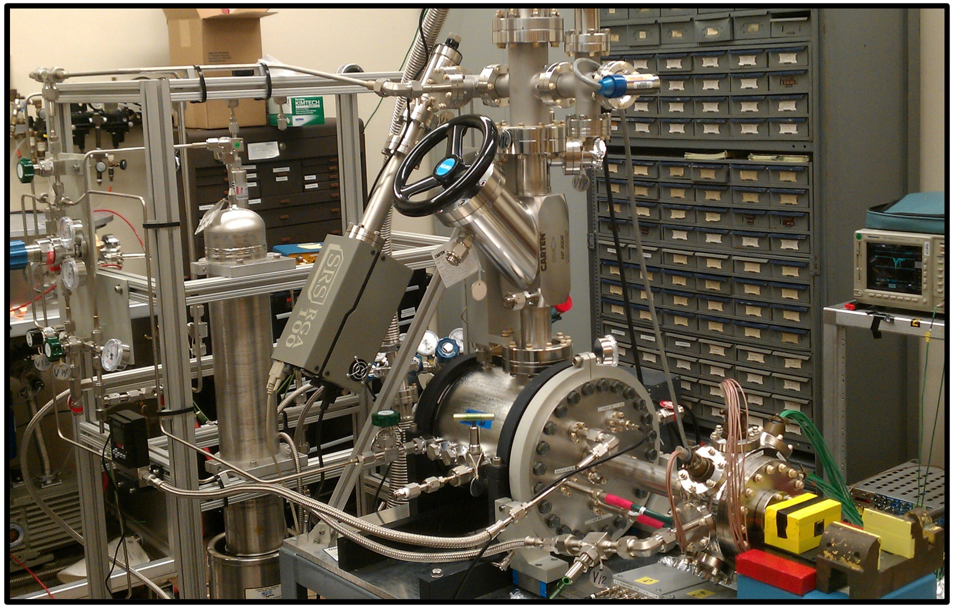


High Pressure Xenon Detectors for Rare Physics Searches

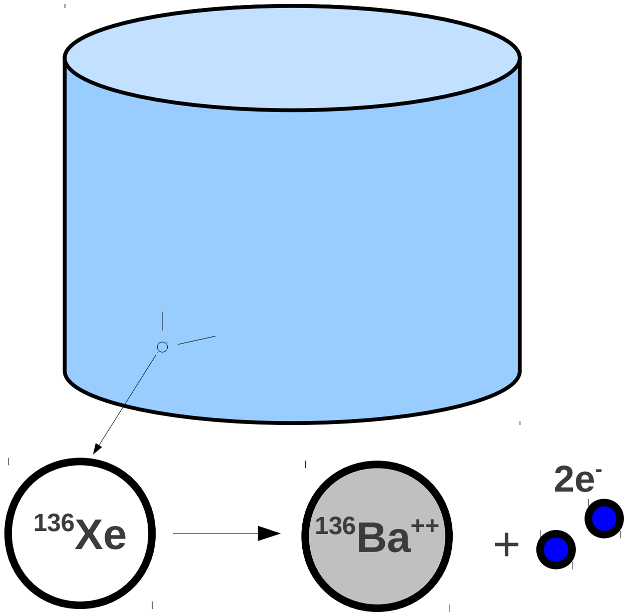
J. Renner[1,2], M. Egorov[1,2], V. M. Gehman[1], A. Goldschmidt[1], B. Hsieh[1,2], J. Joseph[1],
T. Miller[1], D. Nygren[1], C.A.B. Oliveira[1], D. Shuman[1], and T. Weber[1]
and the NEXT Collaboration
[1] LBNL [2] UC Berkeley

SSGF Annual Review
June 25, 2013

Rare physics

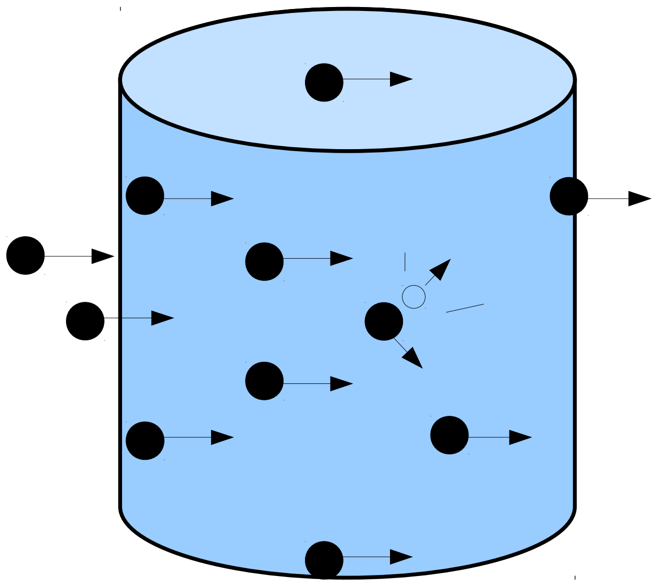
Physical processes that, if they exist, are extremely difficult to detect

Neutrinoless Double-Beta Decay (0νββ)



$${}^{A}_{N}Z \rightarrow {}^{A}_{N-2}(Z+2) + 2e^{-}$$

Interactions of WIMP Dark Matter

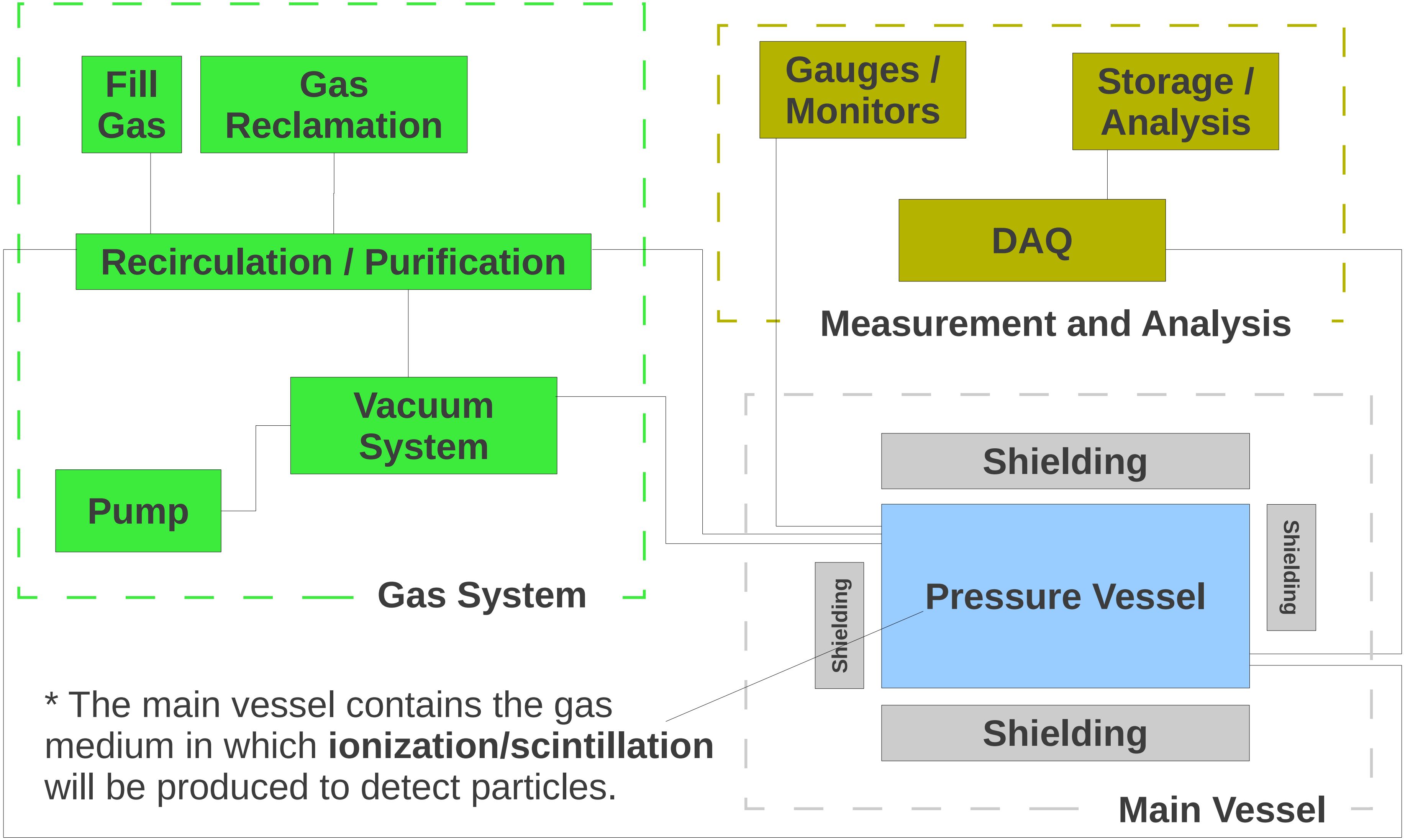


In both cases, one must detect an amount of energy deposited by the energetic particles involved in the processes

Gas-Based Detectors

Gas-based Detectors:

Typical components of a gaseous detector:



Fill Gas

Gas Reclamation

Recirculation / Purification

Vacuum System

Pump

Gas System

Gauges / Monitors

Storage / Analysis

DAQ

Measurement and Analysis

Shielding

Shielding

Pressure Vessel

Shielding

Shielding

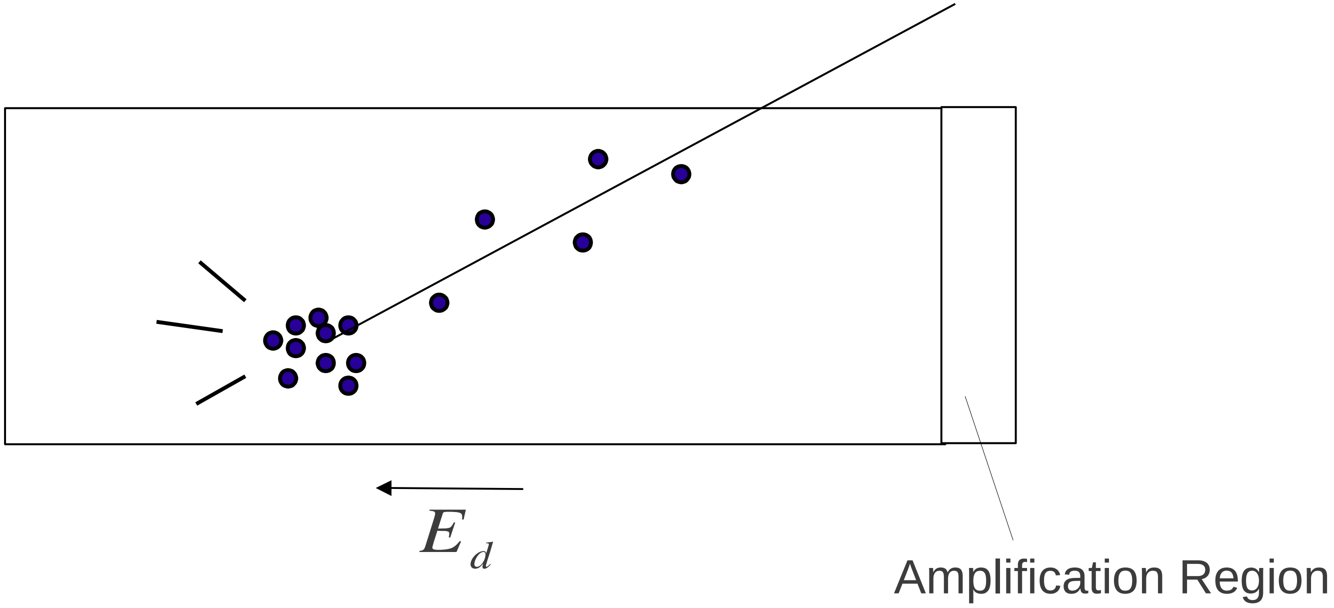
Main Vessel

* The main vessel contains the gas medium in which **ionization/scintillation** will be produced to detect particles.

Gas-based Detectors:

Detection of ionization in gaseous detectors:

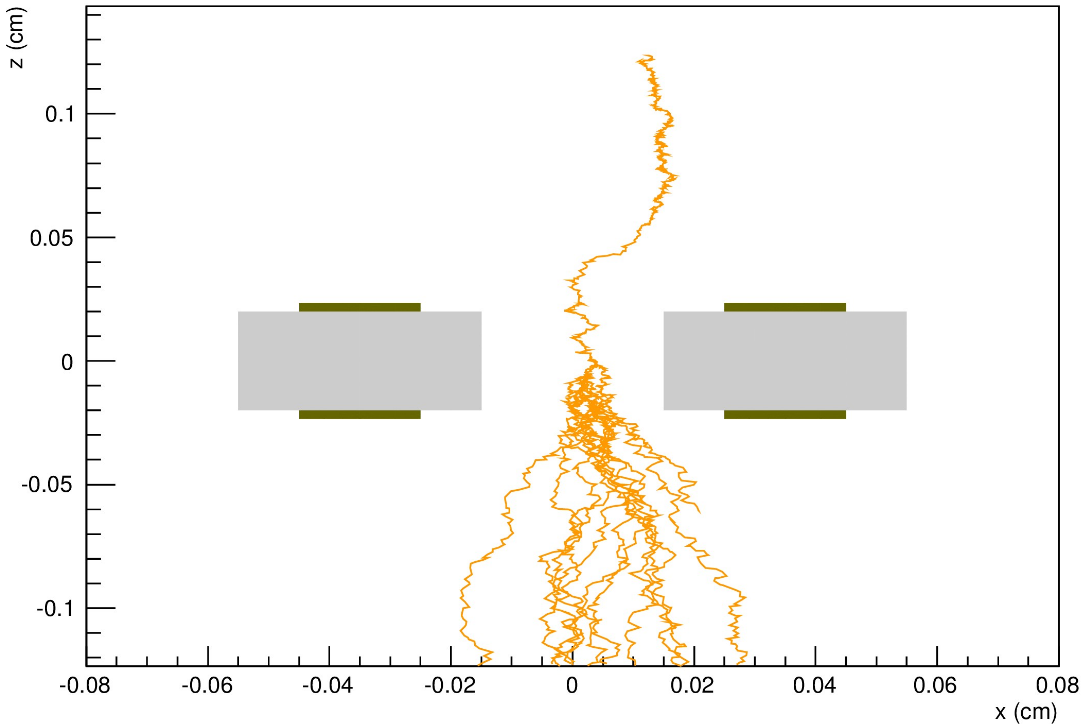
- **Production and drift**: an amount of ionization (dictated by the particle energy E and the W-value of the medium) is produced as N = E/W electron-hole pairs that then drift in an electric field towards an amplification/readout plane.



Gas-based Detectors:

Detection of ionization in gaseous detectors:

- **Amplification**: in this (optional) step, each electron is amplified to produce a detectable signal.



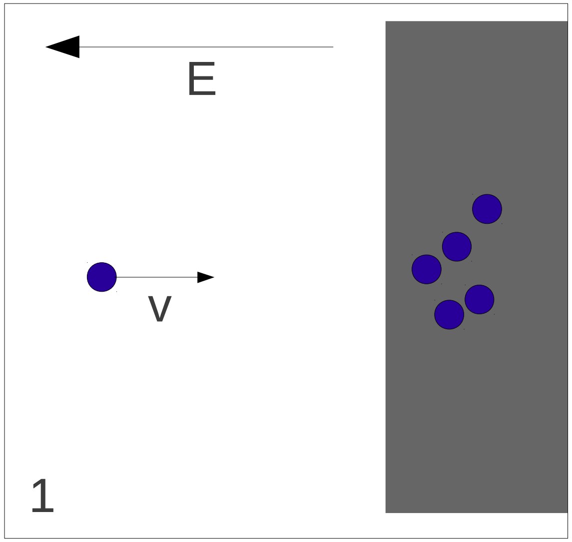
Example: amplification via a LEM (large electron multiplier) simulated using Garfield++ [1]. LEMs can give gains up to ~10^5

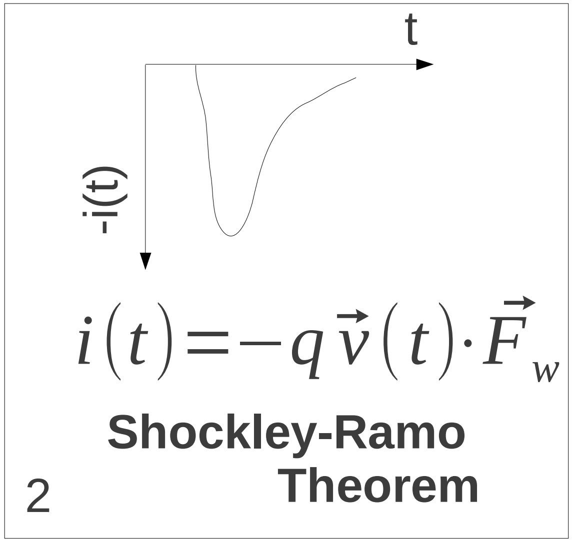
[1] *Garfield++ - simulation of tracking detectors*. http://garfieldpp.web.cern.ch/garfieldpp/
Also used Gmsh: C. Geuzaine, J.-F. Remacle. Int. J. for Numerical Methods in Engineering 79, 1309 (2009). http://geuz.org/gmsh.
and Elmer: CSC IT Center for Science. Elmer. http://www.csc.fi/english/pages/elmer.

Gas-based Detectors:

Detection of ionization in gaseous detectors:

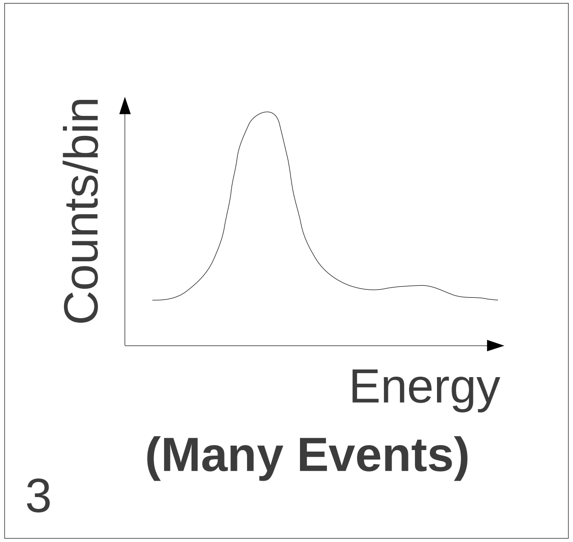
- **Readout**: ionization is converted into an electrical signal and recorded. The amount of ionization produced is related to the energy of the incident particle.





$$i(t) = -q\,\vec{v}(t)\cdot\vec{F}_w$$

Shockley-Ramo Theorem



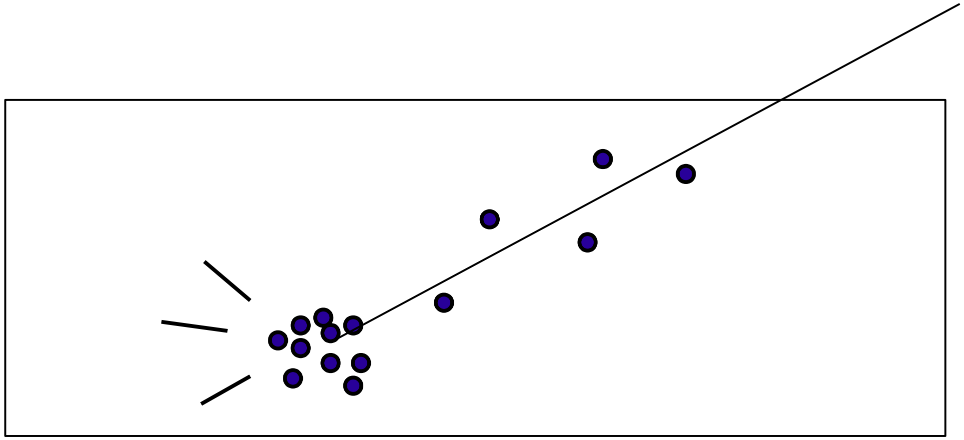
(Many Events)

Example: current induction on a conductor (1), followed by acquisition (2) and analysis (3)

Gas-based Detectors:

Detection of scintillation in gaseous detectors:

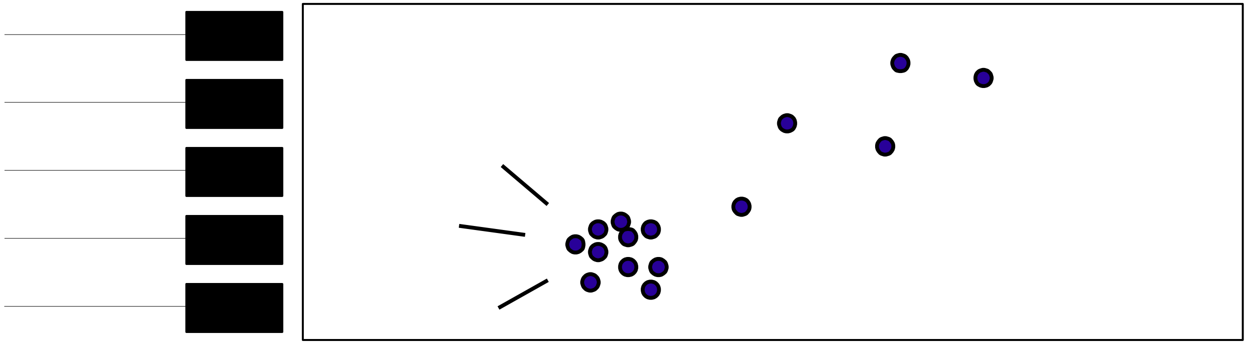
- **Production and propagation**: a number of scintillation photons is produced along with the ionization; some are produced from electron-hole pairs that recombine.



Gas-based Detectors:

Detection of scintillation in gaseous detectors:

- **Amplification/Readout**: photons are detected by some light-sensitive device such as a PMT (photomultiplier tube). (Acquisition is similar to ionization case.)



Example: PMTs convert individual photons into pulses of electrical current.

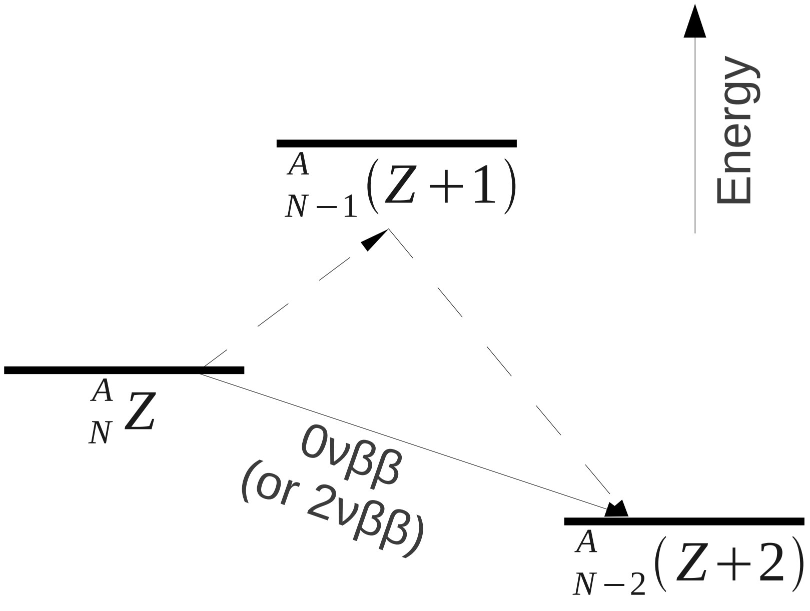
Neutrinoless Double Beta Decay (0νββ)

Neutrinoless Double-Beta Decay:

Nuclear beta decay:

Neutrino

$$n \rightarrow p + e^- + \bar{\nu}_e$$



- Nuclear pairing force can create necessary conditions forbidding single β-decay

- β-decay can occur with 2ν; if the neutrino were its own antiparticle (“Majorana”), it may also occur with 0ν

(^{136}Xe is a candidate nucleus)

Figure after: F. Avignone *et. al.* Rev. Mod. Phys. 80, 481 (2008).

What is the neutrino?

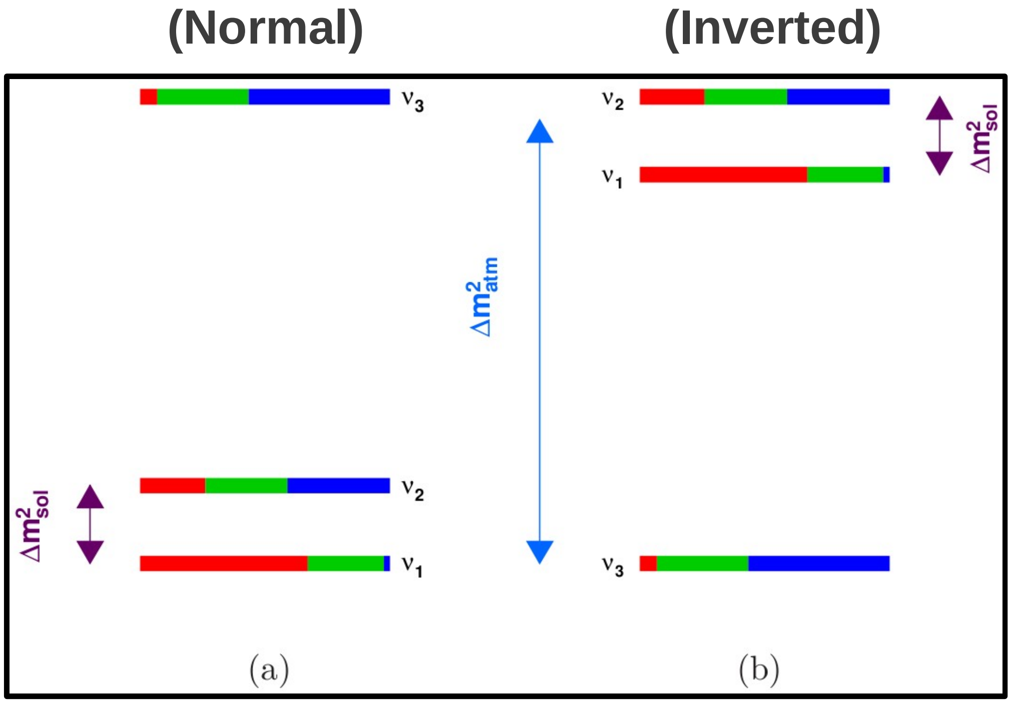
A small neutral particle, exists in 3 types (“flavors”):

$$\begin{pmatrix} e^- \\ \nu_e \end{pmatrix} \quad \begin{pmatrix} \mu^- \\ \nu_\mu \end{pmatrix} \quad \begin{pmatrix} \tau^- \\ \nu_\tau \end{pmatrix}$$

$|\nu_e\rangle$ - red

$|\nu_\mu\rangle$ - green

$|\nu_\tau\rangle$ - blue

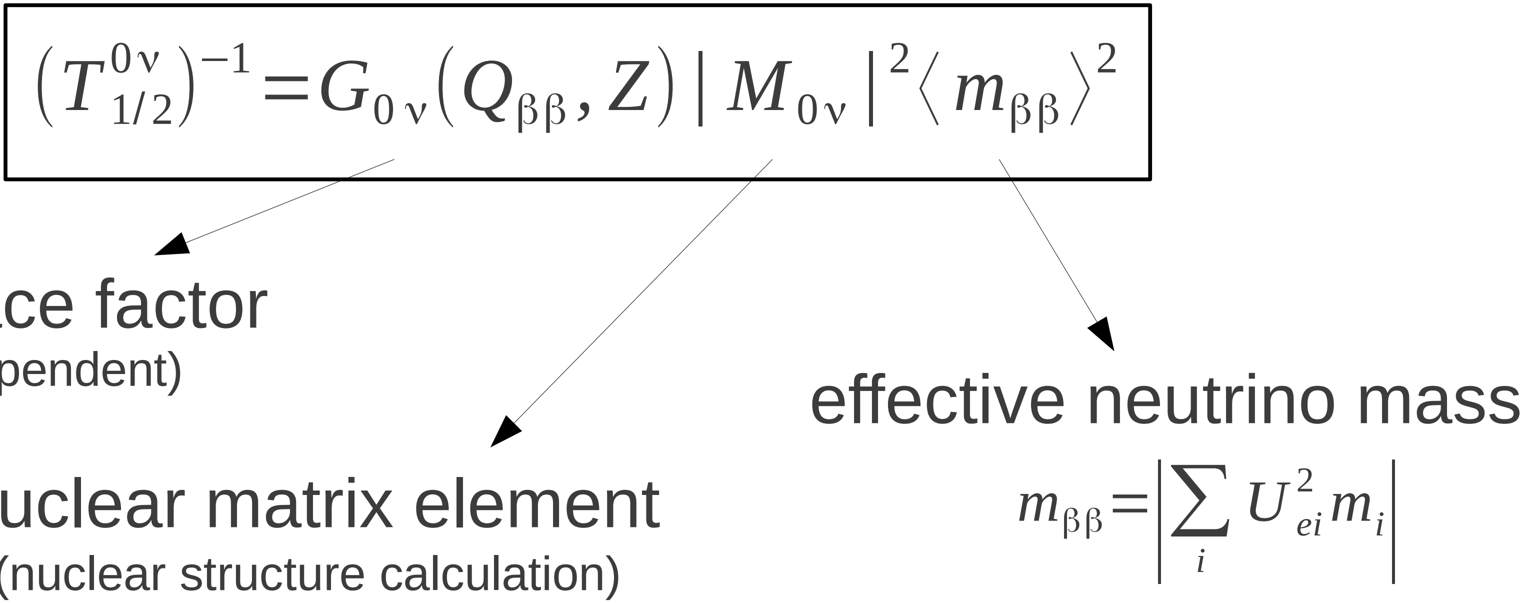


From J. J. Gomez-Cadenas et. al. Riv. Nuovo Cim. 35 (2012) 29-98 (arxiv:1109.5515).

- Flavor and mass are not entirely independent: they mix
- Absolute neutrino mass scale and mass hierarchy unknown

0νββ and the neutrino mass:

Reaction rate [1]:



$$\boxed{\left(T^{0\nu}_{1/2}\right)^{-1} = G_{0\nu}\left(Q_{\beta\beta}, Z\right) |M_{0\nu}|^2 \langle m_{\beta\beta} \rangle^2}$$

phase-space factor
(nucleus-dependent)

nuclear matrix element
(nuclear structure calculation)

effective neutrino mass

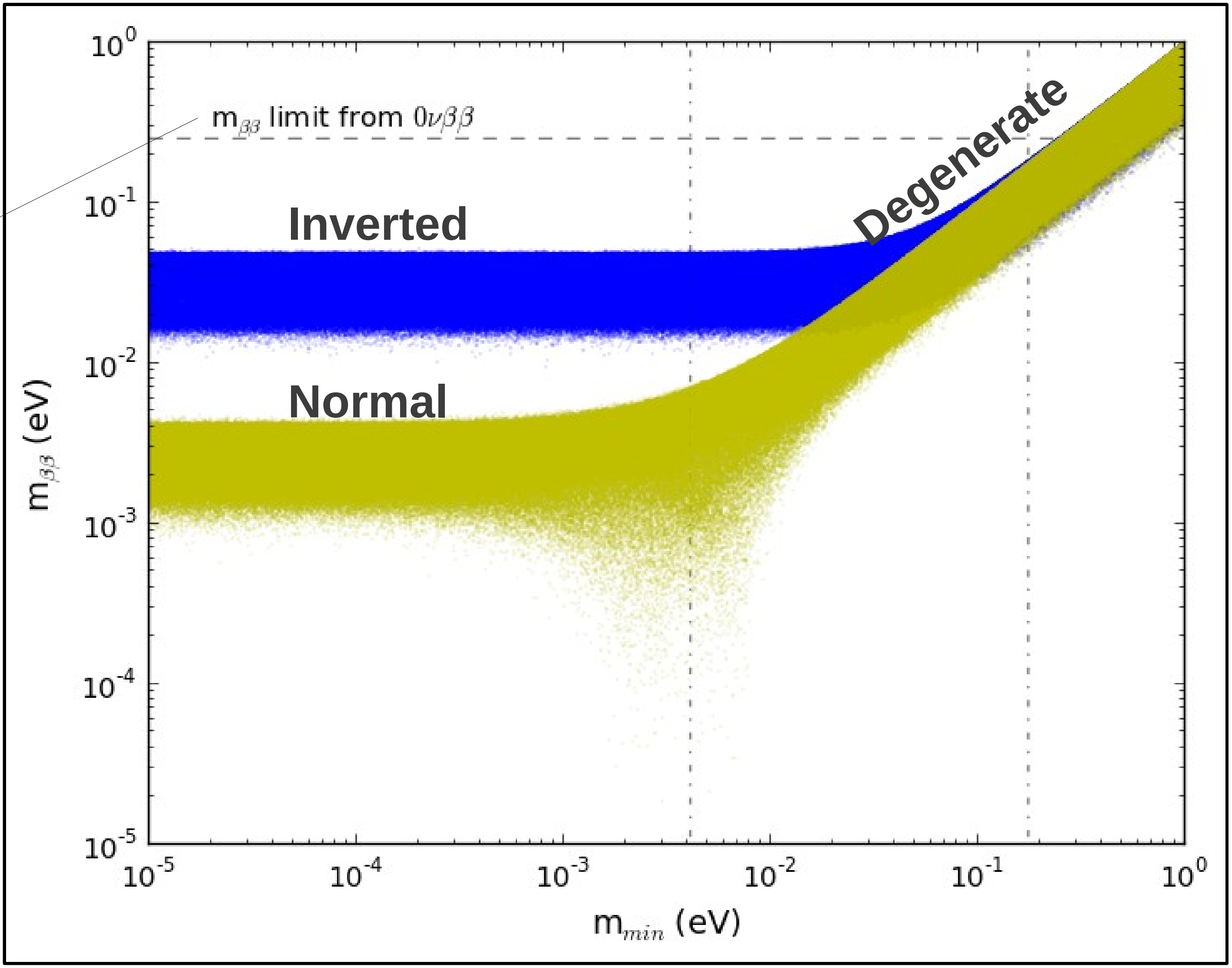
$$m_{\beta\beta} = \left| \sum_i U_{ei}^2 m_i \right|$$

- May tell us something about the scale of the neutrino mass
- Nonzero rate if the neutrino is its own antiparticle

[1] F. Avignone *et. al.* Rev. Mod. Phys. 80, 481 (2008).

0νββ and the neutrino mass:

KamLAND-Zen + EXO Experiments [3]



Thanks to Azriel Goldschmidt for suggesting the Monte-Carlo approach to this plot.

- randomly choose m_{min}, sign of Δm^2_{23}, mixing parameters [1]
- vertical lines are 2σ cosmological limits on the neutrino mass sum [2]

[1] J. Beringer et al. (Particle Data Group), Phys. Rev. D86, 010001 (2012). [3] Gando *et. al.* arXiv:1211.3863.
[2] Z. Hou et al., arXiv:1212.6267v1.

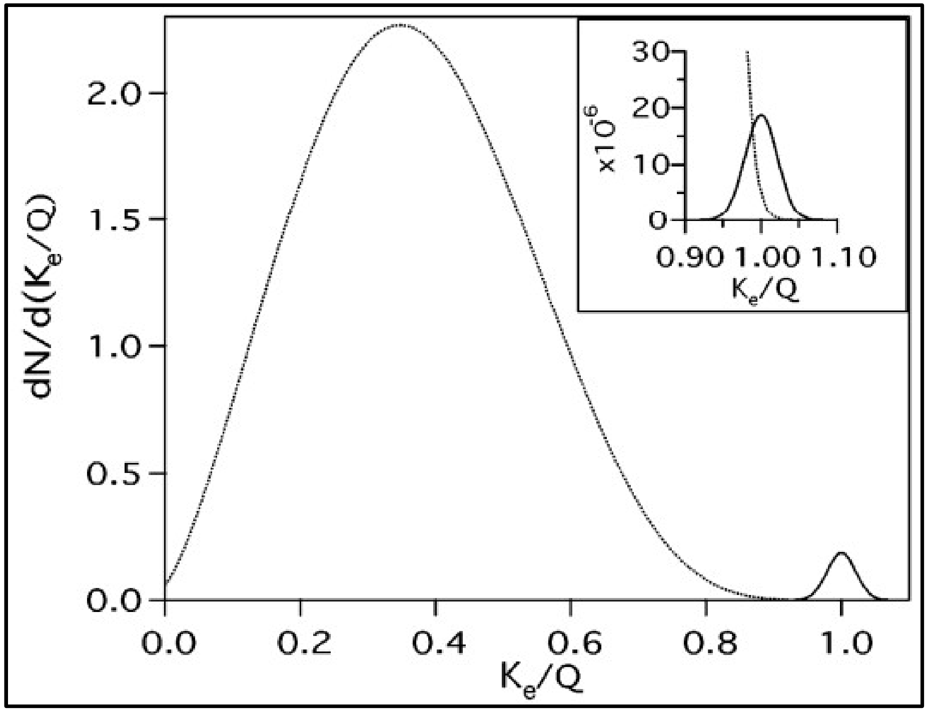
Detection of 0νββ:

A rare process – if it exists; detection demands:

1. Good energy resolution
2. Large detector with significant amount of ββ isotope
3. Low background

Detection of 0νββ:

1. Good energy resolution



Assumes 5% energy resolution, 2νββ peak normalized to 1, 0νββ peak normalized to 10^{-2} and in inset spectrum to 10^{-6}.

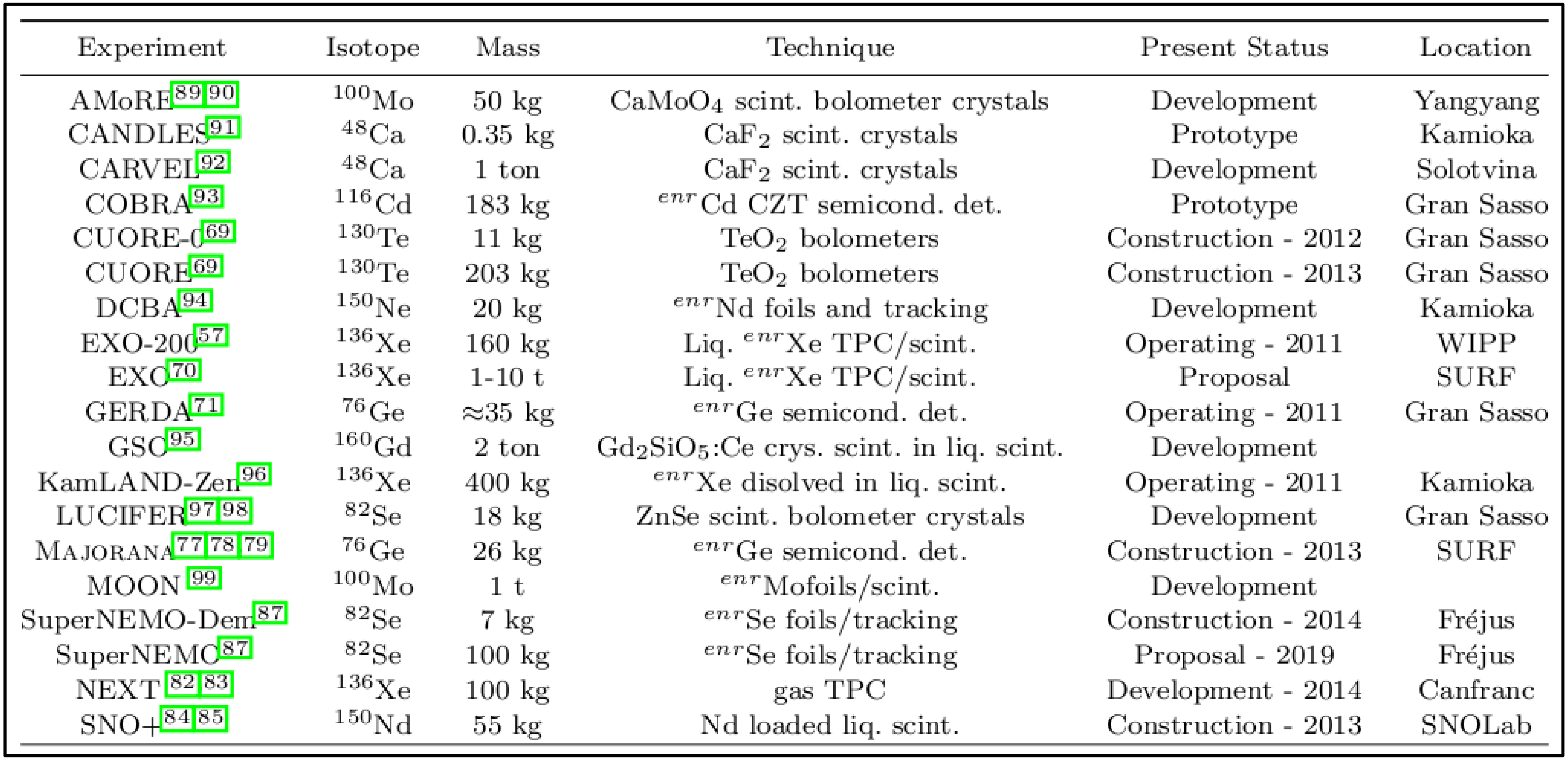
From S. R. Elliot and P. Vogel. Annu. Rev. Nucl. Part. Sci. 2002 52, 115 (2002).

Principle signature of 0νββ is the 2νββ spectrum with an end peak at $Q_{0\nu\beta\beta}$

- good energy resolution required to distinguish the 0νββ peak (2νββ is a background)

Detection of 0νββ:

2. Large detector with significant amount of ββ isotope



Experiment	Isotope	Mass	Technique	Present Status	Location
AMoRE[89][90]	^{100}Mo	50 kg	CaMoO$_4$ scint. bolometer crystals	Development	Yangyang
CANDLES[91]	^{48}Ca	0.35 kg	CaF$_2$ scint. crystals	Prototype	Kamioka
CARVEL[92]	^{48}Ca	1 ton	CaF$_2$ scint. crystals	Development	Solotvina
COBRA[93]	^{116}Cd	183 kg	^{enr}Cd CZT semicond. det.	Prototype	Gran Sasso
CUORE-0[69]	^{130}Te	11 kg	TeO$_2$ bolometers	Construction - 2012	Gran Sasso
CUORE[69]	^{130}Te	203 kg	TeO$_2$ bolometers	Construction - 2013	Gran Sasso
DCBA[94]	^{150}Ne	20 kg	^{enr}Nd foils and tracking	Development	Kamioka
EXO-200[57]	^{136}Xe	160 kg	Liq. ^{enr}Xe TPC/scint.	Operating - 2011	WIPP
EXO[70]	^{136}Xe	1-10 t	Liq. ^{enr}Xe TPC/scint.	Proposal	SURF
GERDA[71]	^{76}Ge	≈35 kg	^{enr}Ge semicond. det.	Operating - 2011	Gran Sasso
GSO[95]	^{160}Gd	2 ton	Gd$_2$SiO$_5$:Ce crys. scint. in liq. scint.	Development	
KamLAND-Zen[96]	^{136}Xe	400 kg	^{enr}Xe disolved in liq. scint.	Operating - 2011	Kamioka
LUCIFER[97][98]	^{82}Se	18 kg	ZnSe scint. bolometer crystals	Development	Gran Sasso
MAJORANA[77][78][79]	^{76}Ge	26 kg	^{enr}Ge semicond. det.	Construction - 2013	SURF
MOON [99]	^{100}Mo	1 t	^{enr}Mofoils/scint.	Development	
SuperNEMO-Dem[87]	^{82}Se	7 kg	^{enr}Se foils/tracking	Construction - 2014	Fréjus
SuperNEMO[87]	^{82}Se	100 kg	^{enr}Se foils/tracking	Proposal - 2019	Fréjus
NEXT [82][83]	^{136}Xe	100 kg	gas TPC	Development - 2014	Canfranc
SNO+[84][85]	^{150}Nd	55 kg	Nd loaded liq. scint.	Construction - 2013	SNOLab

Present/future 0νββ experiments: isotopes, masses, and locations.

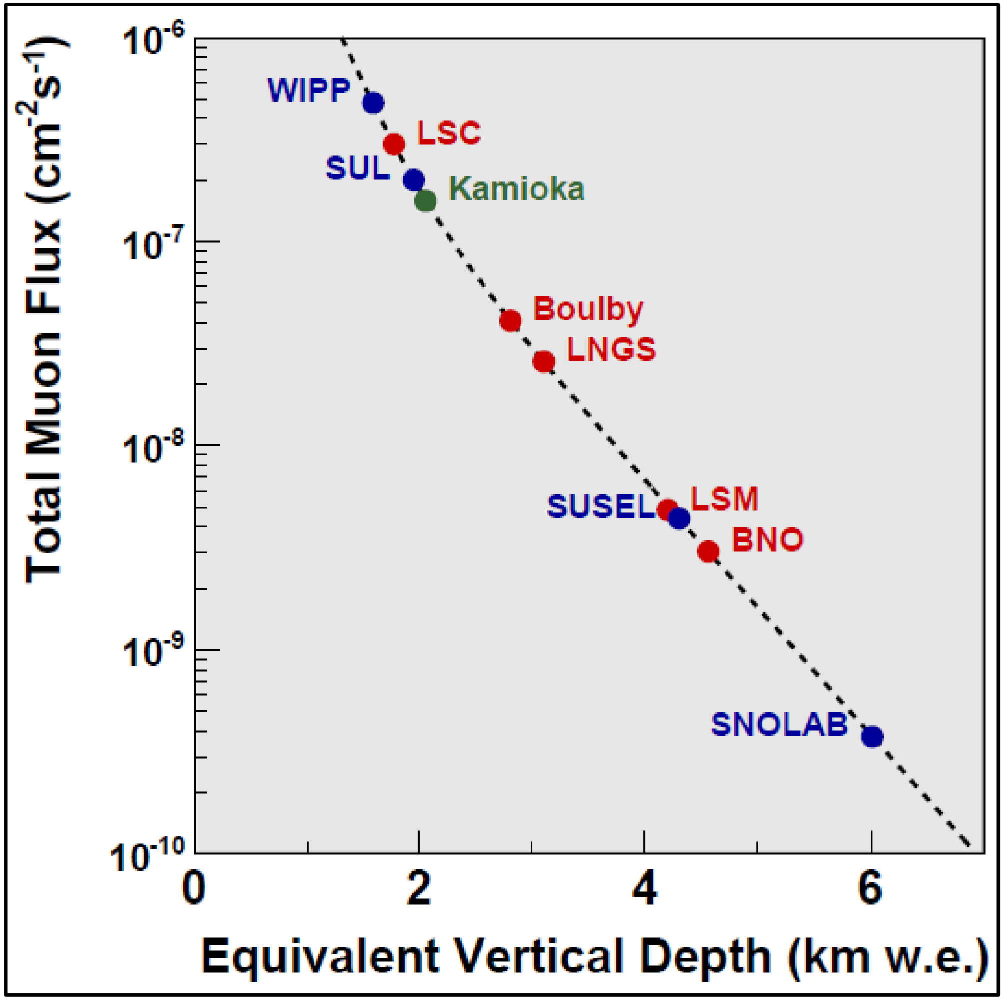
From: S. Elliot. Mod. Phys. Lett. A. 27, 1230009 (2012). (arXiv 1203.1070)

Detection of 0νββ:

3. Low background

Potential background includes cosmic muon interactions and neutrons produced by these muons in rocks

- greatly reduced by placing detector deep underground



Water equivalent depth of several underground labs (from [1]).

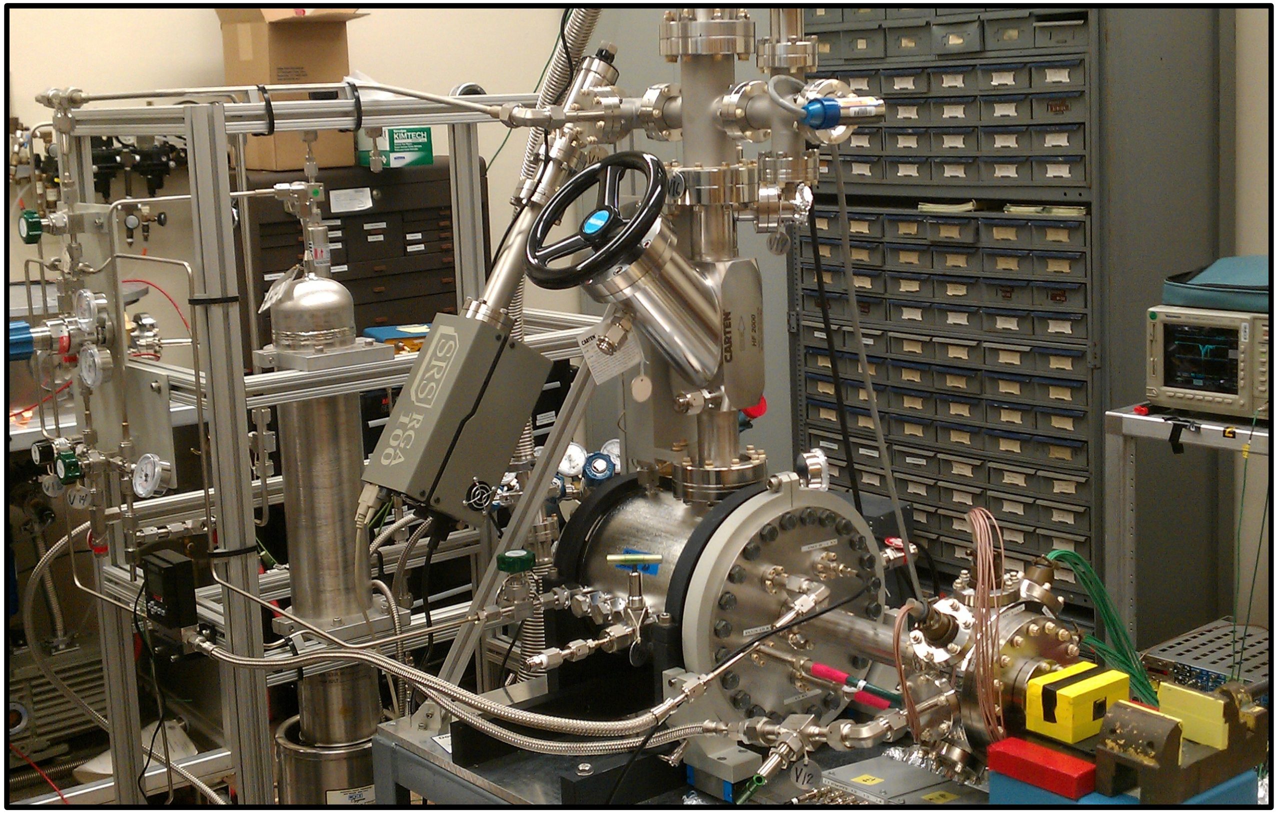
[1] J.J. Gomez-Cadenas *et. al.* Riv. Nuovo Cim. 35 (2012) 29-98. (arxiv:1109.5515)

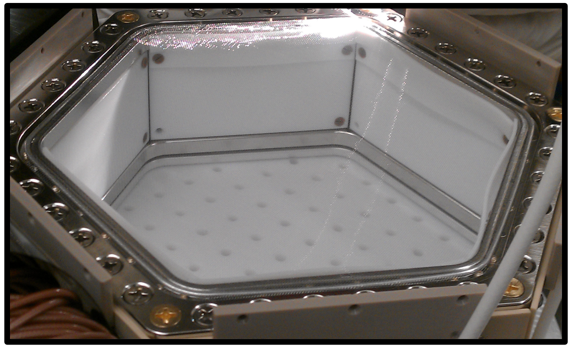
R&D at LBNL

The NEXT-DBDM TPC:

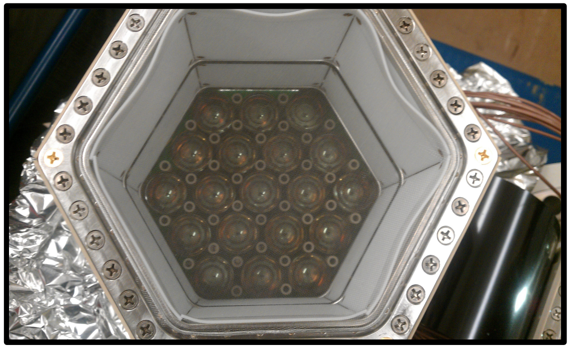
0νββ search with electroluminescence in GXe

- NEXT: **N**eutrino **E**xperiment with a **X**enon **T**PC
- NEXT-DBDM: **NEXT D**ouble-**B**eta **D**ark **M**atter
- Prototype to study energy resolution and tracking [1]





Grid

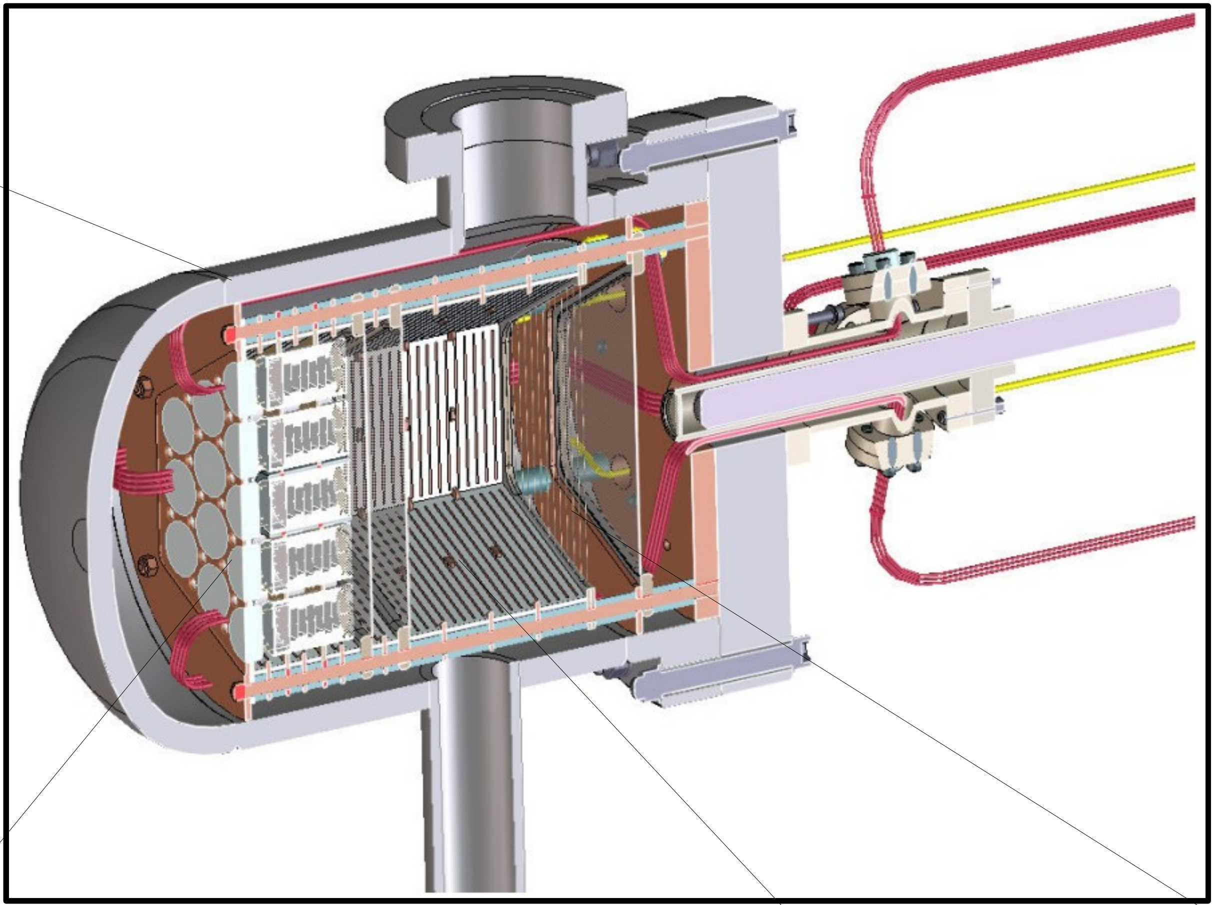


PMT Array

[1] NEXT Collaboration. *Nucl. Instrum. Meth. A* 708, 101 (2013).

The NEXT-DBDM prototype:

Cross-sectional view



10L stainless steel vessel

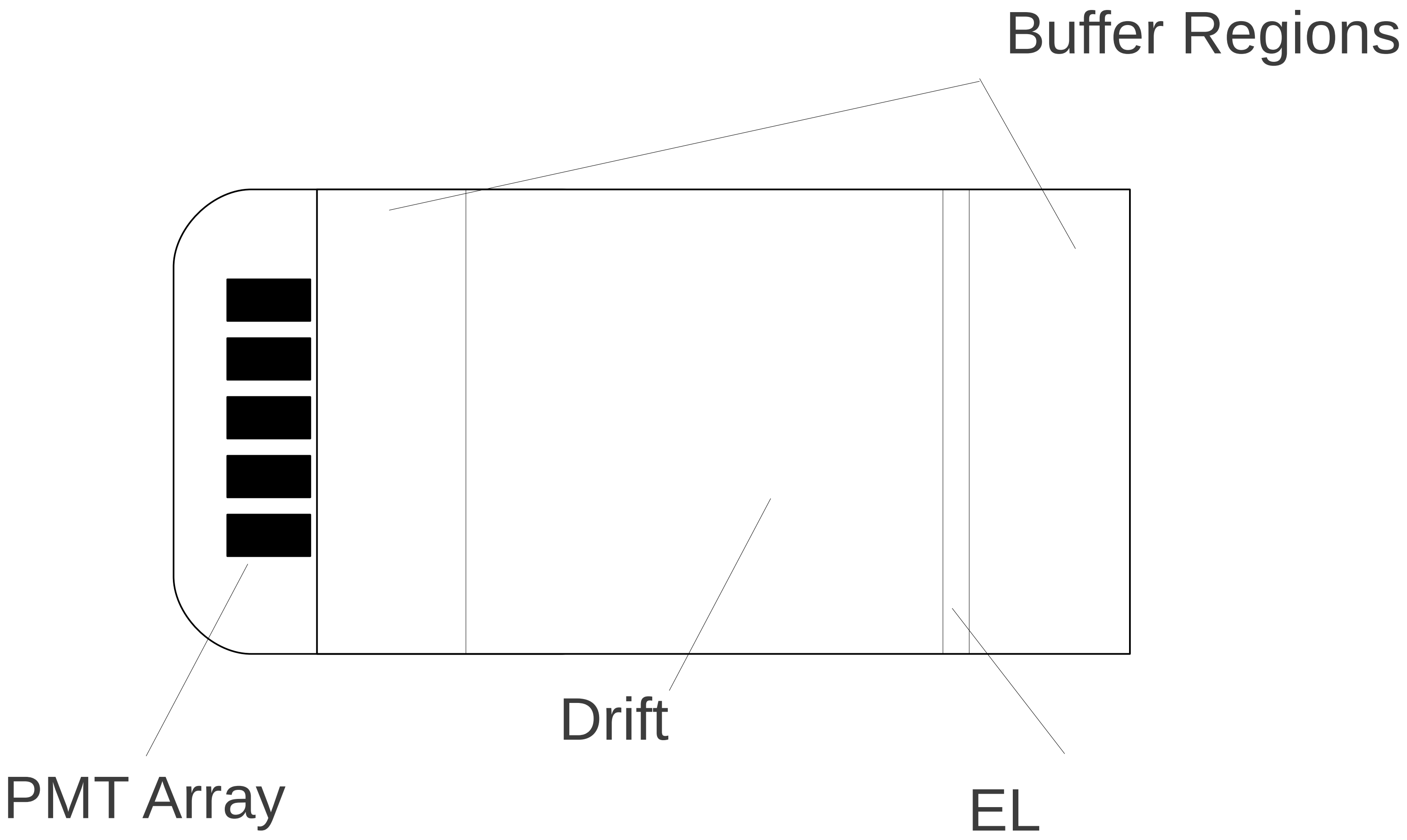
19-PMT array

- Drawing by Robin LaFever

8 cm drift region

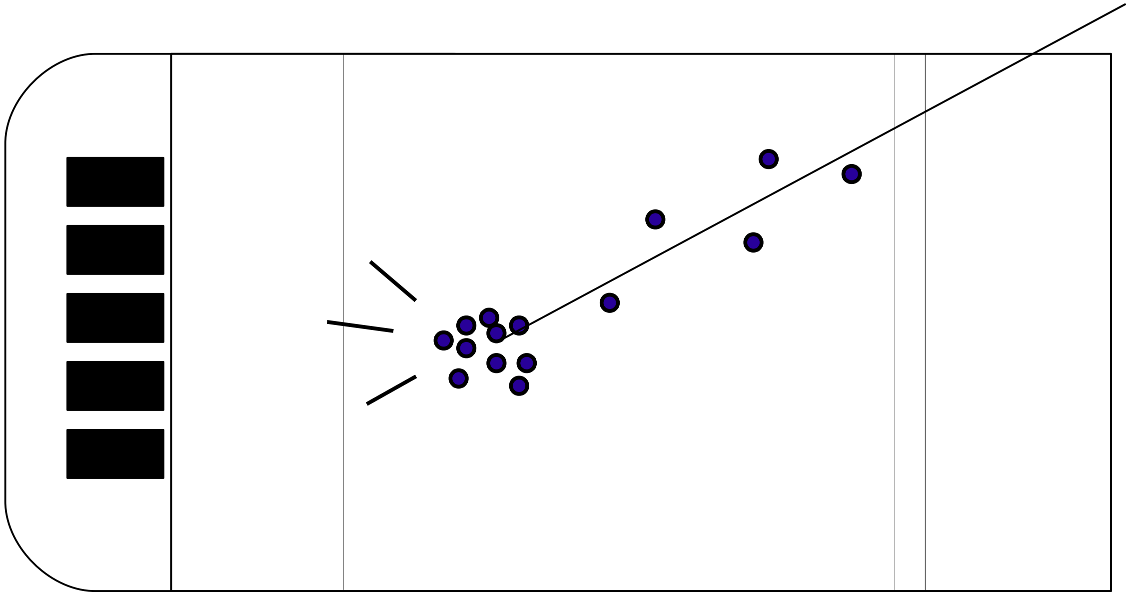
5 mm EL gap

Electroluminescence:



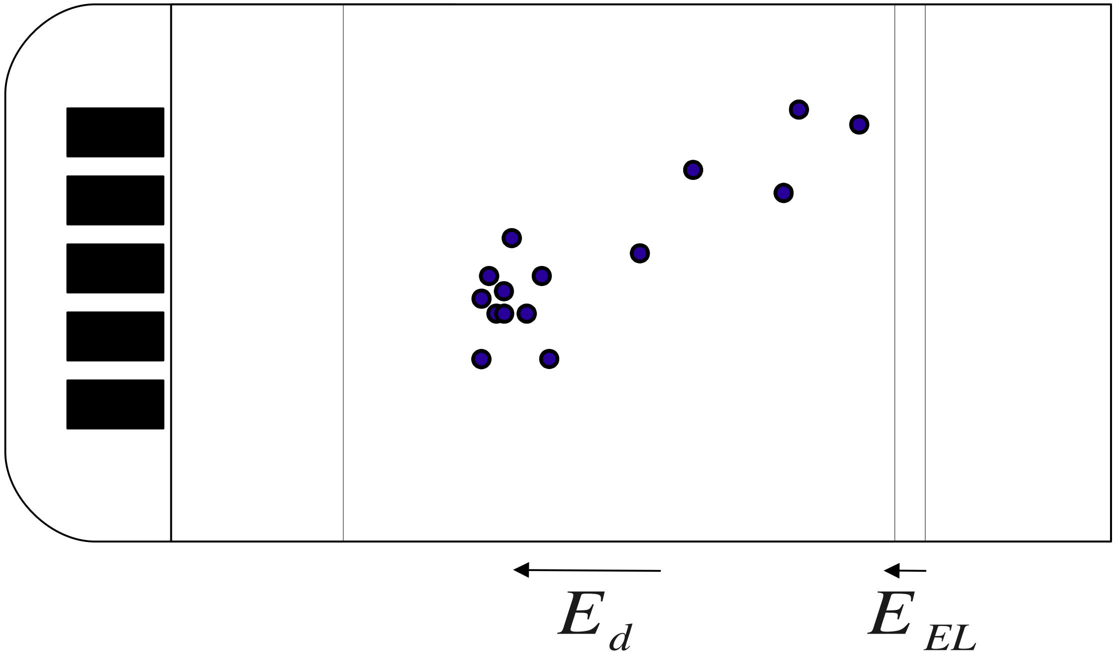
- An electroluminescent TPC: key regions

Electroluminescence:



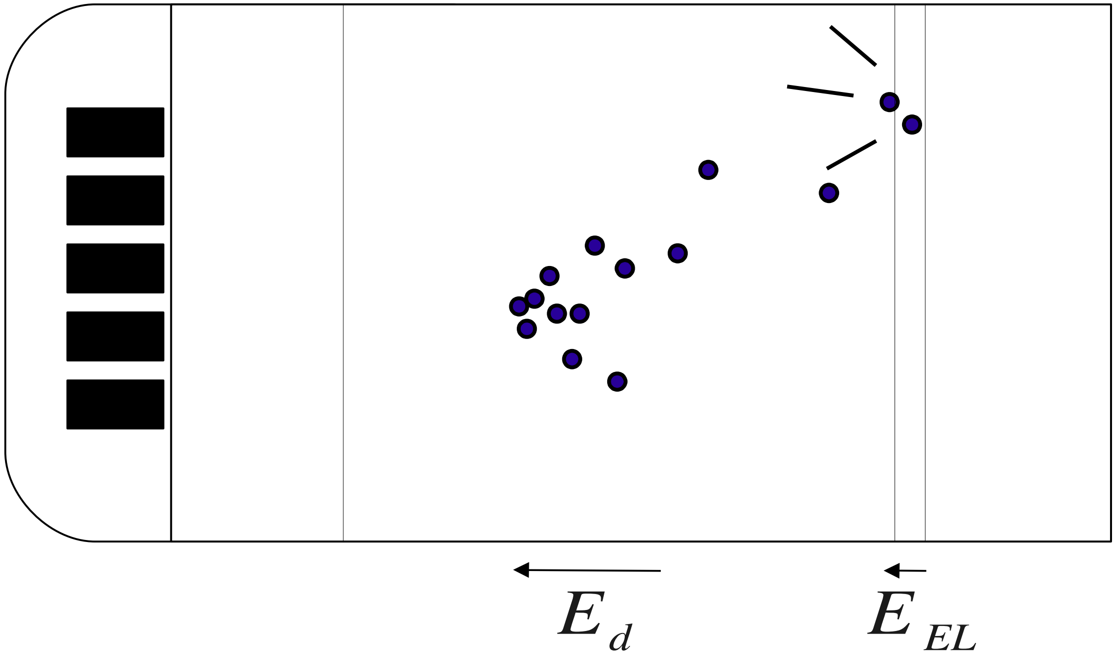
- Incident particle deposits energy, producing ionization (S2) and scintillation (S1)

Electroluminescence:



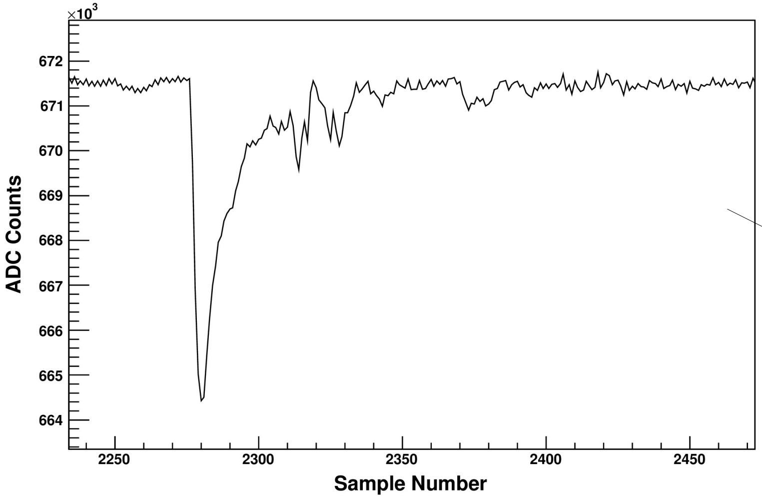
- Electrons drift in an electric field to a narrow region of high field

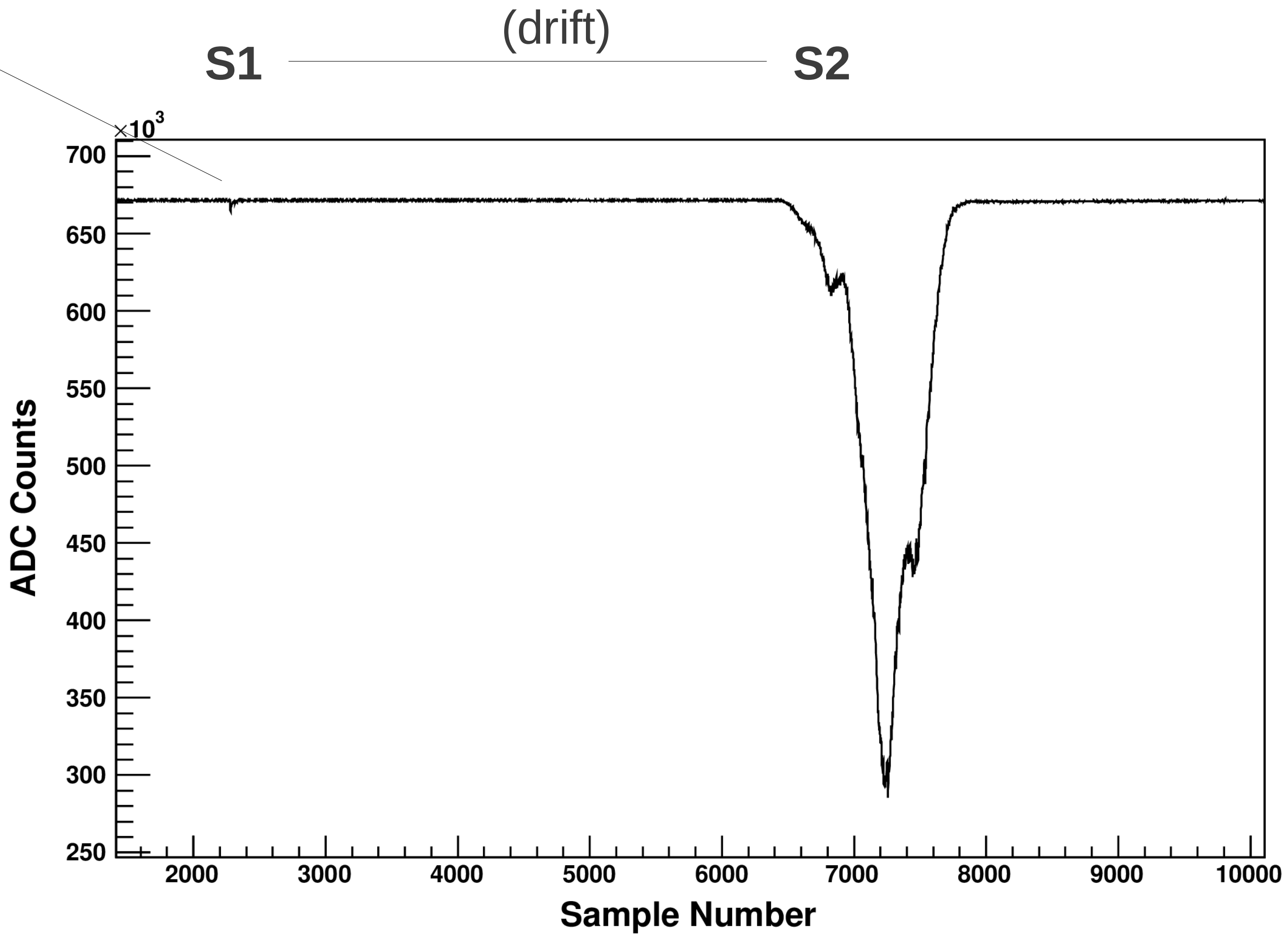
Electroluminescence:



- Xenon medium scintillates as the electrons traverse the EL gap; electrons gain enough energy to excite but not ionize xenon atoms

The NEXT-DBDM prototype:



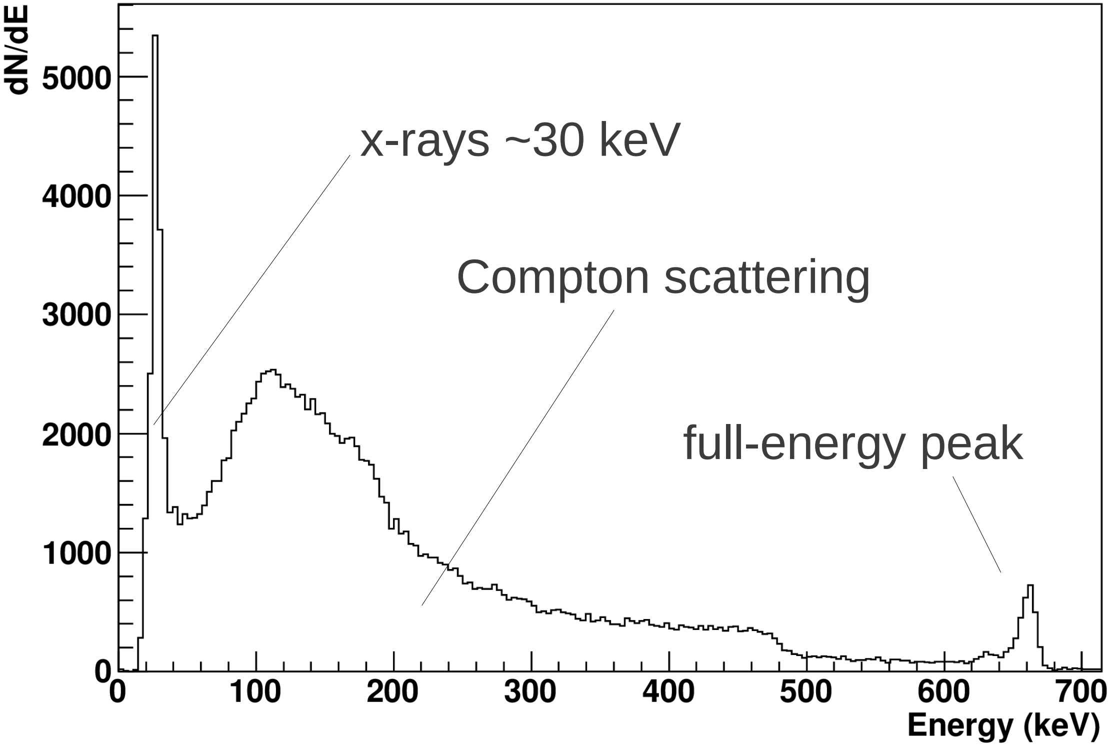


A typical event

The NEXT-DBDM prototype:

Energy spectrum for ^{137}Cs source:

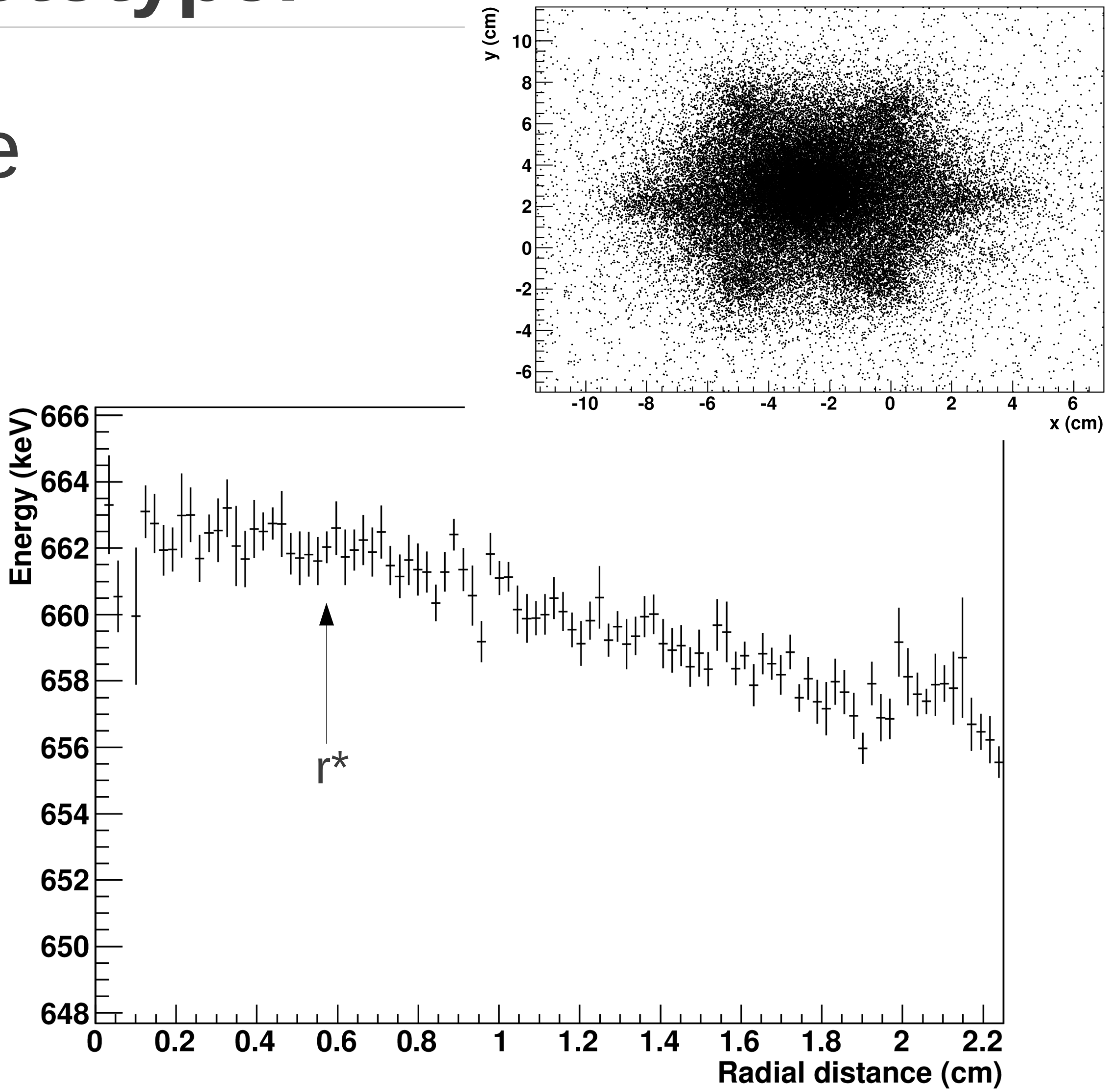
- Peaks integrated and identified as S1 or S2
- S2 proportional to energy of event
- No corrections on physics applied



The NEXT-DBDM prototype:

Position-dependence

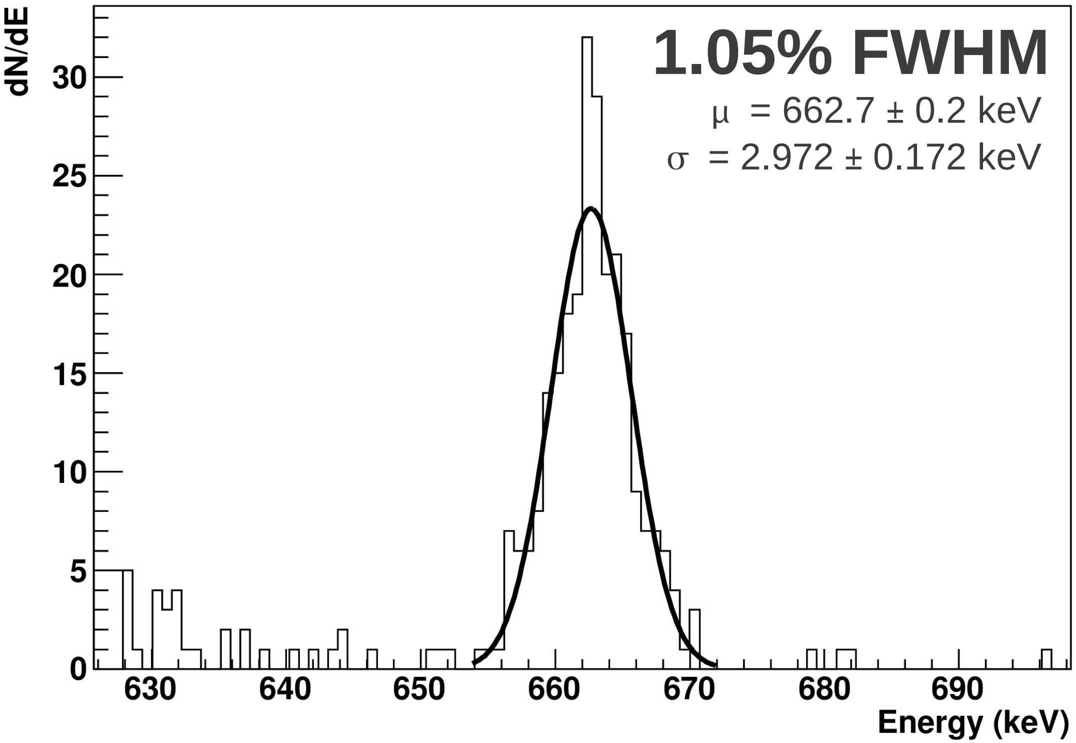
- Events located radially outward from central point register lower in E
- Correct with radial cut (r*) for now
- Better tracking will improve correction capabilities



The NEXT-DBDM prototype:

Energy resolution

- Cut on event radius r* and valid S1
- Near-1% FWHM resolution at 662 keV
- Extrapolate to $Q_{\beta\beta}$= 2458.7 keV [1]: ~0.52% FWHM

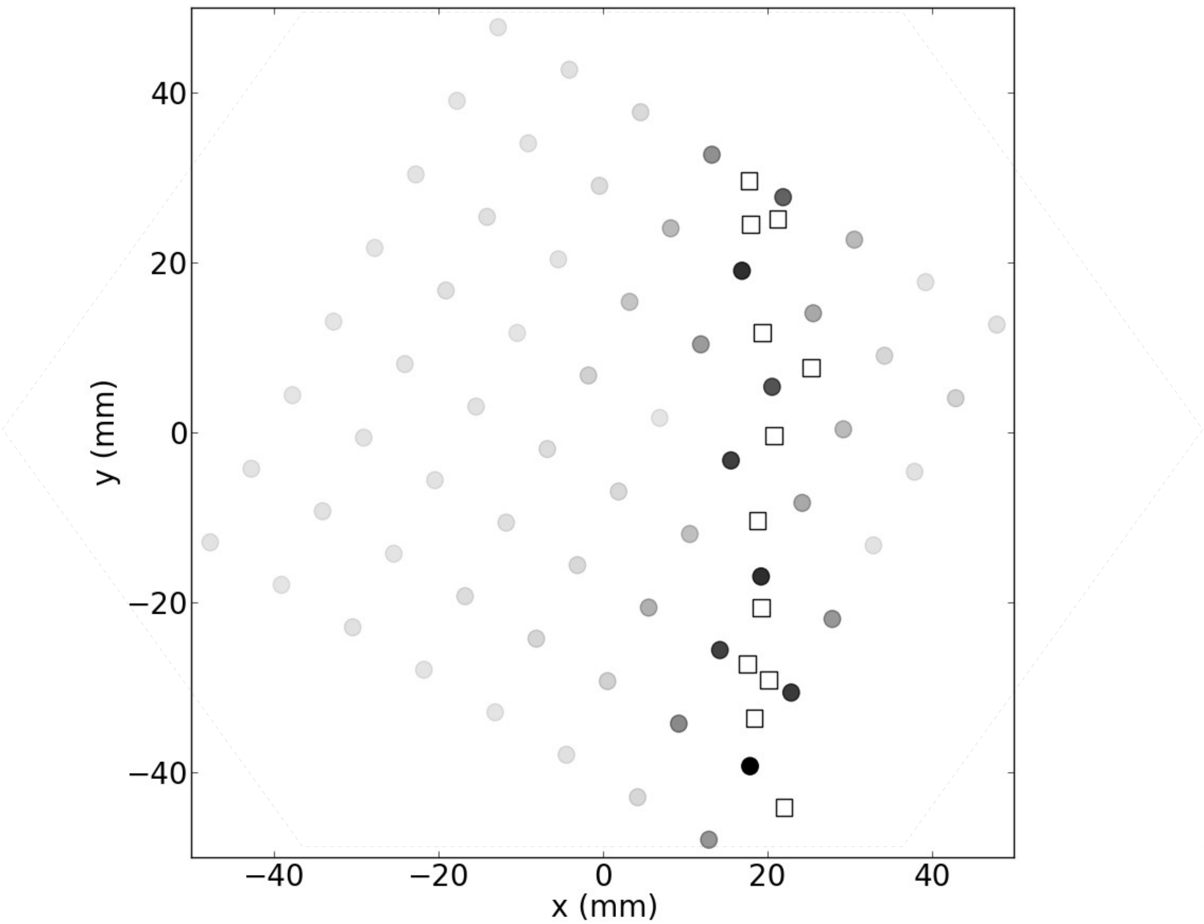


[1] McCowan and Barber. *Phys. Rev. C* 82, 024603 (2010).

The NEXT-DBDM prototype:

Tracking

- 64-SiPM (silicon photomultiplier) plane, 1 cm spacing; provides pixelated photon detection



A reconstructed muon track; SiPMs shown shaded relative to total intensity, and squares are reconstructed points.

NEXT-100:

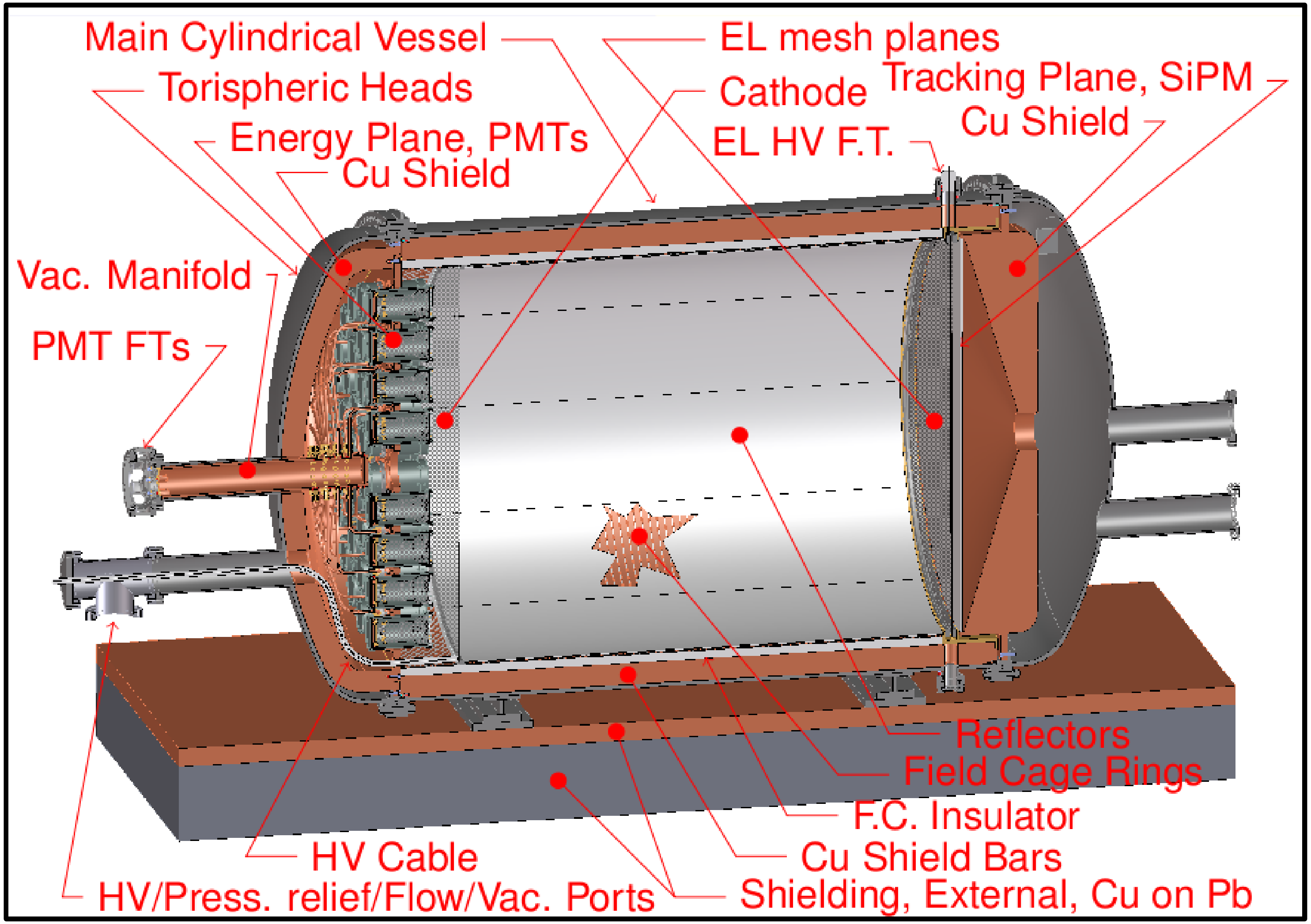
NEXT-100 (Canfranc, Spain):

- up to 150 kg of Xe, enriched to isotope ^{136}Xe
- main vessel is cylindrical, 1.36 m diameter, 2.28 m length
- ~7000 SiPM-tracking plane; 60 3-in. PMT energy plane
- expected resolution near 0.5% FWHM at $Q_{\beta\beta}$

General reference: NEXT Collaboration. JINST 7 T06001 (2012).

NEXT-100:

A high pressure Xe TPC:



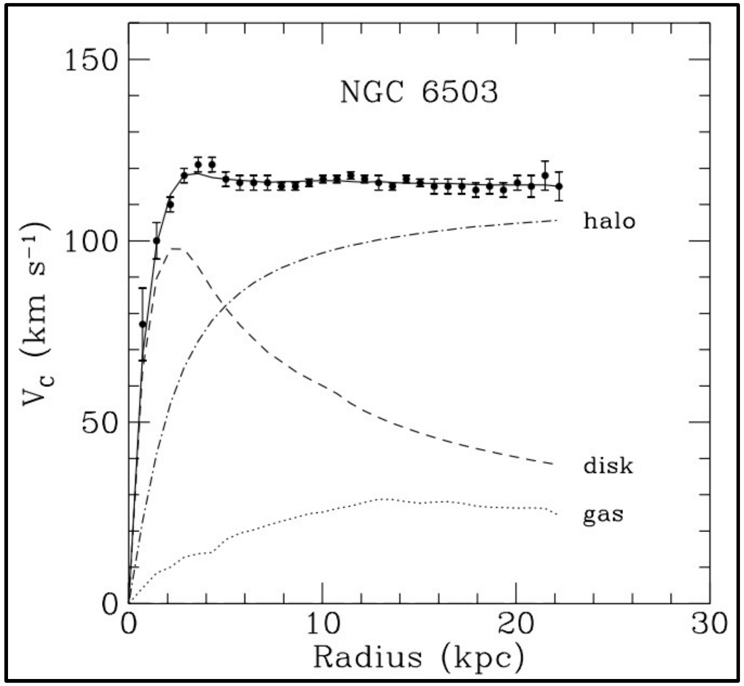
- Drawing by Derek Shuman

Dark Matter

Dark Matter in Our Universe:

How do we know it exists?

- velocities of astronomical objects (rotation of mass in galaxies) unexpected



From: Bertone *et. al.* arxiv0404175v2.

From: Chandra X-Ray Observatory.
Photo 1E 0657-56.
http://chandra.harvard.edu/photo/2006/1e0657

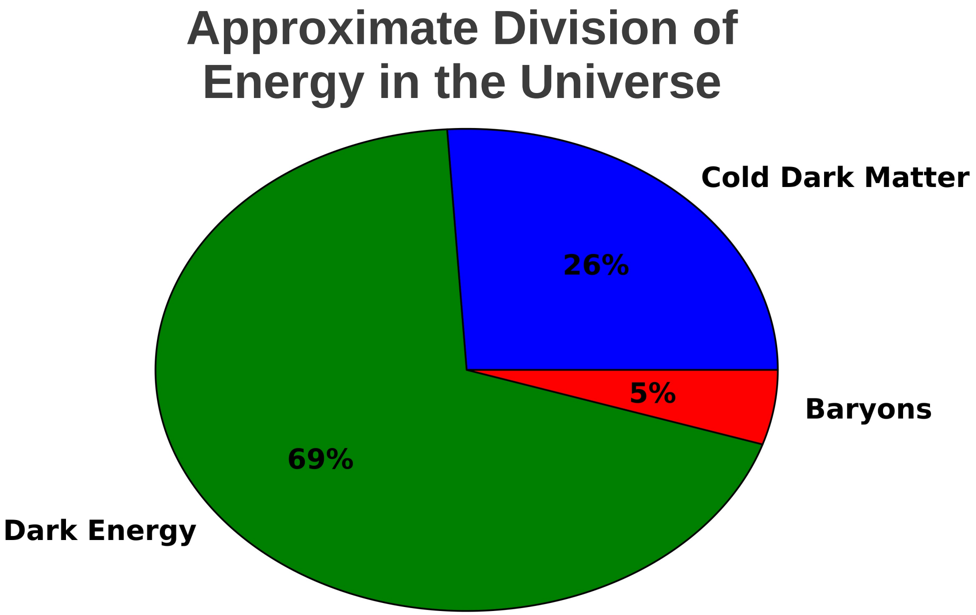
- x-ray and weak lensing imaging

General reference: J. Beringer et al. (Particle Data Group), Phys. Rev. D86, 010001 (2012).

Dark Matter in Our Universe:

What could it be?

- black holes created before synthesis of light elements
- axions: particles proposed in context of QCD
- massive (keV) sterile neutrinos
- **WIMPs:** weakly interacting massive particles



– Data from Planck 2013 results. I.
(Astronomy & Astrophysics manuscript, 2013)

General reference: J. Beringer et al. (Particle Data Group), Phys. Rev. D86, 010001 (2012).

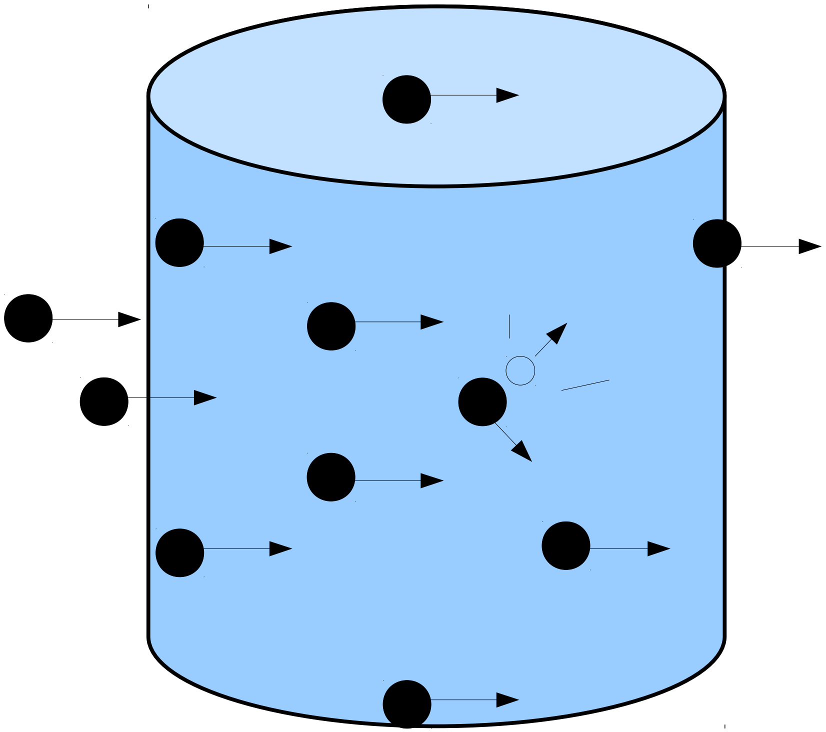
Detection of Dark Matter:

Three general methods [1]:

1. In accelerators such as the LHC
2. Indirectly (e.g., gamma and neutrino fluxes on Earth)
3. **Directly (underground detectors)**

WIMP direct detection [2]:

- Measure energy of WIMP elastic scattering on nuclei
- Large detector, low background, long time
- Rate depends on M_{WIMP} and σ_{WIMP}
- Must have a way to distinguish nuclear recoils from gamma background

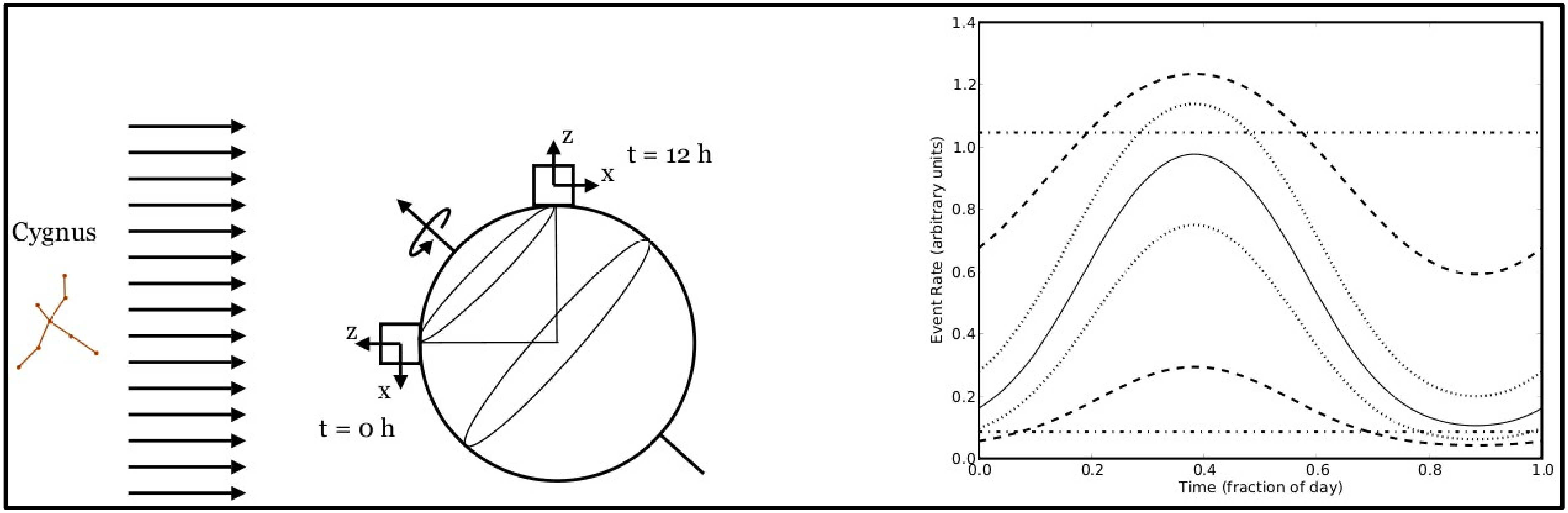


[1] Ahlen *et. al.* arXiv:0911.0323.
[2] J. Beringer et al. (Particle Data Group), Phys. Rev. D86, 010001 (2012).

Detection of Dark Matter:

A dark matter wind:

- Velocity of local WIMP density depends on [1]:
  1. Velocity of the sun in galactic rest frame
  2. Velocity of the earth about sun (annual rate modulation)
  3. Rotational velocity of the earth (daily angular modulation)
- Detecting the direction of a WIMP interaction is important



∡ From equator

-90^{o}

-54^{o}

-18^{o}

0^{o}

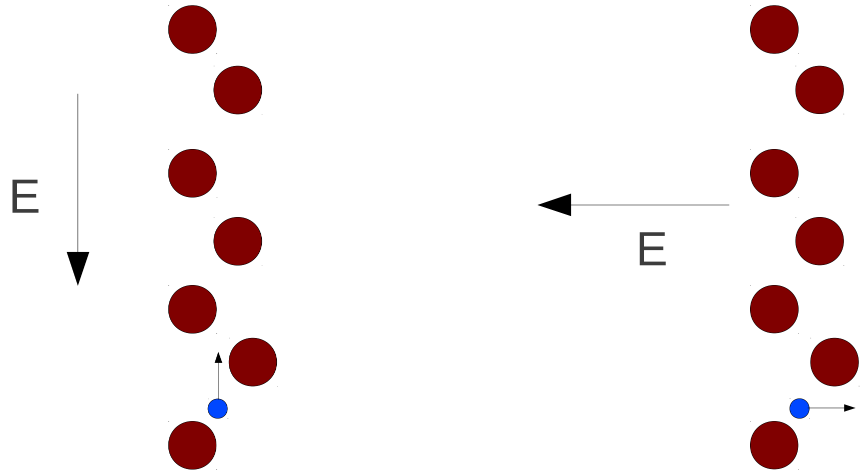
From: Ahlen *et. al.* arXiv:0911.0323

[1.] Drukier *et. al.* Phys. Rev. D 33, 3495 (1986).

Detection of Dark Matter:

Measuring directionality:

- Recombination signal could be used to determine nuclear recoil direction relative to an external field: new idea of Dave Nygren



More columnar recombination

Less columnar recombination

Understanding the response of xenon to nuclear recoils is important to quantifying this effect

[1] Ahlen *et. al.* arXiv:0911.0323.

Nuclear vs. Electron Recoils:

Studies in liquid Xe; gas Xe should be similar

- S2/S1 nuclear recoil discrimination
- use neutrons to produce nuclear recoils for calibration

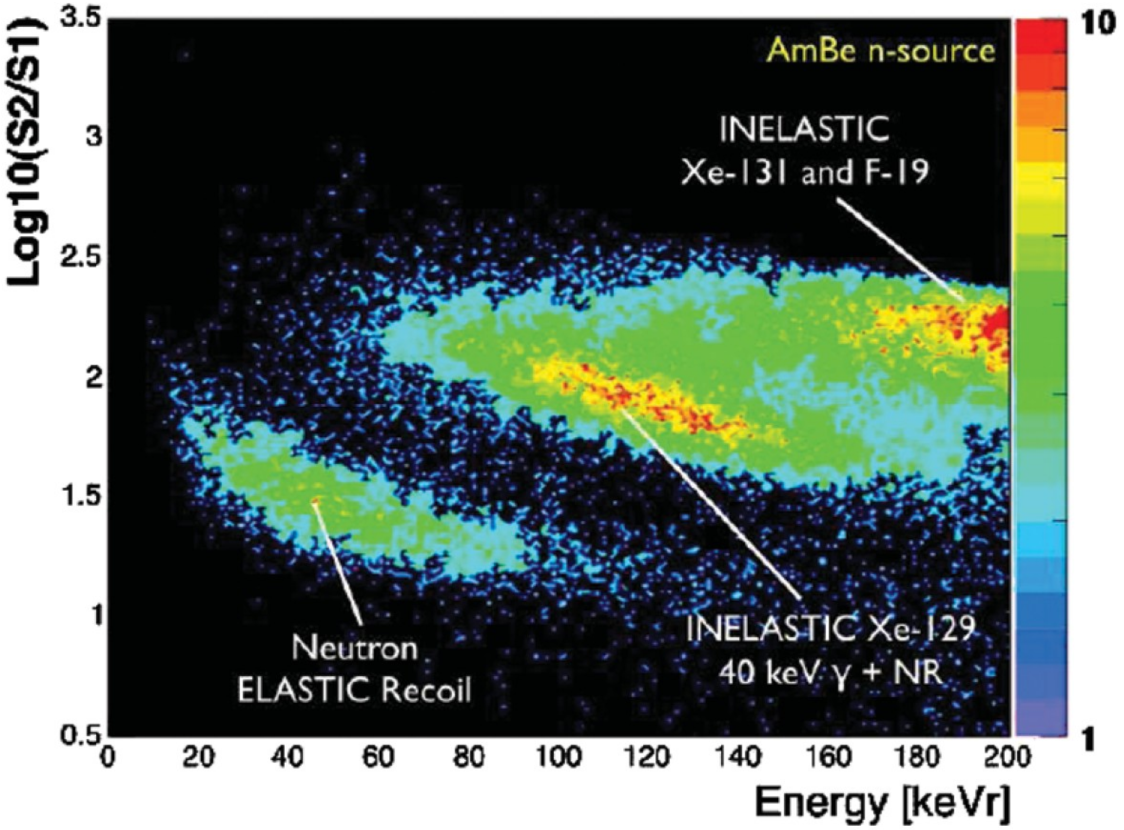
Example: XENON prototype [1]

5 Ci Am/Be neutron source

- 5 pe/keVee (1 pe/keVr) S1
- 8.4 pe/electron S2
- >~7.5% light collection efficiency

We attempt similar measurements in ~14 bar gaseous xenon

From: E. Aprile *et. al*. PRL 97, 081302 (2006)

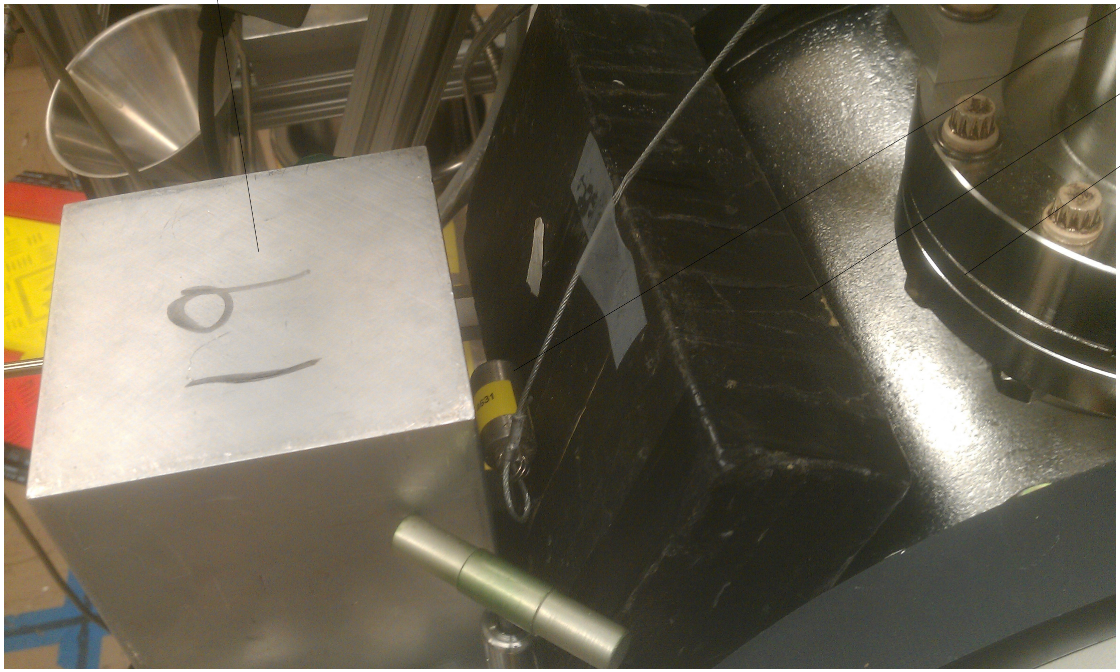


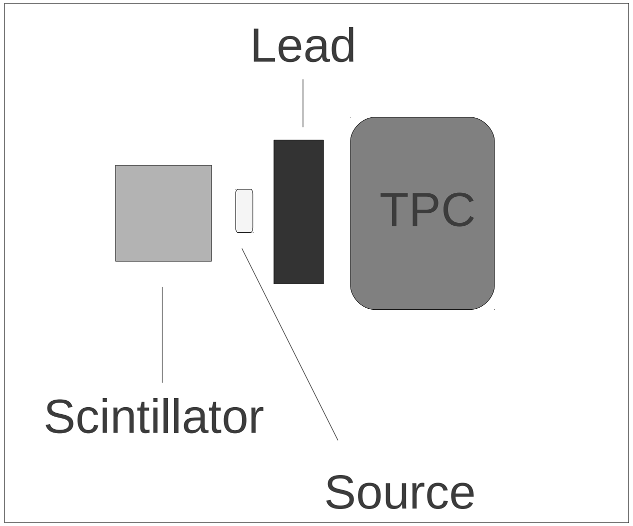
[1] E. Aprile *et. al*. *Phys. Rev. Lett.* 97, 081302 (2006)

Preliminary Detection of Nuclear Recoils:

Neutron source ^{238}Pu/Be (10 mCi ^{238}Pu):

- Approx. 20000 neutrons/second
- Tag 4.4 MeV gamma ray coincident with large % of neutrons
- Max neutron energy $E_n \approx 6$ MeV
- Max recoil energy [1] $[4A/(1+A)^2]E_n \approx 175$ keV





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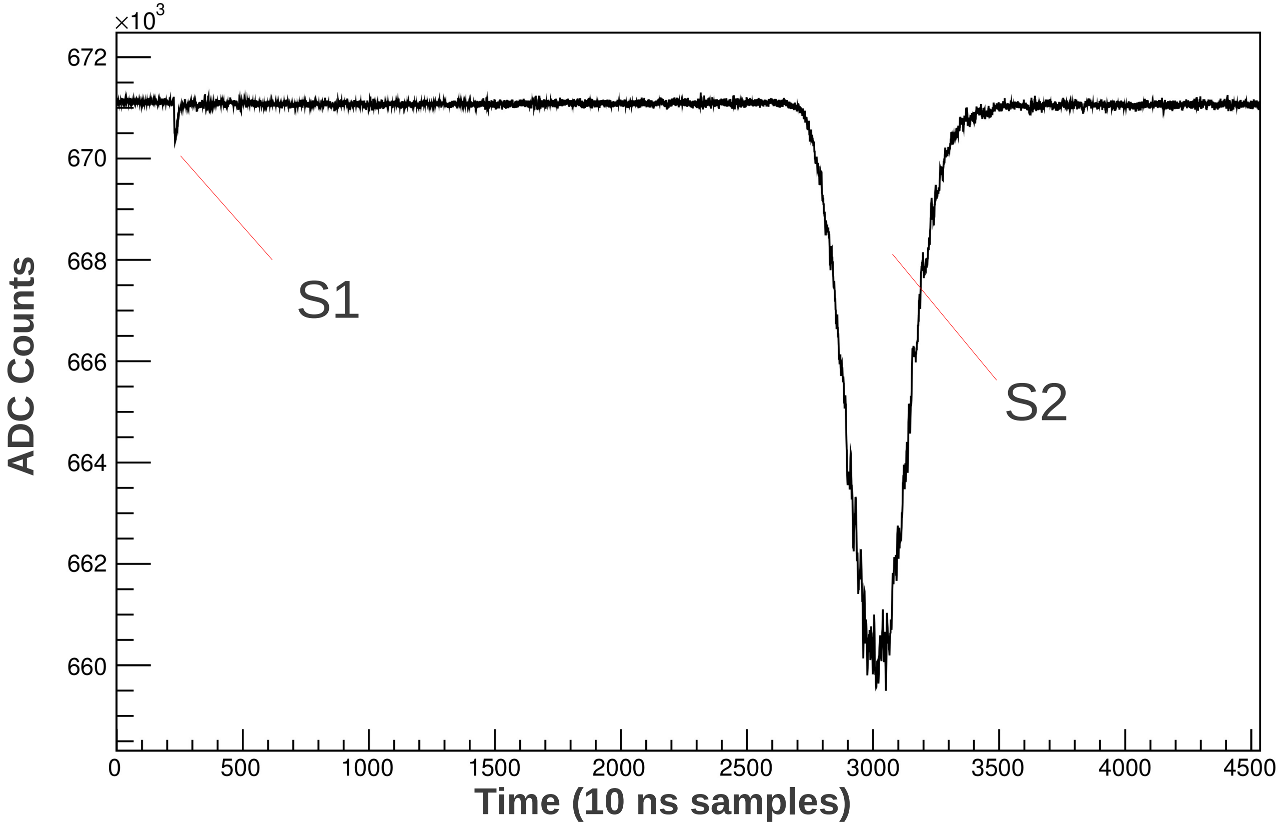
[1] G. Knoll. *Radiation Detection and Measurement, 3rd. ed.* Wiley, Hoboken, NJ (2000).

Preliminary Detection of Nuclear Recoils:

Example of a candidate neutron event:

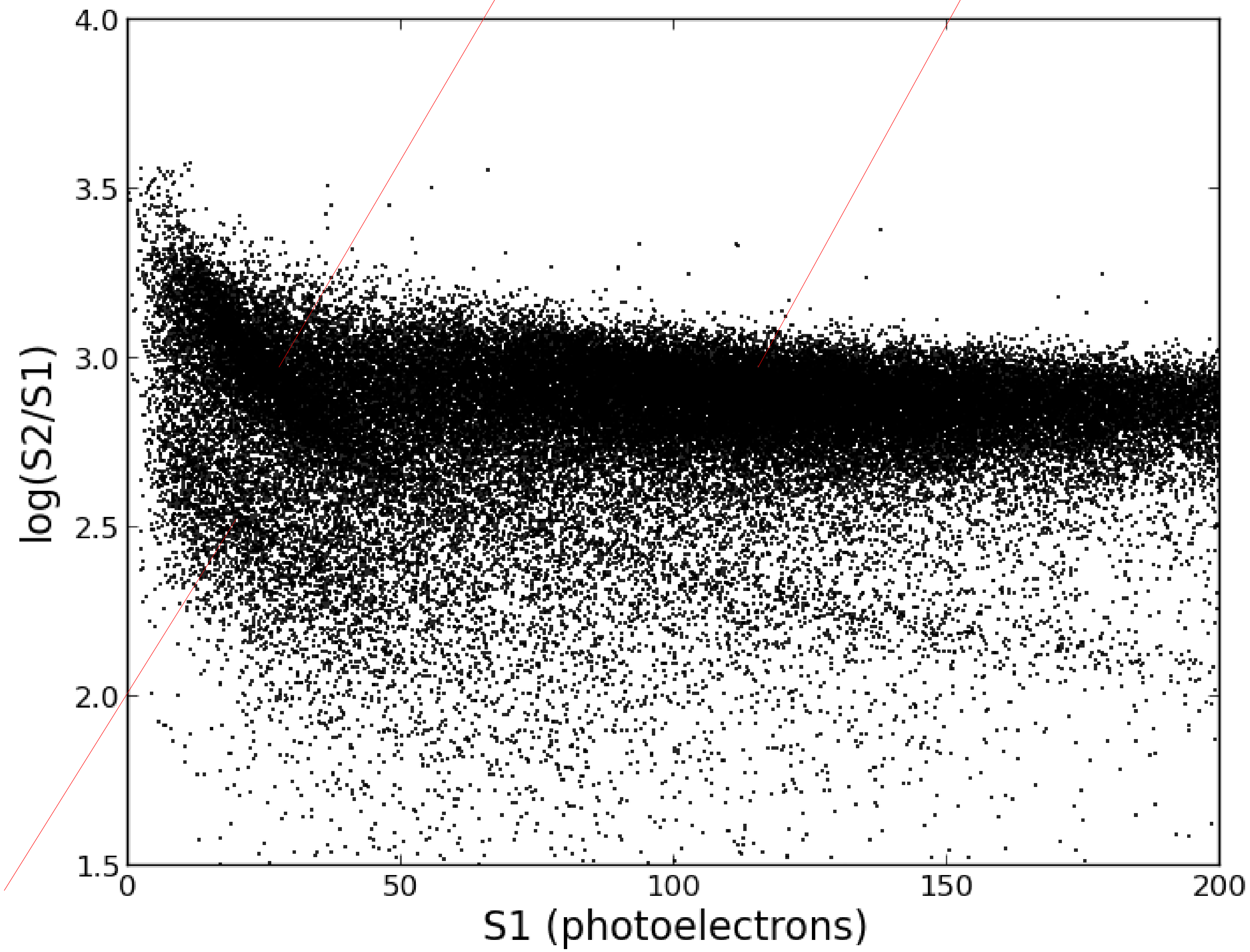
- nuclear recoil produces a short track
- single, Gaussian-shaped pulse



* Thanks to Yasuhiro Nakajima for reducing our electronic noise significantly

Preliminary Detection of Nuclear Recoils:

S2/S1 recoil identification (~14 bar gaseous Xe)



Xenon x-rays

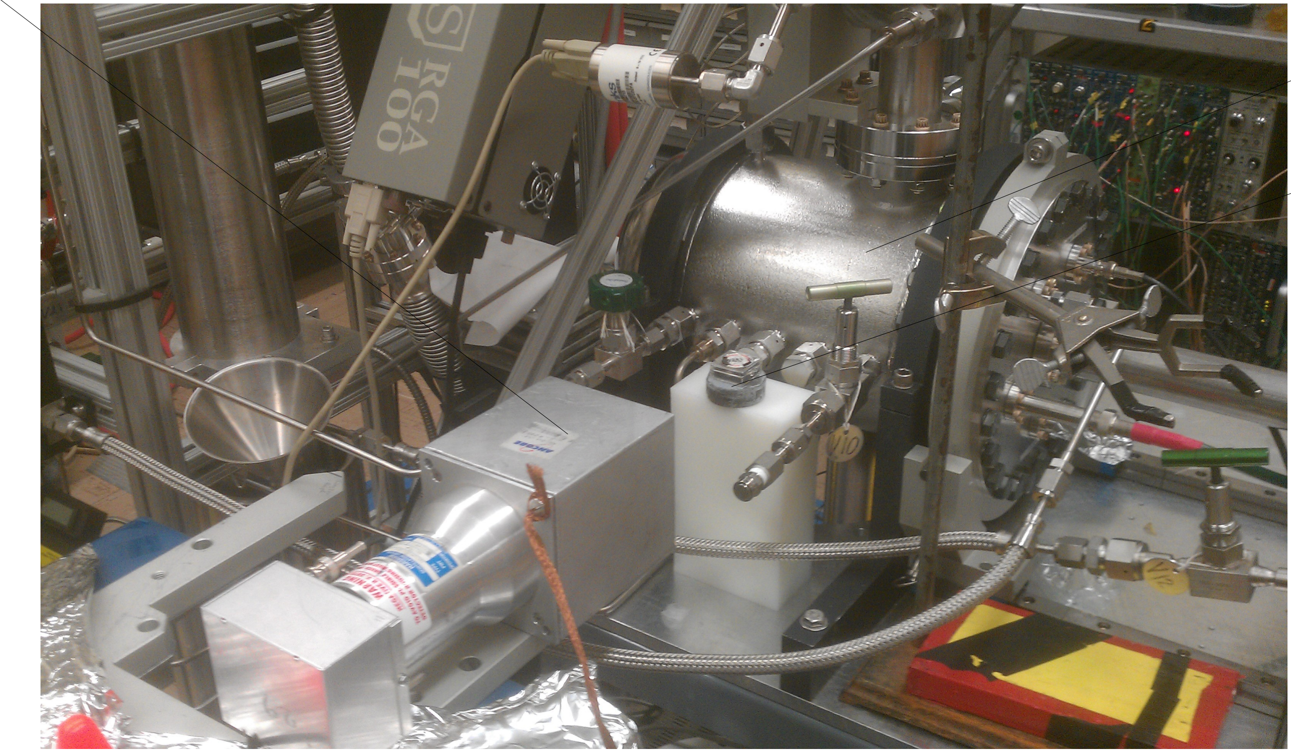
Higher-energy γs

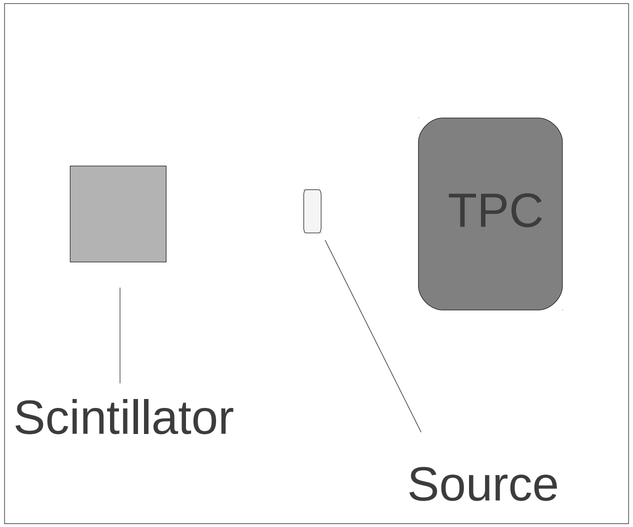
Nuclear recoils

Preliminary Detection of Nuclear Recoils:

Electron-positron annihilation radiation

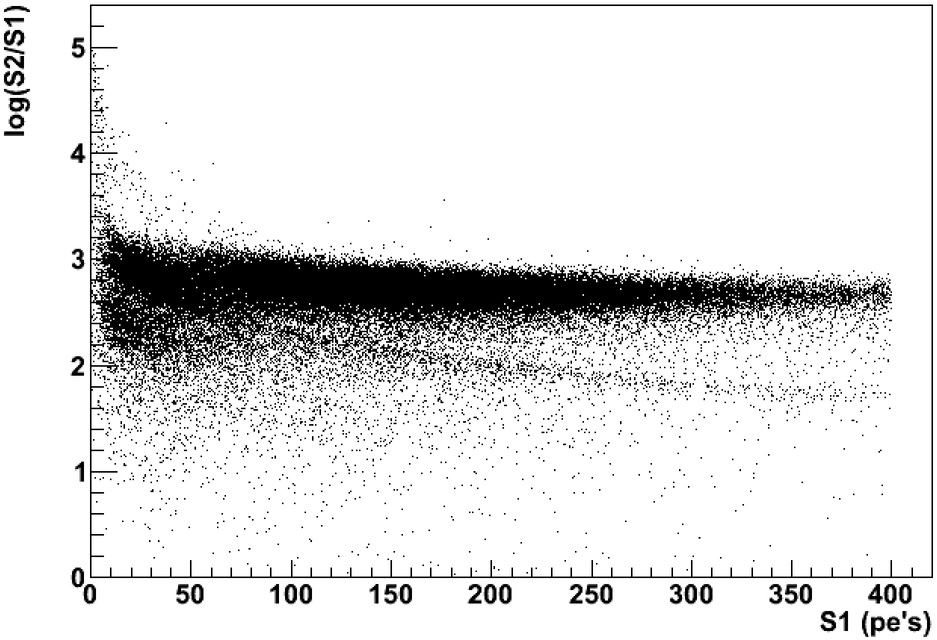
- Coincidence between collinear 511 keV gamma rays
- Same trigger conditions as neutron run (except NaI scintillator region of interest)

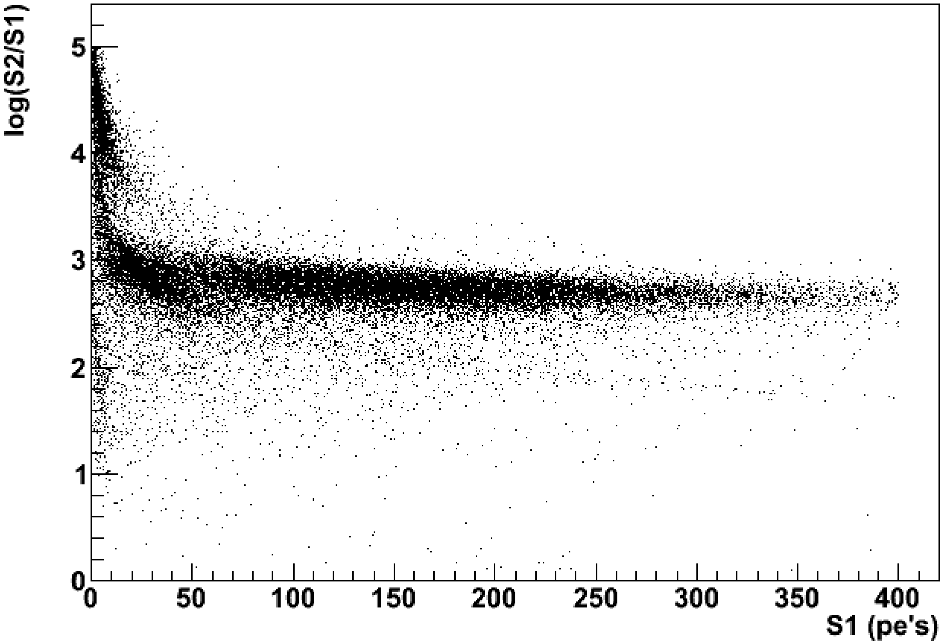




Preliminary Detection of Nuclear Recoils:

S2/S1 recoil identification: γ vs. neutron sources

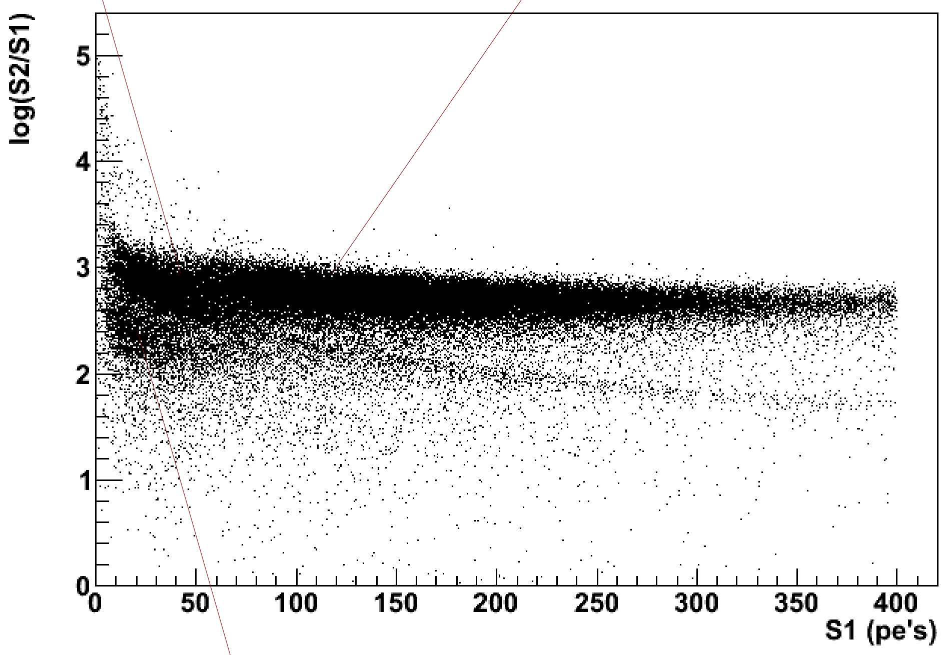




Neutron source

Gamma source

Preliminary Detection of Nuclear Recoils:

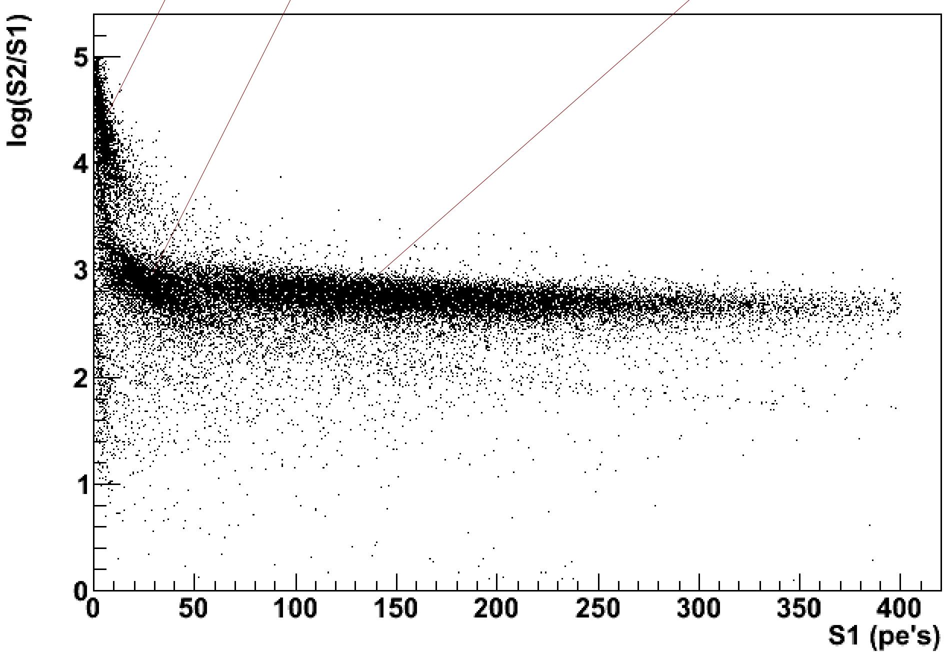


X-rays

Higher-energy γ's (inelastic scatters)

Nuclear recoils

Neutron source



Noise S1s with high-energy γ's

X-rays

Higher-energy γ's

Gamma source

Summary:

0νββ, if detected, has several key implications:

- Violation of total lepton number
- Majorana nature of neutrinos
- Neutrino mass hierarchy and scale (some information whether 0νββ is detected or not)

Gaseous xenon has proven capable of good energy resolution and tracking capabilities needed for a competitive 0νββ experiment

The nature of dark matter is still uncertain, and xenon gas may be a method of direct detection; further development is under way

Acknowledgements:

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- the National Energy Research Scientific Computing Center (NERSC), supported by the Office of Science of the U.S. Department of Energy, (Contract No. DE-AC02-05CH11231)

- a Department of Energy National Nuclear Security Administration Stewardship Science Graduate Fellowship, (Contract No. DEFC52-08NA28752)

Special thanks to the DOE NNSA SSGF and Krell Institute!

Thank You

Additional Slides

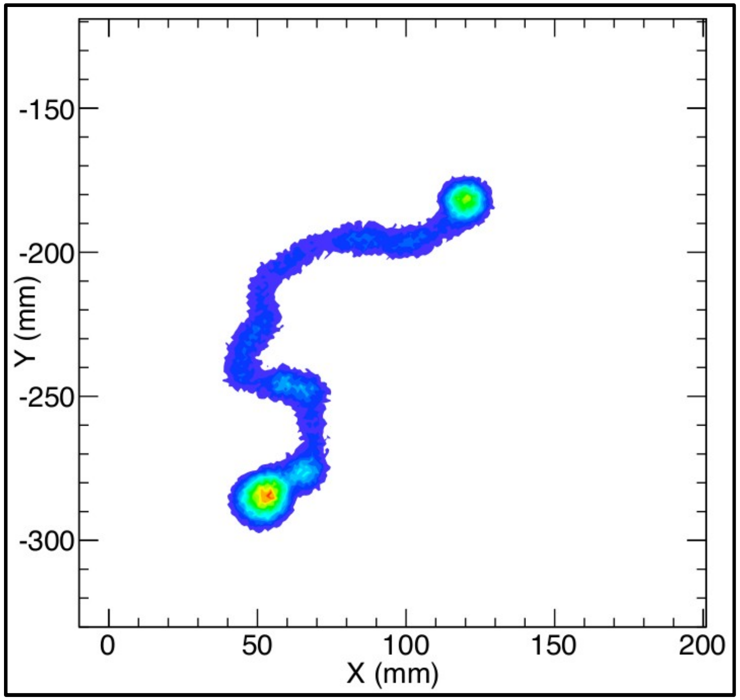
Detection of 0νββ:

3. Low background

Additional mechanisms for background reduction include:

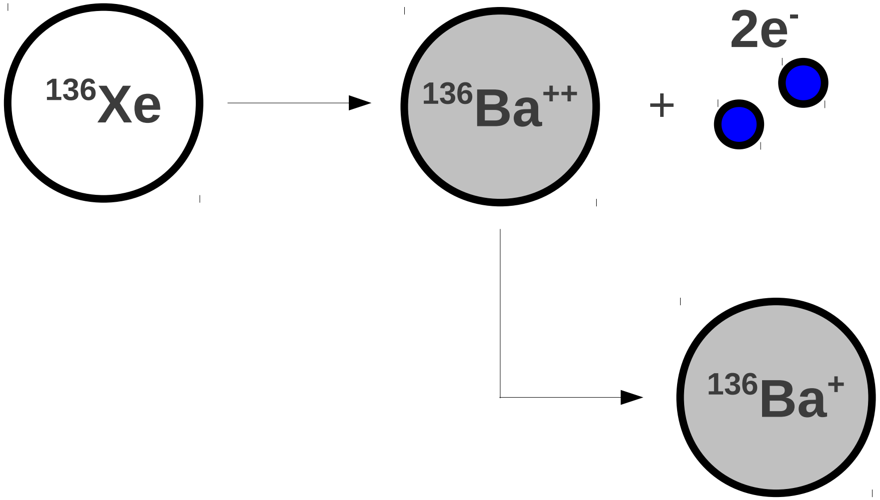
- identification of 2e- track

- tagging of the daughter ion



Simulated ββ 2-electron track.

From: NEXT Collaboration. Conceptual Design Report. arXiv 1106.3630..



EXO [1] is working towards extracting/identifying this Ba+ ion from liquid xenon

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[1] EXO Collaboration. JINST 7 P05010 (2012).

Previous ββ experiments:

Began search for 0νββ, some observed 2νββ:

- Source = detector:
  - → ^{76}Ge, few kg (Heidelberg-Moscow and IGEX)
  - → ^{136}Xe, xenon gas TPC, 3.3 kg enriched to (Gotthard)

- Source ≠ detector:
  - → Geochemical (measure excess of ββ daughter isotope)
  - → Thin-foil sources (small mass, but use of tracking detectors to significantly reduce background - Irvine TPC, ELEGANT, and NEMO)

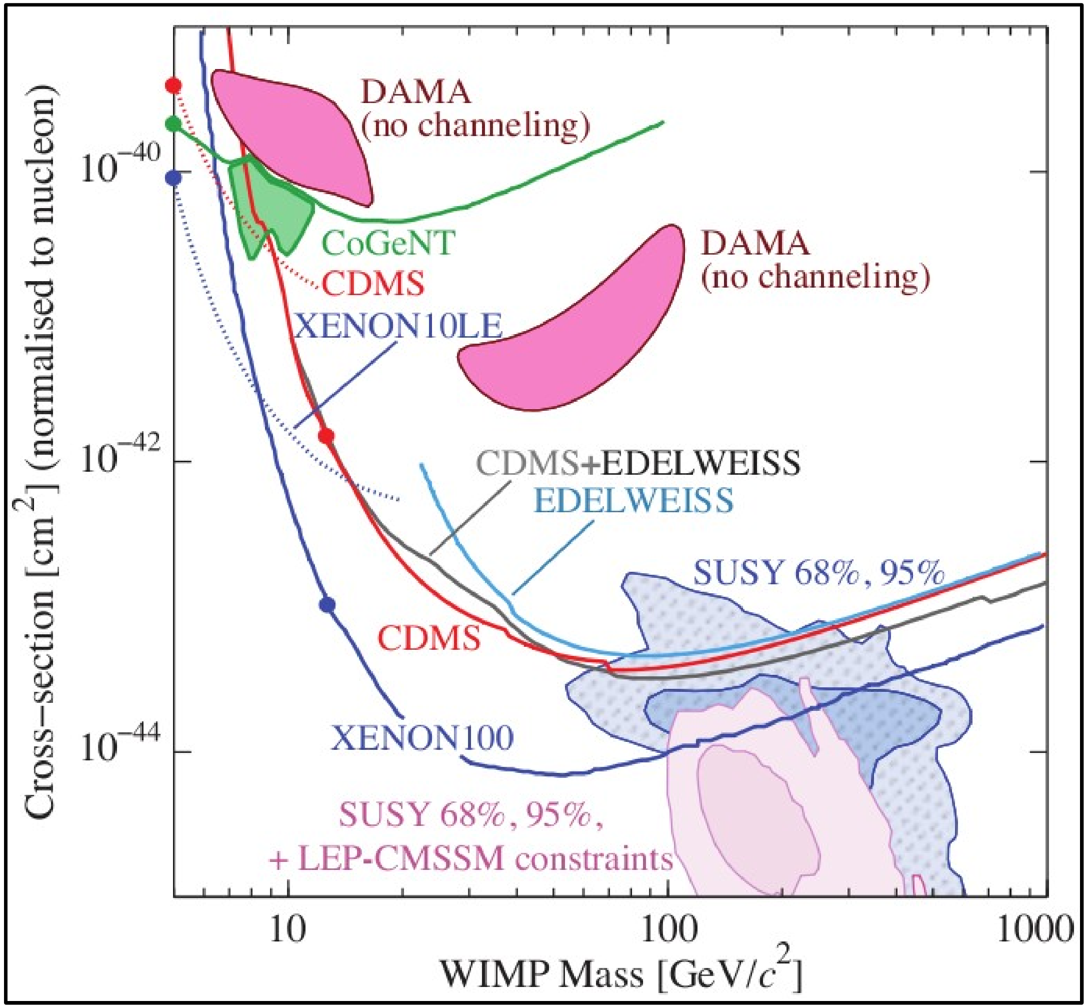
- No widely accepted evidence of 0νββ (though 1 claim)

General references: S. Elliott and P. Vogel. Annu. Rev. Nucl. Part. Sci. 52, 115 (2002).
J.J. Gomez-Cadenas *et. al.* Riv. Nuovo Cim. 35, 29 (2012). (arxiv:1109.5515)

Detection of Dark Matter:

Direct detection limits

- Spin-independent cross section limits
- Note several claims (DAMA, CoGeNT, and another by CRESST[1] not shown) seem to be excluded by low-background experiments

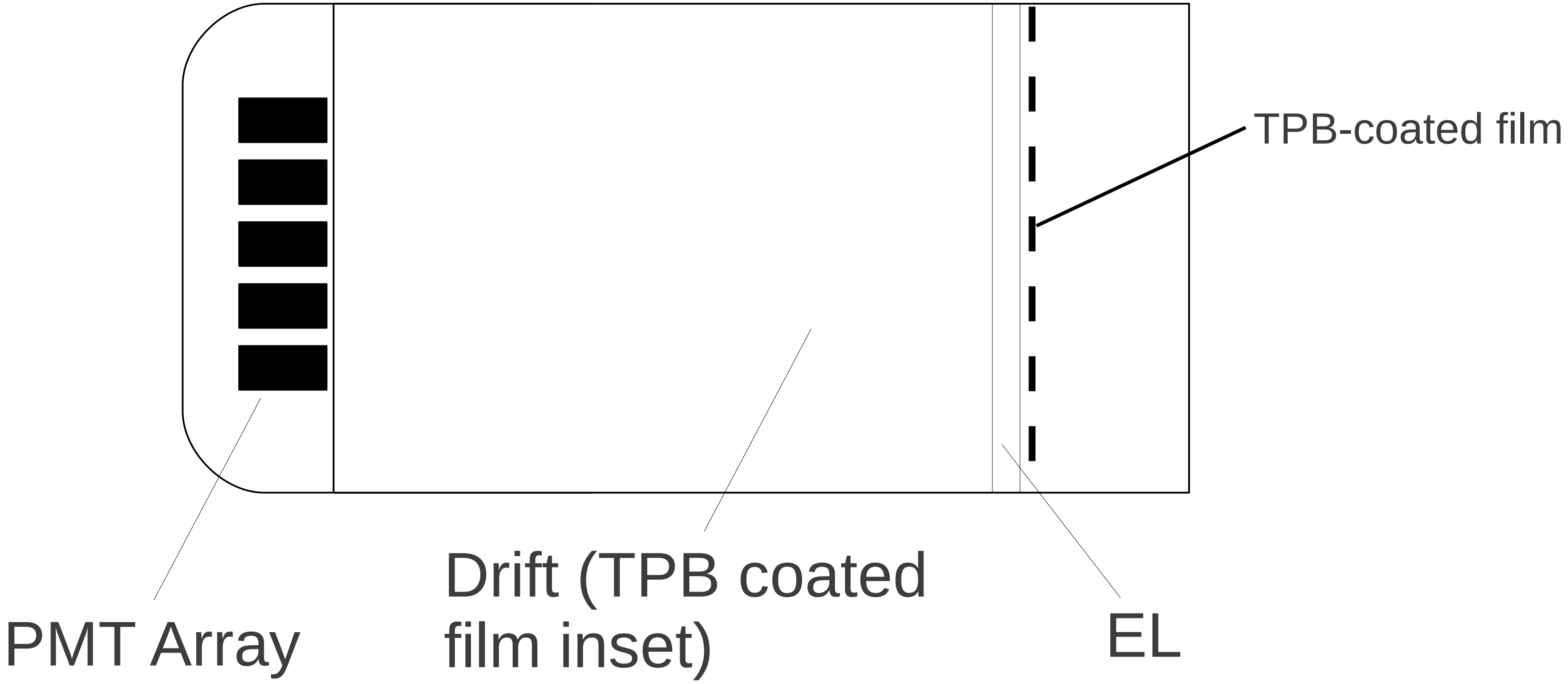


From: J. Beringer et al. (Particle Data Group), Phys. Rev. D86, 010001 (2012).

[1] Angloher *et. al.* (CRESST collaboration) arXiv:1109.0702.

The NEXT-DBDM TPC:

Electroluminescent Readout



TPB-coated film

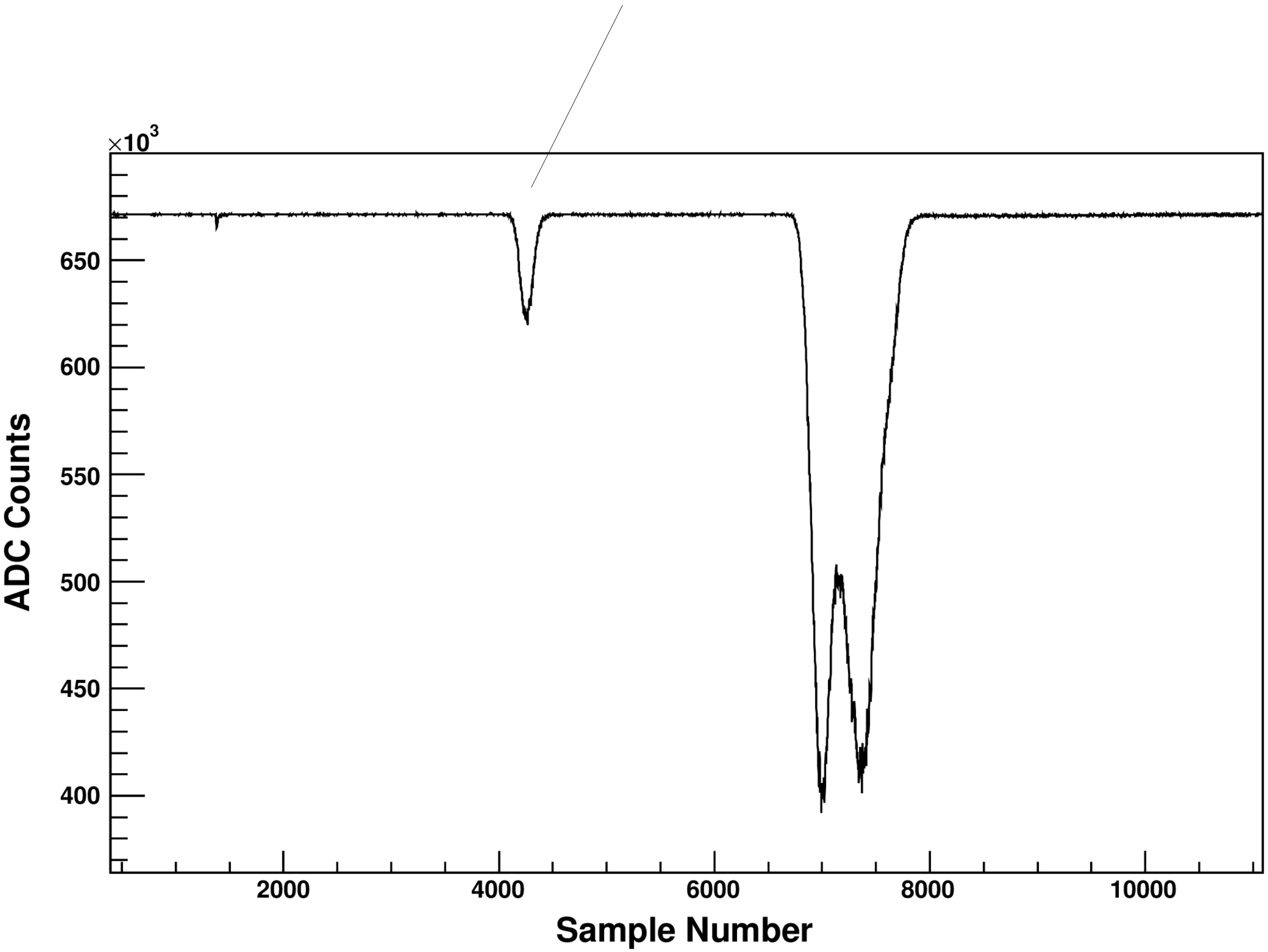
PMT Array

Drift (TPB coated film inset)

EL

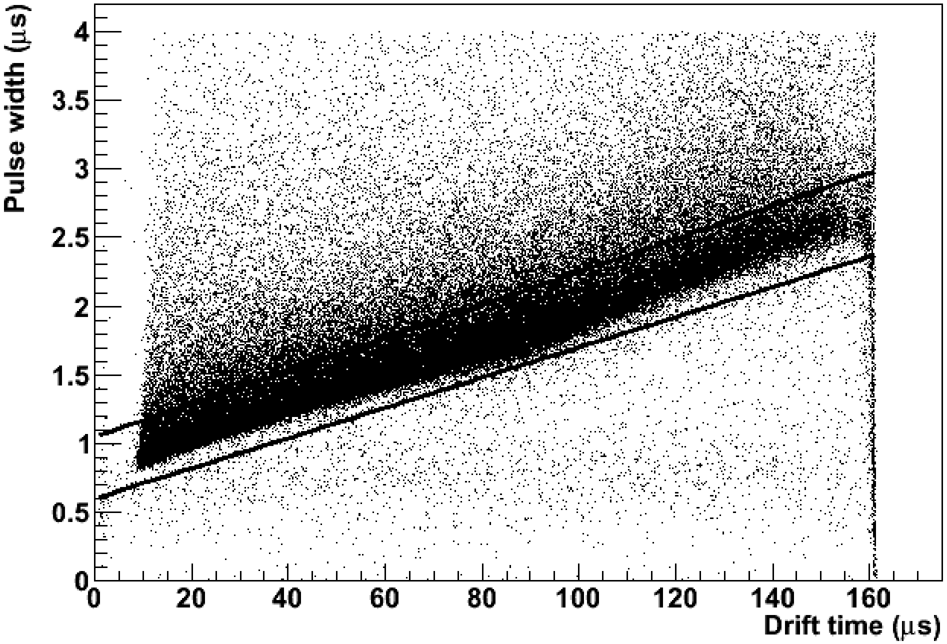
The NEXT-DBDM prototype:

Event with xenon x-ray:

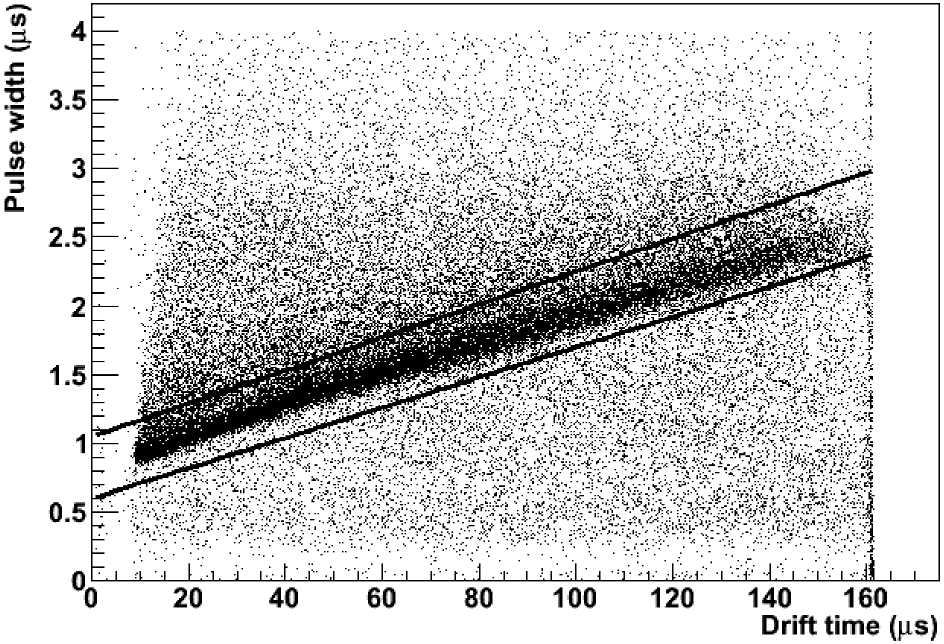


Preliminary detection of nuclear recoils:

- Diffusion cuts (isolate single-pulse events with widths that follow a diffusion curve)



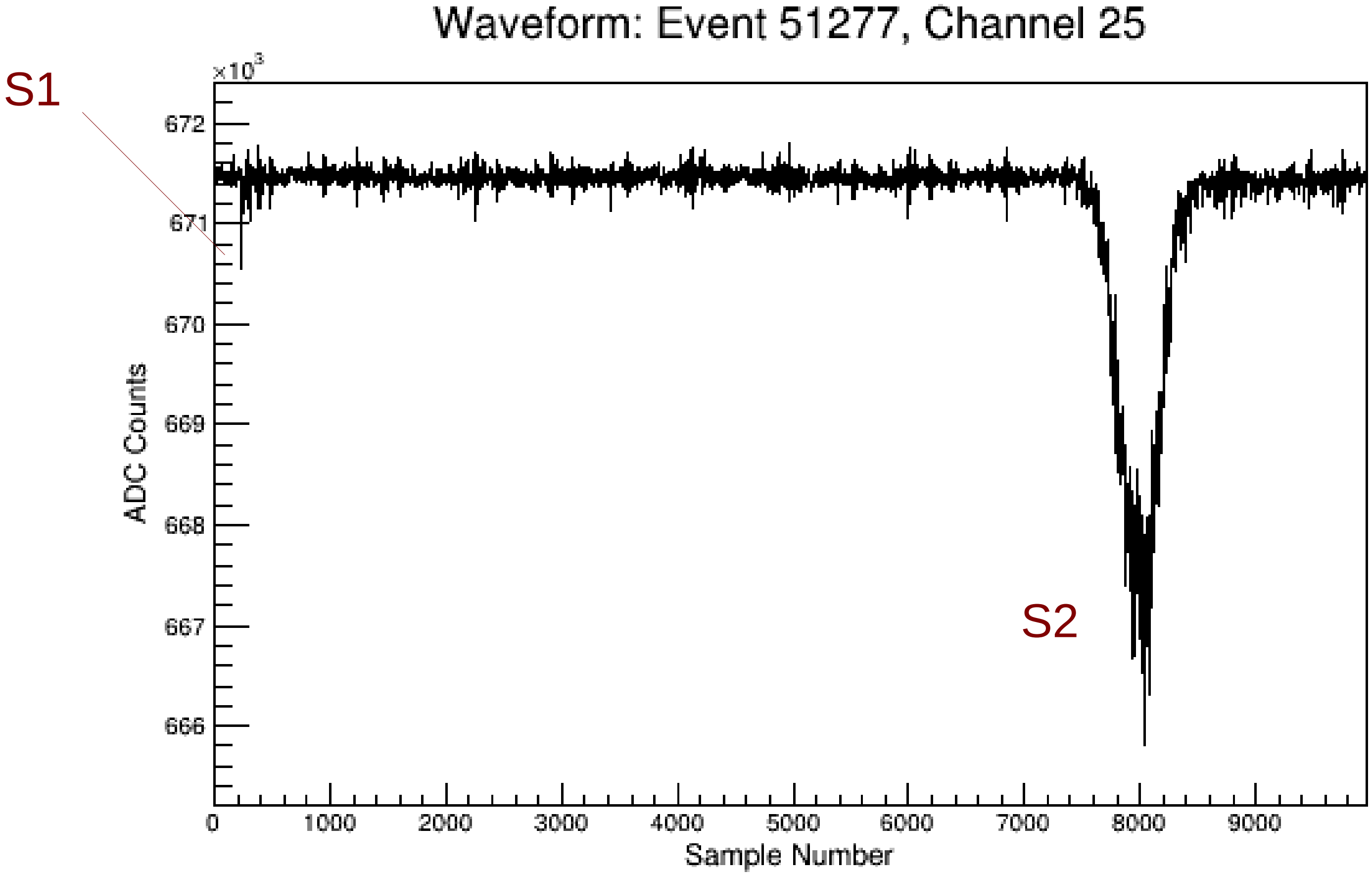
Neutron source



Gamma source

Preliminary detection of nuclear recoils:

- Example of a candidate neutron event (~29 S1 photons, ~5758 S2 photons)



Preliminary detection of nuclear recoils:

- Next steps:

  - Reduce noise in waveforms – should improve S1 threshold

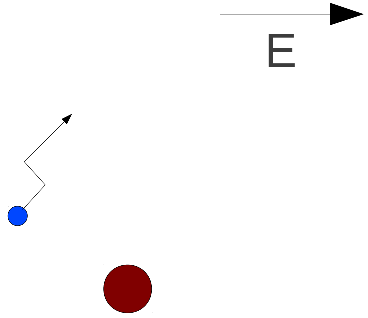
  - Attempt to improve light collection efficiency as much as possible (coat teflon panels directly with TPB?)

  - Better understand neutron source and expected energy spectrum; attempt to obtain recoil energy calibration

  - Move neutron source location to study recombination relative to drift field orientation (directionality)

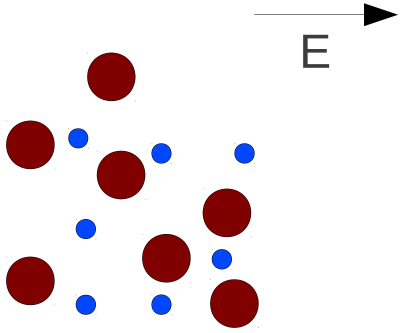
Recombination models:

- Onsager model [1]:
  - Describes “geminate” recombination
  - Considers external + Coulomb fields
  - Single electron/ion pair
  - Collected charge depends linearly on E



$$Q(E) \approx Q_0 + K|E|$$

- Jaffé model [2,3,4]:
  - Describes “columnar” recombination
  - Considers external, but not Coulomb fields
  - Initial distribution of electron-ion pairs
  - Collected charge does not depend linearly on E



$$\frac{\partial N_\pm}{\partial t} = -\mu_\pm \vec{E}\cdot\vec{\nabla} N_\pm + d\nabla^2 N_\pm - \alpha N_+ N_-$$

(Ext. field) (Diffusion) (Recombination)

$$Q(E) = \frac{Q_0}{1 + K/E}$$

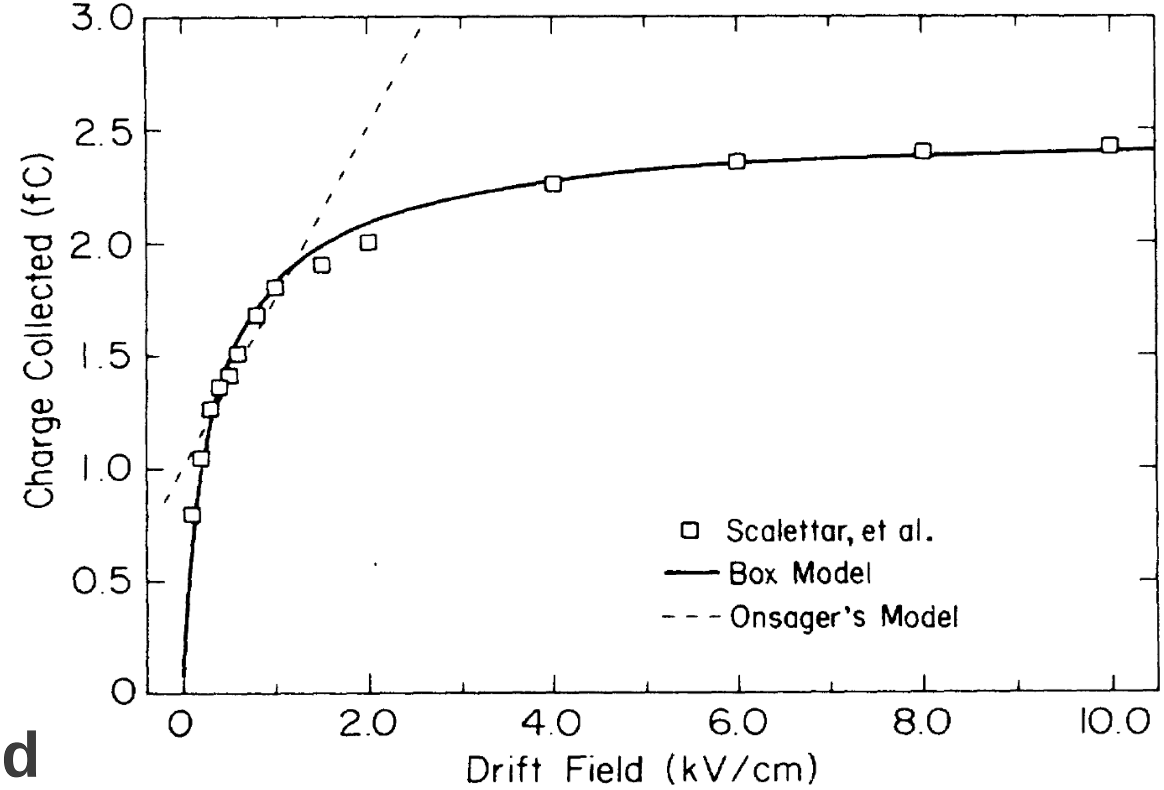
[1] L. Onsager. *Phys. Rev.* 54, 554 (1938).
[2] G. Jaffé. *Ann. Phys.* 42, 303 (1913).
[3] E. Aprile *et. al.* *Noble Gas Detectors*. (Wiley-VCH, Weinheim, 2006).
[4] J. Thomas and D. A. Imel. *Phys. Rev. A*. 36, 614 (1987).

Recombination models:

- No widespread agreement for a single theory:
  - Modifications to models exist to fit experimental data

Thomas-Imel box model [1]

- modified Jaffé model
- no diffusion
- zero positive ion mobility
- +/- charge distributed uniformly in a box
- one free parameter (fit)



Total charge collected (^{113}Sn source) in LAr vs. field, from [1].

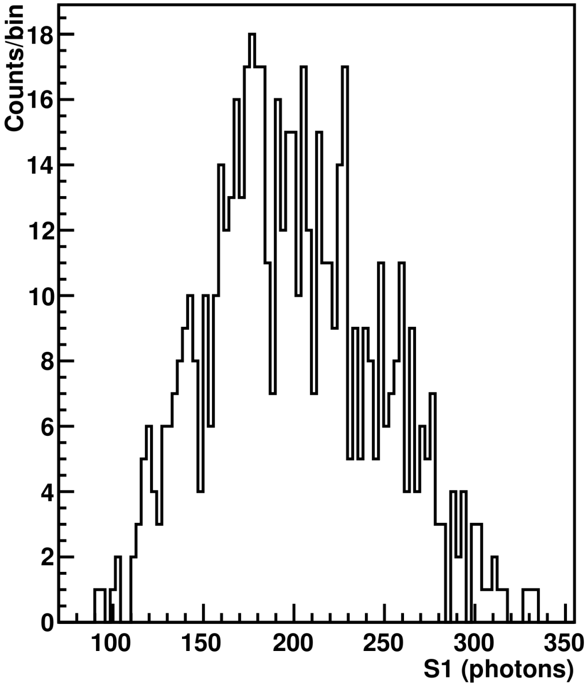
Microphysics encapsulated in a fit parameter: possible to simulate more precisely?

[1] J. Thomas and D. A. Imel. *Phys. Rev. A*. 36, 614 (1987).

Improvements to NEXT-DBDM:

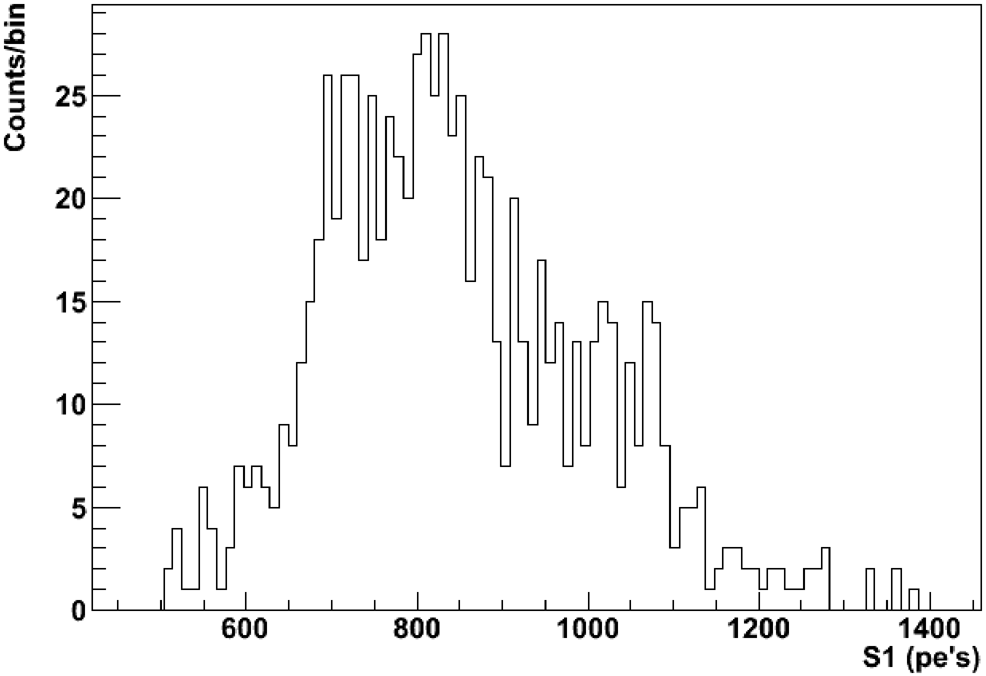
- How TPB helped

Before



~ 511 keV gammas;
~ 200 average S1 photons
~ 0.4 photons/keVee

After

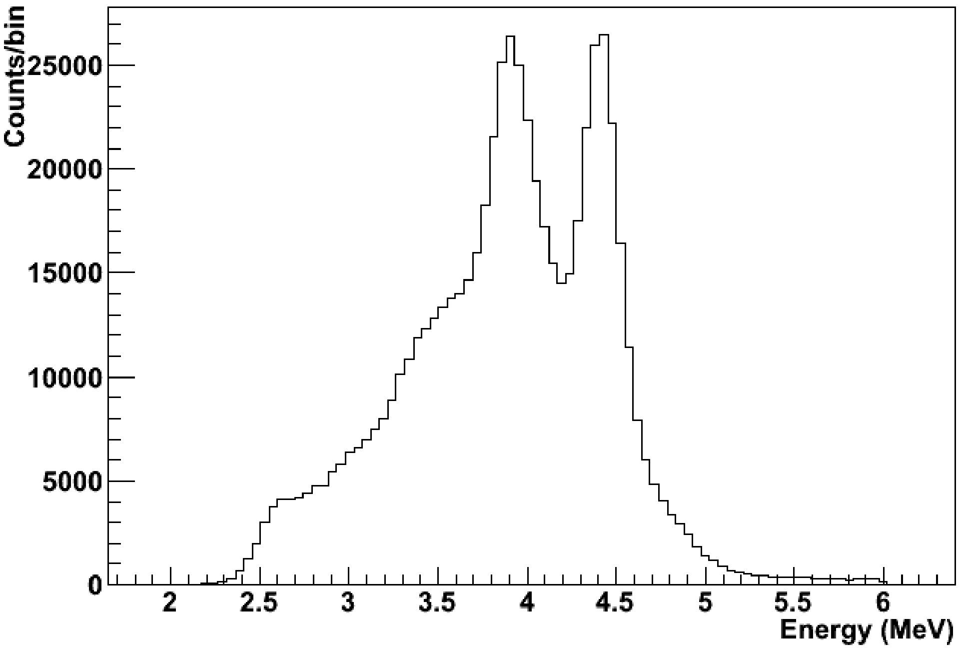


~ 662 keV gammas;
~ 800 average S1 photons
~ 1.2 photons/keVee

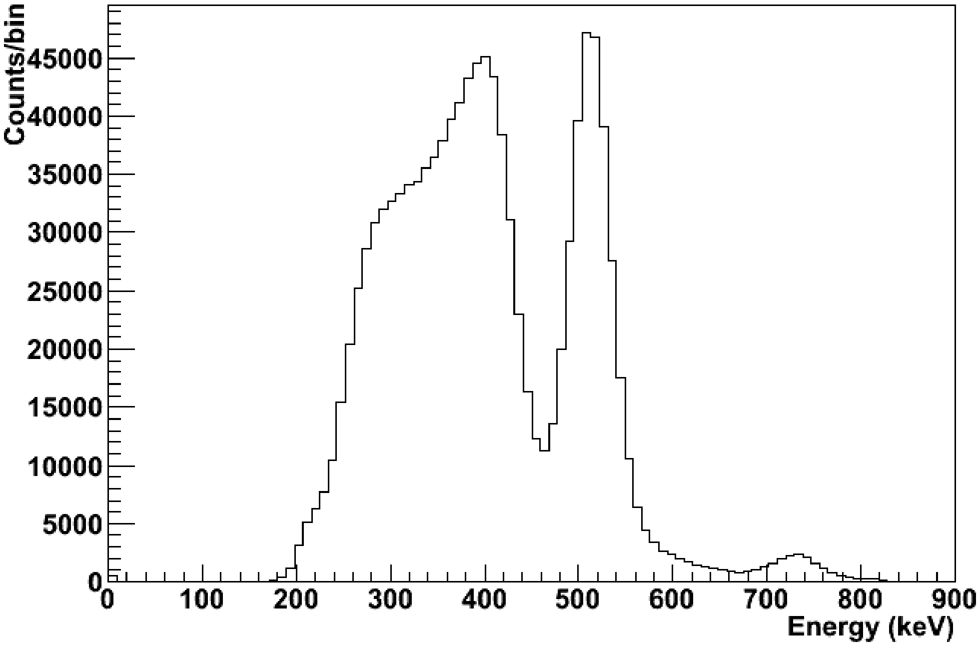
*** Approx. factor of 3 improvement in light yield**
(Note: drift fields were not matched)

Preliminary detection of nuclear recoils:

- NaI spectra, calibrated to 4.4 MeV and 511 keV peaks



Neutron source

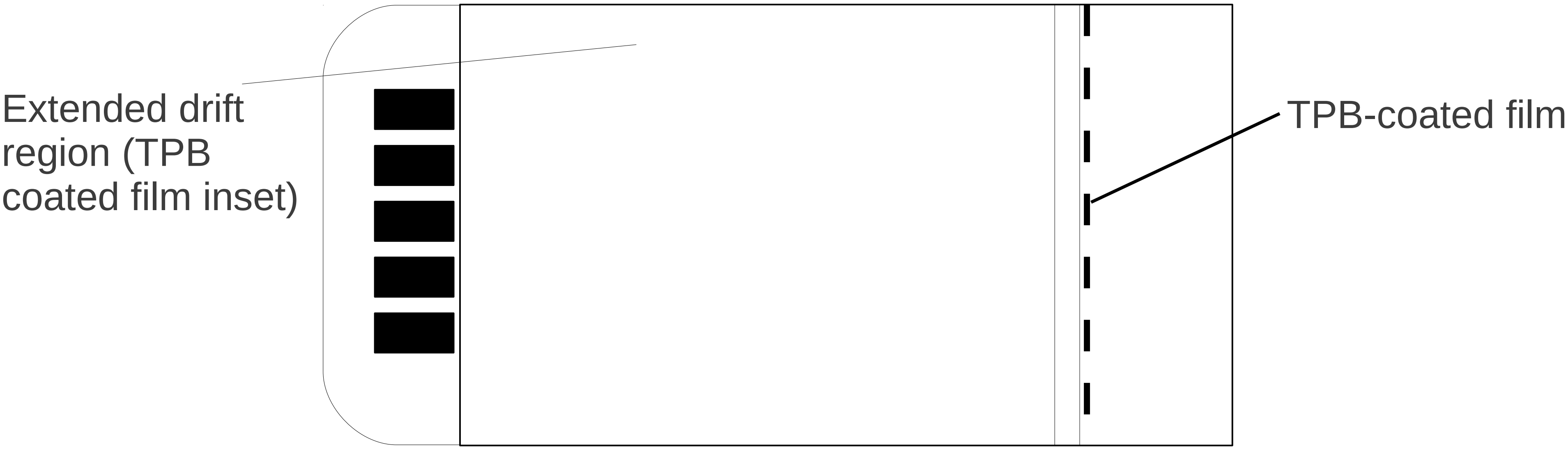


Gamma source

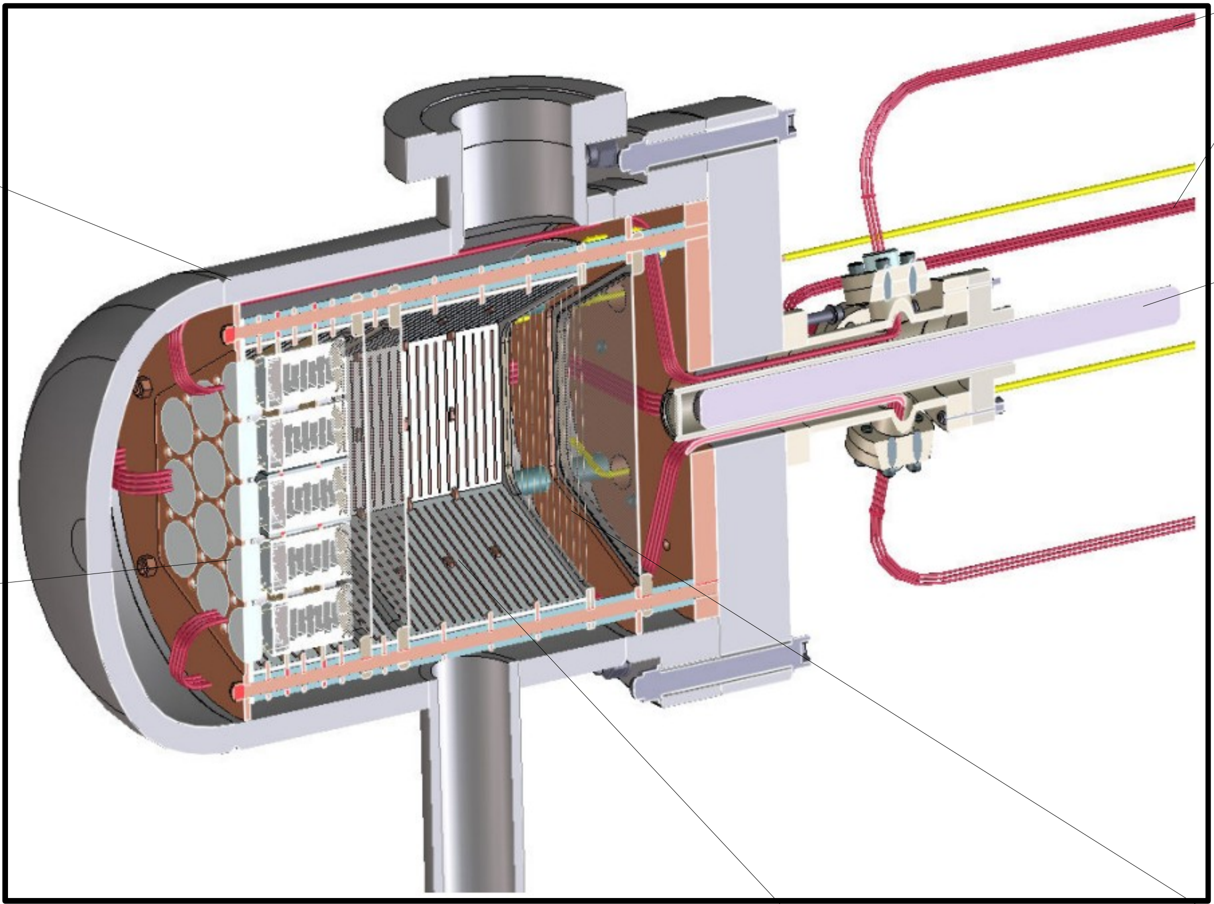
Note: the majority of the coincidences were not in the 511 peak in the NaI spectrum after timing cuts were applied

Improvements to NEXT-DBDM:

- TPB (tetraphenyl butadiene)-coated 3M reflective films
  - - Placed surrounding drift region and just behind EL region
  - - Wavelength shift ~170 nm xenon light to ~ 430 nm
  - - Factor of ~3 better light collection efficiency
- Eliminate buffer regions
  - - Reduces background due to uncollected S2
  - - Deceivingly low S2/S1 from additional S1 photons in buffer regions



The NEXT-DBDM TPC:



Signal/HV cables

10L stainless steel vessel

Source tube

19-PMT array

- Drawing by Robin LaFever

drift region

5 mm EL gap