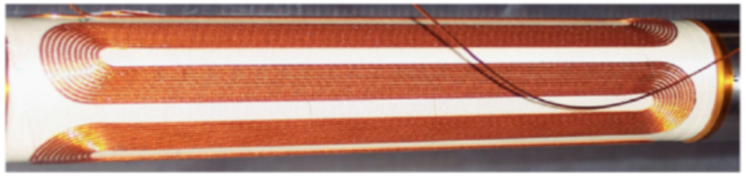
Phase II



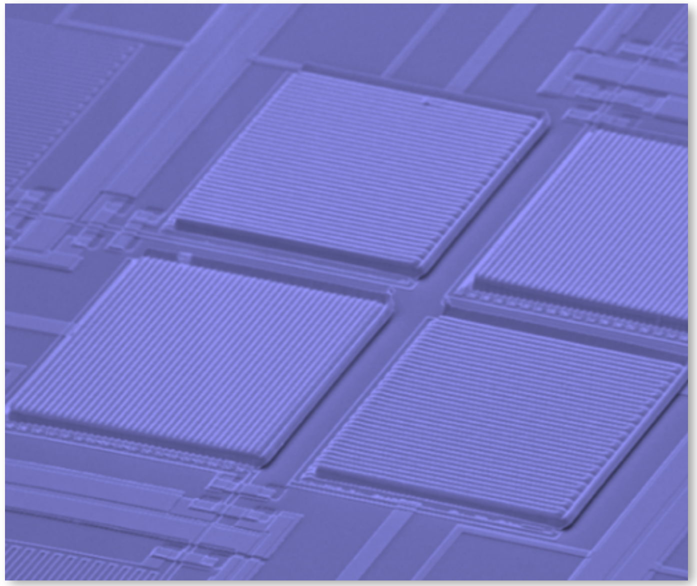
Phase III



Phase IV



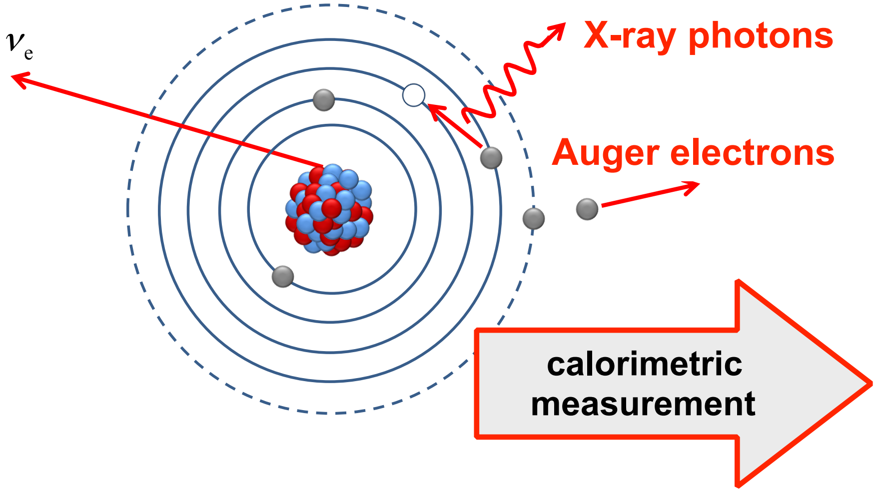
Calorimetric approach using ^{163}Ho



ν-mass from ^{163}Ho electron capture

$^{163}\mathrm{Ho} \rightarrow {}^{163}\mathrm{Dy}^{*} + \nu_e$

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



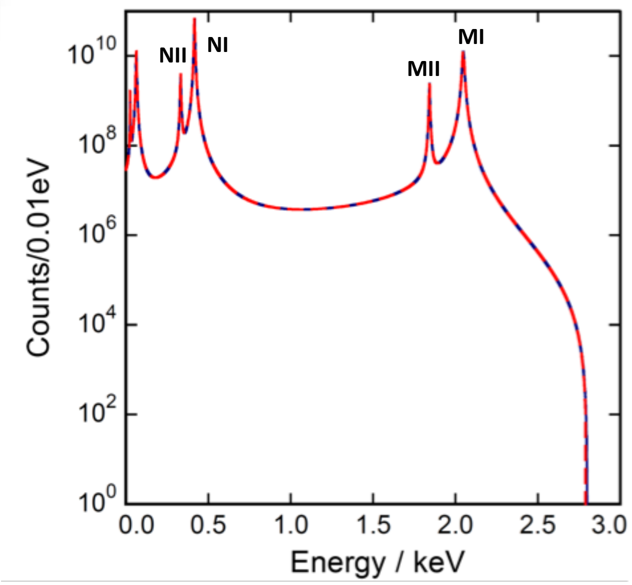
ν_e

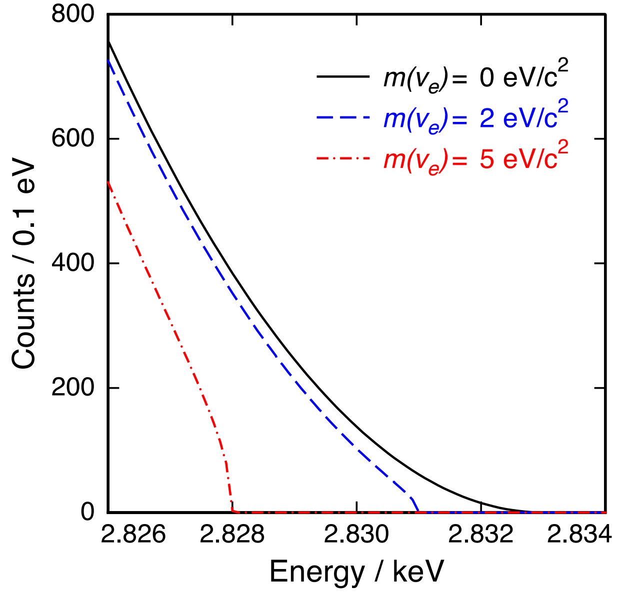
X-ray photons

Auger electrons

calorimetric measurement

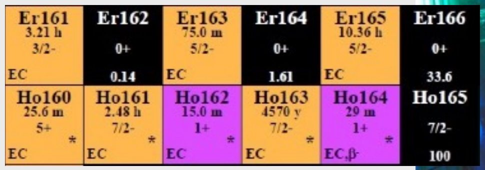
[De Rujula & Lusignoli 1982]





Challenges:

- Production & purification of isotope ^{163}Ho
- Incorporation of ^{163}Ho into high-resolution detectors
- Operation & readout of large calorimeter arrays
- Understanding of calorimetric spectrum (nuclear & atomic physics + detector response)

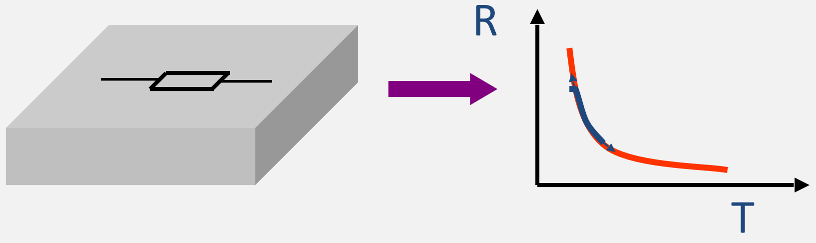


Er161 3.21 h 3/2- EC	Er162 0+ 0.14	Er163 75.0 m 5/2- EC	Er164 0+ 1.61	Er165 10.36 h 5/2- EC	Er166 0+ 33.6
Ho160 25.6 m 5+ * EC	Ho161 2.48 h 7/2- * EC	Ho162 15.0 m 1+ * EC	Ho163 4570 y 7/2- * EC	Ho164 29 m 1+ * EC,β-	Ho165 7/2- 100

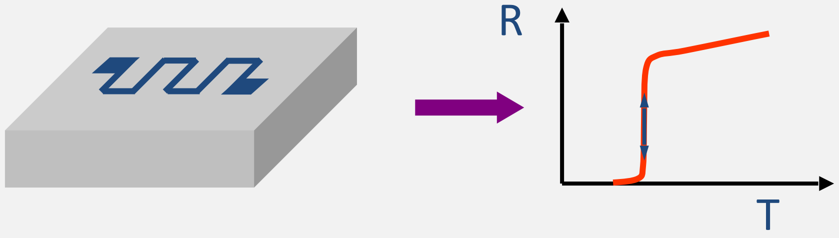
[L. Gastaldo]

Temperature sensors — technologies

Resistance of highly doped semiconductors

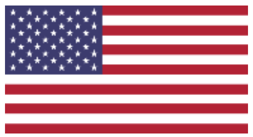


Resistance at superconducting transition, TES

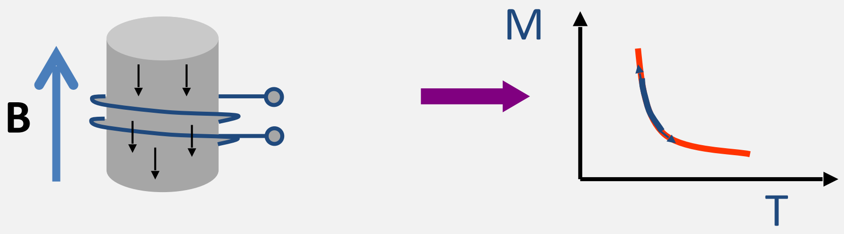


HOLMES

NuMECS



Magnetization of paramagnetic material, MMC



ECHo

CERN

India Slovakia
Hungary Russia

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

World-wide efforts in ^{163}Ho-based ν-mass search

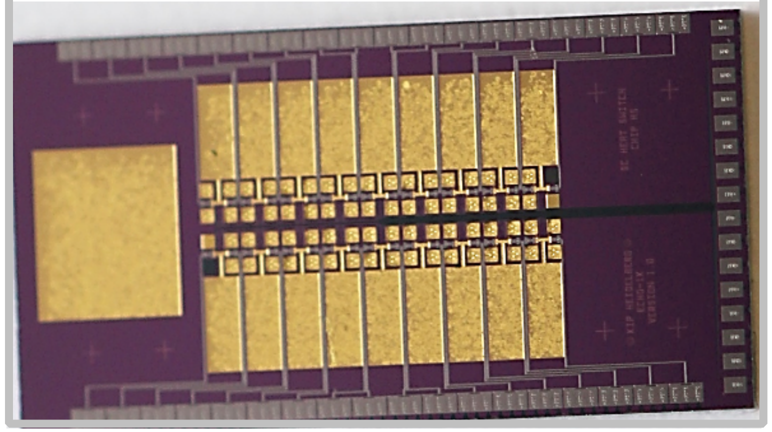
Karlsruhe Institute of Technology

ECHo

CERN
India Slovakia
Hungary Russia

- Metallic Magnetic Calorimeters
- ΔE < 5 eV achieved

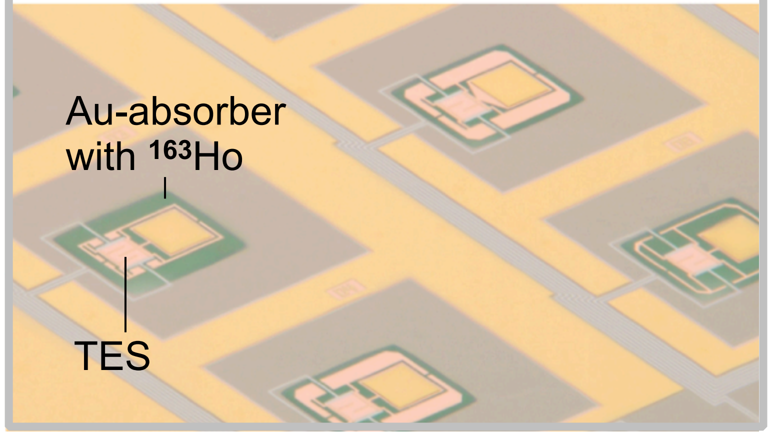
- m(ν) sensitivity:
  10 eV with ECHo-1k (2015-18)
  sub-eV with ECHo-10M



HOLMES

- Transition Edge Sensors
→ detectors from NIST
→ implanting at Genoa
→ cryostat at Milano
- ΔE ~ 1 eV design

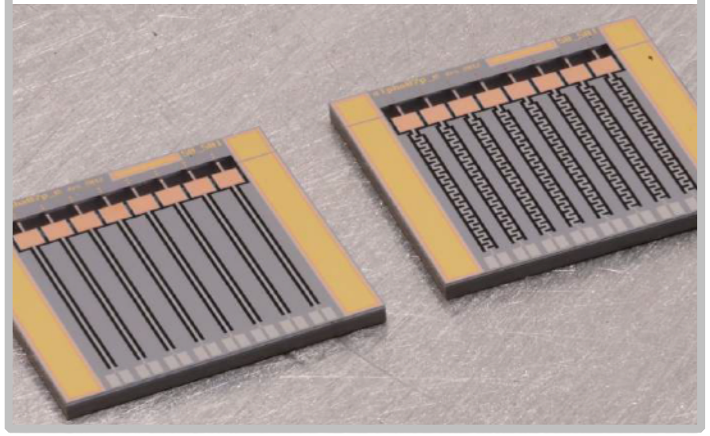
- sensitivity: m(ν) ~ 1 eV
  2018-20



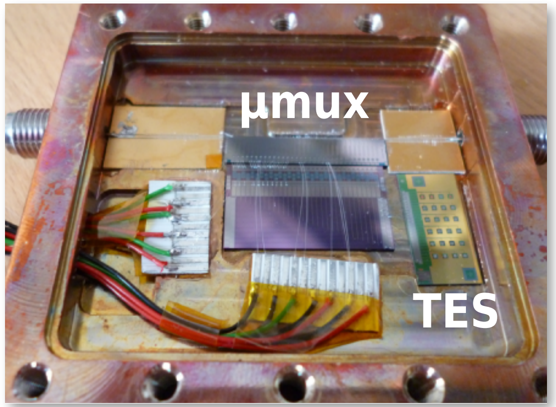
NuMECS

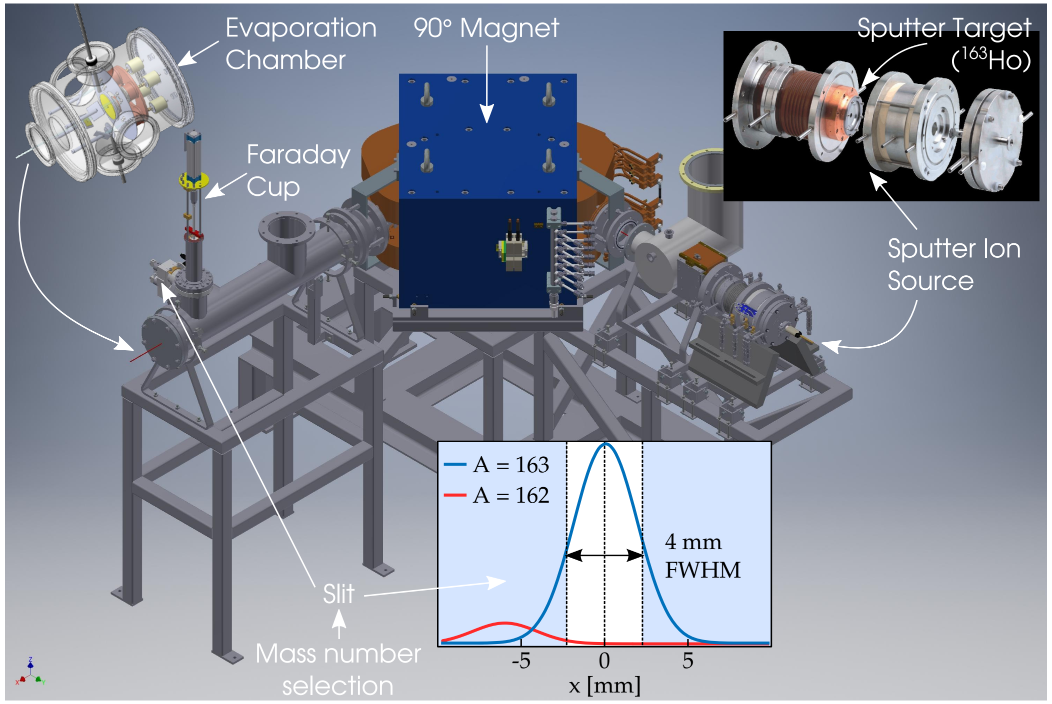
- Testing concepts of ^{163}Ho-incorporation and TES read-out
- ΔE ~ 35 eV achieved

- sensitivity: mostly R&D up to now, maybe large array?

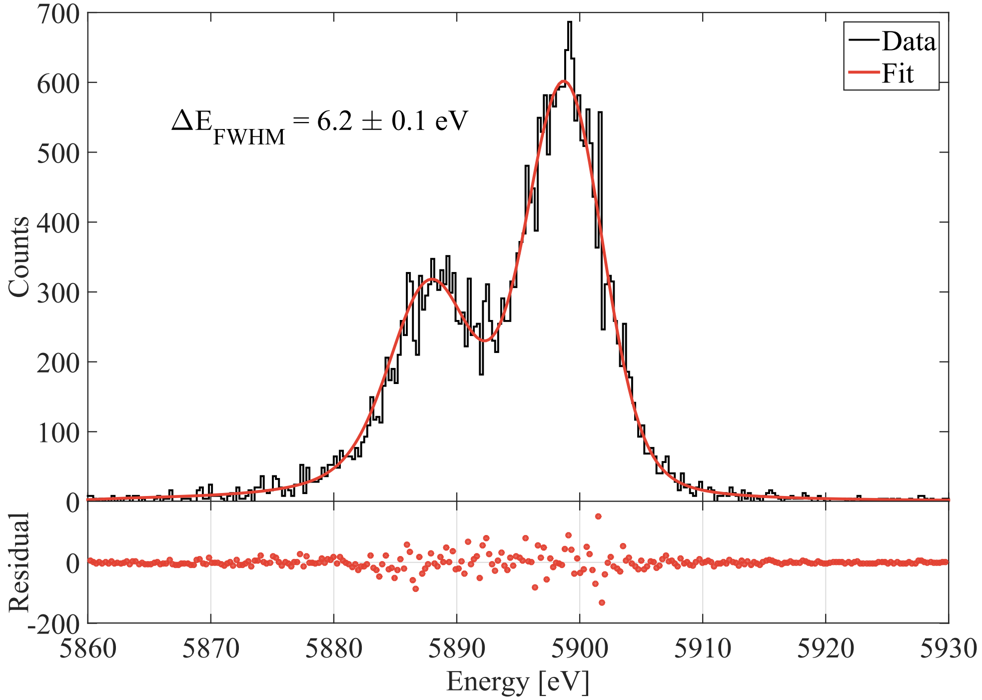


TES technology: HOLMES





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



Custom mass-separator ion implanter at Genova

HOLMES design & timeline:

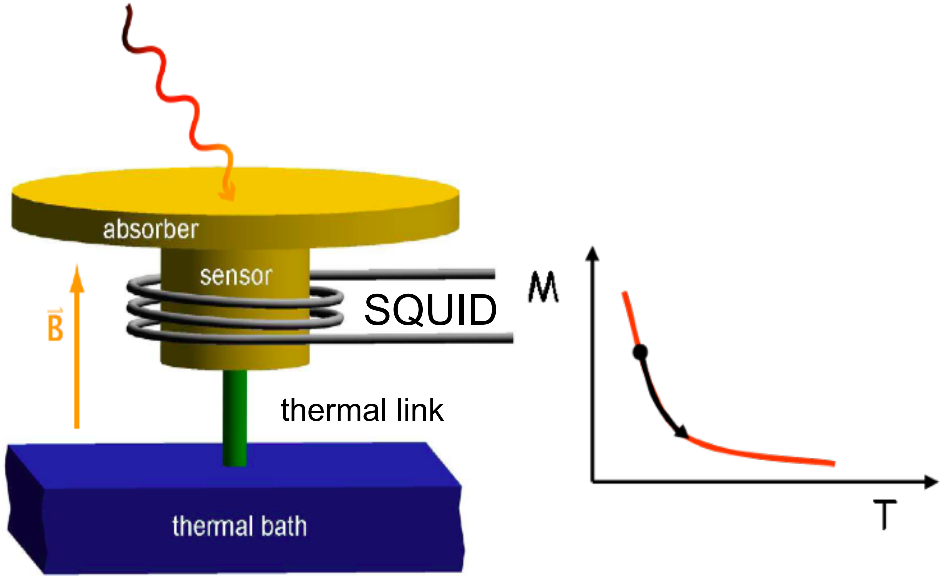
- 6.5 x 10^{13} nuclei ^{163}Ho (~300 Bq) per pixel
- ΔE ~ 1 eV, τ_{rise}~ 1 μs;
  1000-pix array (**1 eV goal**) expected for 2018
- TES array + DAQ ready, first implant. coming up
- Spectrum measurements to begin in late 2017
- **32 pixels for 1 month → m_ν sensitivity ~10 eV**

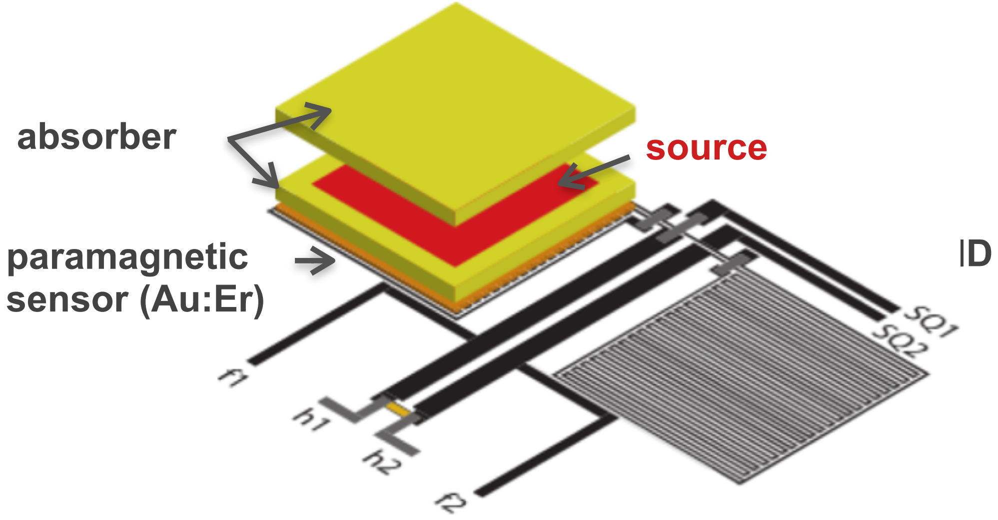
[A. Giachero et al., JINST 12 (2017) C02046]

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

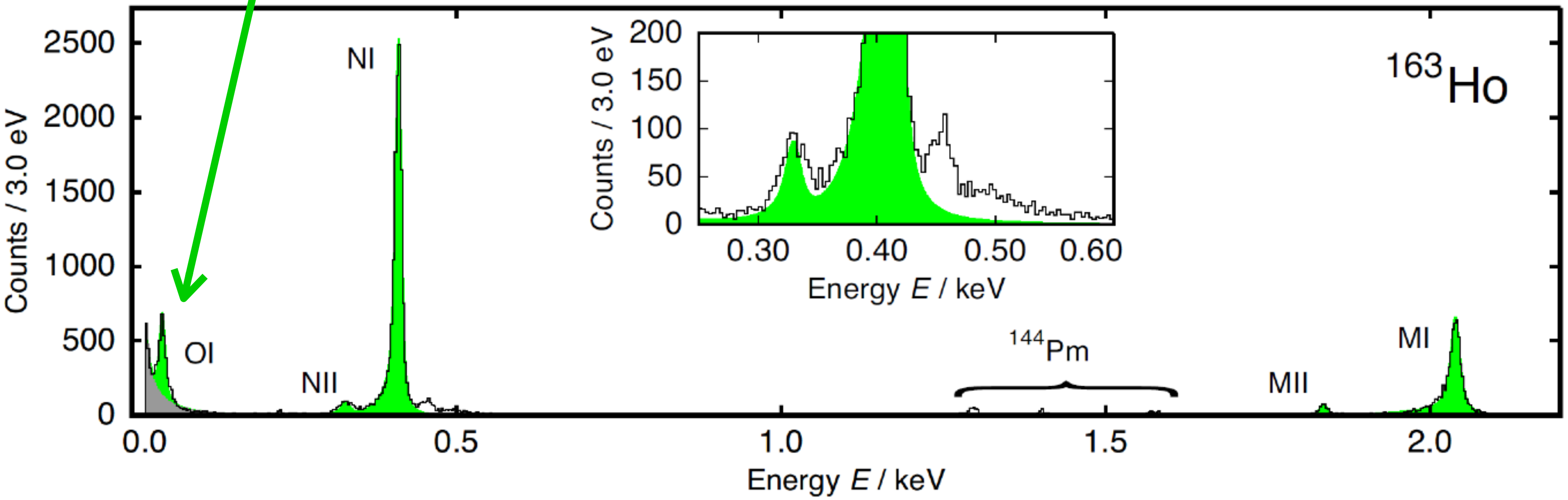
- Fast rise time (~130 ns) and excellent linearity & resolution ($\Delta E_{FWHM} < 5$ eV)
- Production: ^{162}Er(n,γ)^{163}Ho at ILL/Grenoble implantation at ISOLDE-CERN & RISIKO
- Multiplexed readout of MMC arrays

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

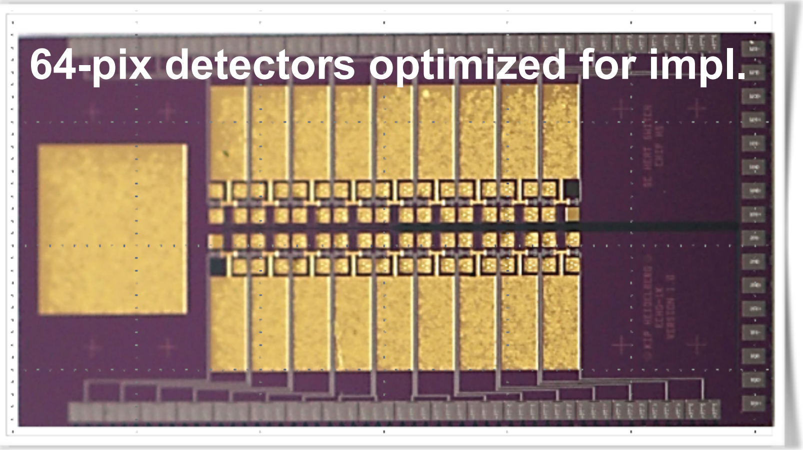
[Gastaldo *et al.* (2014)]

MMC technology: ECHo

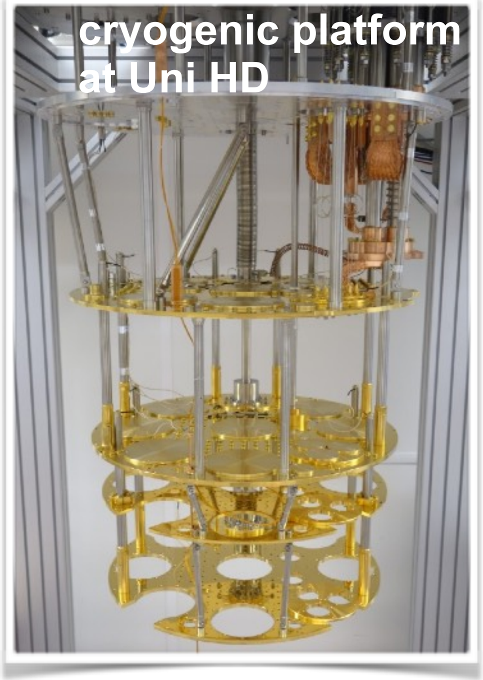
Precision ^{163}Ho spectrum
first calorimetric measurement of OI-line



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

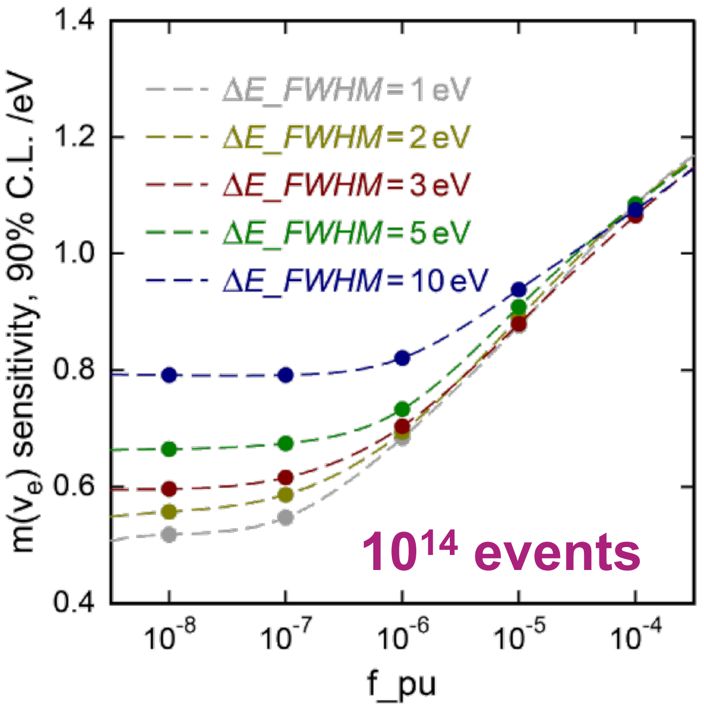

64-pix detectors optimized for impl.


16-ch SQUID MUX, proof of concept


cryogenic platform at Uni HD

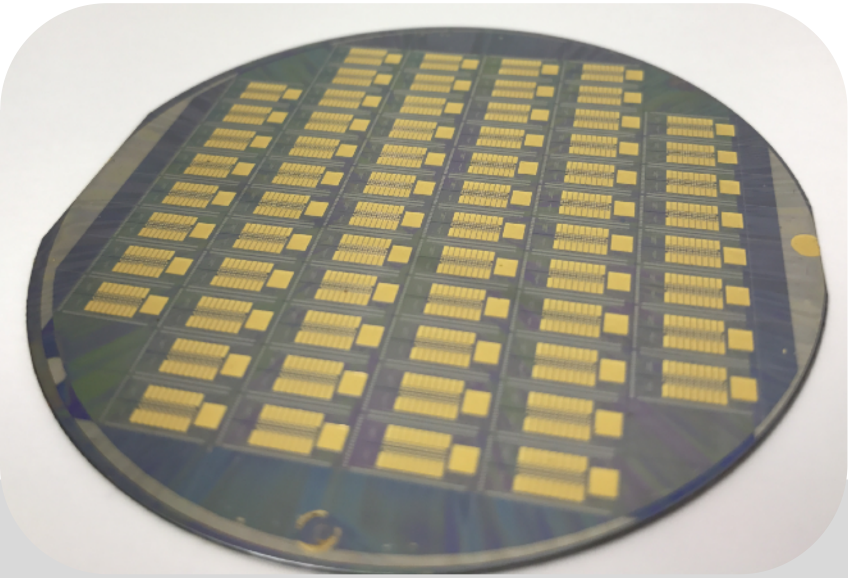
ECHo : Timeline

- **ECHo-1k** (2015-2018)
  - prove scalability with medium-sized array: 100 detectors x 10 Bq
  - 1 yr meas. time for $N_{\mathrm{event}} \sim 10^{10}$:
    ➜ $m(\nu_e) < 10$ eV
- Next step: **ECHo-1M**
  - large-scale experiment for sub-eV sensitivity
    100 arrays of 1000 detectors, at 10 Bq each
  - sterile neutrino search at eV and keV scale

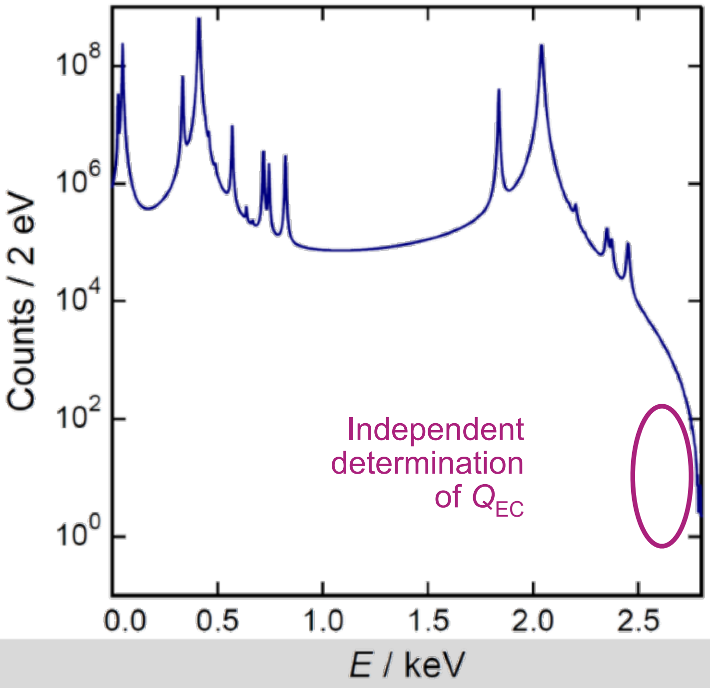


[courtesy L. Gastaldo]

Chip fabrication for multiplexed MMC arrays



Impact of higher-order excitations on ^{163}Ho EC spectrum



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

Direct ν-mass determination: status and outlook

current achievements → **next goals**

KATRIN

Full beamline commissioning with ^{83m}Kr; start of T_2 data in 2018

Long-term data-taking (5 yrs) for full sensitivity **(0.2 eV)**

Project 8

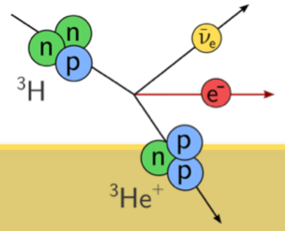
CRES proof of principle with ^{83m}Kr, testing new cell for T_2

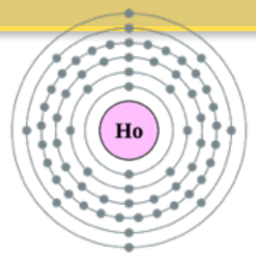
Develop CRES for **10 → 2 eV,** and towards IH (atomic source)

PTOLEMY

R&D for atomic source concept, MAC-E + calorimeter

Devise large-scale experiment to tackle m(ν) and CνB





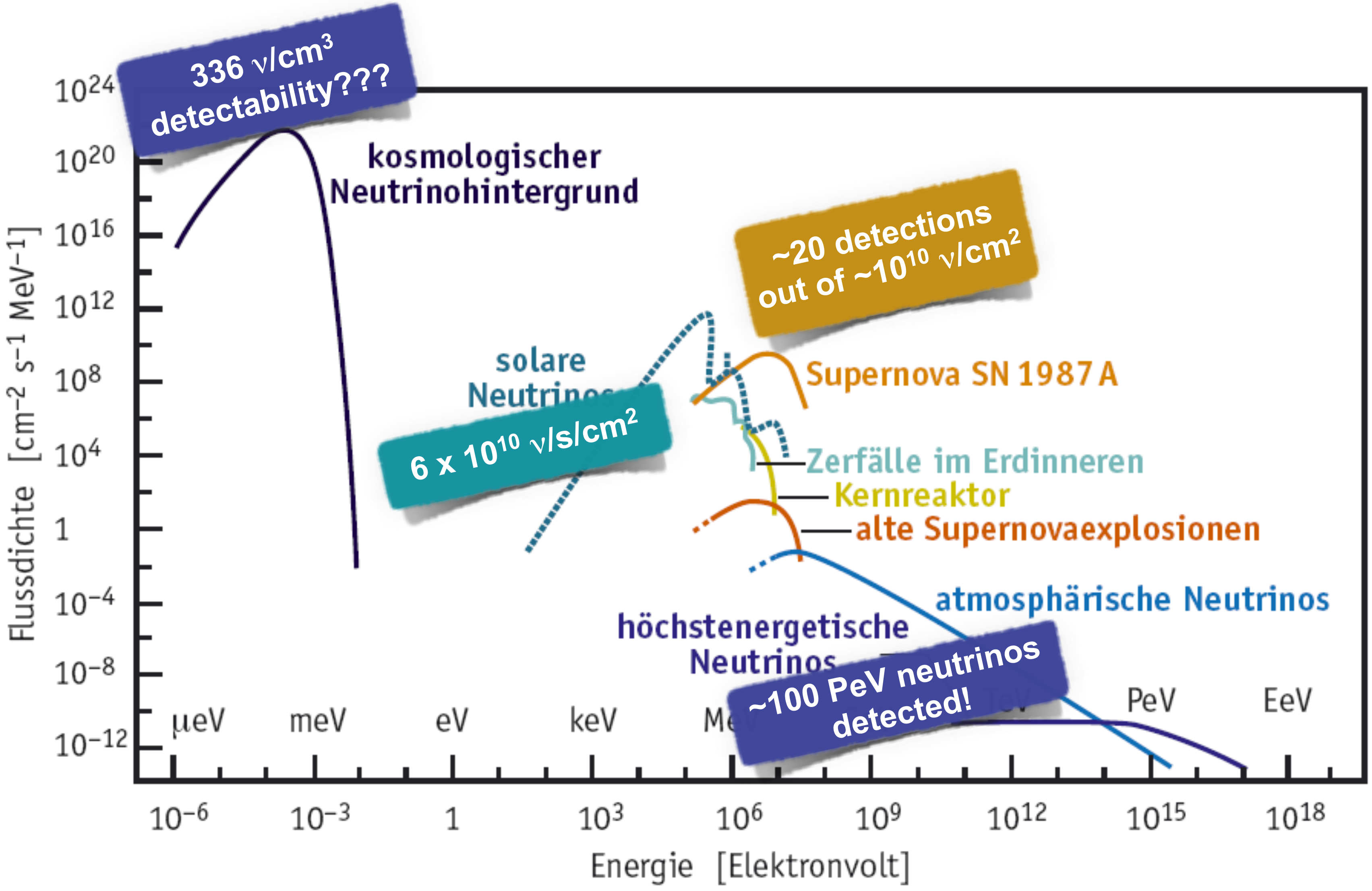
ECHo
HOLMES
NuMECS

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

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

Summary / Take-away

- We learned a lot about neutrinos since their “invention” in 1930
- We exploit a large variety of neutrino sources in our experiments!



$336\ \nu/\mathrm{cm}^3$ detectability???

~20 detections out of $\sim 10^{10}\ \nu/\mathrm{cm}^2$

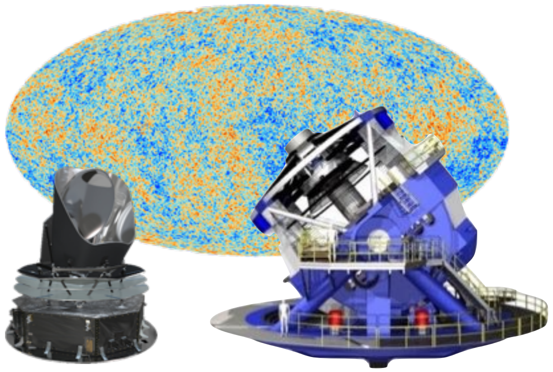
$6 \times 10^{10}\ \nu/\mathrm{s/cm}^2$

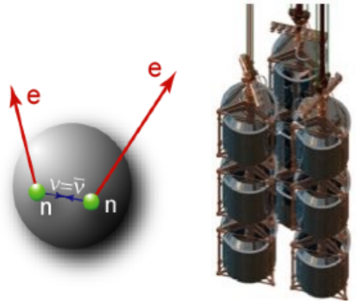
~100 PeV neutrinos detected!

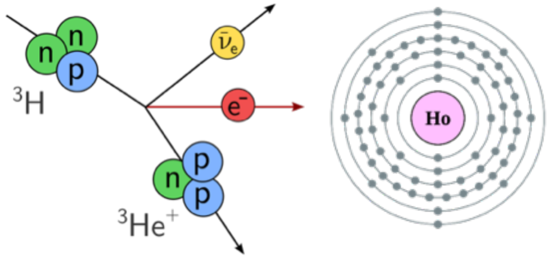
Summary / Take-away

- Massive neutrinos …
  - are evidence for physics beyond the Standard Model
  - are the only currently known form of Dark Matter
    (their contribution is small, their role not quite fixed yet - what about sterile neutrinos?)
- Neutrinos can point us towards …
  - novel mass-generating concepts in particle physics
    (open question regarding Dirac or Majorana nature of neutrinos)
  - lepton flavour violation (oscillations) and lepton number violation ($0\nu\beta\beta$)
  - leptonic CP violation
- We need to understand the mass pattern of neutrinos
  … and be open for (more) surprises. :)

Complementary paths to the ν mass scale



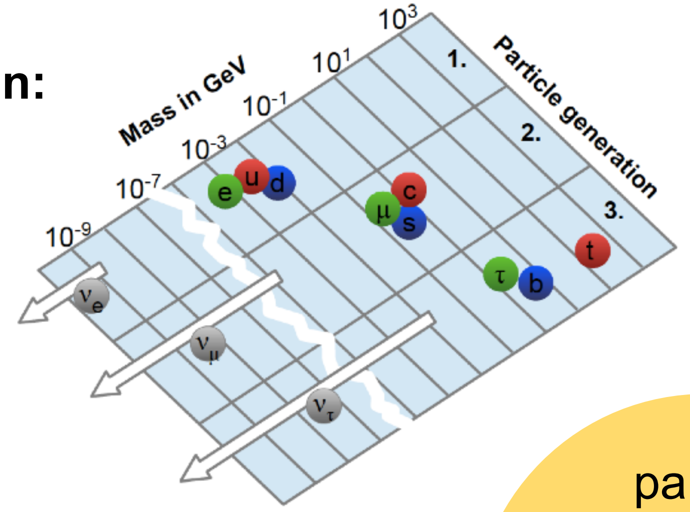




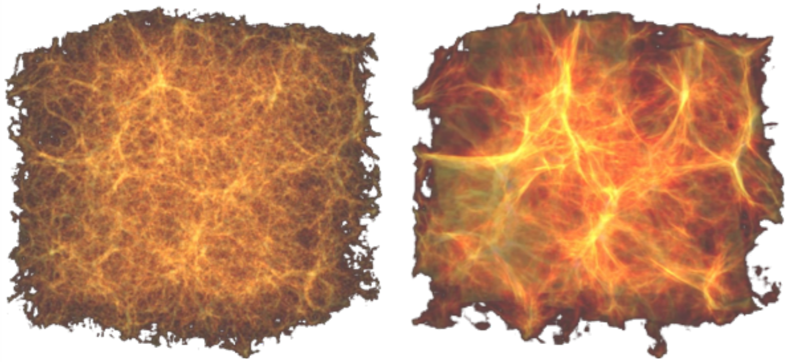
	Cosmology	Search for 0νββ	β-decay & EC
Observable	$M_\nu = \sum_i m_i$	$m_{\beta\beta}^2 = \left\lvert \sum_i U_{ei}^2 m_i \right\rvert^2$	$m_\beta^2 = \sum_i \lvert U_{ei}\rvert^2 m_i^2$
Present upper limit	~0.2 – 0.6 eV	~0.1 – 0.4 eV	2 eV
Potential: near-term (long-term)	60 meV (15 meV)	50 – 200 meV (20 – 40 meV)	200 meV (40 – 100 meV)
Model dependence	Multi-parameter cosmological model	- Majorana ν: LNV - BSM contributions other than m(ν)? - Nuclear matrix elements	**Direct,** only kinematics; no cancellations in incoherent sum

Massive neutrinos: connecting the micro- and the macro-cosmos

mass generation: new concepts

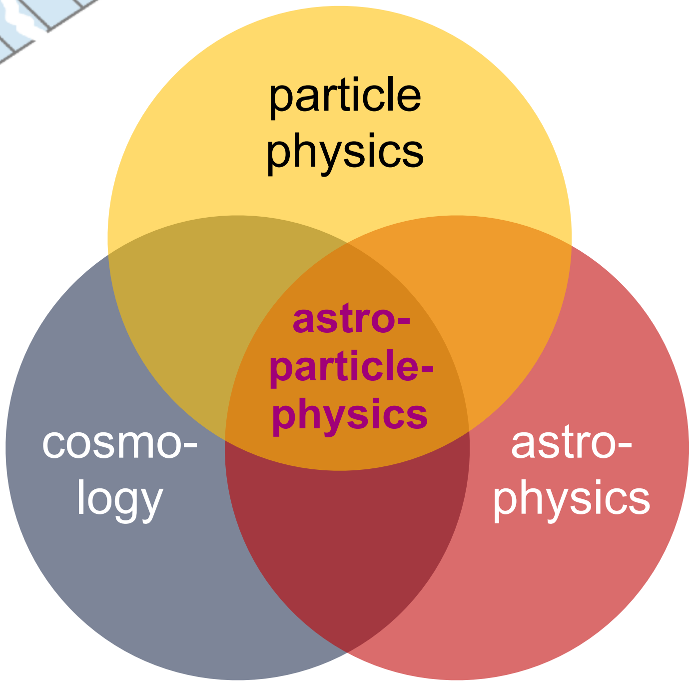


massive neutrinos as “cosmic architects”



Σm_ν = 0 eV

6.9 eV



particle physics

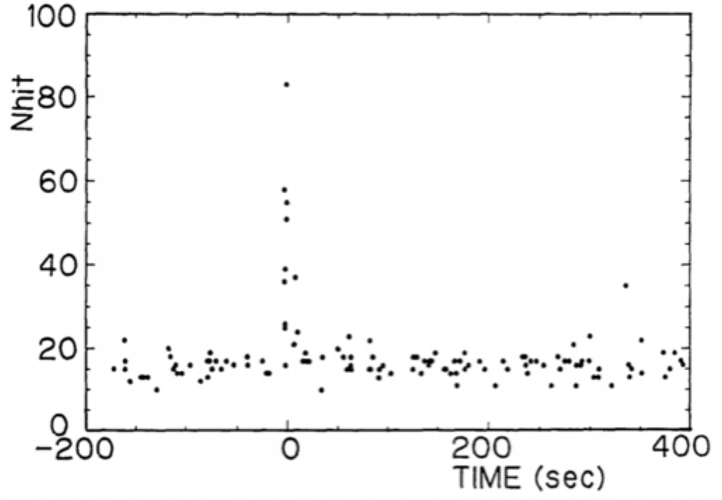
cosmo-logy

astro-physics

astro-particle-physics

understanding astrophysical processes

Neutrino burst from SN 1987a



Matter effects in the sun