Low energy calibration of liquid xenon detectors

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Outline

1. Introduction
2. Scattering of dark matter particles off nuclei ...
3. . . . and off electrons

Motivation

After Planck: 26.8% of the Universe is made of Dark Matter

→ Astronomical evidences:

Star rotation curves, Gravitational lensing, Galaxy clusters ...

Most general theoretical approach:

WIMP

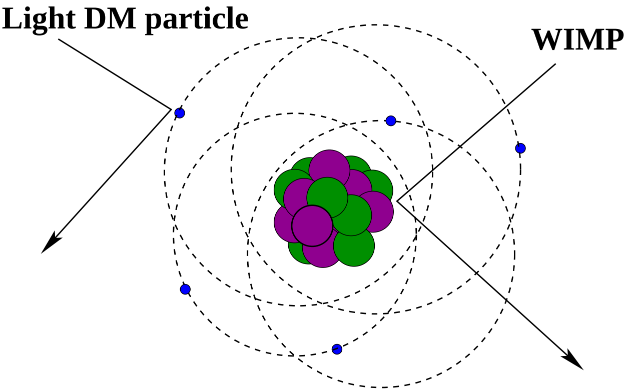
(**W**eakly **I**nteracting **M**assive **P**article)

A different possibility:

Light DM particle

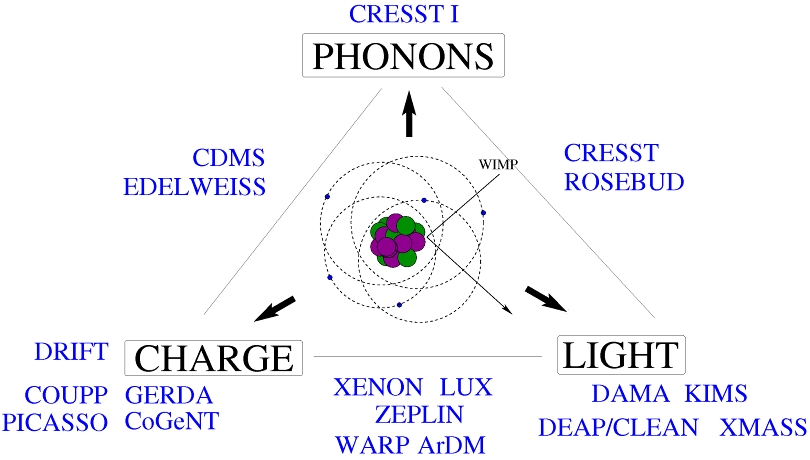
(such that it scatters off electrons)

Direct dark matter detection

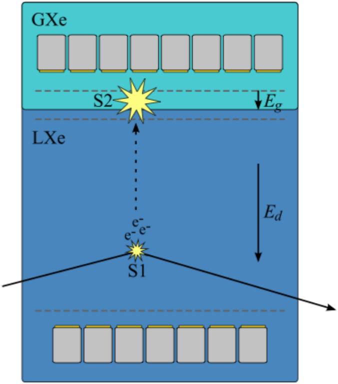


Detection via elastic scattering off
nuclei → nuclear recoils
electrons → electronic recoils

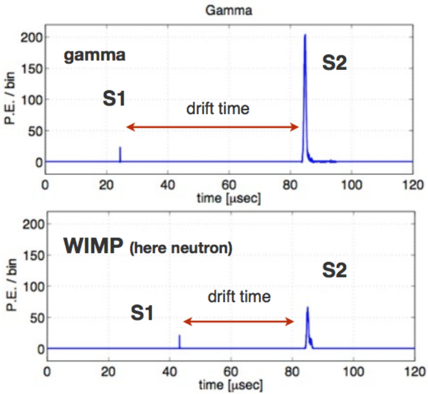
Detector response and discrimination



Two phase xenon TPC



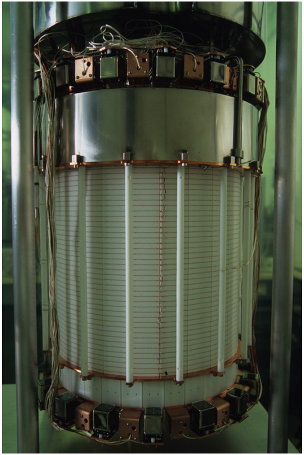
- Scintillation signal (S1)
- Proportional signal (S2)



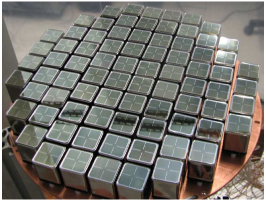
→ Electronic/nuclear recoil discrimination

- Energy scales for NR and ER based on S1!
- Quenching processes are different for NR and ER

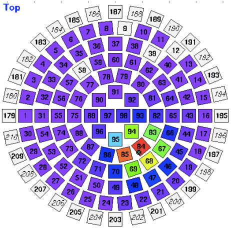
The XENON100 experiment



- International collaboration
- 30 cm length and 30 cm ∅
- 161 kg LXe (30 – 50 kg fiducial mass)
- Selected very low radioactivity materials



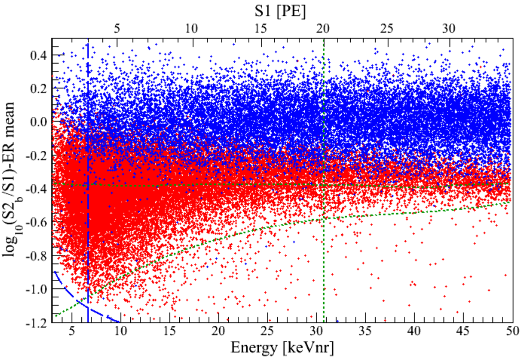
Bottom PMT array



Top PMT array

Located at LNGS underground lab (Italy)

XENON100: discrimination

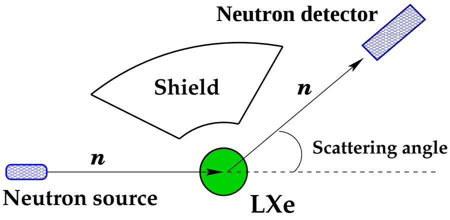


- Electronic recoil band: defined with ^{60}Co and ^{232}Th sources
- Nuclear recoil band: defined with AmBe neutron source

S1: number of photoelectrons detected by the photosensors (corrected for spatial light collection variations)

keV_{nr}: derived energy scale

L_{eff} direct measurements



Nuclear recoil energy (E_{nr}):

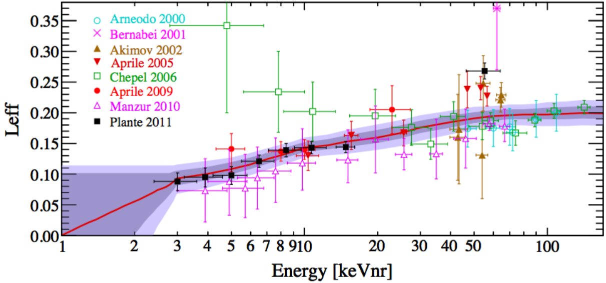
$$E_{nr} = \frac{S1}{L_y L_{eff}} \times \frac{S_e}{S_r}$$

$S1$: measured signal in p.e.

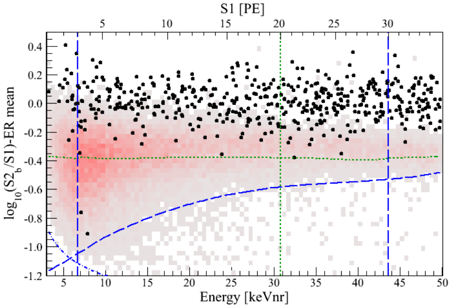
L_y: LY for 122 keV γ in PE/keV

S_e/S_r: quenching for 122 keV γ/NR due to drift field

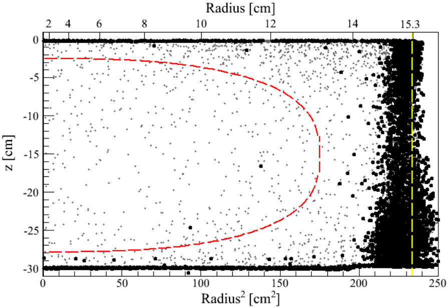
$$L_{eff} = q_{nucl} \times q_{el} \times q_{esc}$$



Results from 225 live days data (2012)



Science data



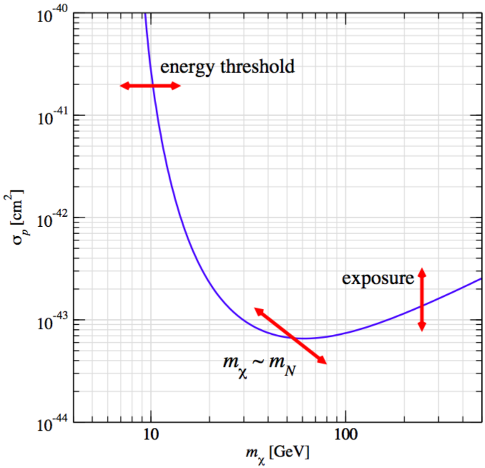
Spatial distribution of events

- Background expectation in the benchmark region: (1.0±0.2) events

→ Exclusion limit derived using profile likelihood method

Result of a direct DM detection experiment

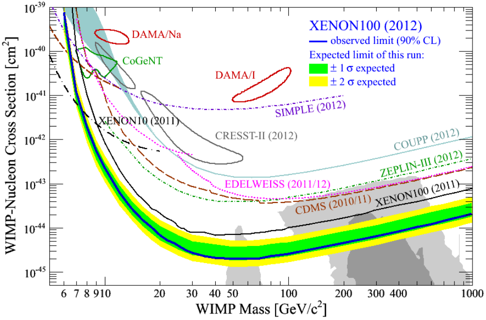
→ Statistical significance of signal over expected background?

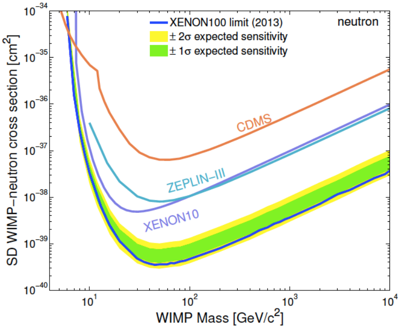


- Positive signal
  - Region in σ_χ versus m_χ
- Zero signal
  - Exclusion of a parameter region

- Low WIMP masses: detector threshold matters
- Minimum of the curve: depends on target nuclei
- High WIMP masses: exposure matters $\epsilon = m \times t$

Results from XENON100





Spin-independent:
2×10^{-45} cm^2 at 55 GeV/c^2
WIMP mass

XENON100, Phys. Rev. Lett. 109 (2012) 181301

Spin-dependent:
3.5×10^{-40} cm^2 at 45 GeV/c^2
WIMP mass

XENON100, arXiv:1301.6620

Verification of nuclear recoil energy scale

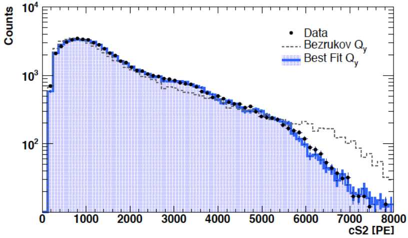
Monte Carlo simulation of neutron source

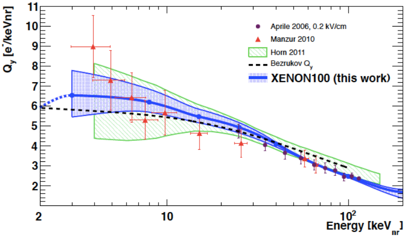
XENON100, arXiv:1304.1427 (work of M. Weber (MPIK))

- Input AmBe spectrum (ISO 8529-1 standard). Analysis robust against variations of this spectrum
- Source strength measured at the German Metrology Institute (PTB) 160 ± 4 n/s
- Complete Monte Carlo description of the detector including detector shield (water, lead, polyethylen and copper)
- E_{dep} is converted to S1 and S2 including thresholds, resolutions and acceptances from data

MC simulation of neutron source

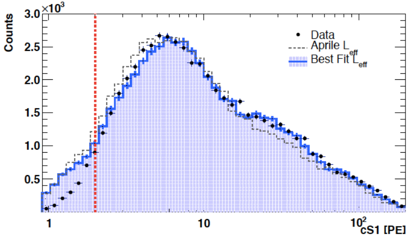
- Step 1: Using L_{eff} from direct measurements, reproduce S2 spectrum $\rightarrow$ obtain optimum Q_y
- Step 2: Using the obtained Q_y, reproduce S1 spectrum $\rightarrow$ obtain a new L_{eff}

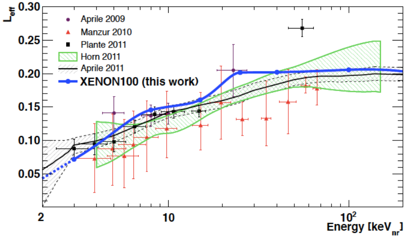




Best fit of source strength: 159 n/s

MC simulation of neutron source

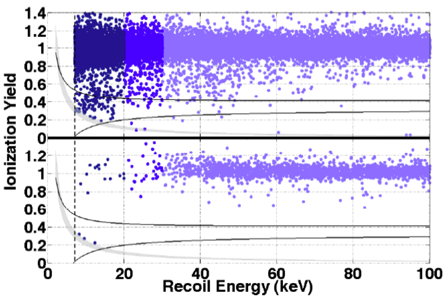


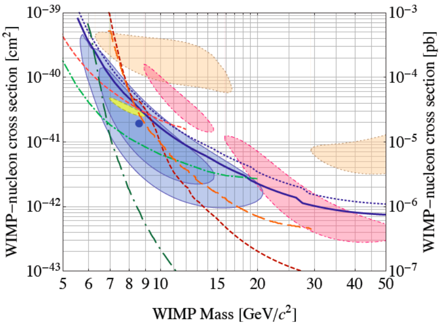


- Poor agreement below 2 PE due to unknown efficiencies below threshold
- Good overall agreement. Best fit L_{eff} matches previous measurements

$\longrightarrow$ Results of XENON100 remain unchanged using this L_{eff}

Recent results from CDMS





CDMS Si results from April 15th

140 kg-day exposure

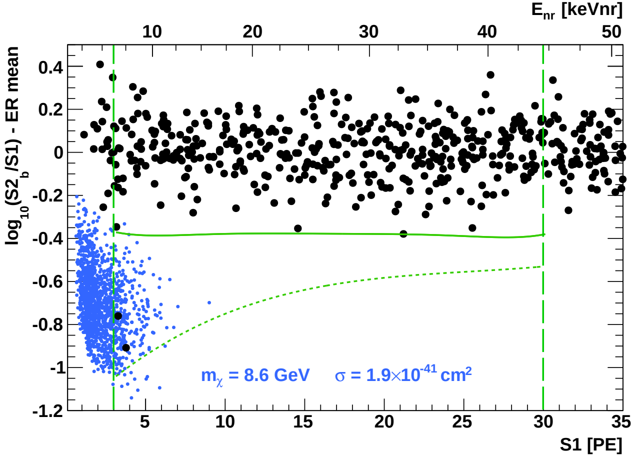
3 events detected (0.7 expected)

Likelihood analysis: 0.19 % probability that the known-background-only hypothesis

- Best fit at 1.9×10^{-41} cm^2 at 8.6 GeV/c^2 WIMP mass

CDMS, arXiv: 1304.4279

How would CDMS signal look in XENON100?

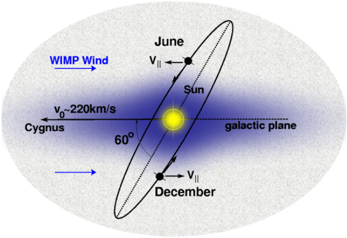


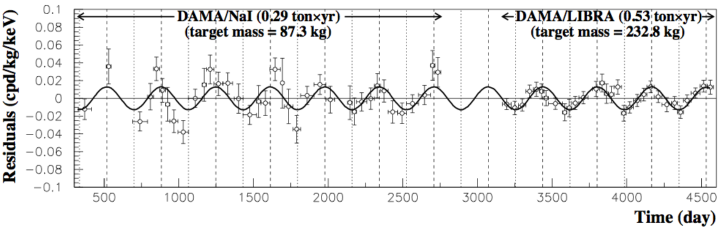
Event distribution that XENON100 would observe for $\sigma = 1.9 \times 10^{-41}$ cm^2 and 8.6 GeV/c^2 WIMP mass

A different signature of dark matter

DAMA annual modulation

- Ultra radio-pure NaI crystals
- Annual modulation of the background rate in the energy region $(2 - 5)\,\mathrm{keV}$
- What if the DM particle scatters off electrons?

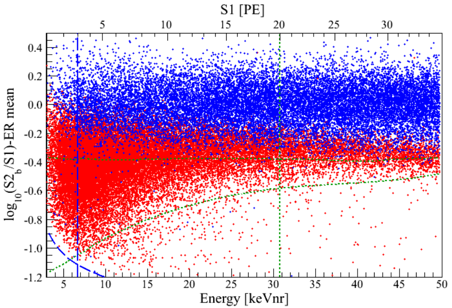




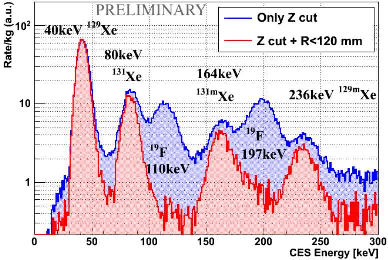
R. Bernabei *et al.*, Eur. Phys. J. C67, 39 (2010)

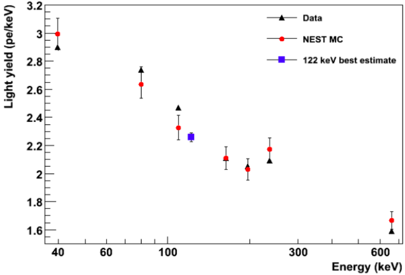
Calibration data in XENON100

Electronic recoil region:
energy calibration necessary



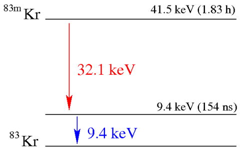
Nuclear recoil calibration
provides inelastic mono-energetic lines and metastable states: 40, 80, 164 and 236 keV

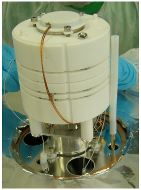


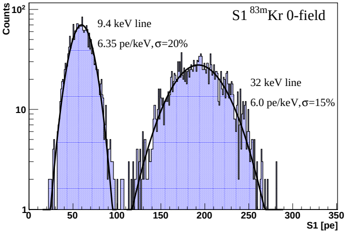


Calibration using ^{83m}Kr

- ^{83m}Kr calibration source:
  - EC decay-product of ^{83}Rb
  - Lines at 9.4 and 32.1 keV
  - Uniform distribution



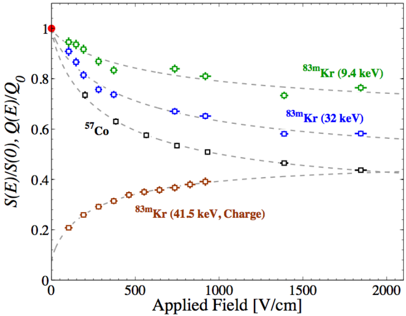




Liquid xenon

- Target mass: $\sim$ 0.1 kg LXe
- Volume: 3 cm drift length and 3.5 cm diameter
- Two R9869 PMTs
- 6 pe/keV in double phase

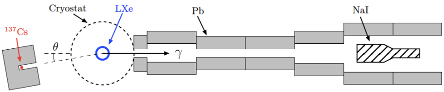
$\rightarrow$ at University of Zürich

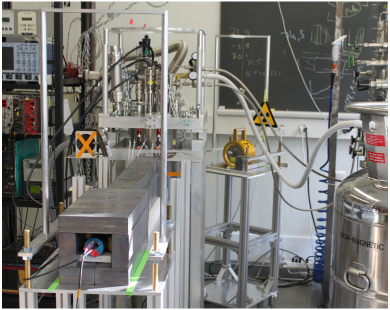


A. Manalasay *et al.*, Rev. Sci. Instr. **81**, 073303 (2010), 0908.0616

Compton measurement: low energy electron recoils

Determination of LXe light yield at small scattering angles
$\rightarrow$ electron energies down to $\sim 1.5\,\text{keV}$

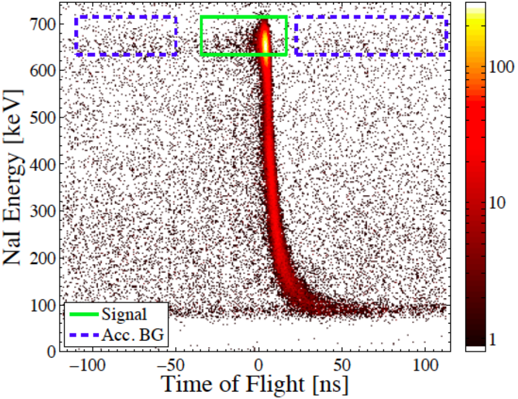




Setup:

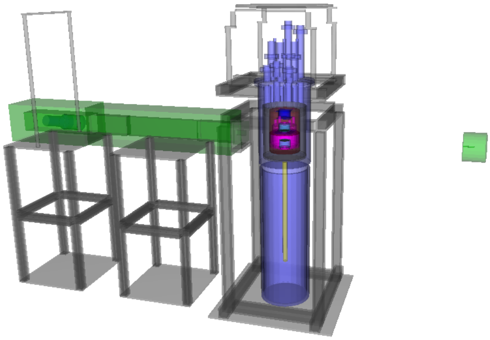
- γ-rays from a ^{137}Cs source
- Energies $< 9.4\,\text{keV}$
  $\rightarrow\ < 8.5^\circ$ scattering angle
- Goniometer 0.25° ticks
- γ's collimated at the source and after LXe scattering
- Coincidence detector: NaI 3" crystal

Data selection

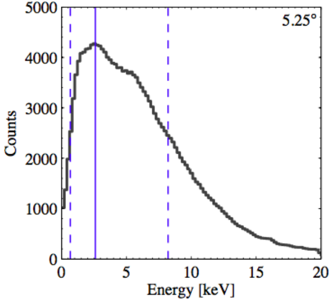


- Selection of full absorption peak (green)
  - asymmetric in energy to reduce multiple scatters
  - asymmetric in ToF to account for early events (few PE pulses in LXe)
- Background estimation from side bands (accidental triggers, blue)

Monte Carlo simulation



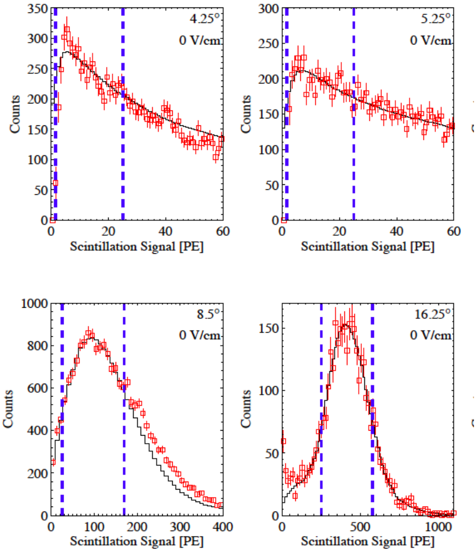
- Broad raw energy spectrum
- Asymmetric spectra: E_{er} quadratic in θ for small θ
- MC data converted into scintillation signal



→ Complete setup simulated with Geant4

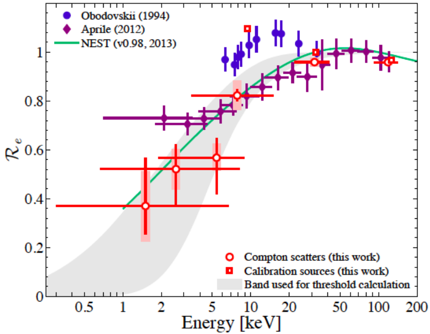
- Multiple scatters: 1.6%
- Scatters off detector materials: 5.8%

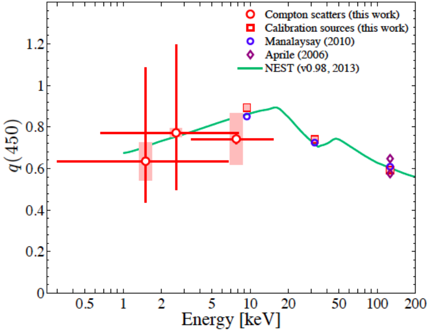
MC/data fitting



- LY is allowed to have a slope in the region fitted
- Systematic uncertainties
  - Scattering angle
  - Variation fit range
  - LY dependence on source strength
  - PMT coincidence requirement
  - LY variations during the measurement

Results of the Compton experiment





- Light yield decreases at 0-field below 40 keV (reduced electron-ion recombination)
- Field quenching $\sim$ 75% at low energies

arXiv:1303.6891

Implications for dark matter search

Experiment	$\lvert\vec{\mathbf{E}}\rvert$ (V/cm)	$S1_{thr}$ (PE)	$LY_{Co}(\frac{PE}{keV})$	E_{thr} (keV)
ZEPLIN-III	3400	2.6	1.3	$2.4^{+0.5}_{-0.4}$
XENON10	730	4.4	3.0	$1.8^{+0.4}_{-0.3}$
XENON100	530	3.0	2.3	$1.7^{+0.4}_{-0.3}$
XMASS	0	4.0	14.7	$1.1^{+0.4}_{-0.2}$

$\rightarrow$ DAMA signal can be tested in XENON100!

Analysis of time variations of ER rate currently ongoing

Summary

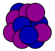
- Scattering of WIMPs off nuclei
  - XENON100 excludes the current indications of DM
  - Energy threshold (L_{eff}) verified with MC/data comparison of an AmBe neutron source

- Scattering of light dark matter particles off electrons
  - Compton experiment to determine the energy threshold for electronic recoils
  - XENON100 threshold is at $\sim 2\,\mathrm{keV}$

  $\longrightarrow$ sensitive to DAMA annual modulation energy region
  - XENON100 analysis of time variations of the background rate ongoing

Noble gas scintillation process

Nuclear recoil



Ionization: $\mathbf{R}^+$ and $\mathbf{e}^-$'s

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

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

$$\mathbf{R}^{**} \rightarrow \mathbf{R}^* + \textbf{heat}$$

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

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

singlet / triplet

singlet	triplet	
19 ns	15 μs	Neon
5 ns	1.6 μs	Argon
3 ns	25 ns	Xenon

Excitation: $\mathbf{R}^*$

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

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

singlet / triplet