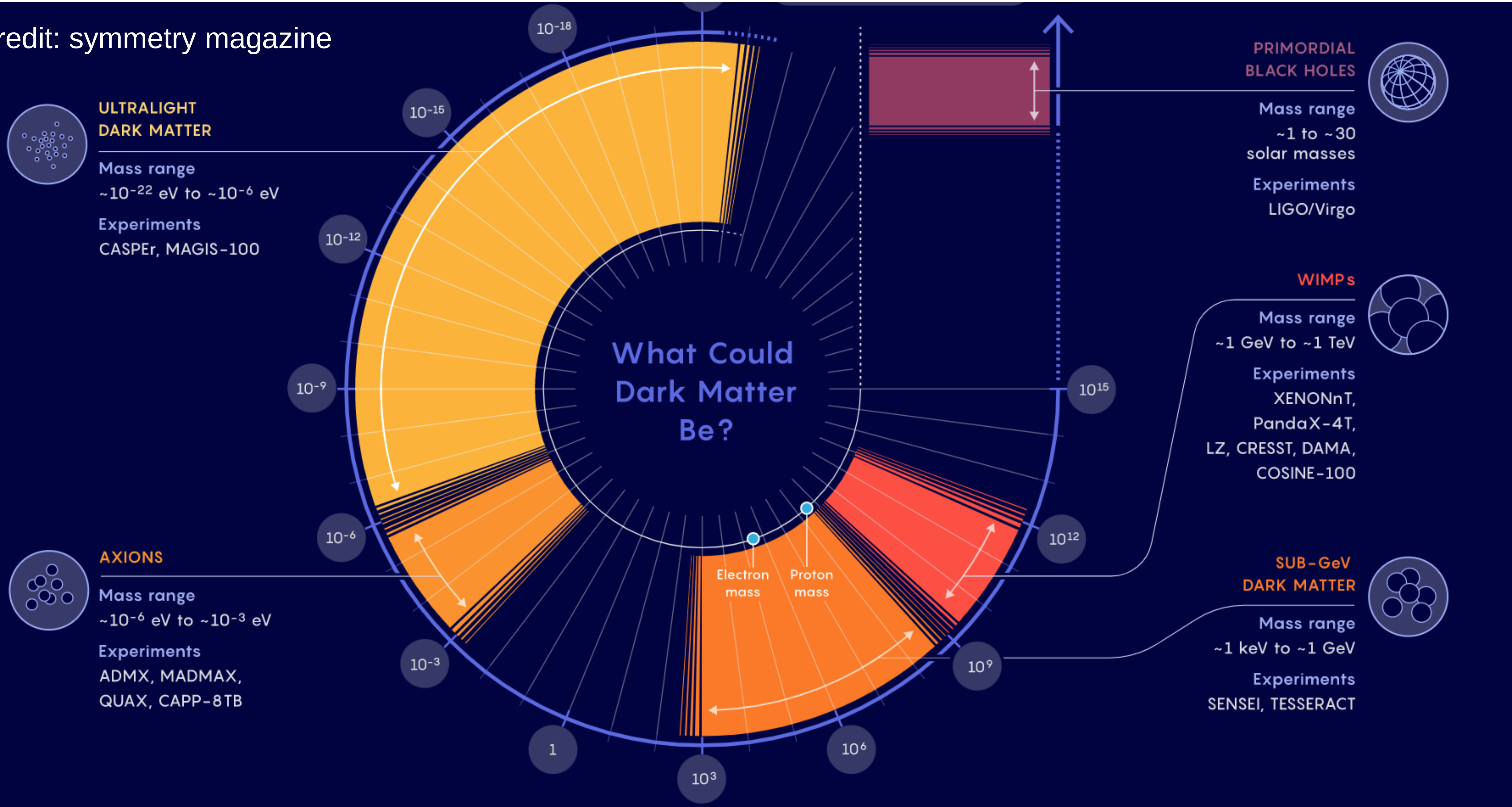
Looking for dark matter with nuclear decays

Ryan Gibbons

290E Seminar

March 13, 2024

Credit: symmetry magazine



Use “priors” to focus in

- WIMPs: thermal freeze-out, hierarchy problem/SUSY
- QCD axion: strong CP problem, “misalignment” production

- Flip this around: ultra-sensitive detectors exist → look for anomalous signal
- Example with LZ experiment
  - Primary goal: WIMP search
  - Many other dark matter searches: dark photons, ultraheavy DM, …

Focusing in further

- Particle-like dark matter (WIMPs etc.)
- Direct-detection avenue
- Signal is a nuclear decay

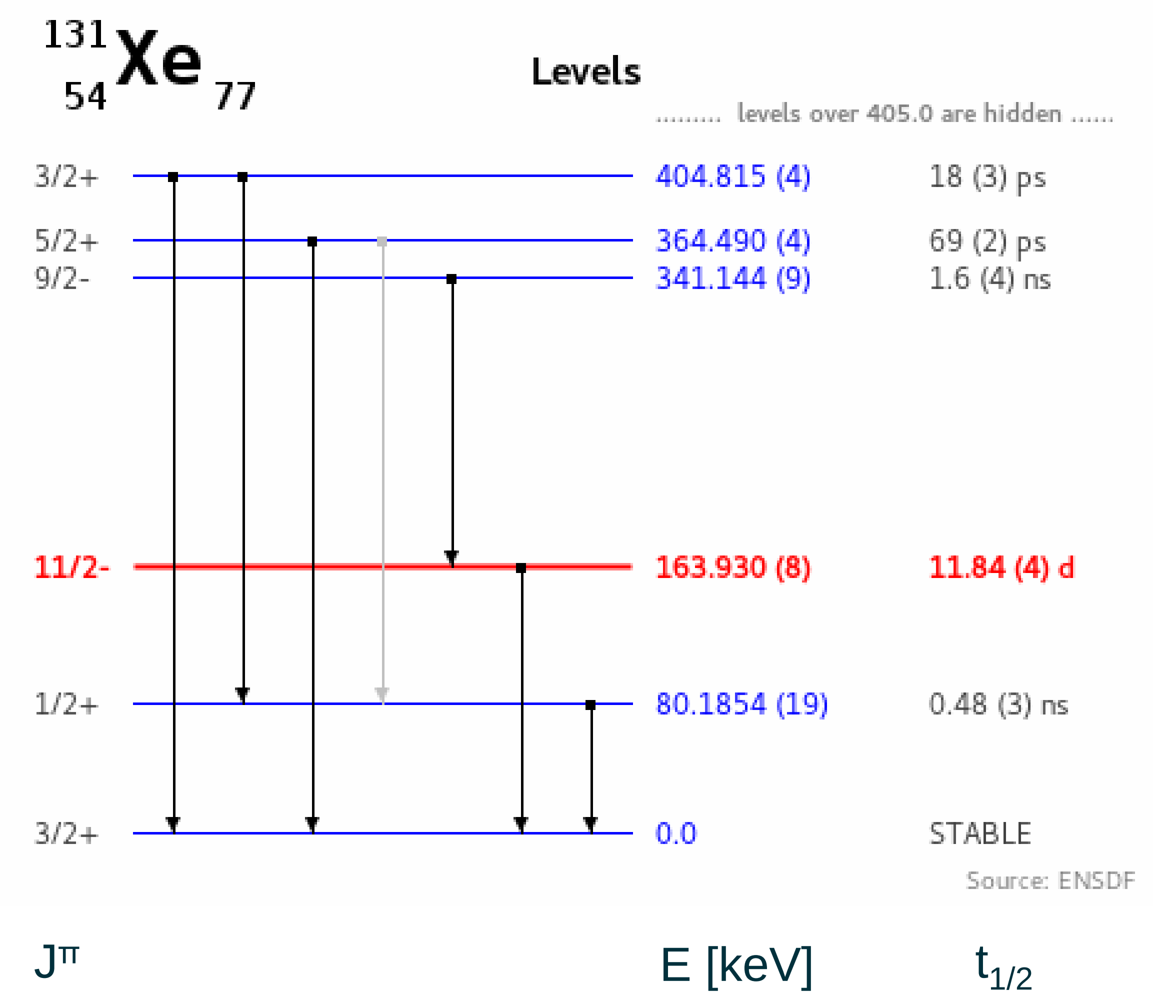
- Example models:
  - **Metastable isomer decay**
  - Charged-current capture (1905.12635, 2301.11893)
  - Neutron-like capture (2005.04240, 2306.11349)

Metastable isomer decay

Nuclear isomers

- Excited nuclei usually decay $t_{1/2}$ < O(ns)
  - γ-ray or internal conversion
- **Isomers:** metastable excited states
  - Suppressed by large ang. mom. transfer
  - Example: ^{131m}Xe

Some good reference articles:
Phys. Scr. 95 (2020) 044004
Rep. Prog. Phys. 79 (2016) 076301



Selected long-lived isomers

- **^{178m}Hf**
  - 2.46 MeV, $J^{\pi} = 16^{+}$, $t_{1/2}$ = 31 years
  - Aside: energy storage/weapons controversy
- **^{180m}Ta**
  - 77.2 keV, $J^{\pi} = 9^{-}$, decay never observed! 0.0120% natural abundance
  - Unstable to weak decays, ground state $t_{1/2}$ = 8.1 hours
  - Aside: important “astromer” (e.g., 2010.15238)

Isomers as dark matter targets

Metastable Nuclear Isomers as Dark Matter Accelerators

Maxim Pospelov,[1,2] Surjeet Rajendran,[3] and Harikrishnan Ramani[4,5,*]

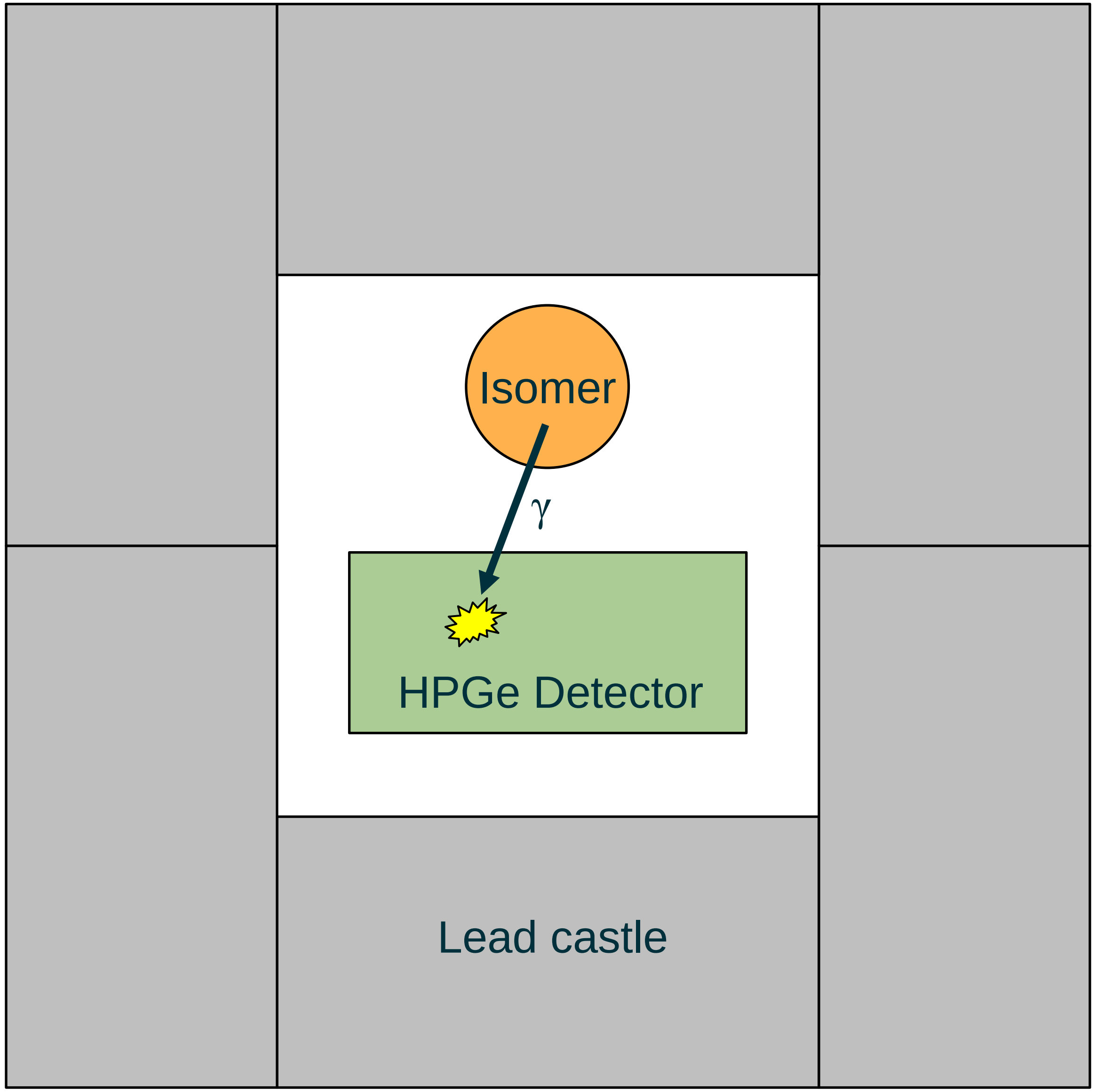
1907.00011

- Dark matter inelastically scatters with isomer inducing isomer decay
- Event signatures
  - **Look for anomalous γ-ray signals**
  - Look for re-scatter of DM particle
- What DM models?
  - Inelastic dark matter
  - Strongly interacting dark matter

$$\chi + N^* \to \chi + N$$

General experimental setup

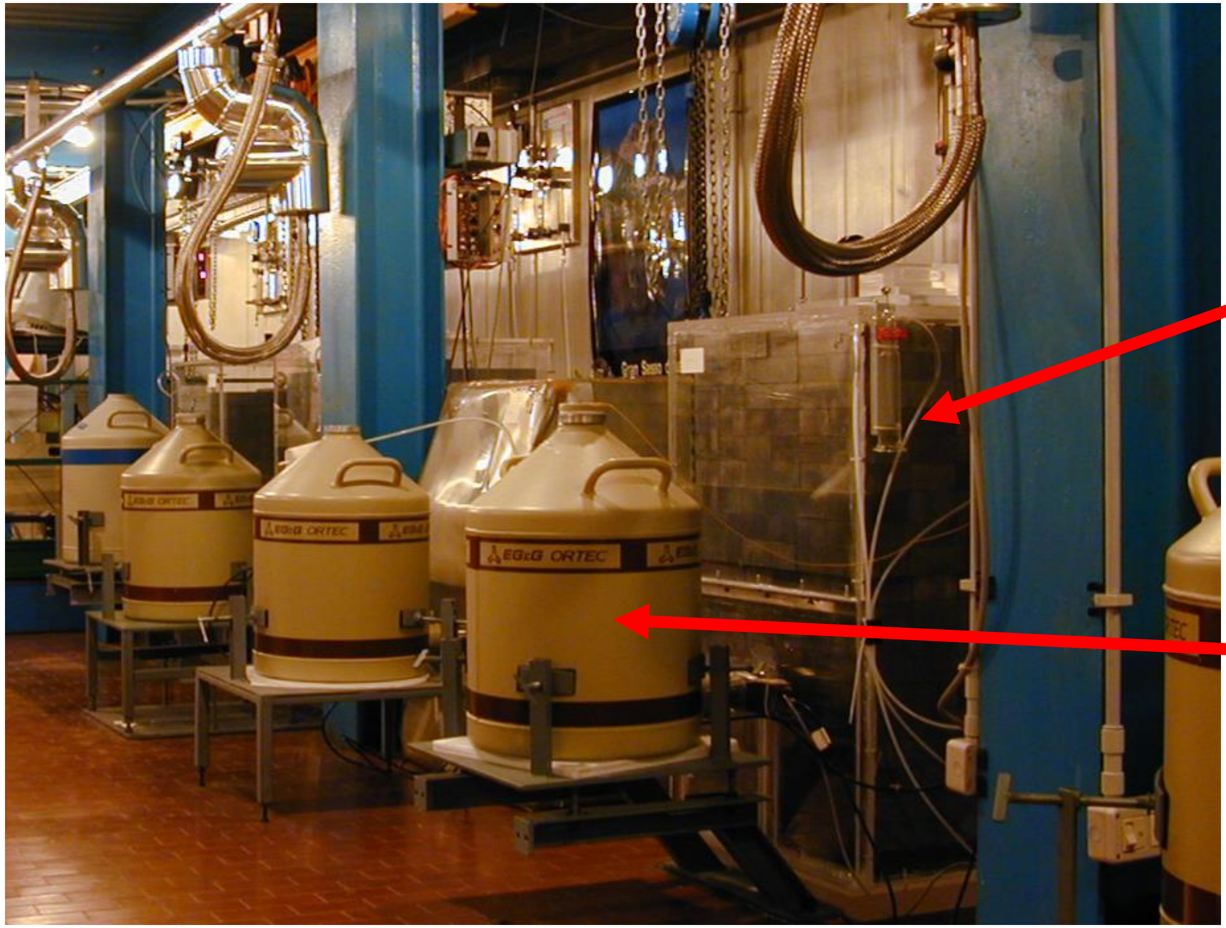
Ideally underground



Other shielding usually present

STELLA Lab at Gran Sasso (LNGS)

Day job: material screening lab for experiments at LNGS



Lead castle

LN dewars

Photo credit: STELLA

MAJORANA DEMONSTRATOR at SURF

^{180m}Ta

HPGe (unenriched)

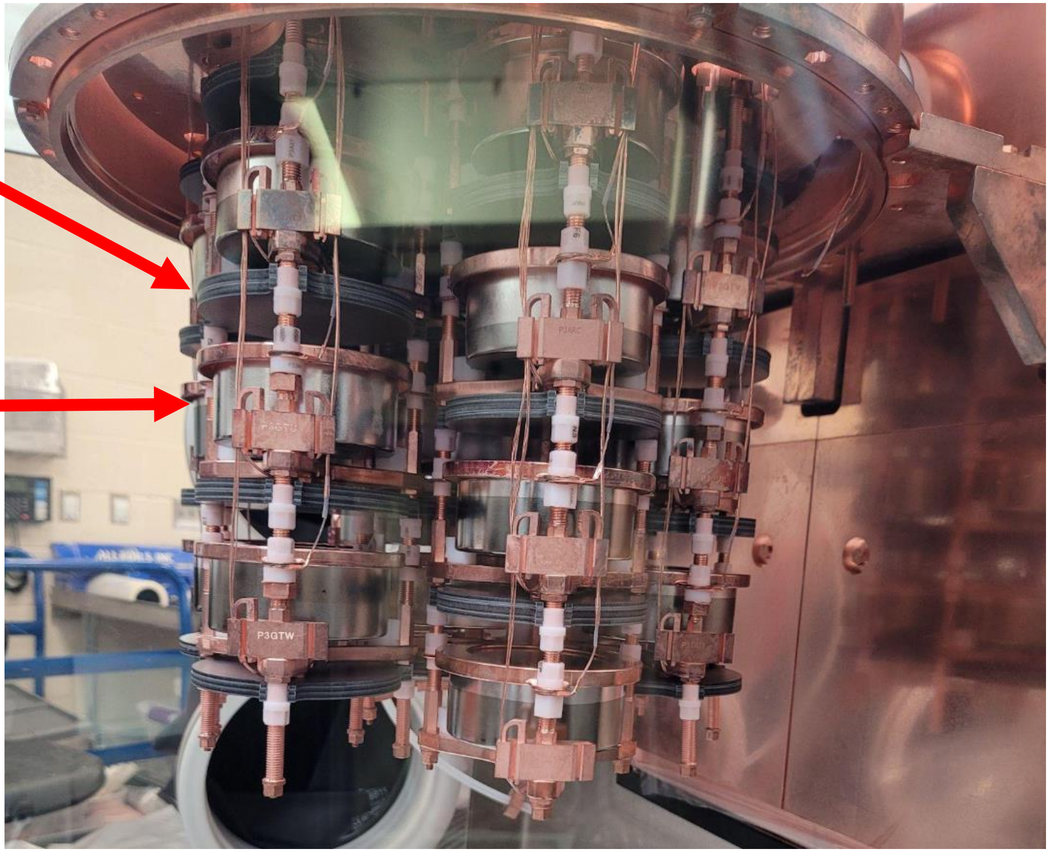
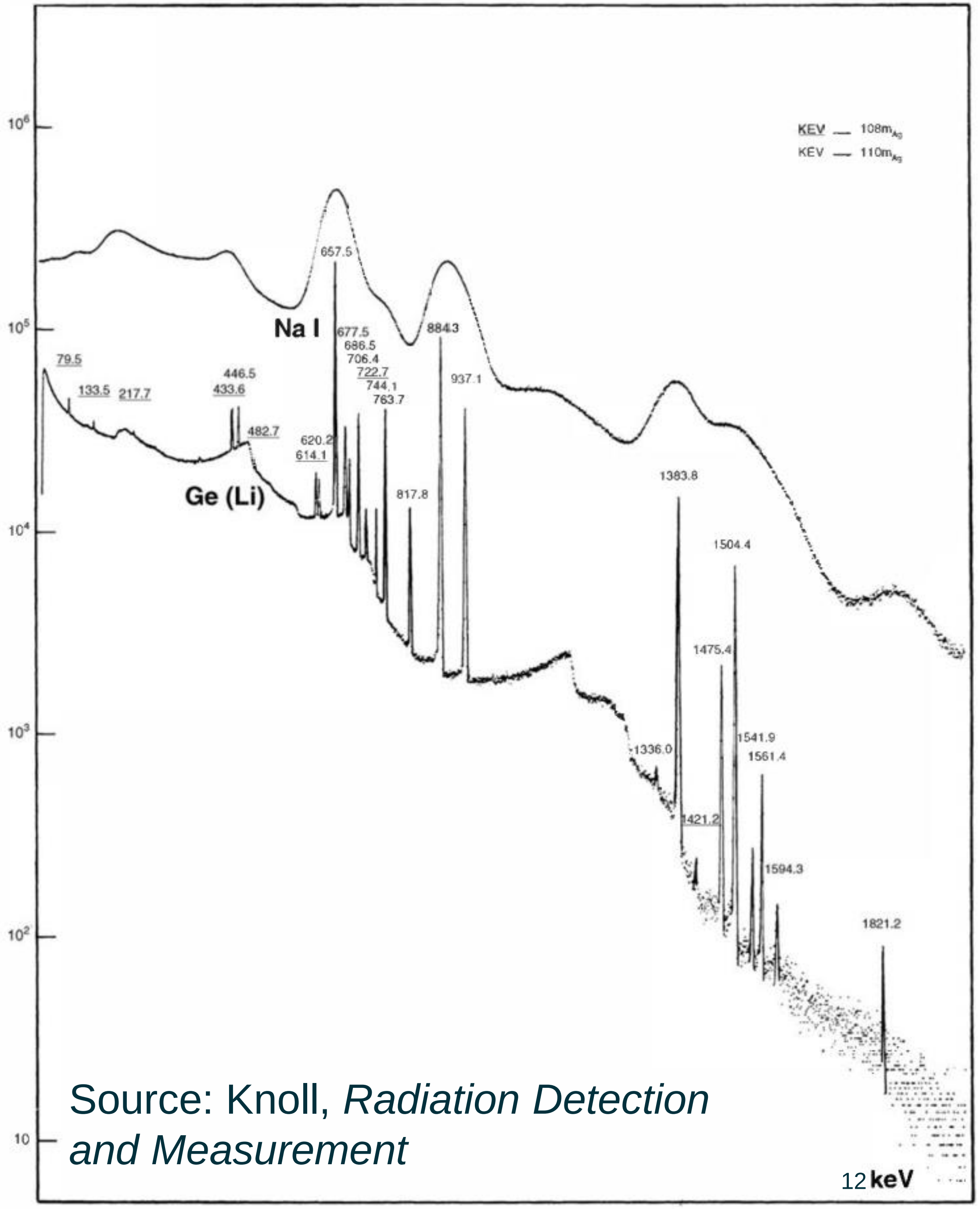


Photo credit: R. Massarczyk, [TAUP 2023 slides]

Main goal: $0\nu\beta\beta$ search, repurposed for isomer study

Germanium detector basics

- Ge is semiconductor similar to Si
- Semiconductor = fantastic energy resolution
  - W ~ 3 eV, f ~ 0.1
  - More directly measuring quanta (i.e., no PMTs)
- Suitable for γ-rays (compared to Si)
  - Large depletion (active) region
  - Higher atomic number
- Need to operate cold (in LN ~77 K)
  - Ge has smaller band gap than Si
- **HPGe** and Ge(Li) types



Source: Knoll, *Radiation Detection and Measurement*

^{178m}Hf signature

1. Start in metastable state

2. DM induced transition (normally suppressed)

3. Emit anomalous γ-rays

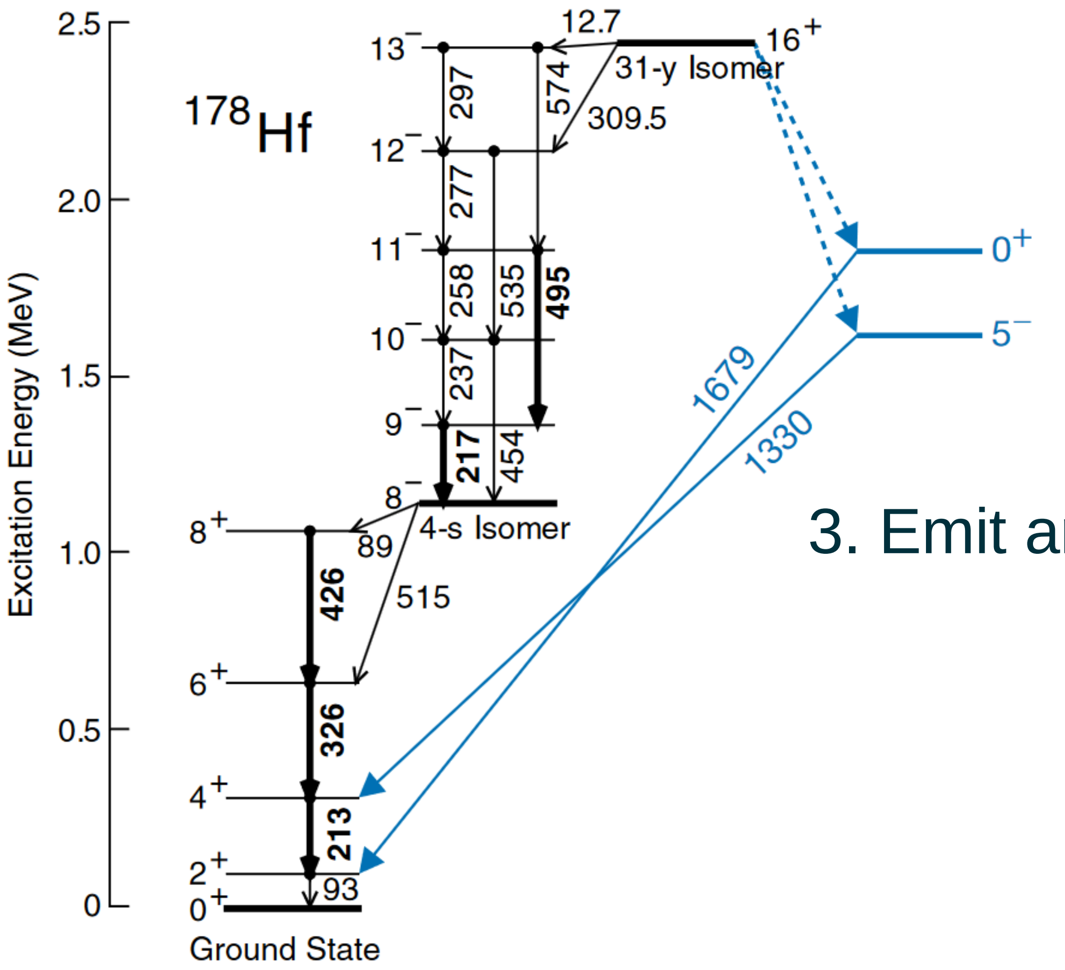


Figure from 2306.04442

^{178m}Hf spectra

Region where most search windows are

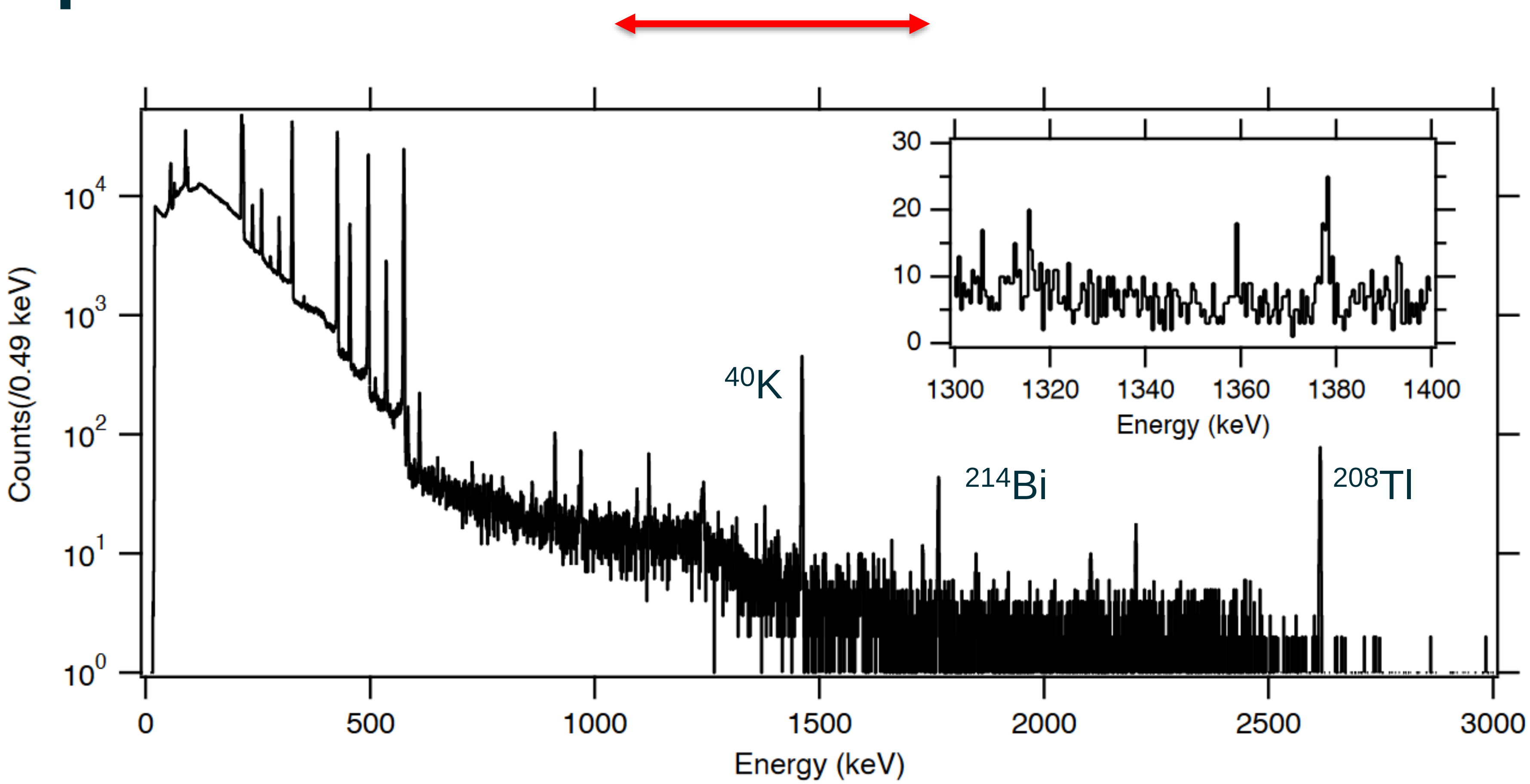


FIG. 2. The observed spectrum from the ^{178m}Hf sample for a live time of 974.2 s. The inset shows the spectrum surrounding 1330 keV. A dark matter-induced γ with this energy proved to be the most sensitive test.

Figure from 2306.04442

^{180m}Ta signature

Similar idea to ^{178m}Hf

Measure/set limit on *total* decay rate
Compare to SM predictions

Potential for theory ambiguity,
no “smoking gun” signal

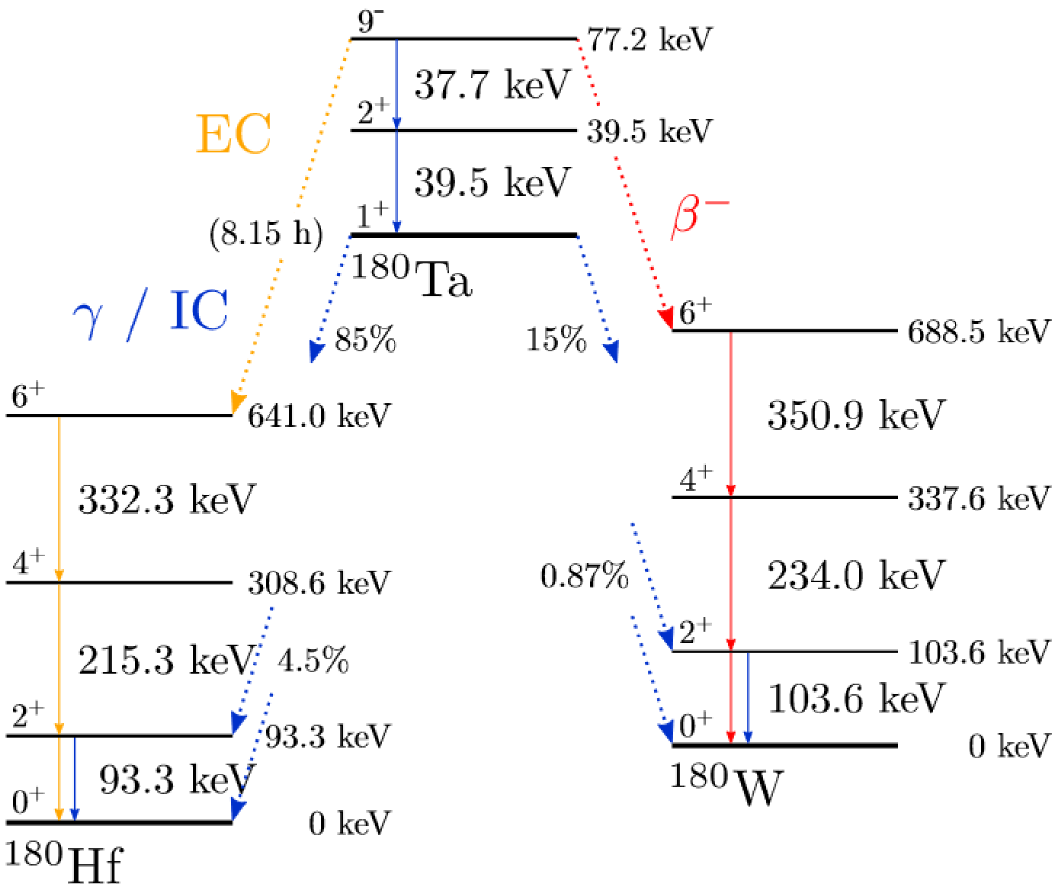


Figure from 2305.17238
(not shown: α decay branch)

Summary of current measurements

No observation of DM or ^{180m}Ta decay, only limits

- ^{178m}Hf
  - Only one measurement: **2023 Los Alamos** (2306.04442)
  - Related search looking for excitations from ground state (2012.08339)
  - IMO unlikely there will be any more sensitive measurements
- ^{180m}Ta
  - 2019 Berkeley-led analysis of existing data as Gran Sasso (1911.07865)
  - 2023 measurement at Gran Sasso (2305.17238)
  - Best limit, 2023 measurement from **MAJORANA** (2306.01965)

	EC	β^-	γ	IC
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}**
Theory	10^{23}	10^{20}	10^{31}	10^{18}

Overview on results, all numbers in years,

Figure: R. Massarczyk, TAUP 2023 slides

Future of ^{180m}Ta measurements

MAJORANA is continuing to take data, potential for sensitivity with SM prediction

MAJORANA limit

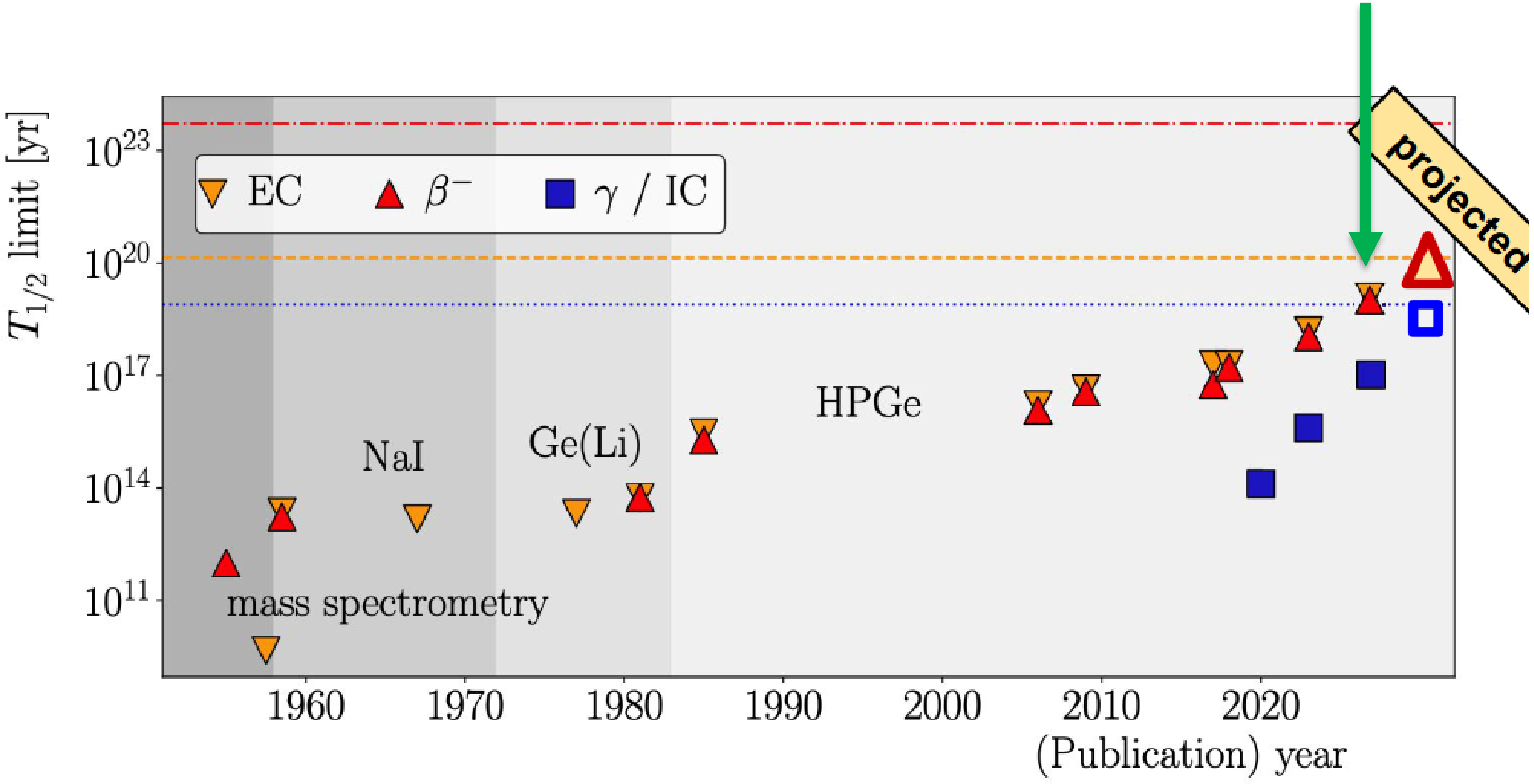


Figure taken and updated from 2305.17238

Figure: R. Massarczyk, [TAUP 2023 slides]

Original theory: hep-ph/0101138

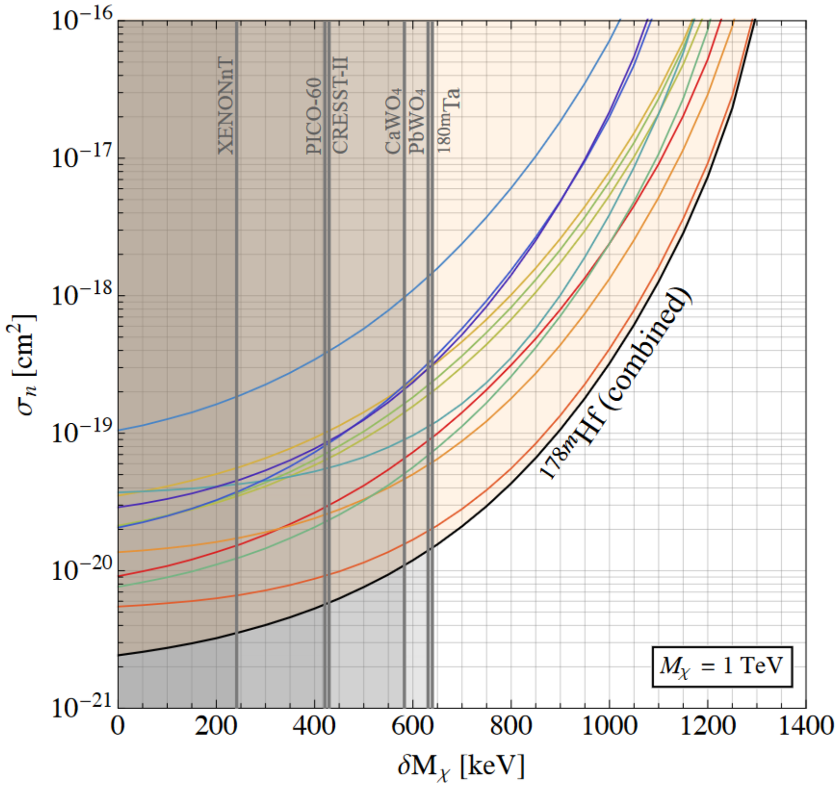
Inelastic dark matter

- Two dark matter states, χ_1 , χ_2 with small mass gap O(100 keV)
  - Analogous to proton/neutron gap
- Hypothesis: elastic scattering suppressed, inelastic possible
- Originally conceived to reconcile DAMA and CDMS…

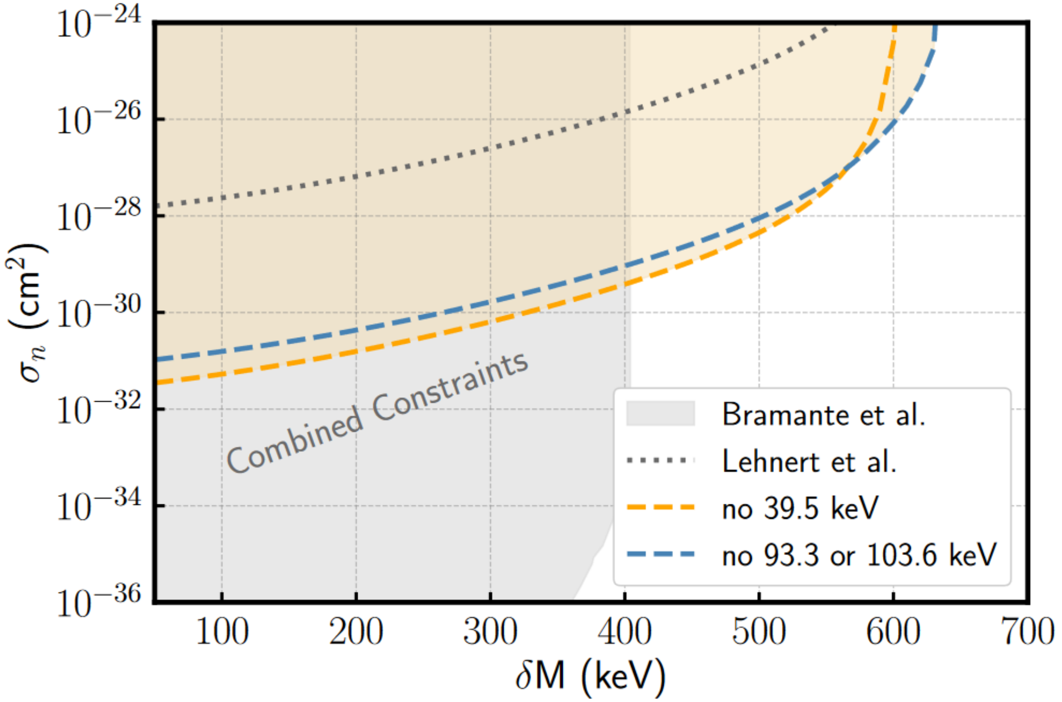
- In detector scatter, go from $\chi_1 \rightarrow \chi_2$
- Mass-splitting sensitivity in traditional detector (LZ) limited by center-of-mass kinetic energy
- Isomers give better sensitivity to higher mass-splitting

Inelastic dark matter

For M_χ = 1 TeV



Limits with ^{178m}Hf
2306.04442



MAJORANA limits with ^{180m}Ta
2306.01965

Summary

- Low-background detectors can explore numerous DM models
- Metastable isomers target models traditional WIMP detectors cannot
- Current limits with ^{178m}Hf, ^{180m}Ta, measurements of latter ongoing