From double to single beta decays – the search for the isomeric decay of ^{180m}Ta in the MAJORANA DEMONSTRATOR

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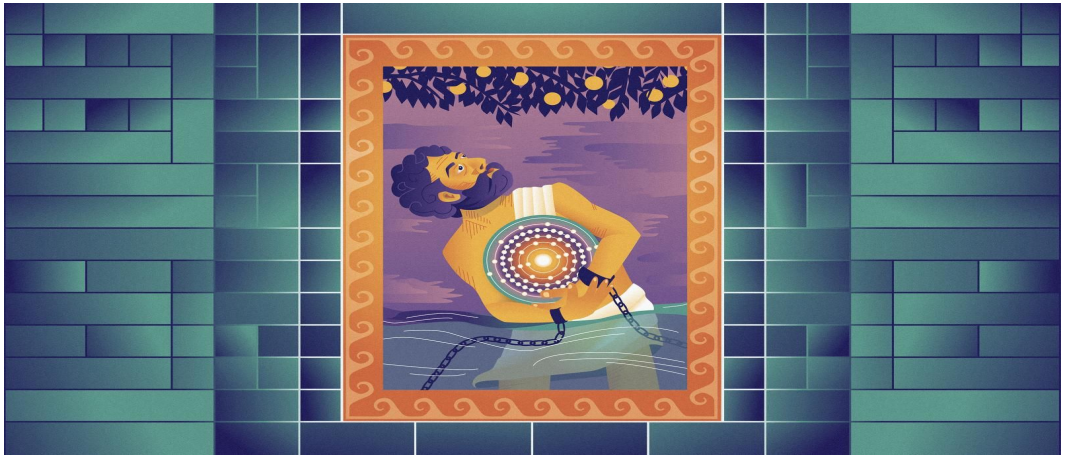
TAUP VIENNA 2023

A bit of (ancient) history…



Tantalus trapped as punishment.

Illustration from
www.symmetrymagazine.org/article/majorana-demonstrator-finds-tantalizing-new-purpose

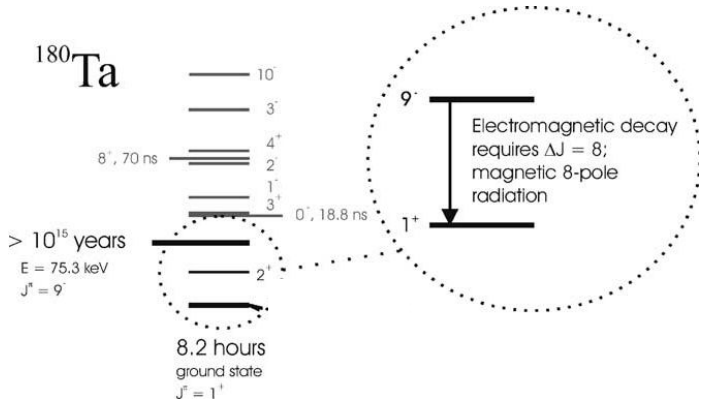
In greek mythology **Tantalus** offended the gods…

… so he was punished to be **trapped** in a pond under a fruit tree.

He could **not** reach **up** to eat.

He could **not** lean **down** to drink.

A bit of (modern) history…



Level scheme of ^{180m}Ta

Ta disks after arrival underground

For nuclear physics **Tantalum** *(named 1802)* is one of the rarest elements and has two isotopes…

… one of them (^{180m}Ta) is **trapped** in an isomeric state while the ground state decays.

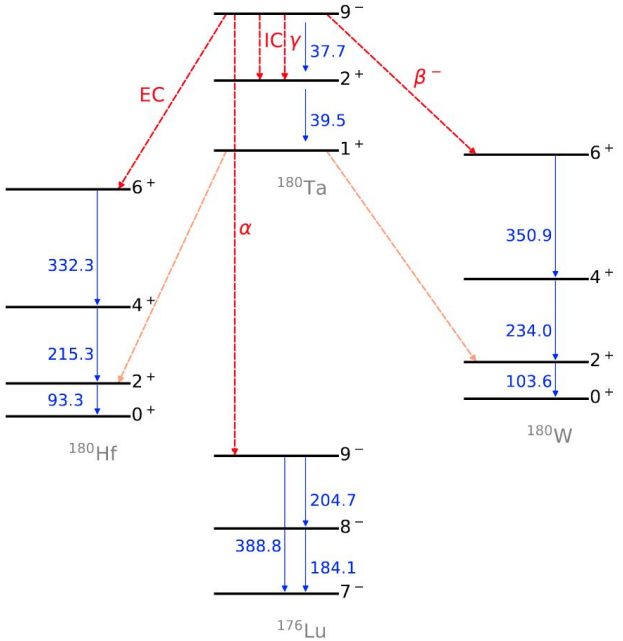
It can **not** go to a **higher** state due to energy.

It can **not** go down to a **lower** state due to spins

Variety of physics studies in the Tantalum system

- <u>The origin of Tantalum in the universe</u> :
  - Study helps to understand the observed abundance of ^{180m}Ta within a wider nucleosynthesis framework
  - Understand which candidate processes are strong enough to produce Ta (*ν-interactions, thermal excitation in early universe*)

- <u>Longest lived metastable state never observed to decay</u>
  - **Most extreme case to study nuclear structure spin traps**
  - Theory varies on predictions for half-life
  - Variety of transitions possible:
    β-decay , electron capture (EC), internal conversion, ɣ-transition, α-decay
  - **Ground-state ^{180}Ta is unstable ($T_{1/2}$ ~ 8 hours)**



Decay scheme of ^{180m}Ta with possible decay channels (red) and detection signatures (blue)

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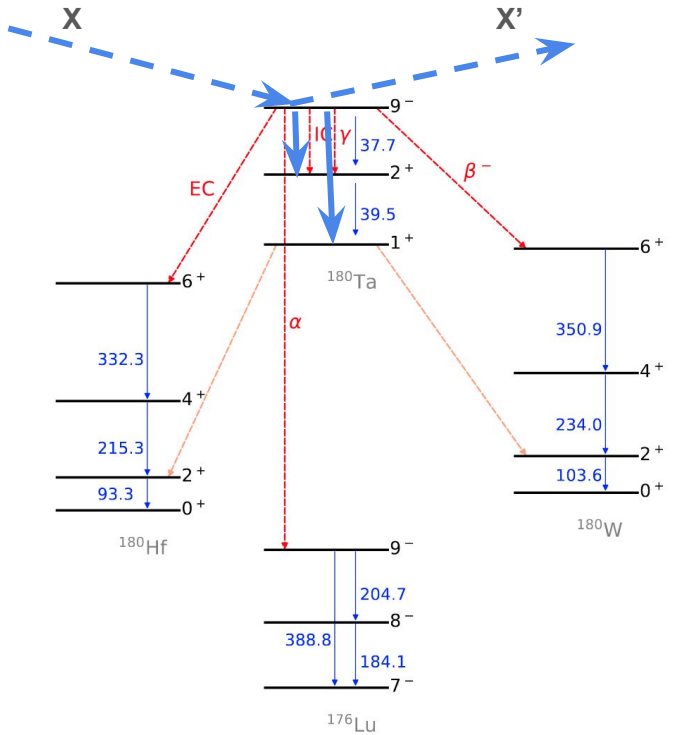
- Search for Dark Matter interaction
  - Additional energy from the isomer allows reaction with particles that would not interact otherwise
  - Candidates: **Strongly Interacting DM, Inelastic DM**

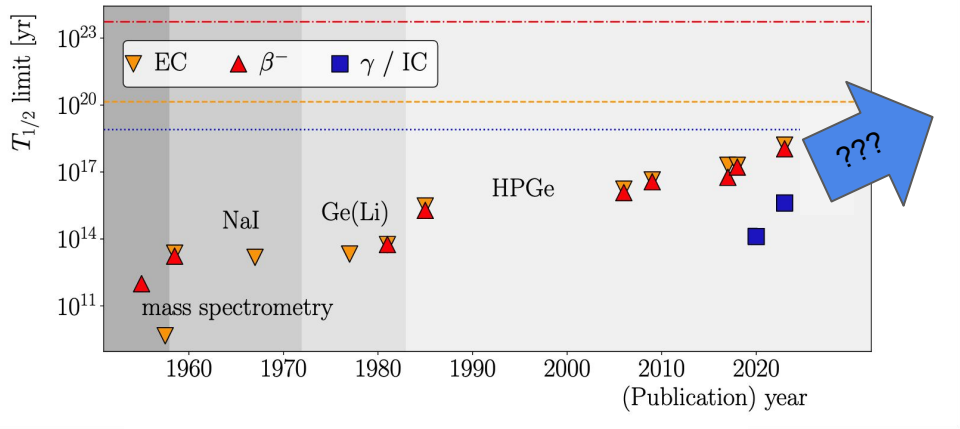


Decay scheme of ^{180m}Ta with possible decay channels (red) and detection signatures (blue)

What is needed for a measurement…

Previous limits:

PRC 95, 044306 (2017)
2305.17238 (2023)



History of Tantalum decay measurements with predictions (dashed lines), from arxiv 2305.17238

- Large exposure (material and time)
  - only 1 - 2 ppm of earth's crust is Ta
  - 99.98% is ^{181}Ta
- Detector with excellent energy resolution
- If possible multiple detectors, that can detect coincidences
- A clean, ultra low-background system and environment

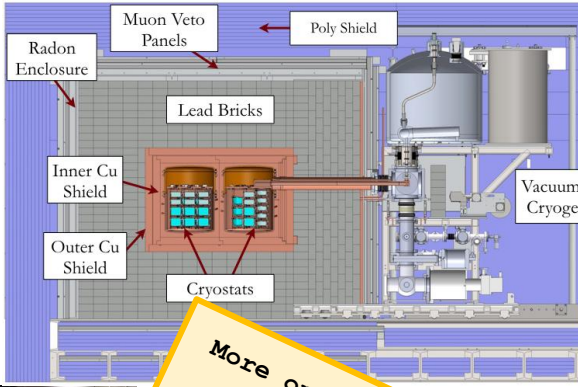
Perfect use of MJD facility after enriched detector removal

MAJORANA DEMONSTRATOR

Searching for neutrinoless double-beta decay of ^{76}Ge in HPGe detectors, probing additional physics beyond the standard model, and informing the design of the next-generation LEGEND experiment

- Source & Detector:
  - Array of p-type, point contact detectors 30 kg of 88% enriched ^{76}Ge crystals
  - Included 6.7 kg of ^{76}Ge inverted coaxial, point contact detectors in final run
  - Enriched detectors removed in 2021 for LEGEND
  - **14 kg of natural Ge crystals**
- **Excellent Energy Resolution**: 2.5 keV FWHM @ 2039 keV
- Low **Analysis Threshold:** 1 keV
- **Low Background:** 2 modules within a compact graded shield and active muon veto using ultra-clean materials

- **Final Result,** *(PRL 130, 062501, 2023)*
  - **65 kg-yr exposure**
  - Median $T_{1/2}$ Sensitivity: 8.1×10^{25} yr (90% C.I.)
  - Limit: $T_{1/2} > 8.3 \times 10^{25}$ yr (90% C.I)

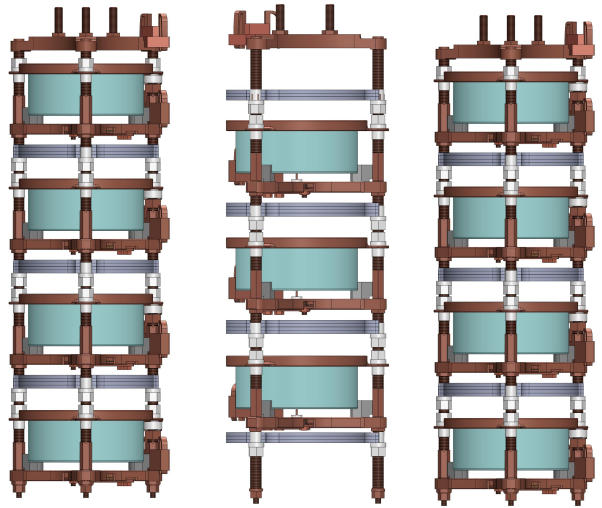


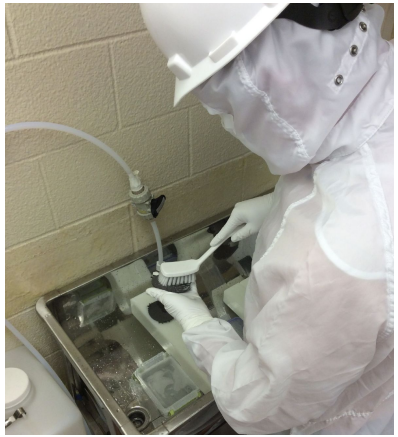
More on MJD background's and results:
8/30 2:00 and 14:15

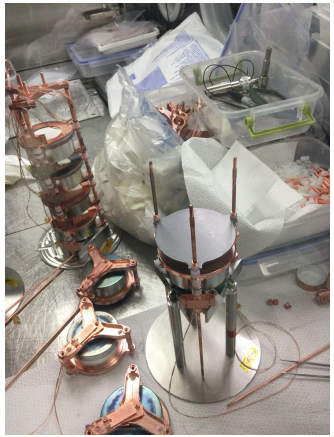
LEGEND@TAUP:
L200: 8/29 16:30
L1000: 8/30 14:45
And many more

Reconfiguring of the DEMONSTRATOR

- **17.4 kg installed** ~ 2 g ^{180m}Ta,
  (x10 more than best previous measurement)
- 23 active detectors
  (before only one or two detector configurations)
- Detectors and Ta arranged to maximize efficiency
- Operating since May 2022

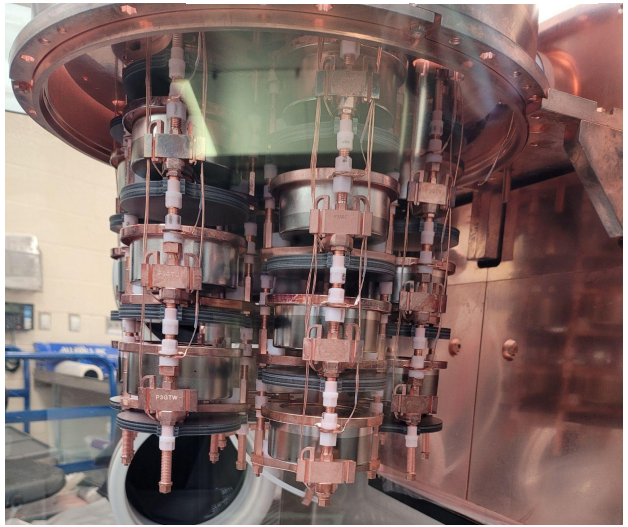






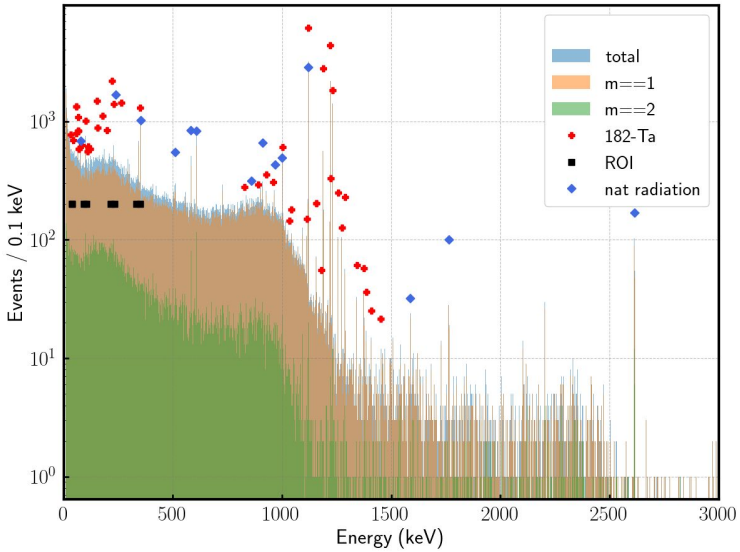
(left) cleaning and installation in the MJD strings

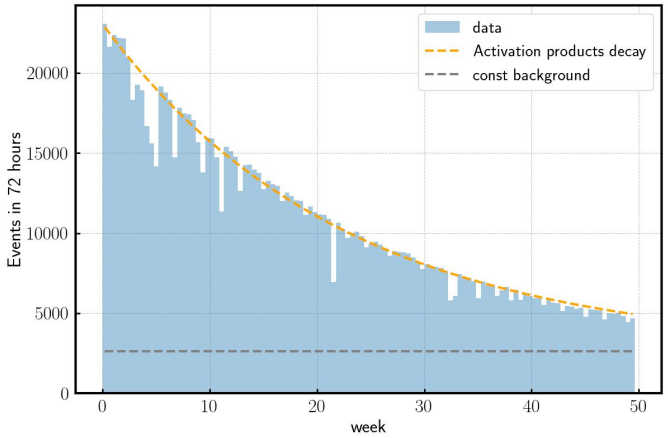
(right) schematic arrangement of detectors, green, and Ta, grey, and photograph of the full detector array



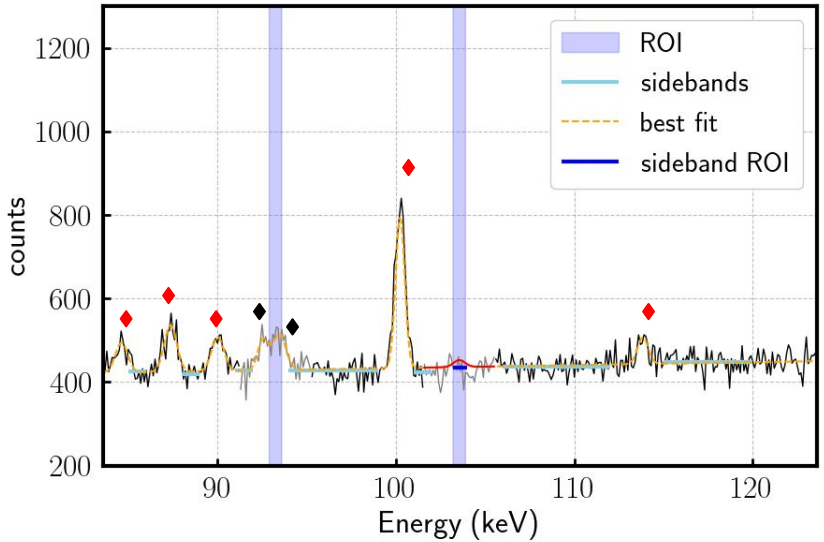
Data Overview and Analysis

- Data Set of 348 days (98.2% live)
- Background contributions from:
  - natural radioactivity within the Tantalum disks (< 0.5 mBq/kg_{Ta})
  - **<u>surface activation in Ta</u>**
    - ^{182}Ta ($T_{1/2}$ = 114 days)
    - ^{175}Hf ($T_{1/2}$ = 70 days)
- Background improving over time

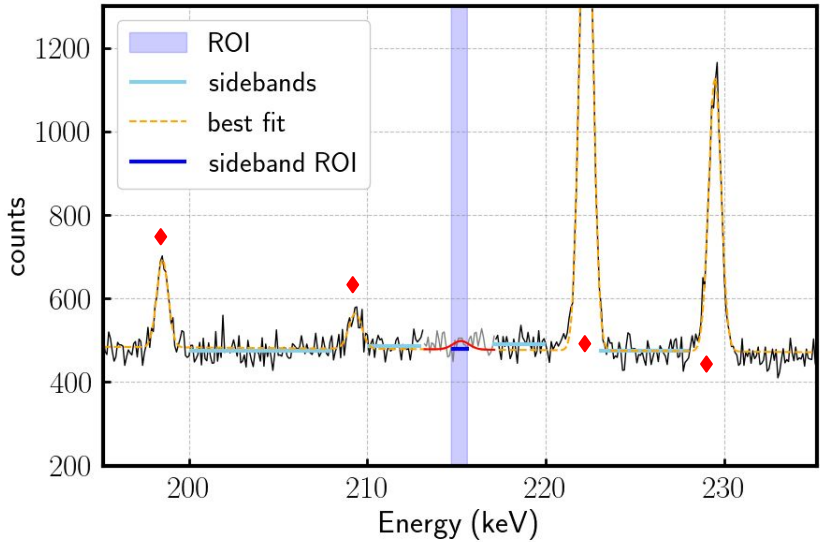




A look in a few region of interests



Signal region for deexcitations after β-decay



Signal region for deexcitations after electron capture

◆ ^{182}Ta
◆ U/Th decay chain

First year results

Previous limits:

PRC 95, 044306 (2017)
2305.17238 (2023)

Submitted and under review
See also arxiv 2306.01965

- Current improvements
  - Efficiency (x 2-3)
  - Mass (x 12)
  - Background
- multiplicity analysis allows high sensitivity search

$$\lambda_{total} = \lambda_{EC} + \lambda_{\beta-} + \lambda_{\gamma} + \lambda_{IC} + \lambda_{\alpha} + \lambda_{DM}$$

	EC	β^-	γ	IC	α
Previous Limits	> 1.6 x 10^{18}	> 1.1 x 10^{18}	> 4.5 x 10^{14}	> 4.5 x 10^{14}	–
MJD - 2023	**> 1.3 x 10^{19} ****	**> 1.5 x 10^{19} ****	**> 6.0 x 10^{17}**	**> 2.9 x 10^{17}**	**> 1.1 x 10^{19} ****
Theory	10^{23}	10^{20}	10^{31}	10^{18}	10^{25}

Overview on results, all numbers in years,
*** limits derived from detector coincidences*

First year results

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First half-life sensitivities for
β-decays and electron captures > 10^{19} years
(only some α and ββ are longer)
Improvements of 1-2 orders of magnitude

	EC				α
Previous Limits				> 4.5 x 10^{14}	–
MJD - 2023	**>**		**> 6.0 x 10^{17}**	**> 2.9 x 10^{17}**	**> 1.1 x 10^{19} ****
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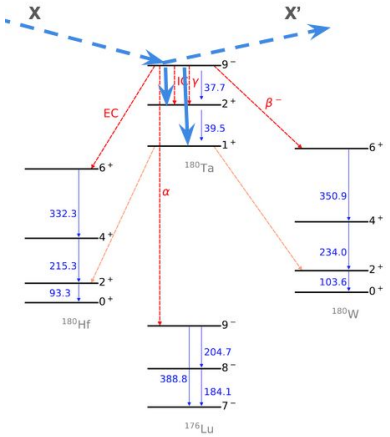
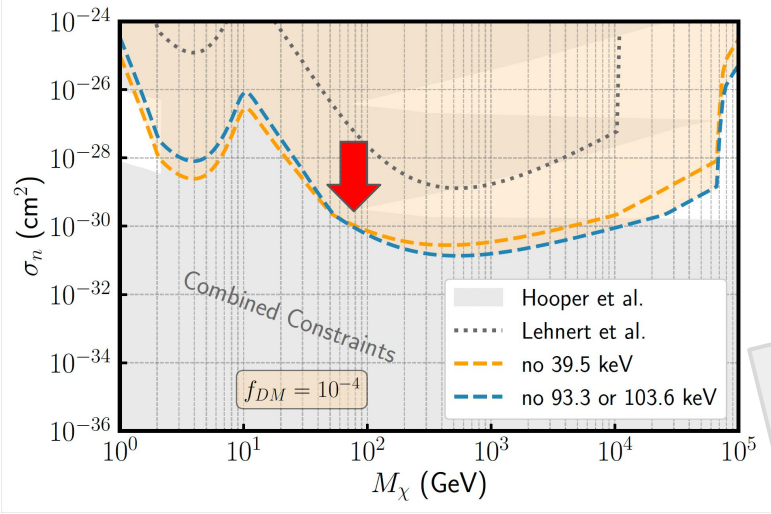
Dark matter induced deexcitation

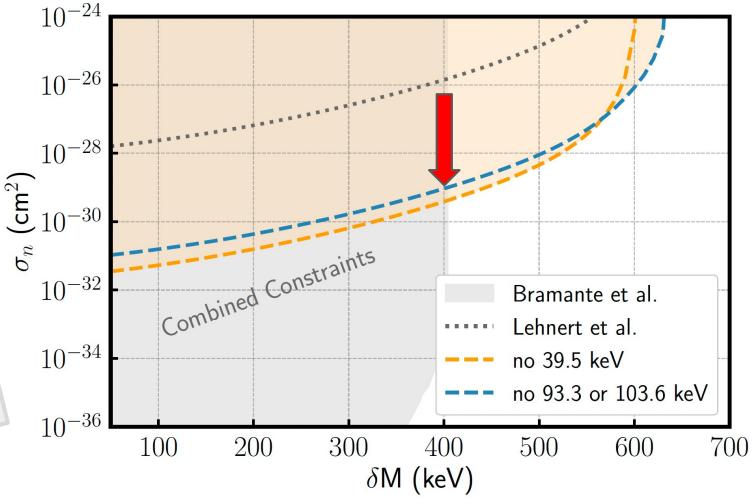
- No observation of ^{180m}Ta decay → no DM-induced decay
- Improved sensitivities to strongly interacting DM (siDM)
- Additional sensitivities to more complex DM with multiple states
- and/or particles via inelastic scattering





Limits on siDM (left) and inelastic scattering (right)

Previous limits:
PRL 124, 181802
PRD 94, 115026
PRD 97, 115006



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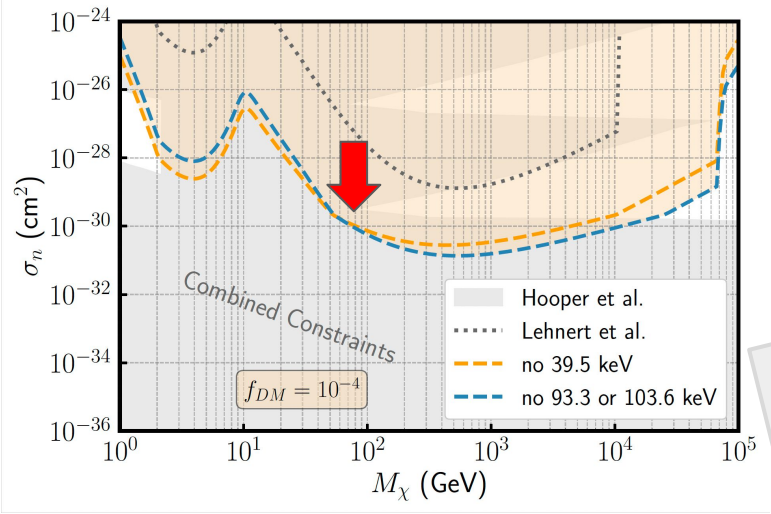
Improvements by two orders of magnitude and complementary to other searches



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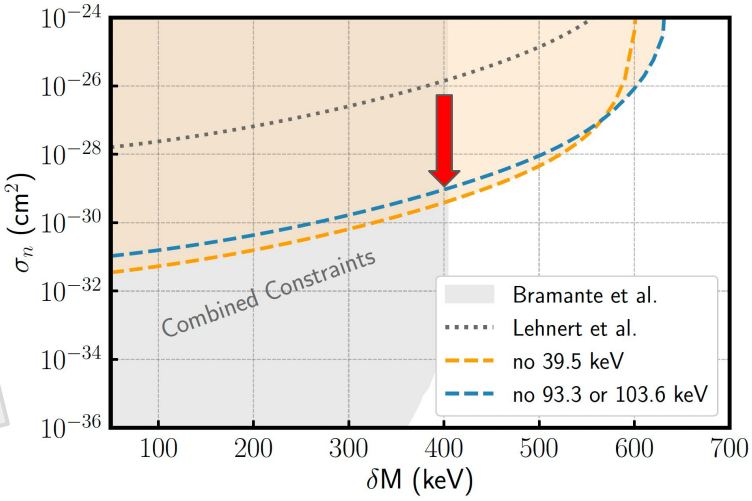

Summary

- Most sensitive search for half-life measurements in isomers world-wide
- First data improved previous measurements by 1-2 orders of magnitude

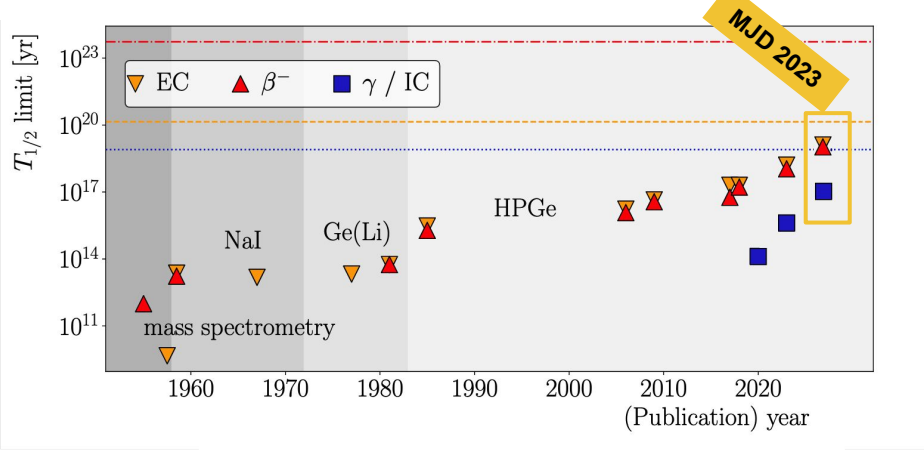

Figure taken and updated from 2305.17238

Submitted and under review
See also arxiv 2306.01965

Sam Meijer having fun cleaning Tantalum

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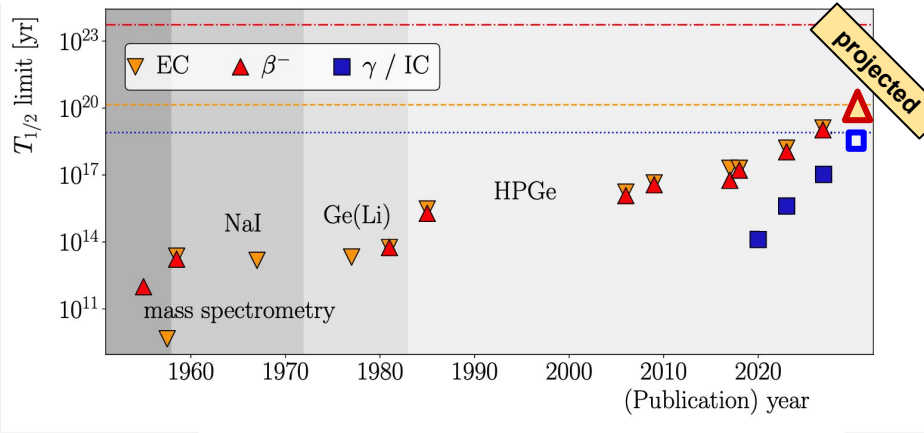
- Most sensitive search for half-life measurements in isomers world-wide
- First data improved previous measurements by 1-2 orders of magnitude
- Background continues to improve
- Estimated final sensitivity has the potential to discover the decay



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