Direct Dark Matter Search with XENON100

Emilija Pantic

UCLA University
on behalf of the XENON100 collaboration

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Aspen 2013 - Closing in on Dark Matter

Direct WIMP detection

Assume DM has non-gravitational interactions = WIMP and interacts with nucleus.
Look for recoil of DM-nucleus scattering.
Measure the event rate (events/kg/keV/day)

$$\frac{dR}{dE_{nr}} = \frac{\rho_\chi}{m_\chi m_A} \int_{v_{min}}^{v_{esc}} \frac{d\sigma}{dE_{nr}} \; v \, f_\oplus(\vec{v}, \mathbf{t}) d^3 v$$

Many types of DM-nucleus interactions:
Spin-independent: $\propto$ nucleon number
Spin-dependent: $\propto$ spin of unpaired nucleon
Cross-sections are small
Large target mass needed.

Non-relativistic DM
$E_{nr} < 100$keV
minimal DM velocity required for E_{nr}

Liquid Xenon as a WIMP target material

DM signal: tiny rate and energy deposition

Large mass number (A∼132) for high SI WIMP rate @ low energy threshold.

∼ 50% isotopes with unpaired neutron for SD WIMP.

Efficient, fast scintillator for low energy threshold.

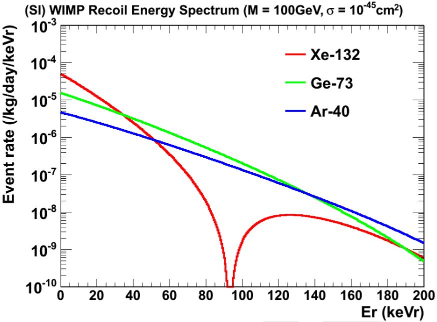
Relatively inexpensive to scale for very large target mass.

Background

Good self-shielding (ρ =3gcm^{-3}).

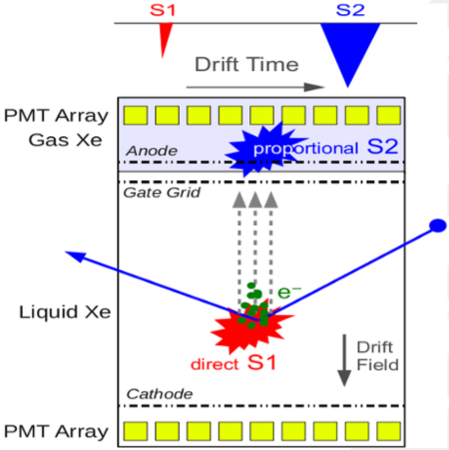
Low intrinsic radioactivity:

Multiple background discrimination

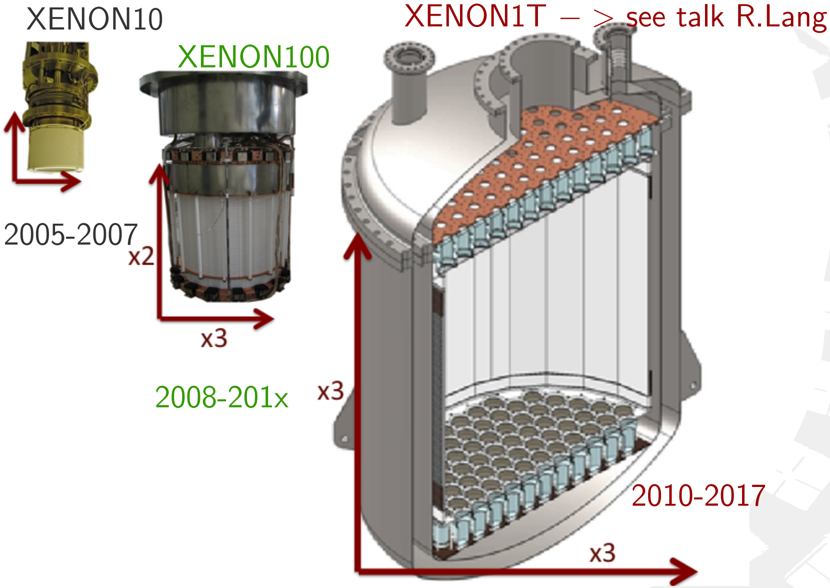


Dual phase LXe Time Projection Chamber

- Interactions in the LXe produce Excitation and Ionization.
- Excitation leads to scintillation light emission.
- With applied electric field part of ionization electrons are drifted and extracted from liquid
- In the gas phase, electrons are further accelerated producing proportional scintillation.
- Both promt scintillation signal (S1) and proportional scintillation signal (S2) are recorded by the arrays of PMTs.



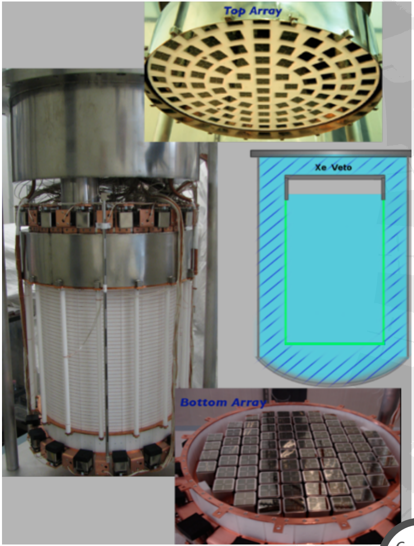
The XENON program



The XENON100 detector operating at LNGS

Gran Sasso underground laboratory has average rock coverage of 1400 m.

- 161 kg of LXe. 62 kg as active target: TPC with 30cm drift x 30cm diameter. LXe active veto 4cm thick, $E_{threshold}$ <200 keVee.
- 242 radiopure PMTs 1“×1“ Top array (QE ∼23%). Bottom array (QE∼33%)
- Homogenous electric field: E_{drift}=530V/cm. $E_{extraction}$=∼12kV/cm.
- Shielding : 5cm Cu,10cm PE, 15+5cm Pb, 20cm $H_2 0$ Radiopure detector material Cryocooler, FTs outside.
- Radiopure Xe:Kr destillation column.



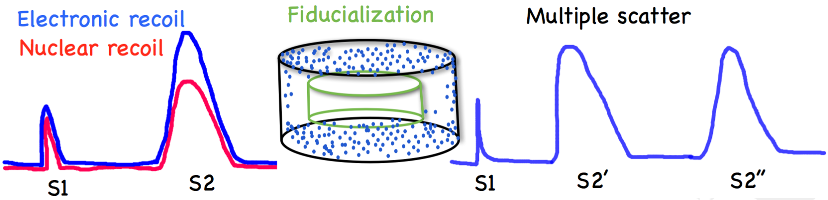
Background rejection in dual phase LXe TPC

Ionization/Scintillation ratio (S2/S1)

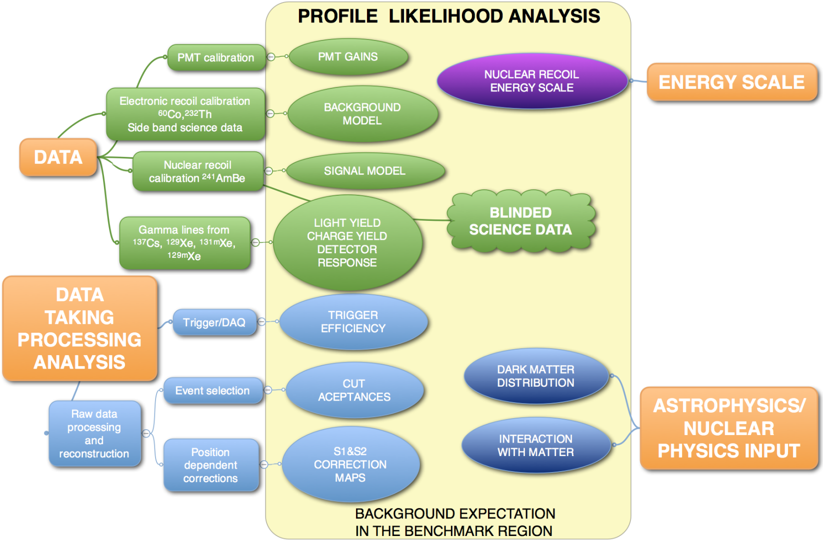
Electronic and nuclear recoil events have different energy sharing.

3D event reconstruction : (XY) from top PMT hit pattern and Z = time between the S1 and S2 signal

Fiducialization and LXe self shielding: Surface sees most of environmental background, radioactive deposits, "edge" effect.
Multiple scatter rejection: mean free path(γ) < m.f.p(n)< m.f.p (χ)$\rightarrow \infty$.



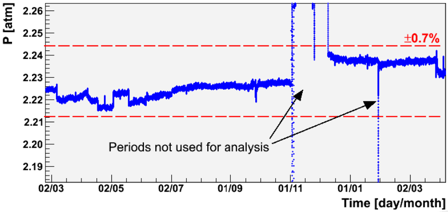
XENON100: Analysis overview

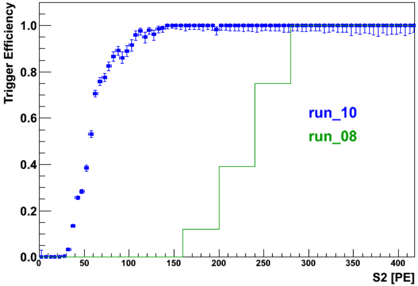


arXiv: 1207.3458, 1107.2155, 1104.2549

Dark matter search run: 225 live days

- Feb 2011 - March 2012
- Excellent stability of the detector parameters.
- Periods of maintenance excluded from the analysis.
- 100% trigger efficiency for events with S2>150PE.
- LXe purity: Electron life time from 374 to 611 μs.
- Improved noise conditions. S1 Energy threshold = 3PE ($\sim$6.6 keVnr)





Nuclear recoil energy scale via S1 signal

From measured
S1(PE) to NR energy:

$$E_{nr} = S1 \frac{1}{\mathcal{L}_y} \frac{S_{ee}}{S_{nr}} \frac{1}{\mathcal{L}_{eff}}$$

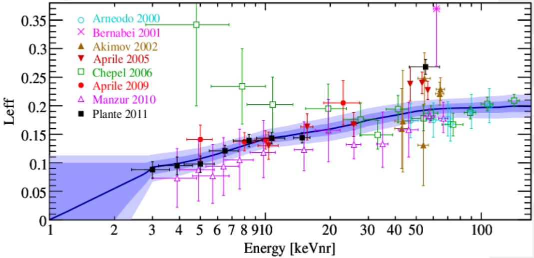
$\mathcal{L}_{eff}(E_{nr}) = \frac{\mathcal{L}_y^{NR}(E_{nr})}{\mathcal{L}_y^{ER}(E{=}122keV_{ee})}$ at zero-field.

measured at different energies

interpolation to $122keV_{ee}$

2.28 ± 0.03 PE/keV_{ee}.

global fit of the available direct scattering data



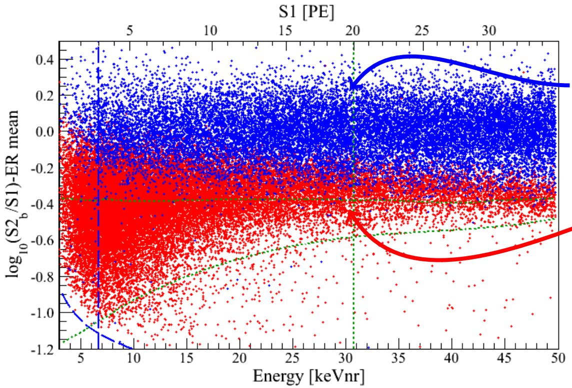
Plante et al., PRC 84, 045805 (2011)

Light quenching due to electric field

S_{ee}=0.58, S_{nr}=0.95

Electronic/nuclear recoil calibration data

~1% accuracy of S1,S2 position corrections using various γ lines.



ER calibration data

^{60}Co and new ^{232} Th source

35× science data

NR calibration data

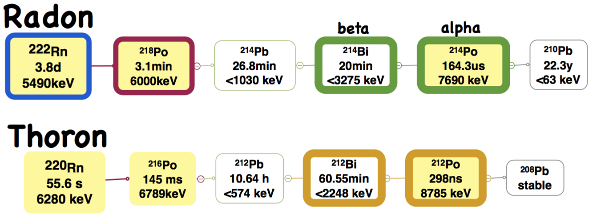
AmBe source

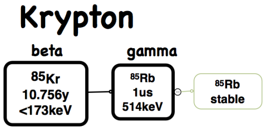
beginning and end of run

~99.5% ER rejection @ 50% NR acceptance

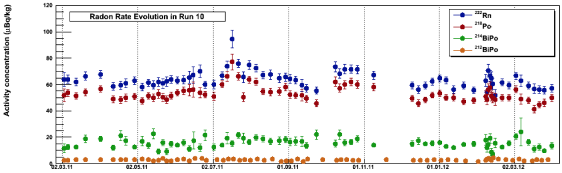
Electronic recoil background: Rn and Kr

Measure Rn concentration via α decay, its daughters via delayed β-α decay.
Measure Kr concentration via 1) delayed β-γ decay $= 18\pm8$ ppt and 2) Rare Gas Mass Spectroscopy $= 19\pm4$ ppt



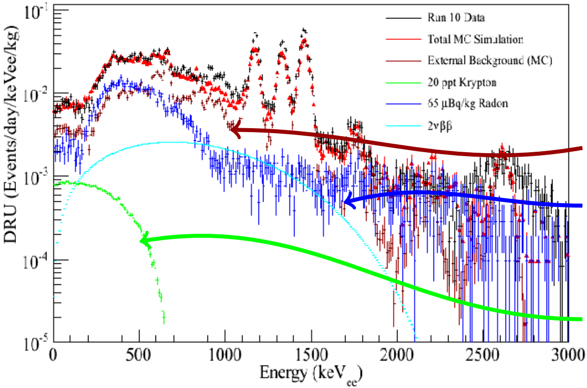


Kr/Xe separation technique with ultra-sensitive rare gas mass spectrometry at MPIK



Electronic recoil background

ER background: 10kg FV no veto cut



$$\text{mDRU} = \frac{events}{day \times keV_{ee} \times t}$$

main background

γ contamination

^{222}Rn contamination via α tagging and delayed coincidence (DC)

Reduced ^{85}Kr

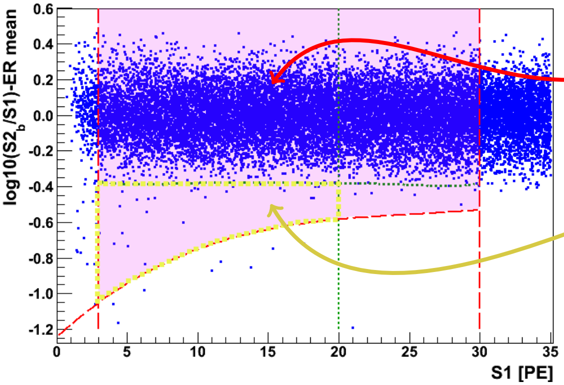
19±4 ppt via RGMS

18±8 ppt via DC

^{85}Kr reduction $>$ a factor of 10 with respect to previous run. Background level (34kg) = 5.3±0.6 mdru with active veto before S2/S1 discrimination.

Fiducial volume and signal region selection

Fiducial Volume optimized on ER calibration data = 34kg.



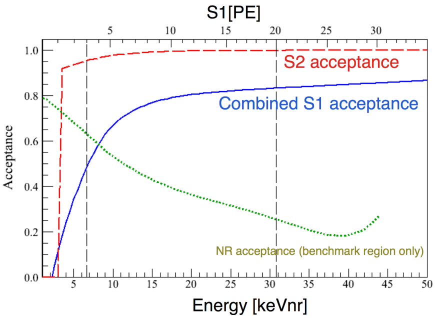
Signal region
above ∼97% NR quantile
S1 range = 3-30PE

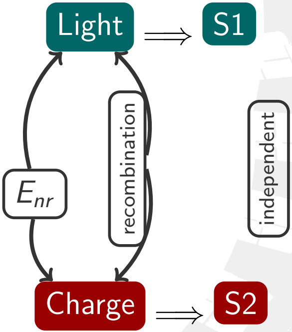
Benchmark region
cross-check
for background prediction
above ∼ 97% NR quantile
below 99.75% rej.line
S1 range = 3-20PE

No hard cut on a signal region in discriminating parameter space. Full use of the calibration data to measure the fractions of background and expected signal.

Cuts acceptance in 34 kg FV

$$\frac{dR}{dS1} \approx \epsilon_1(S1) \int \frac{dR}{dE_{nr}} \, \epsilon_{2,E}(E_{nr}) \, pdf(S1) \, E_{nr} \, dE_{nr}$$

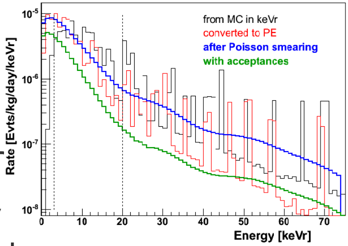




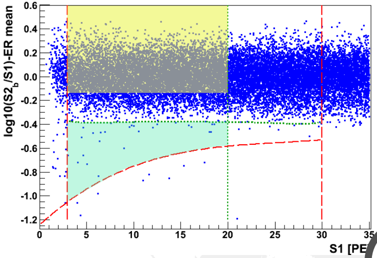
S1 and S2 treated independently. Exception: S2 threshold cut influences S1 via energy sharing

Background expectation in the benchmark region

Nuclear recoil background
(α,n), spont. fission and μ-induced n
MC simulation



Electronic recoil background from
γ in the detector and LXe radioactivity
by scaling ER calibration data

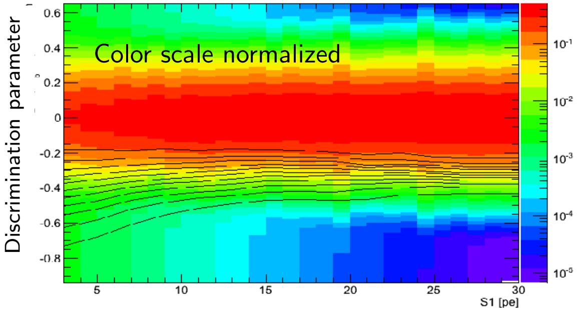


For 224.6 live days$\times$34 kg :
(0.17 +0.12 -0.07) NR and
(0.79$\pm$0.16) ER events.
Total background: 1.0 $\pm$0.2 events.

Signal/Background model for Profile Likelihood

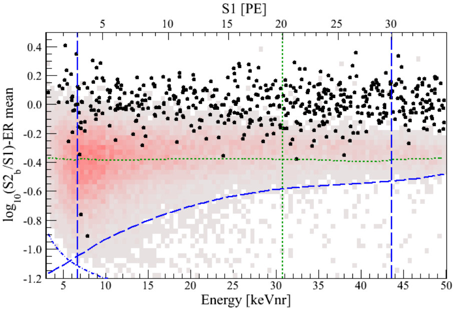
A statistical model to include systematic detector uncertainties

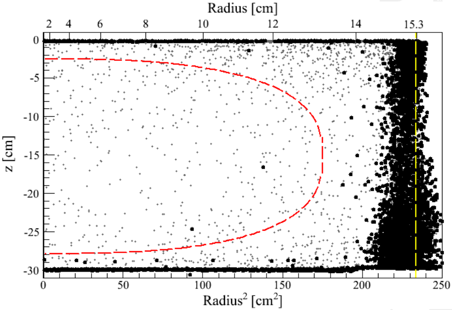
$$\mathscr{L} = \underbrace{\mathscr{L}_1(\sigma, N_b, \epsilon_s, \epsilon_b, \mathcal{L}_{eff}, v_{esc}; m_\chi)}_{\text{DM measurement}} \underbrace{\mathscr{L}_2(\epsilon_s)}_{\text{sig model}} \underbrace{\mathscr{L}_3(\epsilon_b)}_{\text{bck model}} \underbrace{\mathscr{L}_4(\mathcal{L}_{eff})}_{\text{energy scale}}$$



Background model from ER calibration data. Signal model from NR calibration data. Signal-like events are equally distributed between the bands

224.6 live days × 34 kg : Event distribution





2 events observed with 1±0.2 events expected

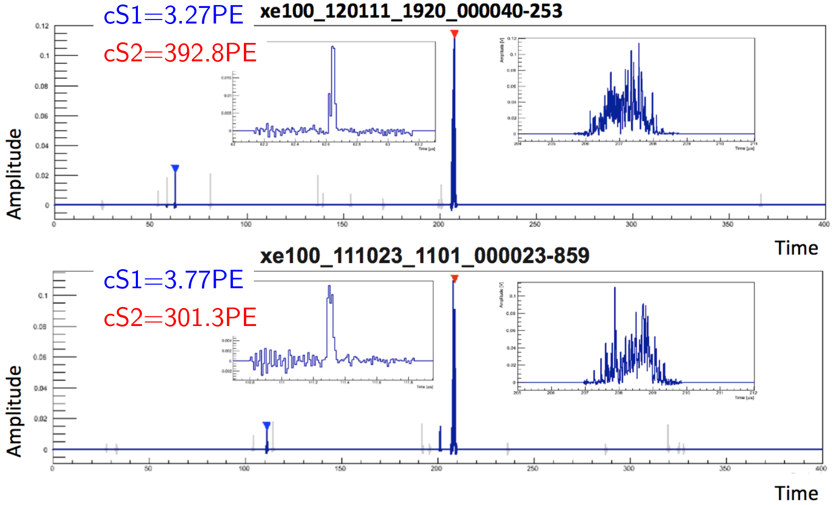
26.4% probability that background fluctuated

Profile Likelihood cannot reject the background only hypothesis

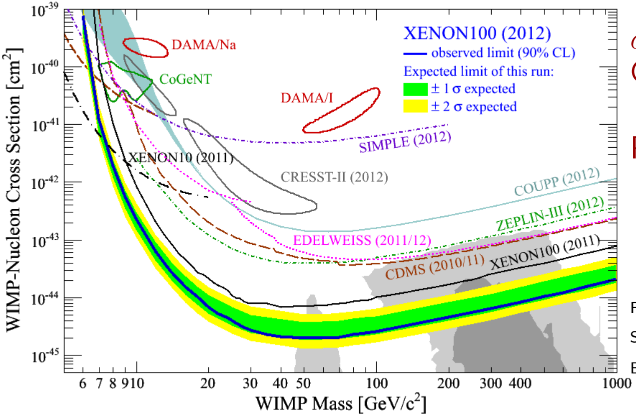
No significant excess due to a signal seen in XENON100 data.

Candidate Events

Valid events on visual inspection.



XENON100 upper limit for SI WIMP interaction



$\sigma = 2.0\,10^{-45}\mathrm{cm}^2$
@ 55 GeV/c^2

PRL 109, 181301

Fowlie et al., arXiv:1206.0264

Strege et al., JCAP 1203, 030(2012)

Buchmueller et al., arXiv:1112.3564

Simple DM halo: DM density = 0.3GeV/cm^2
Maxwellian velocity distribution with v_0=220km/s , v_{esc}=544km/s

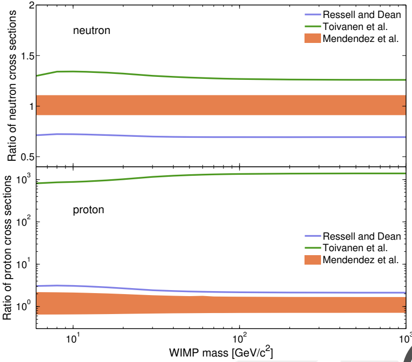
XENON100 upper limit for SD WIMP interaction

Use same data set and data analysis to derive limits on SD interaction for pure proton/pure neutron coupling.

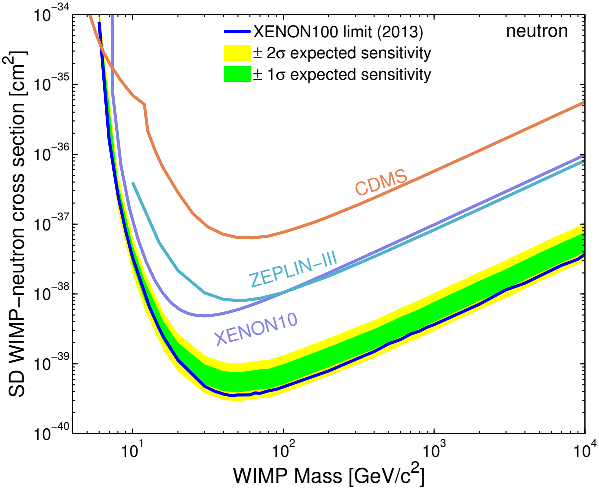
We use the new calculations by Menendez et al. superior agreement between the calculated and measured energy spectra of the ^{129}Xe, ^{131}Xe nuclei.

3 Nuclear Models compared:
Ressell and Dean (Bonn-A)
Toivanen et al., (CD-Bonn)
Menendez et al. (ch. EFT currents)

result for pure neutron coupling is robust;
result for pure proton coupling strongly depends on NM.



XENON100 upper limit for SD WIMP interaction



pure neutron

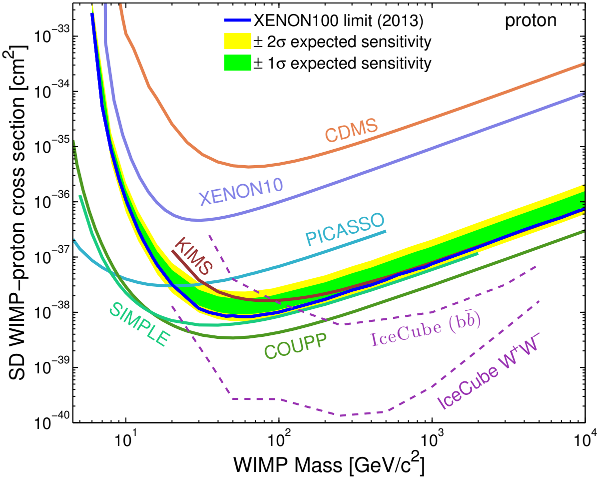
σ=3.5 10^{-40}cm^2
@ 45 GeV/c^2

arXiv:

unpaired neutron in ^{129}Xe, ^{131}Xe

Simple DM halo: DM density = 0.3GeV/cm^2
Maxwellian velocity distribution with v_0=220km/s , v_{esc}=544km/s

XENON100 upper limit for SD WIMP interaction

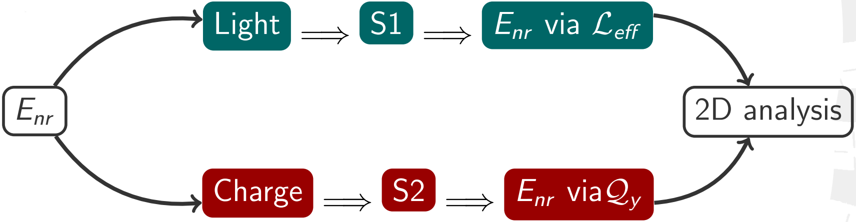


pure proton

Simple DM halo: DM density = 0.3GeV/cm^2
Maxwellian velocity distribution with v_0=220km/s , v_{esc}=544km/s

XENON Program: Ongoing

XENON100 new science data run about to start:
Prove further reduction of Krypton and Radon.
More calibration data for background studies.



2D Monte Carlo/data comparison for nuclear recoils
Extract/measure S2 energy scale for nuclear recoils
Search for light dark matter in low-energy with S2-only
Perform 2D analysis: reduce uncertainties.

XENON Program: Ongoing

Measure S1 energy scale for electronic recoils @Columbia,UZH:
Search for annual modulation in low-energy electronic recoil events
Search for axions and super-WIMPs.

XENON1T construction about to start (see talk of R.Lang)

Thank you!