Search for cosmological dark matter with noble liquids

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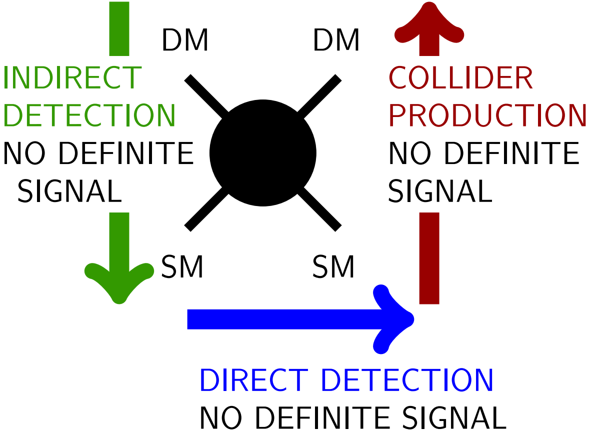
June 23, 2014 at TeVPA/IDM

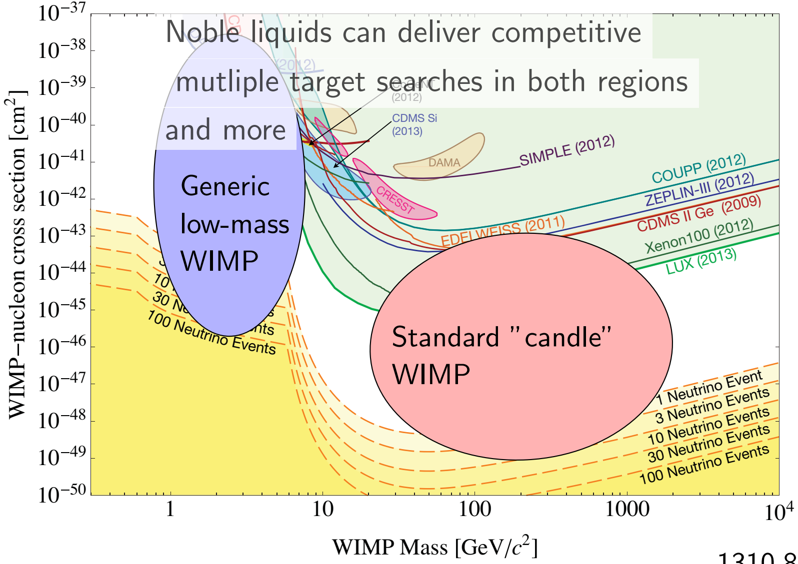
Status of searches for testable DM candidates

DM $\in$ {WIMPs, LSP, Axion, Sterile ν, KKP, gravitinos, Asymm.DM, hidden sector DM ...}



Direct dark matter searches can probe various DM candidates NOT only WIMPs. WIMP class is the most exploited for various reasons so far. No definitive signal is bringing wide DM candidate search back in the focus.

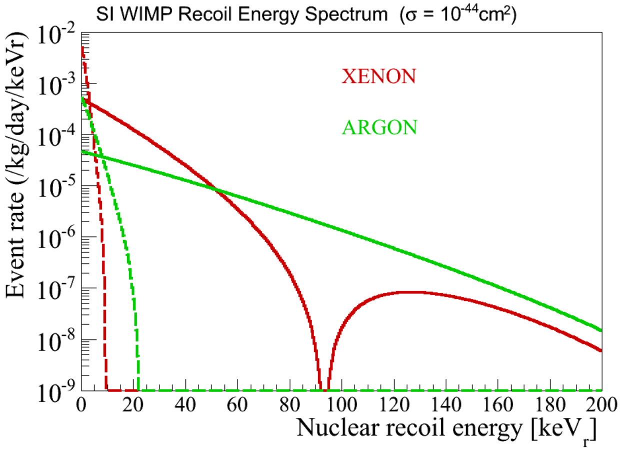
Noble liquids searching for WIMPs ("vanilla" SI interaction)



1310.8214

WIMP Signal in noble liquids ("vanilla" SI interaction)

Mass Range ≈ (1MeV/c^2 - 10TeV/c^2)
Signal (M$\gtrapprox$1GeV/c^2) = single nuclear recoil (NR).
Background = electronic recoil, NR from n, NR of other than target nuclei, degraded α recoil, accidental, ...



Noble liquid targets

Noble liquids are radio-pure, going after ultra radio-pure.

	LXe -nat	LAr-nat	LAr-UG	LHe
A	131.3	40.0		4
ρ [g/cm^3]	2.94	1.40		0.145
λ [nm]	178	125		80
$LY\|_{E=0}$ [$\frac{ph}{MeV}$]	42000	40000		19000
Isotope [mBq/kg]	$\ll^a$ (^{136}Xe)	10^3(^{39}Ar)	$<^b$6.5(^{39}Ar)	none
^{222}Rn [μBq/kg]	^{c}(3-20)	$<^d$0.8-^{e}16	NA	NA
^{nat}Kr	$^f\mathcal{O}$(1ppt)	NA	$\ll^g$	NA

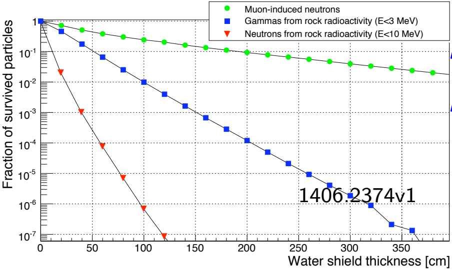
a: ^{136}Xe ($T_{1/2} = 2.2\ 10^{21}$ y); b: Cosmic rays and radiogenic processes induce ^{39}Ar, underground Ar is depleted, 1204.6061, 1204.6024, c: Rn removal using activated carbon, 1309.7024, d: preliminary result from DS-50, e: DEAP 1406.0462; f: ^{85}Kr: removal by cryogenic distillation/chromatography/centrifuges 1309.7024, g: ^{85}Kr: radiogenic origin, should not be present in underground Ar

Against neutron background

n: μ-induced, α-n, fission reactions

Go underground reduce μ flux. Not enough except @CJPL lab.

Shielding against μ-induced n insufficient, but will reduce ext. γ



μ veto required to reduce

μ-induced n <0.01 ev/year

LUX, DS-50, DEAP, CLEAN, XMA

utilize Cherenkov μ veto

To reduce radiogenic neutrons from detector material:

Material screening via Ge, Mass spectroscopy, NAA ...

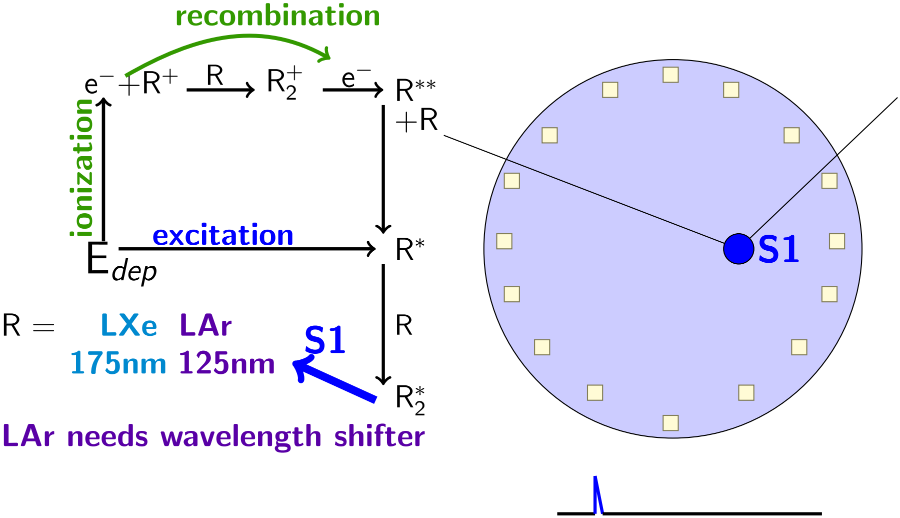
Build neutron veto close to target to detect escaping neutrons

Only DarkSide program uses boron-loaded LSV (1010.3609v1)

Vetos enable both rejection and characterization of the background!

Light in single phase noble liquid detector

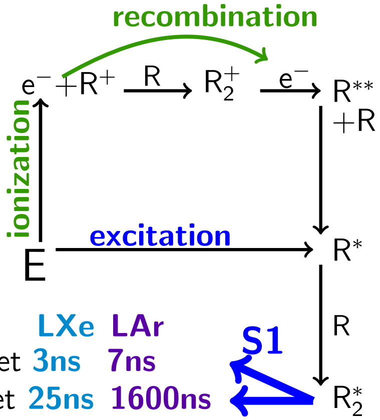
4π coverage of PMTs gives excellent light yield.



LAr needs wavelength shifter

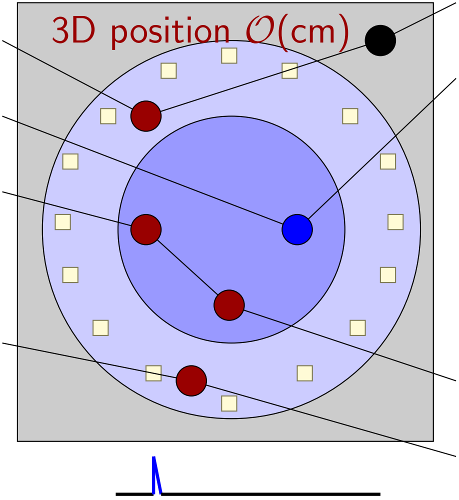
Background rejection in single phase

Fiducialization + Multiple scatter + Active veto



R =	LXe	LAr
singlet	**3ns**	**7ns**
triplet	**25ns**	**1600ns**
	~~PSD~~	**PSD**

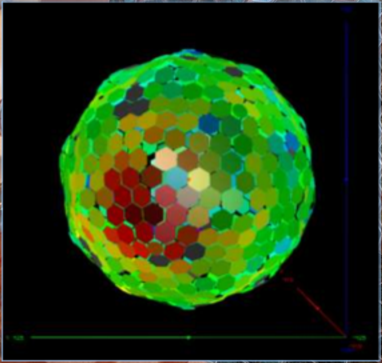
NO other ER rejection
Radio-purity is crucial!



High light yield in single phase - LXe

XMASS-1 (835/100 kg) at Kamioka with water shield

LY=14.7pe/keV$_{ee}$ @ 122keV$_{ee}$ $\Rightarrow$ 4PE = $\sim$ 3keV$_r$



electron coupling of DM

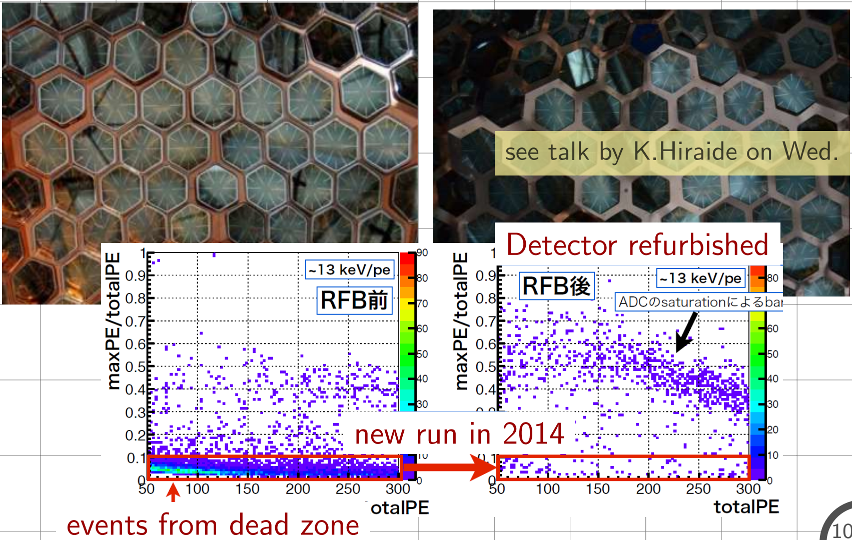
arXiv:1211.5404,1212.6153,1406.0502

arXiv:1301.2815

(c) Kamioka Observatory

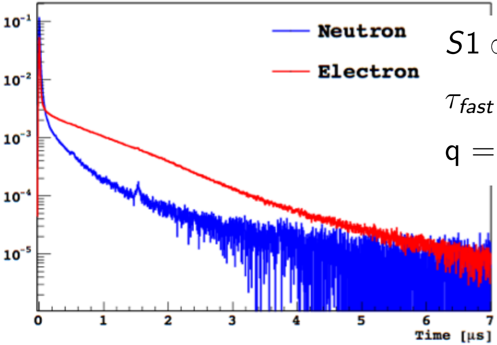
High surface radio-purity in single phase - LXe

Surface contamination of PMTs + poor positioning of surface events limited the sensitivity of first run.



High LY and pulse timing in single phase - LAr

Pulse shape discrimination crucially depends on # of photons.
PSD power $= \mathcal{O}(10^7 - 10^{11})$



$$S1 \propto \left(\frac{q}{\tau_{fast}} e^{-1/\tau_{fast}} + \frac{q}{\tau_{slow}} e^{-1/\tau_{slow}}\right)$$

$\tau_{fast} =$ 7ns, $\tau_{slow} =$ 1600ns

$$q = \frac{Singlet}{Triplet} = f(dE/dx)$$

F90 = fraction of S1 within first 90ns

F90∼0.3. F90∼0.7

Current best PSD =DEAP-1 is 10^8 at ∼100PE (0904.2930)
Challenge for LAr, but validations are ongoing! Model the F90 discrimination parameter to accounts for macroscopic effects related to argon micro-physics, detector properties and reconstruction and noise effects(see DarkSide - talk at UCLA 2014)

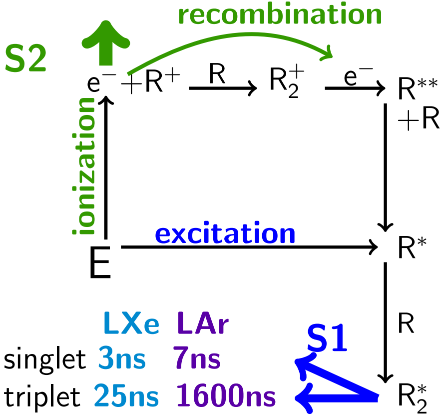
About to take data single phase - LAr + CW

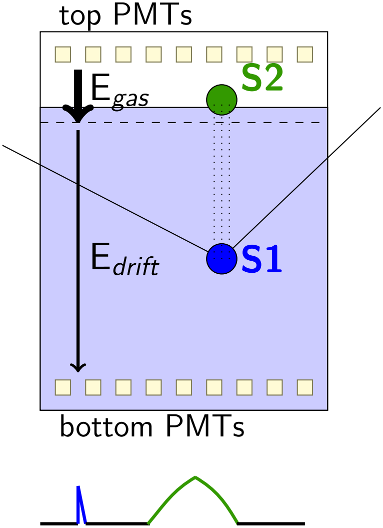
DEAP-3600/1000kg

CLEAN-500/150kg

Light&charge in dual phase noble liquid detector

R = {LXe (LUX, XENON, PandaX), LAr (DarkSide, ArDM)}





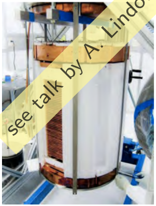
Dual phase noble liquid detectors - Present

XENON100
data taking

161kg
$\gtrsim$**34kg**

see talk by U. Oberlack on Wed

LUX
data taking



370kg
$\gtrsim$**118kg**

see talk by A. Lindote on Wed

PandaX Ia
1st data taking

125kg
$\gtrsim$**25kg**

1405.2882

DarkSide-50
data taking atm Ar

150kg
$\gtrsim$**40kg**

see talk at UCLA DM14'

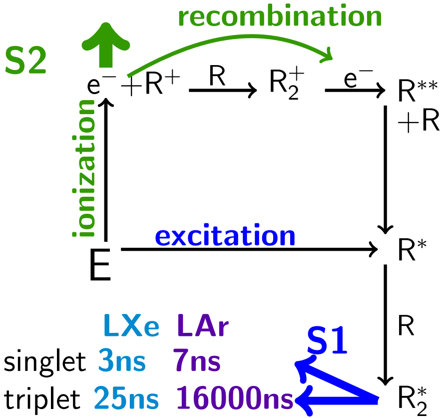
ArDM
1st data taking

850kg
$\gtrsim$**100kg**

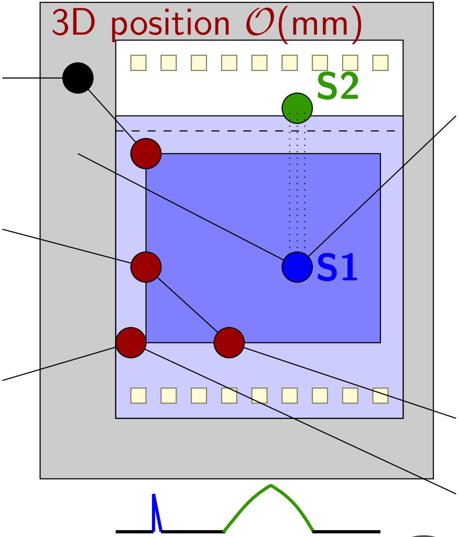
see talk at UCLA DM14'

Background rejection in dual phase

Fiducialization+Multiple scatter+PSD(LAr)+S2/S1+Active veto



	LXe	LAr
singlet	3ns	7ns
triplet	25ns	16000ns



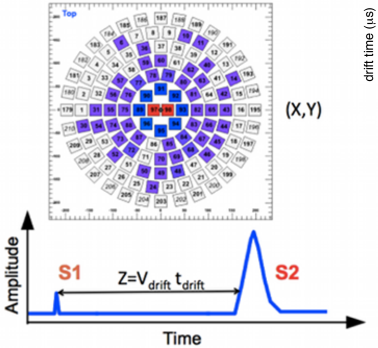
see talk by K. Ni on Wed

Background rejection via 3D event reconstruction

3D event reconstruction

XENON100∼3mm (x,y), ∼0.3mm (z)

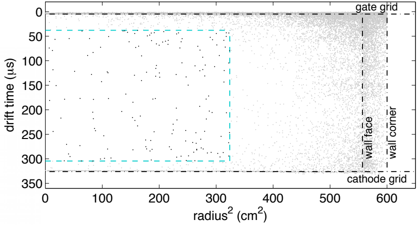
LUX∼4-6mm (x,y)



PandaX, DS-50 algorithms under development

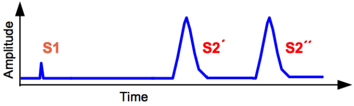
Fiducialization

1310.8214v2

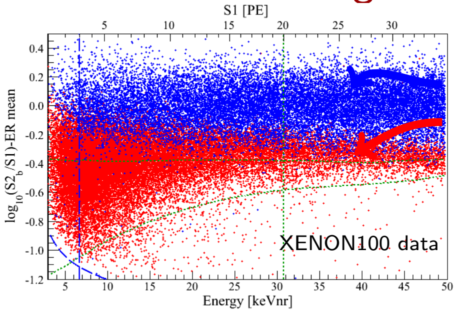


Multiple scatter rejection

XENON100, LUX∼3mm



Electronic recoil background rejection via S2/S1



XENON100@530V/cm

ER Background mod. (^{60}Co,^{232}Th)

NR Signal model (AmBe)

∼99.75% ER rejection

@ 40% NR acceptance in ROI

1310.8214v2

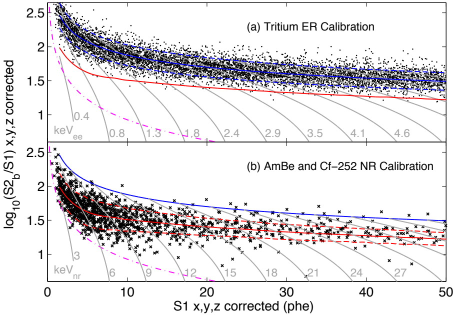
LUX@181V/cm

∼99.6% ER rejection

@ 50% NR acceptance in ROI

Novel calibration method

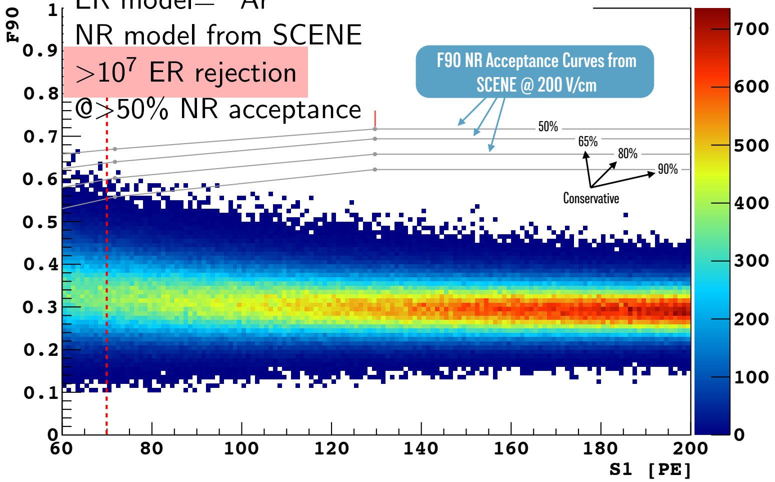
via tritiated methane



Electronic recoil background rejection via PSD

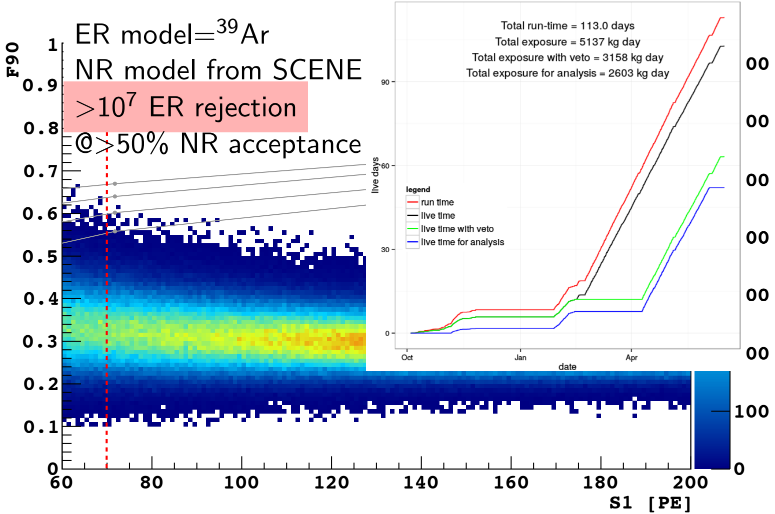
DarkSide-50: Background free exposure of 280kg·day with AAr.
Corresponds to that expected in 2.6 year of UAr DS-50 run.

ER model=^{39}Ar
NR model from SCENE
$>10^7$ ER rejection
@>50% NR acceptance



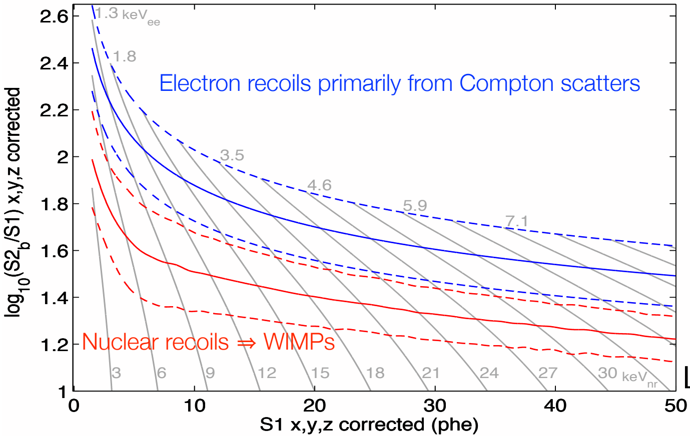
Electronic recoil background rejection via PSD

DS-50 has ×10 more data with AAr⇒ preparing publication.
Final goal is 18ton-y exposure to probe PSD for DS-G2.



Energy scale via S1 or S2 is nonlinear

Twice the energy recoil (NR/ER) $\neq$ twice the signal in S1 (S2).
Same energy NR and ER give different signal in S1 (S2).
Same energy recoil different E-field $\neq$ same signal in S1 (S2).



LUX data

Recoil energy reconstruction via S1 or S2

$E_{er,nr}$

Light $\Longrightarrow$ S1

$$E_{er} = \text{S1}\,\frac{1}{LY(E_{ref})}\,\frac{S_{ee}}{\mathcal{R}_e}$$

$\mathcal{R}_e(E_{er})$= relative ER scintillation efficiency

$$E_{nr} = \text{S1}\,\frac{1}{LY(E_{ref})}\,\frac{S_{ee}}{S_{nr}\mathcal{L}_{eff}}$$

$\mathcal{L}_{eff}(E_{nr}) = \frac{LY(E_{nr})}{LY(E_{ref})}|_{zero-field}$= relative NR scintillation efficiency

Charge $\Longrightarrow$ S2

$$E_{er,nr} = \text{S2}\,\frac{1}{g}\,\frac{1}{\mathcal{Q}_y}$$

$\mathcal{Q}_y(E_{er,nr})$ in #e/keV$_{er,nr}$ at E-field.

Recoil energy reconstruction via S1 + S2

$n_{ph} =$ S1 $\frac{1}{\epsilon 1}$ $= N_{ex} + \mathrm{r} N_i$

Recombination r is E-field, particle dependent

$E_{er,nr} = \frac{1}{\mathcal{QF}} \, W_{eff} \, (N_{ex} + N_i)$

$\mathcal{QF}=$ Electronic excitation quenching, $\mathcal{QF}_{er}=1$

$n_e =$ S2 $\frac{1}{g}$ $= (1\text{-r}) N_i$

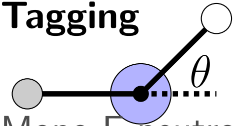
Modeling using experimental data and recombination theory.

Publicly available = NEST 1106.1613

See also 1007.3549, 1101.6080,1011.3990 and **See talk by A. Hitachi on Wednesday**

Light and Charge Yields at low energies

Tagging



Mono-E neutron, γ source

$\mathcal{L}_{eff}$ in LXe:1104.2587

LY(ER) in LXe:1209.3658

LY(ER) in LXe:1303.6891

$\mathcal{L}_{eff} S_{nr}$ in LAr:1306.5675

$\mathcal{Q}_y$(NR) in LAr:1406.4825

End-point

Mono-E neutron source

$\mathcal{Q}_y$(NR) in LAr:1402.2037

(2D) MC-data comparison

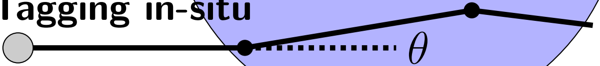
Wide-E neutron source, γ lines

$\mathcal{Q}_y$(NR) and $\mathcal{L}_{eff}$ in LXe: 1304.1427

Internal γ lines: ^{83m}Kr, ^{37}Ar, activ. ^{127}Xe

LY(ER) in LUX, DarkSide-50 and many R&D detectors

Tagging in-situ



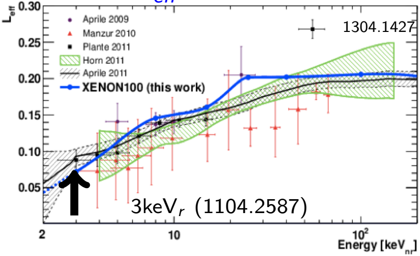
Mono-E neutron source

$\mathcal{Q}_y$(NR) and $\mathcal{L}_{eff}$ in LXe: see LUX UCLA DM '14 talk

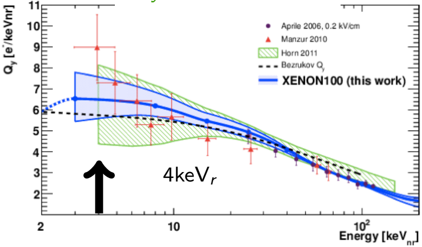
$$E_{nr} = E_n \frac{2 m_n M_{Xe}}{(m_n + M_{Xe})^2} (1 - cos\theta)$$

LXe response to NR via neutron tagging

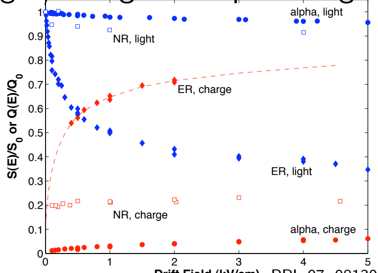
$\mathcal{L}_{eff}$ at zero field



$\mathcal{Q}_y$ at zero field



Light/Charge field quenching



PRL 97, 081302 (2006)

More results SOON

R&D detectors with 3D positioning

NeRiX@Columbia $\Rightarrow \mathcal{L}_{eff}$, $\mathcal{Q}_y$@E-field

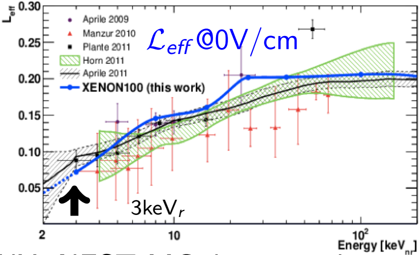
@U-M $\Rightarrow \mathcal{L}_{eff}$, $\mathcal{Q}_y$@E-field

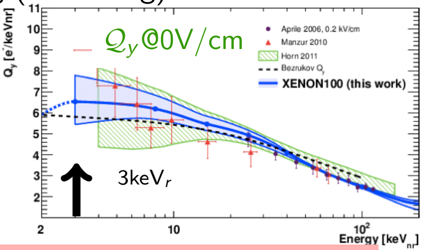
Field quenching at low-E NEEDED!

NEST predicts small field quenching

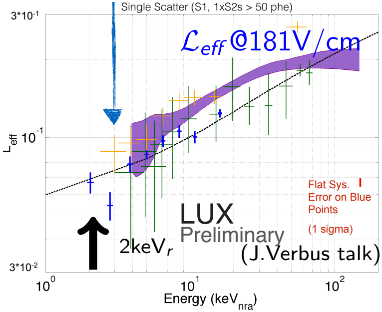
LXe response to NR in situ

XENON100: 2D MC-data matching (no scaling) 1304.1427

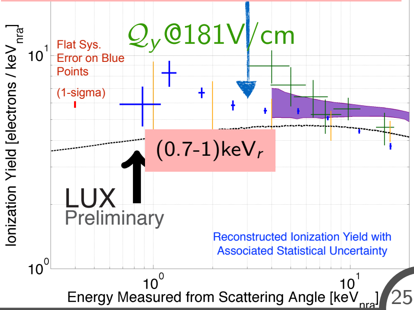




LUX: NEST MC-data matching

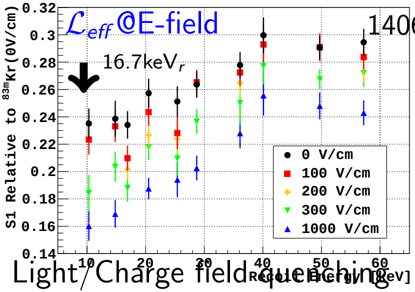


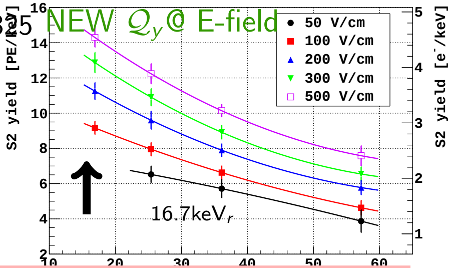
Double scatter with DD gun!



LAr response to NR via neutron tagging/end-point

Tagged neutron beam in SCENE (new results see 1406.4825)

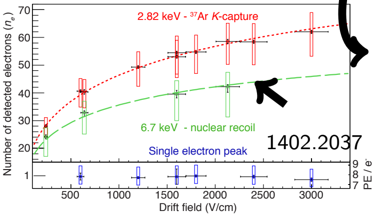




Light/Charge field quenching

Field quenching larger at low-E!

n-beam end point@LLNL



DS-50@200 $\frac{V}{cm}$ to optimize NR LY.

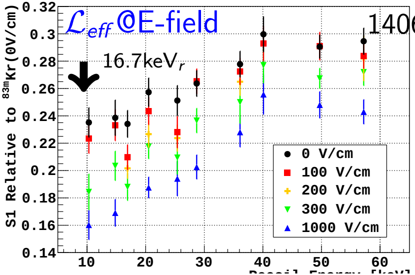
Question of field quench in LXe?

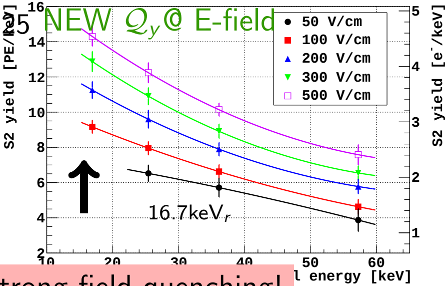
S2/S1 rejection ↗ with Field.

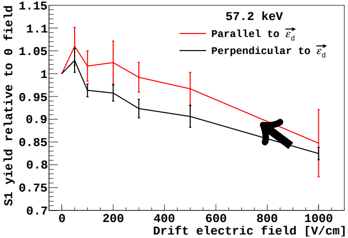
NR S1 ↘ with Field.

LAr response to NR - investigate directionality

Tagged neutron beam in SCENE (new results see 1406.4825)







Strong field quenching!

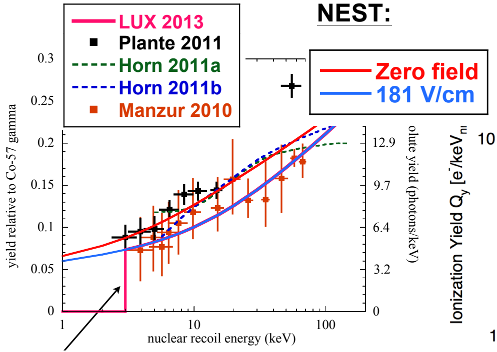
Directional effect on recombination?
via Columnar recombination
expect effect $\gtrsim$35keV$_r$
setup modified to test it
$\exists$ weak effect@57.2keV$_r$
More precise measurement needed!

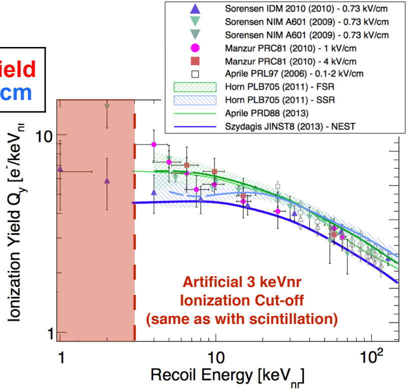
Light and charge yield in LUX

see talk of

Energy scale based on S1 + S2 and modeled using NEST.

Respective $\mathcal{L}_{eff} S_{nr}$ and $\mathcal{Q}_y$ (model NOT fit) in agreement with data





Conservative threshold used in LUX 2014 Result arXiv:1310.8214

Analysis ongoing with data and model driven estimates, including new measurements of $\mathcal{L}_{eff} S_{nr}$ and $\mathcal{Q}_y$ in situ.

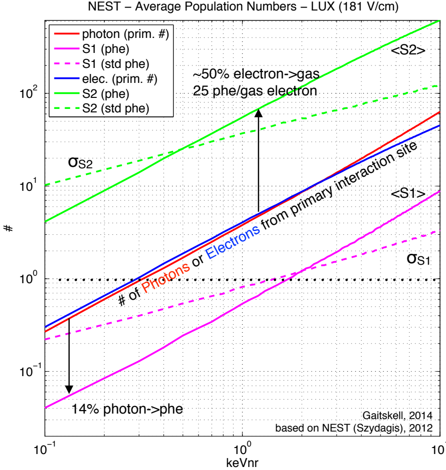
Energy threshold for S1+S2 analysis

$\geq$2PE threshold in S1 to avoid PMT dark counts in LXe.

$\geq \mathcal{O}(10)$PE in S1 for PSD in LAr.

$\geq$1 e^- threshold in S2 to avoid single electron background.

S2 is amplified, the limiting factor is S1 LY.



$LY_{zerofield}(122keV)$ | Threshold

LUX $8.8\frac{PE}{keV_{ee}} \Rightarrow 3keV_{nr}(2PE)$

PandaX$\sim 6.4\frac{PE}{keV_{ee}} \Rightarrow$ soon

Xe100 $3.8\frac{PE}{keV_{ee}} \Rightarrow 6.6keV_{nr}(3PE)$

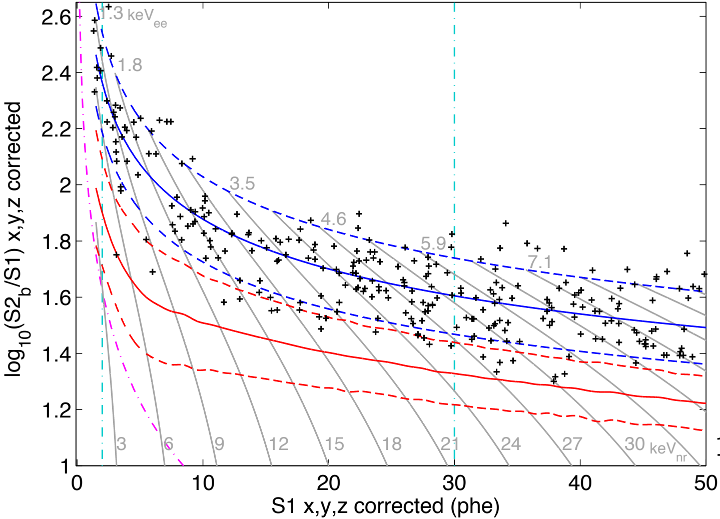
DS-50$\sim 8\frac{PE}{keV_{ee}} \Rightarrow 35keV_{nr}(70PE)$

ArDM$>2\frac{PE}{keV_{ee}} \Rightarrow$ soon

S2 ONLY analysis
promising for subKeV threshold

Most sensitive "standard" WIMP search - LUX

Observation consistent with background only hypothesis (PL).
ER background understood. New run with lower ER background.



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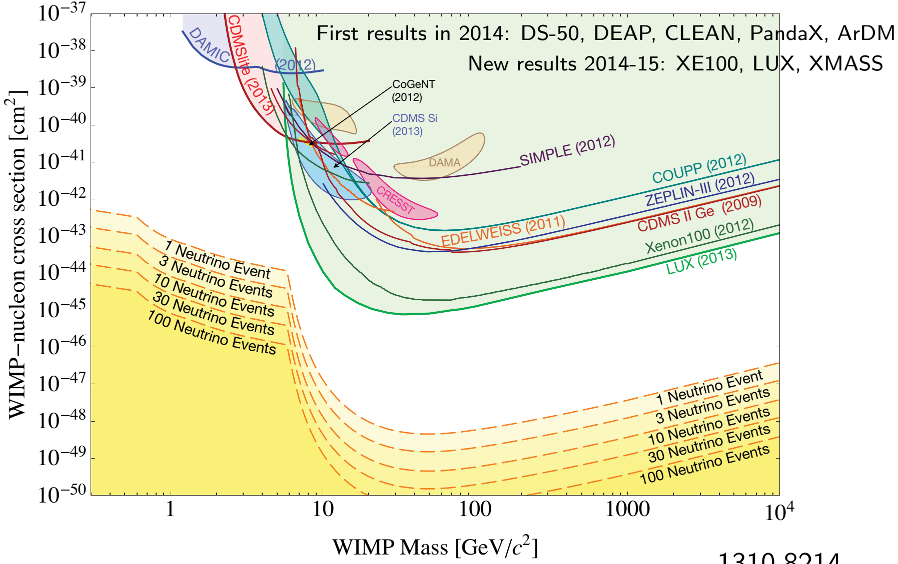
Current limits



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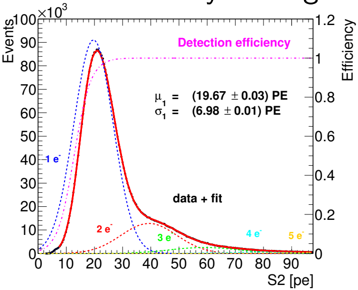
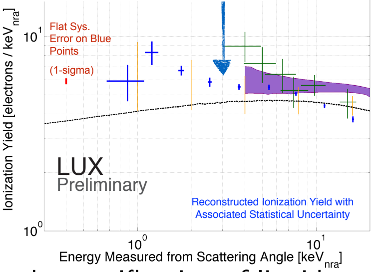
Low mass WIMP S2-only studies to come

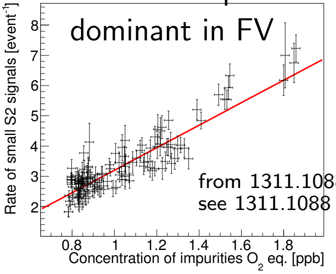
Efficiency to single e$^-$ ✓



Yield at low-E ✓



Photoionization of impurities



dominant in FV

from 1311.1088
see 1311.1088

Further purification of liquid
to reduce 1,2,3 e$^-$ background
optimize threshold

Minimize delayed e^- extraction

with ∼100% extraction

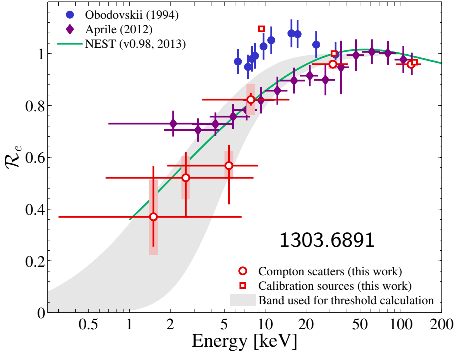
FV with S2 width

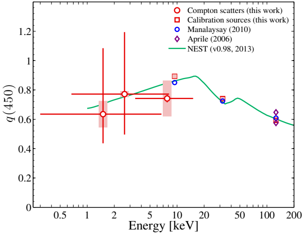
1011.6439, 1104.3088

Energy scale for DM coupling to electrons

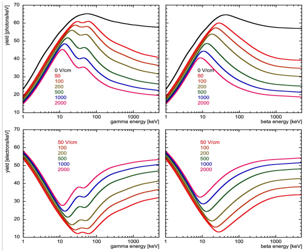
Electronic recoil scale with field quenching.

LY(ER) at zero field in LXe   Field quenching at 450V/cm





1310.8214v2



NEST validation ⇑ predictions ⇒

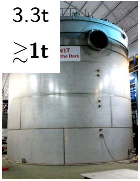
More measurements in LXe, LAr

$\mathcal{Q}_y(ER)$ at E-field soon

Noble liquid detectors - Future

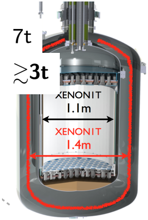
XENON1T
construction

3.3t
$\gtrsim$**1t**



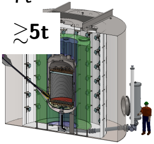
XENONnT
under select.

7t
$\gtrsim$**3t**



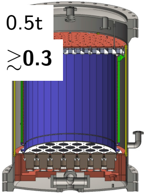
LZ
under select.

7t
$\gtrsim$**5t**



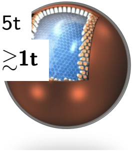
PandaX Ib
∃ III phase

0.5t
$\gtrsim$**0.3**



XMASS-1.5

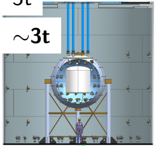
5t
$\gtrsim$**1t**



∃ III phase
25/10t

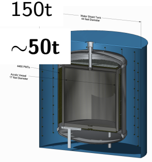
DS-G2
under selec.

5t
$\sim$**3t**



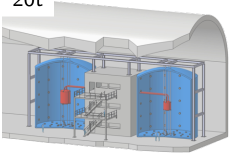
DEAP-50t
R&D

150t
$\sim$**50t**



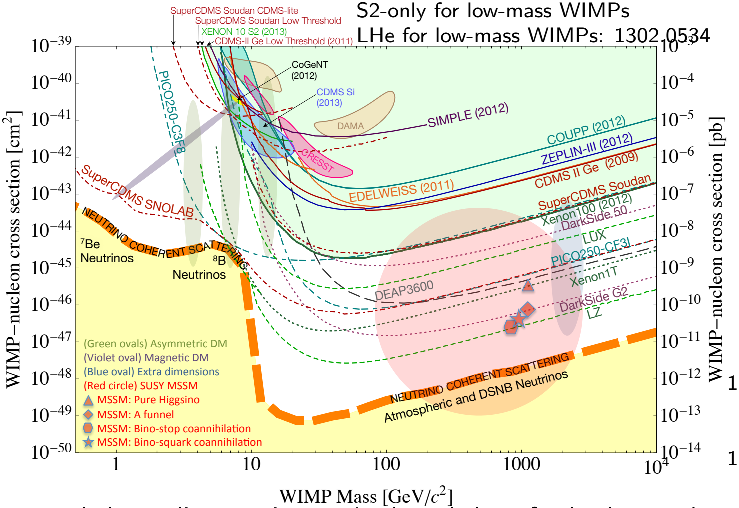
Darwin
R&D LXe/LAr

20t



Noble liquids - sensitivity to WIMPs ("vanilla" SI interaction)

S2-only for low-mass WIMPs
LHe for low-mass WIMPs: 1302.0534



1307.5458

1310.8327

Progress below ν line require precise knowledge of ν background, use of annual modulation or directional detection, target complementarity

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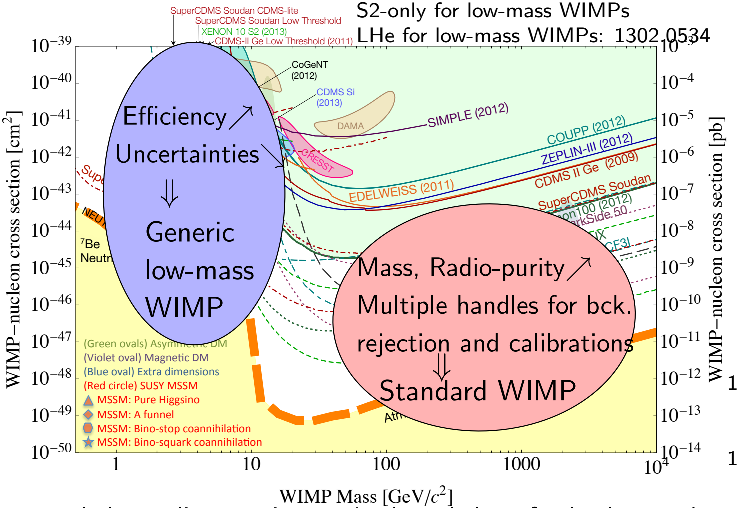

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