KAT Strategy Meeting | Karlsruhe, Oct. 16-18, 2024

Neutrino Properties

Kathrin Valerius

with input from S. Böser, L. Gastaldo, S. Mertens, M. Schlösser, S. Schönert

KAT.Komitee für
Astro.Teilchen.Physik

Key science questions

KAT. Komitee für Astro.Teilchen.Physik

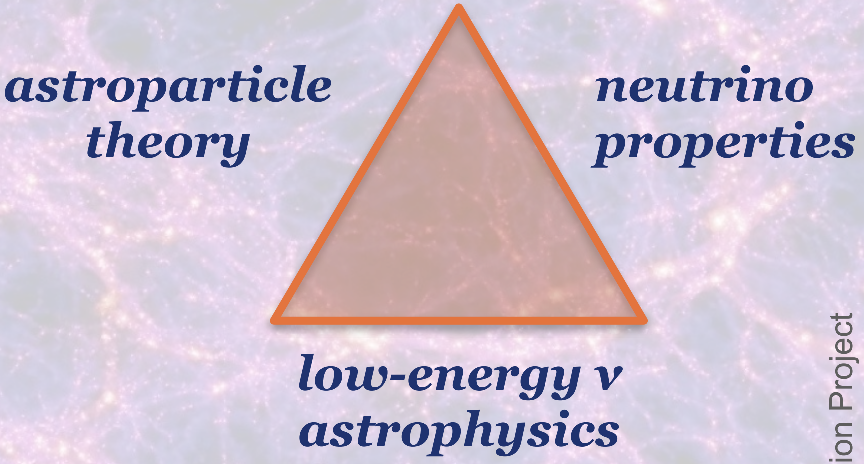
➜ What is the nature of neutrinos (Majorana vs. Dirac)?

➜ What are the (precise) values of neutrino mixing parameters?
CP violating phase?

➜ Which of the ordering schemes of neutrino masses
(normal or inverted) is realized?

➜ Are there more than 3 types of neutrinos?
Sterile neutrinos as potential dark matter contribution?

➜ What is the absolute neutrino mass scale?



astroparticle theory

neutrino properties

low-energy ν astrophysics

© Millennium Simulation Project

Key science questions

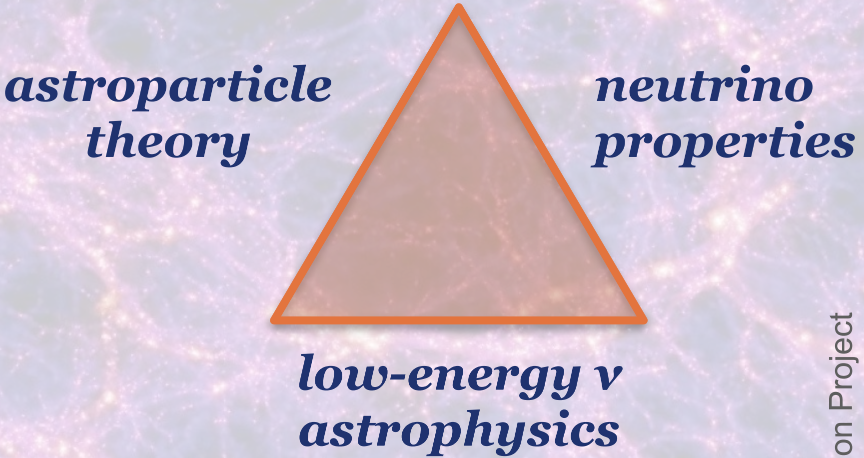
➜ **What is the nature of neutrinos (Majorana vs. Dirac)?**

➜ What are the (precise) values of neutrino mixing parameters?
CP violating phase?

➜ Which of the ordering schemes of neutrino masses
(normal or inverted) is realized?

➜ Are there more than 3 types of neutrinos?
Sterile neutrinos as potential dark matter contribution?

➜ **What is the absolute neutrino mass scale?**



astroparticle theory

neutrino properties

low-energy ν astrophysics

© Millennium Simulation Project

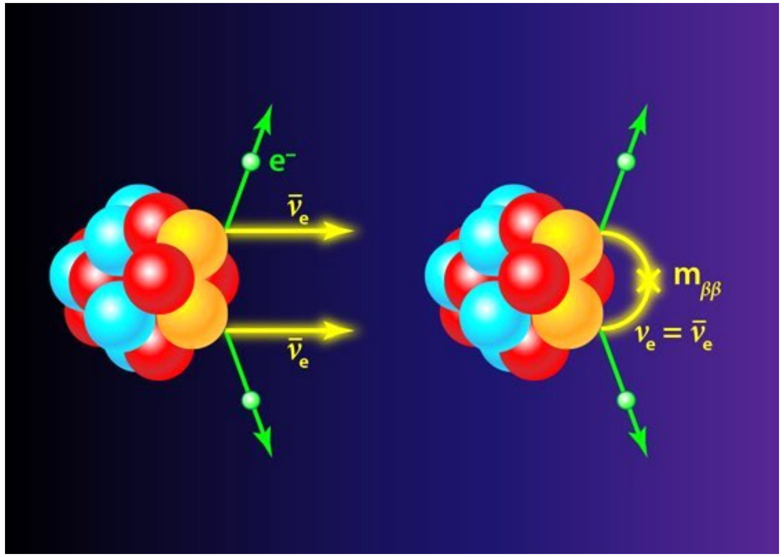
Tasks for this talk

- **The past ~11 months:**
  Brief highlights of the **science** that has happened since the last meeting
  - Search for neutrinoless double beta decay
  - Direct neutrino-mass measurements (tritium & holmium)

new results from
LEGEND-200,
ECHo, HOLMES,
and KATRIN
at Neutrino'24 !

- **The next ~10 years:** contributions to the Strategy Paper
  - Key Science Questions?
  - Areas of thrust?
  - Connections with Theory: see talk by **Th. Schwetz**
  - Connections with Low-energy ν astrophysics: see talk by **M. Wurm**

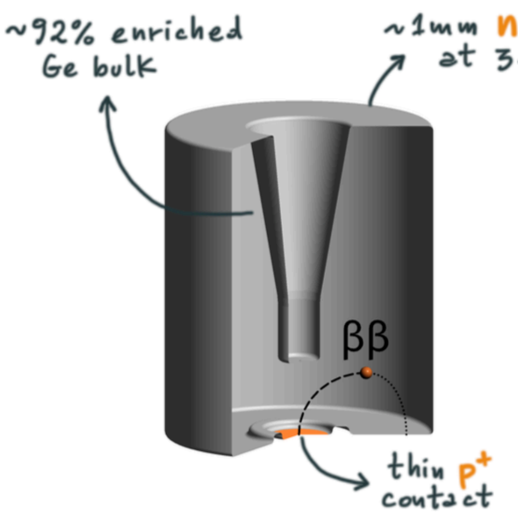
Neutrinoless double beta decay

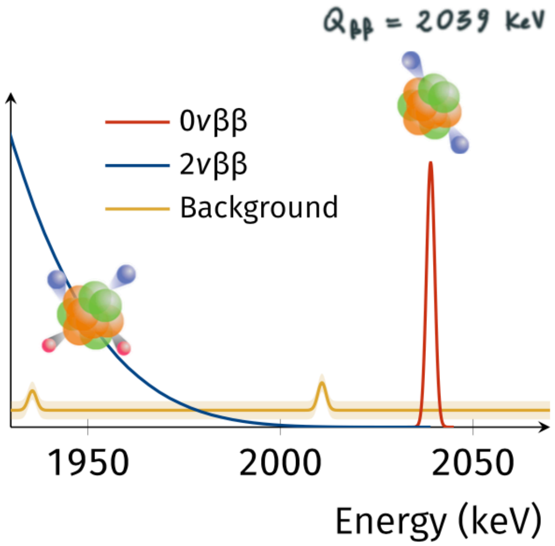


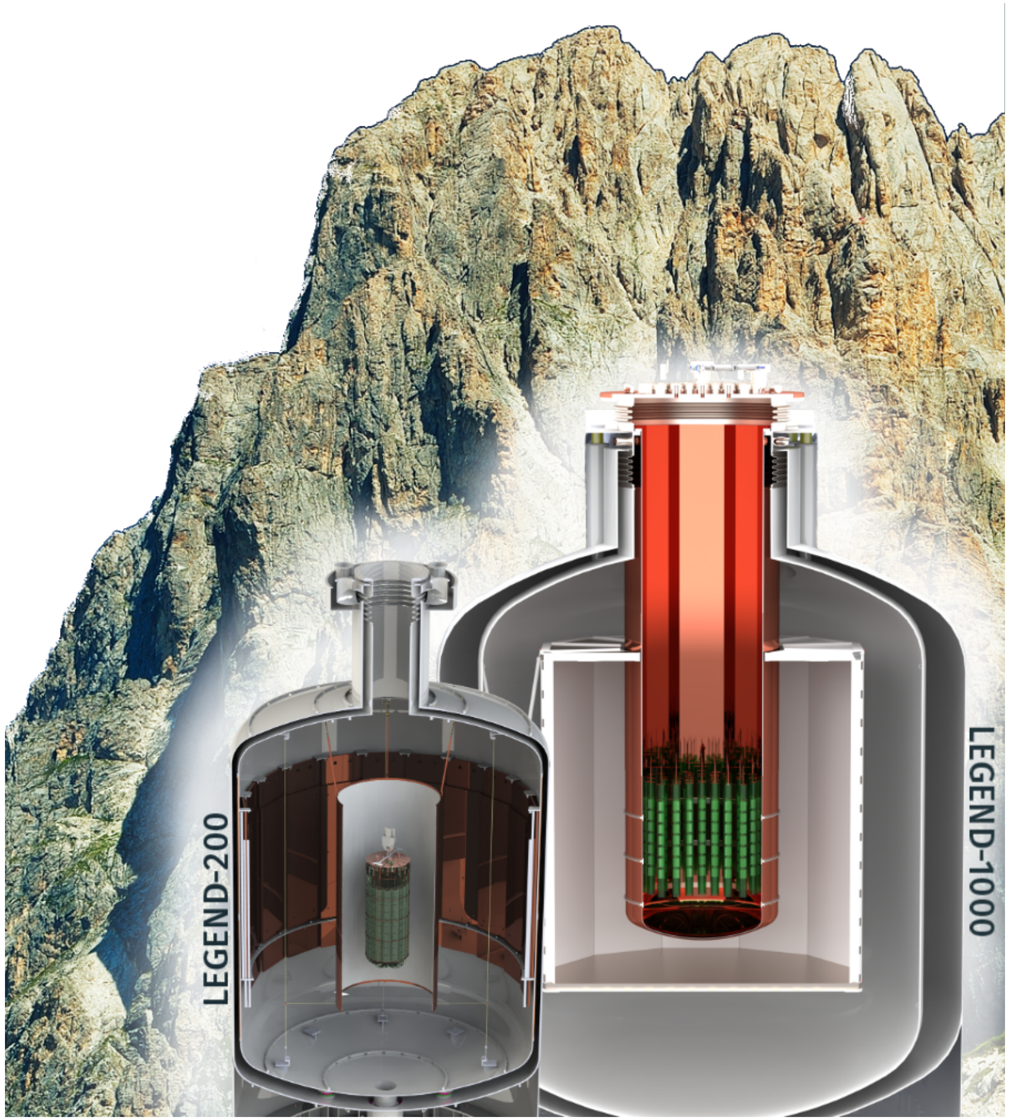
Alan Stonebreaker/APS

The LEGEND program

- High-purity Germanium detectors enriched in ^{76}Ge
- Immersed in liquid Argon







Phased program:

- **200 kg** of ^{enr}Ge (x 5yr) in GERDA cryostat
- **1000 kg** of ^{enr}Ge (x 10yr) in new facility

L. Pertoldi, Neutrino'24

LEGEND-200

Posters
Deckert, Pertoldi

Data taking

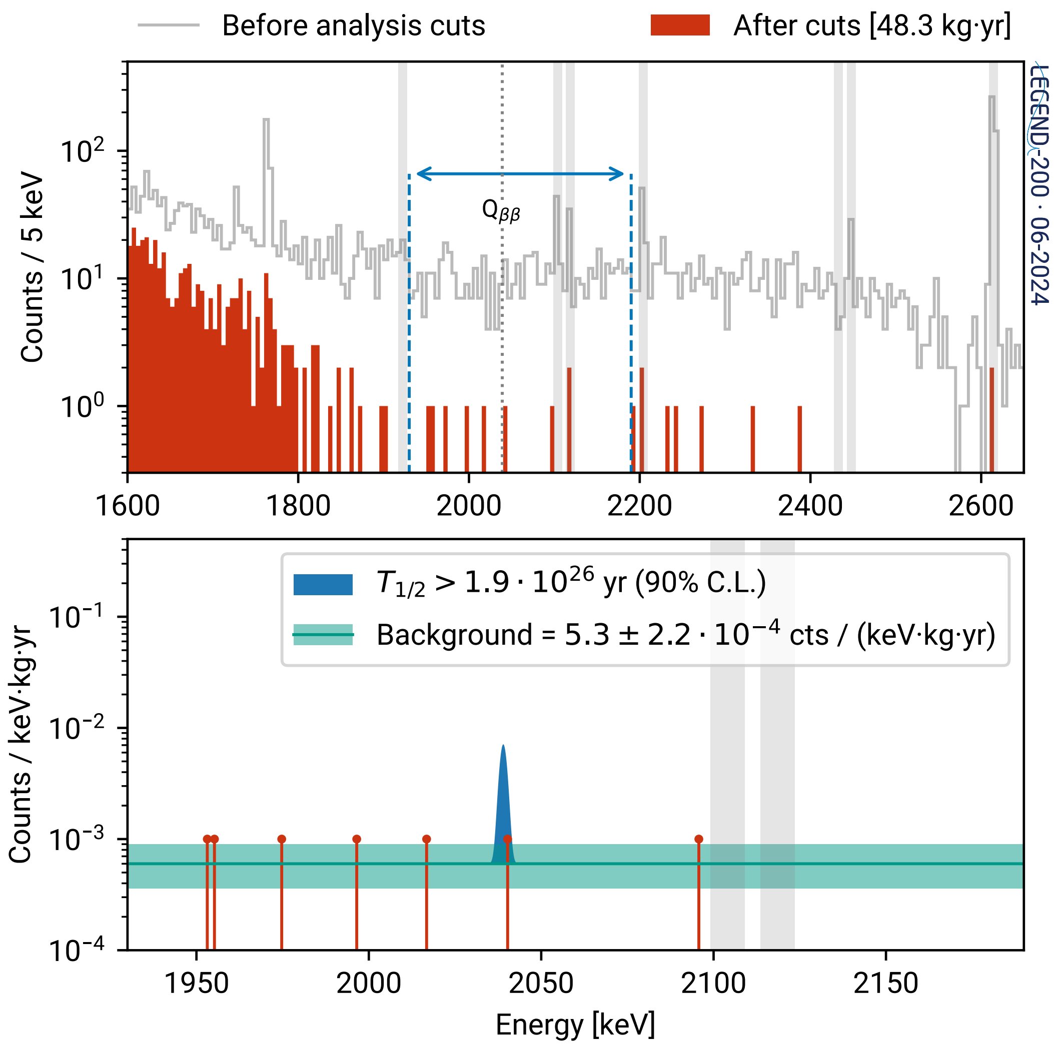
- Exposure accumulated over 1 year
- Golden data set (48.3 kg yr)

Performance

- ~0.1% FWHM at $Q_{\beta\beta}$
- Excellent background rejection using event topology information in time and space (HPGe, LAr, Water Cherenkov)
- Background: 0.5 cts/keV/t/year

New Result (L200 + Gerda + Majorana)

- Median sensitivity: $T_{1/2} > 2.8 \cdot 10^{26}$ y
- Limit (90% C.L): $T_{1/2} > 1.9 \cdot 10^{26}$ y
- $m_{\beta\beta} < 75 – 178$ meV

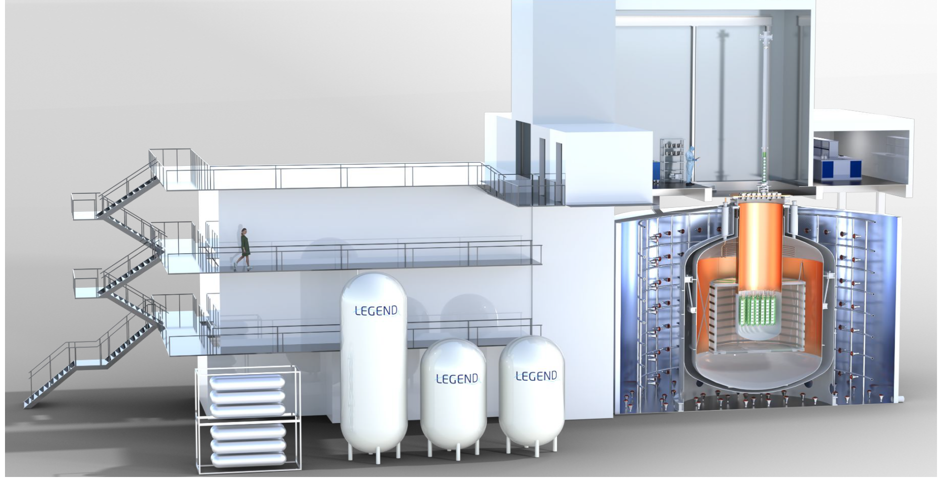


L. Pertoldi, Neutrino'24 (zenodo link)

LEGEND-1000

Posters
Aguilar, Sailer

KAT. Komitee für Astro.Teilchen.Physik



Goals

- 1000 kg of enriched ^{76}Ge
- Background goal <0.025 cts/(FWHM t yr)
- Discovery sensitivity at half-life > 10^{28} years

DE contrib.

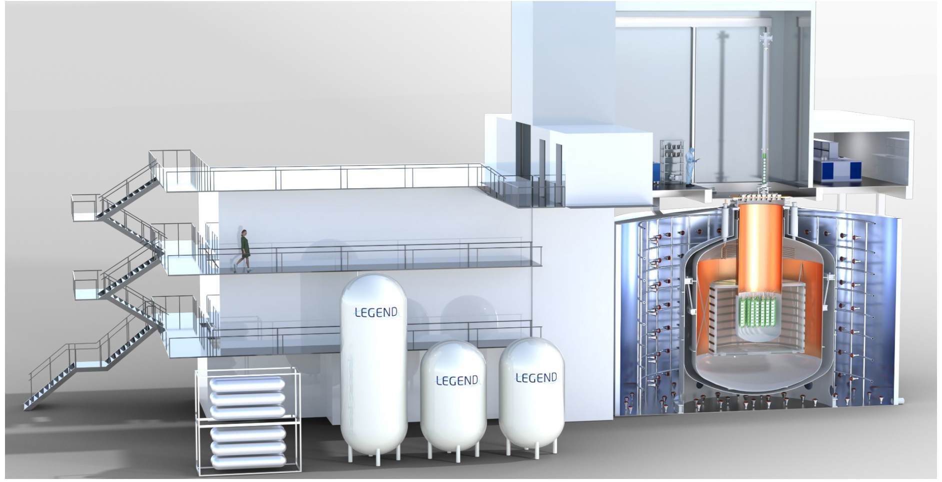
- Cryostat, LAr Instrumentation, Water Cherenkov detector system, electronics
- Substantial contributions to: ^{enr}Ge procurement, Ge detector production, LAr purification & handling, infrastructures (e.g., clean room)

Funding

- Outcome of NSF mid-scale review end of 2024
  → incl. European funding sufficient to start LEGEND-1000 with ~30% Ge
- Successful LEGEND-1000 DOE status review
  → DOE Office of Science project prioritization in Oct/Nov 24
  → CD-1 scheduled for 2025
- Application for BMBF Prioritization process ongoing (→ talk by B. Schwingenheuer on Friday)

from S. Schönert, S. Mertens

LEGEND-1000



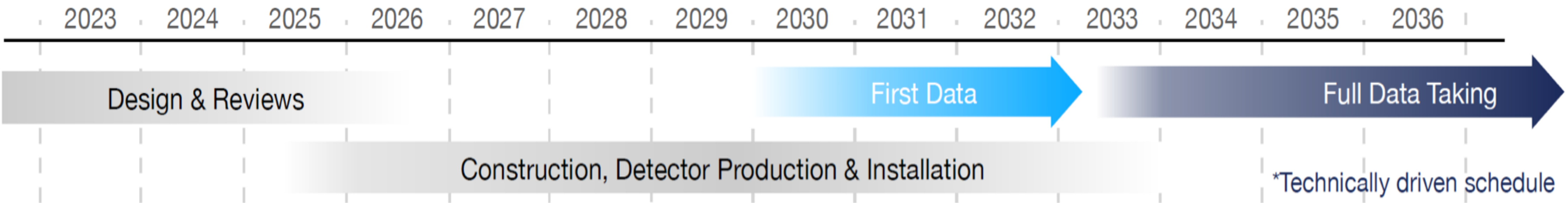
Goals

- 1000 kg of enriched ^{76}Ge
- Background goal <0.025 cts/(FWHM t yr)
- Discovery sensitivity at half-life > 10^{28} years

DE contrib.

- Cryostat, LAr Instrumentation, Water Cherenkov detector system, electronics
- Substantial contributions to: ^{enr}Ge procurement, Ge detector production, LAr purification & handling, infrastructures (e.g., clean room)

Timeline



2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036

Design & Reviews

First Data

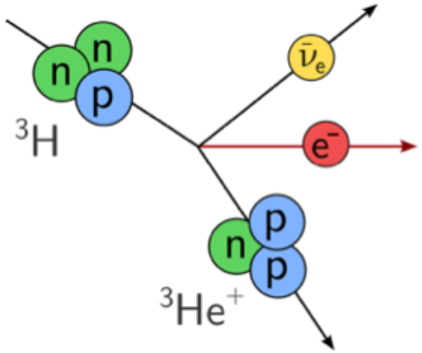
Full Data Taking

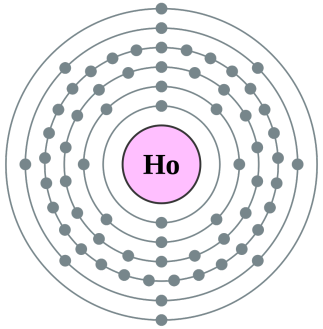
Construction, Detector Production & Installation

*Technically driven schedule

from S. Schönert, S. Mertens

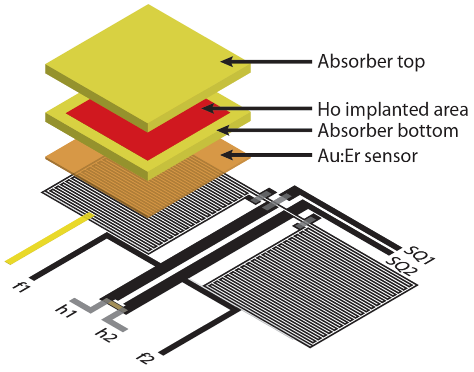
Direct neutrino-mass measurement — tritium β-decay and EC in ^{163}Ho

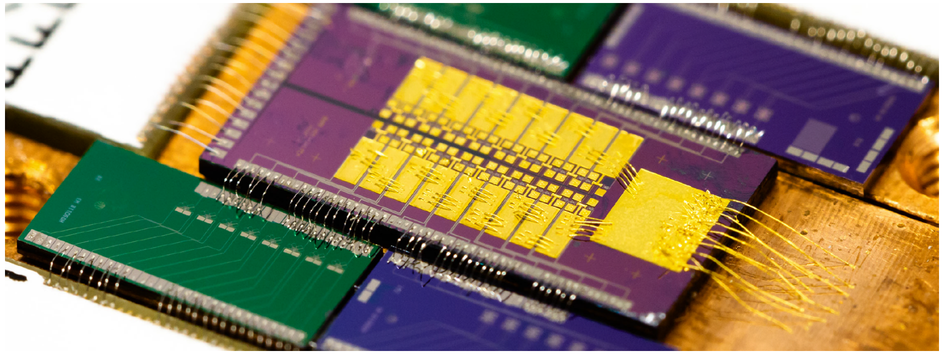


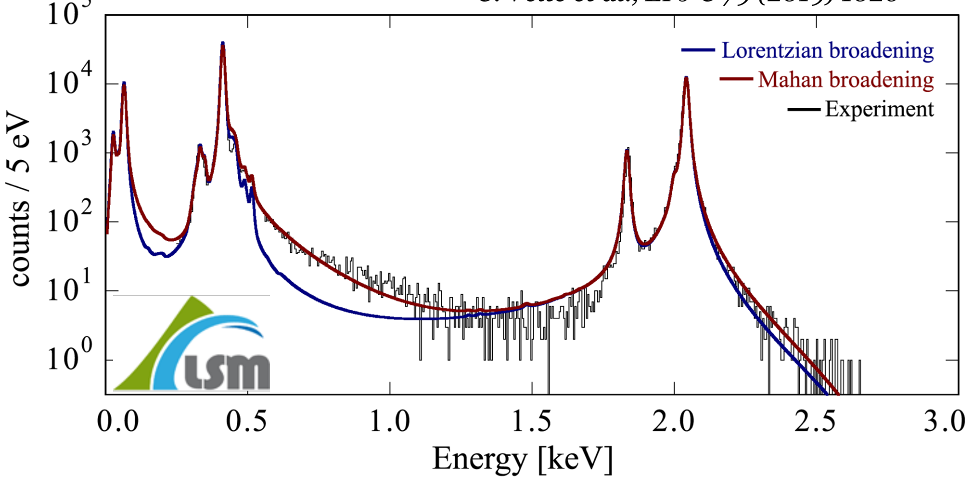


Holmium — the ECHo program

Low-temperature Metallic Magnetic Calorimeters (MMC) implanted with ^{163}Ho for high-resolution (~ eV) measurement of the electron capture spectrum







C. Velte et al., EPJ C 79 (2019) 1026

Proof of concept:

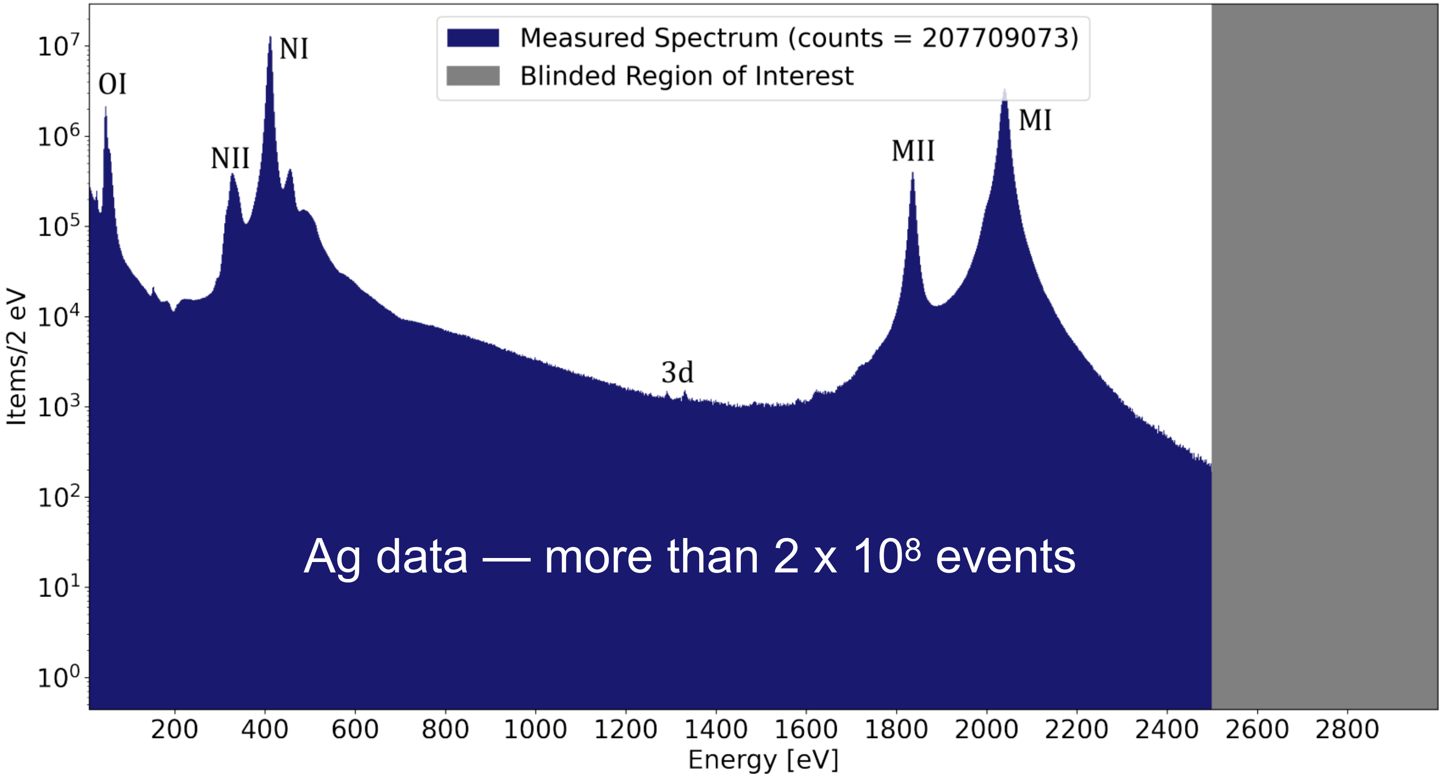
- 4 day measurement with 4 pixels
- underground (Modane)
- test for data reduction and spectral shape analysis

Q_{EC} = (2838 ± 14) eV $m(\nu_e) < 150$ eV (95% CL)

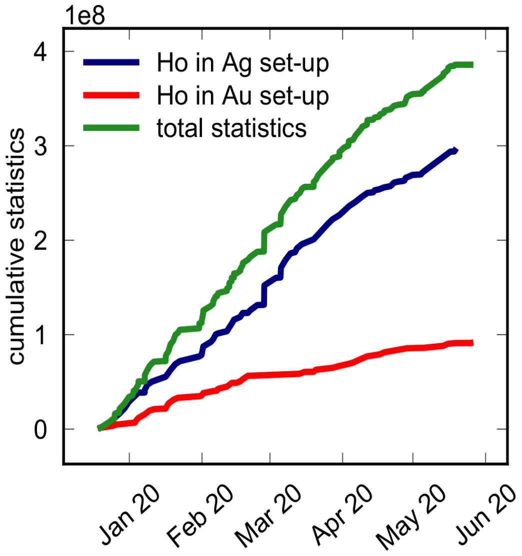
from L. Gastaldo

Holmium — ECHo-1k

ECHo-1k chip-**Au**	23 pixel with ^{163}Ho, 3 background pixels, total activity of 28.1 Bq
ECHo-1k chip-**Ag**	34 pixel with ^{163}Ho, 6 background pixels, total activity of 25.9 Bq



Ag data — more than 2 x 10^8 events



$Q_{EC} = (2862.1 \pm 1.7)$ eV

$m(\nu_e) < 19$ eV @ 95% CL

Neutrino'24
(L. Gastaldo, A. Nucciotti)

Holmium — towards ECHo-100k

ECHo-100k baseline: multiplexing to read out ~12000 detectors, activity of 10 Bq per pixel

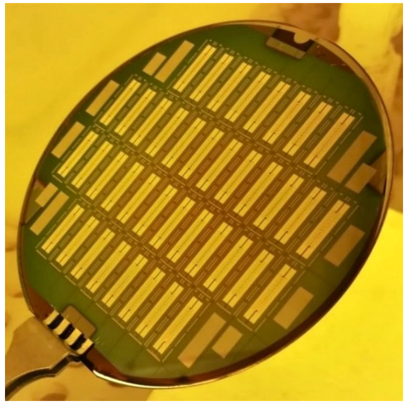
Current status:

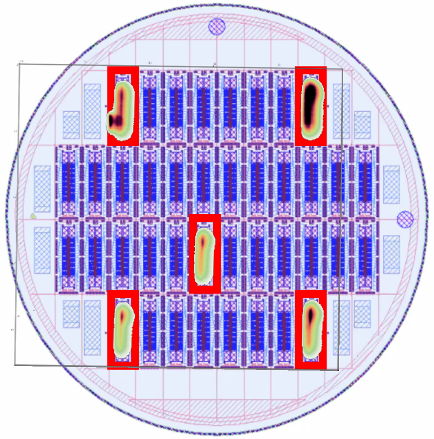
- High Purity ^{163}Ho source: ~30 MBq available
- Wafer-scale ion implantation demonstrated (RISIKO @ MZ)
- MMC arrays: reliable fabrication, characterized with ^{163}Ho
- Multiplexing and DAQ (KA, HD): SDR electronics ready, 8 pix demonstrated, tests with Ho-loaded array under way
- Data analysis (HD, TÜ): reliable data reduction, background study, improved spectral shape analysis

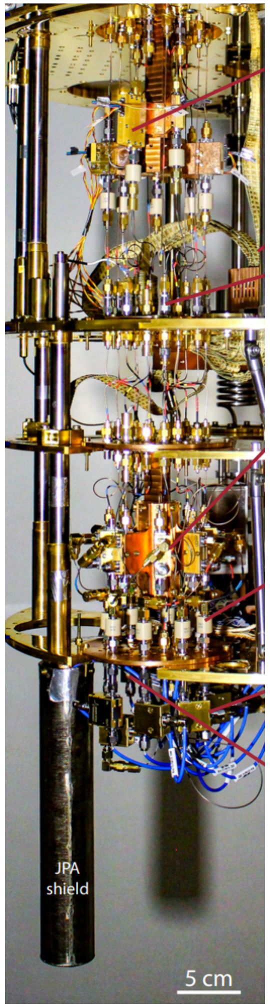
Timeline:

- Fabrication of optimized detectors until early 2025
- Start multiplexed acquisition of ^{163}Ho spectra with reduced number of chips in 2025
- Continue chip production for full ECHo-100k scale until 2026

6" wafer for ECHo-100k







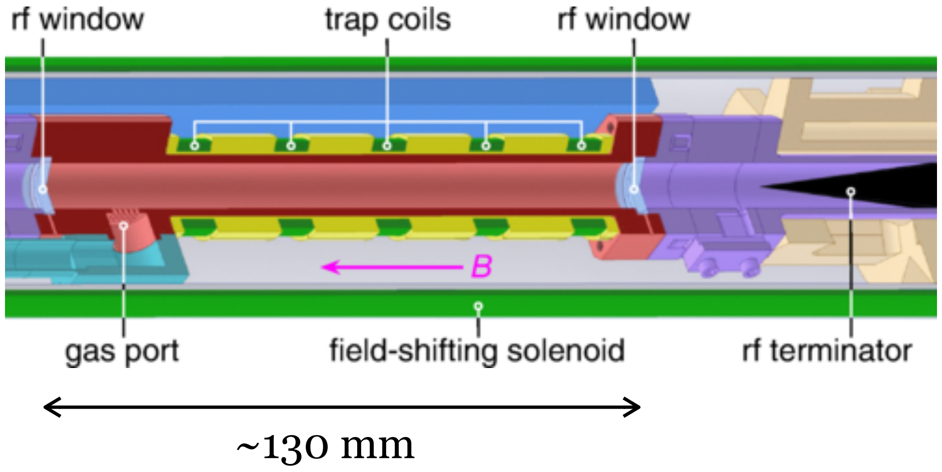
multiplexing tower

from L. Gastaldo

Tritium — the Project 8 experiment

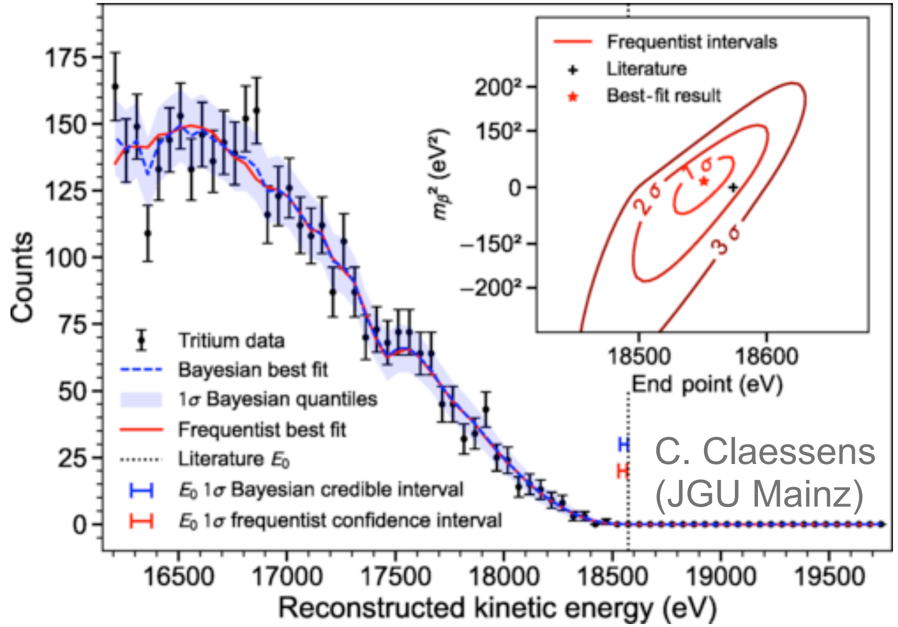
- High-resolution, non-destructive single-electron spectroscopy technology established by P8
- First frequency-based neutrino-mass measurement from mm^3-scale molecular tritium effective volume: **$m_\beta < 152$ eV/c^2 (1σ)**, endpoint $E_0 = 18548^{+19}_{-19}$ eV (1σ), $R_{bg} < 3\times10^{-10}$ eV^{-1} s^{-1} (90%)

Cryogenic CRES cell
(Cyclotron Radiation Emission Spectroscopy)



Energy resolution (1.66 +/- 0.19) eV @ 17.8 keV
and no background observed beyond endpoint

T_2 β-decay spectrum from 82 live days [PRL 131 (2023) 102502]
Frequentist analysis confirmed by Bayesian inference



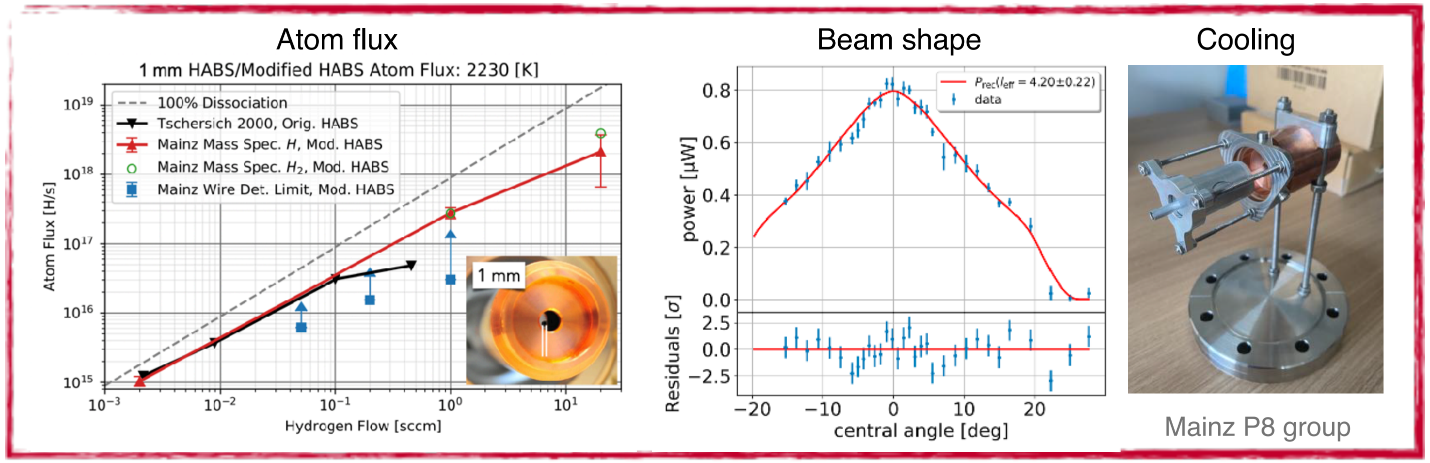
C. Claessens
(JGU Mainz)

from S. Böser & M. Fertl

Project 8 — future plans

Phase III demonstrators:

- Cavity CRES apparatus (CCA): $\sigma(E_e) \sim 100$ meV → demonstrate **precision**
- Low-Frequency Array (LFA): $O(1\,\mathrm{m}^3)$ cavity → demonstrate **scaling**
- Atomic Tritium Demonstrator (ATD): atomic T at ~$10^{16}/\mathrm{m}^3$ → demonstrate **atoms**
  - focus of Mainz efforts:



Atom flux

Beam shape

Cooling

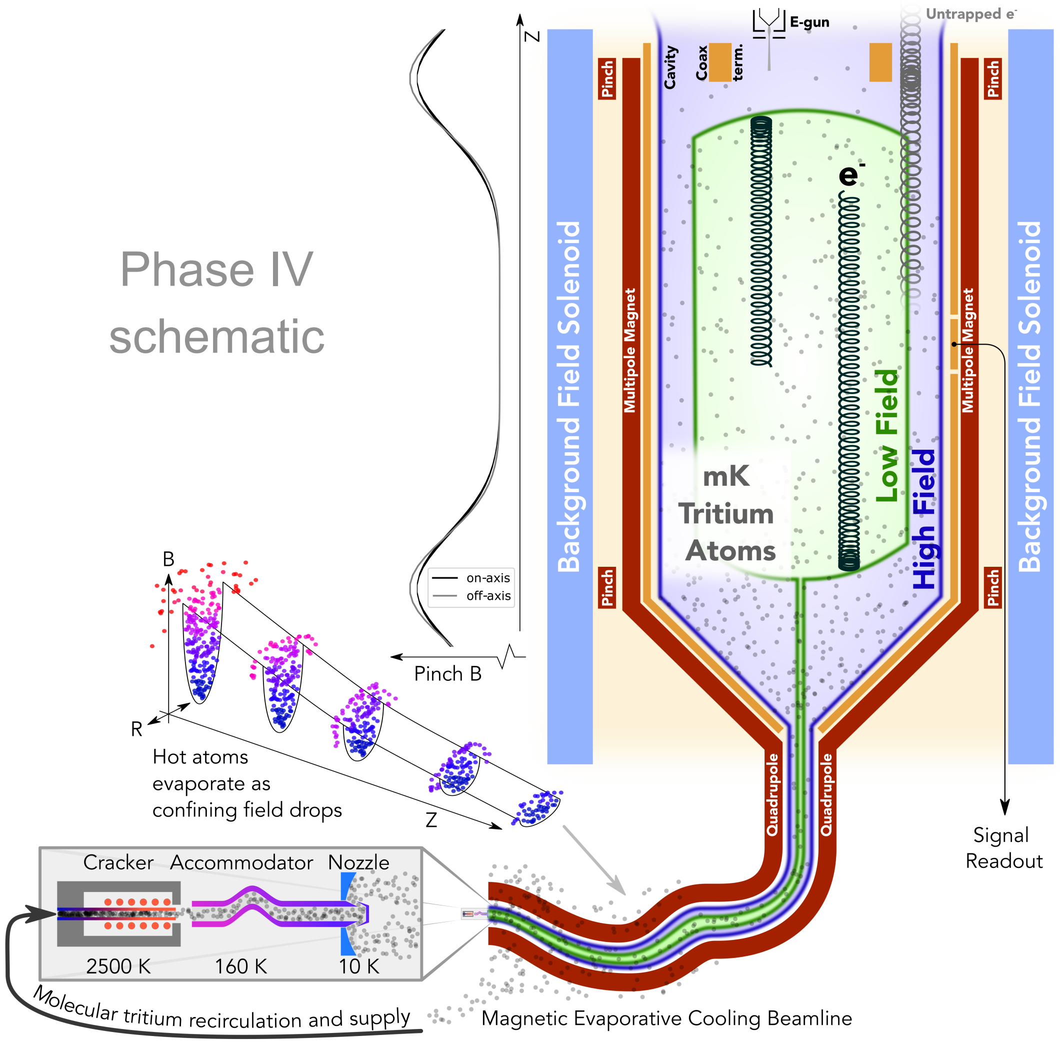
Mainz P8 group

Phase III Pilot experiment: join technologies for $m_\nu < 0.4\,\mathrm{eV}/c^2$

from S. Böser & M. Fertl

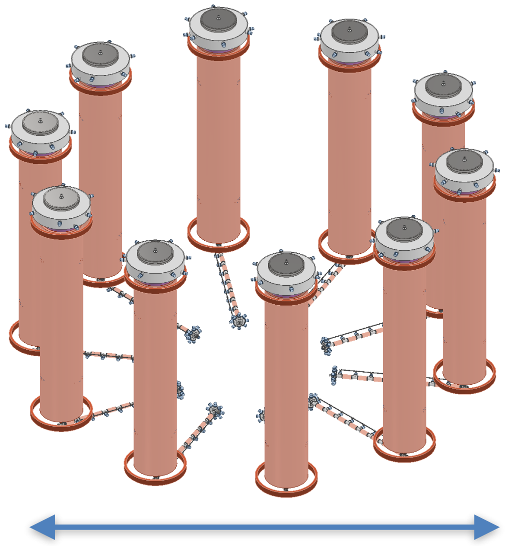
Project 8 — future plans

Phase IV schematic



Phase IV experiment:

scale to target sensitivity $m_\nu < 0.04\ \mathrm{eV}/c^2$



~ 50 m

Final sensitivity:
array of sub-units

TDR of full-scale expt. after 2033

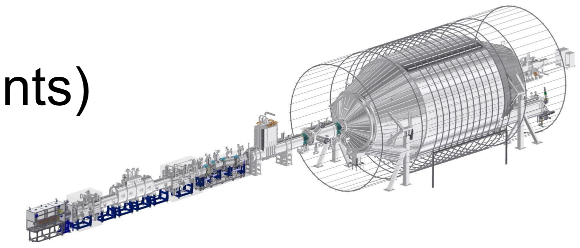
National-laboratory-scale technical infrastructure required.

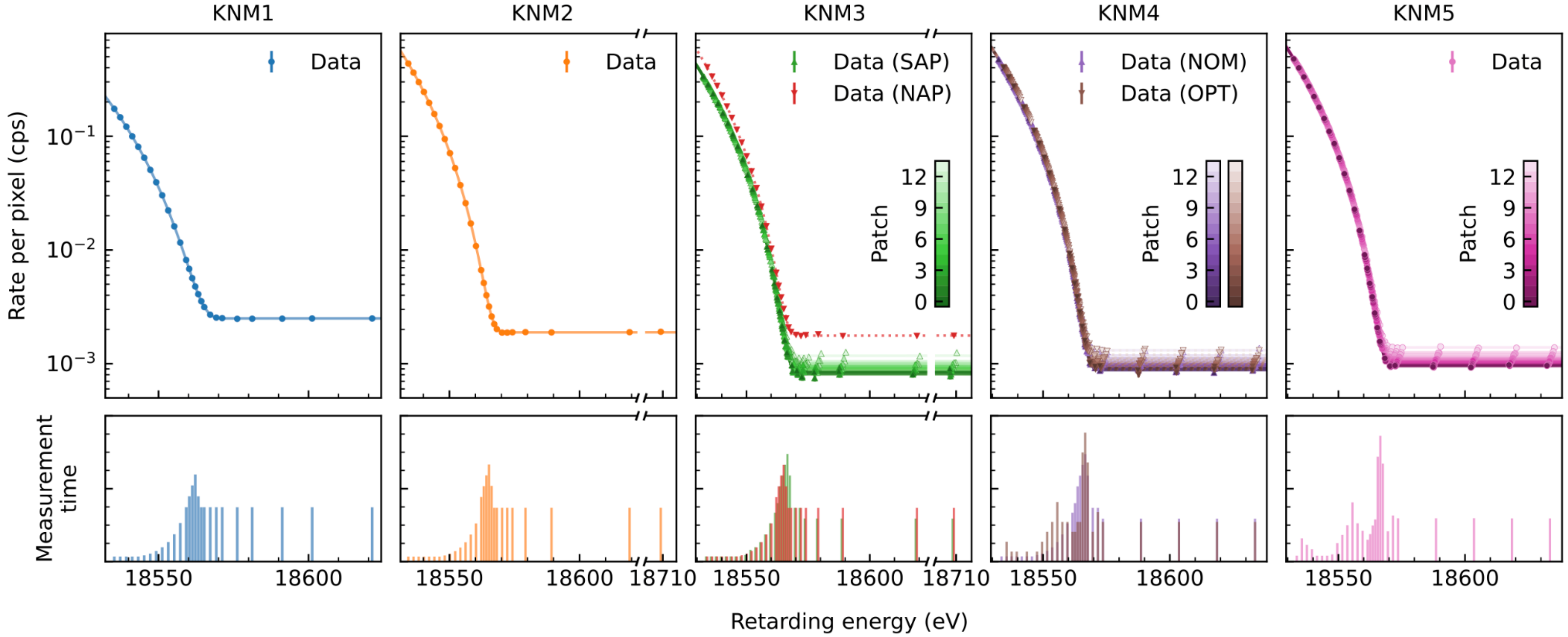
R&D program is part of NSAC Long Range Plan 2023 in US, not yet covered in German roadmaps.

from S. Böser & M. Fertl

Tritium — the KATRIN experiment

- Previously best direct bound on neutrino mass, from first two science runs (6.3 mio. events)
  ➜ $m(\nu_e) < 0.8$ eV (90% CL) *[Nat. Phys. 18 (2022) 160]*
- Summer 2024: Release of analysis of first five science runs (36 mio. events)
  ➜ $m(\nu_e) < 0.45$ eV (90% CL) *[arXiv:2406.13516]*

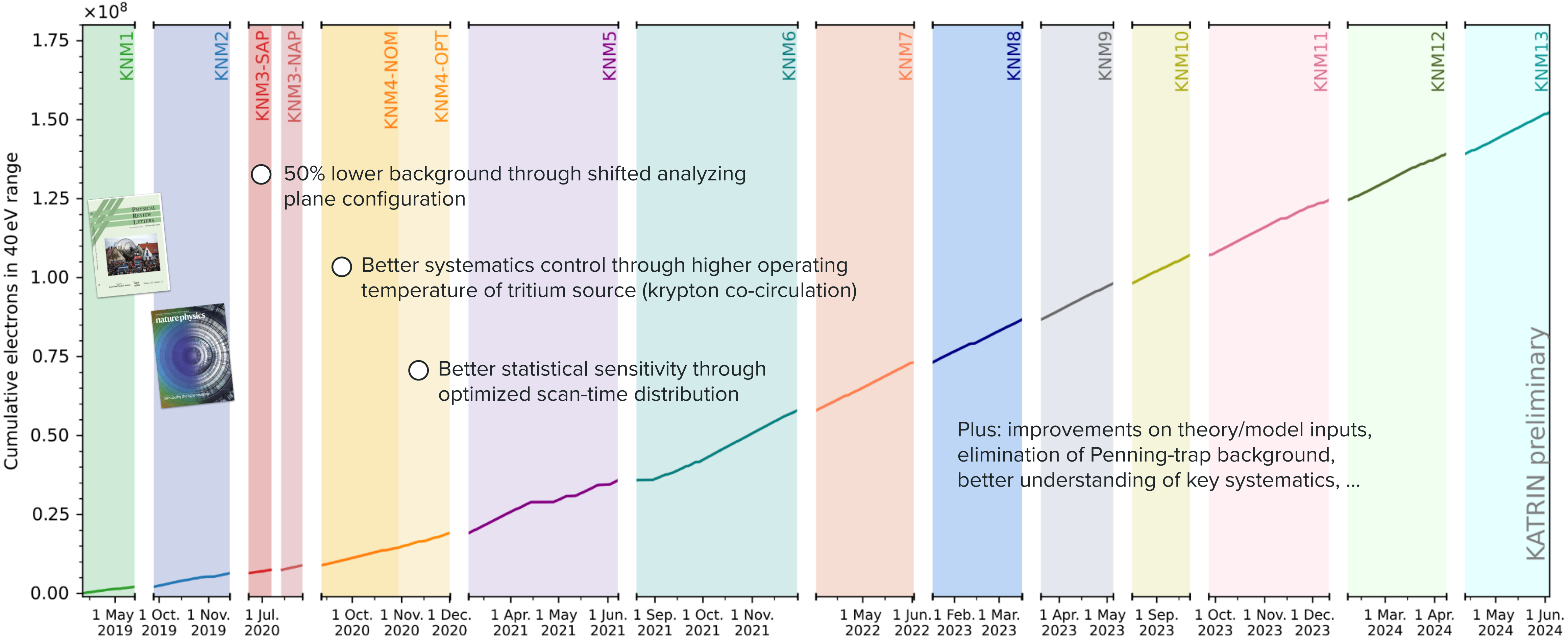




A. Lokhov, Neutrino'24 (zenodo link)

KATRIN data-taking & physics goals

Poster Storek, Habib et al.



○ 50% lower background through shifted analyzing plane configuration

○ Better systematics control through higher operating temperature of tritium source (krypton co-circulation)

○ Better statistical sensitivity through optimized scan-time distribution

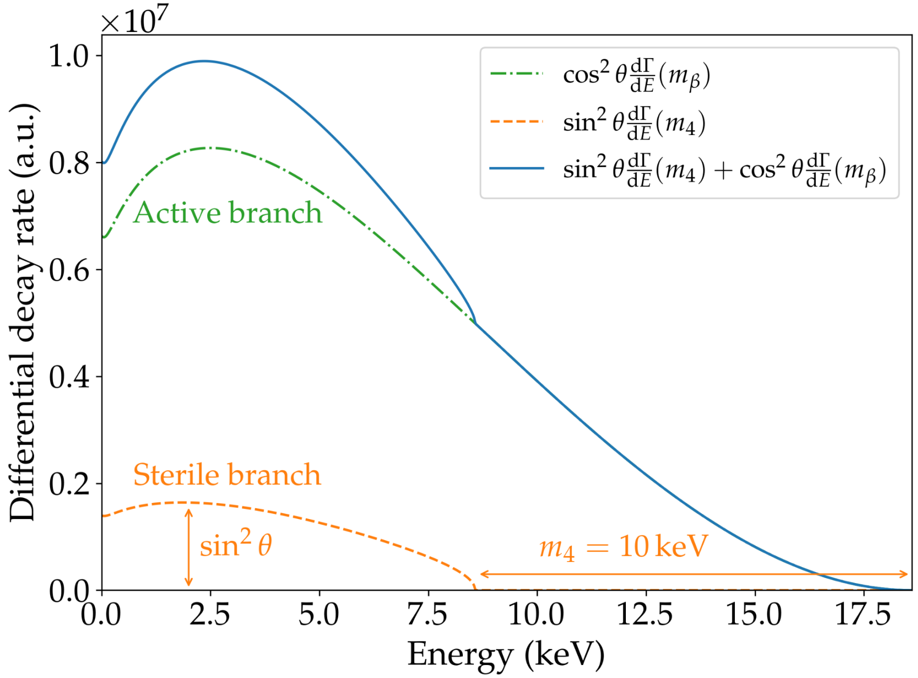
Plus: improvements on theory/model inputs, elimination of Penning-trap background, better understanding of key systematics, …

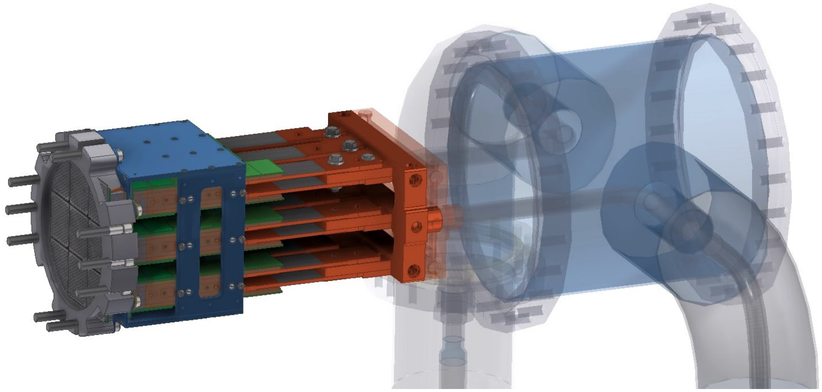
- By end of 2025: complete mission of 1000 measurement days for sensitivity < 0.3 eV.
- Many physics analyses beyond m_ν (sterile ν, non-standard int., LIV search, local ν density, …).

KATRIN — immediate future

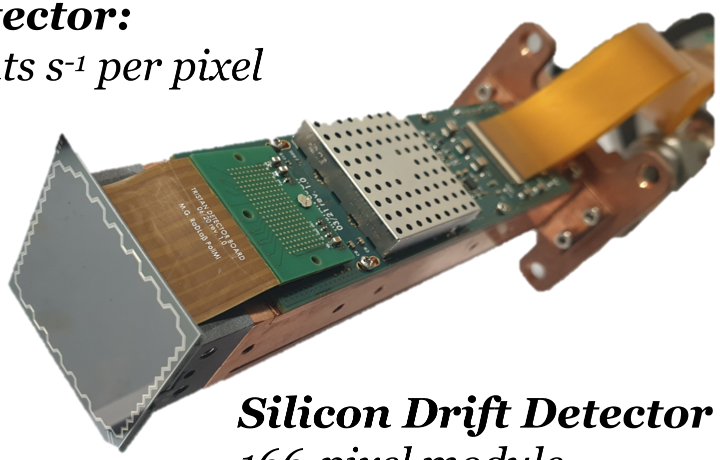
Posters Descher, Forstner et al.

- Next step: Implementation of TRISTAN detector upgrade (operation 2026-27) for differential β-spectrum measurement and full-spectrum search for heavy sterile neutrinos (~10^{16} events)





new focal plane detector:
1500 pixels, 100k counts s^{-1} per pixel

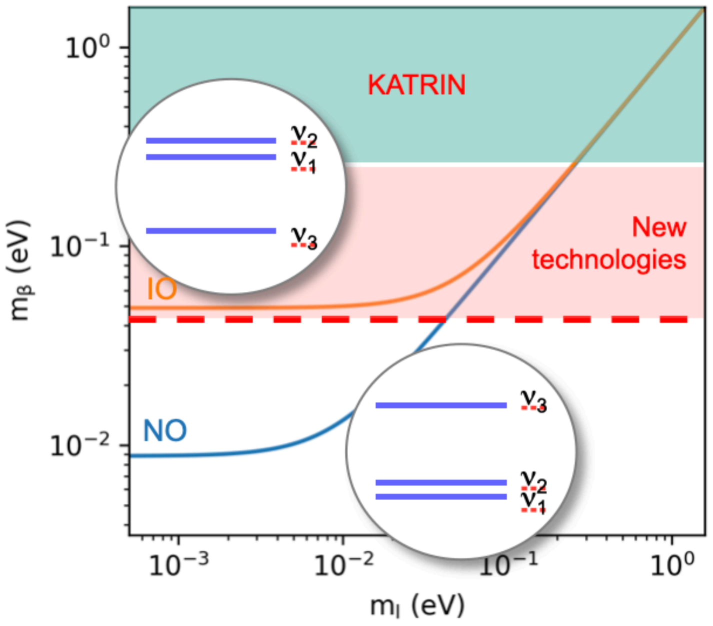


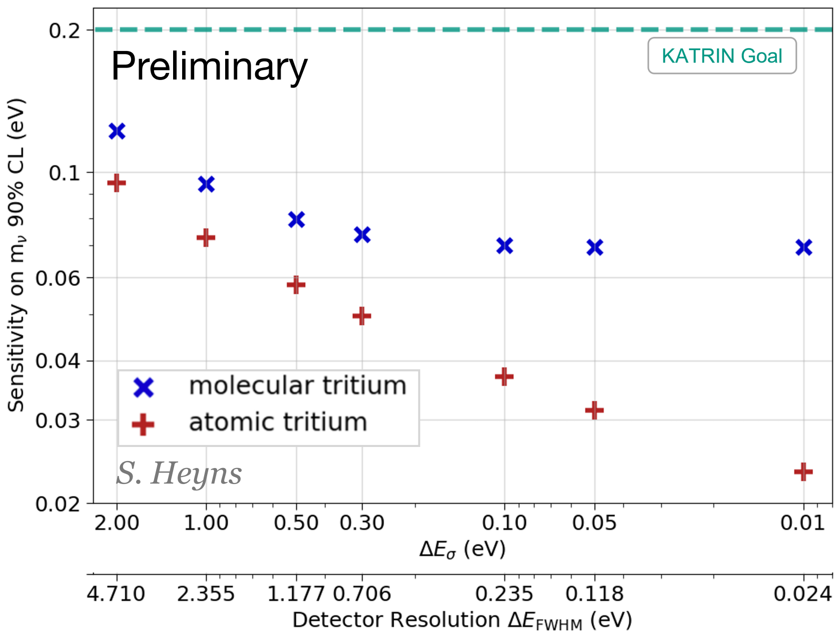
Silicon Drift Detector array:
166-pixel module

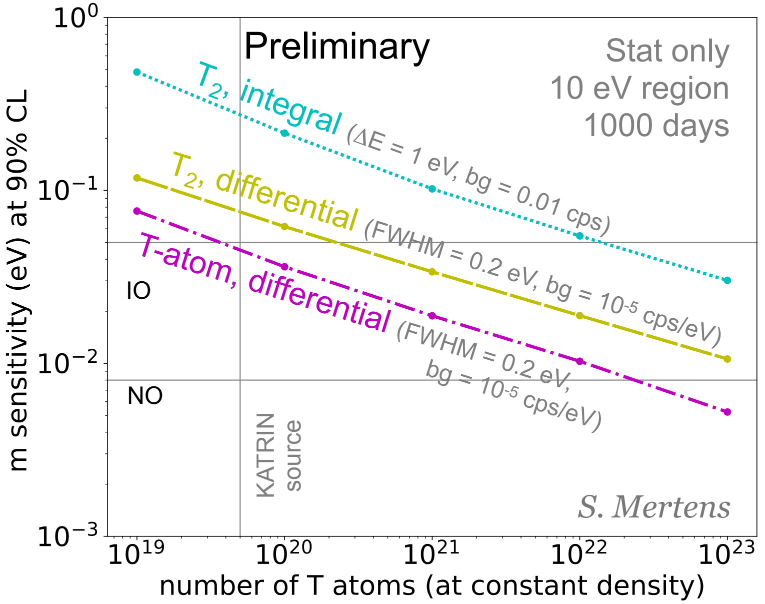
- TRISTAN phase fully funded, detector characterization at „replica“ beamline ongoing to prepare exchange

KATRIN — longer-range plans

- Improving neutrino-mass measurement beyond degenerate mass range requires novel technologies: **(i)** differential energy measurement and **(ii)** improved energy resolution via **quantum sensors (MMC array, ToF / tagger)** and **atomic tritium source.**







Poster Heyns et al.

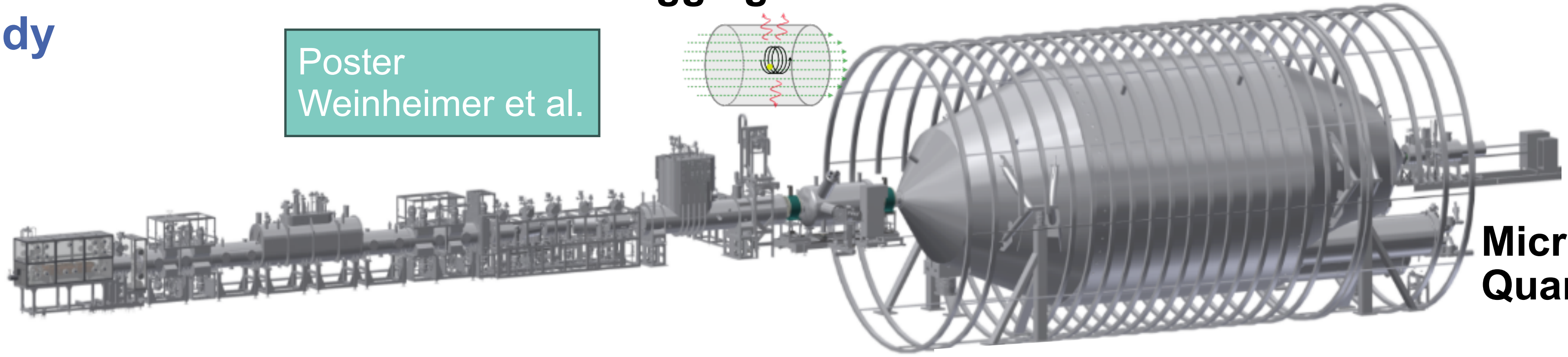
KATRIN++ mission

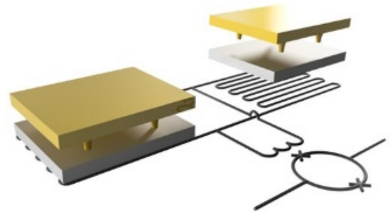
- Next-generation m_ν experiment to address inverted ordering of neutrino masses (and beyond)
- Identify and develop scalable technology (seed funding to explore concepts)
- Use KATRIN/TLK infrastructure for R&D phase (~ 7 years)

R&D already ongoing

Time-of-flight via electron tagging

Poster Weinheimer et al.





Micro-calorimeters / Quantum sensor

Atomic source technology

Poster Hasselmann et al.

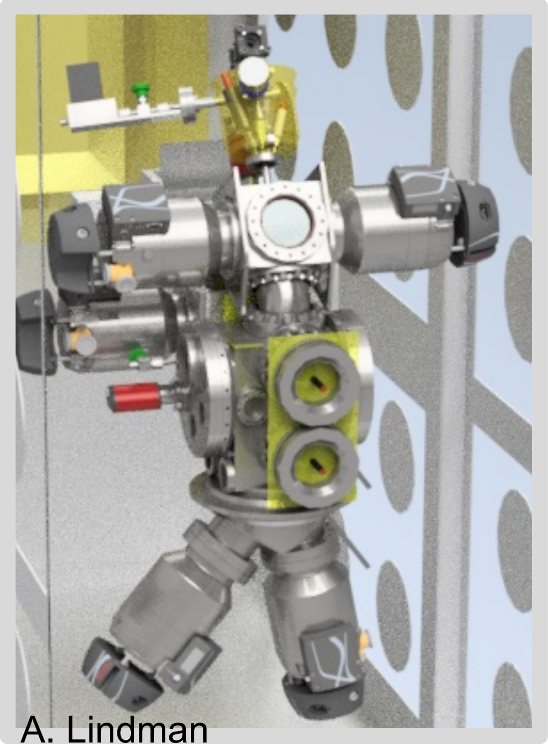
Differential detector technology

Posters Kovac et al., Adam et al.

from M. Schlösser

KAMATE – Karlsruhe Mainz Atomic Tritium experiment

Atomic tritium trap is key for ν mass — regardless of detection technique used.
→ Joint experiment for development of atomic source and cooling concept


A. Lindman

KAMATE 0.5 (at Mainz)
Identify best source at MATS with H/D

KAMATE 1.0 (at TLK)
Operate KAMATE 0.5 setup with T.
T(Beam) ~ 2500 K

KAMATE 2.0 (at TLK)
Add accommodator as first stage cooling.
T(Beam) ~ 150 K

KAMATE 3.0 (at TLK)
Add nozzle for second stage cooling and beam temperature measurement setup (time of flight).
T(Beam) ~ 4 K

Poster
Rodenbeck et al.

Karlsruhe

Tritium Laboratory Karlsruhe

Mainz

PROJECT 8

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

KAMATE as precursor of for a larger
Atomic Tritium Demonstrator Consortium

Work flowing into the Strategy Paper

Chapter 3: Short topical introductions

KAT. Komitee für Astro.Teilchen.Physik

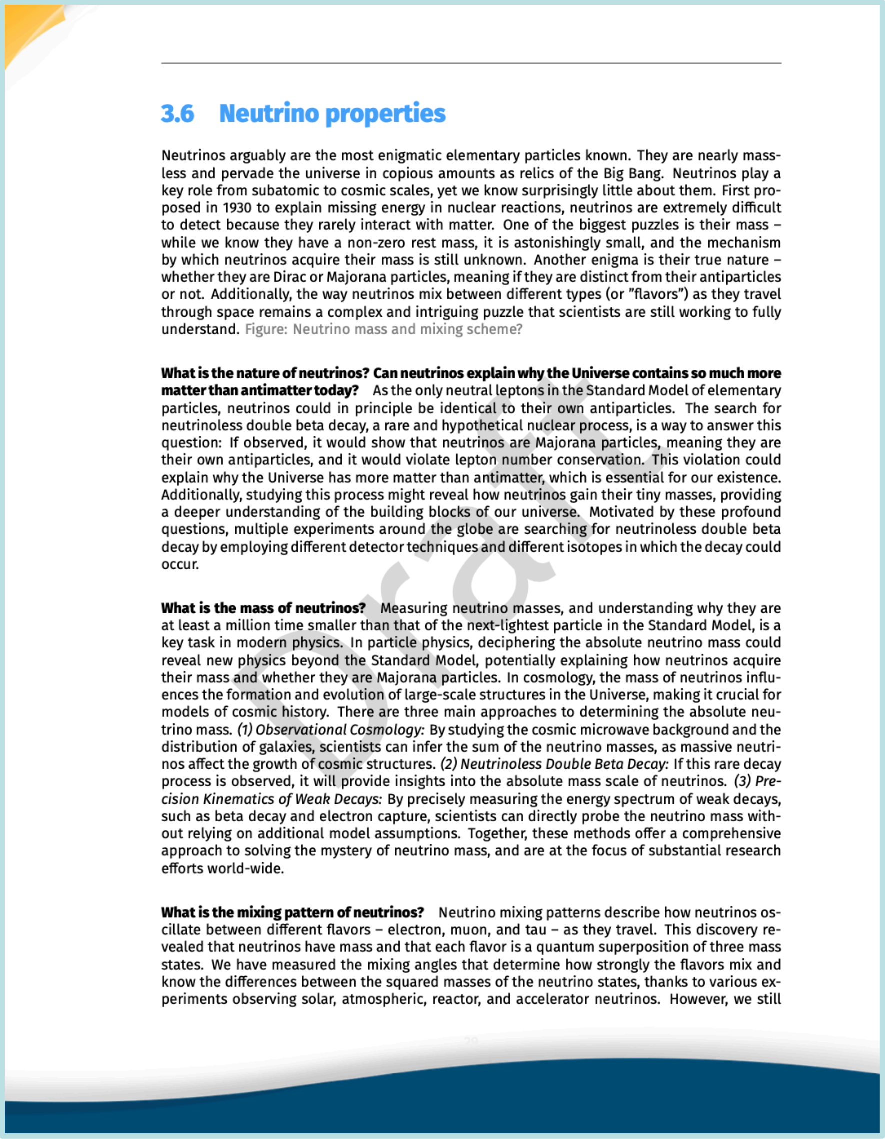
Neutrinos: cosmic enigmas

In the realm of particle physics, neutrinos remain one of the most fascinating and elusive players. Neutrinos are the most abundant and by far the lightest matter particles in the universe. They barely interact with matter, which makes them extremely difficult to detect. Yet they carry valuable information about the processes happening inside stars, in supernova explosions, and even in the earliest moments of the universe after the Big Bang. Almost 100 years after they were introduced to particle physics, we are yet to find out even the most fundamental properties of neutrinos, including the scale and origin of their masses, the way they can change from one type of neutrino into another, and whether they are their own antiparticles. Experiments like IceCube, LEGEND and KATRIN, in which groups based in Germany play a leading role, are helping to unravel the mysteries of these cosmic enigmas.

Draft as of 2024-10-17

- Ready for review and suggestions

Section 3.6: Neutrino Properties



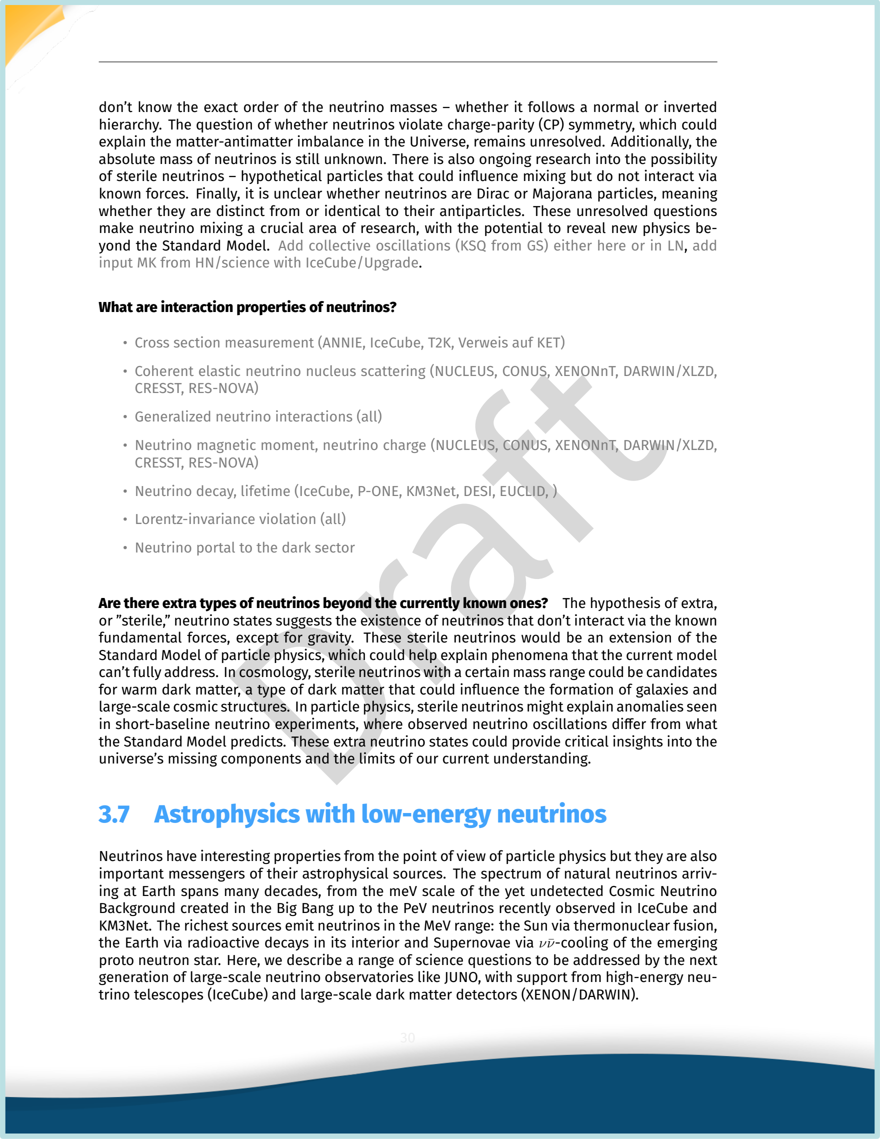
3.6 Neutrino properties

Neutrinos arguably are the most enigmatic elementary particles known. They are nearly massless and pervade the universe in copious amounts as relics of the Big Bang. Neutrinos play a key role from subatomic to cosmic scales, yet we know surprisingly little about them. First proposed in 1930 to explain missing energy in nuclear reactions, neutrinos are extremely difficult to detect because they rarely interact with matter. One of the biggest puzzles is their mass – while we know they have a non-zero rest mass, it is astonishingly small, and the mechanism by which neutrinos acquire their mass is still unknown. Another enigma is their true nature – whether they are Dirac or Majorana particles, meaning if they are distinct from their antiparticles or not. Additionally, the way neutrinos mix between different types (or ”flavors”) as they travel through space remains a complex and intriguing puzzle that scientists are still working to fully understand. Figure: Neutrino mass and mixing scheme?

What is the nature of neutrinos? Can neutrinos explain why the Universe contains so much more matter than antimatter today? As the only neutral leptons in the Standard Model of elementary particles, neutrinos could in principle be identical to their own antiparticles. The search for neutrinoless double beta decay, a rare and hypothetical nuclear process, is a way to answer this question: If observed, it would show that neutrinos are Majorana particles, meaning they are their own antiparticles, and it would violate lepton number conservation. This violation could explain why the Universe has more matter than antimatter, which is essential for our existence. Additionally, studying this process might reveal how neutrinos gain their tiny masses, providing a deeper understanding of the building blocks of our universe. Motivated by these profound questions, multiple experiments around the globe are searching for neutrinoless double beta decay by employing different detector techniques and different isotopes in which the decay could occur.

What is the mass of neutrinos? Measuring neutrino masses, and understanding why they are at least a million time smaller than that of the next-lightest particle in the Standard Model, is a key task in modern physics. In particle physics, deciphering the absolute neutrino mass could reveal new physics beyond the Standard Model, potentially explaining how neutrinos acquire their mass and whether they are Majorana particles. In cosmology, the mass of neutrinos influences the formation and evolution of large-scale structures in the Universe, making it crucial for models of cosmic history. There are three main approaches to determining the absolute neutrino mass. *(1) Observational Cosmology:* By studying the cosmic microwave background and the distribution of galaxies, scientists can infer the sum of the neutrino masses, as massive neutrinos affect the growth of cosmic structures. *(2) Neutrinoless Double Beta Decay:* If this rare decay process is observed, it will provide insights into the absolute mass scale of neutrinos. *(3) Precision Kinematics of Weak Decays:* By precisely measuring the energy spectrum of weak decays, such as beta decay and electron capture, scientists can directly probe the neutrino mass without relying on additional model assumptions. Together, these methods offer a comprehensive approach to solving the mystery of neutrino mass, and are at the focus of substantial research efforts world-wide.

What is the mixing pattern of neutrinos? Neutrino mixing patterns describe how neutrinos oscillate between different flavors – electron, muon, and tau – as they travel. This discovery revealed that neutrinos have mass and that each flavor is a quantum superposition of three mass states. We have measured the mixing angles that determine how strongly the flavors mix and know the differences between the squared masses of the neutrino states, thanks to various experiments observing solar, atmospheric, reactor, and accelerator neutrinos. However, we still



don’t know the exact order of the neutrino masses – whether it follows a normal or inverted hierarchy. The question of whether neutrinos violate charge-parity (CP) symmetry, which could explain the matter-antimatter imbalance in the Universe, remains unresolved. Additionally, the absolute mass of neutrinos is still unknown. There is also ongoing research into the possibility of sterile neutrinos – hypothetical particles that could influence mixing but do not interact via known forces. Finally, it is unclear whether neutrinos are Dirac or Majorana particles, meaning whether they are distinct from or identical to their antiparticles. These unresolved questions make neutrino mixing a crucial area of research, with the potential to reveal new physics beyond the Standard Model. Add collective oscillations (KSQ from GS) either here or in LN, add input MK from HN/science with IceCube/Upgrade.

What are interaction properties of neutrinos?

- Cross section measurement (ANNIE, IceCube, T2K, Verweis auf KET)
- Coherent elastic neutrino nucleus scattering (NUCLEUS, CONUS, XENONnT, DARWIN/XLZD, CRESST, RES-NOVA)
- Generalized neutrino interactions (all)
- Neutrino magnetic moment, neutrino charge (NUCLEUS, CONUS, XENONnT, DARWIN/XLZD, CRESST, RES-NOVA)
- Neutrino decay, lifetime (IceCube, P-ONE, KM3Net, DESI, EUCLID,)
- Lorentz-invariance violation (all)
- Neutrino portal to the dark sector

Are there extra types of neutrinos beyond the currently known ones? The hypothesis of extra, or ”sterile,” neutrino states suggests the existence of neutrinos that don’t interact via the known fundamental forces, except for gravity. These sterile neutrinos would be an extension of the Standard Model of particle physics, which could help explain phenomena that the current model can’t fully address. In cosmology, sterile neutrinos with a certain mass range could be candidates for warm dark matter, a type of dark matter that could influence the formation of galaxies and large-scale cosmic structures. In particle physics, sterile neutrinos might explain anomalies seen in short-baseline neutrino experiments, where observed neutrino oscillations differ from what the Standard Model predicts. These extra neutrino states could provide critical insights into the universe’s missing components and the limits of our current understanding.

3.7 Astrophysics with low-energy neutrinos

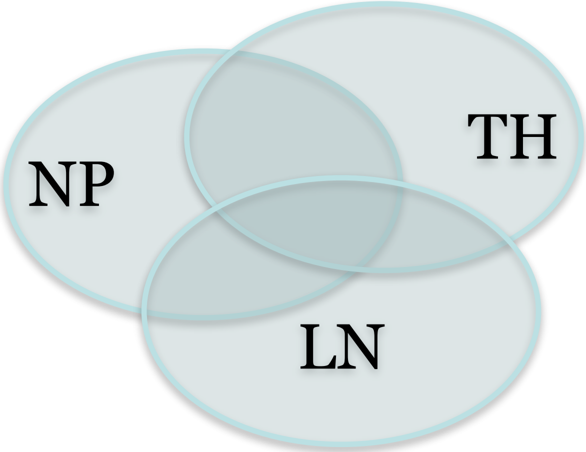
Neutrinos have interesting properties from the point of view of particle physics but they are also important messengers of their astrophysical sources. The spectrum of natural neutrinos arriving at Earth spans many decades, from the meV scale of the yet undetected Cosmic Neutrino Background created in the Big Bang up to the PeV neutrinos recently observed in IceCube and KM3Net. The richest sources emit neutrinos in the MeV range: the Sun via thermonuclear fusion, the Earth via radioactive decays in its interior and Supernovae via $\nu\bar{\nu}$-cooling of the emerging proto neutron star. Here, we describe a range of science questions to be addressed by the next generation of large-scale neutrino observatories like JUNO, with support from high-energy neutrino telescopes (IceCube) and large-scale dark matter detectors (XENON/DARWIN).

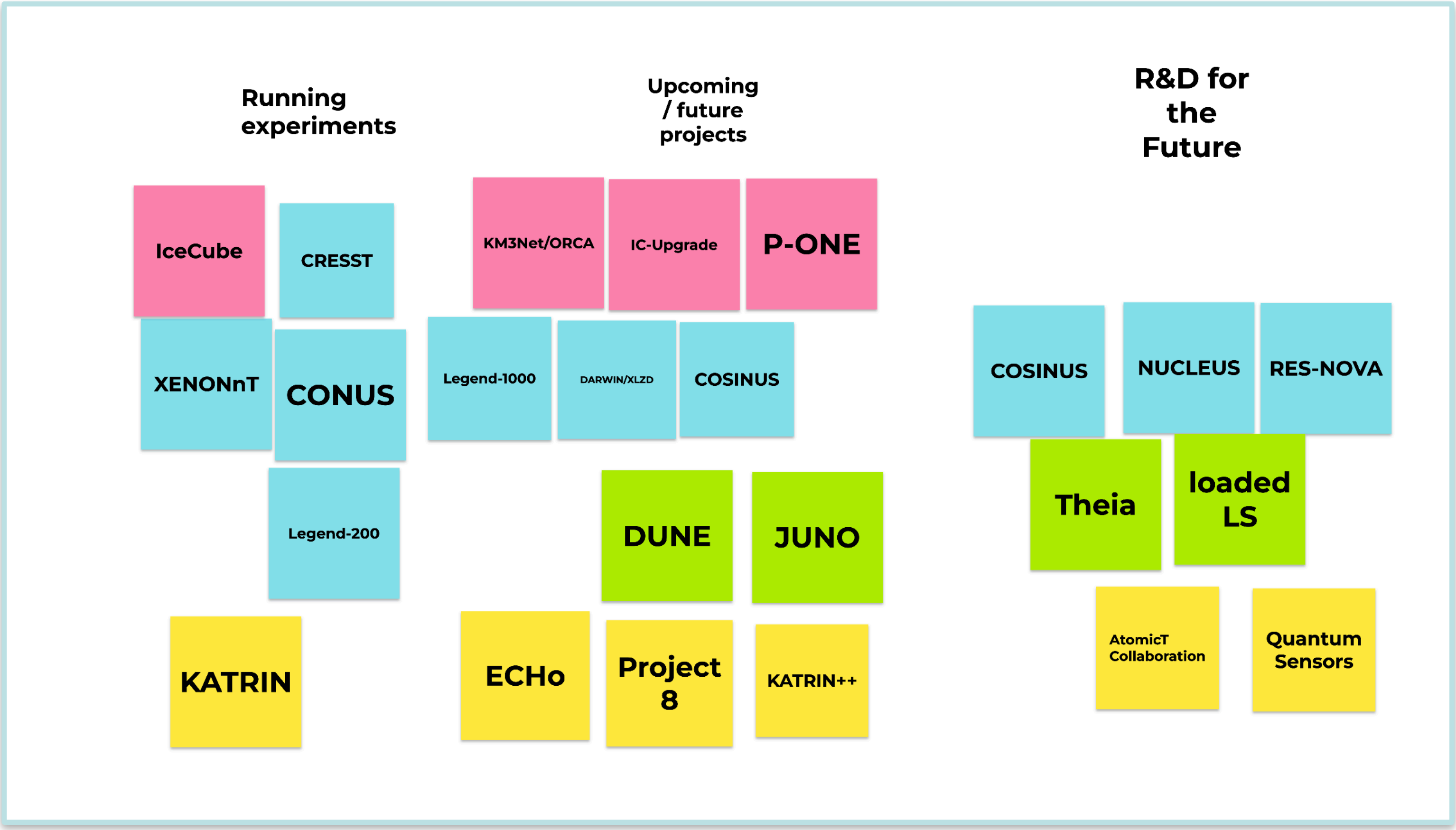
Draft as of 2024-10-17

- Key science questions partly complete
- Current results & achievemens missing

Chapter 4: Plans for the next decade

Joint workshop at U Mainz, June 11, 2024





Running experiments

- IceCube
- CRESST
- XENONnT
- CONUS
- Legend-200
- KATRIN

Upcoming / future projects

- KM3Net/ORCA
- IC-Upgrade
- P-ONE
- Legend-1000
- DARWIN/XLZD
- COSINUS
- DUNE
- JUNO
- ECHo
- Project 8
- KATRIN++

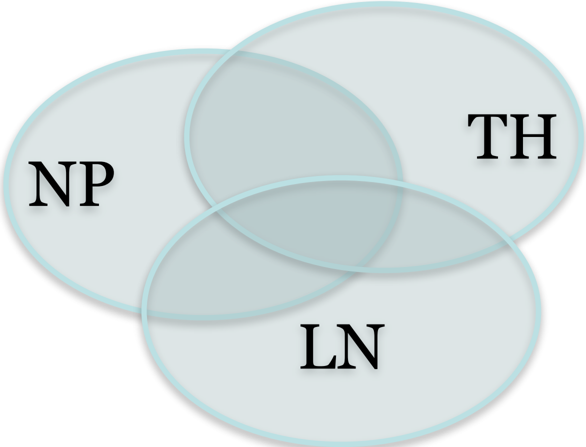
R&D for the Future

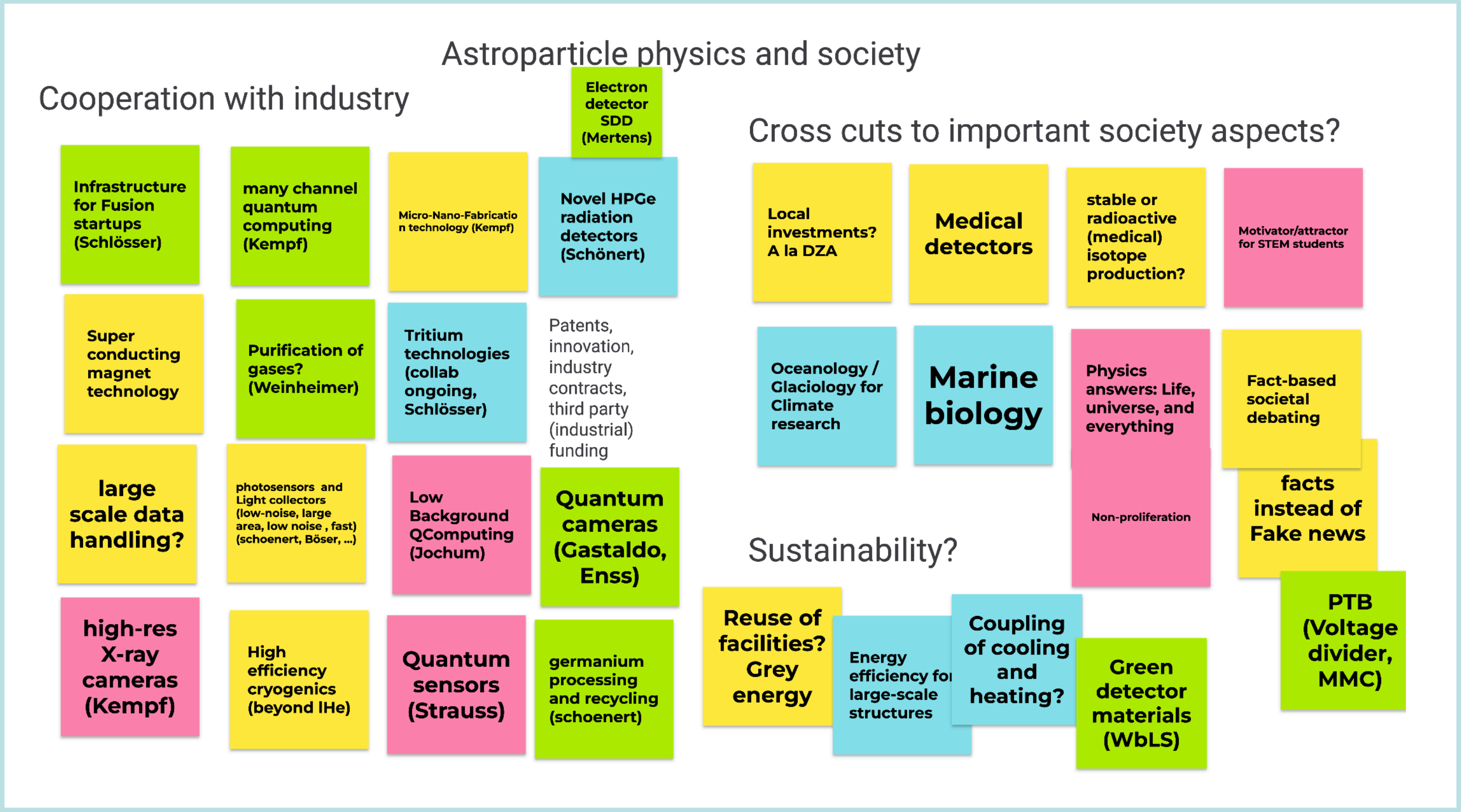
- COSINUS
- NUCLEUS
- RES-NOVA
- Theia
- loaded LS
- AtomicT Collaboration
- Quantum Sensors

Contributions outlined — need to be transferred into the Strategy Paper!

Chapter 5: Overarching topics

Joint workshop at U Mainz, June 11, 2024





Astroparticle physics and society

Cooperation with industry

Electron detector SDD (Mertens)

Infrastructure for Fusion startups (Schlösser)

many channel quantum computing (Kempf)

Micro-Nano-Fabrication technology (Kempf)

Novel HPGe radiation detectors (Schönert)

Super conducting magnet technology

Purification of gases? (Weinheimer)

Tritium technologies (collab ongoing, Schlösser)

Patents, innovation, industry contracts, third party (industrial) funding

large scale data handling?

photosensors and Light collectors (low-noise, large area, low noise , fast) (schoenert, Böser, ...)

Low Background QComputing (Jochum)

Quantum cameras (Gastaldo, Enss)

high-res X-ray cameras (Kempf)

High efficiency cryogenics (beyond lHe)

Quantum sensors (Strauss)

germanium processing and recycling (schoenert)

Cross cuts to important society aspects?

Local investments? A la DZA

Medical detectors

stable or radioactive (medical) isotope production?

Motivator/attractor for STEM students

Oceanology / Glaciology for Climate research

Marine biology

Physics answers: Life, universe, and everything

Fact-based societal debating

Non-proliferation

facts instead of Fake news

PTB (Voltage divider, MMC)

Sustainability?

Reuse of facilities? Grey energy

Energy efficiency for large-scale structures

Coupling of cooling and heating?

Green detector materials (WbLS)

Great collection of ideas — need to be transferred into the Strategy Paper!

Wrap-up

- Research groups in Germany make strong contributions towards solving the persistent puzzles of neutrino properties, and we should transmit that in the Strategy Paper.
- Our plans involve projects (and large-scale research facilities) that extend well into the future — strategy planning for a 10-year scope (and even beyond) is appropriate.
- Funding sought from different sources at the national and international level, and on various project scales and timelines.
- To move the writing process along, **please review the draft document** & **send comments to**

  Kathrin Valerius (kathrin.valerius@kit.edu), NP
  Stefan Schönert (schoenert@ph.tum.de), NP
  Thomas Schwetz (schwetz@kit.edu), EB
  Uli Katz (uli.katz@fau.de), EB
  Christian Stegmann (christian.stegmann@desy.de), EB