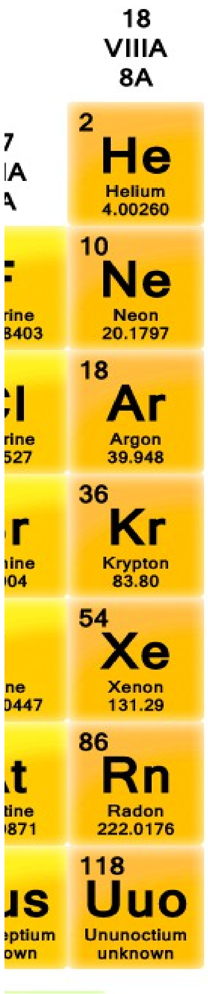
Low Energy Particles in Noble Liquids

Antonio J. Melgarejo Fernandez
Columbia University

Invisibles School, July 14th 2013, Durham

Explaining the title I

- Noble gases are a group of elements found at the right most part of the periodic table
- They have full electron layers, making them very non-reactive
- They can be obtained from air distillation or from natural gas fields (He)
- Rn is radioactive and different isotopes are produced in the U and Th chains



Explaining the title II

- Noble gases can be made liquid at cryogenic temperatures, ranging from ~183K for Xe to ~4K for He
- Liquified noble gases present several important properties as particle detectors:
  - High scintillation yield, comparable to that of scintillators
  - High density, allows to put a large mass together in a small volume
  - Shielding effect from outside radiation

Explaining the title III

- Because of their ability to produce light and electrons following particle interactions liquefied noble gases are used in very different branches of physics:
  - High Energy Particle Physics (GeV-TeV)
  - Neutrino Detection and Proton Decay (MeV-GeV)
  - Neutrinoless Double Beta Decay (MeV)
  - Dark Matter Detection (~10-100 keV)
- This lecture will focus on the last one

Explaining the title ~~(III)~~ IV

- Xe and Ar, and in a lower measure Ne and He, are used to detect low energy interactions
- The basic detection principles are the same for the different elements, although there are some peculiarities that change the way in which a detector is built
- In the field of dark matter, a large fraction of the existing or planned detectors are noble liquid detectors: XENON100/1T, LUX/LZ, Dark Side, ArDM, PandaX, XMASS, CLEAN, Deap,

Summary

	Liquid density (g/cc)	Boiling point at 1 bar (K)	Electron mobility (cm^2/Vs)	Scintillation wavelength (nm)	Scintillation yield (photons/MeV)	Long-lived radioactive isotopes	Triplet molecule lifetime (μs)
LHe	0.145	4.2	low	80	19,000	none	13,000,000
LNe	1.2	27.1	low	78	30,000	none	15
LAr	1.4	87.3	400	125	40,000	^{39}Ar, ^{42}Ar	1.6
LKr	2.4	120	1200	150	25,000	^{81}Kr, ^{85}Kr	0.09
LXe	3.0	165	2200	175	42,000	^{136}Xe	0.03

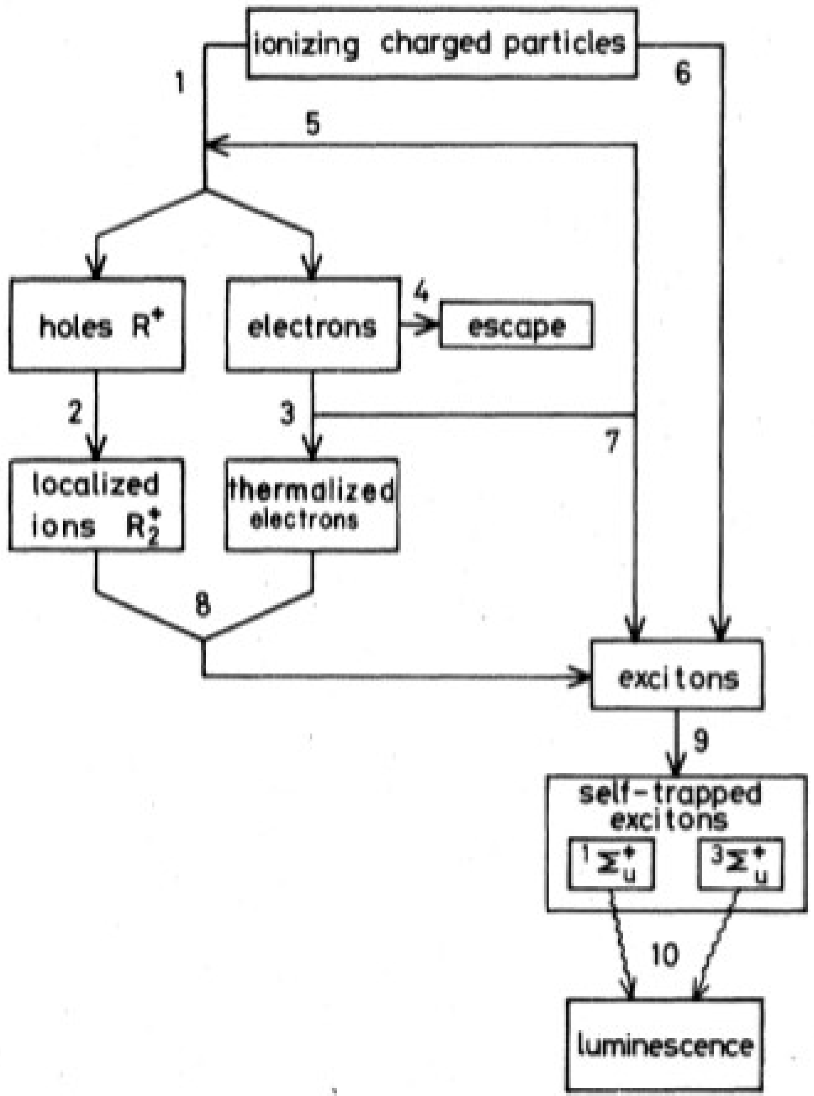
Particle interactions in noble liquids

- When a particle interacts in a noble liquid, energy is split in three processes:
  - Atomic ionization (and production of an electron)
  - Atomic excitation
  - Heat
- Note that at these low energies, the path of a particle will be of the order of 1 micron, which is well below the resolution of any of these detector

Particle interactions in noble liquids

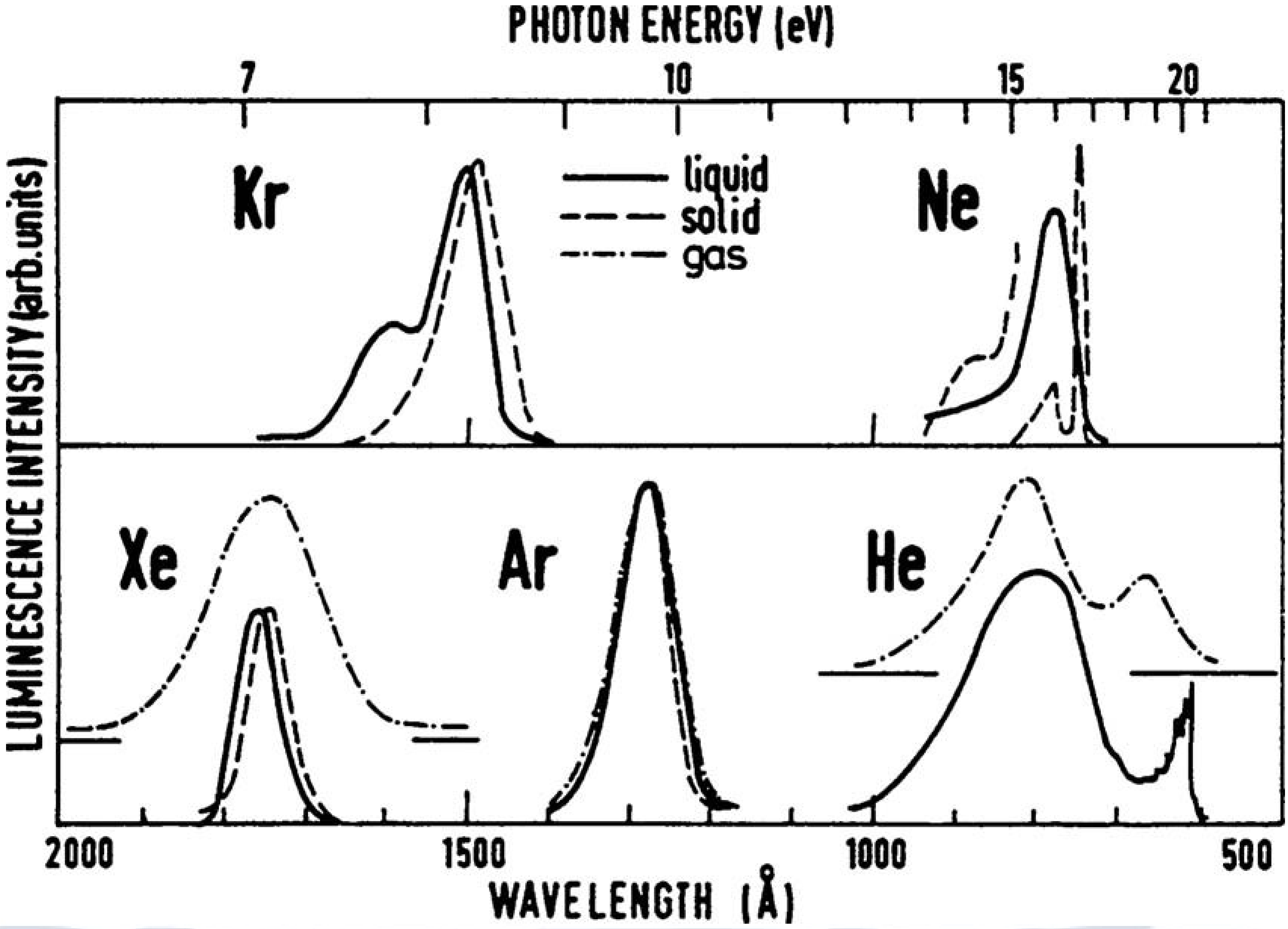
- When an atom is ionized, a free electron is produced, and there is some chance that this will recombine with the existing ions, producing another excited atom
- Excited atoms in both cases will join neutral atoms to produce excited molecules, that will then de-excite producing scintillation light
- A part of the electrons won't recombine in a time scale reasonable for the experiment

Particle interactions in noble liquids



- The molecular de-excitation will happen from the singlet ($^3\Sigma_u$) or triplet ($^1\Sigma_u$) state
- However, the triplet state transition is forbidden, and can only happen through overlap with the $^1\Pi_u$ state, which results in a longer emission time

The scintillation process



The scintillation process

- There are two paths that lead to scintillation (It is the same for any other noble element)

- Direct Excitation

$$Xe^* + Xe + Xe \rightarrow Xe_2^* + Xe$$

$$Xe_2^* \rightarrow 2Xe + h\nu$$

- Recombination

$$Xe^+ + Xe \rightarrow Xe_2^+$$

$$Xe_2^+ + e^- \rightarrow Xe_2^{**}$$

$$Xe_2^{**} \rightarrow Xe_2^* + \text{heat}$$

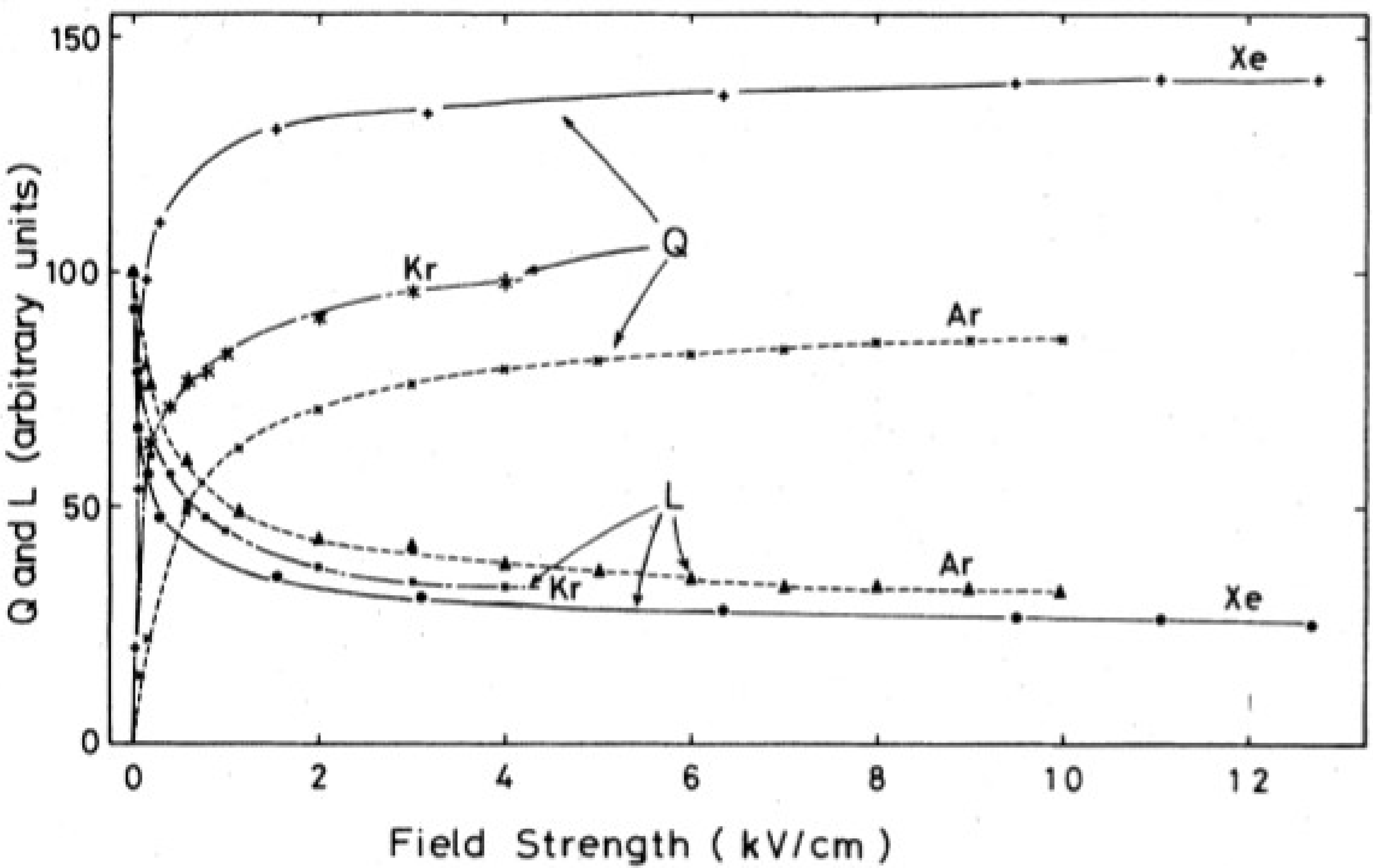
$$Xe^* + Xe + Xe \rightarrow Xe_2^* + Xe$$

$$Xe_2^* \rightarrow 2Xe + h\nu$$

The scintillation process

- The wavelength of the light produced through each of these processes is the same
- However the population of the singlet and triplet state is not
- The fraction of photons produced through each mechanism will depend on the LET
- Moreover, the recombination component will be suppressed in the presence of an electric field, since electrons will drift apart from the interaction site

The scintillation process



Recombination

- The energy deposit in an interaction in the noble liquid is split in electrons and photons

$$E_{\mathrm{er}} = \epsilon(n_\gamma + n_e),$$

$$E_{\mathrm{nr}} = \epsilon(n_\gamma + n_e)/f_n,$$

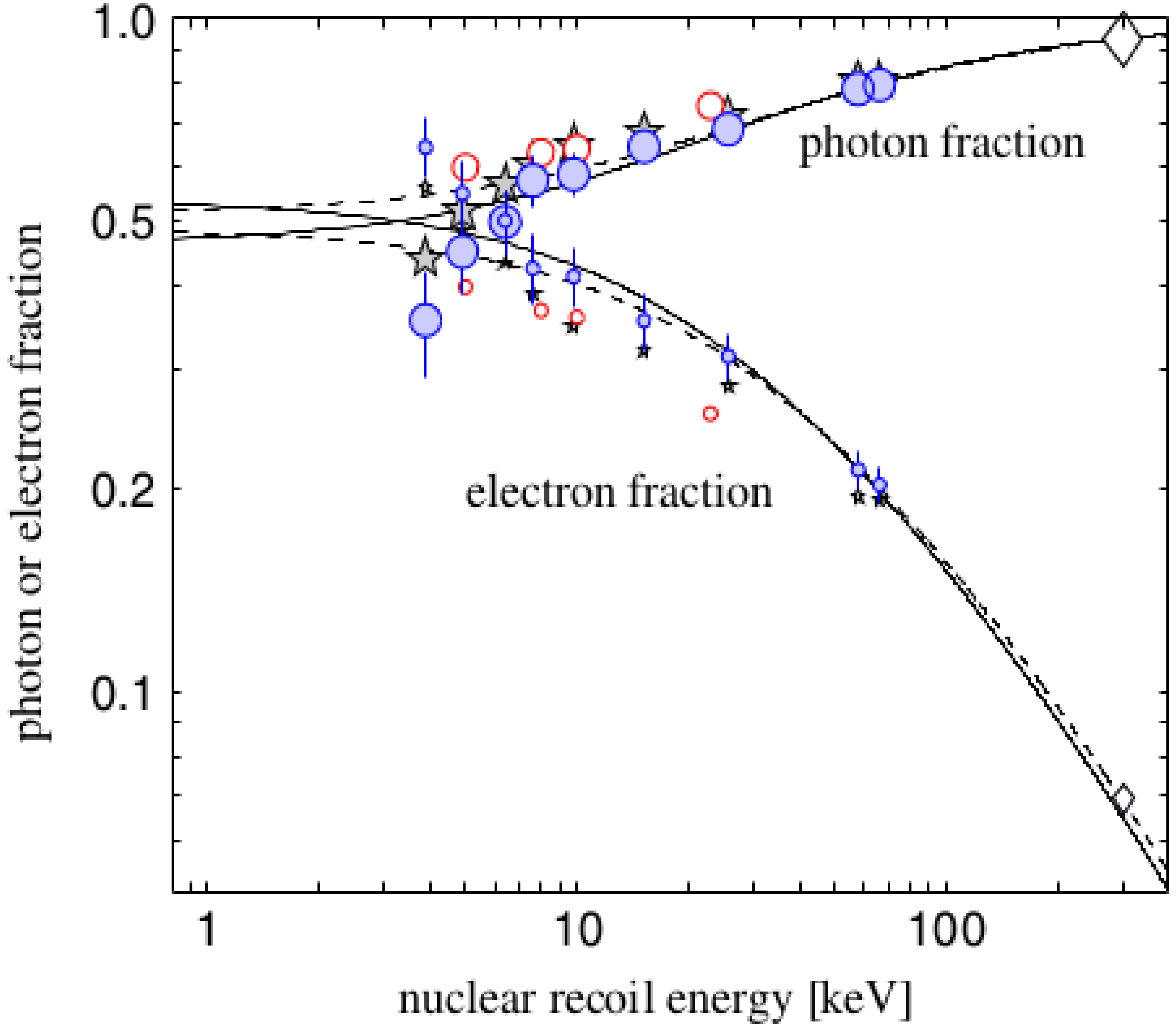
- Some of the initial electrons will recombine with the existing ions and will end up producing new photons
- It is important to understand this mechanisms in order to predict the response of the noble liquid to different particles

Recombination

- There are two different models for how this recombination happens:
  - Local (Onsager)
  - Box (Thomas-Imel)
- The Thomas Imel model predicts a recombination that depends on the number of produced ions and is able to reproduce the existing data

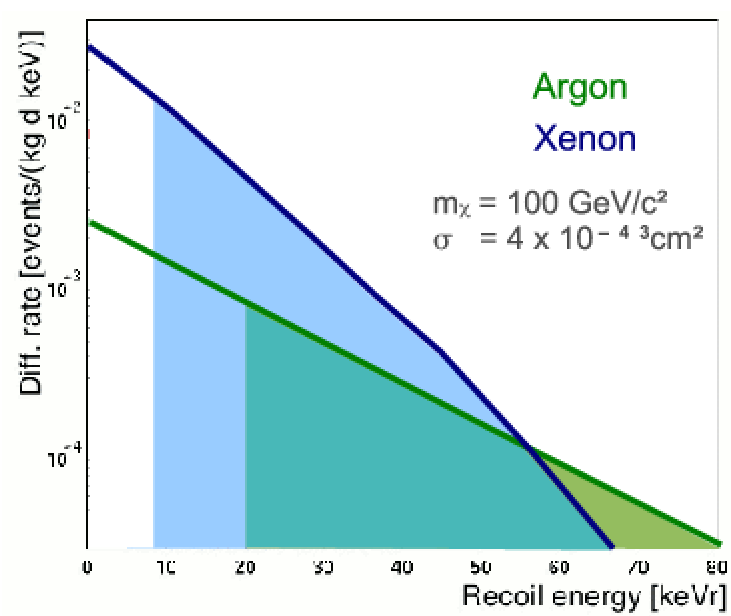
$$\frac{n_e}{N_i} = \frac{1}{\xi} \ln(1 + \xi),$$

Recombination



Detecting Nuclear Recoils: Nuclear Form Factor

- When the momentum transfer between a WIMP and a nucleus is small enough that the de Broglie wavelength of the incoming particle is no longer large compared to the nuclear radius, the cross section of scattering is reduced by a factor $F^2(qr_n)$
- This reduces the cross section and makes necessary low thresholds



Detecting Nuclear Recoils: Quenching

- When a nuclear recoil deposits energy in a medium, a much larger fraction of this is transformed in heat than for the case of electrons
- In LXe this has typically been measured through the so called Leff
- Since the light yield depends on the geometry of the detector, this quantity relates the light measured for a given nuclear recoil to that of a given fixed energy

Detecting Nuclear Recoils: Quenching

- Leff is the ratio of the scintillation yield for a nuclear recoil of given energy and the scintillation yield of an electronic recoil of 122 keV at 0 field

Light yield of the NR interaction

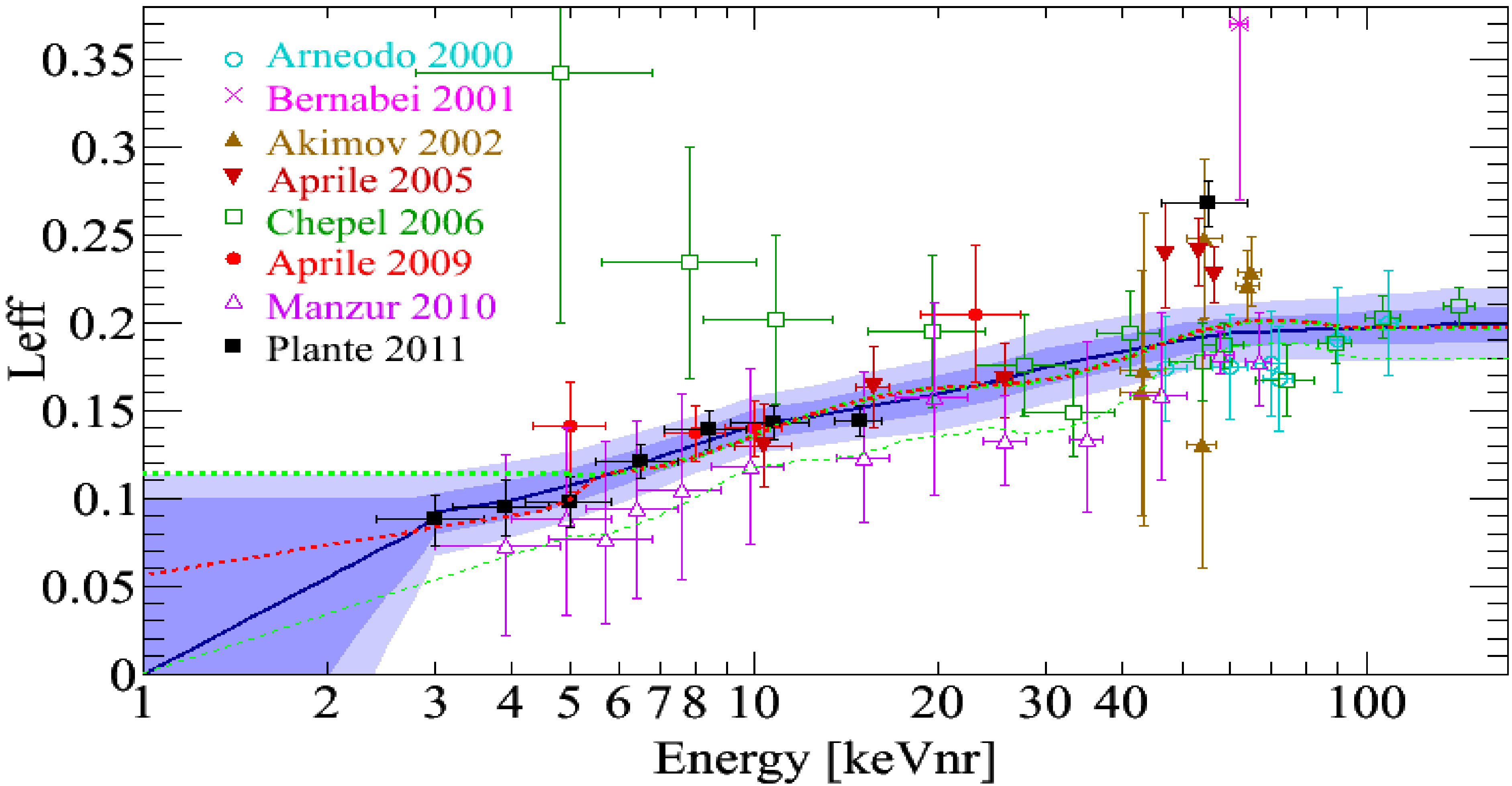
=1 at 0 field

$$L_{eff} = \frac{S1}{E_{nr}} \frac{1}{L_y} \cdot \frac{S_e}{S_r}$$

Light yield for gamma @122 keV

- It is a property of the noble liquid, it does NOT depend on the detector

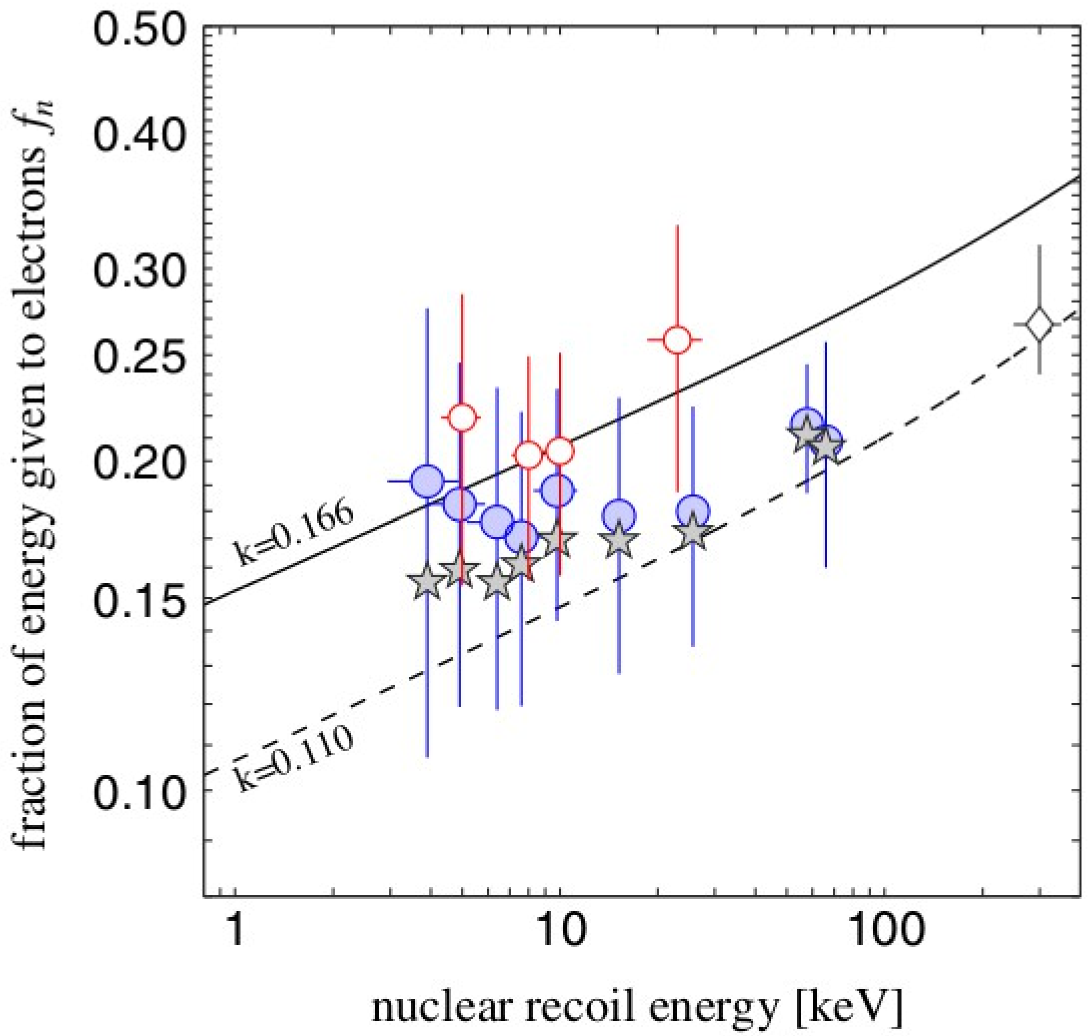
Detecting Nuclear Recoils: Quenching



Detecting Nuclear Recoils: Quenching

- Lindhard theory predicts successfully the reduction in energy transferred to electrons in many crystals. However, it fails to properly predict Leff
- It has been noticed recently, though, that when Lindhard theory is applied to the number of produced quanta, whether these are electrons or photons, a much better agreement with the data is reached

Detecting Nuclear Recoils: Quenching



Detecting Nuclear Recoils: Ionization density

- Nuclear recoils due to the larger mass have a much larger ionization density than electronic recoils
- This produces two effects:
  - The amount of charge not recombining is much smaller than for electronic recoils
  - The amount of molecules in the triplet state is much smaller than for electronic recoils

Liquid Noble Detectors

- We have reviewed all the basics physics of light production in liquid noble gases
- At this point we can try to understand what's the optimal way to build a detector, given what we know
- For simplicity, we will just focus on the case of dark matter

Liquid Noble Detectors

- If we restrict ourselves to the dark matter problem, most theories predict that WIMPs will interact with target nuclei (in some searches we may look for electron recoils too)
- We are hence interested in detecting nuclear recoil in the media
- Natural radioactivity will produce a background to these searches in the form of electron recoils

Liquid Noble Detectors

- A dark matter detector should be able to detect small energy depositions
- Moreover, there should be some tool helping to determine the origin of such interactions
- Some noble liquids have radioactive isotopes:
  - ^{39}Ar
  - ^{85}Kr (also present in Xe due to extraction process)
- It is necessary to reduce these as much as possible, since shielding can't be used

Liquid Noble Detectors

- From what we have seen, there are several ways in which we can tell (with certain probability) if a particle is an electronic recoil (background) or a nuclear recoil (WIMP or neutron):
  - Ratio between charge and light
  - Ratio between triplet and singlet component
  - Position of the interactions in the detector

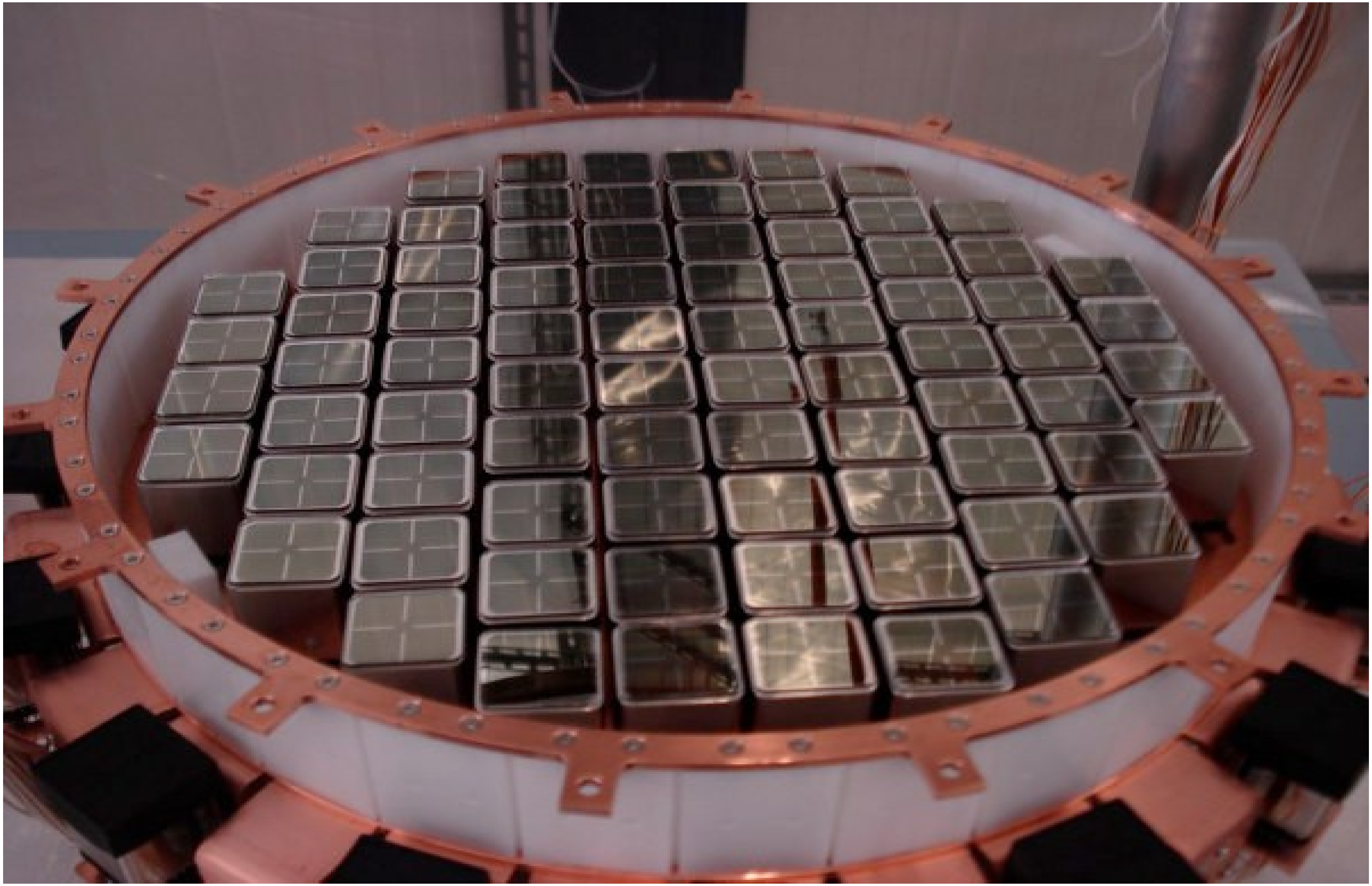
Detection principle

- All detectors are able to detect the primary light produced in the interactions
- Then one or several of the following are used for background reduction:
  - Measure the charge signal (single vs double phase detector)
  - Measure the pulse shape of the signals (singlet to triplet ratio)
  - Measure the position of the interactions (fiducialize)

Light detection

- The most used way of detecting light is by means of photomultipliers
- These are sensitive to single photons, and for every photoelectron detected produce an amplification of 10^6-10^8
- For Xe it is possible to use PMTs that are sensitive to the scintillation wavelengths
- For other elements, though, it is necessary to use wavelength shifters

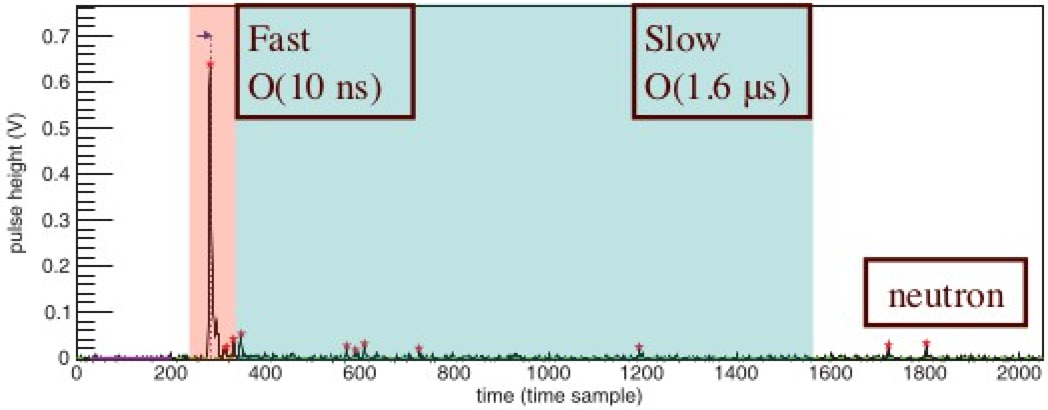
Light detection

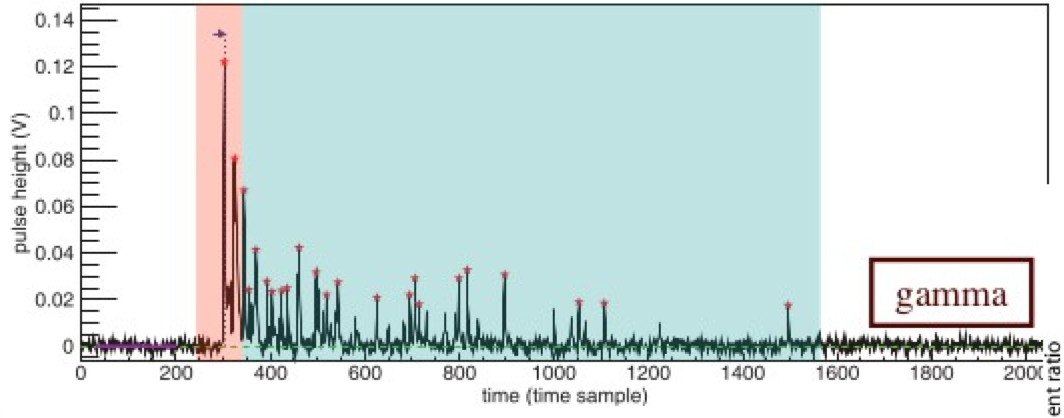


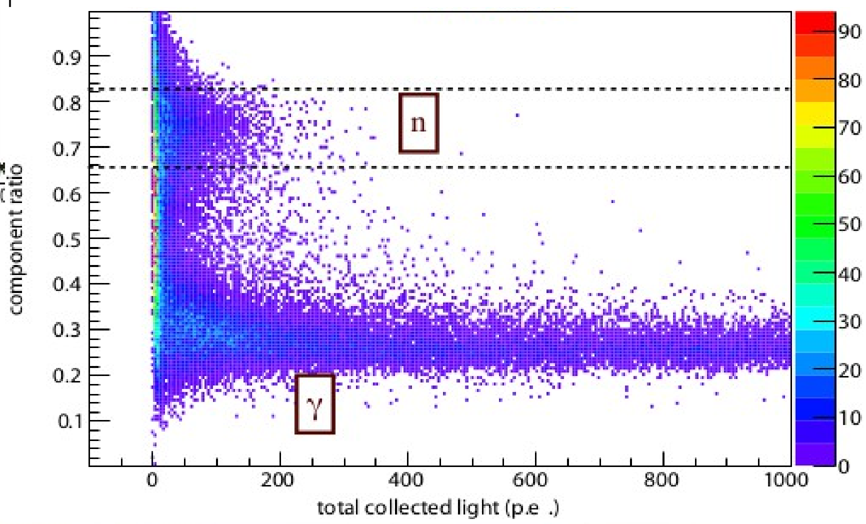
Pulse Shape Discrimination

- It is very hard to use for Xe, but much easier for all the other noble elements provided that enough light is collected
- It is easy to implement just as part of the light measurement process
- Discriminations above 10^7 between electronic and nuclear recoils have been reported

Pulse Shape Discrimination





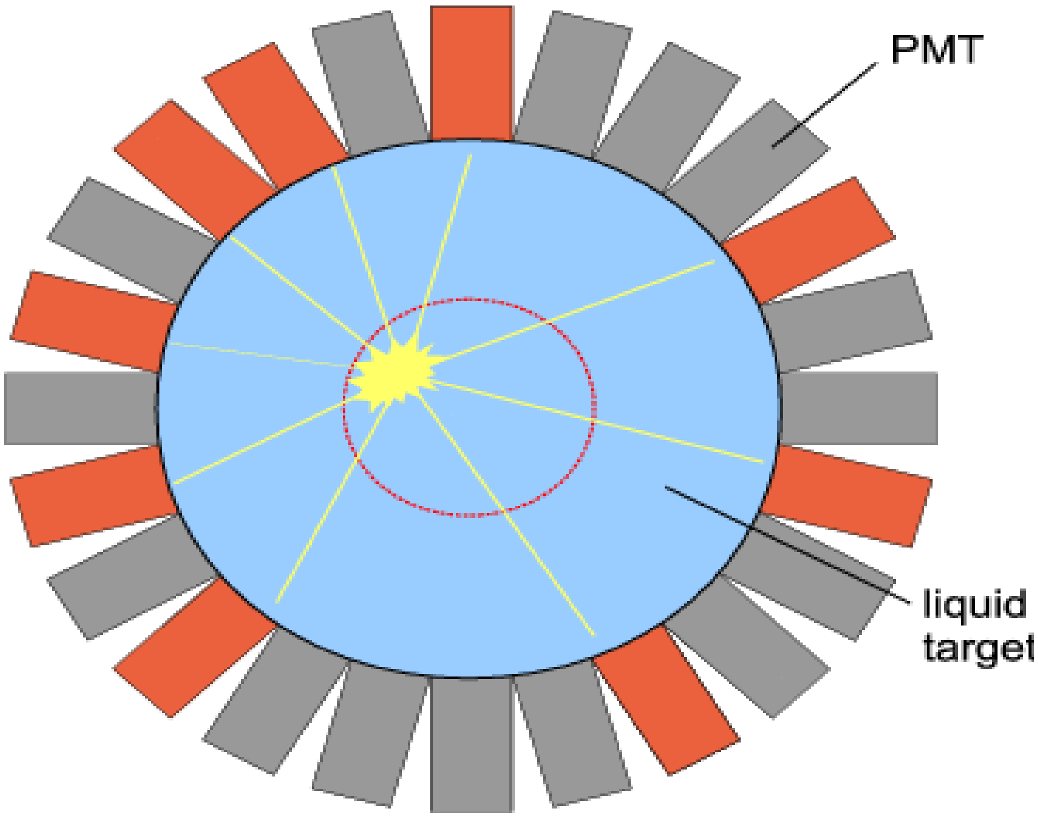


Fiducialization

- Heavier elements (e.g. Xe) have a high density and a high atomic number
- A particle produced outside the detector has a higher probability of interacting near the borders
- For particles like WIMPs or axions, a detection is equally likely in the whole volume
- Hence, selecting an inner core guarantees less background rate

Fiducialization

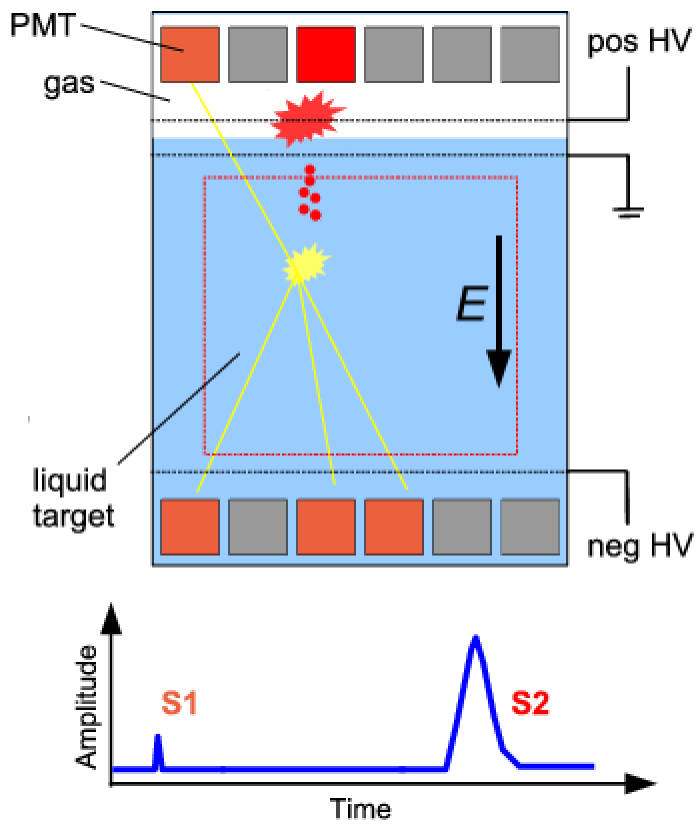
- Single Phase Detectors



- The position of the interactions can be reconstructed by placing the PMTs in a sphere and computing the light ratio

Fiducialization

- Dual Phase Detectors



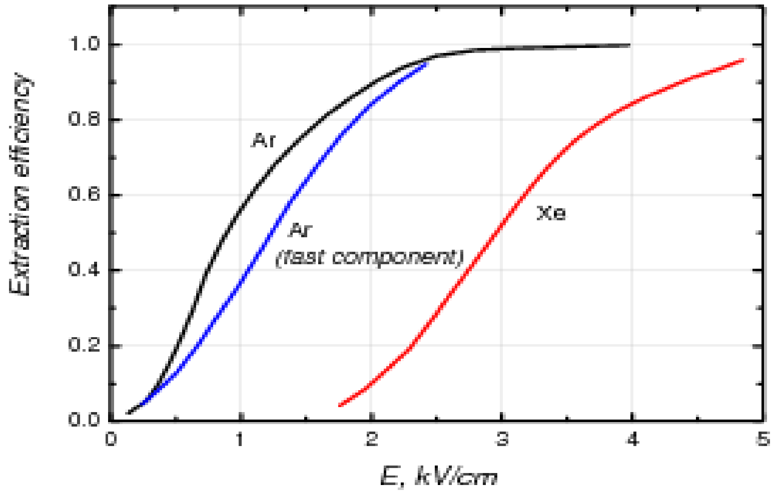
- Electrons are drifted towards the top of the detector with an electric field
- The time difference between light and electron signals is proportional to Z
- X, Y can be reconstructed from the electron signal distribution

Electron Emission and Proportional Scintillation

- During the initial interaction in the target material, electrons and ions are produced
- Reading these electrons gives additional information about the interaction
- The number of these electrons is going to be small, so some amplification mechanism is used

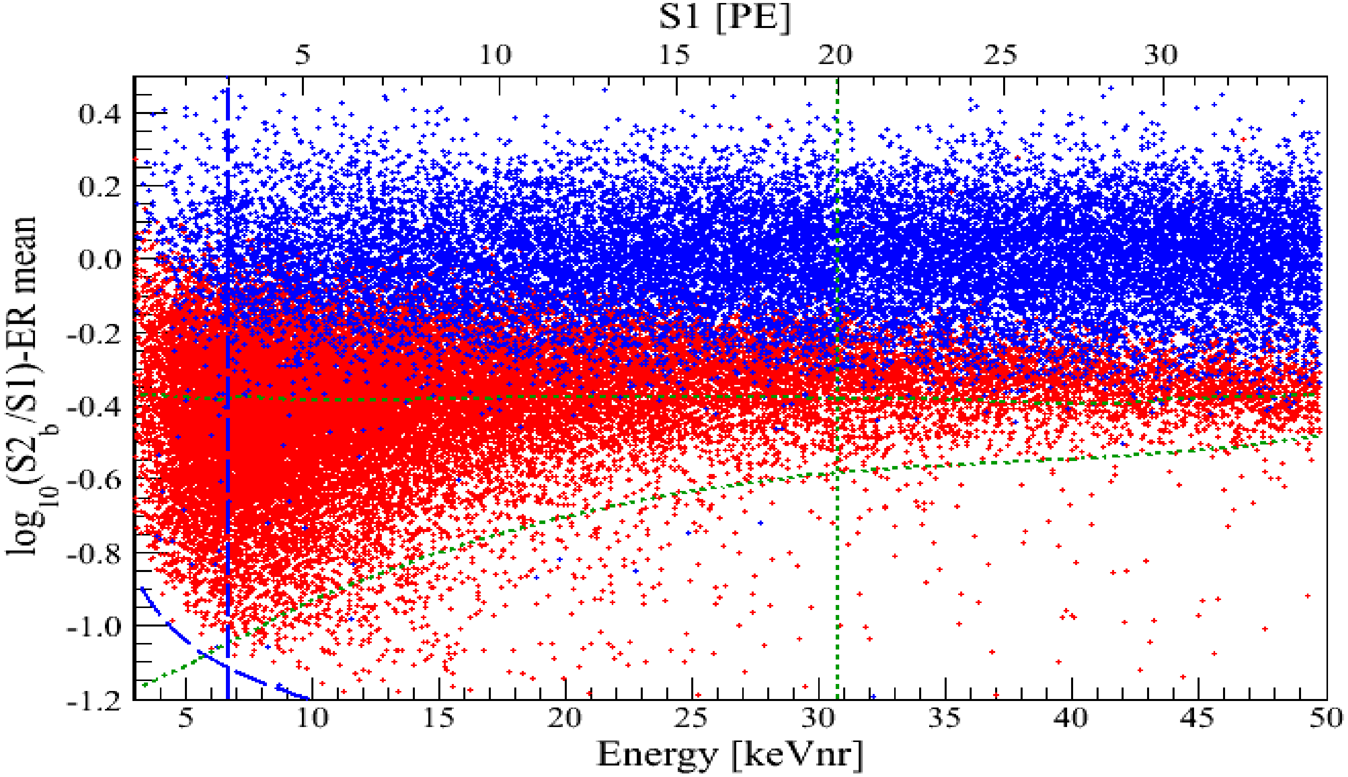
Electron Emission and Proportional Scintillation

- One of the most common mechanisms to measure these electrons is to transport them to a gas phase, where they are extracted with a high electric field and then excite atoms in the gas, producing a secondary proportional scintillation signal
- We are able to detect single electrons
- A WIMP signal can have as few as 10 electrons



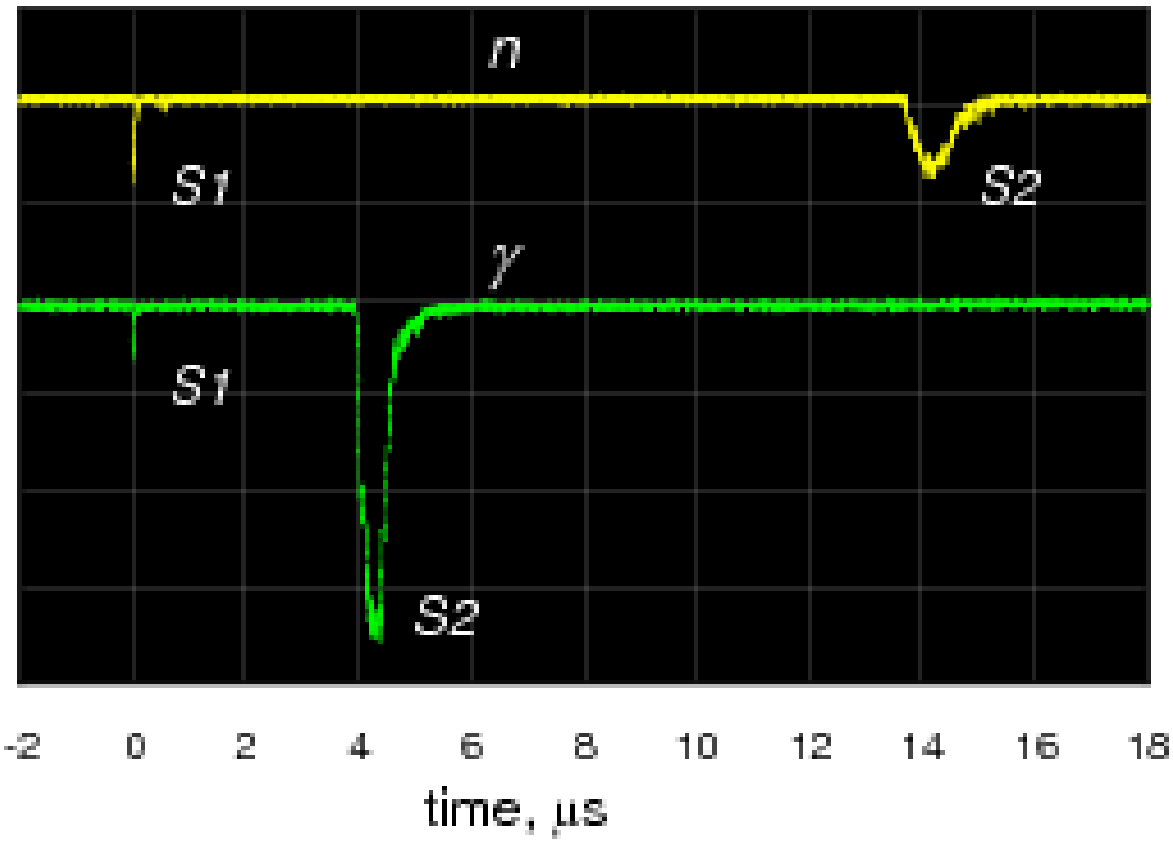
Electron Emission and Proportional Scintillation

- The proportional scintillation signal (S2) provides a way to distinguish electronic from nuclear recoils



Electron Emission and Proportional Scintillation

- The ratio between charge and light can be used to distinguish a nuclear recoil from an electronic recoil, with discrimination of the order of 99.5%

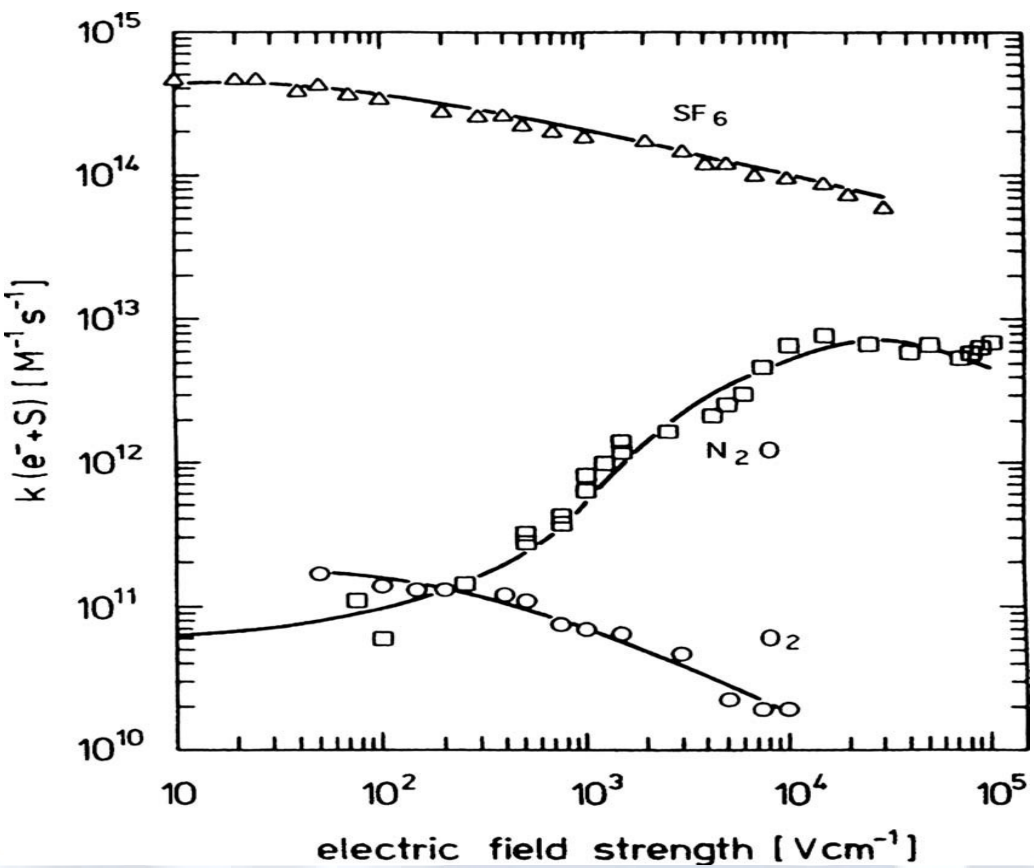


Signal reduction from detector effects (you can't always get what you want)

- Both the light and charge signal in a detector will be attenuated respect to the produced signal
- In the case of electrons, these can be absorbed by the presence of electronegative impurities dissolved in the liquid
- The probability of absorbing one electron will depend in its path length
- Different impurities contribute with different cross sections

Signal reduction from detector effects (you can't always get what you want)

- The effect is usually reported through the oxygen equivalent impurity concentration



Signal reduction from detector effects (you can't always get what you want)

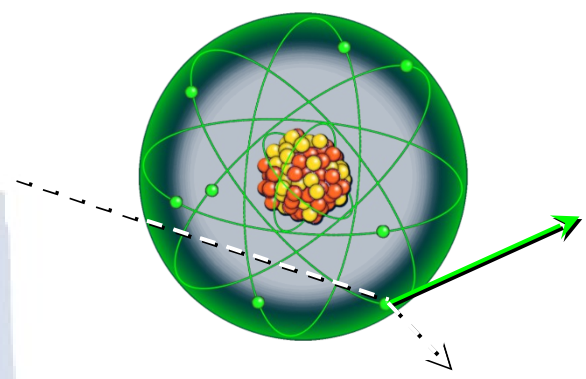
- Light can be attenuated in multiple ways
  - The presence of impurities in the liquid noble can reduce the number of photons
  - When photons hit the different components of the detector, they have some probability of being absorbed
  - The photomultipliers have a quantum efficiency below 100%
- It's not unlikely that the number of photoelectrons detected is below 10% of the photons produced

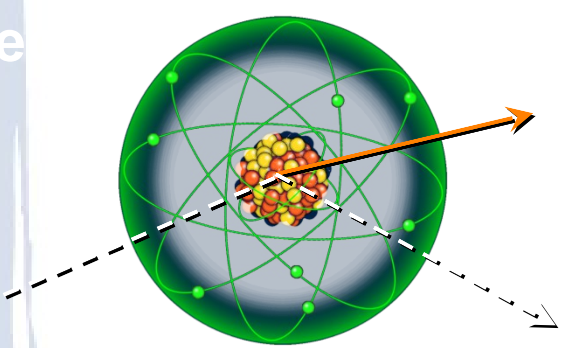
Signal reduction from detector effects (you can't always get what you want)

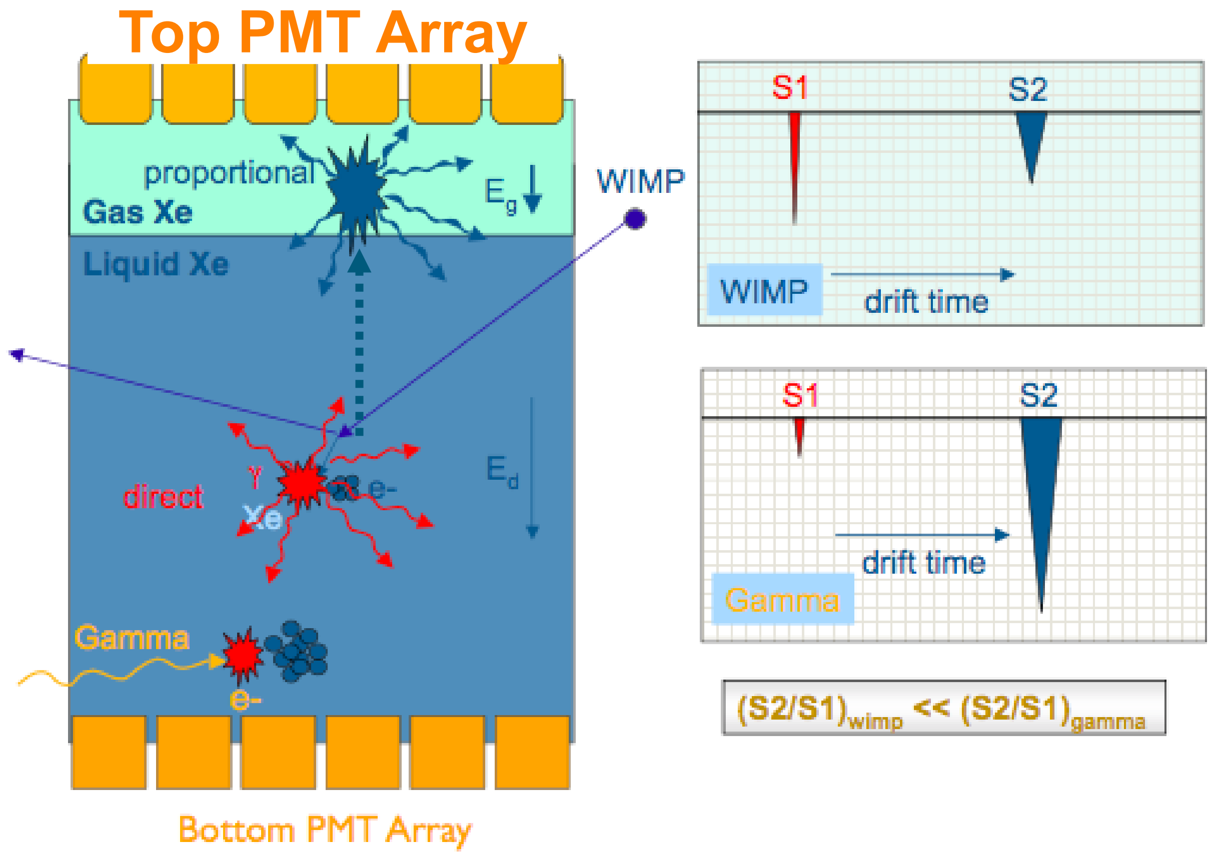
- In noble liquid detectors, impurities are constantly introduced through outgassing of the materials
- It is necessary to continuously purify the liquid in order to measure as much signal as possible
- Detectors usually have recirculation systems that drive the liquids through getters that chemically remove the impurities

Let's look at one actual detector: XENON100

The XENON two phase TPC



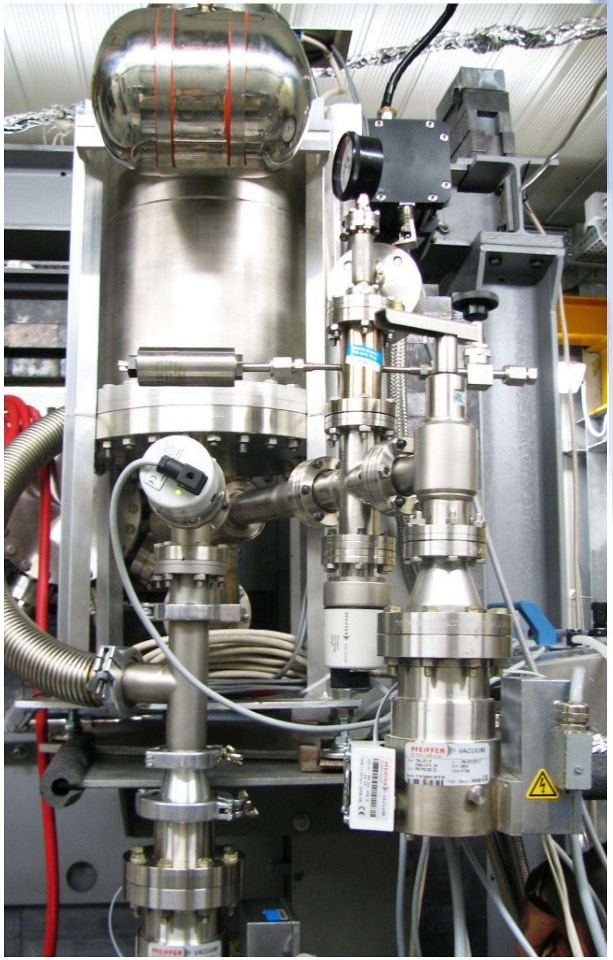




- Single electron and single photon measurement sensitivity
- > 99.5% ER rejection via Ionization/Scintillation ratio (S2/S1)
- 3D event-by-event imaging with millimeter spatial resolution

Cryogenics

- Liquid Xenon is cooled down by a Helium pulse tube refrigerator
- Drops are collected with a fannel and go back into the detector trhough a pipe with a small inclination
- A liquid nitrogen emergency cooling is set up in case of power failure

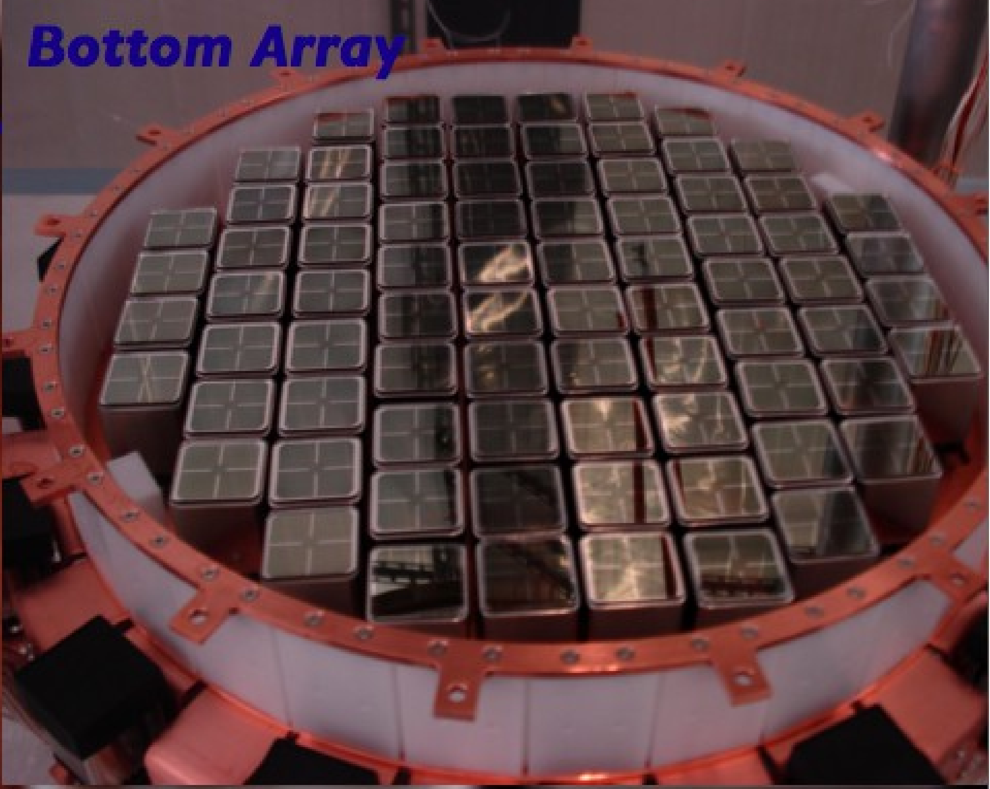


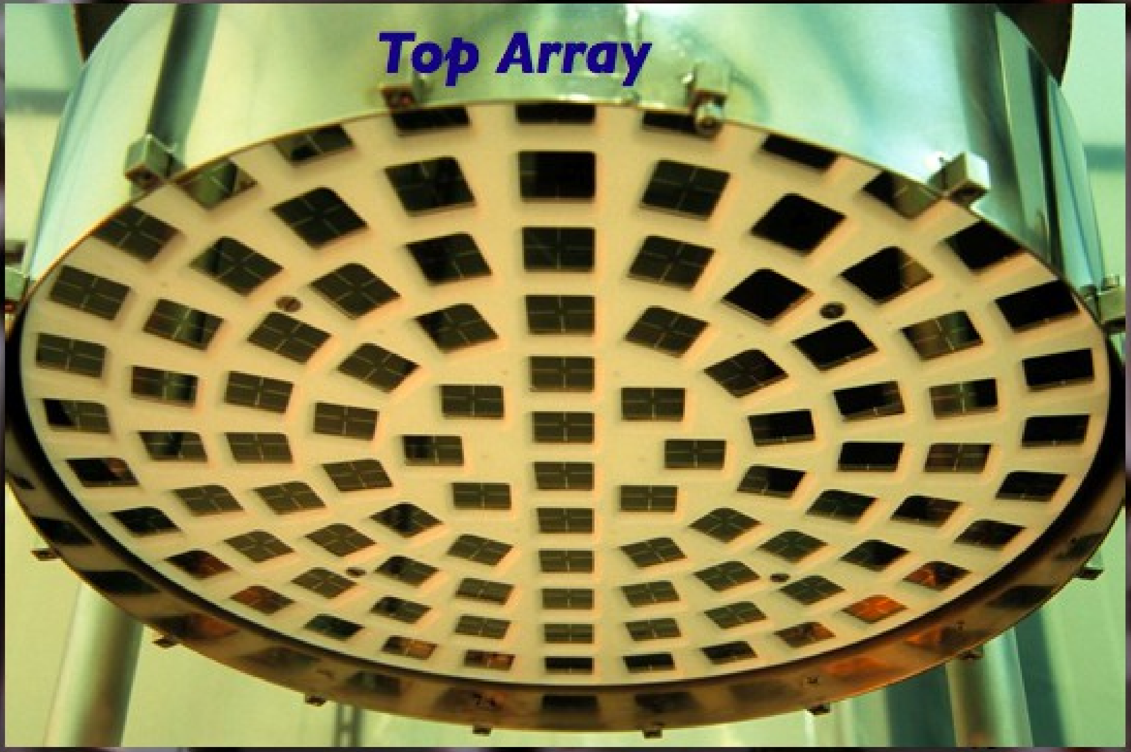
Recirculation and purification

- Gas purification with continuous re-circulation of the 170 kg of Xe gas through hot getter (SAES) at 10 slpm
- Impurities in LXe affect both charge and light
- Source of Impurities: 1) leaks, 2) materials outgassing and 3) Xe gas contamination.
- Light is strongly absorbed by H2O. Charge is strongly reduced by electronegative substances
- We have succeeded to reduce the H2O level to < 1ppb as measured with dedicated IR detector
- We have succeeded in drifting electrons through entire 30 cm gap as measured directly with S2

XENON100: The PMTs

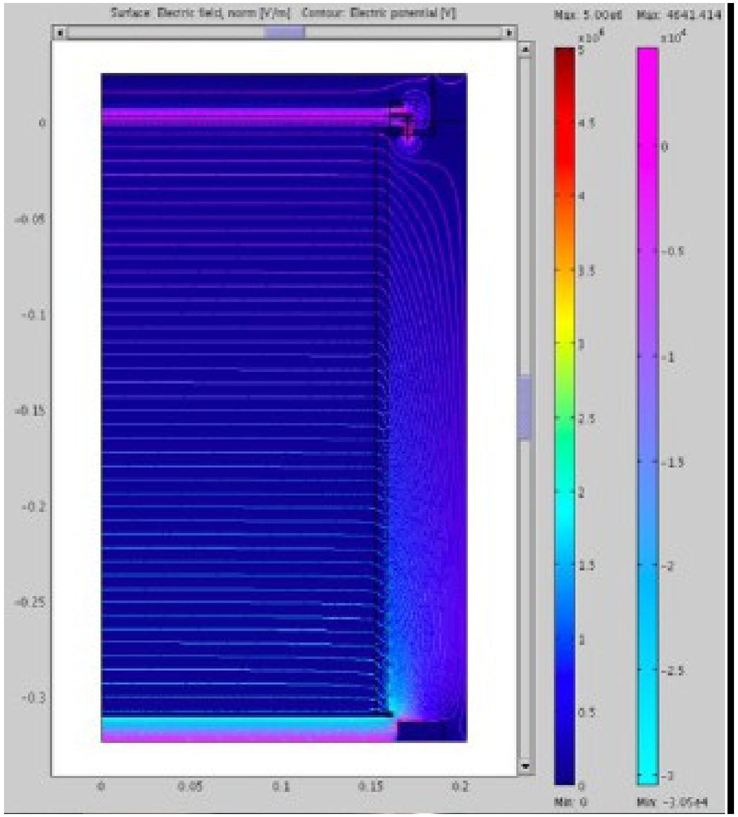
- 242 PMTs (Hamamatsu R8520-06-Al)
- 1 “ square metal channel developed for XENON
- Low radioactivity (<1 mBq U/Th per PMT)
- 80 PMTs for bottom array (33% QE)
- 98 PMTs for top array (23% QE)
- 64 PMTs for top/bottom/side Veto (23% QE)

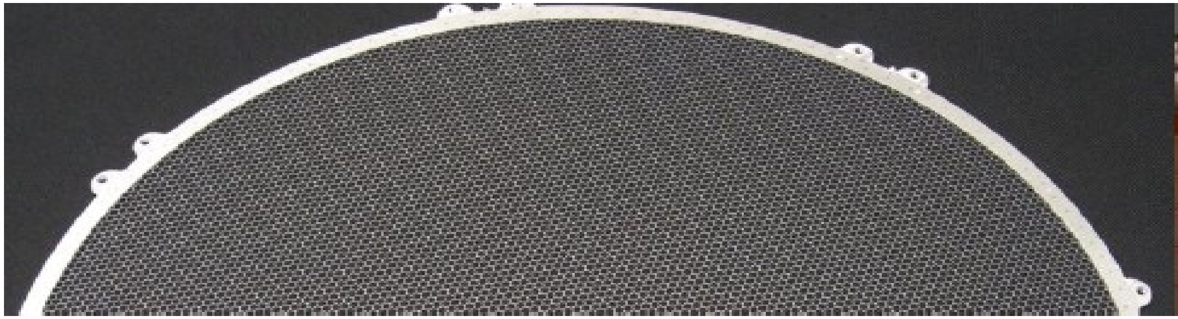




Electric field cage

- Cathode @ -16 kV
- Anode @ -4.5kV. Extraction field ~ 10 kV/cm
- 40 copper double field shaping rings for field homogeinity
- Anode stack optimized for optical transparency and S2 energy resolution





XENON100 Krypton removal system

- Xe has no long lived isotopes but has traces of radioactive Kr85
- Kr85 (Emax = 687 keV, t~11 yr) is produced in nuclear explosions and is present in natural Kr at $\sim 10^{-11}$
- The Kr level in XENON100 fill gas is ~1ppb, measured with delayed coincidence events
- A dedicated cryogenic distillation tower designed for Kr reduction by 3 orders of magnitude has been commissioned and installed next to XENON100

Shield

- 4 layers of material
  - Water: Stop neutrons from the outside
  - Lead: Stop gammas from the outside
  - Polyethylene: Stop neutrons from outside and from lead
  - Copper: Stop gammas from polyethylene

The statistical nature of the detection process

- We have discussed that with noble liquid detectors we can detect photons and electrons
- But if we really want to see a WIMP, how many photons and how many electrons are we looking for?
- Let's go to a limit case, a 3 keV nuclear recoil deposition in XENON100. This is what we would expect from an 8 GeV WIMP

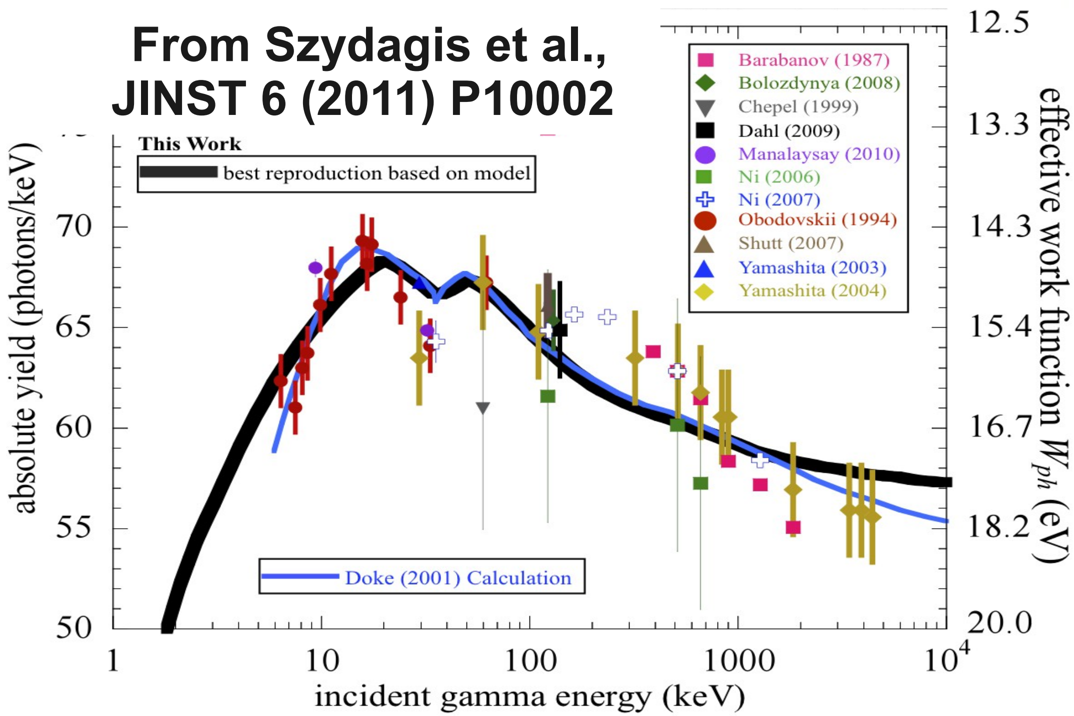
The statistical nature of the detection process

- We have discussed that with noble liquid detectors we can detect photons and electrons
- But if we really want to see a WIMP, how many photons and how many electrons are we looking for?
- Let's go to a limit case, a 3 keV nuclear recoil deposition in XENON100. This is what we would expect from an 8 GeV WIMP

The meaning of below threshold fluctuations

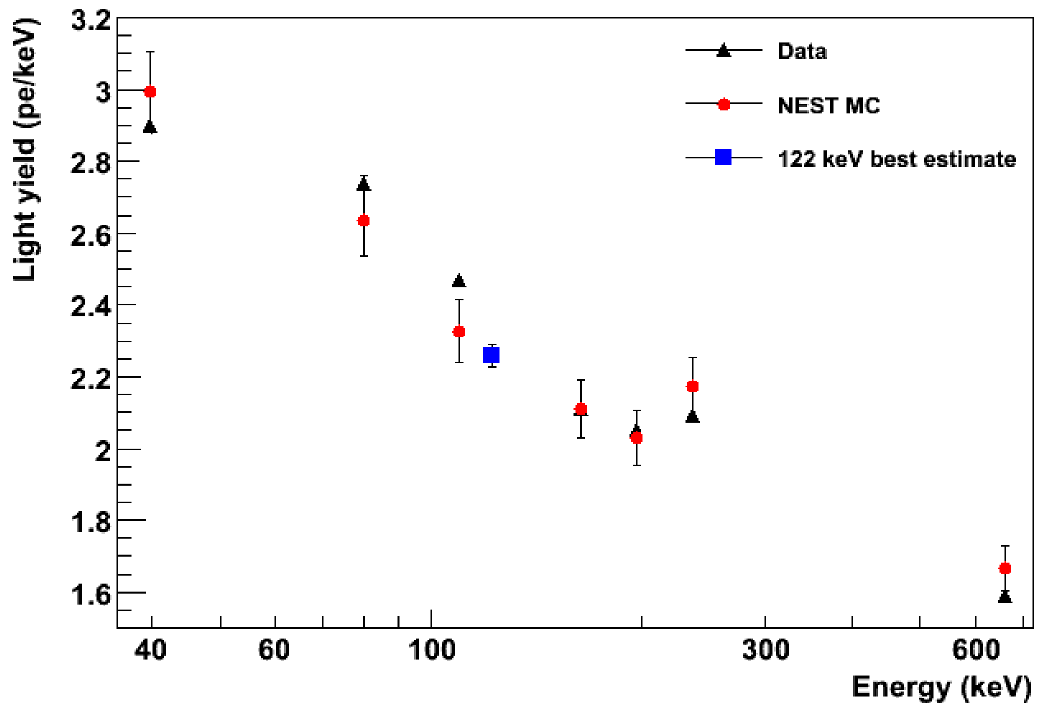
- For LXe the effective work function to create a photon in the absence of electric field is approximately 15.4 eV for a 122 keV electronic recoil
- This means that for 122 keV 7900 photons are created
- In the presence of a 0.53 kV/cm electric field the light quenching is 0.58
- Hence, in such an electric field only 4600 photons are produced

From Szydagis et al., JINST 6 (2011) P10002



The meaning of below threshold fluctuations

- In XENON100 we have a light yield of 2.28 pe/keV for 122 keV which means 278 pe detected on average
- With the ratio between these two numbers, we can see that the probability for detecting a photon in XENON100 is only ~6%

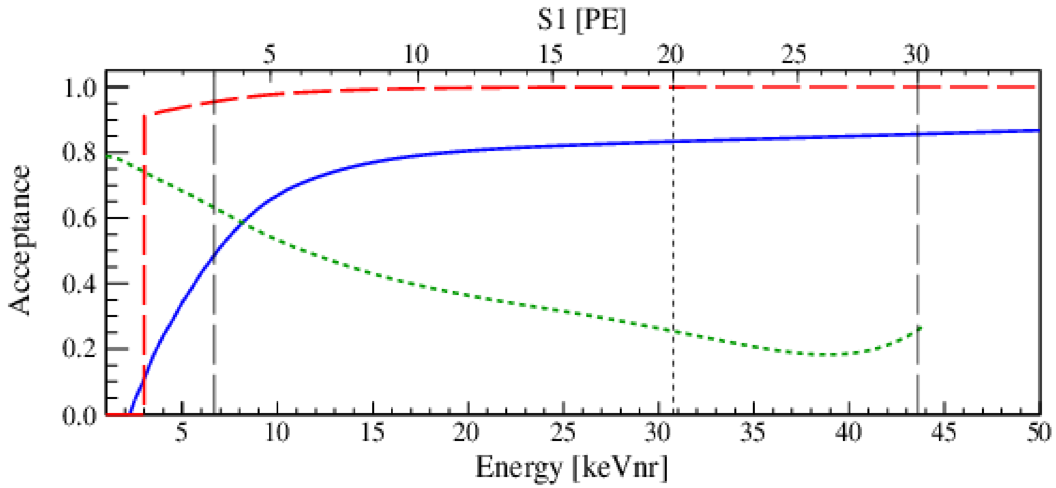


The meaning of below threshold fluctuations

- The measured value of Leff at 3keVnr is 0.092 (from XENON100 best fit)
- This means that for a 3 keV nuclear recoil we detect, on average, 1.03 pe (Note that the quenching factor for NR is 0.95)
- However, the number of photons generated is much larger (~17), and each of those has a probability of ~6% of being detected
- Hence, while on average we will detect 1.03 pe, we will have events in which the detected number of pe will be larger
- For simplicity, and since the probability for detecting a photon is low, we represent this process with a Poisson function
- Note that we don't consider other effects as recombination

The meaning of below threshold fluctuations

- All our cut efficiencies are also applied for these events, further reducing the detection probability
- S2 fluctuates independently from S1, i.e., if S1 happens to be over threshold this does not mean that S2 is larger too



- Hence, the value of the discrimination parameter, log(S2/S1), will be lower that for a more energetic recoil for which the same amount of light was detected
- The acceptance of the S2 signal is hence computed before S1 fluctuations. However, given the much better threshold for this run, the effect is much less important than in the previous one

Summary (again)

- Noble Liquid detectors are one of the most pushing technologies in the field of dark matter
- Understanding the energy depositions in the media is key to design an optimum detector and interpret its response
- Many techniques can be combined to allow to differentiate between electronic recoils and nuclear recoils

Summary (again)

- Different elements have advantages and disadvantages
- However, they are complimentary and provide a very good opportunity to one day find a WIMP

	Liquid density (g/cc)	Boiling point at 1 bar (K)	Electron mobility (cm^2/Vs)	Scintillation wavelength (nm)	Scintillation yield (photons/MeV)	Long-lived radioactive isotopes	Triplet molecule lifetime (μs)
LHe	0.145	4.2	low	80	19,000	none	13,000,000
LNe	1.2	27.1	low	78	30,000	none	15
LAr	1.4	87.3	400	125	40,000	^{39}Ar, ^{42}Ar	1.6
LKr	2.4	120	1200	150	25,000	^{81}Kr, ^{85}Kr	0.09
LXe	3.0	165	2200	175	42,000	^{136}Xe	0.03

If you want to know more...

- “Noble Gas Detectors”, E. Aprile, A.E. Bolotnikov, A.I. Bolozdynya, T. Doke, Wiley-VCH, 2006
- “NEST: a comprehensive model for scintillation yield in liquid xenon”, M. Szydagis et al. JINST 6 (2011), 10002
- “Liquid noble gas detectors for low energy particle physics”, V. Chepel, H. Araujo, JINST 8 (2013), R04001
- “Liquid xenon detectors for particle physics and astrophysics”, E. Aprile, T. Doke, Reviews of Modern Physics, Volume 82 (2010)

And references therein

Thanks a lot!