MAX-PLANCK-INSTITUT
FÜR PHYSIK

PROGRESS OF THE GERMAN ESPP CONTRIBUTION ON NON-COLLIDER PROJECTS

GERMAN ESPP CONTRIBUTION(S) ON NON-COLLIDER PROJECTS

- Non-Collider Particle Physics Projects → KET contribution
- Astroparticle Physics Projects → KAT contribution

Intent to coordinate the contributions for the projects which are in the intersection

KET
Komitee für Elementarteilchenphysik

Annual meeting 2024 of particle physicists in Germany and German strategy workshop "The Future of Non-Collider Particle Physics" in preparation of the ESPP update

https://indico.desy.de/event/45358/

Summarise ongoing non-collider (particle physics) experiments with a significant German contribution and prioritise the next major projects

- Emphasise particle physics topics that cannot be explored with colliders
- Promote a diverse experimental landscape

"THE FUTURE OF NON-COLLIDER PARTICLE PHYSICS" WORKSHOP

Final version of summary distributed to participants last week

Structured along research directions*:

- Particle-like Dark Matter searches**
- Axions and wave-like Dark Matter**
- Feebly Interacting Particles
- Precision experiments
- Neutrino Physics
  - Long-baseline neutrinos
  - Non-accelerator neutrinos
  - Astrophysical Neutrinos
- Gravitational waves

* The ordering is the one of the timetable and not my ranking.

** Only "direct" searches.

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THE QUESTIONS TO BE ADDRESSED

1. What are the important/primary scientific questions of the field?

   Which experimental options exist to answer them (completely, partially,?) and when?

   For proposed projects: Are scientifically important results guaranteed, likely or possible?

   Which secondary topics are covered by the project, and what are chances for success?

2. Estimate the time scales, costs (investment) and structures (collaboration size and international composition).

   Which risks exist? Which competing projects exist world-wide for the physics question, also taking realistic schedules and progress into account?

3. Where is the specific German interest? Do special strengths of German groups play a role?

   Are there enough interested groups/people for a meaningful contribution?

   Will the participation create synergies and international visibility?

   How does the required funding fit to the German funding structure (which funding line, volume)?

4. Where could the project be realised?

WIMP EXPERIMENTS

Federica Petricca
MAX-PLANCK-INSTITUT FÜR PHYSIK

"The Future of Non-Collider Particle Physics”
Physikzentrum Bad Honnef, 23 November 2024

Particle-like Dark Matter

~~WIMP~~ Experiments

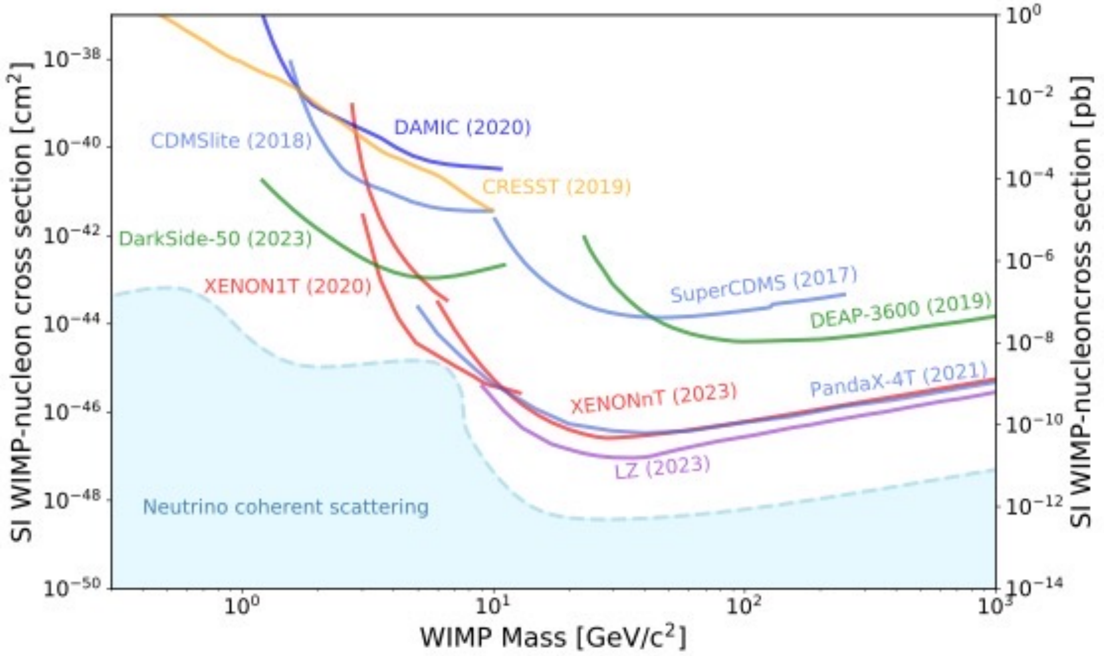
WIMP EXPERIMENTS

Direct detection experiments

Search for signals induced by dark matter from the galactic halo in terrestrial detectors

From PDG 2024:
Only a sense of the diversity of the experimental landscape

From now on, projects with a strong German contribution*
→ KAT perspective



* Thanks to the colleagues who kindly provided the material

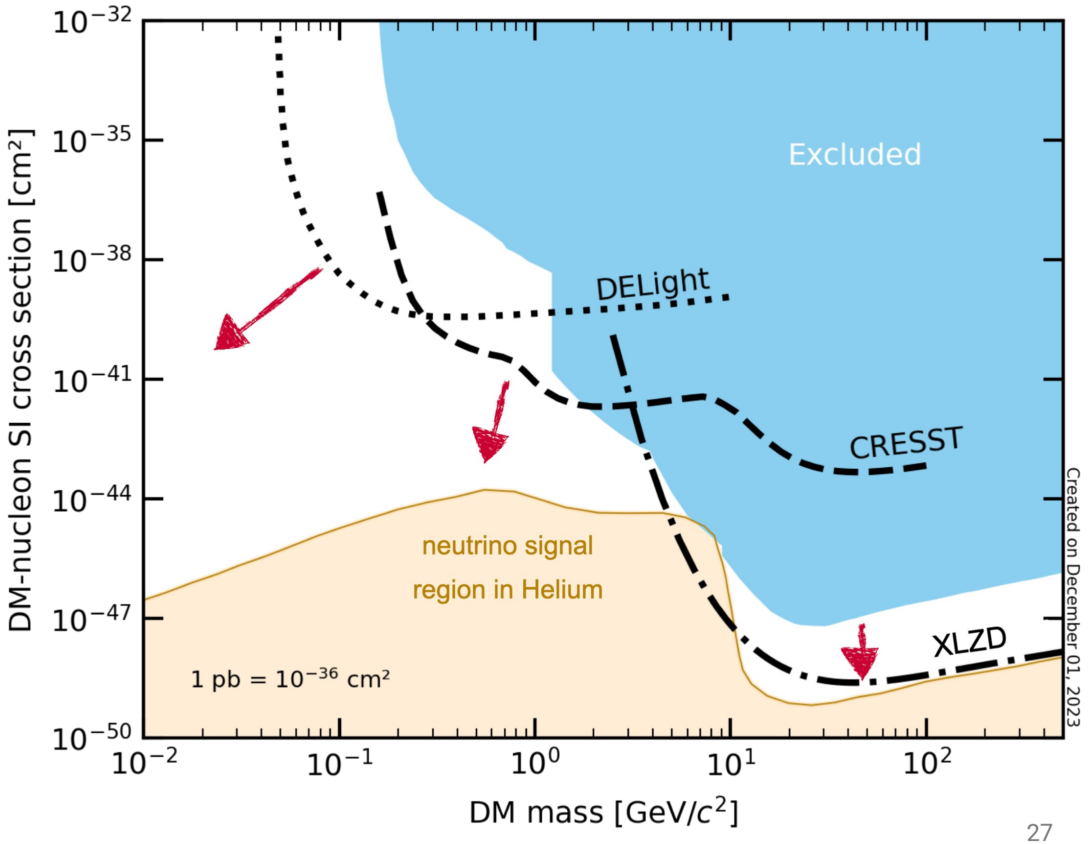
WIMP EXPERIMENTS

Complementarity of direct DM searches with significant German involvement

Germany has a recognised leadership role in the field with very complementary experimental efforts.

DM direct search is a crucial ingredient to shed light on our understanding of the universe.

A breakthrough may be just “around the corner”.

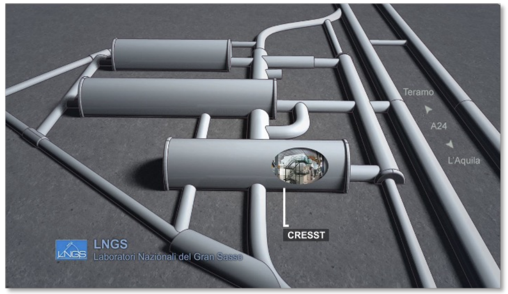


WIMP EXPERIMENTS

CRESST

9 institutions (4 German)
5 countries
~60 members (~60% from German institutions)

Located in LNGS hall A

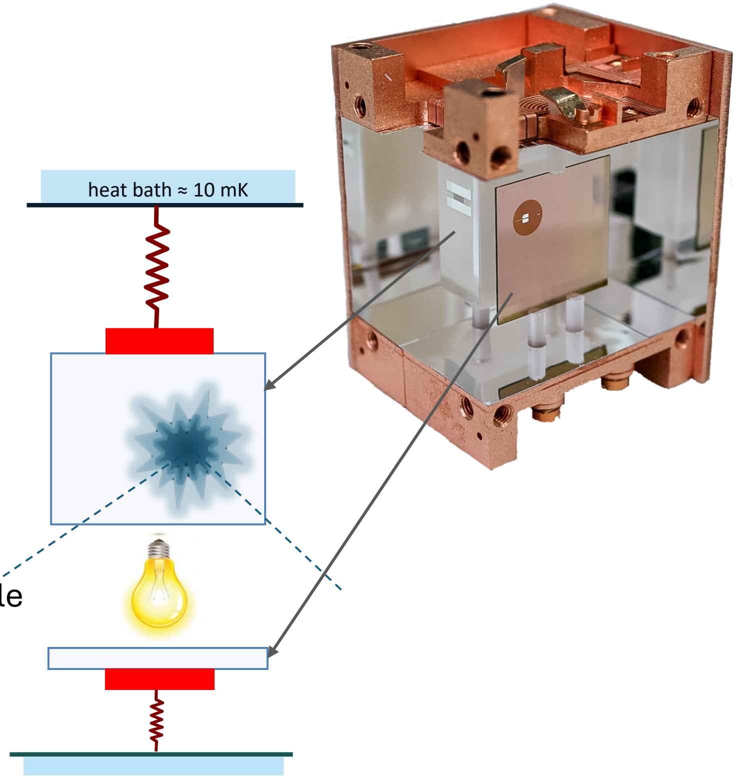


COMENIUS UNIVERSITY BRATISLAVA · UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386 · HEPHY INSTITUTE OF HIGH ENERGY PHYSICS · TU WIEN · INFN LNGS Istituto Nazionale di Fisica Nucleare Laboratori Nazionali del Gran Sasso · MAX PLANCK INSTITUTE FOR PHYSICS · EBERHARD KARLS UNIVERSITÄT TÜBINGEN · UNIVERSITY OF OXFORD · TECHNISCHE UNIVERSITÄT MÜNCHEN

WIMP EXPERIMENTS

Detection concept

- Scintillating cryogenic *O*(10mk) calorimeters
  - *O*(kg) detector mass
- Separate light detector for active background discrimination
- Quantum-enabled Transition Edge Sensors for temperature read-out
  - **Lowest nuclear recoils threshold (*O*(10)eV)**



Leading limits on low-mass dark matter

The CRESST technology was developed in Germany.
The technology has applications in many other fields (CEνNS, double beta decay, astrophysics, ...)

Maintain German leadership and unique expertise.

CRESST timeline

CRESST

New CRESST setup:

100 24g-$CaWO_4$ CRESST modules with 30 eV energy threshold and no low-energy-excess background

CRESST sensitivity upgrade program:

- Performance improvement (lower threshold): done ✓
- Background reduction: ongoing ✓
- Exposure increase: extended readout to be installed ✓

Installation planned after the end of ongoing data-taking

2024 2025 2026 2027 2028 2029 2030

Data taking

System upgrade→ data taking

R&D towards next-gen experiment

SUMMARY

The German (particle physics) community therefore recommends to prioritise the XLZD, the CRESST-III as well as the DELight experiment in the future, which all cover different WIMP mass ranges.

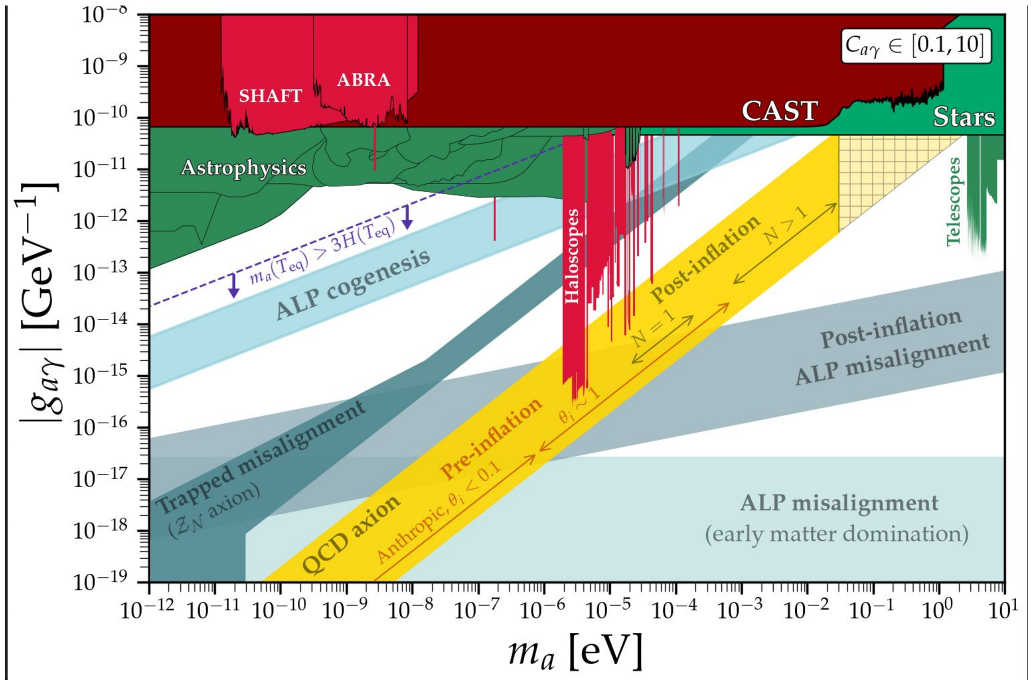
The goal here is not to improve limits, but to be first in detecting Dark Matter.
CRESST-III consolidates the opportunity of MPP to maintain a leadership role in the race.

AXION EXPERIMENTS

AXION EXPERIMENTS

Community Glossary: axion, axion-like and axion-DM

- The `vanilla' axion lives in the yellow region
- The axion-DM lives below approx ~10^-2 eV
- The axion-like particle lives anywhere that experiments/astro-probes haven't probed yet (and may in some regions still be DM). *Though note uncertainties in some exclusions!* It is phenomenologically motivated & appears in SM extensions (e.g. string theory)
- This is the most commonly shown plot: photon coupling



[this and most overview limit plots taken from Ciaran's Github]

AXION EXPERIMENTS

Important major ongoing and future activities with relevance for Germany

1. **Helioscopes: babyIAXO & IAXO**

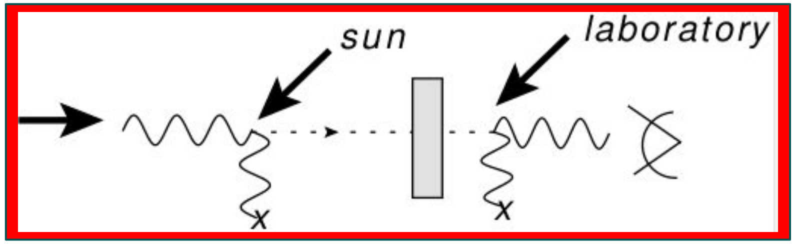
   (also sensitive to axion electron and nucleon coupling)

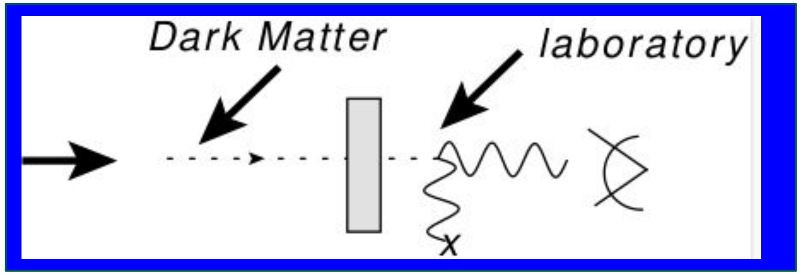
2. **Haloscopes & dielectric**

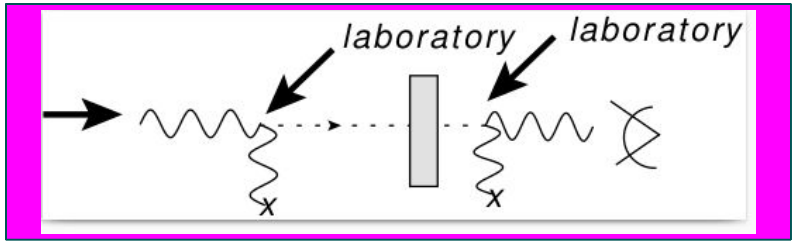
   Haloscopes: MADMAX, RADES@babyIAXO, SUPAX, Brass , WISPLC

   Non-photon: CASPEr

3. **Lab-tests: ALPS-II ,** ARIADNE and WISPFI





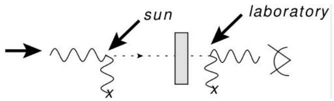


**I apologize for likely (!) omissions and not going through all the above in details for the lack of time*

**Noteworthy European larger experimental efforts that will appear in plots: FLASH@Frascati, QUAX@INFN, GraHal@Grenoble , others..

AXION EXPERIMENTS

Haloscopes: babyIAXO & IAXO



- Foreseen successor of the strongest-to-date helioscope CAST@CERN is the babyIAXO experiment @DESY
- babyIAXO: Exceptional magnetic volume (2 bores of 70cm, with 10m length at ~2T) , to be succeeded by full IAXO: 7 bores, 22m
- ~ 120 collaborators, 9 German institutions

Rendering of the babyIAXO magnet at HERA-south hall at DESY

Full members: Kirchhoff Institute for Physics, Heidelberg U. (Germany) | Siegen University (Germany) | University of Bonn (Germany) | DESY (Germany) | University of Mainz (Germany) | Technical University Munich (TUM) (Germany) | University of Hamburg (Germany) | MPE/PANTER (Germany) | MPP Munich (Germany) | IRFU-CEA (France) | CAPA-UNIZAR (Spain) | INAF-Brera (Italy) | CERN (Switzerland) | ICCUB Barcelona (Spain) | Barry University (USA) | MIT (USA) | LLNL (USA) | University of Cape Town (S. Africa) | CEFCA-Teruel (Spain) | U. Polytechnical of Cartagena (Spain)
Associate members: DTU (Denmark) | U. Columbia (USA) | SOLEIL (France) | IJCLab (France) | LIST-CEA (France)

AXION EXPERIMENTS

babyIAXO & IAXO

European Research Council
Established by the European Commission

- **Time-line and progress impacted by political situation with Russia**
- **Rutherford cable (40% of BabyIAXO needs) production ongoing at WST, China.**
- **`magnetless' commissioning is a possibility**

In 2022 BabyIAXO was basically ready to start construction, but experienced a serious setback after the Russian invasion into the Ukraine and the subsequent discontinuation of collaborations with Russian partner institutes.

This mainly affected the BabyIAXO magnet.

Thanks to the collaboration and engagement by CERN and DESY, the magnet is in reach again!

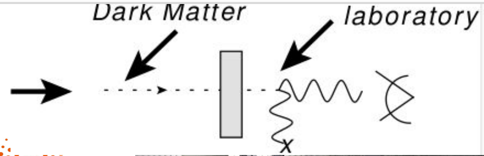
Component / Status	Technical	Funding
Structure & Drive system	(✓)	(✓)
Vacuum & Gas System	✓	✓
Magnet	(✓)	(?)
X-ray Telescopes	✓	✓
Detectors	✓	✓

AXION EXPERIMENTS

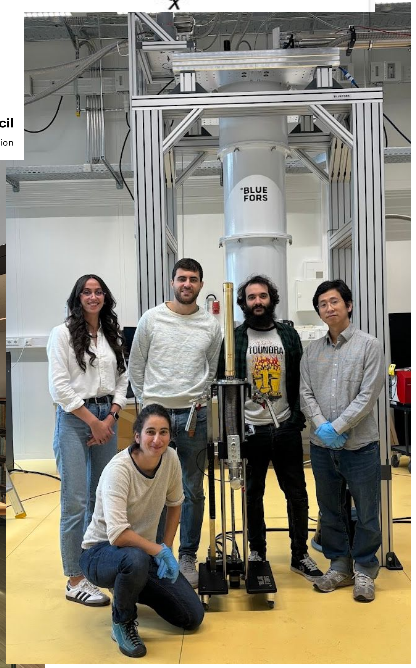
babyIAXO & RADES-HF

- babyIAXO would lend itself also to a cavity search (haloscope) at few hundreds of MHz [2306.17243] (or act as a generic platform for other axion search concepts such as dielectric haloscopes)
- Prototyping and starting axion data-taking within RADES (ERC-StG AxScale)
- Recently attracted several grants for the prospect of quantum-limited detection (ERC-SYG & QUANTERA)
- Aalto, Barcelona (x3), Cartagena-UPCT, CERN, KIT, MPP, Mainz, OAN Yebes, ENS-Paris, TRIUMF, Valencia, Zaragoza

*axion/particle *quantum *cryo *HTS *RF *radiopure



Collaboration meeting 2024

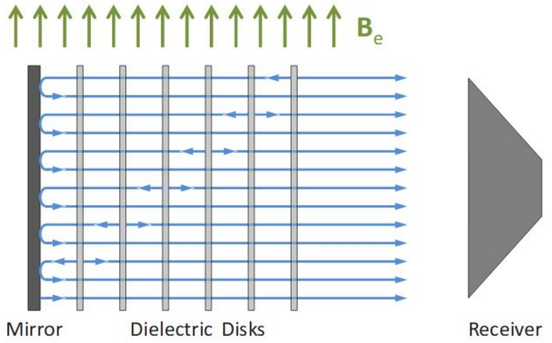


Cryostat with T<7mK and B=12T installed at MPP in early November

AXION EXPERIMENTS

Tackling the higher mass range with a dielectric Haloscope:

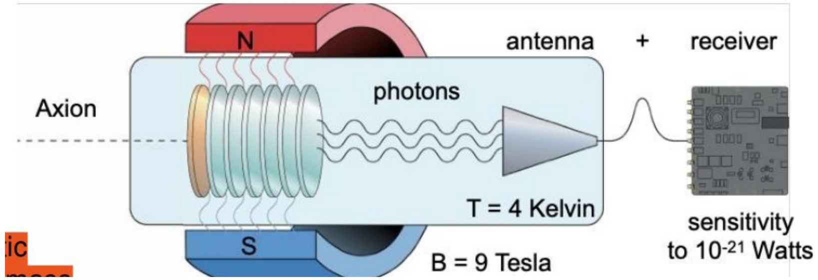
- Elegant solution to circumvent the m ~ f_resonance problem (causing small volume) present in haloscopes [1611.05865]
- Booster: a stack of dielectric plates inside a strong magnetic dipole tuned to the radiofrequency corresponding to axion mass (“replaces” Q in cavities)
- 11 institutes (Germany: MPIR, MPP, DESY, Tuebingen & Hamburg) with ~30 collaborators

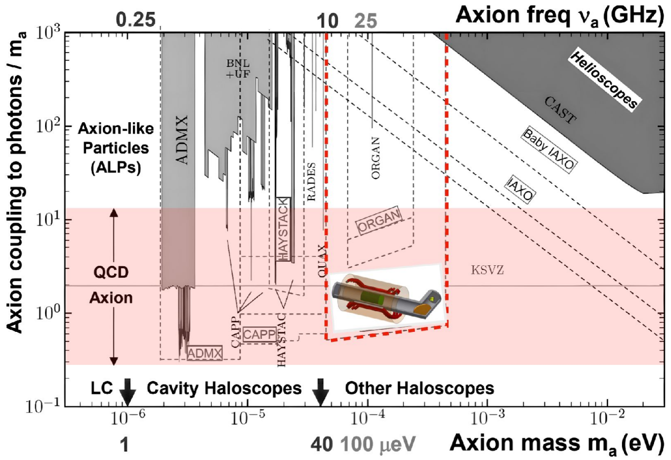


AXION EXPERIMENTS

Tackling the higher mass range with a dielectric Haloscope:

- By tuning the disks distances adjust the resonance frequency band over a large range (~10-100 GHz) and broadband (~100 MHz per tuned configuration)
- Staged approach of prototypes to demonstrate feasibility of concept and scaling at MORPURGO@CERN & planned @Fermilab
- For example: Complex booster calibration method developed at MPP Munich and Hamburg University

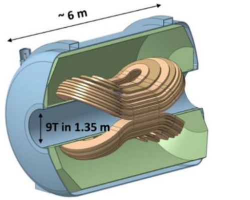




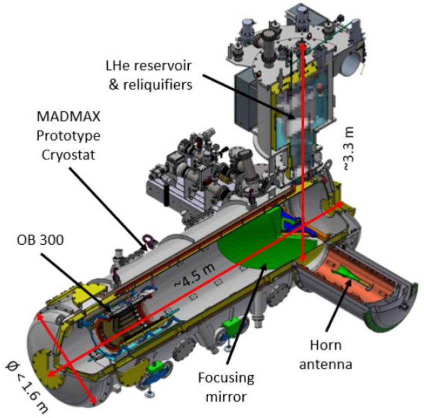
AXION EXPERIMENTS

Towards the full-scale MADMAX experiment

- `Full-scale experiment’ planned @DESY, HERA north
- ~9T magnet at 1.3m diameter disks -> enable scan of significant portion of “large DM axion mass” parameter space: 40-100 ueV with sensitivity to QCD axion
- Provided funds become available: magnet production start in 2027, first science run in 2032



Prototype cryostat to be used at MORPURGO gives a sense of scale ->



SUMMARY

The community prioritises the two complementary concepts of MADMAX and IAXO together with its precursor experiment BabyIAXO as large-scale experiments on an international level.

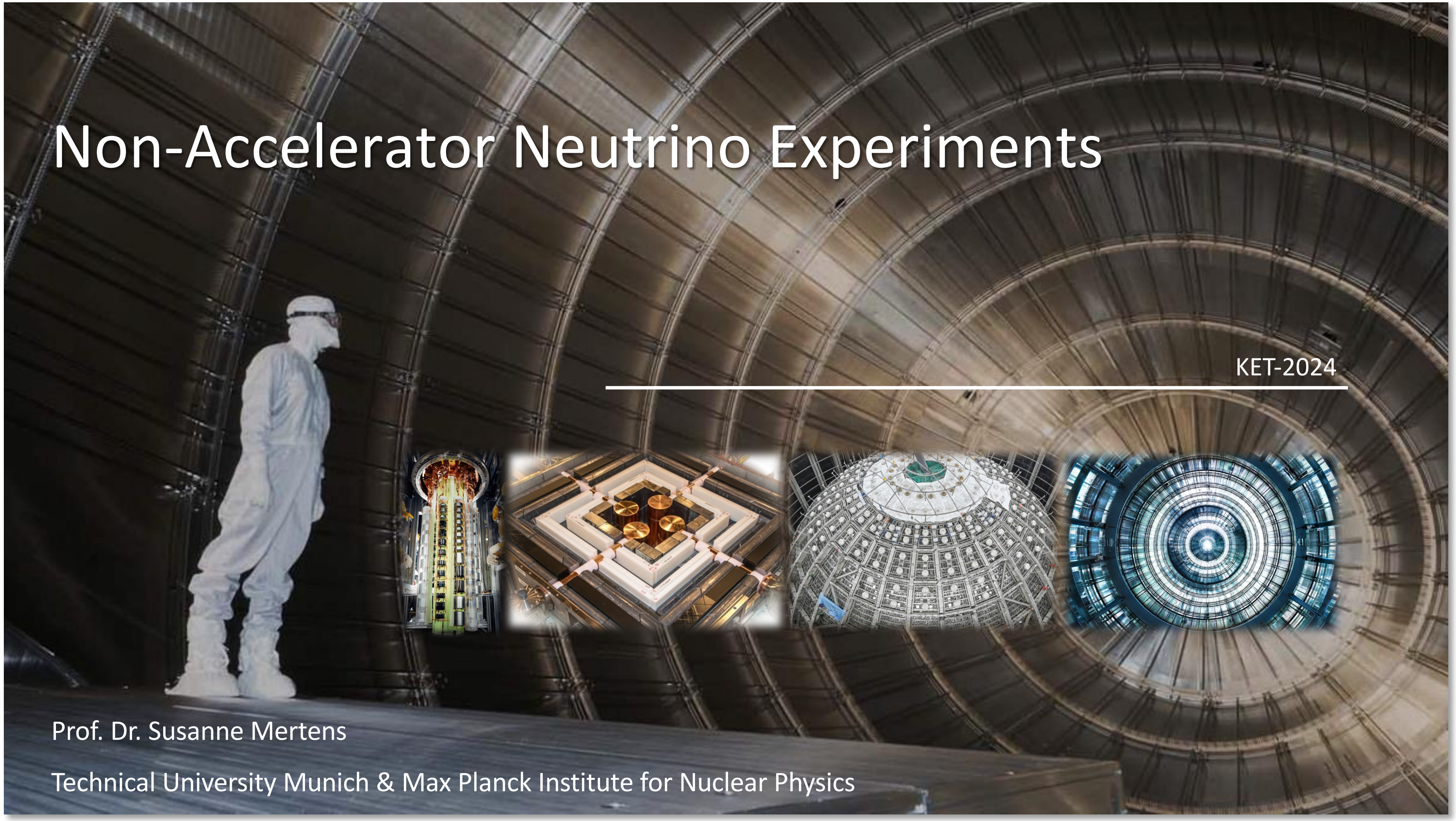
Lead MPP involvement in MADMAX and *RADES*

Complementary mass ranges
Many common challenges→ Synergetic in large parts

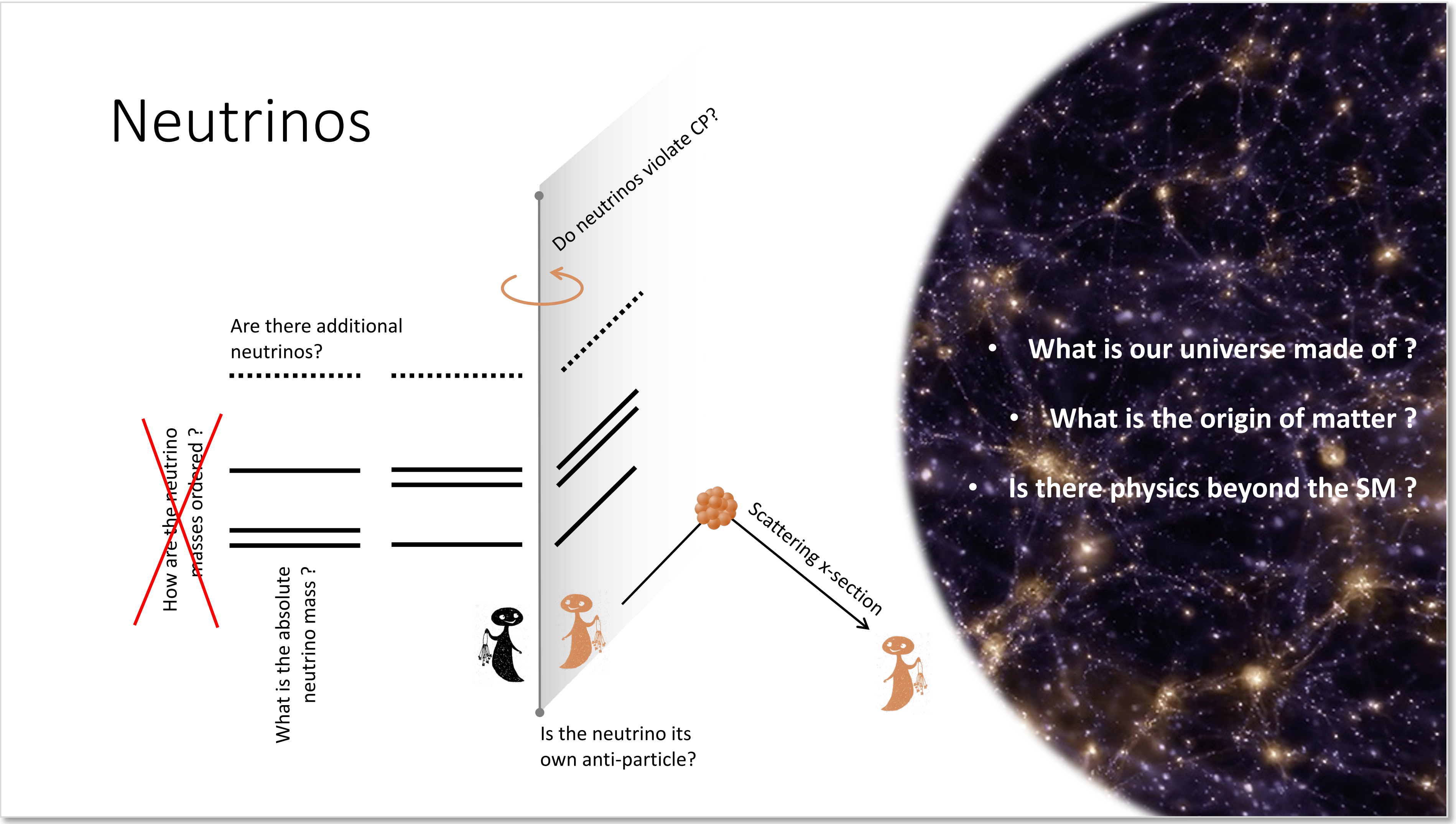
Close cooperation between two groups@ MPP / collaborations

Both experiments will be hosted at DESY
→ Significant MPP contribution to envisioned German/European axion hub

NON-ACCELERATOR NEUTRINO EXPERIMENTS



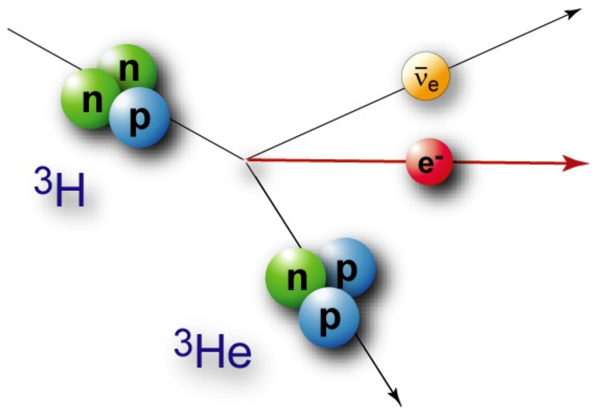
NON-ACCELERATOR NEUTRINO EXPERIMENTS



NON-ACCELERATOR NEUTRINO EXPERIMENTS

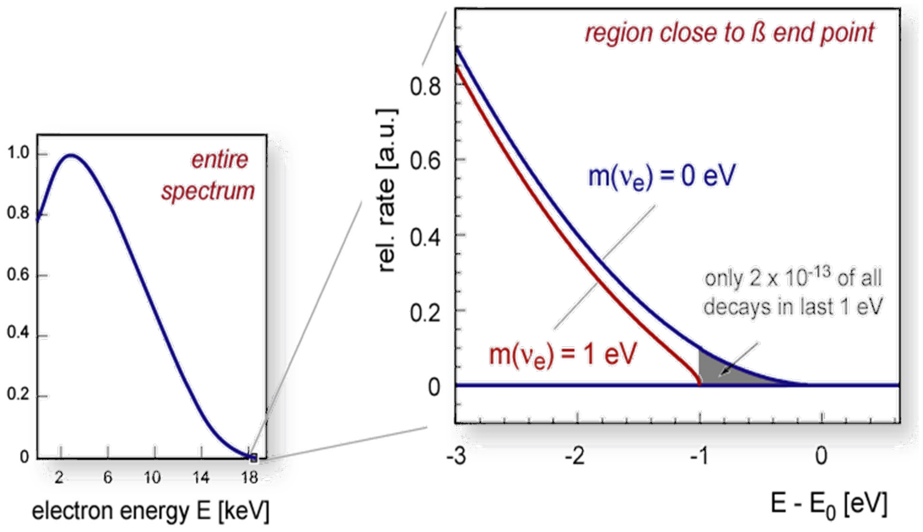
Measurement of β-decay spectra

The signature



- ✓ Incoherent sum of neutrino masses
- ✓ Independent of neutrino nature (Dirac or Majorana)

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



NON-ACCELERATOR NEUTRINO EXPERIMENTS

KATRIN

- **Experimental site: Karlsruhe Institute of Technology (KIT)**
- **International Collaboration with strong German contributions (10 institutions)**
- **Main goal: direct measurement of the neutrino mass with 0.3 eV sensitivity**

Karlsruher Institut für Technologie

Max-Planck-Institut für Kernphysik Heidelberg

Max-Planck-Institut für Physik

Westfälische Wilhelms-Universität Münster

Hochschule Fulda University of Applied Sciences

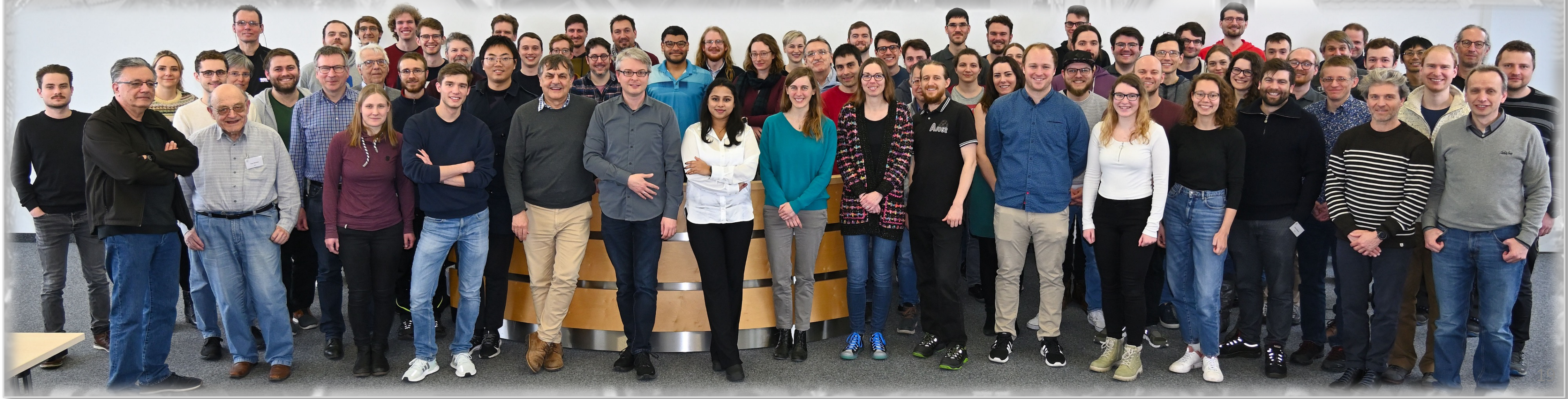
universität bonn

Johannes Gutenberg Universität Mainz

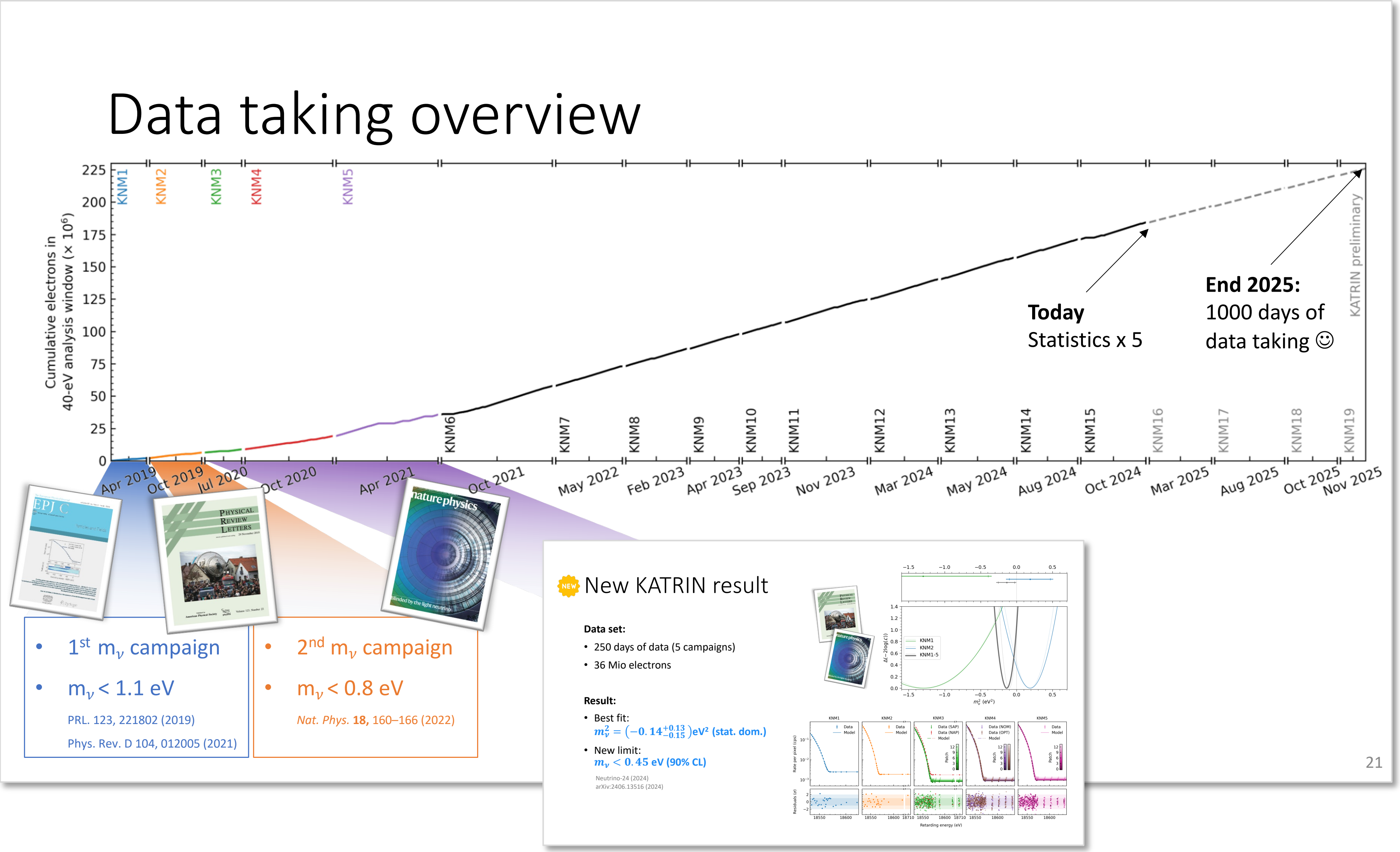
Humboldt-Universität zu Berlin

Bergische Universität Wuppertal

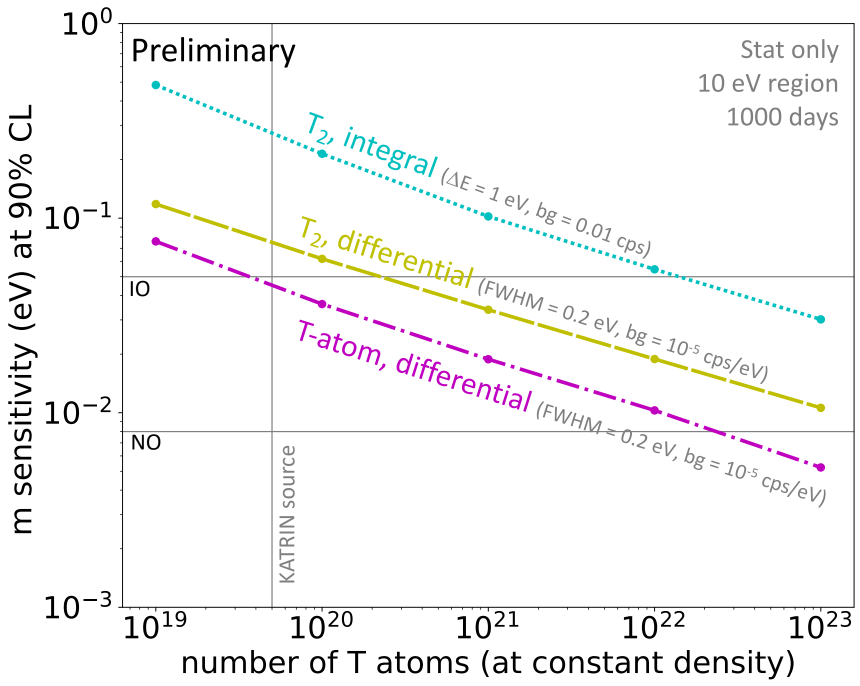
Technische Universität München



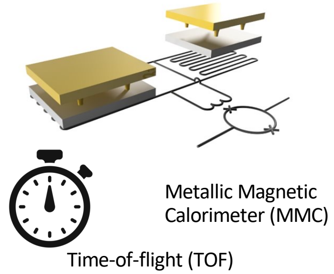
NON-ACCELERATOR NEUTRINO EXPERIMENTS



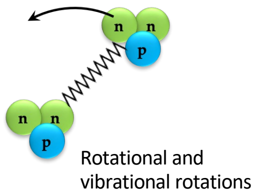
R&D program: KATRIN ++



- **Differential measurement (FWHM < 1 eV)**
  - ✓ Better use of statistics
  - ✓ Lower background



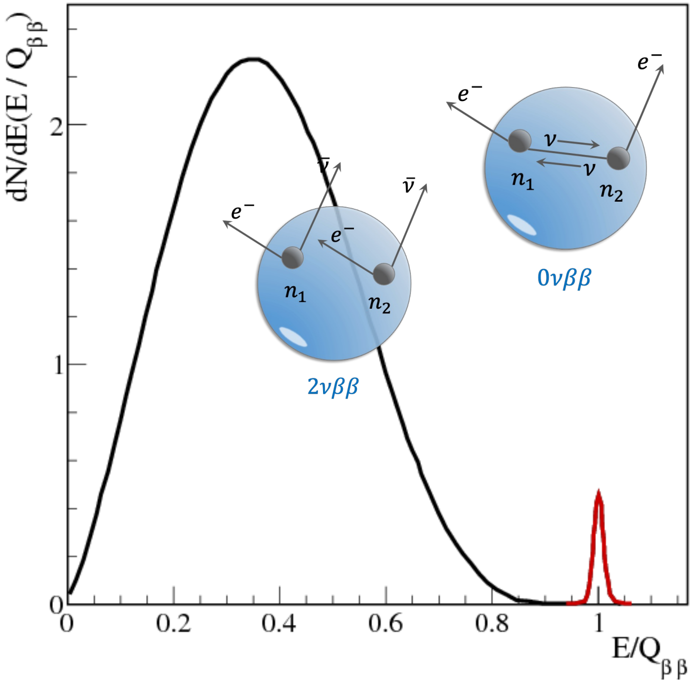
- **Atomic tritium**
  - ✓ Avoid broadening (~ 1 eV)
  - ✓ Avoid limiting systematics of T_2



NON-ACCELERATOR NEUTRINO EXPERIMENTS

Measurement of 0νββ-decay

The signature



Discovery of 0νββ:

- Process which creates matter, without the balancing amount of anti-matter
- Neutrino is a Majorana particle
- Lepton-number violation
- Half life reveals neutrino mass:

$$\frac{1}{T_{1/2}^{0\nu}} = G_{0\nu}(Q,Z) \cdot |M^{0\nu}|^2 \cdot \boldsymbol{m_{\beta\beta}^2}$$

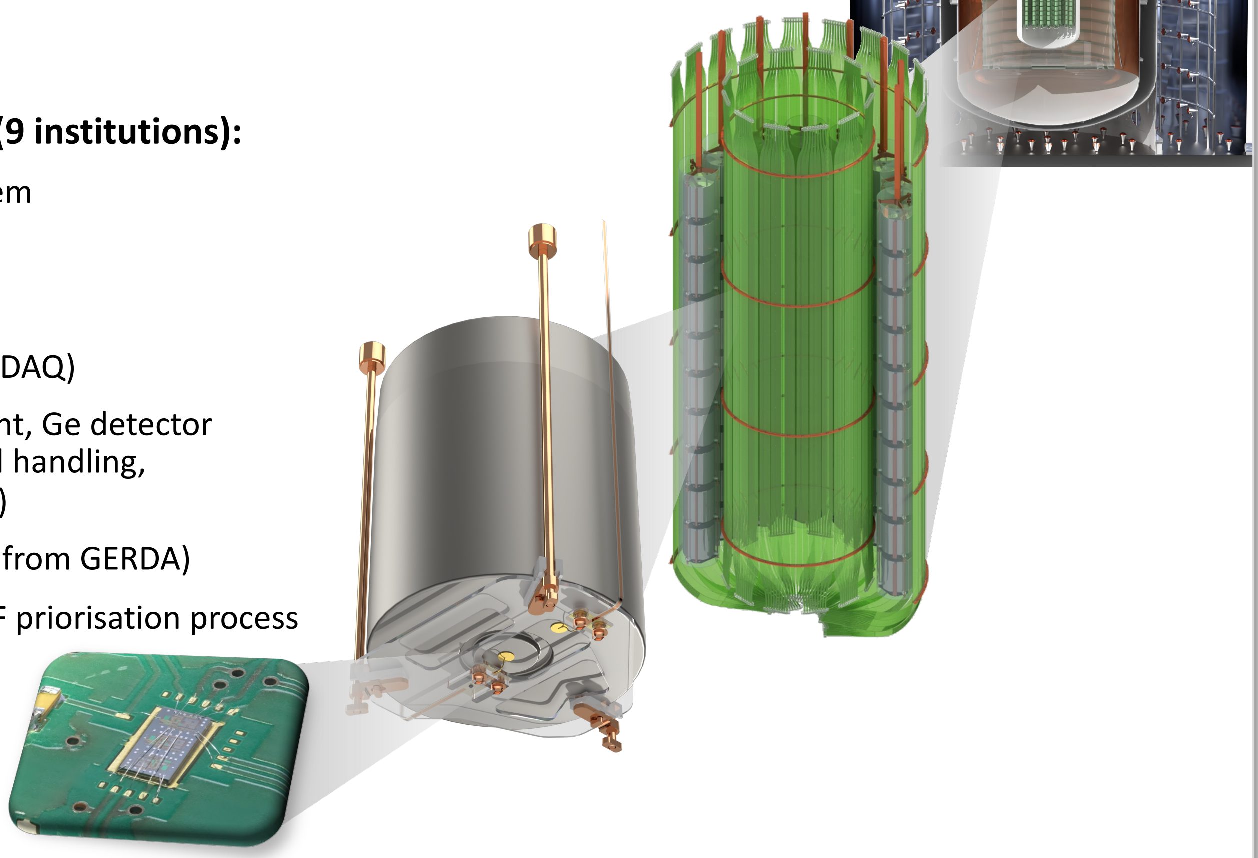
35

NON-ACCELERATOR NEUTRINO EXPERIMENTS

LEGEND

Strong German contributions (9 institutions):

- Water Cherenkov detector system
- Cryostat
- LAr instrumentation
- Electronics (front-end R&D and DAQ)
- Contributions to Ge procurement, Ge detector production, LAr purification and handling, infrastructures (e.g. clean room)
- Analysis (built upon experience from GERDA)
- Kurzkonzept submitted to BMBF priorisation process



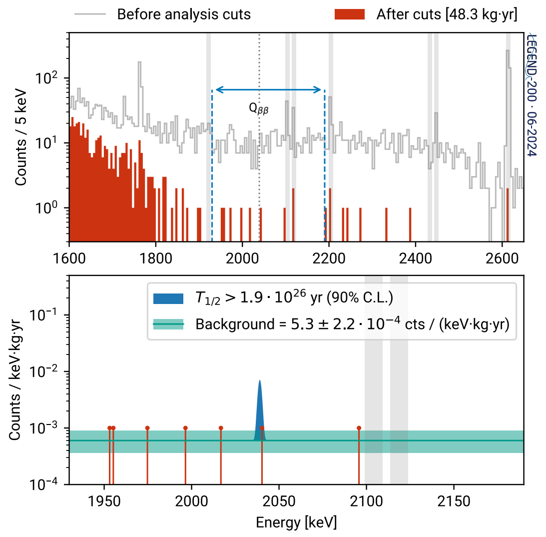
NON-ACCELERATOR NEUTRINO EXPERIMENTS

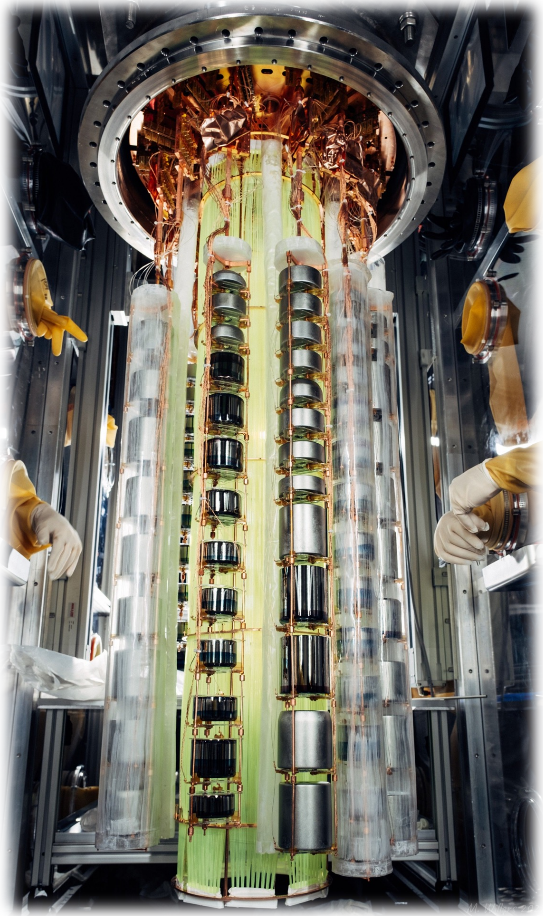
LEGEND 200 @ LNGS

- **Data taking:**
  - ~100 detectors running in GERDA cryostat
  - Exposure accumulated over 1 year
- **World-leading performance:**
  - ~0.1% FWHM at $Q_{\beta\beta}$
  - Background: 0.5 cts/keV/t/year

NEW

- **New Result** (LEGEND + GERDA + MAJORANA)
  - $T_{1/2} > 1.9 \cdot 10^{26}$ y (90% CL)
  - $m_{\beta\beta} < 75 – 178$ meV



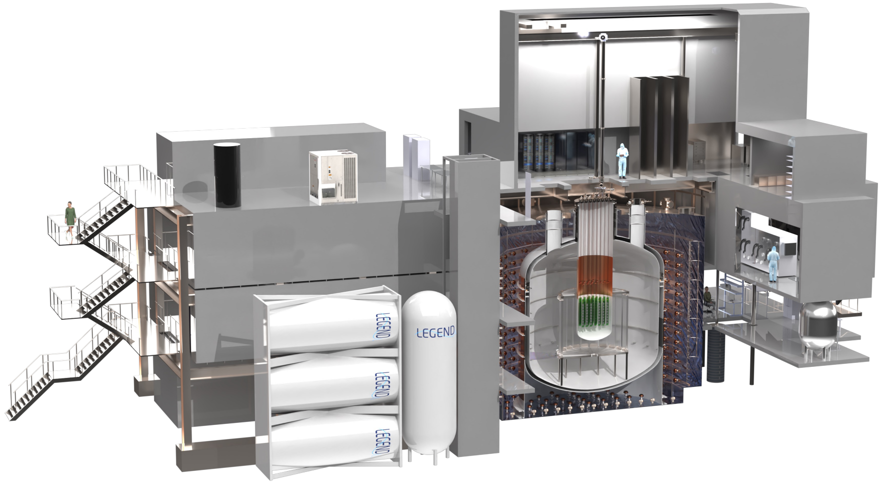


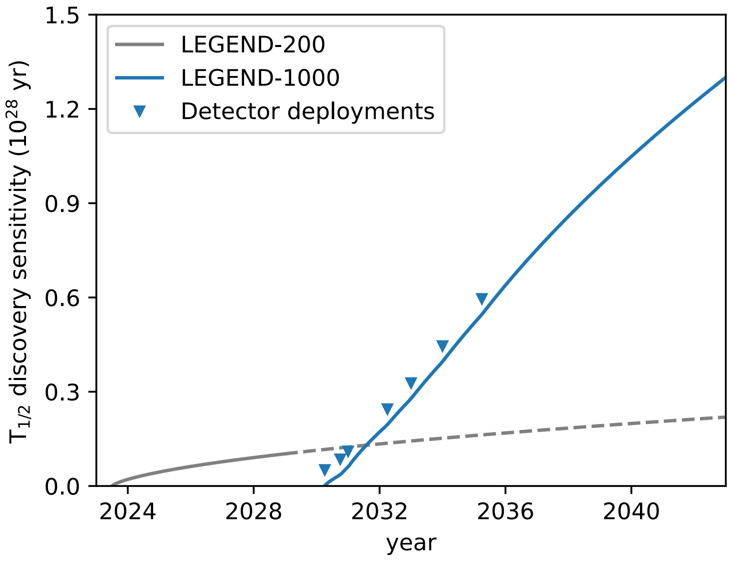
PRL 125, 252502 (2020)
PRL 130, 062501 (2022)
Neutrino-24 (2024)

*Exposure: 240 kg · y ^{76}Ge, NME = 1.6 - 4.8

LEGEND 1000 @ LNGS

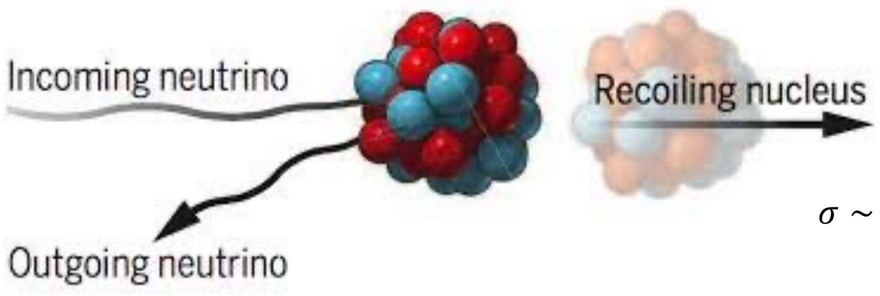
- **Upgrades:** 5 x more mass (1000 kg) and ÷ 20 lower background (0.01 cts/keV/t/year)
- **Goal:** cover IO ($T_{1/2} > 10^{28}$ years)
- **Status:** construction starts 2025, data taking in 2030



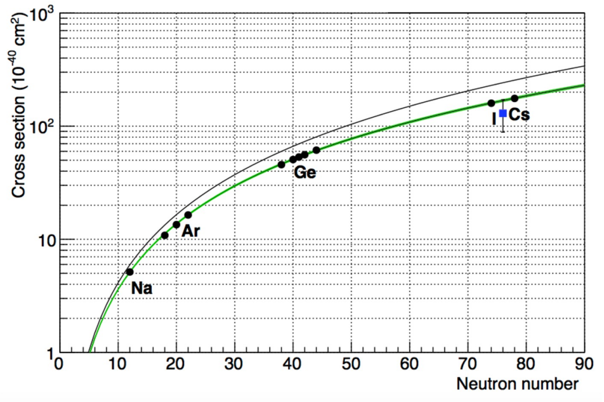


NON-ACCELERATOR NEUTRINO EXPERIMENTS

Coherent Elastic ν Nucleus Scattering



$\sigma \sim N^2$

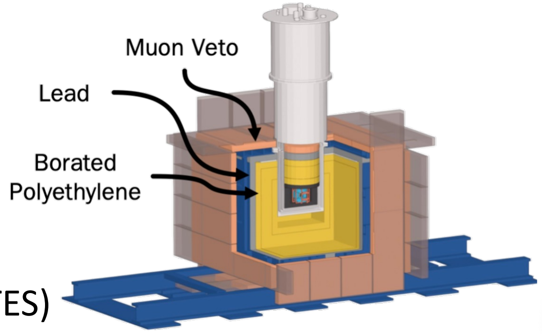


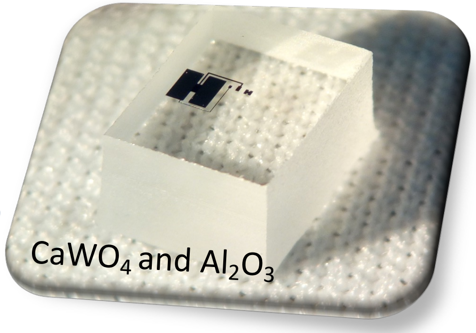
Motivations:

- Precision test of SM → BSM searches
- Nuclear physics
- Reactor physics
- Solar + Supernova physics
- Dark Matter
- Application for non-proliferation

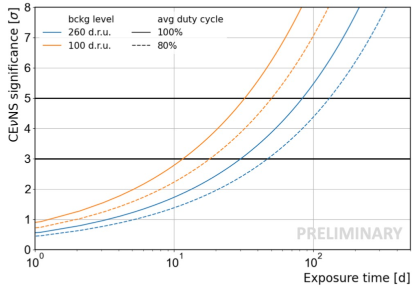
NON-ACCELERATOR NEUTRINO EXPERIMENTS

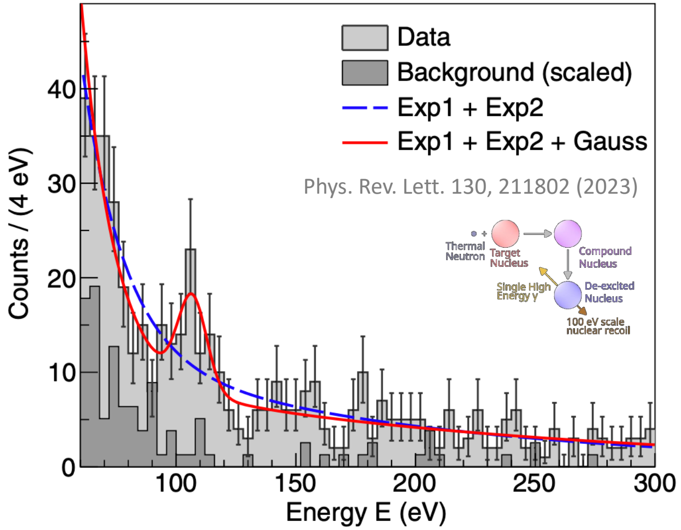
NUCLEUS





- gram-scale cryogenic detectors read out with transition edge sensors (TES)
- Lowest threshold: < 20 eV
- Operation at Double Chooz reactors at 70 – 100 m distance
- Status:
  - Validation of calibration methods (e.g. CRAB)
  - Long background run at TUM
  - Installation at Chooz in 2025





SUMMARY

The German community prioritises next-generation experiments in both fields* aiming to reach beyond the neutrino mass range indicated by the inverted mass ordering. KATRIN++, Project-8 as well as ECHo aim on different time scales with different technologies at the absolute neutrino mass. LEGEND 1000 aims at double beta decays, which violate lepton number, which relates to neutrino masses if they are Majorana particles.

The German community considers support for the small-scale experiments CONUS and NUCLEUS important, since CEvNS experiments will open with higher statistics within a few years a new direction with significant physics potential.**

MPP contribution to LEGEND in close collaboration with MPI-K (Mertens) and TUM (Schönert)
LEGEND 1000 is the top next generation $0\nu\beta\beta$ experiment. Continued MPP participation would guarantee a role in a leading project.

* Absolute mass scale and ordering.

** “First observation of reactor antineutrinos by coherent scattering” published last week https://arxiv.org/pdf/2501.05206

TAKE HOME MESSAGE

To address the fundamental questions of particle physics, the community considers a diverse experimental landscape of non-collider experiments with a high physics potential being essential.

MPP has a primary role in projects aiming to address these fundamental questions.

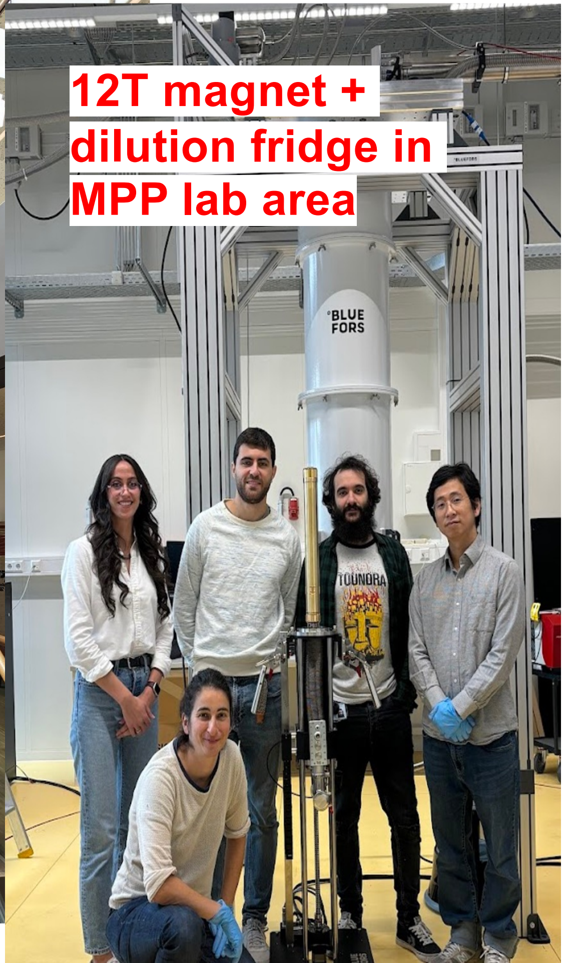
ADDITIONAL MATERIAL

MAX-PLANCK-INSTITUT
FÜR PHYSIK

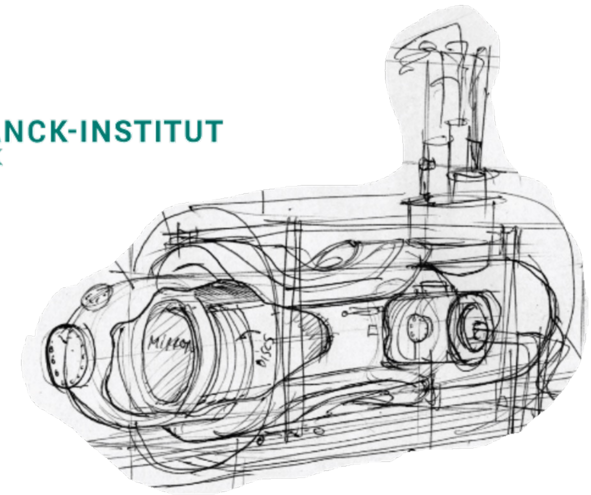
BABYIAXO/IAXO & RADES @M

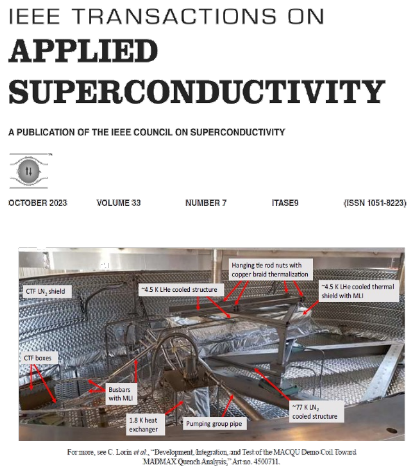
European Research Council
Established by the European Commission

- ***BabyIAXO* is well on track for construction:** CERN-TE involvement in the magnet construction is under discussion, good prospects regarding magnet funding and on the procurement of the needed SC cable.
- Preparation activities for *IAXO* should proceed in parallel with BabyIAXO construction so that the collaboration is ready to make a decision regarding the full IAXO after the first BabyIAXO data run. Potential host for IAXO is DESY
- **Lead MPP involvement in *RADES*:** Preparation to exploit babyIAXO also for direct DM axion search using RF cavities (RADES-LF). In addition, experiments with small cavities (RADES-HF) ongoing
- Strong third party support started in 2024: ERC-SYG 2024 (MPP is partner), QUANTERA (MPP hosts PI)



MADMAX @ MAX-PLANCK-INSTITUT FÜR PHYSIK





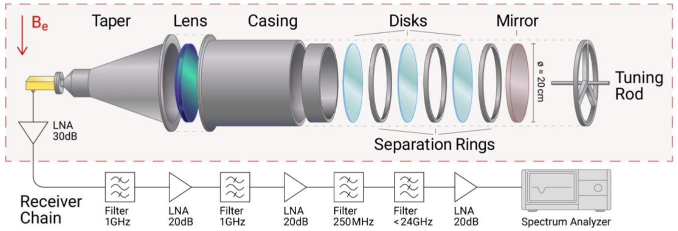
Goal: discover axion dark matter!

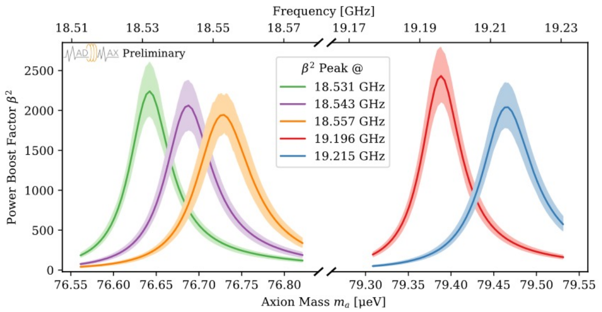
MADMAX collaboration formed in 2017 as MAX-PLANCK-INSTITUT FÜR PHYSIK initative

So far: 11 institutes from France, Germany, Spain, US

MPP is lead institute with key responsibilites:
Spokesperson, magnet R&D, Booster development and RF understanding, detector R&D, …

Many technological issues solved:
Actuation of disks at 4K and high B-field, magnet technology feasible, „Calibration" of boost factor





RWTH AACHEN UNIVERSITY · NÉEL institut · DESY. · Universität Hamburg · CPPM · MAX-PLANCK-INSTITUT FÜR PHYSIK · EBERHARD KARLS UNIVERSITÄT TÜBINGEN · Universidad Zaragoza · IJCLab Irène Joliot-Curie · Fermilab

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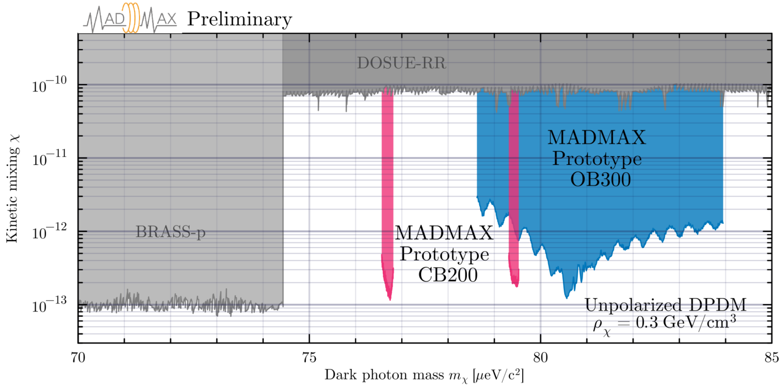
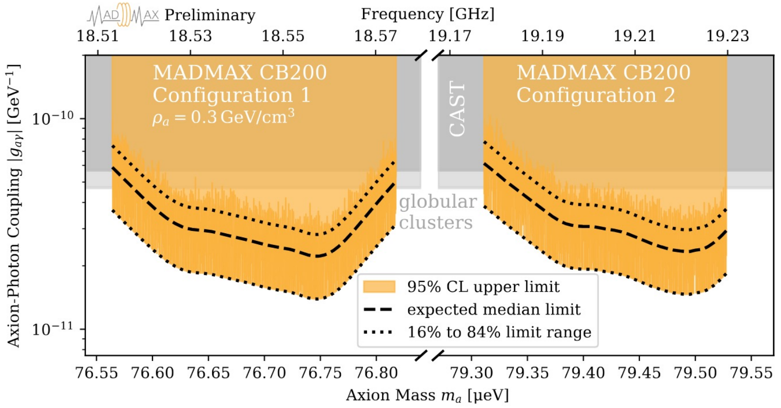
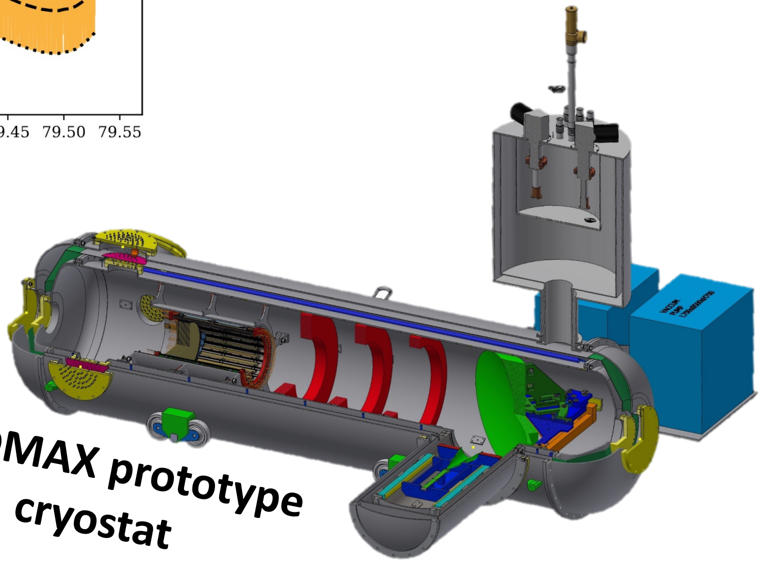




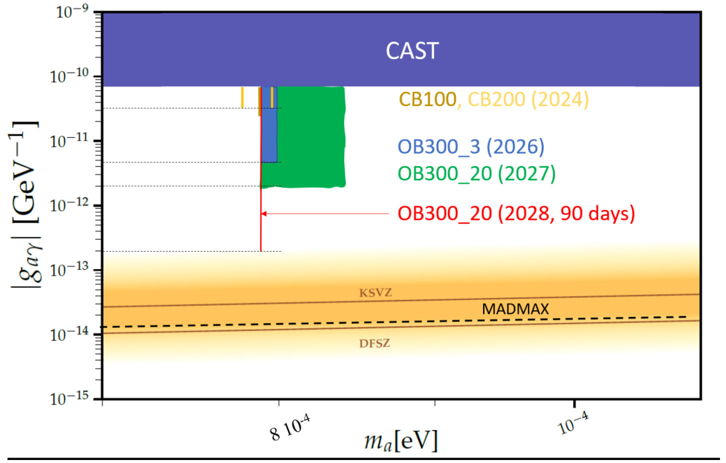
First physics results published in 2024:
Competitive ALP ([arXiv:2409.11777]) and hidden photon ([arXiv:2408.02368]) dark matter limits

Next plans:

- **Increase booster: # of disks, increase diameter**
- **Long shutdown 3 at CERN:**
  Use tunable booster at cryogenic temperature
- **Once budget available: build full scale magnet**
- **>2030: start measurements at DESY**



MADMAX prototype cryostat

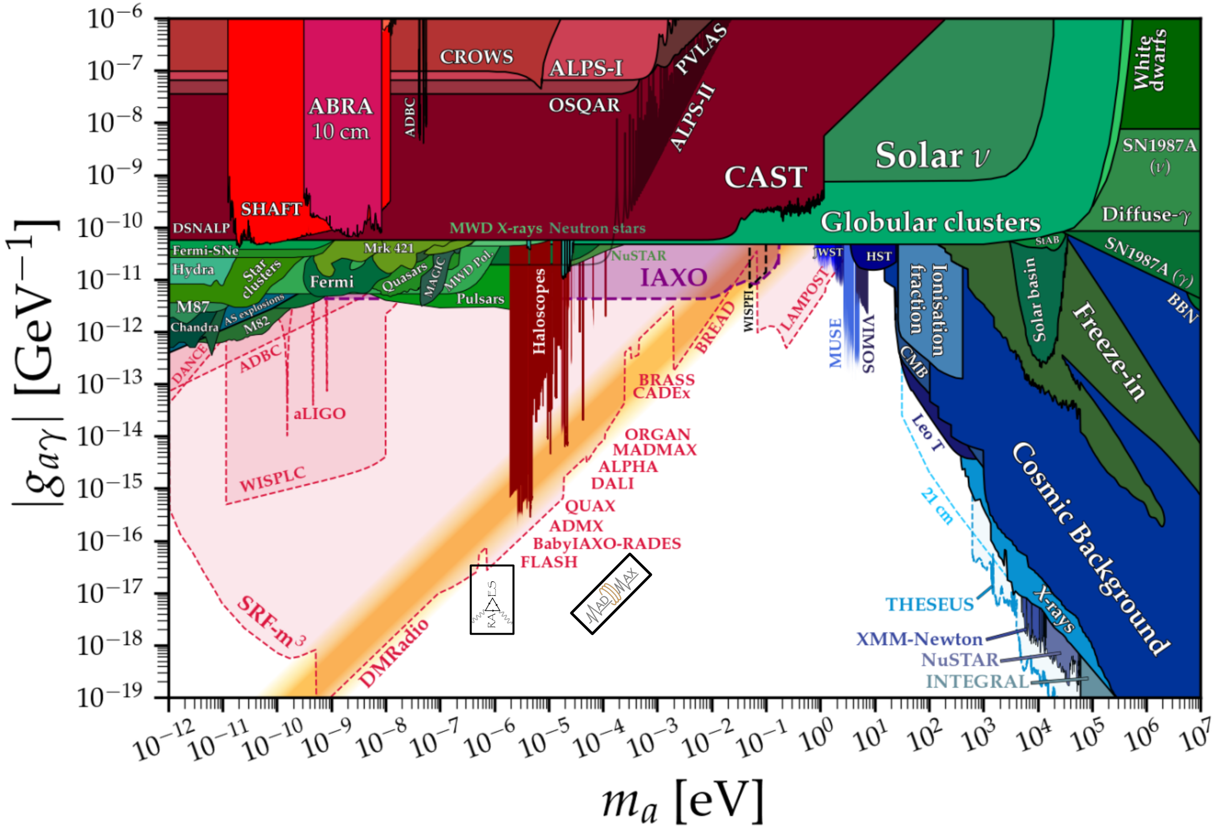


- **Complementary mass ranges**

- **Many common challenges: detector R&D, cryogenic infrastructure, RF technologies**
  → Synergetic in large parts

- **Close cooperation between two groups@ MPP / collaborations**
  Common collaboration meeting Oct. 2025 in Ringberg

- **Both experiments will be hosted at DESY**
  → Significant MPP contribution to envisioned German/European axion hub



LEGEND @ MAX-PLANCK-INSTITUT FÜR PHYSIK

Goal: Discovery of Neutrinoless double beta decay:
→ Neutrino as Majorana particle
→ Explain baryon asymmetry of the Universe

Merger of GERDA and Majorana collaborations + other instituts:
~50 institutes from around the world
~ 250 researchers

Current status:
Inherited GERDA infrastructure at LNGS + Germanium detectors from GERDA & MAJORANA
LEGEND 200 running at LNGS with 140 kg detector mass

Further plans:
New cryostat at LNGS + additional germanium detectors
Further improvement of background mitigation and identification
→ Final sensitivity $T_{1/2} > 10^{-28}$ yrs $m_\nu < 0.02$ eV

MPP contributions: Data analysis, Pusle shape simulation, scintillating structural low background components: PEN
Work being performed in close collaboration with MPI-K (Mertens) + E15 at TUM (Schönert)