Physics Beyond 0νββ with Germanium Detectors

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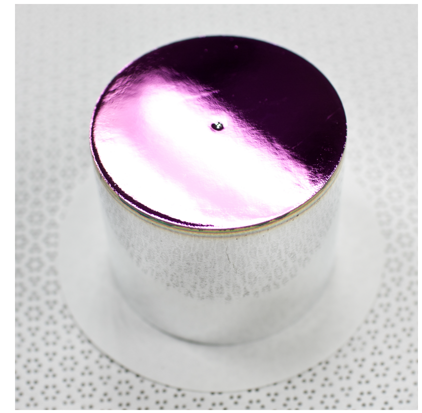
Physics Reach of a Large-Scale Ge Detector Array

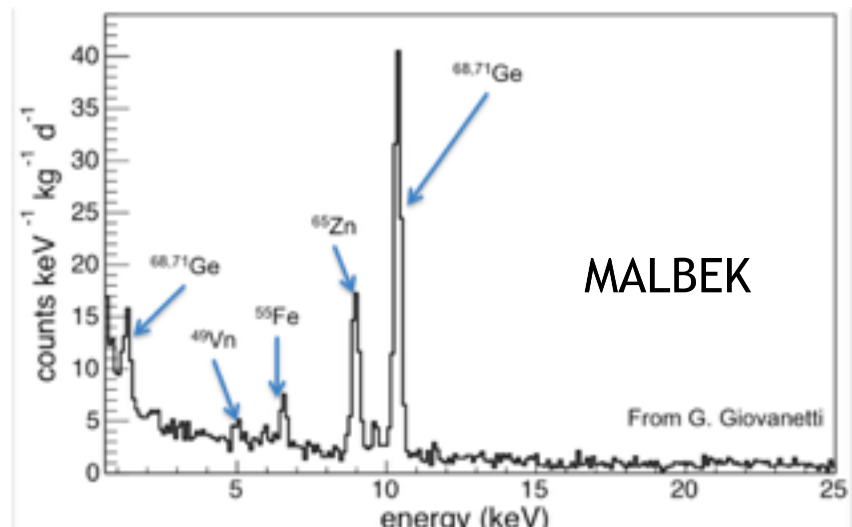
- Low Mass Dark Matter direct detection*
- Bosonic Superweak Dark Matter*
- Solar Axions*
- Pauli Exclusion Principle Violation*
- Finite Electron Lifetime*
- Lorentz Violation
- Coherent Elastic Neutrino Nuclear Scattering (CEvNS)*

*Enabled by low backgrounds below 500keV

PPCs at Low Energy

- Small capacitance: ~1pF
  - Low noise
  - Sub-keV thresholds
  - Excellent energy resolution near threshold.
- Low intrinsic backgrounds
  - Improved by enrichment, controlled surface exposure.

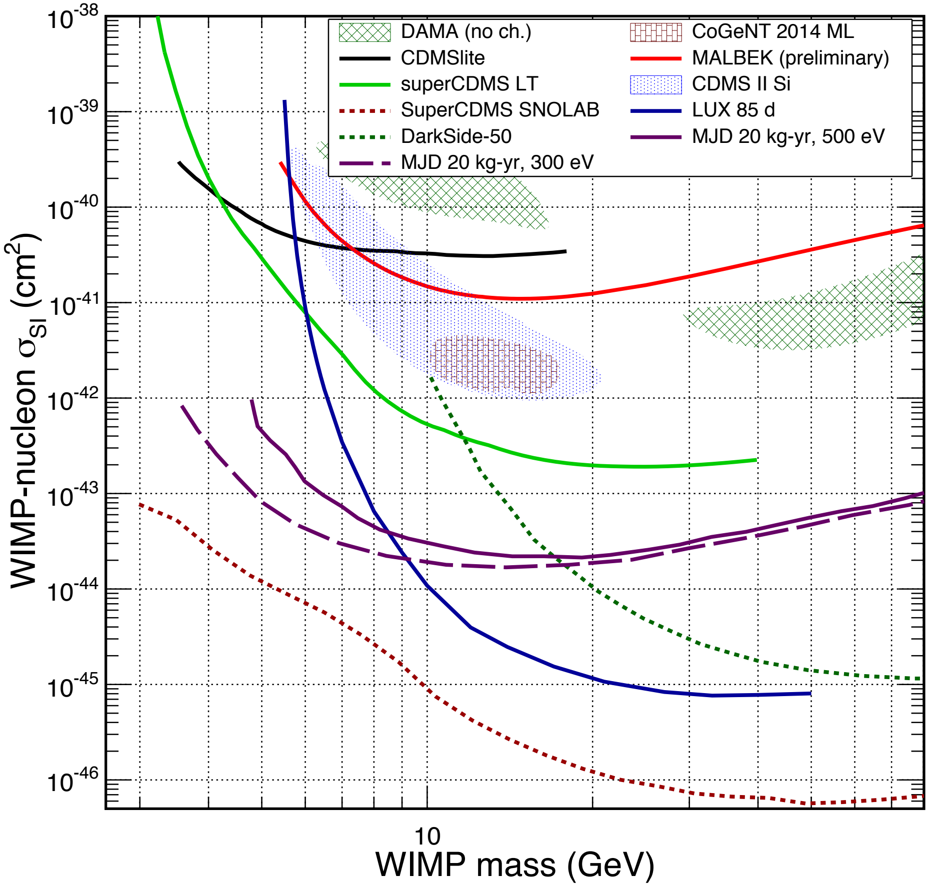




P. S. Barbeau, J. I. Collar, and O. Tench, J. Cosm. Astro. Phys. 0709 (2007)
P. Luke et al., IEEE trans. Nucl. Sci. 36 , 926(1989)

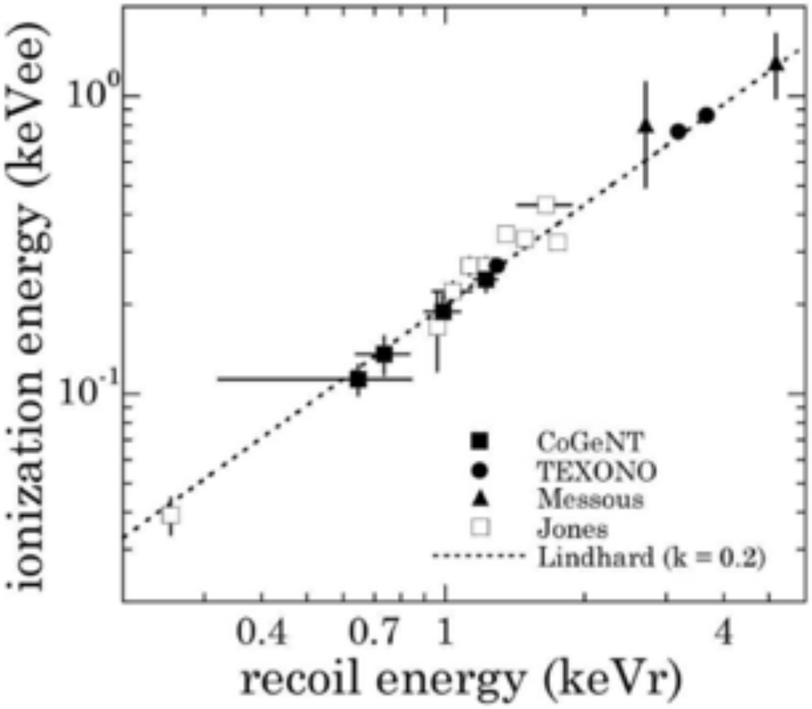
Low-Mass Dark Matter

- Low-mass WIMP scatters yield low-energy nuclear recoils.
- Sensitivity requires sub-keV ionization energy thresholds.
- Germanium nuclear recoil quenching factors well-understood near threshold.



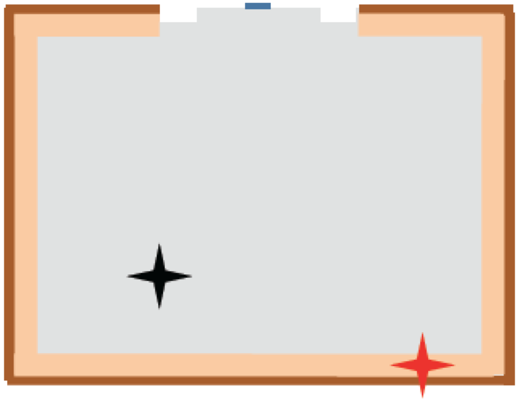
PPC Quenching Factors

- Well-understood nuclear recoil quenching factors



C.E. Aalseth et. al. arXiv:1208.5737

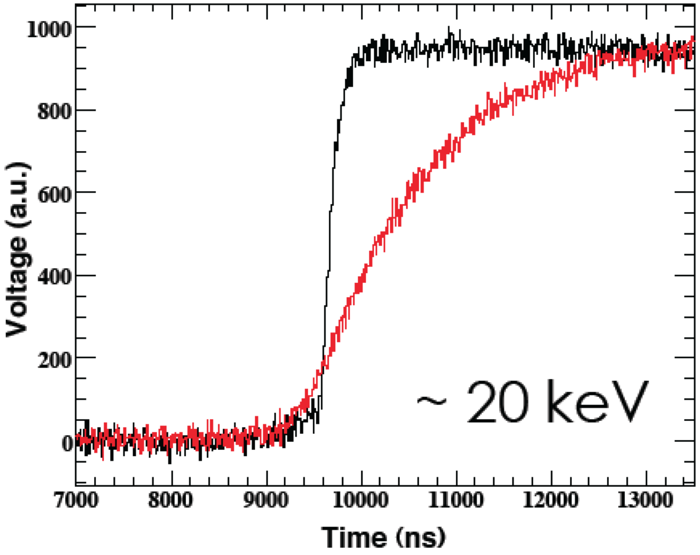
Low Energy Background Considerations: Slow Surface Events



active volume

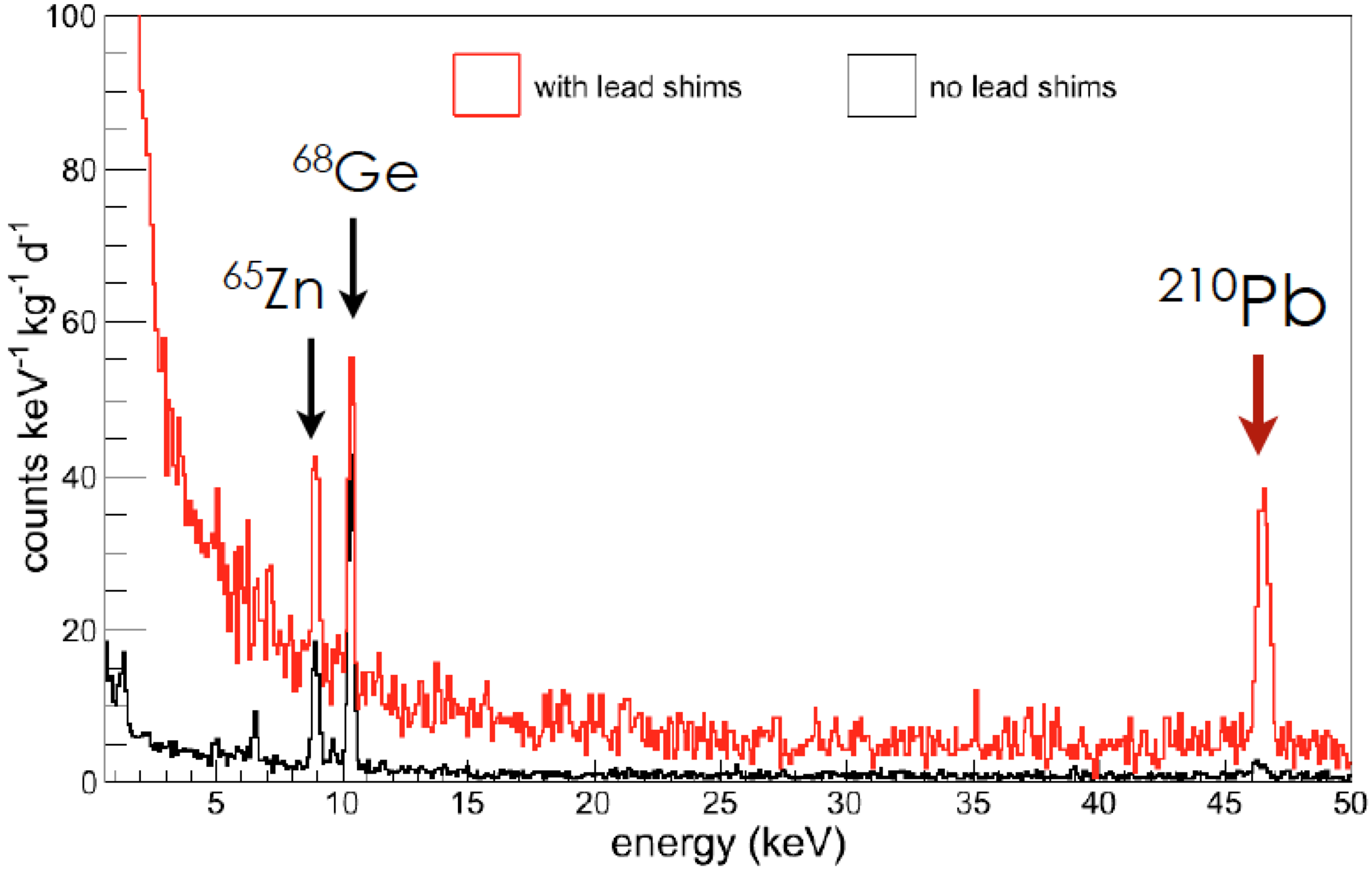
n+ dead layer

transition region – partial charge collection

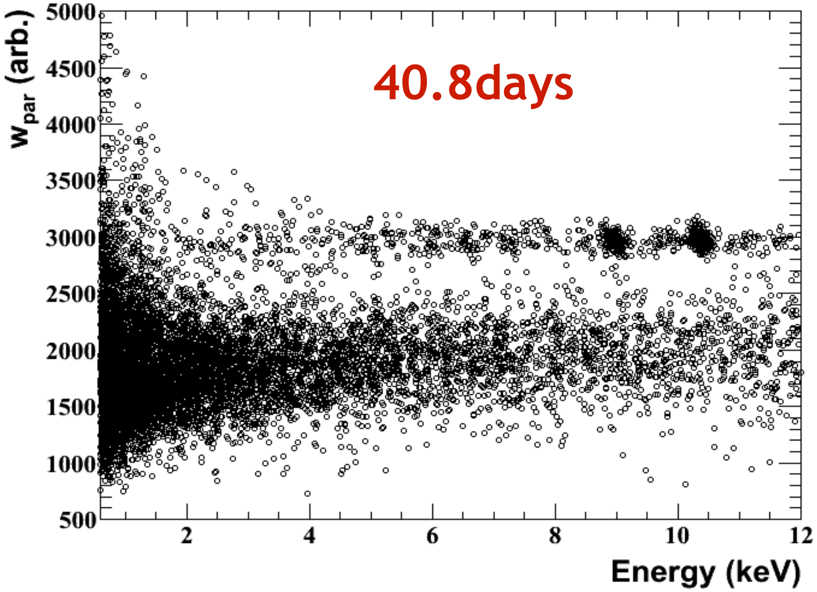


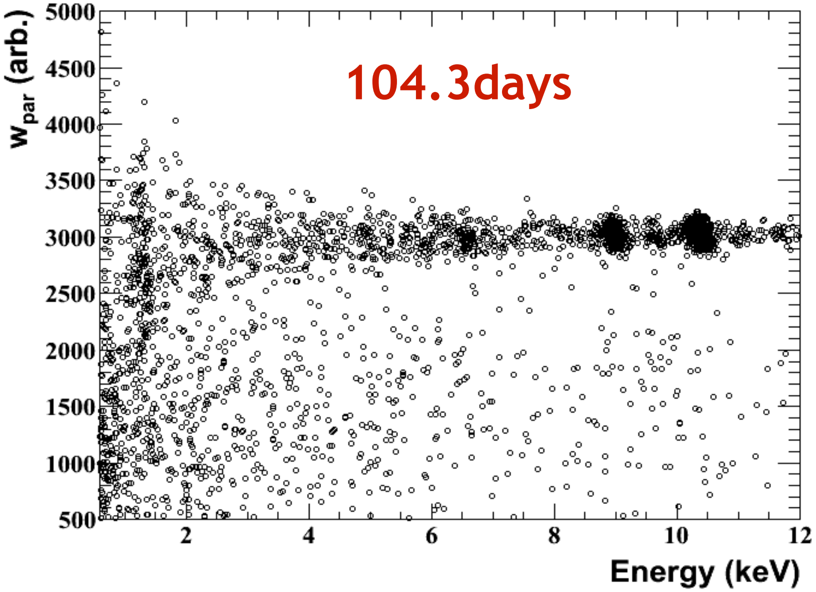
From G. Giovanetti

Pb shims in MALBEK - Degraded Energy Events

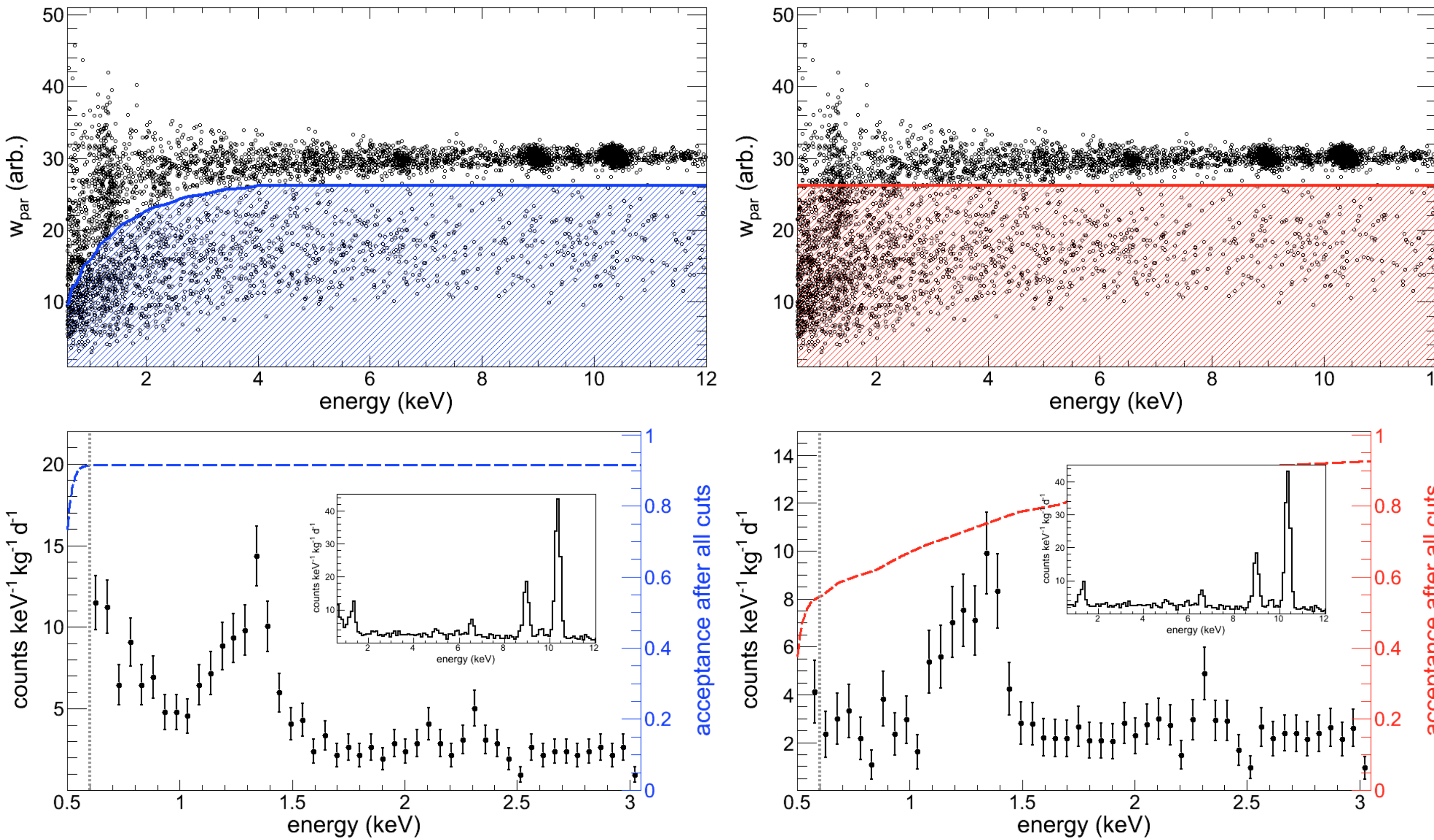


Low Energy Background Considerations: Different Sources & Systematics



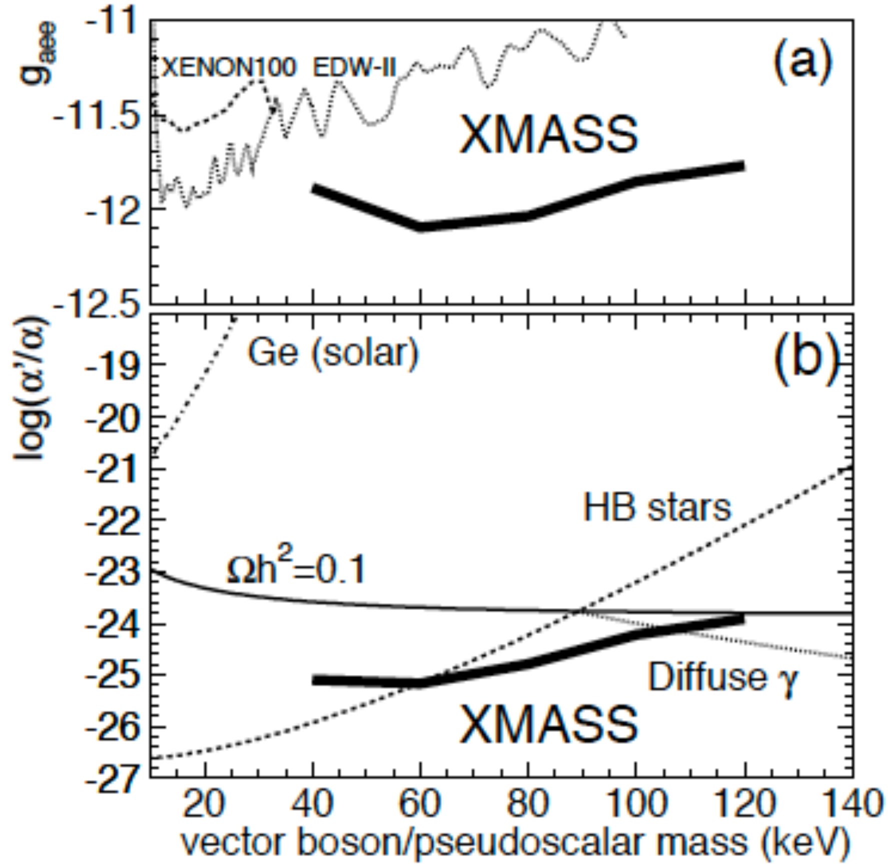


Low Energy Background Considerations: Different Sources & Systematics



Bosonic Superweak Dark Matter

- An alternate analysis channel for exotic Dark Matter.
- Presents as anomalous peak below 200keV.
- Peak corresponds to DM particle mass.
- Cross section related to photoelectric cross section; advantageous for Xe.
- Better energy resolution leads to lower backgrounds for Ge.



Solar Axions

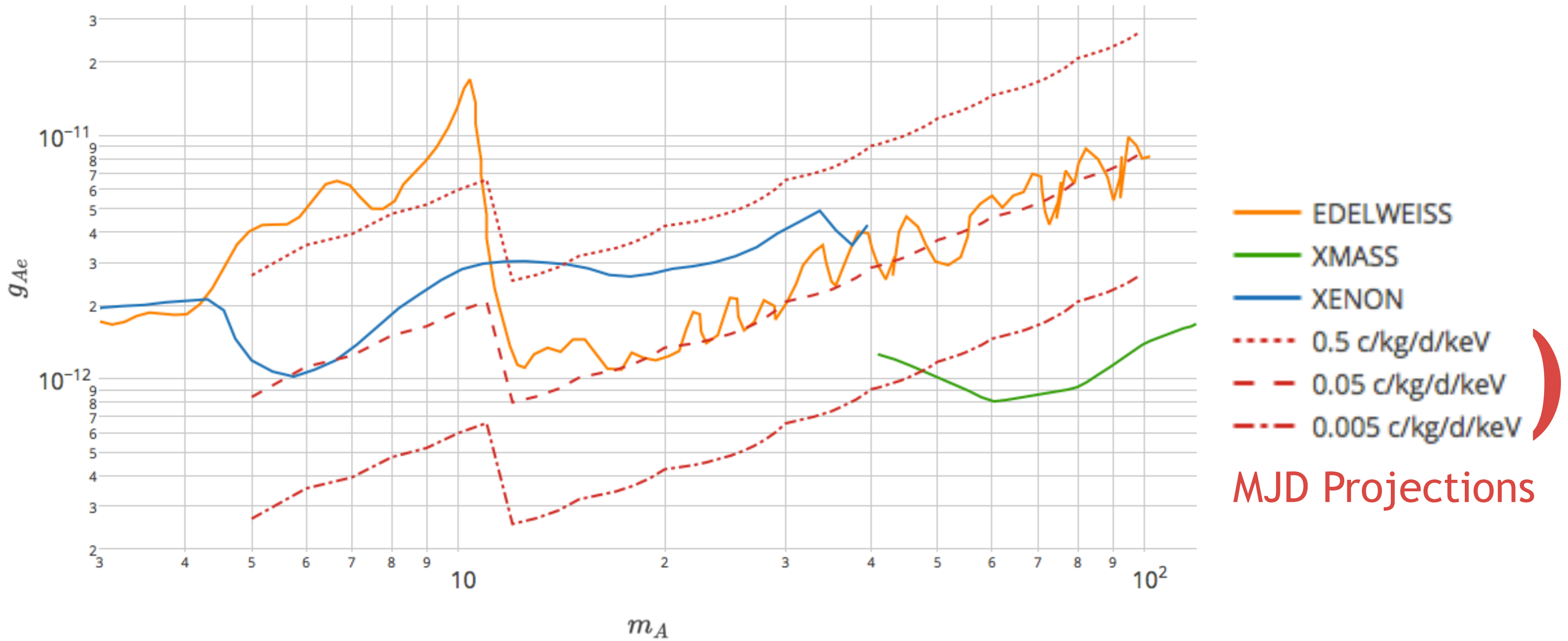
- Production through a number of potential processes
- Ge detectors allow detection via:
  - Axio-Electric Effect
  - Bragg-Coherent Primakoff Conversion
  - M1 nuclear transition in ^{57}Fe, ^{169}Tm

$g_{a\gamma}$ {
Primakoff Production: in presence of charged particles
g → a

g_{aN} {
Nuclear magnetic transition of ^{57}Fe
$^{57}Fe^* \rightarrow {}^{57}Fe + a$

g_{ae} {
Compton-like Scattering
$e + \gamma \rightarrow e + a$
Axion Bremsstrahlung: in presence of charged particles
$e \rightarrow e + a$
Axio-Recombination: where I is an ion
$e + I \rightarrow I^- + a$
Axio-Deexcitation:
$I^* \rightarrow I + a$

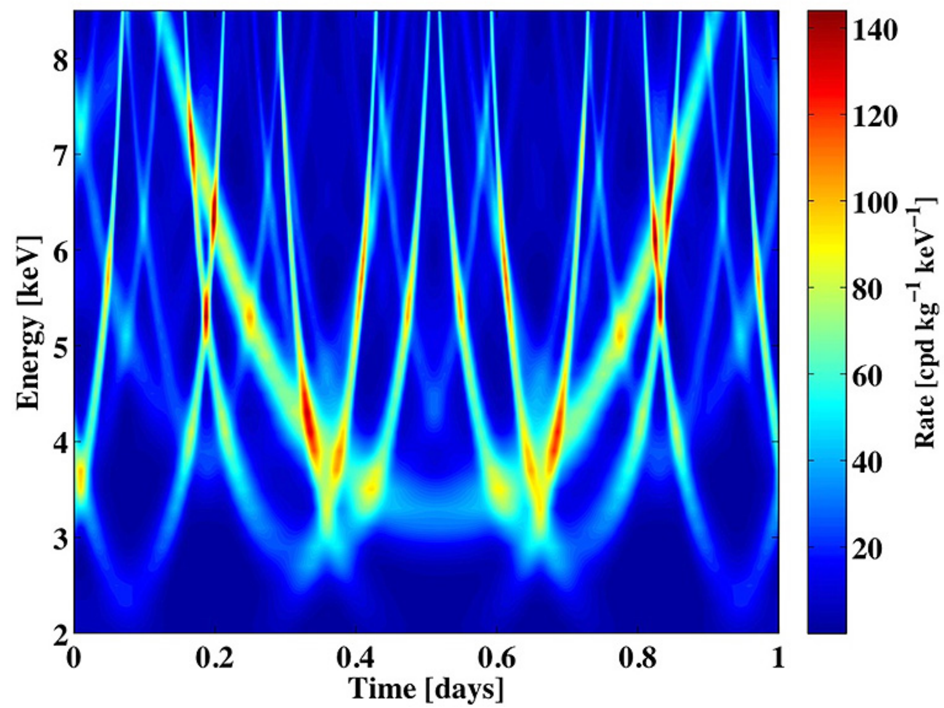
Axion (and ALP) Axio-Electric Effect



Search for monoenergetic peak between 2-30keV.

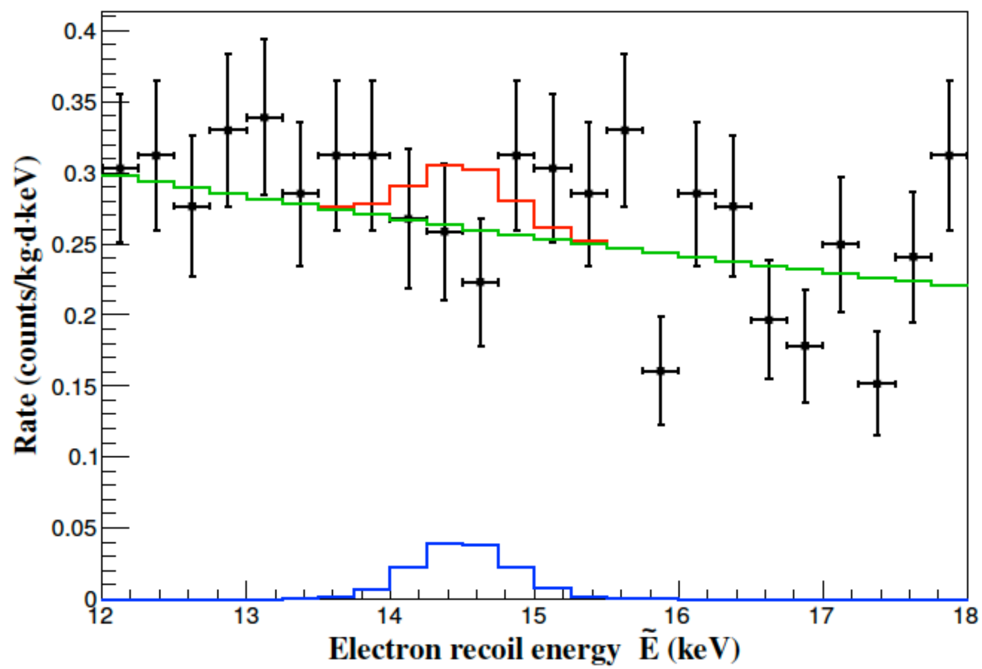
Bragg-Coherent Primakoff Conversion

- Aided by knowledge of crystal axis orientation w.r.t. sun of ~1°.
- CDMS limit:
  - $g_{a\gamma} < 2.4*10^{-9}$/GeV
  - PRL 103, 141802 (2009)
- Edelweiss limit:
  - $g_{a\gamma} < 2.15*10^{-9}$/GeV
  - JCAP 11 (2013) 067



Axions - M1 Transition in ^{57}Fe

- M1 nuclear transition in solar-abundant ^{57}Fe, ^{169}Tm.
- Observe an 14.4keV x-ray peak
- Current best limit: Edelweiss



Pauli Exclusion Principle

- Possible electron wave-functions have a small symmetric component.
- A Pauli-Exclusion Principle violating transition yields an over-crowded state.
- In Ge: Look for a transition to the K-shell with shifted energy (3 electrons)
  - Found Phys (2012) 42:1015
- Also 2vββ spectral distortion (Phys.Lett. B621 (2005) 1-10)

Process	Type	Experimental limit	$\frac{1}{2}\beta^2$ limit	Reference
Atomic transitions				
$\beta^- + \mathrm{Pb} \to \breve{\mathrm{P}}\mathrm{b}$	Ia		3×10^{-2}	[23]
$e^-_{pp} + \mathrm{Ge} \to \breve{\mathrm{G}}\mathrm{e}$	Ia		1.4×10^{-3}	This work
$e^-_I + \mathrm{Cu} \to \breve{\mathrm{C}}\mathrm{u}$	II		1.7×10^{-26}	[48]
$e^-_I + \mathrm{Cu} \to \breve{\mathrm{C}}\mathrm{u}$	II		4.5×10^{-28}	[8]
$e^-_I + \mathrm{Cu} \to \breve{\mathrm{C}}\mathrm{u}$	II		6.0×10^{-29}	[9]
$e^-_I + \mathrm{Pb} \to \breve{\mathrm{P}}\mathrm{b}$	II		1.5×10^{-27}	This work
$e^-_f + \mathrm{Pb} \to \breve{\mathrm{P}}\mathrm{b}$	IIa		2.6×10^{-39}	This work
$\mathrm{I} \to \breve{\mathrm{I}} + \text{X-ray}$	III	$\tau > 2 \times 10^{27}$ sec	3×10^{-44}	[49]
$\mathrm{I} \to \breve{\mathrm{I}} + \text{X-ray}$	III	$\tau > 4.7 \times 10^{30}$ sec	6.5×10^{-46}	[13]
Nuclear transitions				
${}^{12}\mathrm{C} \to {}^{12}\tilde{\mathrm{C}} + \gamma$	III	$\tau > 6 \times 10^{27}$ y	1.7×10^{-44}	[38]
${}^{12}\mathrm{C} \to {}^{12}\tilde{\mathrm{C}} + \gamma$	III	$\tau > 4.2 \times 10^{24}$ y		[3]
${}^{12}\mathrm{C} \to {}^{12}\tilde{\mathrm{C}} + \gamma$	III	$\tau > 5.0 \times 10^{31}$ y	2.2×10^{-57}	[11]
${}^{16}\mathrm{O} \to {}^{16}\tilde{\mathrm{O}} + \gamma$	III	$\tau > 4.6 \times 10^{26}$ y	2.3×10^{-57}	[51]
${}^{12}\mathrm{C} \to {}^{12}\tilde{\mathrm{N}} + \beta^- + \bar{\nu}_e$	IIIa	$\tau > 3.1 \times 10^{24}$ y		[3]
${}^{12}\mathrm{C} \to {}^{12}\tilde{\mathrm{N}} + \beta^- + \bar{\nu}_e$	IIIa	$\tau > 3.1 \times 10^{30}$ y		[11]
${}^{12}\mathrm{C} \to {}^{12}\tilde{\mathrm{N}} + \beta^- + \bar{\nu}_e$	IIIa	$\tau > 0.97 \times 10^{27}$ sec	6.5×10^{-34}	[35]
${}^{12}\mathrm{C} \to {}^{12}\tilde{\mathrm{B}} + \beta^+ + \nu_e$	IIIa	$\tau > 2.6 \times 10^{24}$ y		[3]
${}^{12}\mathrm{C} \to {}^{12}\tilde{\mathrm{B}} + \beta^+ + \nu_e$	IIIa	$\tau > 2.1 \times 10^{30}$ y	2.1×10^{-35}	[11]
${}^{12}\mathrm{C} \to {}^{11}\tilde{\mathrm{B}} + p$	III	$\tau > 8.9 \times 10^{29}$ y	7.4×10^{-60}	[11]
${}^{23}\mathrm{Na} \to {}^{22}\tilde{\mathrm{N}}\mathrm{e} + p$	III	$\tau > 7 \times 10^{24}$ y	10^{-54}	[12]
${}^{127}\mathrm{I} \to {}^{126}\tilde{\mathrm{T}}\mathrm{e} + p$	III	$\tau > 9 \times 10^{24}$ y	10^{-54}	[12]
${}^{23}\mathrm{Na} \to {}^{22}\tilde{\mathrm{N}}\mathrm{e} + p$	III	$\tau > 5 \times 10^{26}$ y	2×10^{-55}	[13]
${}^{127}\mathrm{I} \to {}^{126}\tilde{\mathrm{T}}\mathrm{e} + p$	III	$\tau > 5 \times 10^{26}$ y	2×10^{-55}	[13]
Neutron emission from Pb	III	$\tau > 1.0 \times 10^{20}$ y		[37]
${}^{12}\mathrm{C} \to {}^{11}\tilde{\mathrm{C}} + n$	III	$\tau > 3.4 \times 10^{30}$ y		[11]
${}^{16}\mathrm{O} \to {}^{15}\tilde{\mathrm{O}} + n$	III	$\tau > 1.0 \times 10^{20}$ y		[37]
${}^{16}\mathrm{O} \to {}^{15}\tilde{\mathrm{O}} + n$	III	$\tau > 3.7 \times 10^{26}$ y		[4]
${}^{12}\mathrm{C} \to {}^{8}\tilde{\mathrm{B}}\mathrm{e} + \alpha$	III	$\tau > 6.1 \times 10^{23}$ y		[4]
$\mathrm{Na/I} \to \tilde{\mathrm{N}}\mathrm{a}/\tilde{\mathrm{I}} \to X$	III	$\tau > 1.7 \times 10^{25}$ y	1.5×10^{-53}	[21]

Electron Lifetime

- Disappearance:
  - Look for anomalous rate of K x-rays
  - Present limit: $4.3*10^{23}$yrs (Ge detector)
  - ^{68}Ge limits sensitivity.
- e ➜ νγ
  - Look for 255.5keV γ-ray
  - Present limit: $6.6*10^{28}$yrs (Borexino)
  - Phys. Rev. Lett. 115, 231802 (2015)
- Germanium has ~2.5e29 electrons/ton
  - For a BG rate of 3cnts/(keV-ton-yr) at 250keV:
  - Resolution ~2keV, Eff ~100%
  - 1yr gives sensitivity of 10^{29}- 10^{30}yrs

Lorentz Violation

- 0vββ: Modifies neutrino dispersion relation and propagator.
  - Enhances the effective majorana mass, even if that mass is negligible.

$$m_\nu^2 = m_\nu^2 + m_\nu g/R + (g/R)^2$$

  - Effect can be disentangled by comparing 0vββ measured in nuclei of varying radius.
- 2vββ: Appears as spectral shape distortion.
  - Maximal at 810keV for Ge, varies between nuclei.

$$\frac{d\Gamma}{dK} = C(K^4 + 10K^3 + 40K^2 + 60K + 30)\,K \times \left[(K_0 - K)^5 + 10\mathring{a}^{(3)}_{of}(K_0 - K)^4\right],$$

PRD 88, 071902 (2013)
PRD 89, 036002 (2014)

Coherent Elastic Neutrino Nucleus Scattering

- Coherent Elastic Neutrino Nuclear Scattering (CEvNS).
- Ultimate irreducible background to future Dark Matter searches.
- Expect ~100 events/(ton-yr) from ^{8}B solar neutrinos from 0.5keV - 2keV
- Expect a few events/(ton-yr) from atm vs and diffuse SN vs

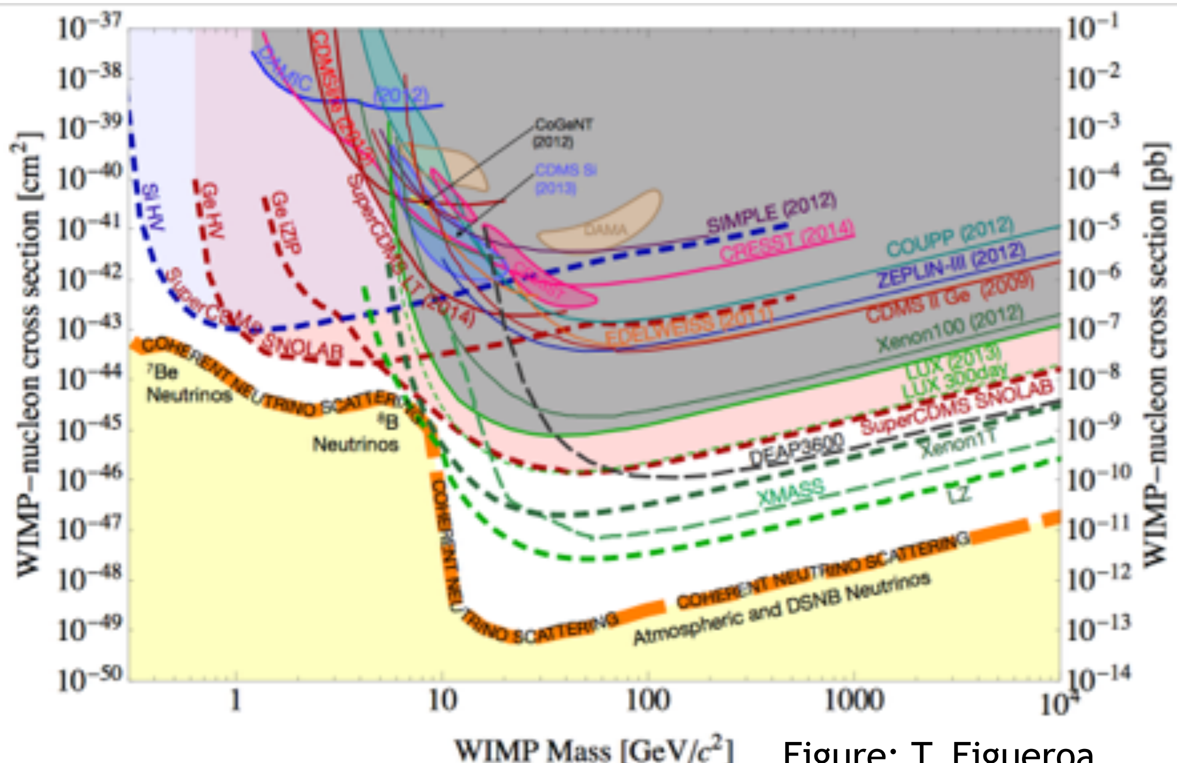


Figure: T. Figueroa

Conclusions

- A large-scale Ge-based 0νββ-decay experiment offers many avenues for the pursuit of new physics.
- A rich physics program will go a long way towards justifying the cost of a next-generation experiment.
- Many of these searches rely upon the low-energy performance of PPC detectors; low-energy backgrounds key to extending physics reach.