Potential Isotope Needs of Double Beta Decay and Dark Matter Experiments

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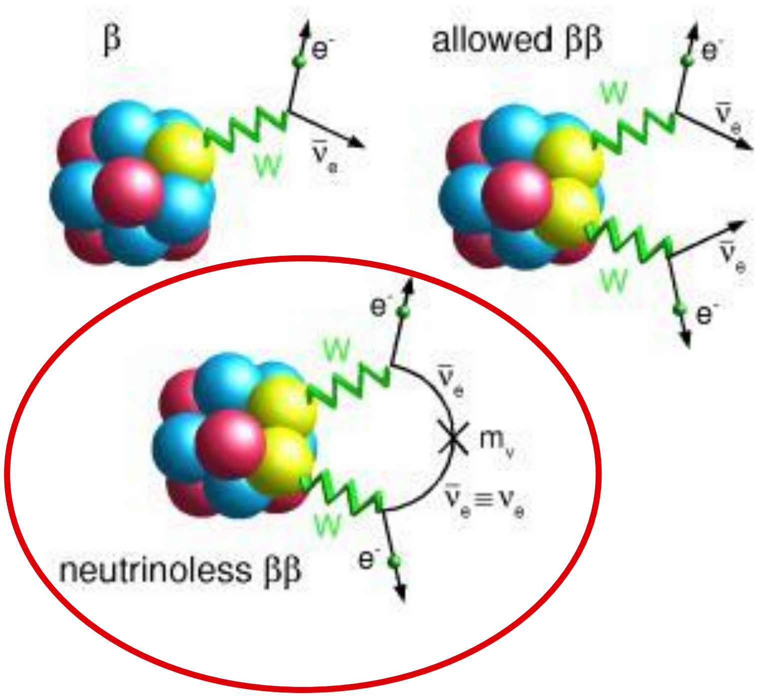
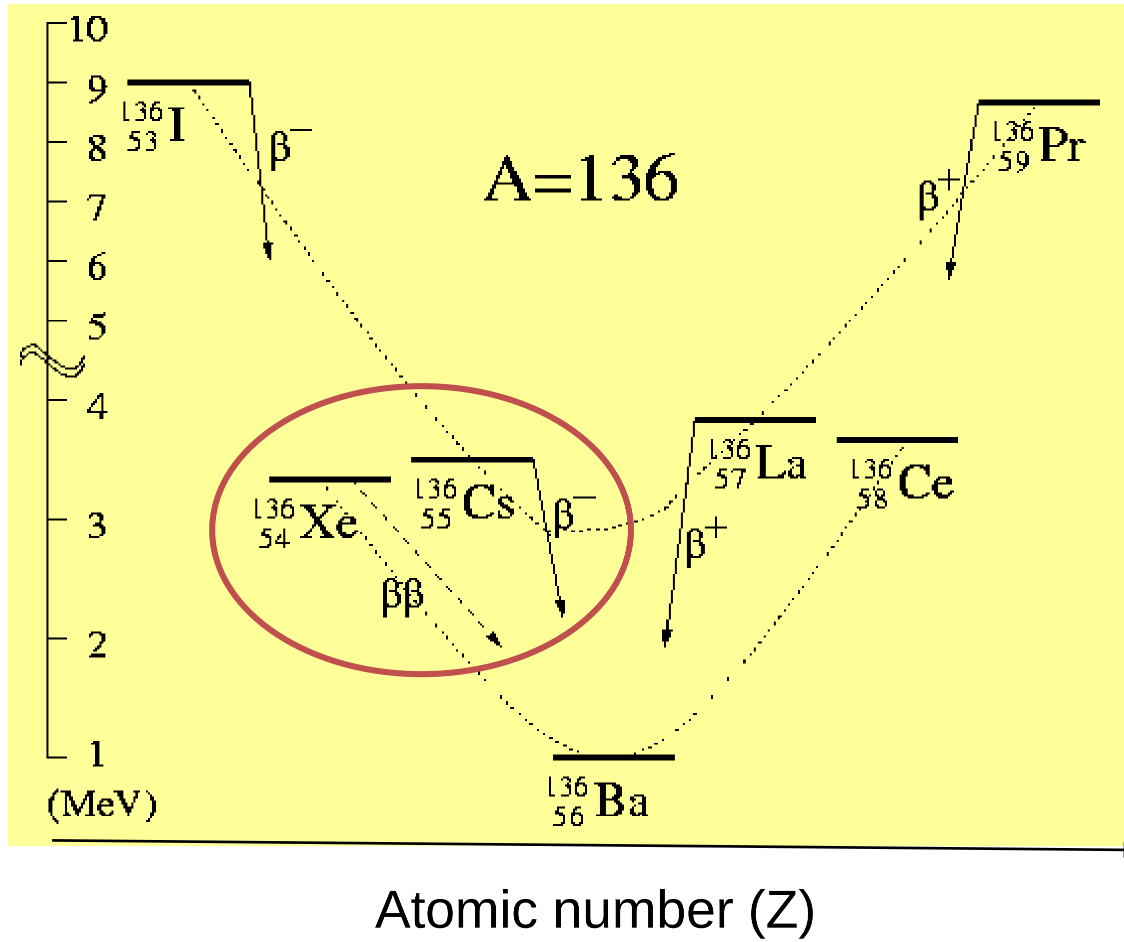
- Issues for NLDBD Experiments
- Issues for Dark Matter Experiments
- Isotope Needs

Double Beta decay

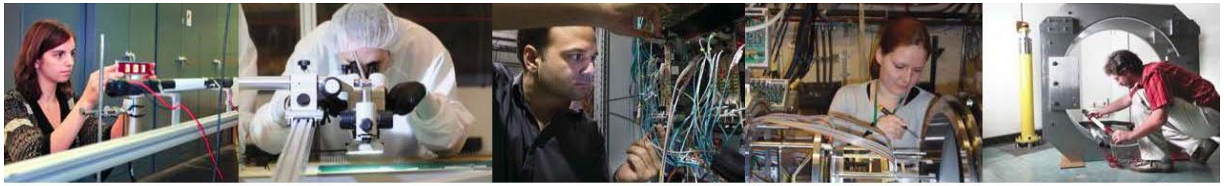
M.Goeppert-Mayer, Phys. Rev. 48 (1935) 512



Can only occur for a Majorana neutrino!



Some candidate nuclei: ^{76}Ge, ^{82}Se, ^{100}Mo, ^{130}Te, ^{136}Xe



The 2015 LONG RANGE PLAN for NUCLEAR SCIENCE

RECOMMENDATION II:

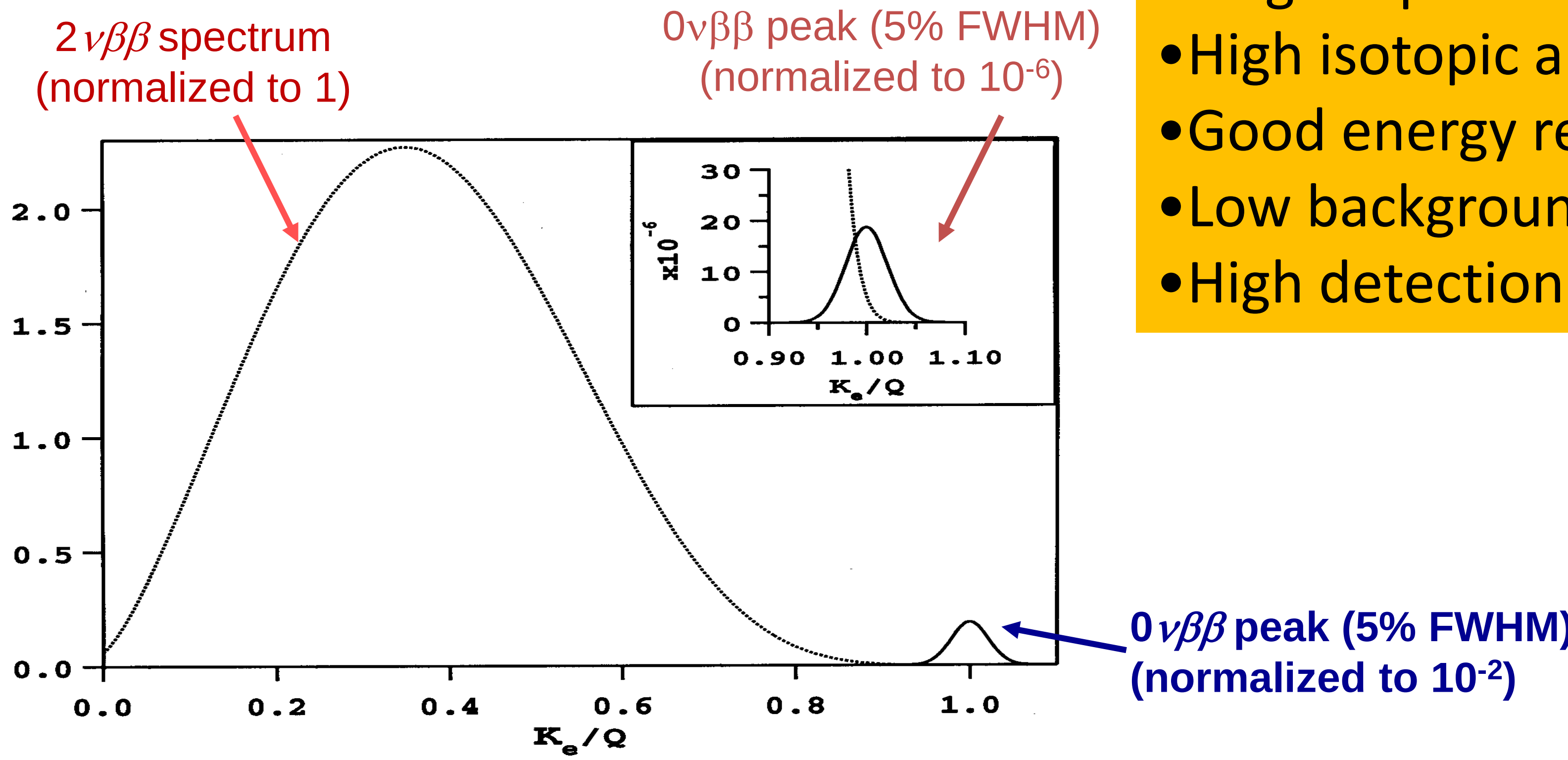
"The excess of matter over antimatter in the universe is one of the most compelling mysteries in all of science. The observation of neutrinoless double beta decay in nuclei would immediately demonstrate that neutrinos are their own antiparticles and would have profound implications for our understanding of the matter-antimatter mystery.

"We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment."

INITIATIVE B:

"We recommend vigorous detector and accelerator R&D in support of the neutrinoless double beta decay program and the EIC."

Neutrinoless Double Beta Decay

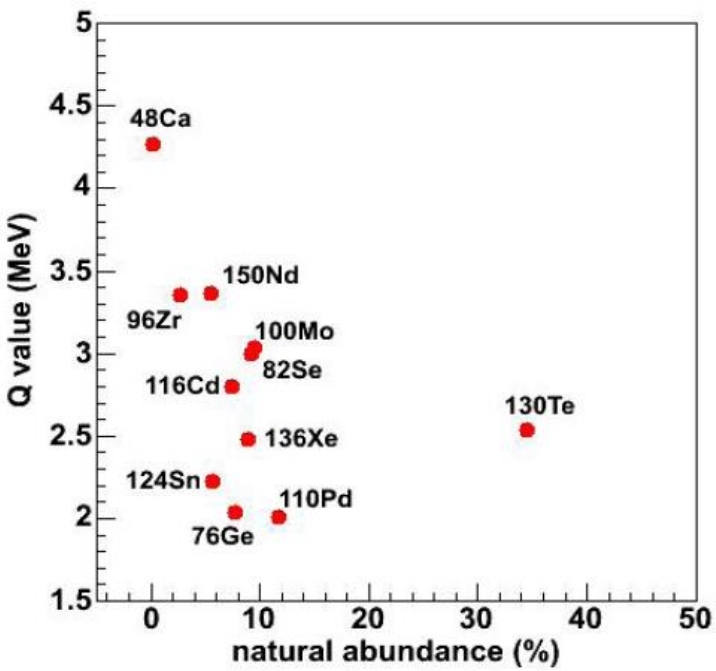


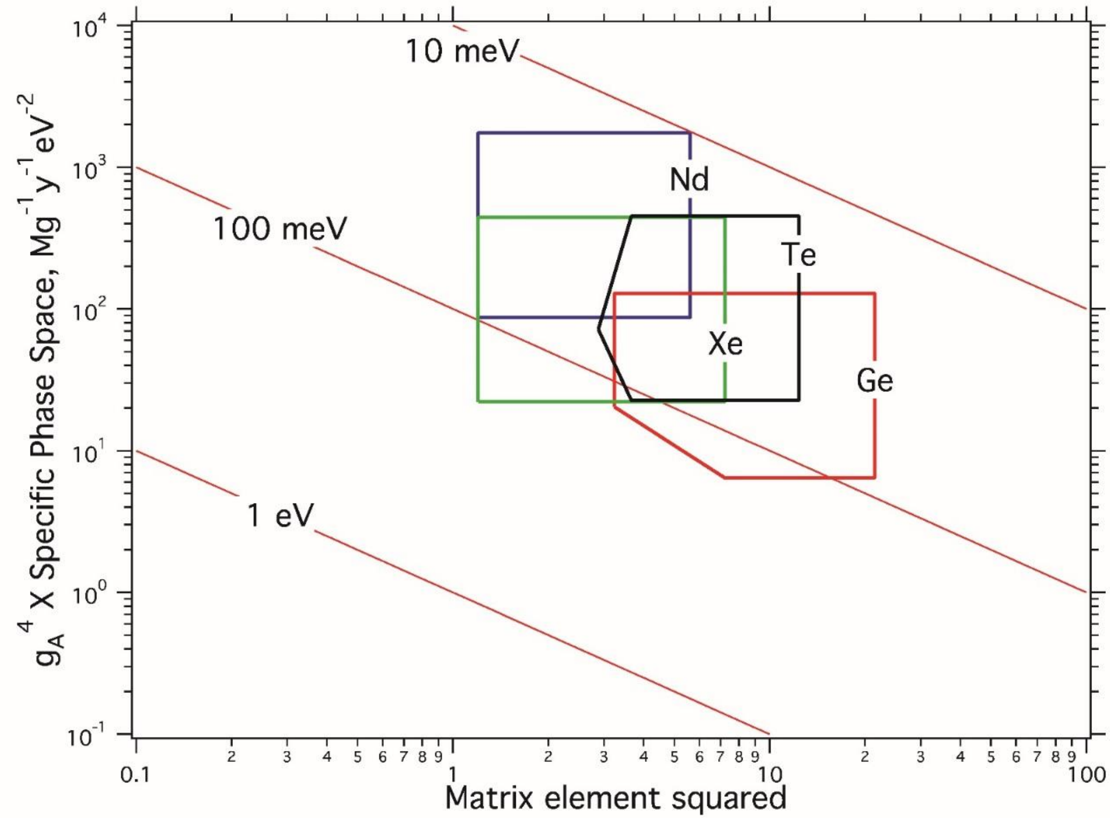
- Large exposure
- High isotopic abundance
- Good energy resolution
- Low background
- High detection efficiency

Isotope choice

$$\langle m_{bb} \rangle^2 = \left(T_{1/2}^{0nbb} \, G^{0nbb}(E_0, Z) \left| M_{GT}^{0nbb} - \frac{g_V^2}{g_A^2} M_F^{0nbb} \right|^2 \right)^{-1}$$

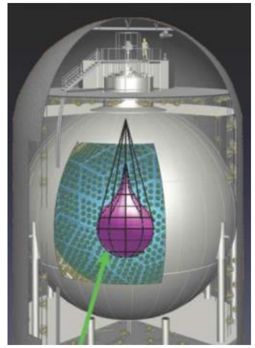
(light Majorana neutrino exchange mechanism only)





R.G.H. Robertson, Mod. Phys. Lett. A 28, 1350021 (2013).

Liquid (organic) scintillators:
- KamLAND-ZEN (^{136}Xe)
- SNO+ (^{130}Te)



Pros: “Simple”, large detectors exist, self-shielding
Cons: Poor energy resolution, 2v background

Crystals:
- GERDA,
  Majorana Demonstrator (^{76}Ge)
- CUORE, CUPID (^{130}Te)

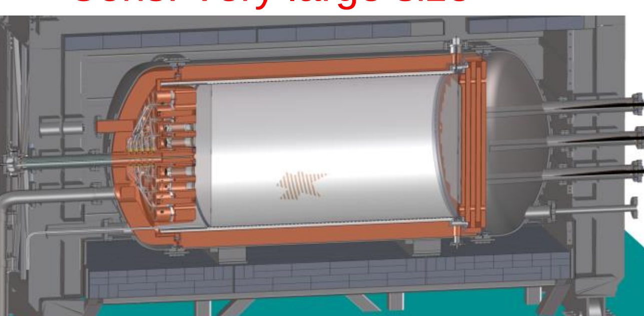
Pros: Superb energy resolution, possibly 2-parameter measurement

Cons: Intrinsically fragmented

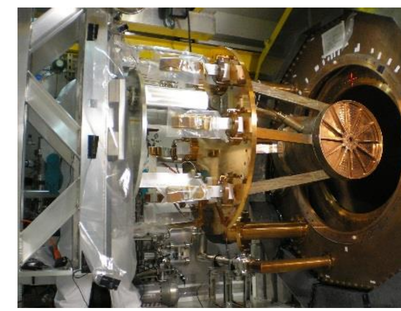
Low density trackers:
- NEXT, PandaX (^{136}Xe gas TPC)
- SuperNEMO (foils and gas tracking, ^{82}Se)

Pros: Superb topological information

Cons: Very large size



Liquid TPC:
- EXO-200, nEXO (^{136}Xe)



Pros: Homogeneous with good E resolution and topology
Cons: Does not excel in any single parameter

Currently Requested Enriched Isotopes for Future 0νββ Experiments

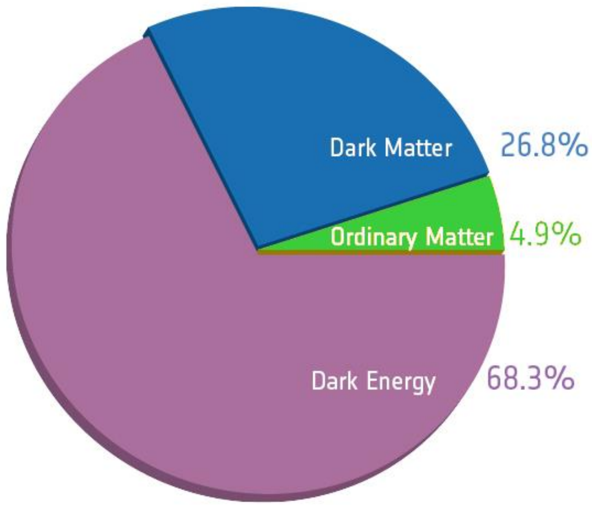
Isotope	% Nat Abund	% Desired Enrich't	Enrich't Method	Chem Form for Enrich't	Total Amount (kg)	Experiment
^{76}Ge	7.73	>86	GC	GeF_4	1200	GERDA/MJD
^{82}Se	8.73	>90 >96	GC	SeF_6	50 150	SuperNEMO CUPID
^{100}Mo	9.7	>90	GC	MoF_6	240	CUPID
^{130}Te	34.2	>90	GC	TeF_6	1200 4000	CUPID SNO+
^{136}Xe	8.9	>85	GC	Xe	5000	nEXO + 2 others
^{150}Nd	5.6	>80	GC	?	100	SuperNEMO

GC = Gas Centrifuge

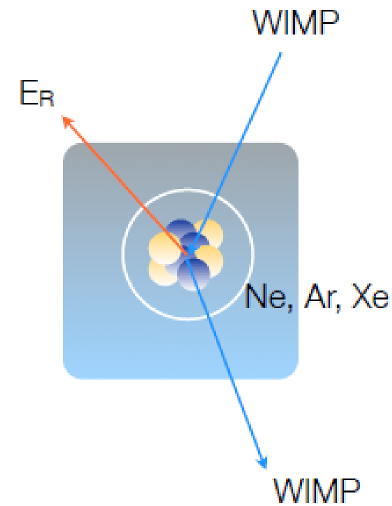
Previous or existing enrichment facilities used for current generation experiments:

- JSC Production Association Electrochemical Plant (ECP), Russia
- URENKO, UK
- Alemelo, The Netherlands

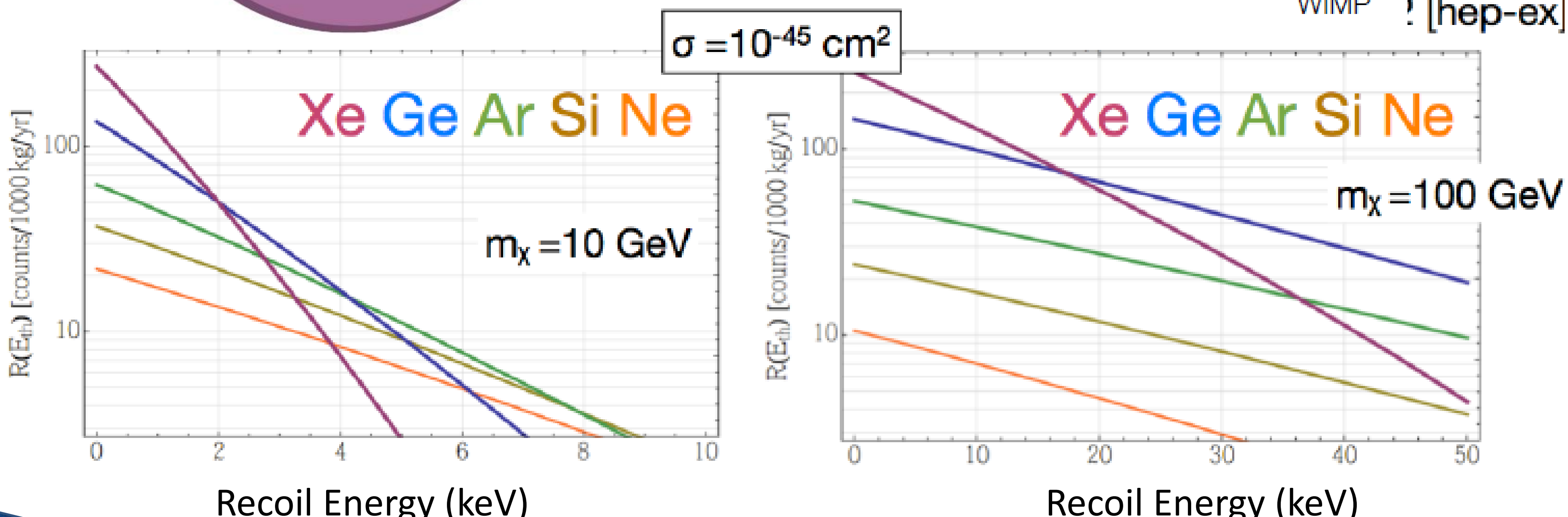
Isotopes for Direct Dark Matter Detection



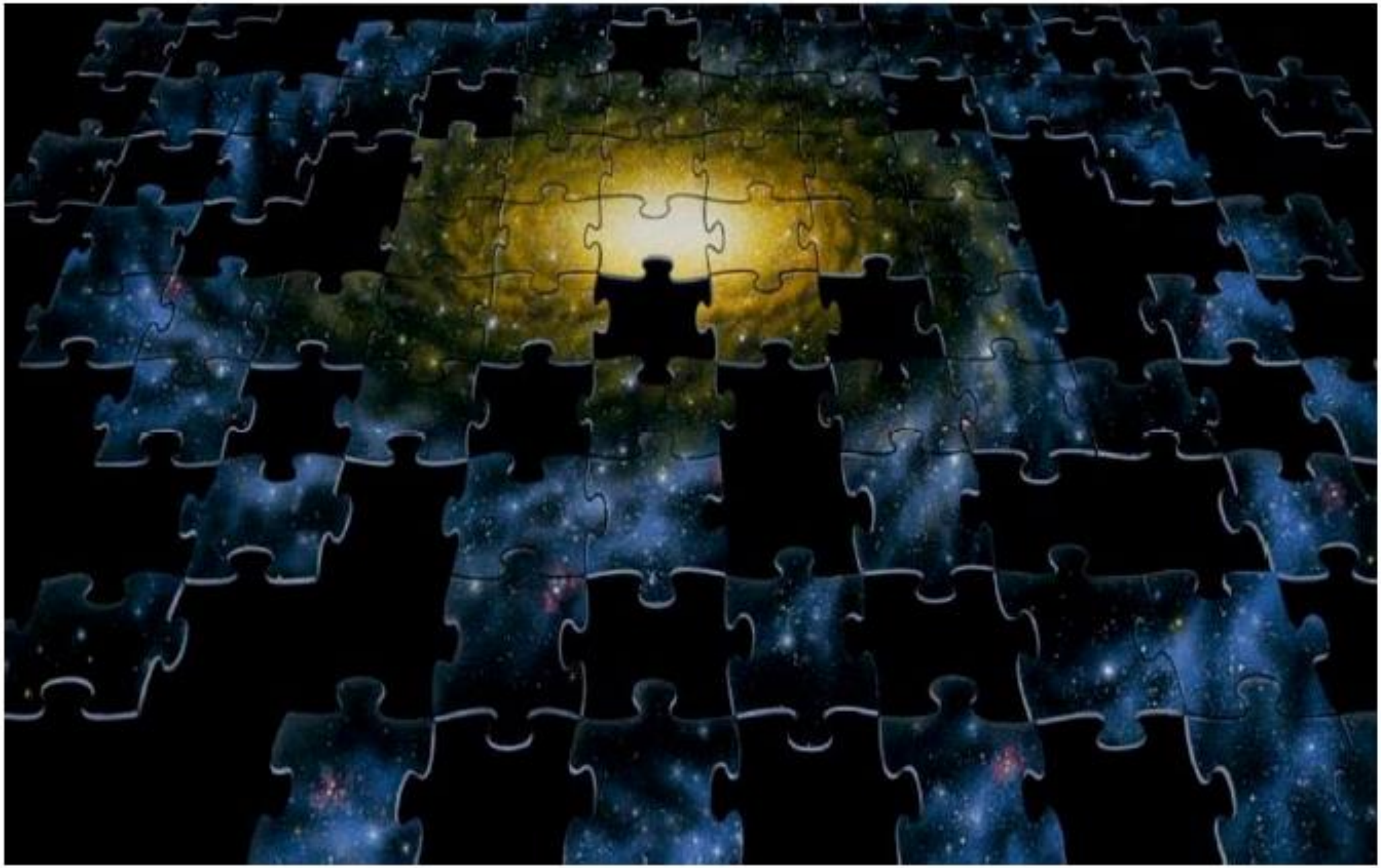
From Planck



! [hep-ex]



Noble Liquids: Solving the Dark Matter Puzzle?



Why noble Liquids?

- Good Nuclear vs Electron Recoil discrimination
  - Pulse shape of scintillation signal (esp. argon)
  - Ratio of ionization to scintillation signals
- High Scintillation Light yields; transparent to their own light
  - Low energy thresholds can be achieved
- Large Detector Masses are feasible
  - Self-shielding => low-activity of inner fiducial volumes
  - Good position-resolution in TPC operation mode (use ionization signal) characterizes the detector as a finely granulated, homogeneous calorimeter.
- Easy to purify: Ionization Drift » 1 m achieved
  - Corresponding to « ppm electronegative impurities
- Competitive Costs and Practicality of large instruments
- Main drawback to atmospheric argon: ^{39}Ar (1 Bq/kg)

Extraction of UAr and ^{4}He

- From a **2007 NSF R&D** award originally designed to search for underground argon which might be depleted in the radioactive isotope ^{39}Ar (achieved with a factor of 1400±200 relative to atmospheric argon), a unique new plant for extracting ^{4}He has been realized.
- The R&D effort, ongoing since 2008 for the collection of underground argon by the **DarkSide Dark Matter** collaboration at the CO_2 extraction plant owned by Kinder Morgan in Cortez, Colorado, has resulted a 7-year monitoring of noble gases in the CO_2 stream.
- The monitoring results identified the presence of a valuable new source of helium.
- In June 2015, Air Products commenced production at its new Doe Canyon helium production facility in Colorado.
- This helium plant is the only one in the world extracting helium from a gas stream composed primarily of carbon dioxide.
- The plant is expected to produce up to 230 million standard cubic feet of helium per year, replacing more than 15 percent of the current United States Bureau of Land Management reserve helium supply as that system continues to declines.

ARIA: a project to extract precious elements

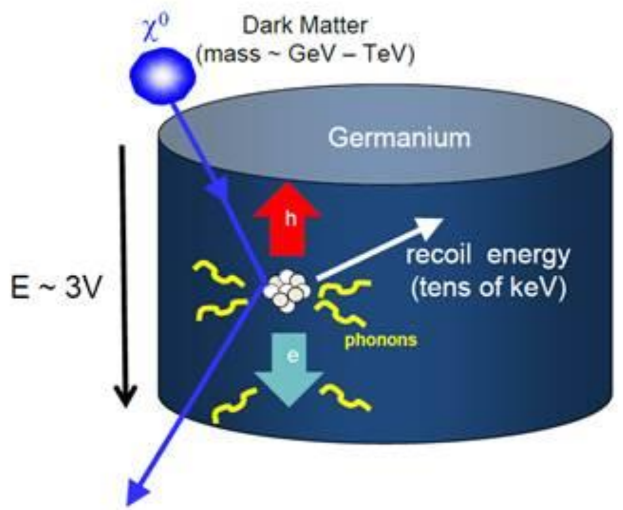
- The objective of the **ARIA project** is the separation of Earth's atmosphere into its fundamental components to obtain precious elements that find application in various areas of research and technology, including diagnostic techniques for the detection of cancer.
- The project is led by the Italian National Institute of Nuclear Physics (INFN), which will coordinate the creation of an innovative research infrastructure in the Sulcis coalfield in Sardinia
- The new agreement signed by INFN and the Autonomous Region of Sardinia is the first step of the ARIA project.
- The project is made possible by the cooperation between INFN and Princeton University while the first design phase has started thanks to the funding provided by the **NSF**.
- The first step will be the installation of a cryogenic distillation column: a prototype of a size that makes it unique (350 m).

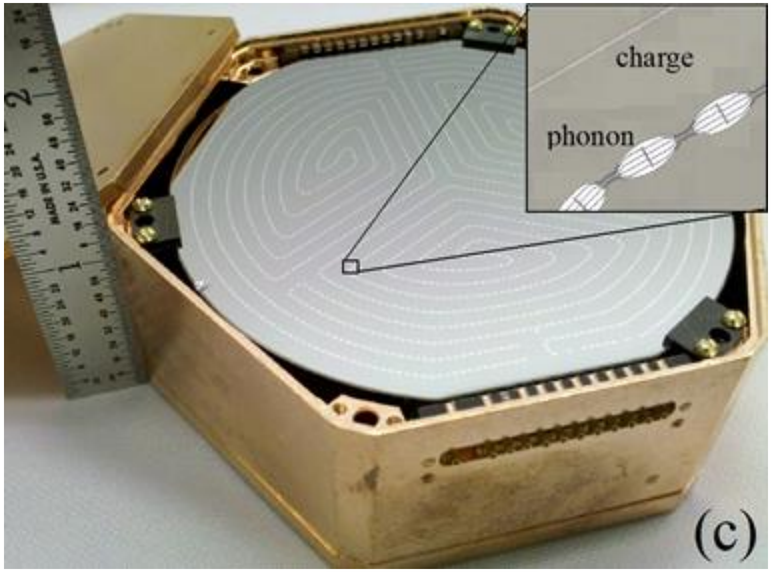
ARIA: a project to extract precious elements

- Among them, the precious **argon-40**, currently obtained from the Colorado mines in the US, used for the DarkSide experiment in INFN's Gran Sasso National Laboratories for the "hunt" for dark matter. Other components such as **oxygen-18** and **carbon-13** have an international market of great importance and may help improve medical screening and **diagnostic technologies** for the fight against cancer.
- In addition to medical diagnostics, other fields such as **energy**, **climate** and **agriculture** will benefit from the new infrastructure. This project is of strategic national and regional importance, with a significant impact on the economic sector and on research.
- https://www.researchitaly.it/en/projects/aria-a-project-to-extract-precious-elements-from-the-components-of-the-atmosphere/

Dark Matters Detectors with Ge and Si

The CDMS experiment has pioneered the use of cryogenic silicon and germanium detectors to perform sensitive searches for dark matter. The recoiling nucleus from a dark matter interaction produces crystal lattice vibrations (phonons) and also electron-hole pairs (left). The phonon and charge signals are captured by electrodes applied to the face of the crystal using photolithography (right). These detectors provide unique capabilities for background rejection and offer unmatched sensitivity for the very small energy deposits associated with low-mass dark matter interactions.



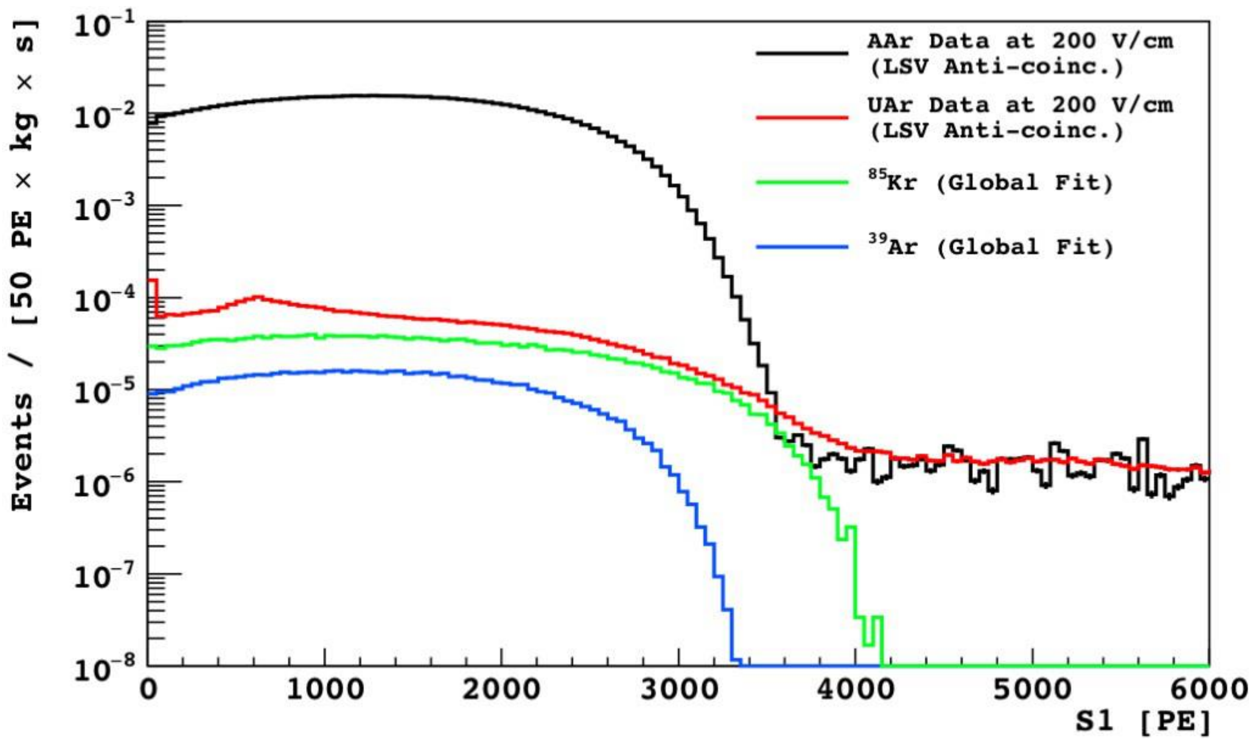


Sodium Iodide as a Dark Matter Detector

- The SABRE (Sodium iodide with Active Background REjection) experiment:
- The signature feature is the development of ultra-high purity NaI(Tl) crystals
- Such crystals can be developed using high-purity powders already produced in collaboration with industrial partners.
- The primary aim has been to reduce ^{40}K levels below 13 ppb; currently at 3.5 ppb in the powder; also concerned with ^{87}Rb, ^{232}Th and ^{238}U content.
- Through several industrial partnerships, they have also made significant progress toward the development of new ultra-high purity crystal growth techniques.
- Working to produce 4” (diam) x 10” crystals (8-10 kg each)
- Planning for a 50-60 kg array of ultra-pure NaI crystals
- This process may have applications for other materials

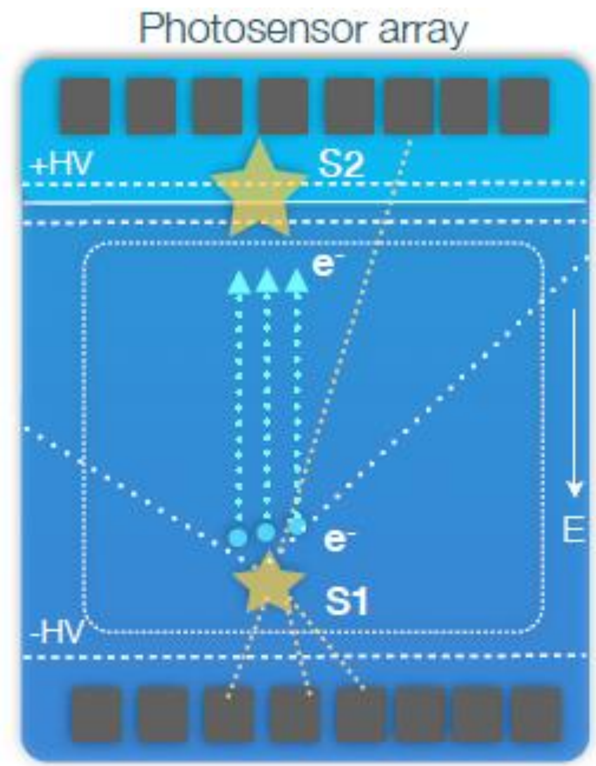
Backup Slides

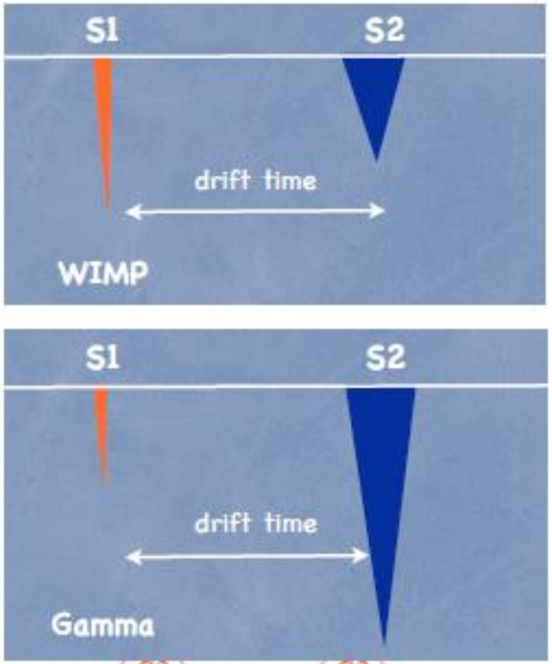
Underground vs atmospheric argon



Factor of 1400±200 relative to atmospheric argon

2-Phase (Liquid/Gas) Detection Principle



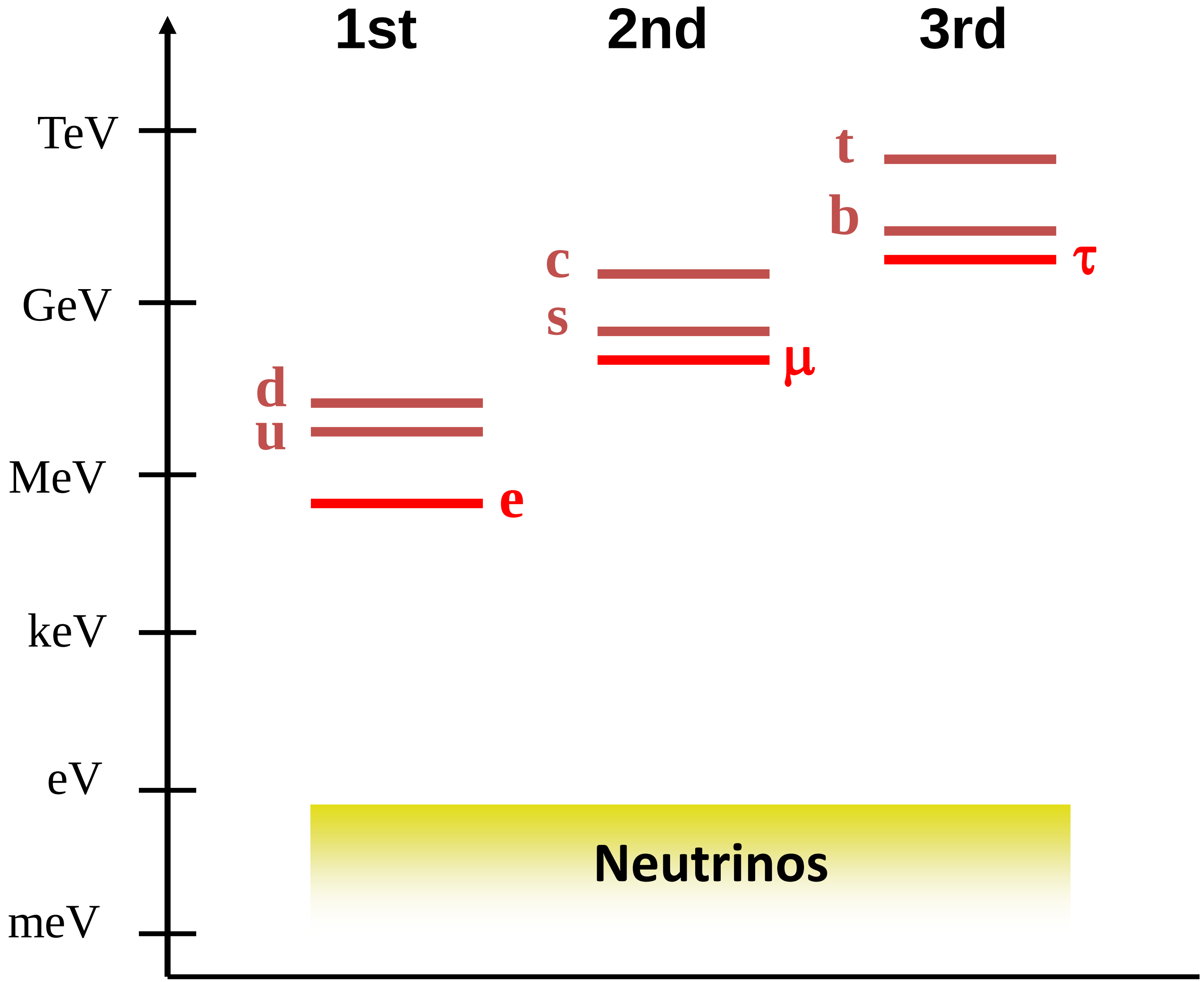


$$\left(\frac{S2}{S1}\right)_{WIMP} \ll \left(\frac{S2}{S1}\right)_{gamma}$$

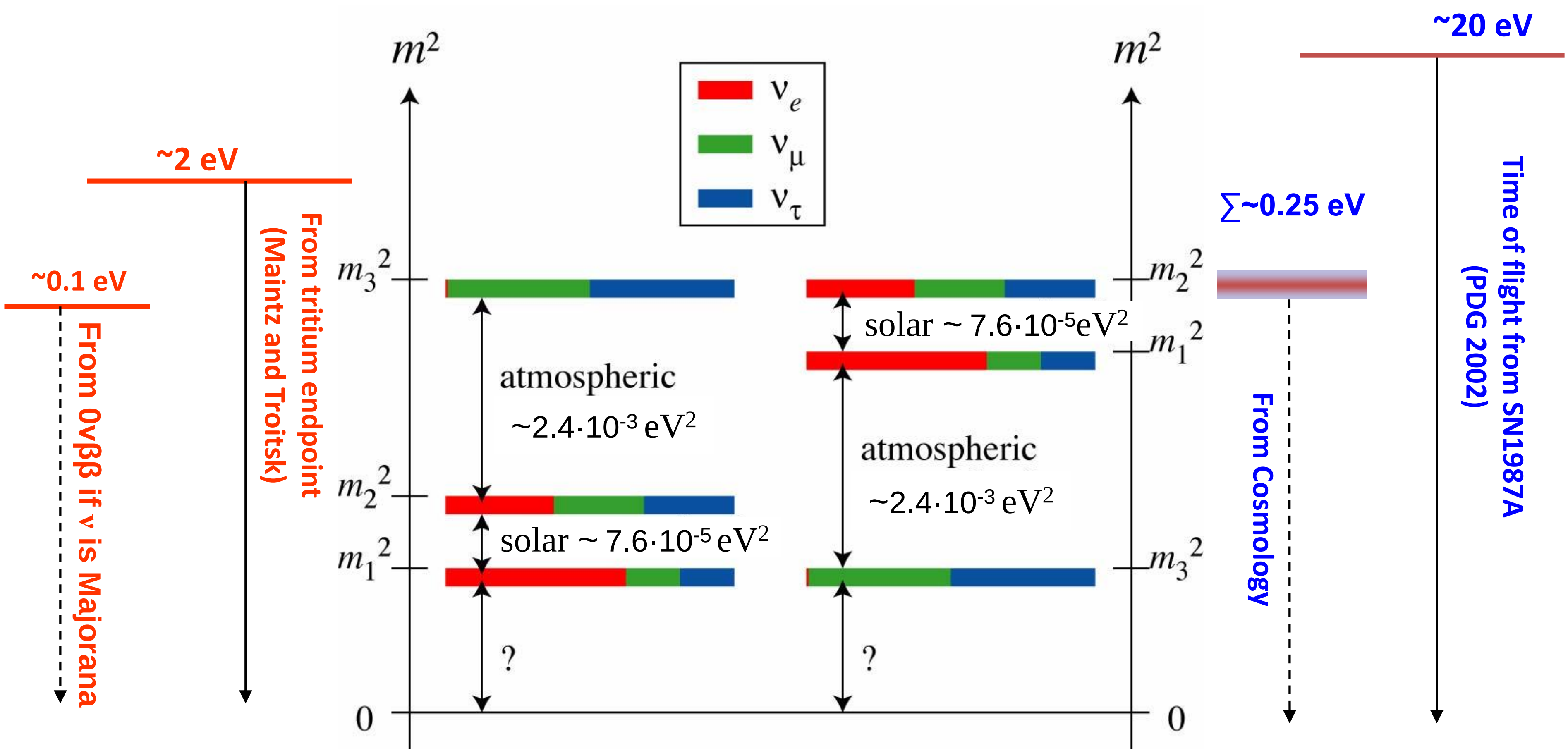
Prompt (S1) light signal after interaction; charge is drifted, extracted into gas phase and detected (S2)

Concept of a XENON experiment: any particle interaction in the liquid xenon (blue) yields two signals: a prompt flash of light, and a delayed charge signal. Together, these two signals yield the energy and position of the interaction as well as the type of the interacting particle.

Neutrino mass



What we know about neutrinos



The matter-antimatter asymmetry

"The excess of matter over antimatter in the universe is one of the most compelling mysteries in all of science."

Instead of starting with a baryon number violating process (baryogensis), leptogenesis relies on violating **lepton number**, *then* converting *L* into *B*.

Neutrinos could be the key to explaining the matter-antimatter asymmetry in the universe…

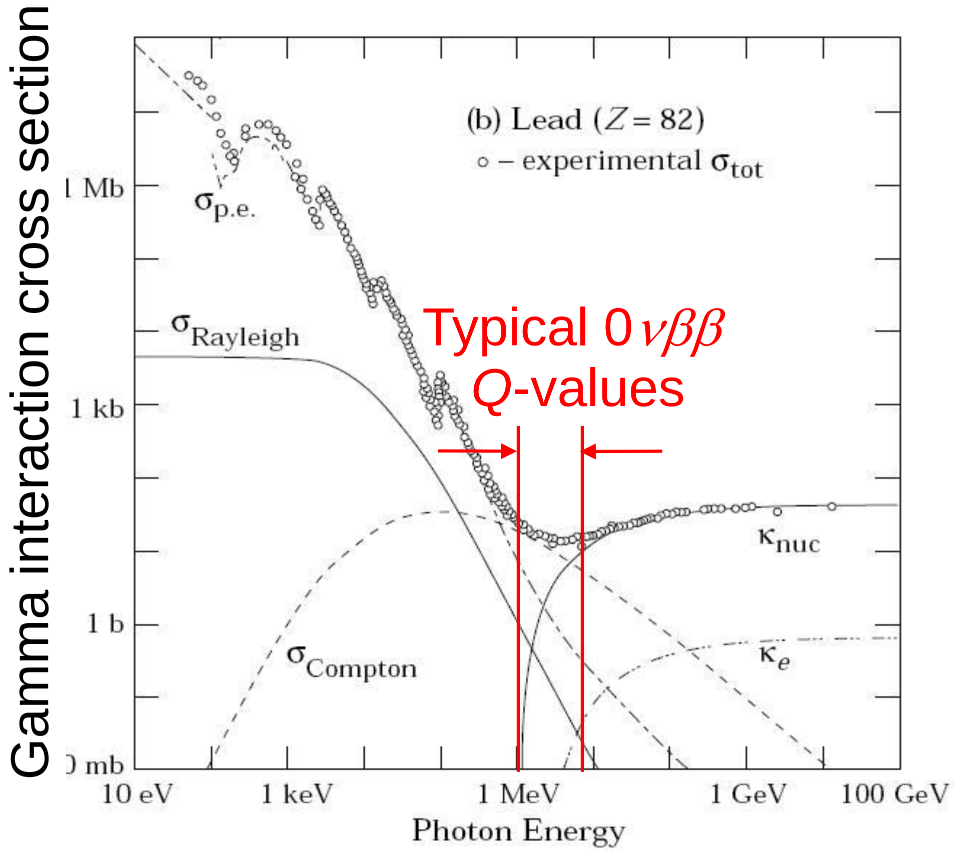
"Dirac" neutrinos $\nu \neq \bar{\nu}$

"Majorana" neutrinos $\nu = \bar{\nu}$

The two descriptions are distinguishable only if $m_\nu \neq 0$.

As a bonus, Majorana νs may be tied to the mystery of small ν masses

Challenges of the ton-scale



Shielding a detector from MeV gammas is difficult!

Example:

γ–ray interaction length in Ge is 4.6 cm, comparable to the size of a germanium detector.

Shielding $0\nu\beta\beta$ decay detectors much harder than shielding DM detectors

Detector sizes exceed interaction length → "golden era" of $0\nu\beta\beta$ experiments

Recent results (> 10^{25} yr half-life)

Isotope	Experiment	Exposure (kg yr)	$T^{0\nu\beta\beta}_{1/2}$ average sensitivity (10^{25}yr)	$T^{0\nu\beta\beta}_{1/2}$ (10^{25}yr) 90%CL	$< m_\nu >$ (meV) Range from NME*	Reference
^{76}Ge	Gerda	21.6	2.4	>2.1	200-400	Agostini et al., PRL 111 (2013) 122503
^{136}Xe	EXO-200	100	1.9	>1.1	190-450	Albert et al. Nature 510 (2014) 229
	KamLAND-ZEN	504**	4.9	>11 (run 2)	60-161	Gando et al., PRL 117 (2016) 082503

- Note that the range of "viable" NME is chosen by the experiments and uncertainties related to g_A are not included
- Fiducial Xe is more like ~150 kg yr