Dark Matter Searches with Xenon TPCs

and

First Results from XENON1T

Michelle Galloway, Universität Zürich

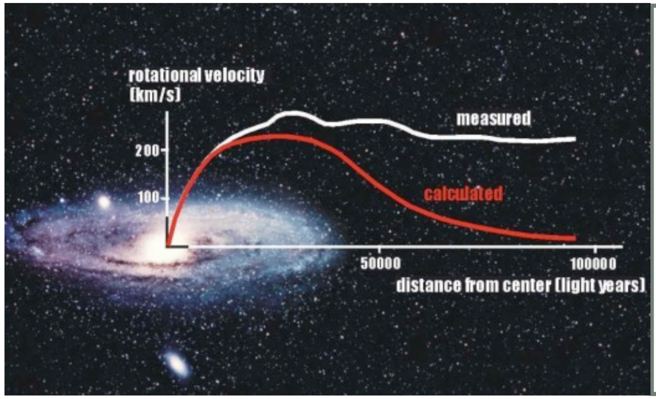
Vistas on Detector Physics

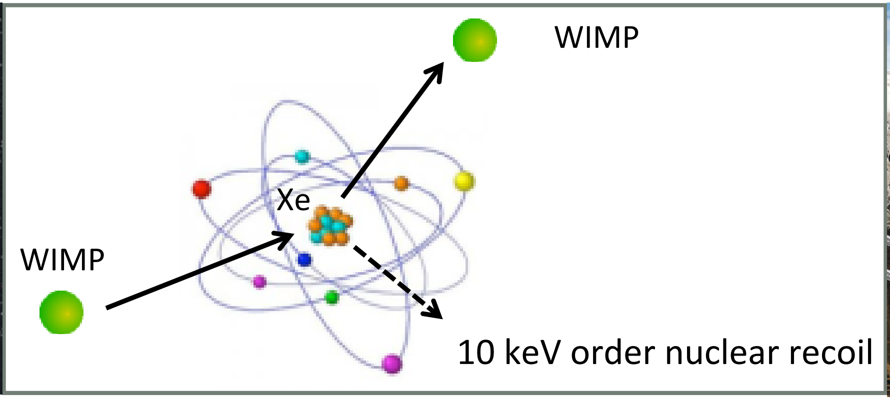
Universität Heidelberg, December 11-12, 2017

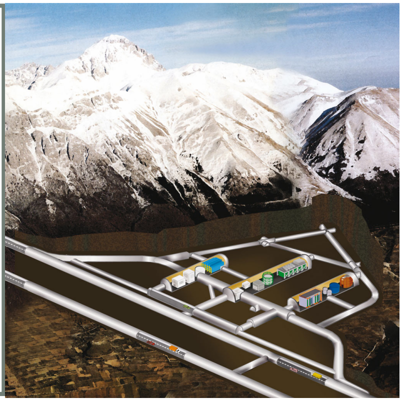
Xe
XENON
Dark Matter Project

WIMP Detection on Earth

If Weakly Interacting Massive Particles (WIMPs) have electroweak-scale interactions with Standard Model particles, terrestrial detection may be possible via elastic scattering off of target nuclei (Goodman and Witten, 1985).







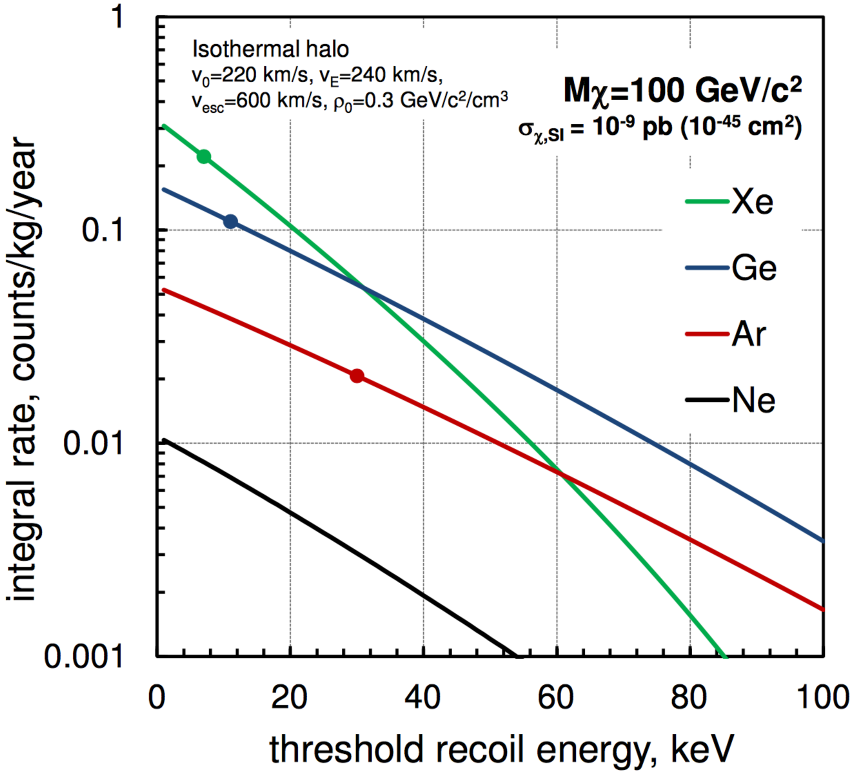
Event rate approximation for 100 GeV WIMPs:

$$R \sim 0.1 \, \frac{\text{events}}{\text{kg year}} \left[\frac{100}{A} \times \frac{\sigma_{\chi\mathcal{N}}}{10^{-38}\,\text{cm}^2} \times \frac{\langle v \rangle}{220\,\text{km}\,\text{s}^{-1}} \times \frac{\rho_0}{0.3\,\text{GeV}\,\text{cm}^{-3}} \right]$$

Necessitates high exposure (kg year), very low backgrounds and good discrimination!

Xenon as WIMP Target

WIMP interaction rates with different, complementary targets



Chepel, Araujo, JINST 8 (2013)

Advantages of Xe as target:

- odd and even isotopes (~50/50); spin-independent (SI) and spin-dependent (SD) couplings to WIMPs
- high mass number (A~131); SI cross section scales as A^2
- Easily scaled to increase mass (exposure)

For low-backgrounds:

- low intrinsic radioactivity
- high density (~3 g/cm^3) stops external gamma-ray backgrounds

As detection medium:

- it scintillates, and is transparent to its own emission (~178 nm)
- high ionisation yield and dielectric medium (free electrons that can be used for detection)

—> allows for two separate detection channels for each interaction

Dual-phase Time Projection Chamber (TPC) Concept

Dolgoshein Lebedenko, Rodionov,
JETP Letters 11:11 (1970)

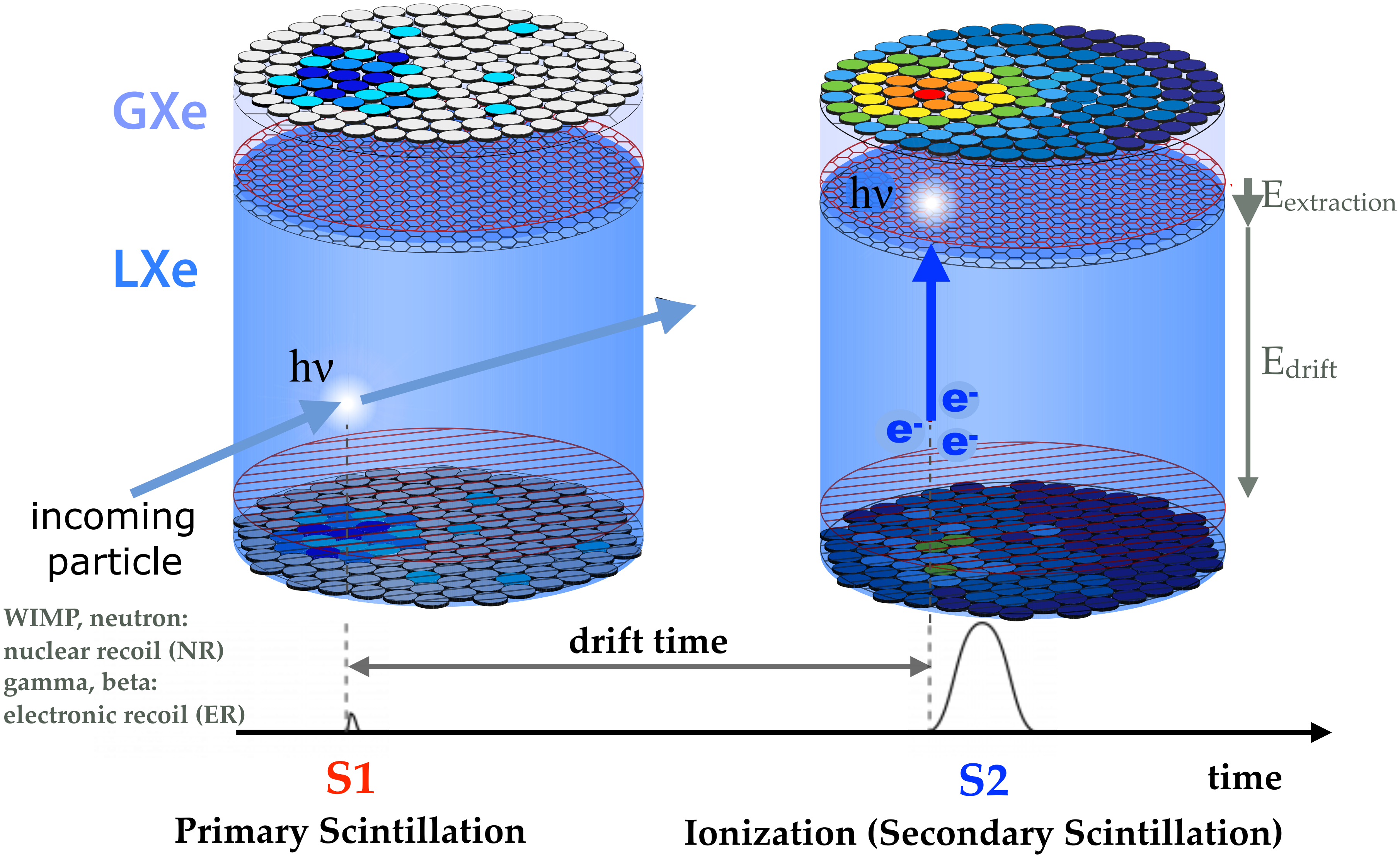
Liquified noble gases as detection medium

- Particle interaction produces scintillation flash and free electrons
- An applied field between cathode (C) and gate (G) causes electrons to drift upwards
- A second field between gate and anode (A) can extract electron cloud\
- into gas phase, amplified, collected and imaged (imaging tracks)
- the time difference between the scintillation and electron collection depends on the drift velocity of the electrons

—-> the drift time gives the depth of interaction

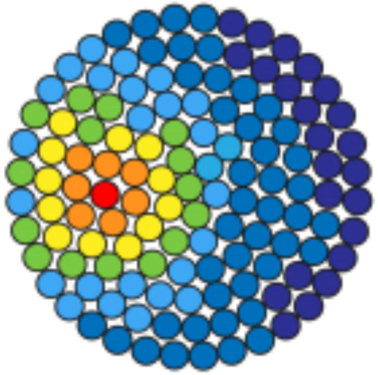
TPC: A detector that uses a time-to-space projection of the drift coordinate to image particle interactions in a medium

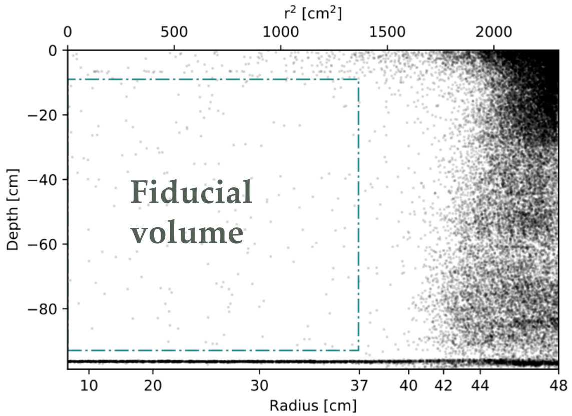
Xenon Time Projection Chamber

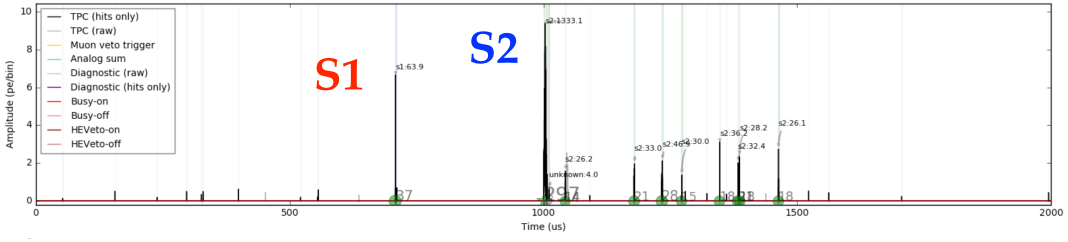


Xenon Time Projection Chamber

Vertex Reconstruction/Fiducialization:
x-y spatial coordinate from pattern on top array of photosensors
z- depth of interaction from drift time



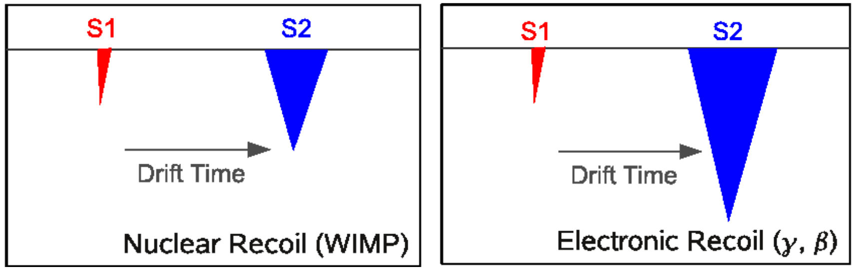


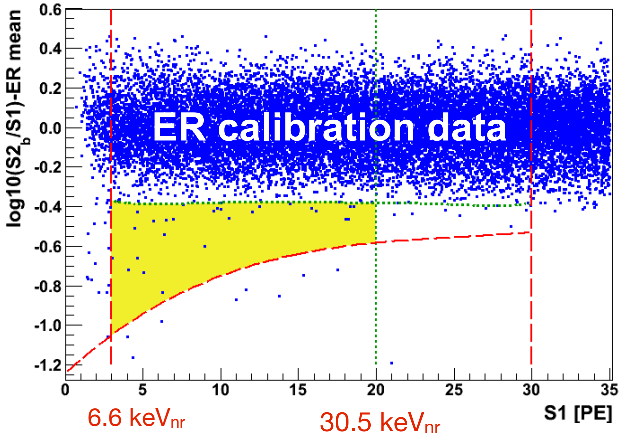


Aprile, et al. Phys. Rev. D (2017)

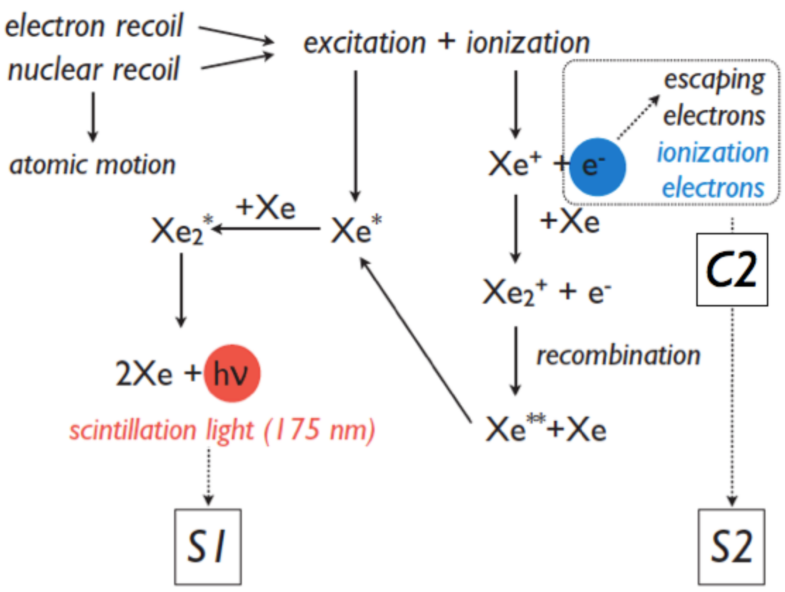
Particle identification:
track length is different for Electronic Recoils (ER) than for Nuclear Recoils (NR) for the same energy deposition

$$\frac{S2}{S1}_{NR} < \frac{S2}{S1}_{ER}$$

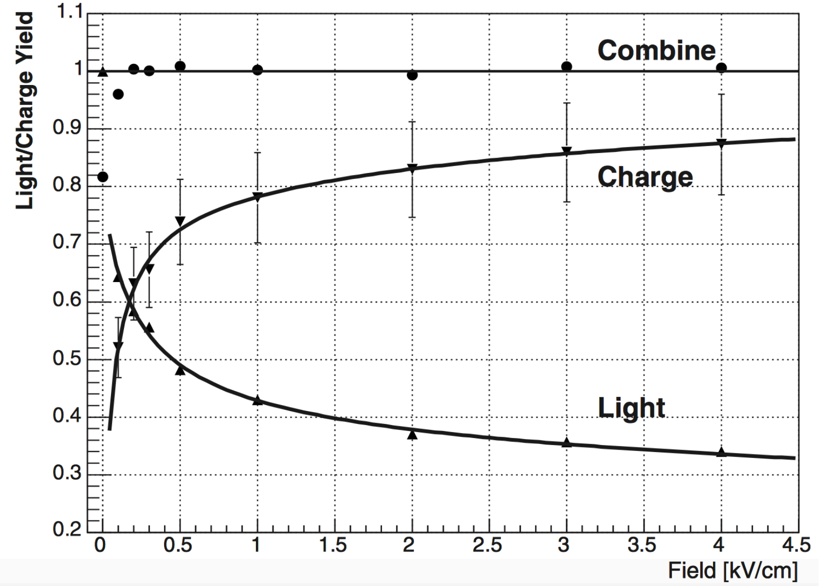




Particle Identification (PID)



Manzur, Phys. Rev. C 81 (2010)



Aprile, et al, Phys. Rev. B 76 (2007)

- Neutrons, WIMPS (NR) yield denser tracks (higher dE/dx) as gamma, beta (ER), leads to higher recombination rate (S1) for the same energy deposition
- Charge (S2) and light (S1) distribution channels are anti-correlated (can be combined to improve energy resolution)
- The S2/S1 ratio increases with higher applied drift fields

Xenon-based Dark Matter Experiments

XMASS
(single-phase)
Kamioka, Japan
Total Xe: 835 kg
Fiducial: 100 kg
Photosensors: 642

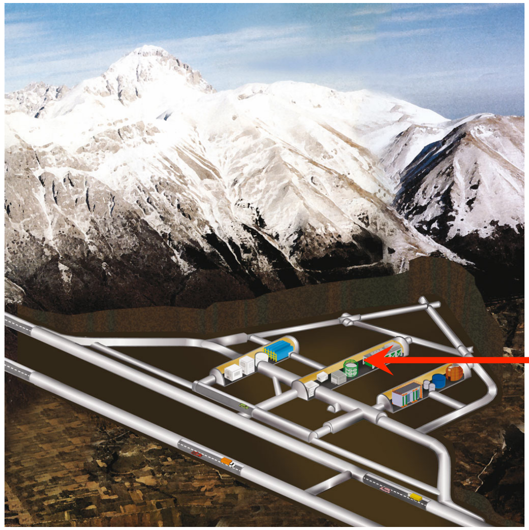
LUX
South Dakota, US
(SURF)
Total Xe: 350 kg
Fiducial: 100 kg
Photosensors: 122

PandaX-II
Jinping, China
(CJPL)
Total Xe: 580 kg
Fiducial: 362 kg
Photosensors: 110

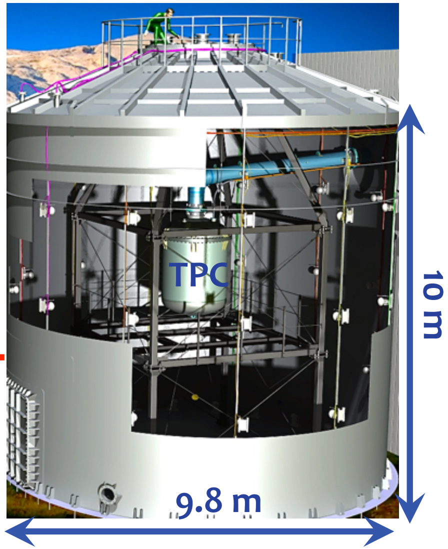
XENON1T
Gran Sasso, Italy
(LNGS/INFN)
Total Xe: 3.2 ton
Fiducial: 1 ton
Photosensors: 248

Aprile, et al. Phys. Rev. D (2017)
Aprile, et al. arXiv:1708.07051 (2017)

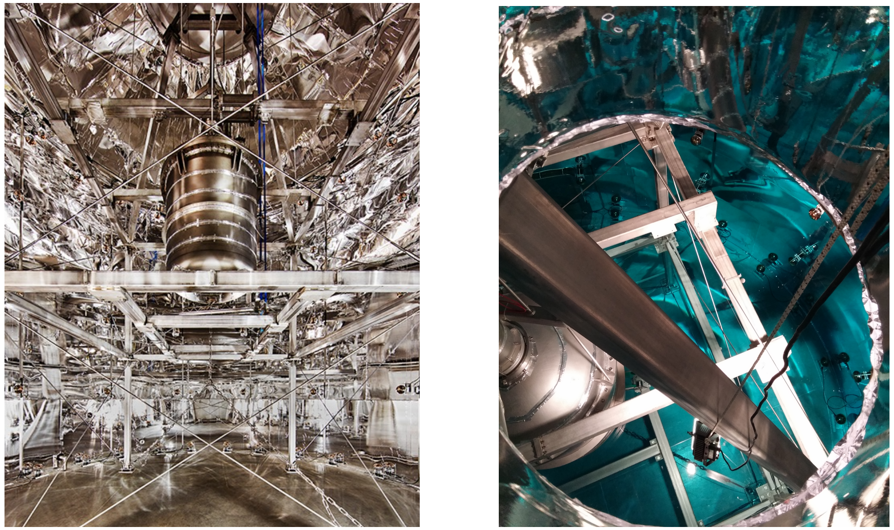
XENON1T at LNGS



Laboratori Nazionali del Gran Sasso (LNGS)
3600 m water equivalent
Muon reduction by factor of 10^6

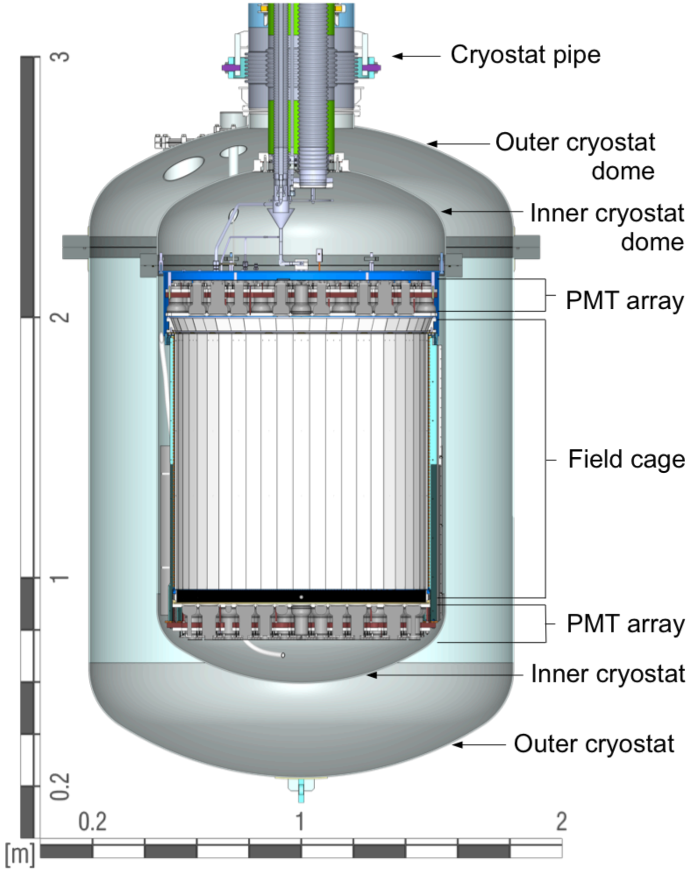


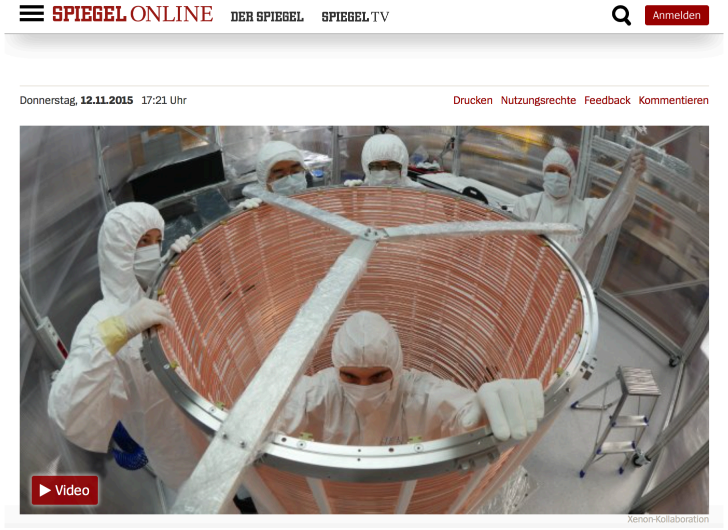
Water Shield
~700 m^3 H_2O
muon, hadron background reduction

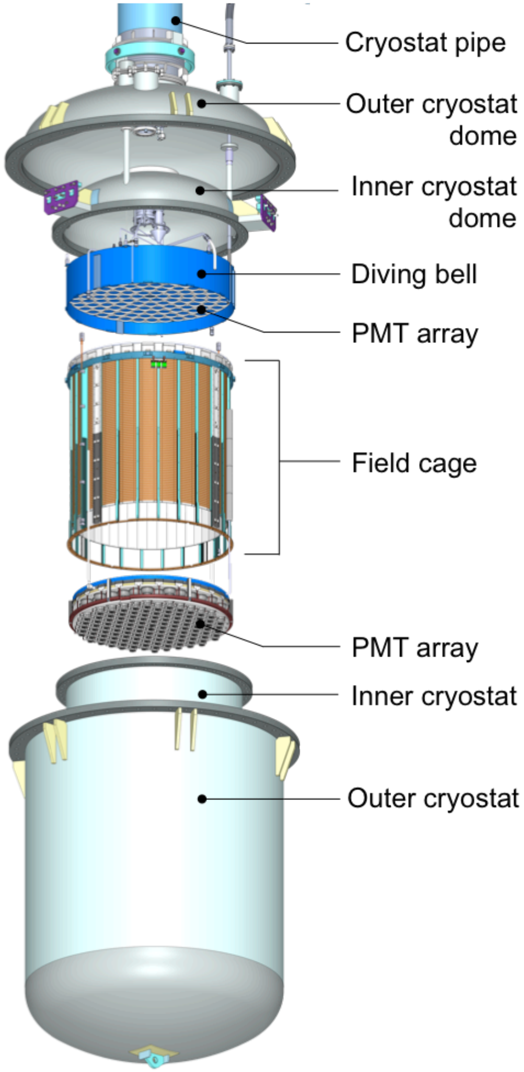


Cherenkov Detector
Tank instrumented with 84 high-QE 8” PMTS
Active rejection through coincidence tagging

The XENON1T TPC



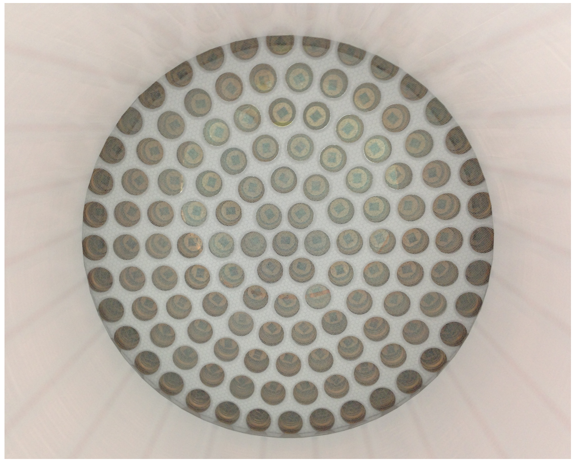




- 1x1 m: 2 tons LXe (3.2 t total)
- double-walled vacuum cryostat
- copper rings for uniform field
- low-activity, selected materials

XENON1T: Photosensors

121 bottom



127 top

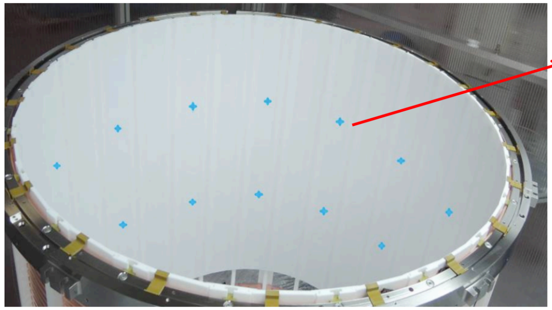
PMT arrays and reflectors

- bottom array: maximum light collection
- top array: radial position reconstruction
- diamond-polished PTFE for high reflectivity in VUV
- The amount of light collected depends upon interaction position

Hamamatsu R11410

PMTs

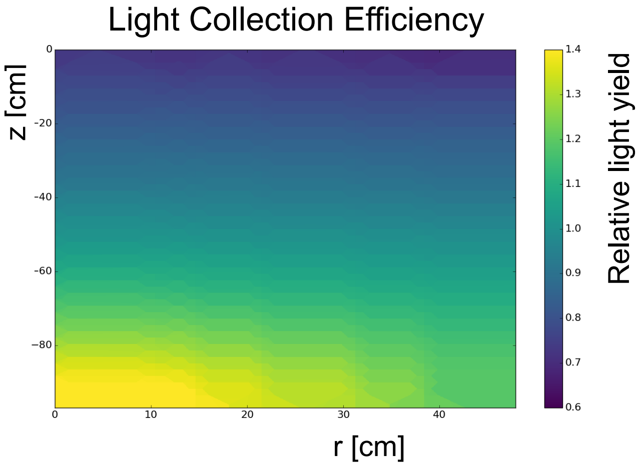
- 3”, bialkali window
- High QE ~34% @175 nm
- average gain ~5x10^6 @ 1500 V
- cryogenic, low-radioactivity



blue LED from fibers

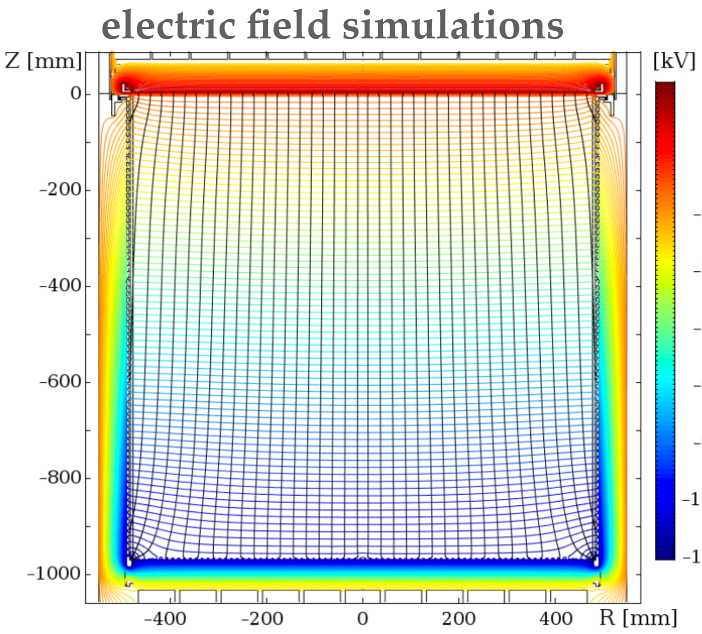
regular gain, performance calibrations (leaks, noise)

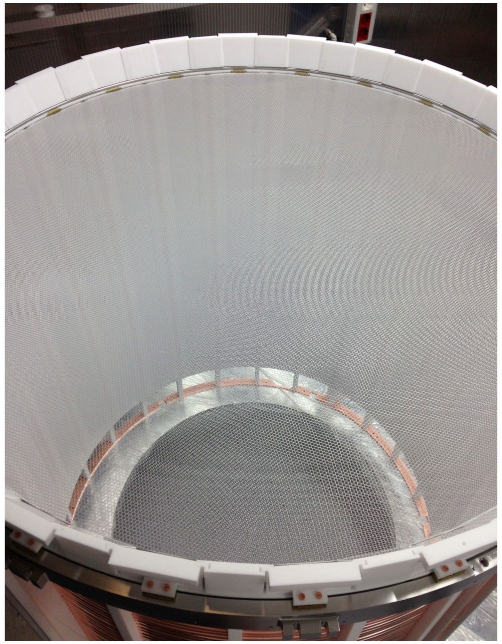
`Eur. Phys. J. C75, 11, 546 (2015)`
`JINST 8, P04026 (2013)`
`JINST 12, P01024 (2017)`

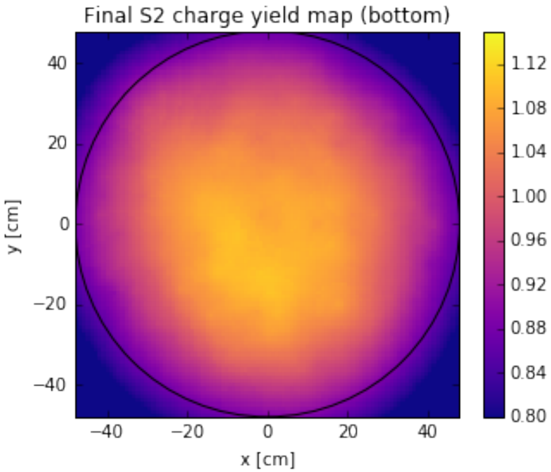


S1 signal correction for spatial response (using ^{83m}Kr source)

XENON1T: Applied Fields

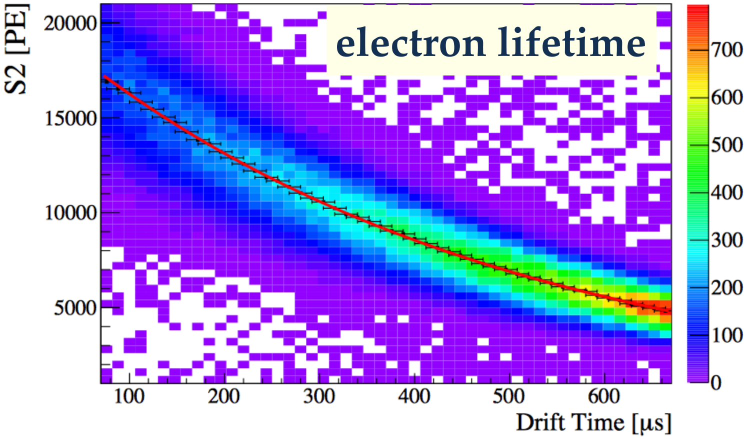






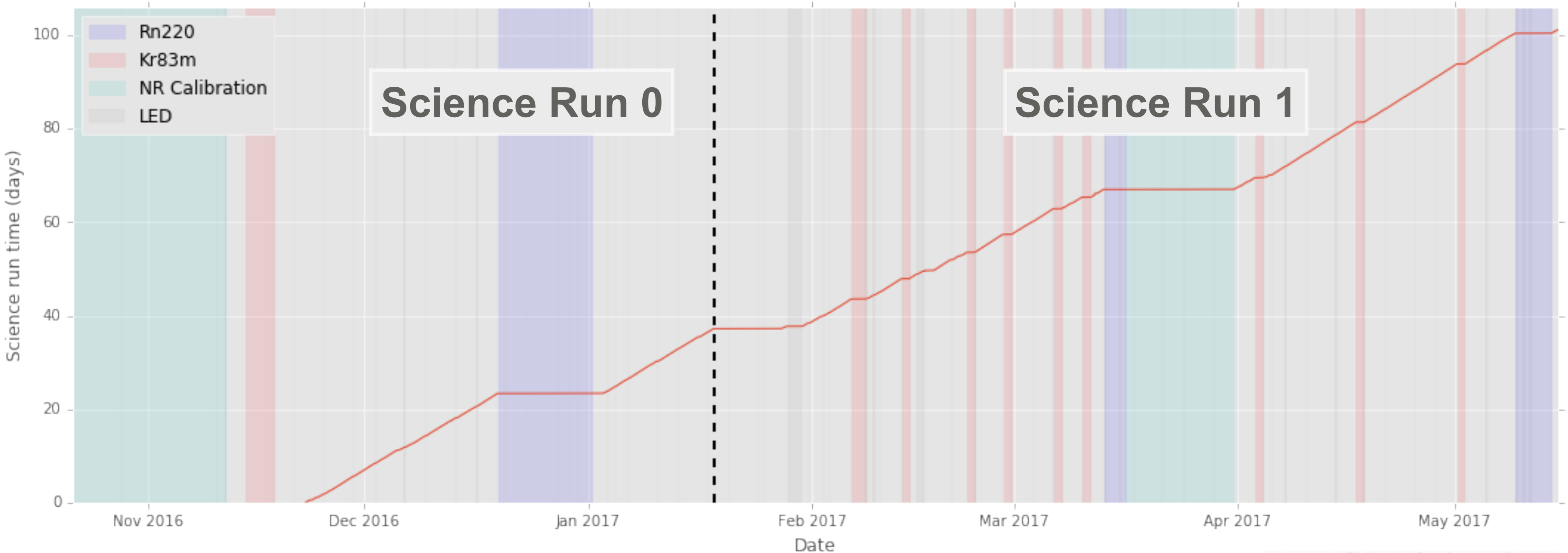
S2 spatial corrections

- electric field non-uniformities (+ PTFE charge-up)
- position-dependent S2 amplification (mesh warping)
- electron lifetime - loss due to electronegative impurities in the xenon



See next talk by Constanze Hasterok

XENON1T: First Science Run



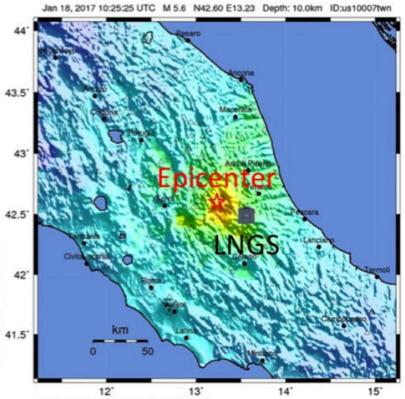
34.2 live days dark matter exposure

3.0 days ^{220}Rn for low-energy electronic recoil band calibration

16.3 days ^{241}AmBe for low-energy nuclear recoil calibration

3.3 days ^{83m}Kr: for spatial response correction

Geological interruption defined first science run;
Still running with more than 130 days exposure.

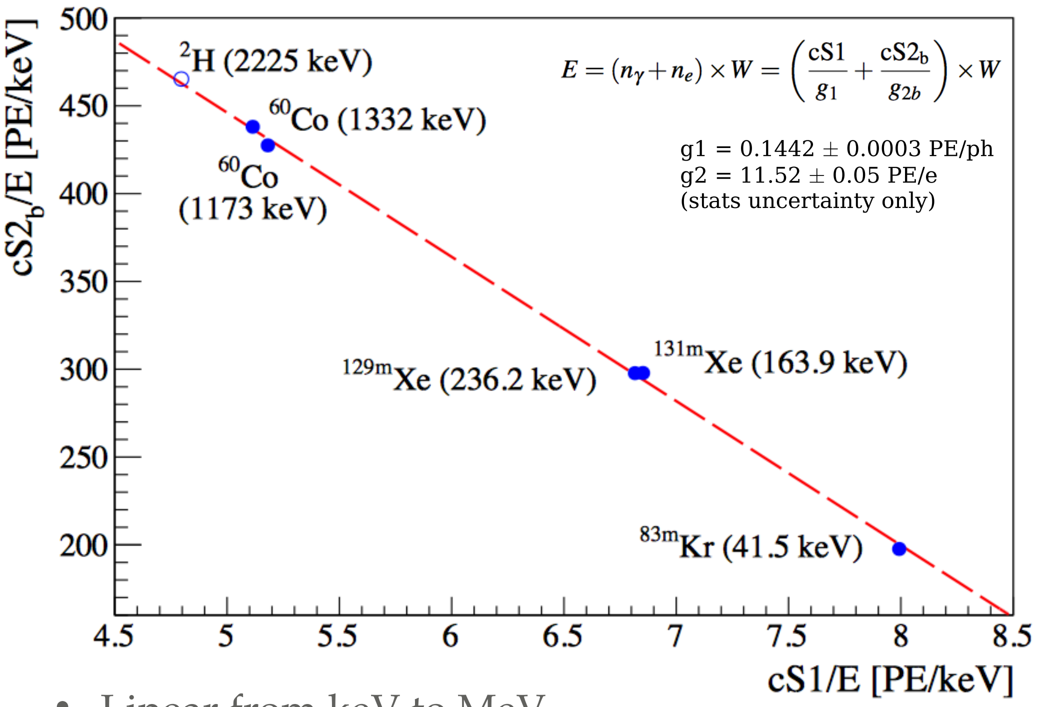


Earthquake magnitude 5.5
Jan. 18, 2017

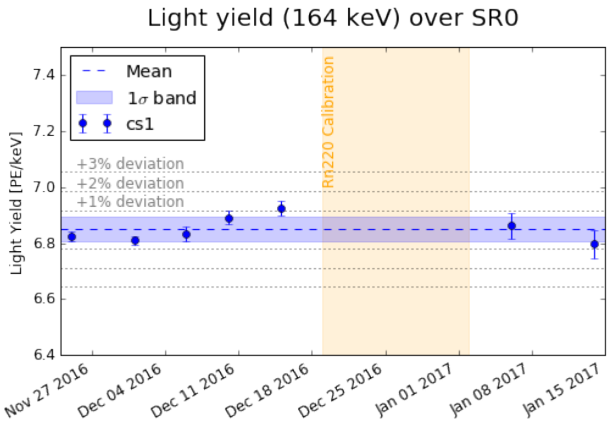
Energy Resolution

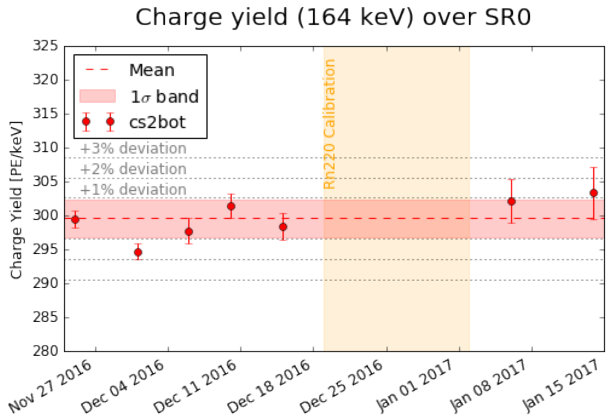
Energy scale

The efficiency to detect light and charge are given by the primary and secondary scintillation gains, g1 and g2, where W is energy needed to produce one electron-ion pair in xenon (W = 13.7 eV)



- Linear from keV to MeV
- light detection efficiency (12.5 ± 0.6)% (predicted 12.1%)
- 96% charge extraction efficiency



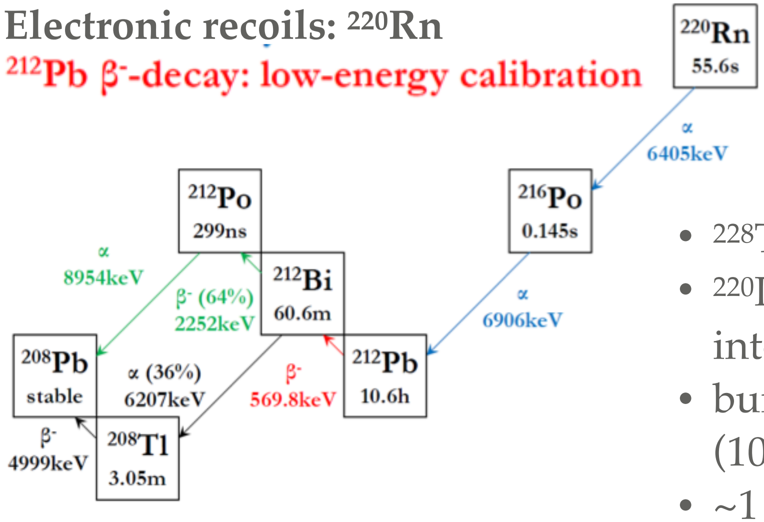


Light and Charge Yield stable within 1%
internal source monitoring (^{131m}Xe, ^{83m}Kr)

Calibrations

Electronic recoils: ^{220}Rn

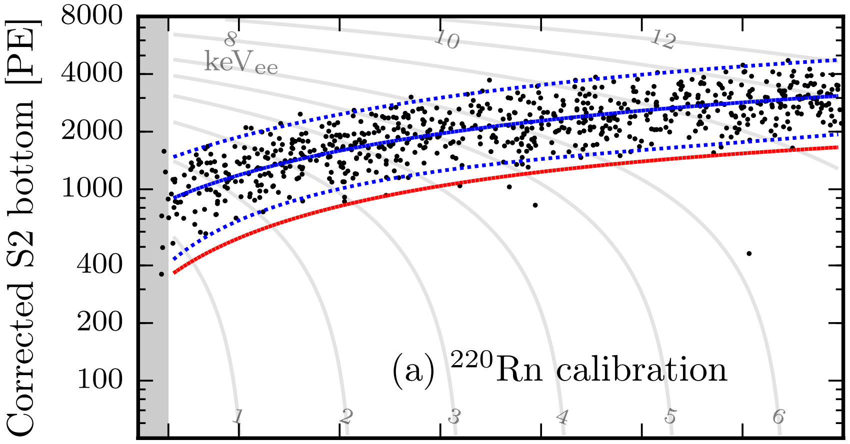
^{212}Pb β$^-$-decay: low-energy calibration



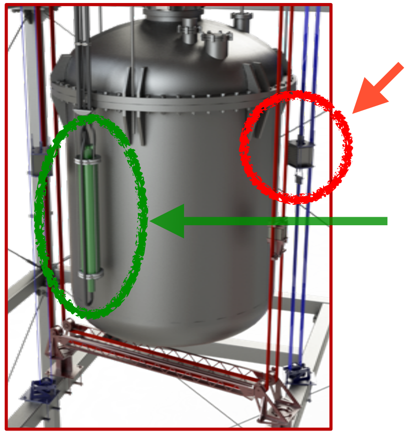
Phys. Rev. D 95, 72008 (2017)

- ^{228}Th source
- ^{220}Rn emanates into xenon gas
- builds to ^{212}Pb (10.6 h): 2-30 keV
- ~1 week decay

Blue: ER
Red: NR

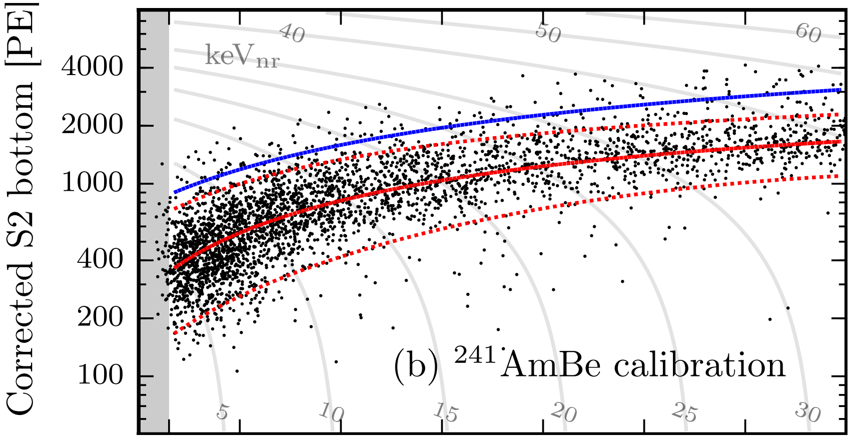


Nuclear recoils: AmBe

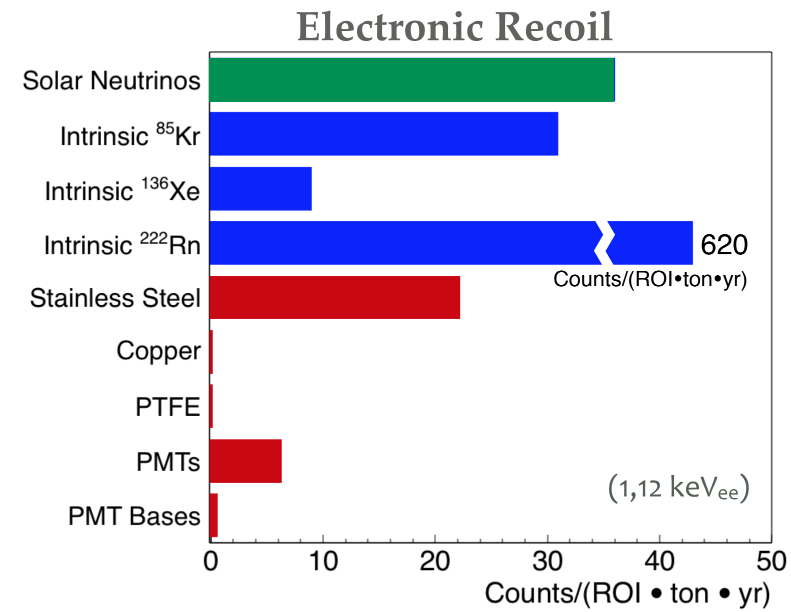


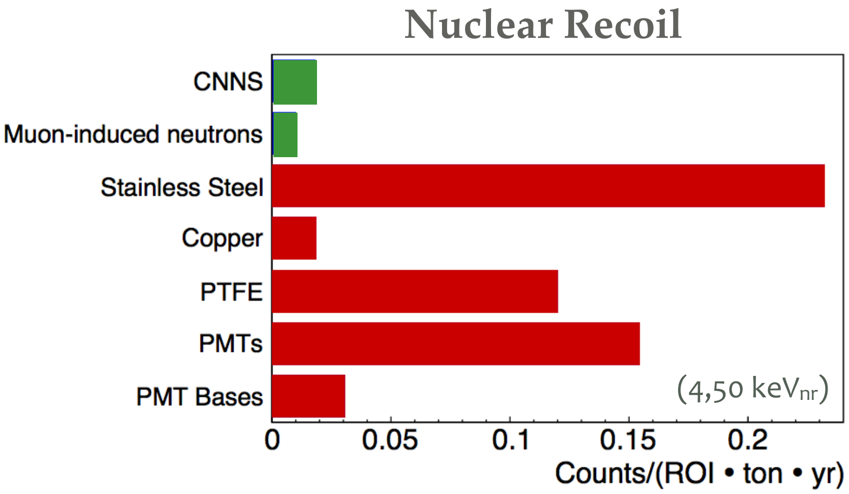
arXiv: 1705.04741

- ^{241}AmBe external source (belt system) emits 1-10 MeV neutrons
- neutron generator commissioned May 2017, peaks 2.2 and 2.7 MeV
- reduced calibration time from weeks to ~days



Backgrounds





Reduction Methods:

- materials radioassay & selection
- cryogenic distillation to remove Kr:
  ^{nat}Kr/Xe < 0.048 · 10^{-12} (<48 ppq)
- Rn distillation (in-situ: 20% lower tests: >27x decrease in Xe100) : **^{222}Rn 10 μBq/kg target concentration**
- future: active neutron veto!

arXiv:1705.01828 (2017)
EPJ C 77, 275 (2017)
arxiv:1702.06942 (2017)

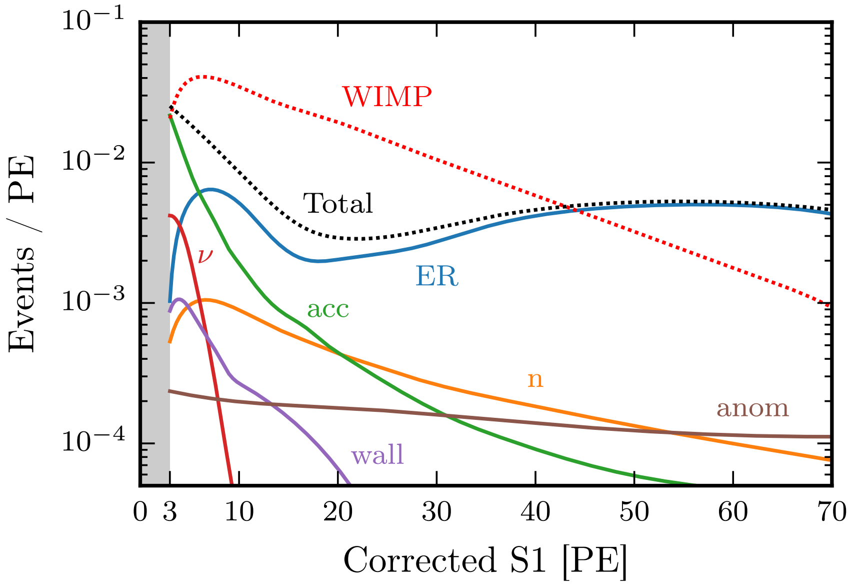
MC predictions
(2.3±0.2) ×10^{-4}
events/kg/day/keV$_{ee}$

Measured
(1.93±0.25) ×10^{-4}
events/kg/day/keV$_{ee}$

Lowest background ever achieved in a dark matter detector!

See next talk by Constanze Hasterok

Total Background

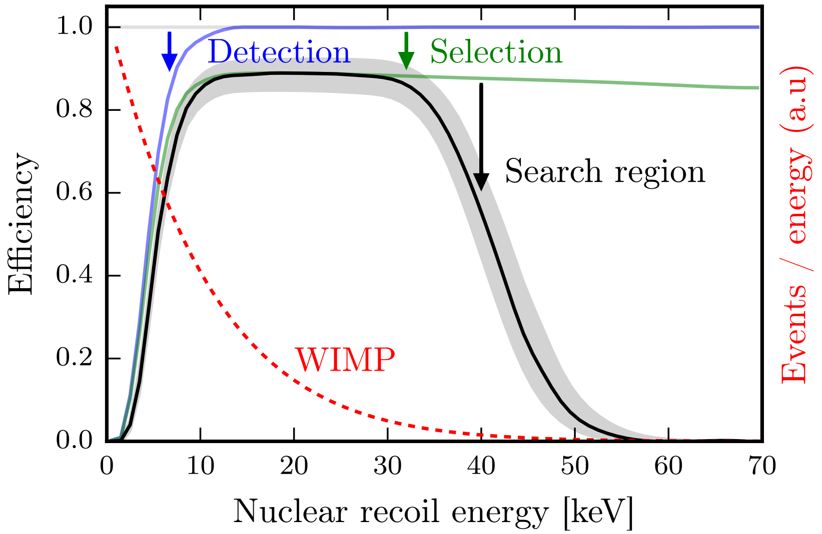


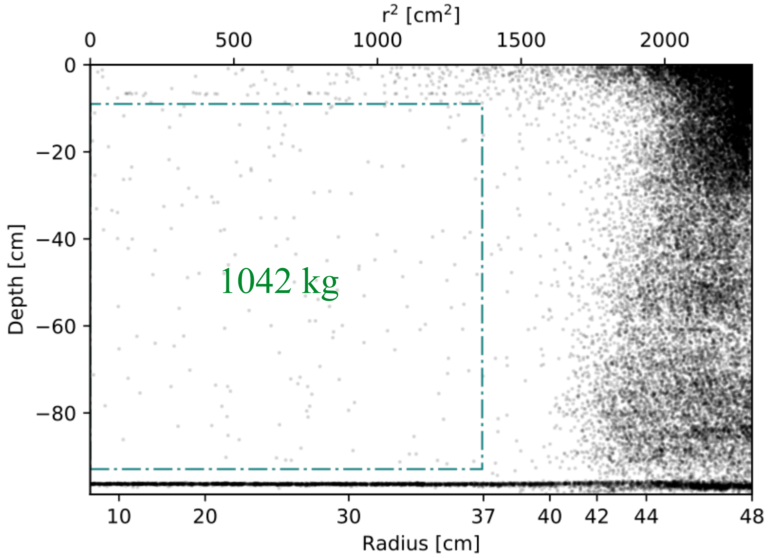
Background Model

- ER and NR spectral shapes derived from models fitted to calibration data
- NR energy conversion is based on the model and parametrisation from simulation (NEST)
- background expectations are data-driven, derived from control samples

Background & Signal Rates	**Total**	**NR median -2σ**
Electronic recoils (*ER*)	62 ± 8	0.26 (+0.11)(-0.07)
Radiogenic neutrons (*n*)	0.05 ± 0.01	0.02
CNNS (ν)	0.02	0.01
Accidental coincidences (*acc*)	0.22 ± 0.01	0.06
Wall leakage (*wall*)	0.52 ± 0.32	0.01
Anomalous (*anom*)	0.09 (+0.12)(-0.06)	0.01 ± 0.01
Total background	**63 ± 8**	**0.36 (+0.11)(-0.07)**
50 GeV/c^2, 10^{-46} cm^2 WIMP (*NR*)	**1.66 ± 0.01**	**0.82 ± 0.06**

Event Selection





Nuclear recoil detection efficiency

Signal reconstruction algorithms tuned with MC

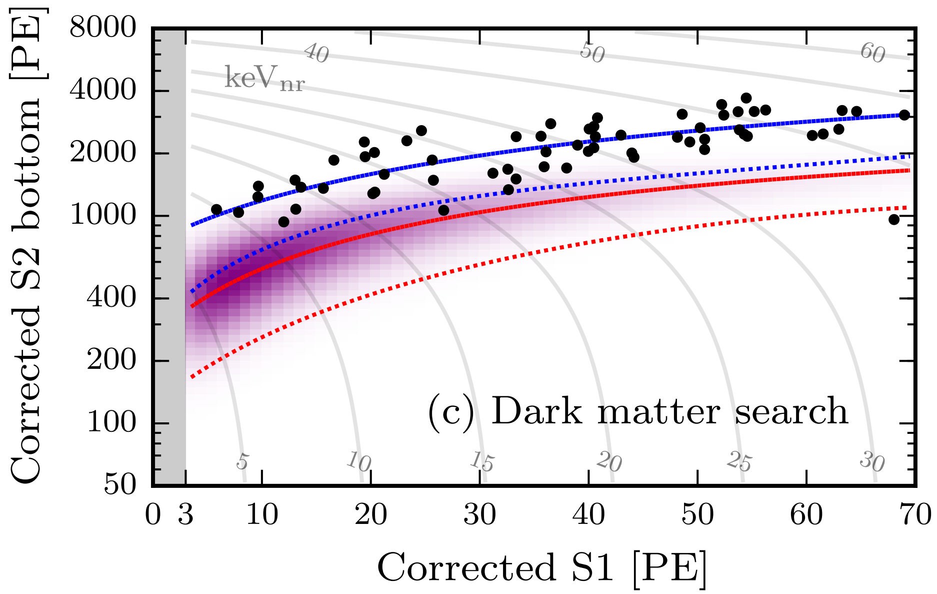
- modeled light propagation and detector electronics (noise)
- validated S1/S2 waveforms

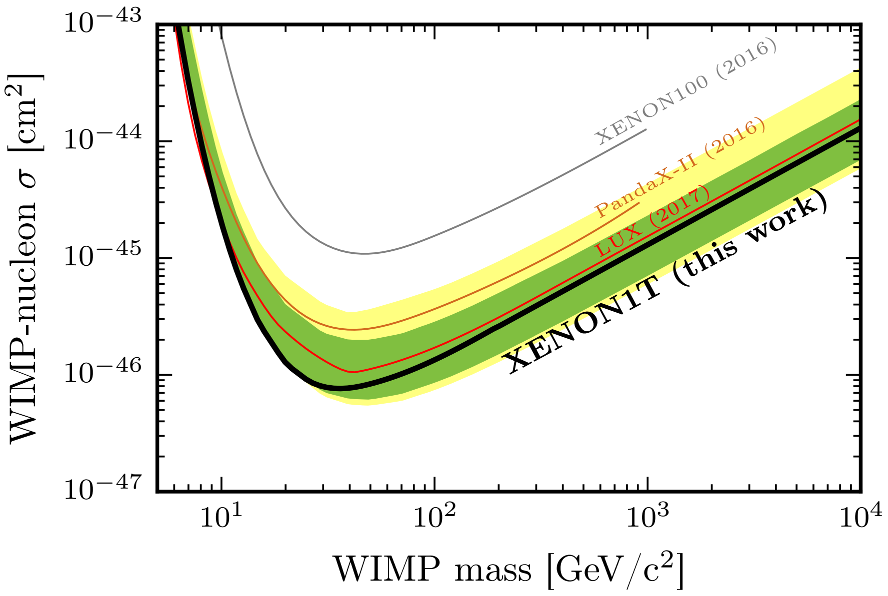
Selections

- WIMPs are expected as low-energy, single scatters
- reject events with uncorrelated signals before main S2 & events after a high-energy event
- S2 width and PMT hit patterns must be consistent with reconstructed vertex

Cut	Events remaining
All ($cS1 < 200$ PE)	128144
Selections	48955
1 t Fiducial volume	180
S1 range ($3 < cS1 < 70$)	63

First Results





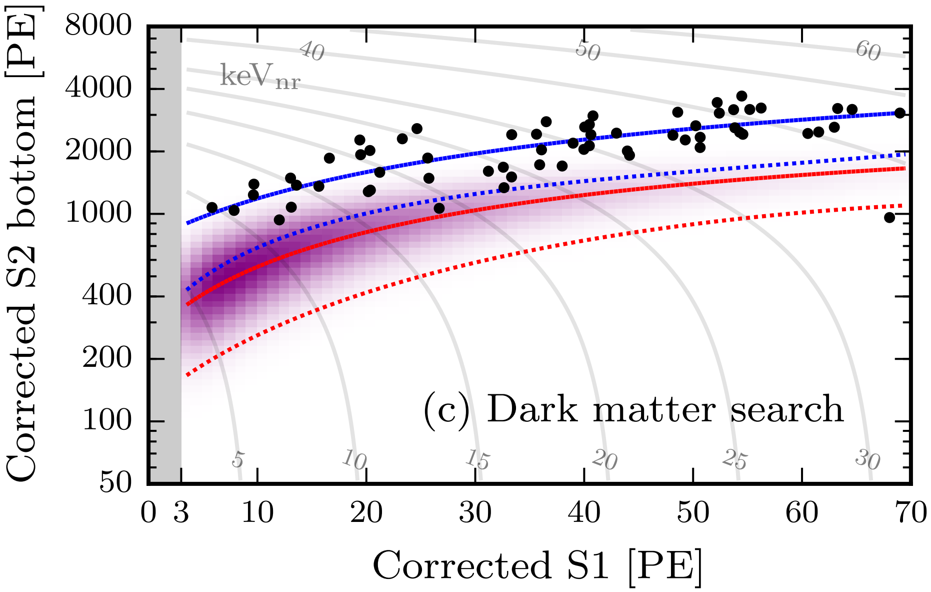
Results consistent with null hypothesis

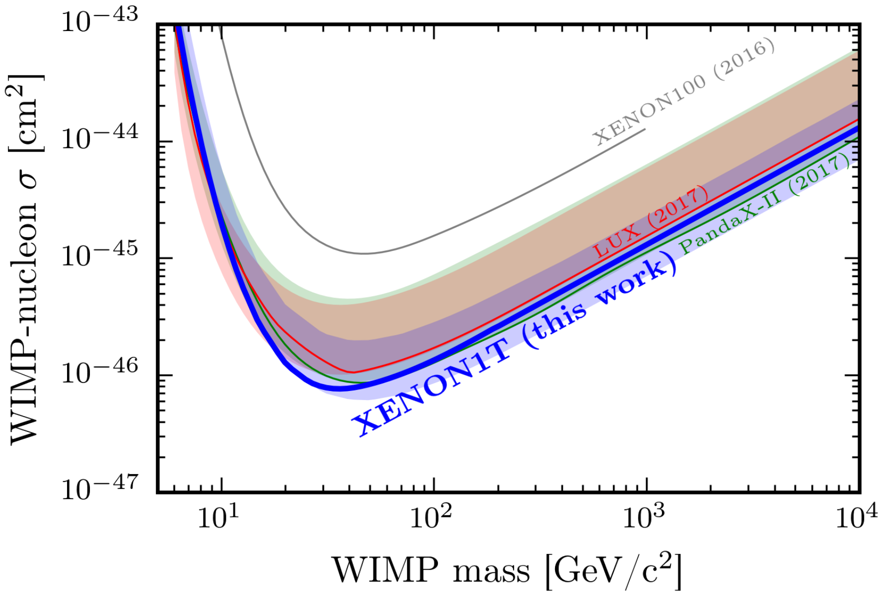
- WIMP region blinded until fiducial mass and event selections were finalized
- Extended unbinned profile likelihood analysis for statistical interpretation
  ER/NR shape parameters from calibration fits
- Standard isothermal WIMP halo model + Helm form factor
- No significant excess was observed above the expected background

Strongest exclusion limit for spin-independent WIMPs at 35 GeV/c^2 of 7.7×10^{-47} cm^2

Aprile, et al. Phys. Rev. D (2017)

First Results





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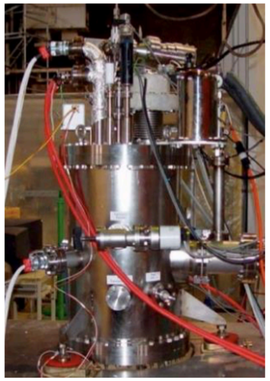
Still strongest exclusion limit for spin-independent WIMPs at 35 GeV/c^2 of 7.7×10^{-47} cm^2

Aprile, et al. Phys. Rev. D (2017)

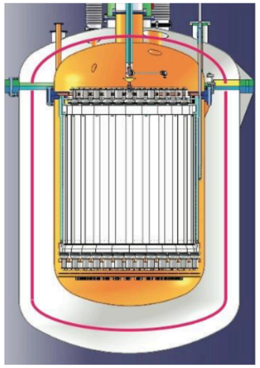
The XENON (to DARWIN) Project



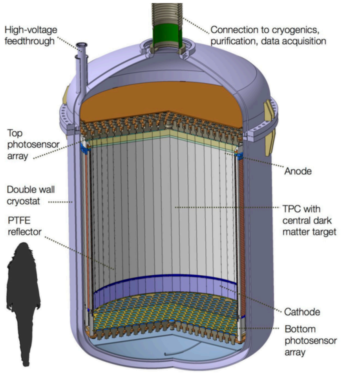
XENON10
Total Xe: 25 kg
Target: 14 kg
Fiducial: 5.4 kg
Limit: ~10^{-43} [cm^2]

XENON100
Total Xe: 162 kg
Target: 62 kg
Fiducial: 34/48 kg
Limit: ~10^{-45} [cm^2]

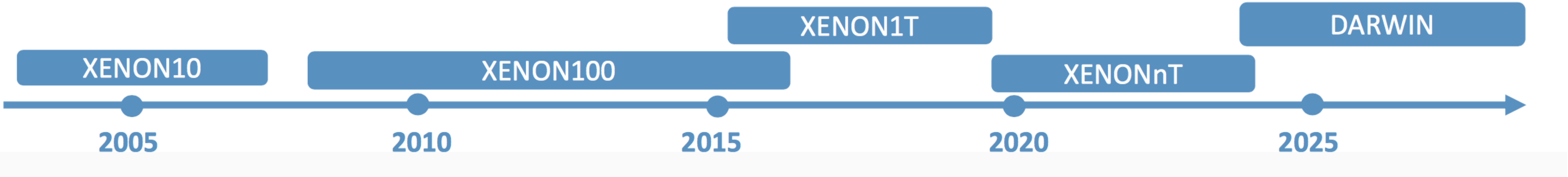
XENON1T
Total Xe: 3.2 ton
Target: 2 ton
Fiducial: 1 ton
Limit: ~10^{-47} [cm^2]



XENONnT
Total Xe: ~8 ton
Target: ~6.5 ton
Fiducial: ~5 ton
Limit: ~10^{-48} [cm^2]



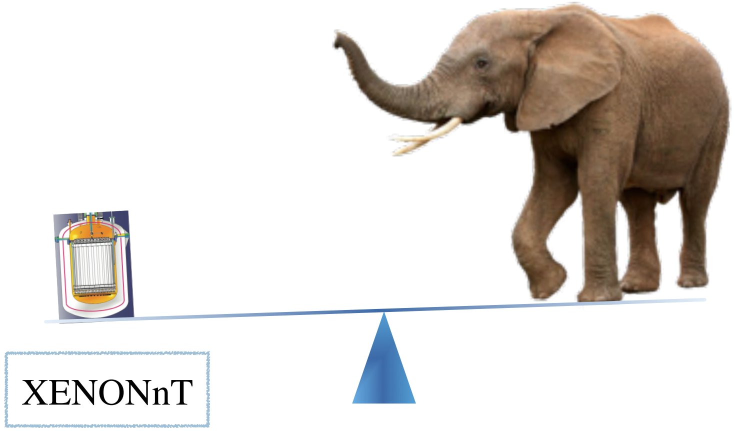
DARWIN
Total Xe: ~50 ton
Target: ~40 ton
Fiducial: ~30 ton
Limit: ~10^{-49} [cm^2]

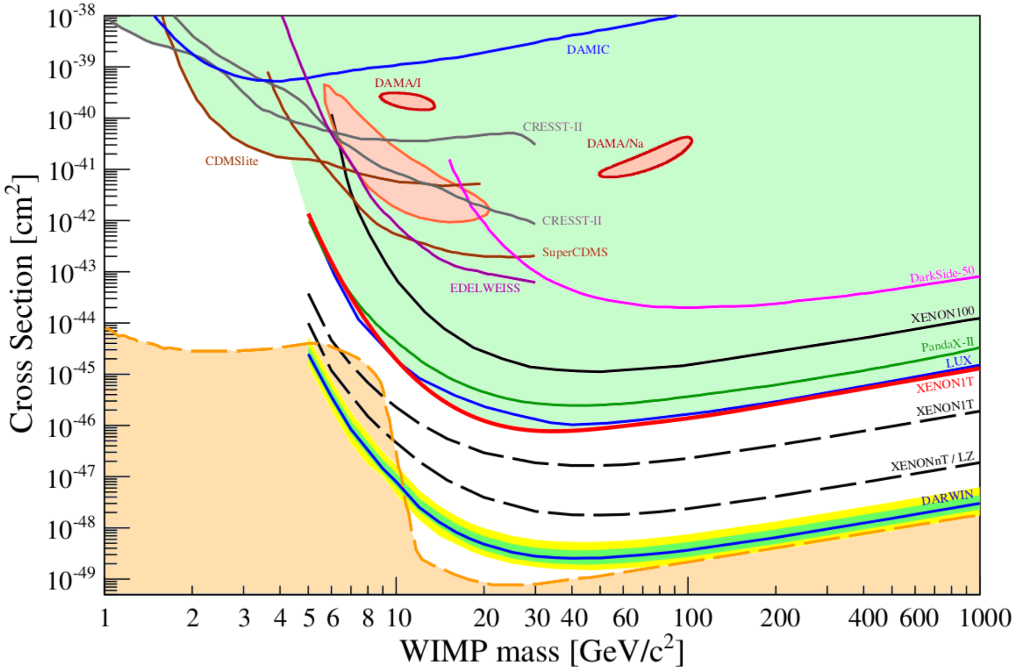


-> Sensitivity improves with exposure (mass, T_{obs}), lower backgrounds, and improved PID

Outlook

- More parameter space to be covered by future WIMP searches (XENONnT, LZ, DARWIN)
- Several challenges ahead as we scale up the dual-phase TPC:
    - increase sensitivity to lower-mass WIMPs (lower threshold, neutrino background)
    - technical challenges (larger electrodes, field nonuniformities, photosensor optimization)
    - high purity of xenon needed to drift electrons over longer drift lengths
    - low backgrounds - neutron rejection capability through an active veto
- XENON1T next results coming very soon!





Spin-independent WIMP-nucleon parameter space: exclusion limits and expectations from liquid xenon-based experiments

Thank you for your attention!

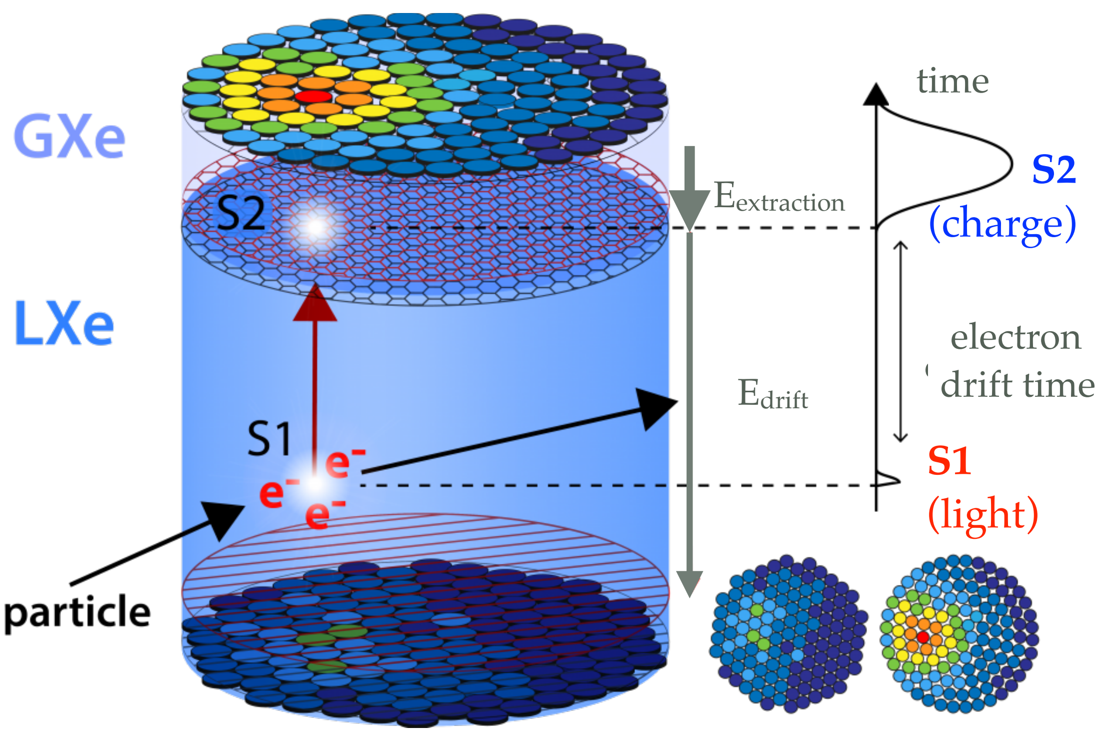
Questions?

backup

Key Points

- Dual-phase TPCs use both prompt scintillation and extracted charge from an interaction with liquid xenon to look for WIMPs.
- By this method, the particle interaction location can be deduced and used a tool for discrimination.
- The difference in track length (-dE/dx) forms the basis to distinguish signal from background, and is preserved by the charge-to-light ratio.
- Detection sensitivity improves upon exposure (target mass, time), and the ability to minimize and discriminate background interactions

Dual-phase Time Projection Chamber (TPC)

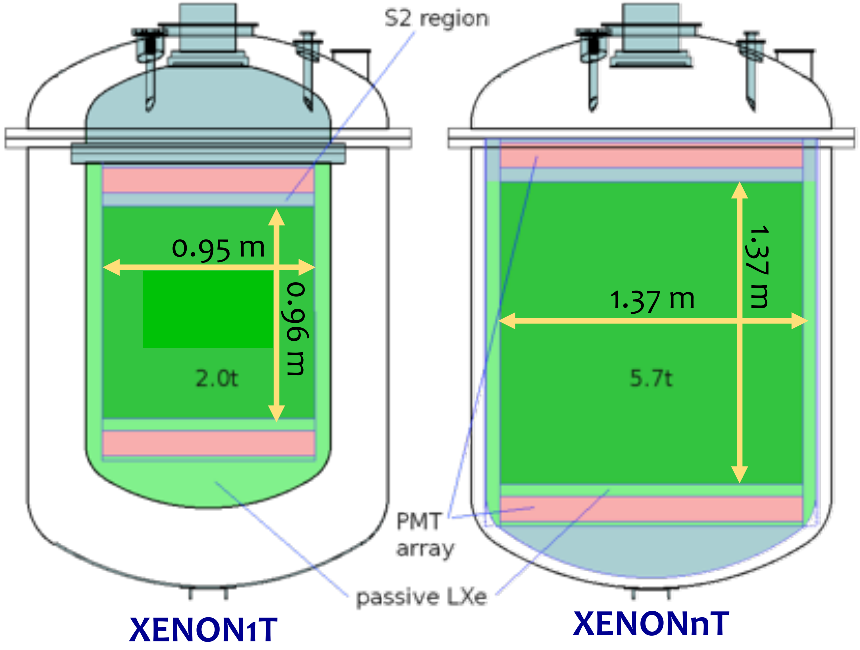


backup


Columbia
RPI
Nikhef
Stockholm
Muenster
Mainz
MPIK
Chicago
Freiburg
UCLA
Zurich
UCSD
NYUAD
Rice
Weizmann
Purdue
Coimbra
Subatech
LPNHE
LAL
Bologna
LNGS
Torino

XENONnT

New TPC and inner cryostat with increased linear dimensions



Scaled XENON1T design

significantly reduced time needed for design, construction, and commissioning (XENON1T experience!).

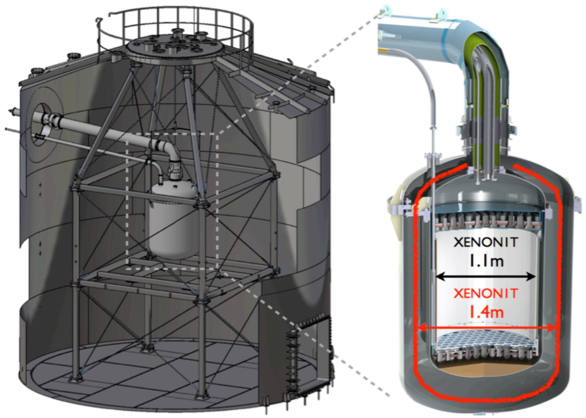
Materials

sources of clean materials and expected backgrounds known based on XENON1T.

Xenon Gas

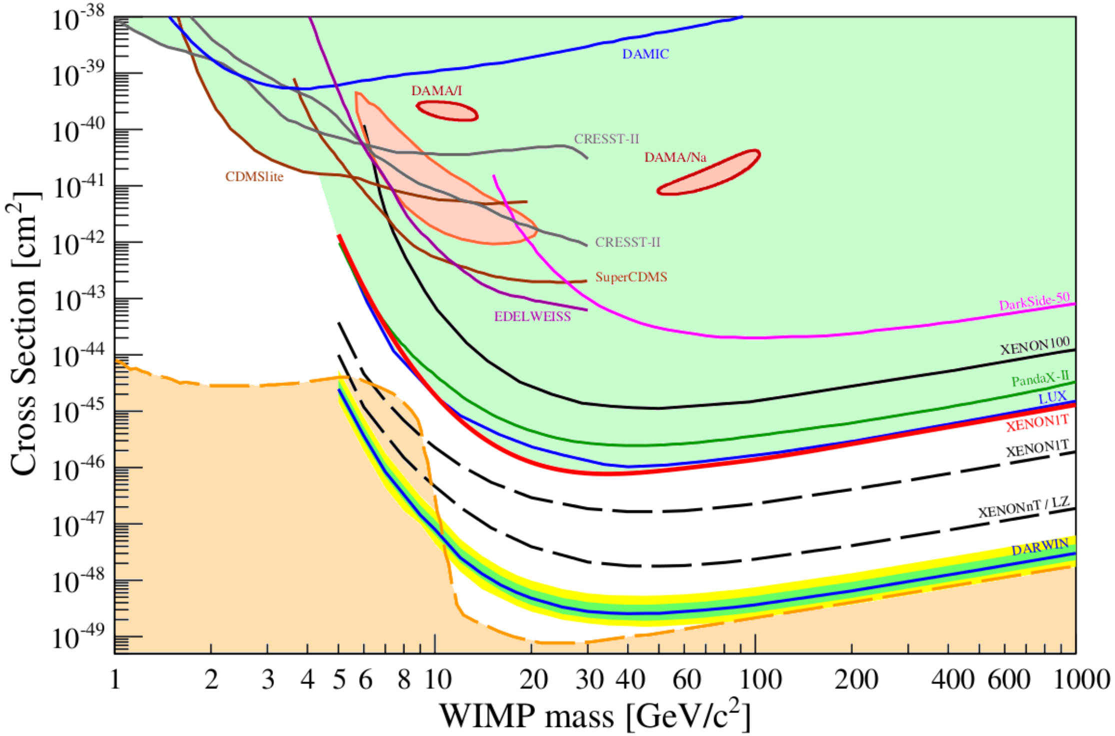
7.25 t needed (7.5 t inc. gas)

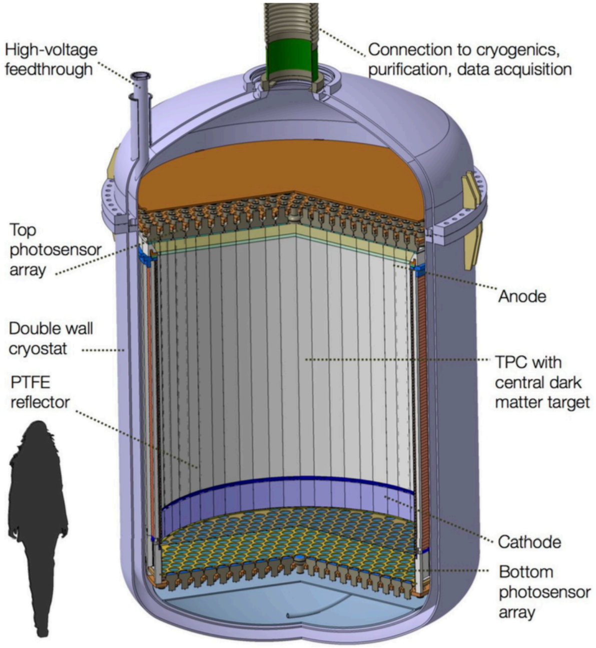
More than 50% in place: 3.7 t in XENON1T, acquisition ongoing.



DARWIN

DARk matter Wimp search with liquid xenoN





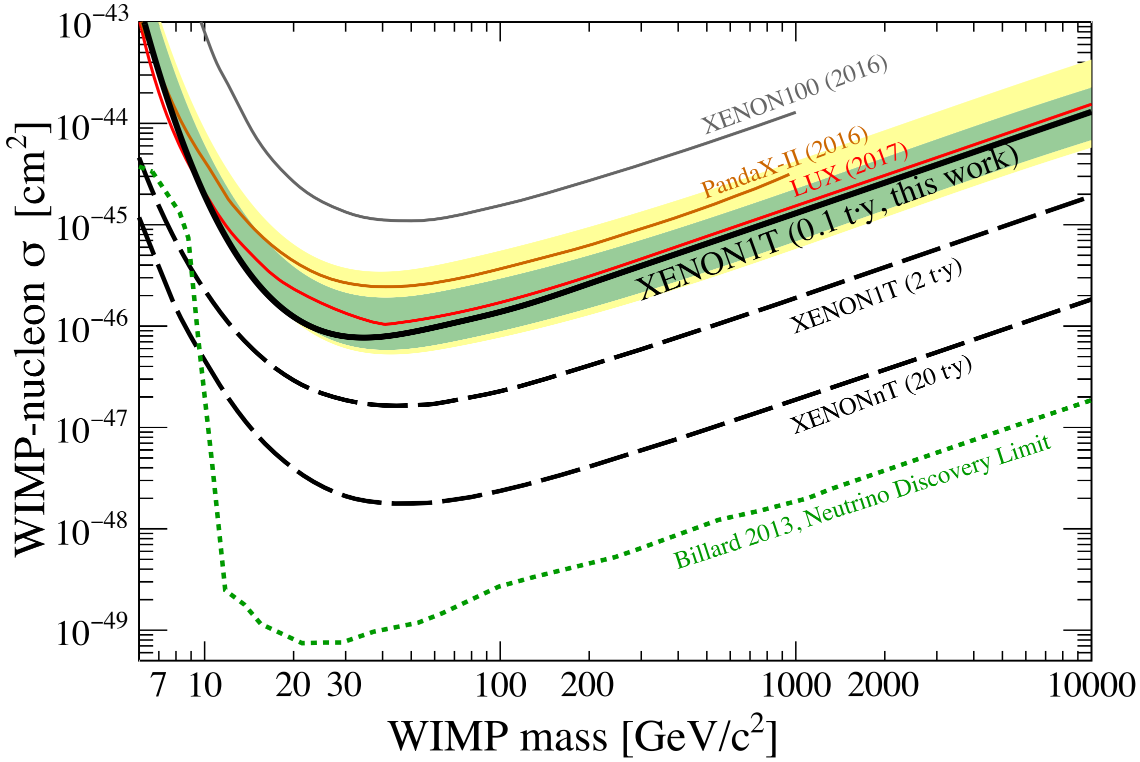
DARWIN

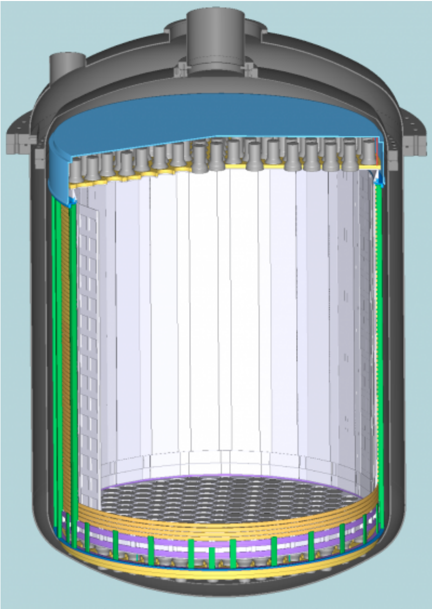
$\sigma_{SI} \sim 10^{-49}$ cm^2

Summary and Outlook

XENON1T is currently the most sensitive direct dark matter search experiment

- The detector has the lowest background ever achieved
- Results with 34.2 live days are now published
- An additional > 85 days of data already acquired
- A fast upgrade to XENONnT is planned, using most of the existing infrastructure.

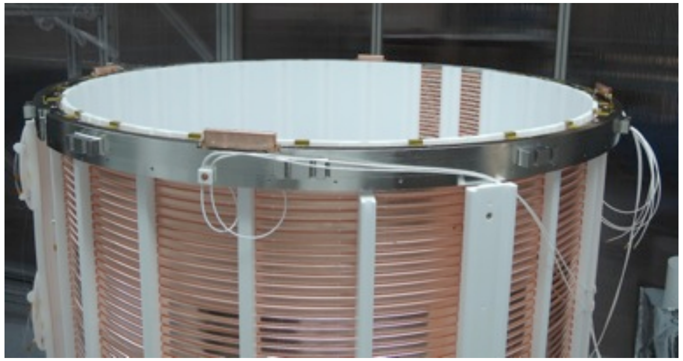




XENONnT: 2019-2023
144 cm drift TPC
~8000 kg
Projected (2023)
$\sigma_{SI} = 1.6 \times 10^{-48}$ cm^2

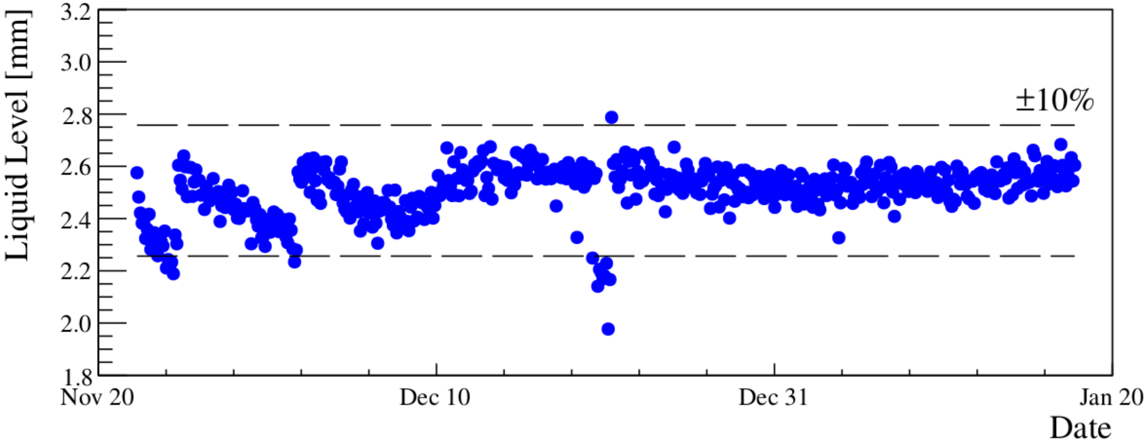
XENON1T TPC

Optical fibers



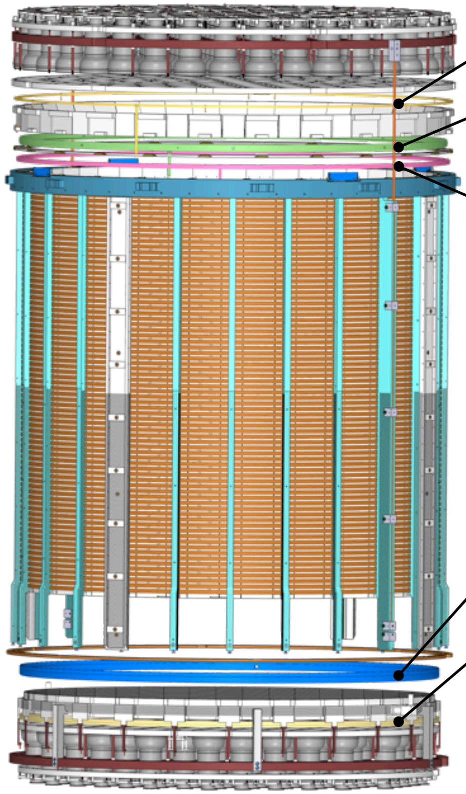
Levelmeters

Diving Bell



LXe level stability: (2.5 ± 0.2) mm

backup



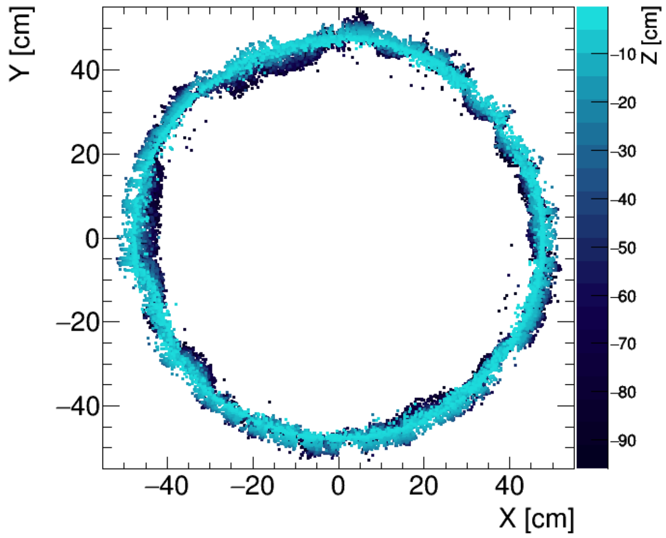
Top screening mesh -1.5 kV

Anode 4-5 kV

Gate (ground)

Cathode -12 kV
(Science Run 0)

Bottom screening mesh
-1.5 kV



Interactions in Noble Liquids

- An energetic particle loses energy through:
    - ➡ inelastic interactions with electrons in the medium *(electronic stopping)*
    - ➡ elastic collisions with nuclei *(nuclear stopping)*
- Electrons, gamma rays and fast ions lose most of their energy through electronic stopping
- Nuclear recoils lose a considerable fraction of their energy through nuclear stopping

Important Concepts:

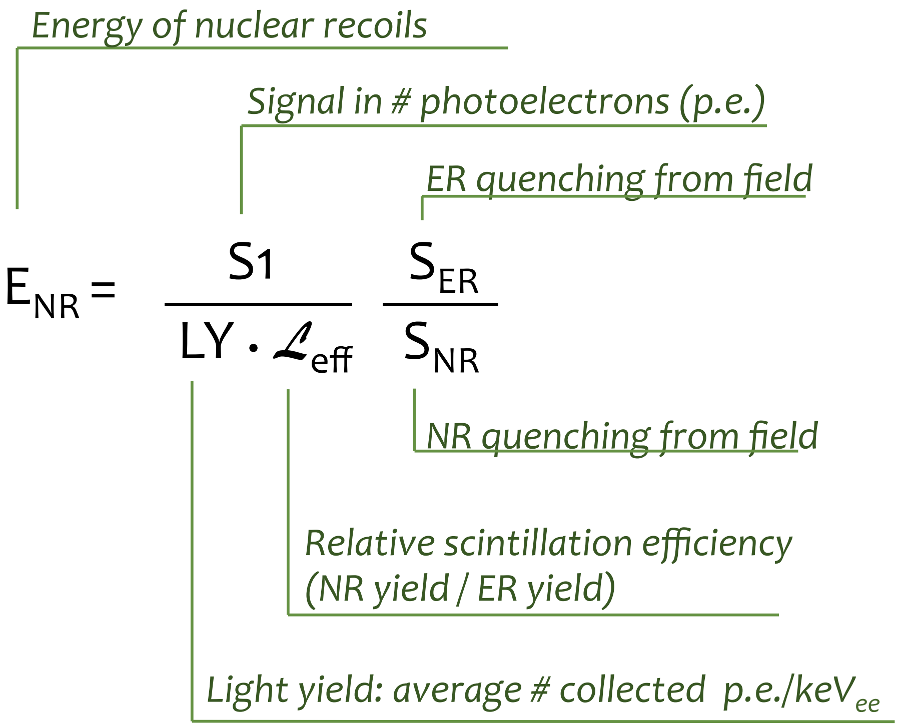
→Deposited energy goes into scintillation (luminescence), ionization (free electrons), and sub-excitation electrons

→Linear Energy Transfer (LET) is the energy loss (or transfer) per unit path length: dE/dx in typical units [MeV/cm], also referred to as stopping power, is different depending upon interacting particle

→Quenching in scintillators generally refers to reduced light output, i.e. lower scintillation efficiency. The latter is described by a relative scintillation efficiency referred to as "L effective" (L_{eff}). Can also refer to reduced ionization efficiency.

Energy Reconstruction

To reconstruct nuclear recoil energy from S1 and S2 ...



Energy of nuclear recoils

Signal in # photoelectrons (p.e.)

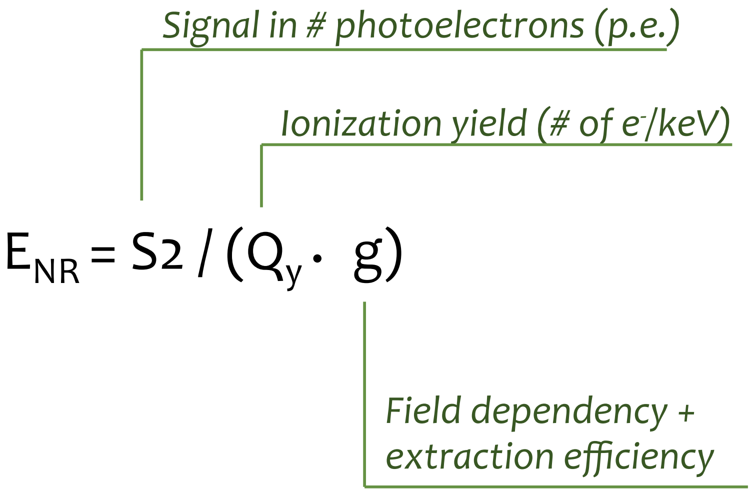
ER quenching from field

$$E_{NR} = \frac{S1}{LY \cdot \mathcal{L}_{eff}} \; \frac{S_{ER}}{S_{NR}}$$

NR quenching from field

Relative scintillation efficiency (NR yield / ER yield)

Light yield: average # collected p.e./keV$_{ee}$



Signal in # photoelectrons (p.e.)

Ionization yield (# of e$^-$/keV)

$$E_{NR} = S2 \, / \, (Q_y \cdot \; g)$$

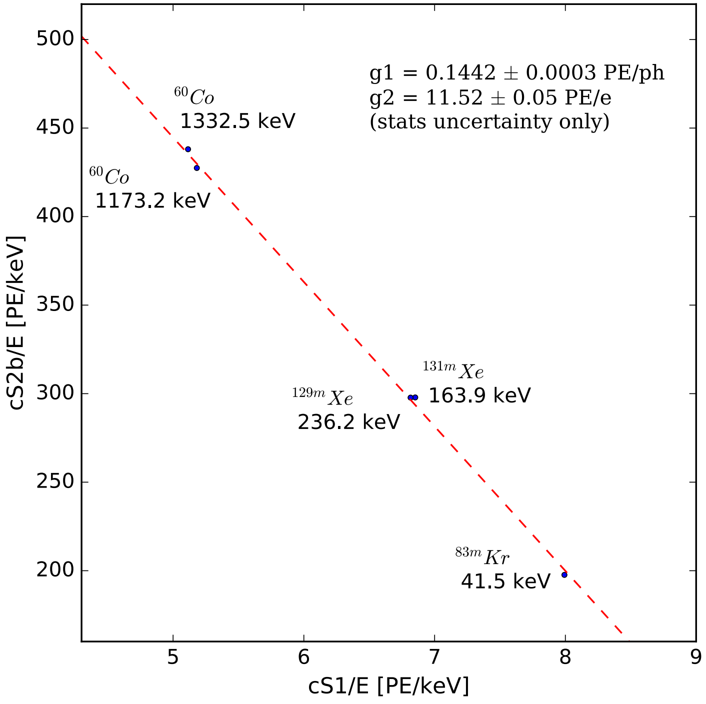
Field dependency + extraction efficiency

**… one needs to know LY, $\mathcal{L}_{eff}$ and Q_y
(all functions of E_{NR})
within region of interest.**

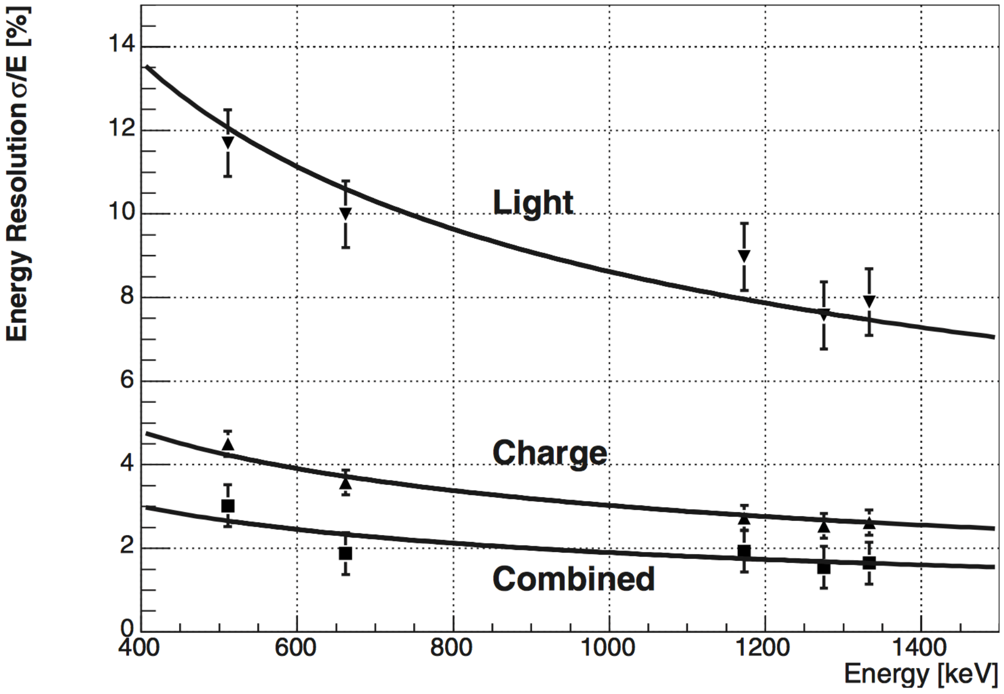
Energy Resolution

Energy scale (example: XENON1T)

- linear from keV to MeV using known calibration sources (^{83m}Kr, ^{129m,131m}Xe, ^{60}Co)
- **g1** = 0.1442 ± 0.0068 (sys) PE/photon
- light detection efficiency (12.5 ± 0.6)%,   Monte Carlo prediction 12.1%
- **g2**= ~100% charge extraction

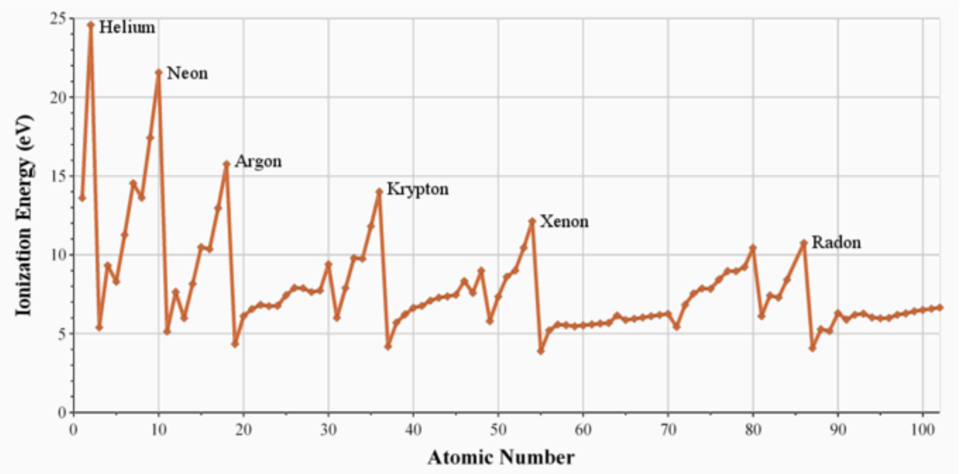


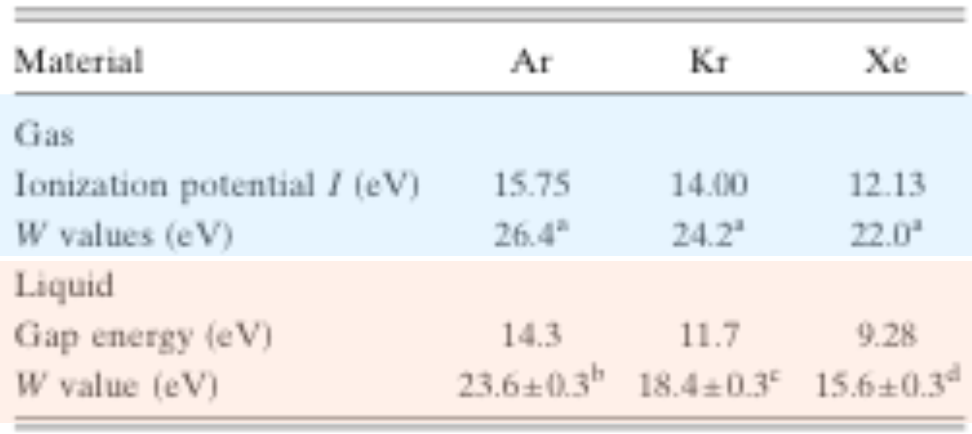
Aprile, et al. Phys. Rev. D (2017)



Aprile, et al, Phys. Rev. B 76 (2007)

Yields in Noble Liquids





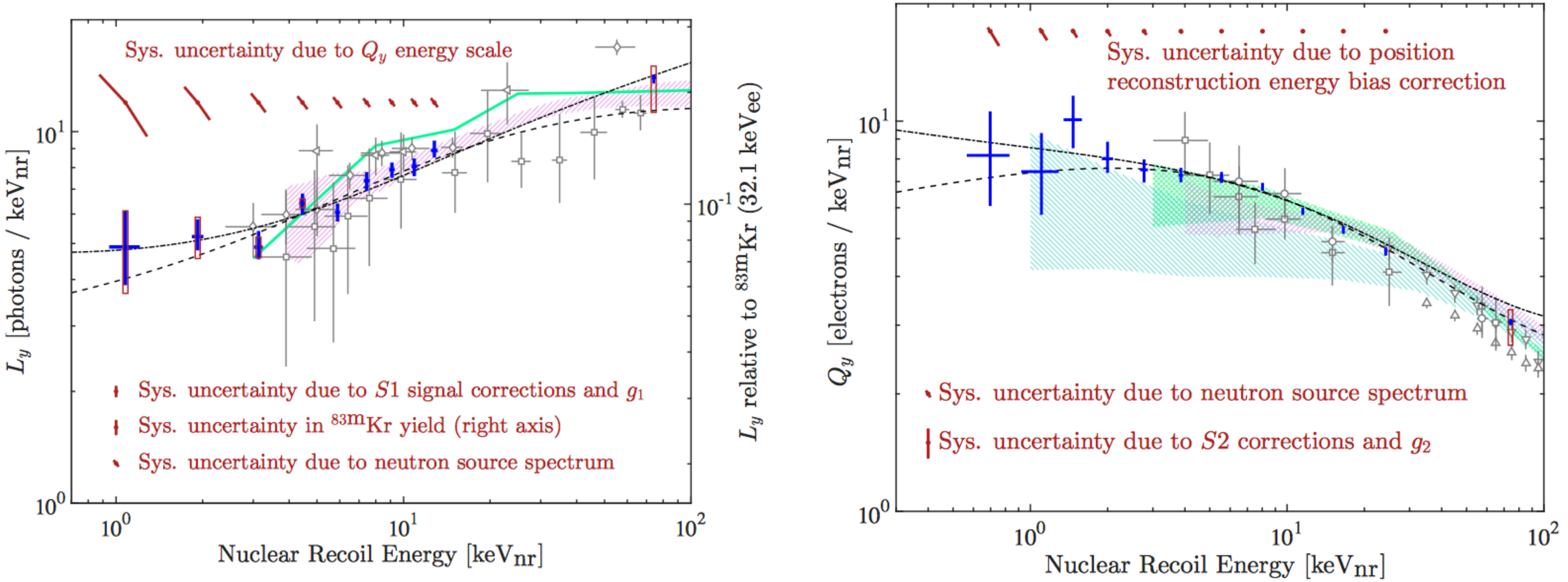
Material	Ar	Kr	Xe
Gas			
Ionization potential I (eV)	15.75	14.00	12.13
W values (eV)	26.4[a]	24.2[a]	22.0[a]
Liquid			
Gap energy (eV)	14.3	11.7	9.28
W value (eV)	23.6±0.3[b]	18.4±0.3[c]	15.6±0.3[d]

- The average energy loss in ionization is slightly larger than the ionization potential or the gap energy, because it includes multiple ionization processes
- The effect of sub-excitation electrons can be absorbed into a higher value for the work function
- as a result, the ratio of the W-value (= average energy required to produce an electron-ion pair) to the ionization potential or gap energy = 1.6 - 1.7

- W-value liquid phase < W-value gaseous phase
- W-value in Xe < W-value in Ar, Kr (& Ne)

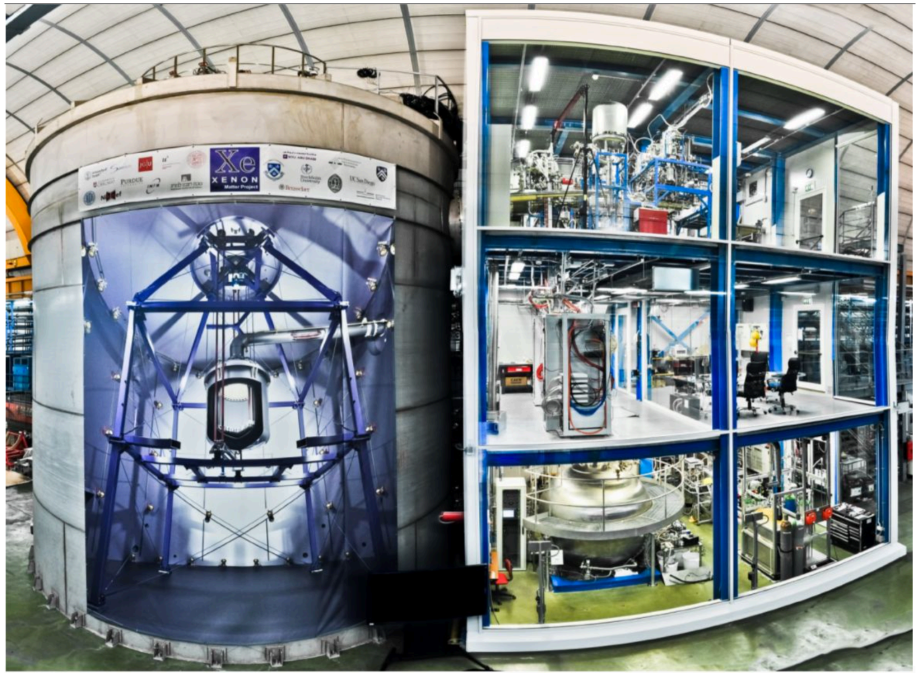
=> the ionization yield is highest in liquid xenon (of all noble liquids)

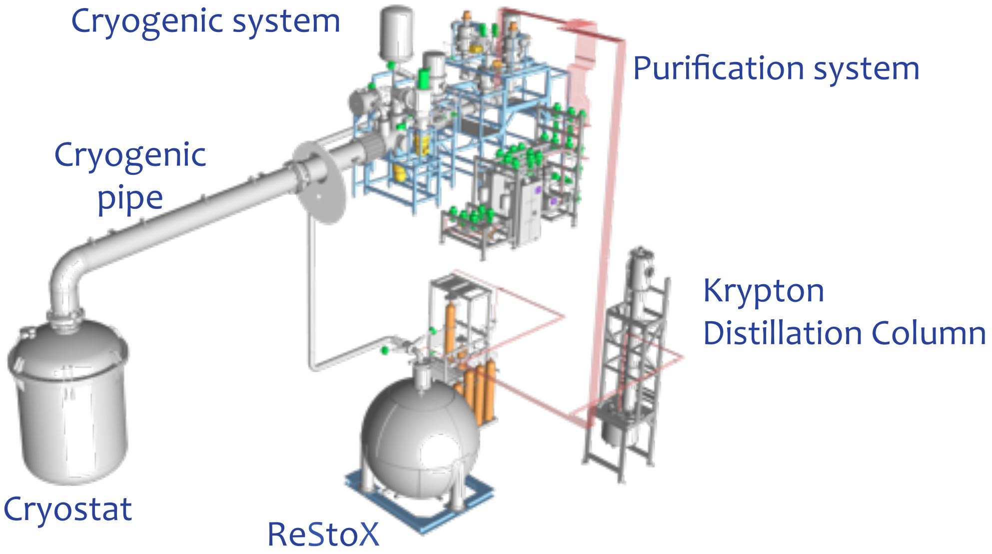
Light and Charge Yields



Low-energy (0.7–74 keV) nuclear recoil calibration of the LUX dark matter experiment using D-D neutron scattering kinematics, Akerib, et al., arXiv:1608.05381v1, 18 Aug 2016

Infrastructure





All critical detector parameters must be kept stable:

- LXe temp: (177.08 ± 0.04) K
- GXe pressure:(1.934 ± 0.001) bar
- LXe level: (2.5 ± 0.2) mm