SOUP 2024

NOBLE LIQUID DETECTORS, PART 1

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CONTENTS, PART 1

- Noble liquids for particle detection
  - Ionisation in noble liquids
  - Scintillation 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
- Energy calibration and resolution, the W-value
- Pulse shape discrimination
- Noble liquid detector technologies
  - Single-phase detectors and time projection chambers, detection principles

Slides courtesy of L. Baudis and R. Calabrese

CONTENTS, PART 2

- Applications to direct dark matter detection and experiments
  - Brief review of direct detection principles
  - Argon DM detectors: ArDM, Darkside-50, DEAP-3600, DarkSide-20k
  - Xenon DM detectors: XMASS, XENON, LZ, PandaX, DARWIN/XLZD
- Applications to neutrino physics and experiments
  - Brief motivation and open questions in neutrino physics
  - DUNE (LAr)
  - EXO-200, nEXO (LXe)
- Summary

Slides courtesy of L. Baudis and R. Calabrese

NOBLE LIQUIDS

PARTICLE DETECTION

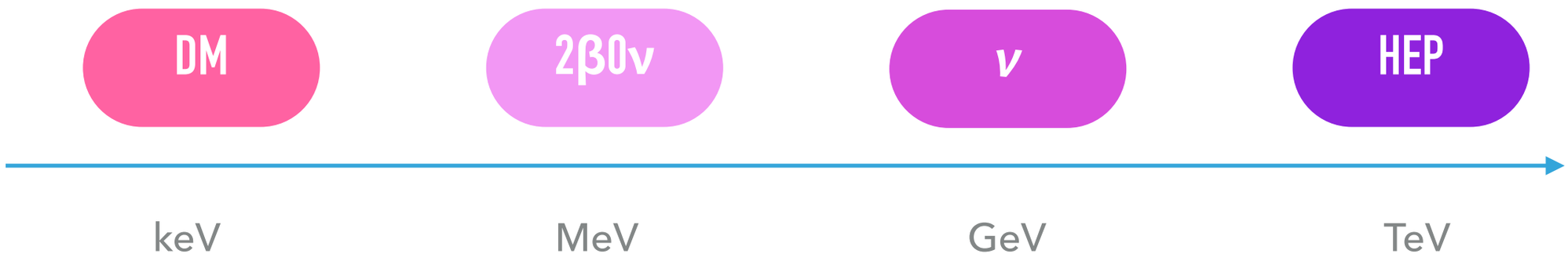
NOBLE GASES

- 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
- Rn is radioactive and different isotopes are produced in the U and Th chains
- 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:
  - They have higher density and larger stopping power (compared to gas)
  - They provide both scintillation/ionization with high yields
  - Can be obtained commercially and purified in situ

Earth's Atmosphere	
Gas	Abundance
N_2	78,09%
O_2	20,94%
Ar	0,93%
CO_2	350 ppm
Ne	18.2 ppm
He	5.2 ppm
Kr	1.14 ppm
H_2	0.5 ppm
Xe	0.087 ppm

NOBLE LIQUIDS AS PARTICLE DETECTORS

- 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)



PROPERTIES OF NOBLE LIQUIDS AS PARTICLE DETECTORS

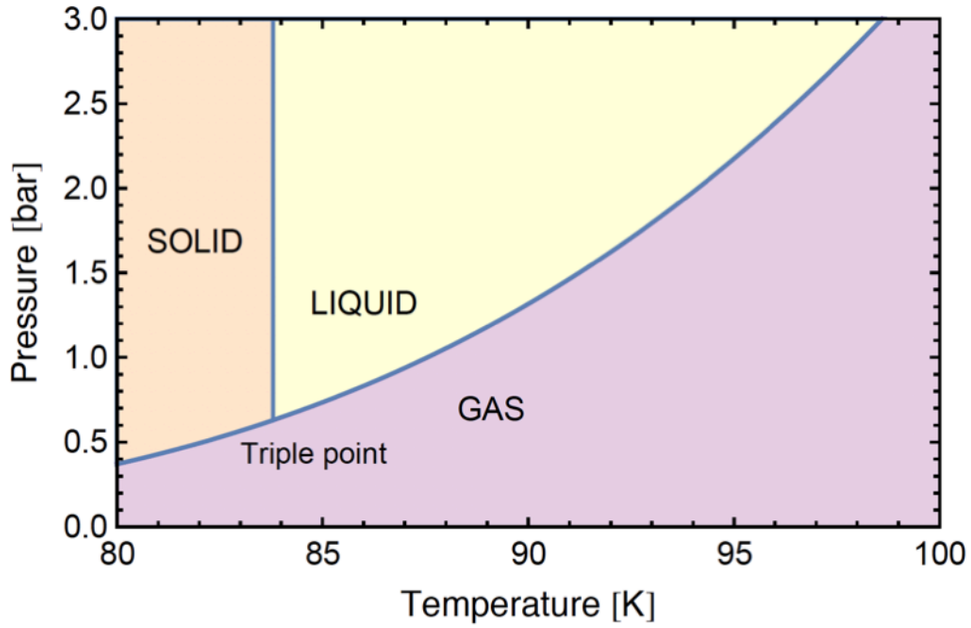
Suitable materials for detecting ionization tracks:

- high charge and light yields
  - Calorimetry, excellent energy resolution
  - Particle identification
  - Precise timing
- no e- attachment, which allows for long drift distance
  - Tracking, 3D reconstruction
- inert, non flammable, very good dielectrics which allows for high voltages to drift over long distances
- transparent to their own scintillation light, which can be collected in large volumes

Element	Z(A)	BP @ 1 atm [K]	Liquid density @ BP [g/cc]	Dielectric constant	Ionisation [e^-/keV]	Scintillation [photon/keV]
He	2 (4)	4,2	0,13	1,06	39	15
Ne	10 (20)	27,1	1,21	1,53	46	7
Ar	18 (40)	87,3	1,40	1,51	42	40
Kr	36 (84)	119,8	2,41	1,66	49	25
Xe	54 (131)	165	2,95	1,95	64	46

NOBLE LIQUIDS FOR UNDERGROUND PHYSICS

- Most underground experiments use **argon** and **xenon** (helium and neon detectors are proposed)
  - Dense, homogeneous targets for rare event searches
  - Detectors with self-shielding and fiducialisation
  - Large detector masses with ultra-low levels of radioactivity



Properties	Xe	Ar
Atomic number	54	18
Mean relative atomic mass	131,3	40,0
Boiling point (BP) @ 1 atm [K]	165,0	87,3
Melting point @ 1 atm [K]	161,4	83,8
Gas density @ 1 atm and 298 K [g/l]	5,40	1,63
Gas density @ 1 atm and BP [g/l]	9,99	5,77
Liquid density @ BP [g/cm^3]	2,94	1,40
Dielectric constant of liquid	1,95	1,51
Volume fraction in Earth's atmosphere [ppm]	0,09	9340

ENERGY LOSS IN NOBLE LIQUIDS

- Energy loss (E_0) of an incident particle in noble liquids: shared between ionization, excitation, and sub-excitation electrons (E_{kin} < energy of first excited level) freed in the ionization process

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

- N_i, N_{ex} are the mean number of ionized and excited atoms; E_i, E_{ex} are the mean energies to ionize and excite the atoms; ϵ is the average kinetic 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

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

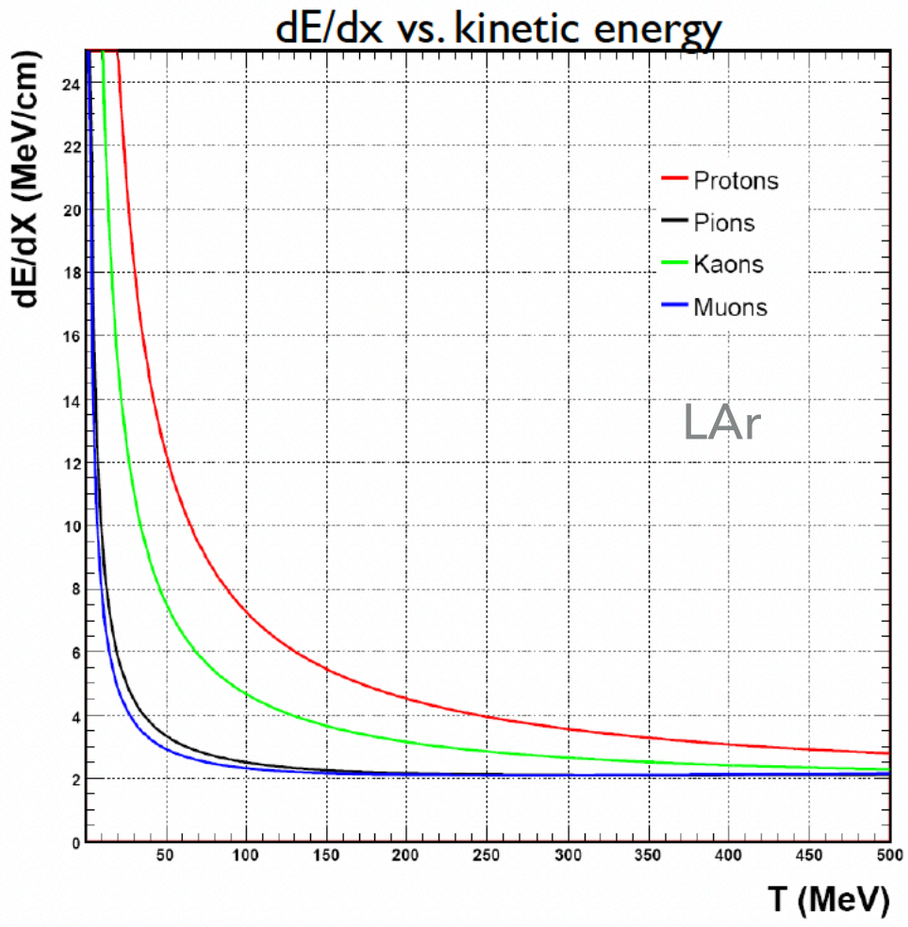
- To obtain: $$\frac{W_i}{E_g} = \frac{E_i}{E_g} + \frac{N_{ex}}{N_i} \times \frac{E_{ex}}{E_g} + \frac{\epsilon}{E_g}$$

THE IONIZATION PROCESS IN NOBLE LIQUIDS

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

$$\frac{W_i}{E_g} = 1.6 - 1.7$$

Material	LAr	LKr	LXe
Gap energy [eV]	14,3	11,6	9,3
W-value [eV]	23,6	20,5	15,6
dE/dx for a MIP (βγ=3.5)	2.2	3.5	4

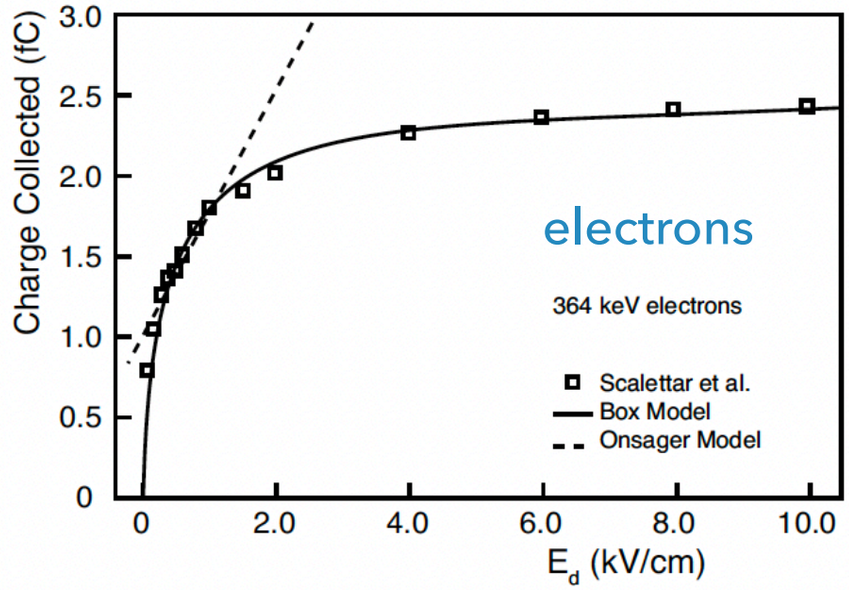


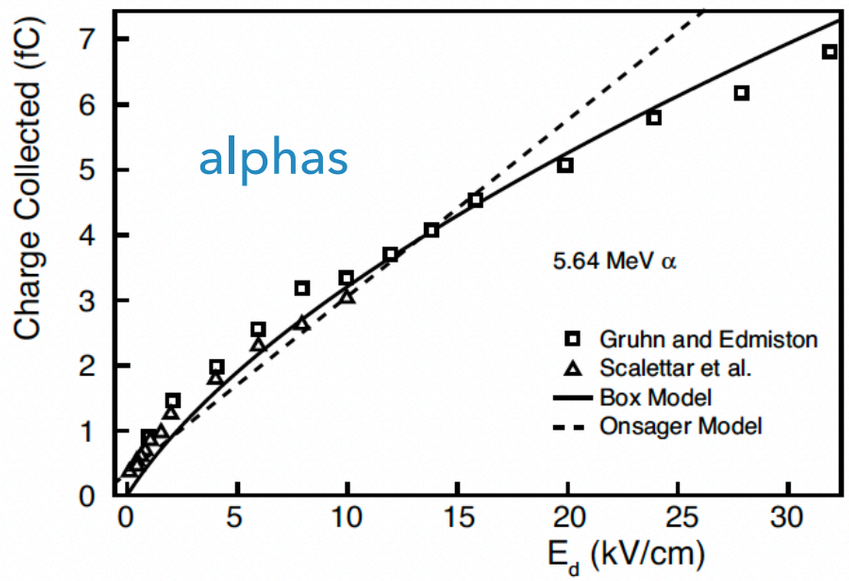
IONIZATION RECOMBINATION PROCESS

- After being created electron and ion can recombine
- The recombination process is strongly dependent
  - on the external applied electric field,
  - on the nature and on the kinematical properties of the ionizing particle (dE/dx)
- Many theoretical and phenomenological models to fit the data

Birk's Model: $\frac{Q}{Q_0} = \frac{A}{1+\frac{k}{\mathscr{E}}\frac{dE}{dx}}$

Box Model: $\frac{Q}{Q_0} = \frac{1}{\xi} ln(1+\xi)$ with $\xi = \alpha Q_0 / \mathscr{E}$





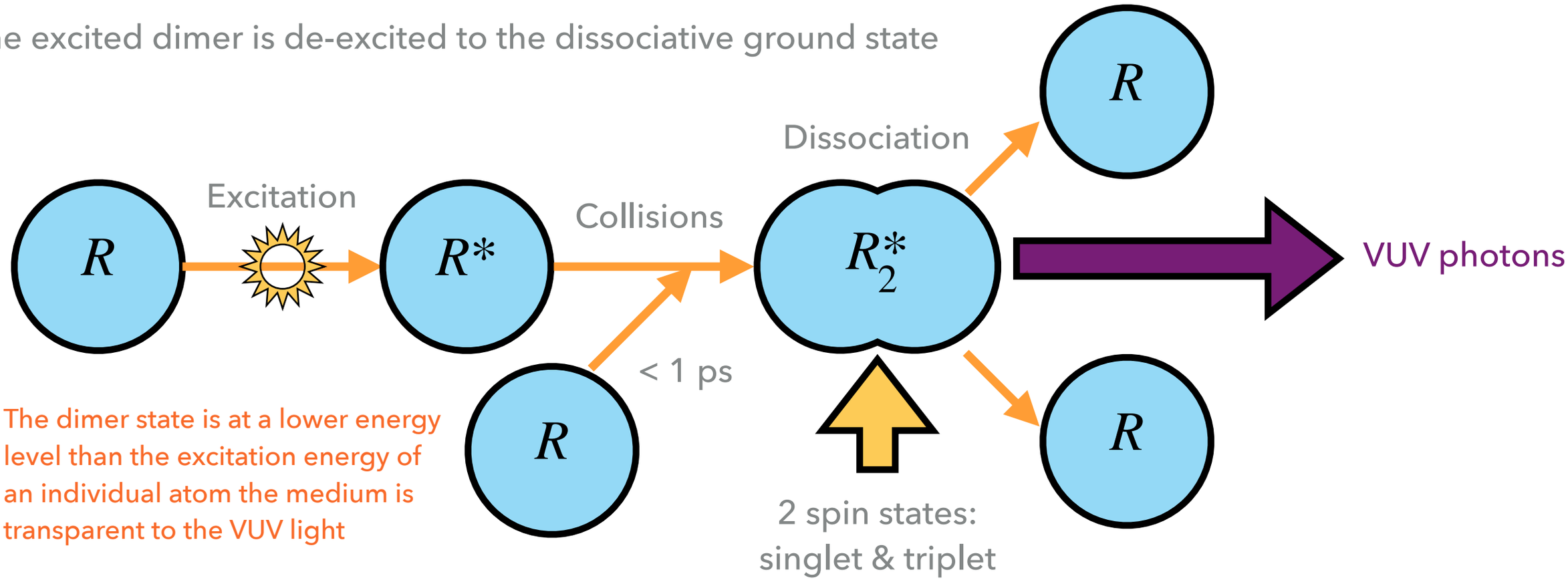
THE SCINTILLATION PROCESS IN NOBLE LIQUIDS

Two distinct processes: *excitation luminescence* and r*ecombination luminescence*

Excitation luminescence

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*

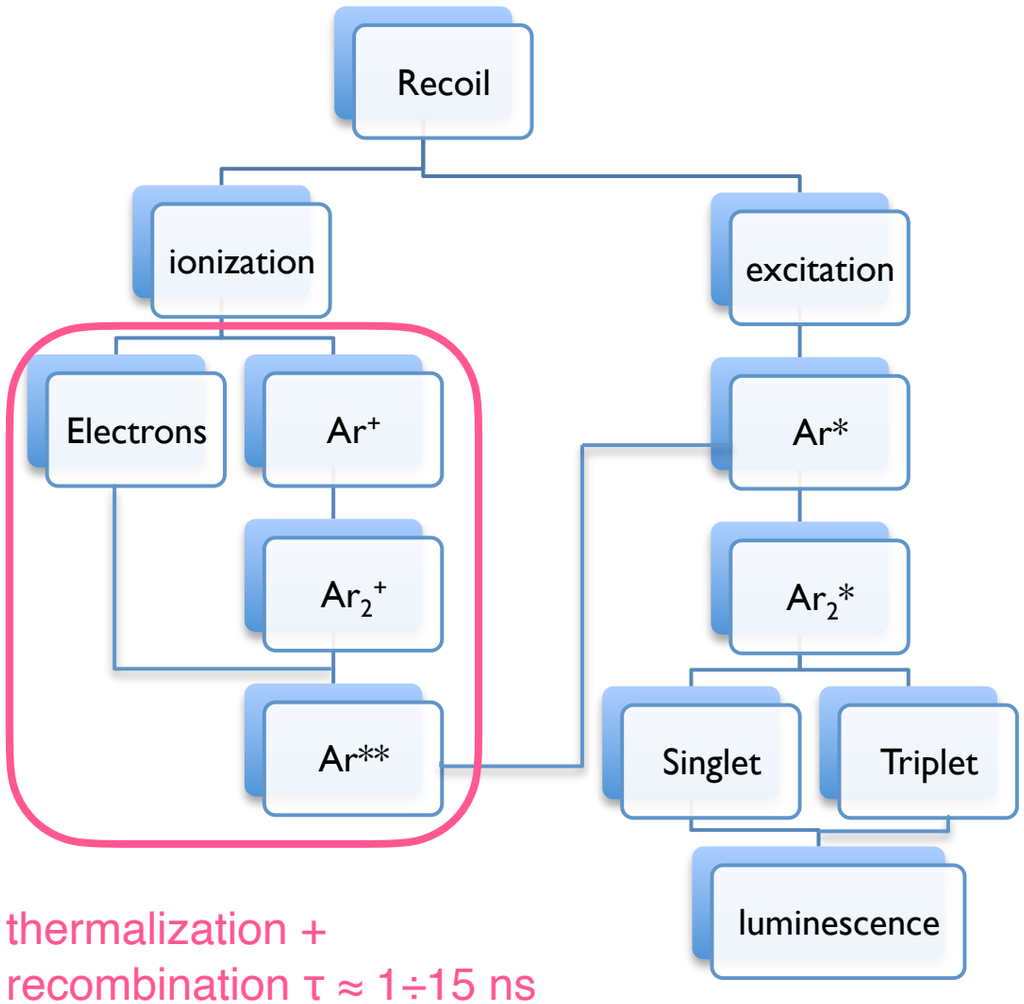
the excited dimer is de-excited to the dissociative ground state



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

- 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



thermalization +
recombination τ ≈ 1÷15 ns

Recombination luminescence:

A fraction of the ionization electrons will recombine with ions and produce a scintillation photon in the following processes

$$R^+ + R \rightarrow R_2^+$$

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

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

$$R^* + R + R \rightarrow R_2^* + R$$

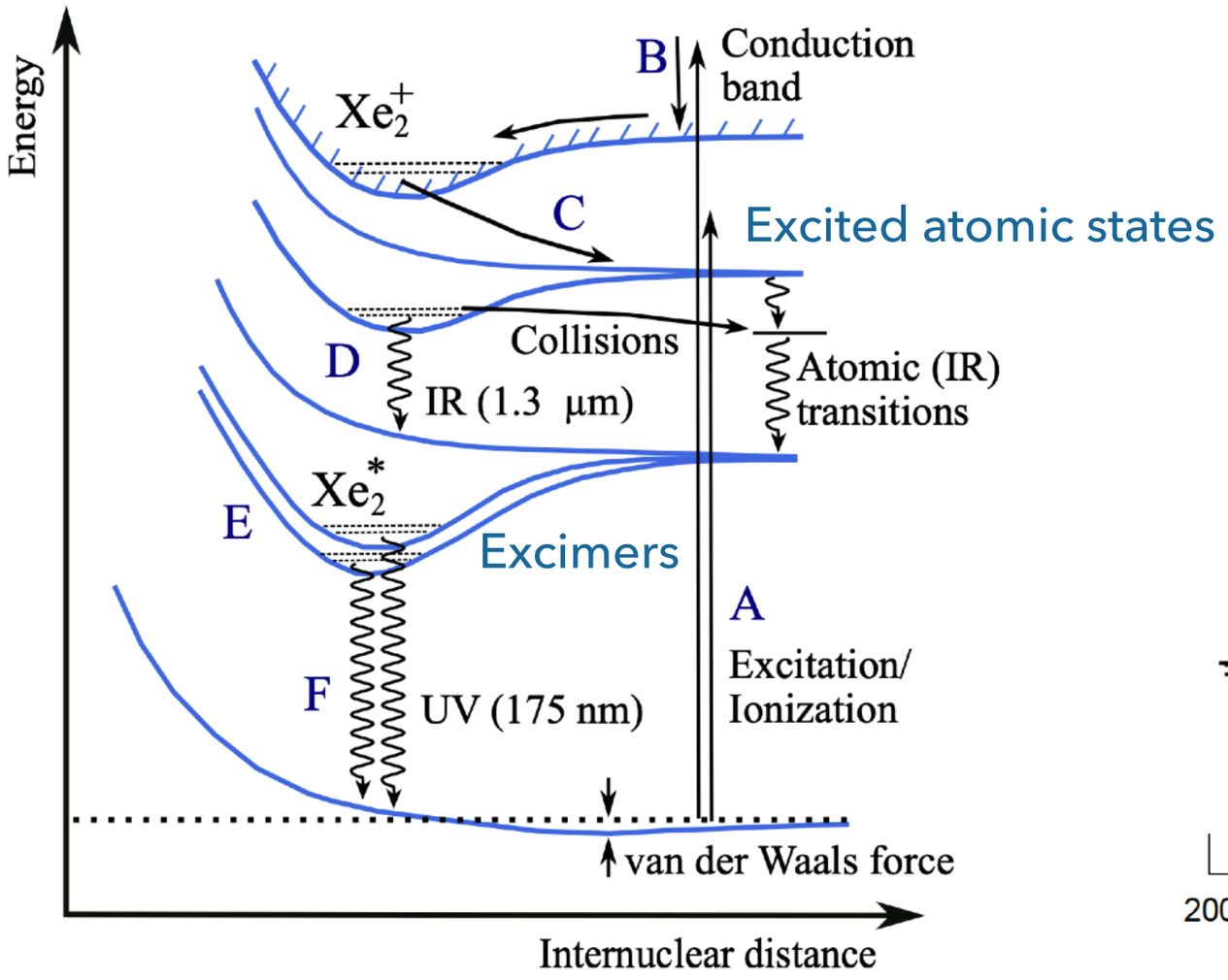
$$R_2^* \rightarrow 2R + h\nu$$

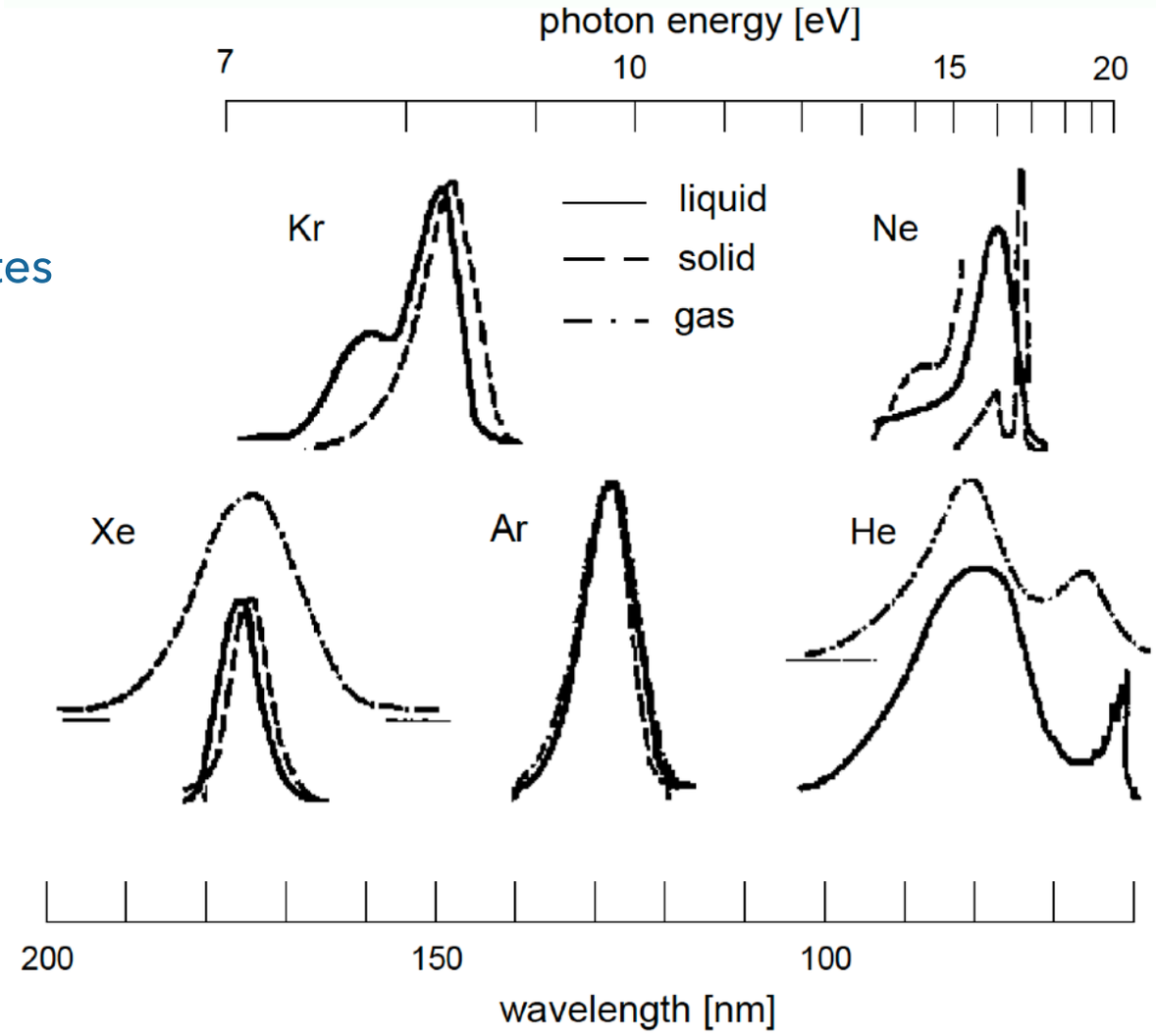
- Electrons that thermalize far from their parent ion may escape recombination
- A mechanism called "bi-excitonic quenching" can also reduce the scintillation yield in very dense tracks

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

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 EXCITATION PROCESS AND THE PHOTON ENERGY





The dimer (or exciton) can not exist in the ground state (the transition from the lowest electronic excited states to the ground state occurs at short distances, where the ground state potential is repulsive, thus resulting in dissociation of the molecule):

$\lambda_{LNe} \sim 78\,\text{nm}$

$\lambda_{LAr} \sim 128\,\text{nm}$

$\lambda_{LXe} \sim 178\,\text{nm}$

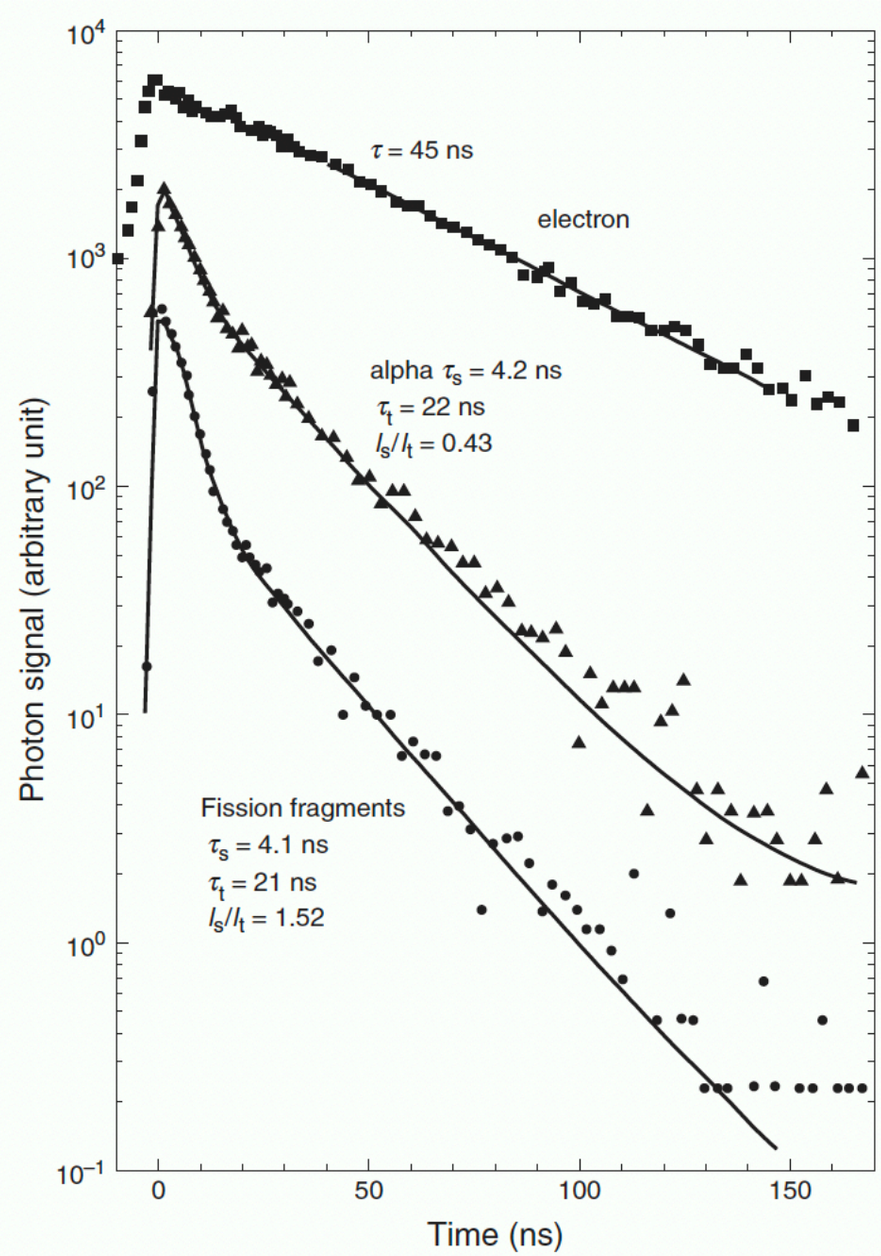
THE SCINTILLATION PULSE SHAPE

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:

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

- The figure shows
  - α 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

Specie	Time constants
Ne	Few ns vs 15.4 μs
Ar	7 ns vs 1.5 μs
Xe	4 ns vs 27 μs



Decay curves of luminescence from liquid xenon excited by electrons, alpha-particles and fission fragments, without an external electric field

THE SCINTILLATION PROCESS IN NOBLE LIQUIDS

- We define as 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 et al, 2002

- E_0 is the energy loss, N_{ex}, N_i are the mean number of excitons and electron-ion pairs, E_i, E_{ex} are the mean energies to ionize and excite the atoms, and $\alpha = N_{ex}/N_i$ (~ 0.2 for LAr, and LXe)

- We assume the efficiency for exciton and electron-ion pair creation are unity, namely

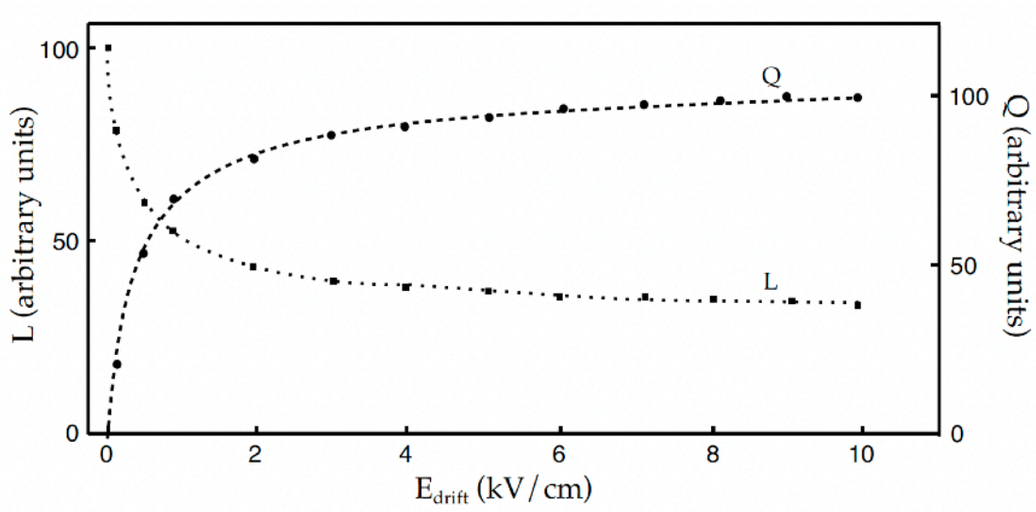
$$N_{ph} = N_{ex} + r \cdot N_i$$

- Where r is the 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

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

Charge and light are complementary!



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)

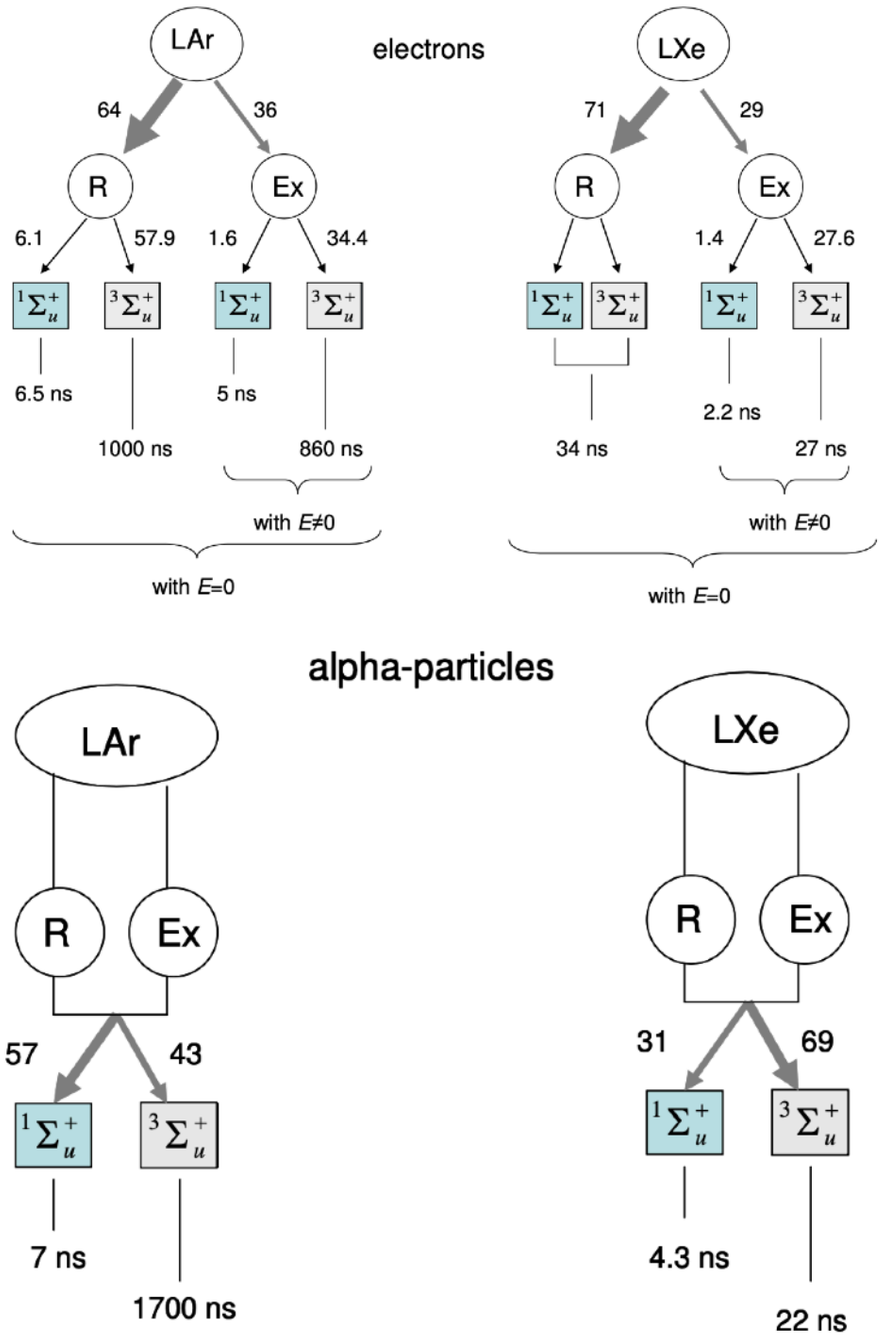
- We will thus use $W_{ph} = W$ (this assumes that each recombining electron-ion pair produces an exciton, which leads to a photon)

- 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 types of interactions (as we shall see later as well, in particular, liquid argon, due to the different time scales for the singlet and triplet states)
  - fast electrons (with energies [0.5-1] MeV): transitions from the singlet state to the direct excitation channel are only about 1.5% of the total number of emitted photons
    - LAr: the fast component is enhanced through the recombination channel resulting in about 8% of the total number of photons
    - LXe: the fast component for e^- only observed with an E-field (to suppress recombination)
  - α-particles: high LET, no difference in time decay constants between R and Ex; LET ~ 100 higher than for e^-, higher densities of ionized and excited species along the tracks, thus stronger and faster recombination

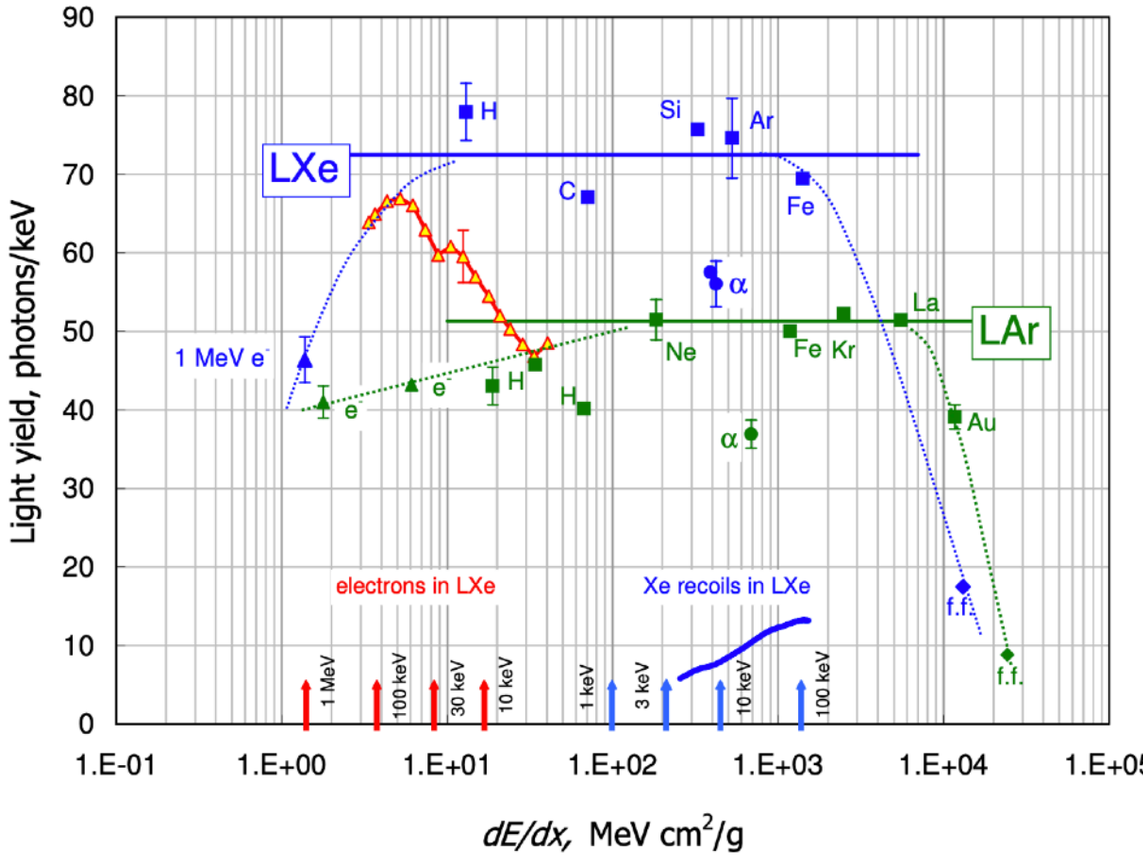


V. Chepel, H. Araujo, JINST 8, 2013

SCINTILLATION LIGHT YIELD IN ARGON AND XENON

- In the absence of electric field and for medium track density, practically all electron-hole pairs created initially recombine and give rise to recombination luminescence; the primary scintillation component of the signal is at its maximum, and the number of emitted photons is $N_{ph} \simeq N_i + N_{ex}$.
- For low density tracks, some electrons escape recombination even at zero field, and so $N_{ph} < N_i + N_{ex}$.
- For high density tracks, the luminescence signal is suppressed because of two effects
    1. The increasing contribution of the nuclear component called *nuclear quenching*
    2. a high probability of collision between excited species, leading to bi-excitonic quenching *(electronic quenching)*.

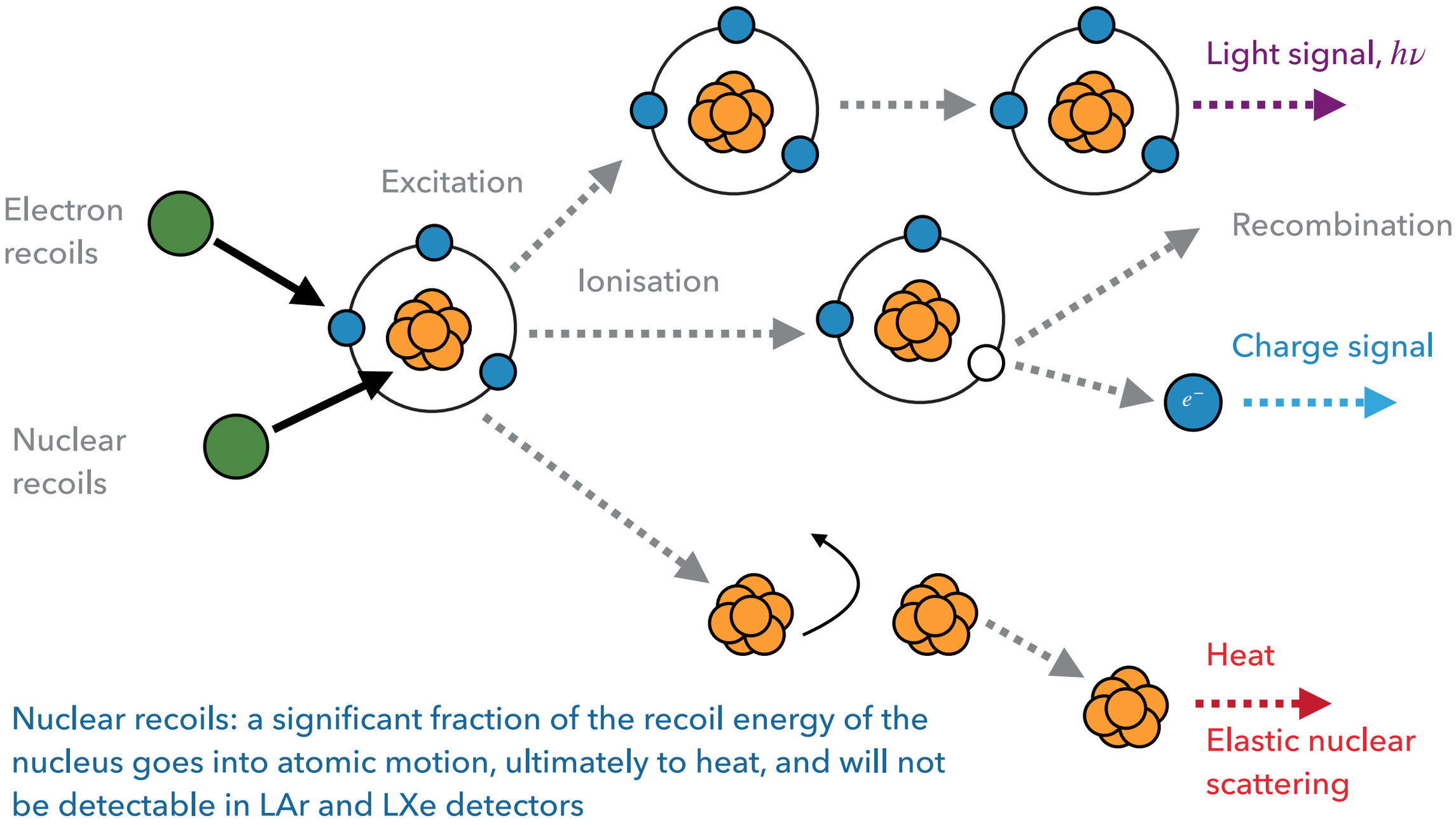
V. Chepel, H. Araujo, JINST 8, 2013



SIGNALS IN NL

QUENCHING

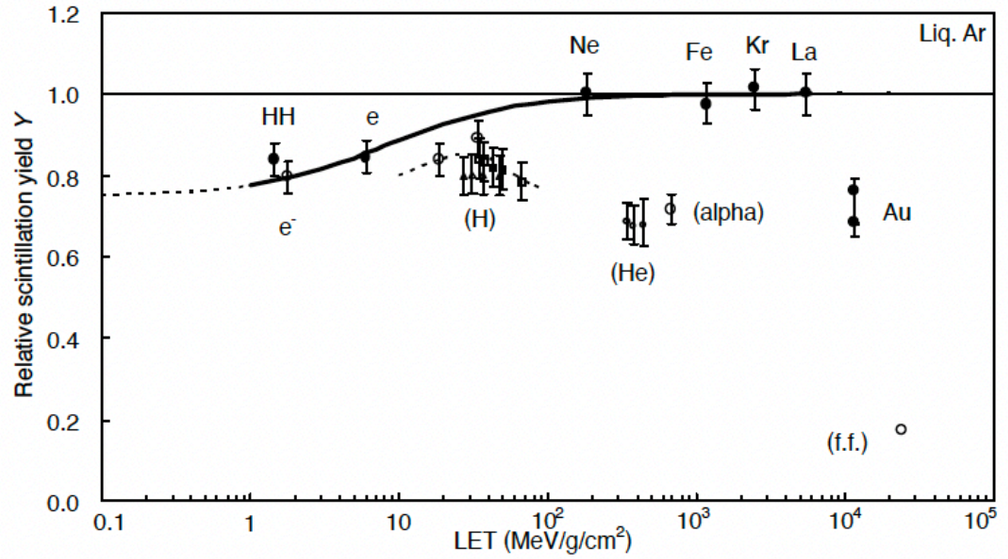
ELECTRONIC AND NUCLEAR RECOILS IN NOBLE LIQUIDS

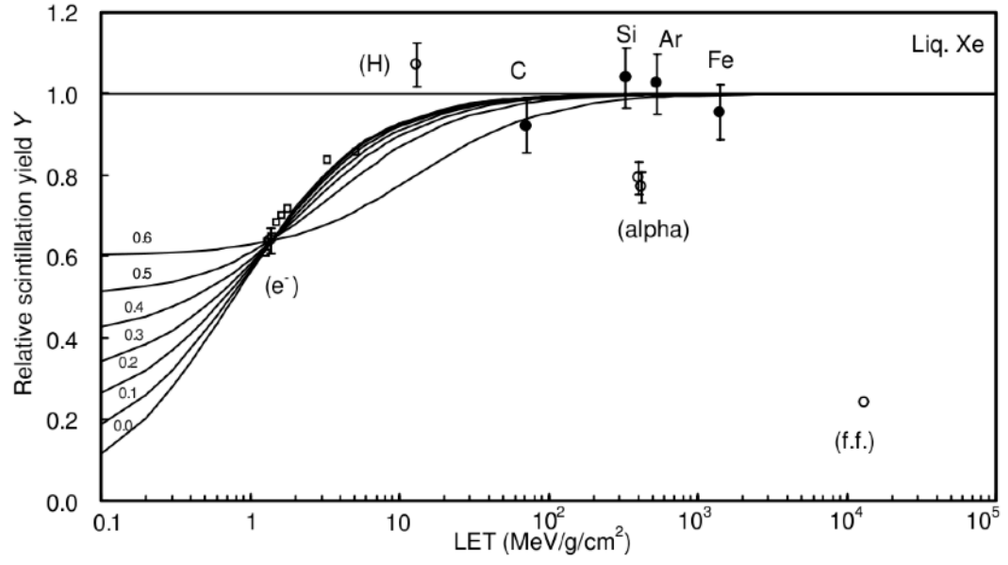


Nuclear recoils: a significant fraction of the recoil energy of the nucleus goes into atomic motion, ultimately to heat, and will not be detectable in LAr and LXe detectors

SCINTILLATION YIELD IN NOBLE LIQUIDS

- An energetic particle looses energy through:
  - Inelastic interactions with electrons in the medium (electronic stopping power $\eta(E)$)
  - Elastic collisions with nuclei (nuclear stopping power $\nu(E)$)
- 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 ($q_T = q_{nc}q_{el}$)





T. Doke at al., Jpn J. Appl. Phys, 2002, 41

THE LINDHARD FACTOR

- Lindhard computer the fraction of the initial recoil energy lost to electronic excitation, f_n

$$f_n = \frac{\eta(E_R)}{E_R} = \frac{\eta(E_R)}{\eta(E_R) + \nu(E_R)}$$

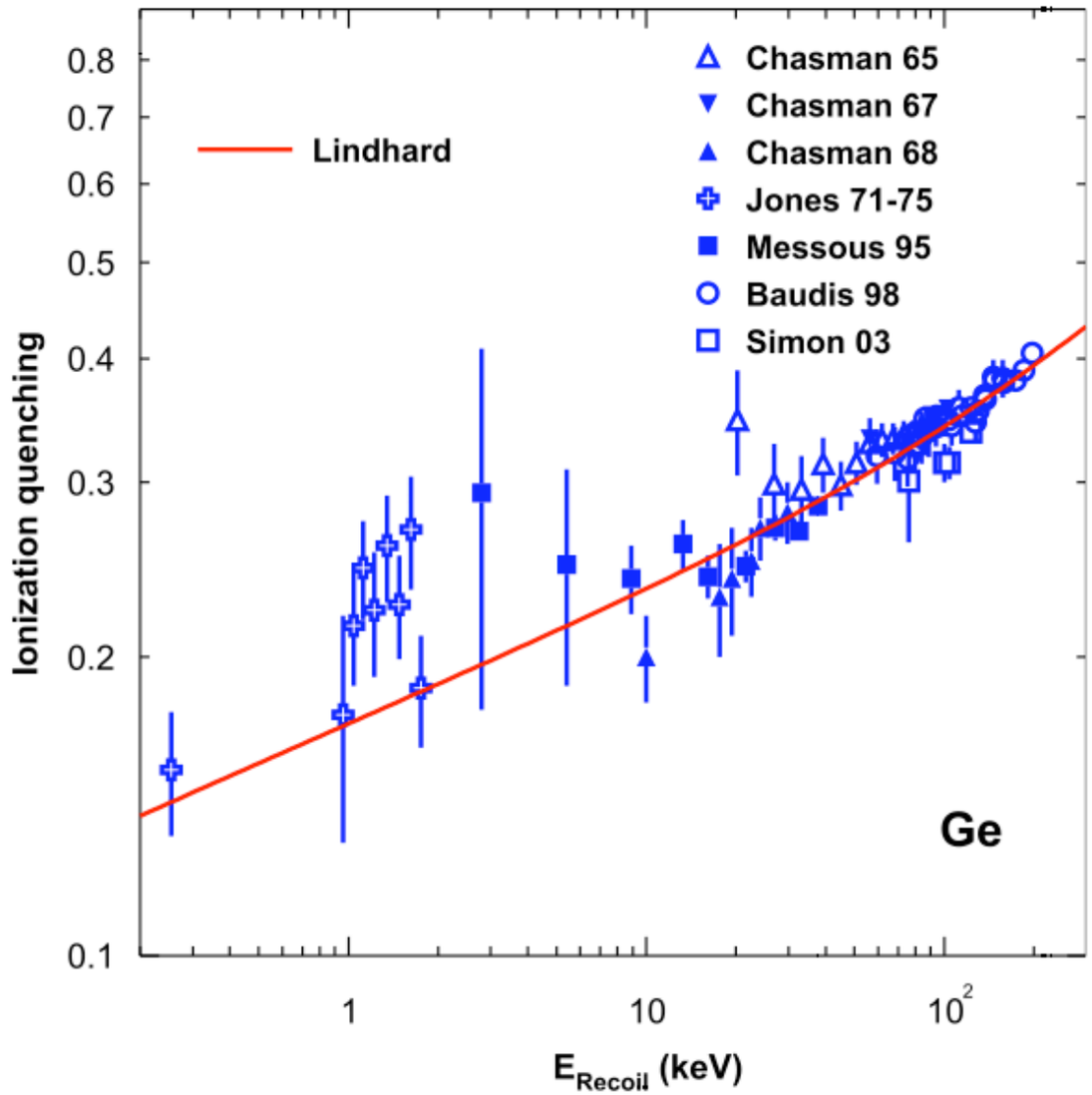
- His theory describes quite well the ionization signal in semiconductors:

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

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

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

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



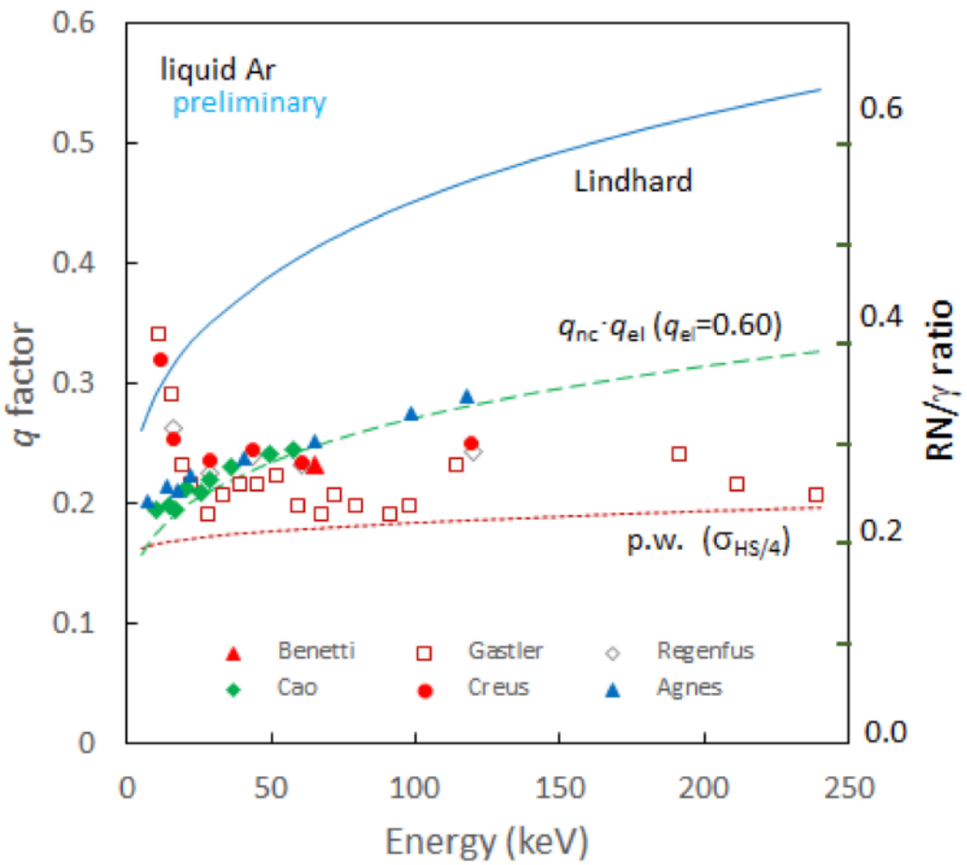
- ϵ: reduced energy = dimensionless deposited energy, with Z = atomic number of nucleus
- k: proportionality constant between the electronic stopping power dE/dx and the velocity of the projectile (which is the recoiling atom)
- $g(\epsilon)$: proportional to the ratio of electronic stopping power to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

THE LINDHARD FACTOR IN NOBLE LIQUIDS

- Historically, the measured values of the scintillation efficiency in noble liquid were considerably lower than the Lindhard prediction (k = 0.165 for Xe and k = 0.144 for Ar)

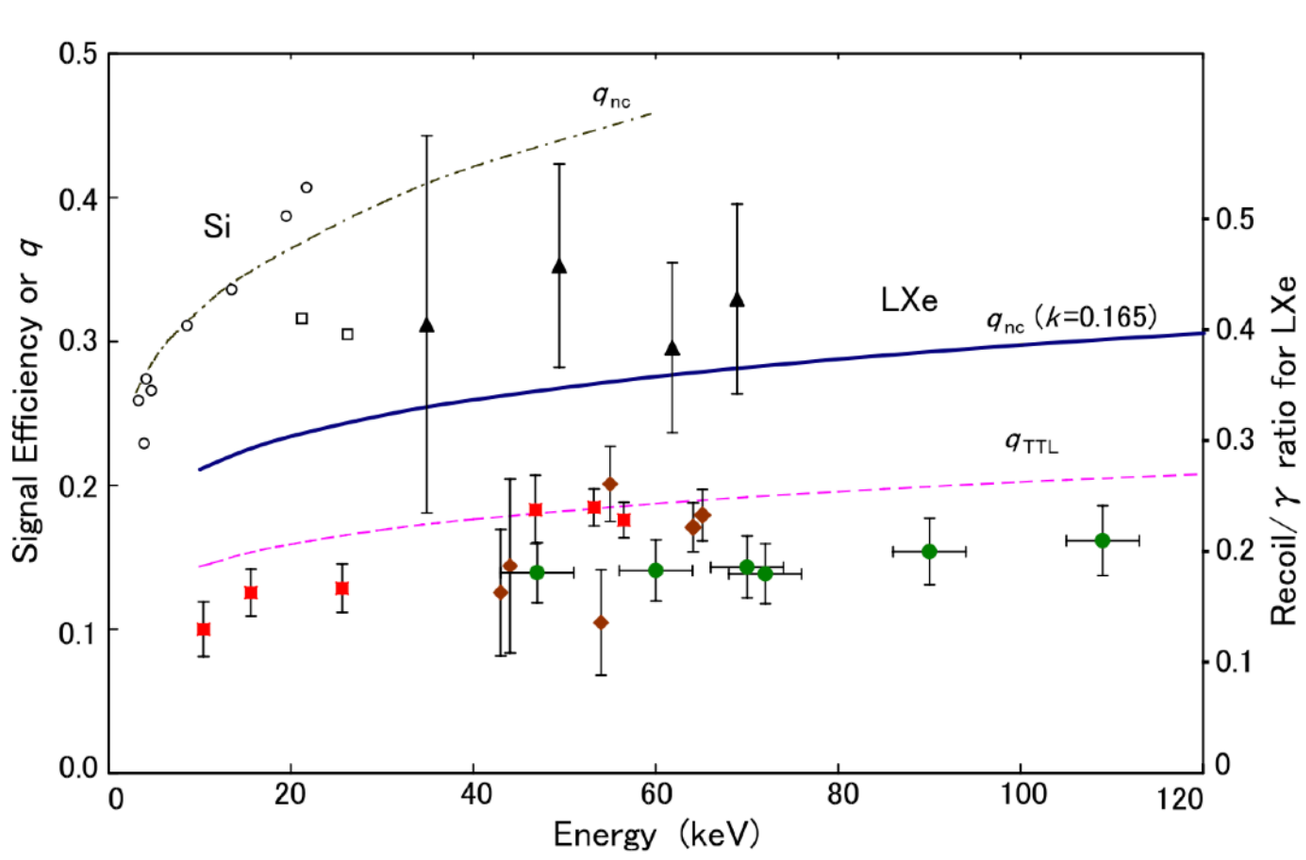
- It was believed that this may be due to electronic quenching and possibly to escape electrons

LIQUID ARGON



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

LIQUID XENON



A. Hitachi, Astropart. Phys. 24 247, (2005)

THE LINDHARD FACTOR IN NOBLE LIQUIDS

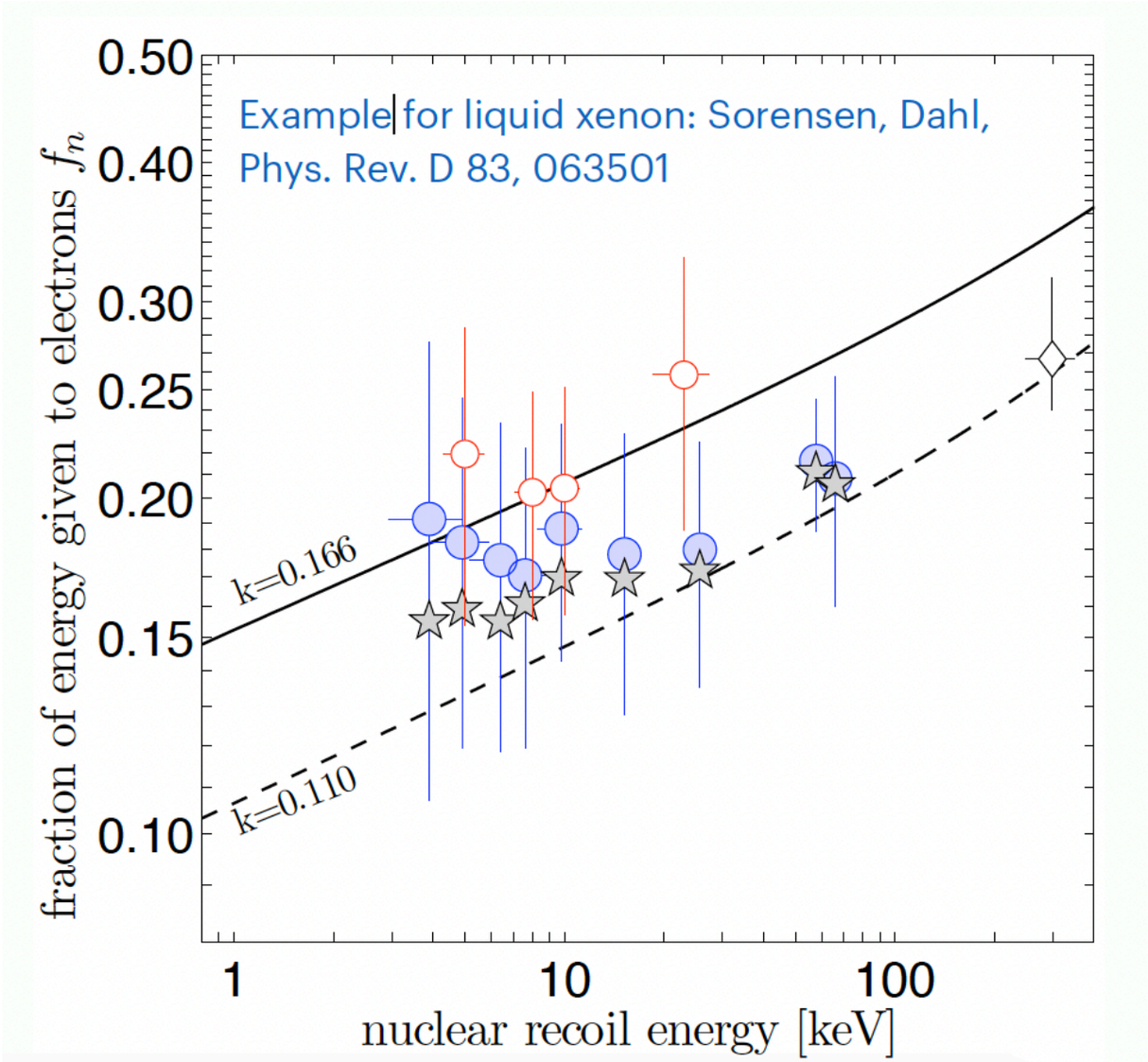
- Lindhard prediction works better if the nuclear recoil is reconstructed using both scintillation and ionization signals (hence the total quanta, for example in two-phase TPCs), the so called “combined energy scale”:

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

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

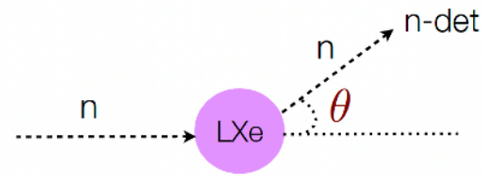
$$f_n = \frac{W \cdot (N_{ph} + N_q)}{E_{NR}}$$

- N_q is the number of primary electrons
- N_{ph} is the number of primary UV photons
- W is the average energy to produce an electron or a photon

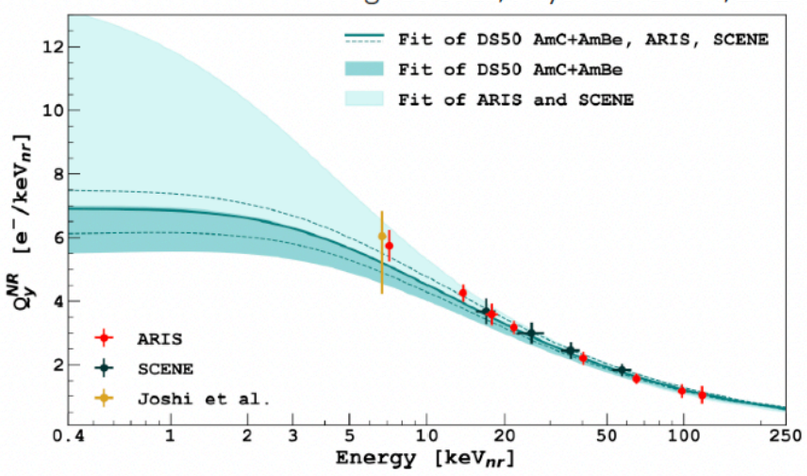


LIGHT AND CHARGE YIELDS OF NUCLEAR RECOILS

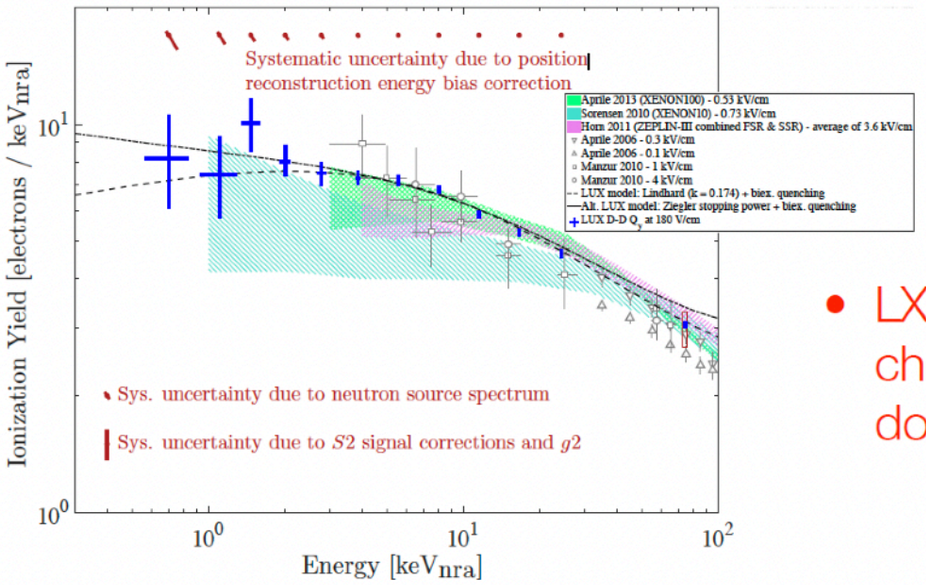
- Must be determined based on NR data, using two methods
- direct: observe mono-energetic neutrons scatters which are tagged with n-detectors
- indirect: measure energy spectra from calibration n-sources, compare with MC predictions



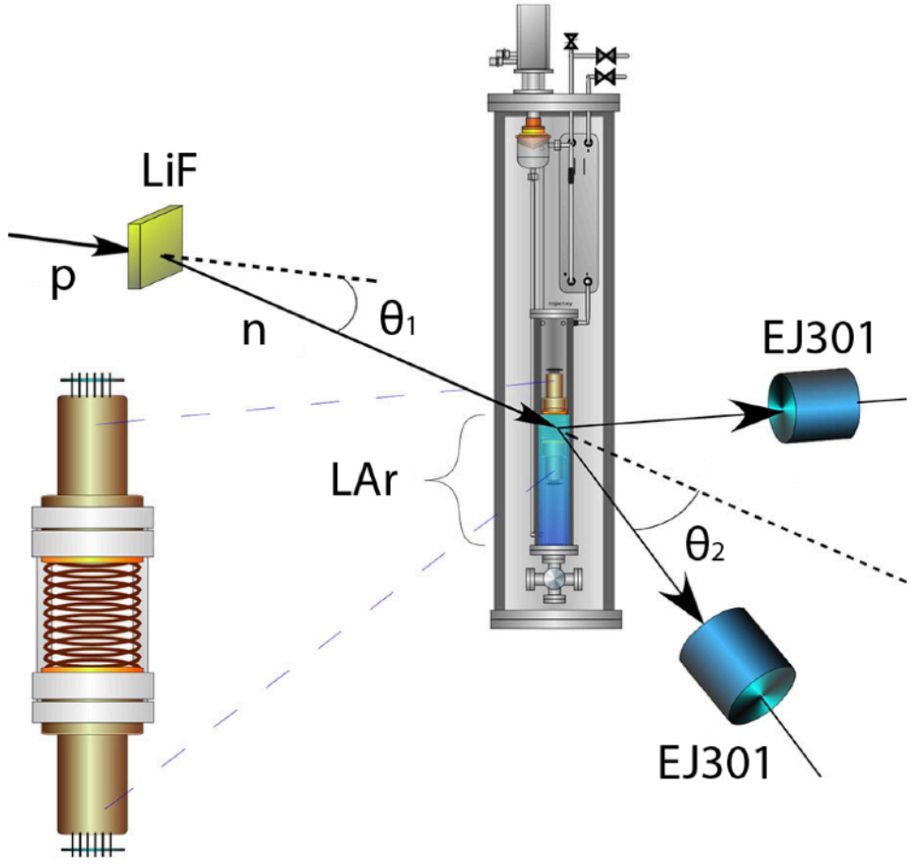
P. Agnes et al., Phys. Rev. D 104, 2021



- LAr: charge yield measured down to ~ 0.5 keV$_{NR}$ (≡ 3 ionisation electrons)



- LXe: here data from LUX; charge yield measured down to 0.7 keV$_{NR}$



SCENE collaboration, PRD 91, 2015

SIGNALS IN NL

NOBLE ELEMENT SIMULATION TECHNIQUE

LIGHT AND CHARGE YIELDS FROM NEST

- NEST (Noble Element Simulation Technique): a MC framework that allows for simulation of scintillation and ionization-yield averages
  - based on semi-empirical models, as a function of incoming or deposited energy, electric field, interaction type (electronic and nuclear recoils, α-particles)
  - calculates average light and charge yields, recombination and simulates actual energy deposits in a. Detector
  - models are validated against real data and updated when new data becomes available
- Primary code in C++, bindings available to use in Python; available for xenon and argon

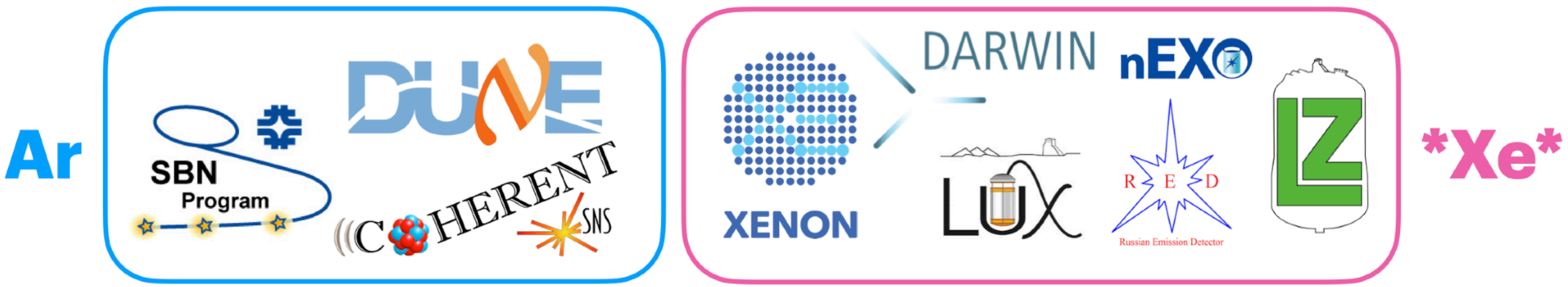
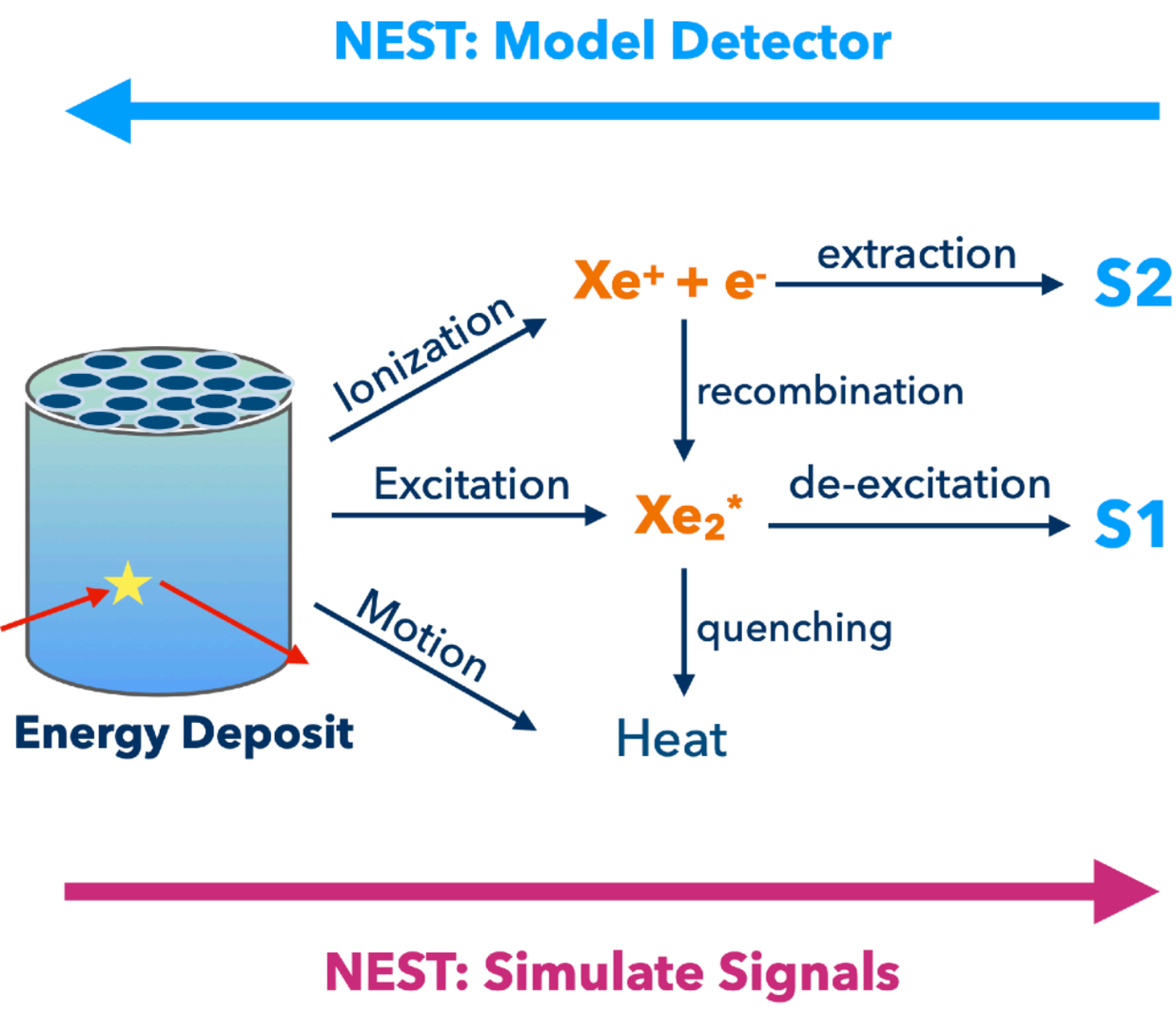


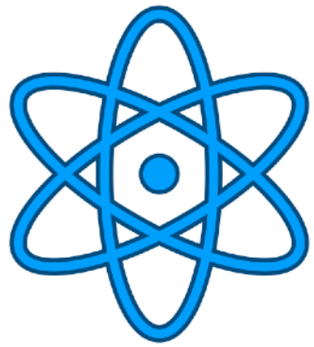
Figure by Sophia Andaloro

https://nest.physics.ucdavis.edu

LIGHT AND CHARGE YIELDS FROM NEST



Macroscopic



Microscopic

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

Figures by Sophia Andaloro, APS meeting April 2021

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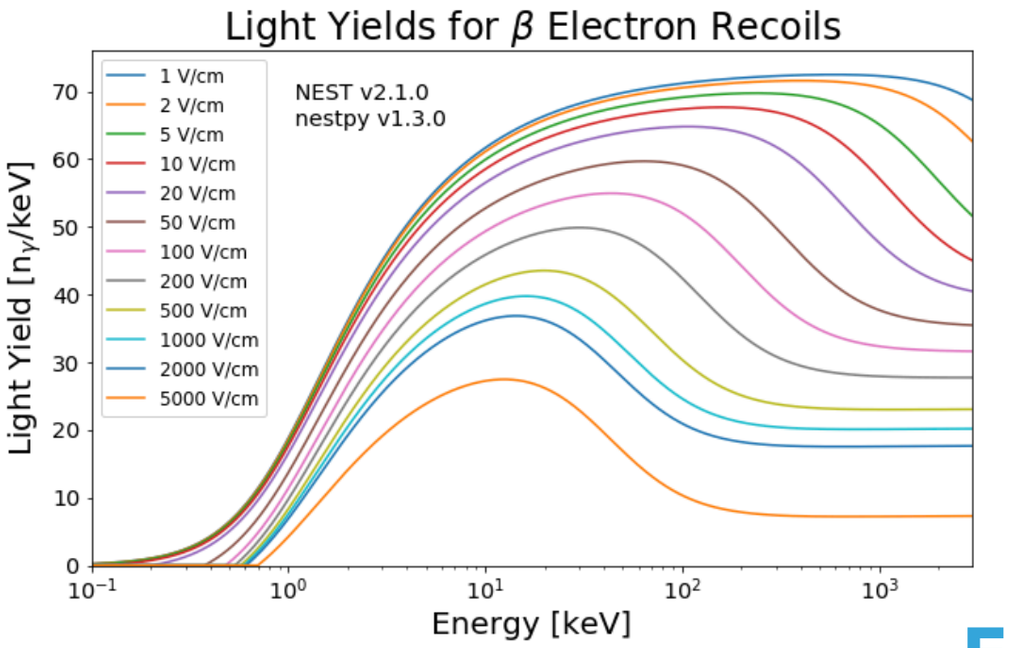
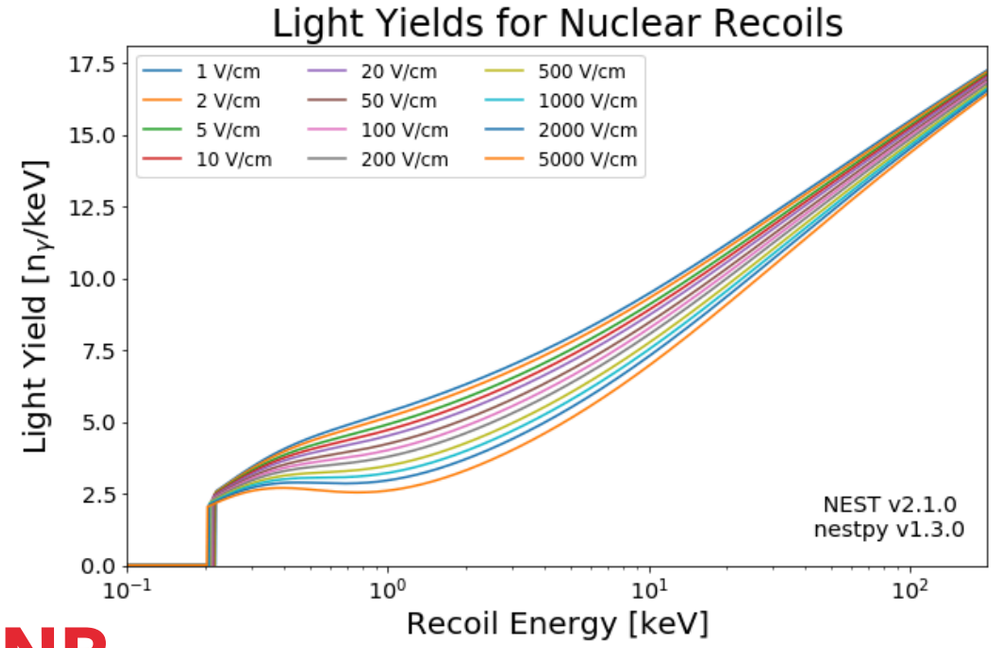
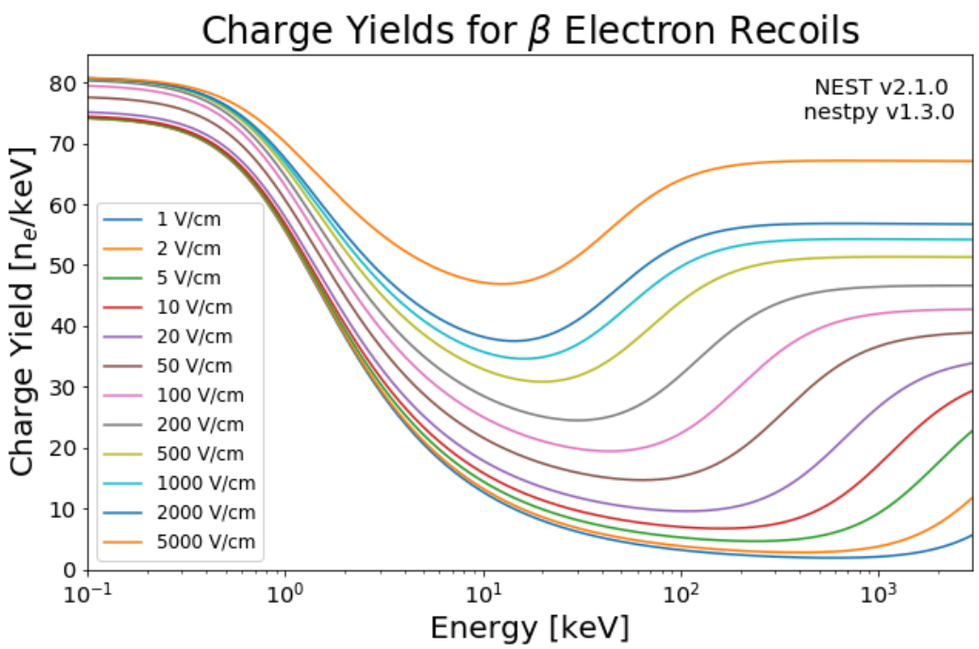
LIGHT AND CHARGE YIELDS FROM NEST: XENON



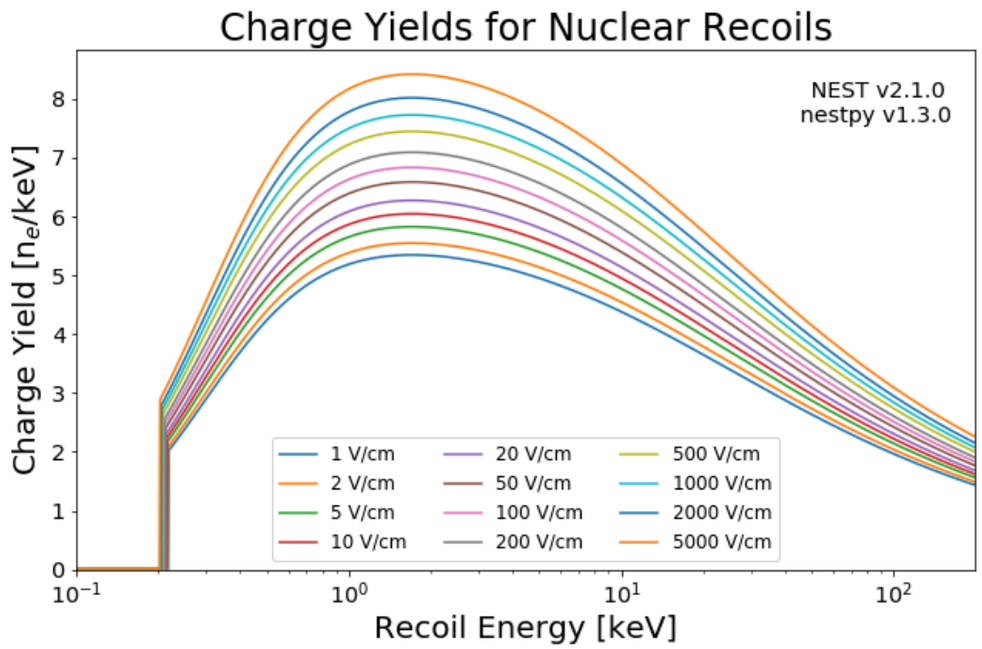
Light yield



ER **NR**



Charge yield



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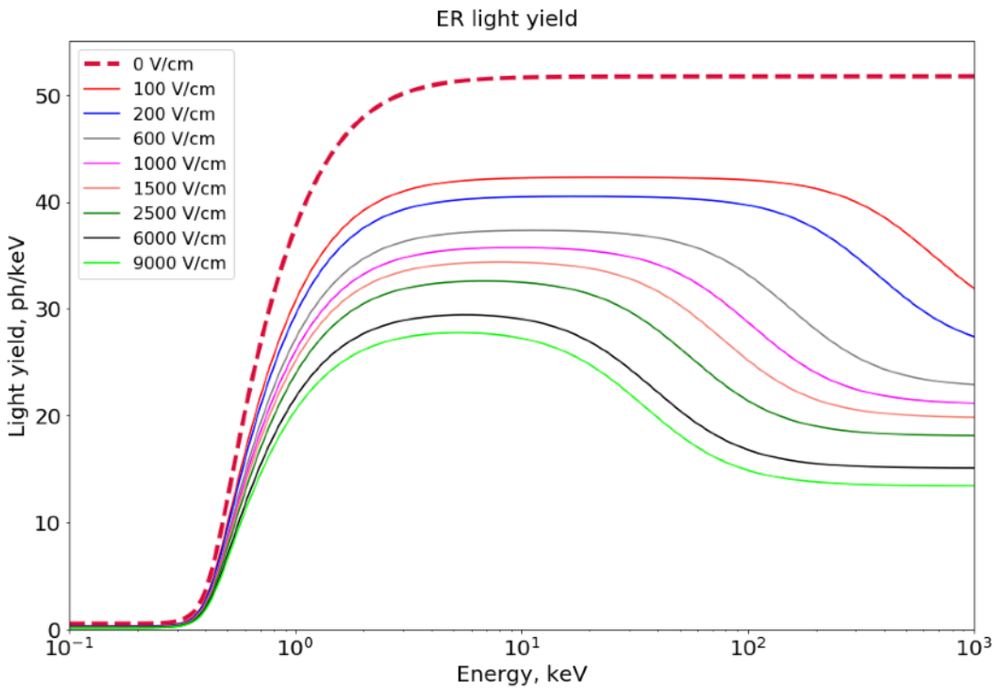
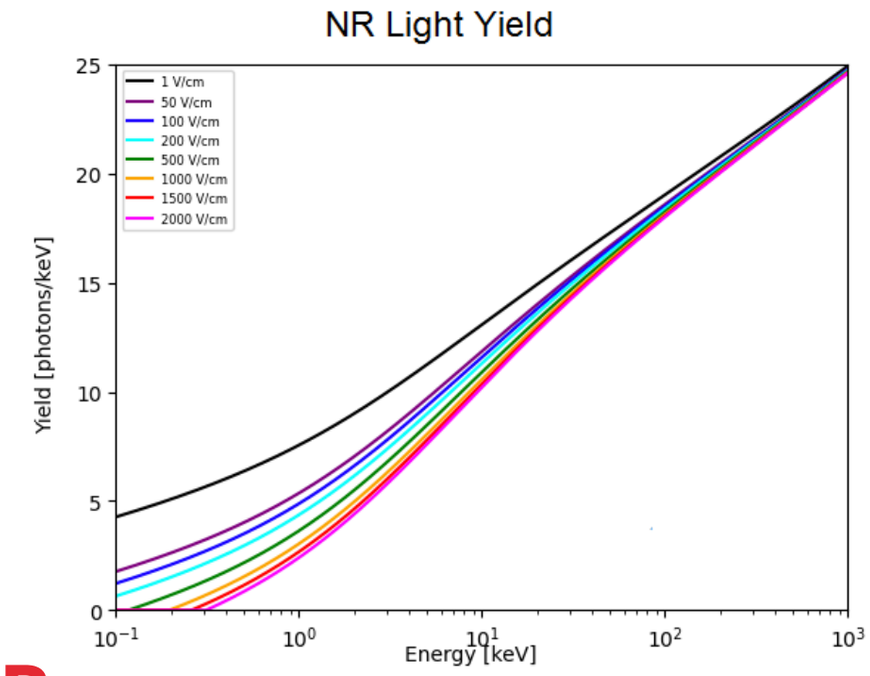
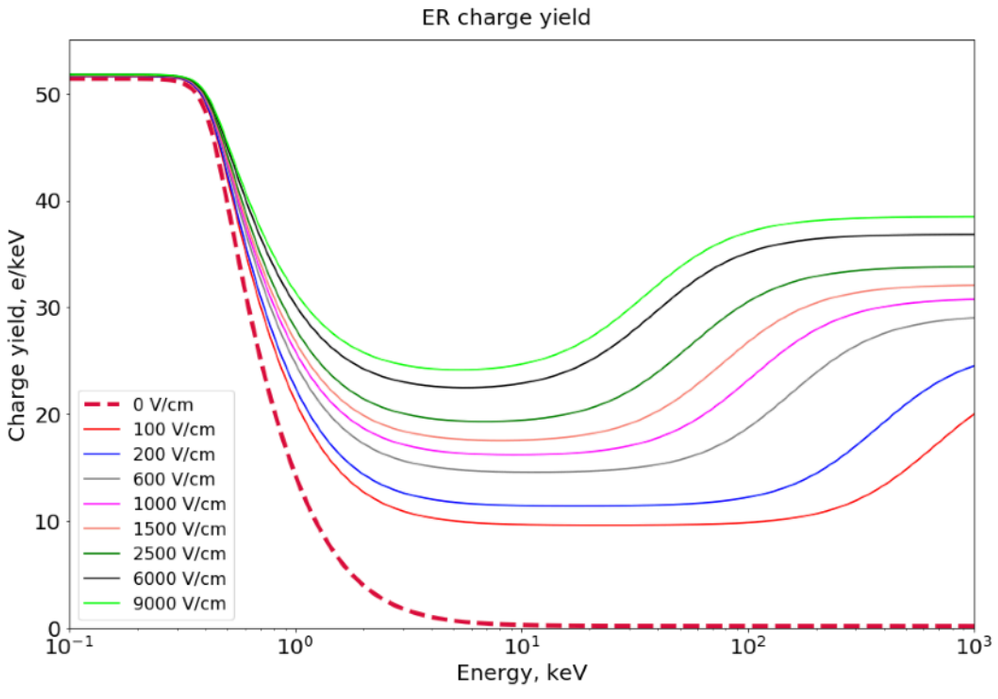
LIGHT AND CHARGE YIELDS FROM NEST: ARGON



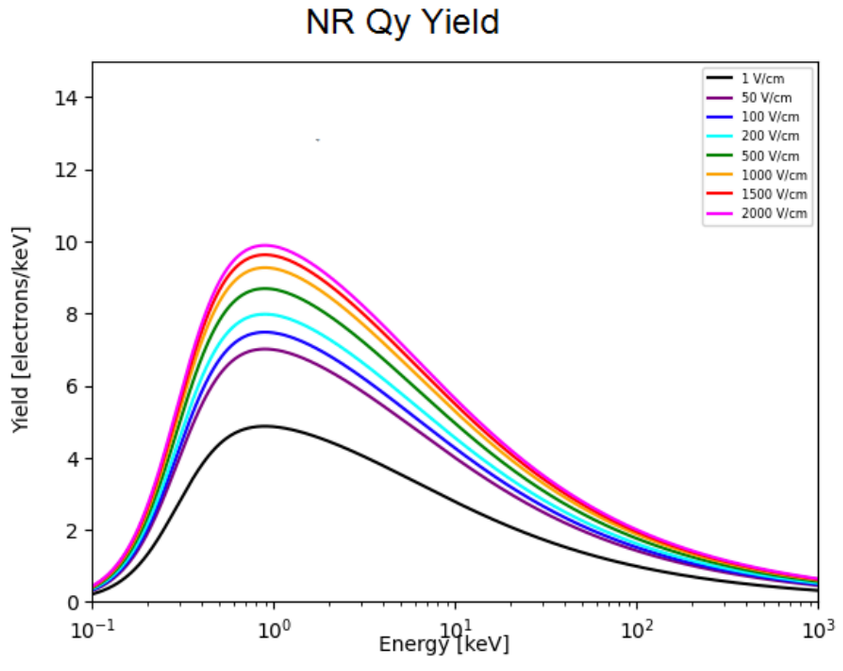
Light yield



ER **NR**



Charge yield



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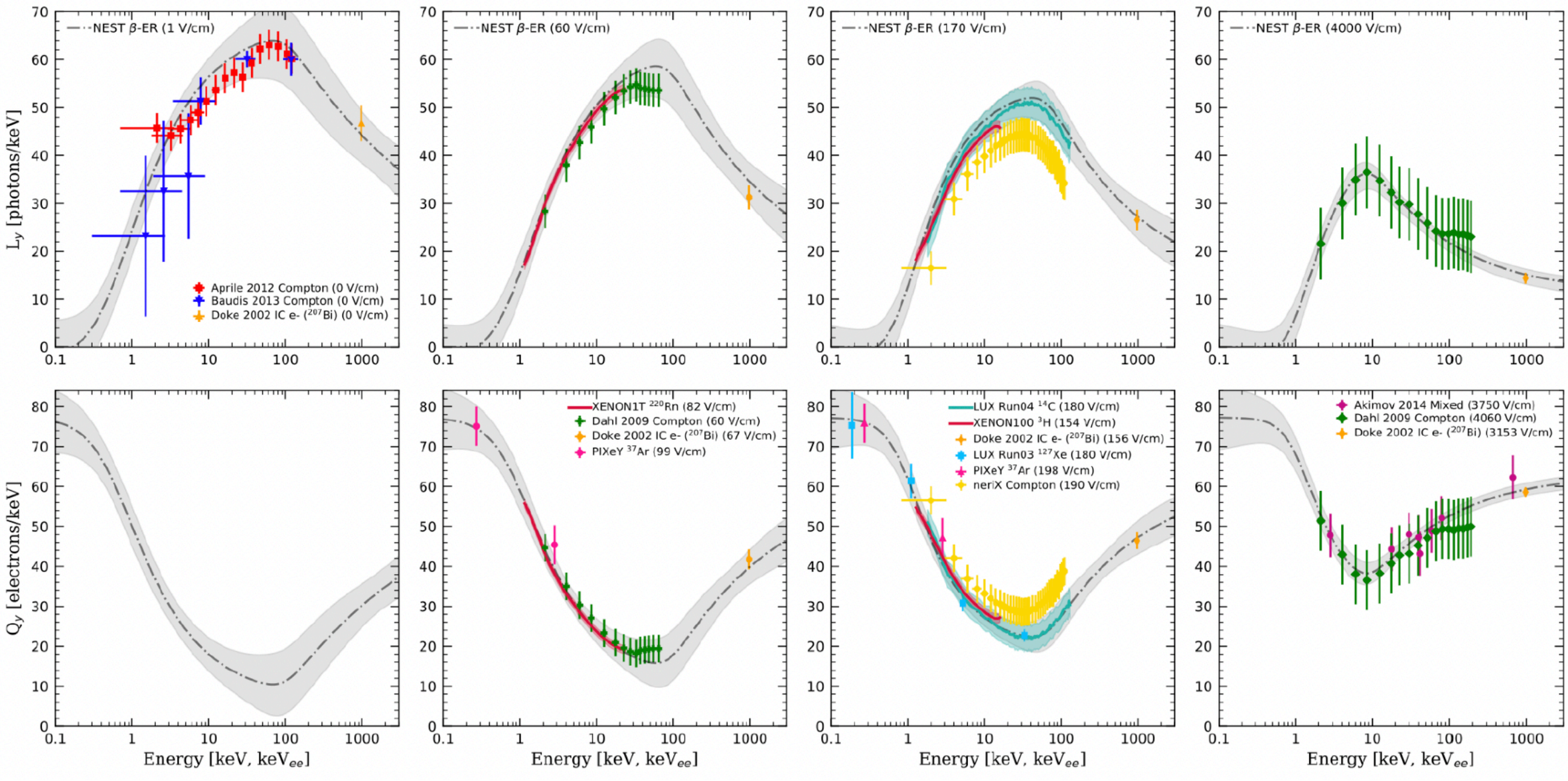
LY AND QY FROM NEST AGAINST DATA: XENON ER β

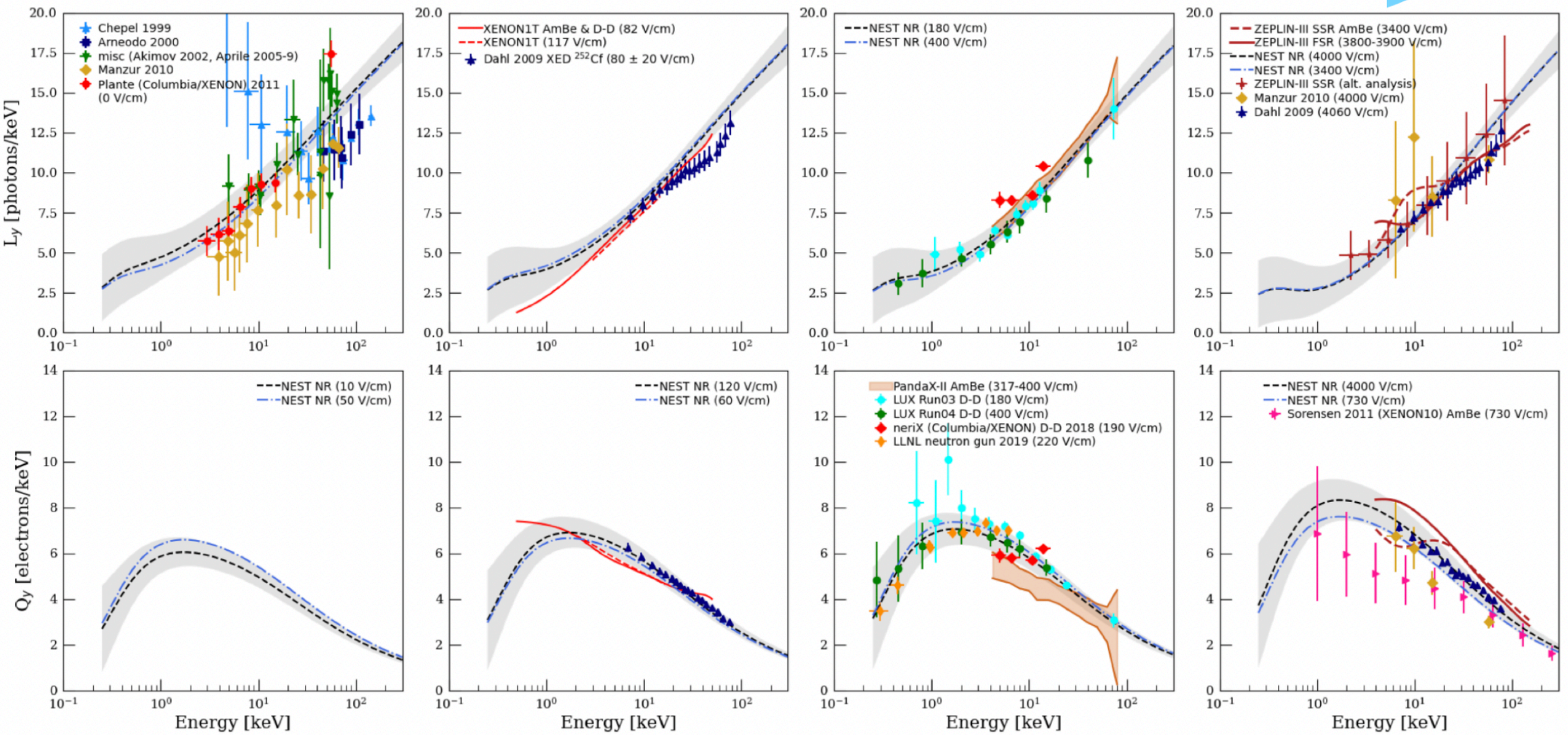
lower drift fields → higher drift fields



arXiv:2211.10726

LY AND QY FROM NEST AGAINST DATA: XENON NR

lower drift fields → higher drift fields



arXiv:2211.10726

SUMMARY LIGHT AND CHARGE YIELDS IN XENON

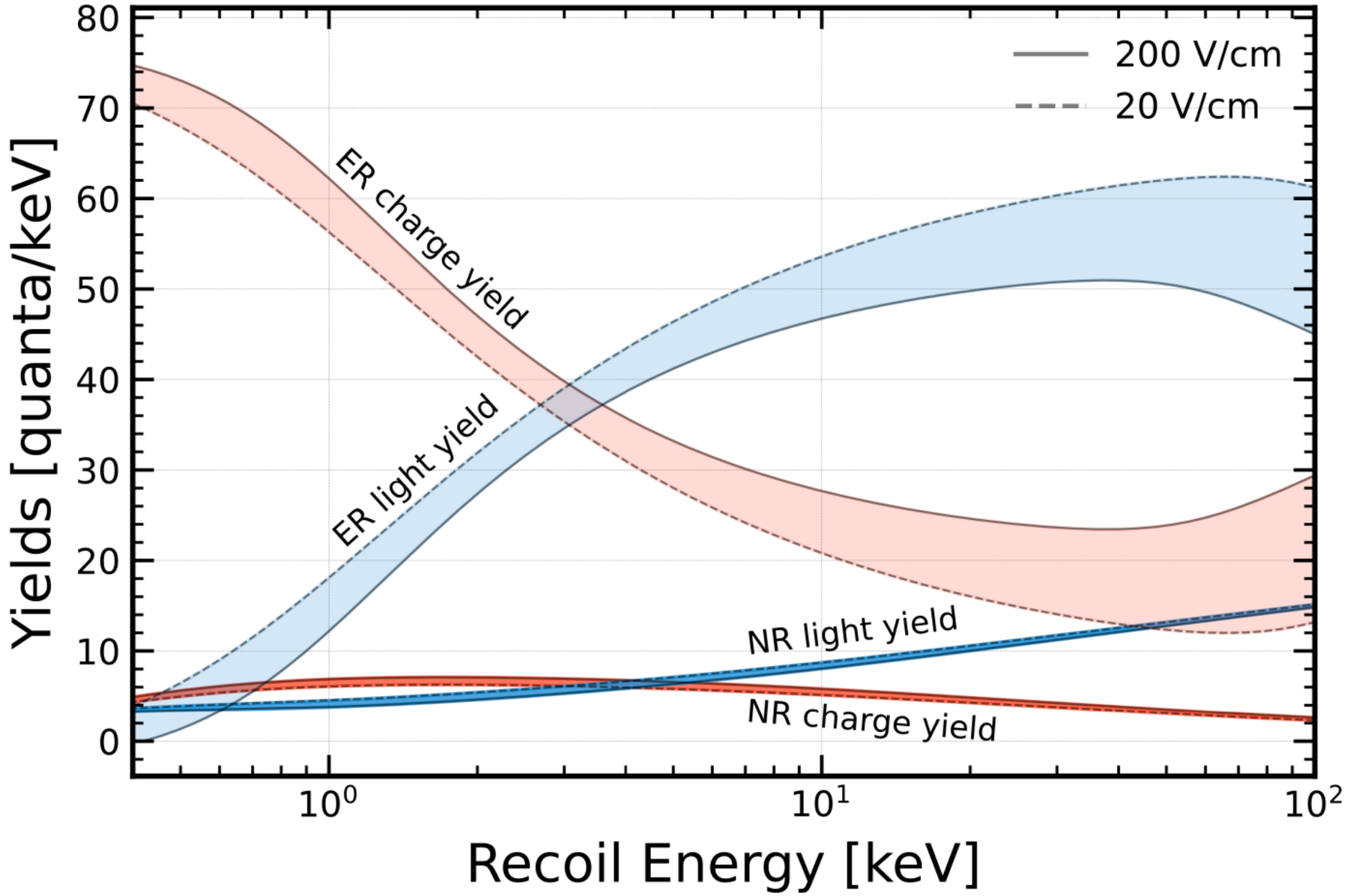
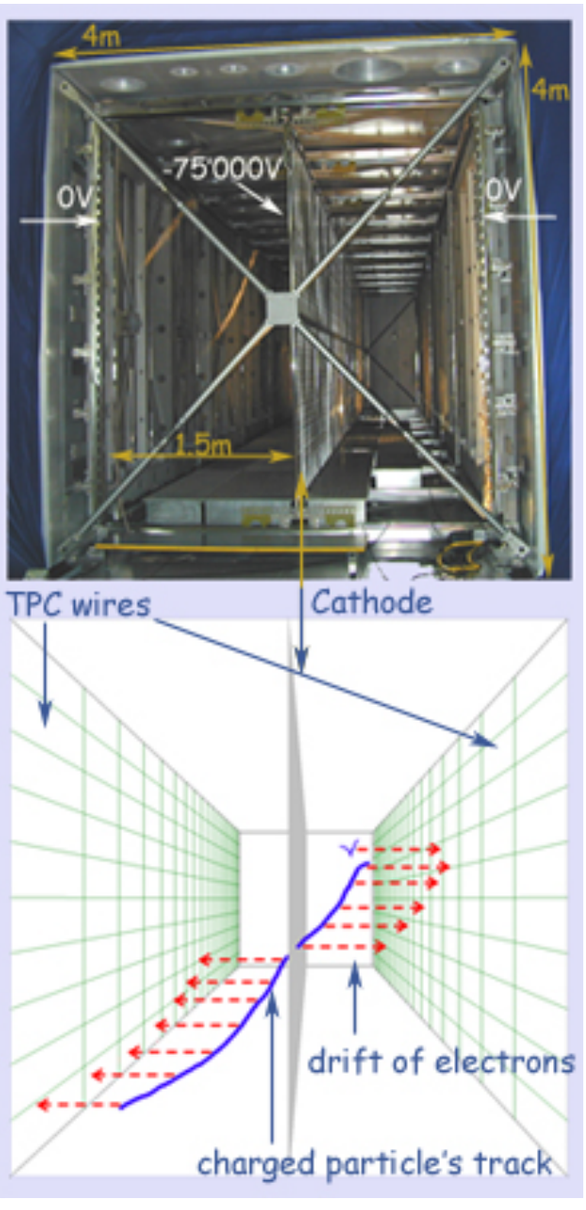


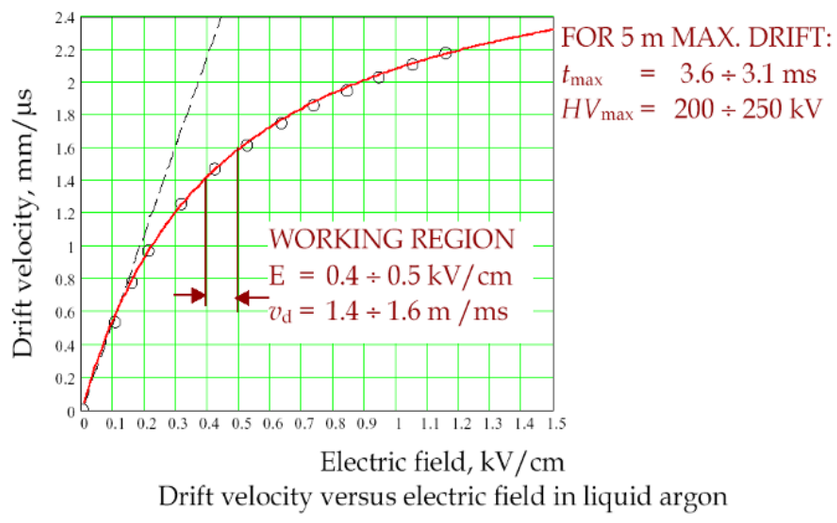
Figure by G. Volta with NEST

SIGNALS IN NL

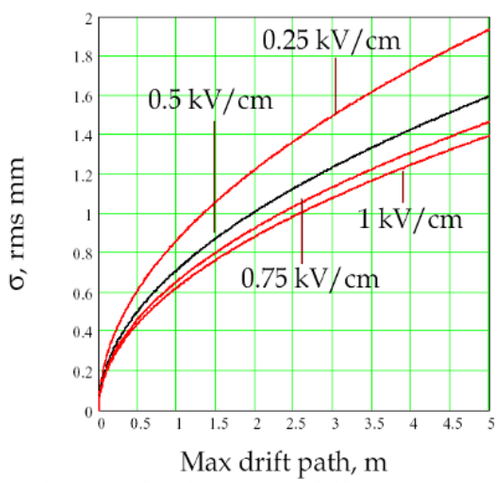
ELECTRON DRIFT

ELECTRON DRIFT PROPERTIES IN LIQUID ARGON





Drift velocity versus electric field in liquid argon



Longitudinal rms diffusion spread versus drift paths at different electric field intensities

$$\sigma_D = \sqrt{2 \cdot D \cdot \frac{x}{v_d}}$$

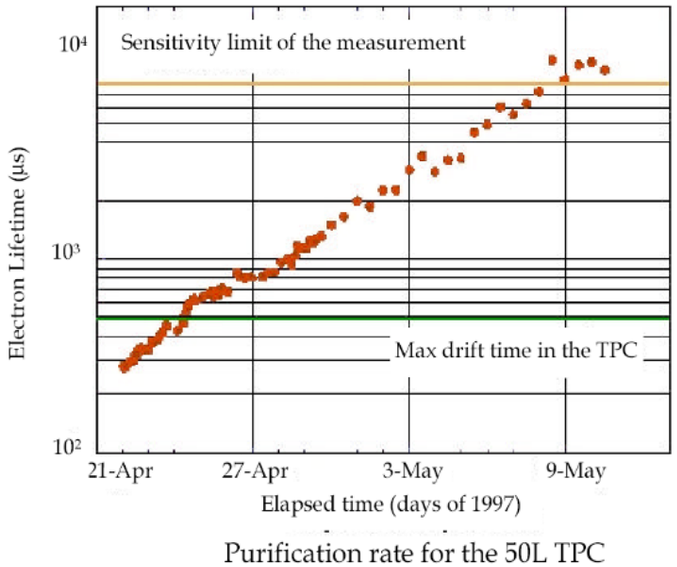
$D = 4.06\ \text{cm}^2/\text{s}$

$\sigma_D = 0.9\ \text{mm} \cdot \sqrt{T_D[\text{ms}]}$

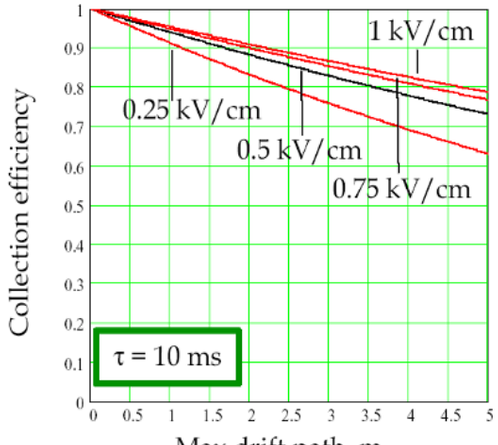
Longitudinal rms diffusion spread at 0.5 kV/cm

Average $\langle\sigma_D\rangle$ = 1.1 mm

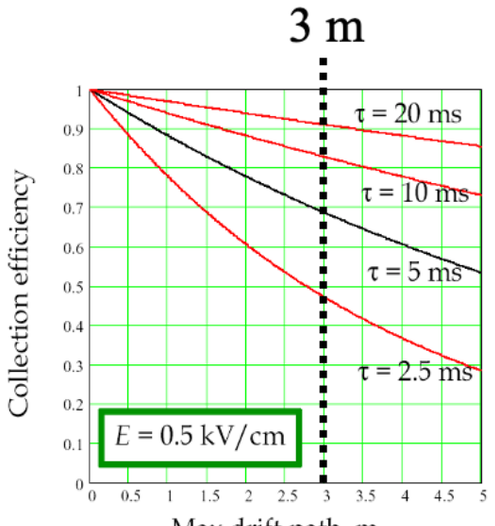
Maximum σ_{Dmax} = 1.6 mm



Purification rate for the 50L TPC



Drifting charge attenuation versus drift paths at different electric field intensities (τ = 10 ms)



Drifting charge attenuation versus drift path at different electron lifetimes (E = 0.5 kV/cm)

SIGNALS IN NL

PURITY

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 electron 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_{O_2} is used as benchmark (O_2 usually the dominant contributor)

- The O_2- equivalent model fraction (x_{O_2}) is expressed in pub (part per billion)

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

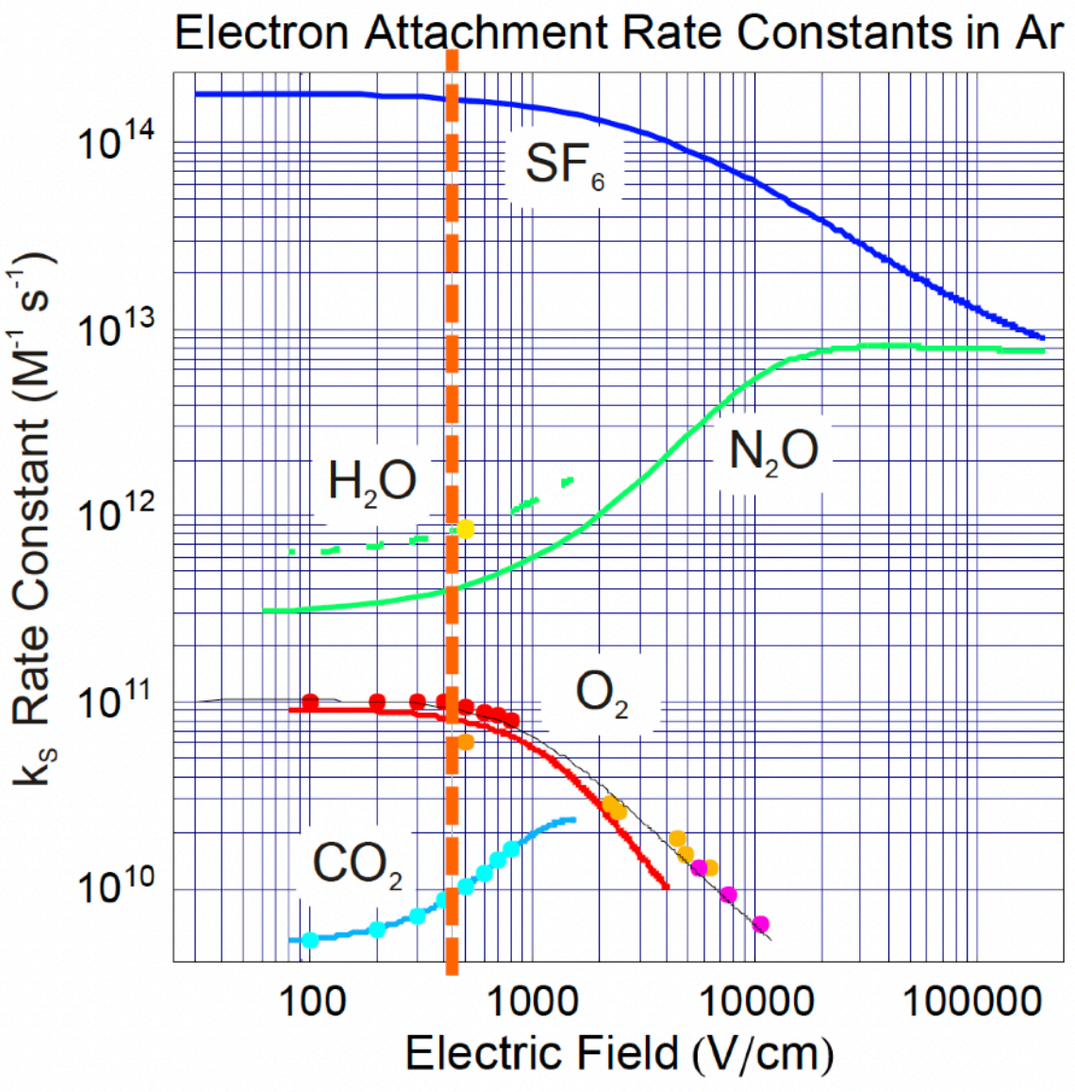
  - Where ρ is the density of the noble liquid and M the molar mass. The constant of electron attachment k_{O_2} depends on the drift field (it decreases with increasing field), and it is given in [$ppb^{-1}\mu s^{-1}$]

ELECTRON ATTACHMENT AND LIGHT ABSORPTION

To achieve a high collection efficiency for both ionization 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 vapor
- The ionization 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)

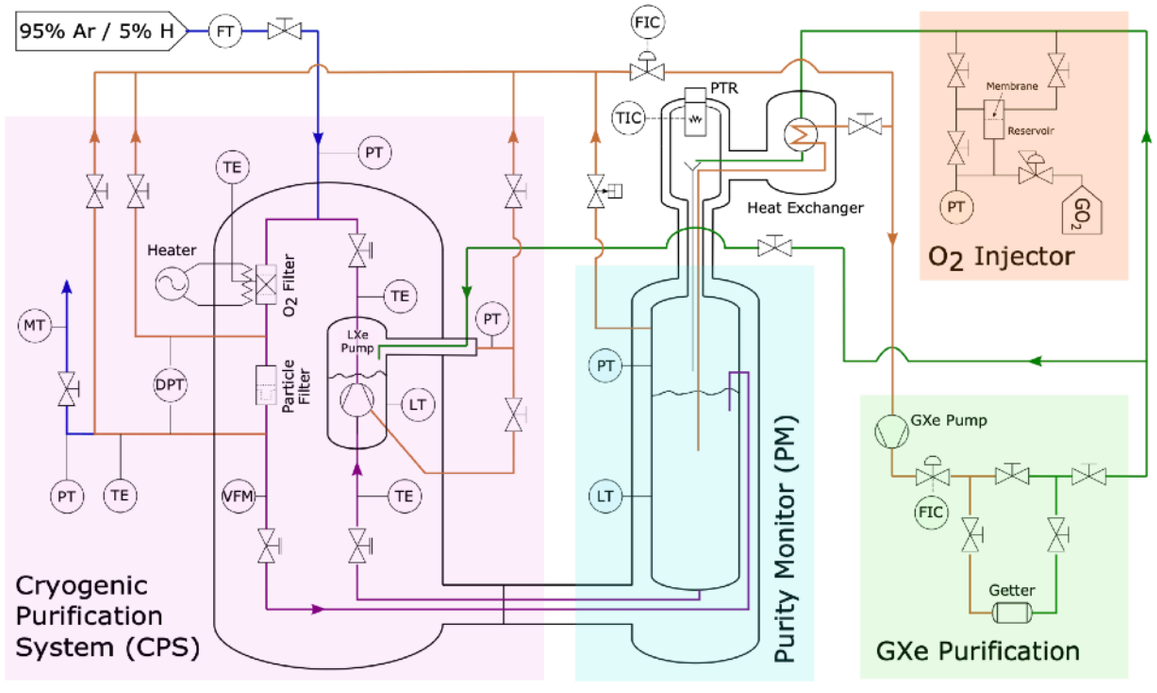
Attenuation lengths of ~1 m for electrons and photons were already achieved > 1m and are necessary for multiton-scale experiments



33. G. Bakale, U. Sowada, and W.F. Schmidt, *Effect of electric field on electron attachment to SF_6, N_2O, and O_2 in liquid argon and xenon*, J. Phys. Chem. **80** (1976) 2556.
34. A. Bettini, *et al.*, *A study of the factors affecting the electron lifetime in ultra pure liquid argon*, NIM **A305** (1991) 177.
35. E. Aprile, K.L. Giboni, and C. Rubbia, *A study of ionization electrons drifting large distances in liquid and solid argon*, NIM **A241** (1985) 62.
36. M. Adams, *et al.*, *A purity monitoring system for liquid argon calorimeters*, NIM **A545** (2005) 613.

THE ELECTRON DRIFT LIFETIME IN NOBLE LIQUIDS

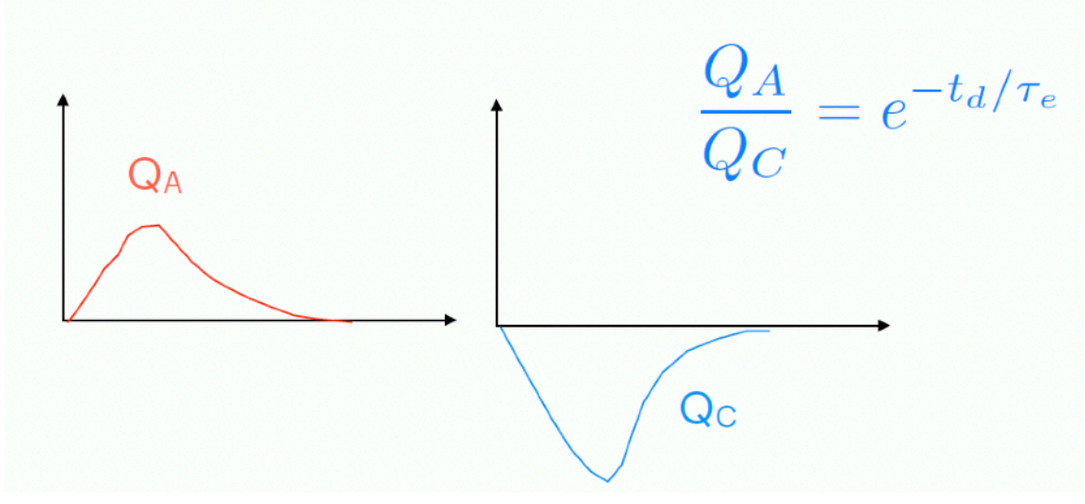
- In general, electronegative impurities in noble liquids increases over time due to the continuous description from materials
- To achieve very low concentration and high electron lifetimes, continuous removal of impurities is required
  - By gas purification through high-temperature (400°C) zirconium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

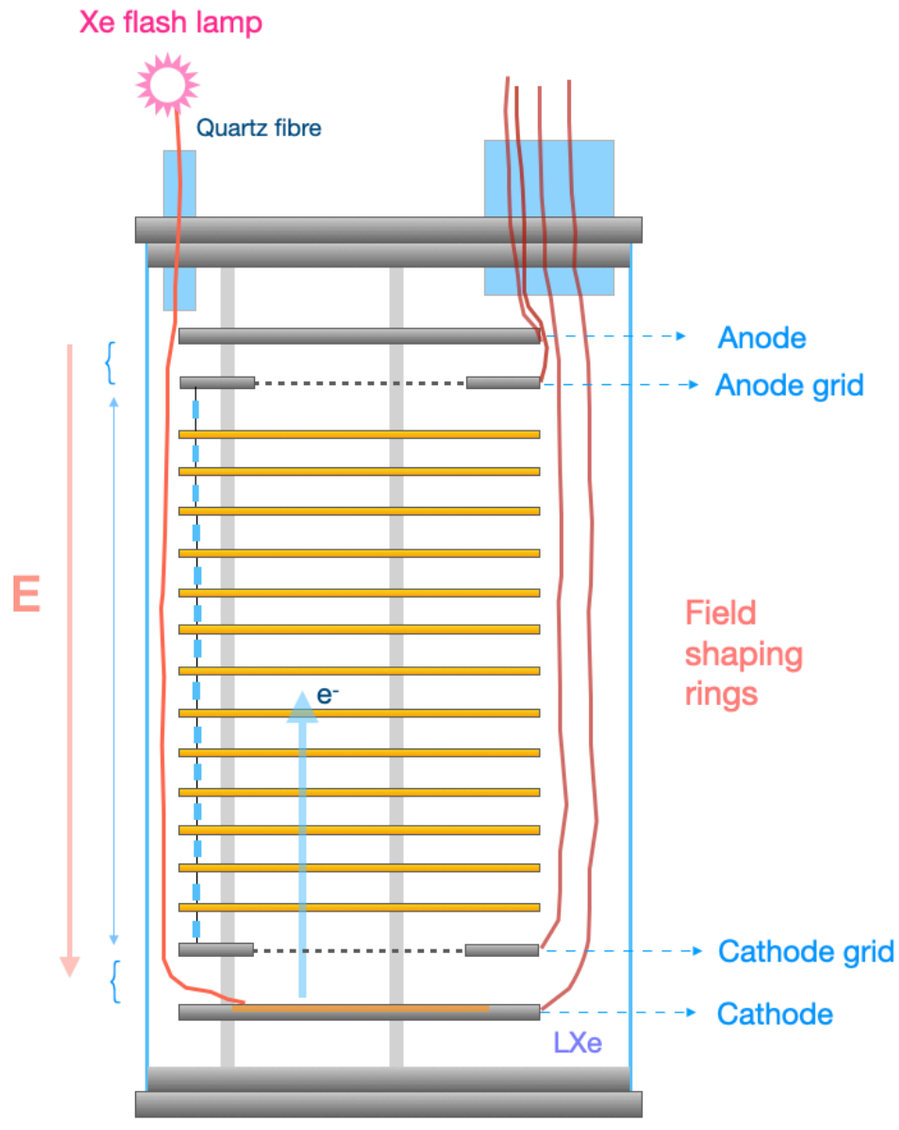


Example: Xeclipse, a xenon purification system at Columbia University (demonstrator for XENONnT at LNGS), Plante, Aprile, Howlett, Zhang, arXiv:2205.07336

HOW TO MEASURE THE ELECTRON DRIFT LIFETIME

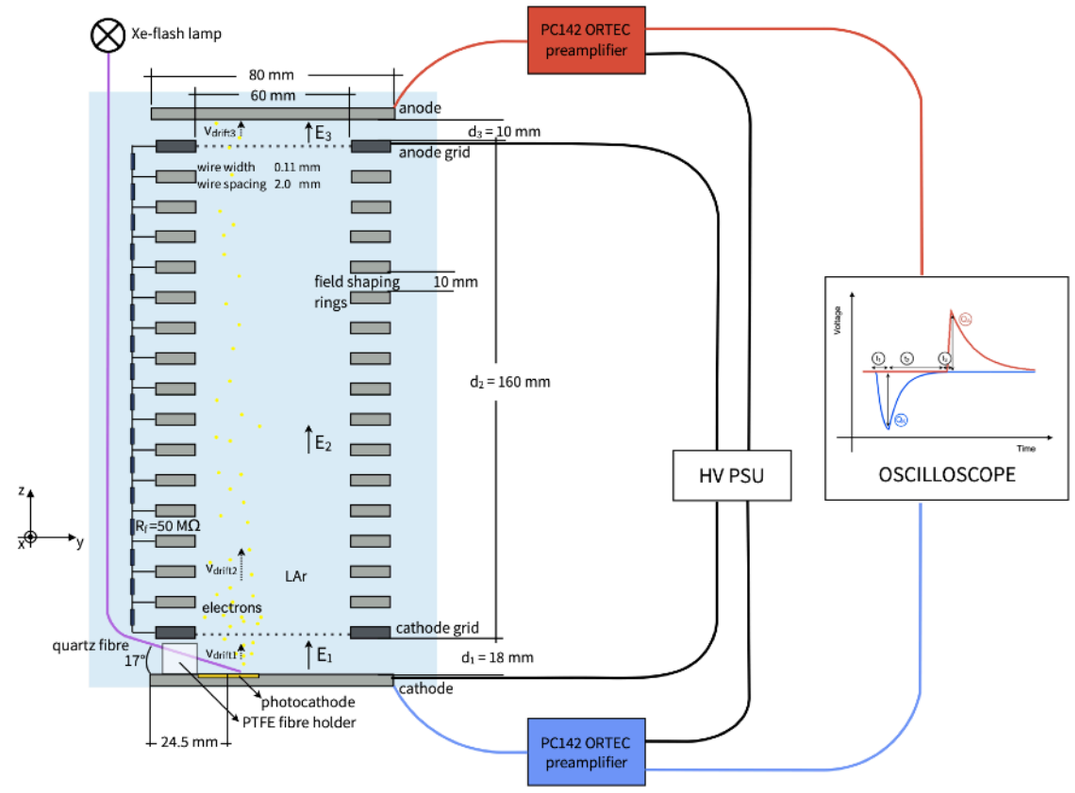
- The electron lifetime τ_e is usually measured with purity monitors.
- The concept:
  - Release a cloud of electrons, drift the cloud a fixed distance through uniform electric field
  - Measure the size of the cloud at the beginning and at the end via the induced current on a cathode and anode as the 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



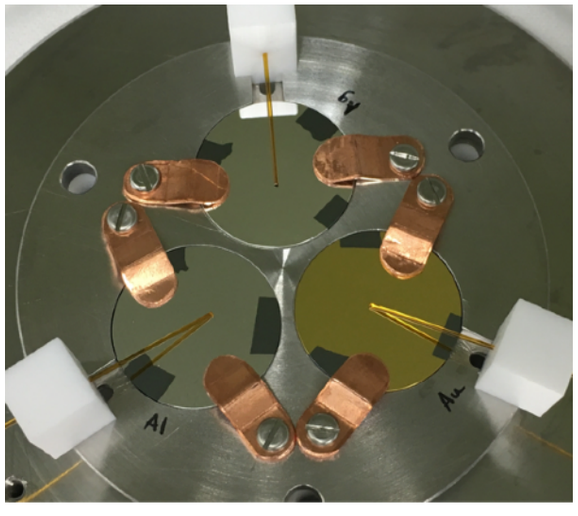


EXAMPLE: A PURITY MONITOR FOR LIQUID ARGON

- 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 signals: $\propto$ electron lifetime τ_e

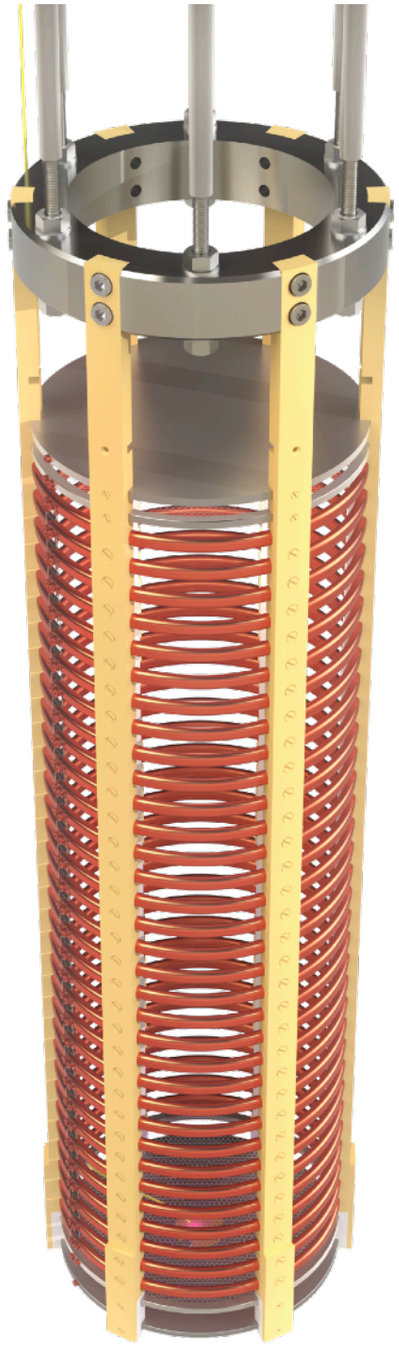


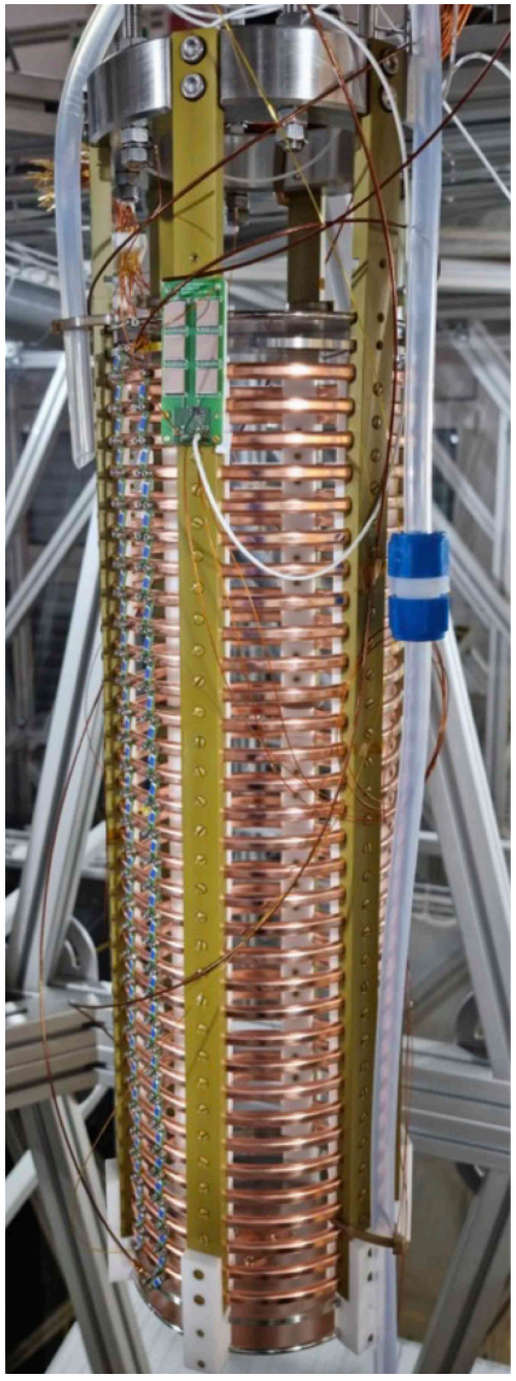
L. Manenti et al., JINST 15, 2020

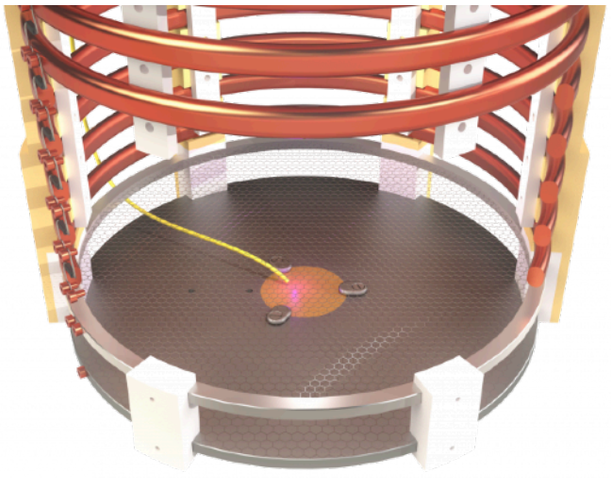


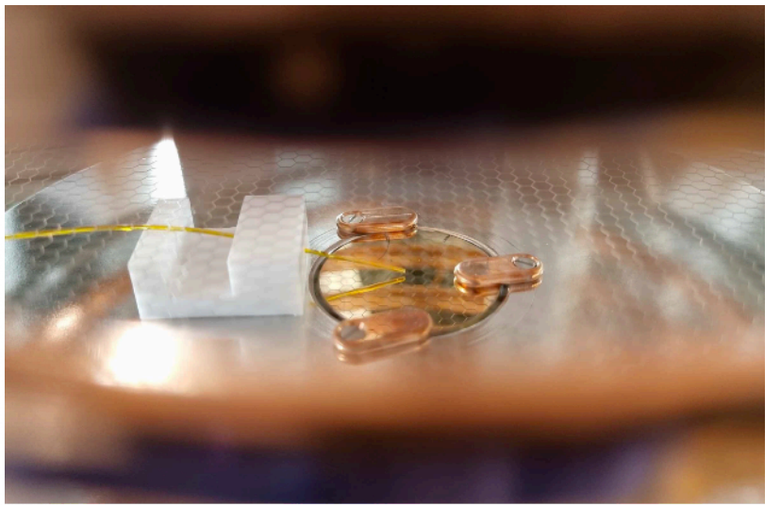
EXAMPLE: A PURITY MONITOR FOR LIQUID XENON

- Drift length: 525 mm
- Electron cloud: produced form in-house made, thin film Ag photocathode (on quartz substrate) via pulsed xenon flash lamp (Hamamatsu L7865)
- 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 signal: $\propto$ electron lifetime τ_e







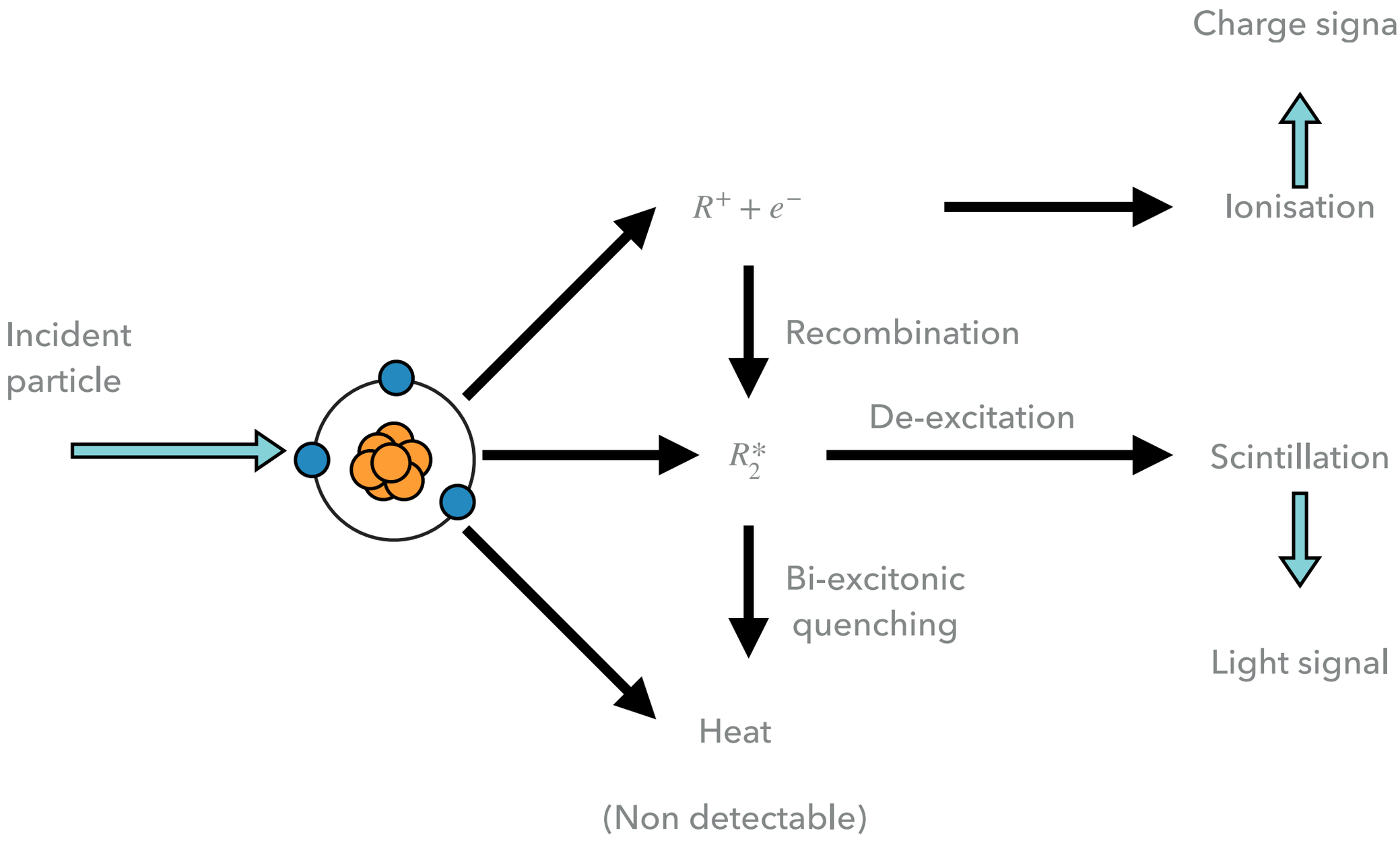


SIGNALS IN NL

ENERGY CALIBRATION

ENERGY CALIBRATION

We look at the way energy is deposited in a noble liquid target by particle interactions



ENERGY CALIBRATION

- With the energy deposition being described as

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

  - W is the average energy required to produce a single excited or ionized atom (and for NRs we must also consider the "quenching factor")

- As we shall see, in two-phases TPCs, the observed light and charge signage 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 is the total photon detection efficiency, g_2 is the 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

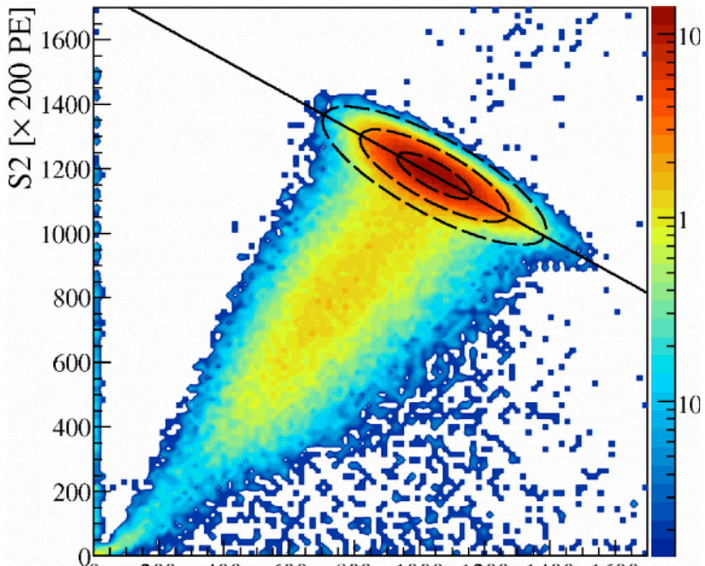
$$L_y \equiv \frac{S1}{E_0} \qquad Q_y \equiv \frac{S2}{E_0}$$

- And are estimated by 2D gaussian fits to mono-energetic lines, form the measured $S1$ and $S2$

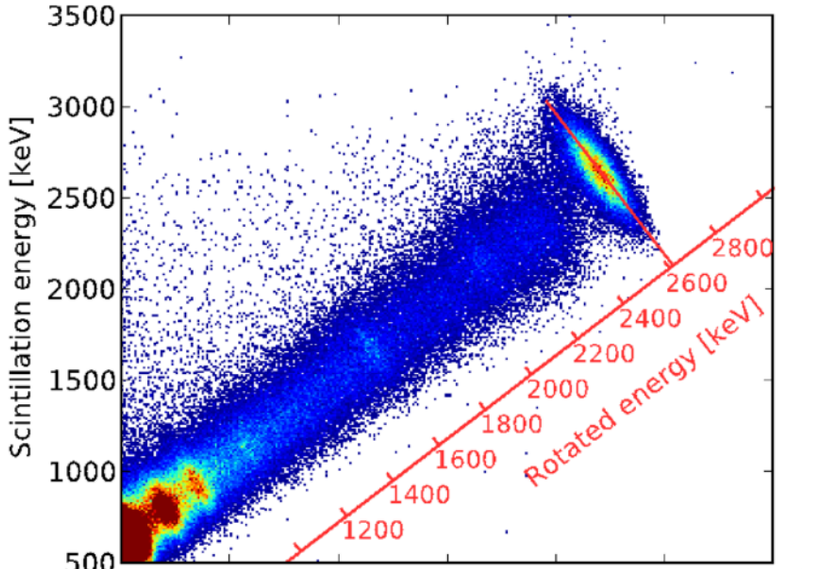
- Knowing L_y, Q_y from mono-energetic lines, one can measure the energy resolution (usually with an empirical fit to a number of measurements at different energies). The relative resolution scales as

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

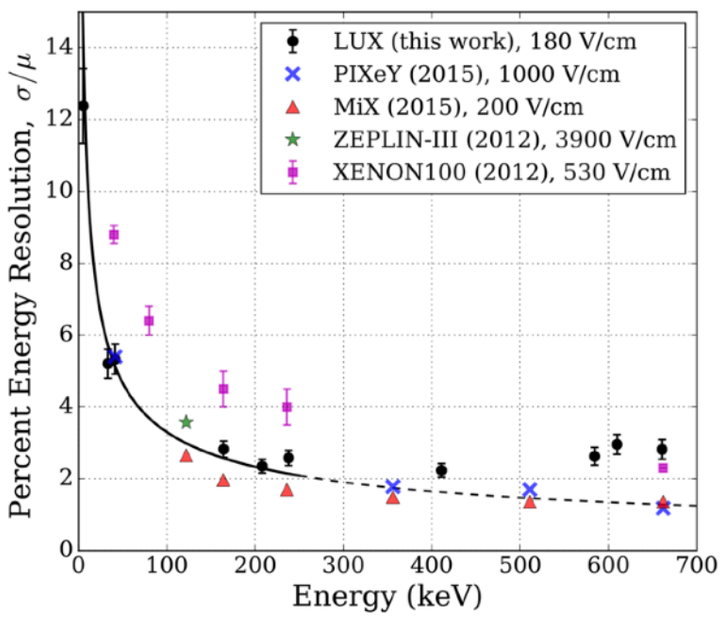
Example XENON100



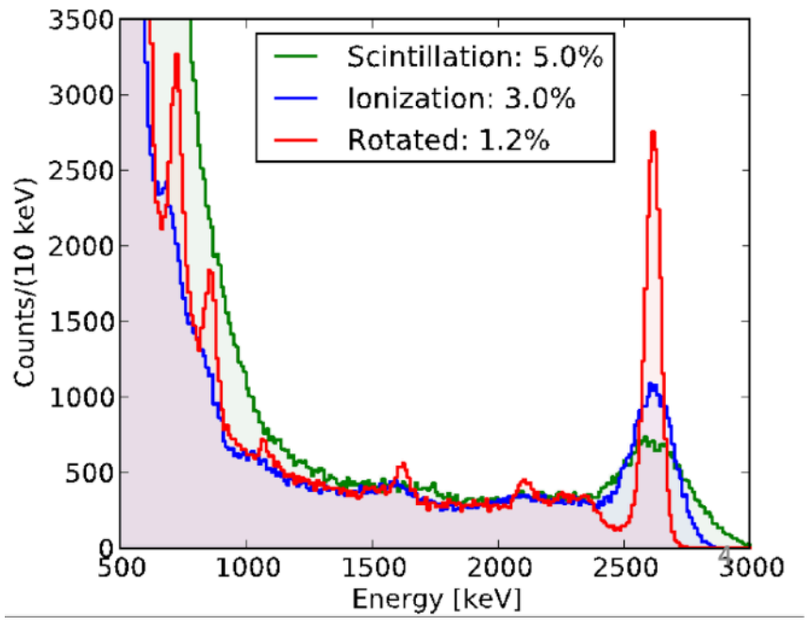
Example EXO-200



Example LUX



Example EXO-200



THE DOKE PLOT

- One can also rewrite the previous equation as follows:

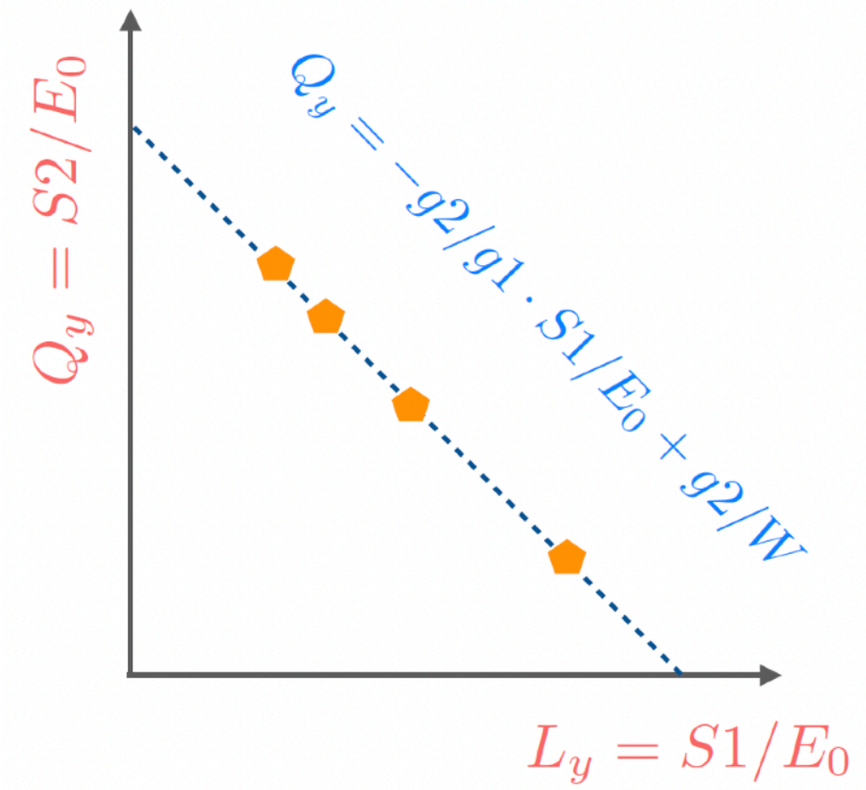
$$Q_y = -\frac{g_2}{g_1} L_y + \frac{g_2}{W}$$

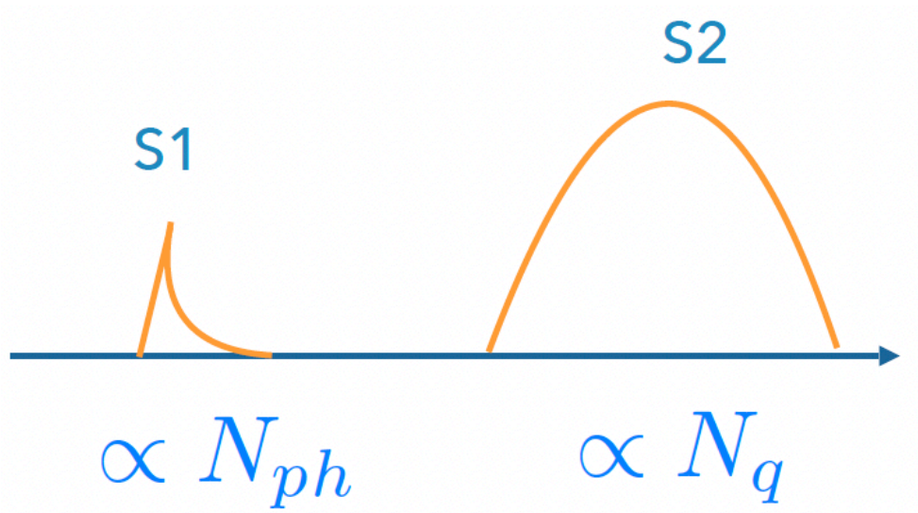
- since we can measure $S1$ and $S2$ for clear spectral features, and E_0 is known, one can estimate g_1 and g_2 from a so-called Doke plot: a plot of $Q_y (= S2/E_0)$ versus $L_y (= S1/E_0)$

- 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 g_1 and g_2 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





$$N_{ph} = N_{ex} + r \cdot N_i \quad N_q = (1 - r) \cdot N_i$$

THE DOKE PLOT

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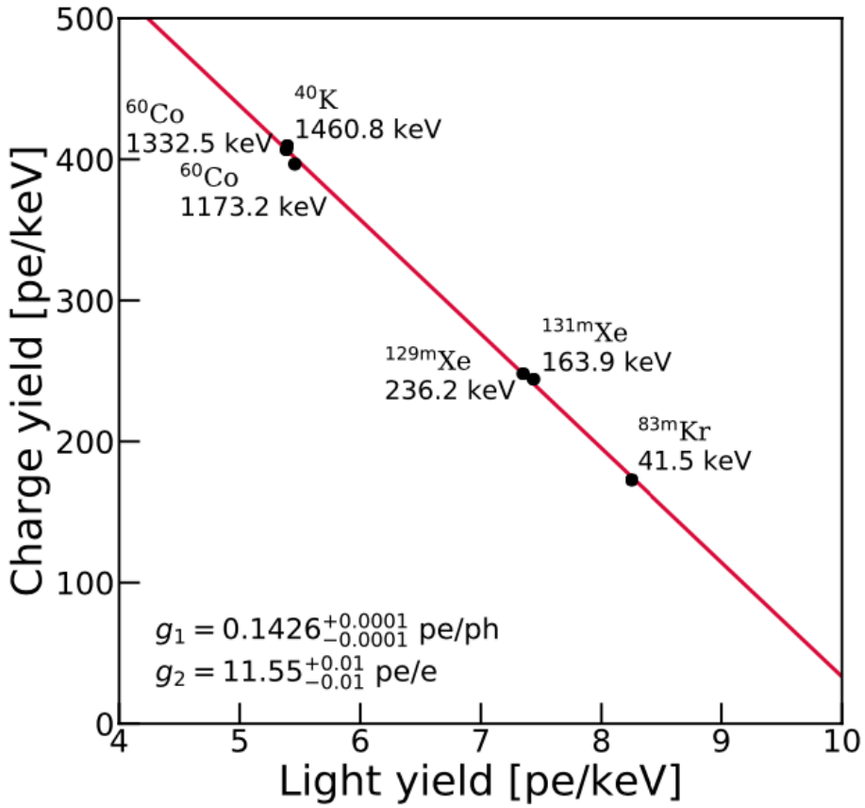
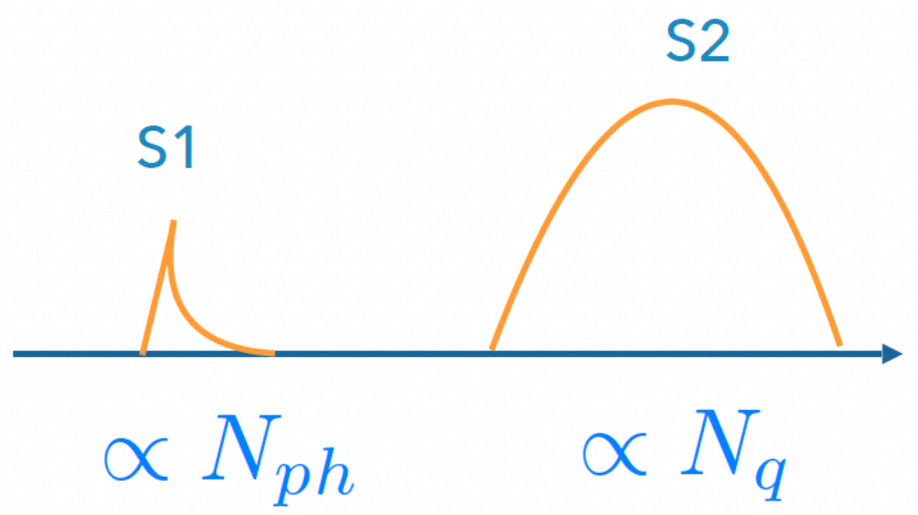
Example Doke plot from XENON1





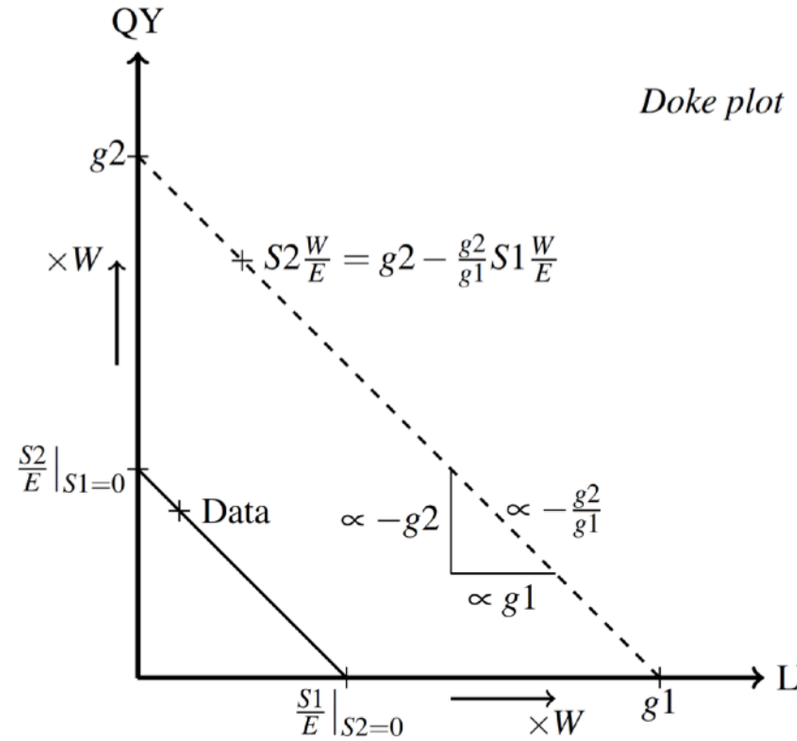
$$N_{ph} = N_{ex} + r \cdot N_i \quad N_q = (1 - r) \cdot N_i$$

THE W-VALUE

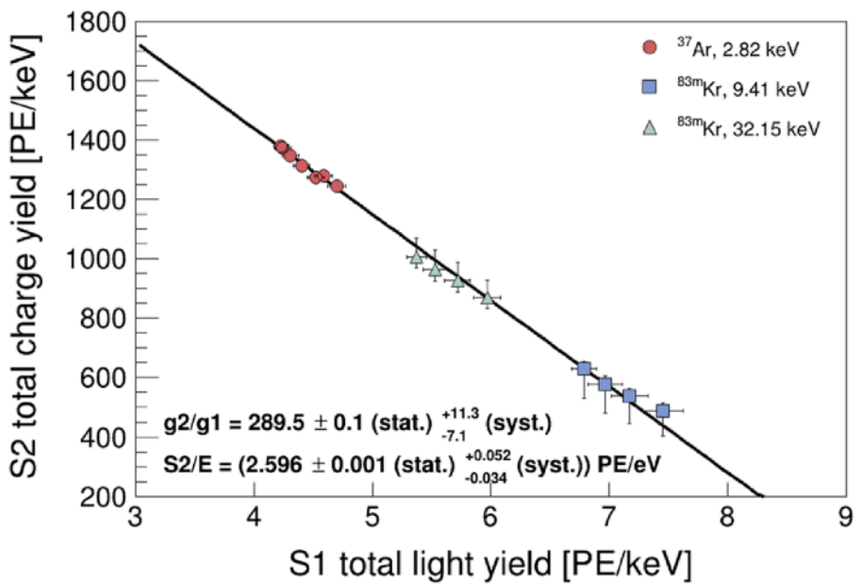
- On the other hand, one can also use the Doke plot to determine the W-value in a noble liquid
- First, we rewrite the previous equation as:

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

- 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 g_2, the ionization gain parameter (either by measuring the charge directly, or by using a single electron population extracted to the gas phase, for which $g_2 = S2$)
  - the negative slope g_2/g_1 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)



Doke plot



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

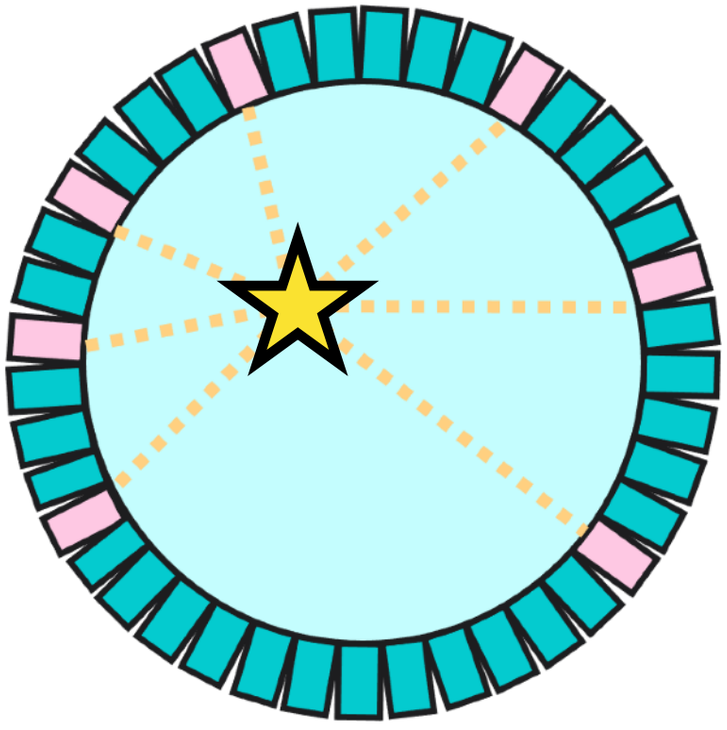
NOBLE LIQUID DETECTORS

TECHNOLOGIES

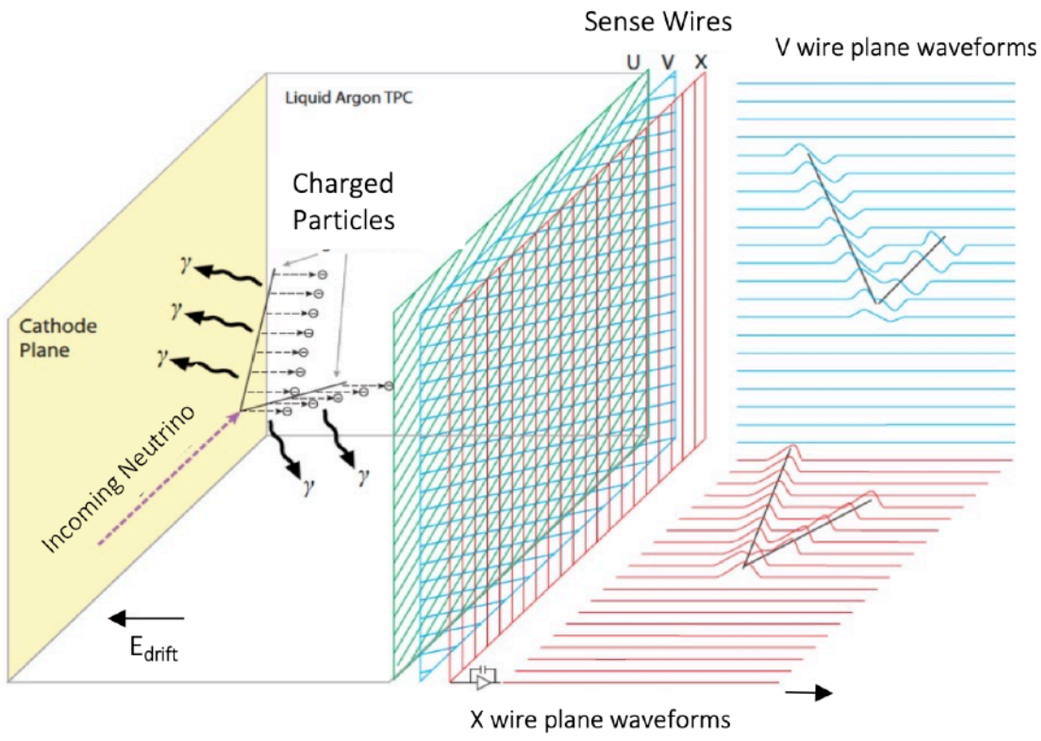
CRYOGENIC NOBLE LIQUIDS: SOME CHALLENGES

- 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 $\ll 1$ppb (O_2 equivalent) for e^--lifetime > 1 ms (commercial or custom-made purifiers and continuous circulation, in gas and/or liquid phase)
  - electric drift fields ~ few 100 V/cm required for maximum yield for MIPs; for α and NRs the field dependence is much weaker, challenge to detect a small charge in presence of HV

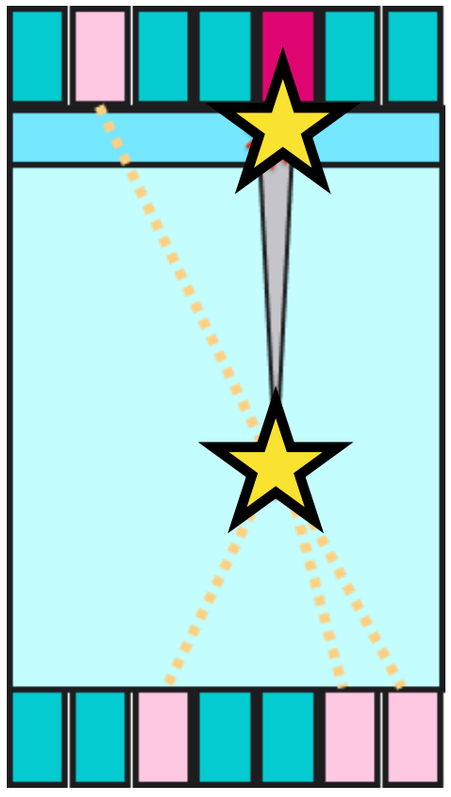
TYPES OF NOBLE LIQUID DETECTORS



Single phase detector



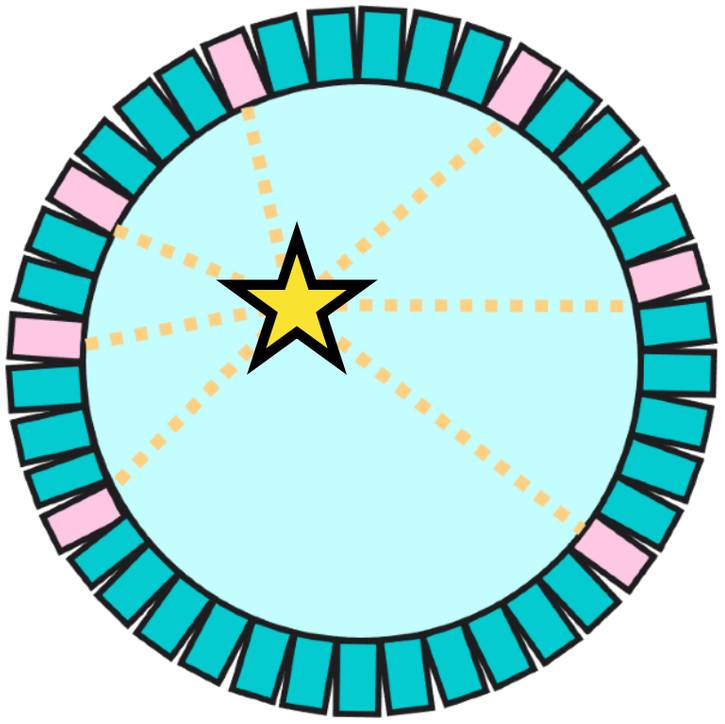
Single phase TPC



Double phase TPC

SINGLE PHASE DETECTORS

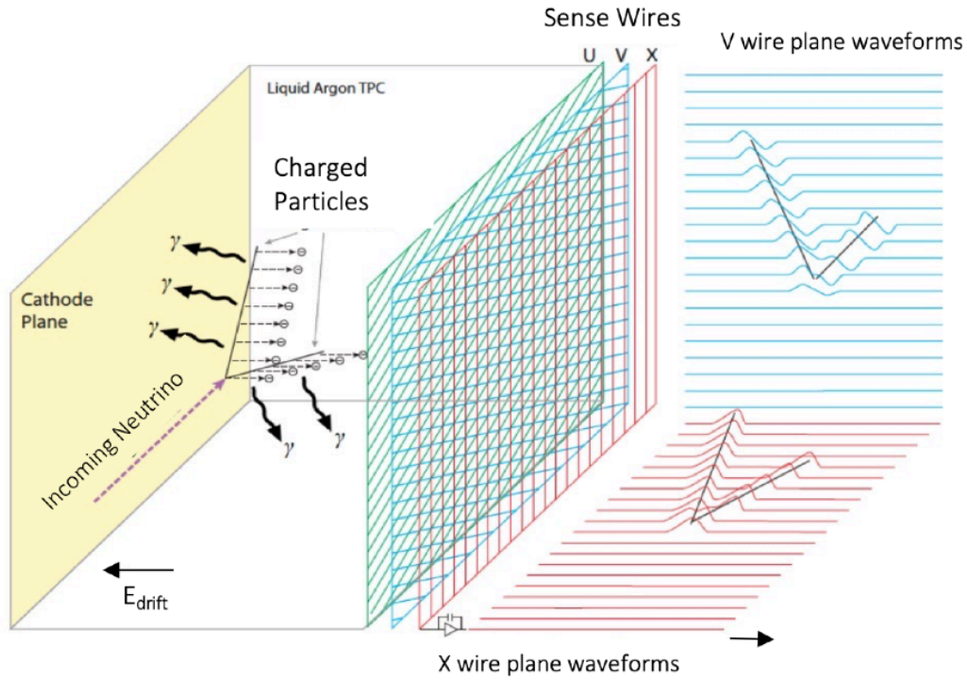
- Observe the prompt scintillation light in a large, homogeneous volume of liquid argon or xenon
- Particle discrimination via pulse shape analysis (in LAr)
- Advantages
  - High light yield (4-π coverage with photosensors; e^--ion recombination)
  - Simpler detector geometry, no electric fields and 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 at SNOLAB
  - LXe: XMASS at Kamioka

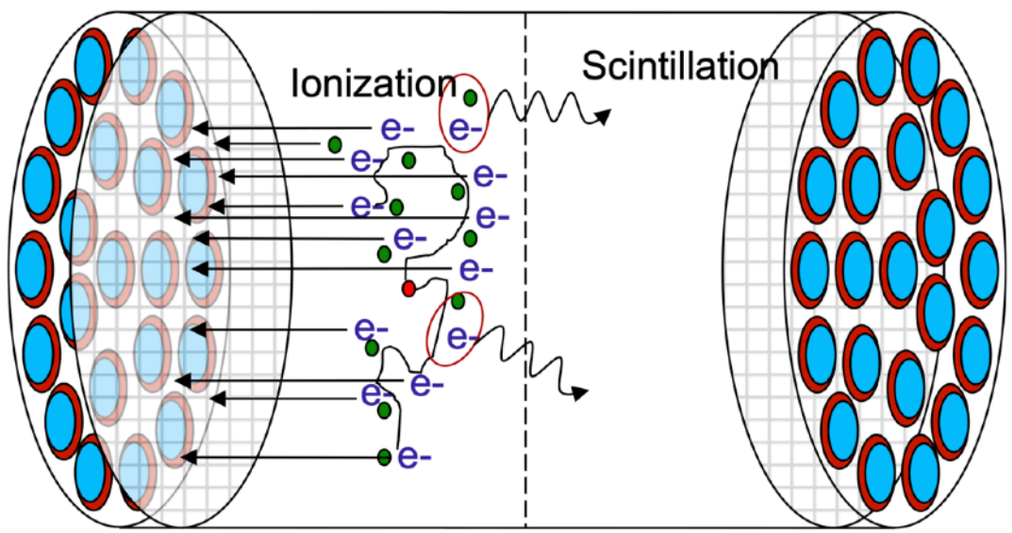


Single phase, light readout

SINGLE PHASE TPC

- 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, ICARUS, μBooNE, LArIat, ArgonCube, SBND at FNAL, ProtoDUNE at CERN
  - LXe: EXO-200 at WIPP, nEXO proposed for SNOLAB

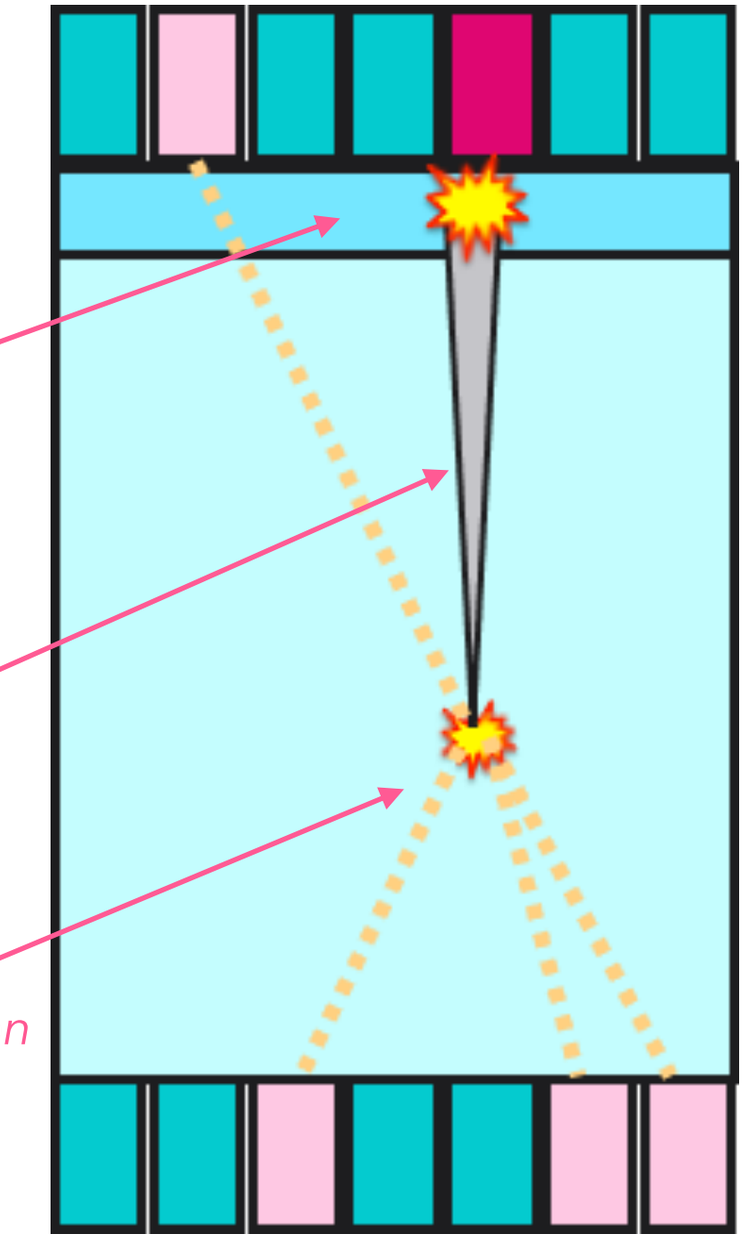




Single phase TPC, charge and light readout

DOUBLE PHASE TPC

- Observe the prompt scintillation light and electroluminescence 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 at LNGS
  - LXe: LZ at SURF, PandaX at Jinping, XENON at LNGS



Dual phase, light readout

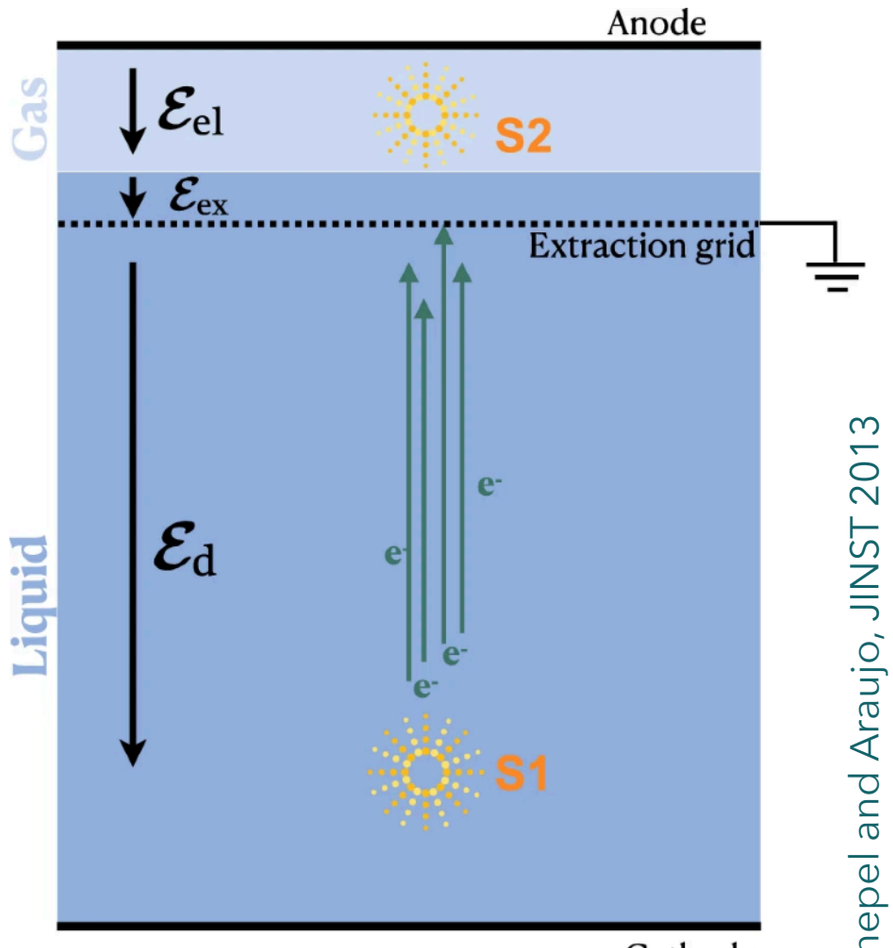
NL DETECTORS

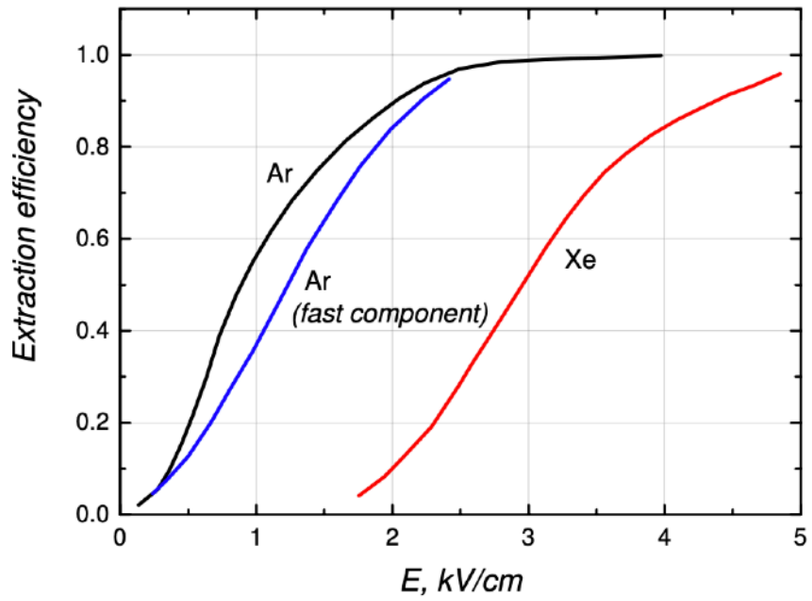
DOUBLE PHASE DM DETECTORS

DOUBLE PHASE DETECTION PRINCIPLE

Time projection chambers

- Prompt scintillation light signal in the liquid from the direct excitation process (S1 signal)
- Electrons drifted away from the interaction site via an electric drift field ~ $\mathcal{O}(100\ \mathrm{V/cm})$
- Electrons extracted from the condensed liquid into the vapor phase by a stronger electric field ~ $\mathcal{O}$(few kV/cm), also called "extraction field" (e^- need sufficient momentum to overcome the potential barrier at the liquid/gas interface)
- Electrons in the gas phase are accelerated by the electric field and gain sufficient energy to excite atoms in collisions
- These create electroluminiscence (EL; also called proportional scintillation), with similar emission spectra to those of direct scintillation (S2 signal)





Probability of e- emission. Chepel and Araujo, JINST 2013

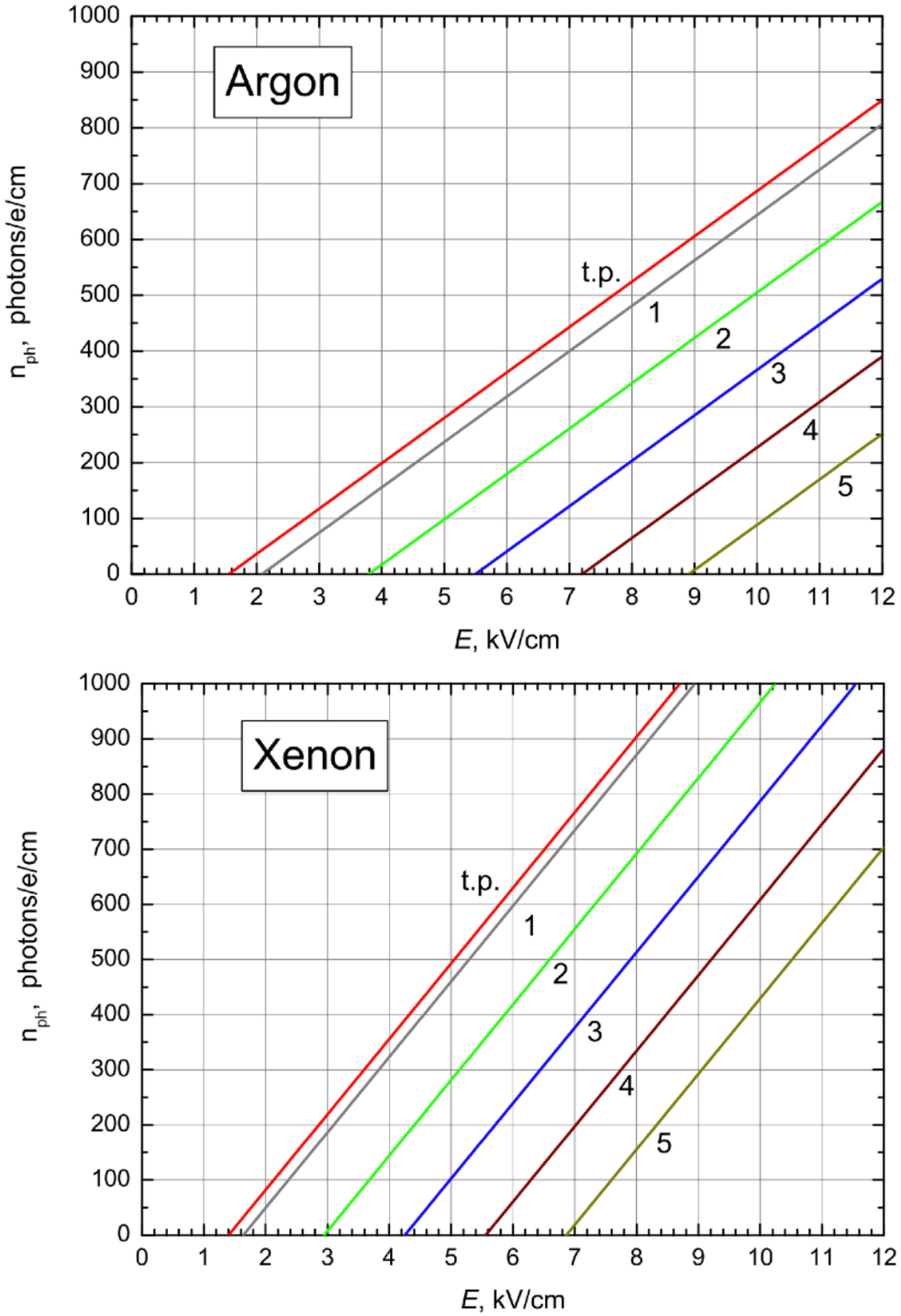
DOUBLE PHASE DETECTION PRINCIPLE

Time projection chambers

- A single extracted e- can produce ~ $\mathcal{O}(100)$ of photons, which then produce tens of photoelectrons in the photosensors
- The number of generated S2 photons will depend on the drift path, the field strength E (in V/cm) and the gas density. The yield per cm can be written as:

$$\frac{1}{n}\frac{dN_{ph}}{dx} = a\frac{E}{n} - b$$

- with n being the number of gas atoms/cm^3, n = N_A ρ/A, a and b being gas-specific empirical coefficients
- Important: the EL process is linear, since *the energy of the drifting e- is dissipated via photon emissions* (and these do not participate further in the process)

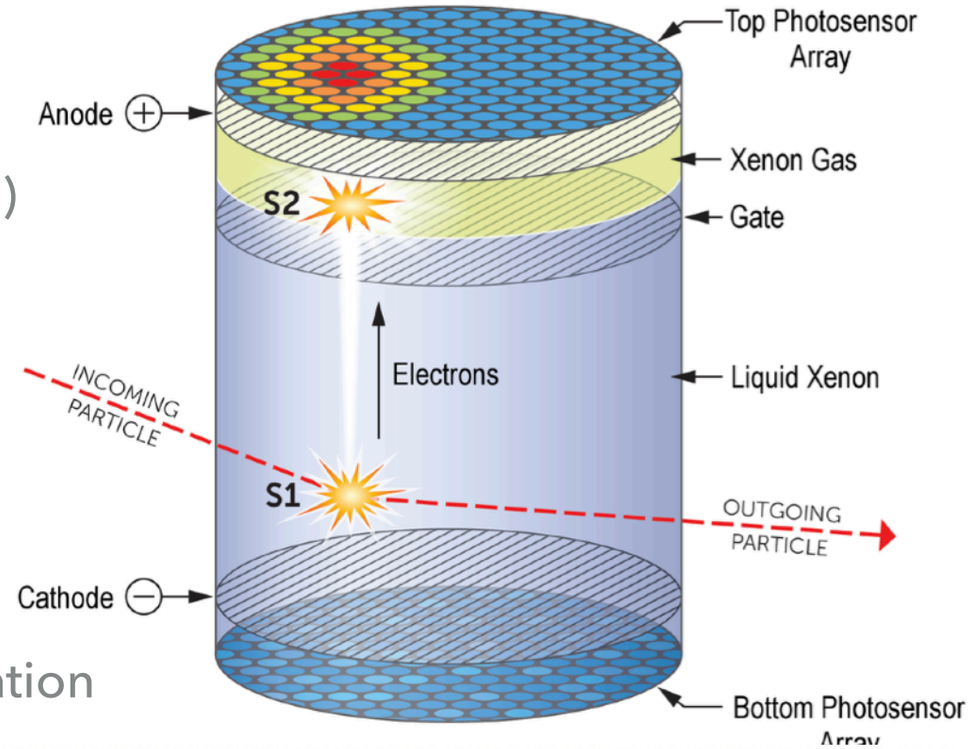


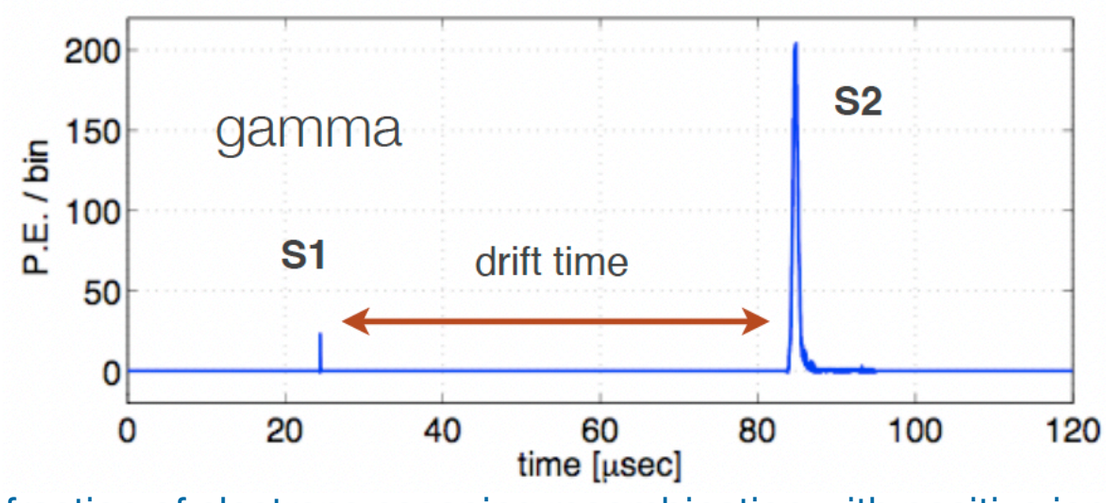
Number of photons generated in 1 cm, as a function of the field and of the gas pressure. Chepel and Araujo, JINST 2013

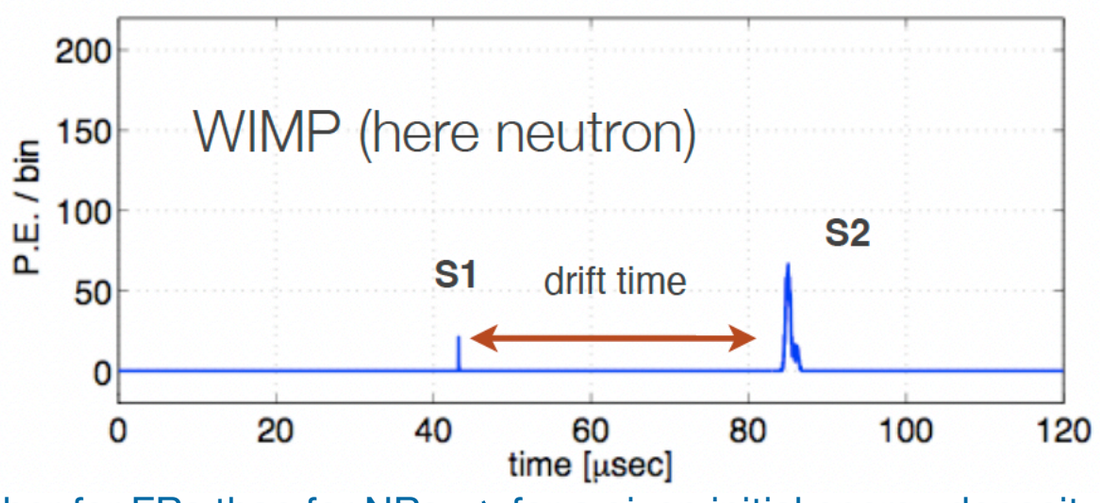
DOUBLE PHASE DETECTION PRINCIPLE

Time projection Chambers

- Signals detected with arrays of photosensors
- Energy determination based on light (S1) and charge (S2) signals
- 3D position resolution, which allows for fiducialization
- Identification of single versus multiple interactions
- S2 over S1 ⇒ ER versus NR discrimination
- Pulse shape information (LAr) ⇒ ER versus NR discrimination

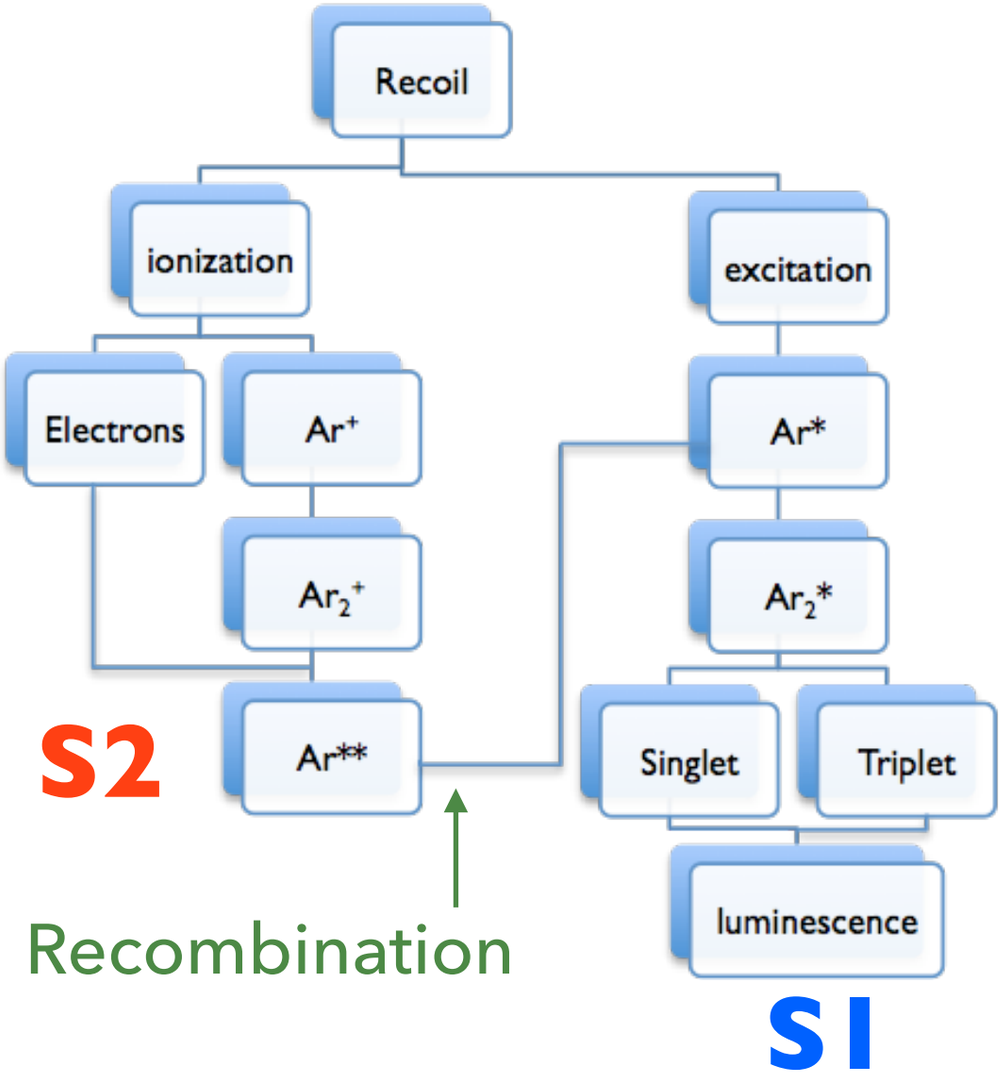




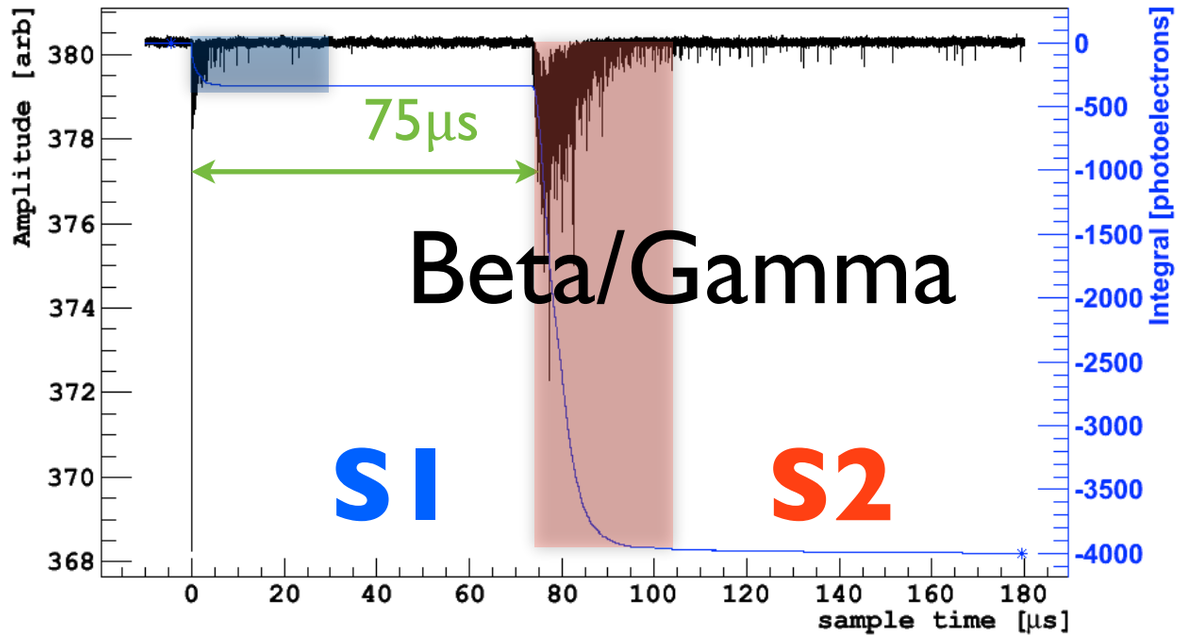


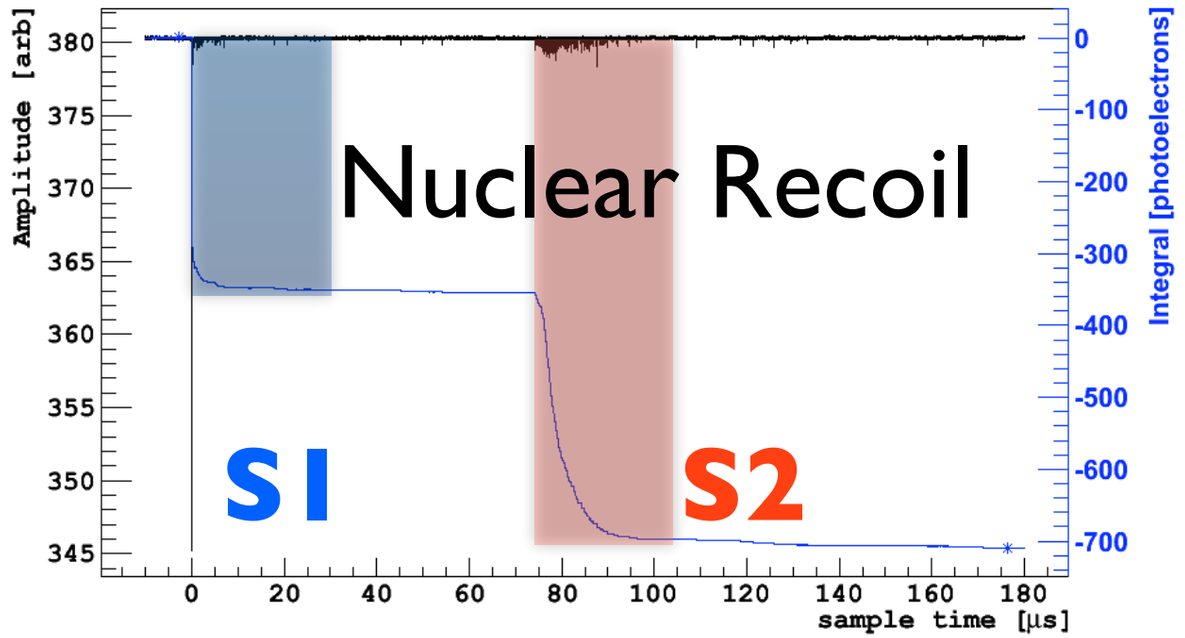
The fraction of electrons escaping recombination with positive ions: higher for ERs than for NRs ⇒ for a given initial energy deposit, the S2 signal is higher for ERs compared to NRs

IONIZATION/SCINTILLATION

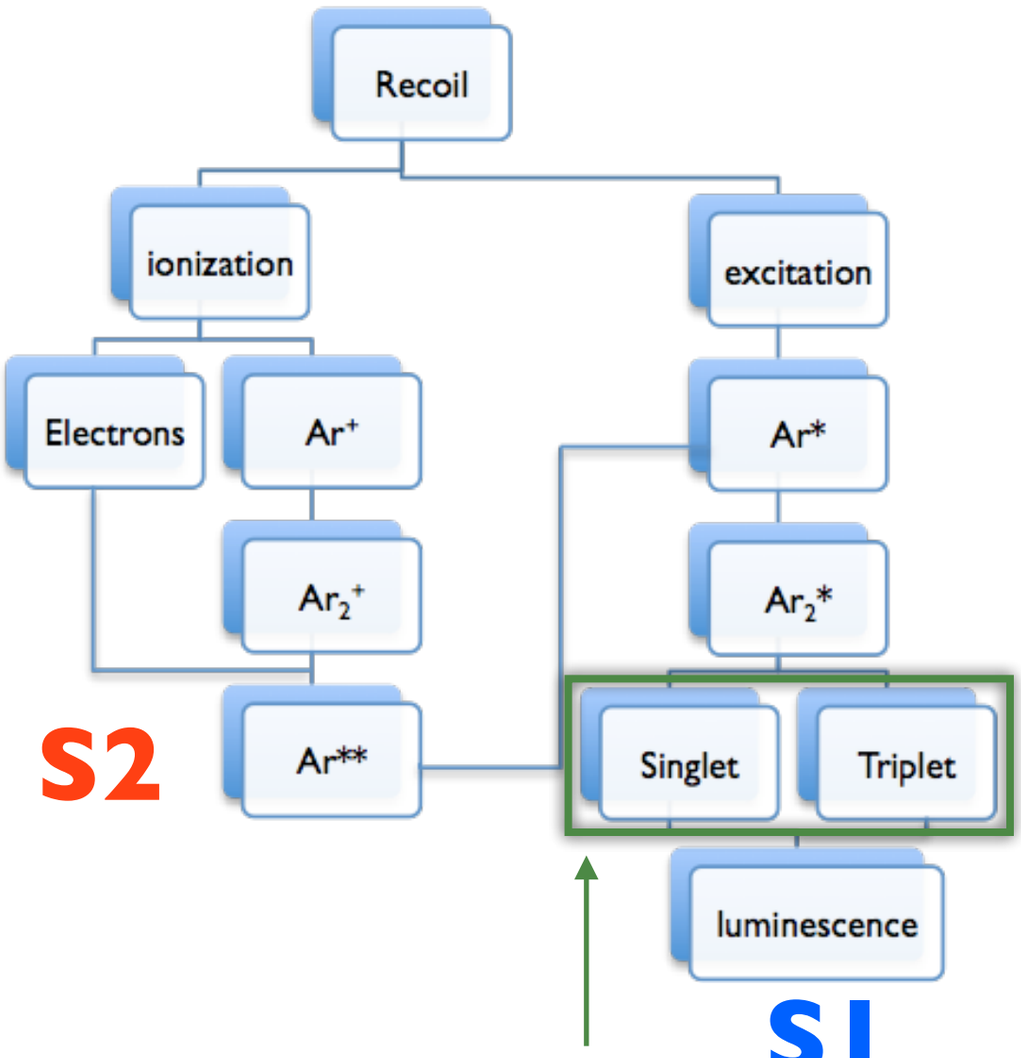


The ratio of S2 to S1 depends on ionization density





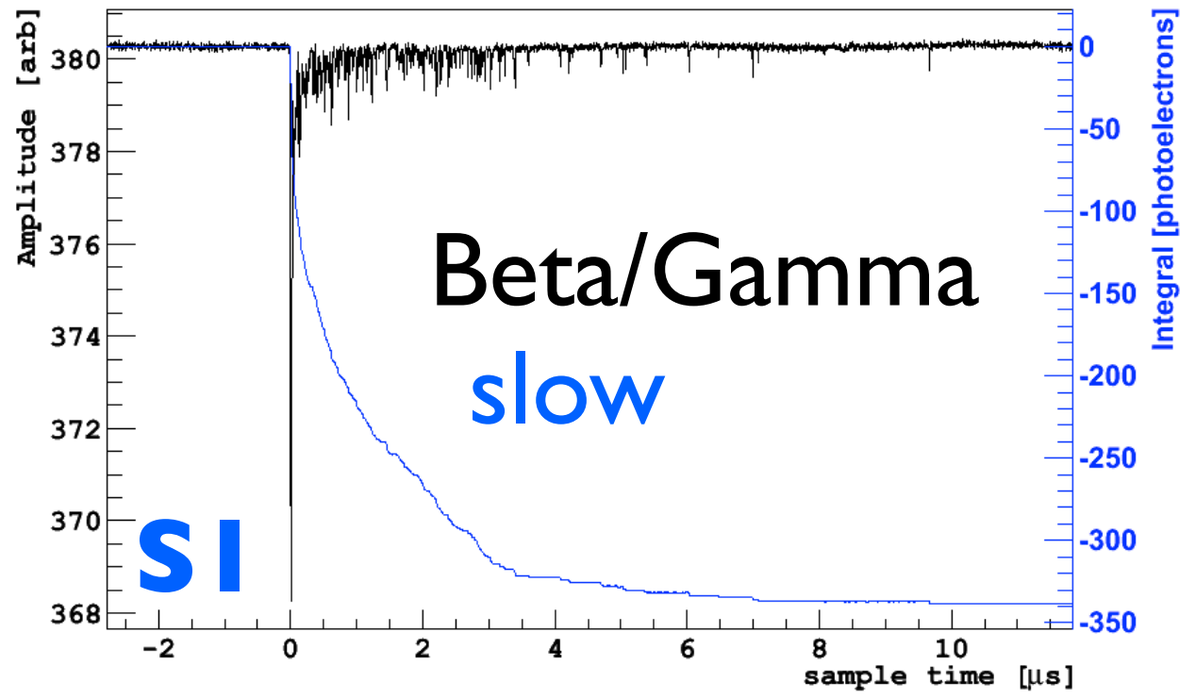
PULSE SHAPE DISCRIMINATION

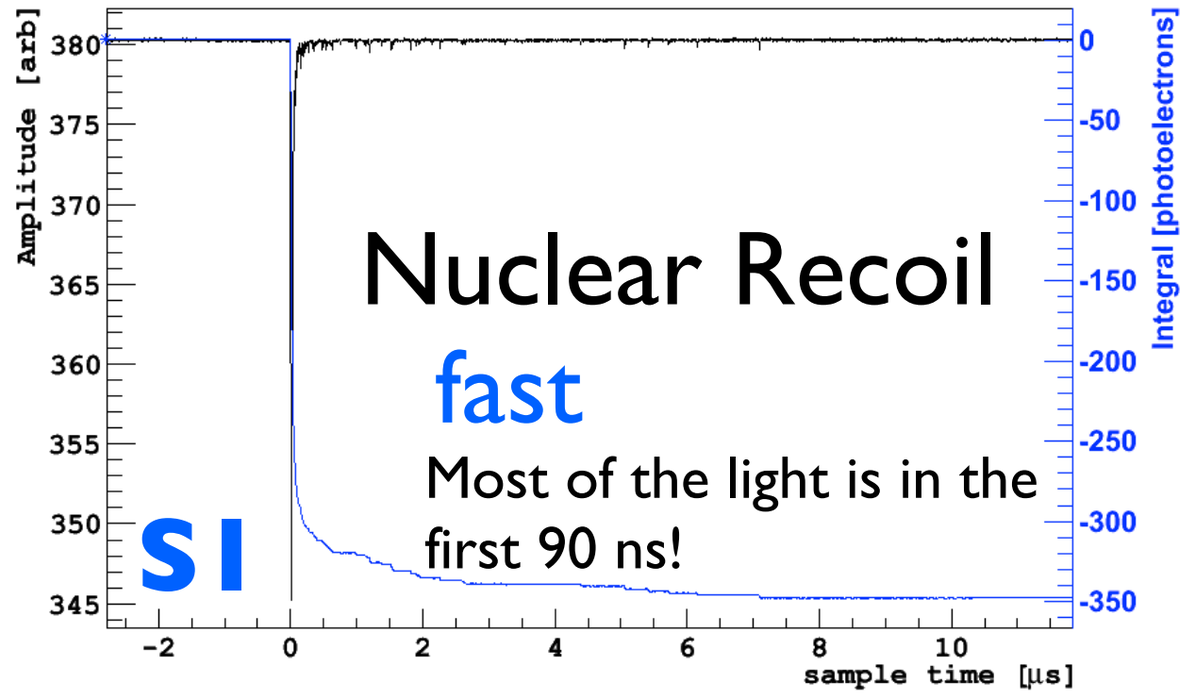


The ratio of light from singlet and triplet depends on ionization density

Ar $t_{singlet} = 7$ ns $t_{triplet} = 1600$

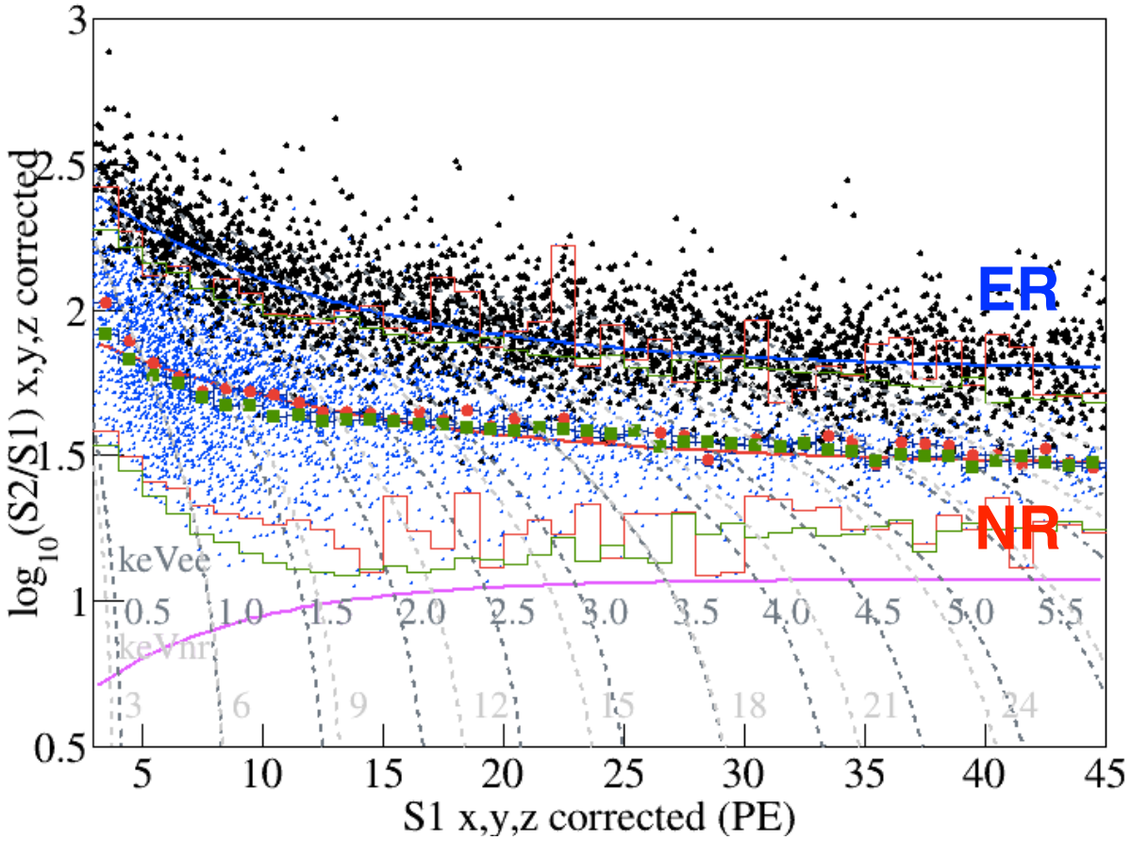
Xe $t_{singlet} = 3$ ns $t_{triplet} = 27$ ns





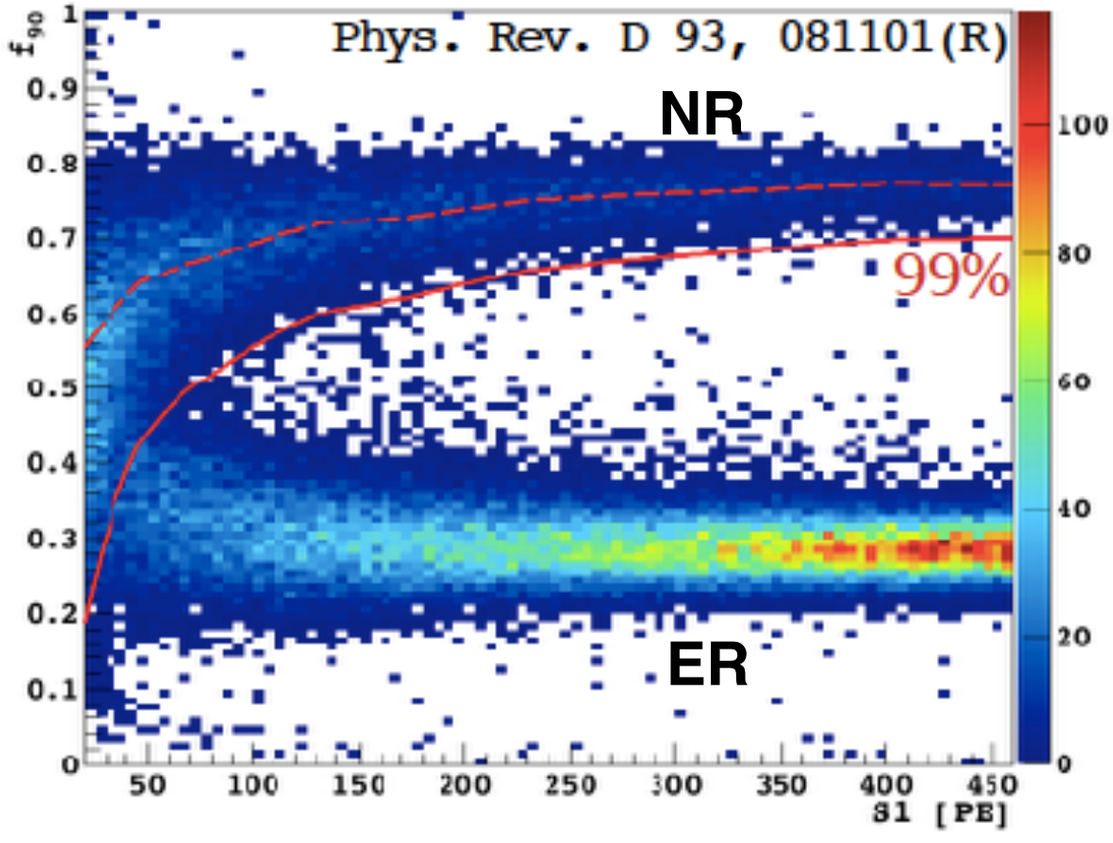
PARTICLE DISCRIMINATION IN NOBLE LIQUIDS

Ratio of charge to light in LXe:



Tritium and AmBe calibrations in PandaX

Pulse Shape Discrimination in LAr:



NR band from the AmBe calibration and lower ER band from β-γ backgrounds in DarkSide-50

Discrimination power ~ 10^3

Discrimination power > 10^8