Interesting Isomers

- From classic nuclear physics to dark matter -

Ralph Massarczyk (LANL)

NEWS Seminar Feb 20, 2024

LA-UR-23-30890

- **Nuclear Isomers -**
  a crash course in nuclear physics from the first half of the 20th century

- **Dark Matter -**
  a crash course in astrophysics of the late 20th century

- **2 extreme cases:**
  a crash course in my work of the last 2 years

  - One year from most sensitive search for electron capture and β-decays

  - a 15-min experiment

From nuclei to isotopes to isomers

Frederick Soddy
Chemistry Nobel prize 1921

> *"We can have isotopes with identity of atomic weight, as well as of chemical character, which are different in their stability and mode of breaking up."(1917)*

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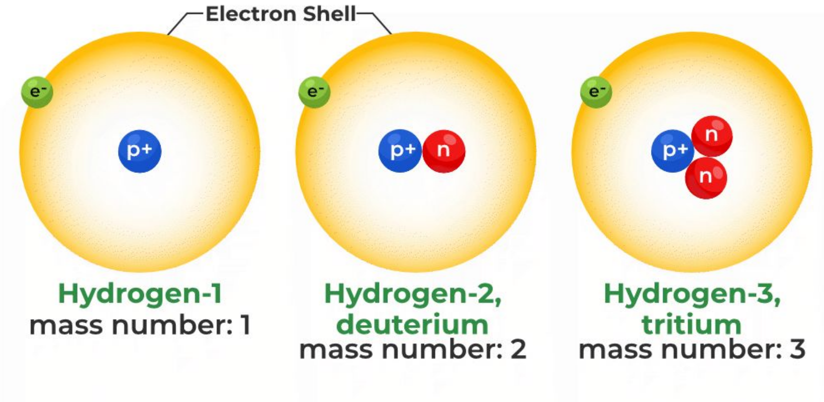
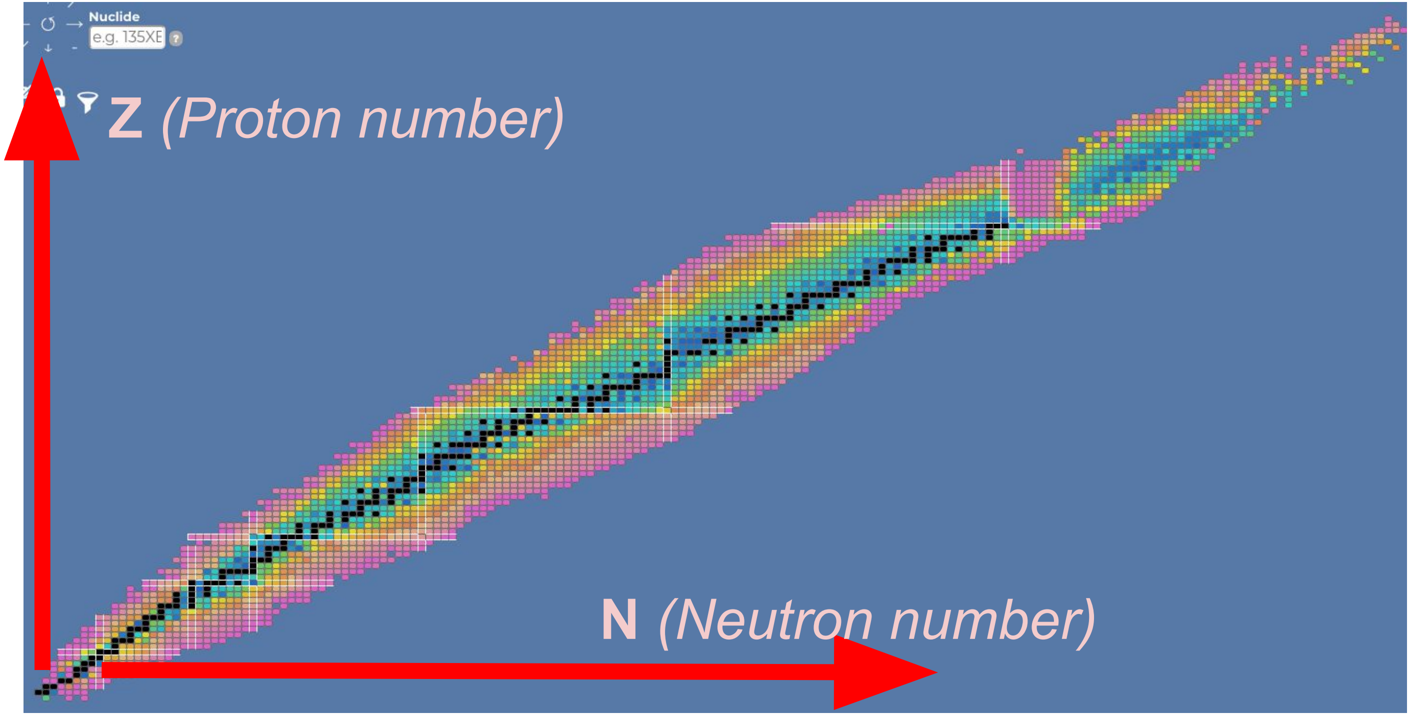


- Isotopes -
similar proton number Z,
different neutron numbers N

From nuclei to isotopes to isomers



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- From ^{1}H to ^{294}Lv
- Only 250 are considered stable

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similar proton number Z,
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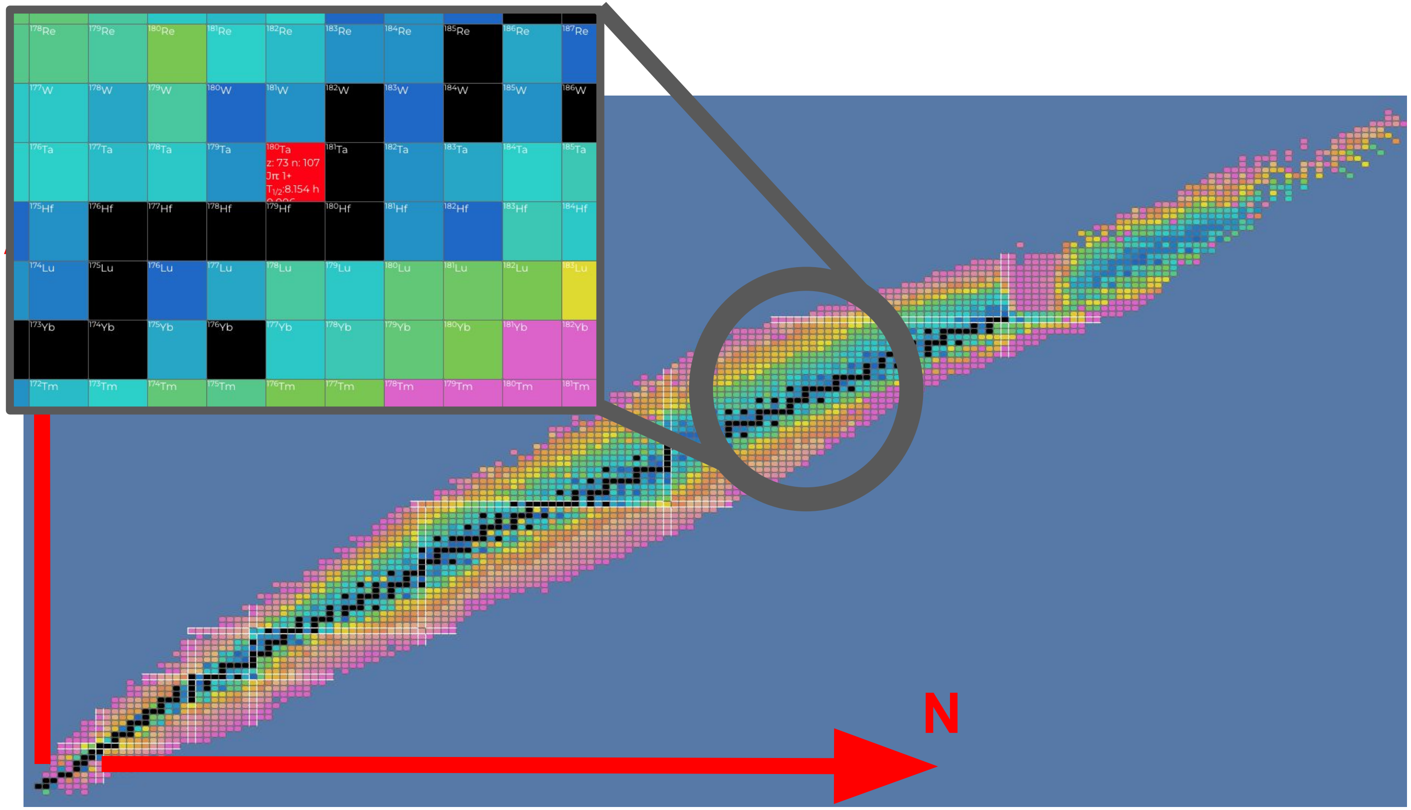
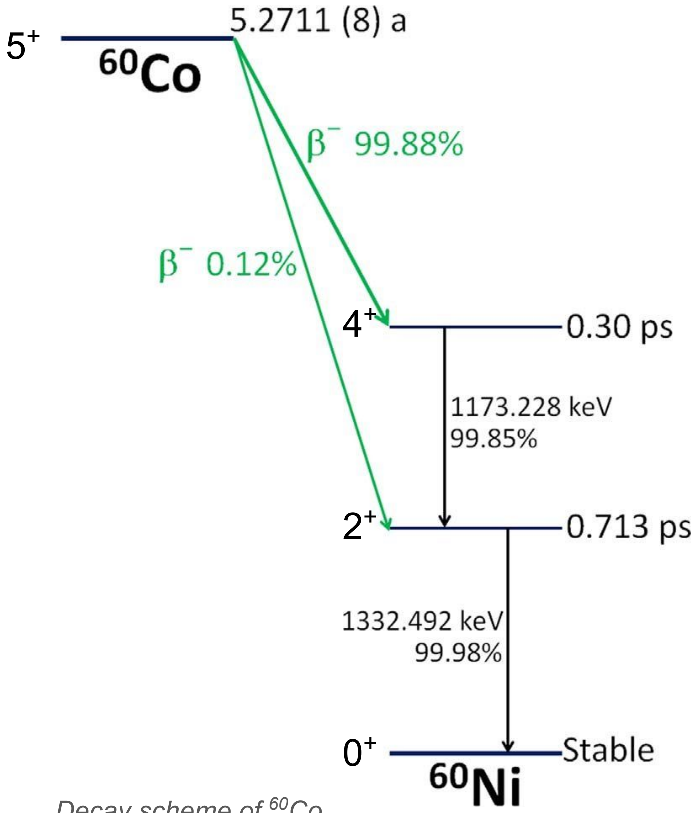


- We know over 3000 isotopes
- From ^{1}H to ^{294}Lv
- Only 250 are considered stable
- Some elements have only one stable isotope, others up to 10 (tin)

- Isotopes -
similar proton number Z, different neutron numbers N

Properties of nuclear states - level schemes

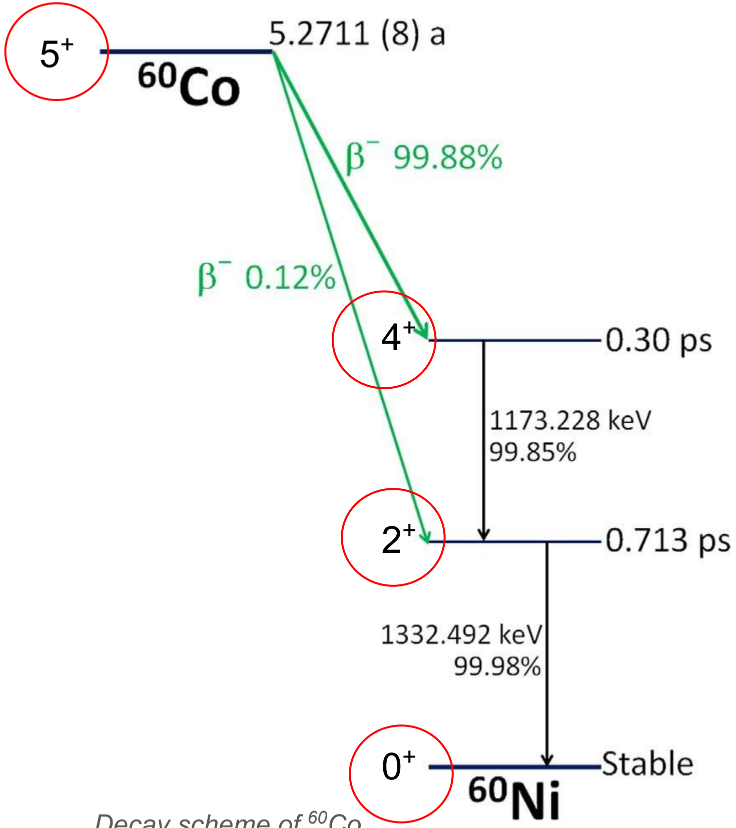


Decay scheme of ^{60}Co

- Information of nuclear states
  From a shell model point of view

Maria Goeppert-Mayer
Physics Nobel prize 1963

Properties of nuclear states - level schemes



Decay scheme of ^{60}Co

- Information of nuclear states
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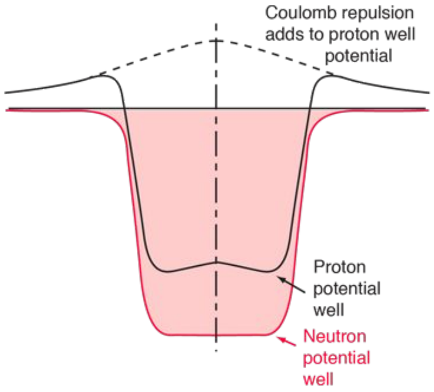
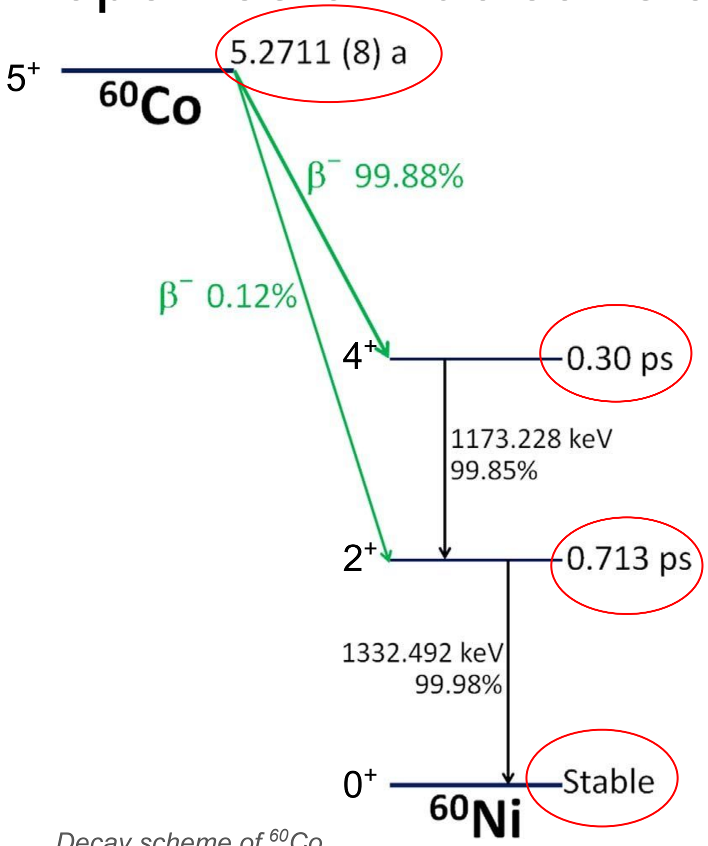
- Spins and Parity



Potential schematic in the Shell model

Properties of nuclear states - level schemes



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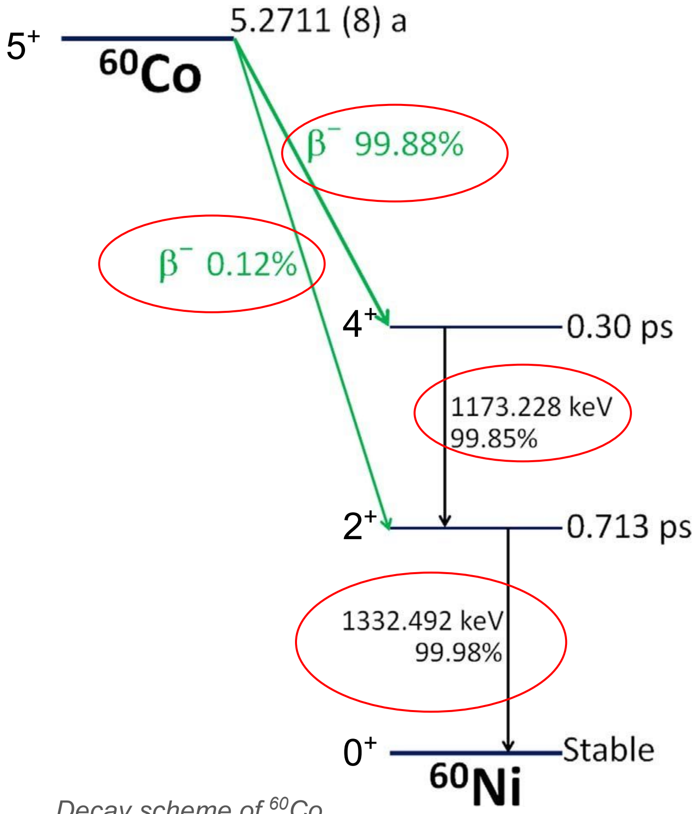

Decay scheme of ^{60}Co

- Information of nuclear states
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- Spin and Parity
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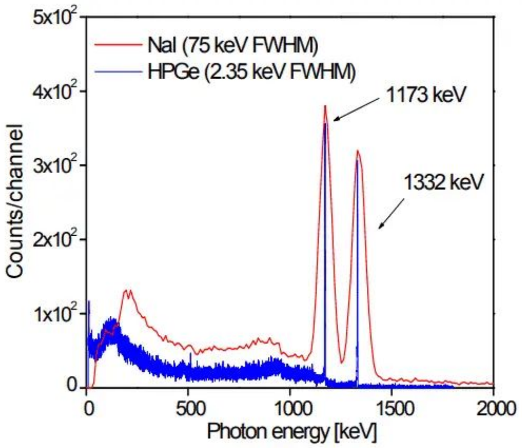
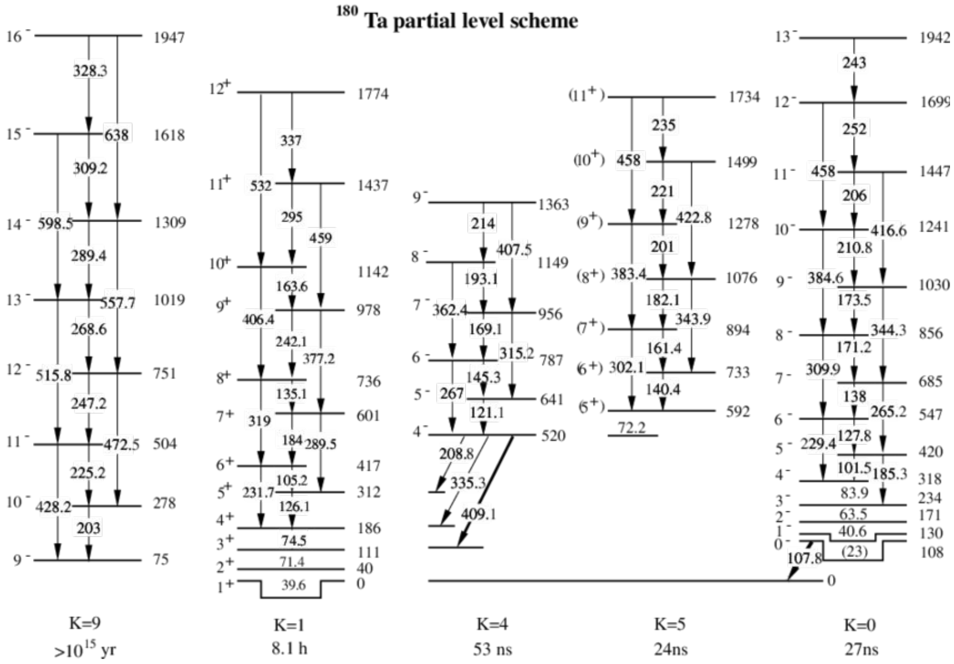
- Energies and transition probabilities



Measurement of the energy of the emitted photons

Properties of nuclear states - level schemes

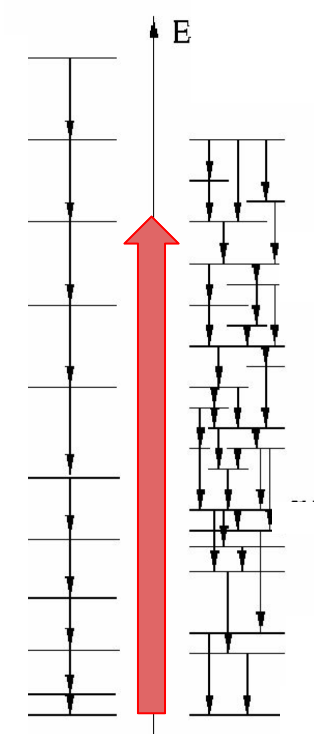


- Information of nuclear states
  From a shell model point of view
- Spin and Parity
- Lifetimes
- Energies and transition probabilities

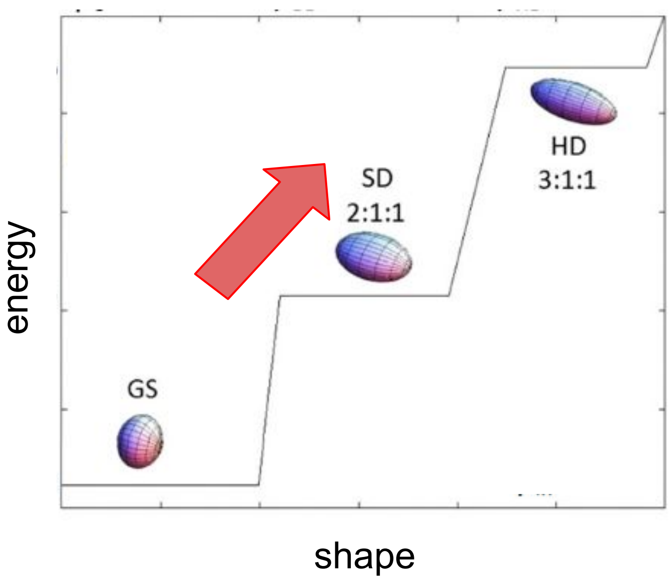
Of course, it's always more complicated

Level Scheme of ^{180}Ta

Properties of nuclear states - excitation

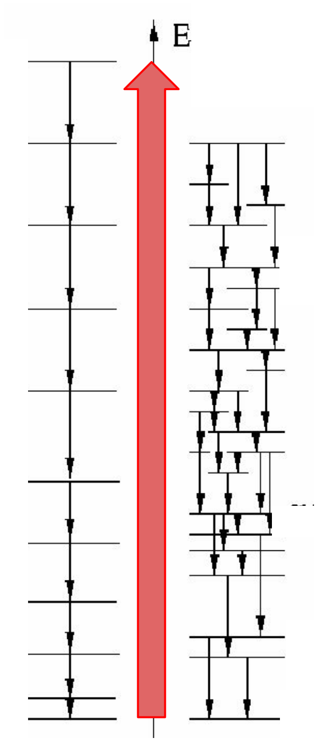


Excitation and deexcitation in a nuclear level scheme



Excitation energy and shape deformation

Properties of nuclear states - particle seperation



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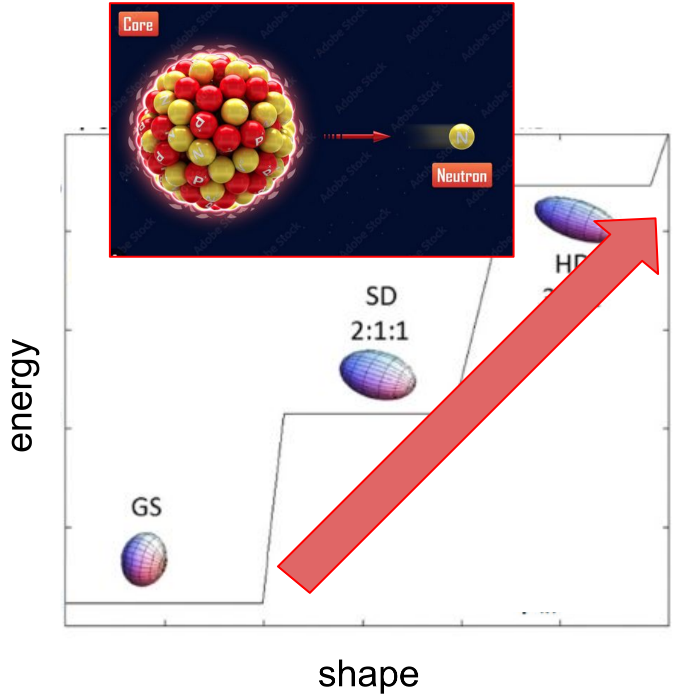
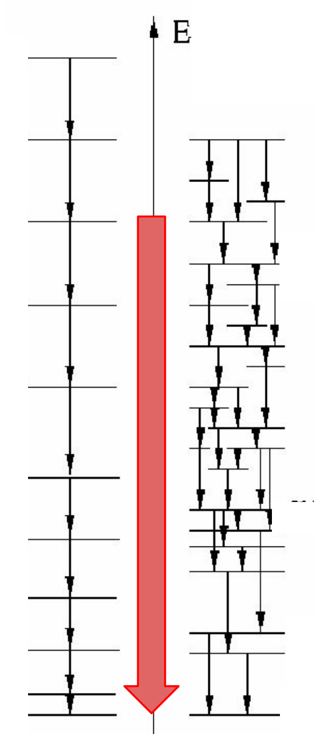


Excitation energy and shape deformation

Properties of nuclear states - deexcitation



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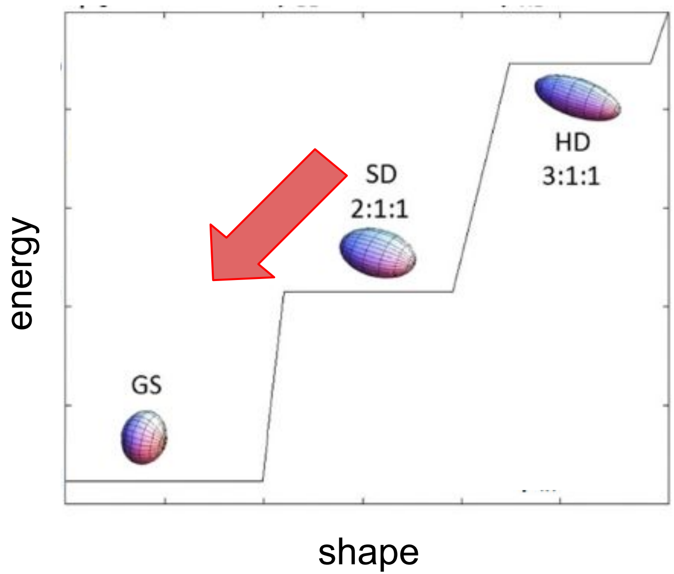

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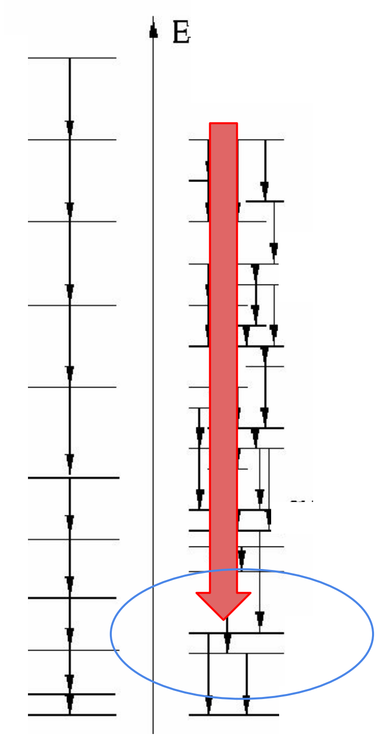

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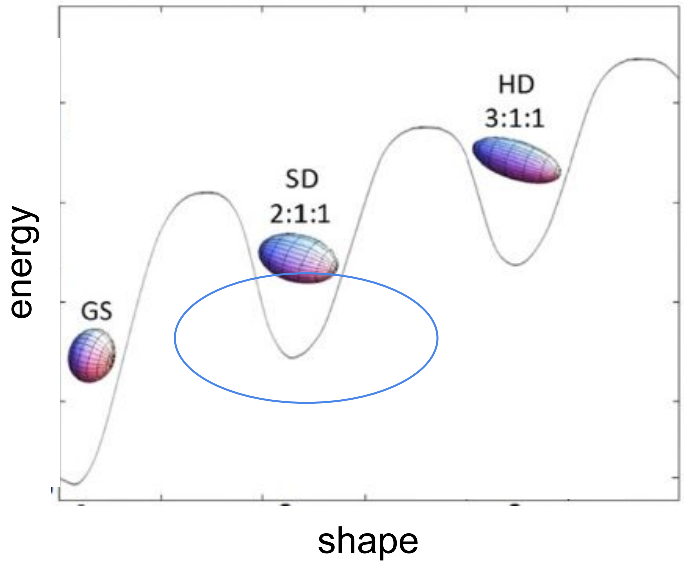
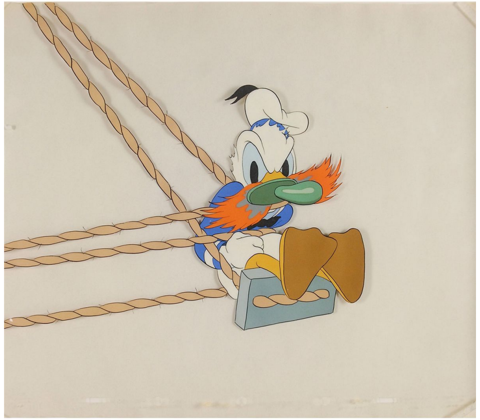
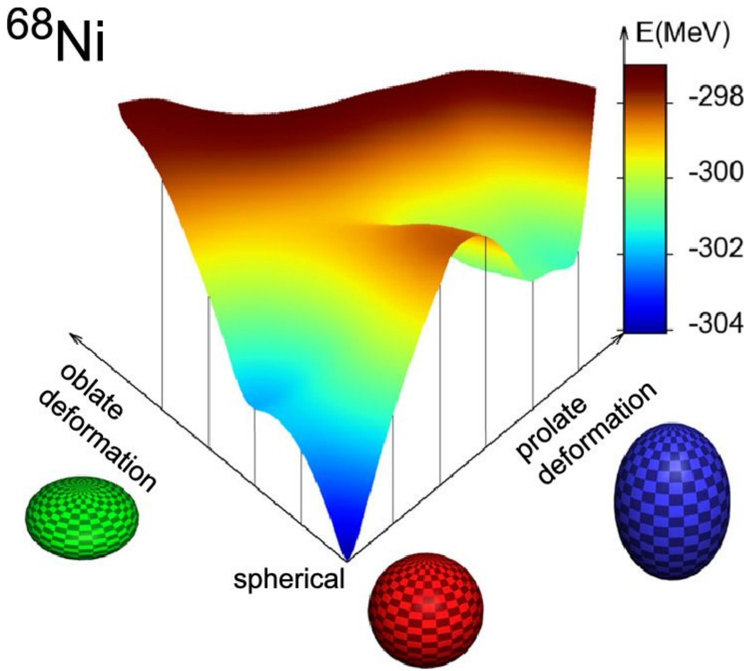




Excitation energy and shape deformation with local minima in the potential

Properties of nuclear states - an example with theory



Potential map as a function of the deformation parameters

E(level)†	J^π	$T_{1/2}$	XREF	
0.0‡	0^+	29 s *2*	ABCDEFGHI	$\%\beta^-$=100 $T_{1/2}$: from 19 s +*3*–
1770 *30*	0^+	270 ns *5*	EF I	$T_{1/2}$: from I(e^+,e^-)(t J^π: L=0 in
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3120.9 *3*			A	E(level): Th ^{198}Pt(^{70}Z evaluator Iγ(272γ): with this
3149.2‡ *3*	(4^+)		B GH	J^π: ≤4 from multiplet.
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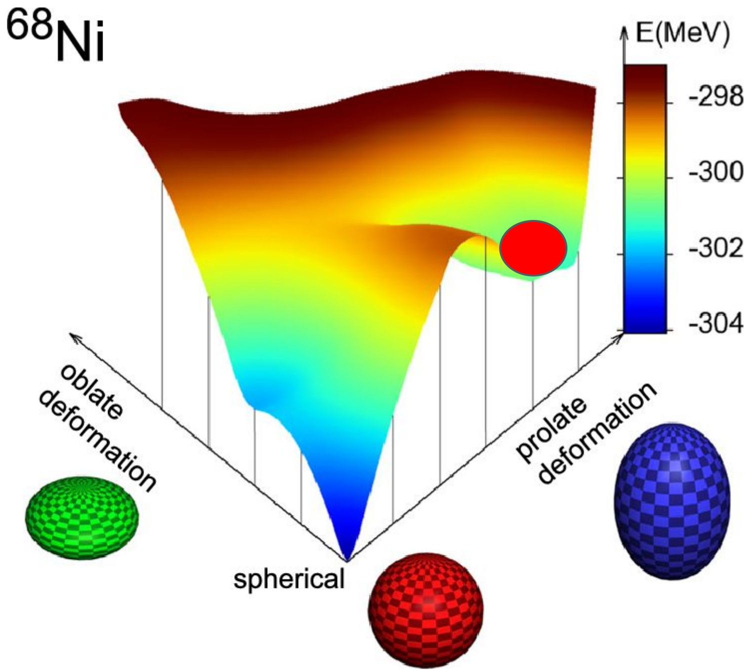
Level information on ^{68}Ni from ENSDF database

Properties of nuclear states - an example with theory



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Physics of isomers

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> Spin (due to shape) is the important quantity (1936)

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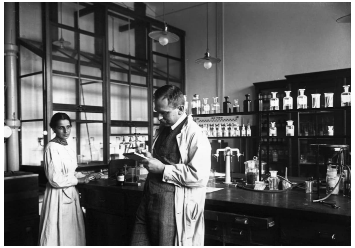

Lise Meitner and Otto Hahn

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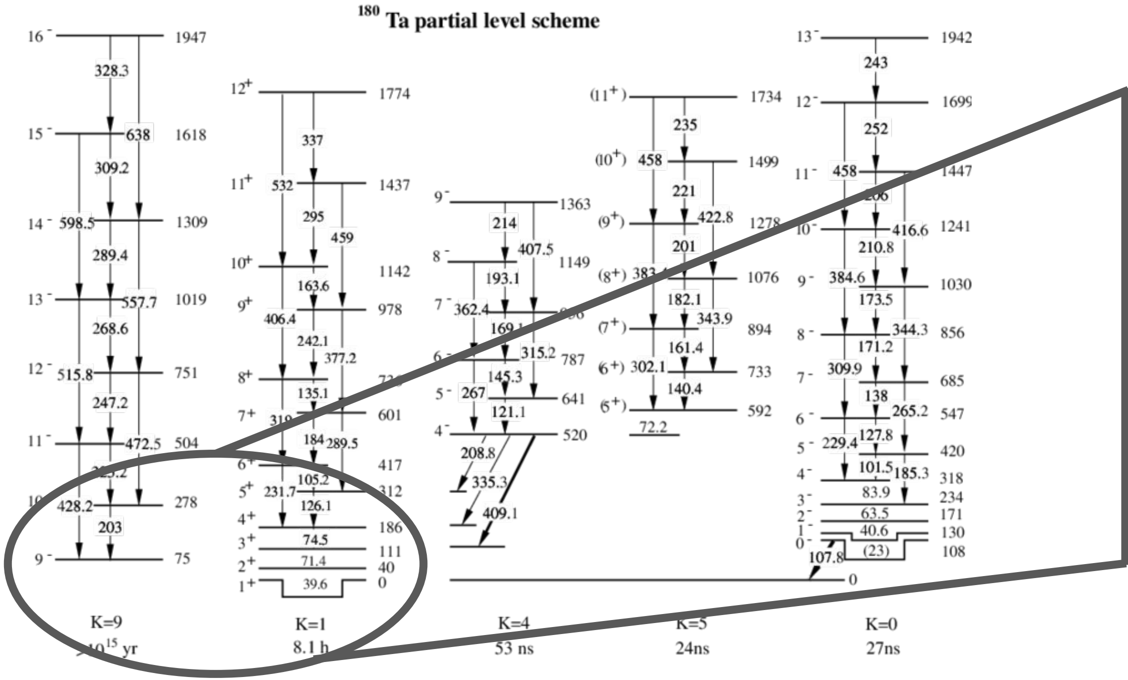
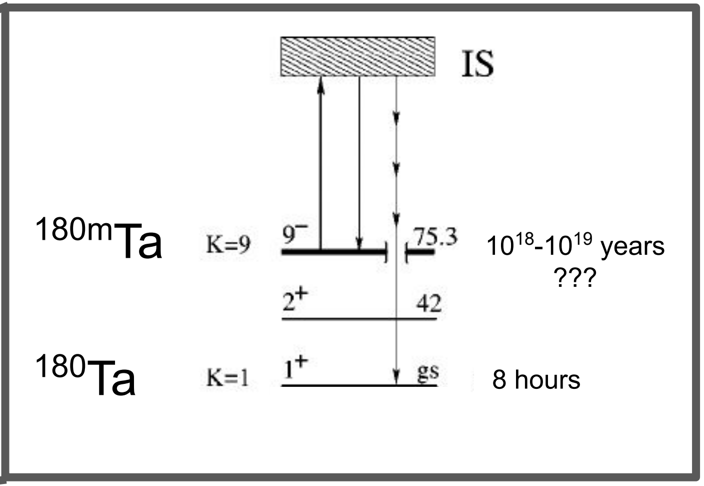
Systematic studies and experimental proof on Uranium (1938)

Today isomers we have found from 10^{-9} seconds … >10^{16} years

Properties of nuclear states - long lived isomers





Three lowest energetic states in ^{180}Ta

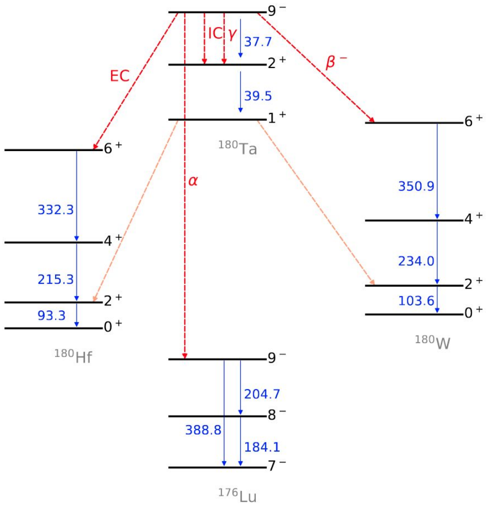
Back to the origins

> *"We can have isotopes with identity of atomic weight, as well as of chemical character,* ***which are different in their stability and mode of breaking up.****"(1917)*

^{180}Ta

Short half-live in the ground state (8 hours)

Decay to the neighboring isotopes to first excited or ground state



^{180m}Ta

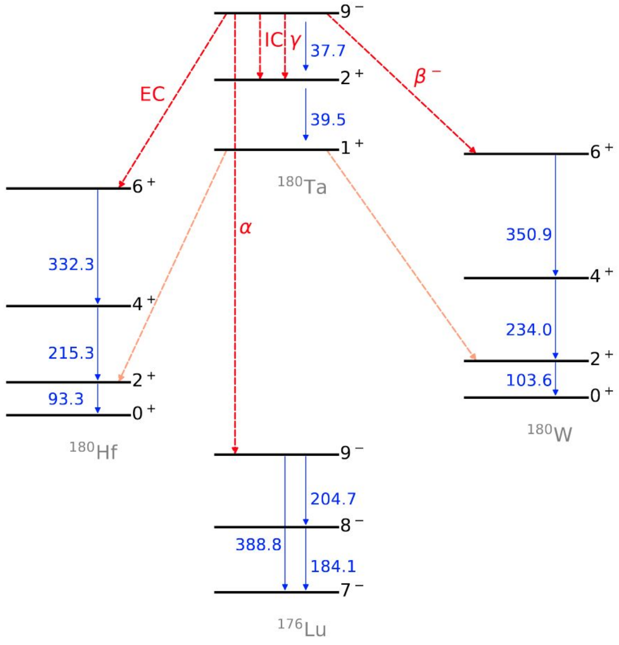
Extremely half-live (not observed yet, > 10^{17} years)

Decay to the neighboring isotopes to highly excited states

So why do we care ?

- The origin of Tantalum in the universe :
  - 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*)

- Longest lived metastable state never observed to decay
  - **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, γ-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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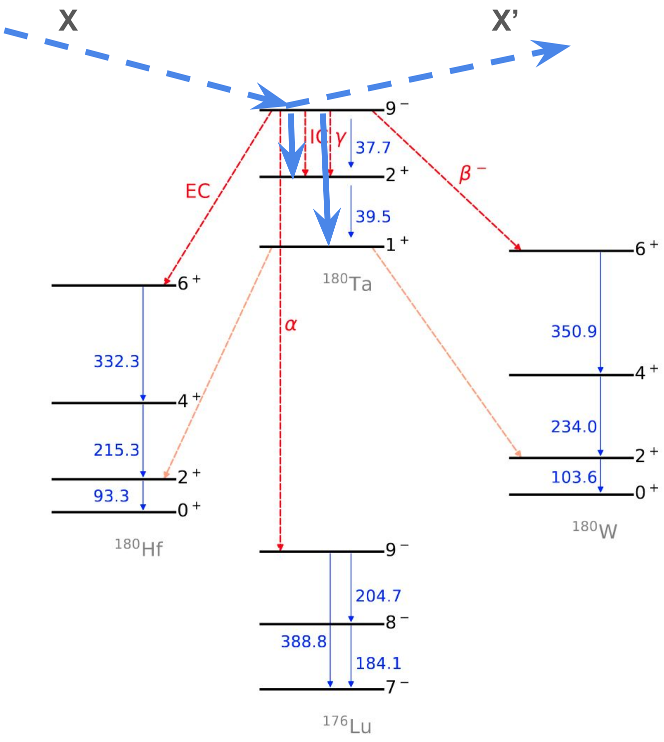
- Search for Dark Matter interaction
  - Additional energy from the isomer allows reaction with particles that would not interact otherwise
  - Candidates: **Strongly Interacting DM, Inelastic DM**



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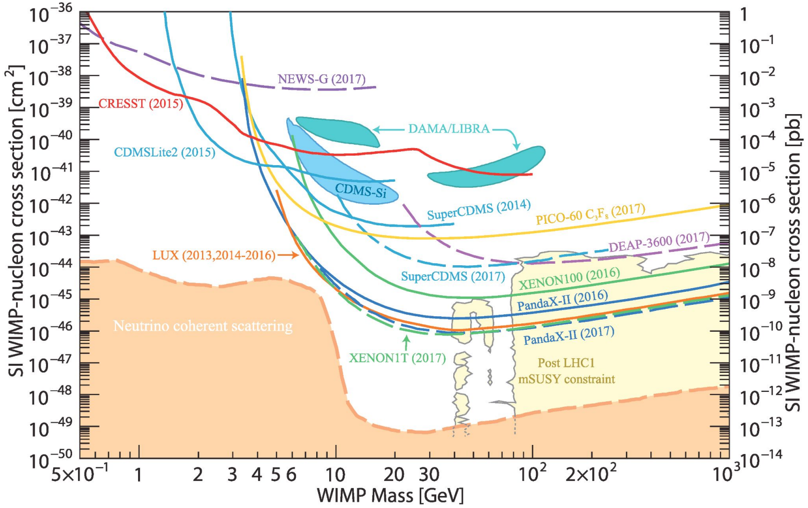
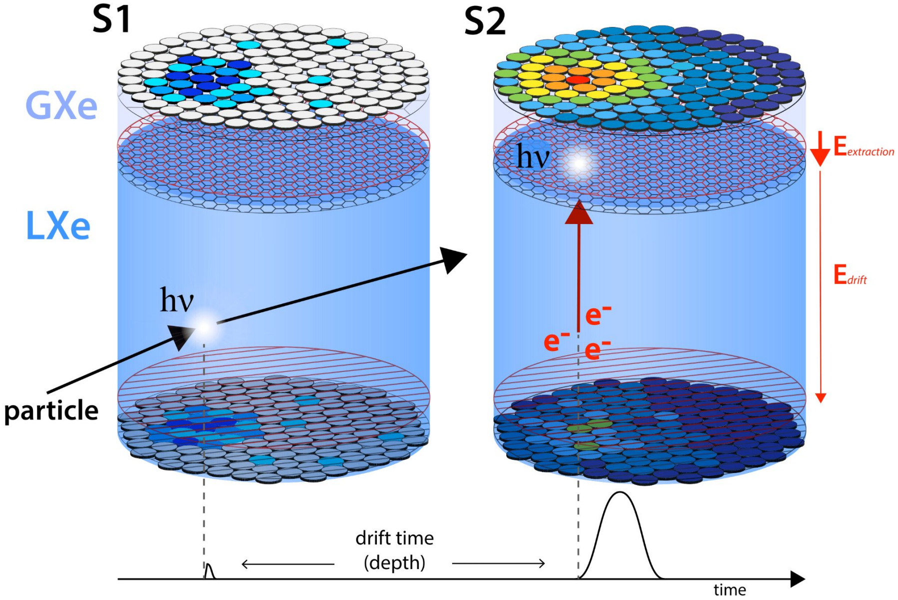
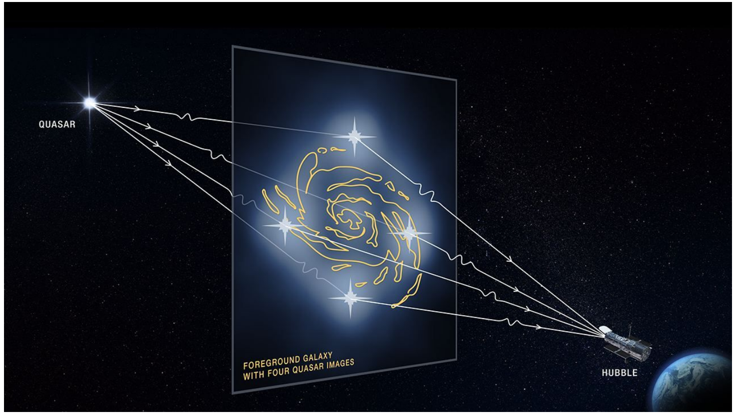
DM ? again ???

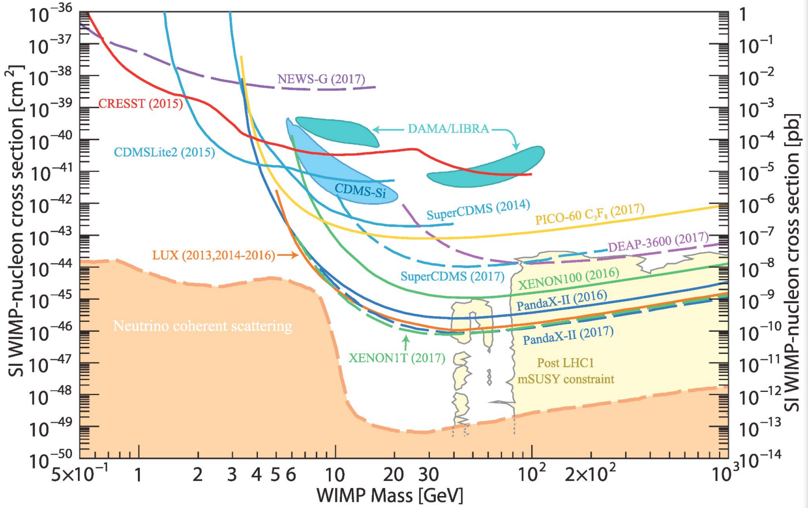






Cross section limits on DM, Large Xe detector schematics, and gravitational lensing with matter and dark matter

DM ? again ???



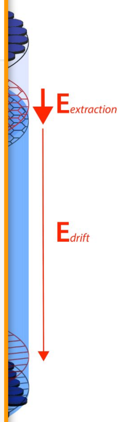
what is dark matter

Dark matter is a mysterious and invisible substance that makes up a significant portion of the universe's mass and seems to exert a gravitational force on visible matter, such as galaxies and galaxy clusters. Despite its name, dark matter does not emit, absorb, or reflect electromagnetic radiation (like light), which is why it's considered "dark" and remains mostly undetectable using conventional methods of observation.

Here are some key points about dark matter:

1. **Abundance**: Dark matter is thought to constitute approximately 27% of the universe's total mass-energy content, making it one of the most substantial components of the cosmos.
2. **Gravitational Effects**: The primary evidence for dark matter comes from its gravitational effects on visible matter. For instance, galaxies rotate at speeds that would be impossible if their mass were only accounted for by visible stars and gas. The additional mass from dark matter is required to explain these observations.
3. **Cosmic Microwave Background**: The cosmic microwave background radiation, a relic of the early universe, also supports the existence of dark matter. Its distribution of temperature fluctuations can be explained more accurately when dark matter is taken into account.
4. **Particle Nature**: Despite extensive efforts, the exact nature of dark matter remains unknown. It is generally believed to consist of some type of particle, but these particles have not been directly observed. Various candidates for dark matter particles include axions, WIMPs (Weakly Interacting Massive Particles), and sterile neutrinos.
5. **Dark Matter Halo**: Dark matter is distributed throughout the universe in a web-like structure, forming what is often called a "dark matter halo" around galaxies. This halo is thought to provide the gravitational scaffolding that allows galaxies to form and maintain their structure.
6. **Unaffected by Electromagnetism**: Dark matter does not interact via the electromagnetic force, which means it doesn't emit, absorb, or scatter light. This property makes it extremely challenging to detect directly.

Scientists continue to conduct experiments and observations in the hopes of detecting or identifying dark matter particles and better understanding their properties. The existence of dark matter is a crucial component of current cosmological models, helping explain the observed large-scale structure and dynamics of the universe. However, many questions about dark matter remain unanswered, making it one of the most significant unsolved mysteries in astrophysics and cosmology.



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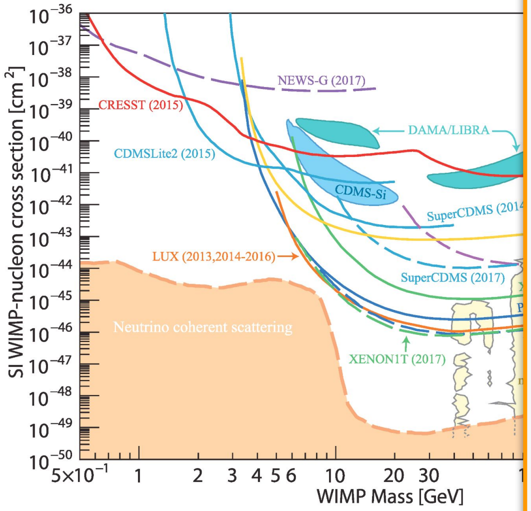

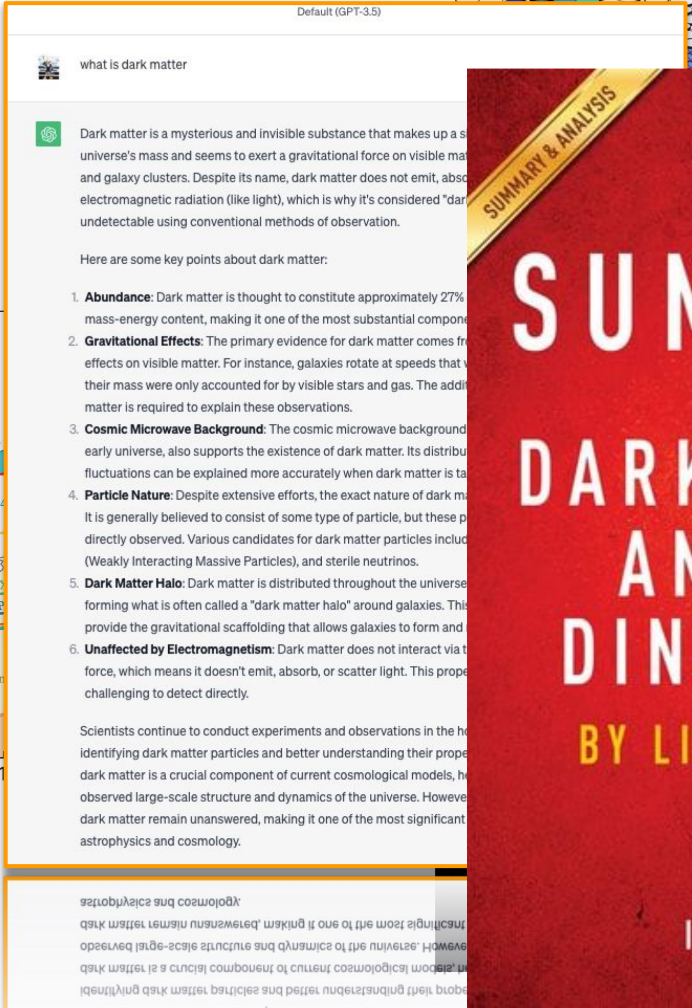
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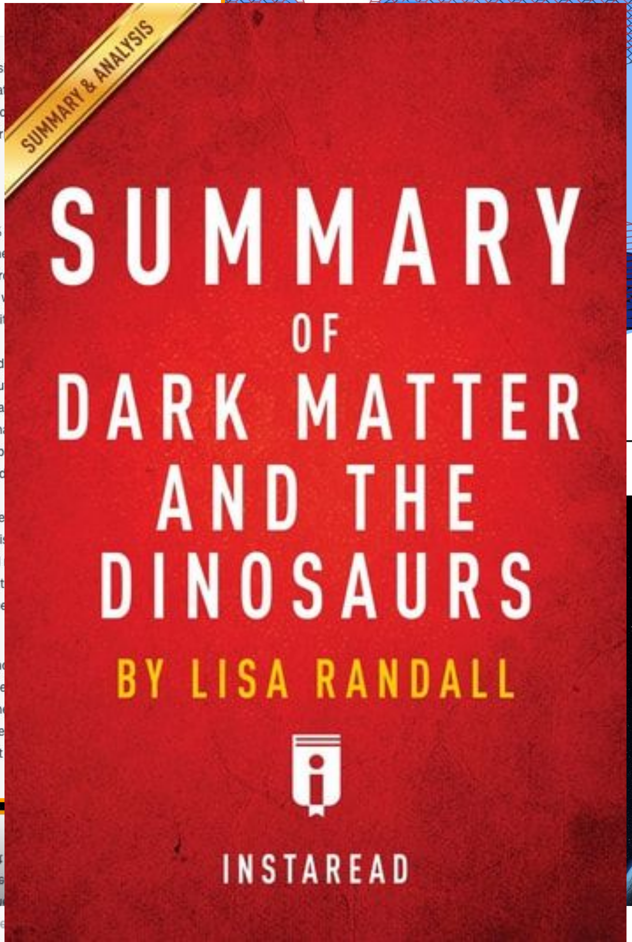
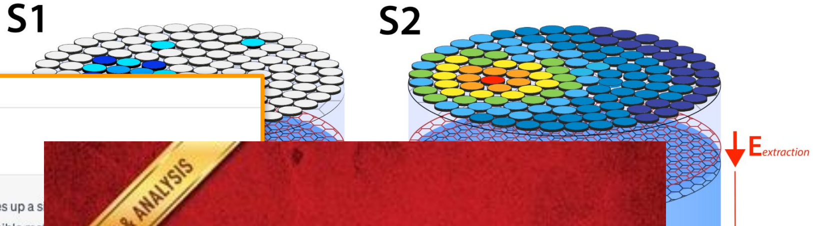
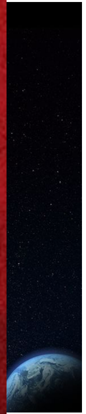
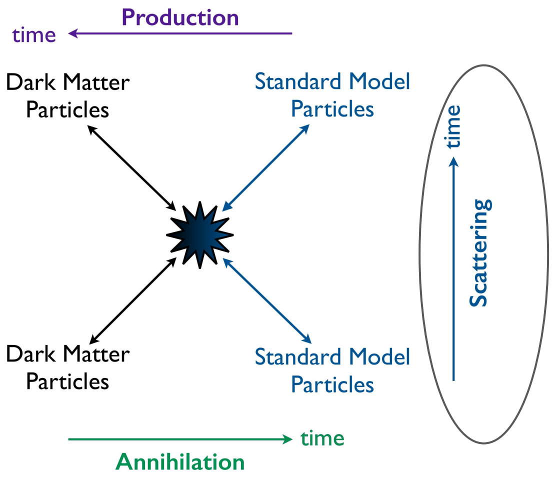






Inelastic dark matter motivation

- What if the DM species evade direct detection ?
- Production in colliders possible, but very low
- No reason that there is no a whole DM zoo of particles or composite DM



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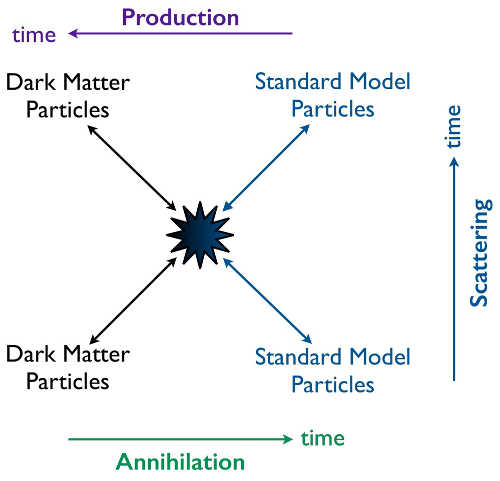

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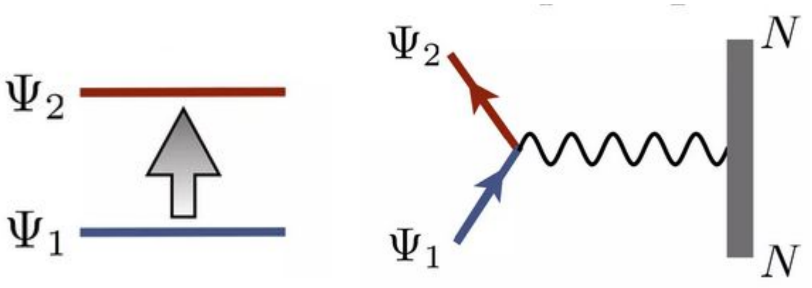

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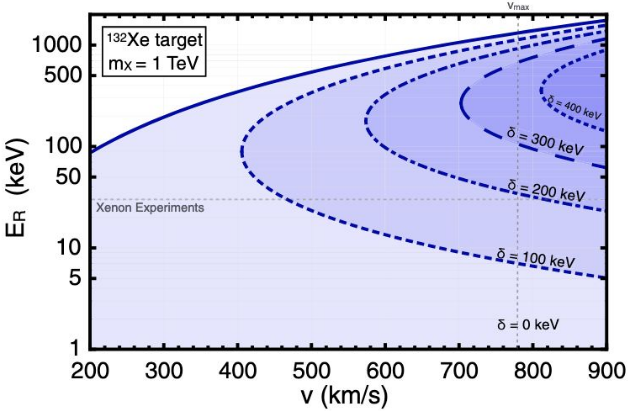
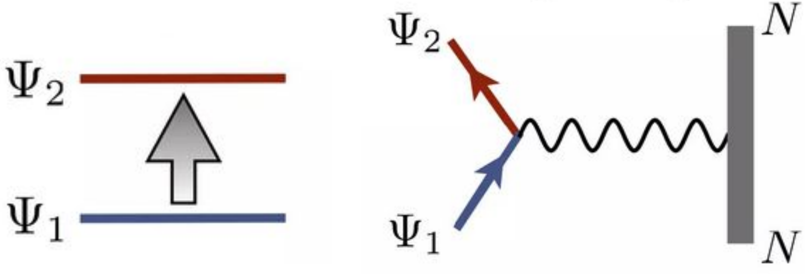
- Based on Tucker-Smith & Weiner (2001) or Alves et al (2010)
- Requires additional “energy” in the system
  - Sufficiently fast DM interacts with standard detectors measuring nuclear recoils
    OR
  -



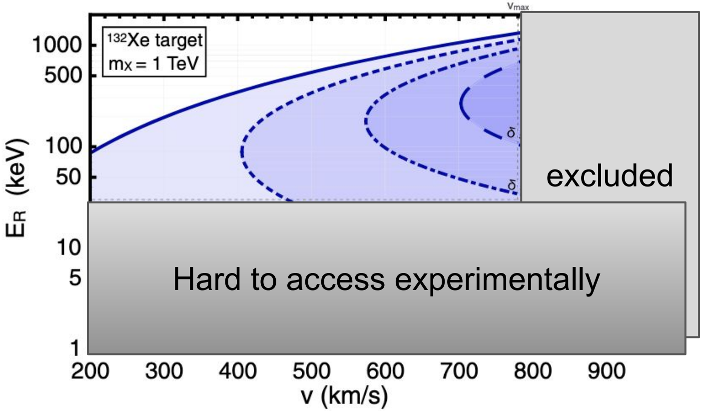
Recoil energy as a function of incoming DM velocity for non-isomers

Detect recoil E_r

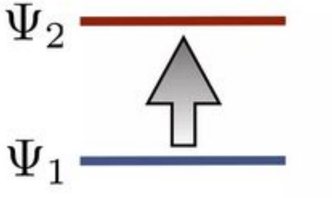


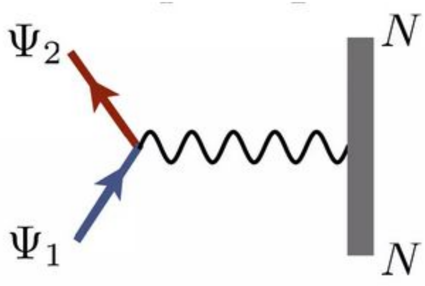
Inelastic dark matter motivation

- What if the DM species evade direct detection ?
- Production in colliders possible, but very low
- No reason that there is no a whole DM zoo of particles or composite DM
- Based on Tucker-Smith & Weiner (2001) or Alves et al (2010)
- Requires additional “energy” in the system
    - Sufficiently fast DM interacts with standard detectors measuring nuclear recoils
      OR
    - **Deexcitation of isomers**
      (no velocity requirement)



Recoil energy as a function of incoming DM velocity for non-isomers





- **Nuclear Isomers -**
  a crash course in nuclear physics from the first half of the 20th century

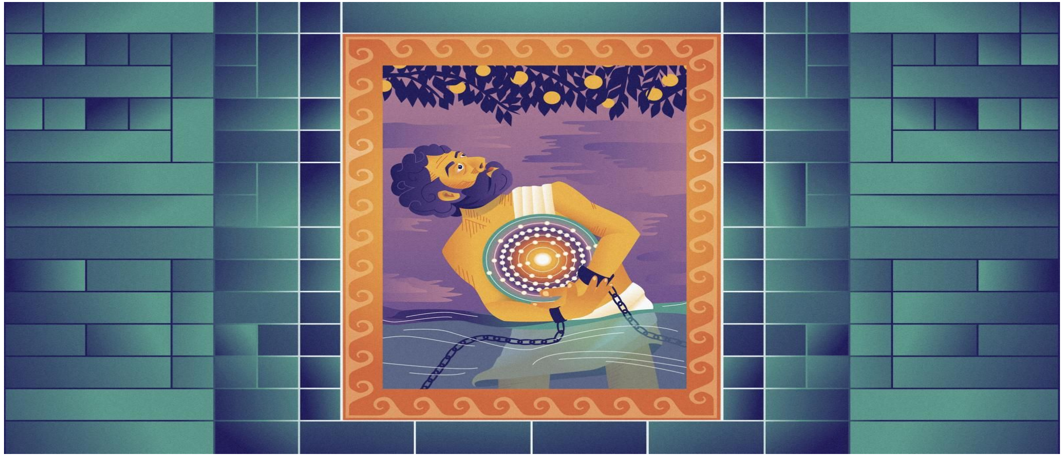
- **Dark Matter -**
  a crash course in astrophysics of the late 20th century

- **2 extreme cases:**
  a crash course in my work of the last 2 years

  - One year from most sensitive search for electron capture and β-decays

  - a 15-min experiment

A bit of (ancient) history…



Tantalus trapped as punishment.

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

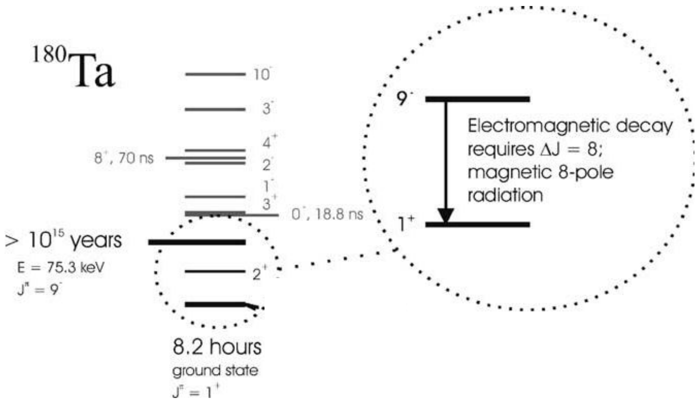
In greek mythology **Tantalus** offended the gods…

… 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

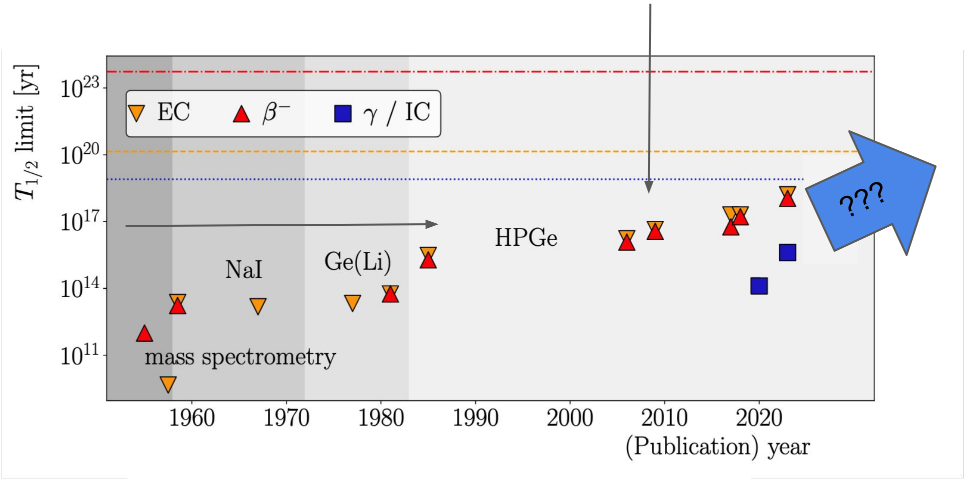
For nuclear physics **Tantalum** *(named 1802)* is one of the rarest elements and has two isotopes…

… 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

What is needed for a measurement…



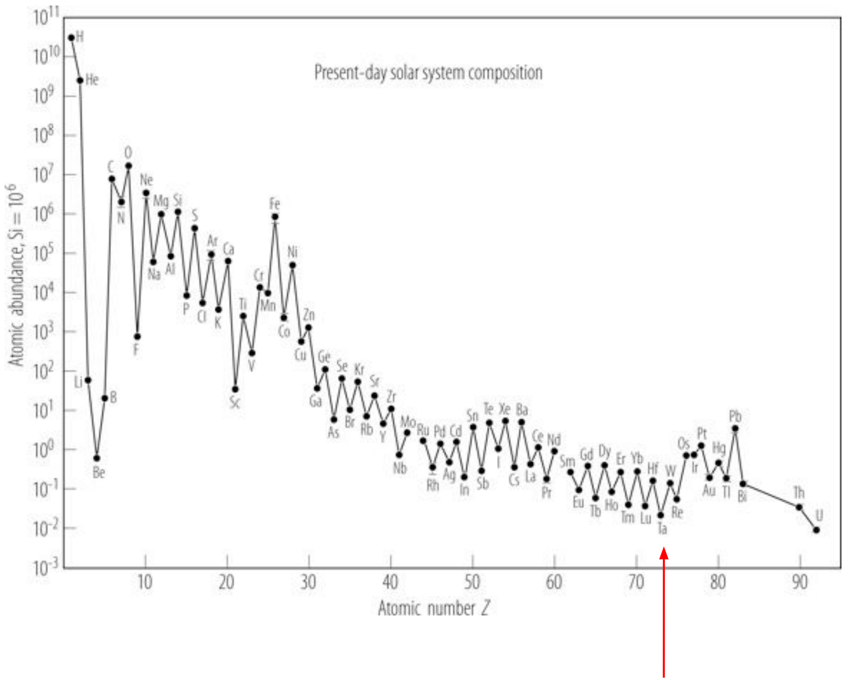
History of Tantalum decay measurements with predictions (dashed lines), from arxiv 2305.17238

Til 1985 ground state and isomer switched
2006 the spin of the isomer was determined

- 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

What is needed for a measurement…



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- 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

Experimental searches - the decay of ^{180m}Ta

- 1 - 2 ppm of earth's crust is Ta
- 99.98% is ^{181}Ta
- Best previous measurement used ~1kg of ^{nat}Ta (~0.2 g of ^{180m}Ta)
- All the ^{180}Ta is metastable:

the only naturally occurring long-lived isomer

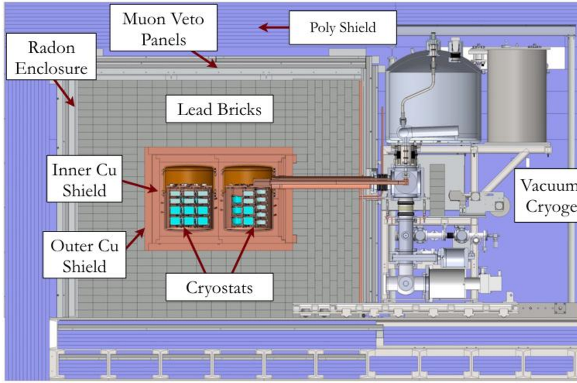
Testing basic nuclear physics on the extremes

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

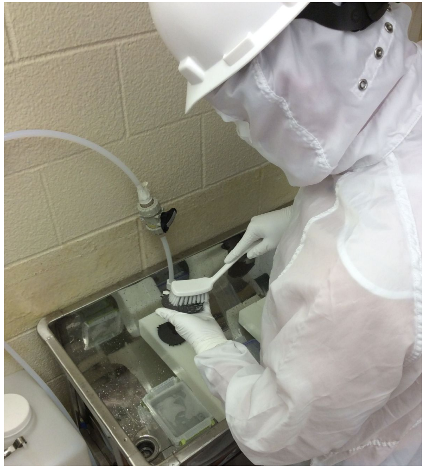
- **Final Result,** *(PRL 130, 062501, 2023)*
  - **65 kg-yr exposure**
  - Median $T_{1/2}$ Sensitivity: 8.1×10^{25} yr (90% C.I.)
  - Limit: $T_{1/2} > 8.3 \times 10^{25}$ yr (90% C.I)

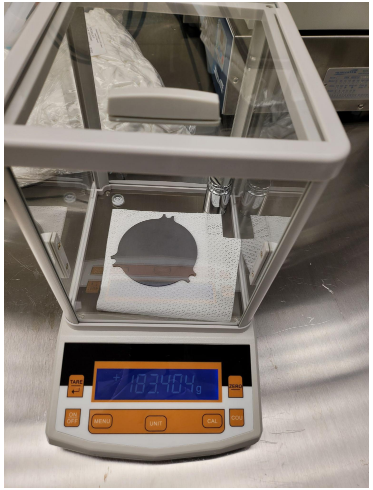


Schematics of the MJD experiment

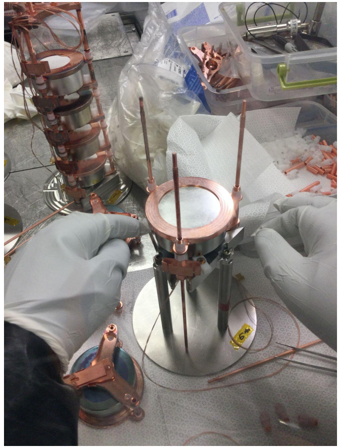
Installation and preparation

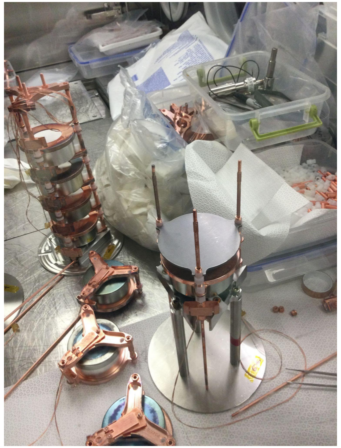
- Material cleaning following MJD standards
- 120 disks, each 180g, 2mm thick
- Limit for mass:
  - MJD geometry
  - Efficiency

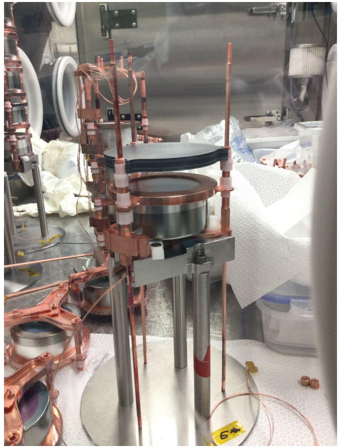


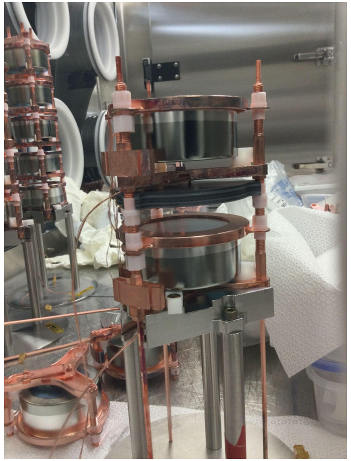


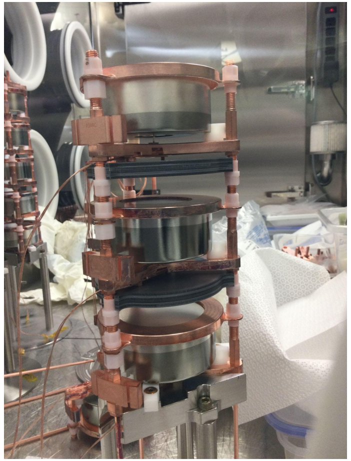
Installation





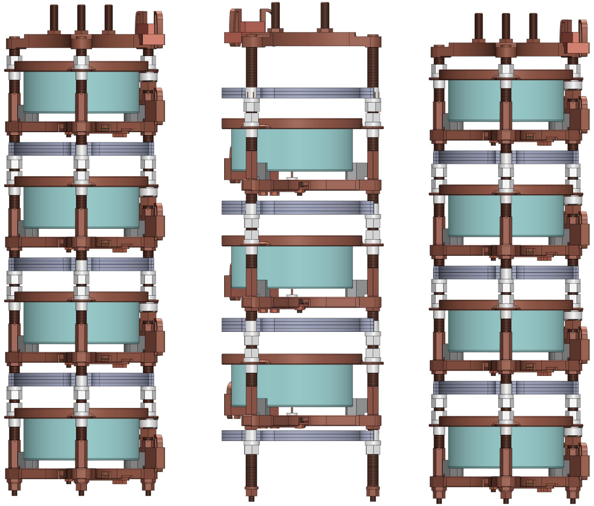


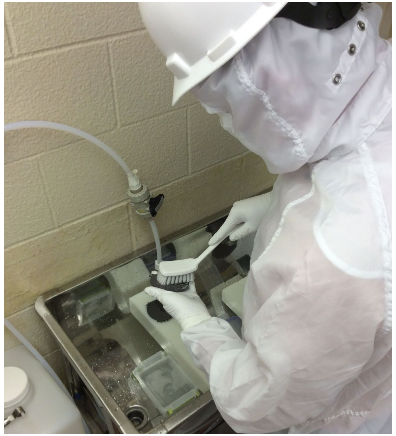


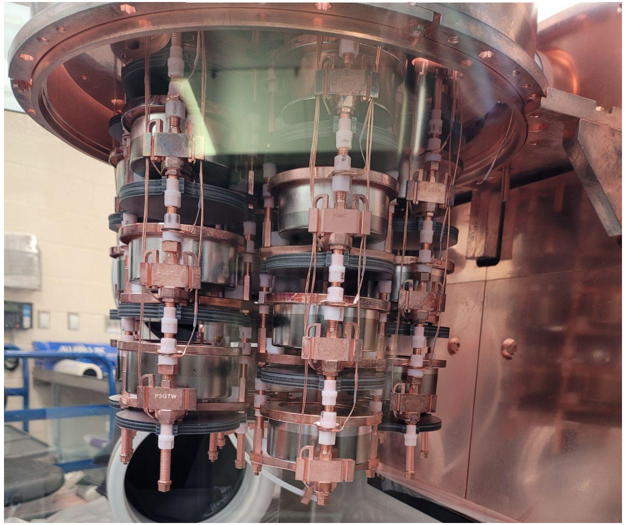


Reconfiguring of the DEMONSTRATOR

- **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





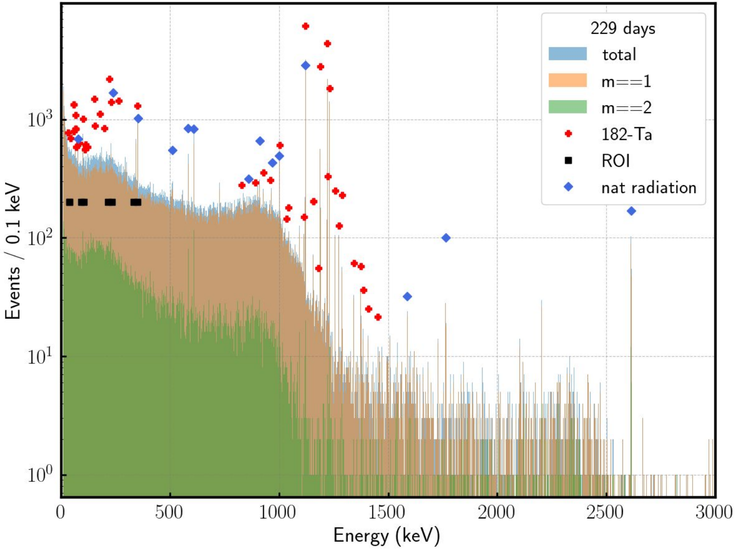


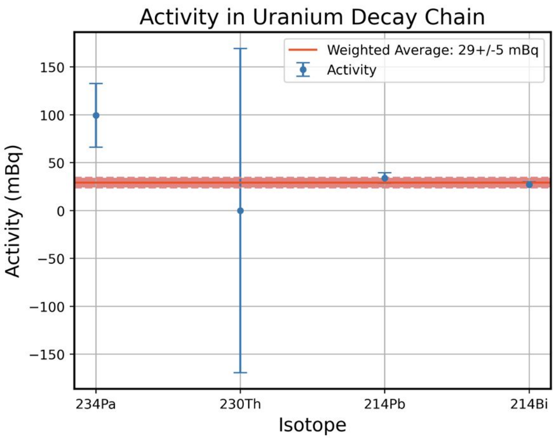
(left) cleaning and installation in the MJD strings

(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 (~ µBq/g_{Ta})





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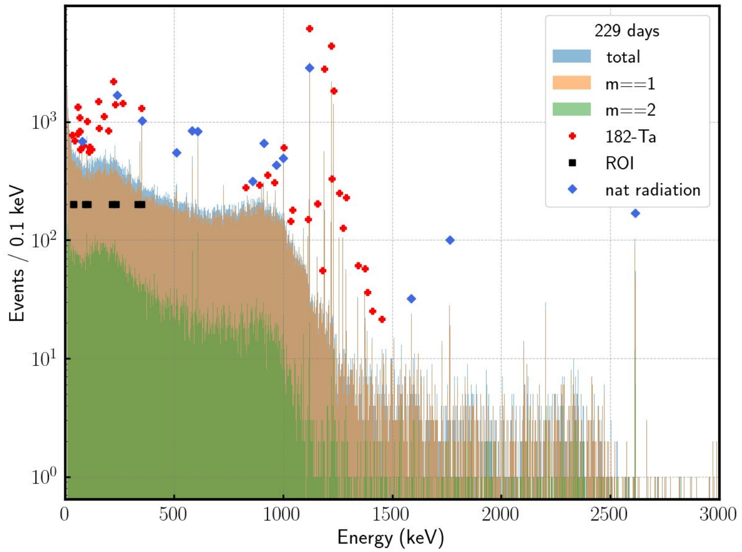
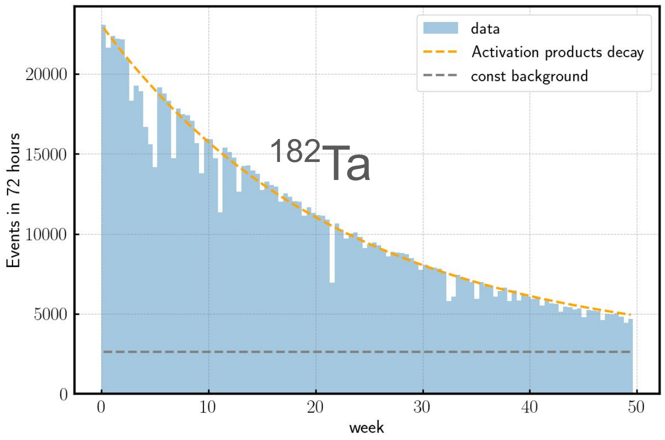
  - **surface activation in Ta**
    - ^{182}Ta ($T_{1/2}$ = 114 days) - n-capture
    - ^{175}Hf ($T_{1/2}$ = 70 days)
- Background improving over time





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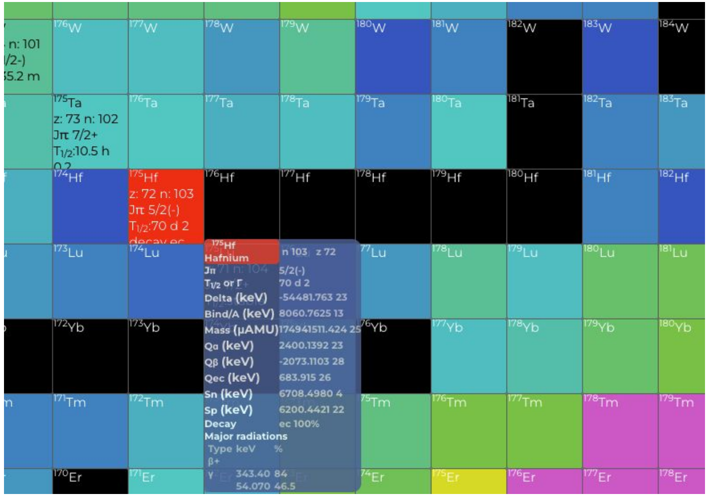
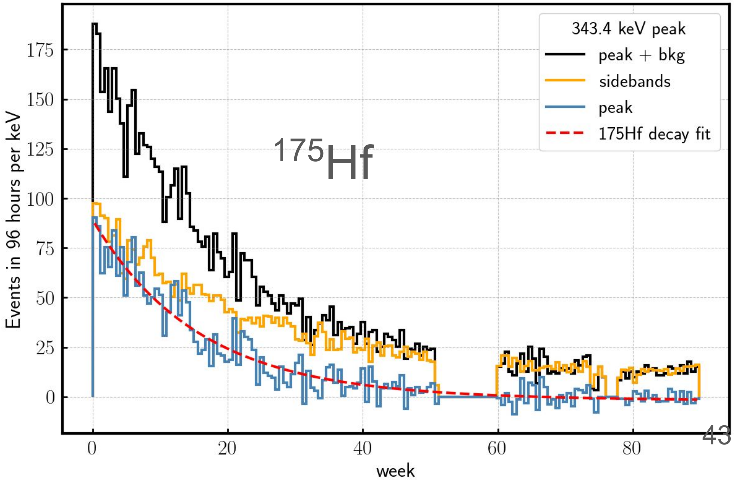
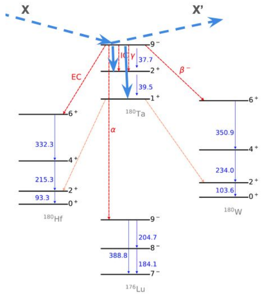
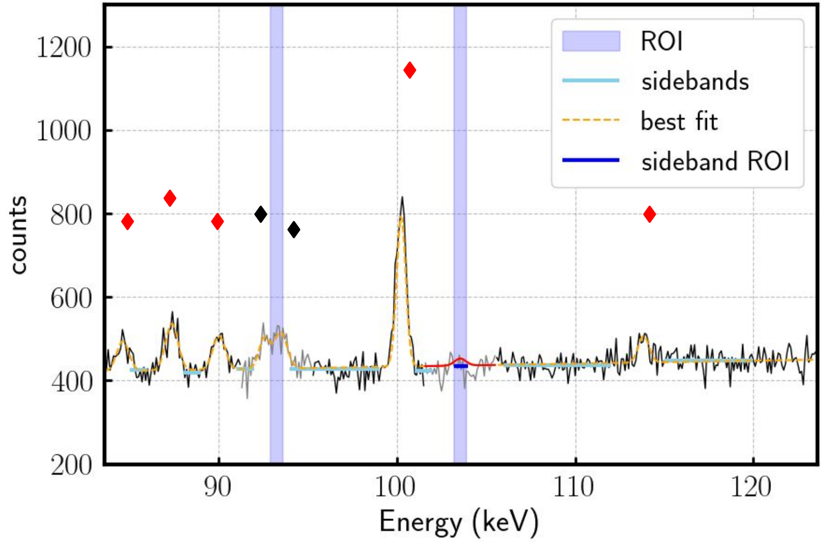
        - ^{182}Ta ($T_{1/2}$ = 114 days)
        - <u>^{175}Hf ($T_{1/2}$ = 70 days) - knockout of 1 p and 5 n !</u>
- Background improving over time



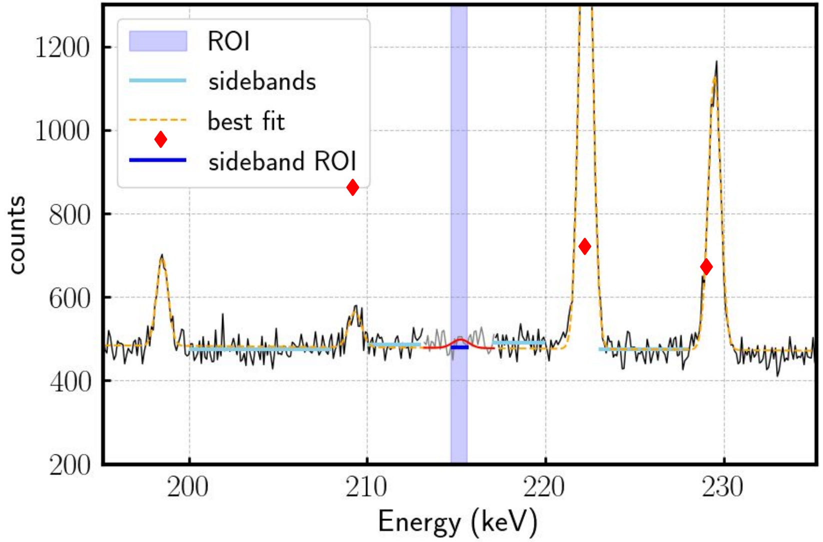


A look in a few region of interests





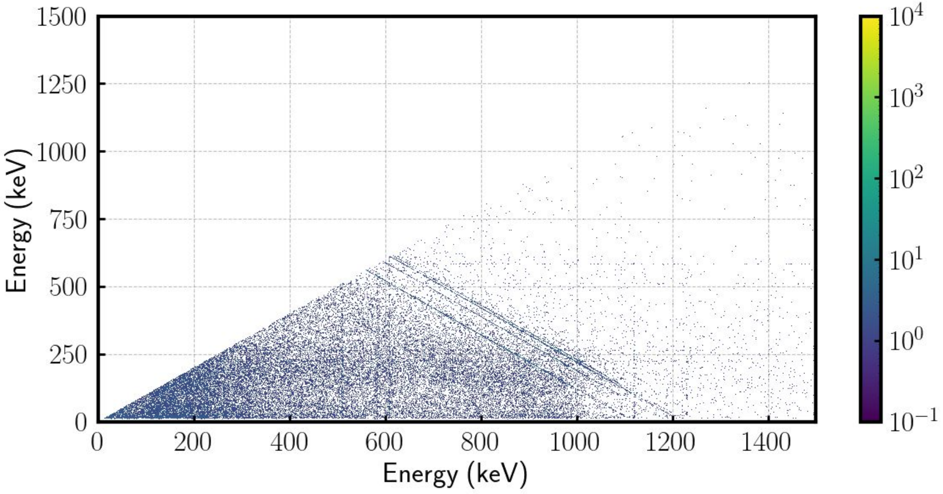
Signal region for deexcitations after β-decay

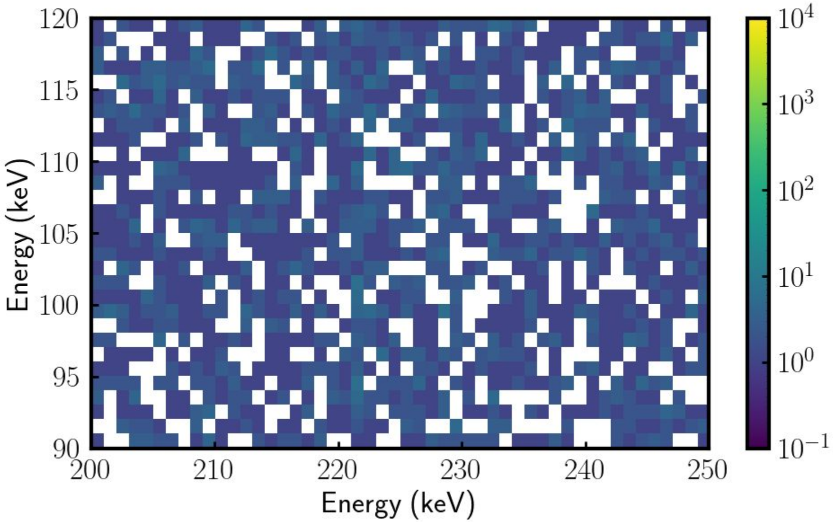


Signal region for deexcitations after electron capture

◆ ^{182}Ta
◆ U/Th decay chain

Multiplicity analysis





- Replaces search of individual signatures
- Efficiency lower
- Background much lower !
- Simple side-"box" analysis

First year results

Submitted and accepted in PRL
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	> 1.6×10^{18}	> 1.1×10^{18}	> 4.5×10^{14}	> 4.5×10^{14}	–
MJD - 2023	**> 1.3×10^{19} ****	**> 1.5×10^{19} ****	**> 6.0×10^{17}**	**> 2.9×10^{17}**	**> 1.1×10^{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

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

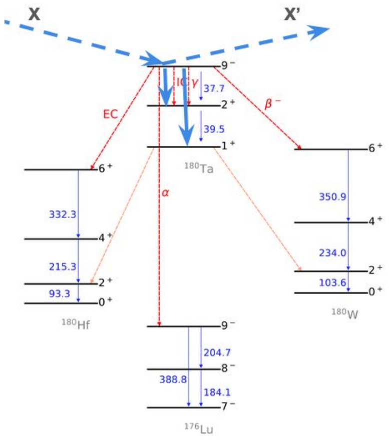
$$\lambda_{total} = \lambda_{EC} + \lambda_{\beta-} + \lambda_{\gamma} + \lambda_{IC} + \lambda_{\alpha} + \lambda_{DM}$$

First half-life sensitivities for
β-decays and electron captures > 10^{19} years
(only some α and $\beta\beta$ are longer)

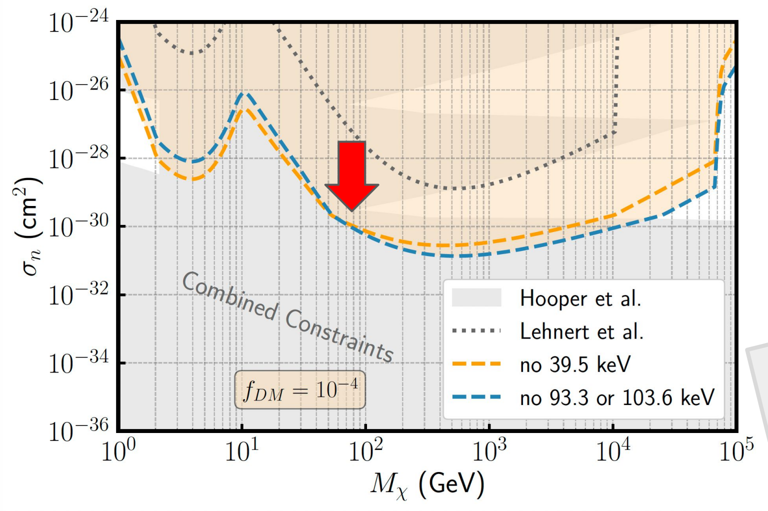
Improvements of 1-2 orders of magnitude

	EC	[illegible]	[illegible]	[illegible]	**α**
Previous Limits	[illegible]	[illegible]	[illegible]	> 4.5 x 10^{14}	–
MJD - 2023	**> [illegible]**	**[illegible] 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}

Dark matter induced deexcitation

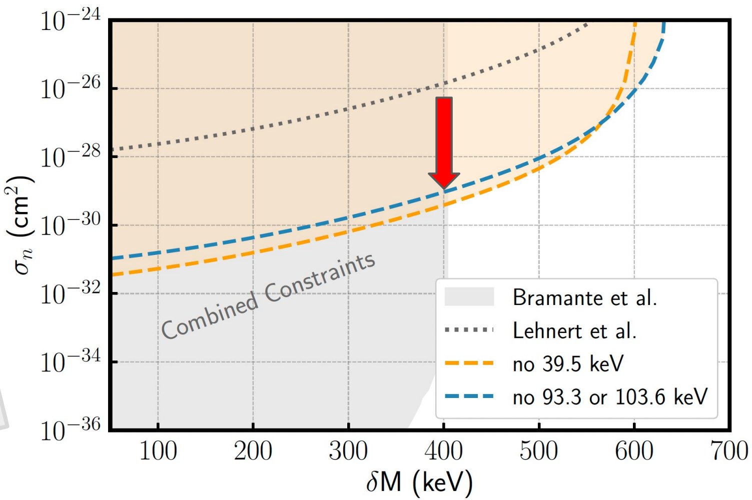


- No observation of ^{180m}Ta decay → no DM-induced decay
- Improved sensitivities to strongly interacting DM (siDM)
- Additional sensitivities to more complex DM with multiple states
- and/or particles via inelastic scattering



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

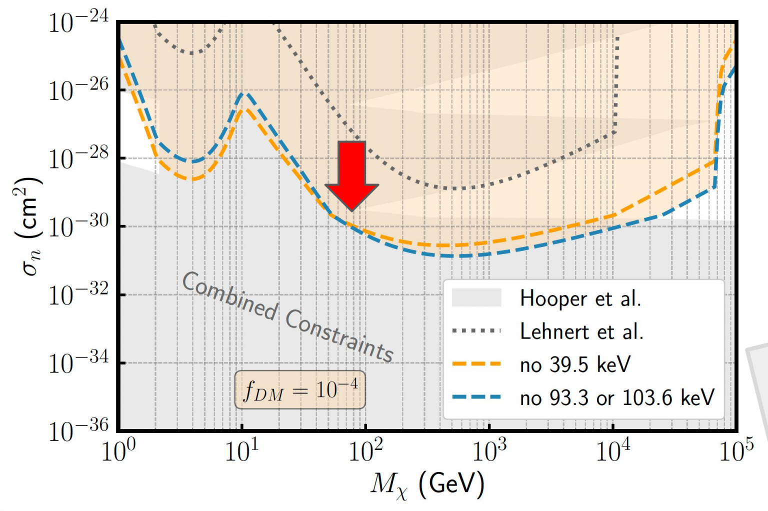
Previous limits:
PRL 124, 181802
PRD 94, 115026
PRD 97, 115006



Dark matter induced deexcitation

Improvements by two orders of magnitude and complementary to other searches

- 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



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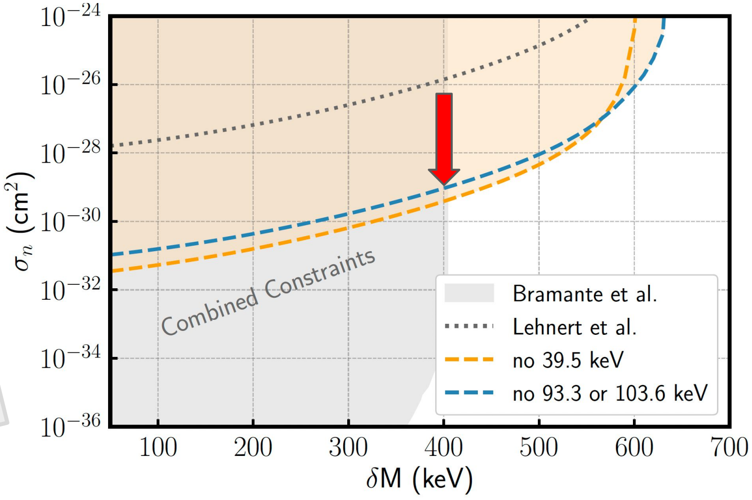


Tantalum Results

- 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

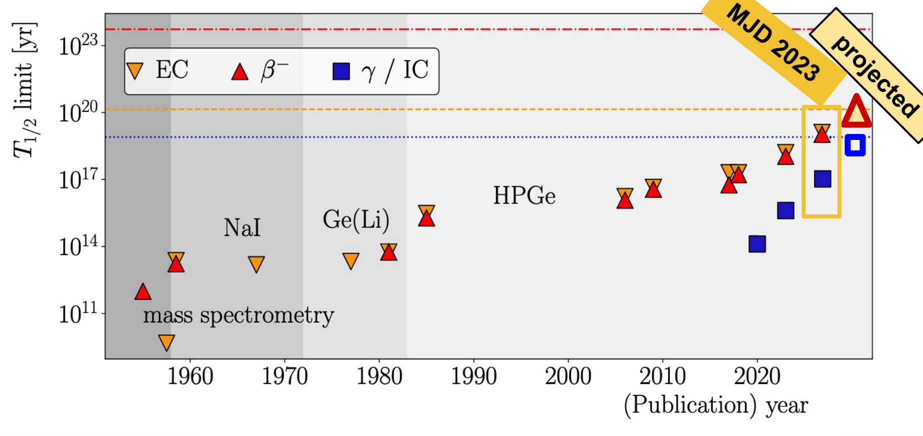


Figure taken and updated from 2305.17238

PRL 131, 152501 (2023)

Sam Meijer having fun cleaning Tantalum

Los Alamos NATIONAL LABORATORY EST. 1943

LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

Tantalum Outlook

- Data taking continues (planned mid 2025)
- Update data analysis
    - Time-correlated fits

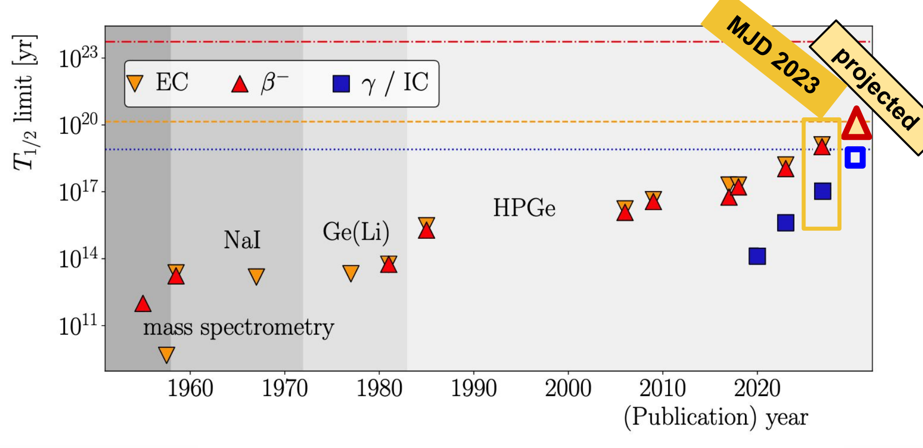
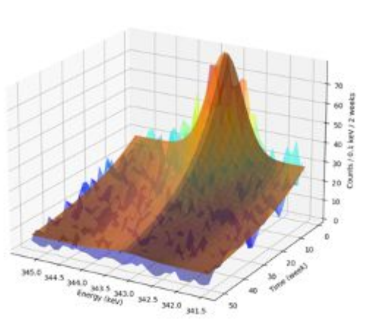
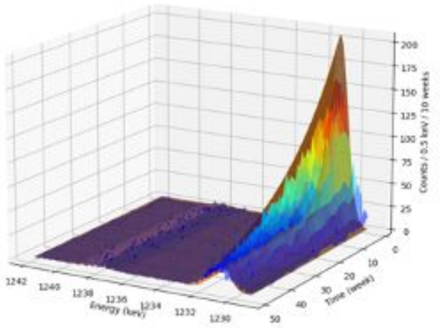
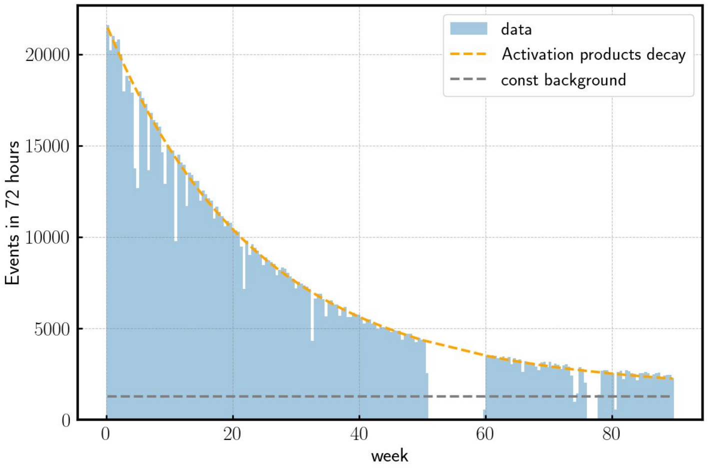


Figure taken and updated from 2305.17238

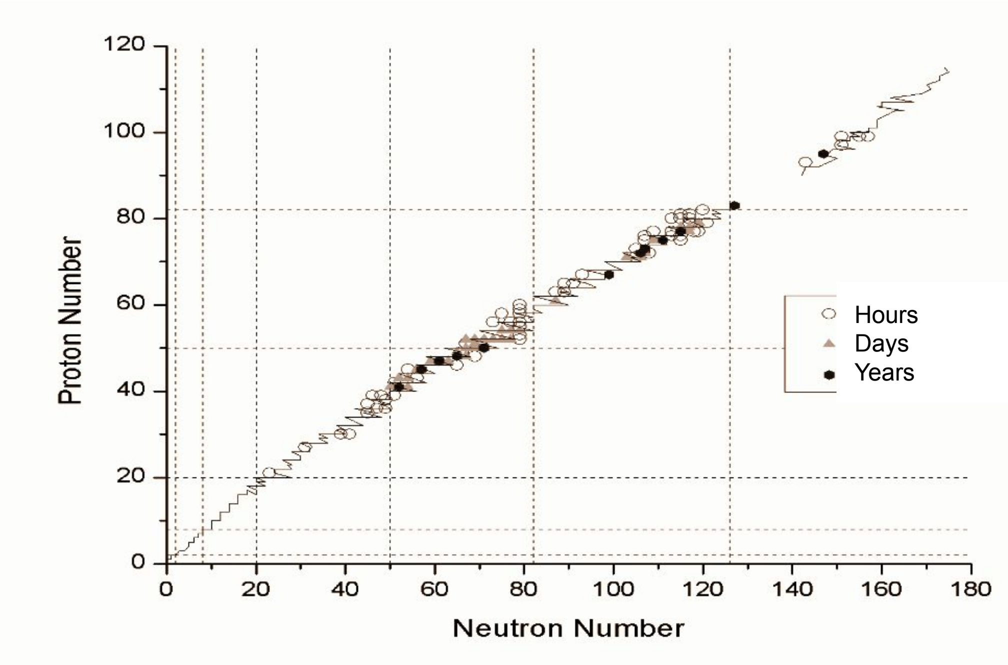


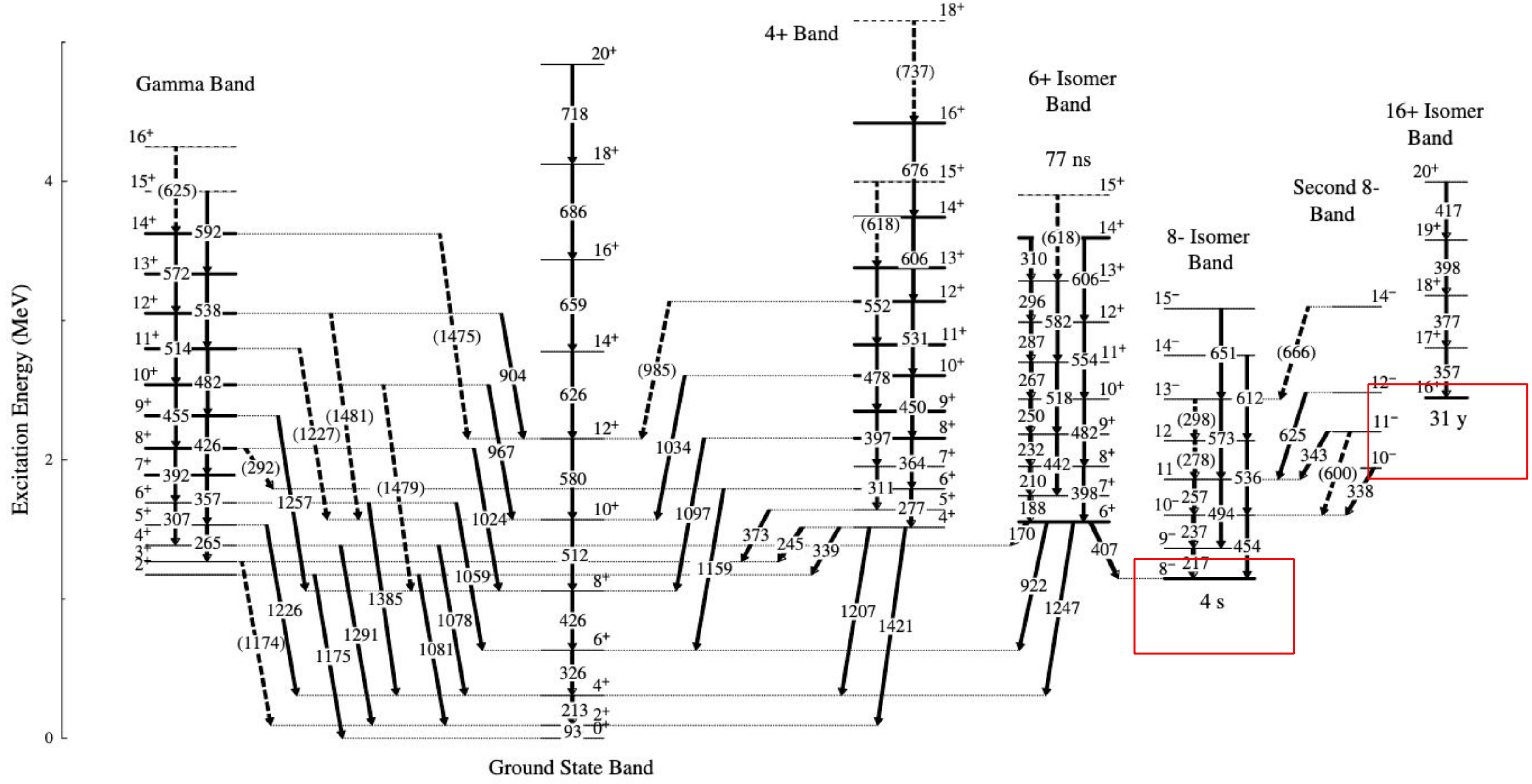




Other isomers ?

- A wide number of isomers exis
- Most are short lived
  - Hard to access experimentally
  - Mostly low energy transitions
- One candidate
  - ^{178}Hf
  - 2 isomers
  - Higher excitation energy

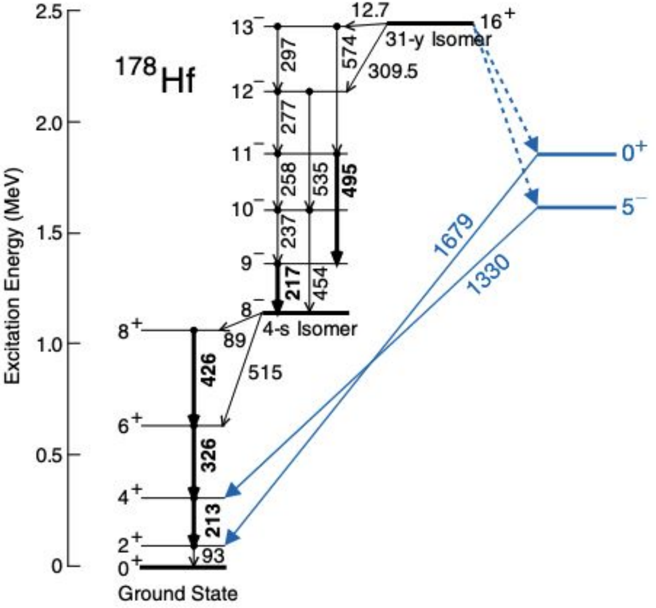



Excitation Energy (MeV)
Gamma Band
Ground State Band
4+ Band
6+ Isomer Band
77 ns
8- Isomer Band
4 s
Second 8- Band
16+ Isomer Band
31 y

Experimental searches - ^{178m}Hf

$$\chi + {}^{178m}\mathrm{Hf} \rightarrow \chi^* + {}^{178}\mathrm{Hf}_j$$

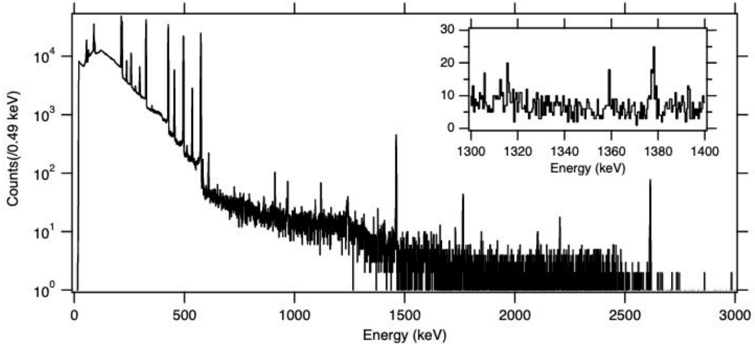
- Different approach
  - Short half life
  - high activity
- Portable Ge detector and short measurement time (15mins)
- Search of new transitions next to Standard transitions

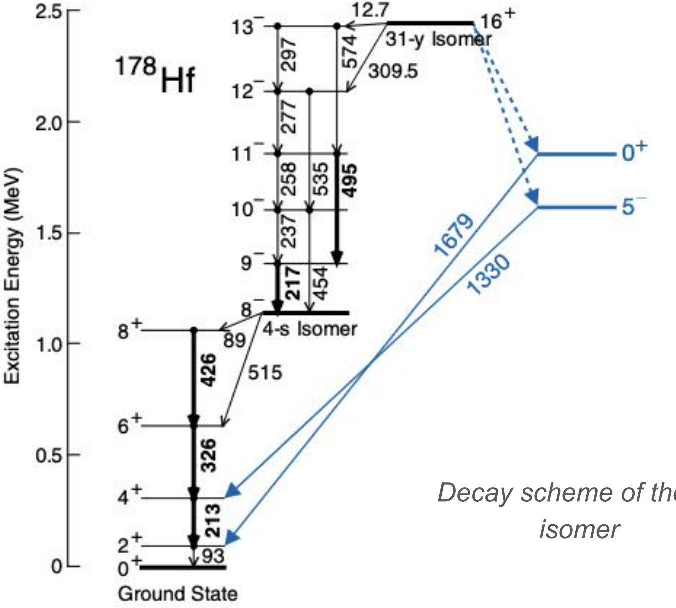


Experimental searches - ^{178m}Hf

$$S_\gamma^{(j)} = N_T \Delta t \times (\sigma_{inel}^{(j)} \Phi_\chi) \times (b_\gamma^{(j)} \mathcal{A}_\gamma^{(j)} \epsilon_\gamma^{(j)})$$

- Different approach
  - Short half life
  - high activity
- Portable Ge detector and short measurement time (15mins)
- Search of new transitions next to Standard transitions



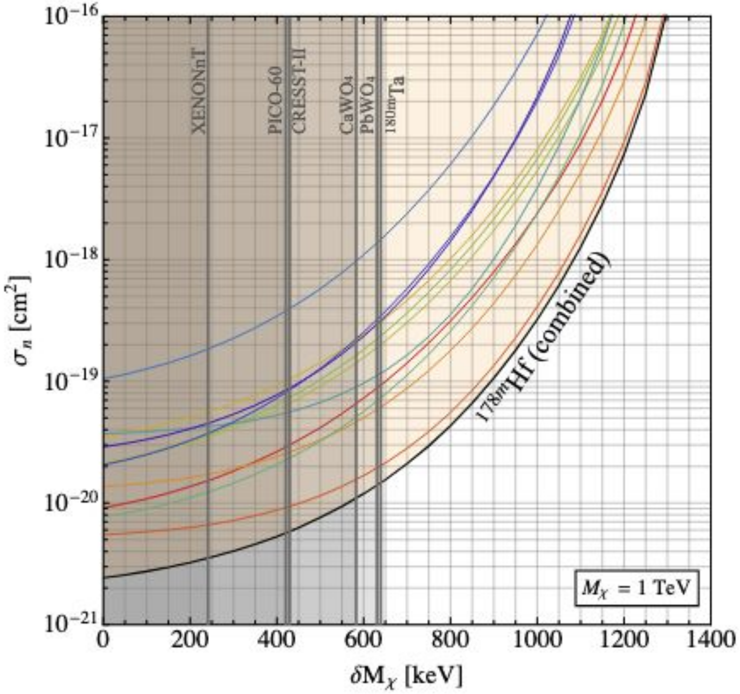


Decay scheme of the Hf isomer

Experimental searches - ^{178m}Hf

PRL 131, 141801 (2023)

- Different approach
  - Short half life
  - high activity
- Portable Ge detector and short measurement time (15mins)
- Search of new transitions next to Standard transitions
- Results background limited
- No observation of excess signals
- Complimentary to larger and longer efforts



Summary

- The physics of isomers is almost a century old
- While a lot of isomers are studied, the most extreme cases remain unexplored
- Testing classic nuclear physics in the extrema
- A door into dark sector that is allows us to look for DM types that are not accessible in larger efforts