Advances and Challenges in Dark Matter Searches with Noble Liquids

Emilija Pantic

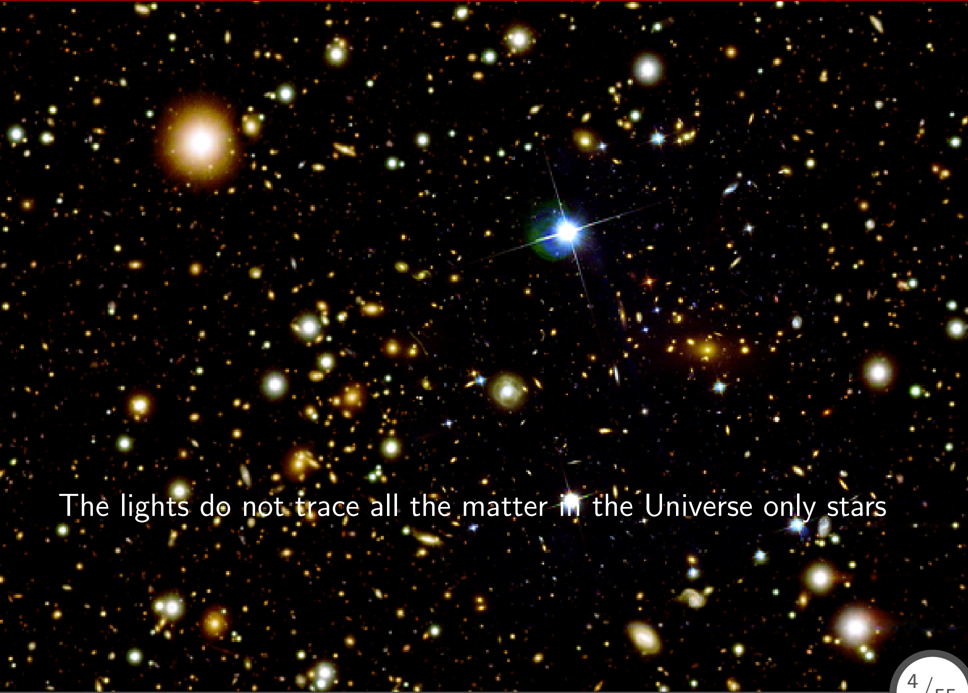
UCLA

UC Davis, 17th of April, 2013

Overview

- Brief intro to Dark Matter
- Direct detection technique
- Advances of LXe DM detectors: XENON
- Advances of LAr DM detectors: DarkSide
- Challenges and strategies for future detectors

The lights do not trace all the living matter at Earth only humans!



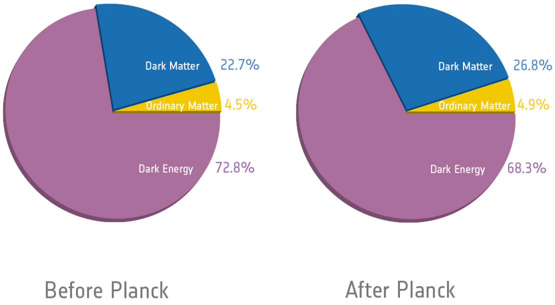
The lights do not trace all the matter in the Universe only stars

The lights do not trace all the matter in the Universe only stars and intergalactic gas!

Gravity traces all the matter!
It tells us that there must be more mass present that is seen.

Dark Matter Share as of 2013

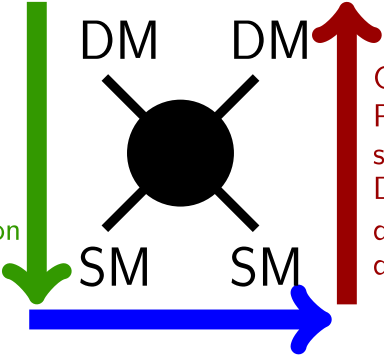
Dark matte is about 5 times as heavy as all the matter we know.



Dark Matter candidate is neutral, cold, stable on cosmological scales and has the right relic density.
Existence of dark matter is perhaps the strongest evidence for physics beyond the standard model.

Dark Matter parameter space is Huge

DM $\in$ {LSP, Axion, KKP, Asymmetric DM,...}



INDIRECT DETECTION
search for SM byproducts of DM annihilation

COLLIDER PRODUCTION
search for DM production direct or via decay of new particles

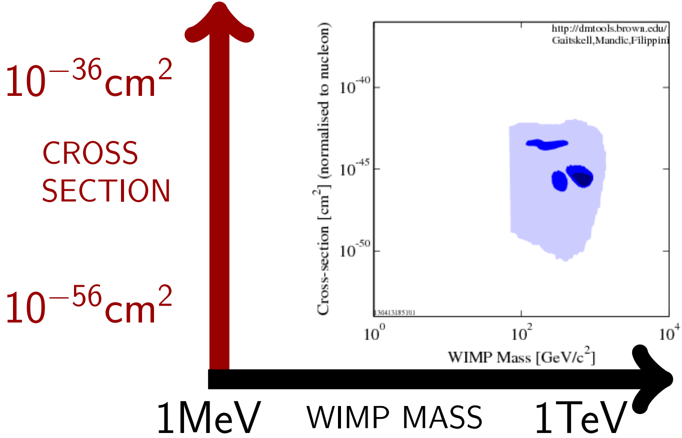
DIRECT DETECTION
search for DM scattering off SM particles
simple scenario: detector on Earth passing through a DM halo

WIMP Candidate: χ LSP

Weakly **I**nteracting **M**assive **P**articles are one of the most attractive TYPE of candidates.

Lightest Sypersymmetric Particle is stable through R-parity.

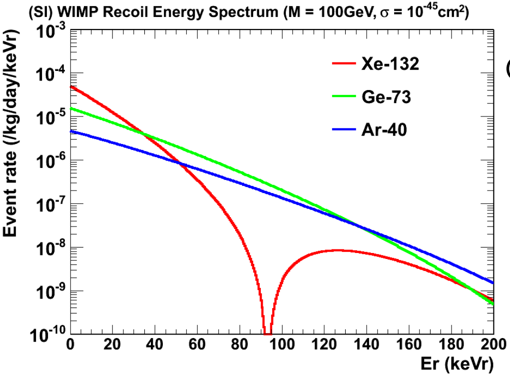
SUSY provides sharp predictions for experiments.



WIMP Direct Detection

SIGNAL = single nuclear recoil with energy E_r.
Consider elastic spin-indepenent WIMP-nucleon scattering.

$$\frac{dR}{dE_r} = \frac{\sigma_{SI}^{nucleon}}{2\mu^2_{nucleon}} A^2 F^2(E_{nr}, A) \quad \frac{\rho_\chi}{m_\chi} \quad \int_{v_{min}}^{v_{esc}} \frac{f_\oplus(\vec{v}, \mathbf{t})}{v} d^3v$$



Quasi-exponential spectrum
Recoil energy <100keV$_r$

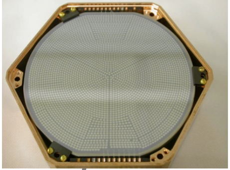
Integrated rate
< 0.01 events/kg/day

Choose your technology and detection channel(s)

HEAT

COUPP, PICASSO

HEAT+CHARGE



CDMS, EDELWEISS

HEAT+LIGHT

LIGHT+CHARGE

XENON, DarkSide, LUX, ZEPLIN, PANDA-X, ...

CHARGE

CoGeNT

DM-TPC

...

LIGHT

DAMA/LIBRA

DEAP, XMASS

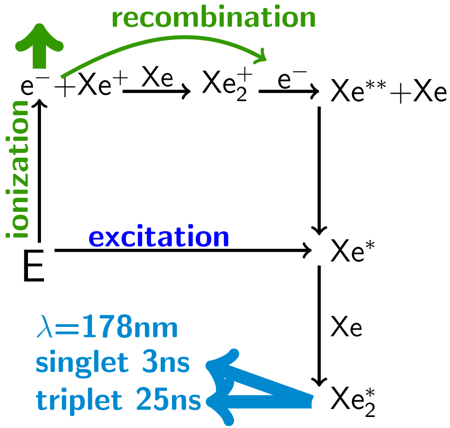
...

	LXe
Mass number	131.3
Density [g/cm^3]	2.94
Boiling point [K@1bar]	165
e^- mobility [cm^2/Vs]	2200
LY [ph/MeV, E=0]	42000
Radioactive isotopes	^{136}Xe

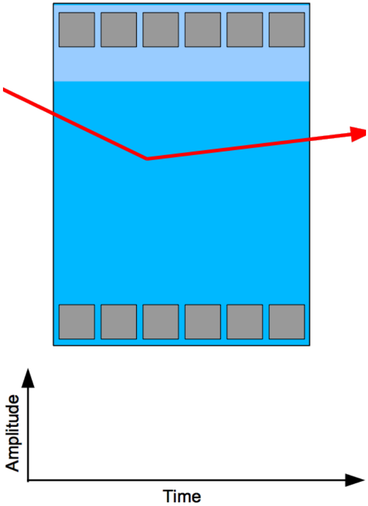
100 scientists from 16 institutions.

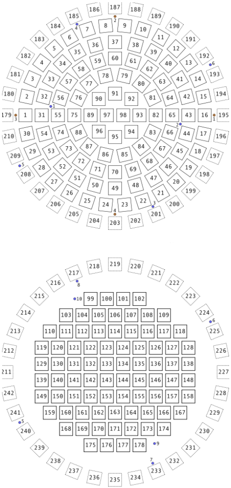
Columbia University New York
Rice University Houston
University of California Los Angeles
Purdue University
Universität Zürich
Universidade de Coimbra
Laboratori Nazionali del Gran Sasso
Max-Planck-Institut Heidelberg
INFN and Università di Bologna
Jiao Tong University Shanghai
Willhelms Universität Münster
Subatech Nantes
NIKHEF Amsterdam
Universität Bern
J. Gutenberg-Universität Mainz
Weizman Institute Rehovot

Interactions in Xenon

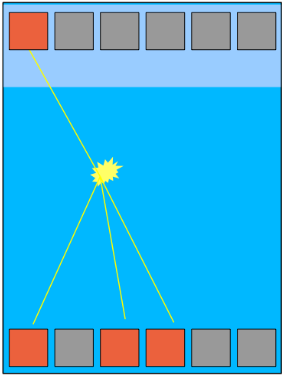


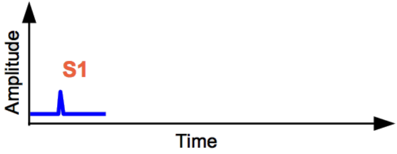
Dual phase LXe Time Projection Chamber

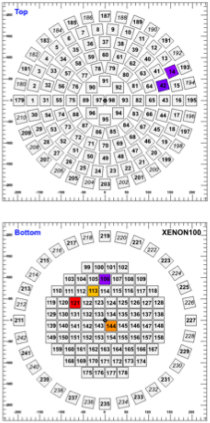




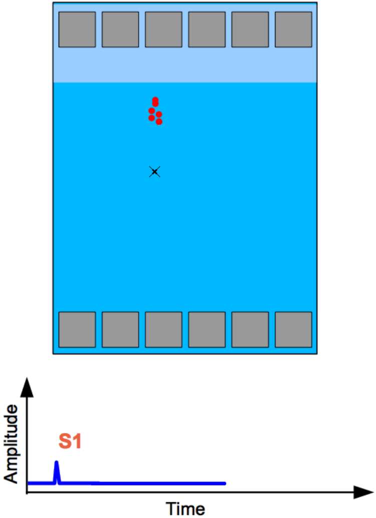
Dual phase LXe Time Projection Chamber

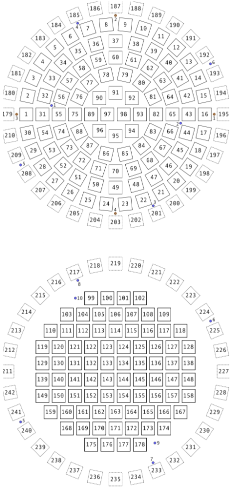




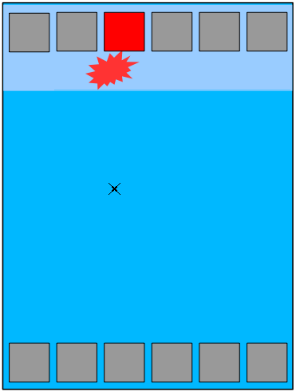


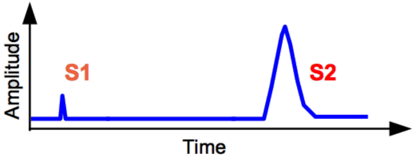
Dual phase LXe Time Projection Chamber

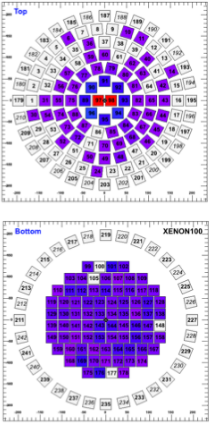




Dual phase LXe Time Projection Chamber



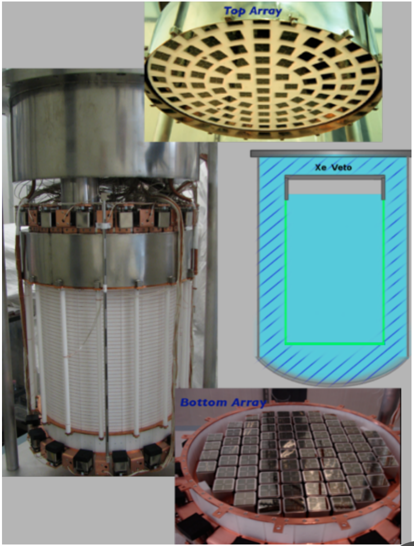




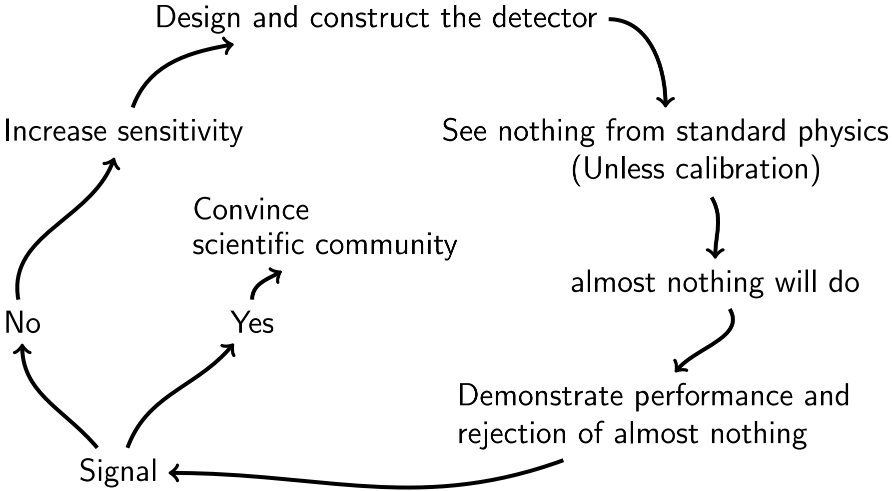
The XENON100 detector operating at LNGS

- 161 kg of LXe. 62 kg as active target: TPC with 30cm drift x 30cm diameter. LXe active veto 4cm thick.
- 98 (top) + 80 (bottom) + 64 (veto)
  1" PMTs QE (23-33%)
- Homogenous electric field:
  E_{drift}=0.53kV/cm.
  $E_{electroluminescence}$=∼12kV/cm.

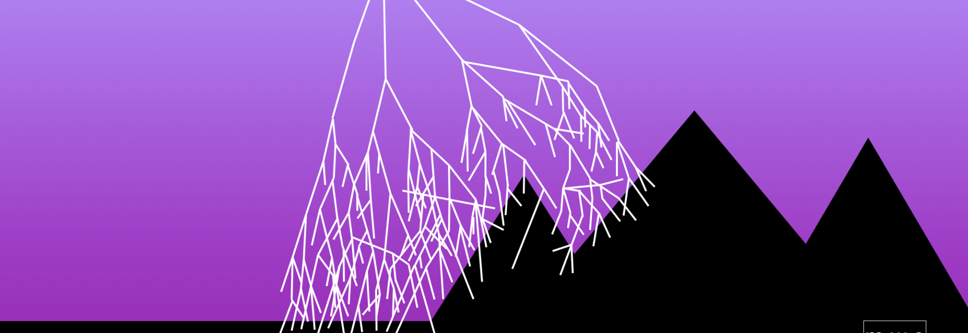
Last DM search run
225 live days in 2011/2012



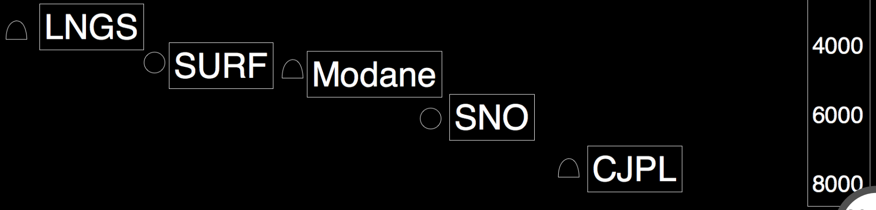
Direct detection search strategy



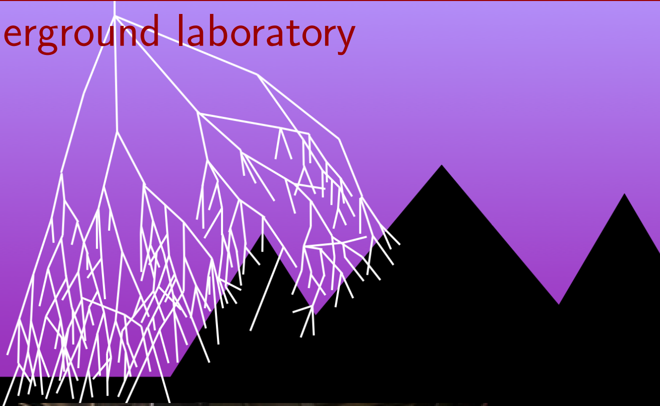
Shielding experiment from cosmic rays



Cosmic rays create high-energy muons in the atmosphere.
muons induce high-energy neutrons



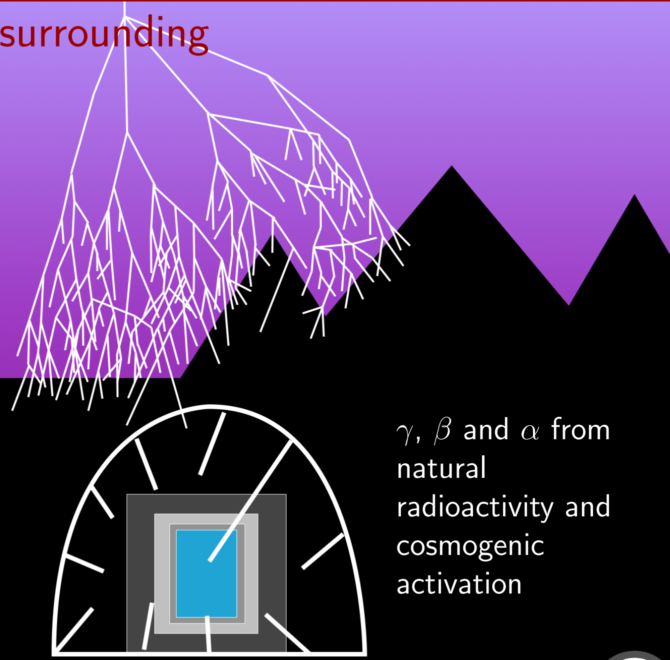
Gran Sasso Underground laboratory



μ flux $\sim 1\ \mathrm{m^{-2}h^{-1}}$

XENON
DarkSide
CRESST-II
DAMA/LIBRA

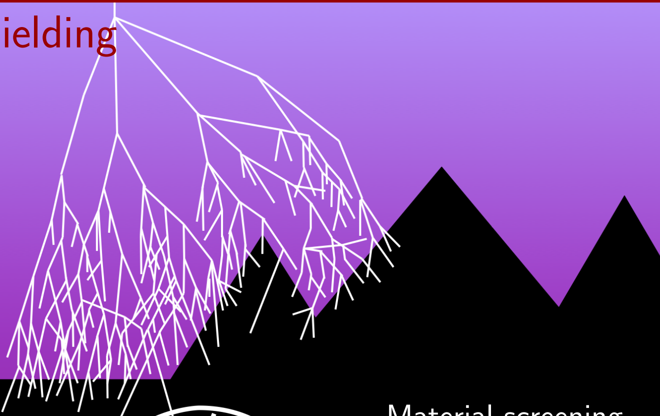
Shielding from surrounding



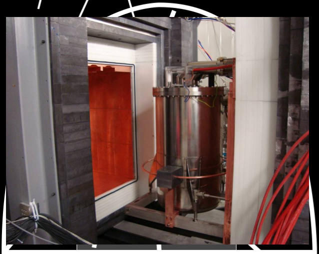
radiogenic neutrons from (α,n) reactions and spontaneous fission

γ, β and α from natural radioactivity and cosmogenic activation

XENON100 Shielding



5cm Cu
20cm PE
15+5cm Pb
20cm H_20



Material screening via
Ge spectroscopy
Mass spectroscopy
Neutron Activation Analysis

Background rejection in dual phase LXe TPC

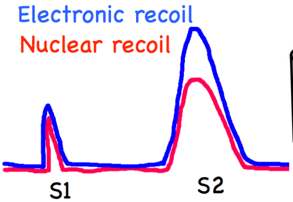
Ionization/Scintillation ratio (S2/S1):

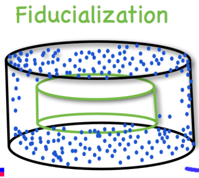
Electronic and nuclear recoil events have different energy sharing.

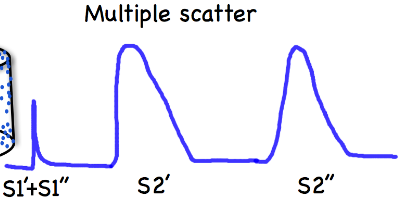
3D event reconstruction and LXe self shielding:

Fiducialization: Surface sees most of environmental background

Multiple scatter rejection: mean free path(γ) $<$ m.f.p(n)$<$ m.f.p (χ)$\to \infty$.

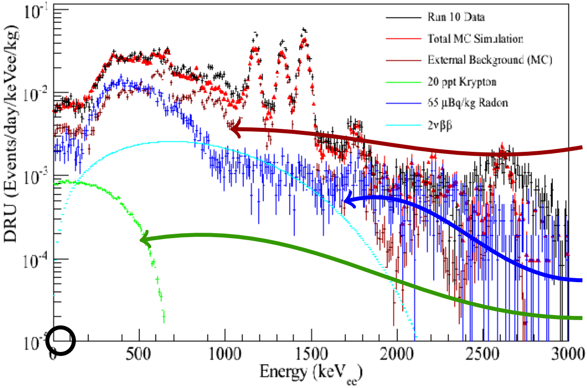






Electronic recoil background = 5mDRU

ER background: 10kg FV no veto cut



$$DRU = \frac{events}{day \times keV_{ee} \times kg}$$

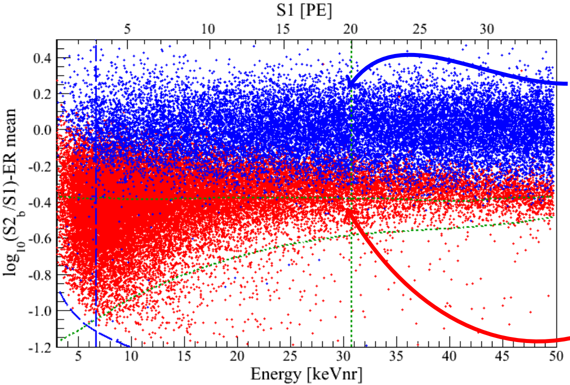
main background γ contamination PMTs, PMTs bases cryostat

65μBq/kg of ^{222}Rn in LXe

20ppt Kr in LXe

Kr reduction via cryogenic distillation.
Recently achieved Kr <1.3ppt.

Electronic recoil background rejection via S2/S1



ER Background model

ER calibration data

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

35× science data

Signal model

NR calibration data

AmBe source

beginning and end of run

∼99.5% ER rejection @ 50% NR acceptance.

XENON100 Analysis overview

arxiv:1207.3458

PROFILE LIKELIHOOD ANALYSIS

Background expectation in benchmark region

DATA

- PMT calibration ⟶ PMT gains
- Gamma lines ⟶ Charge/light yield
- ER calibration) (^{60}Co, ^{232}Th, side band) ⟶ Background model
- NR calibration (AmBe) ⟶ Signal model

Blinded science data

DATA PROCESSING RECONSTRUCTION

- Trigger/DAQ ⟶ Trigger efficiency
- Event selection ⟶ Cuts acceptance
- Spatial dependence ⟶ XYZ corrections

NR ENERGY SCALE

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

ASTROPHYSICS

Dark matter density, velocity distribution

NUCLEAR PHYSICS

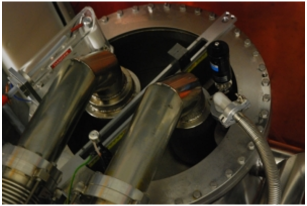
Elastic SI DM-nucleon interaction

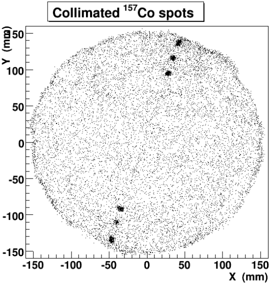
X-Y position resolution studies

Training of (x,y) position reconstruction algorithms via Monte Carlo simulated S2 distributions for top PMTs.

A dedicated setup to test them
Pb collimator (2mm opening)
^{57}Co data at different radii.
Resolution <3mm.

Primary algorithm with the most homogeneous response.
Other algorithms used in quality cuts.

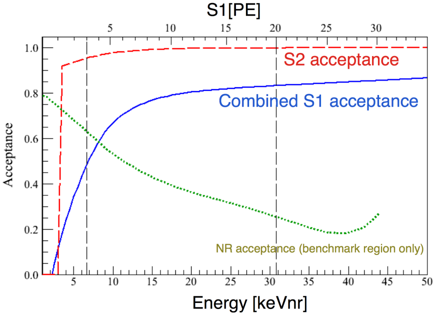


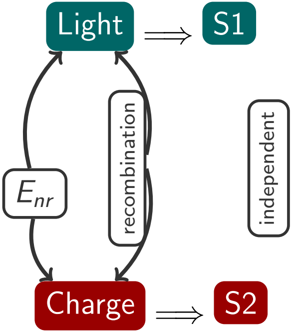


Cuts acceptance in S1

Cuts ={single scatter, threshold, quality, consistency ...}

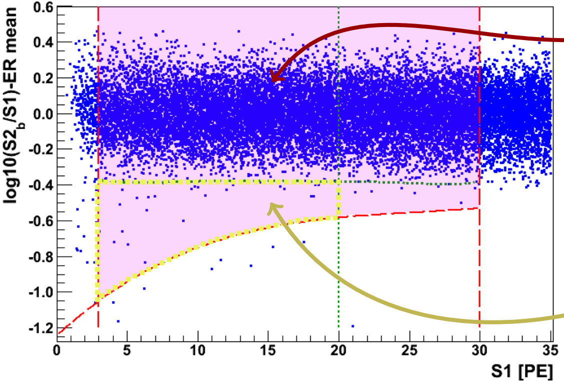
$$\frac{dR}{dS1} \approx \epsilon_1(S1) \int \frac{dR}{dE_{nr}} \epsilon_{2,E}(E_{nr}) \; pdf(S1) \; E_{nr} \, dE_{nr}$$





Fiducial volume and signal region selection

Fiducial Volume optimized on ER calibration data = 34kg.

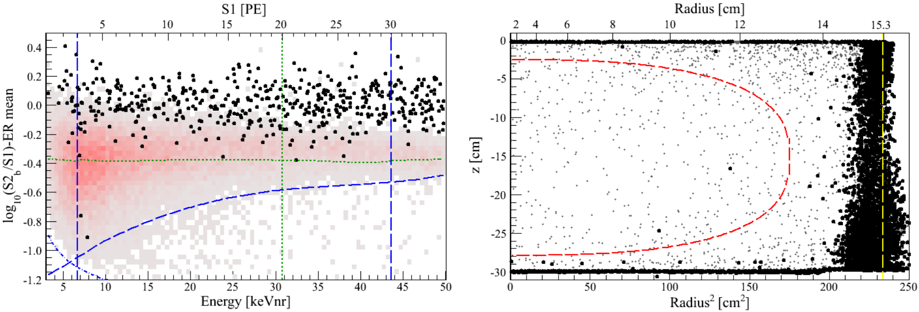


PL Signal region
S1 range = 3-30PE

Benchmark region
for background prediction
1.0 ± 0.2 events

Profile Likelihood approach: No hard cut in discriminating parameter space.

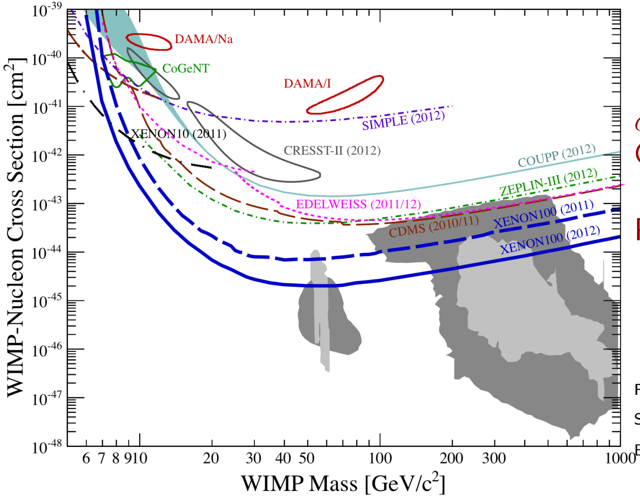
224.6 live days×34 kg: Event distribution



2 events observed with 1±0.2 events expected

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

XENON100 upper limit for SI WIMP interaction



σ=2.0 10^{-45}cm^2
@ 55 GeV/c^2

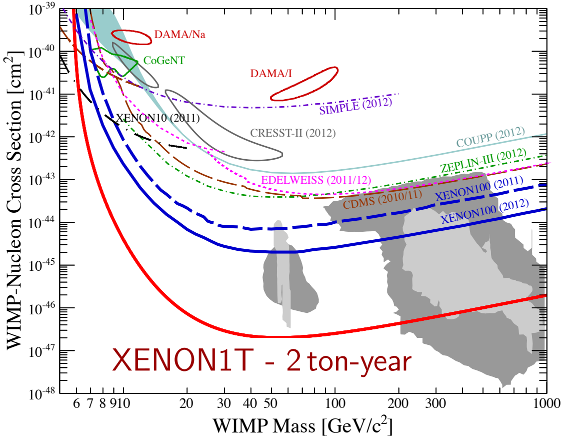
PRL 109, 181301

Fowlie et al., arXiv:1206.0264

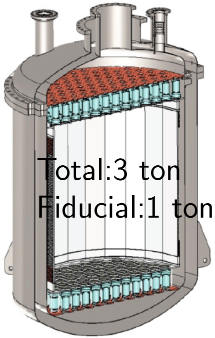
Strege et al., JCAP 1203, 030(2012)

Buchmueller et al., arXiv:1112.3564

Increase × 100 sensitivity: XENON1T



σ=2.0×10^{-47}cm^2
@ 55 GeV/c^2



	LAr
Mass number	40
Density [g/cm^3]	1.4
Boiling point [K@1bar]	87.3
e^- mobility [cm^2/Vs]	400
LY [ph/MeV, E=0]	40000
Radioactive isotopes	$^{39,42}Ar$

DARKSIDE

136 scientists from 23 institutions.

INFN Universita degli Studi Genova, IT
INFN Universita degli Studi Milano, IT
INFN Universita degli Studi Napoli, IT
INFN Universita degli Studi Perugia, IT
INFN Universita degli Studi Roma 3, IT
Black Hills State University, USA
University College London, UK
Joint Institute for Nuclear Research, RU
University of Massachusetts-Amherst, USA

Fermilab, USA
Augustana College, USA
IHEP, CN
INFN LNGS, IT
Temple University, USA
UCLA, USA
University of Hawaii, USA

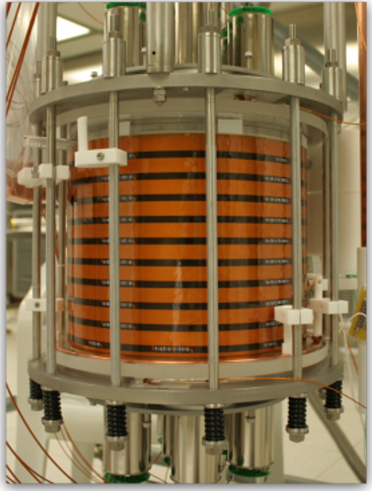
Princeton University, USA
Jagiellonian University, PL
RRC Kurchatov Institute, RU
St. Petersburg NPI, RU
University of Arkansas, USA
University of Chicago, USA
University of Houston, USA

DarkSide-10 detector operated (†) at LNGS

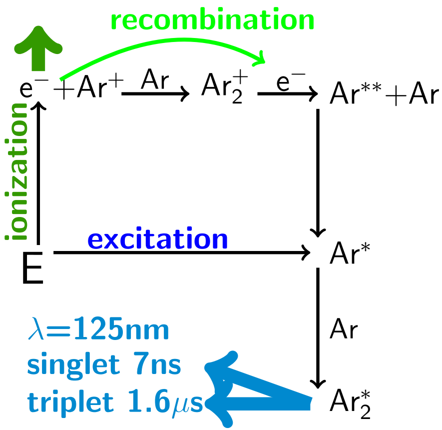
- Active target: 10kg of Atm LAr. TPC with 24cm drift x 21cm diameter.
- 7 (top) + 7 (bottom) 3" PMTs QE (30-36)%
- Electric field: E_{drift}=1kV/cm. $E_{extraction}$=∼6kV/cm.

Not DM search run
^{39}Ar Rate= 1Hz/kg

9 PE/keV_{ee} at 662keV_{ee}&0kV/cm
Stable cathode at 36kV.

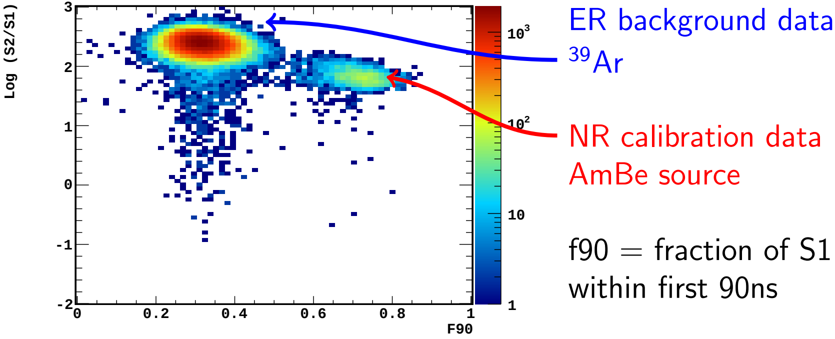


Dual phase LAr Time Projection Chamber



Electronic recoils rejection via pulse shape = PSD

Singlet/Triplet ratio depends on incoming particle (dE/dx).



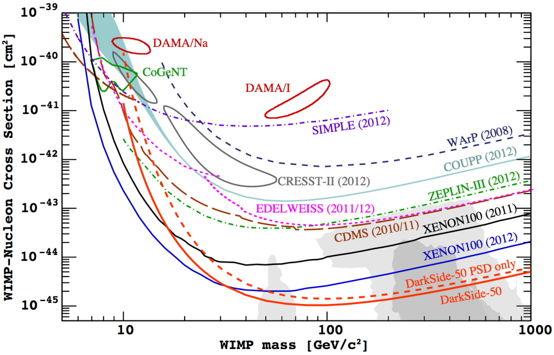
f90 = fraction of S1 within first 90ns

Detailed model to describe f90 down to 20keV$_r$.

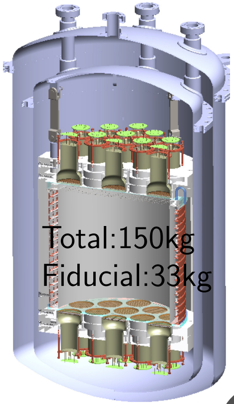
$> 10^7$ ER rejection @ $\sim$ 50% NR acceptance at $\sim$40 keV$_r$

DarkSide-50: DM Search with Underground Ar

Major milestone: ^{39}Ar rate in UAr $<$ 6.5 mBq/kg !
Detector in late construction-phase. First data expected this year!

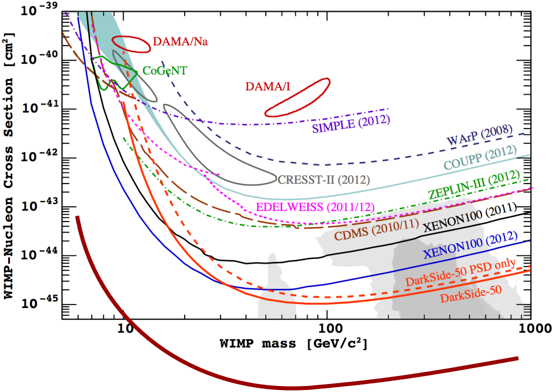


σ=1 $\times 10^{-45}$cm^2
@ 100 GeV/c^2
0.1 ton-year

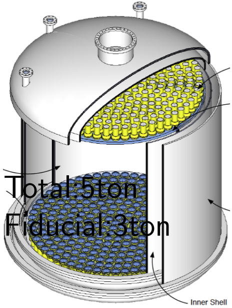


Increase sensitivity ×100: DarkSide-G2

Next phase: use most of the existing infrastructure.



$2\times10^{-47}\text{cm}^2$
@ 100 GeV/c^2
14 ton-year

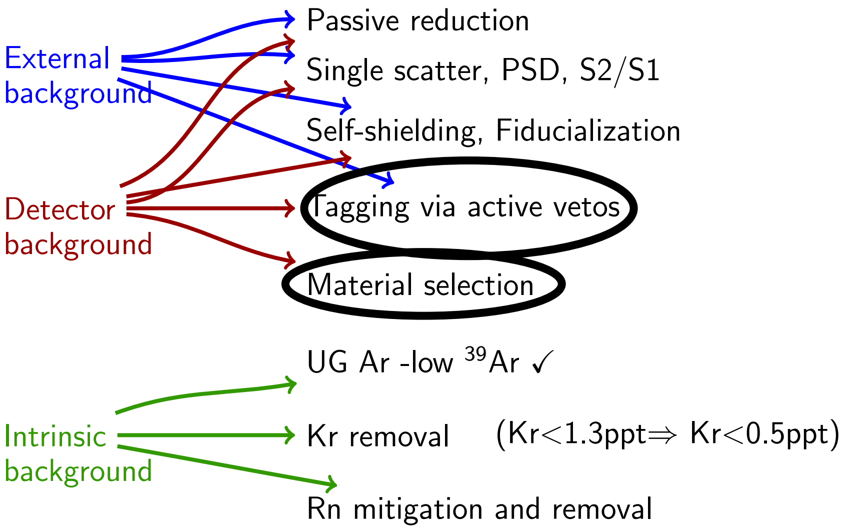


Key Technical and Physics Challenges

- **Ultra-low controlled background**
- **High charge and light yield**
- **Ultra-low electro-negative impurity**
- **Uniform electric field of desired strength**

- Demonstrate low-threshold
- Demonstrate understanding of detector response
- Calibrate energy scales
- Efficient calibration (background, signal model)

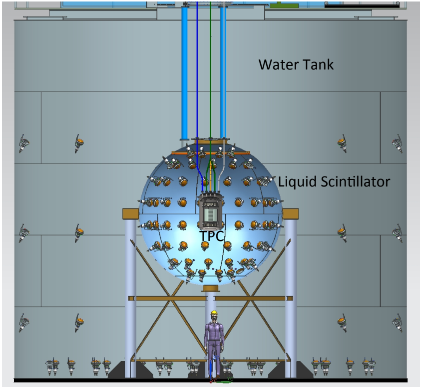
Key Challenge: Ultra-low controlled background

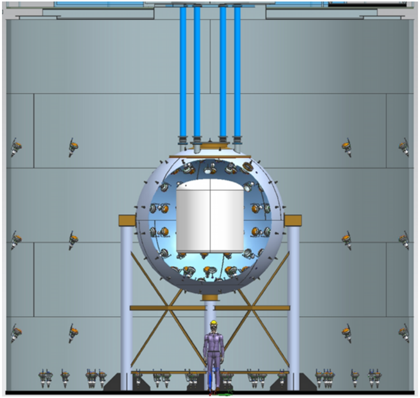


Future detectors: Larger and nested

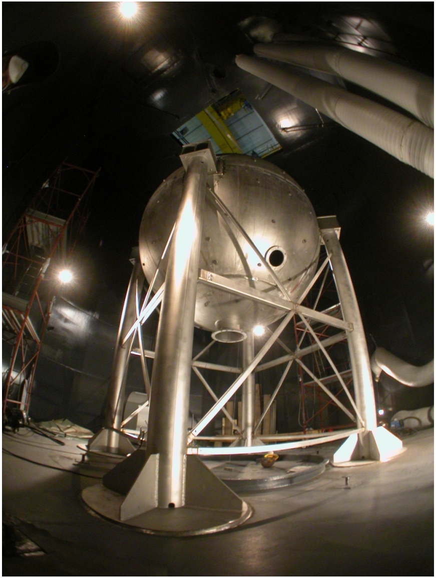
DS-50: Muon& Neutron Veto
cosmogenic ns < 0.01 ev/yr
radiogenic ns < 0.1 ev/yr

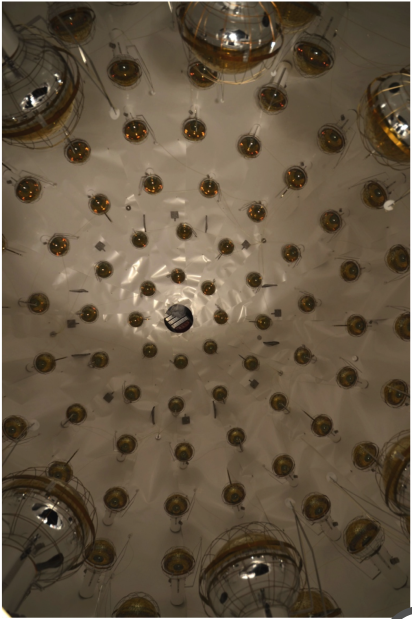
DS-G2: Muon& Neutron Veto
cosmogenic ns < 0.1 ev/yr
radiogenic ns < 1 ev/yr



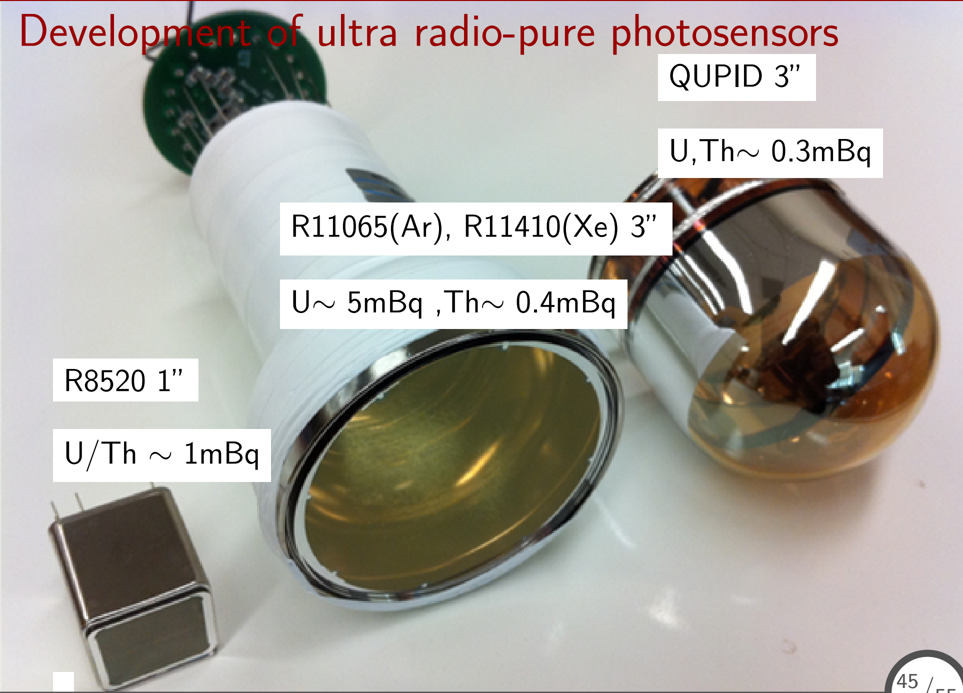


Reduce systematics: use tagged ns to characterize background

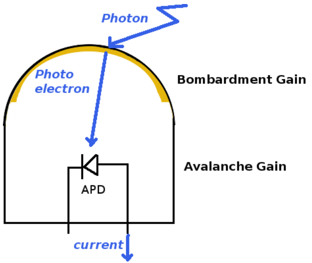




Development of ultra radio-pure photosensors



QUPID - Quartz Photon Intensifying Detector



Hybrid photosensor
Hamamatsu-UCLA

Ultra-low intrinsic radioactivity ✓

High QE and total gain>10^6 ✓

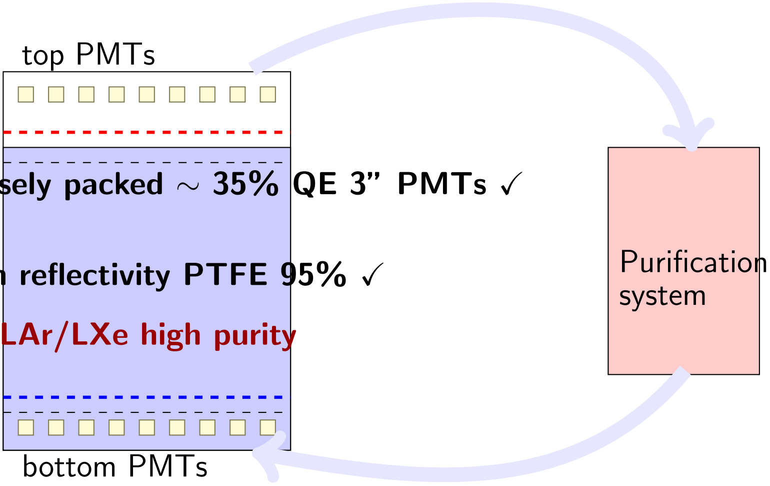
Wide dynamic range ✓

Very good charge resolution ✓
Pulse width <10ns ✓

High voltage >6kV
unstable operation of APD
amount of indium

Hamamatsu stopped but R&D at UCLA continues.

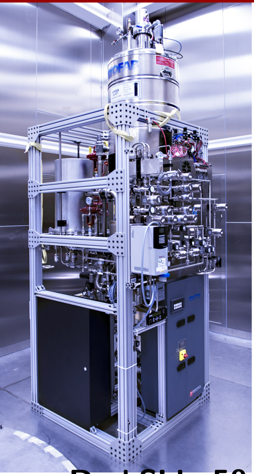
Key Challenge: Efficient and fast purification

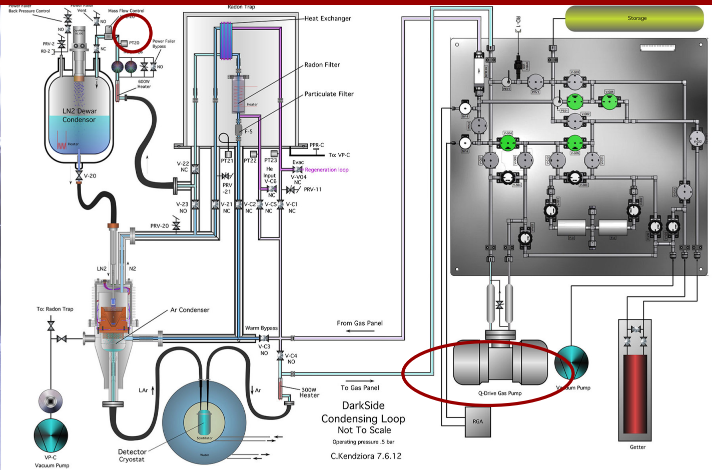


Densely packed ∼ 35% QE 3” PMTs ✓

High reflectivity PTFE 95% ✓

Electro-negative impurities affect both charge and light yield



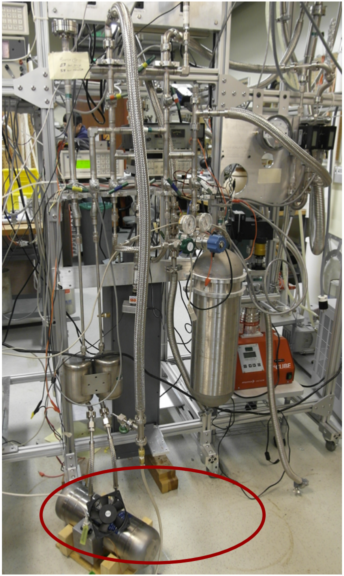


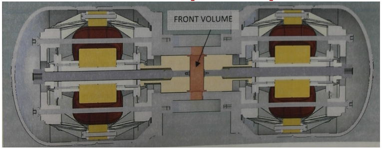
DarkSide-50 recirculation and purification system

Cooling power 300W, max rec. speed $\sim$ 75kg/day

Prototypes of remote-LN_2 Cryocooler, LAr condenser, and gas recirculation systems tested at UCLA/Princeton/FNAL

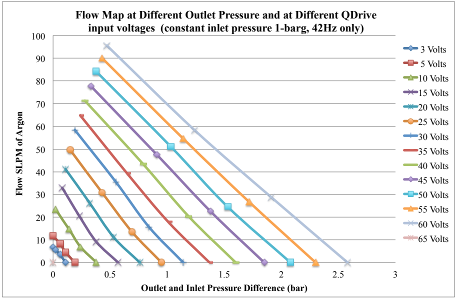
Development of a novel recirculation pump





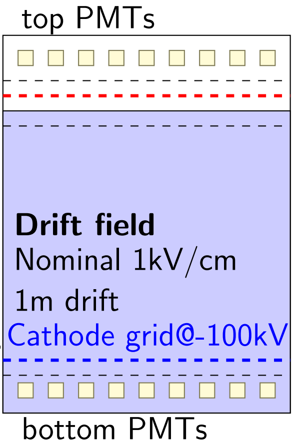
fail safe QDrive-UCLA pump

pressure wave generator + reed valves



Key Challenge: E-field in the TPC

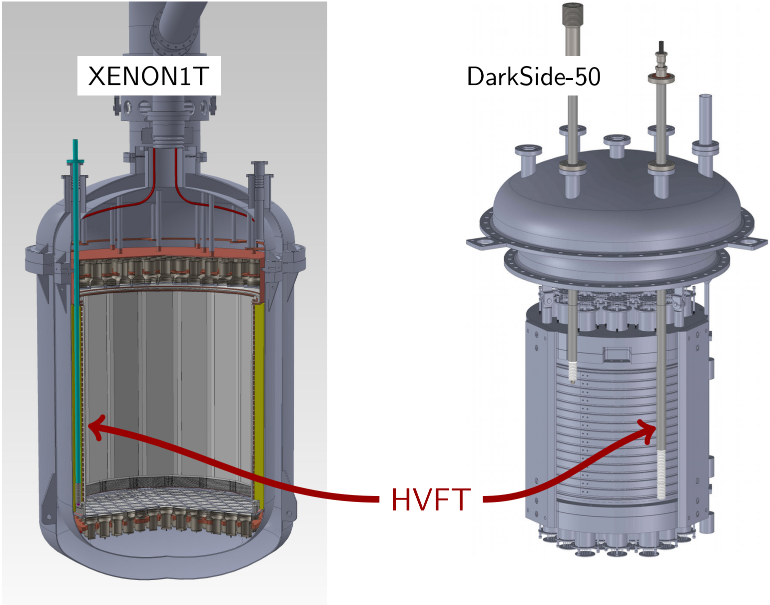
Uniformity key to background rejection via 3D event reconst.



Magnitude influences S2/S1 rejection power
@ 0.5kV/cm $\sim$ 99.75%
@ 3.9kV/cm $\sim$ 99.99%

Transmit high voltage to cathode

High voltage feedthrough development



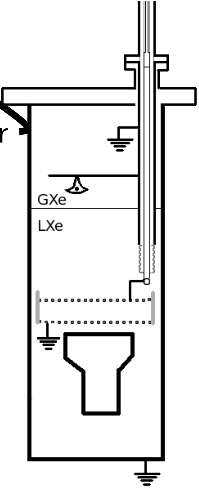
High voltage feedthrough testing

Components cryo-fitted in LN_2. Seal at room temperature.
Robust construction using radio-pure materials.

SS outer shield

SS inner conductor

Polyethylene insulator



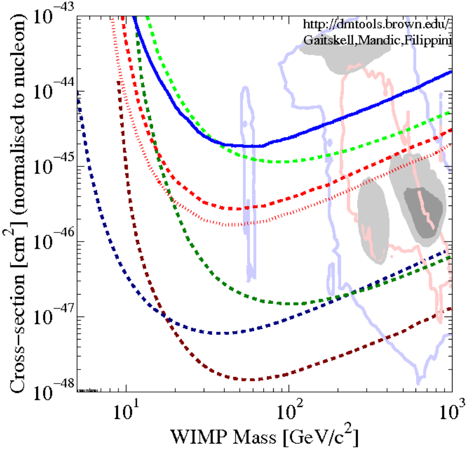
2" to wall: tested up to -130kV in LAr

5mm to wall: tested up to -110kV in LXe

3" PMT trigger rate stable with
cathode grid at -90kV
cathode-ground distance 3cm

Future dual-phase noble liquid detectors

- Ultra-low controlled background✓
- High charge and light yield ✓
- Ultra-low electro-negative impurity ✓
- Uniform electric field of desired strength ✓



XENON100 in 2102
LUX in 2013/14
DS-50 in 2016

XENON1T in 2017
DS-G2 in 2019
LZ in 2019

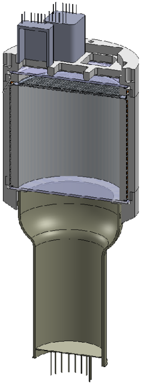
Next steps

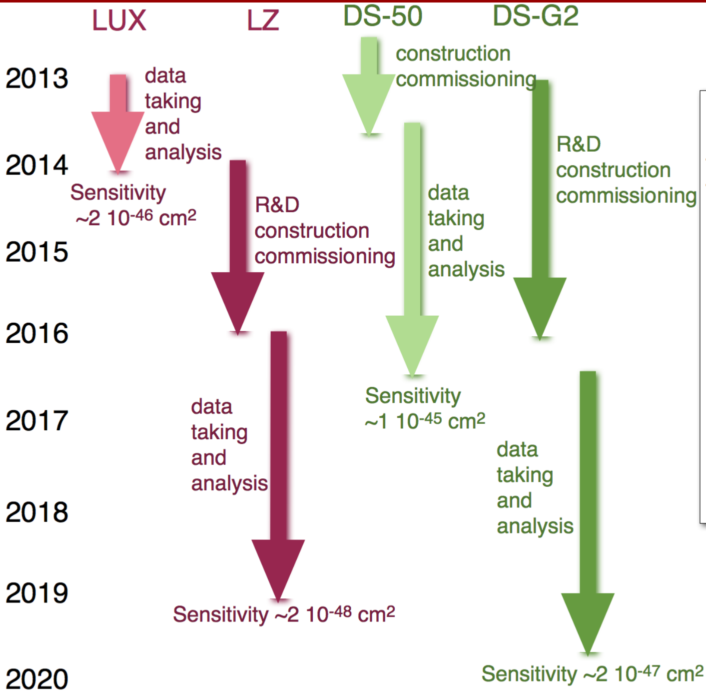
Analysis

- continue on XENON100 data analysis: new science run starting (single e^- related background)
- upcoming DS-50 data analysis: many possibilities

R&D

- Test new HVFTs up to -150kV.
- Build new setup for HHV testing.
- Relevance of LXe/LAr purity for HHV tests (purity monitor made)
- Set-up vacuum deposition and sealing system -novel photodector development
- Guide PhD students: dedicated dual phase LAr/LXe system for S2 signal study (dependence of field configuration, purity, gas gap ...) Feedback to big experiments.





UCLA R&D:

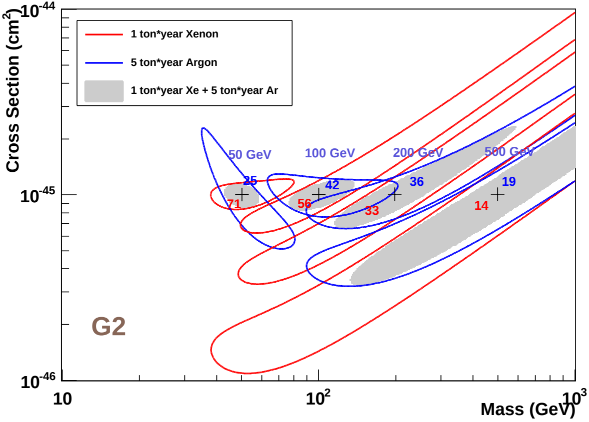
TPC HHV system
TPC dedicated tests
Cryogenic system
Recirculation pump
Photosensor study
S2 signal study in LAr-PhD
S2 signal study in LXe-PhD
Purity monitor-PhD

UCLA Participation:

DS-50 Operation
DS-50 Analysis

Thank you for listening!

Imagine WIMPs are around the corner: $\sigma = 1.0 \times 10^{-45} \text{cm}^2$



$\sigma = 1.0 \times 10^{-45} \text{cm}^2$

Combine targets to improve extraction of particle physics.

Extra Slides

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

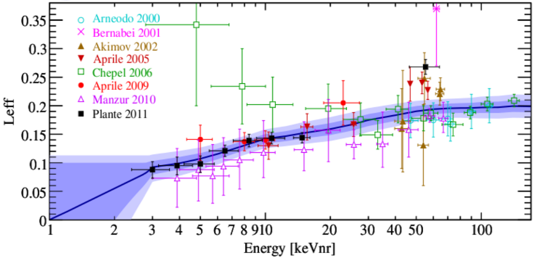
interpolation to 122keV$_{ee}$

2.28±0.03 PE/keV$_{ee}$.

Light quenching due to electric field

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

global fit of the available direct scattering data

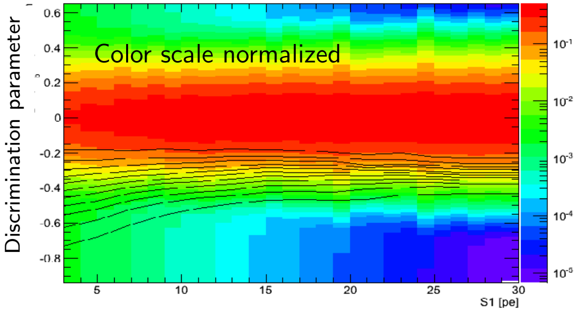


Plante et al., PRC 84, 045805 (2011)

Signal/Background model for Profile Likelihood

A statistical model to include systematic detector uncertainties

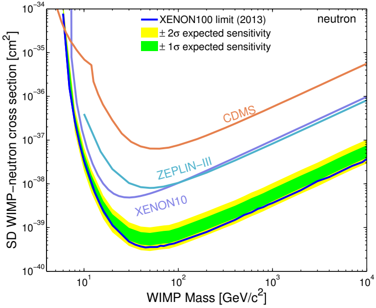
$$\mathscr{L} = \underbrace{\mathscr{L}_1(\sigma, N_b, \epsilon_s, \epsilon_b, \mathcal{L}_{eff}, v_{esc}; m_\chi)}_{\textit{DM measurement}} \underbrace{\mathscr{L}_2(\epsilon_s)}_{\textit{sig model}} \underbrace{\mathscr{L}_3(\epsilon_b)}_{\textit{bck model}} \underbrace{\mathscr{L}_4(\mathcal{L}_{eff})}_{\textit{energy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

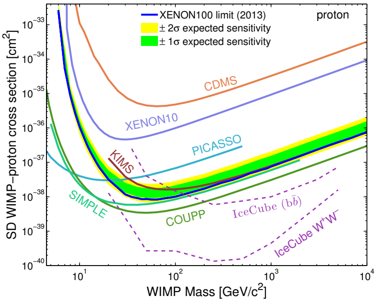


Background model from ER calibration data.
Signal model from NR calibration data.
Signal-like events are equally distributed between the bands

XENON100 upper limit for SD WIMP interaction

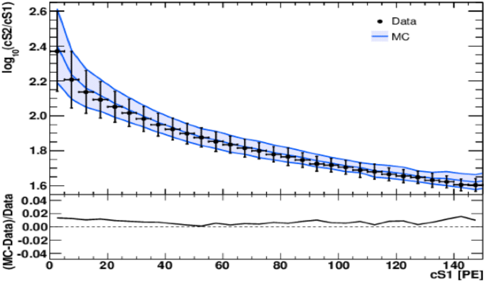
σ=3.5 10^{-40}cm^2@45 GeV/c^2
unpaired neutron in ^{129}Xe, ^{131}Xe

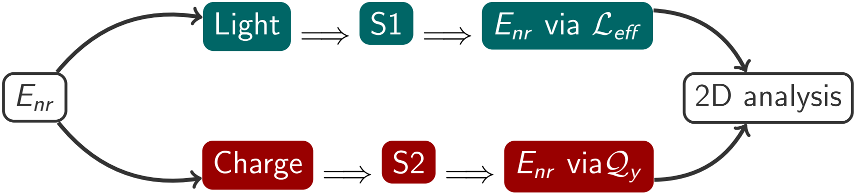


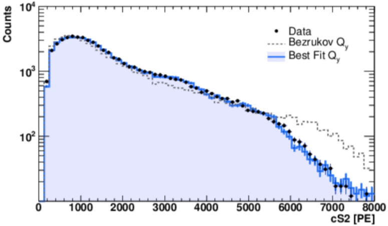


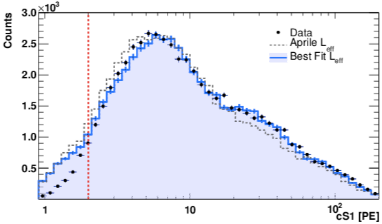
Simple DM halo: DM density = 0.3GeV/cm^2
Maxwellian velocity distribution with v_0=220km/s , v_{esc}=544km/s

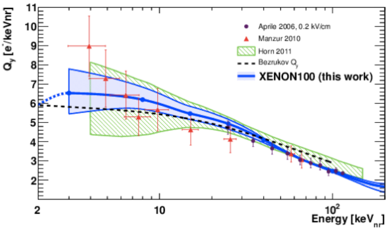
2D analysis

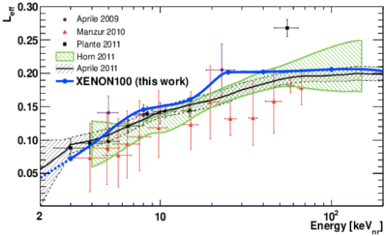

log10(cS2/cS1)
Data
MC
(MC-Data)/Data
cS1 [PE]
2.6
2.4
2.2
2.0
1.8
1.6
0.04
0.02
0.00
-0.02
-0.04
0
20
40
60
80
100
120
140


E_{nr}
Light
S1
E_{nr} via $\mathcal{L}_{eff}$
Charge
S2
E_{nr} via $\mathcal{Q}_y$
2D analysis

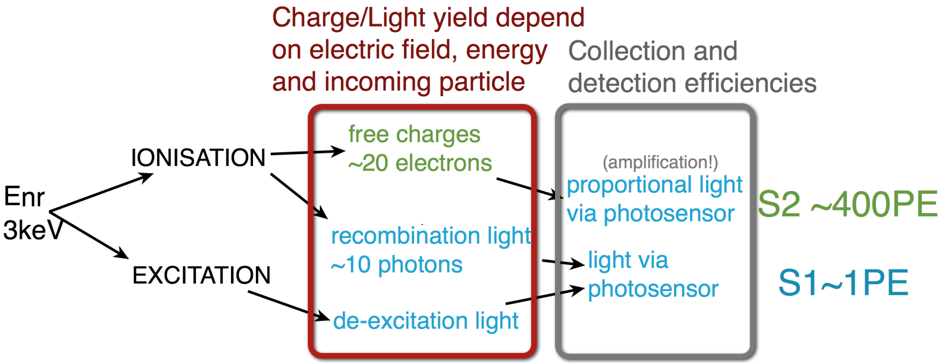

Counts
Data
Bezrukov Q_y
Best Fit Q_y
cS2 [PE]


Counts
Data
Aprile L_eff
Best Fit L_eff
cS1 [PE]


Q_y [e⁻/keVnr]
Aprile 2006, 0.2 kV/cm
Manzur 2010
Horn 2011
Bezrukov Q_y
XENON100 (this work)
Energy [keV_nr]


L_eff
Aprile 2009
Manzur 2010
Plante 2011
Horn 2011
Aprile 2011
XENON100 (this work)
Energy [keV_nr]

Low energy threshold

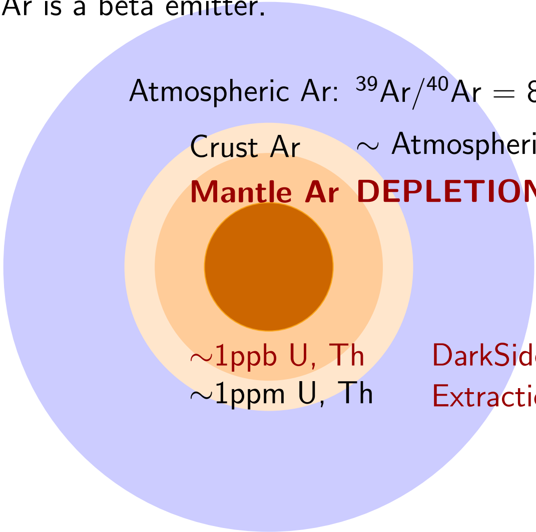


Low threshold achievable in both channels.

Underground Argon - a target for WIMP Search

Cosmic rays and radiogenic processes induce: ^{40}Ar (n,2n)$\rightarrow$ ^{39}Ar

^{39}Ar is a beta emitter.



Atmospheric Ar: $^{39}\mathrm{Ar}/^{40}\mathrm{Ar} = 8\times10^{-16}$. Rate $\sim$1Hz/kg

Crust Ar $\sim$ Atmospheric Ar

Mantle Ar DEPLETION FACTOR $>$100

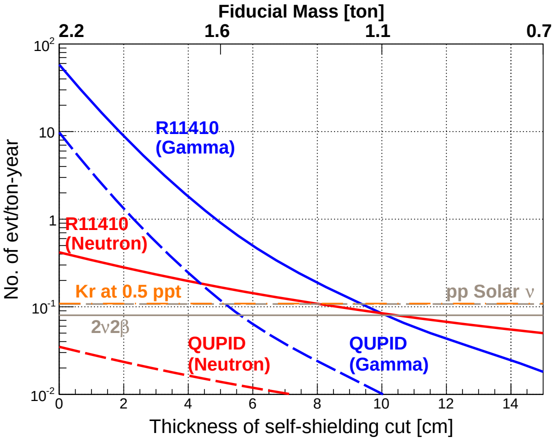
$\sim$1ppb U, Th

$\sim$1ppm U, Th

DarkSide has 150 kg of UG Ar

Extraction continues

Expected background from photosensors



Example of XENON1T: no S2/S1 rejection applied (PMT base not included). Present state-of-art 3" PMTs seem sufficiently radio-clean!

Development of >3" photodetectors would give the same photocathode coverage and reduce the (cost) # of channels.

Intrinsic background: Radon

Radon produced

inside detector region
must be minimized.
Low radon emanation material.
Radon-suppressed clean rooms.
Cleaned passivated material.

in the gas purification system
can be reduced via cryogenic
adsorption on charcoal.
Slow down Rn enough to decay.
Rn atoms $>>$ Ar atoms. ✓
Rn atoms $\sim$ Xe atoms.

Rn-free clean room for DS-50 installation: Rn $<$30mBq/m^3

Low mass WIMP in XENON100