University of Zurich[UZH]

Noble liquid detectors, part one

SOUP2022: the second INFN school on underground physics
LNGS, June 20, 2022

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Content, first part

- Properties of noble liquids as detector media
- Ionisation in noble liquids
- The scintillation process in noble liquids
- Electronic and nuclear recoils
- Scintillation and ionisation yields
- Light and charge yields from NEST (Noble Element Simulation Technique)
- Electron attachment and electron drift lifetime, purity monitors
- Light attenuation in noble liquids
- Energy calibration and resolution, the W-value
- Pulse shape discrimination
- Single-phase detectors and time projection chambers, detection principles

Content, second part

- Applications to direct dark matter detection and experiments
    - Brief review of direct detection principles
    - Single-phase: DEAP (LAr), XMASS (LXe)
    - Two-phase: DarkSide (LAr), ARGO; XENON, LZ, PandaX, DARWIN (all LXe)
- Applications to neutrino physics and experiments
    - Brief motivation and open questions in neutrino physics
    - EXO-200, nEXO (LXe)
    - DUNE (LAr)
- Summary

Literature

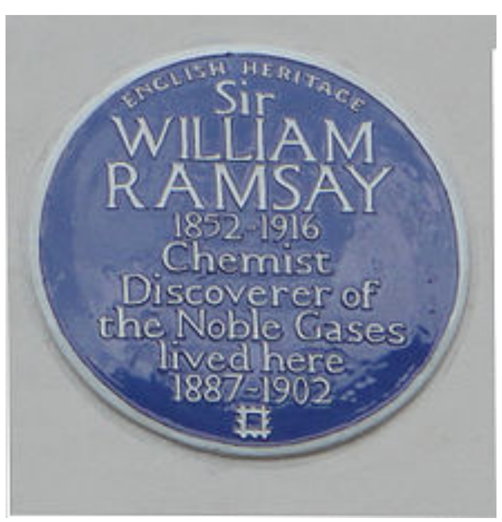
- E. Aprile, A.E. Bolotnikov, A.I. Bolozdynya, T. Doke, Noble Gas Detectors, Wiley-VCH 2006
- V. Chepel, H. Araujo, Liquid noble gas detectors for low energy particle physics, JINST 8, 2013
- E. Aprile, T. Doke, Liquid xenon detectors for particle and astrophysics, Review of Modern Physics, Vol. 82, 2010
- D. Gonzalez-Diaz, F. Monrabal, S. Murphy, Gaseous and dual-phase time projection chambers for imaging rare processes, NIM A 878, 2018
- M. Szydagis et al., A review of basic energy reconstruction techniques in liquid xenon and argon detectors for dark matter and neutrino physics using NEST, Instruments, 5, 2021
- T. Shutt, Large time-projection chambers for rare event detection, PDG 2022
- Talks at XeSAT workshop, Coimbra, May 2022: https://indico.in2p3.fr/event/20879/

Noble gases

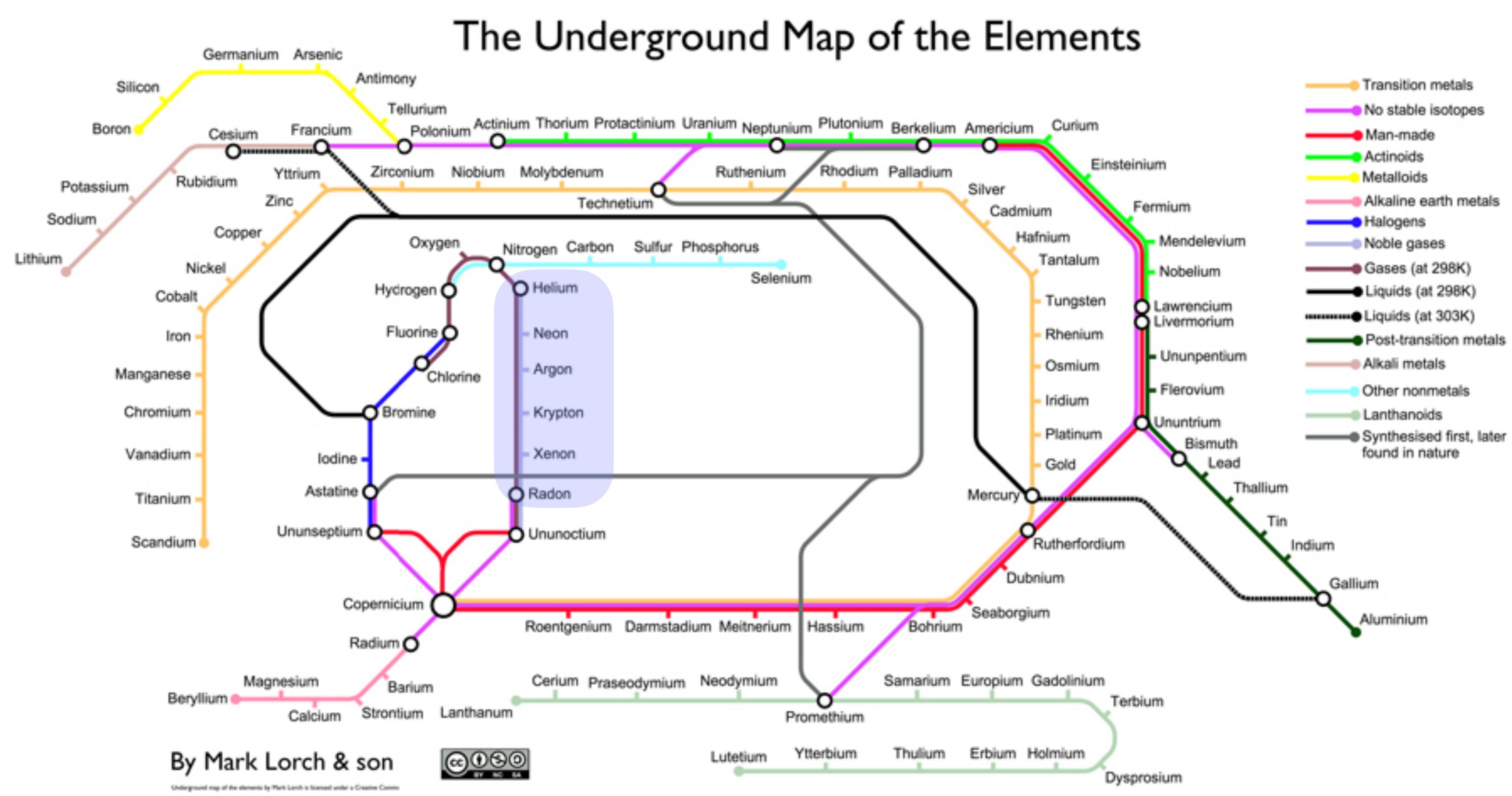
- Discovered by William Ramsay, student of Bunsen and professor at UC London (1904 Nobel prize in chemistry)

- W. Ramsay: "These gases occur in the air but sparingly as a rule, for while argon forms nearly 1 hundredth of the volume of the air, neon occurs only as 1 to 2 hundred-thousandth, helium as 1 to 2 millionth, krypton as 1 millionth and xenon only as about 1 twenty-millionth part per volume. *This more than anything else will enable us to form an idea of the vast difficulties which attend these investigations*"

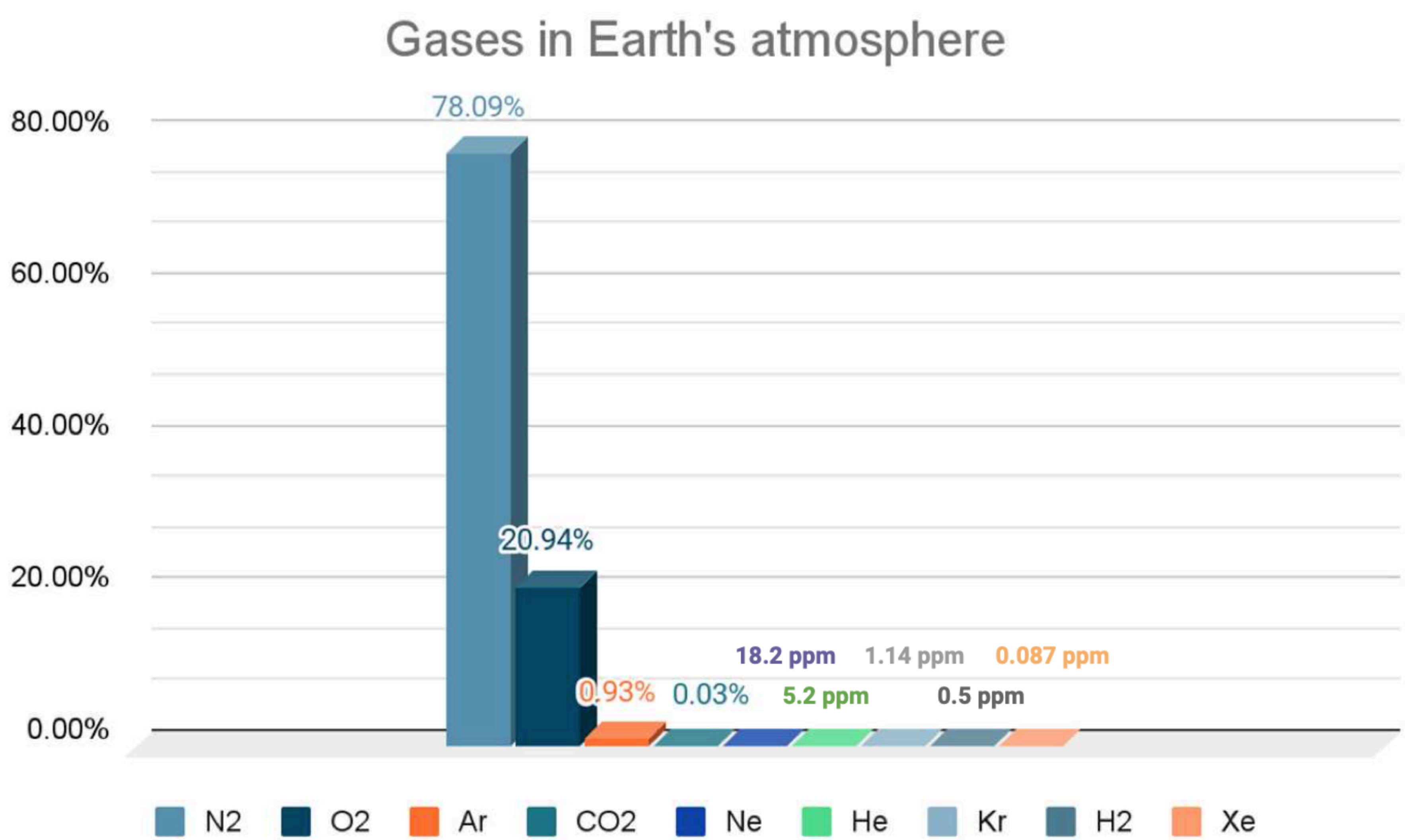
- Argon - "the inactive one"; neon - "the new one", krypton - "the hidden one", xenon - "the strange one"



"in recognition of his services in the discovery of the inert gaseous elements in air, and his determination of their place in the periodic system".



Noble gases in the Earth's atmosphere



Gaz	Abundance
N2	78,09 %
O2	20,94 %
Ar	0,93 %
CO2	350 ppm
Ne	18,2 ppm
He	5,2 ppm
Kr	1,14 ppm
H2	0,5 ppm
Xe	**0,087 ppm**

AirLiquide, XeSAT workshop, Coimbra 2022

Properties of noble gases for radiation detectors

- Underground experiments: mostly argon and xenon are used (helium and neon detectors also proposed)
- Liquefied noble gases allow for:
    - dense, homogeneous targets for ionising radiation
    - detectors with self-shielding and fiducialisation
    - large detector masses with ultra-low levels of radioactivity

Properties [unit]	**Xe**	**Ar**	**Ne**
Atomic number:	54	18	10
Mean relative atomic mass:	131.3	40.0	20.2
Boiling point T_b at 1 atm [K]	165.0	87.3	27.1
Melting point T_m at 1 atm [K]	161.4	83.8	24.6
Gas density at 1 atm & 298 K [$\mathrm{g\,l^{-1}}$]	5.40	1.63	0.82
Gas density at 1 atm & T_b [$\mathrm{g\,l^{-1}}$]	9.99	5.77	9.56
Liquid density at T_b [$\mathrm{g\,cm^{-3}}$]	2.94	1.40	1.21
Dielectric constant of liquid	1.95	1.51	1.53
Volume fraction in Earth's atmosphere [ppm]	0.09	9340	18.2

Cryogenic noble liquids

- Suitable materials for detecting ionisation tracks
  - do not attach electrons; inert, non flammable, very good dielectrics
  - can be obtained commercially, and purified
  - high charge and light yields

Element	Z (A)	BP (T_b) at 1 atm [K]	liquid density at T_b [g/cc]	ionisation [e^-/keV]	scintillation [photon/keV]
He	2 (4)	4.2	0.13	39	15
Ne	10 (20)	27.1	1.21	46	7
Ar	18 (40)	87.3	1.40	42	40
Kr	36 (84)	119.8	2.41	49	25
Xe	54 (131)	165	2.95	64	46

The ionisation process in noble liquids

- Energy loss of an incident particle in noble liquids: shared between ionisation, excitation and sub-excitation electrons (E_{kin} < energy of first excited level) liberated in the ionisation process:

$$E_0 = N_i E_i + N_{ex} E_{ex} + N_i \epsilon$$

Platzmann equation

- N_i, N_{ex} = mean number of ionised and excited atoms; E_i, E_{ex} = mean energies to ionise and excite the atoms; ε = average kin. energy of sub-excitation electrons (energy eventually goes into heat)
- In their condensed states: noble liquids exhibit a band-like structure of electronic states
- We divide all terms by the band-gap energy E_g and define the W_i-value as the energy required to produce an electron-ion pair:

$$W_i \equiv \frac{E_0}{N_i}$$

- to obtain:

$$\frac{W_i}{E_g} = \frac{E_i}{E_g} + \frac{N_{ex}}{N_i} \times \frac{E_{ex}}{E_g} + \frac{\epsilon}{E_g}$$

The ionisation process in noble liquids

- The average energy loss in ionisation is slightly larger than the ionisation potential or the band gap energy E_g, because it includes multiple ionisation processes
  - as a result, the ratio of the W_i-value to the ionisation potential or band gap energy is:

$$W_i/E_g = 1.6 - 1.7$$

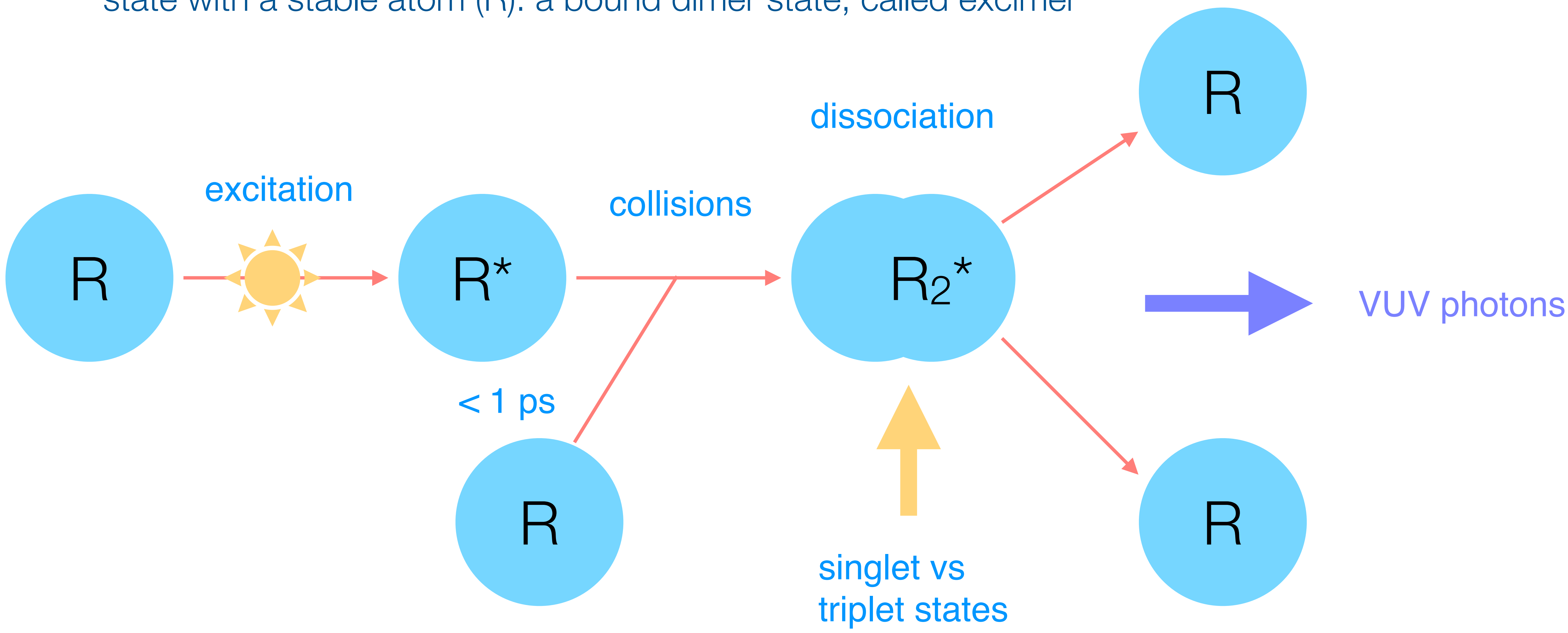
- about 40-60% of absorbed energy is converted into free charge carriers

Material	Ar	Kr	Xe
Gas			
Ionisation potential [eV]	15.75	14.00	12.13
W-value [eV]	26.4	24.2	22
Liquid			
Gap energy [eV]	14.3	11.6	9.3
W-value [eV]	19.5±1.0	18.4±0.3	13.7±0.2

- the W-value in the liquid phase is smaller than in the gaseous phase
- the W-value in xenon is smaller than the one in liquid argon, and krypton (and neon)
- the ionisation yield is highest in liquid xenon (of all noble liquids)

The scintillation process in noble liquids

- Scintillation in noble liquids arises in two distinct processes
  - excited atoms R* (excitons) and ions R^+, both produced by ionising radiation
  - direct excitation: less than 1 ps after the excitation, the excited atom (exciton, R*) forms a bound state with a stable atom (R): a bound dimer state, called excimer



- the 2 spin states refer to the combined spin state of the electron and the angular momentum due to the molecular orbit

The scintillation process in noble liquids

- Scintillation in noble liquids arises in two distinct processes: excited atoms R* (excitons) and ions R+, both produced by ionising radiation

$$\mathrm{R}^* + \mathrm{R} + \mathrm{R} \rightarrow \mathrm{R}_2^* + \mathrm{R}$$

$$\mathrm{R}_2^* \rightarrow 2\mathrm{R} + h\nu$$

Excitons (R*) will rapidly form excited dimers (R*₂) with neighbouring atoms

The excited dimer R^*_2, at its lowest excited level, is de-excited to the dissociative ground state *by the emission of a single VUV photon*

$$\mathrm{R}^+ + \mathrm{R} \rightarrow \mathrm{R}_2^+$$

$$\mathrm{R}_2^+ + e^- \rightarrow \mathrm{R}^{**} + \mathrm{R}$$

$$\mathrm{R}^{**} \rightarrow \mathrm{R}^* + \mathrm{heat}$$

$$\mathrm{R}^* + \mathrm{R} + \mathrm{R} \rightarrow \mathrm{R}_2^* + \mathrm{R}$$

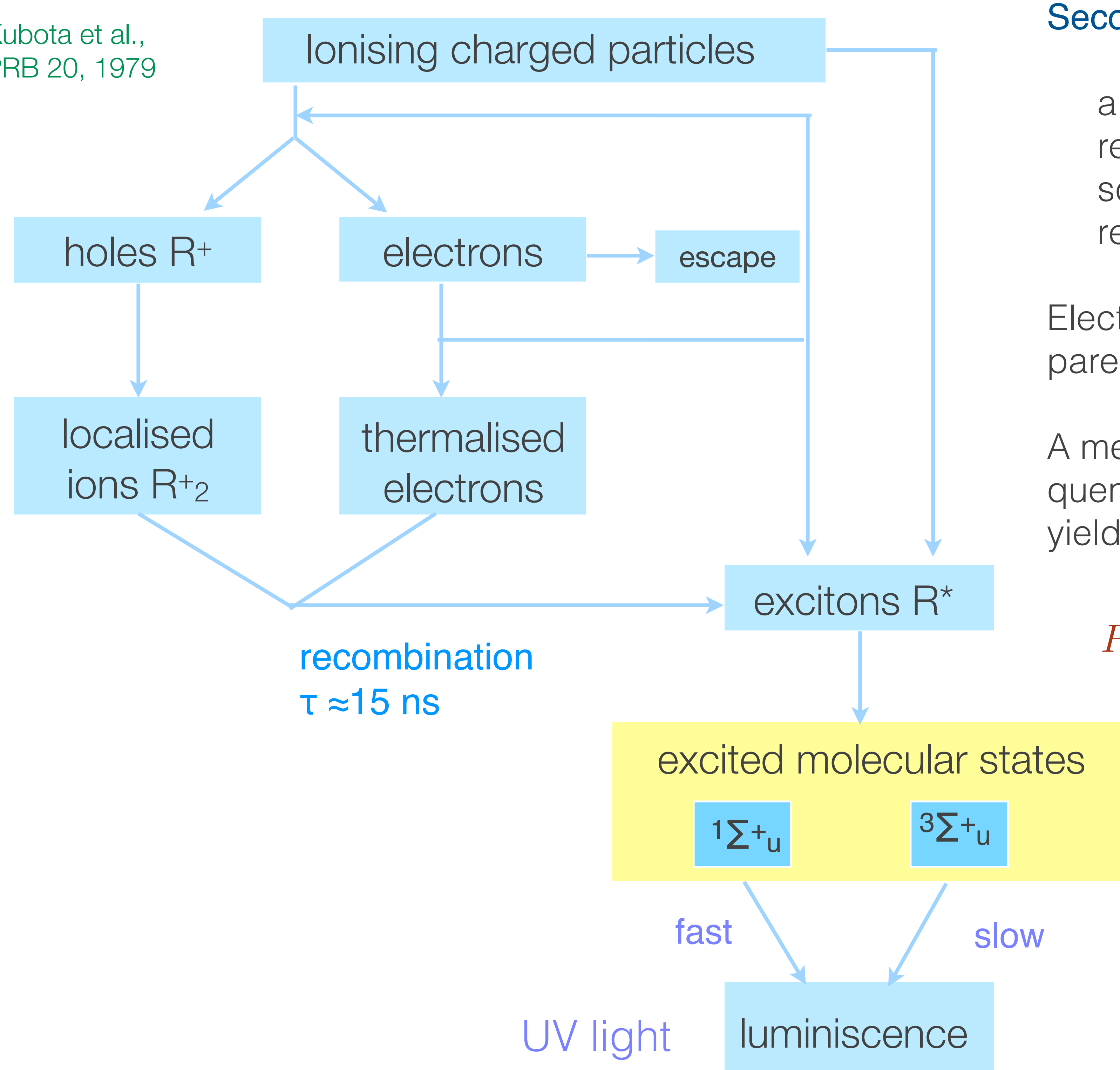
$$\mathrm{R}_2^* \rightarrow 2\mathrm{R} + h\nu$$

The dimer state is at a lower energy level than the excitation energy of an individual atom: the medium will thus be transparent to the VUV light

hv = VUV photon emitted in the process

The scintillation process in noble liquids

Kubota et al.,
PRB 20, 1979



Second process producing scintillation light:

a fraction of the ionisation electrons will recombine with ions and produce a scintillation photon in a process called recombination

Electrons that thermalise far from their parent ion may escape recombination

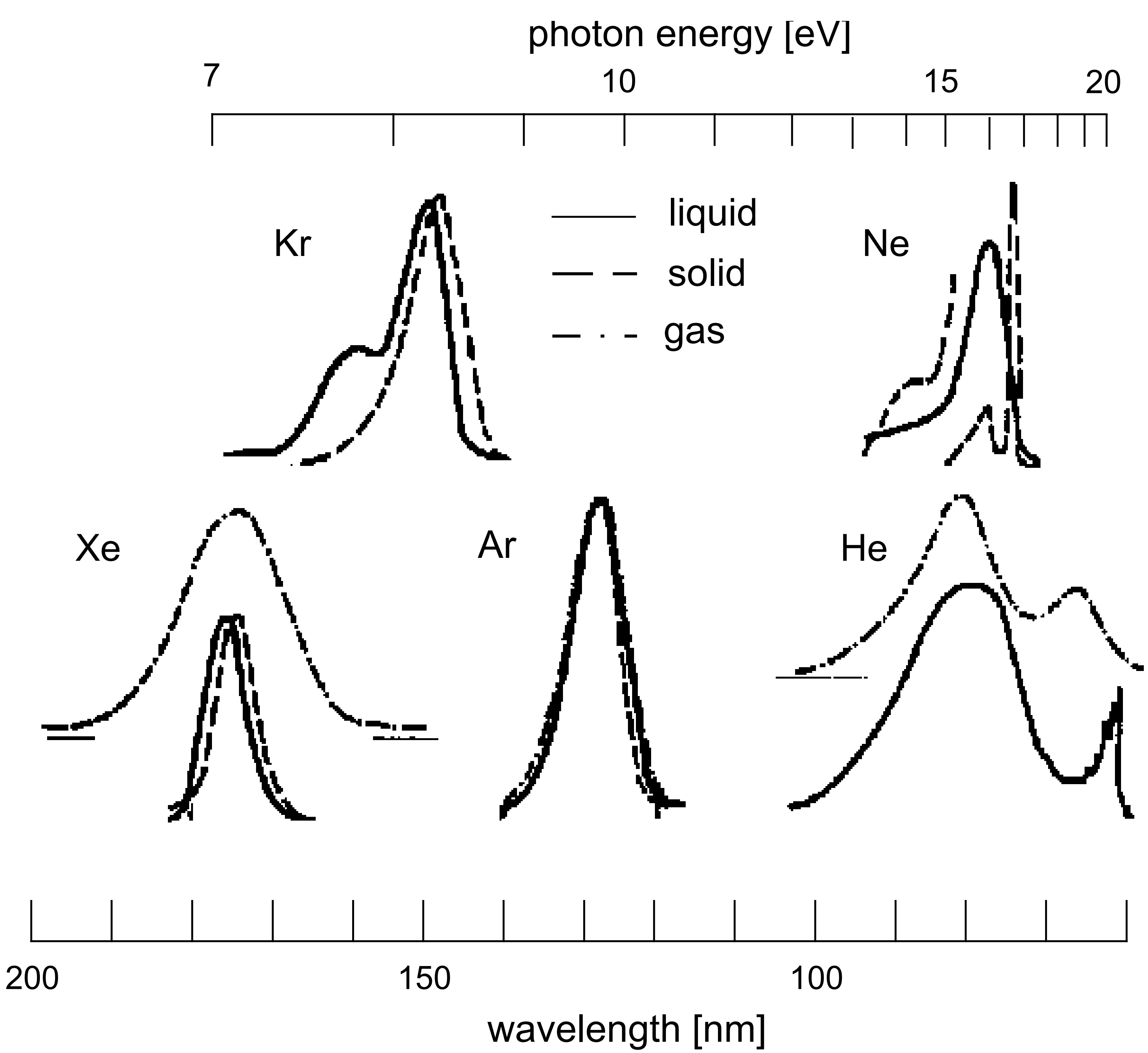
A mechanism called “bi-excitonic quenching” can also reduce the scintillation yield in very dense tracks:

$$R^* + R^* \longrightarrow R_2^{**} \longrightarrow R + R^+ + e^-$$

Bi-excitonic quenching (or Penning quenching): two excitons combine to form an electron-ion pair and a ground-state atom

Hence only a single electron or photon (in case of recombination) is produced, instead of two

The energy of the UV photons



$$\lambda_{\mathrm{LNe}} \sim 78\,\mathrm{nm}$$
$$\lambda_{\mathrm{LAr}} \sim 128\,\mathrm{nm}$$
$$\lambda_{\mathrm{LXe}} \sim 178\,\mathrm{nm}$$

The dimer (or exciton) can not exist in the ground state => the photon emission has practical applications in dense, noble scintillators

The scintillation process in noble liquids

- We define W_{ph} as the average energy required to produce a single photon:

$$W_{ph} = \frac{E_0}{N_{ex} + N_i} = \frac{W_i}{1 + N_{ex}/N_i} = \frac{W_i}{1 + \alpha}$$

Doke at al, 2002

- E_0 = energy loss, N_{ex}, N_i = mean number of excitons and electron-ion pairs; E_i, E_{ex} = mean energies to ionise and excite the atoms; α = ratio N_{ex}/Ni (~0.2 for LAr, and ~ 0.2 for LXe)
- We assume the efficiencies for exciton and electron-ion pair creations are unity, namely:

$$N_{ph} = N_{ex} + r \cdot N_i$$

  - with r = recombination fraction

- If an electric field is applied, one can measure the electrons which do not recombine, with the amount of extracted charge defined as:

$$N_q = (1 - r) \cdot N_i$$

The scintillation process in noble liquids

- With the previous equations we can define the recombination-independent sum

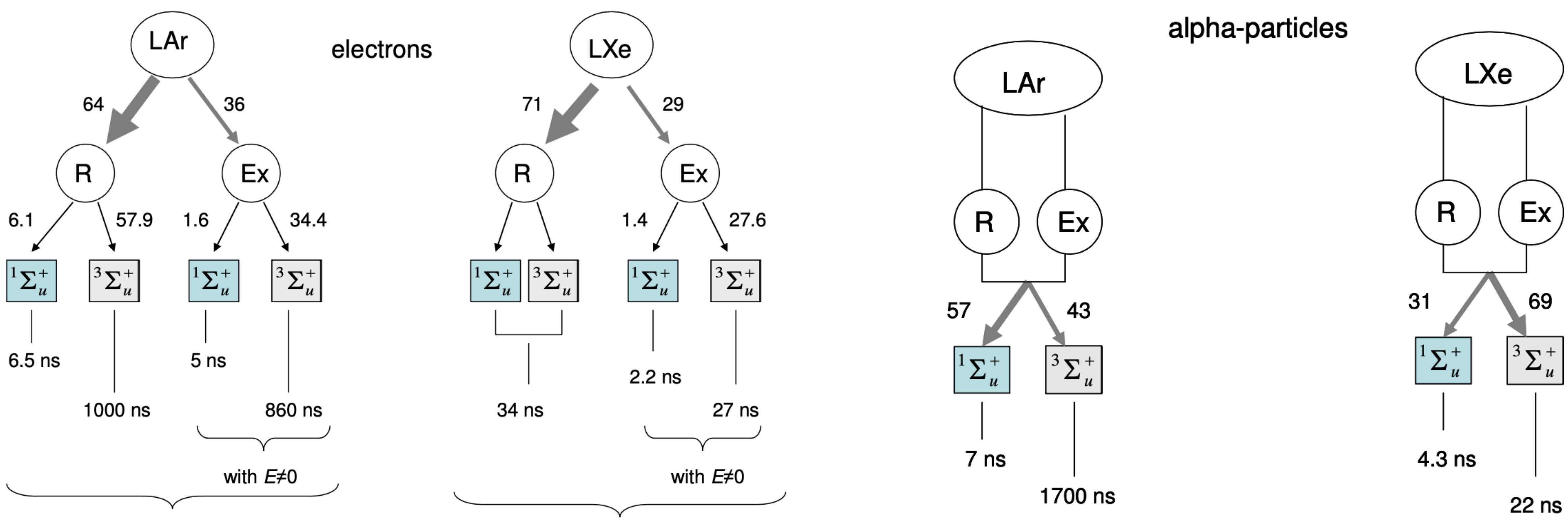
$$E_0 = (N_q + N_{ph}) \cdot W_{ph}$$

- The recombination-independent energy required to produce a single detectable quantum, N_q or N_{ph} is also called the W-value (note that $N_q + N_{ph} = N_i + N_{ex}$ for any value of r)
- We will thus use $W_{ph} = W$ (this assumes that each recombining electron-ion pair produces an exciton, which leads to a photon)
- Later we will see how it can be measured (for example, at fixed energy interactions, by varying the electric field, or using different lines at different energies, for a given field)

Material	Ar	Xe
W-value [eV]	19.5±1.0	13.7±0.2 11.5±0.2

The scintillation process in noble liquids

- The distribution of the total number of emitted scintillation photons between different excitation channels depends on the type of particle (and thus linear energy transfer, LET)
- It can be used to discriminate between different type of interactions (as we shall see later as well, in particular in liquid argon, due to the different time scales for the singlet and triplet states)
  - Example: fast electrons (with energies 0.5 MeV - 1 MeV) and alpha particles; R = recombination; Ex = direct excitation -> distribution of the number of emitted scintillation photons between different excitation channels
  - LXe: the fast component for e- only observed with an E-field (to suppress recombination); alphas: high LET, no difference in time decay constants between R and Ex; LET ~ 100 higher than for e-, higher densities of ionised and excited species along the tracks, thus stronger and faster recombination

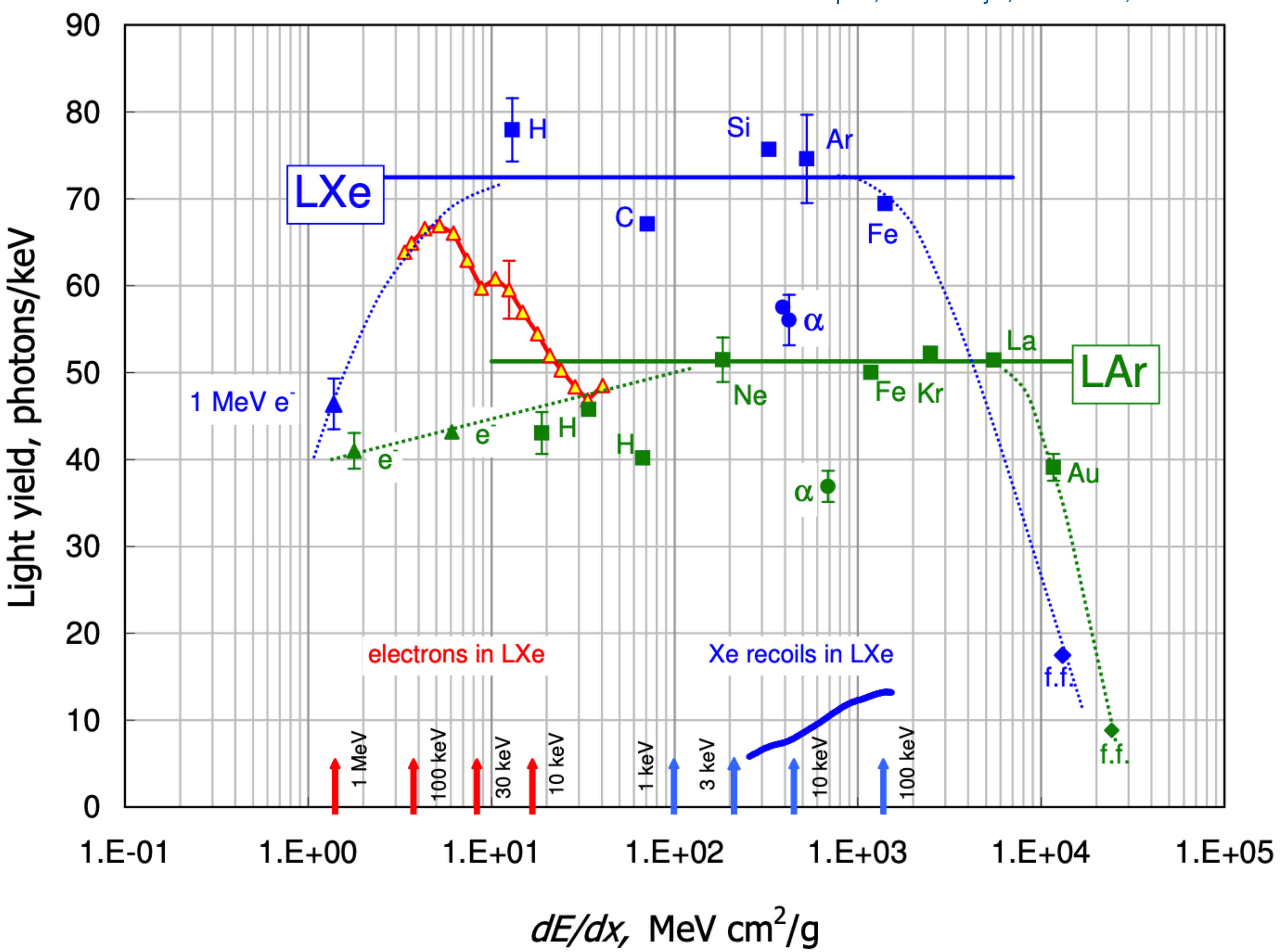


V. Chepel, H. Araujo, JINST 8, 2013

Scintillation light yield in Ar and Xe

- Light yield as a function of LET for various particles. Data shown in green (LAr) and blue (LXe)

V. Chepel, H. Araujo, JINST 8, 2013



The scintillation pulse shape

- The scintillation light from pure noble liquids has two decay components due to the de-excitation of the singlet and triplet states of the excited dimer:

$$R_2^* \longrightarrow 2R + h\nu$$

- Figure:
  - Alphas and fission fragments: the shorter decay time comes from the de-excitation of singlet states, the longer from triplet states
  - Relativistic electrons: only one decay component
- As we shall see later, the difference in pulse shape between different type of particle interactions is used to discriminate among the various particles via PSD

Time constants:

- Ne: few ns versus15.4 μs
- Ar: 10 ns versus 1.5 μs
- Xe: 4 ns versus 27 ns Xe

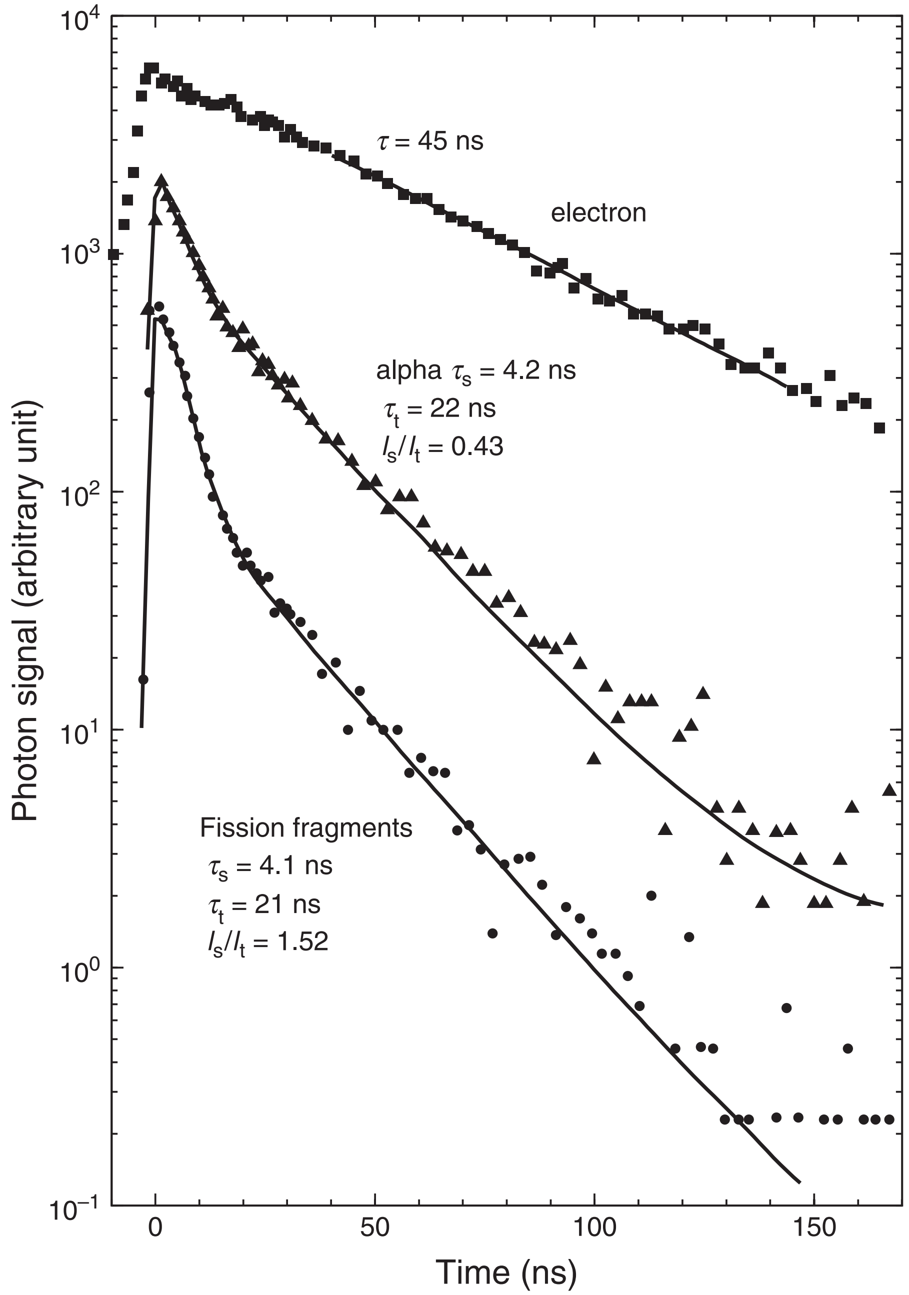
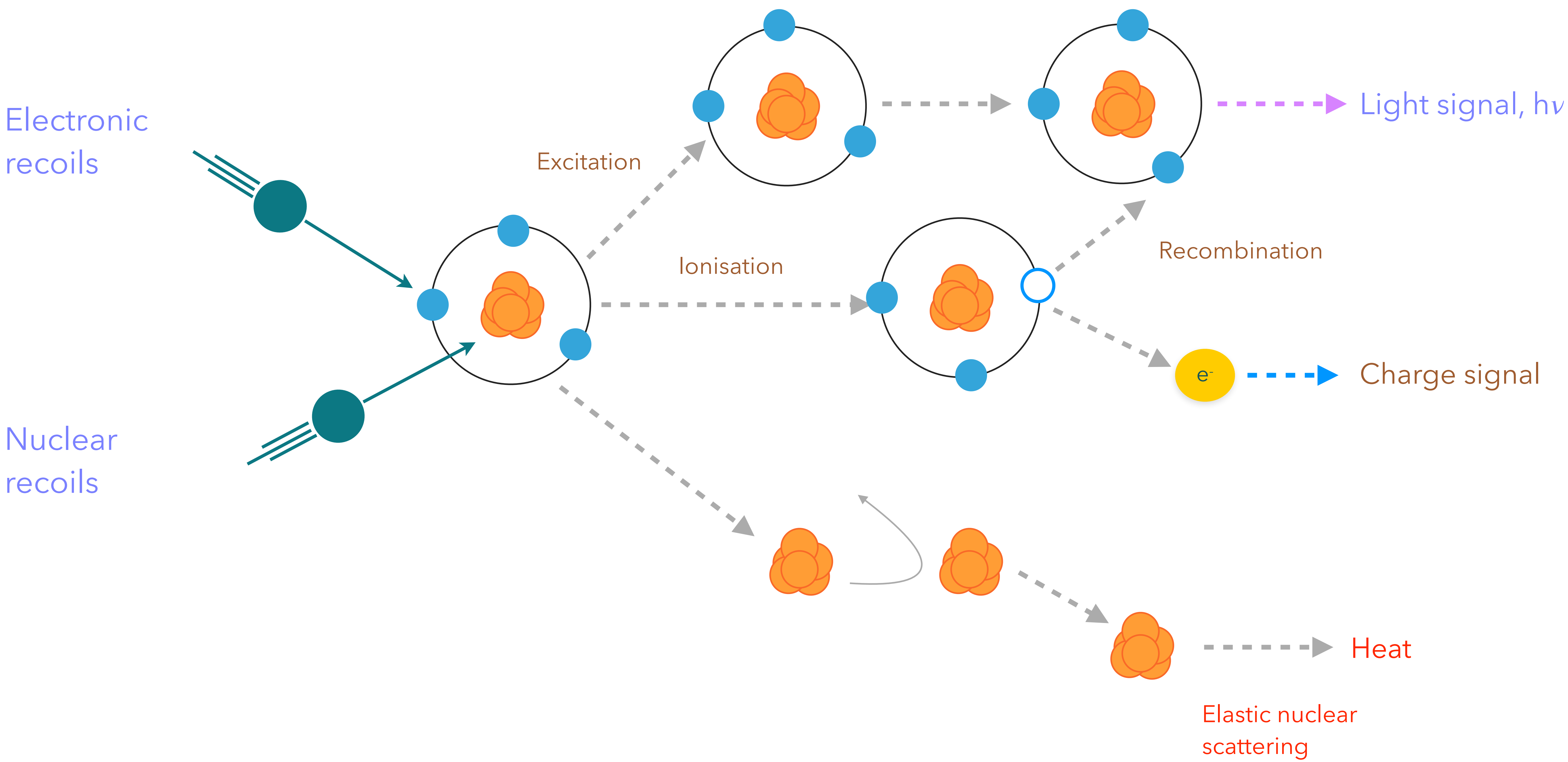


Fig. 21.1. Decay curves of luminescence from liquid xenon excited by electrons, α-particles and fission fragments, without an external electric field [1109; 1283].

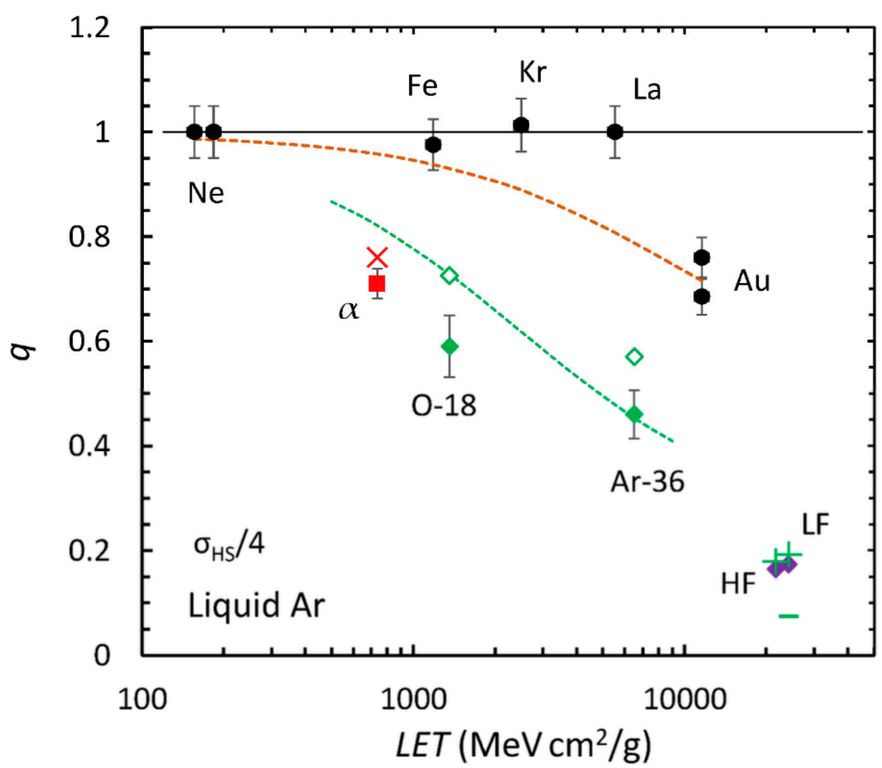
Electronic and nuclear recoils in noble liquids



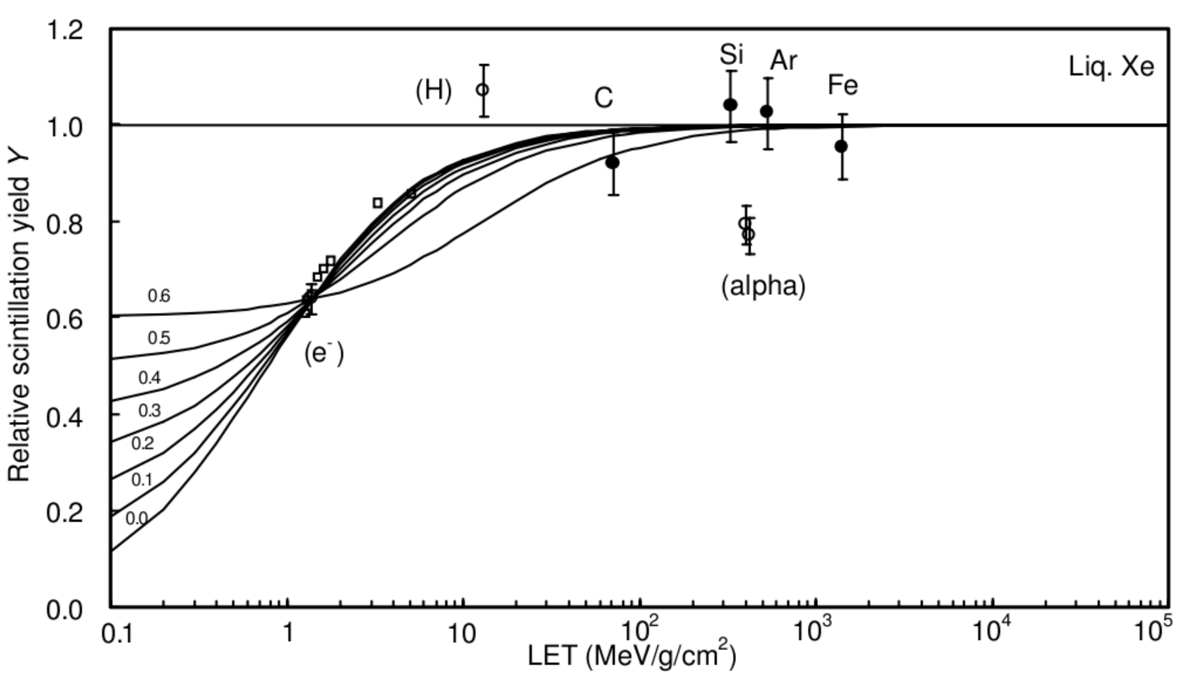
Scintillation yield in noble liquids

- An energetic particle looses energy through:
  - inelastic interactions with electrons in the medium (electronic stopping)
  - elastic collisions with nuclei (nuclear stopping)
- Electrons, gamma rays and fast ions loose most of their energy through electronic stopping
- Nuclear recoils loose a considerable fraction of their energy via nuclear stopping (nuclear quenching, q_{nc})
- The lower scintillation yield of alpha tracks is attributed to bi-excitonic quenching (electronic quenching, q_{el}) and nuclear recoils will also suffer from this effect

Liquid argon quenching factor for ions:
A. Hitachi, Instruments 2021, 5



Liquid xenon relative scintillation yield:
T. Doke at al., Jpn J. Appl. Phys, 2002, 41



The Lindhard factor

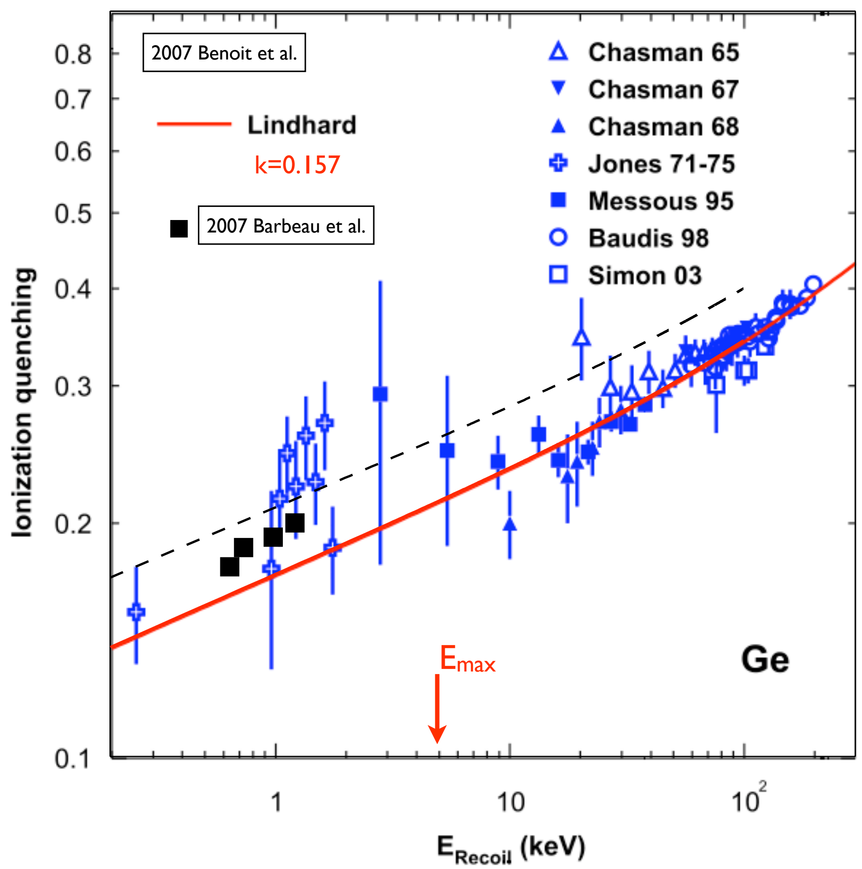
- Lindhard computed the fraction of the initial recoil energy lost to electronic excitation, f_n
- His theory describes quite well the ionisation signals in semiconductors:

$$f_n = \frac{kg(\epsilon)}{1 + kg(\epsilon)}$$

$$\epsilon = 11.5\, E_R(\mathrm{keV}) Z^{-7/3}$$

$$k = 0.133\, Z^{2/3} A^{-1/2}$$

$$g(\epsilon) = 3\epsilon^{0.15} + 0.7\epsilon^{0.6} + \epsilon$$

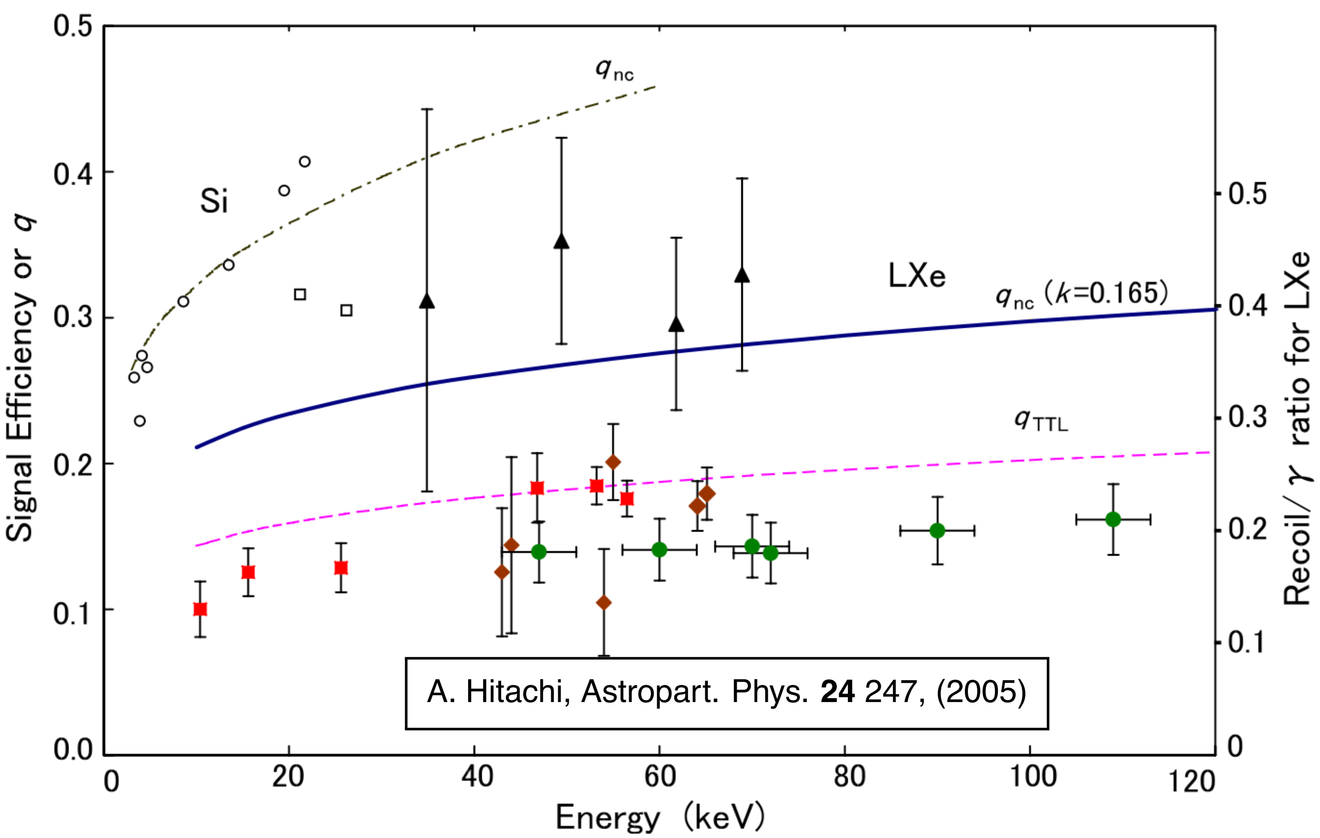


- ε: reduced energy = dimensionless deposited energy, with Z = atomic number of nucleus
- k = proportionality constant between the electronic stopping power dE/dx and the velocity of the projectile (which is the recoiling atom)
- g(ε): proportional to the ratio of electronic stopping power to nuclear stopping power

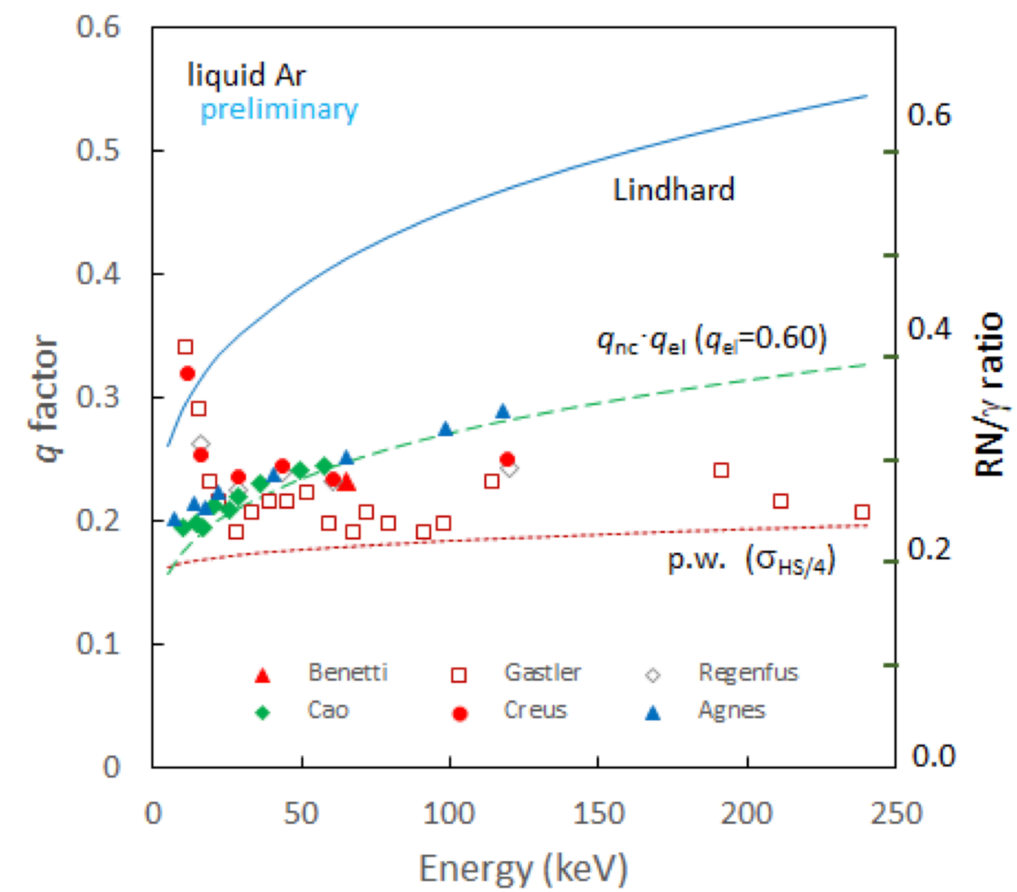
The Lindhard factor in noble liquids

- Historically, the measured values of the scintillation efficiency in noble liquids were considerably lower than the Lindhard prediction (k = 0.165 for xenon, k = 0.144 for argon)
- It was believed that this may be due to electronic quenching and possibly to escape electrons

Liquid xenon



Liquid argon



A. Hitachi. A. Mozumder, arXiv:1903.05815, 2019

The Lindhard factor in noble liquids

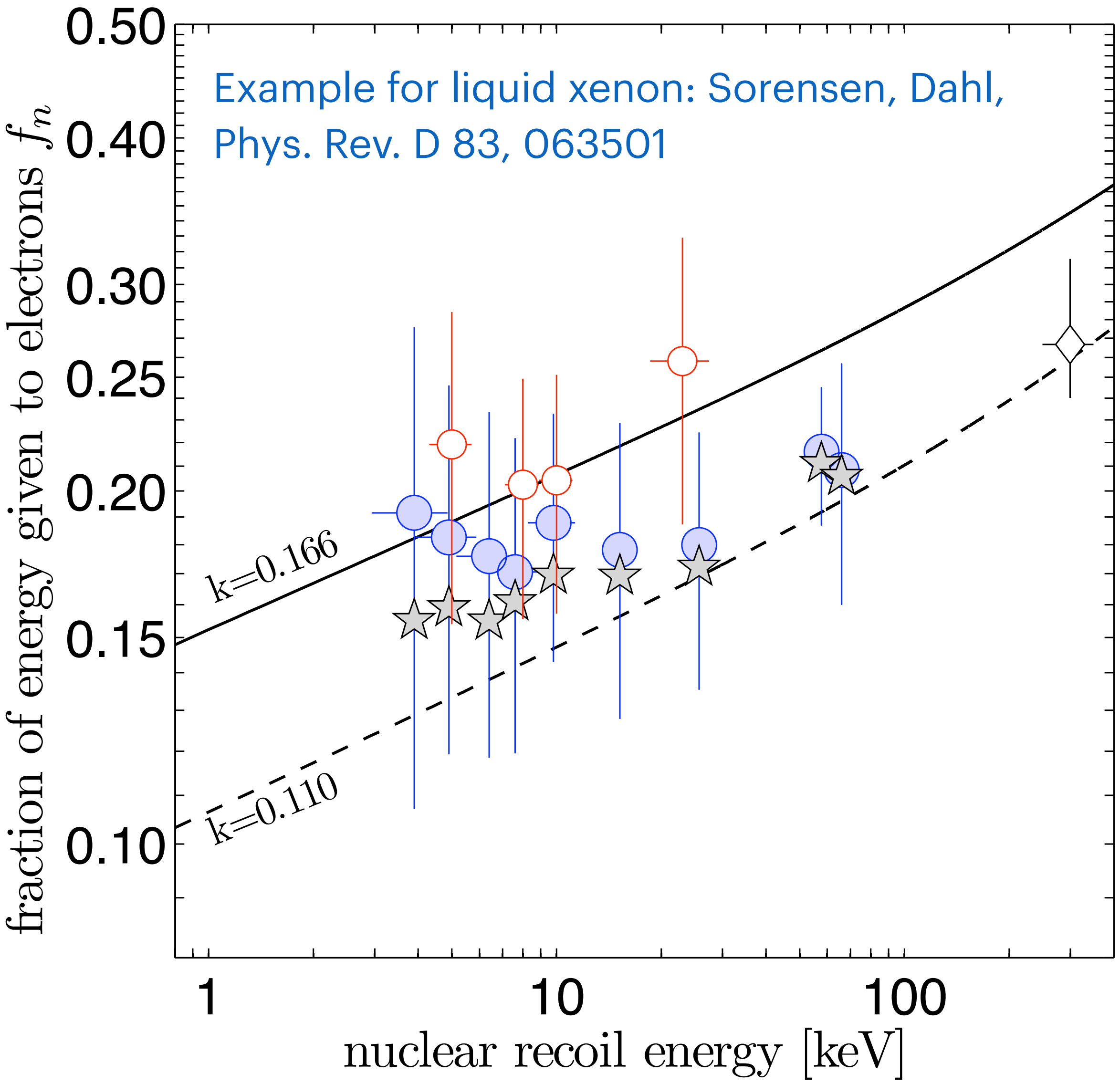
- More recently: the Lindhard prediction seems to apply if the nuclear recoil energy is reconstructed using both scintillation and ionisation signals (hence the total quanta, for example in two-phase TPCs, more on this later in the lecture), the so-called "combined energy scale":

$$E_{ER} = W \cdot (N_{ph} + N_q)$$

$$E_{NR} = W \cdot (N_{ph} + N_q) \cdot \frac{1}{f_n}$$

$$f_n = \frac{W \cdot (N_{ph} + N_q)}{E_{NR}}$$

- N_q = nr. of primary electrons
- N_{ph} = nr of primary UV photons
- W = average energy to produce an electron or a photon



Relative scintillation efficiency of nuclear recoils

- The scintillation light yield of nuclear recoils in noble liquids is different than the one produced by electron recoils of the same energy
- The ratio of the two = relative scintillation efficiency (L_{eff}) is important for the determination of the sensitivity of noble liquids as dark matter detection media
- Experimentally this quantity is defined as the zero-field value of light yield of nuclear recoils (generated with n-sources) and electronic recoils (generated with β- and γ-sources):

$$\mathcal{L}_{eff} = \frac{L_{y,NR}}{L_{y,ER}} = \frac{E_{ER}}{N_{ph,ER}} \frac{N_{ph,NR}}{E_{NR}} = \frac{1}{L_y} \frac{N_{PE,NR}}{E_{NR}} = \frac{E_{ee}}{E_{NR}}$$

- $N_{ph,\,ER}$ = nr. of primary photons from electronic recoils
- $N_{ph,NR}$ = nr of primary photons from nuclear recoils
- $N_{PE,\,NR}$ = nr of primary photoelectrons from nuclear recoils

- E_{ee} = "electron-equivalent" energy, obtained from the light yield (L_y) of mono-energetic lines from calibration sources (e.g., ^{83m}Kr)

Light yield in noble liquids (nuclear recoils): argon

- Two methods:
  - direct: mono-energetic neutrons scatters which are tagged with a n-detector
  - indirect: measure energy spectra from n-sources, compare with MC predictions

$$\mathcal{L}_{eff}(E_{NR}, \mathcal{E}_d) = \frac{L_{y,NR}(E_{NR}, \mathcal{E}_d)}{L_{y,ER}(E_{Kr}, \mathcal{E}_d = 0)}$$

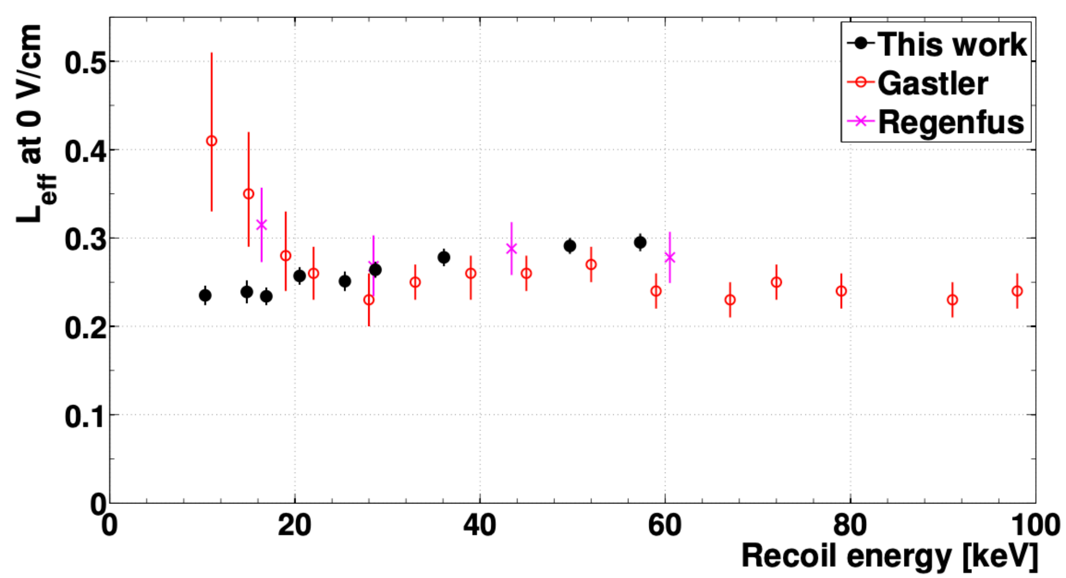
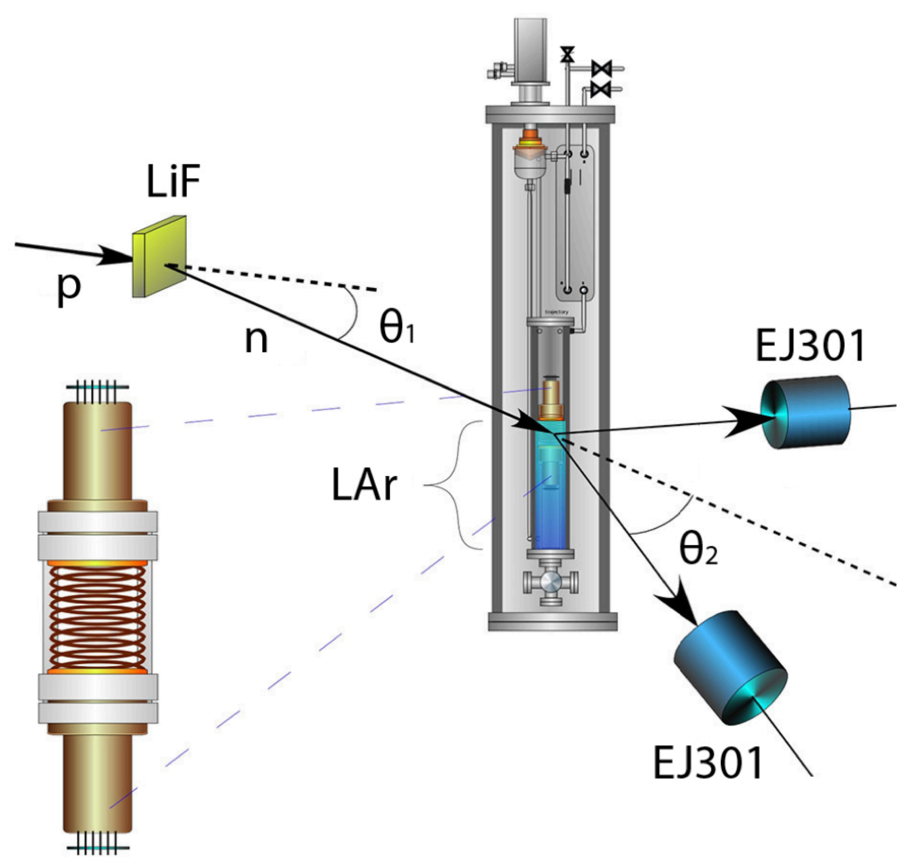


FIG. 10. S1 yield as a function of nuclear recoil energy measured at zero field relative to the light yield of ^{83m}Kr at zero field, compared to previous measurements[8, 9].

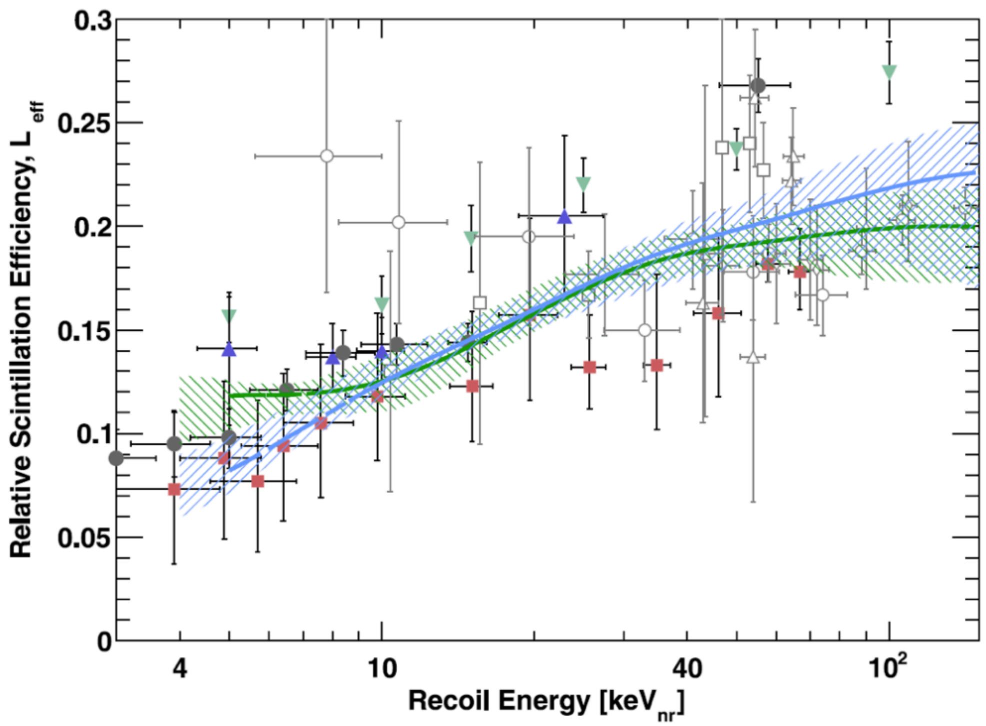
SCENE collaboration, PRD 91, 2015

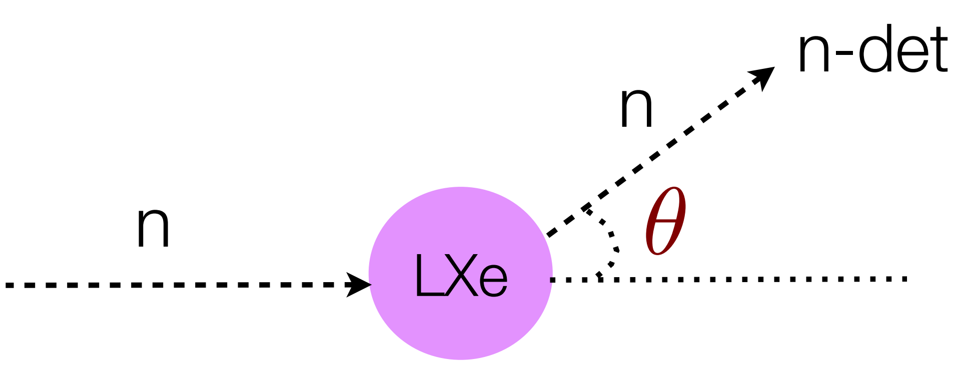


Light yield in noble liquids (nuclear recoils): xenon

- Two methods:
  - direct: mono-energetic neutrons scatters which are tagged with a n-detector
  - indirect: measure energy spectra from n-sources, compare with MC predictions

$$\mathcal{L}_{eff}(E_{NR}) = \frac{L_{y,NR}(E_{NR})}{L_{y,ER}(E_{ee} = 122\,\mathrm{keV})}$$





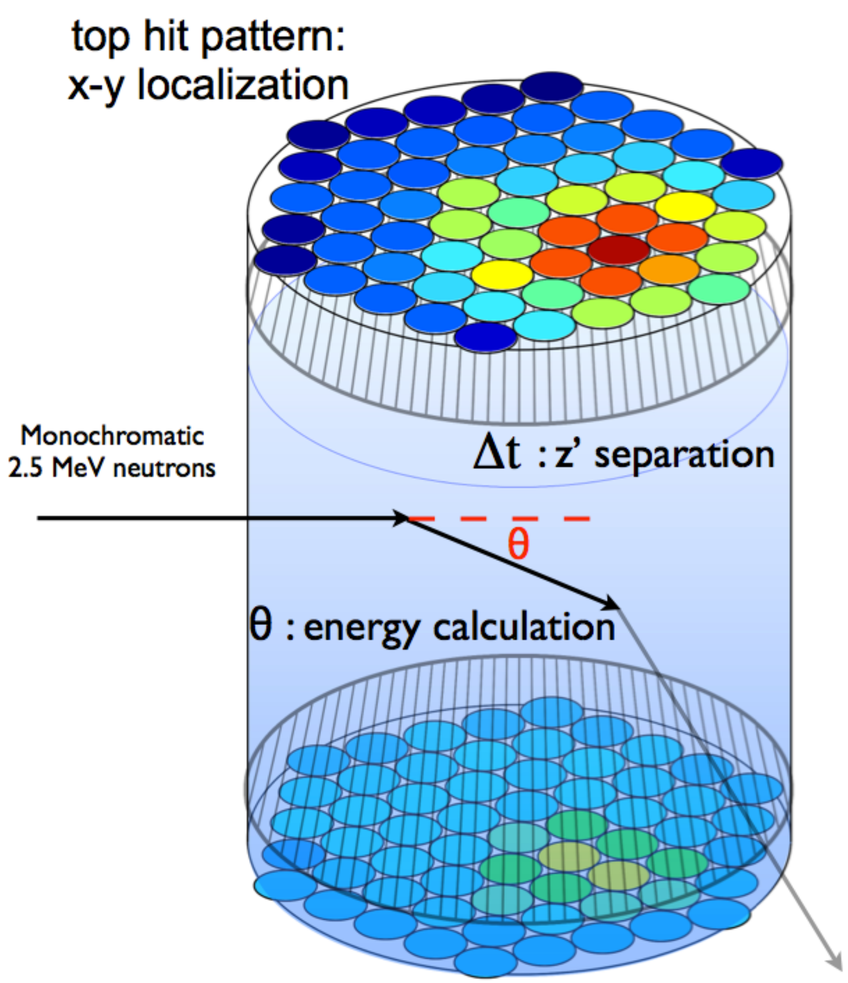
Early measurements in liquid xenon: mean (solid) and 1-, 2-sigma uncertainties (bands)

V. Chepel, H. Araujo, JINST 8, 2013

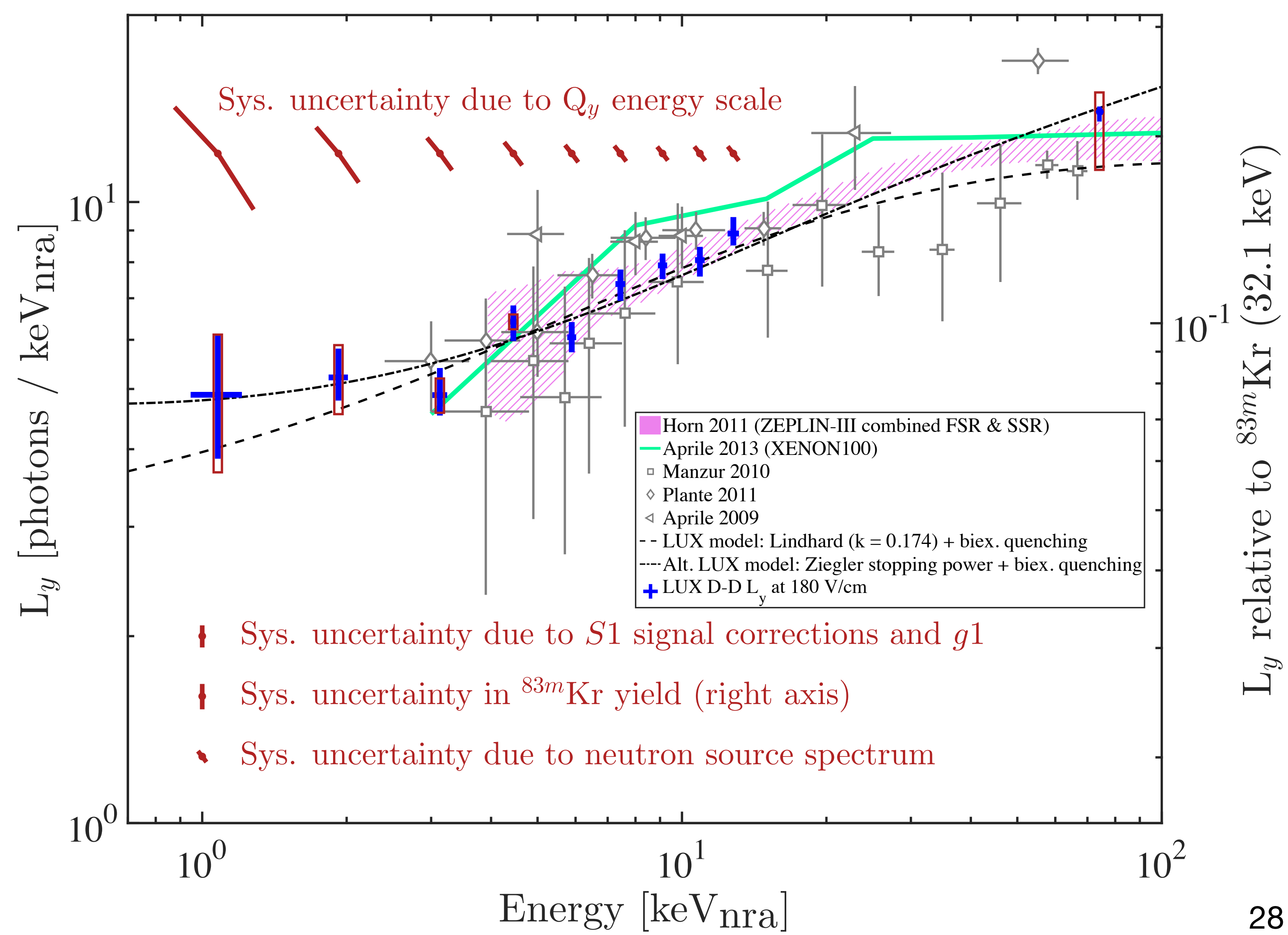
Light yield at low energies: data from LUX

- Use data acquired in situ with monochromatic 2.5 MeV neutrons (D-D generator)
- Calculate energy (via angle) from x-y position and Δt (z separation)
- Light yield measured down to 1 keV

D. Huang, UCLA DM2016



$$E_r = E_n \frac{4 m_n m_{Xe}}{(m_n + m_{Xe})^2} \frac{1-\cos\theta}{2}$$

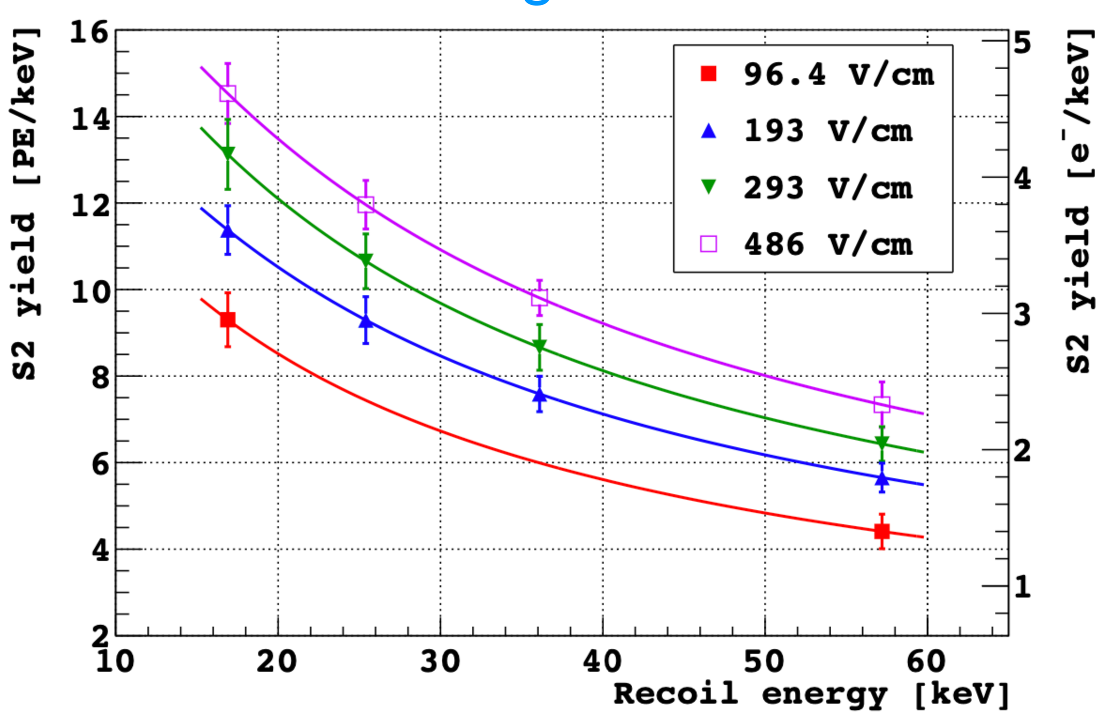


Charge yield in noble liquids for nuclear recoils

- Nuclear recoils: denser tracks, hence larger electron-ion recombination than electronic recoils
  - the collection of ionisation electrons becomes more difficult for nuclear than electronic recoils
- Ionisation yield of nuclear recoils: number of observed electrons per unit recoil energy

$$Q_{y,NR} = \frac{N_{q,NR}}{E_{NR}}$$

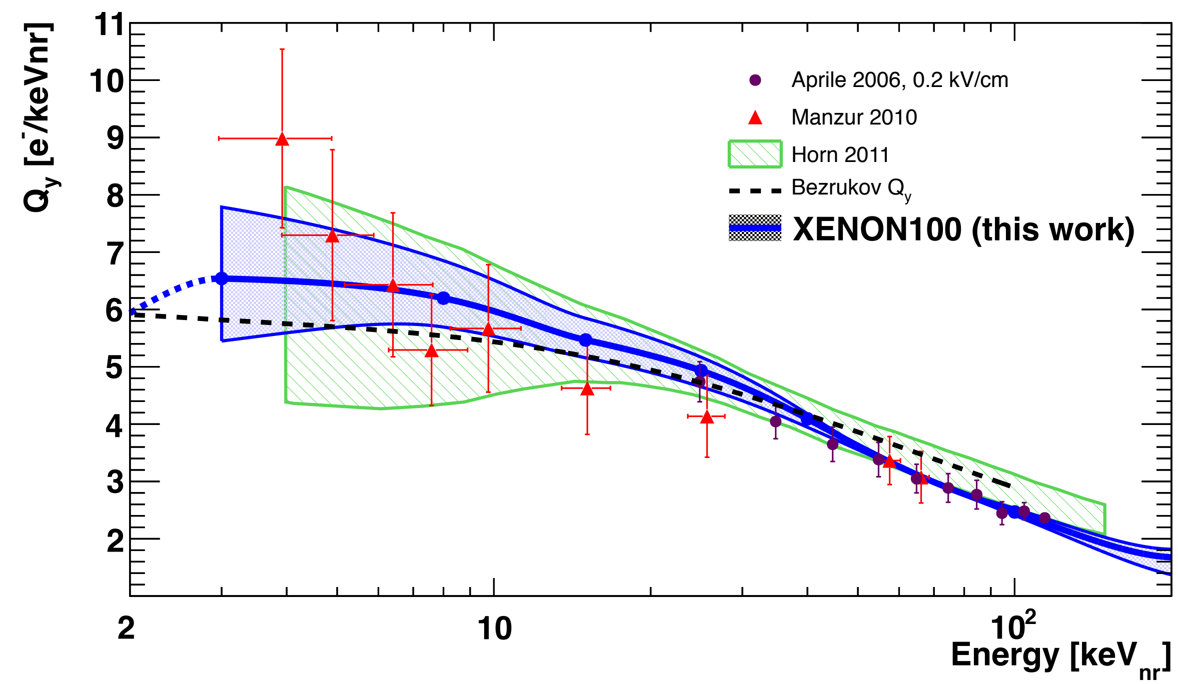
Argon



charge yield for different drift fields

SCENE collaboration, PRD 91, 2015

Xenon

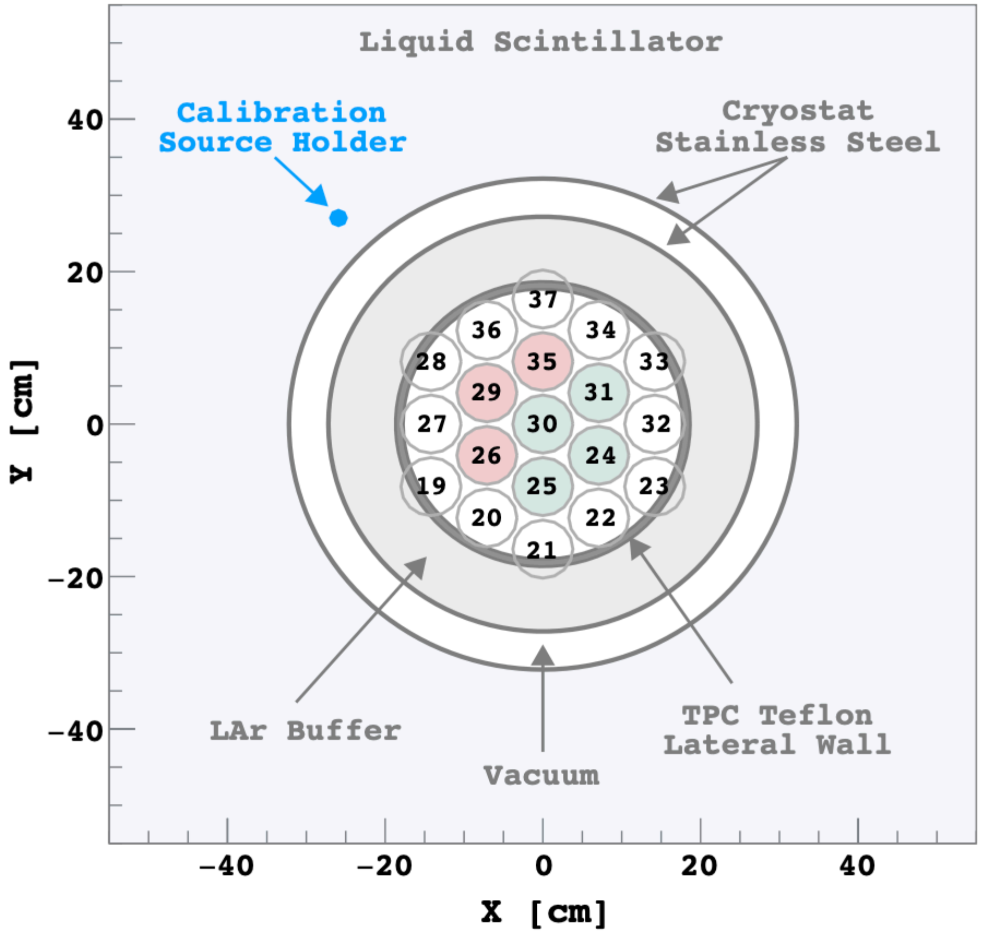


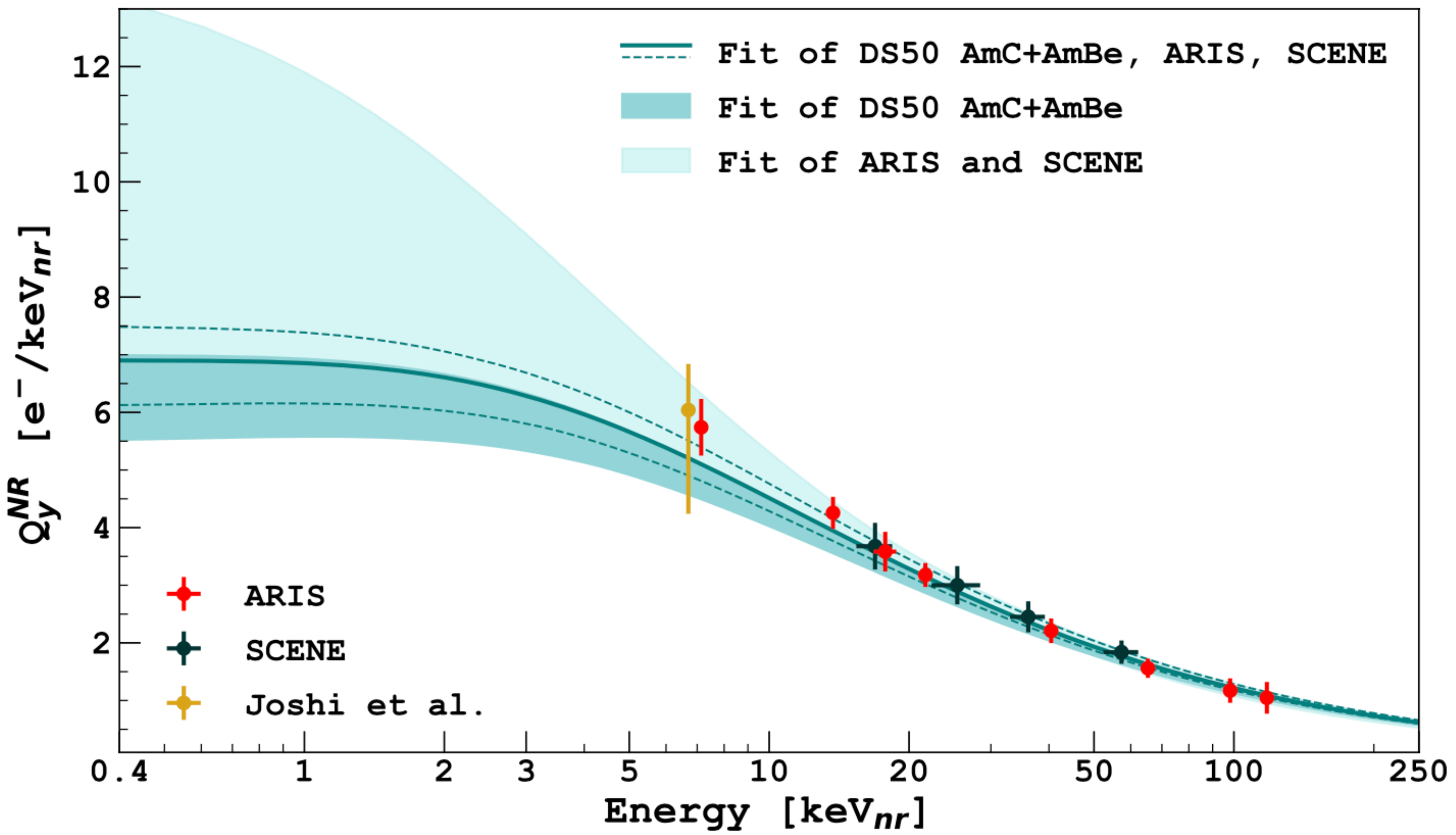
blue: indirect measurement, by data/MC comparison of AmBe neutron calibration data

Phys. Rev. D 88, 012006, 2013

Charge yield for NRs in LAr: data from DarkSide-50

- Use data acquired in situ with AmBe and AmC calibration sources
- Fit of the NR ionisation yield, together with data sets from direct measurements
- Charge yield measured down to ~ 0.5 keV_{NR} (corresponds to 3 ionisation electrons)

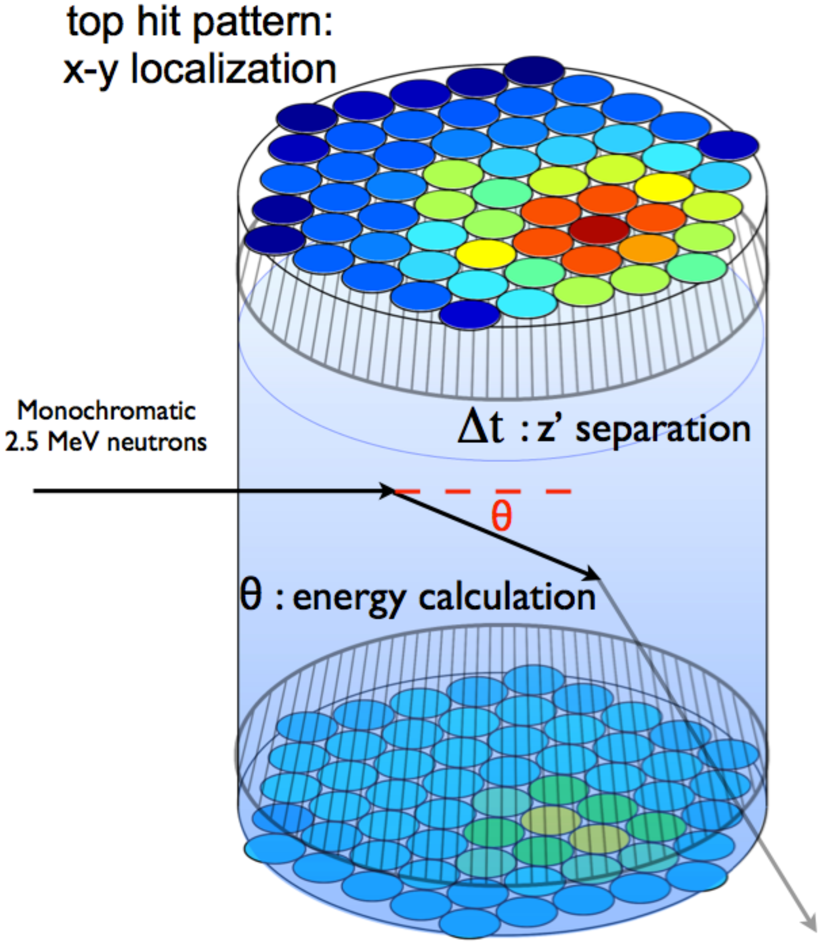




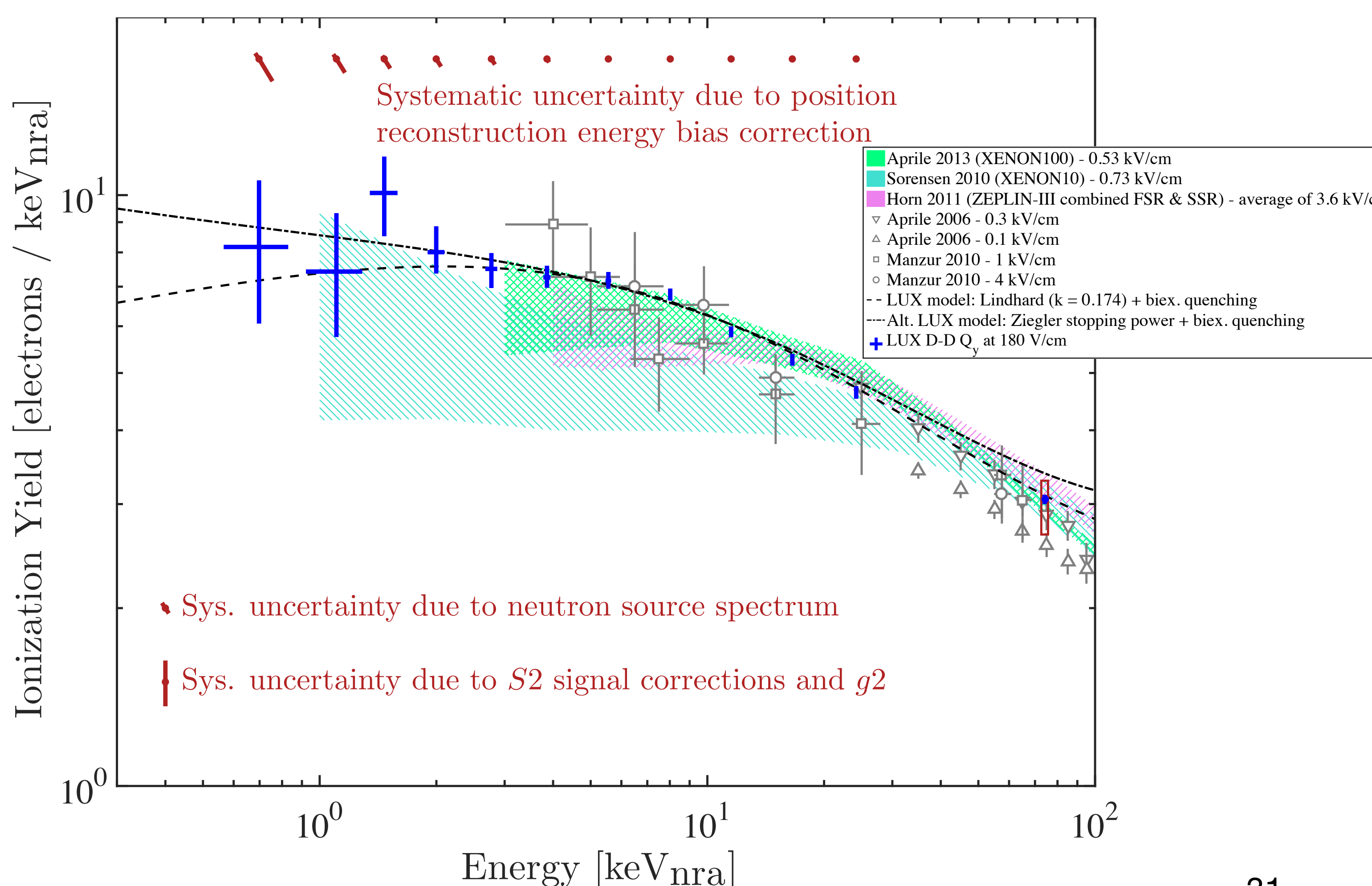
P. Agnes et al., Phys. Rev. D 104, 2021

Charge yield for NRs in LXe: data from LUX

- Use data acquired in situ with monochromatic 2.5 MeV neutrons (D-D generator)
- Calculate energy (via angle) from x-y position and Δt (z separation)
- Charge yield measured down to 0.7 keV_{NR}

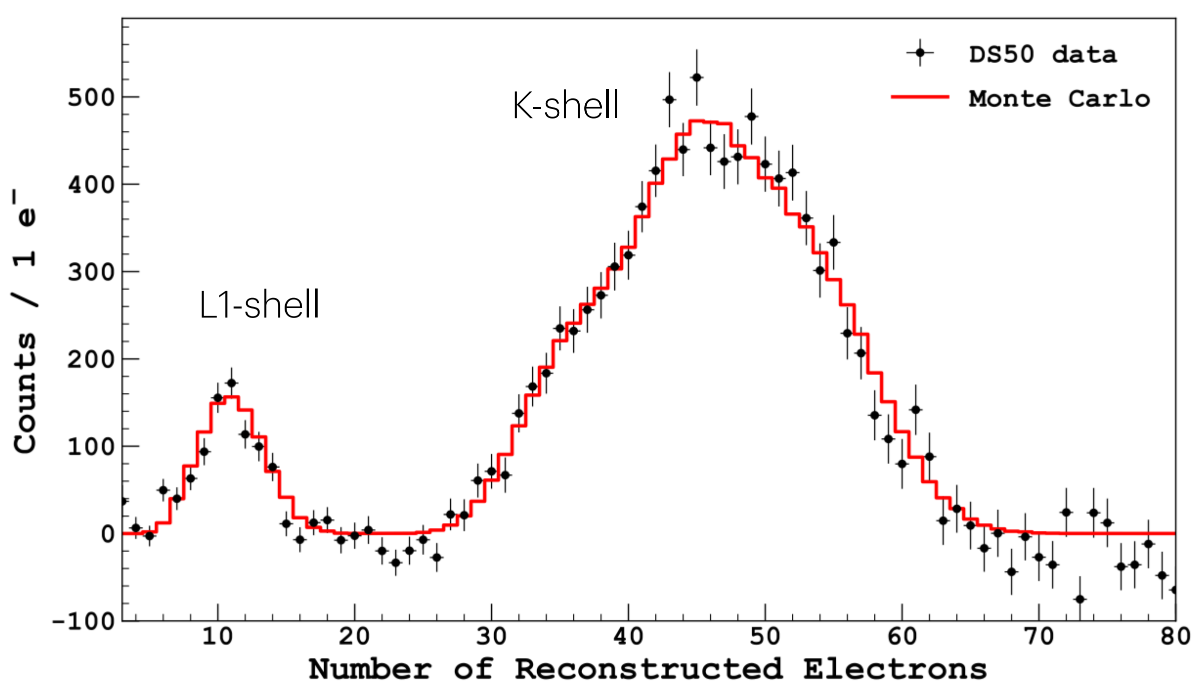


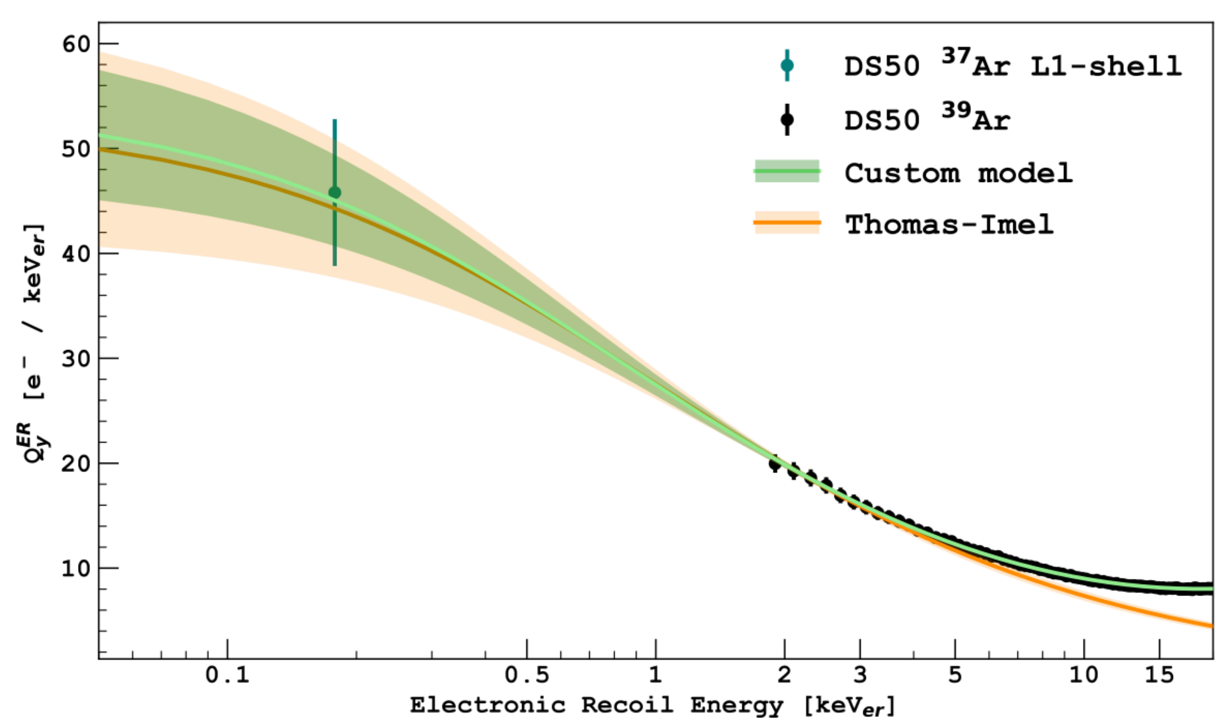
$$E_r = E_n \frac{4 m_n m_{Xe}}{(m_n + m_{Xe})^2} \frac{1 - \cos\theta}{2}$$



Charge yield for ERs in LAr: data from DarkSide-50

- Use data acquired in situ with ^{37}Ar and ^{39}Ar calibration sources
- Fit of the ER ionisation yields
- Charge yield of ERs measured down to ~ 0.179 keV_{ee} (L1-shell Auger electron from ^{37}Ar)



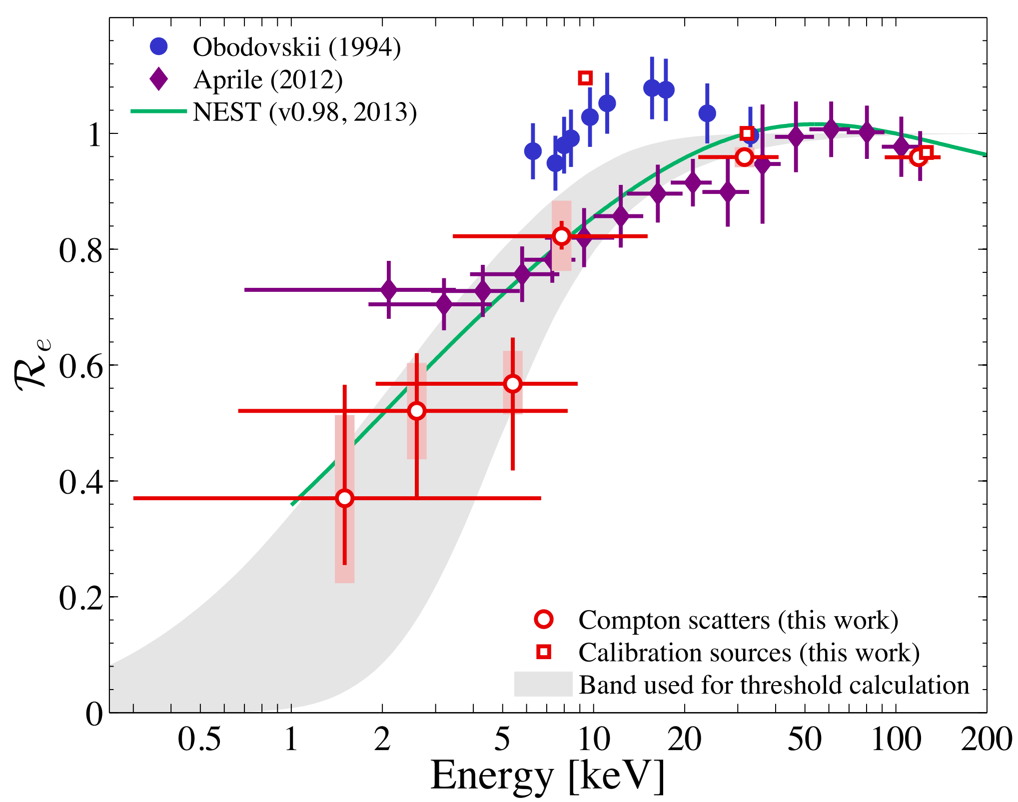


P. Agnes et al., Phys. Rev. D 104, 2021

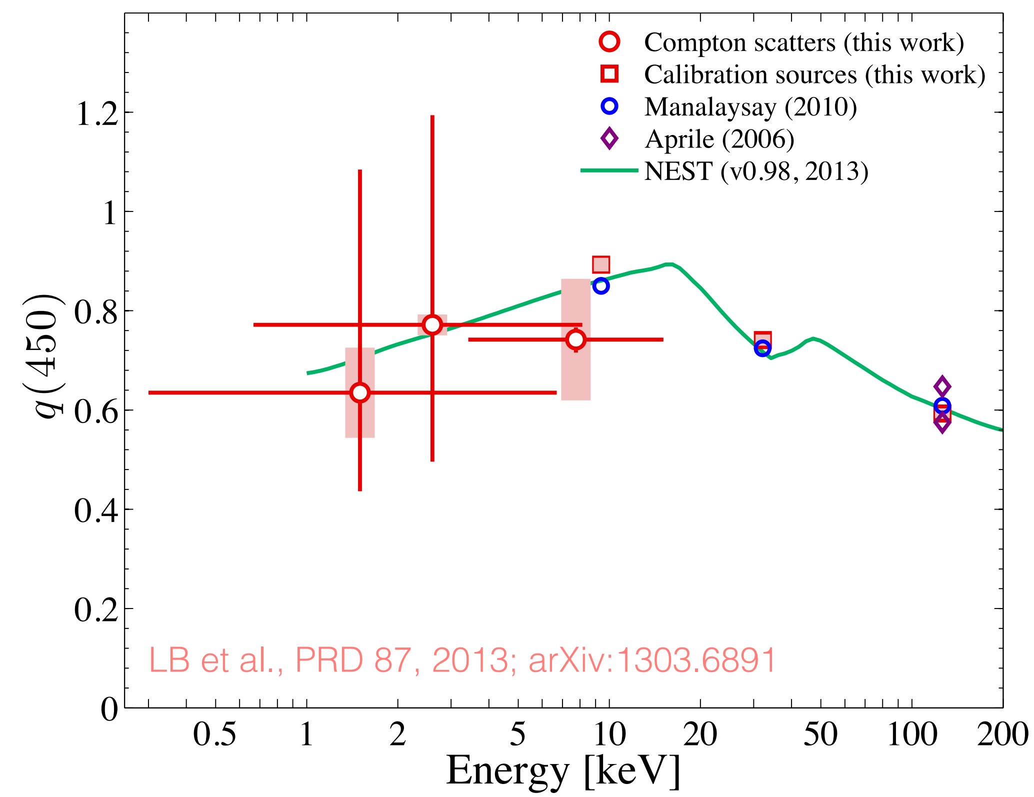
Light yield for ERs in LXe: data from Xürich

- Light yield decreases with lower deposited energies in the LXe
- Field quenching is ~ 75%, only weak field-dependance

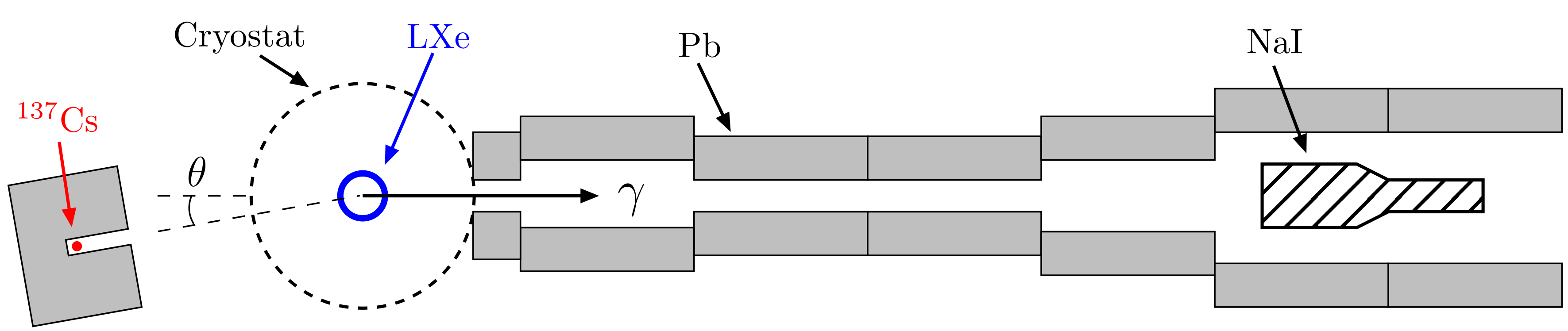
Relative light yield to 32.1 keV of ^{83m}Kr



Quenching of the scintillation light at a field of 0.45 kV/cm



17.3 MBq



Light and charge yields from NEST

- NEST (Noble Element Simulation Technique): a MC framework that allows for simulation of scintillation and ionisation-yield averages
    - based on semi-empirical models, as a function of incoming or deposited energy, electric field, interaction type (electronic and nuclear recoils, alpha particles)
    - calculates average light and charge yields, recombination and simulates actual energy deposits in a detector
- Primary code in C++, bindings available to use in Python; available for xenon and recently also argon

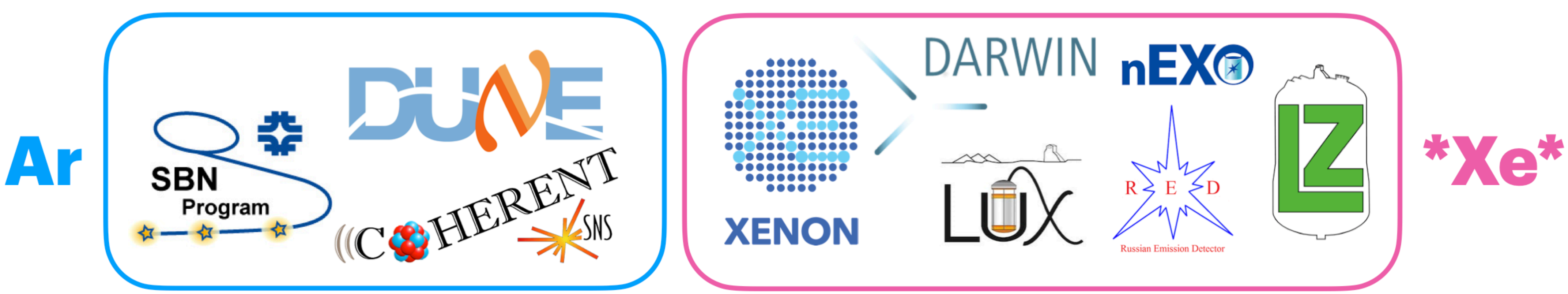
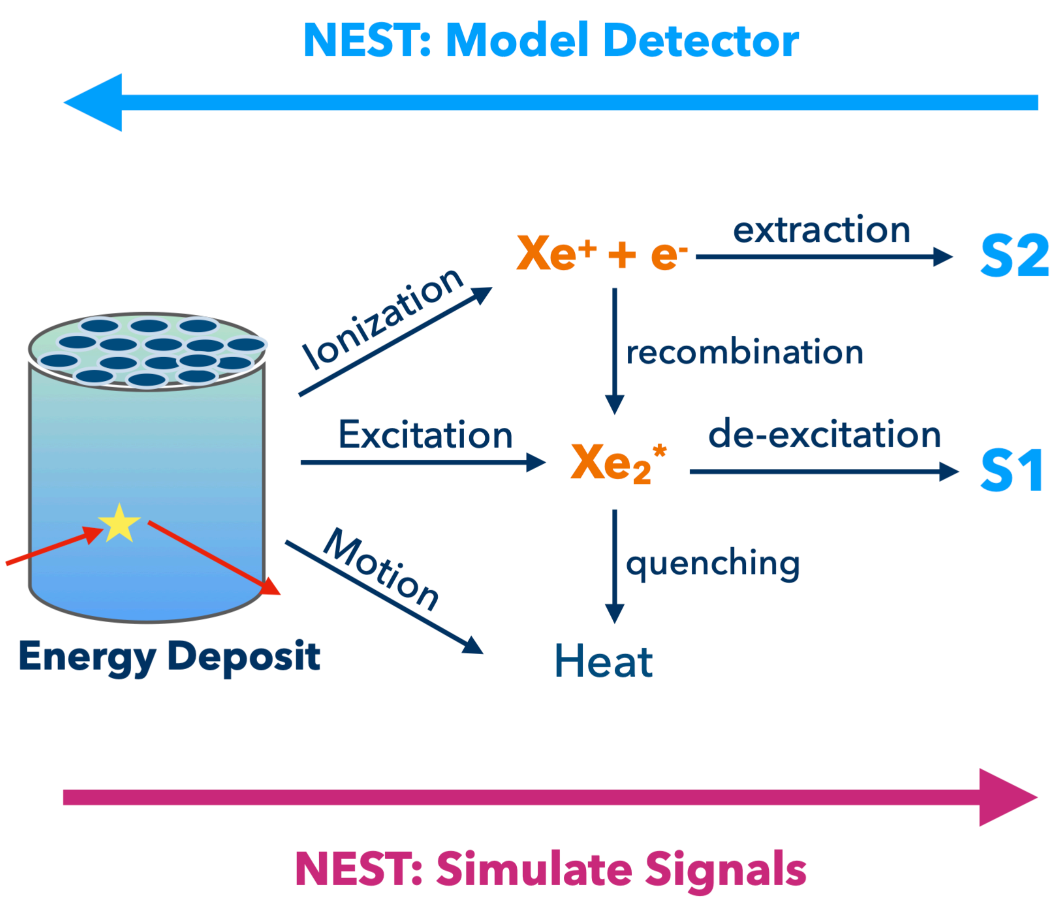


Figure by Sophia Andaloro

https://nest.physics.ucdavis.edu

Light and charge yields from NEST



Macroscopic

- Fields (drift, gap)
- Density, Temp, Phase
- Geometry, PMTs…

Microscopic

- Particle types
- Recombination, dE/dx
- Nex/Ni

ER	***NR***	***Other***
Photons (γ)	**Neutrons**	**α (alphas)**
β^-, μ^- (leptons)	**Heavy Nuclei**	**^{83m}Kr**
expanding…	**WIMPs**	**Protons**

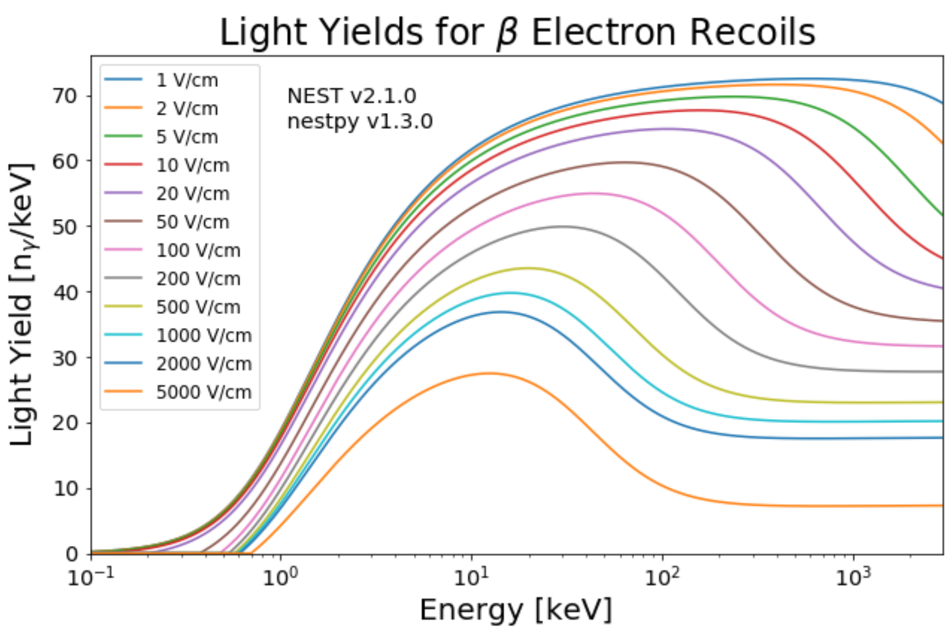
Ar: SBN Program, DUNE, COHERENT SNS

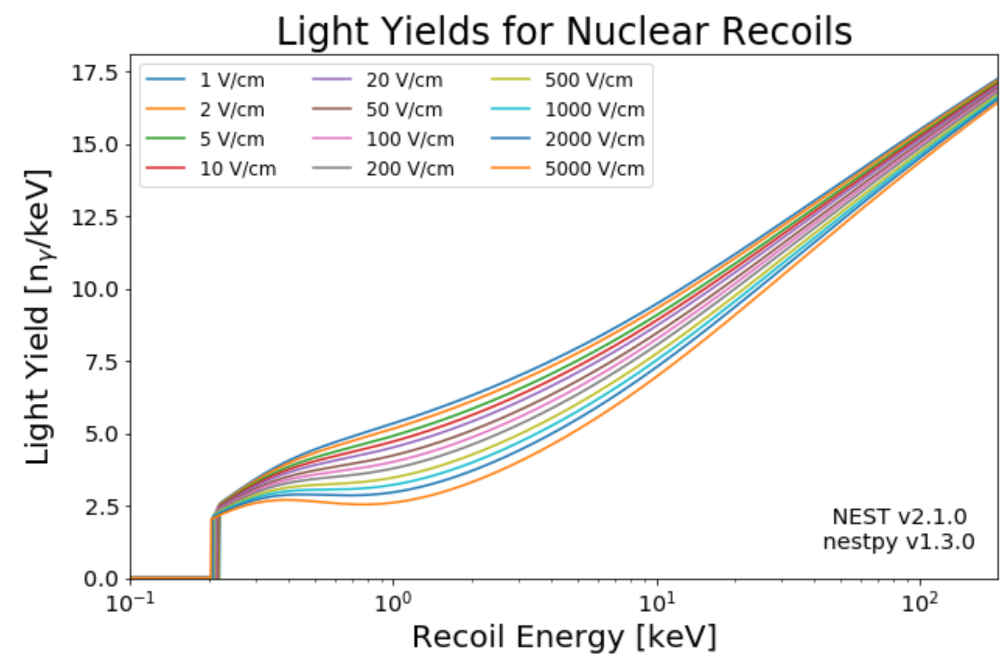
Xe: XENON, DARWIN, LUX, nEXO, RED (Russian Emission Detector), LZ

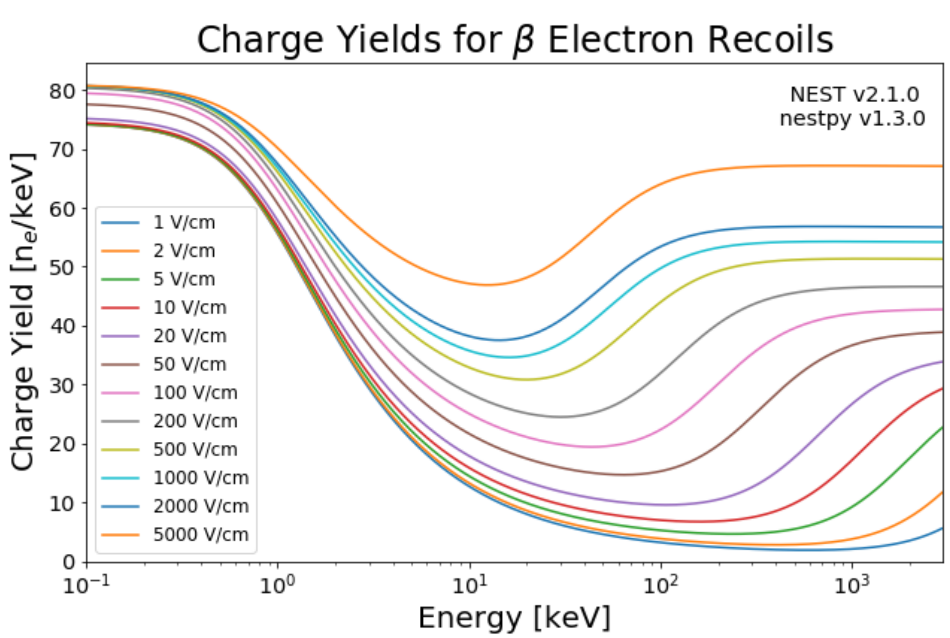
https://nest.physics.ucdavis.edu

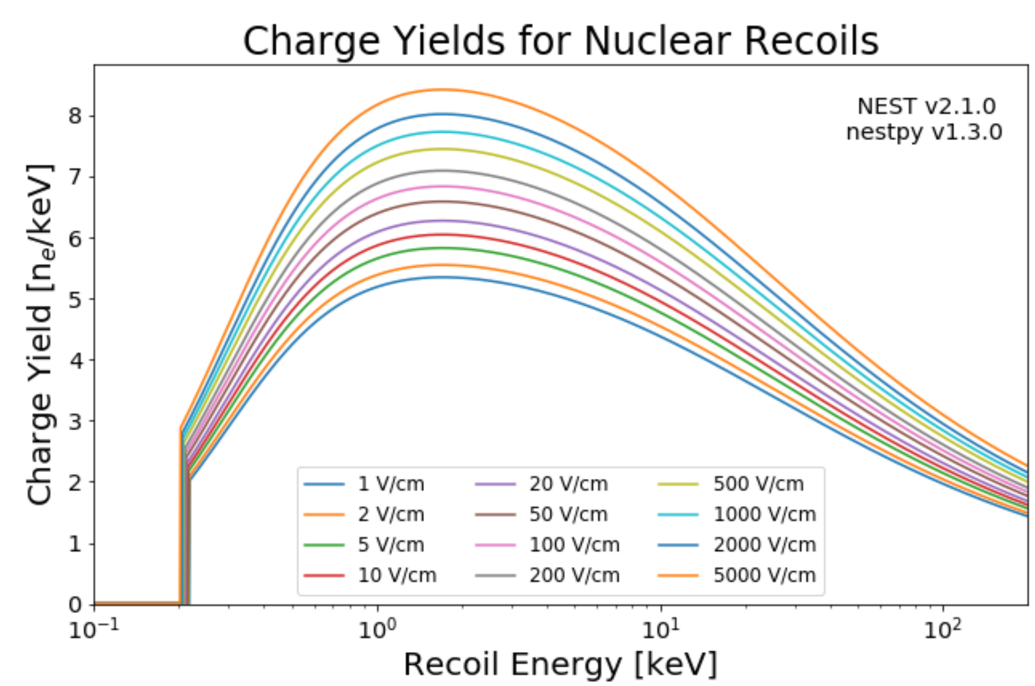
Figures by Sophia Andaloro, APS meeting April 2021

Light and charge yields from NEST: Xenon









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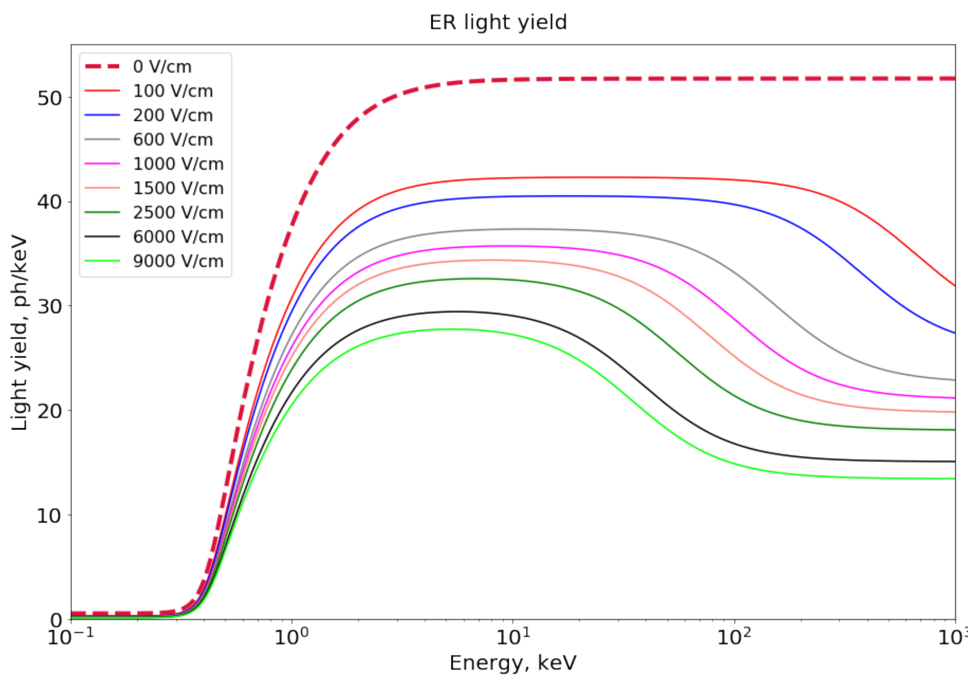
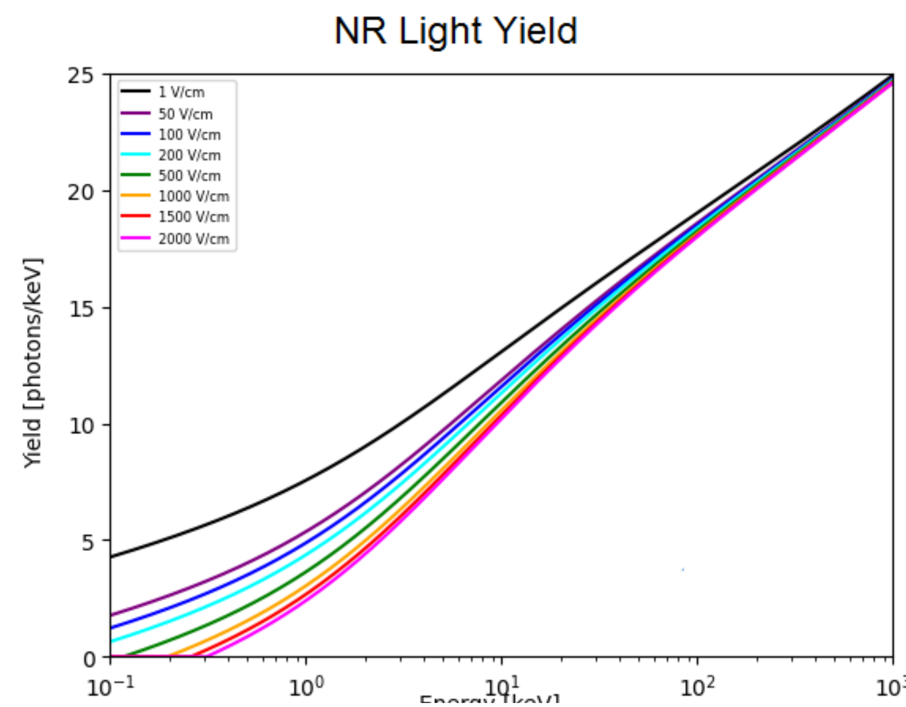
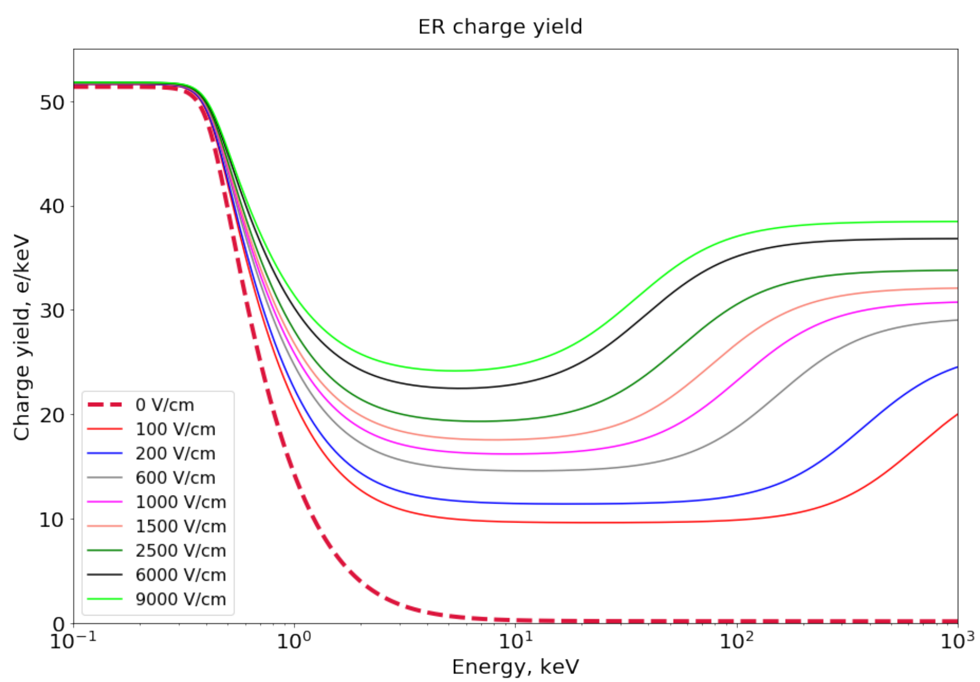
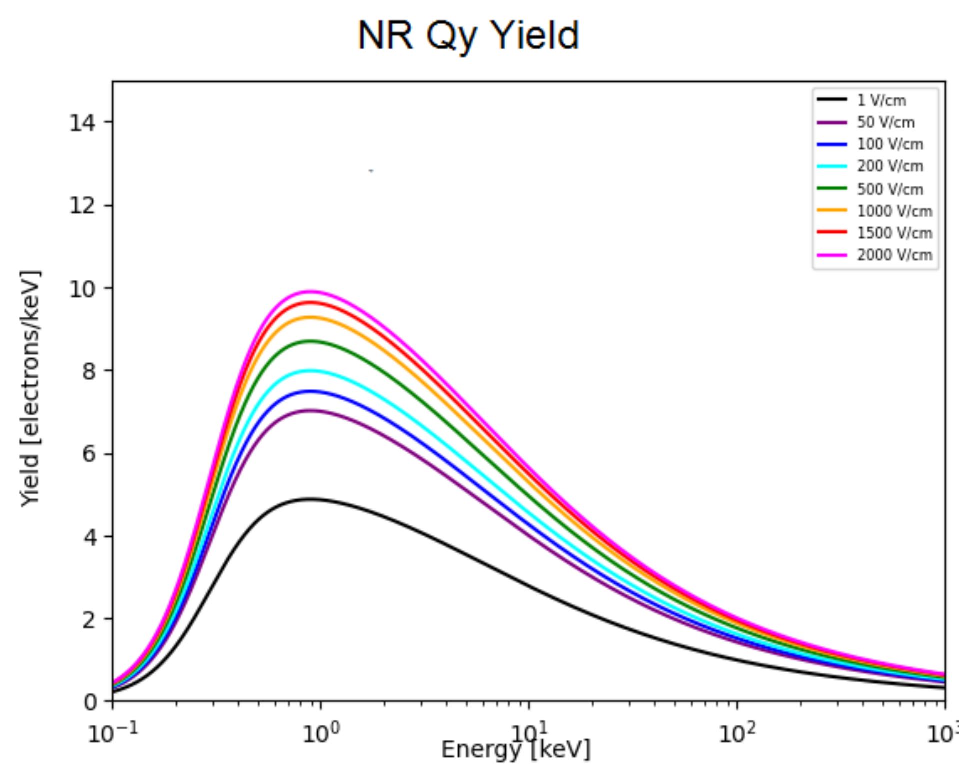
Light and charge yields from NEST: Argon









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Electron attachment and light absorption

- To achieve a high collection efficiency for both ionisation and scintillation signals, the concentration of impurities in the liquid has to be reduced and maintained to a level below 1 part per 10^9 (part per billion, ppb) oxygen equivalent
  - The scintillation light is strongly reduced by the presence of water vapour
  - The ionisation signal requires both high liquid purity (in terms of substances with electronegative affinity, SF_6, N_2O, O_2, etc) and a high field (typically ~ few 100 V/cm)
- Attenuation lengths of ~1 m for electrons and photons were already achieved > 1m and are necessary for multiton-scale experiments

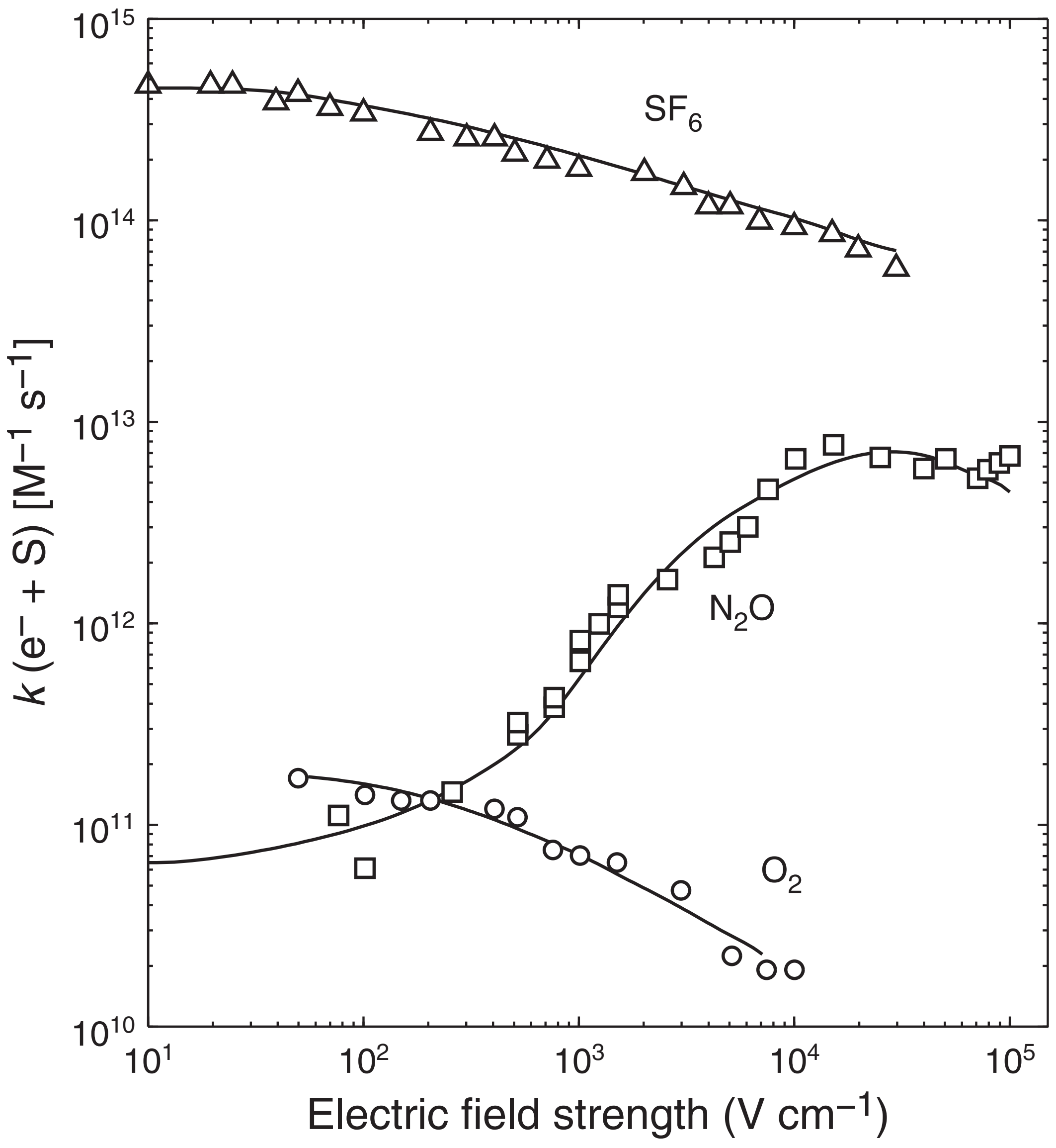


Fig. 21.4. Rate constant for the attachment of electrons in liquid xenon (T = 167 °K) to several solutes: (△) SF_6, (□) N_2O, (○) O_2 [174].

The electron drift lifetime in noble liquids

- The purity of the noble liquid is commonly expressed via the "electron lifetime" τ_e
  - the time over which the number of drifting electrons N_e is reduced by a factor 1/e:

$$N_e(t) = N_e(t_0)\, e^{-t/\tau_e}$$

- The electron lifetime is related to the concentration of impurities (C_i) and their constants of attachment (k_i), as follows:

$$\tau_e = \frac{1}{\sum_i k_i C_i} = \frac{1}{k_{O_2} C_{O_2}}$$

  - where often the O_2-equivalent impurity concentration C_{O2} is used as benchmark (O_2 usually the dominant contributor)

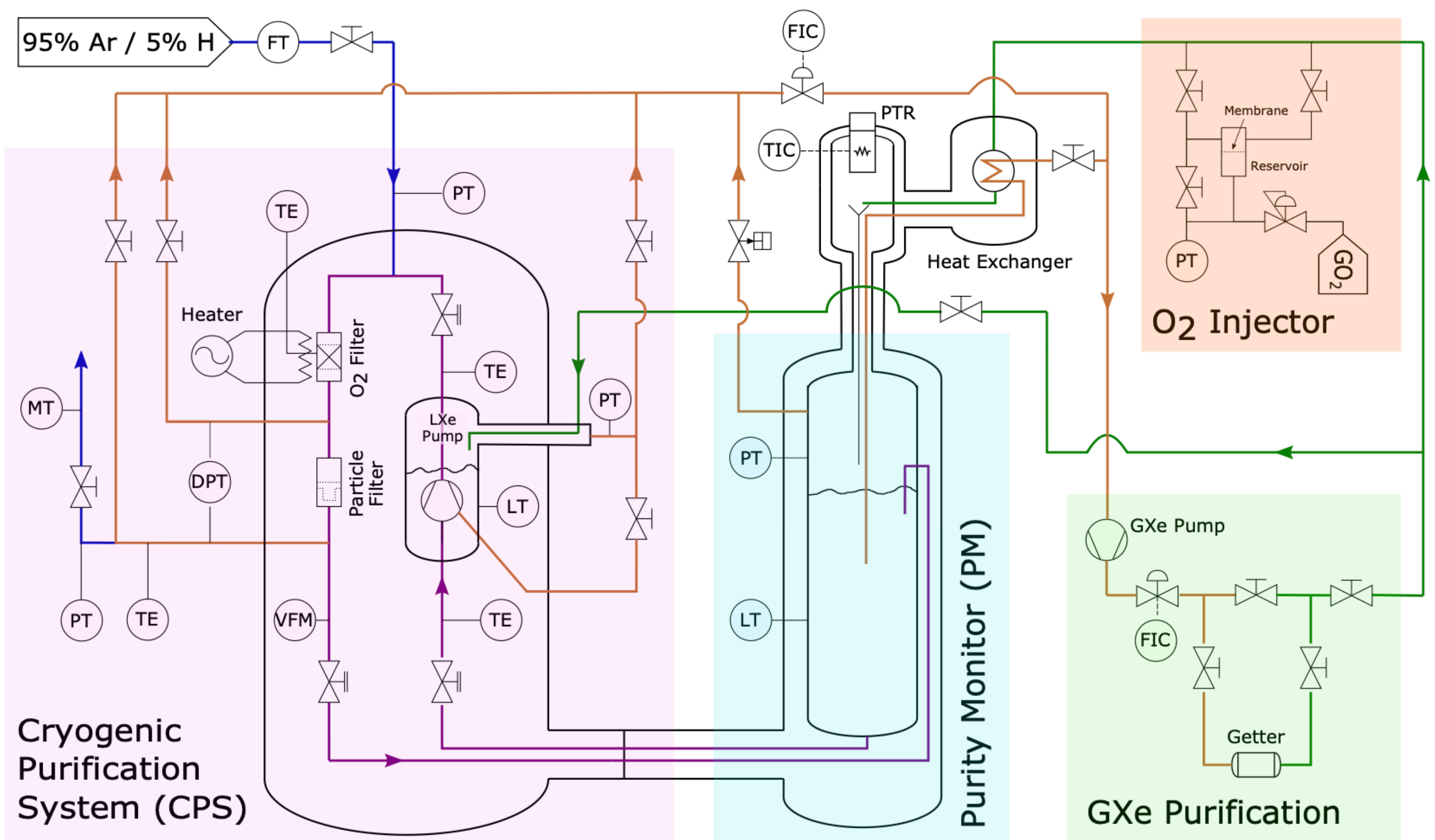
- The O_2-equivalent mole fraction (x_{O2}) is expressed in ppb (parts per billion):

$$\frac{1}{\tau_e} = k_{O_2} C_{O_2} = k_{O_2} x_{O_2} \frac{\rho}{M}$$

  - where ρ is the density of the noble liquid and M the molar mass. The constant of electron attachment k_{O2} depends on the drift field (it decreases with increasing field)

The electron drift lifetime in noble liquids

- In general, electronegative impurities in noble liquids increase over time due to the continuous desorption from materials
- To achieve very low concentrations and high electron lifetimes, continuous removal of impurities is required
    - by gas purification through high-temperature (400 °C) zirconium getters (using highly-efficient liquid-gas heat exchangers to minimise the heat input)
    - by liquid purification through filters which contain pellets with high-surface area copper, which binds the impurities on the surface

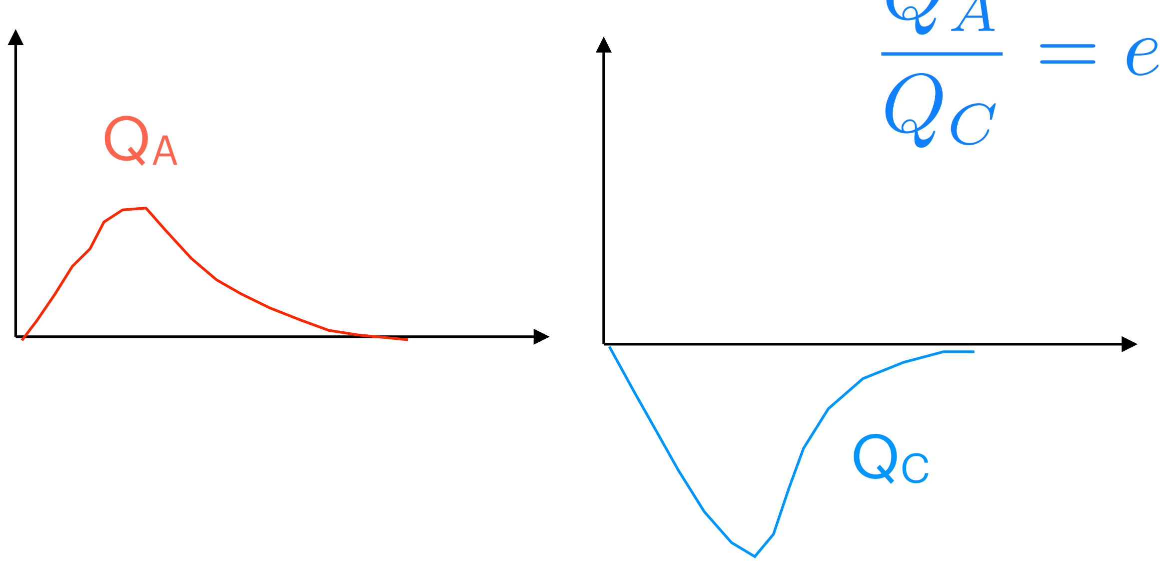


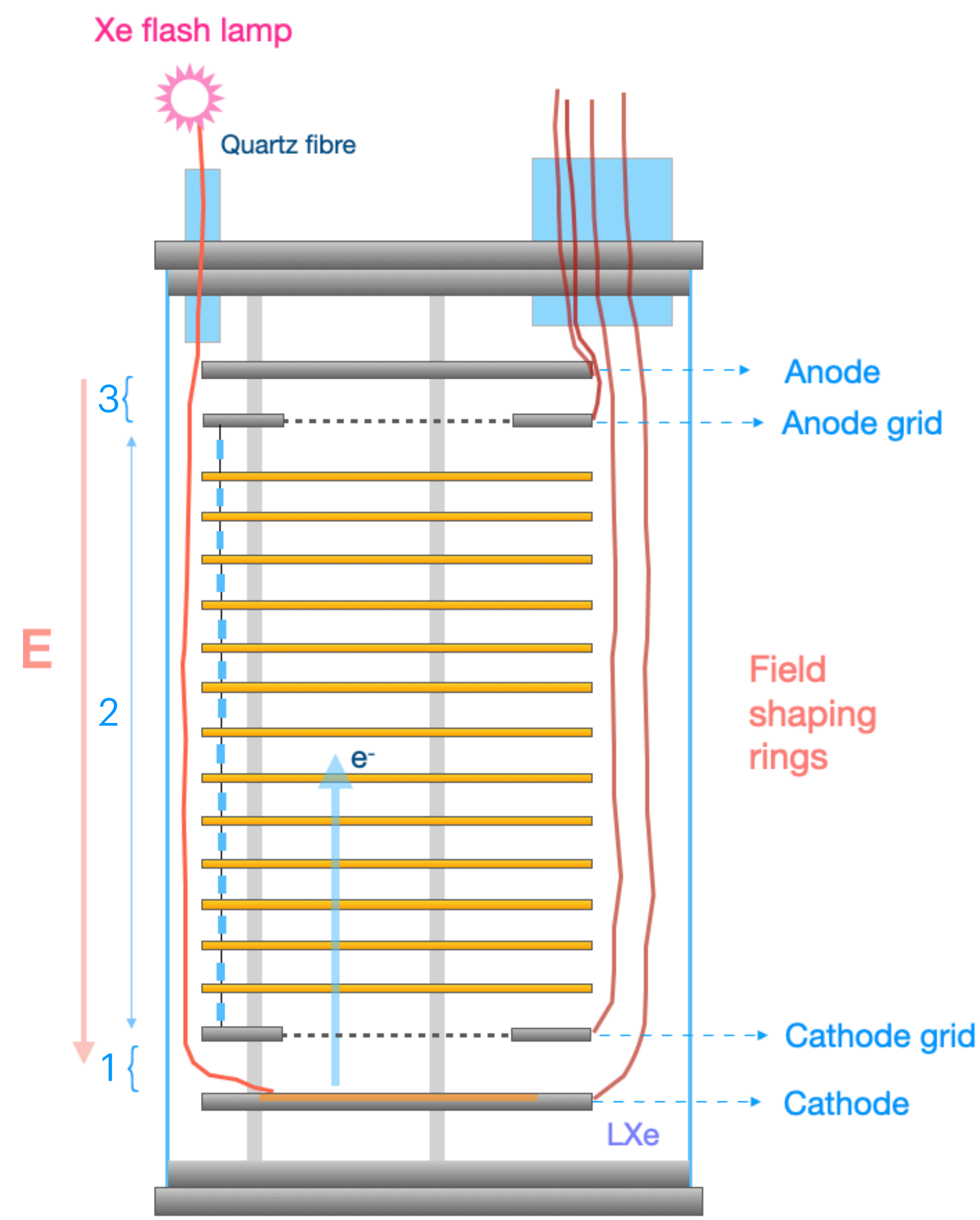
Example: Xeclipse, a xenon purification system at Columbia University (demonstrator for XENONnT at LNGS), Plante, Aprile, Howlett, Zhang, arXiv:2205.07336

How to measure the electron drift lifetime

- The electron lifetime" τ_e is usually measured with purity monitors. The concept:
    - release a cloud of electrons, drift the cloud a fixed distance through uniform electric field
    - measure the size of the cloud at the beginning and at the end via the induced current on a cathode and anode as the e- drift from and towards these, respectively
    - electrodes are equipped with grids to shield them from the effects of the e- cloud except when the e- are drifting in the space in between
    - determine τ_e from the ratio of the induced currents and their separation in time which is the drift time t_d

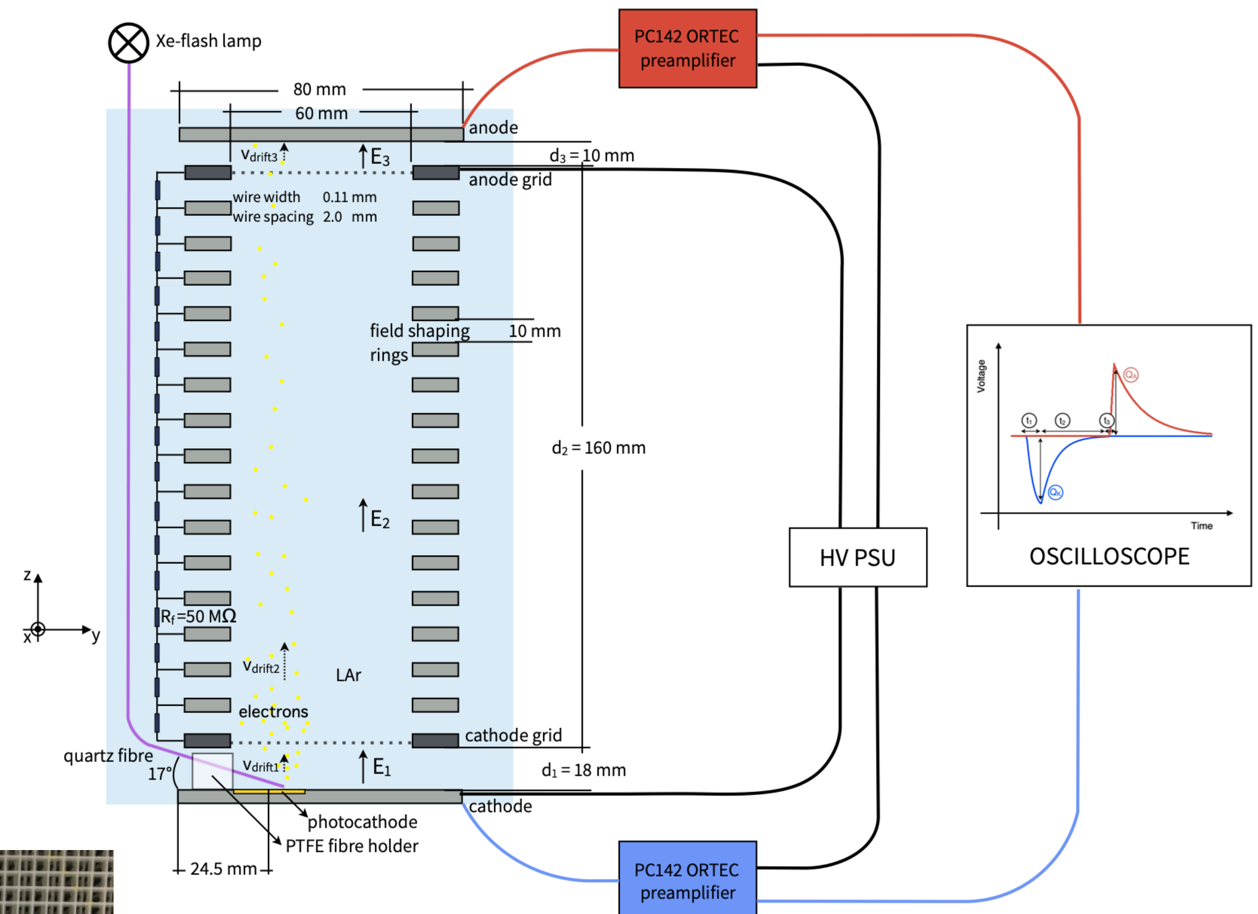
$$\frac{Q_A}{Q_C} = e^{-t_d/\tau_e}$$



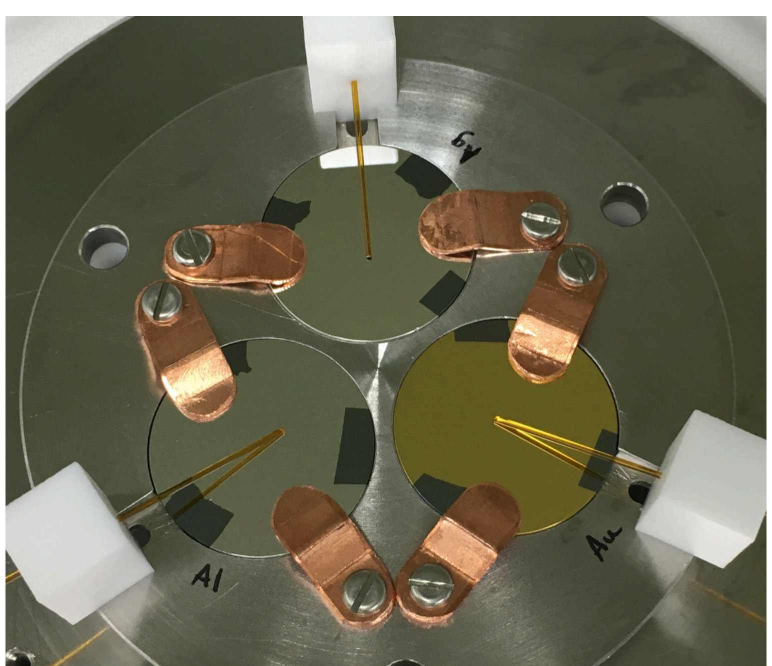


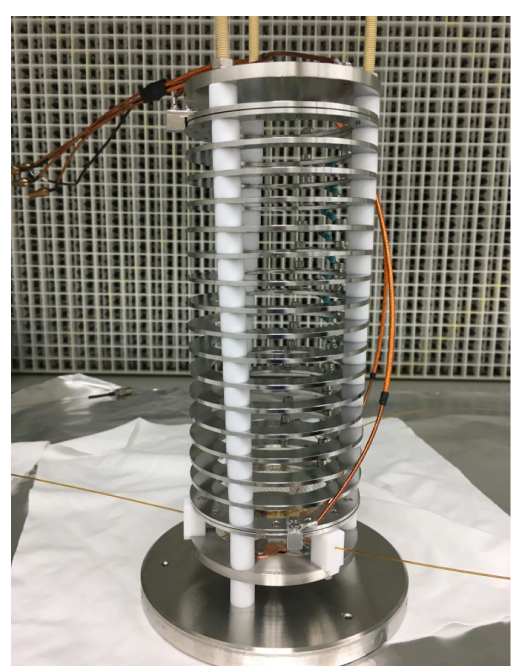
Example: a purity monitor for liquid argon

- Successfully deployed in ICARUS, ProtoDUNE and others
- Drift length: 188 mm
- Electron cloud: produced from thin film Au, Ag, Ti, Al photocathodes (on quartz substrate) via pulsed xenon flash lamp (Hamamatsu L7685)
- Charge readout on top (Q_A) and bottom (Q_C)
- Electrons are absorbed as they drift upwards (in region 2) towards the anode
- Ratio of signals: $\propto$ electron lifetime τ_e



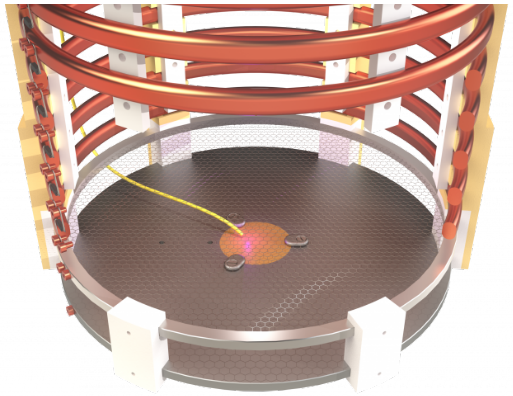
L. Manenti et al., JINST 15, 2020

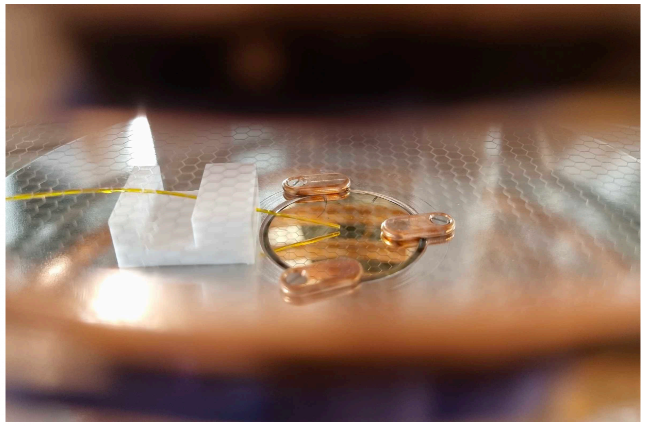


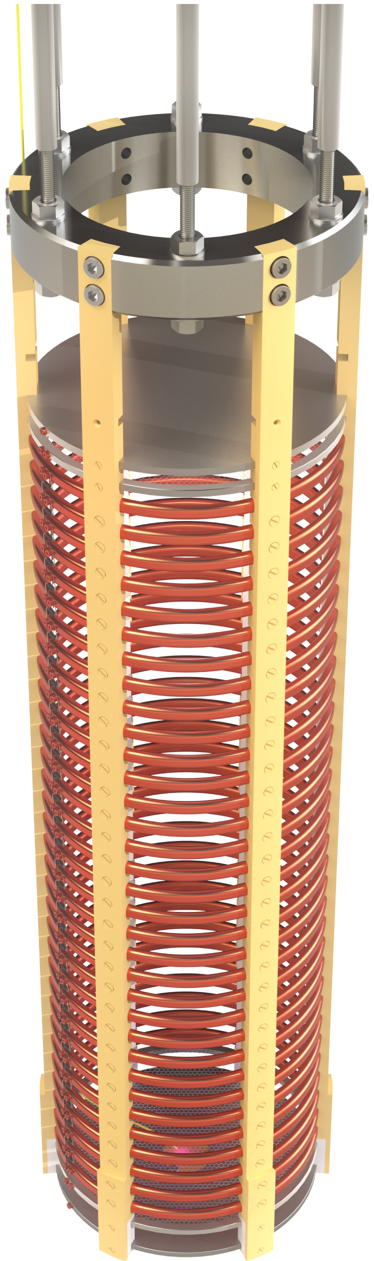


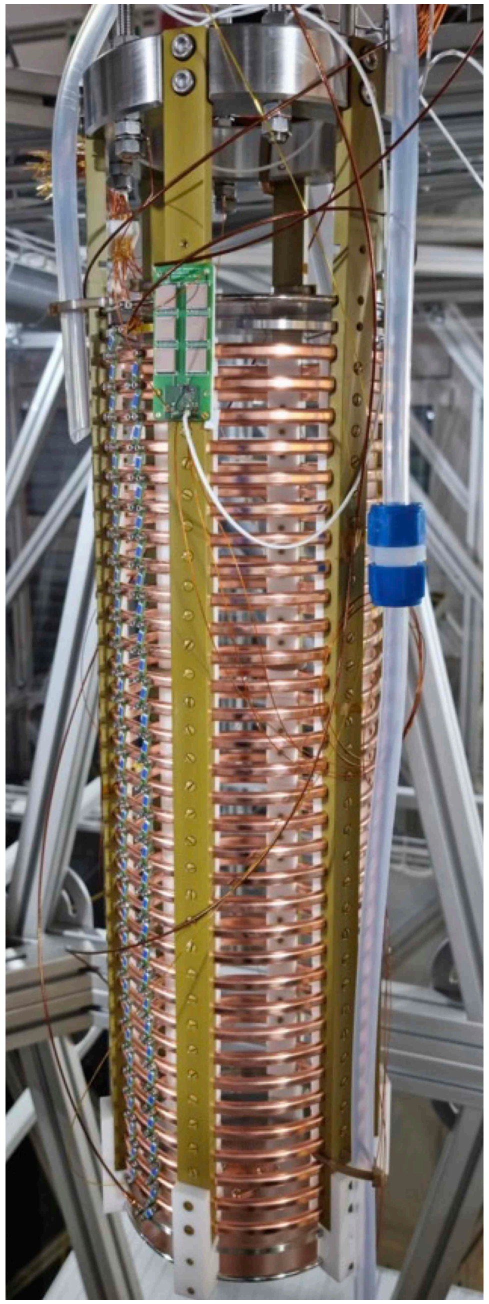
Example: a purity monitor for liquid xenon

- Drift length: 525 mm
- Electron cloud: produced from in-house made, thin film Ag photocathode (on quartz substrate) via pulsed xenon flash lamp (Hamamatsu L7685)
- Charge readout on top (Q_A) and bottom (Q_C)
- Electrons are absorbed as they drift upwards (in region 2) towards the anode
- Ratio of signals: ∝ electron lifetime τ_e



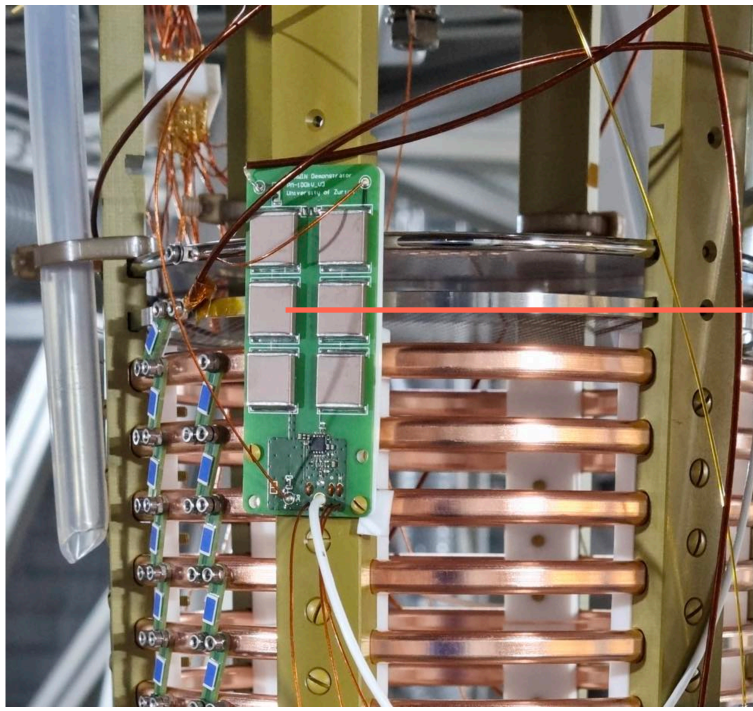




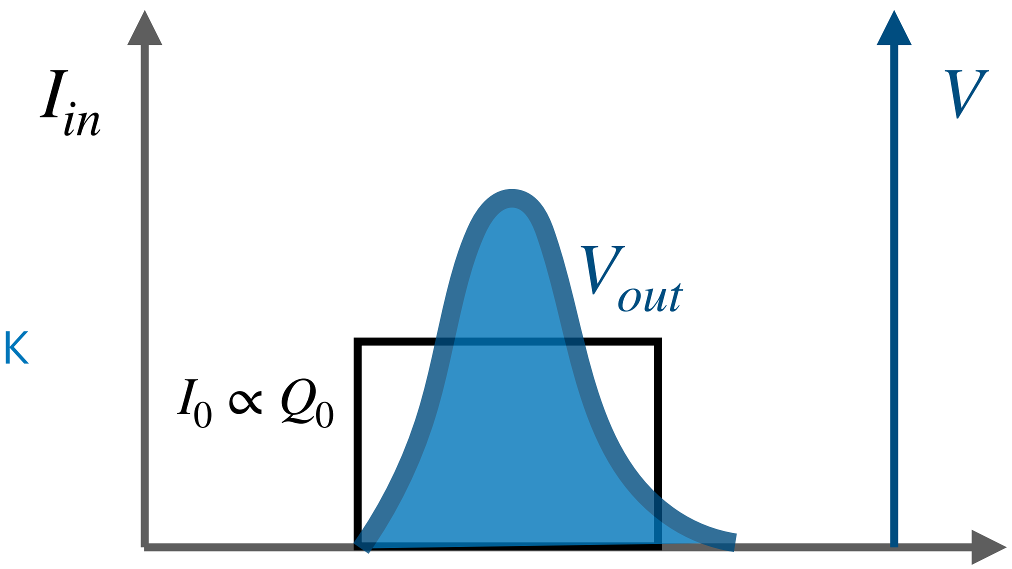


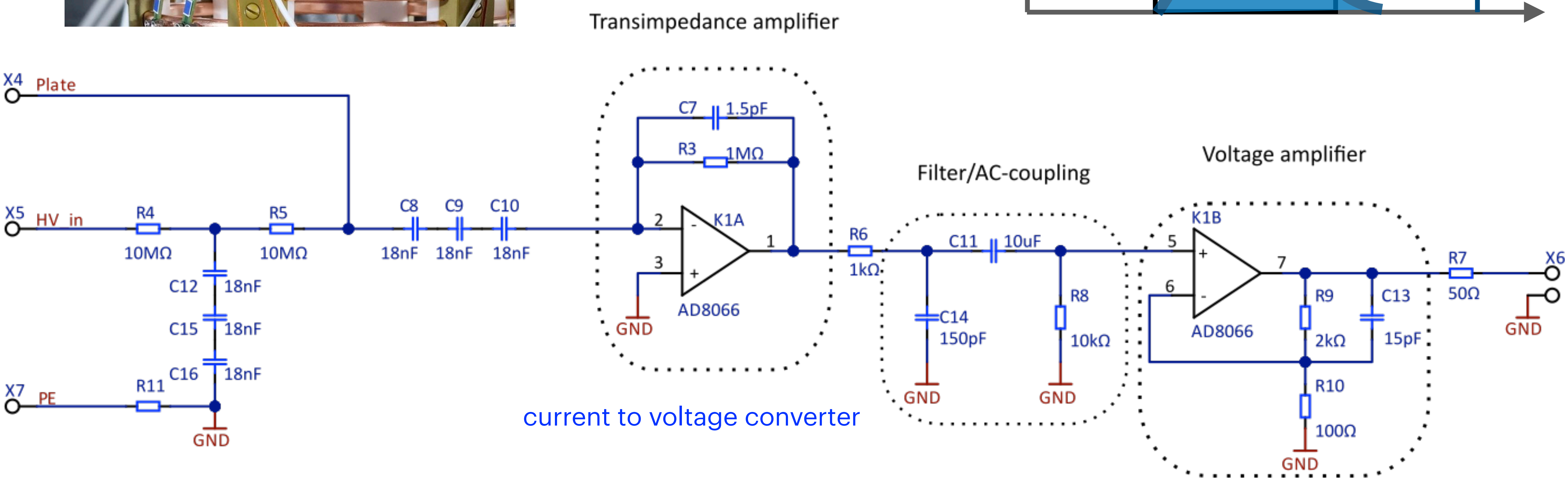
Purity monitor for Xenoscope

Purity monitor signal readout



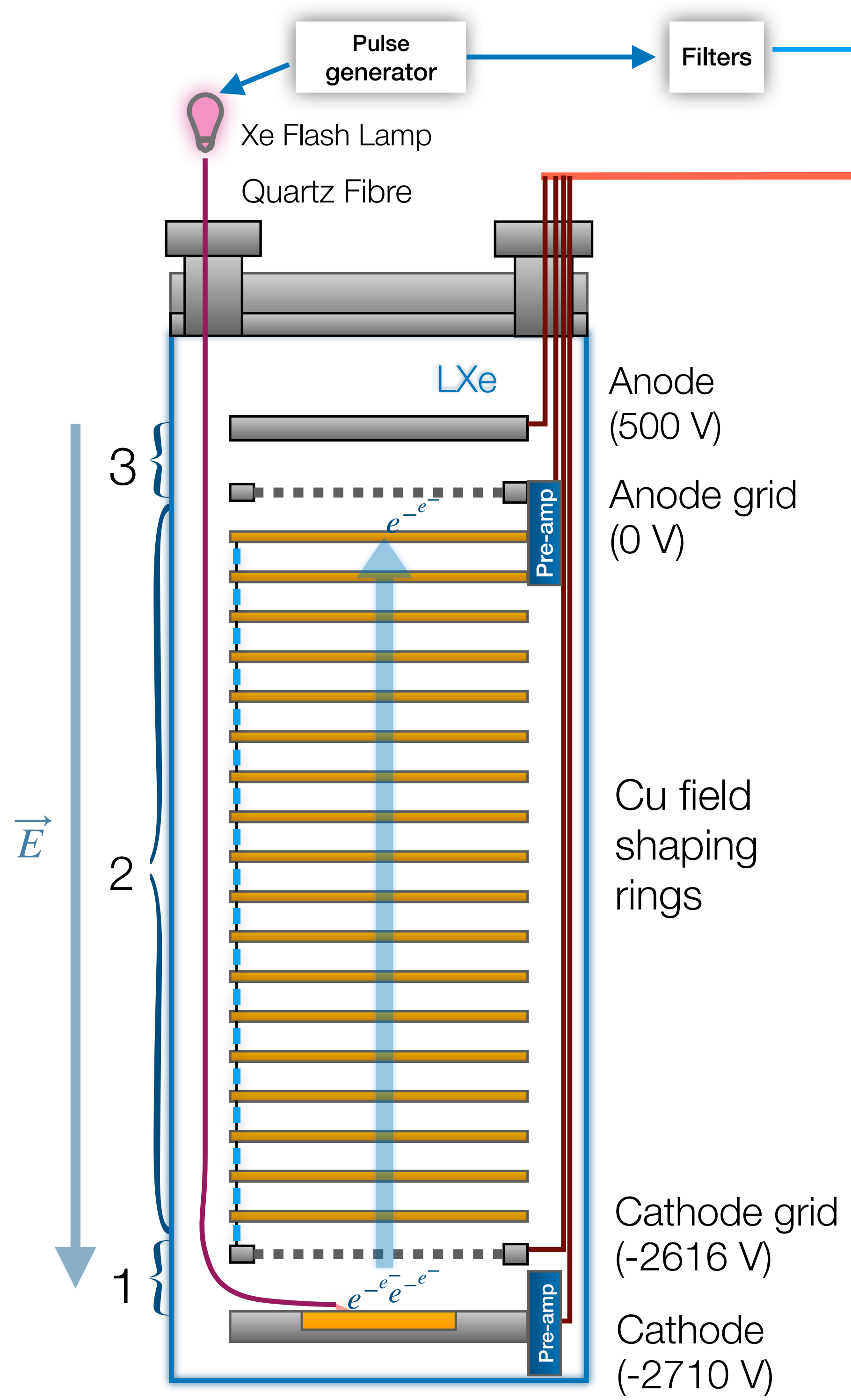
Cryogenic read-out: AC coupling followed by a trans-impedance preamplifier + voltage amplifier operating at <180K

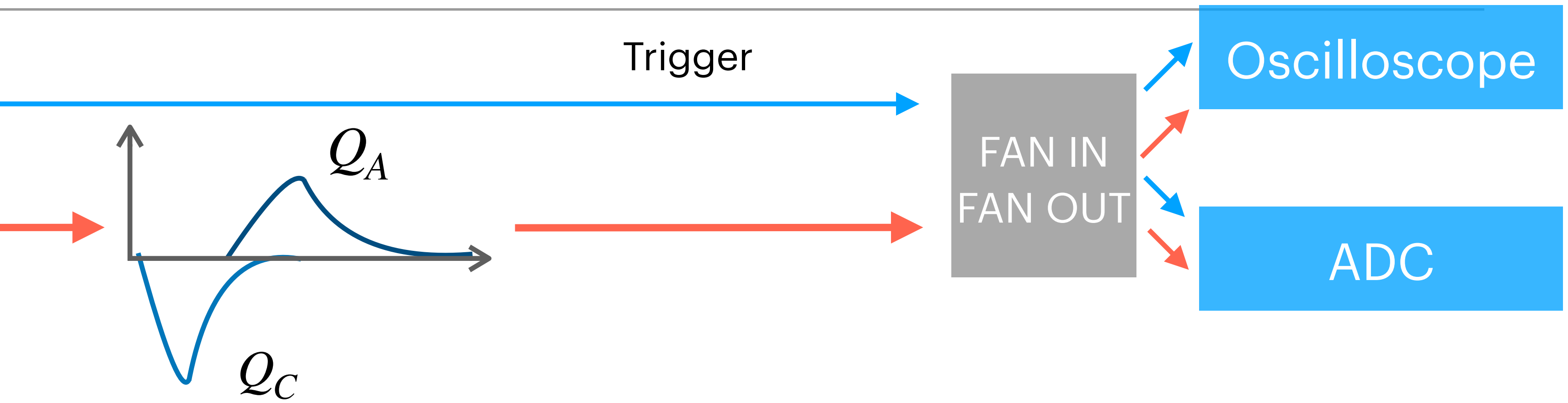




Amplification: ~ 1.4 V/pC

Purity monitor signal readout





1: 18 mm, 2: 503 mm, 3: 10 mm

Lamp on at 1 Hz, for 7 μs

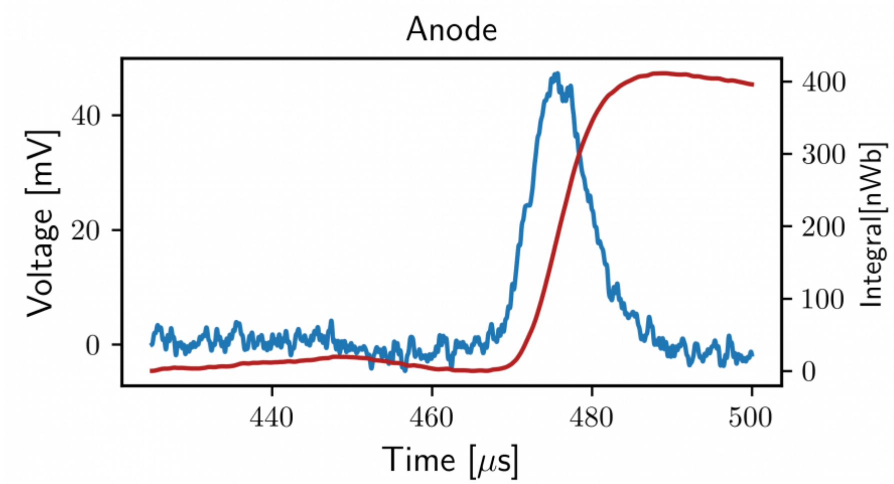
10^3 waveforms acquired

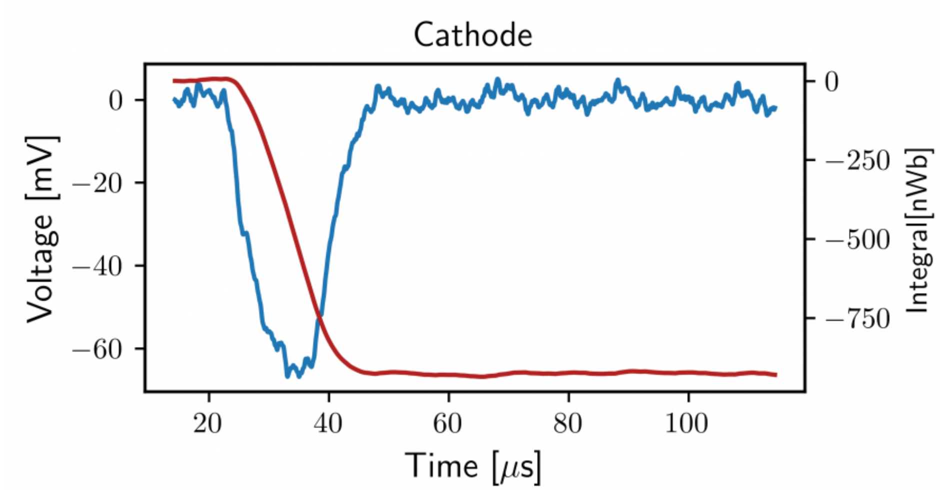
$\Rightarrow$ average waveform

Waveform filtered for low noise

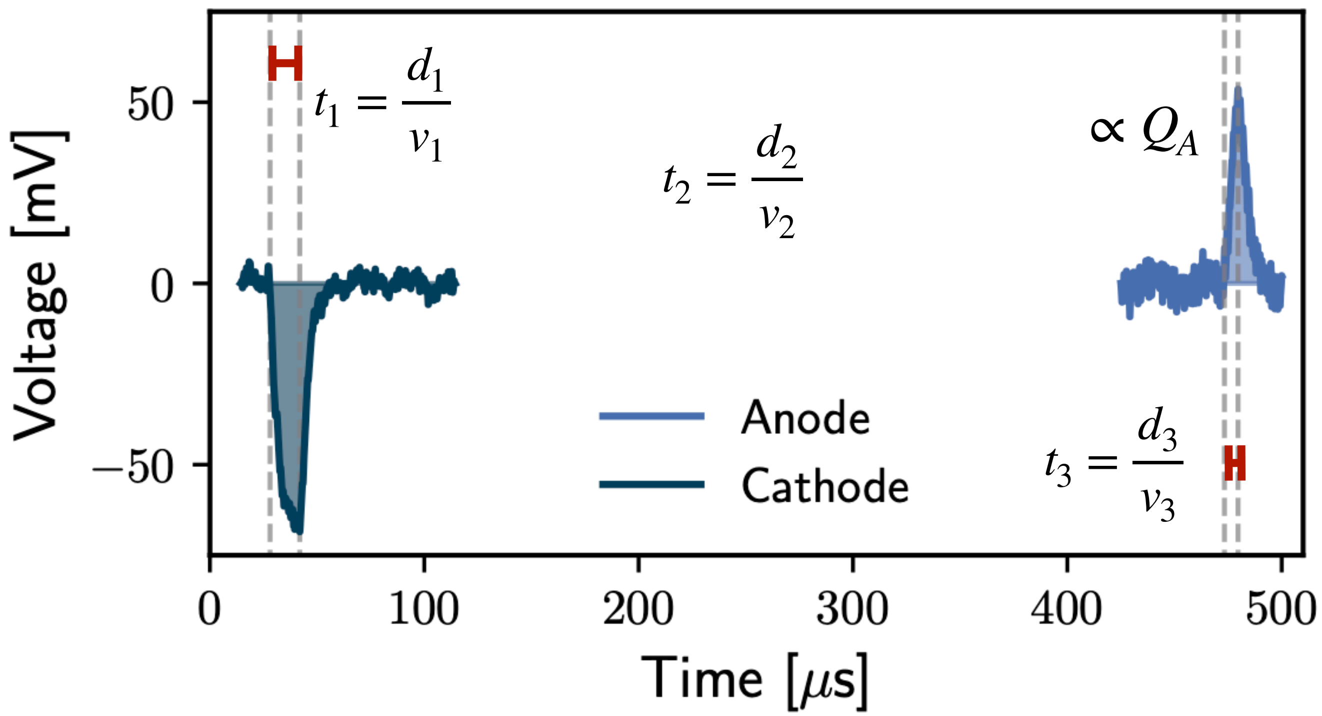
Integral of waveform

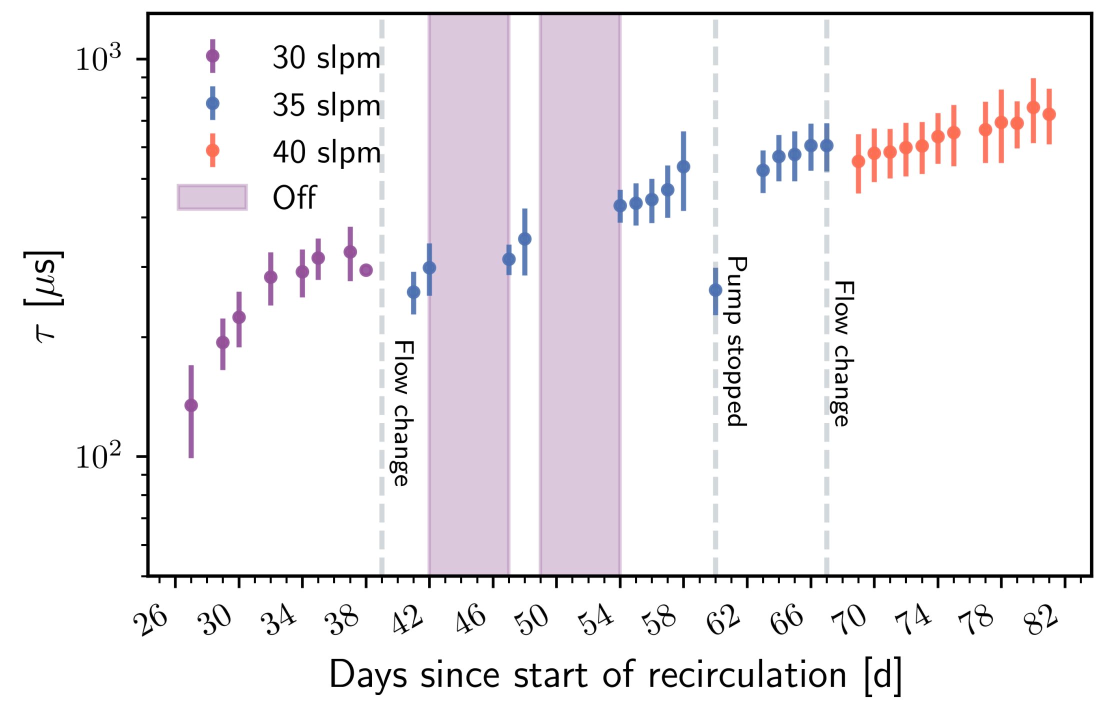
$\Rightarrow$ charge measured in the drift regions





Electron lifetime determination





- Waveforms: acquired by oscilloscope and ADC
- Charges: integrals of the current pulses
- The e-lifetime (with $\Delta t = t_2$, rise times t_1, t_3):

$$\tau_e \approx \frac{1}{\ln(Q_A/Q_C)} \left(t_2 + \frac{t_1 + t_3}{2} \right)$$

Light attenuation in noble liquids

- Pure noble liquids are transparent to their own scintillation light
- However light can be attenuated by impurities dissolved in the liquid (which can absorb VUV photons) and due to Rayleigh scattering (elastic scattering of light off particles smaller than its wavelength)
- The light attenuation is described by:

$$I(x) = I(0)\, e^{-x/L_{att}}$$

  - with L_{att} being the photon attenuation length, which depends on the absorption length L_{abs} and the Rayleigh scattering L_R length as:

$$L_{att}^{-1} = L_{abs}^{-1} + L_R^{-1}$$

- The Rayleigh scattering length strongly depends on the wavelength of the photons λ and on the optical properties of the material, and can be expressed as:

$$L_R^{-1} = \frac{8\pi^3 k_B T \rho^2 \kappa_T}{3\lambda^4} \left[\frac{(n^2-1)(n^2+2)}{3} \right]^2$$

- where n = index of refraction corresponding to the wavelength λ, T = temperature, ρ = density, κ_T = isothermal compressibility. The index of refraction must be evaluated at the given T, ρ and λ.

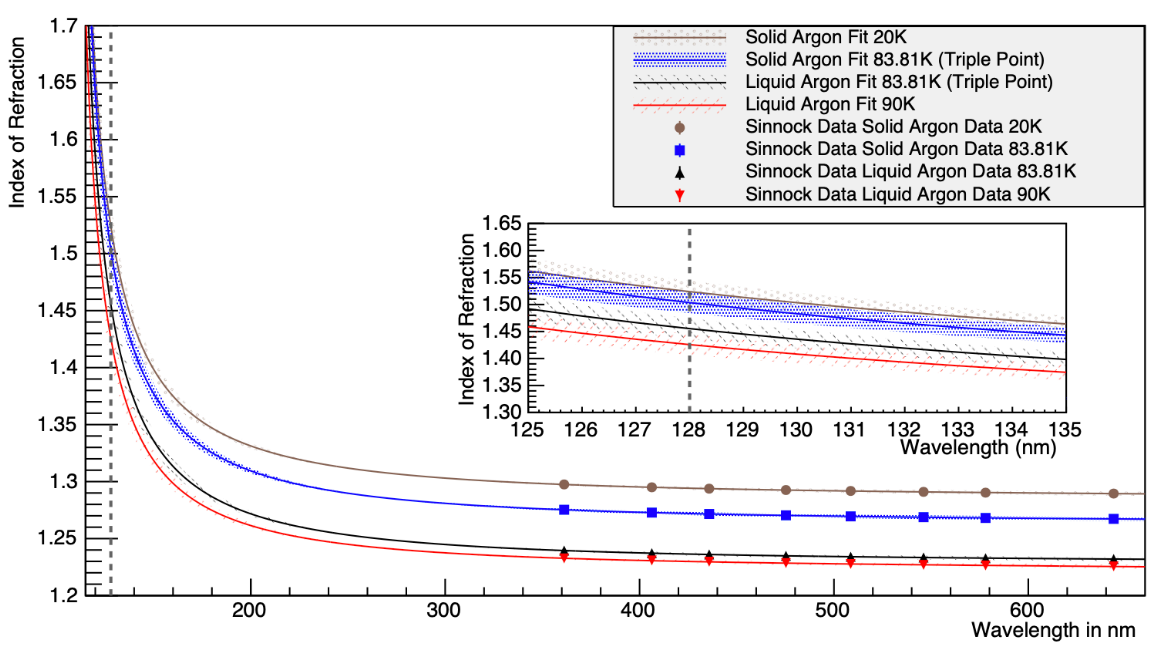
Light attenuation in noble liquids

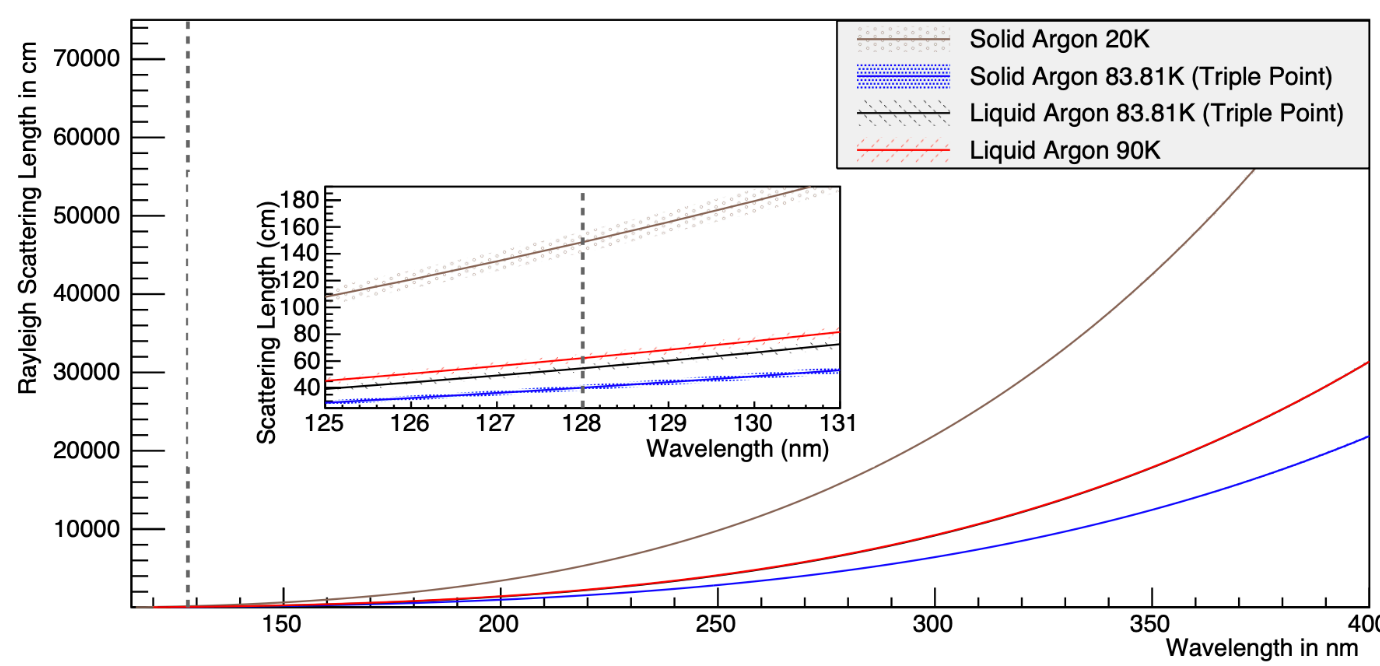
- The index of refraction n depends on the wavelength of the photons λ being

$$n^2 = a_0 + \sum_i \frac{a_i \lambda^2}{\lambda^2 - \lambda_i^2}$$

- with a_0, a_i = Sellmeier coefficients (a_i correspond to resonances occurring at wavelengths λ_i) - these are experimentally determined for a given medium
- (a_0, a_i): typically (1.3, 0.23) in liquid argon, (1.4, 0.4) in liquid xenon*

Calculated n and L_R for argon as a function of λ*





*see E. Grace et al., arXiv:1502.04213 for details

Light attenuation in noble liquids

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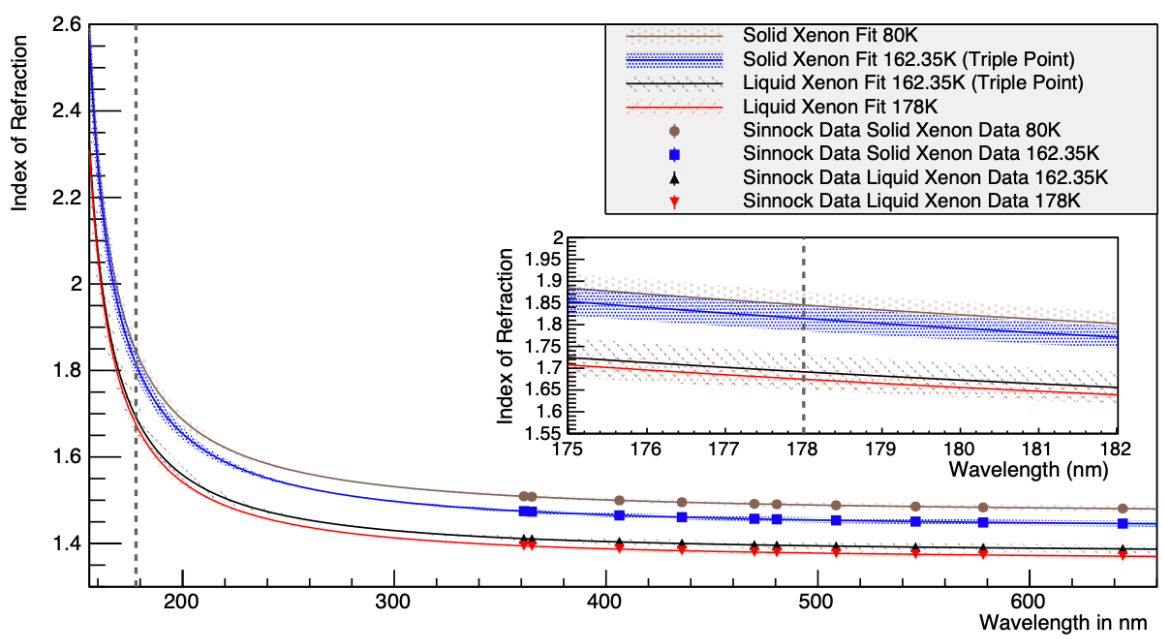
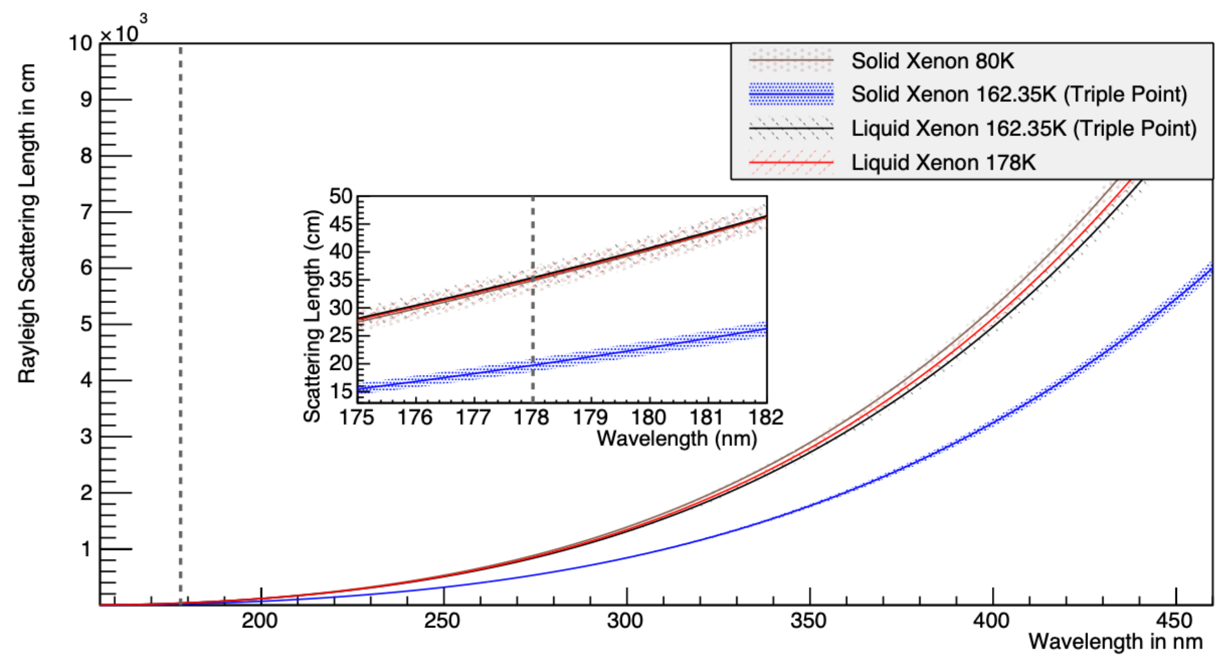




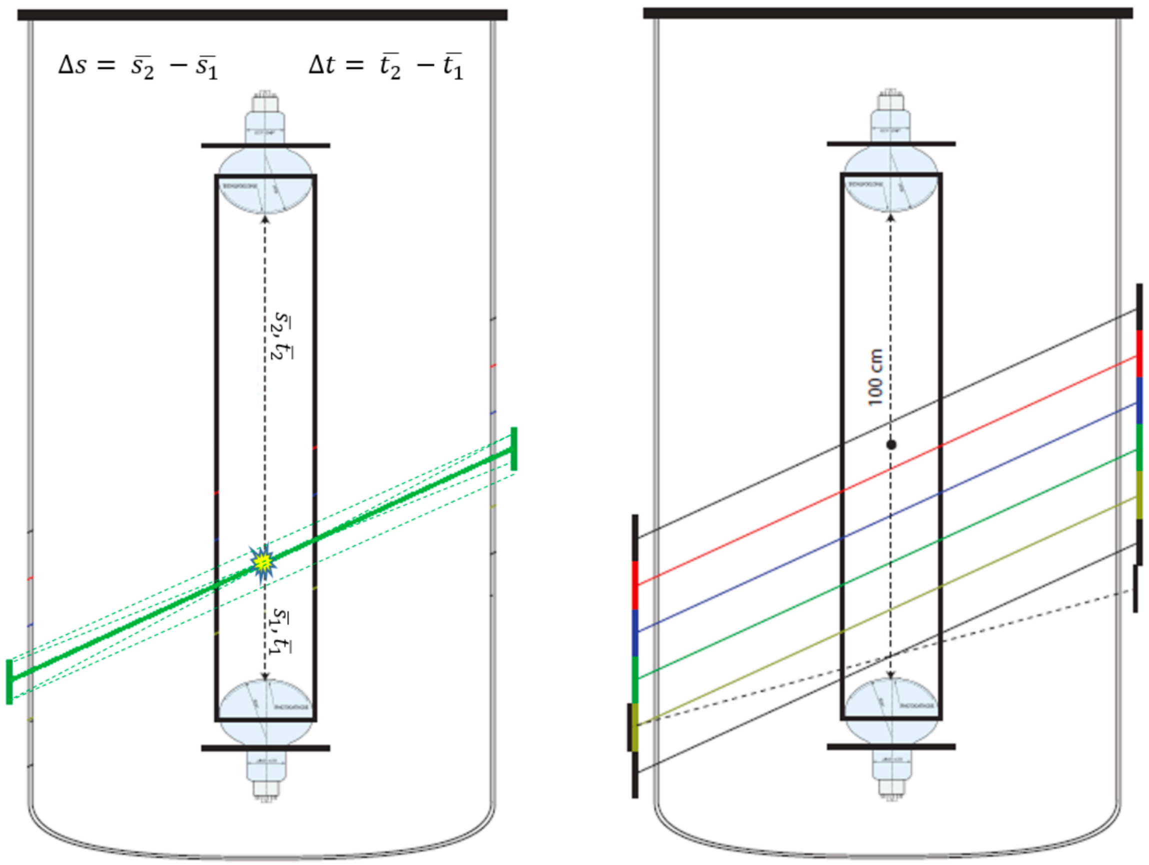
*see E. Grace et al., arXiv:1502.04213 for details

Light attenuation in noble liquids

- Recent first measurements of the group velocity of LAr scintillation light, and derivation of n and L_R
- Motivation: wide range for L_R, L_{att} in the literature
- Concept:
  - 2 PMTs immersed in LAr, facing each other at 1 m distance
  - External movable cosmic hodoscope positioned around a LAr cryostat, allows for triggering muons crossing the LAr at various distances from the PMTs
  - Measure the difference in path-length Δs and light arrival time Δt at the PMTs for different positions of the hodoscope
  - Extract the scintillation light velocity from a linear fit

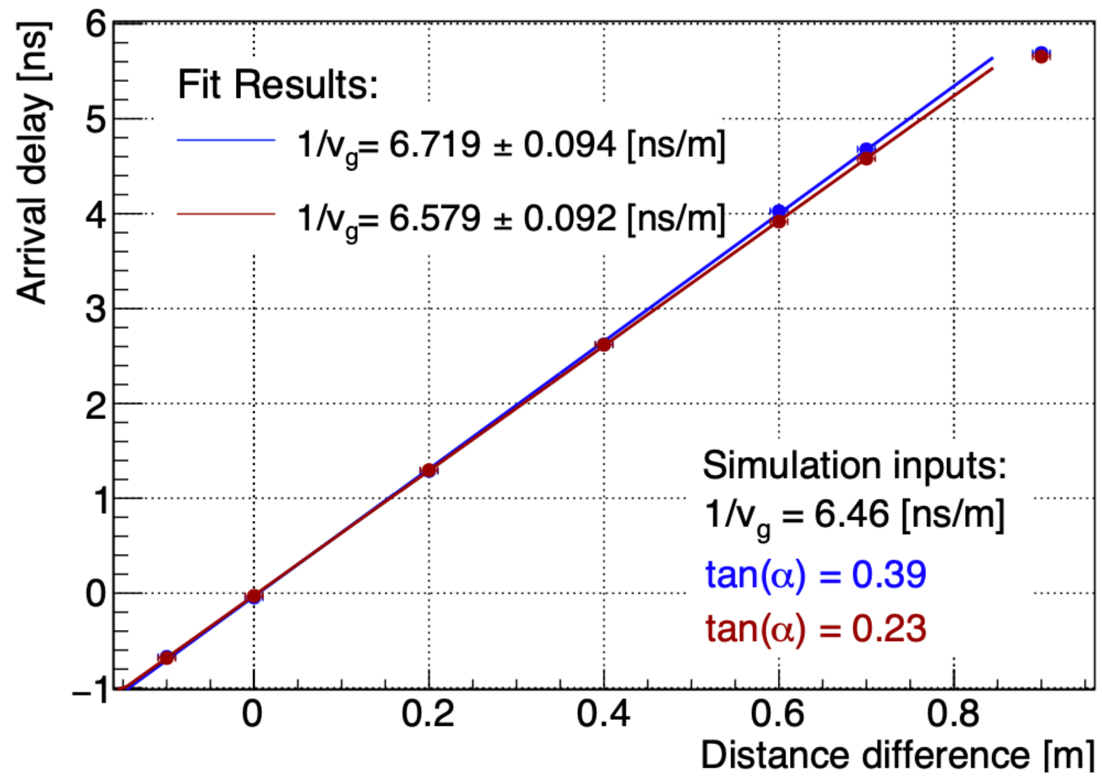
see M. Babicz et al., JINST 15, 2020, for details

Parameter:	Value:	Measured/calculated by:
Refractive index n	1.37	(calc.) [8]
	1.45 ± 0.07	(calc.) [9]
Attenuation length (cm)	66 ± 3	(exp.) [10]
	52 ± 7	(exp.) [11]
	> 110	(exp.) [12]
Rayleigh scattering length (cm)	90	(calc.) [8]
	55 ± 5	(calc.) [9]



Light attenuation in noble liquids

- Recent first measurements of the group velocity of LAr scintillation light, and derivation of n and L_R
- Motivation: wide range for L_R, L_{att} in the literature
- Results:
  - Value for the inverse velocity: (7.46 ± 0.03 (stat) ± 0.07 (sys)) ns/m
  - Derived refraction index n = 1.358 ± 0.003
  - Derived Rayleigh scattering length: (99.1 ± 2.3) cm at 128 nm



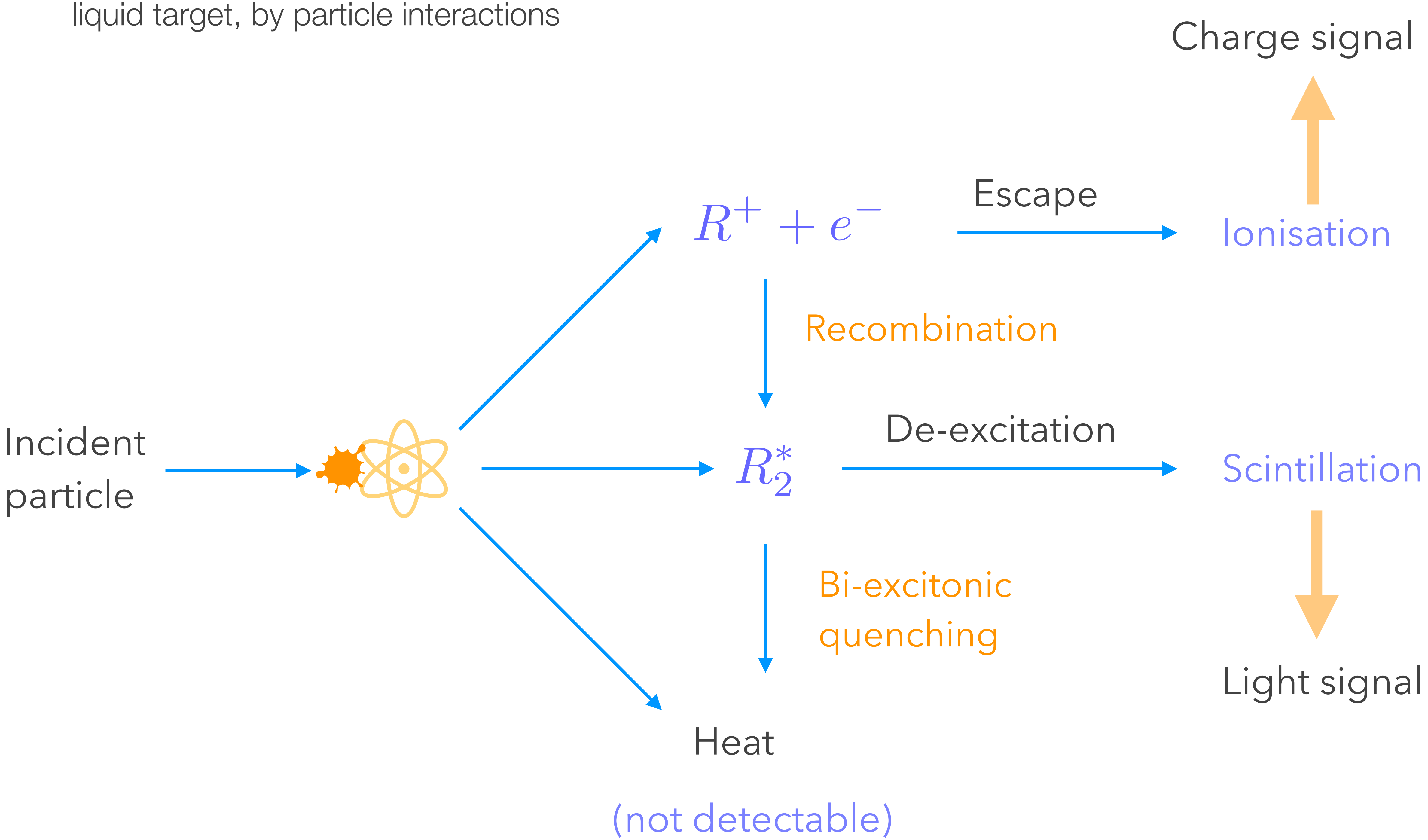
$$v_g = \frac{c}{n - \lambda \frac{dn}{d\lambda}}$$

$$L_R^{-1} = \frac{8\pi^3 k_B T \rho^2 \kappa_T}{3\lambda^4}\left[\frac{(n^2-1)(n^2+2)}{3}\right]^2$$

see M. Babicz et al., JINST 15, 2020, for details

Energy resolution

- We had looked at the way energy is deposited in a noble liquid target, by particle interactions



Energy resolution

- With the energy deposition being described as

$$E_0 = (N_{ph} + N_q) \cdot W$$

- W was the average energy required to produce a single excited or ionised atom (and for NRs we must also consider the "quenching factor")
- As we shall see, in two-phase TPCs, the observed light and charge signals are called S1 and S2, respectively, and these are related to the detector-specific gains g_1 and g_2. We then obtain:

$$E_0 = \left(\frac{S1}{g_1} + \frac{S2}{g_2}\right) \cdot W$$

- g_1 = total photon detection efficiency, g_2 = charge amplification factor. These are determined by using mono-energetic lines from various calibration sources.
    - g_1 and g_2 are typically given in terms of number of photoelectrons (PE) per quantum, or in terms of detected photons (phd) per quantum
    - typical values: g_1 = 0.15 PE/photon (XENON1T), 0.11 phd/photon (LUX), g_1 = 0.16 PE/photon (DarkSide-50); g_2 = 10 PE/electron (XENON1T) , g_2 = 12 phd/electron (LUX), g_2 = 23 PE/electron (here per extracted electron, DarkSide-50)

Energy resolution

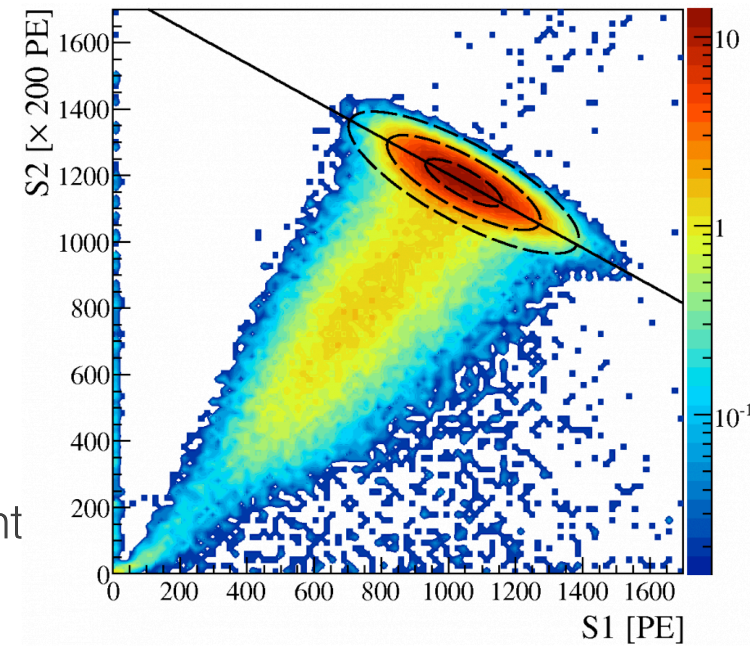
- The mean light and charge yields (L_y and Q_y) are then defined as:

$$L_y \equiv \frac{S1}{E_0} \qquad Q_y \equiv \frac{S2}{E_0}$$

- and are estimated by 2D Gaussian fits to mono-energetic lines, from the measured S1 and S2
- Knowing Ly, Qy from these mono-energetic lines, one can measure the energy resolution (usually with an empirical fit to a number of measurements at different energies). The relative resolution scales as:

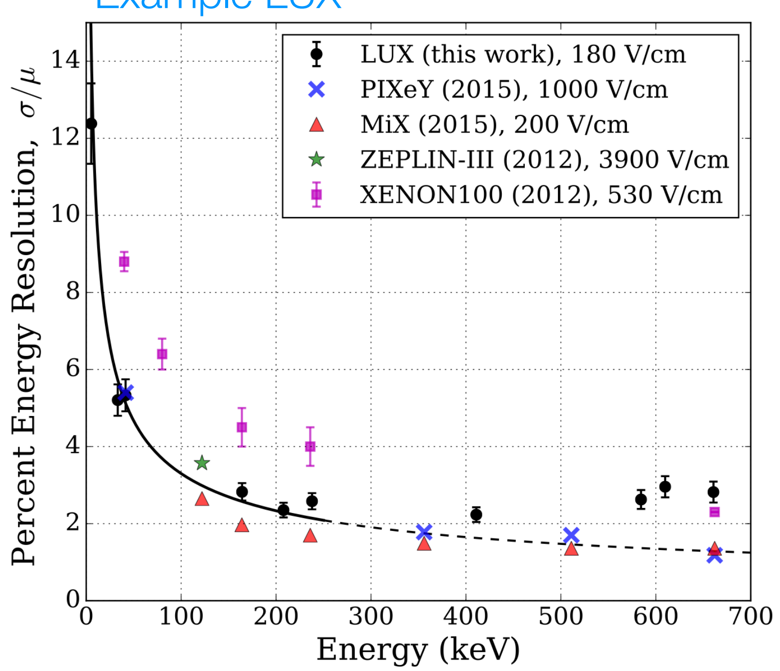
$$\frac{\sigma}{E} \propto \frac{a}{\sqrt{E}} + b$$

Example XENON100

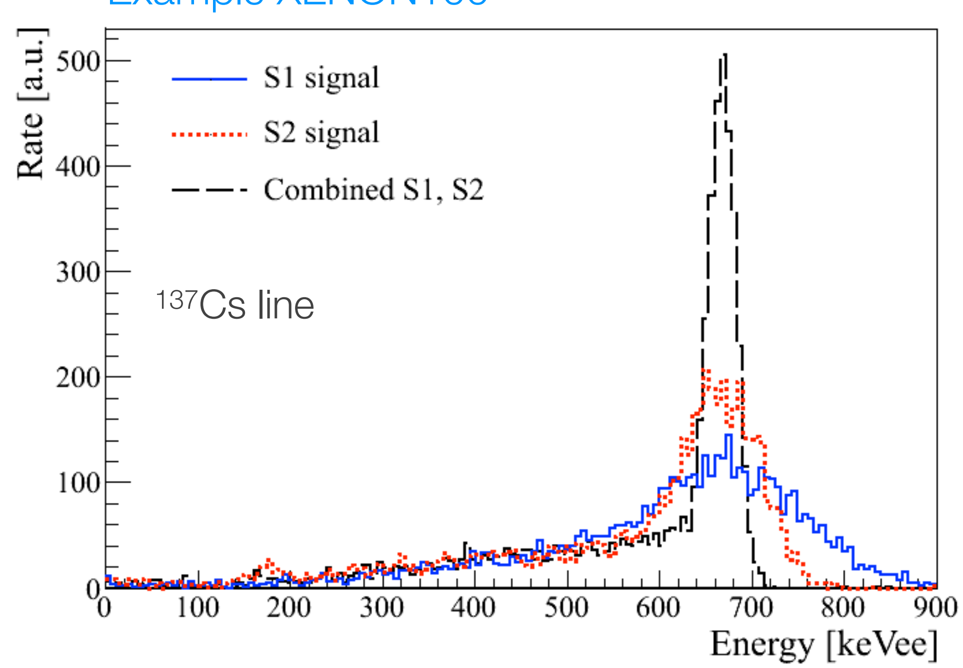


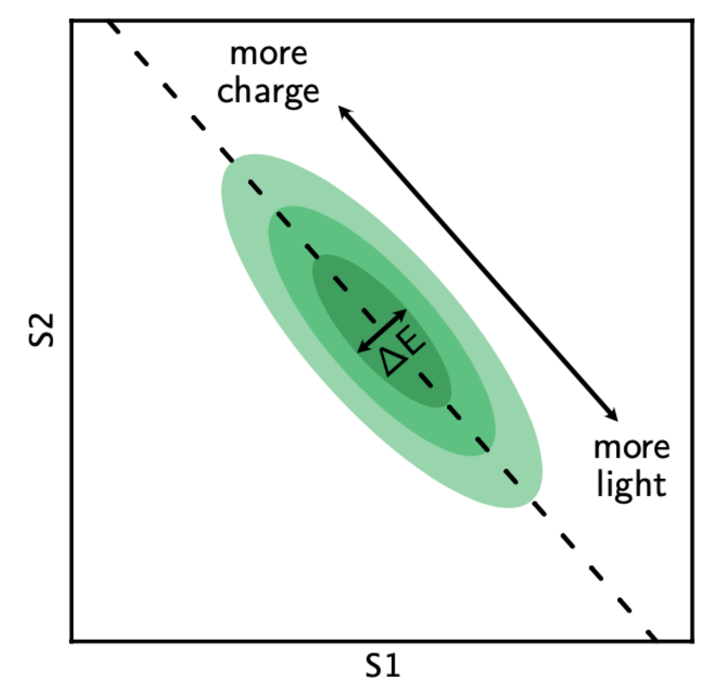
anti-correlation of charge and light signals

Example LUX



Example XENON100





The Doke plot

- One can also rewrite the previous equation as follows:

$$Q_y = -\frac{g_2}{g_1} L_y + \frac{g_2}{W}$$

- since we can measure S1 and S2 for clear spectral features, and E_0 is known, one can estimate g_1 and g_2 from a so-called Doke plot: a plot of Qy (=S2/E_0) versus Ly (=S1/E_0)
- From a linear fit one can thus extract g_1, g_2, and once these are known, reconstruct the energy of an event

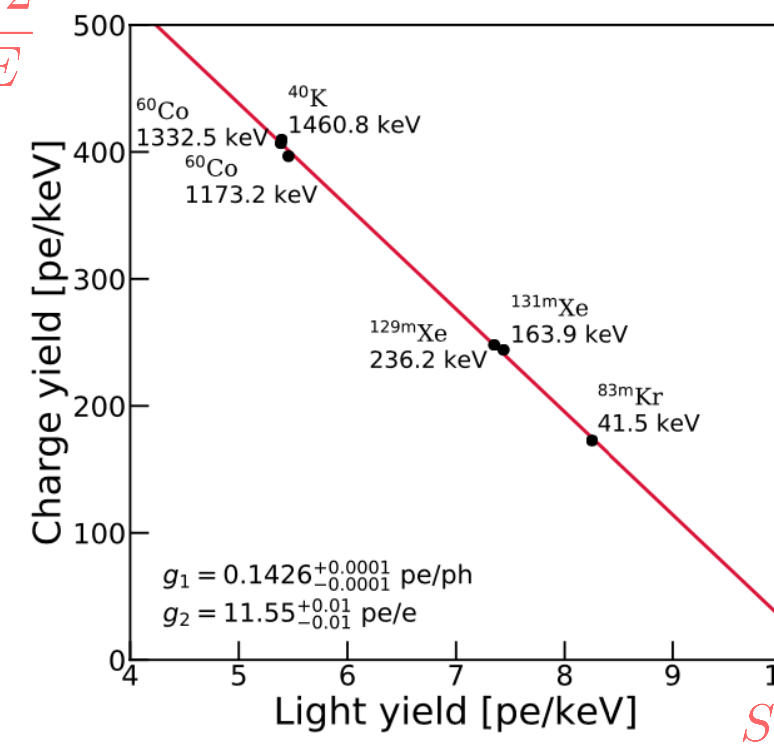
$$E_0 = \left(\frac{S1}{g_1} + \frac{S2}{g_2}\right) \cdot W$$

- Hence g1 and g2 are simply the proportionality factors between produced number of photons and electrons, and detected ones, for each signal
    - for S1: mostly the efficiency of detecting photons
    - for S2: it includes the extraction efficiency, secondary amplification, etc

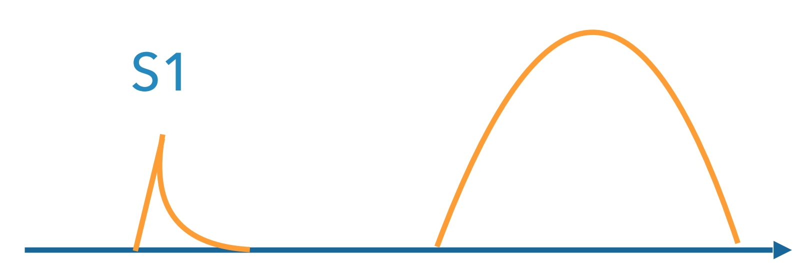
Example Doke plot from XENON1T

$$\frac{S2}{E} = \frac{g2}{W} - \frac{g2}{g1}\frac{S1}{E}$$

$\frac{S2}{E}$



$\frac{S1}{E}$



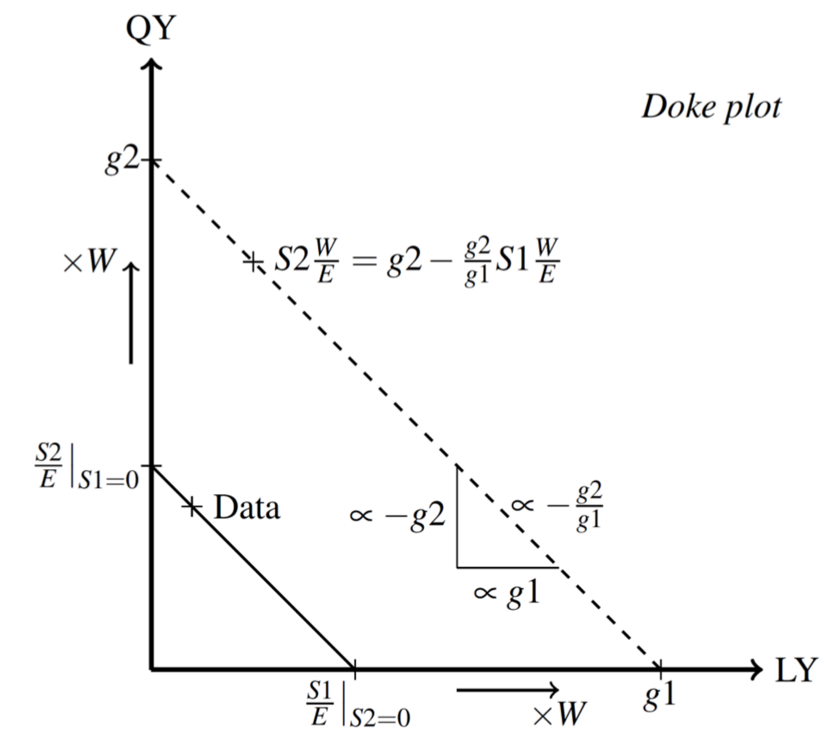
$\propto N_{ph}$ $\propto N_q$

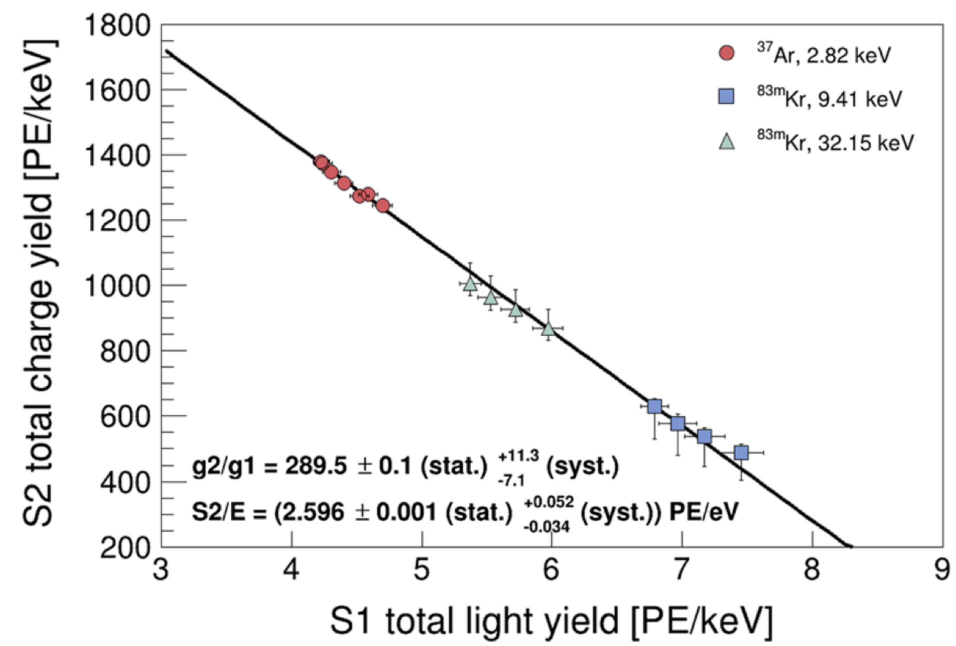
The W-value

- On the other hand, one can also use the Doke plot to determine the W-value in a noble liquid
- First, we rewrite the previous equation as:

$$W = g_2 \cdot \frac{E_0}{\frac{g_2}{g_1} \cdot S1 + S2}$$

- Then, we can determine the W-value from:
  - an event population in (S1, S2)-space from a known calibration source giving ERs at an energy E_0
  - an independent measurement of g2, the ionisation gain parameter (either by measuring the charge directly, or by using a single electron population extracted to the gas phase, for which g2 = S2)
  - the negative slope g2/g1 in charge yield versus light space (namely from the Doke plot)
- Both g_2/g_1 and the offset $S2/E_0$ at S1 =0 require at least 2 different energy lines at a given electric field, or a single line at 2 different drift fields (given the field-dependent recombination fraction)

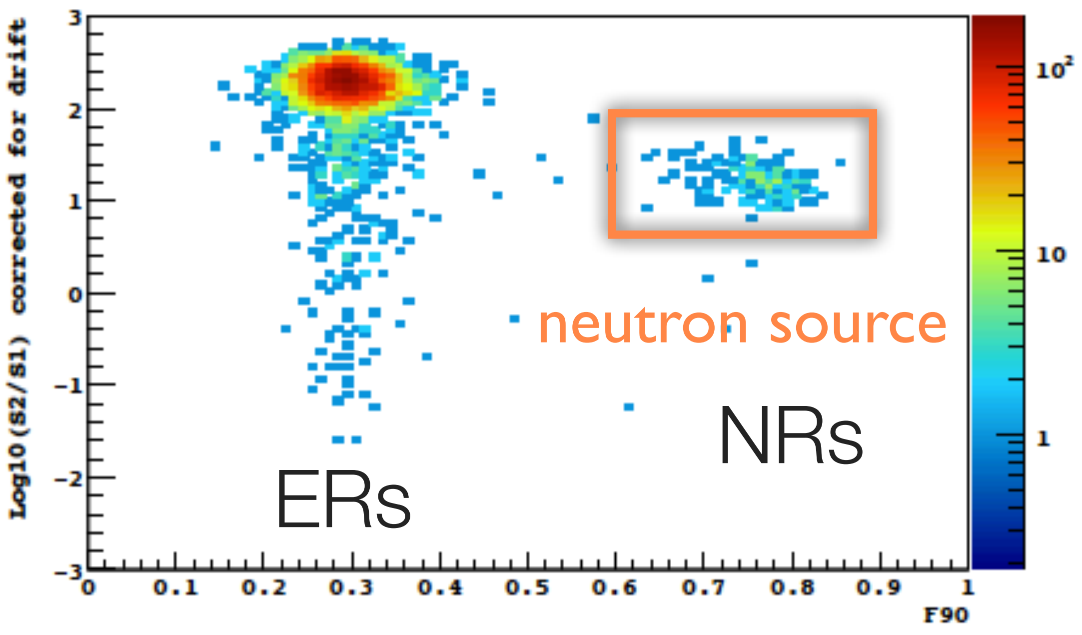




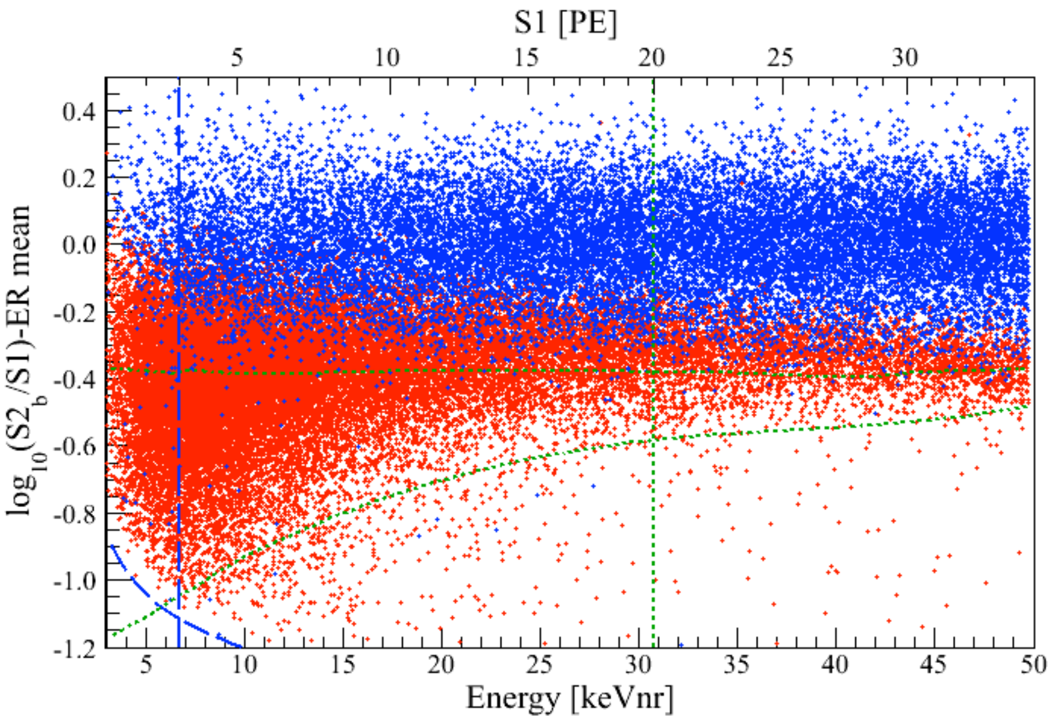
Xürich: three energies, various drift fields, EPJ-C 81, 2021

Particle discrimination in noble liquids

- Pulse shape of prompt scintillation signal (in liquid argon)
  - the ratio of light from singlet and triplet depends on dE/dx (~ 10:1 for NRs:ERs)
- Charge versus light (in LAr and LXe)
  - the recombination probability, and thus the S2-to-S1 ratio depends on dE/dx



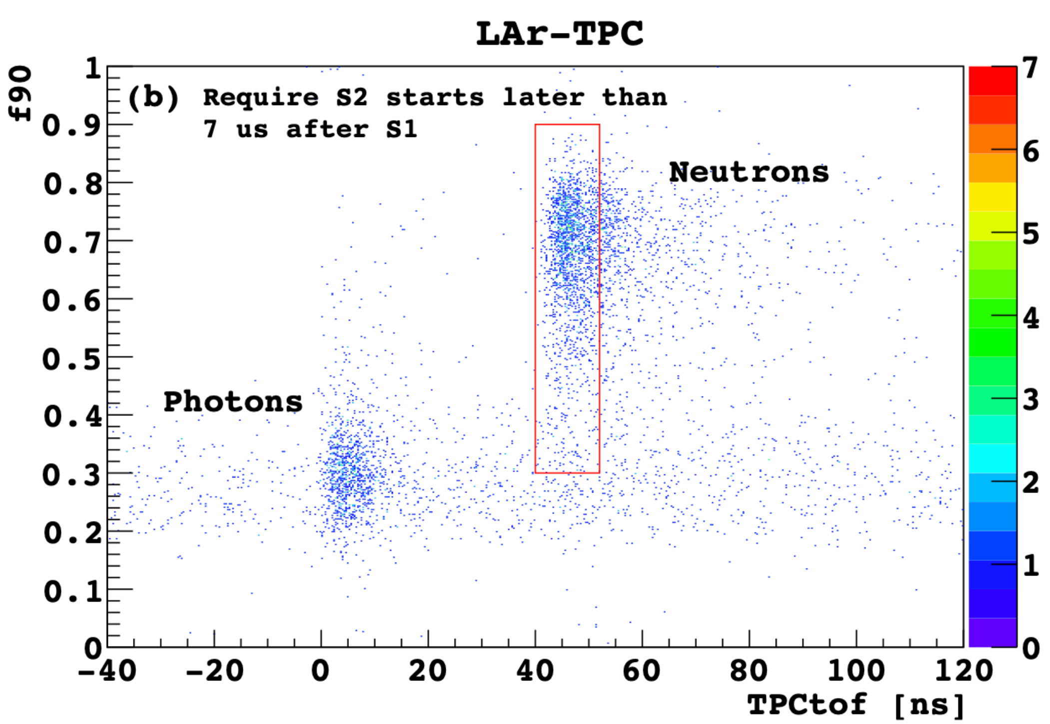
Example for LAr (DarkSide-10)

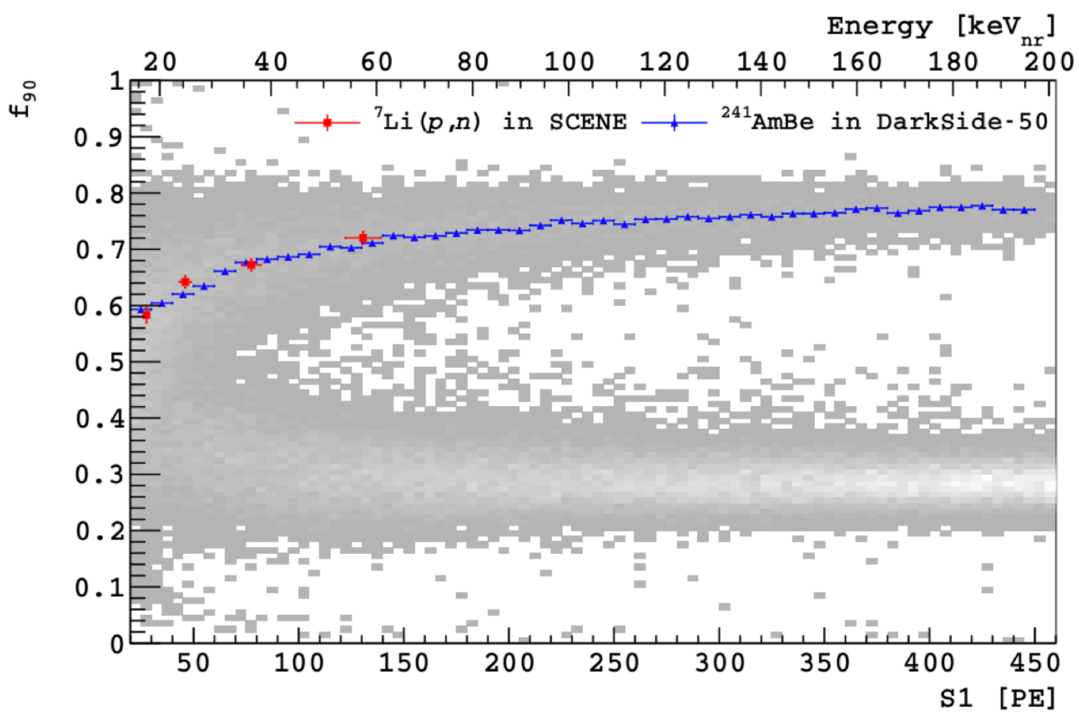


Example for LXe (XENON100)

Pulse shape discrimination in liquid argon

- Lifetime difference between the excimer's singlet (~ 6 ns) and triplet (~ 1.4-1.6 μs) states
- Singlet and triplet photons are well-separated in time, and the ratio for individual events can be estimated with high precision: the expectation value of the ratio depends on the linear energy transfer of the interacting particle (fewer triplet excimers are produced at higher LET)
  - Intensity ratio of fast/slow component: ~ 0.3 for ERs and in the range 1.3 - 3.3 for NRs
  - PSD methods thus usually use the ratio of prompt scintillation light to the total light, for example f_{90} = fraction of S1 light detected in the first 90 ns of a pulse
  - low f_{90} values (<0.5) ≊ ERs, high f_{90} values (> 0.5) ≊ NRs





Median f_{90} values from SCENE and from high-activity AmBe data in DarkSide-50

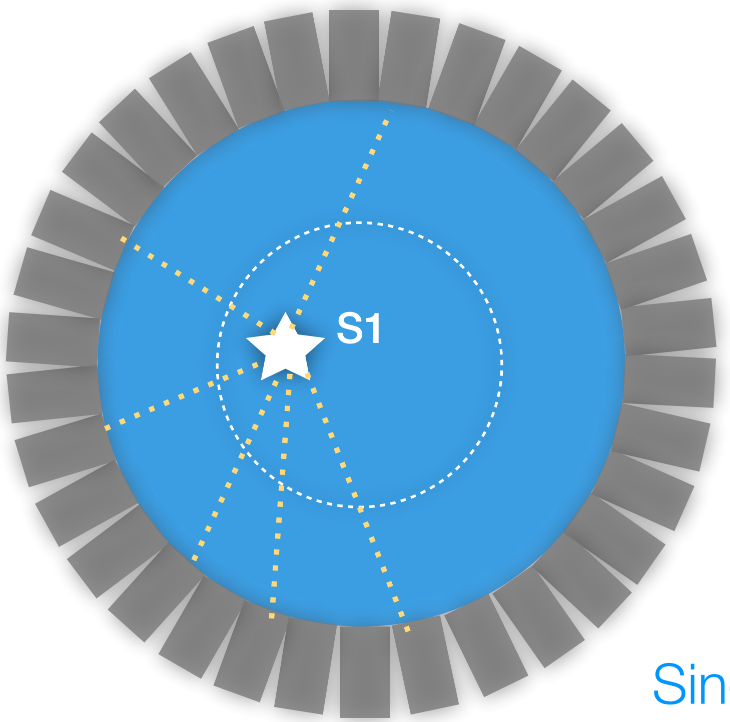
Cryogenic noble liquids: some challenges

- Cryogenics: efficient, reliable and cost effective cooling systems
- Detector materials: compatible with low-radioactivity and purity requirements
- Intrinsic radioactivity: ^{39}Ar and ^{42}Ar in LAr, ^{85}Kr in LXe, ^{222}Rn emanation and diffusion

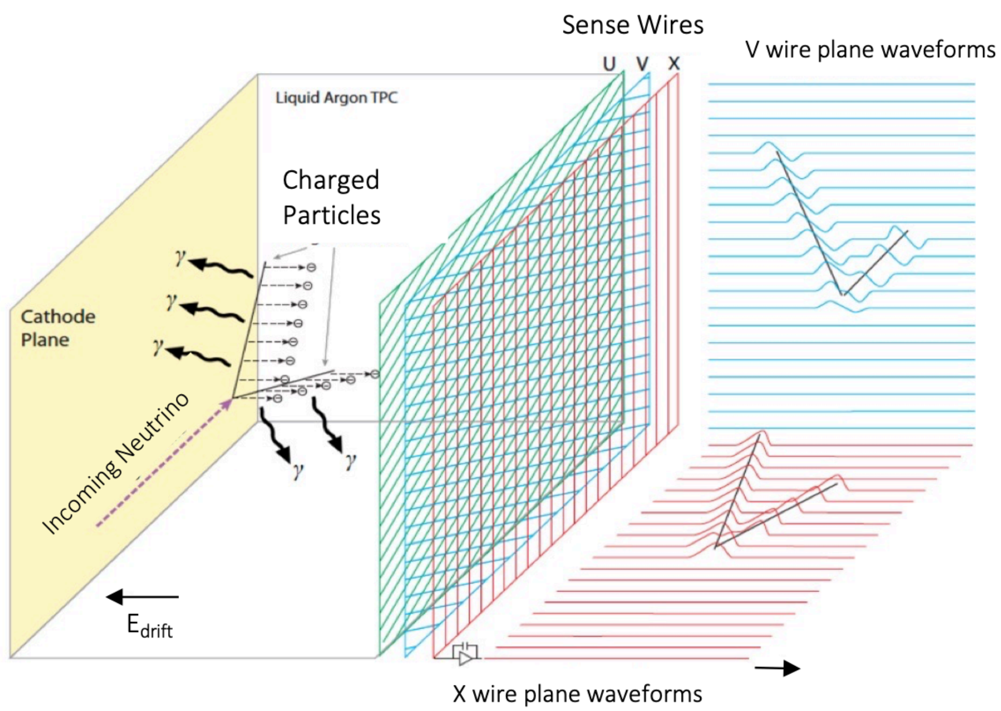
- Light detection:
  - efficient VUV photosensors, directly coupled to liquid (low T and high P capability, high purity), effective UV reflectors and wavelength shifters (WLS) (in LAr)
  - light can be absorbed by H_2O and O_2: continuous recirculation and purification
- Charge detection:
  - requires $\ll$ 1ppb (O_2 equivalent) for e^--lifetime > 1 ms (commercial or custom-made purifiers and continuous circulation, gas and liquid)
  - electric drift fields ~ few 100 V/cm required for maximum yield for MIPs; for alphas and NRs the field dependence is much weaker, challenge to detect a small charge in presence of HV

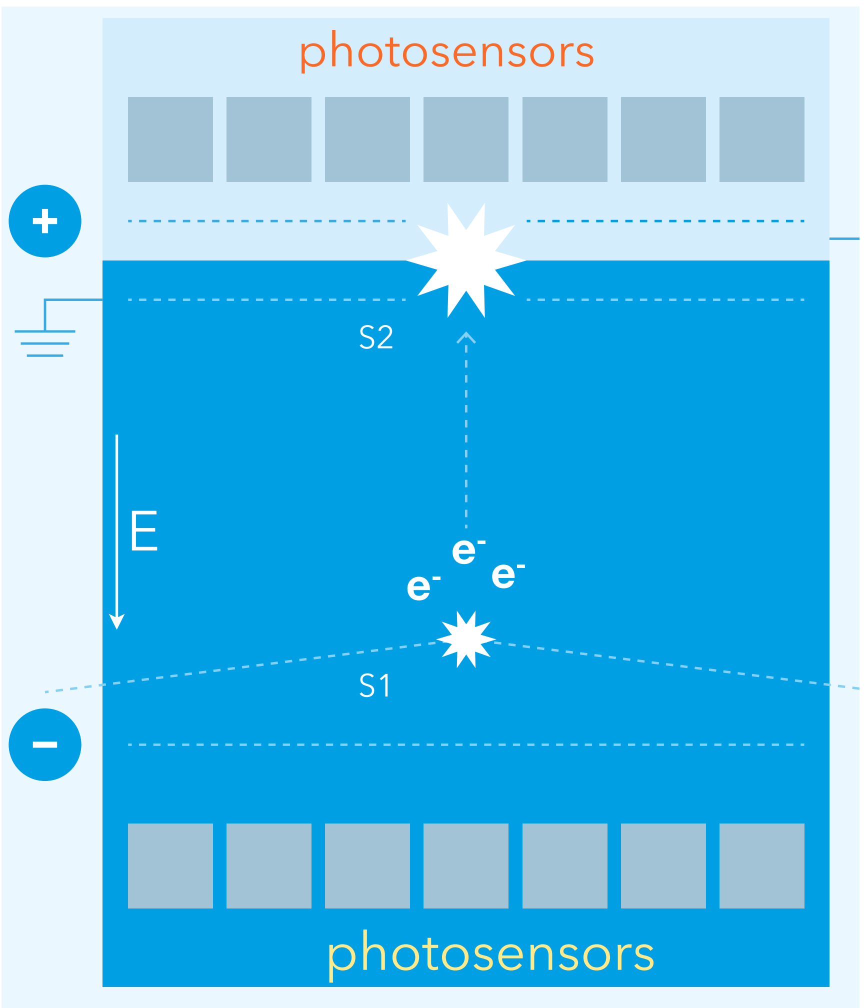
Types of noble liquid detectors

Single phase, light readout



Single phase TPC with charge readout

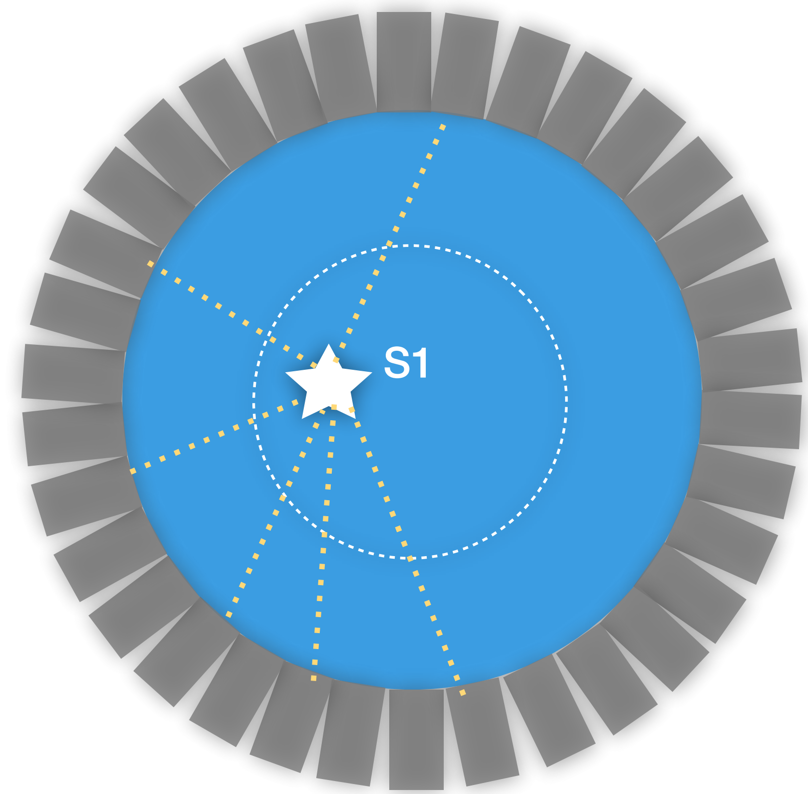




Two-phase TPC with light readout

Single phase detectors

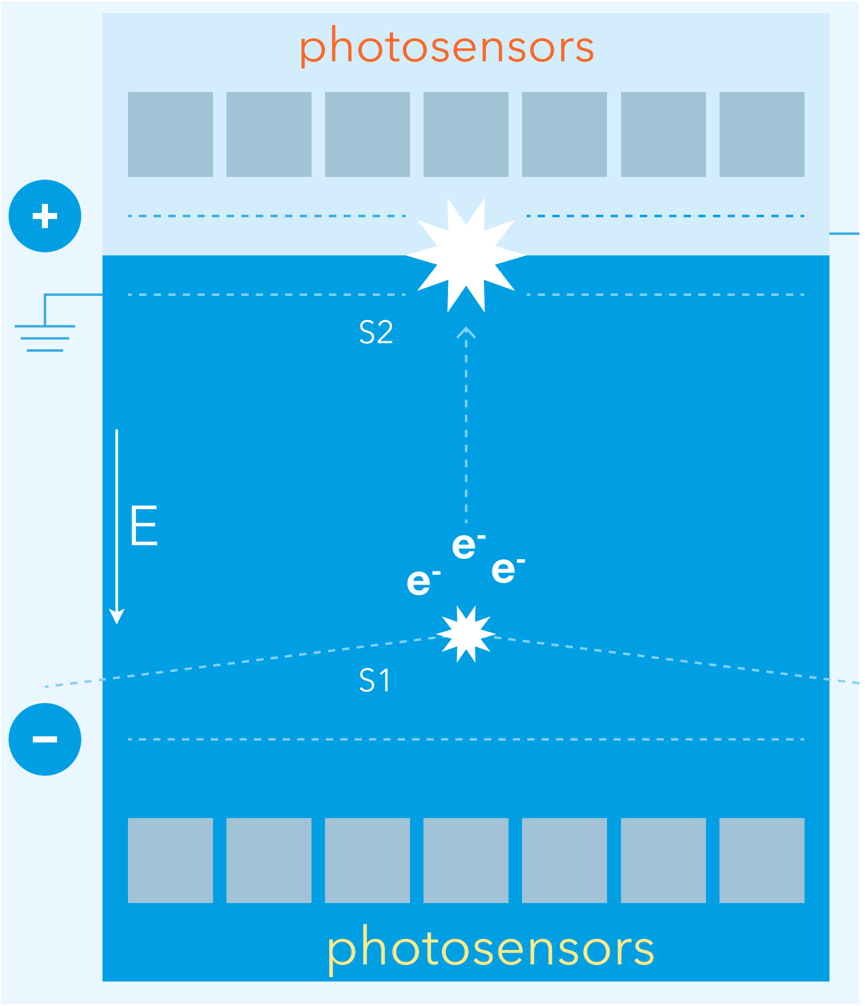
- Observe the prompt scintillation light in a large, homogeneous volume of liquid argon or xenon
- Particle discrimination via pulse shape analysis (in LAr)
- Advantages
  - High light yield (4-π coverage with photosensors; e^--ion recombination)
  - Simpler detector geometry, no electric fields and high-voltage, cheaper
  - Large, homogeneous target with ultra-low backgrounds
- Disadvantages
  - No particle discrimination in LXe
  - Position resolution typically few cm
  - Very low energy thresholds ("S2-only") not possible
- Examples
  - LAr: DEAP-3600 and MiniCLEAN at SNOLAB
  - LXe: XMASS at Kamioka



Single phase, light readout

Two-phase TPCs

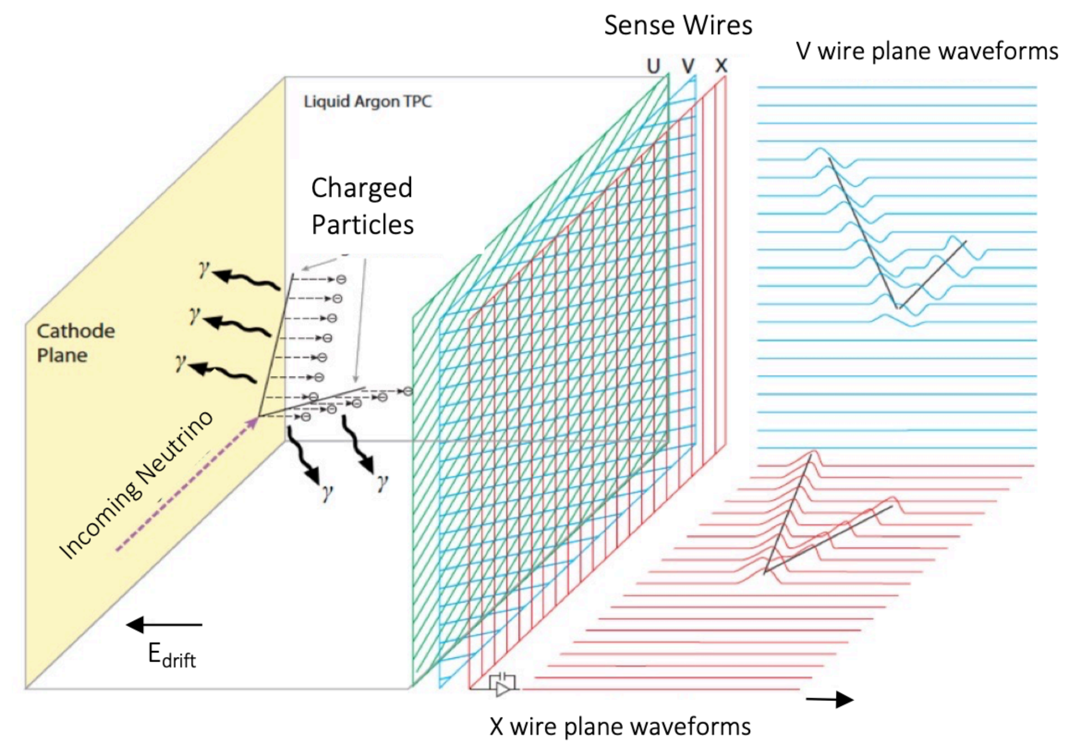
- Observe the prompt scintillation light and electroluminiscence in a large, homogeneous volume of liquid argon or xenon
- Particle discrimination via pulse shape analysis (in LAr) and via ratio of charge to light yield
- Advantages
  - Three dimensional position reconstruction
  - Improved energy resolution and lower energy threshold ("S2-only")
  - Improved single versus multiple scatters discrimination
- Disadvantages
  - Complex detector geometry
  - Electric fields and high-voltage FTs, large, uniform electrodes
  - Precise control of liquid level needed
- Examples
  - LAr: DarkSide, ArDM
  - LXe: LUX/LZ, PandaX, XENON

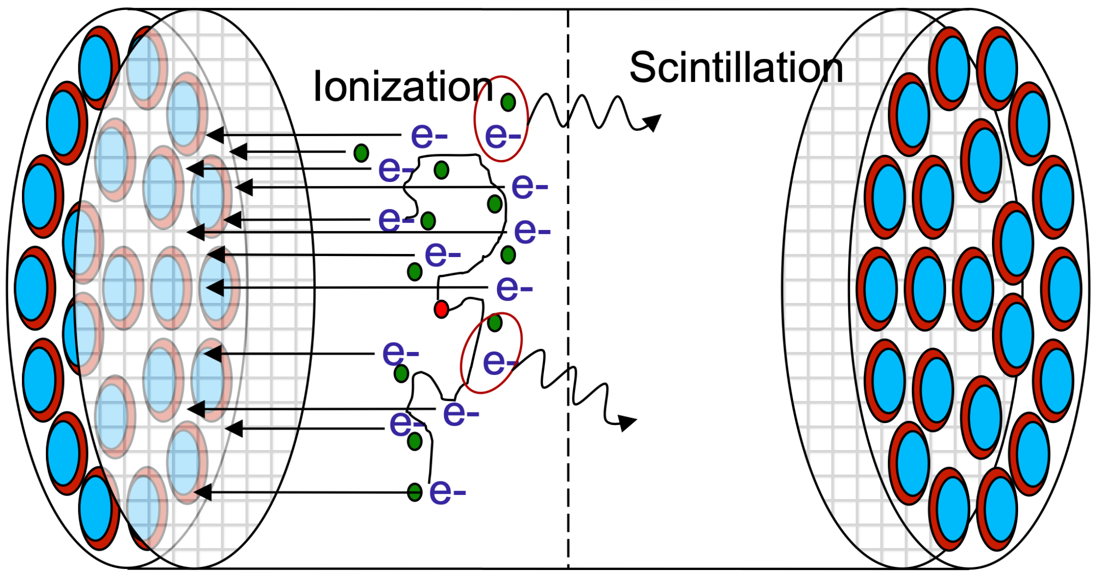


Two-phase TPC with light readout

Single-phase TPCs

- Observe the prompt scintillation light, as well as the charge induced by the drifting electrons
- Record the tracks of particles (in the case of HE neutrino interactions)
- Advantages
  - Different charge readout possibilities (pixelated, wire, perforated PCB)
  - Light readout with photosensors
  - Good position resolution, 3D imaging
  - Modular design, horizontal TPC possible
- Disadvantages
  - Higher energy thresholds
- Examples
  - LAr: DUNE at SURF
  - LXe: EXO-200 at WIPP, nEXO proposed for SNOLAB





End of first part