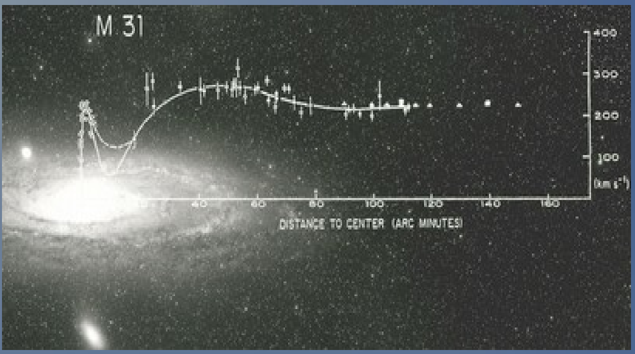
The XENON Dark Matter Project

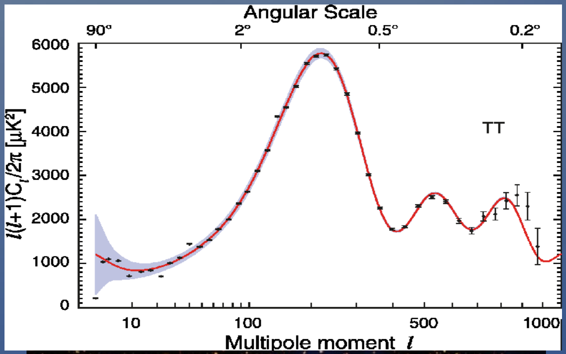
Ethan Brown
On behalf of the XENON collaboration

Evidence for Dark Matter

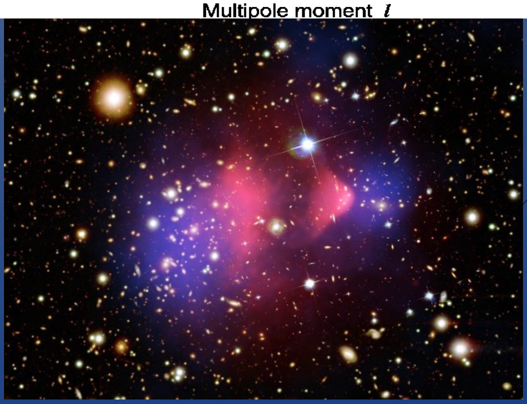
Galactic rotation curves
Galactic dark matter halo



Anisotropy of CMB
$\Omega_{tot} = 1$
$\Omega_m = 0.27$
$\Omega_b = .045$

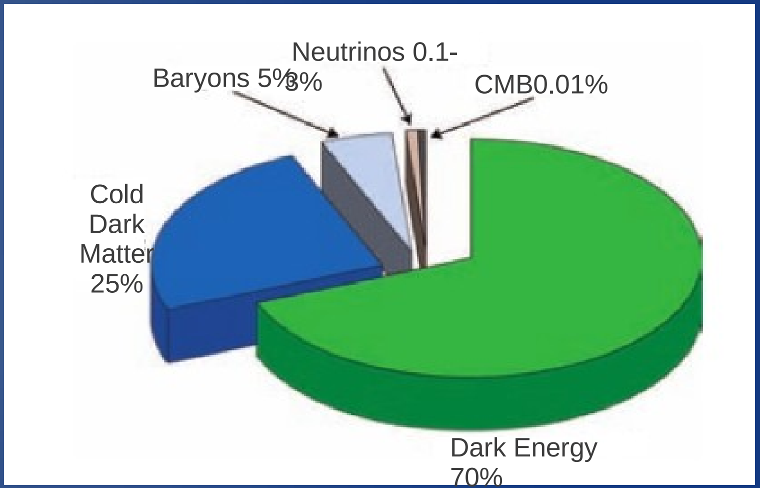


Graviational lensing
Non-collisional gravitational mass



ΛCDM model of the universe

Non-baryonic cold dark matter



WIMP Dark Matter

Dark matter in thermal equilibrium in early universe

Decouples as universe expands

Thermal relic → present today

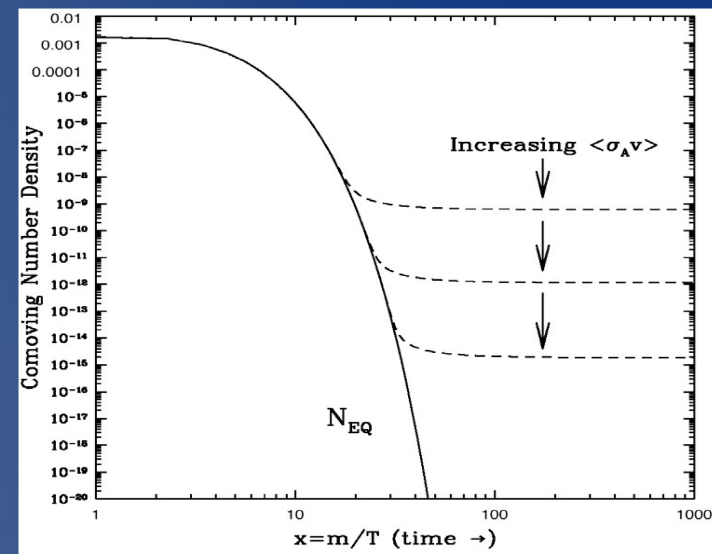
<u>The WIMP coincidence</u>

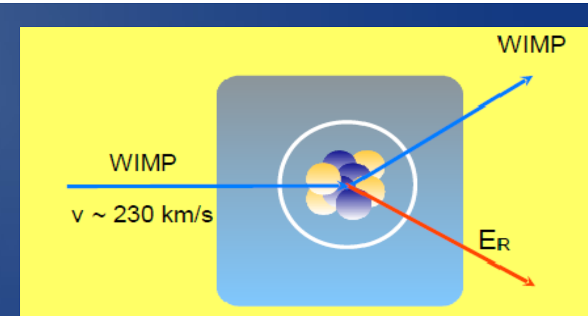
$$\Omega h^2 = \frac{3 \cdot 10^{-27} cm^3 s^{-1}}{\sigma_A v}$$

Weak scale cross section yields correct abundance

Weakly Interacting Massive Particle (WIMP)

SUSY provides natural candidate
→ LSP is stable WIMP





$$\frac{dR}{dQ} = \frac{\sigma_0 \rho_0}{2 m_\chi m_r^2} F^2(Q) \int_{v_{min}}^{v_{max}} \frac{f(v)}{v} dv$$

The XENON Collaboration

Columbia | Rice | UCLA | U Zürich | Coimbra | LNGS | Mainz | SJTU

Bologna | MPIK | Bern | NIKHEF | Purdue | Subatech | Münster | WIS

The Phased XENON Program

Past: 2005 - 2007

XENON10

$\sigma_{SI} < 8.8 \times 10^{-44}$ cm^2

Present: 2008 - 201x

XENON100

$\sigma_{SI} < 2.0 \times 10^{-45}$ cm^2

Future: 2012 - 2017

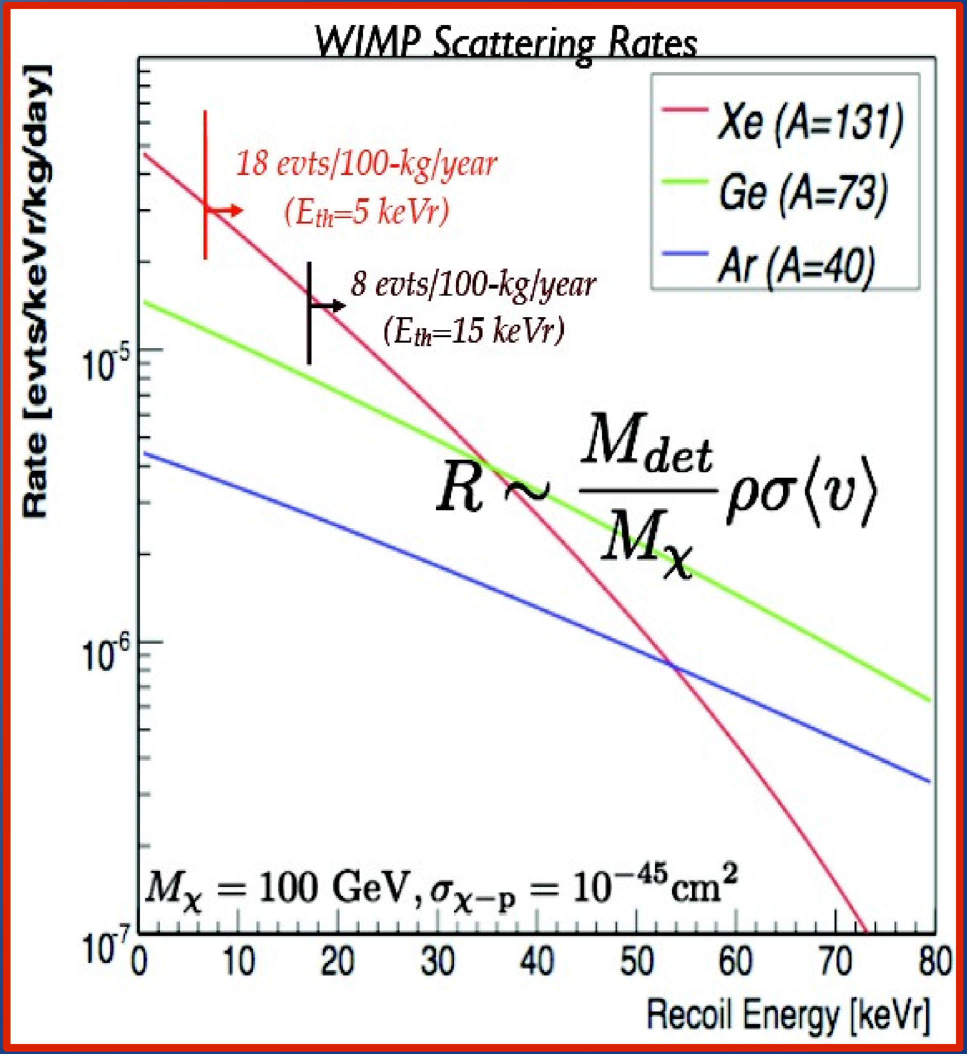
XENON1T

$\sigma_{SI} = 2 \times 10^{-47}$ cm^2

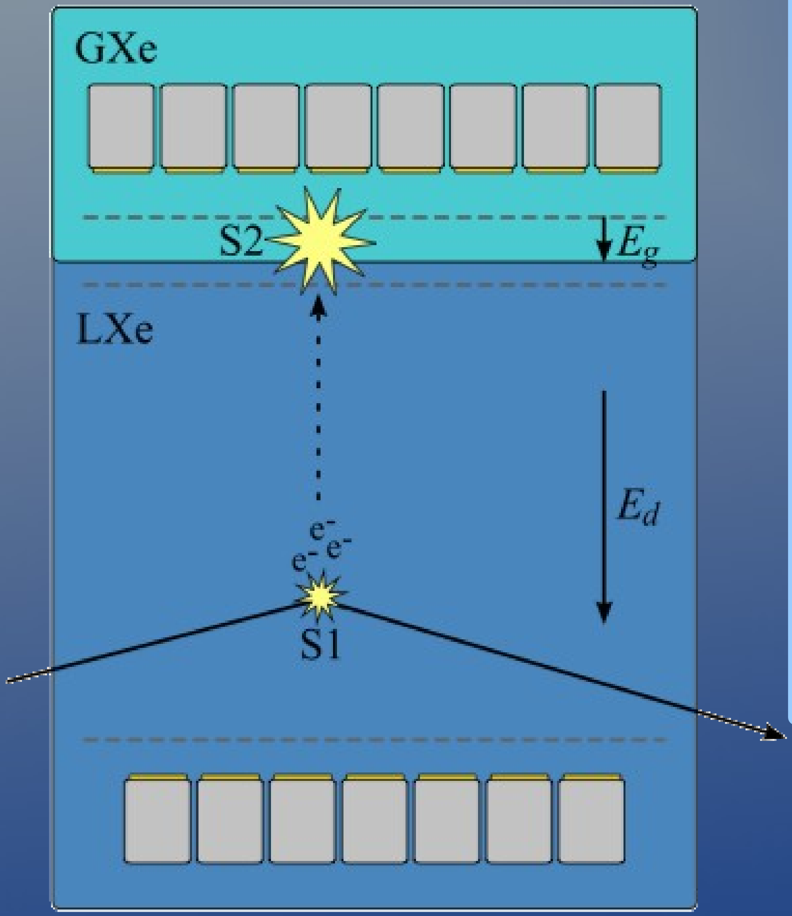
(projected)

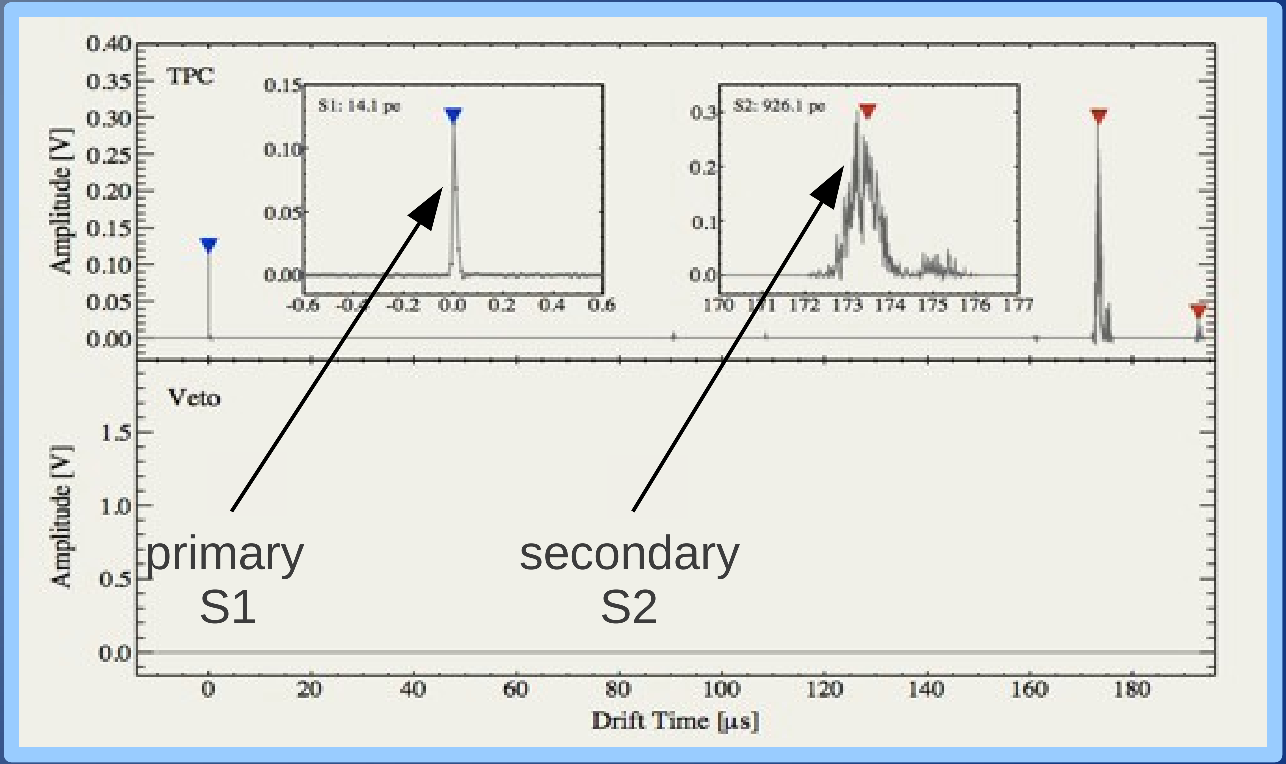
Xenon as a Detector Material

- Heavy nucleus (A~131): good for SI (coherent scattering off all nucleons) plus SD sensitivity (~50% odd isotopes)
- Charge & Light: highest yield among noble liquids and best self-shielding
- Low energy threshold: PMTs within liquid for efficient light detection
- Background rejection: by charge-to-light ratio, 3D-event reconstruction and fiducialization, LXe self-shielding
- Intrinsically pure: no long-lived radioactive isotopes
- Scalability: massive target at modest cost (<1k$/kg), effort scales with surface while sensitivity scales with volume



Xenon Dual Phase TPC





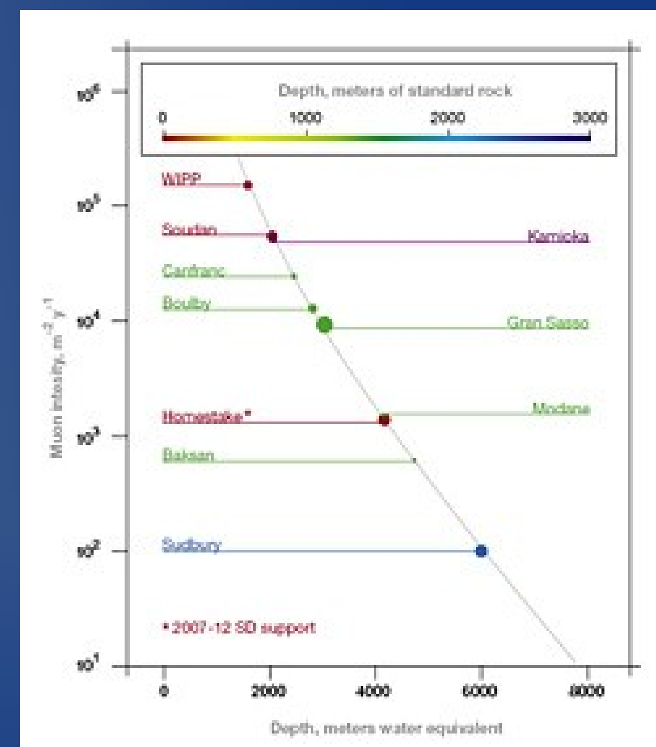
Detect two signals with photomultipliers:

→ Prompt scintillation (S1)

→ Ionization via proportional scintillation (S2)

Location: LNGS Italy

Depth of 3100 mwe
Shield from cosmic rays



The XENON100 Detector

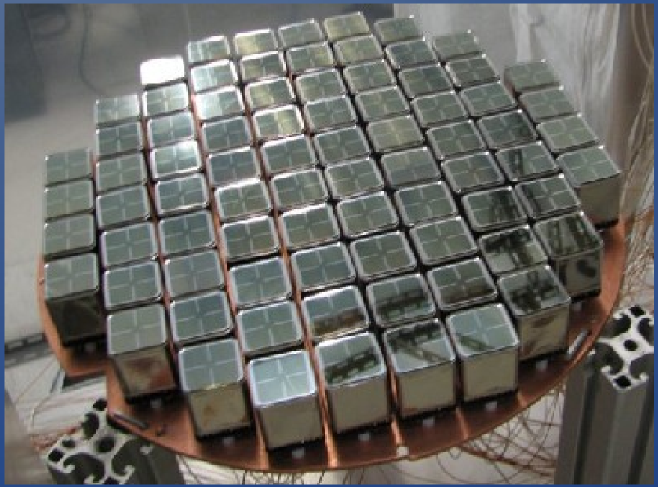
TPC:

- 30 cm drift length and 30cm ϕ
- 161 kg total (62 kg sensitive volume)
- Material screening and selection
- Active liquid xenon veto
- 100x lower background than XENON10

E. Aprile et al. Phys.Rev.D83:082001,2011

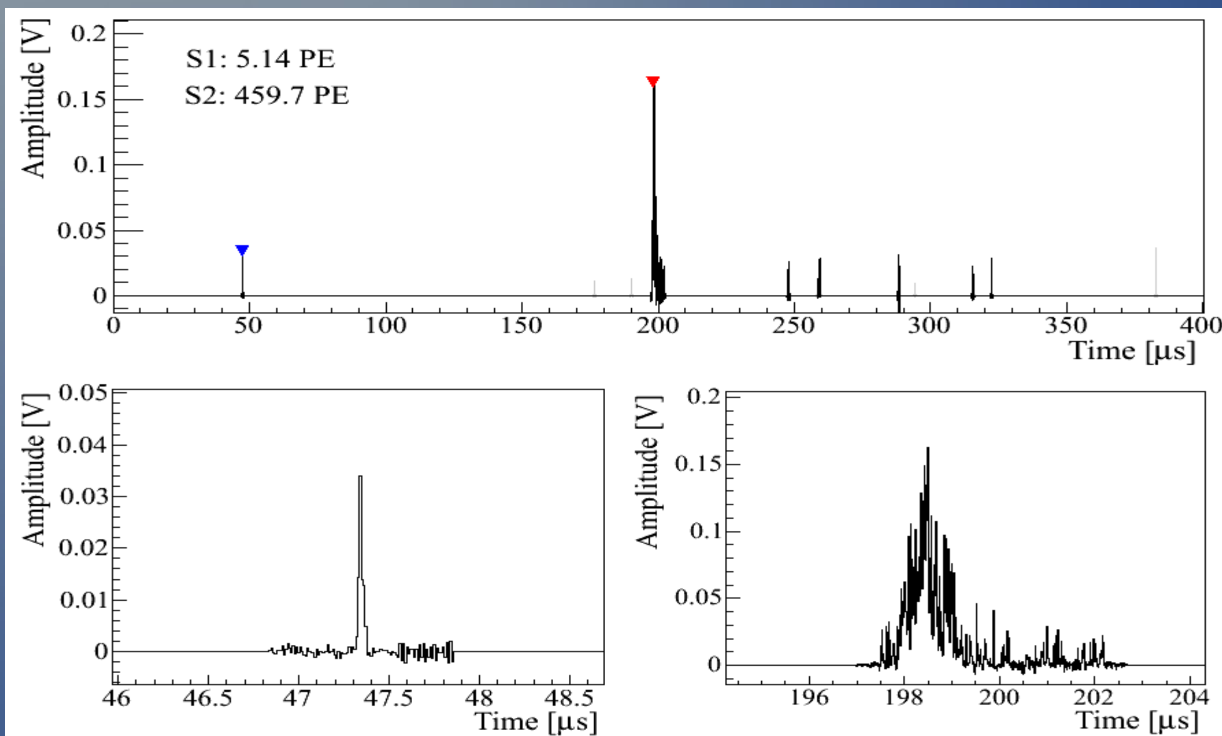
PMTs:

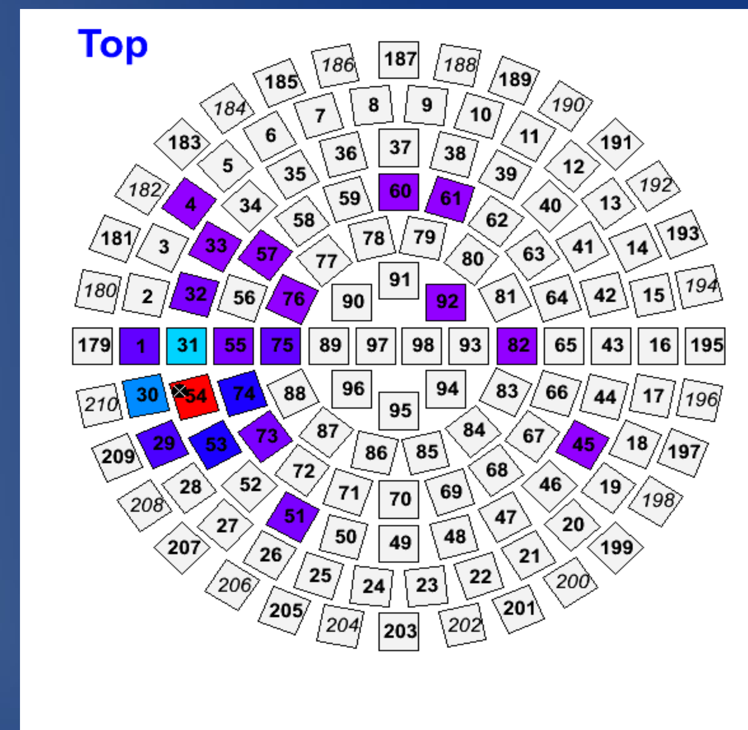
- 242 Hamamatsu R8520 in TPC and Active Veto
- High QE: Bottom tubes > 30%
- Low Radioactivity: < 10 mBq/PMT



E. Aprile et al. (XENON100), Astroparticle Physics 35, 573 (2012).

Position Reconstruction





Z position given by drift time t(S2) - t(S1)
→ δz < 300 µm

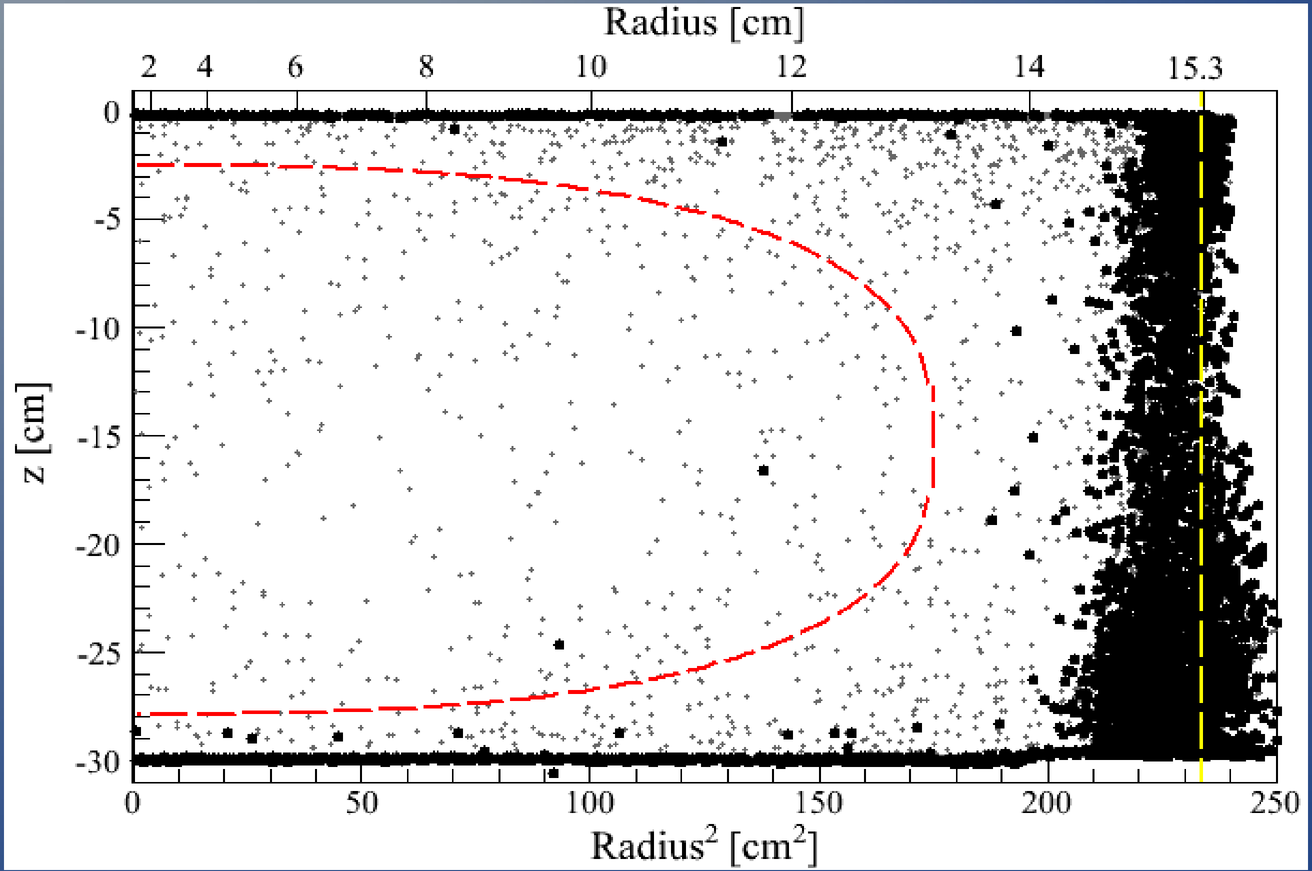
XY position given by S2 hit pattern:
→ δr < 3mm

Fiducialization

Westfälische Wilhelms-Universität Münster

XENON Dark Matter Project

E. Aprile et al. (XENON100), Phys. Rev. Lett. 109, 181301 (2012)

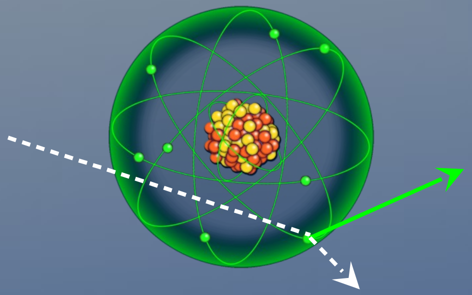


Background from published data

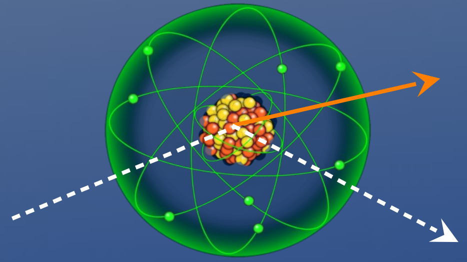
- Look only in quiet central region
- Take advantage of LXe self shielding
- Gammas from external sources and detector components stopped at edges
- Remaining BG dominated by internal impurities (eg ^{85}Kr)

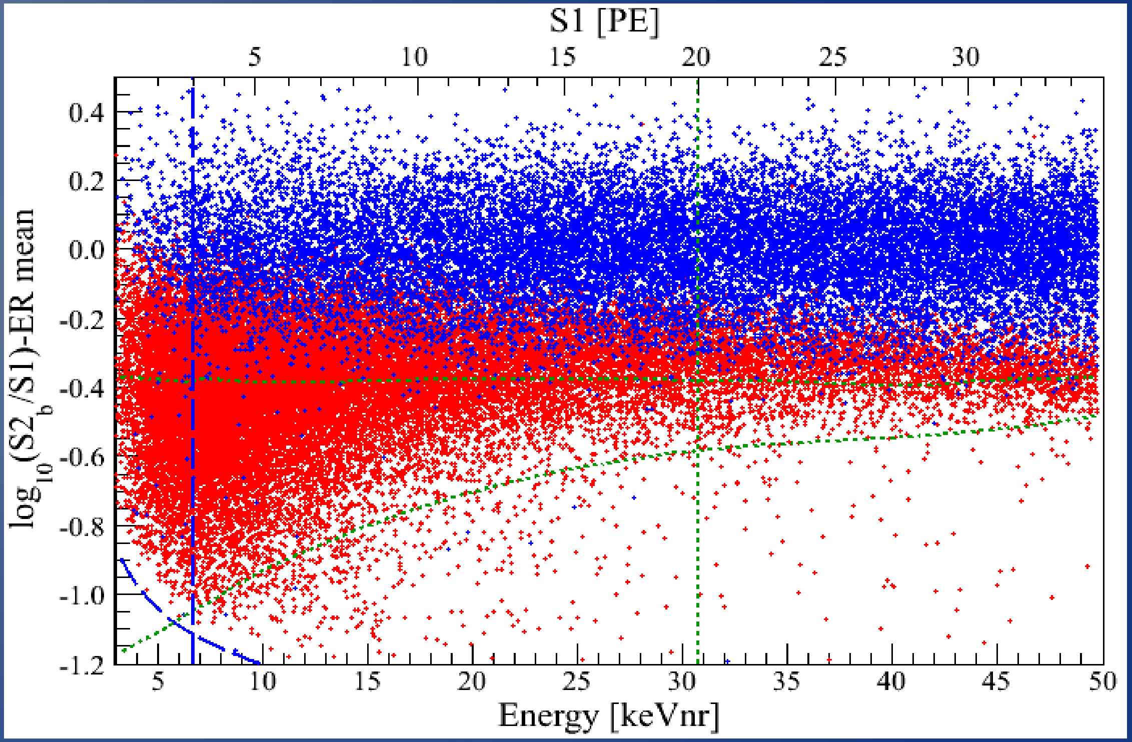
Recoil Descrimination

e-/γ: electronic recoil



n/WIMPs: nuclear recoil





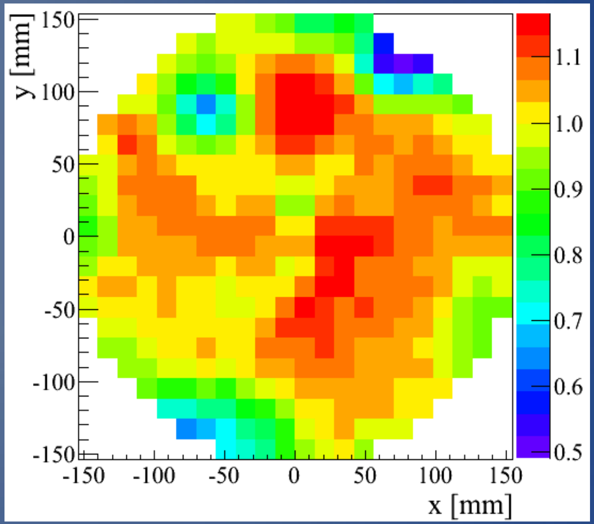
Calibration data

$$(S2/S1)_{n,\chi} << (S2/S1)_{e^-,\gamma}$$

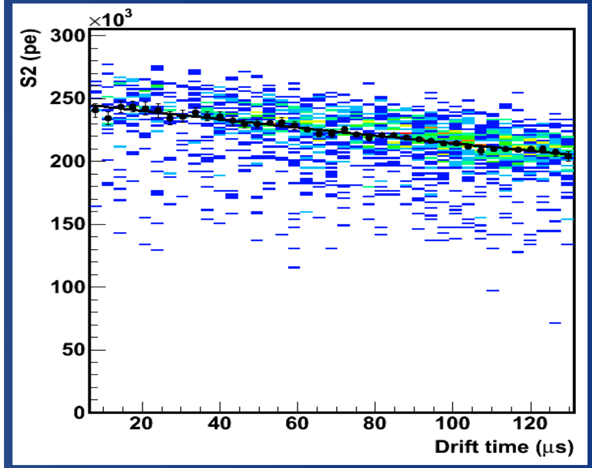
Characterization of XENON100

<u>Gamma Calibrations:</u>
662 keV (^{137}Cs)
1.17/1.33 MeV (^{60}Co)
40 keV (^{129}Xe (n,n'γ)^{129}Xe) by ^{241}AmBe
80 keV (^{131}Xe (n,n'γ)^{131}Xe) by ^{241}AmBe
164 keV (^{131m}Xe) by ^{241}AmBe
236 keV (^{129m}Xe) by ^{241}AmBe

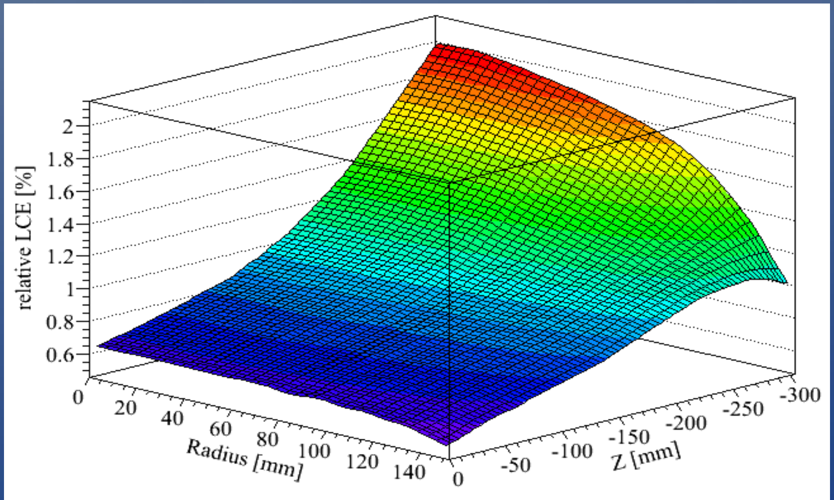
<u>Neutron Calibrations</u>
^{241}AmBe



S2 X-Y uniformity



Electron drift lifetime



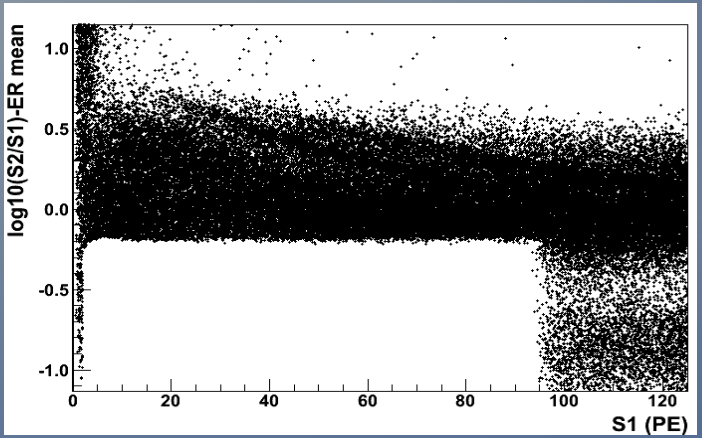
Map light yield in 3D

Correct S2 for charge attenuation by drift time

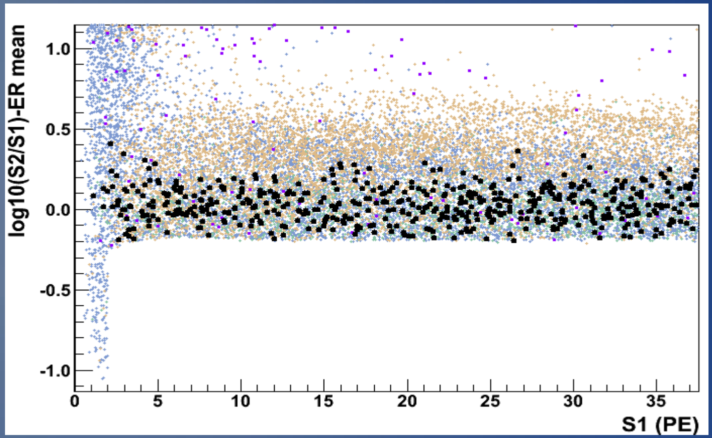
Correct S1 and S2 for position dependence (3D)

E. Aprile et al. (XENON100), Astroparticle Physics 35, 573 (2012).

Blinded Dark Matter Search with XENON100



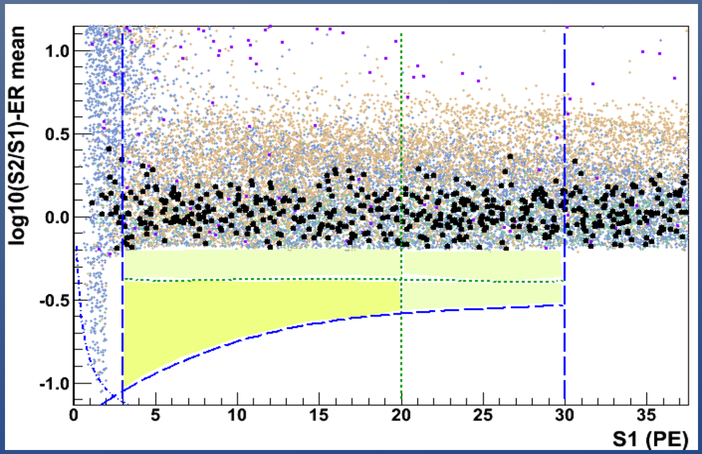
Blind data around WIMP region



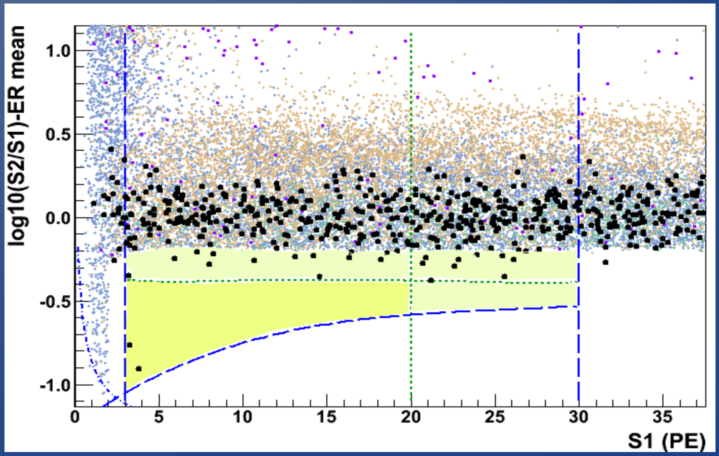
Apply data quality cuts

Define analysis on calibration data

→ All data quality cuts
→ Event selection
→ Search region



Define search region



Unblind

Unblind

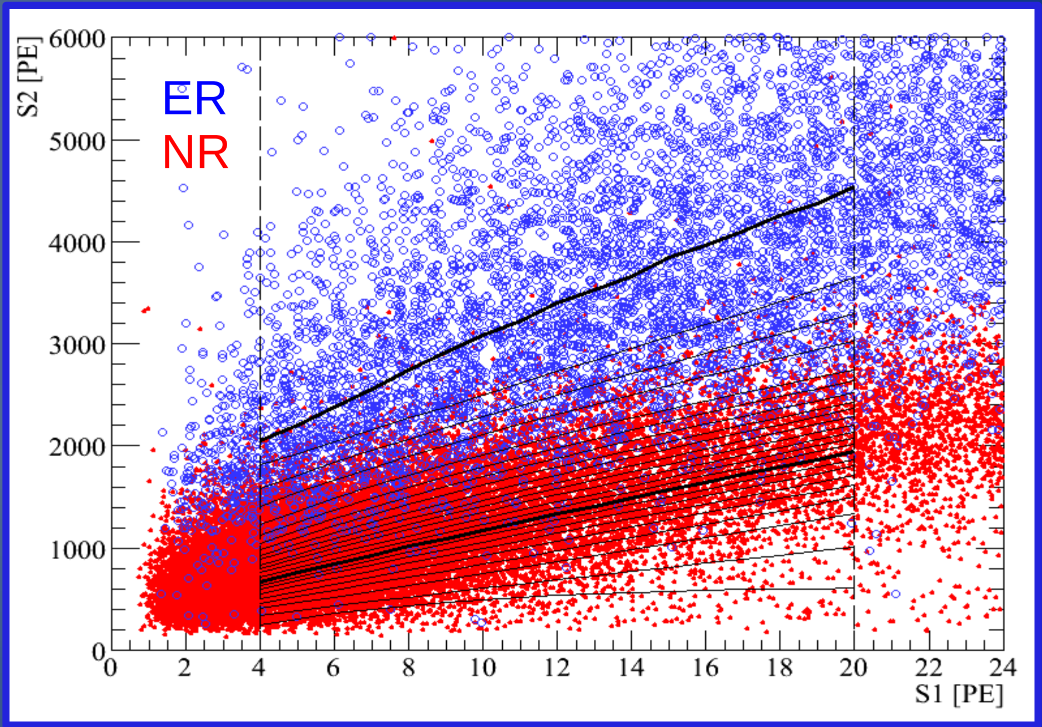
Perform pre-defined analysis on DM search data

E. Aprile et al, arXiv:1207.3458

Profile Likelihood Analysis

Statistical likelihood analysis
Profile over variables:

All calibration and DM search data
Systematic uncertainties
(energy scale, astrophysics input, etc)
Define distribution of BG and signal
Background only and signal hypotheses
→ Natural transition from limit to discovery



Phys. Rev. D 84, 052003 (2011)

225 Live Day Dark Matter Search

Data collected from Mar 2011 – May 2012
BG prediction (for cut based analysis):

NR: $0.17^{+0.12}_{-0.07}$
ER: 0.79 ± 0.16
Total: 1.0 ± 0.2

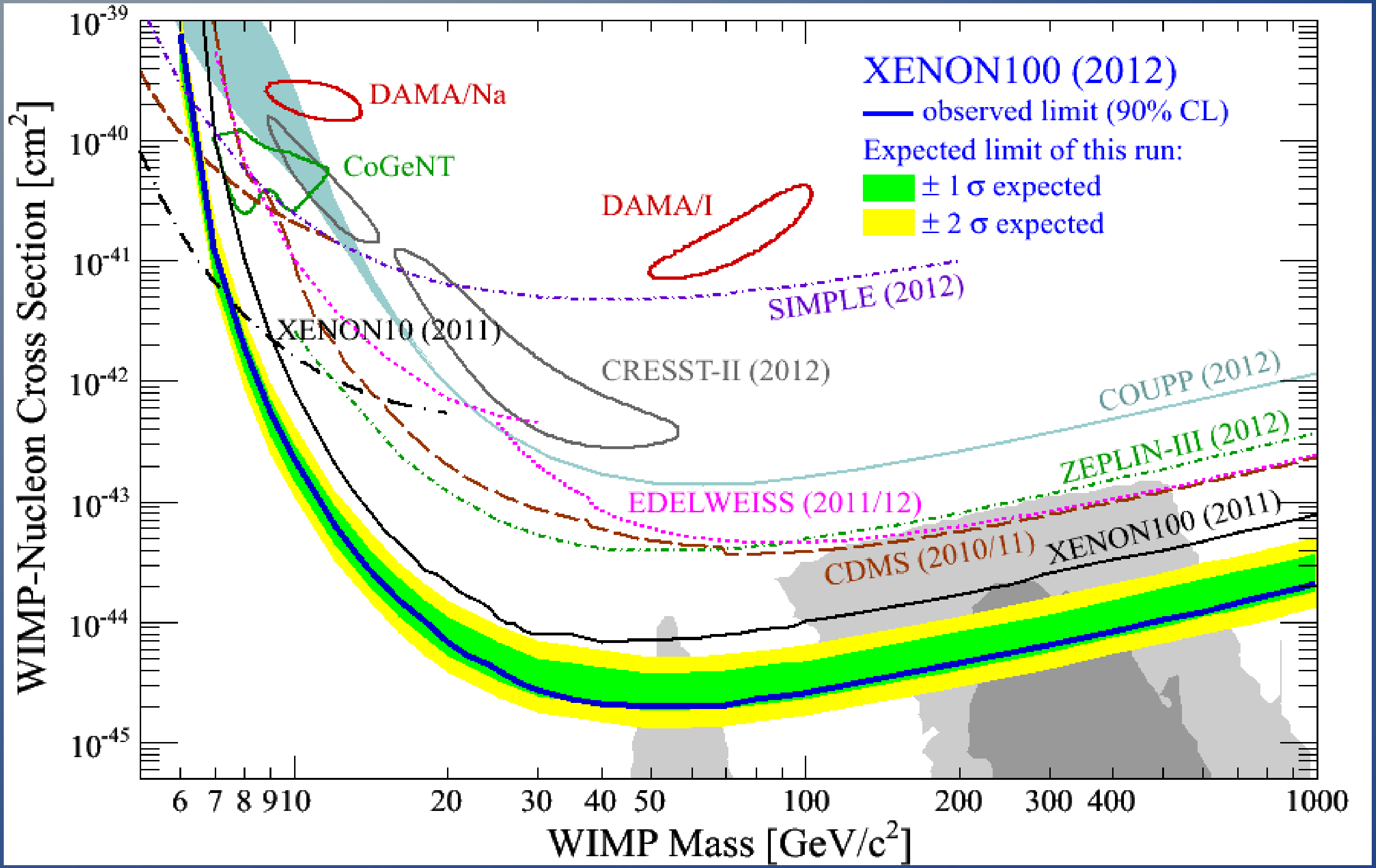
RESULT: 2 events in benchmark region

→ PL

Distribution of all events (including ER band)

Our search inconsistent with signal + BG

Results of 225 Live Days



E. Aprile et al. (XENON100), Phys. Rev. Lett. 109, 181301 (2012)

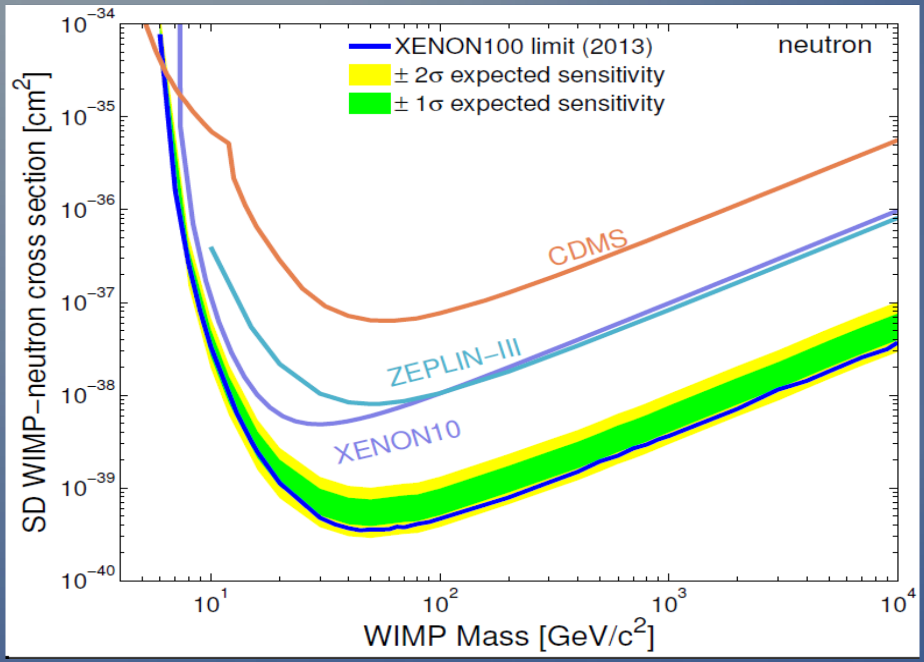
Results inconsistent with dark matter signal

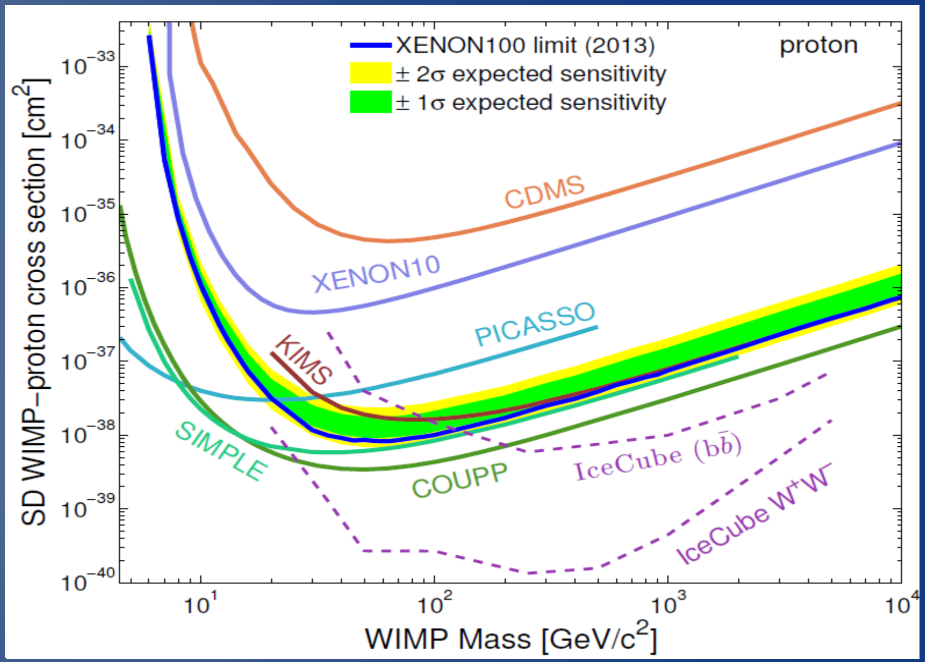
Set upper limit on WIMP-nucleon SI cross section

Worlds most sensitive limit to date:

$\sigma_{SI} < 2.0 \times 10^{-45}$ cm^2 for 50 GeV/c^2 WIMP

New Results for Spin Dependent Search

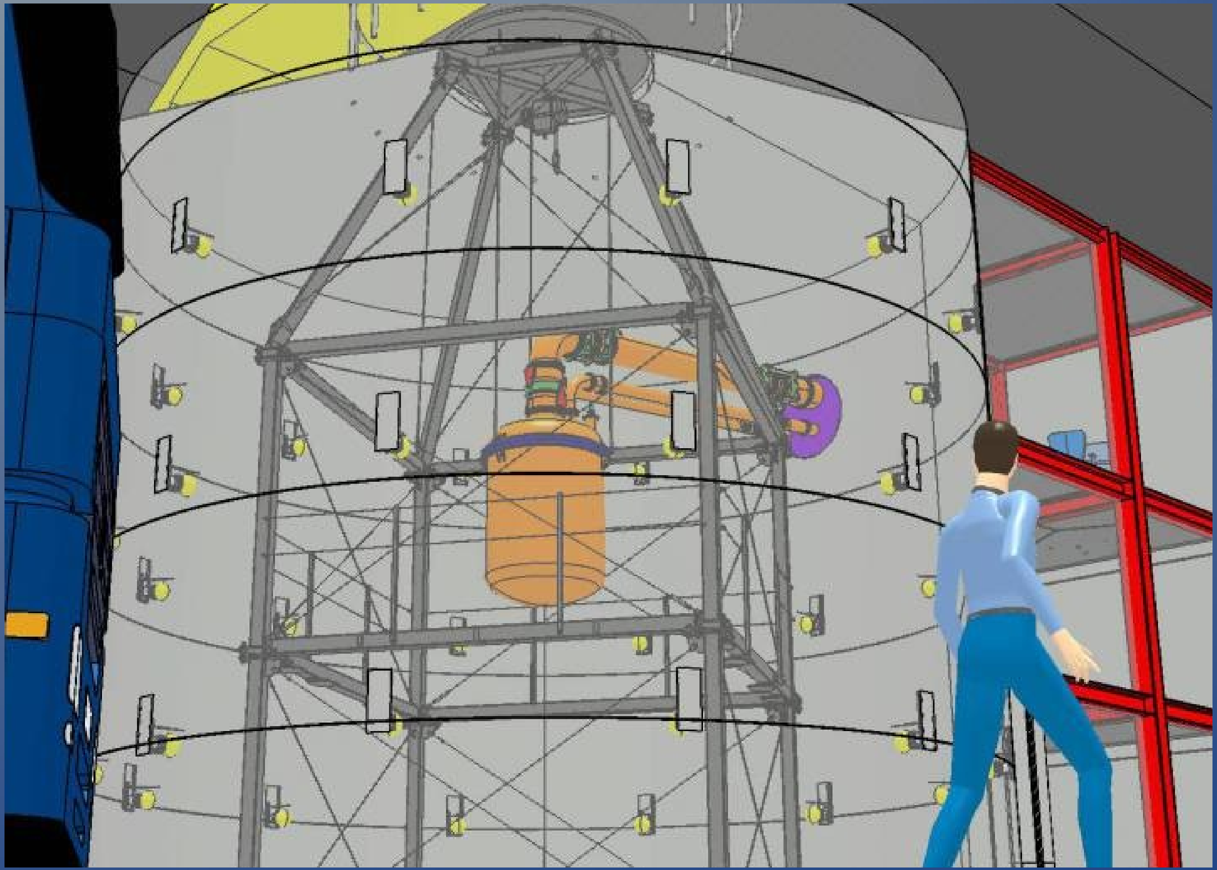




Same data and event selection as SI search
Look for spin dependent coupling
→ Odd Xe isotopes (unpaired neutron)
Set limit on pure neutron and pure proton coupling
Most sensitive limit on pure neutron coupling above 6 GeV/c^2
$\sigma_n < 3.5 \times 10^{-40}$ cm^2 for 45 GeV/c^2 WIMP

E. Aprile et al. (XENON100), arXiv:1301.6620

The Future is Now: XENON1T



2.2 ton target (1T fiducial)

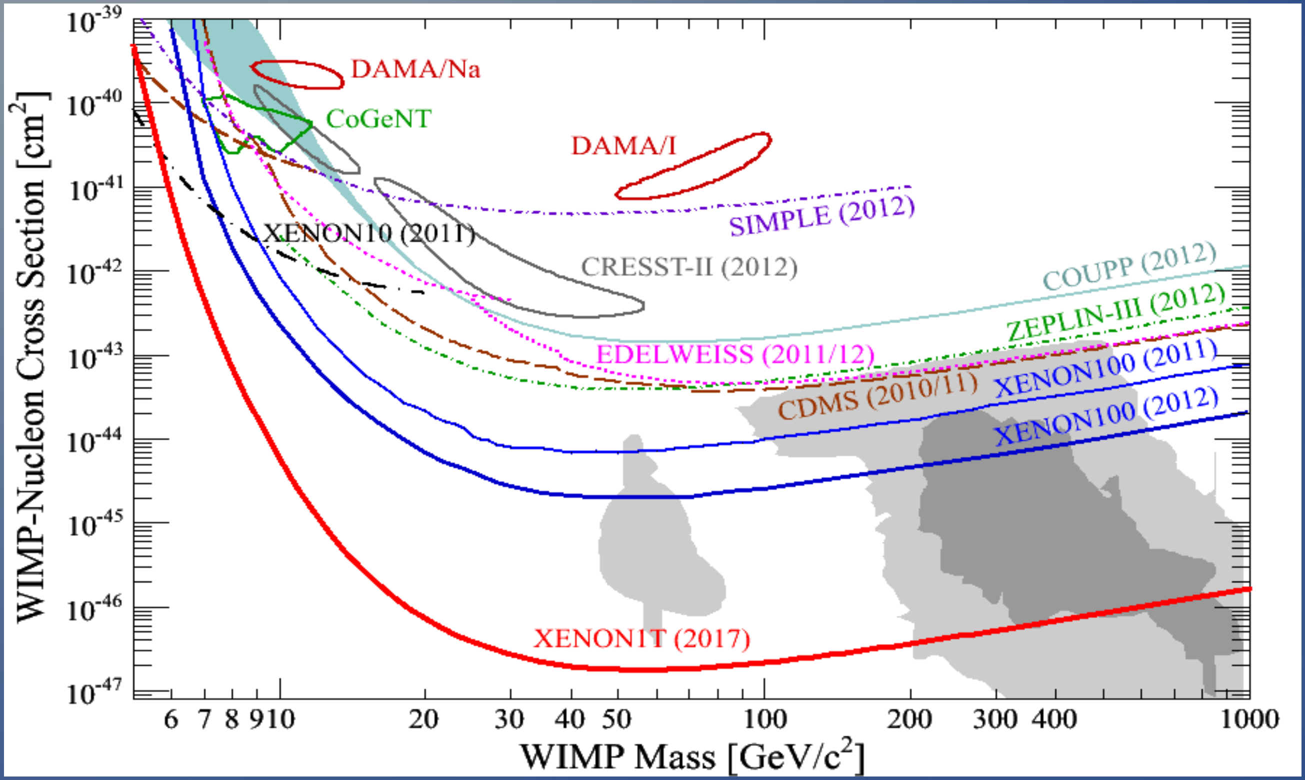
1m height X 1m diameter

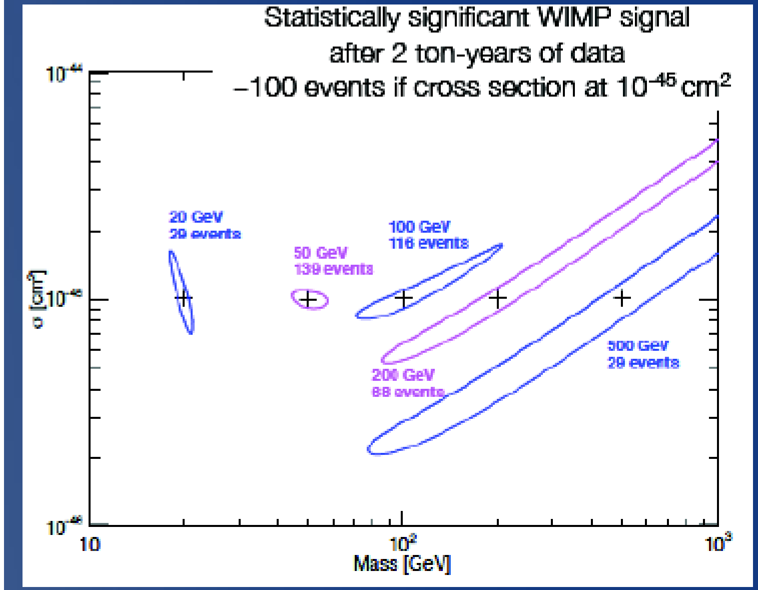
10m water shield

Reduce background 100 X from XENON100
→ Goal: < 1 event in 2 years

Increase sensitivity by factor 100

Projected Sensitivity





Example of discovery at current sensitivity

$\sigma_{SI} = 2 \times 10^{-47}$ cm² for 50 GeV/c² WIMP

Probe majority of SUSY-favored phase space
Buchmueller et. al, arXiv:1112.3564 (2011), A Fowli et. al, arXiv:1112.3564 (2012)

Strong discovery potential

Background Reduction for XENON1T

The backgrounds:

Gamma suppression comes “for free”
→ Self shielding of Xe
Dominant backgrounds become:
Neutrons (spontaneous fission, α-n, and muon induced)
Betas (^{85}Kr, ^{222}Rn daughters)

How to suppress them:

Select materials with low ^{222}Rn emanation
- Screen and carefully select detector materials
- Investigate construction techniques (eg clean welding)
- Ultra-clean gas purification units (pumps, getters)

Remove internal impurities
- Reduce ^{222}Rn with charcoal filter
- Remove ^{85}Kr via cryogenic distillation

Reject muon induced neutrons with water shield

Krypton Removal

Cryogenic distillation
Goal: < 0.5 ppt Kr/Xe
Input gas ~10 ppb → Separation factor 10^4
Currently achieved 19 ± 3 ppt
E. Aprile et al. (XENON100), Phys. Rev. Lett. 109, 181301 (2012)
High throughput: 3 kg/h (3.5 tons in ~1 month)
Xenon consumption: 1%

Distillation column under construction
(talk of S Rosendahl T107.7, poster of M Murra HK 58.1)
1m test column being built
3m final version to come by 2014

Development of diagnostics
^{83m}Kr tracer (10^{-16} ^{83m}Kr/Xe doping)
Detect scintillation of ^{83m}Kr decays in custom-built detectors (poster of A Fieguth NK 58.2)
Measure mass flow of Kr in column
(talk of S Rosendahl T107.7)

^{222}Rn Removal

^{222}Rn produced inside closed Xe system

Two types of sources:
- Type I: Inside detector region
- Type II: In gas purification loop

Type I must be minimized (clean materials)
Type II can only be reduced to a point
- Getter and pumps for Xe purification are “dirty”

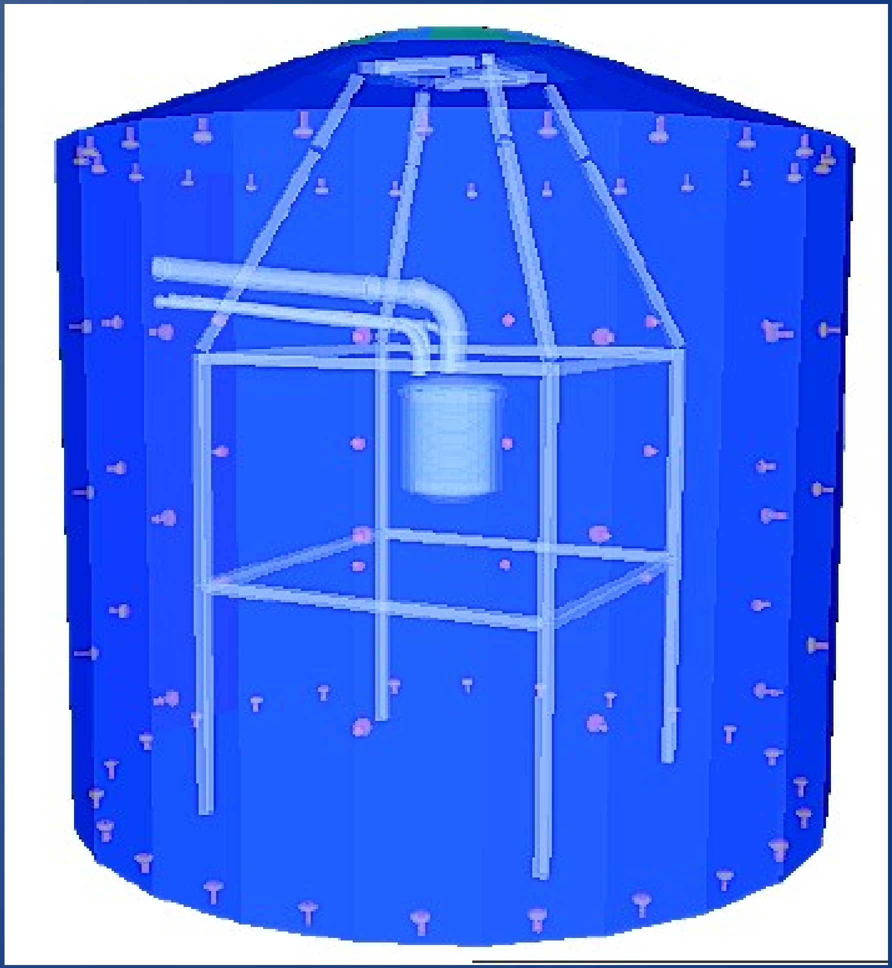
Reduce type II sources by charcoal filter
Rn sticks to charcoal → slow velocity through column
Activity reduced at outlet of column

Muon Veto

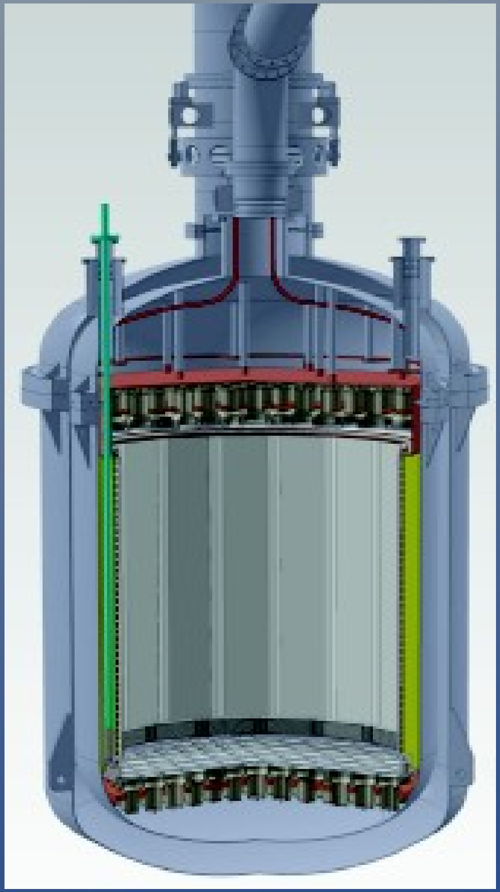
<u>Muon veto:</u>
10 m water cherenkov detector
84 8 inch PMTs (Hamamatsu R5912)
Specular reflector foil (DF2000MA)
    >99% reflectivity at optical wavelengths

<u>Triggering:</u>
Single photoelectron
4-fold coincidence
300 ns window
    → Optimized for tagging efficiency

Rejection power:
>99.5% of neutrons with muon in veto
>74% of showers with muon outside veto
Muon induced neutrons: < 0.01 / year



Detector Design



Cryostat:
- Type 316TI stainless steel
- 1.5 m high by 1.3 m ∅

TPC:
- Teflon UV reflector
- High Transparency meshes for HV

Cryogenics:
- Pulse tube refrigerators
- Long term stability in XENON100
- Redundant system

Purification:
- Continuously recirculate xenon
- High recirculation rate (~100 SLPM)
- Two heated getters in parallel

Westfälische
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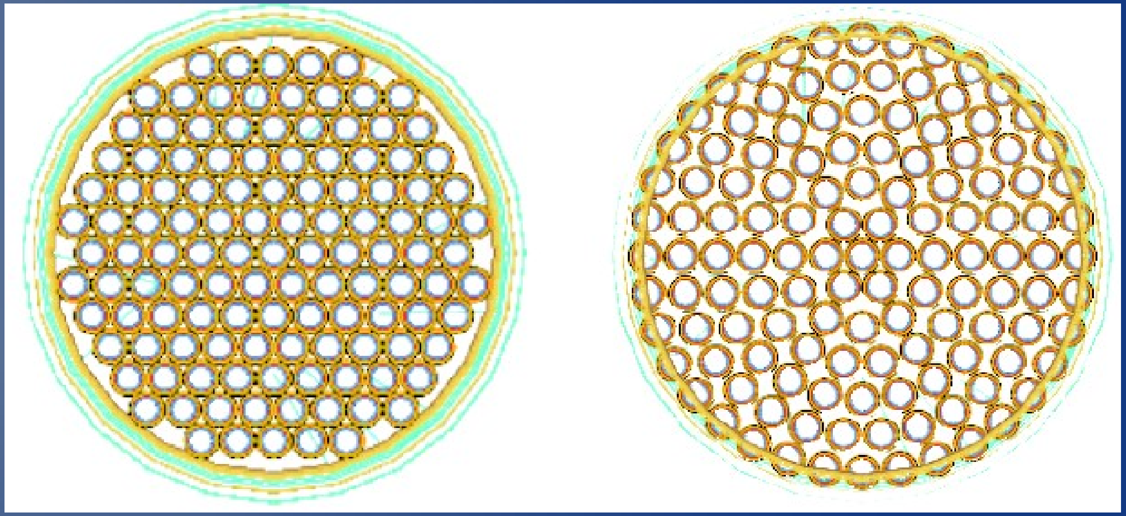
Münster

PMTs for TPC

XENON
Dark Matter Project



8 inch Hamamatsu R11410

High quantum efficiency (average 32.5%)

Low radioactivity (few mBq / PMT)

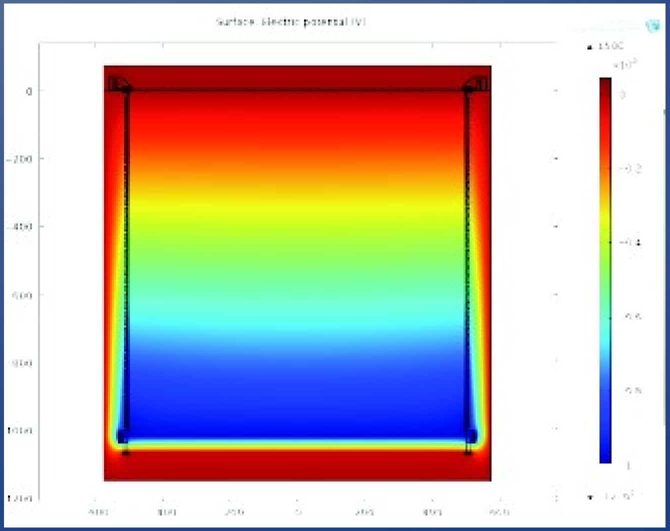
Bottom Array:
121 close packed for max light collection

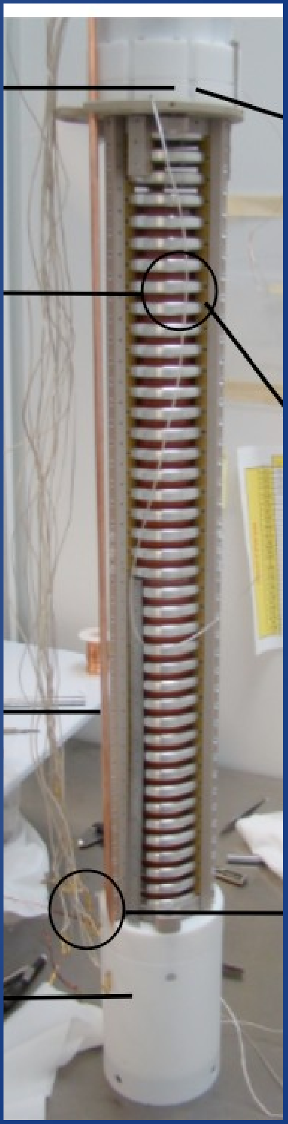
Top Array:
127 circular arrangement
cylindrically symmetric position reconstruction

Development Tests for TPC

Tests of high voltage and long electron drift underway:

HV stable at 100 kV in liquid xenon
60 cm drift demonstrated
1 m drift tests ongoing
Field uniformity simulations

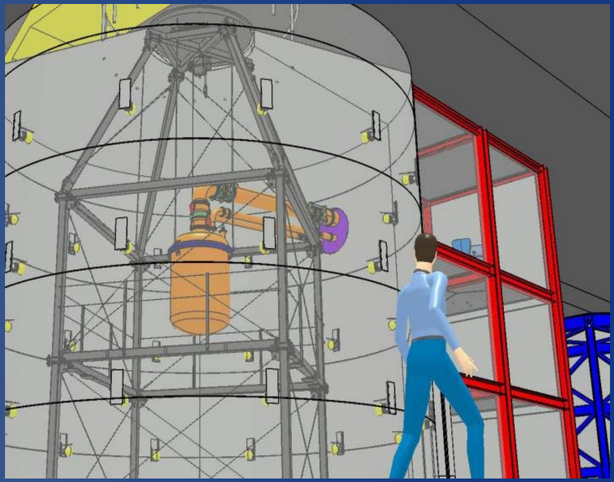


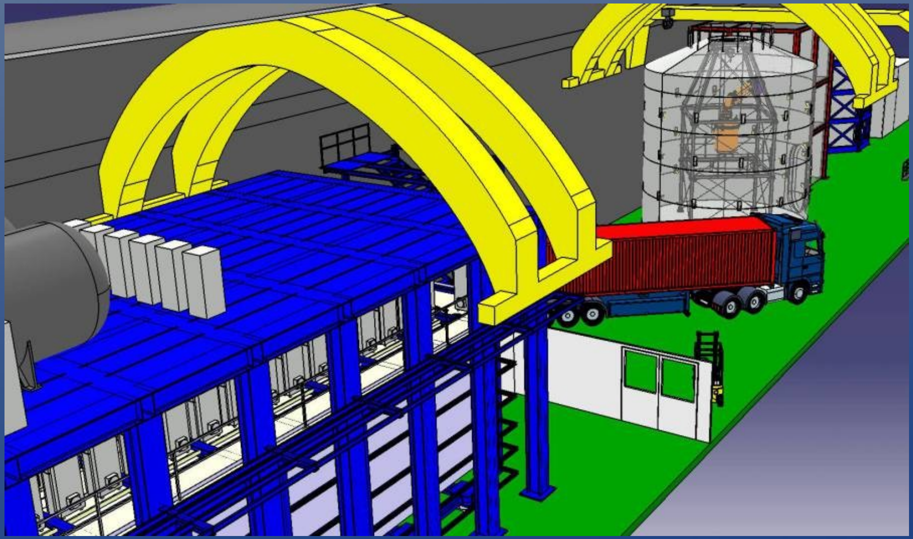


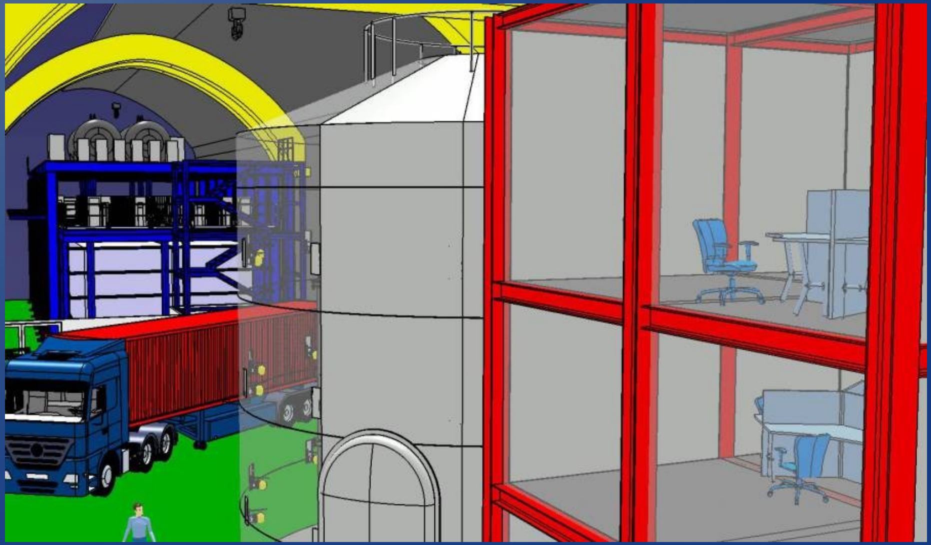
Construction Beginning This Spring

Extensive safety review conducted
- Risk analysis on all major systems

3D models of all systems constructed
- Detailed construction scenario developed
- All possible actions in underground lab foreseen







Summary and Outlook

The XENON project continues to lead the field for direct dark matter detection

XENON100:

Most sensitive spin independent limit

$\sigma_{SI} < 2.0 \times 10^{-45}$ cm^2 at 50 GeV/c^2

New spin dependent results:

Most sensitive limit above 6 GeV/c^2 for pure neutron coupling

$\sigma_n < 3.5 \times 10^{-40}$ cm^2 at 45 GeV/c^2

Also sensitive to pure proton coupling, consistent with other limits

XENON1T:

Sensitivity goal: $\sigma_{SI} = 2 \times 10^{-47}$ cm^2 by 2017

Reduce background by factor 100

10 m water shield + intrinsic radiopurity

Design of major systems underway

Construction to begin this spring