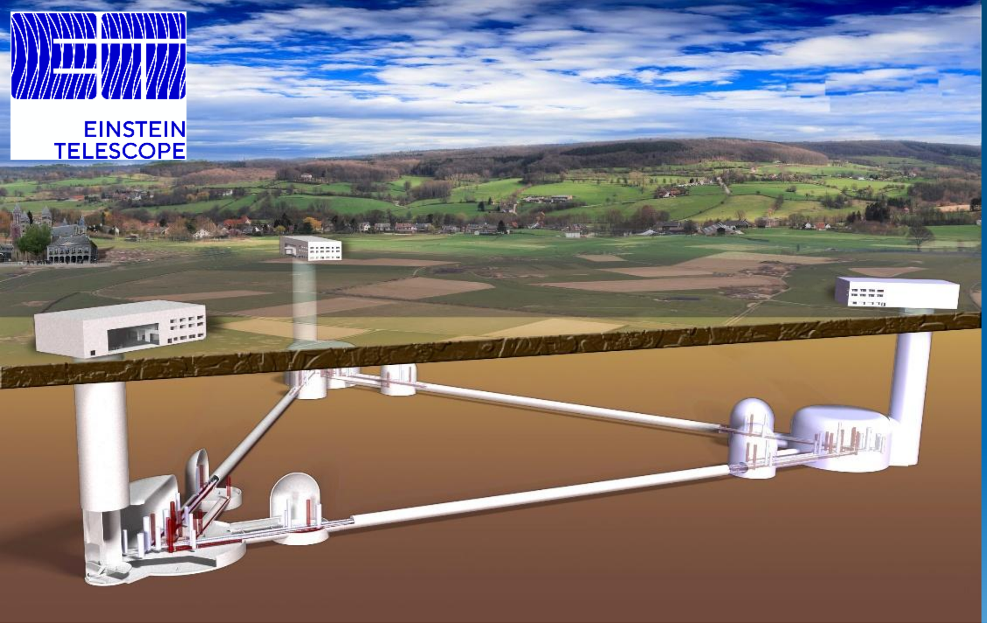


Field Emission Sources for Astro-Particle Physics Projects

10th VDE ITG Int. Vacuum Electronics Workshop 2026 and 16th Int. Vacuum Electron Sources Conference 2026

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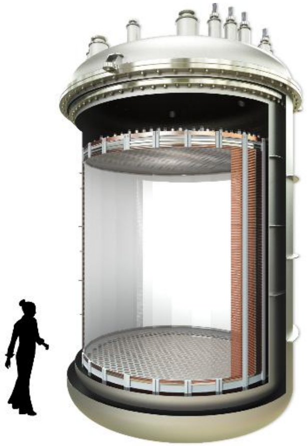
APP experiments covered in this talk

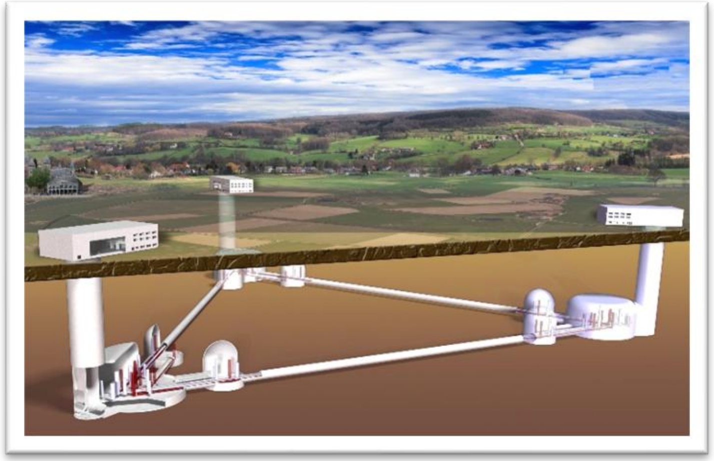
KATRIN

- Measurement of the **neutrino mass**
- Tritium beta-decay electrons
- Tritium source with 10^{11} decays/s
- Method:
  - Gaseous tritium source: 18.6 keV e^-
  - Electro-static high pass filter (MAC-E)
  - Segmented Si-detector (SDD)
  - Energy resolution: 1 eV @ 20 keV
- Ca. 150 collaboration members



XLZD

- Search for **WIMP dark matter**
- **Neutrinoless double-beta-decay**
- Sensitive to neutrinos: sun, SN, …
- Method:
  - 2-phase Liquid/gaseous Xe TPC (80 t)
  - 3-D track reconstruction
  - High voltage drift field
  - Ultra low background (<0.1µBq/kg Rn)
- Ca. 500 collaboration members



Einstein Telescope

- Observation of **gravitational waves**
- Merger of black holes, neutron stars, …
- Sensitivity: change of earth‘s diameter by one proton diameter
- 3rd gen. GW observatory
  - 6 IR interferometers, 10 km each leg
  - UHV with < 10^{-10} mbar
  - Cryogenic mirrors (10 K) ➔ ice !!!
- Ca. 2000 collaboration members

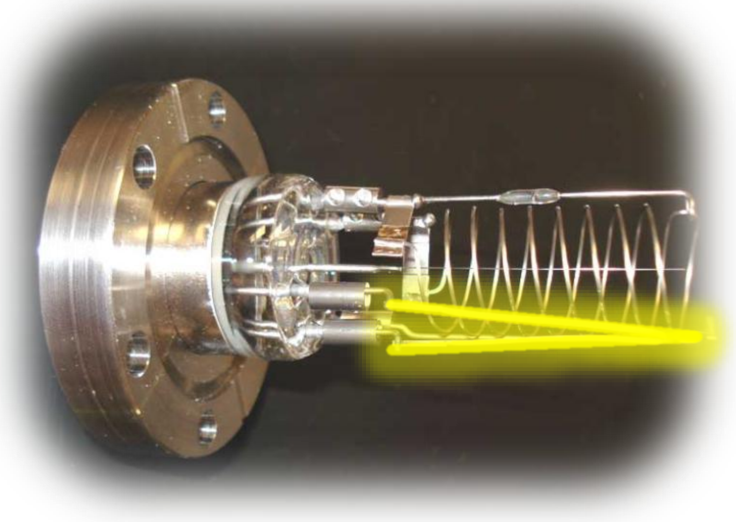
Why are FE electron sources interesting for these APP experiments?

- **Technologies used in APP experiments:**
  - Ultra-high vacuum (< 10^{-10} mbar)
  - Cryogenics
    - Cold mirrors (for noise reduction in ET)
    - Solid state detectors: mK – 230 K
    - Liquid nobel gases (e.g. Ar, Xe)
  - Light sensitive detectors (e.g. PIN diodes, Photo-Multiplier, SDD detectors, …)

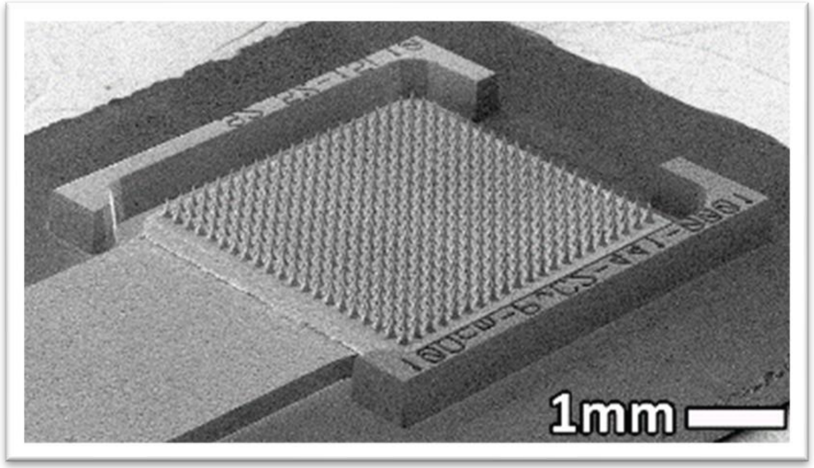
- **Applications with electrons**
  - E-gun for detector calibration
    - Post acceleration for mono-energetic electrons with 1 – 40 keV energies
    - X-ray source for detector calibration
  - e-beam for in-situ cleaning of cryogenic surfaces (ESD, electron stimulated desorption)
  - Ionization of molecules (e.g. for Rn removal, vacuum gauges, RGA, …)

Why are FE electron sources interesting for these APP experiments?

- **Standard electron source:**
  - **hot filaments** (e.g. tungsten with 2200 – 2600 K)
    - Increased outgassing from walls ➔ increased local pressure
    - Light background for detectors ➔ increased dark current
    - Radiative heat source in cryogenic applications
  - **UV light (photo-electric effect)**
    - Light background for detectors
- **Cold electron source:**
  - Penning discharge in CC vacuum gauges (less accurate)
  - **Field Emission**
    - Single tip or arrays
    - Requires R&D for **homogeneity** (arrays) and **long-term stability**

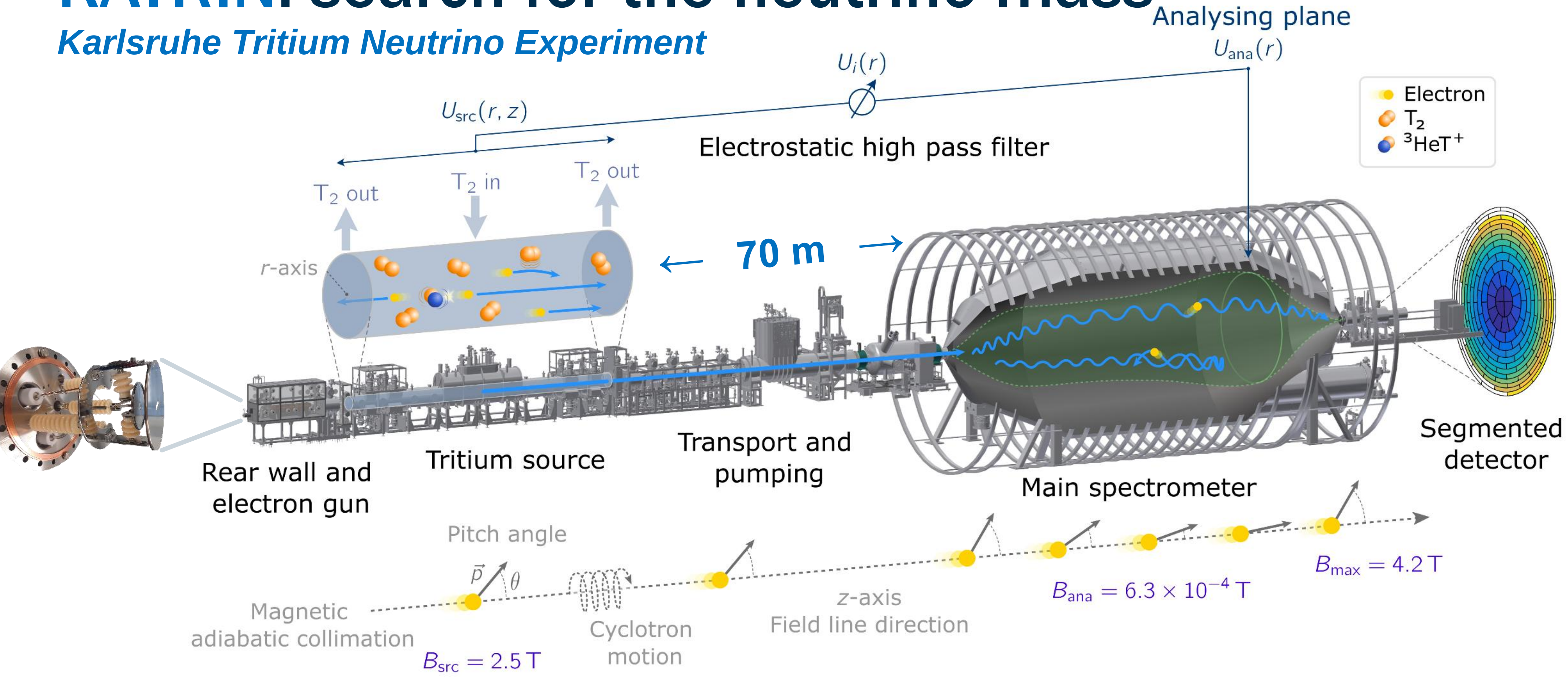


By K. Murray (Kkmurray) *- Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=1974522*



KATRIN: search for the neutrino mass

Karlsruhe Tritium Neutrino Experiment



Electron gun
- Quasi-monoenergetic electrons from 0 – 30 keV
- Low rates: 100 - 10^5 electrons/s ➔ aA – fA (per detector pixel)
- Electron production with pulsed UV-laser on gold-coated glas tip

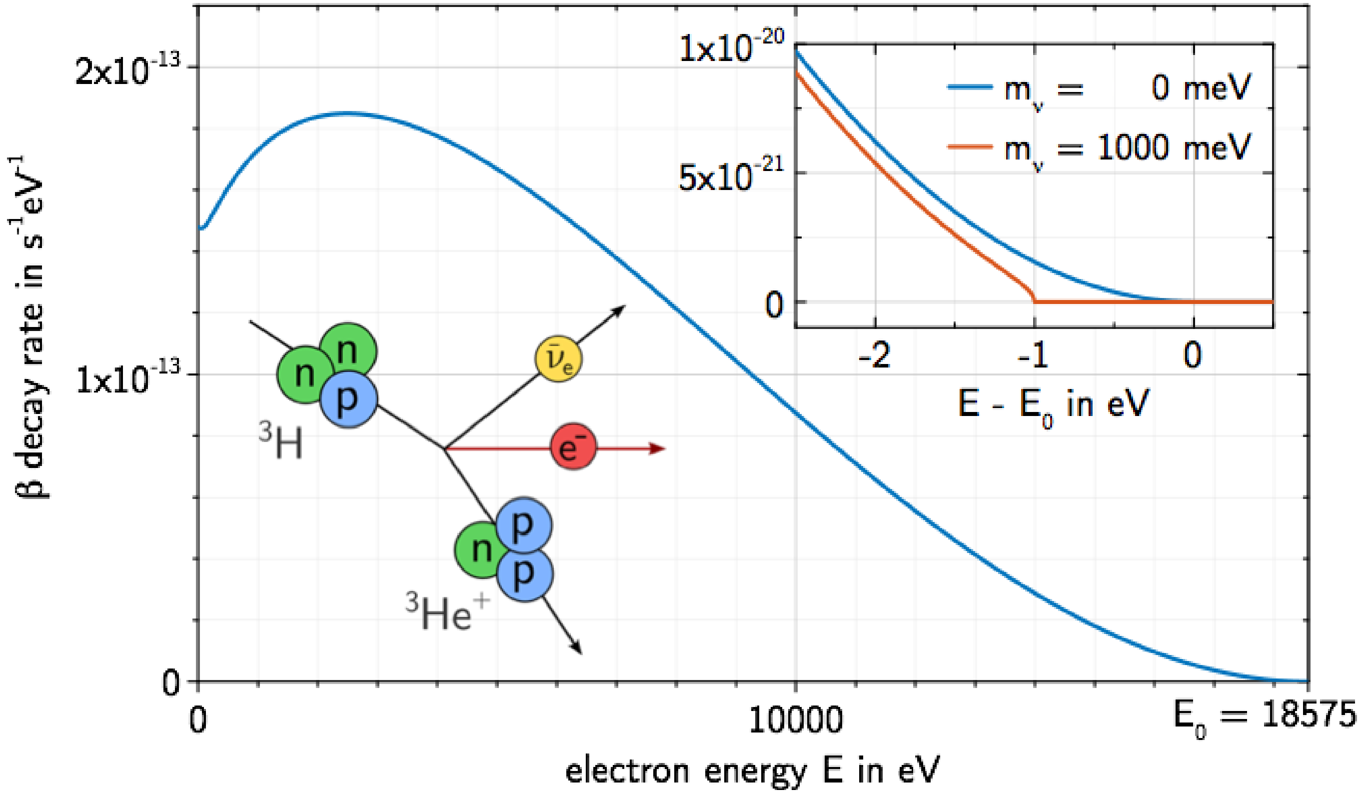
Main Spectrometer
- V = 1240 m³, p = 10^{-11} mbar
- Extractor gauges and RGA (hot filaments ➔ FEA ?)

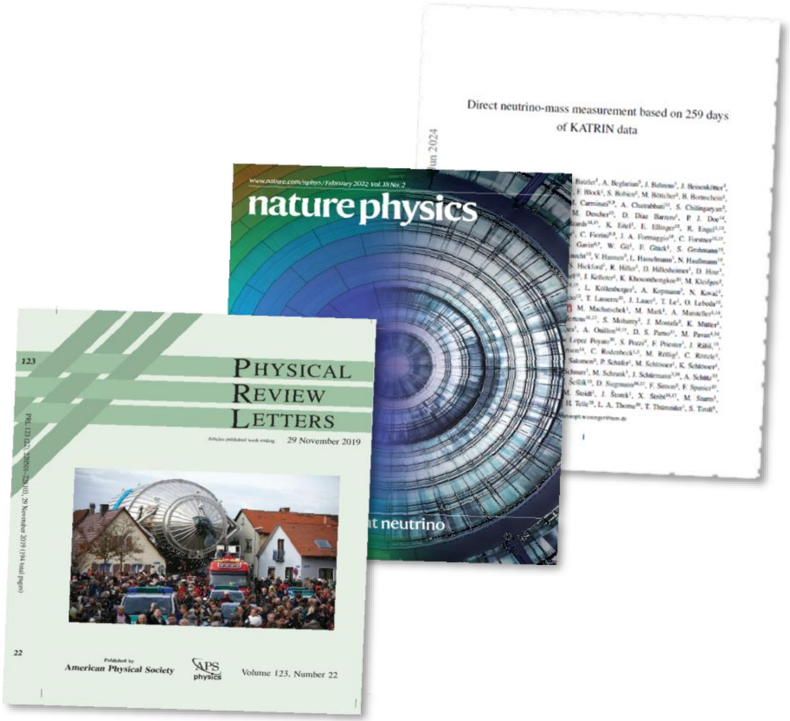
Detector
- 148 pixel PIN-diode
- AmBe calibration
- Goal: X-rays (FEA)

KATRIN: search for the neutrino mass

Next steps for KATRIN:

- **Phase I (2001 – 2026):**
  - Search for the effective neutrino mass (best limit: < 0.45 eV/c², 20% of data)
  - Status: data acquisition finished, analysis ongoing (goal: < 0.3 eV/c²)





Direct neutrino-mass measurement based on 259 days of KATRIN data

*The KATRIN Collaboration, Science **388** (issue 6743), 180–185 (2025)*

KATRIN: search for the neutrino mass

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  - Search for the effective neutrino mass (best limit: < 0.45 eV/c², 20% of data)
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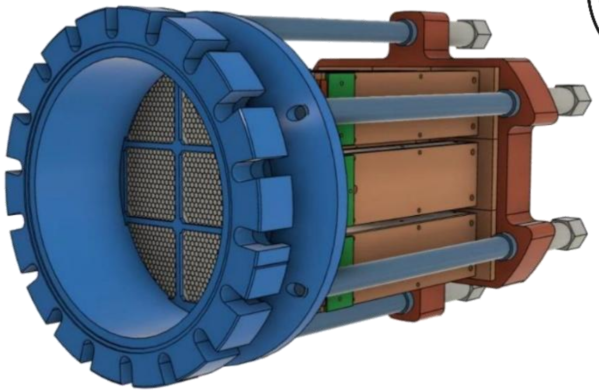
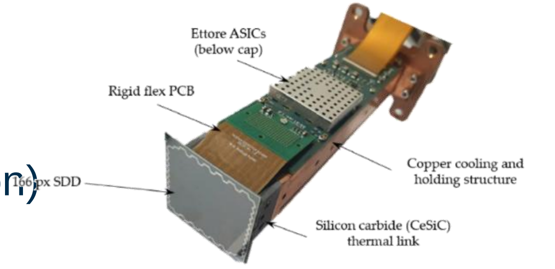
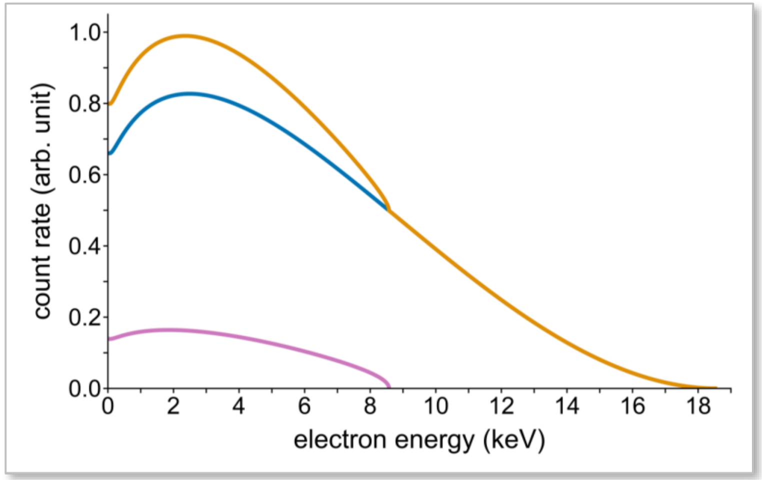
- **Phase II (2026): Silicon-Drift-Diode (SDD) detector with ~1000 pixel**
  - Search for sterile neutrinos
  - ~ 1000 pixel SDD-modules: diff. Spectrum with 200 eV @ 20 keV
  - Molecular gaseous tritum source (vibrational and rotational modes limit resolution)
  - Signature: ~10^{-6} admixture to active neutrinos ➔ tiny kink in spectrum
  - Very sensitive to tiny systematic effects, e.g. backscattering from SDD
  - Accurate calibration of required with e^- and X-rays close to the SDD





***TRISTAN detector module** with 166 pixels*



KATRIN: search for the neutrino mass

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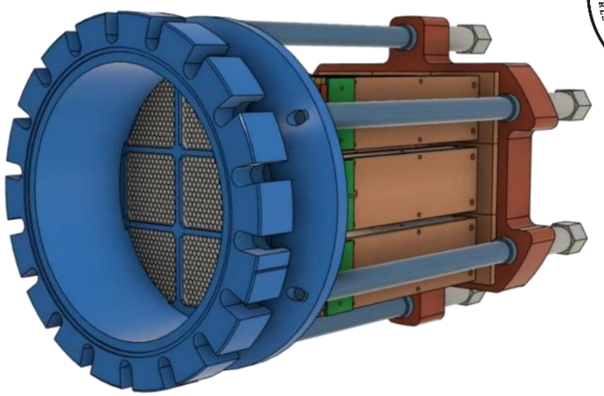
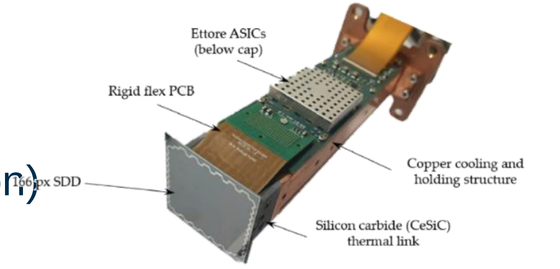
  - Very sensitive to tiny systematic effects, e.g. backscattering from SDD
  - Accurate calibration of required with e^- and X-rays close to the SDD
- **Phase III (10 years ?): 10-times improved sensitivity for neutrino mass**
  - Time of Flight spectroscopy
  - Cryogenic quantum sensor array, ~ 10^6 pixels, T = 10 mK
  - Atomic gaseous tritium source
  - No heat source allowed in direct line of sight of the detector
  - Even higher requirements for calibration and systematic effects





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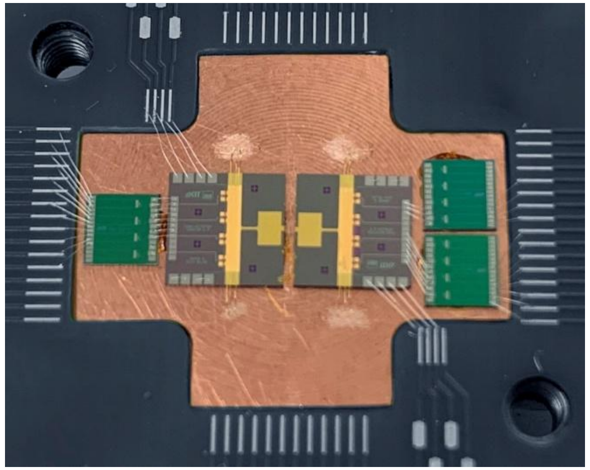
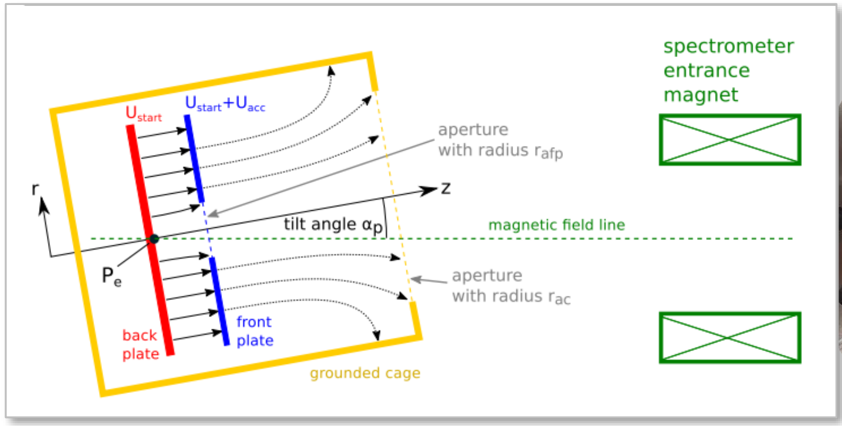


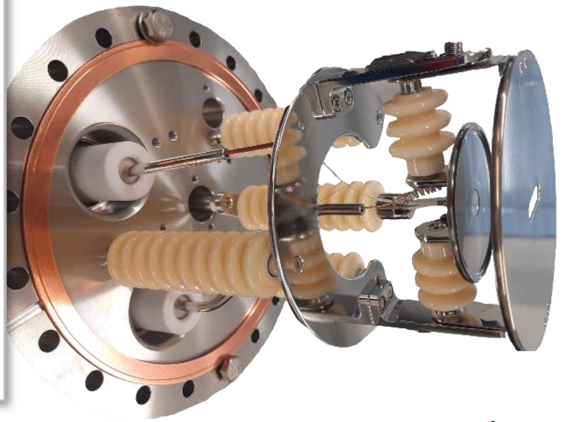
R&D: 8 channel detector chips & front-end SQUID chips

KATRIN: search for the neutrino mass

FE arrays for KATRIN

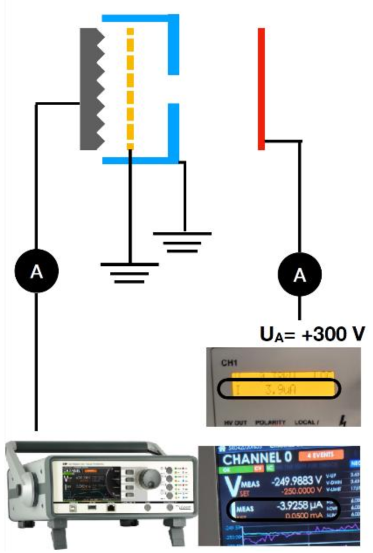
- **e-gun**
  - Post acceleration up to 30 kV
  - Adjustable emission angle

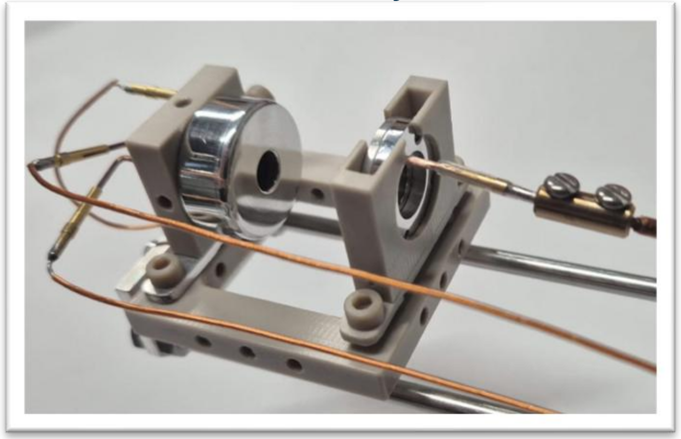




Münster University

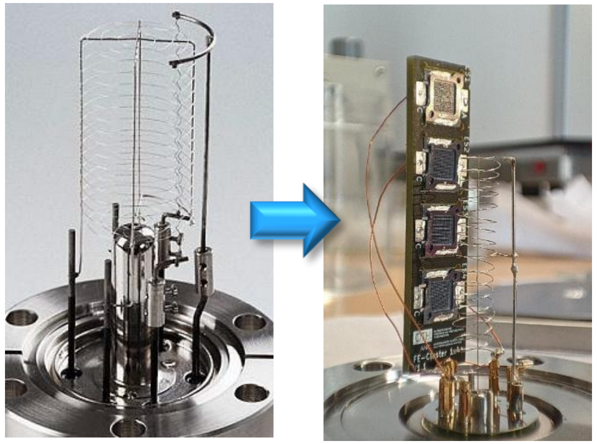
- **X-ray source**
  - Post acceleration up to 30 kV
  - Different metal targets





Wuppertal University

- **Vacuum gauges**
  - Bayert-Alpert
  - Extractor



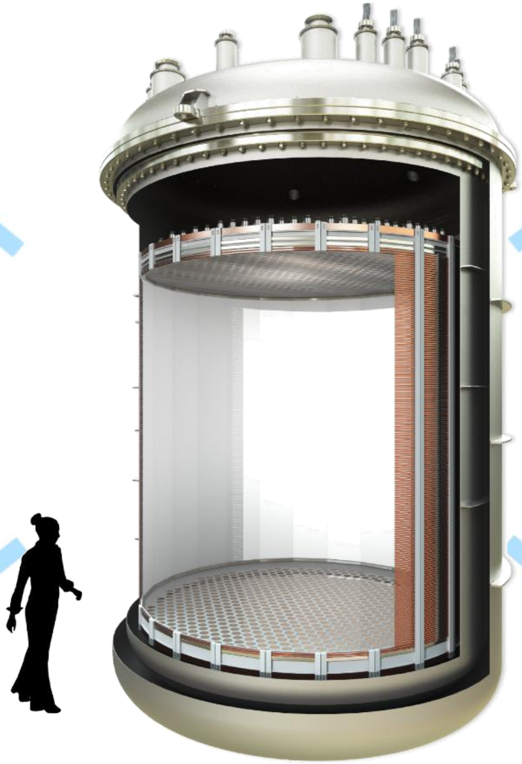
OTH Regensburg

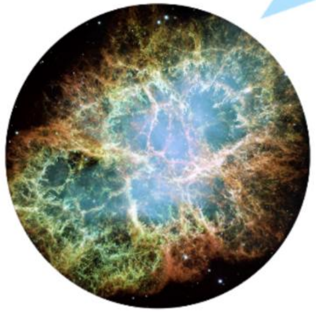
- **RGA**

XLZD: search for dark matter and more

Dark Matter
WIMPs
Sub-GeV
Inelastic
Axion-like particles
Planck mass
Dark photons

Neutrino nature
Neutrinoless double beta decay
Neutrino magnetic moment
Double electron capture





Supernovae
Early alert
Supernova neutrinos
Multi-messenger astrophysics

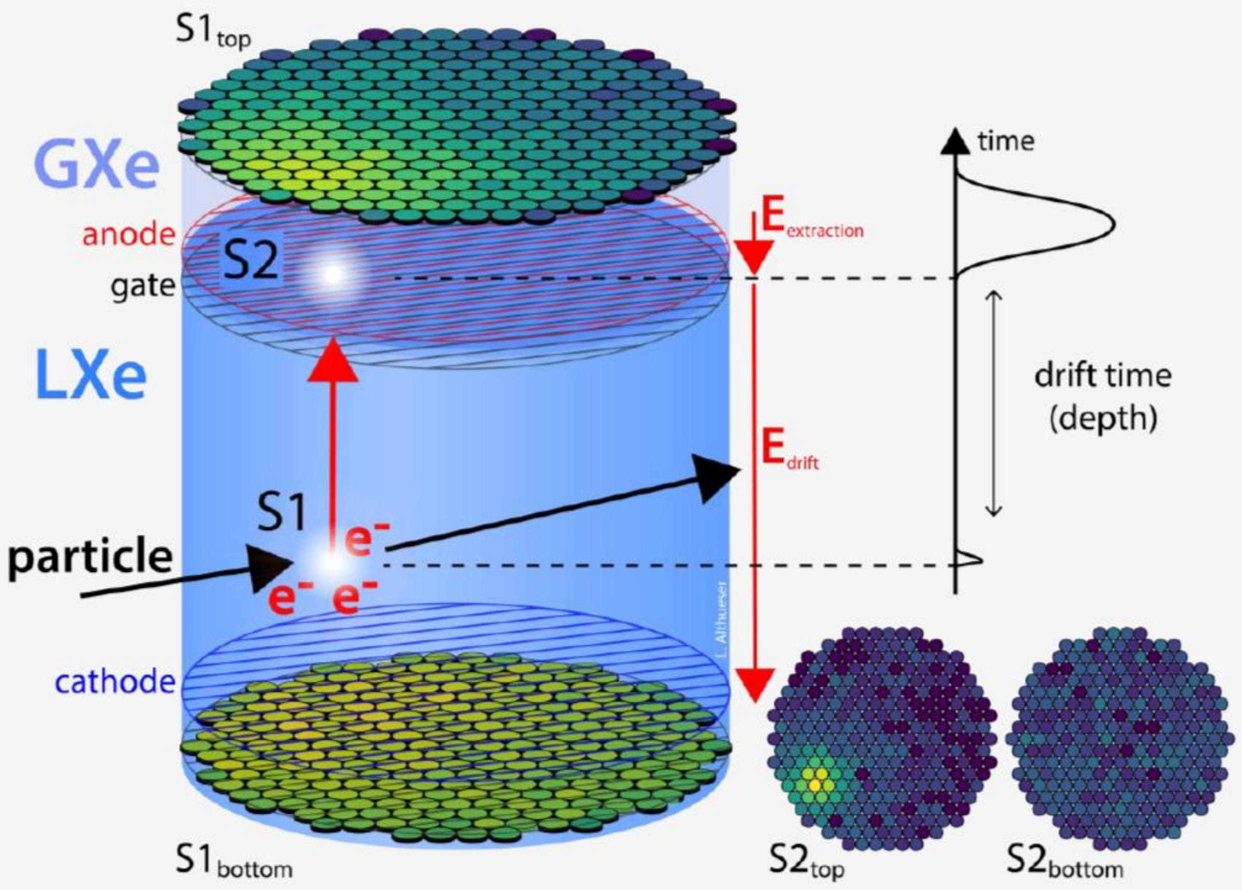
Sun
pp neutrinos
Solar metallicity
^{7}Be, ^{8}B, hep

XLZD: search for dark matter and more

Dark Matter
WIMPs
Sub-GeV
Inelastic
Axion-like particles
Planck mass
Dark photons

Supernovae
Early alert
Supernova neutrinos
Multi-messenger astrophysics

2-phase liquid Xe TPC
S1: Prompt scintilation signal
S2: delayed scintillation signal after drift time



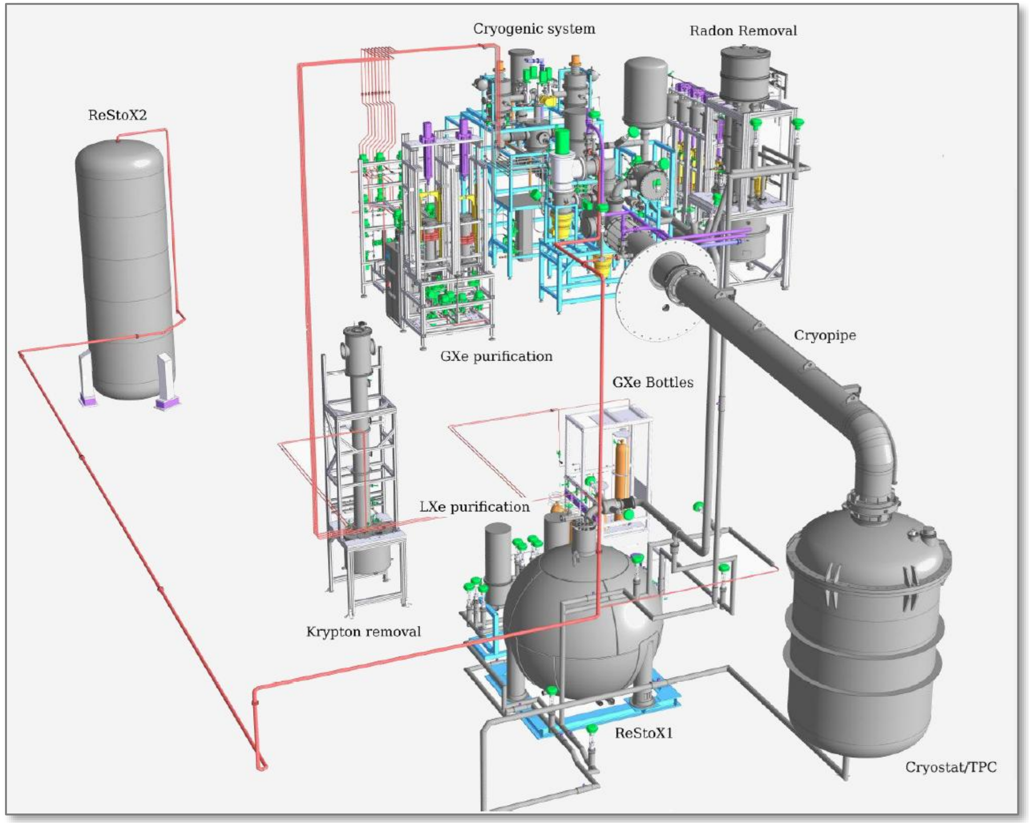
Neutrino nature
Neutrinoless double beta decay
Neutrino magnetic moment
Double electron capture

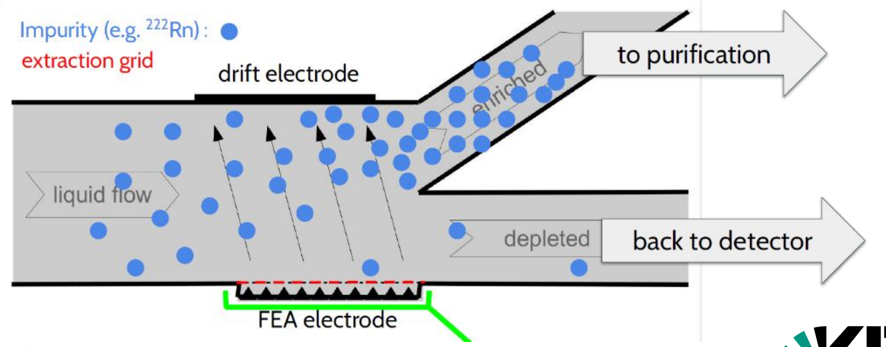
Sun
pp neutrinos
Solar metallicity
^{7}Be, ^{8}B, hep

XLZD: search for WIMP dark matter

Challenges for 2-phase LXe experiments

- **Radioactive purity (^{222}Rn, …)**
  - Reduced sensitivity for rare signals
  - Ultra-low background required: 0.1 µBq/kg
  - Radon removed by destillation
- **Reduced electron life-time in LXe**
  - Drifting electrons attach to electro-negative molecules (O_2, …)
  - S2 signal is reduced ➔ lower sensitivity for small signals
  - O_2, … removed by SAES heated getter unit
- **Improved efficiency for Xe purification**
  - Attach charge (injected by FE arrays) to contaminants
  - Drift and thus concentrate the charged contaminants
  - Purify only the contaminant concentrate



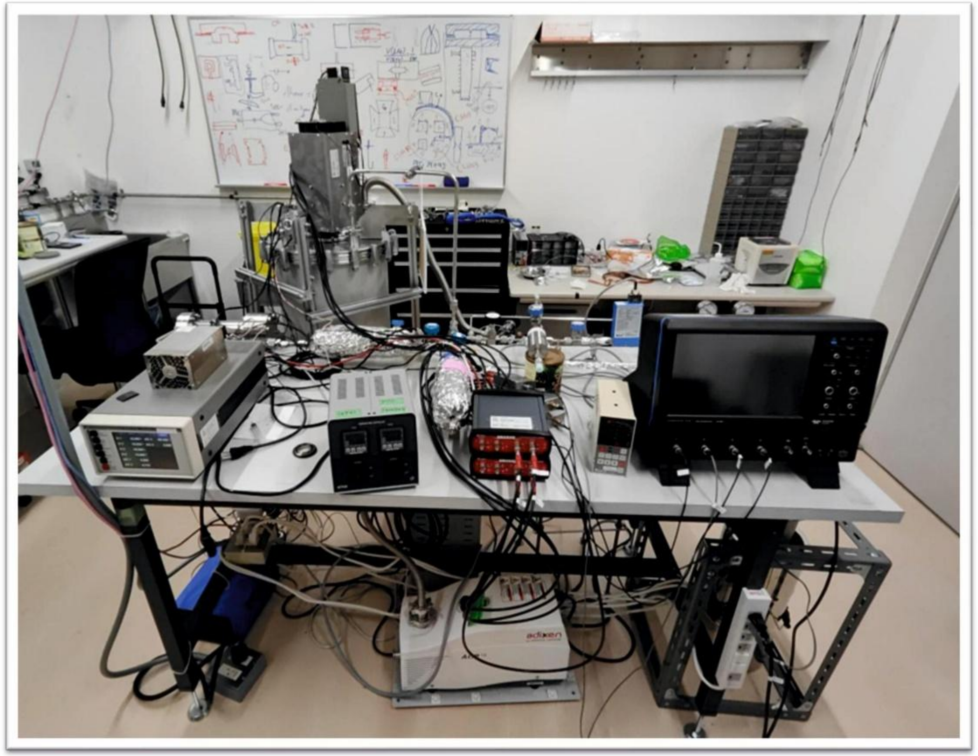


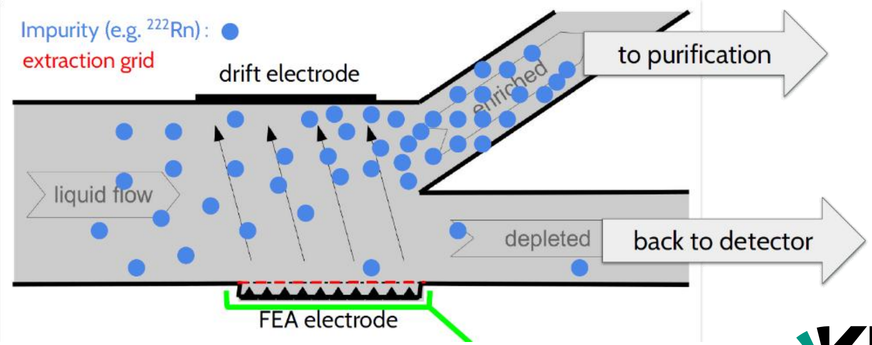
XLZD: search for WIMP dark matter

FE arrays for XLZD

- **Proof of principle tests in Japan**
  - Hole emission in LXe requires large E-field (~10 MV/cm)
  - Lifetime of Si-FE tips in liquid Xe (array was readily available)
  - Stable operation with degrading tips

- **Challenges, next steps**:
  - Attachment of charge to Xe
  - Charge transfer: Xe^+ (hole) + Rn ➔ Rn^+ + Xe
  - Is the attachment time long enough to drift Rn^+ over sizable distance ?





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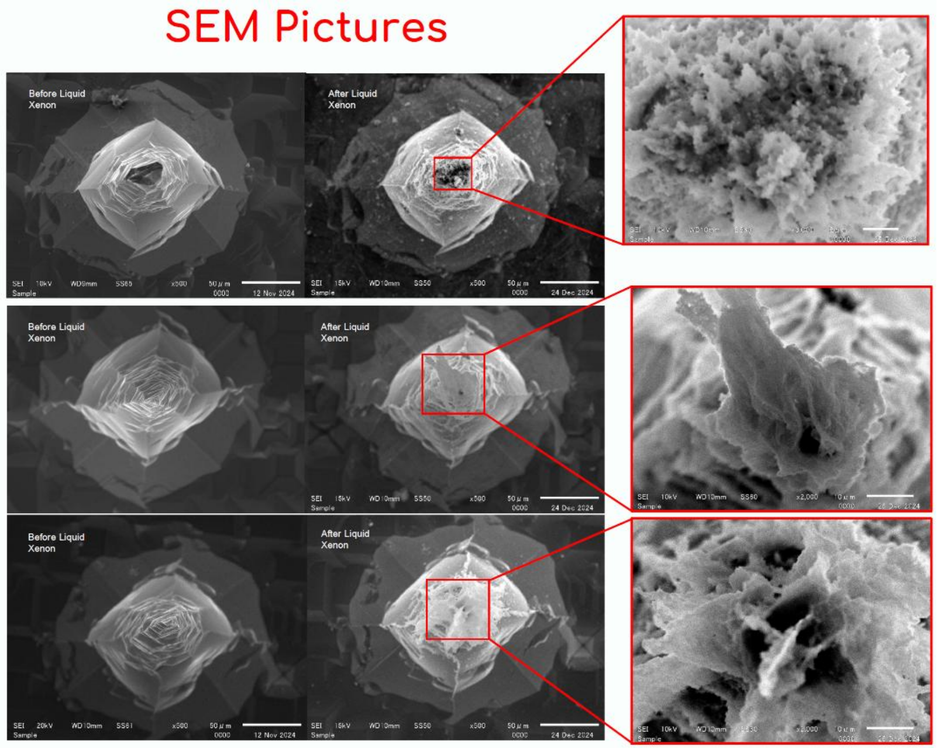
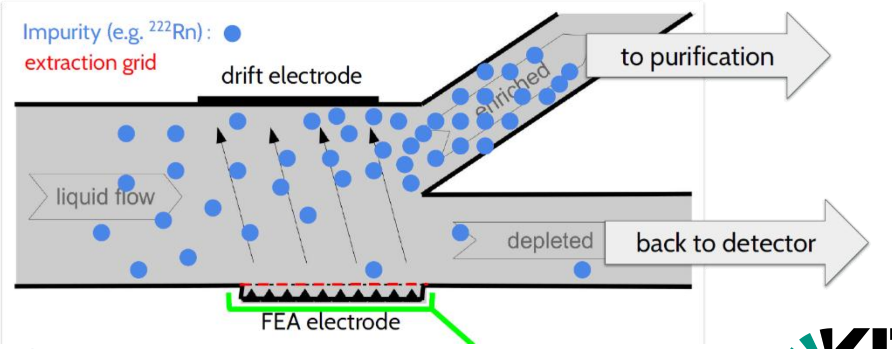
  - Attachment of charge to Xe
  - Charge transfer: Xe^+ (hole) + Rn ➔ Rn^+ + Xe
  - Is the attachment time long enough to drift Rn^+ over sizable distance ?
- **Results after first tests:**
  - Successful injection of current into LXe.
  - Si-tips damaged (outgrowth of molten Si)

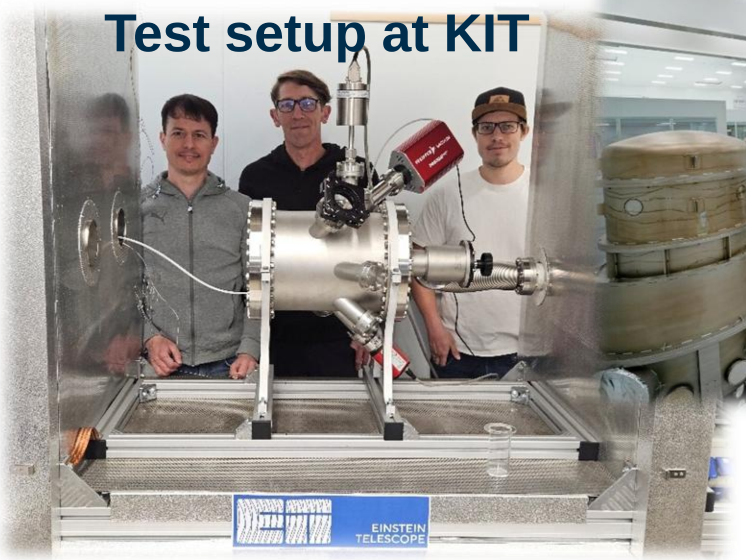
➔ Test more robusts material for tips: Cu, Ti, W, …

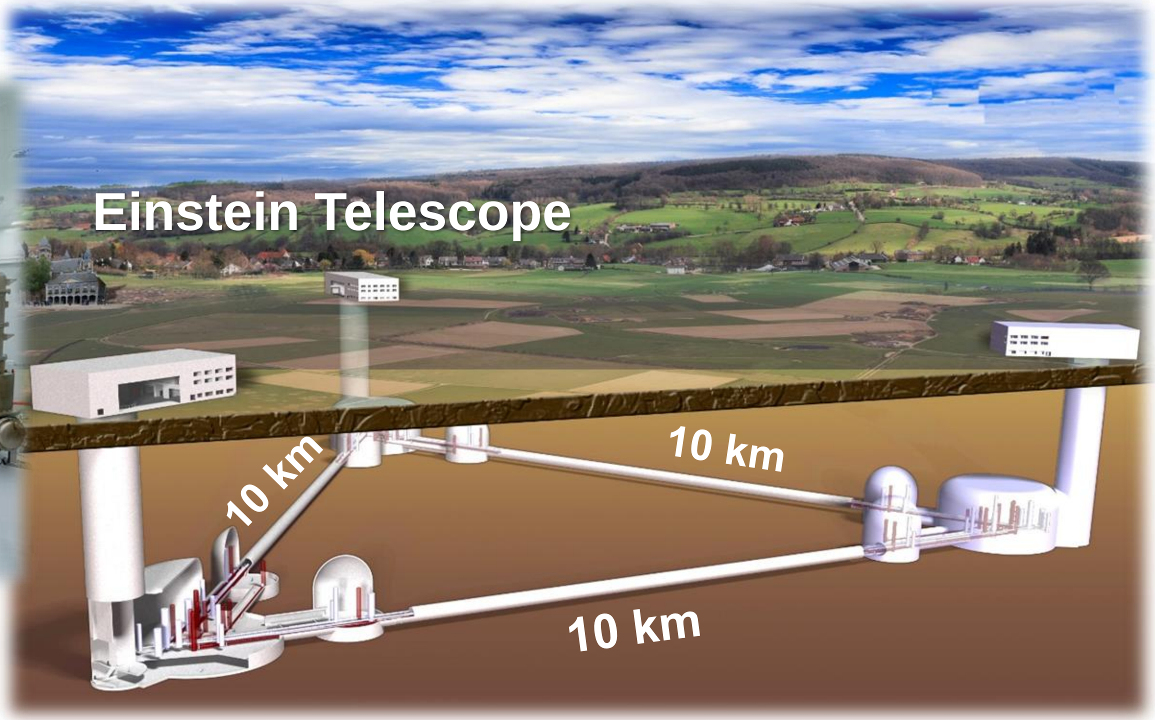




Einstein Telescope: gravitational wave observatory

- **Next generation gravitational wave observatory in Europe**
  - **10-times higher sensitivity** than existing GW observatories
  - **Sensitivity:** detect **10^{-18} m change** between mirrors **10 km** apart.
- **Triangular baseline design:**
  - **6 laser interferometers** (3 @ cryogenic temperature, 3 @ room temperature)
  - Total length of beamline: **120 km**





Einstein Telescope: gravitational wave observatory

EINSTEIN TELESCOPE

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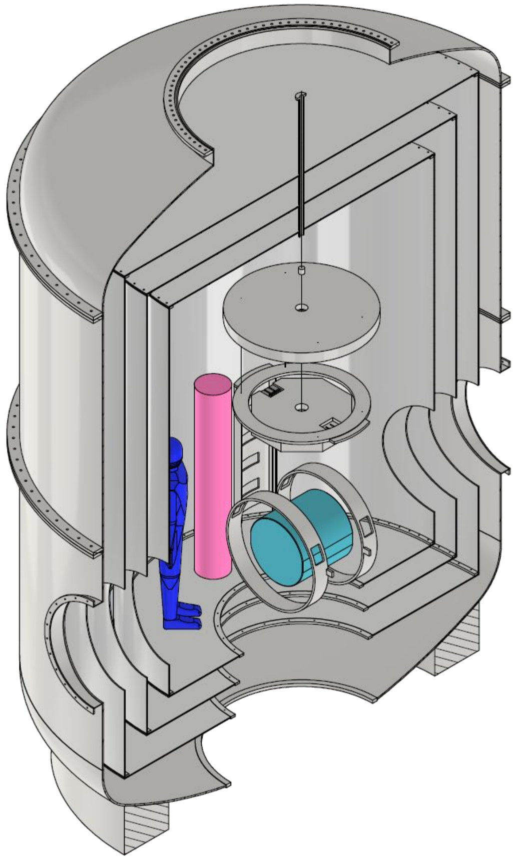
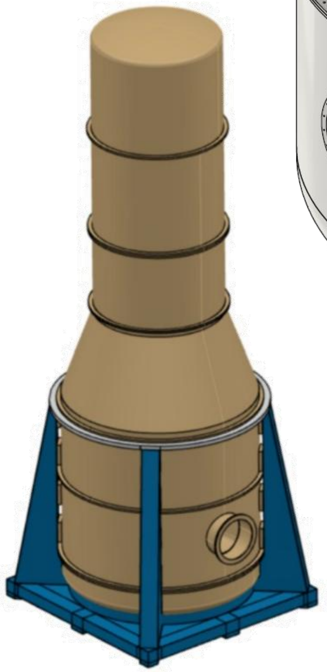
- **Triangular baseline design:**
  - **6 laser interferometers** (3 @ cryogenic temperature, 3 @ room temperature)
  - Total length of beamline: **120 km**
  - **Cryogenic mirrors at 10 K**
    - ~ 200 kg mono-crystalline Si (transparent for IR laser)
    - Adsorption on cold surface: **< 0.1 mono-layer/year of ice**
      - Absorption of IR laser light ➔ **heat load on cryo-system**
      - Scattering of IR laser light
    - High demands on vacuum system:
      - **P < 10^{-10} mbar (H_2), H_2O, N_2, H-C, … < 10^{-14} mbar** (condensation)
      - **No baking:** non-thermionic conditioning (UV-light, plasma, ozone, … ?)
      - **In-situ cleaning** of cold mirror surfaces with 100 - 200 eV electrons
      - **No heat or light** to produce electrons ➔ **field emission** source @ 10 K





Einstein Telescope: gravitational wave observatory

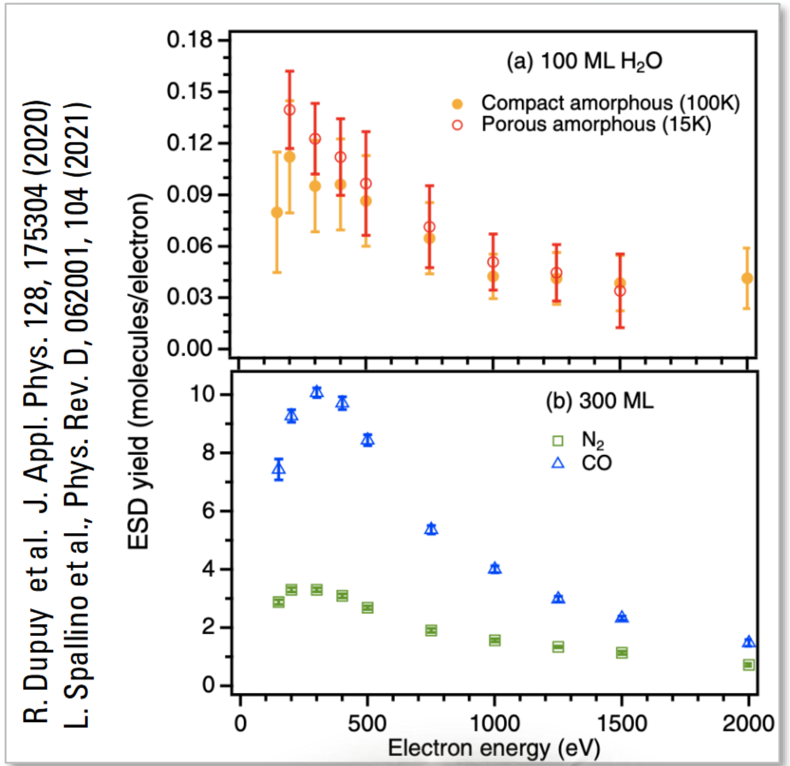
FE arrays for ET

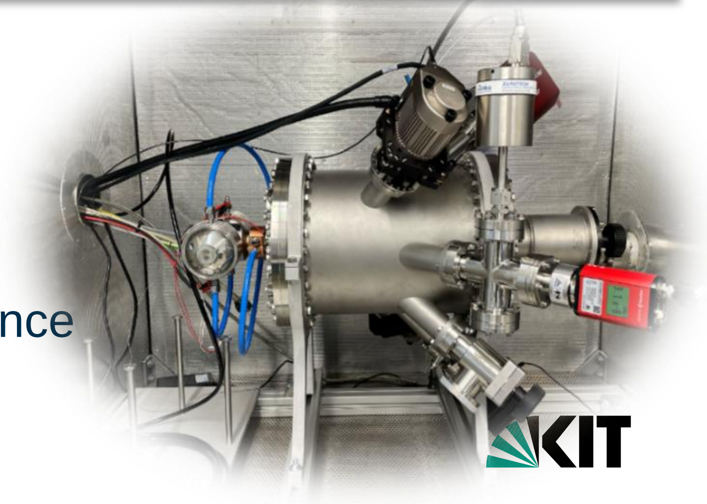
- **In-situ ice removal from cryogenic mirrors with electrons**
  - **Energy: ~ 200 eV,** no damage to optical coatings
  - **Development of e-gun:** no heat or light ➔ **FE array at 10 K**
  - Tests prepared at **LNF (Frascati)** with **OTH FE array**

- **Compensation of electrostatic charging of mirror surfaces**
  - Charge can cause tiny movement of mirror
  - Electrons with different energies ➔ **SEY < 1 or > 1**
  - Same e-gun as used for ice removal **(FE array)**

- **Vacuum gauges and RGA with cold electron source (FE array)**

- **Test setup at KIT with cryogenic Si mirror samples**
  - **Develop monitoring** of ice layer with ellipsometry and cold quartz micro balance
  - Test of **e-gun and vacuum gauges** on growth and reduction of ice layer

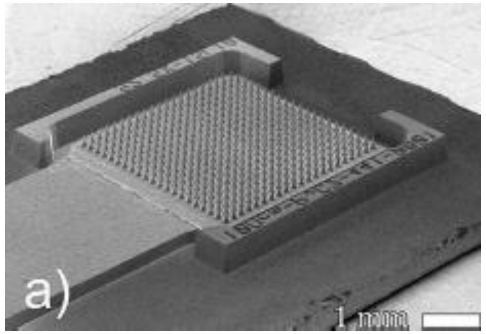


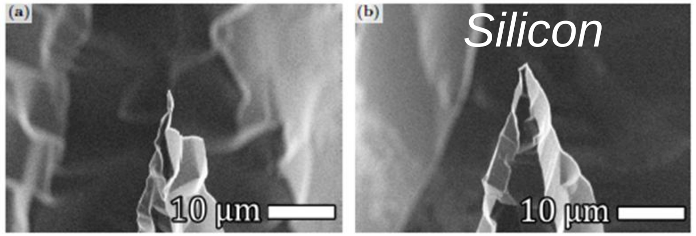


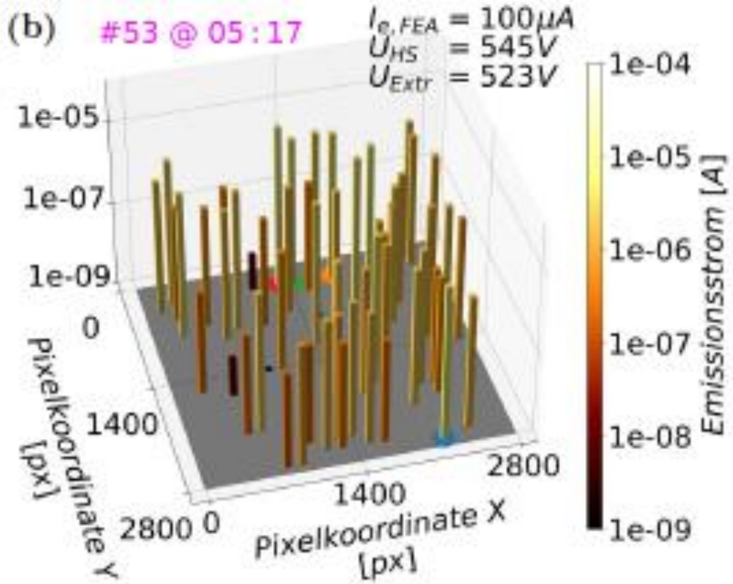
Conclusions: FE-Arrays - general challenges

- **Issues:**
  - **Large variations** in individitual emitter geometry
  - **Long-term stability** in gas and liquids
  - **Homogeneity** of tips in an array
  - **Currents** from fA to mA
  - **Electron** energy from 40 eV to 40 keV

- **Solutions**:
  - Improve reproducability with a **ps-laser**
  - Other production technologies ?
  - Test other materials (bulk and coating)
  - Post acceleration of electrons
  - …







FE array with 441 individual tips (fabricated with ns-laser at OTH)

ns-laser

ps-laser

Conclusions

- **Field Emission Electron Sources are an interesting technology for large-scale experiments**
- **Potential to solve many challenging problems in detector technology, UHV and cryogenics**
  - Cryogenic detector calibration (electrons, X-rays in keV range)
  - Electron guns for in-situ cleaning
  - Removal of radioactive isotops from cryogenic liquids
  - Cold „hot cathode“ vacuum gauges, RGA in UHV and cryogenic environments
  - …