Direct Dark Matter Search with XENON

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On behalf of the XENON Collaboration

PRISMA

Bundesministerium
für Bildung
und Forschung

Outline

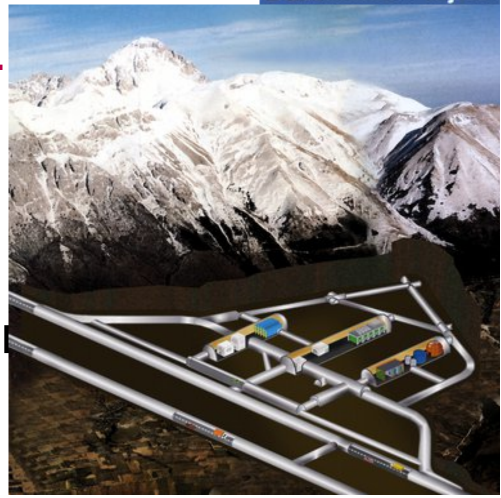
- XENON Dark Matter Search
  - The program
  - Dual Phase Liquid Xenon TPC
- XENON100
- Status of XENON1T
- Future Prospects

The XENON Program

GOAL: Explore WIMP Dark Matter to a sensitivity of σ_{SI} ~10^{-48} cm^2.

CONCEPT:

- Target LXe: excellent for DM WIMPs scattering.
  Sensitive to both axial and scalar coupling.
- Detector: two-phase LXeTPC: 3D position sensitive calorimeter
- Background discrimination:
  - simultaneous charge & light detection
  - single site interactions, fiducialization, self shielding
- High light yield + proportional scintillation
  → low energy threshold for nuclear recoils (~ 5 keV, lower for ionization only).



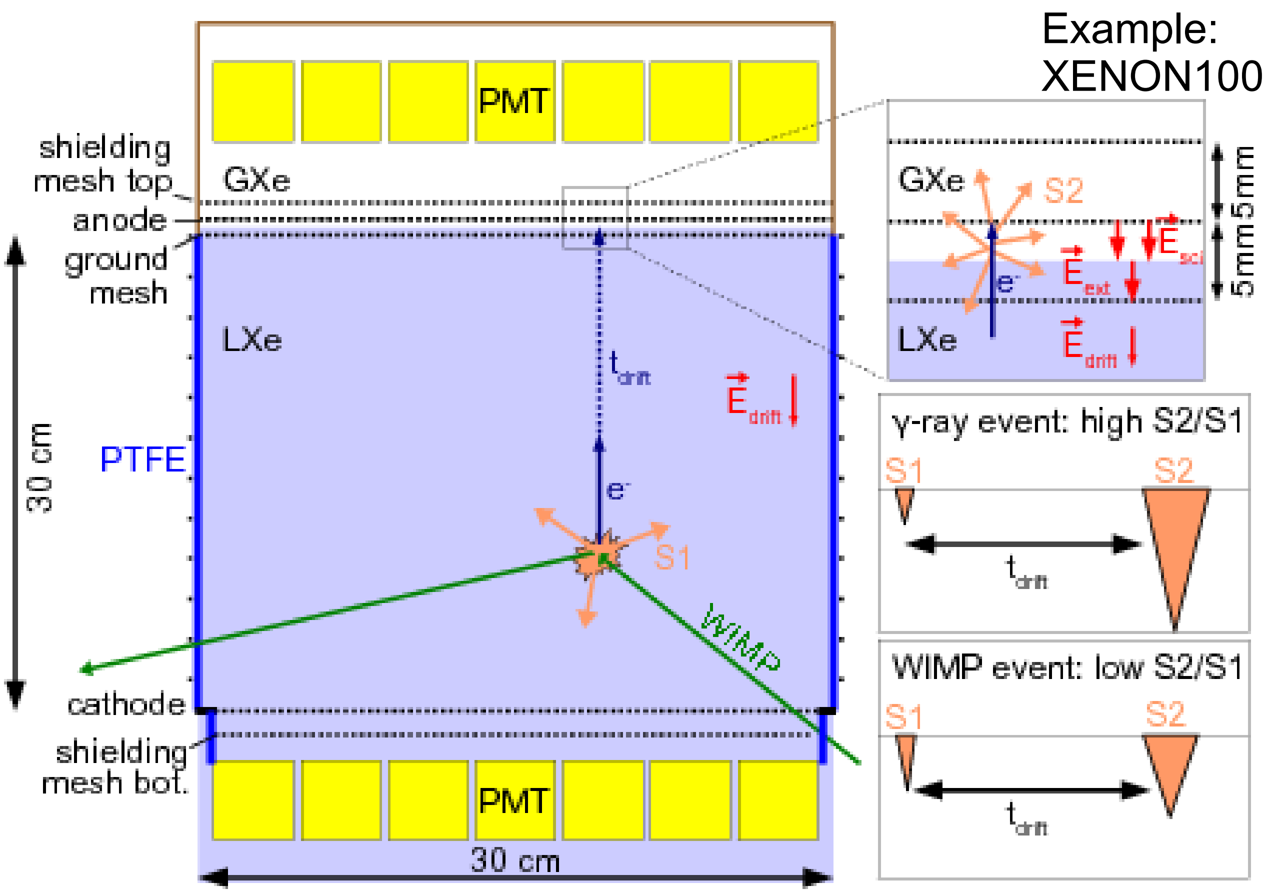
Location: LNGS

PHASES:

R&D	XENON10	XENON100	XENON1T	XENONnT
Start: 2002	2005-2007	2007 → ...	2011 → DM search '16	2018 →
	Proof of concept. Total mass: 14 kg 15 cm drift. Best limit in '07: σ_{SI}~10^{-43} cm^2	Ongoing DM search. Total mass: 161 kg 30 cm drift. Best limits in '11, '12: σ_{SI}~ 2 x 10^{-45} cm^2	Construction ongoing. Total mass: ~ 3.2 t 1 m drift. Goal: σ_{SI} ~ 2 x 10^{-47} cm^2	Goal: σ_{SI} ~ 10^{-48} cm^2

The Dual Phase Liquid Xenon (LXe) Time Projection Chamber (TPC)

- WIMP recoil on nucleus in dense liquid
→ Ionization + UV Scintillation
- Detection of primary scintillation light (S1) with PMTs.
- Charge drifts towards liquid/gas interface (low field: ~0.1-1 kV/cm).
- Charge extraction liquid/gas at high field between ground mesh (liquid) and anode (gas)
- Charge produces proportional scintillation signal (S2) in the gas phase (high field: ~10 kV/cm)

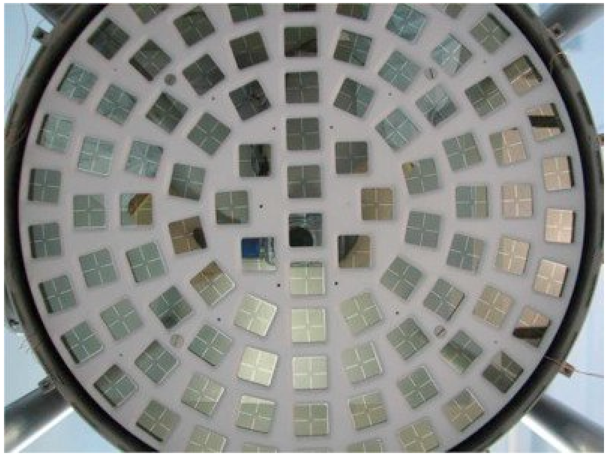


- **3D position measurement**
  - X/Y from S2 signal. Resolution few mm.
  - Z from electron drift time (~0.3 mm).

The XENON100 TPC

Astropart. Phys. 35 (2012), 573

Top array: 98 PMTs



gamma event localized

Top PMT array

TPC

R8520, QE >32% @ 178 nm
(~25% on top array)

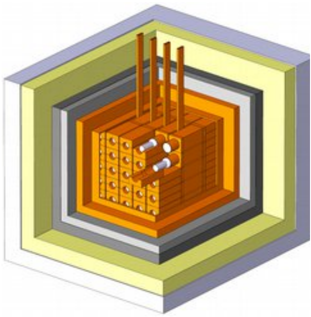
Bottom array: 80 PMTs

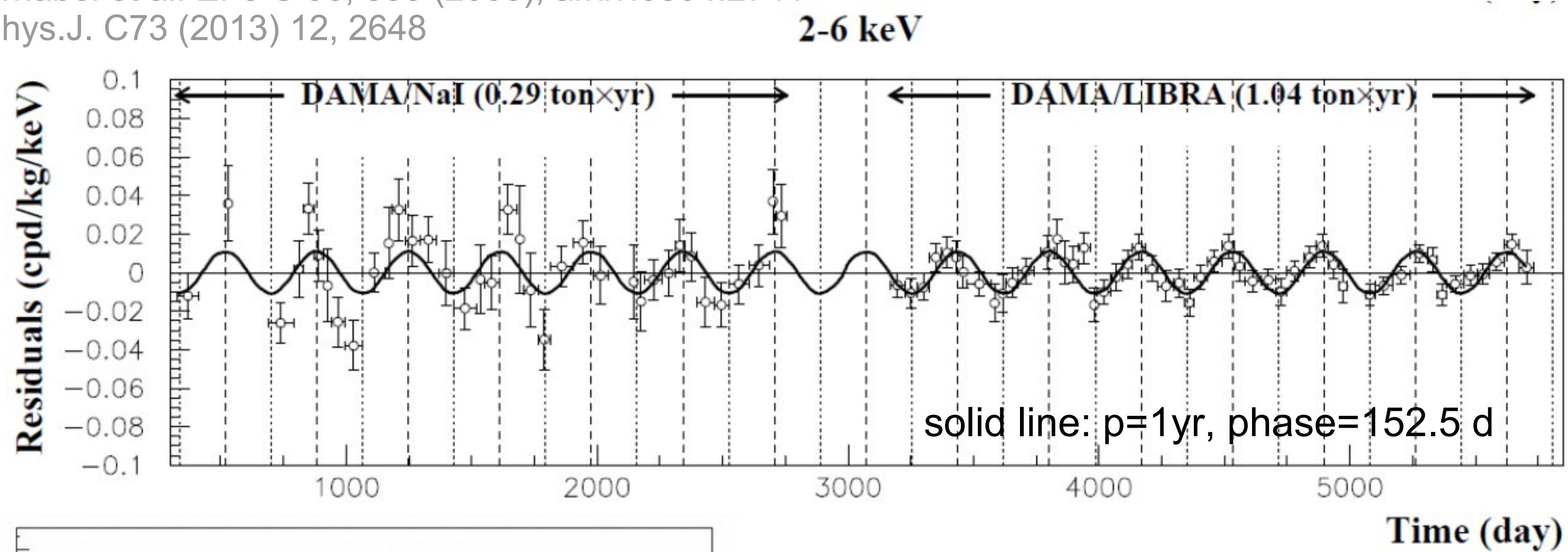
- 161 kg Xe, 62 kg target
- 30 cm drift
- radiopurity:
  - material screening
  - ^{85}Kr: distillation column
  - ^{222}Rn: avoid/monitor
- LXe veto
- Passive shielding: water, Pb, PE, copper

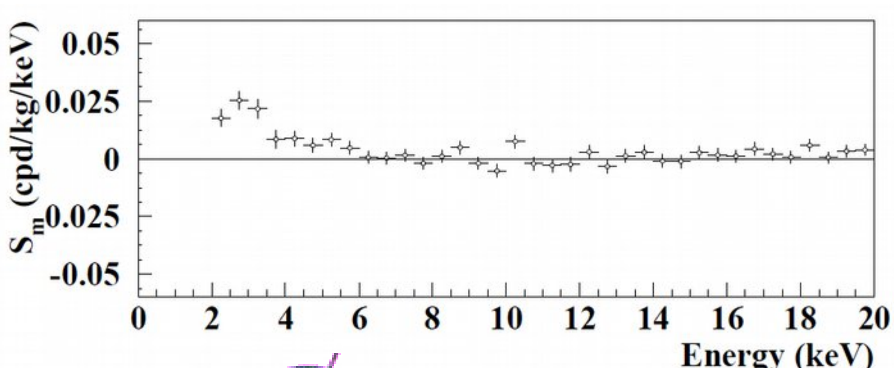
Veto PMTs

DAMA/LIBRA Annual Modulation

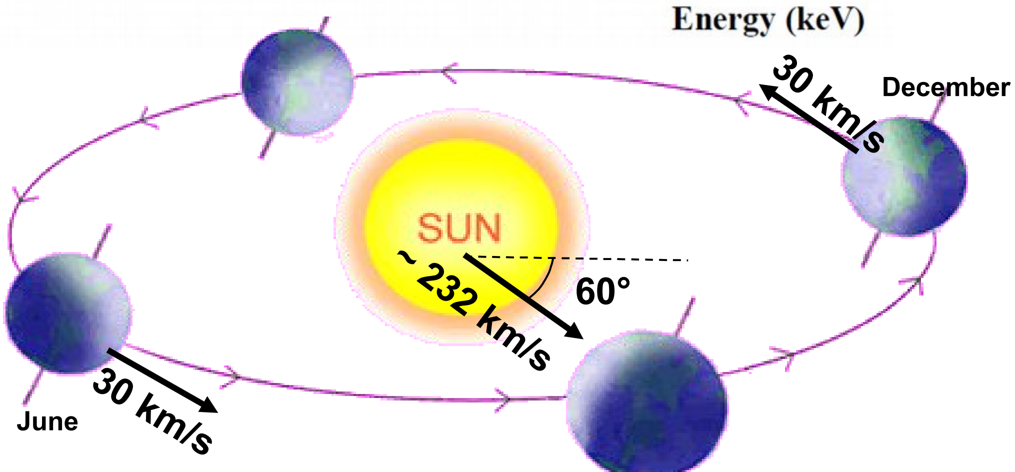
R. Bernabei et al. EPJ C 56, 333 (2008), arxiv:0804.2741
Eur.Phys.J. C73 (2013) 12, 2648





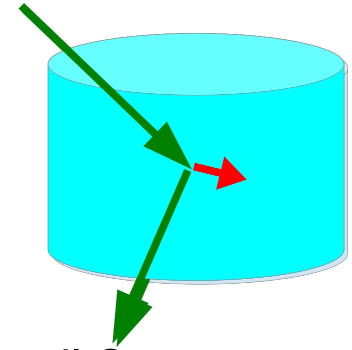


- 1.33 ton × yr, 14 annual cycles
- Modulation in 2-6 keV single hits: 9.3 σ
  0.0112 ± 0.0012 cts/d/kg/keV
- Total single rate ~1 cts/d/kg/keV
- Standard DM distribution: < ~5% modulation
- Period & phase (144 ± 7) d: about right for DM.
- No annual modulation in 6-14 keV.
- No annual modulation in multiple hits.
- **DM detection??**
- Conflict with other experiments in standard scenarios that test the larger steady state effect.
- *Which other options?*

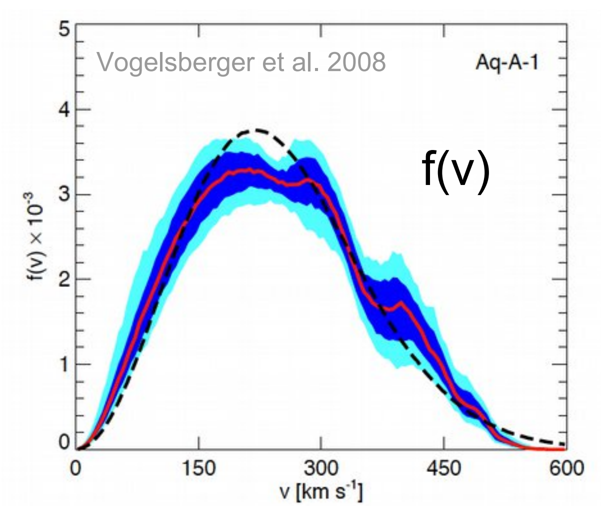


Drukier, Freese, Spergel PRD 86
Freese et al. PRD 88

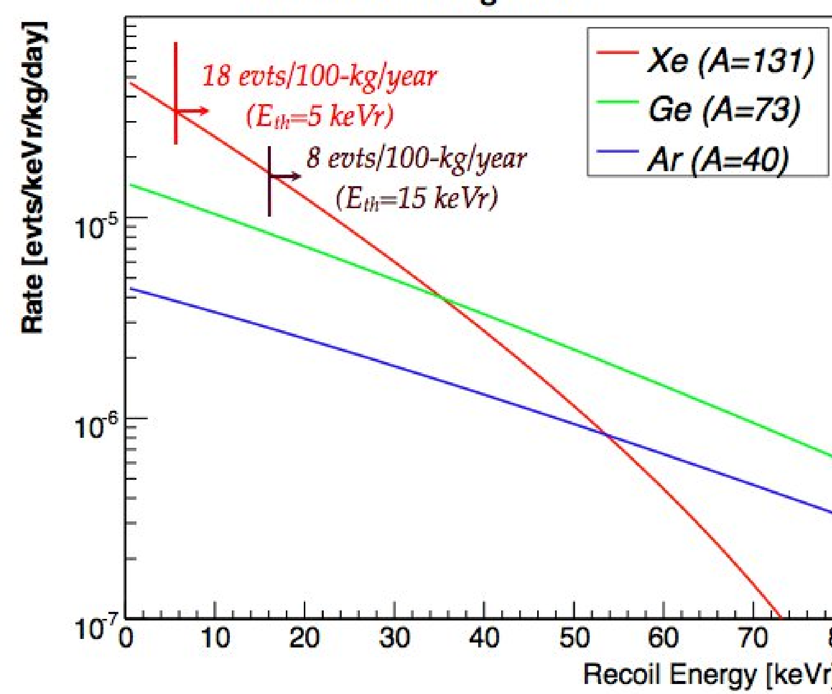
WIMP Dark Matter Direct Detection



- Scattering of WIMPs χ off nuclei A. Nj nuclear recoil
  - elastic or inelastic?
  - spin-independent (~A^2) or spin-dependent?
- WIMP velocity distribution:



WIMP Nuclear Recoil Spectrum



  - m_χ ~ 10 - 10^4 GeV/c^2, $\mu = (m_\chi m_n)/(m_\chi + m_n)$
  - v_χ ~ 230 km/s
  - "Standard" spherical halo:
    Featureless recoil spectrum <E> ~ O(10 keV)
  - ρ_χ/m_χ: local number density of WIMPs
    ρ_χ ~ 0.3 GeV/c^2/cm^3, ρ_χ/m_χ µ 10 / L
  - σ_s cross section per nucleus.

Typical rate < 10^{-3} events / kg / day

$$\frac{dR}{dE} = \frac{\rho_\chi \sigma_s}{2 m_\chi \mu^2} |F(E)|^2 \int_{v_{min}}^{v_{esc}} \frac{f(\mathbf{v}, t)}{v} d^3 v$$

$$f(\mathbf{v}, t) \propto \exp\left(\frac{-(\mathbf{v} + \mathbf{v}_E(t))^2}{2 \sigma_v^2}\right)$$

Maybe Electron-DM Interactions dominate? “Leptophilic” DM

PHYSICAL REVIEW D **77,** 023506 (2008)

Investigating electron interacting dark matter

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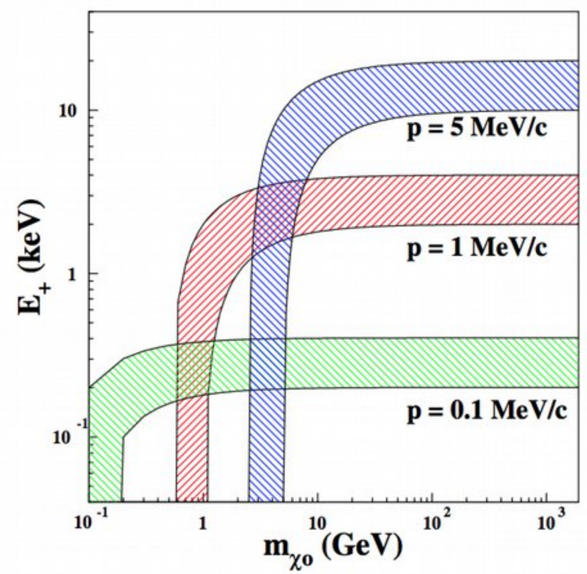
IHEP, Chinese Academy, P.O. Box 918/3, Beijing 100039, China
(Received 20 November 2007; published 10 January 2008)

Some extensions of the standard model provide dark matter candidate particles which can have a dominant coupling with the lepton sector of the ordinary matter. Thus, such dark matter candidate particles (χ^0) can be directly detected only through their interaction with electrons in the detectors of a suitable experiment, while they are lost by experiments based on the rejection of the electromagnetic component of the experimental counting rate. These candidates can also offer a possible source of the 511 keV photons observed from the galactic bulge. In this paper this scenario is investigated. Some theoretical arguments are developed and related phenomenological aspects are discussed. Allowed intervals and regions for the characteristic phenomenological parameters of the considered model and of the possible mediator of the interaction are also derived considering the DAMA/NaI data.

DOI: 10.1103/PhysRevD.77.023506 PACS numbers: 95.35.+d

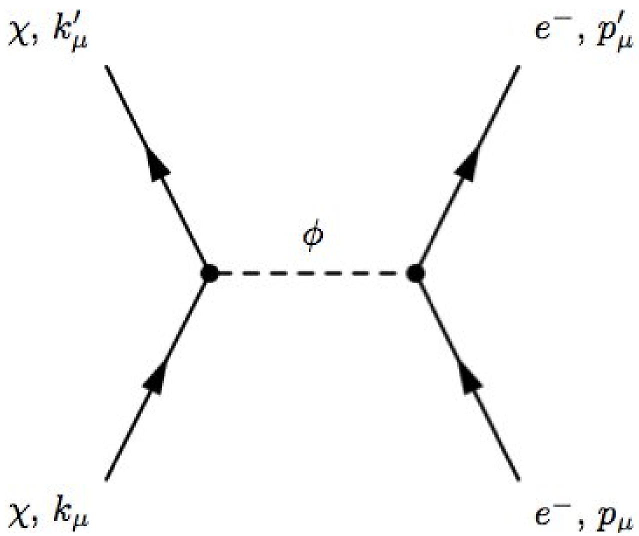


Possible for m_{DM}> few GeV/c^2 interacting with inner bound electrons.

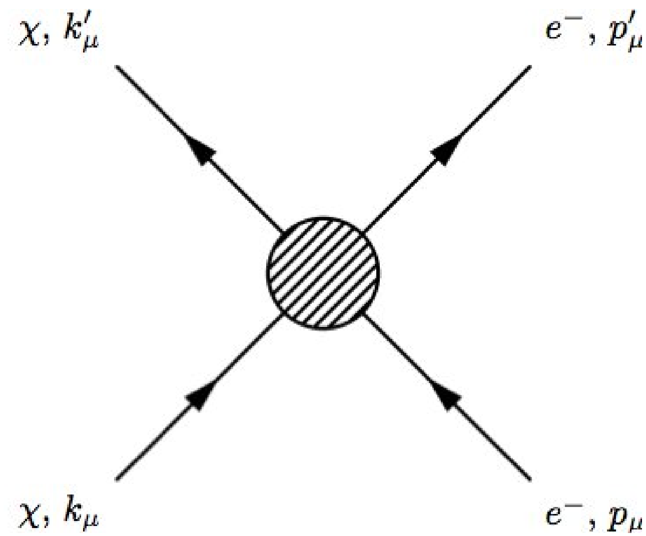
XENON100: new Constraint on DAMA Modulation as DM Interpretation

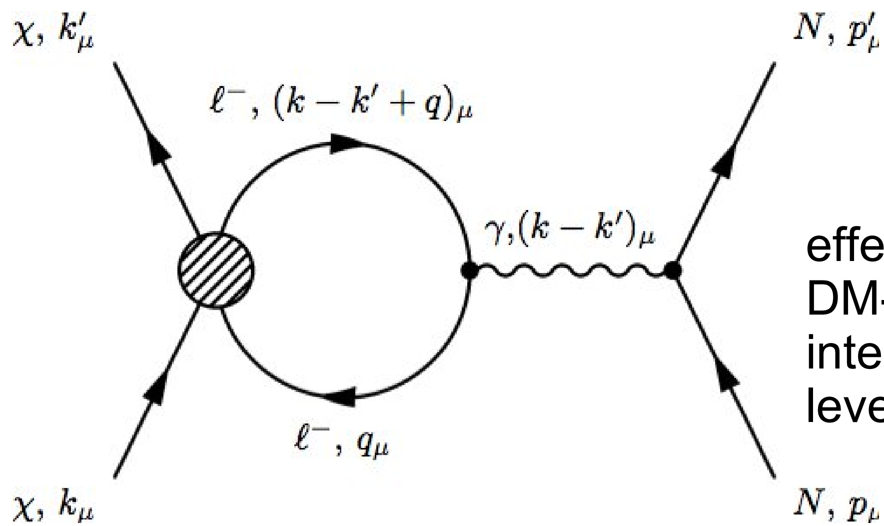
Even if DM only interacts with electrons at tree-level, loop induced DM-hadron interactions dominate → back to the usual NR limits J. Kopp et al. PRD 80, 083502 (2009)

Loop-hole: axial-vector couplings Ar' A: loop-effects vanish,
DM-electron couplings are not suppressed.



effective
DM-electron
interaction
⟶

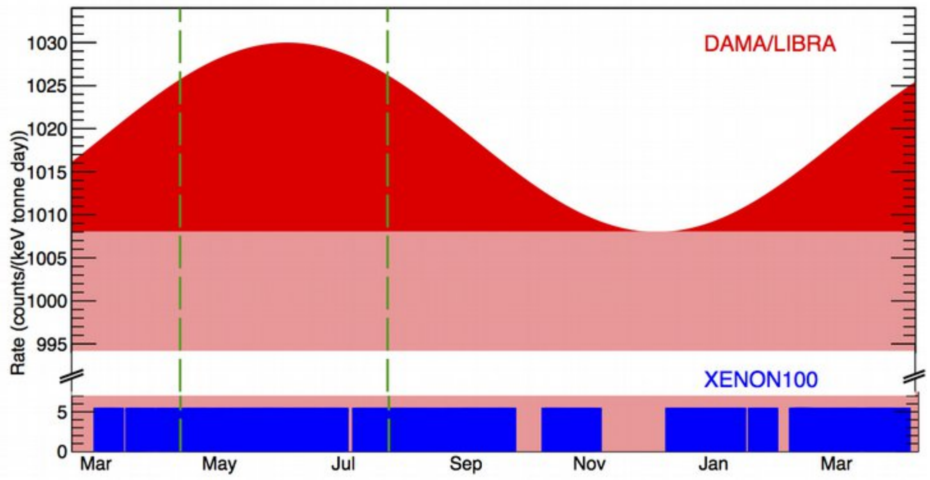




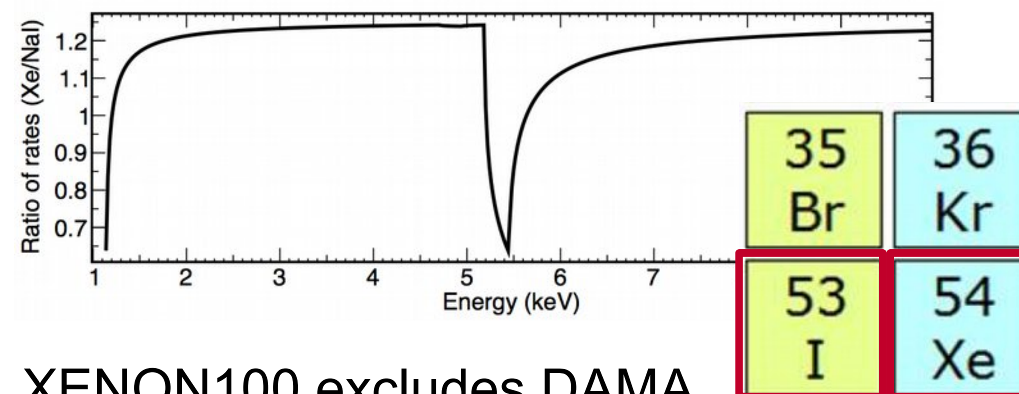
effective
DM-nucleus
interaction at 1-loop
level

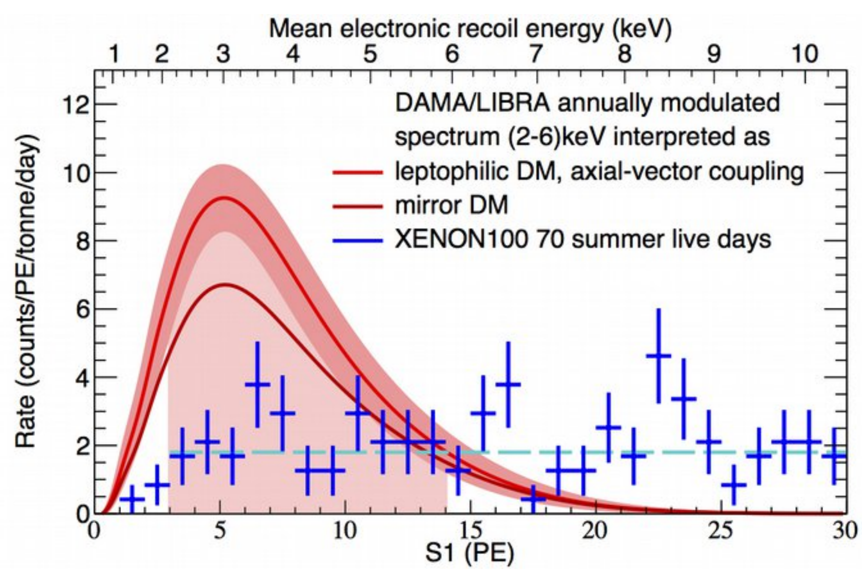
XENON100: new Constraint on DAMA Modulation as DM Interpretation

Loop-hole: axial-vector couplings Ar' A: loop-effects vanish, DM-electron couplings are not suppressed.



XENON Coll.,
Science 349 no. 6250 pp. 851-854 (2015)



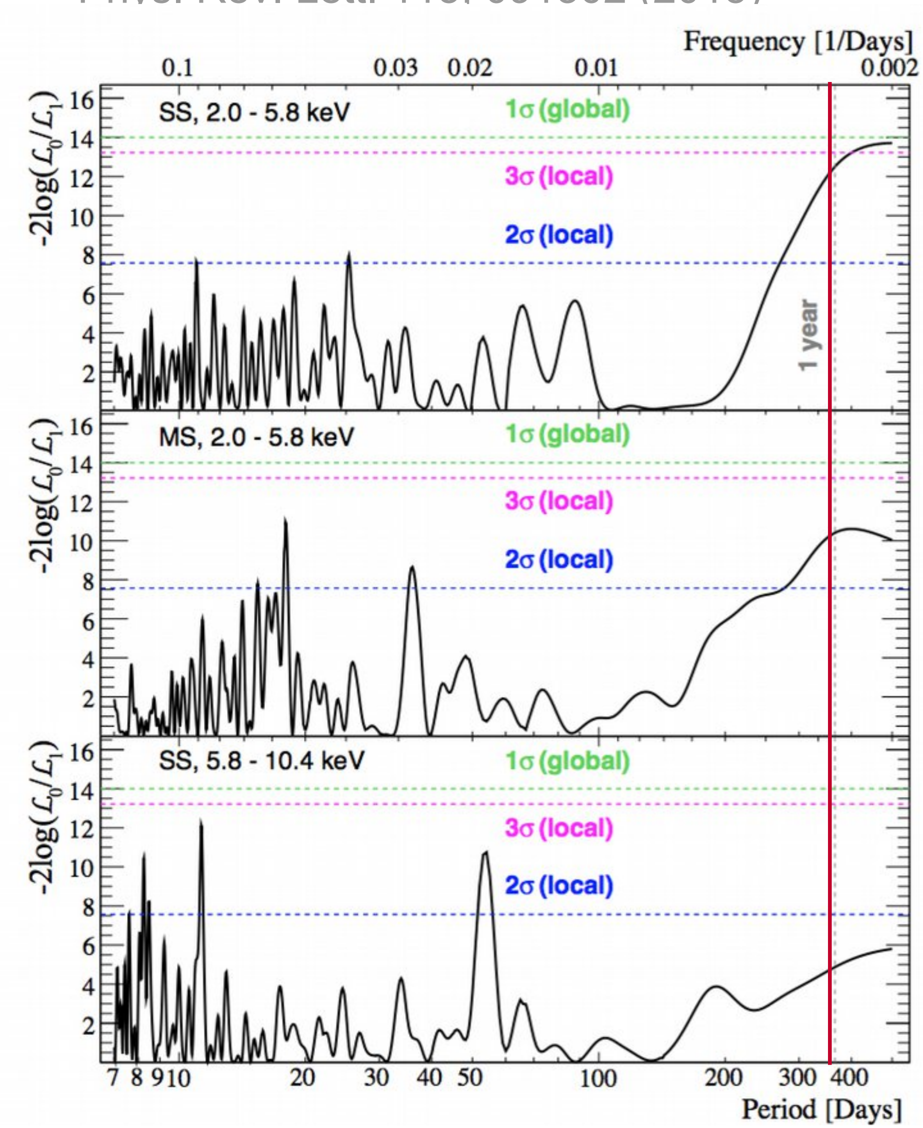


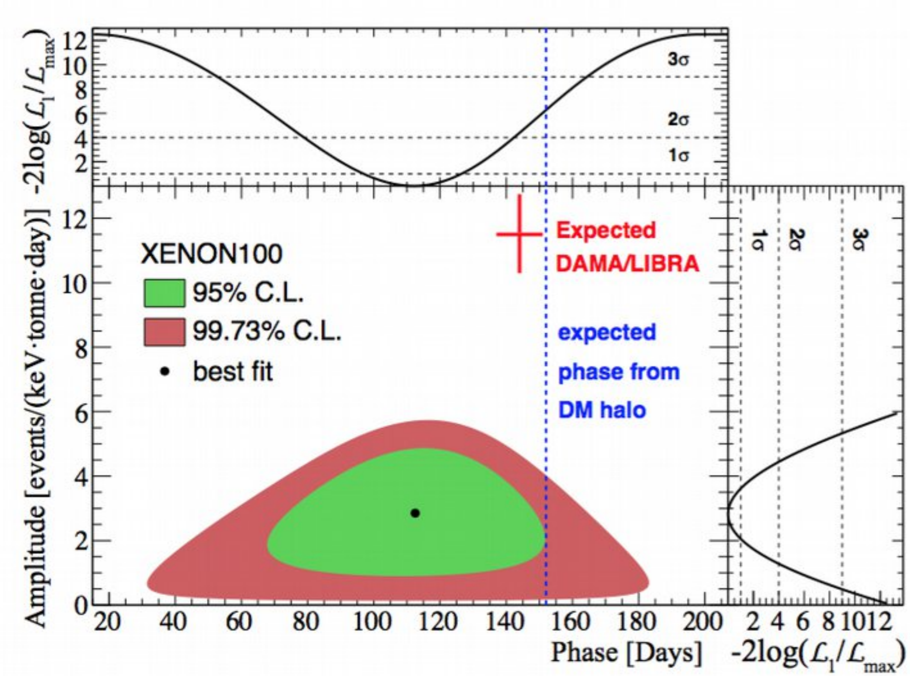
XENON100 excludes DAMA modulation as being due to

- DM-electron axial-vector couplings at 4.4σ
  (interpreting all XENON100 events as signal)
- luminous dark matter at 4.6σ
- mirror dark matter at 3.6σ

Search for Modulations in XENON100 Data

XENON Coll.,
Phys. Rev. Lett. 115, 091302 (2015)





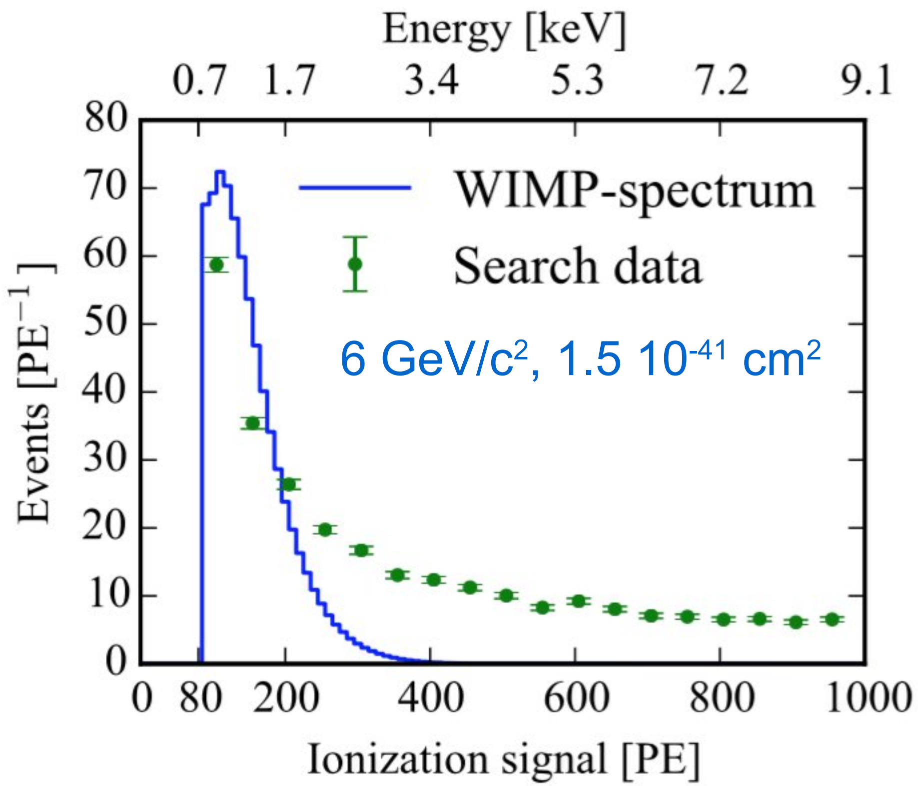
- Unbinned Profile Likelihood search for periodic signals in XENON100 data. For random period, no significant signal observed.
- Fixed 1 year period, phase unconstrained: weak effect observed, both in single and multiple site events 2.0-5.8 keV.
- Combination of amplitude and phase inconsistent with interpretation of DAMA modulation as WIMP-electron scattering through axial-vector coupling at 4.8 σ.

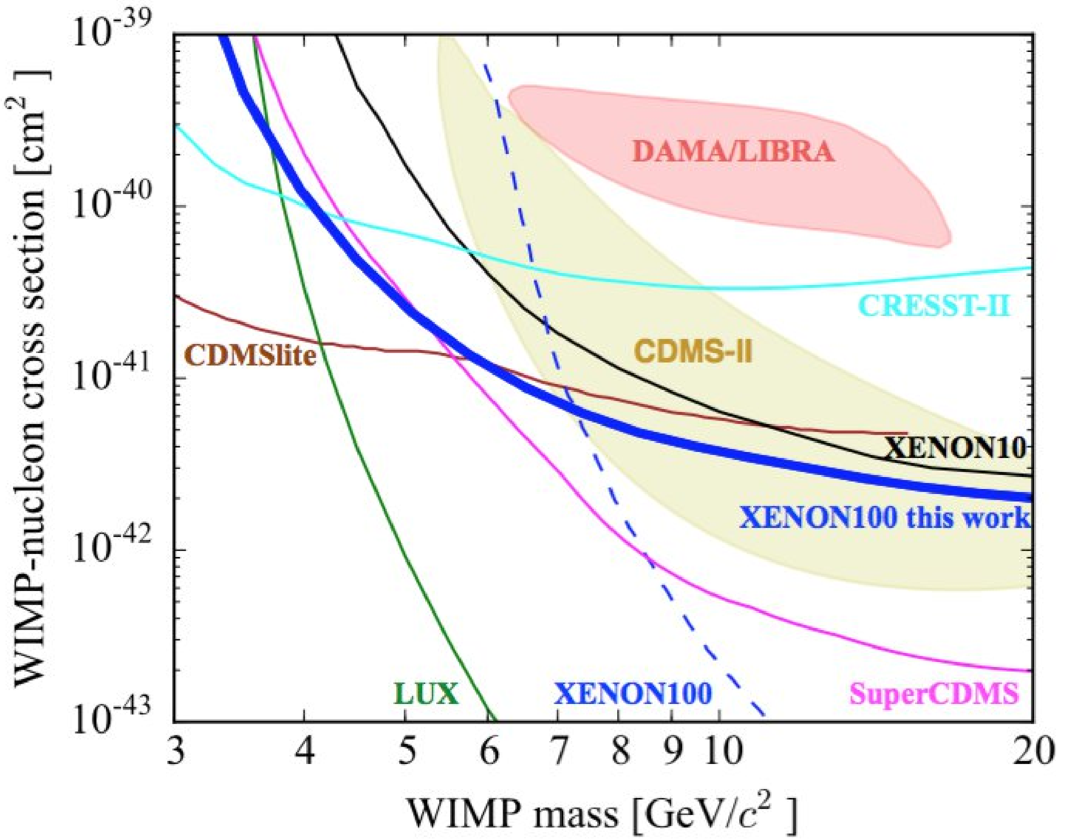
Combination with additional run should soon provide important additional constraints for periods of 1 year and above.

Search for Low Mass WIMPs with XENON100

XENON Coll., arXiv:1605.06262

- Approach: look at ionization signals S2 without primary scintillation S1 → lower threshold 0.7 keV_{nr} ☺
- Disadvantages: ☹
  - No z position
  - No S2/S1 ER discrimination



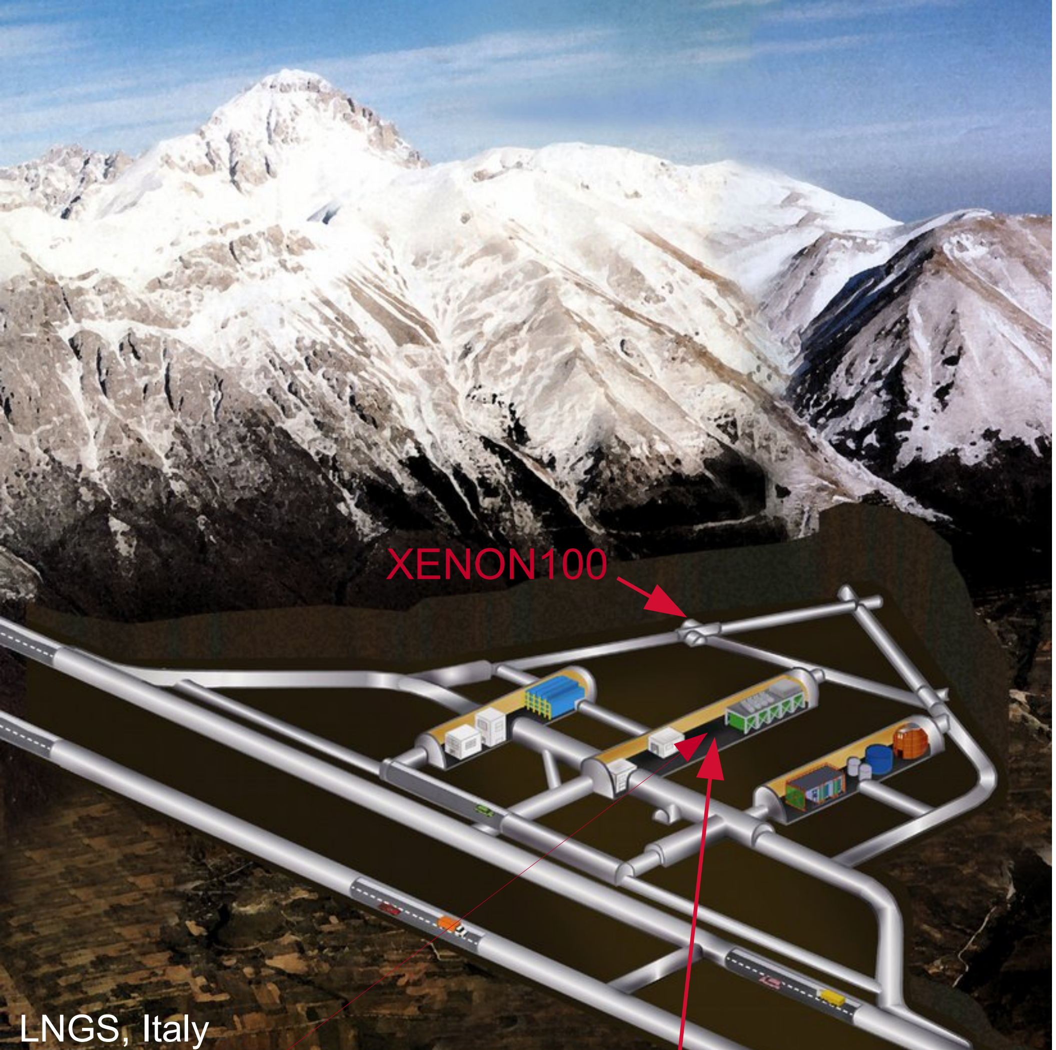


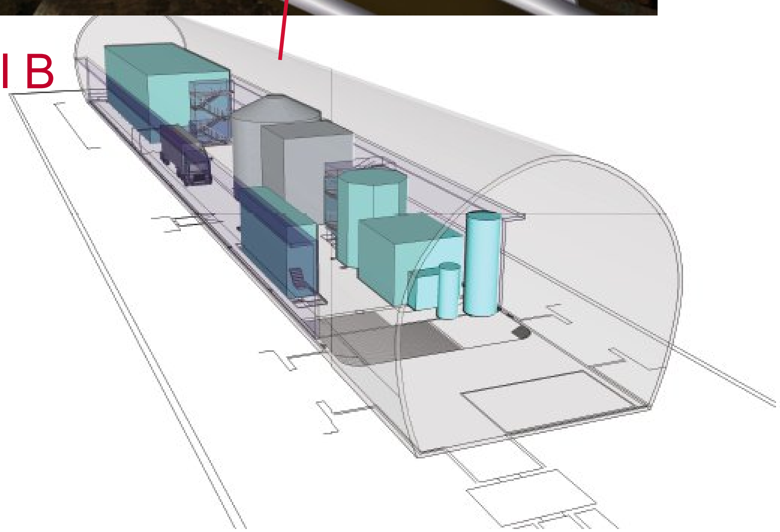
- No bgd model → interprete all events after cuts as potential WIMP candidates to set an upper limit.
- Exclusion limit at M_χ = 6 GeV/c^2 :

$\sigma_\chi = 1.1\ 10^{-41}\ cm^2$

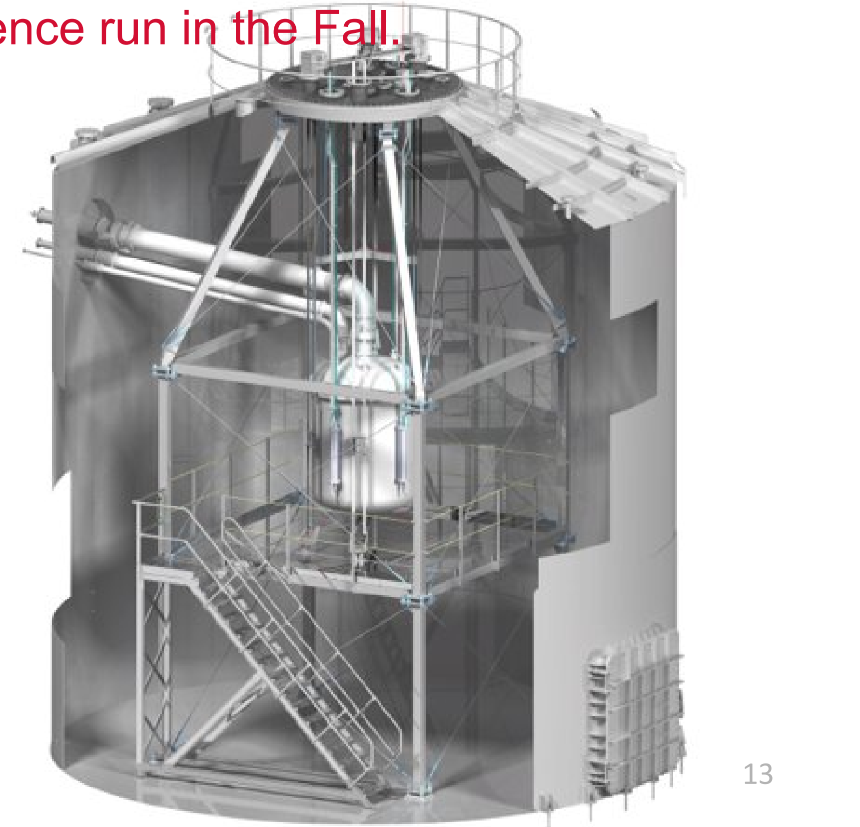
XENON1T
The next generation dual-phase LXeTPC

- Goal: 100× more sensitive than XENON100
- ~ 1 m^3, ~ 3.2 t LXe, 2.0 t active mass
- 248 PMTs (3”)
- Water Cherenkov Muon Veto ~10 m x 9.6 m
- Cryogenic Plants: Xe cooling, purification, distillation, storage systems handle up to 10 t of Xe.
- All systems tested. Commissioning ongoing. Science run in the Fall.





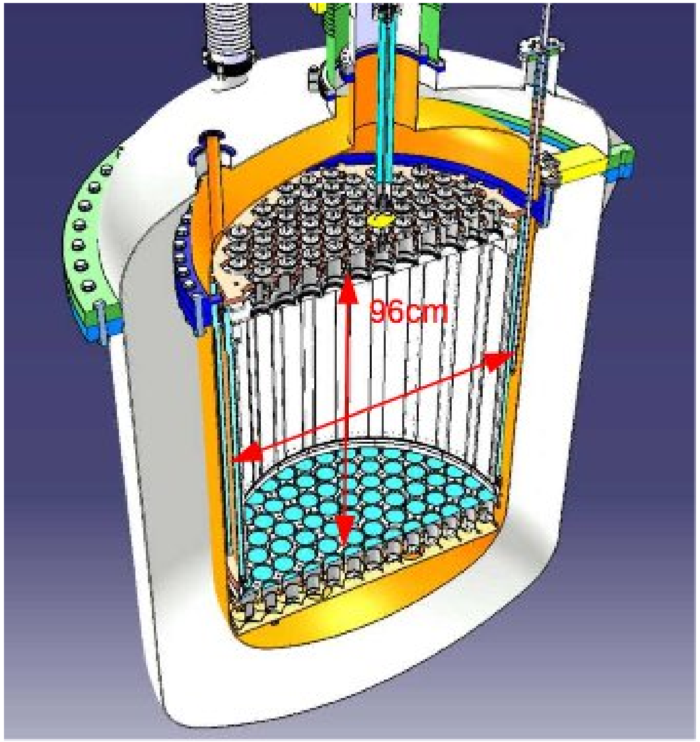
XENON1T in Hall B



XENON1T

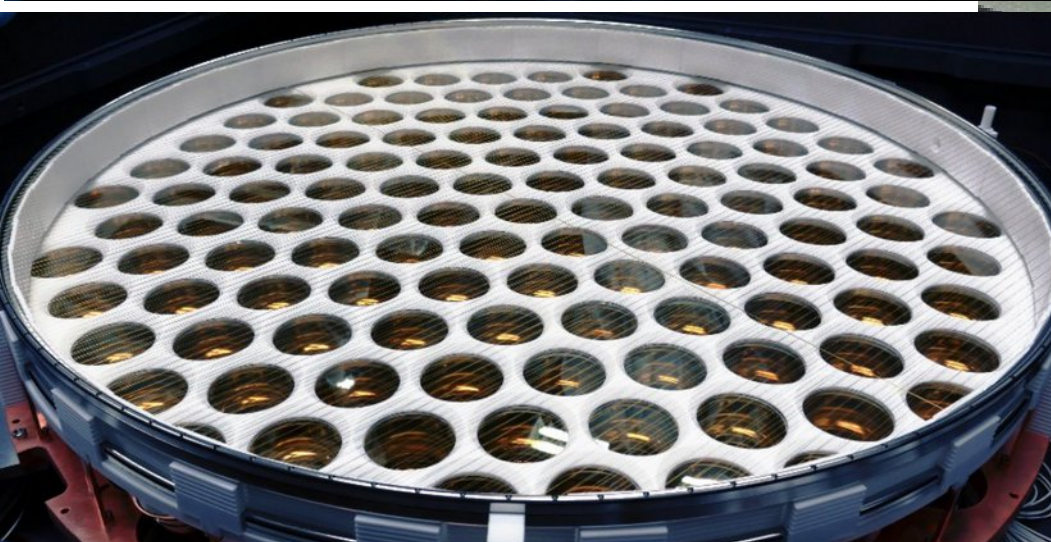
The next generation dual-phase LXeTPC

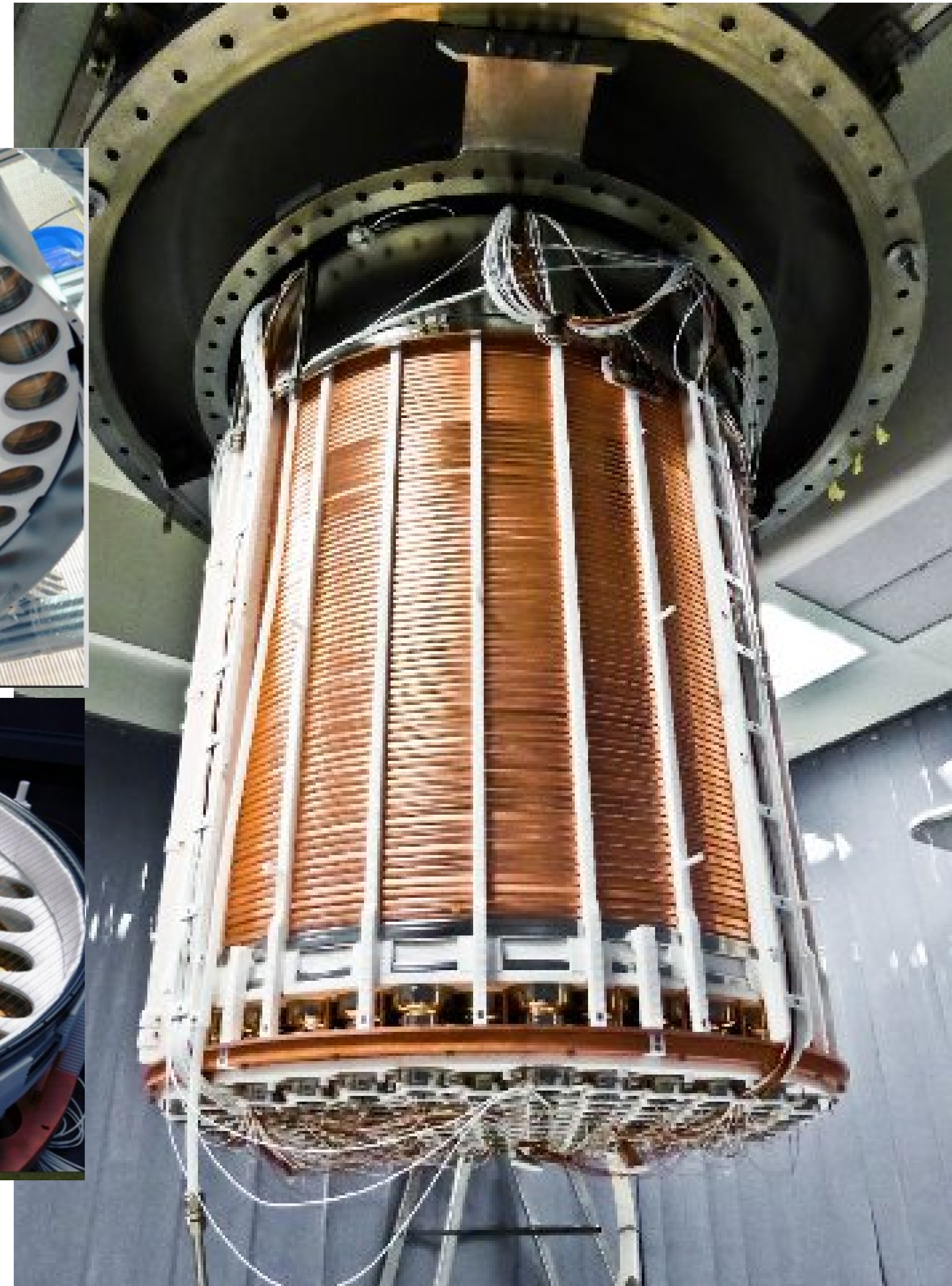
XENON1T TPC



- XENON1T Time Projection Chamber (TPC) filled, since April 2016, with high-purity Xenon.
- Active mass: 2.0 t.
- High reflectivity PTFE walls.
- 248 low-background 3” PMTs (Hamamatsu R11410-21).

XENON1T TPC

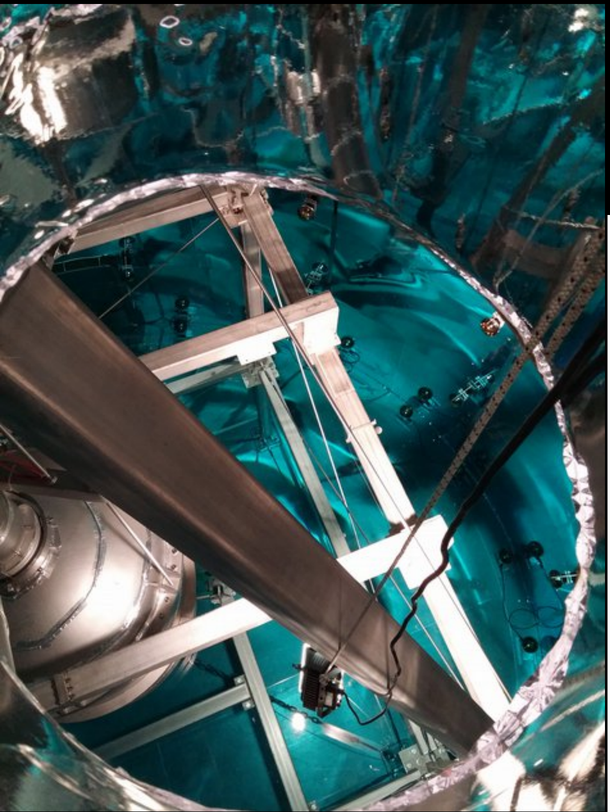


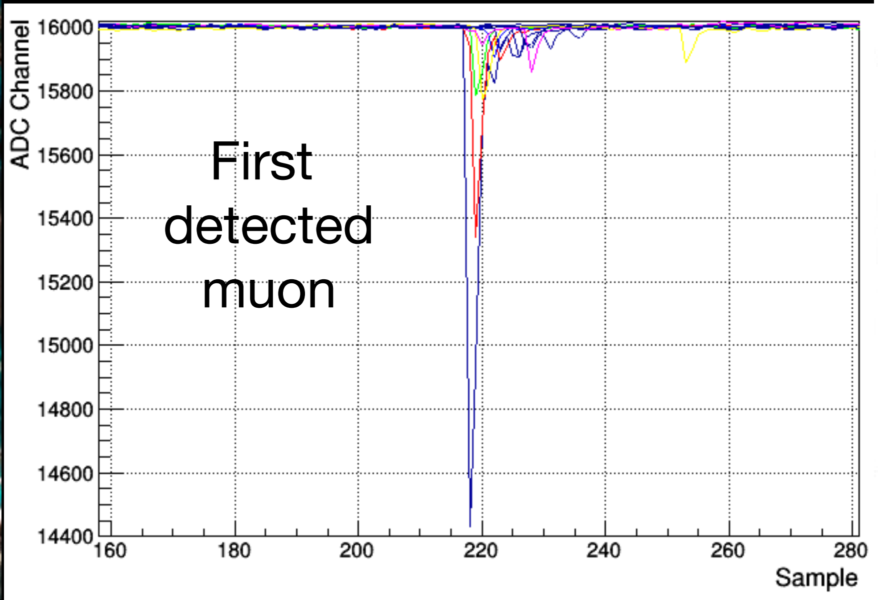


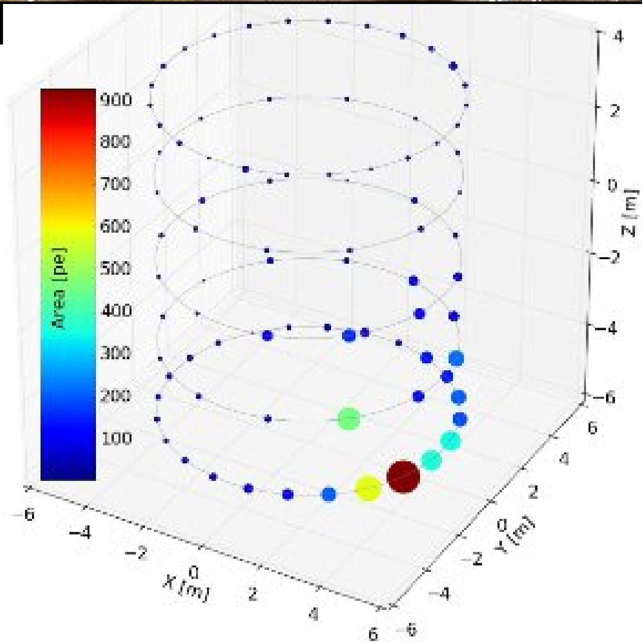
- 248 low-background 3” PMTs (Hamamatsu R11410-21).

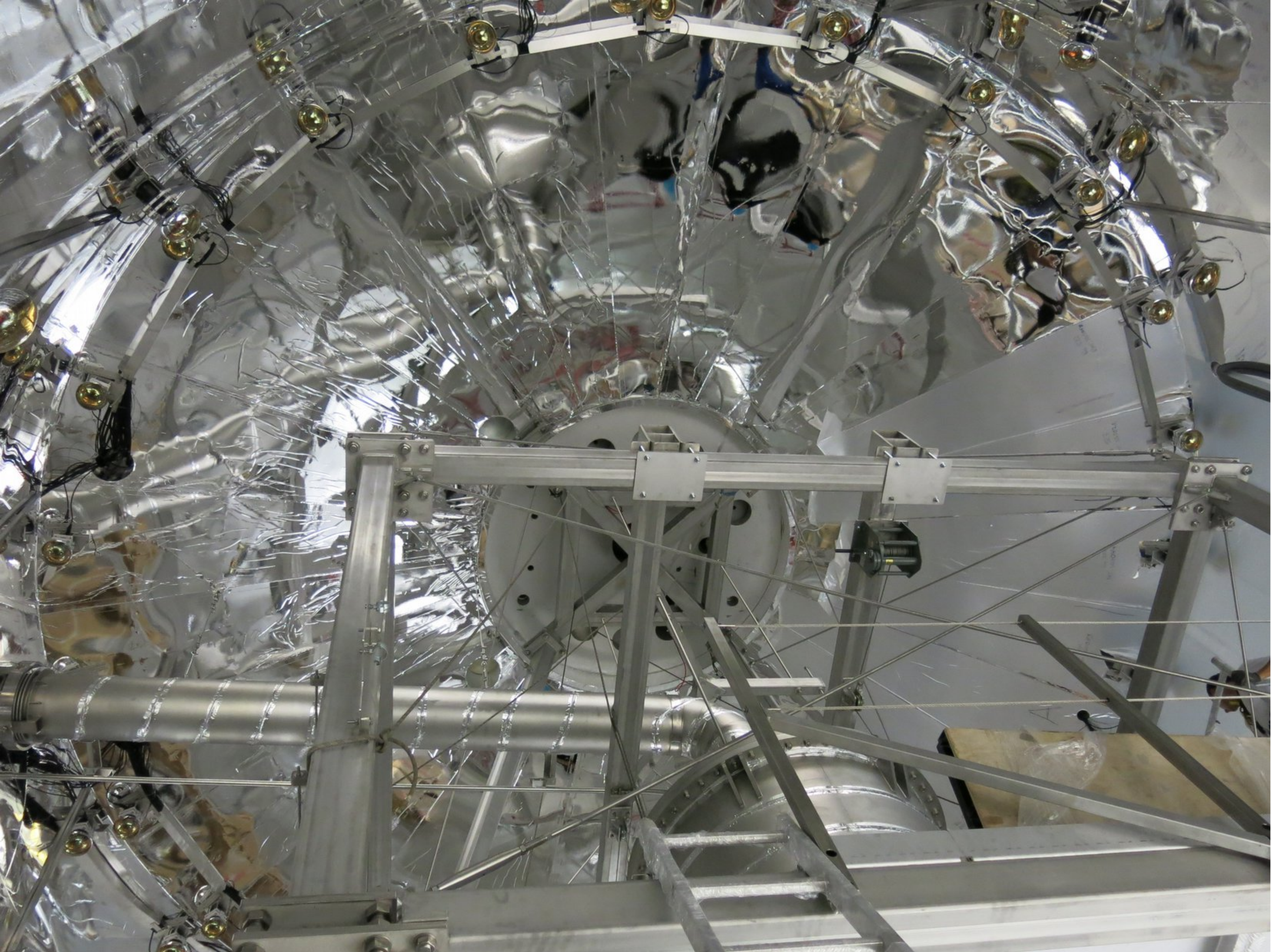
MUON VETO

- XENON1T cryostat immersed in a tank filled with 700 t of continously purified water.
- Tank clad with high-reflectivity and wavelength shifting foil, instrumented with 84 high-QE, 8” PMTs as a Water Cherenkov detector and tag muon-induced background.
- Passive shield against external radioactivity.
- First commissioning completed in March 2016.



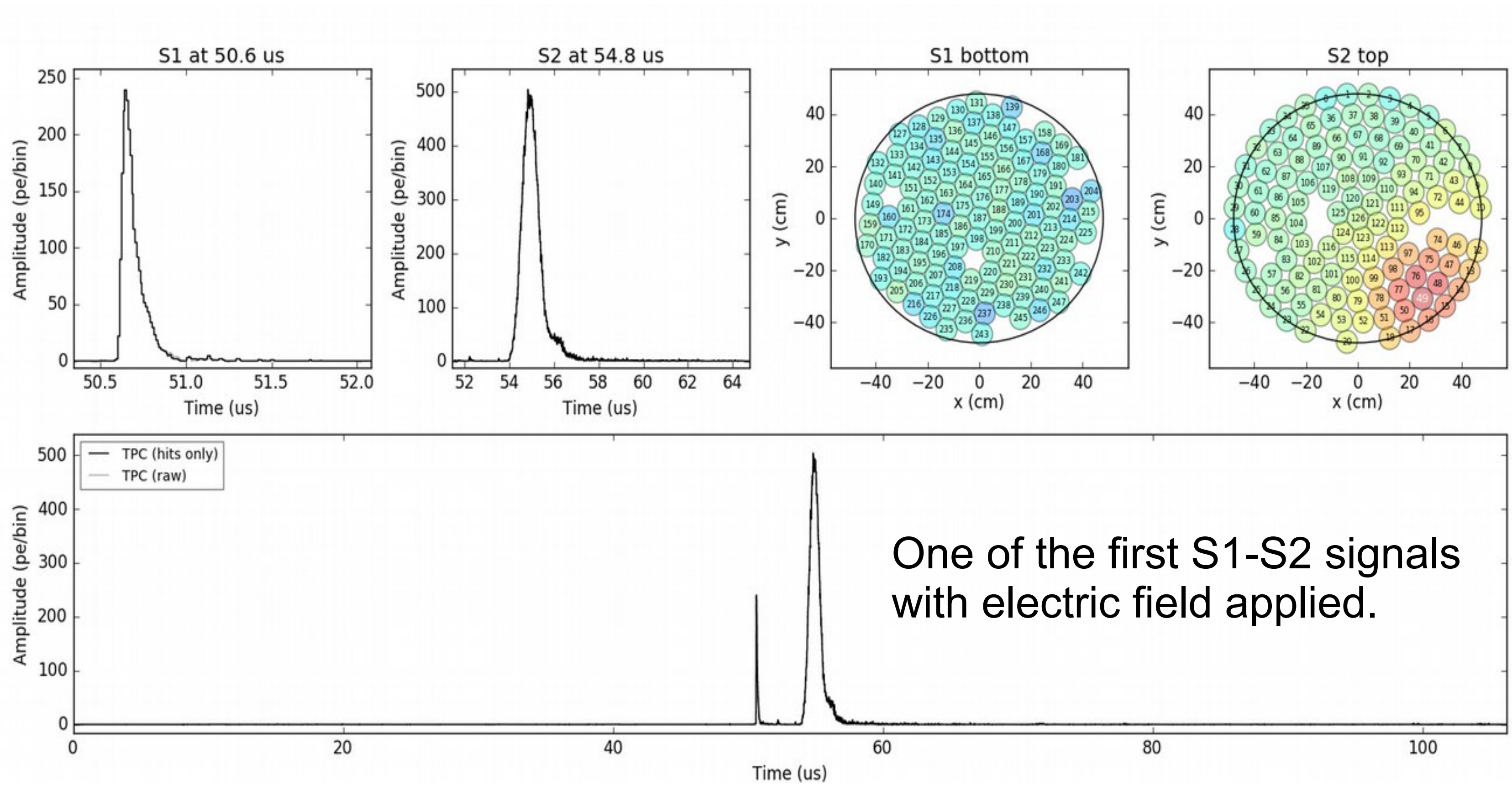






XENON1T TPC COMMISSIONING

- The XENON1T TPC and associated cryogenic systems are presently under commissioning.
- Both charge and light are being detected. The total mass of 3.2 t of LXe is being continuously purified to reach the desired charge yield at the applied field.



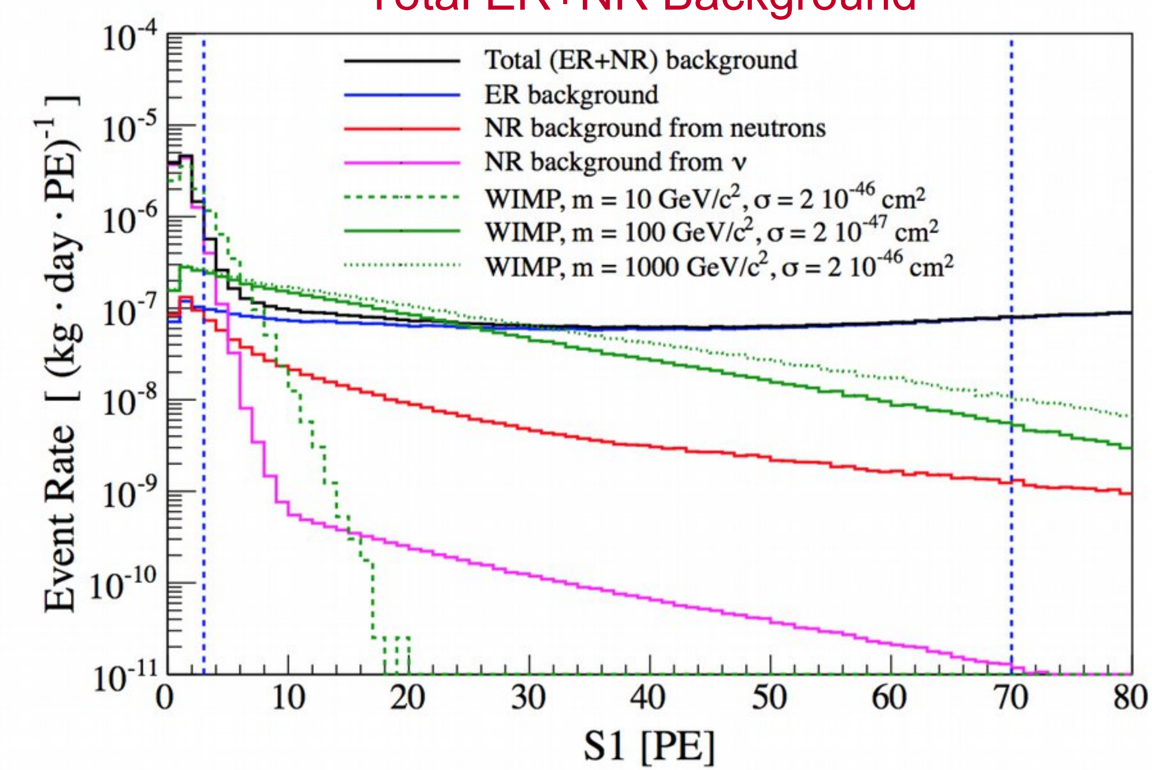
XENON1T Background Budget

- GEANT4 Monte Carlo simulation of the detector: TPC, PMTs, cryostat, water, shield. Informed by material screening.
- Neutrons from (α,n) and spontaneous fission predicted with SOURCES- 4A.

XENON Coll.
JCAP 04 (2016) 027

Source	Background (ev/y)
ER from materials	~0.07
^{222}Rn (10 μBq/kg)*	~1.39
^{85}Kr (0.2 ppt of natKr)	~0.07
^{136}Xe 2ν2β	~0.02
Solar neutrinos	~0.08
Total ER	**~1.62**
Total NR	**~0.46**

Total ER+NR Background

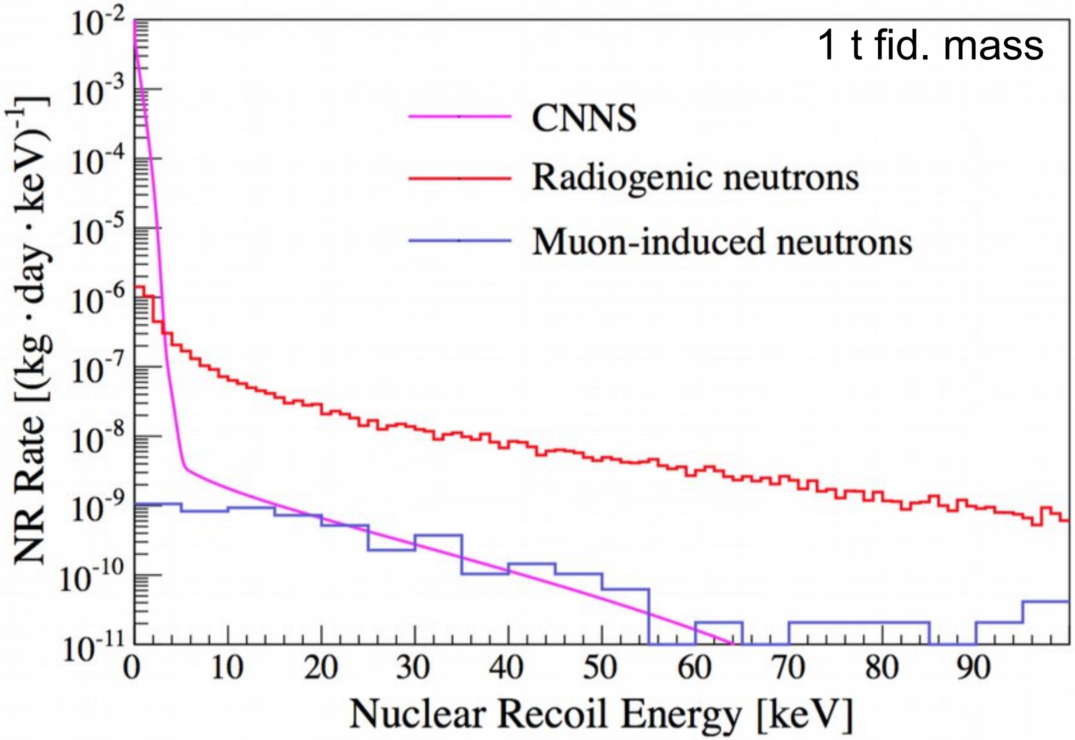


Single Scatter, 1 t fiducial mass, [1, 12] keV_{ee}, [4, 50] keV_{nr}, 99.75% S2/S1 discrimination, 40% NR acceptance.

* In agreement with Radon emanation measurements performed on the XENON1T detector after final assembly and before xenon filling.

More in Detail:

XENON1T Nuclear Recoil Background



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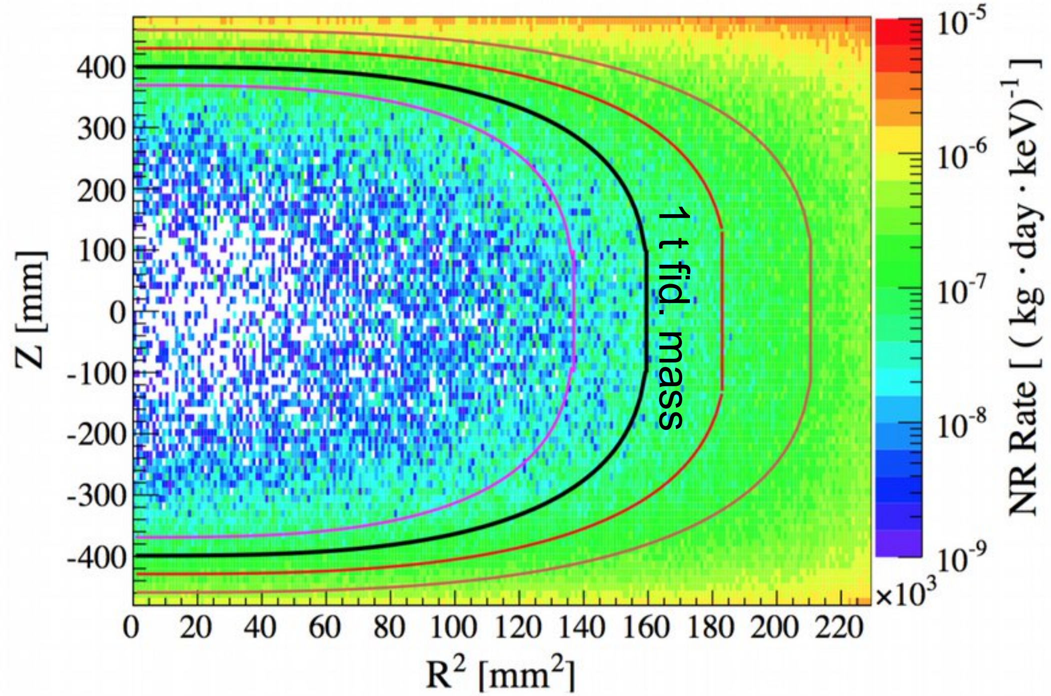
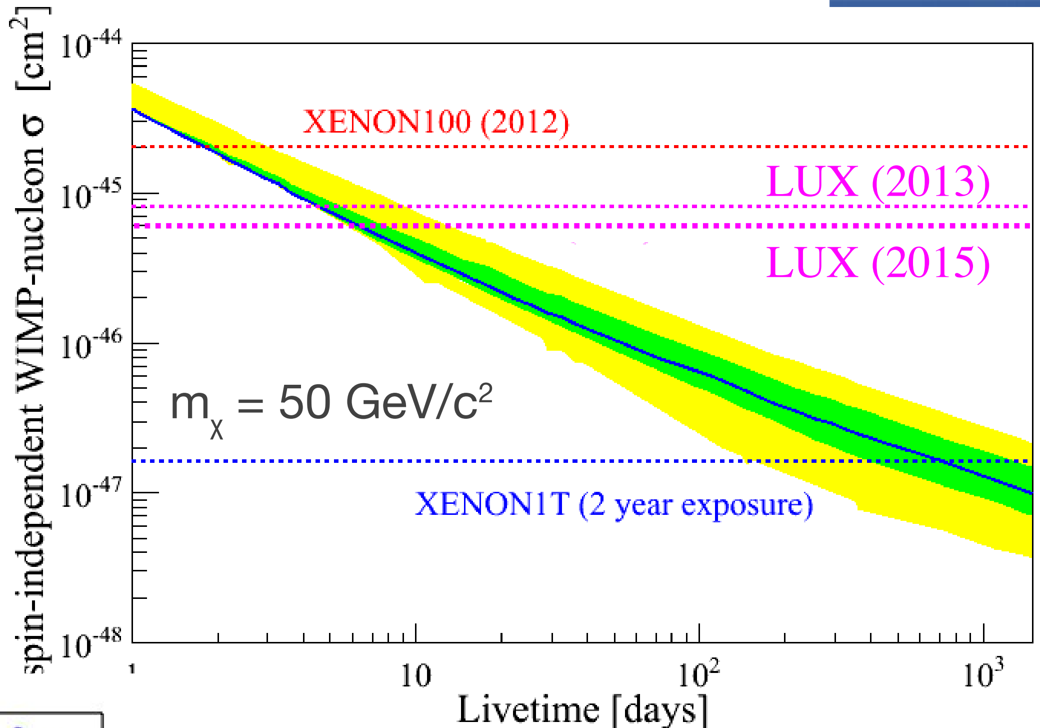
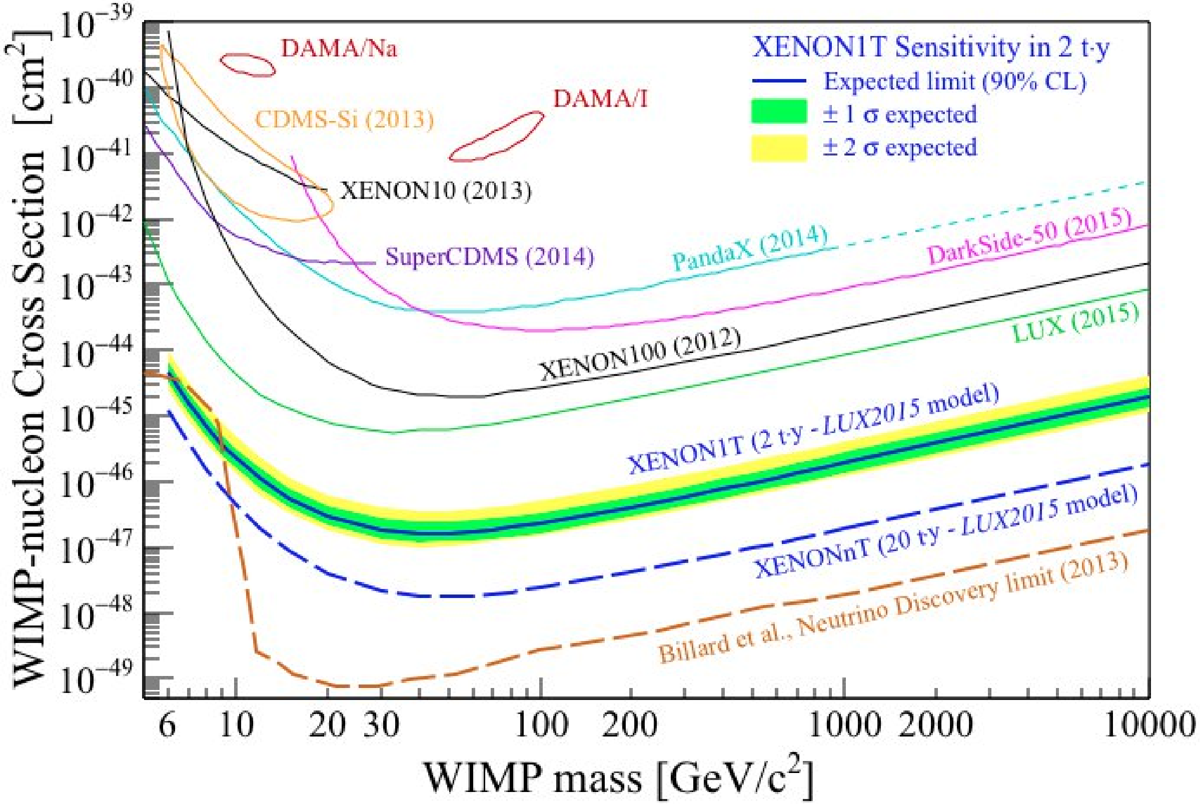
- Spatial distribution of NR background events from radiogenic neutrons in [4, 50] keV



XENON1T Projected Sensitivity





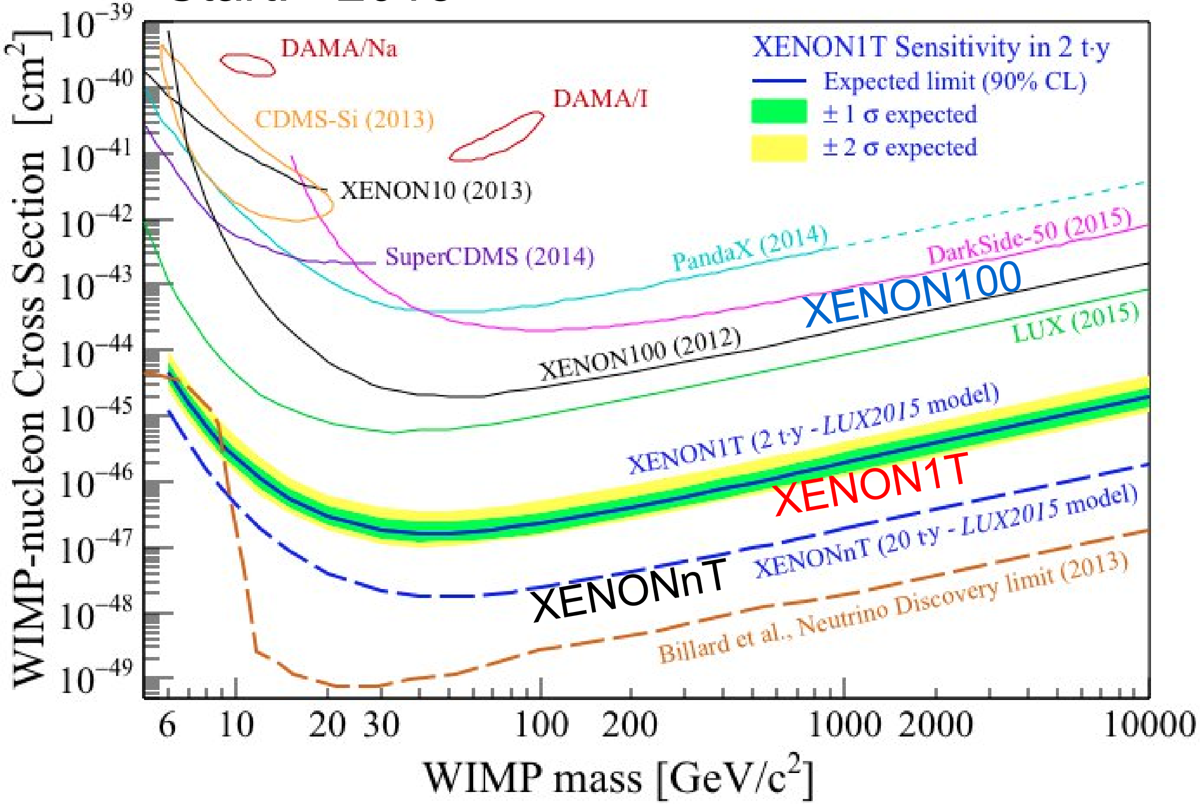
- Expected to overcome presently world-leading limits within 10 days of data taking in dark matter mode.

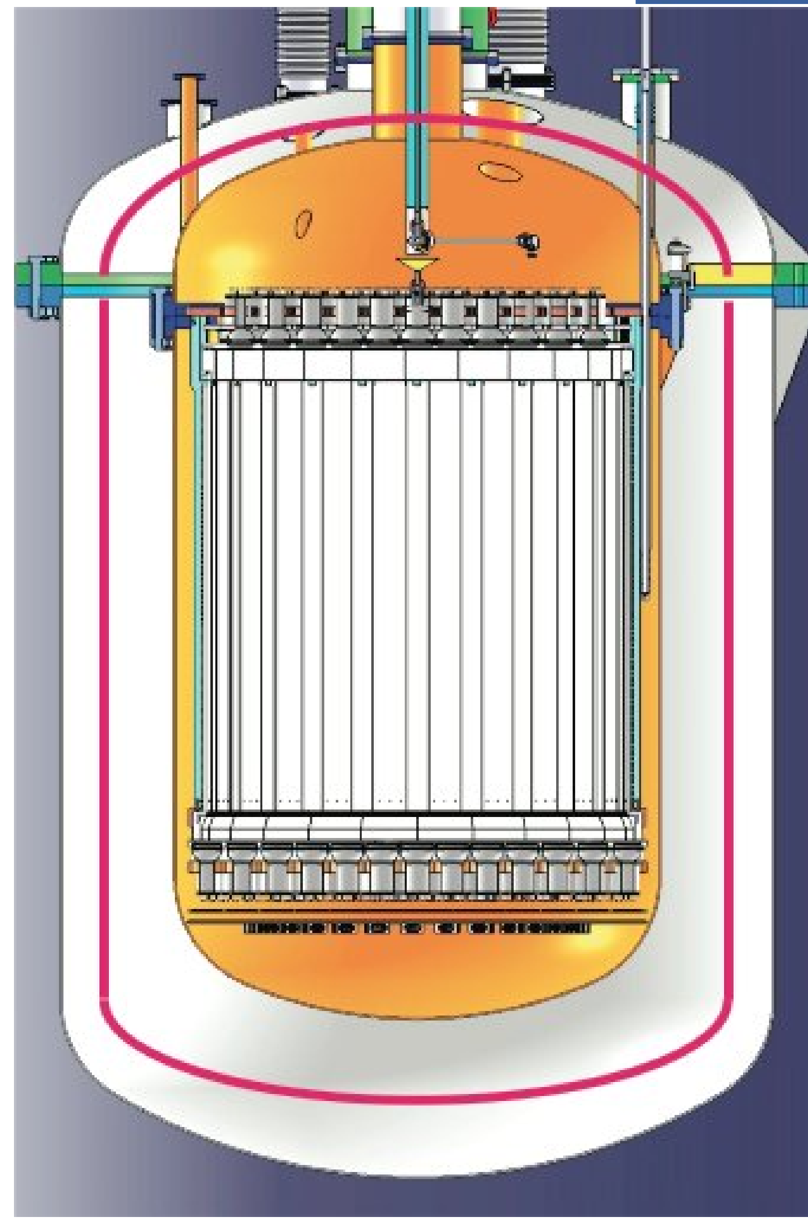
$1.6\ 10^{-47}$ cm^2 @ 50 GeV/c^2
for 2 t·y exposure

XENON Coll.
JCAP 04 (2016) 027

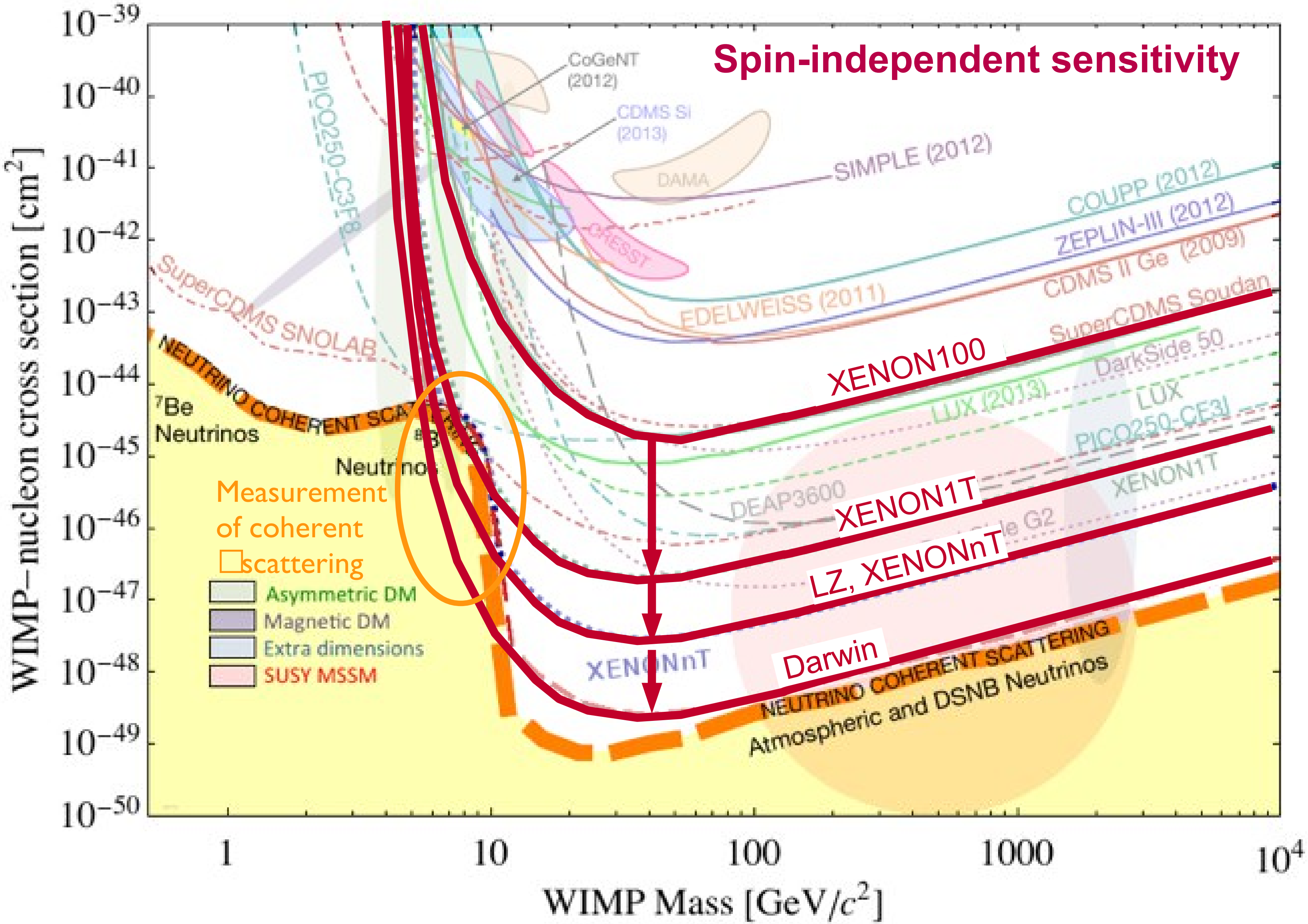
XENONnT

- XENONnT: larger TPC & larger inner vessel to fit inside XENON1T outer cryostat.
  Other systems will be largely reused.
- Aim: 20 ton-years exposure, reduced background to reach few 10^{-48} cm^2 sensitivity.
- Start: ~2018





Current Status and Future Goals



XENON Collaboration

21 institutions
10 countries
130 scientists