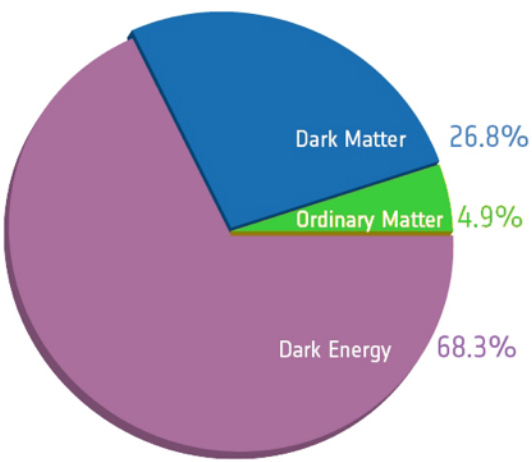
The 11th International Workshop
Dark Side of the Universe 2015
14th-18th December, Kyoto, Japan

XENON1T: THE START OF A NEW ERA IN THE SEARCH FOR DARK MATTER

Sara Diglio
Subatech - Nantes
on behalf of the XENON Collaboration

WHY DO WE NEED DARK MATTER?

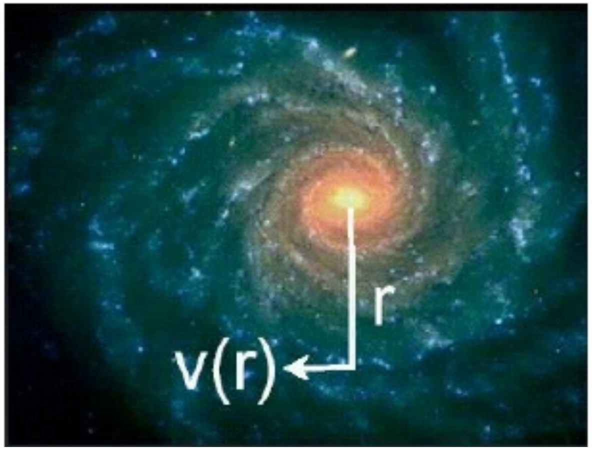
Evidences at different scales: galaxies, clusters, CMB

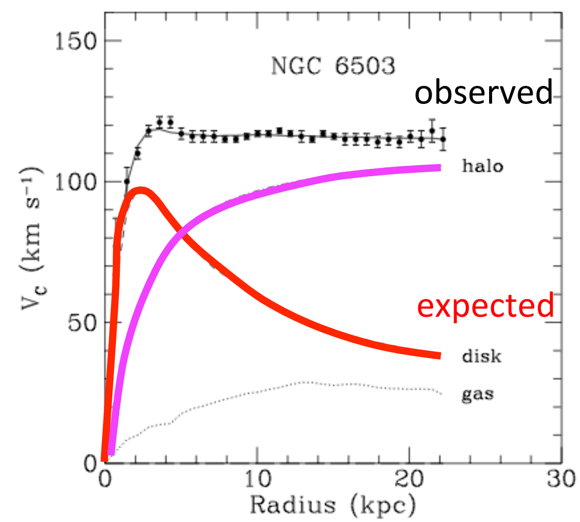


What we know about dark matter ?

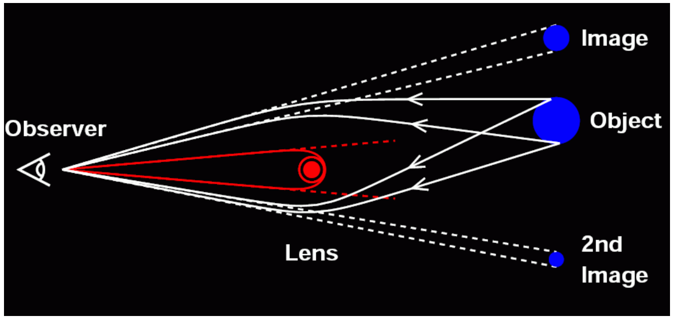
- Neutral
- Non-baryonic → weakly interacting
- Not a Standard Model (SM) particle → New Particle

Galactic Rotation Curves





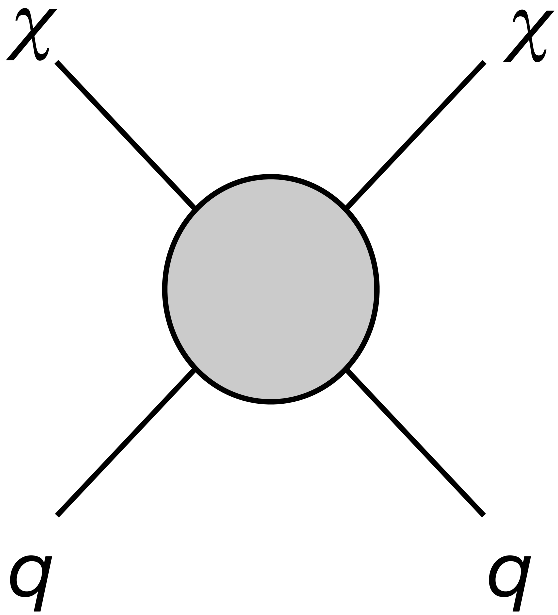
DM Distribution Gravitational Lensing



DARK MATTER DETECTION

Indirect Detection

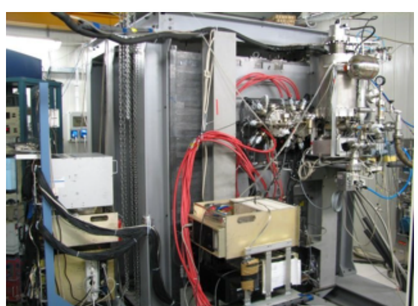
DM annihilation into SM particles



Direct or by decay DM production

Particle Colliders

Direct Detection

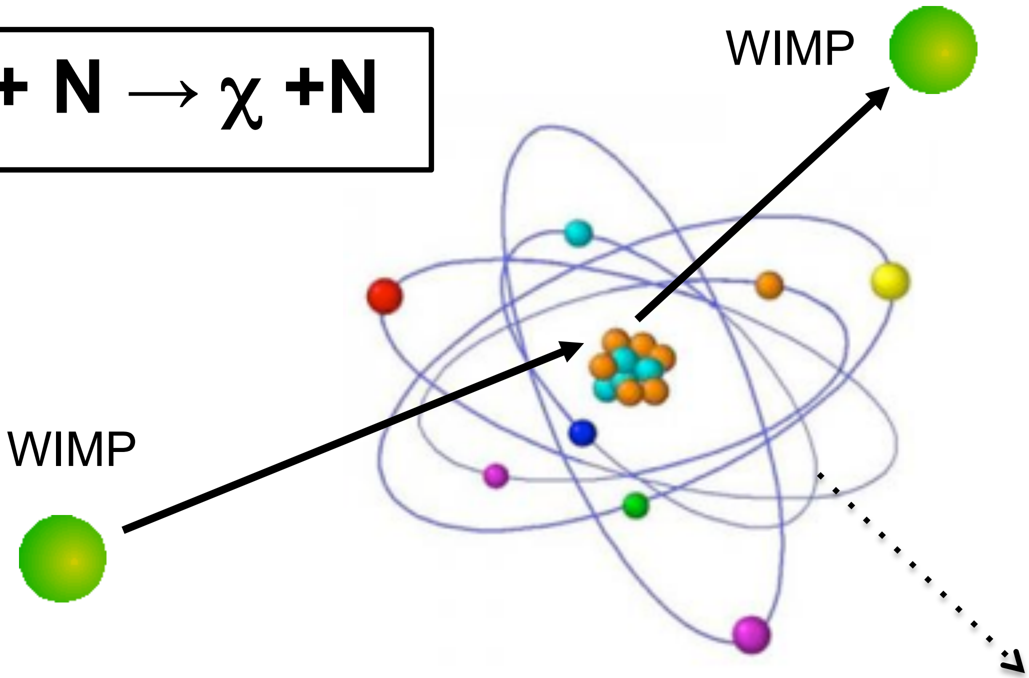


DM scattering off SM particles

The Direct Detection Principle

WIMPs elastically scatter off nuclei in targets, producing Nuclear Recoils (NR)

$$\chi + N \rightarrow \chi + N$$



NR: Detectable Signal

$$E_{recoil} \lesssim 100 \text{ keV}$$

For example, by assuming

- WIMP mass: $M_\chi = 100$ GeV/c^2
- WIMP velocity: $v_0 = 220$ km/s

we have the average recoil energy: $E_0 = \frac{1}{2} M_X v_0^2 \sim 30 \text{ keV}$

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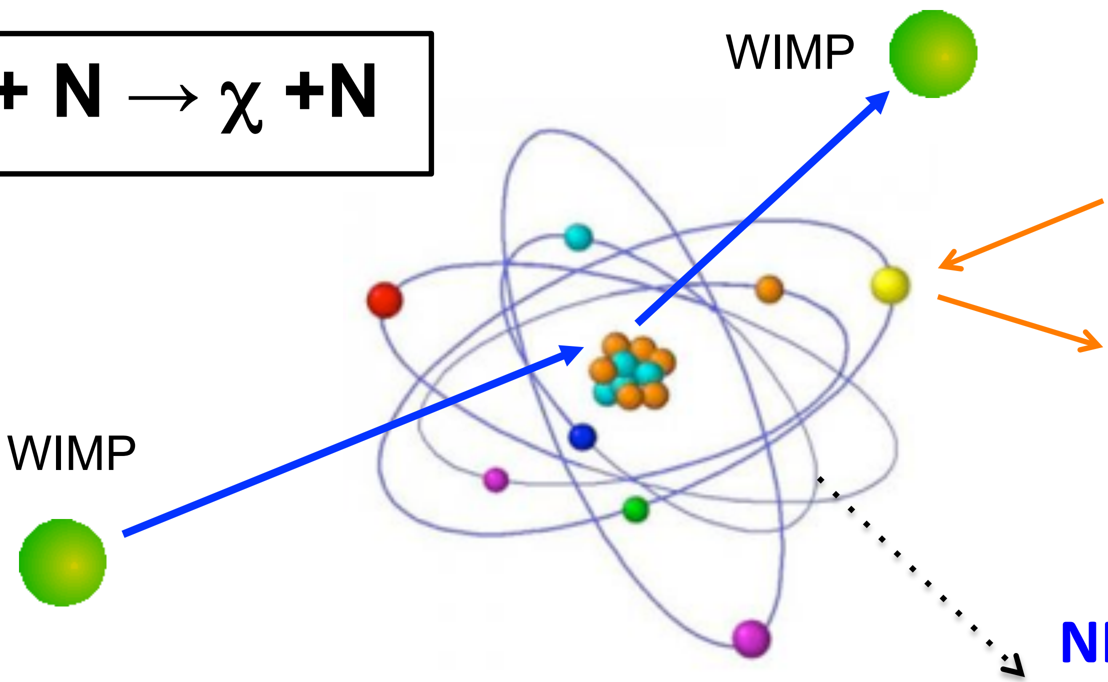

γ- and β-particles (**bkg**) interact with the atomic electrons

→ **electronic recoil (ER)**

NR: Detectable Signal

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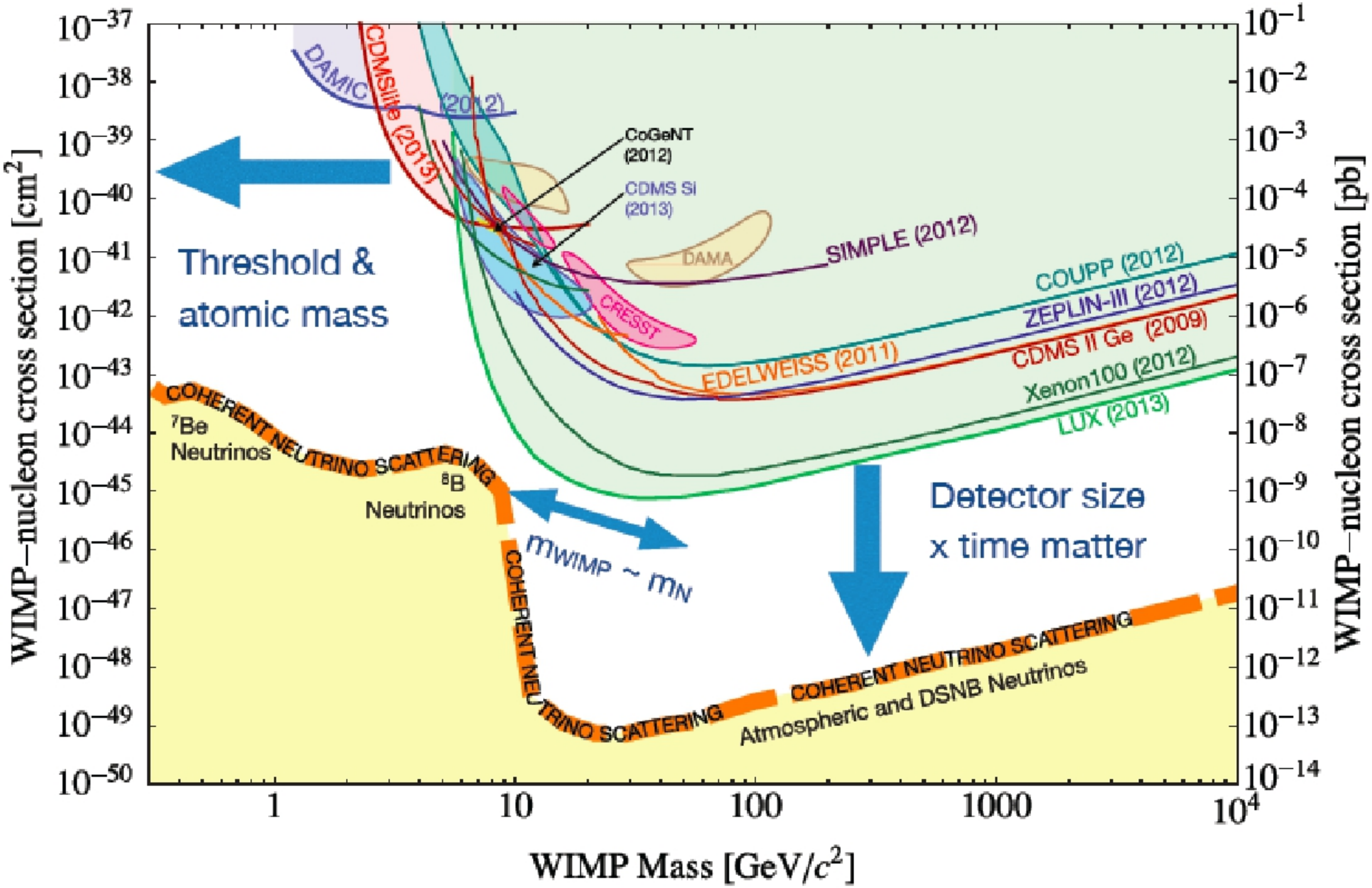
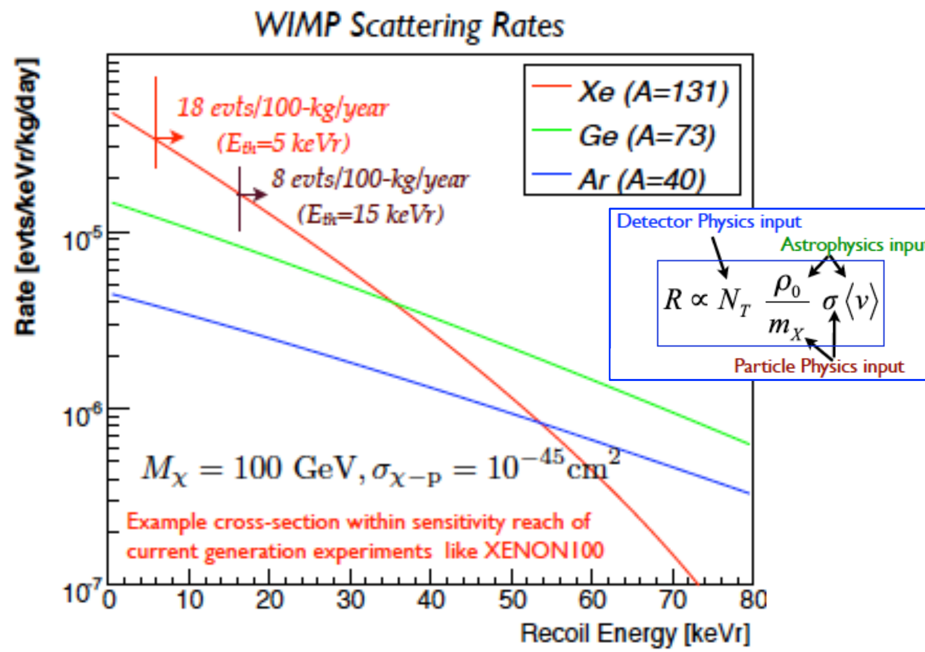
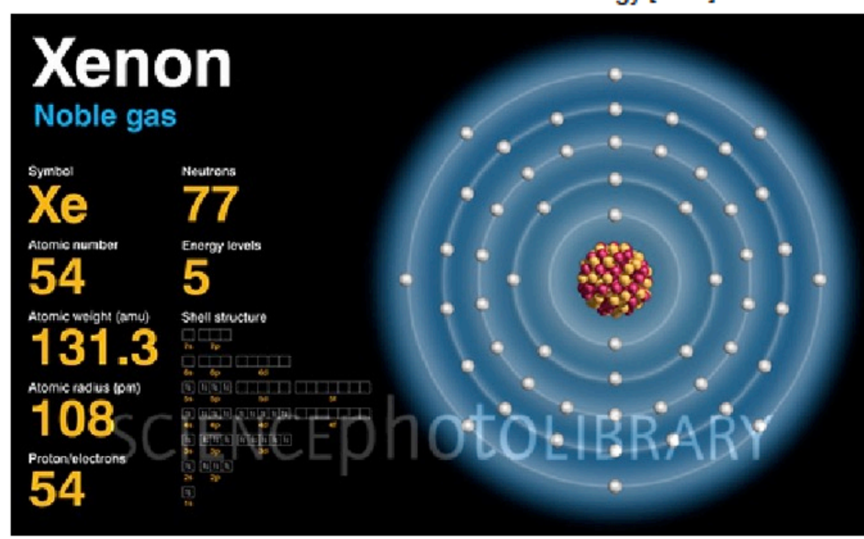
WHERE IS THE FIELD OF DIRECT DETECTION TODAY?



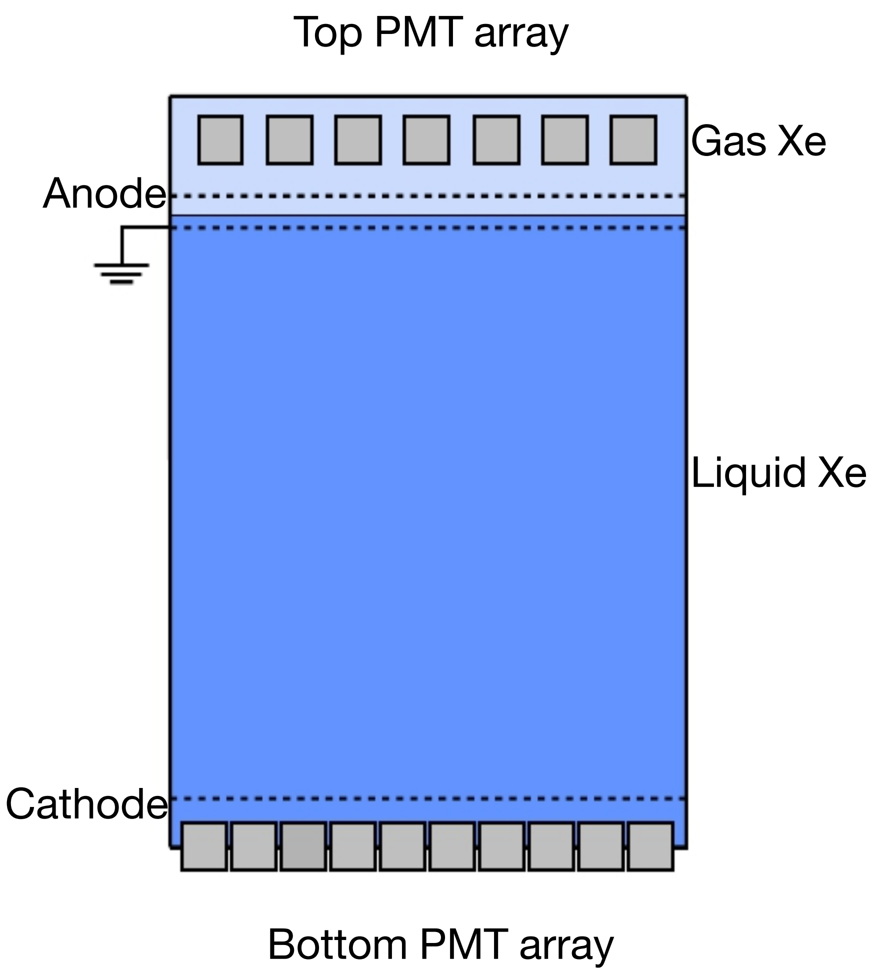
LIQUID XENON AS A DETECTOR MEDIUM

- Heavy nucleus (A~131):
  good for Spin Independent ($\sigma \sim A^2$) and for Spin Dependent (~50% odd isotopes)
- Self-shielding:
  effective background rejection via self-shielding and ratio of ionization/scintillation
- Charge & Light signals:
  highest yield among noble liquids
- Intrinsically pure:
  no long-lived radioactive isotopes; free of intrinsic radioactivity other than Kr which we know how to remove
- "Easy" cryogenics:
  high boiling point allows to cool and keep cold for long time a massive Xe target
- Scalability:
  possible to scale detectors to large dimensions for an affordable cost (~1 k$/kg)





Dual Phase Time Projection Chamber



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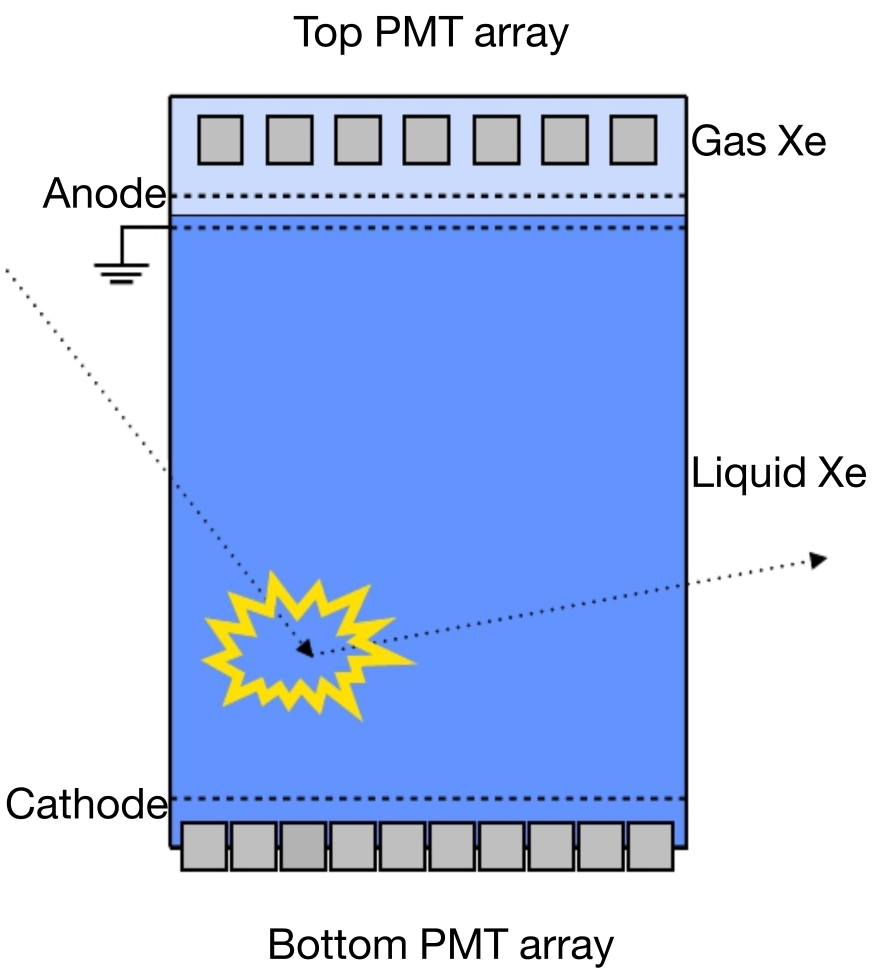
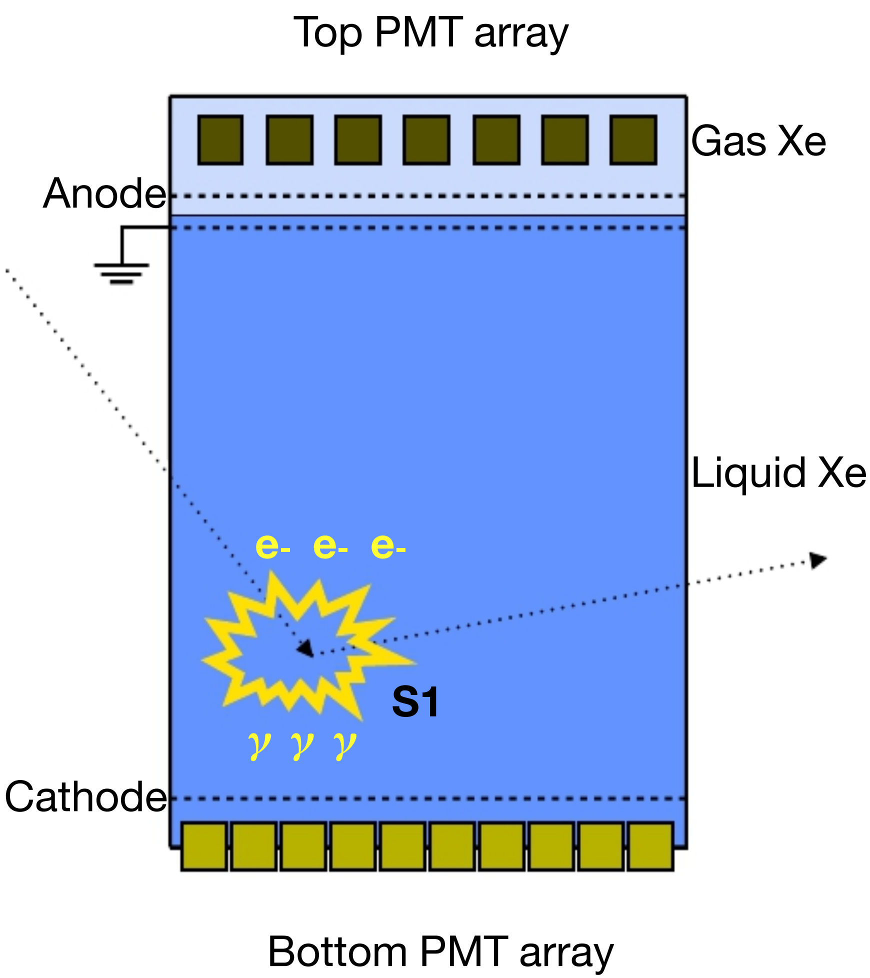
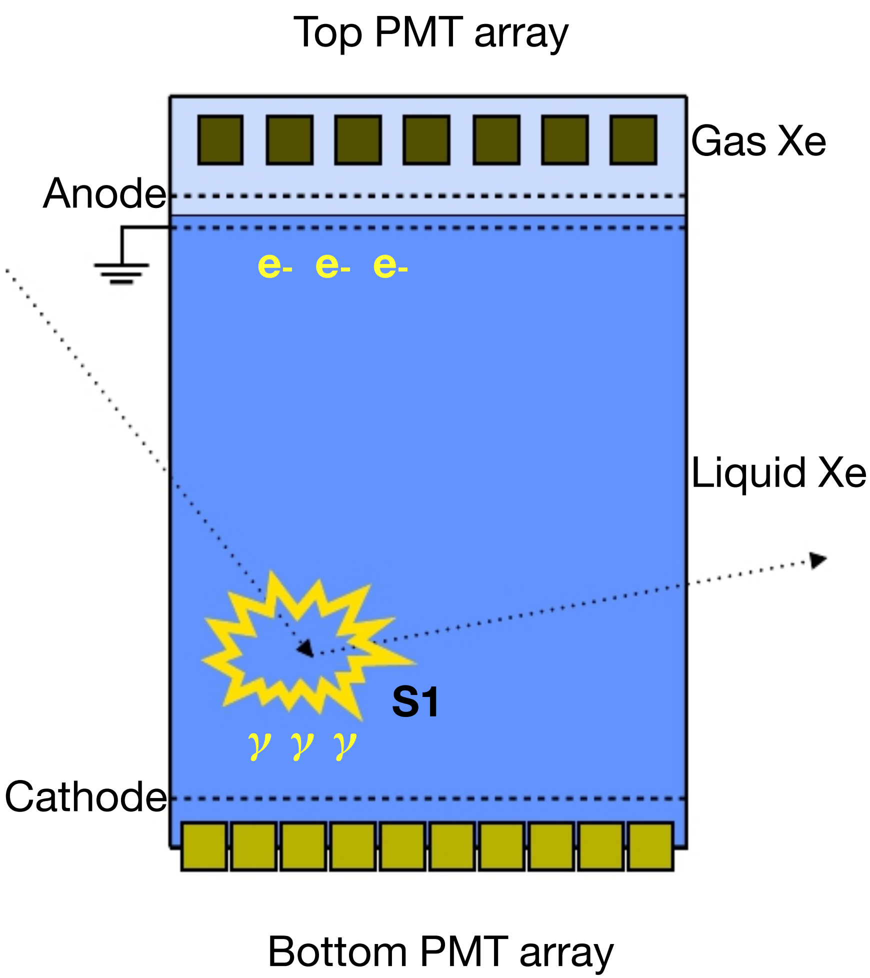



Top PMT array
Gas Xe
Anode
Liquid Xe
e- e- e-
S1
γ γ γ
Cathode
Bottom PMT array

Dual Phase Time Projection Chamber



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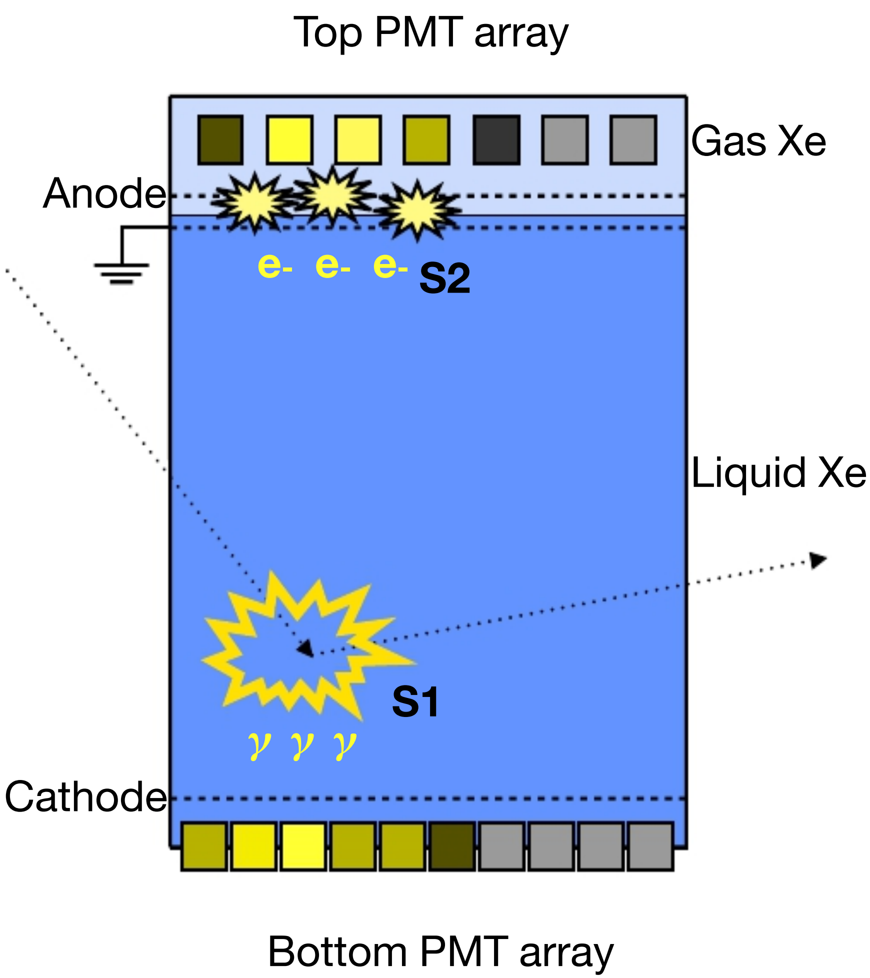
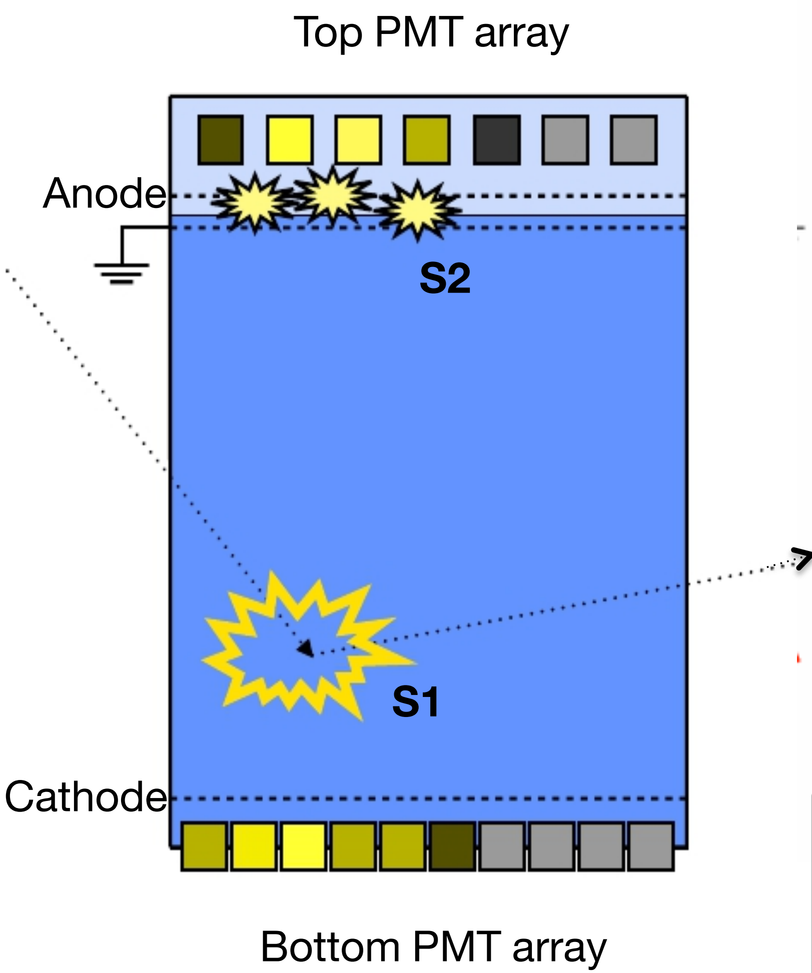


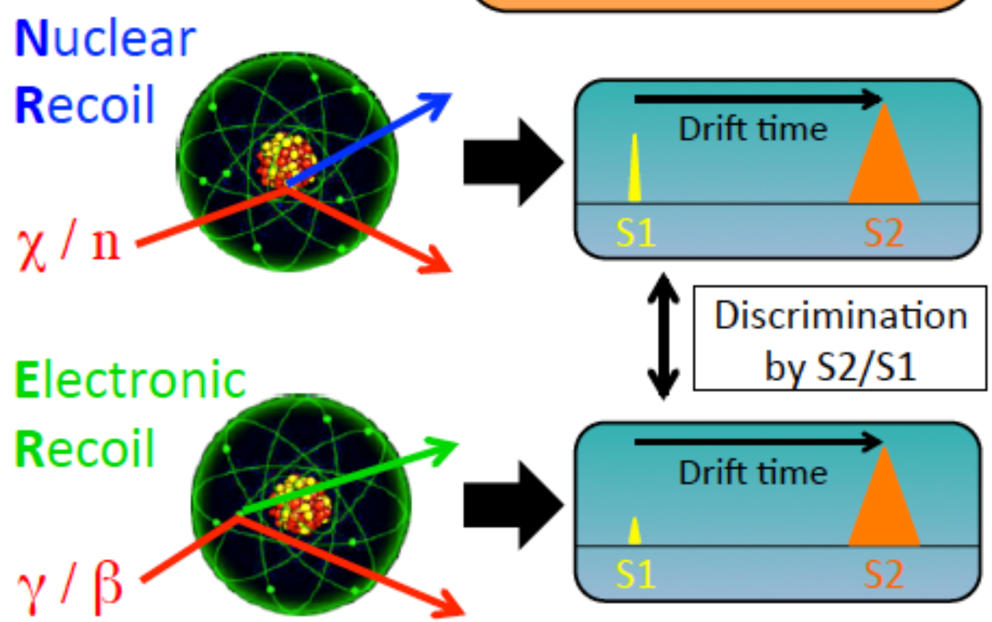
DUAL PHASE TIME PROJECTION CHAMBER

$(S2/S1)_{n,WIMP} < (S2/S1)_{e,\gamma}$

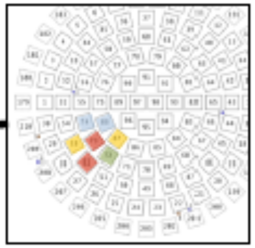


S1: Prompt scintillation

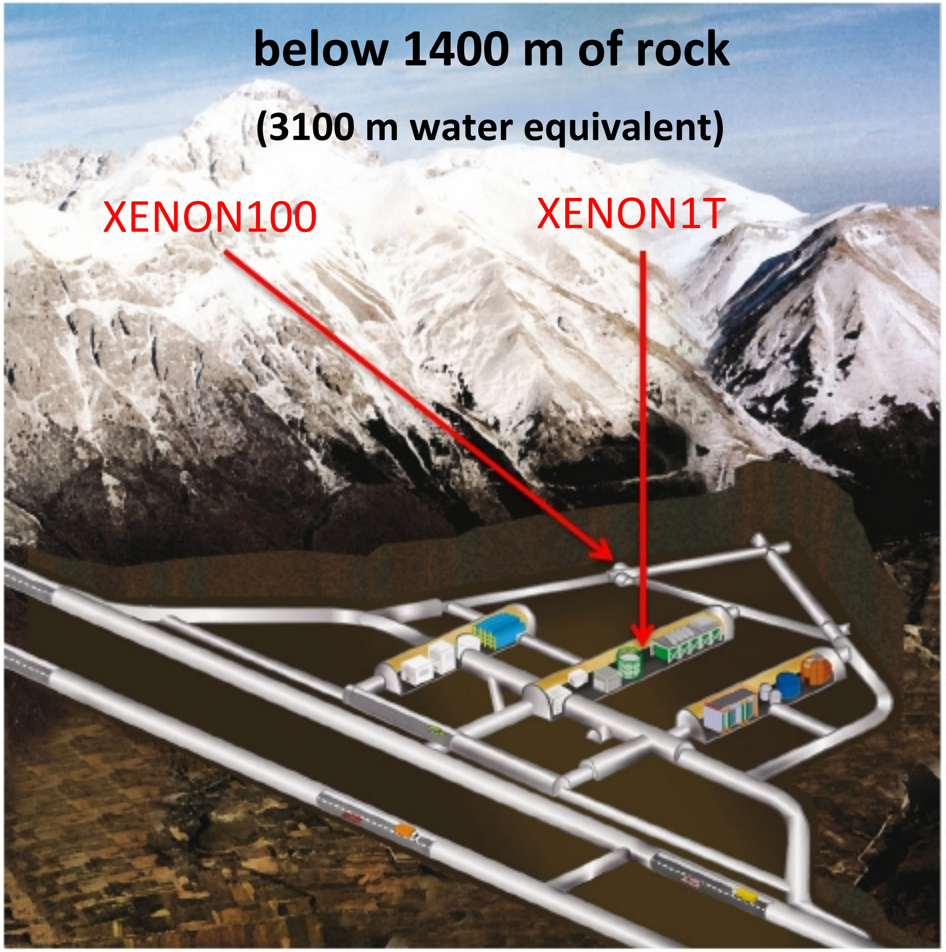
S2: Proportional scintillation following e^- drift and extraction into gas



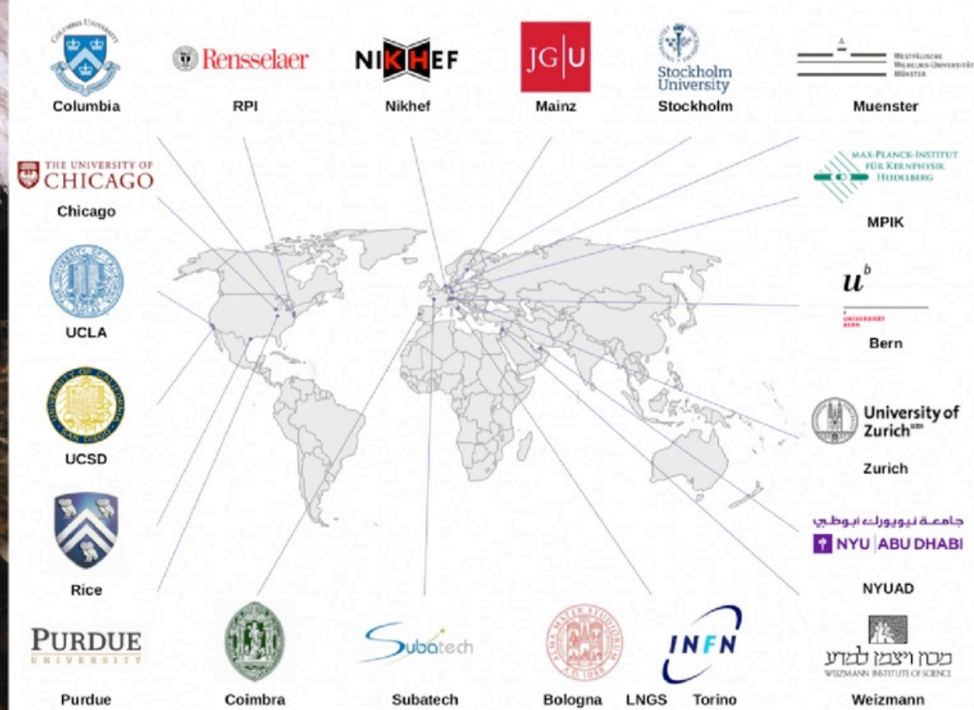
Interaction vertex reconstruction:
- Horizontal from top PMT array
- Vertical from drift time



THE XENON COLLABORATION

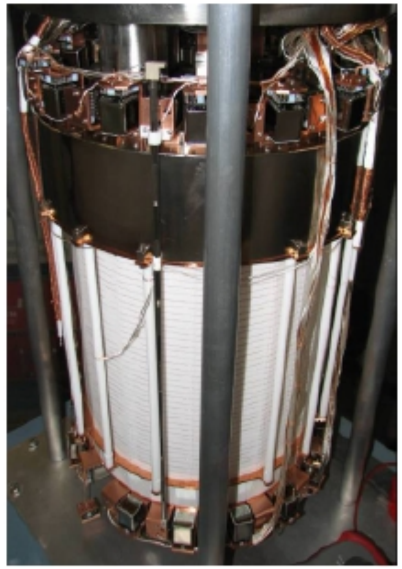
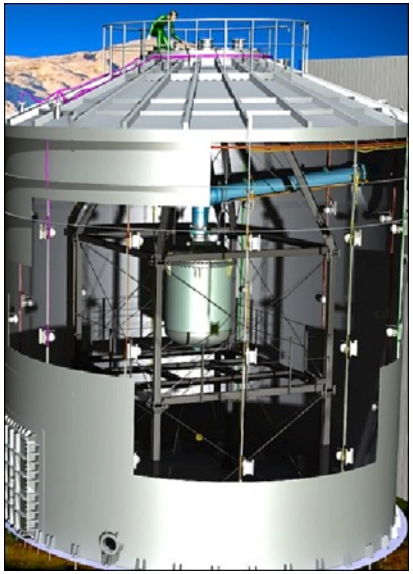
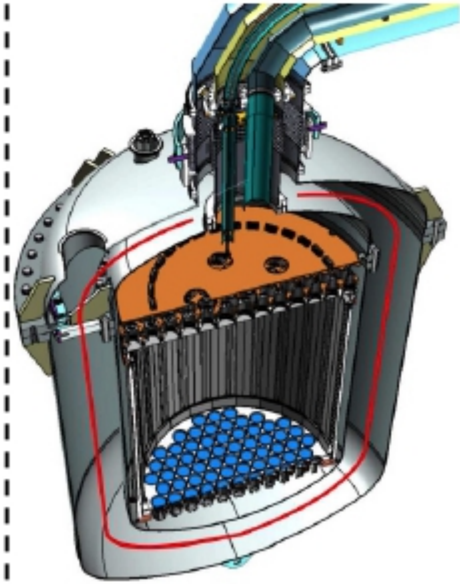


21 institutions
~ 130 scientists



XENON experiments at Gran Sasso National Laboratory (LNGS) in Italy

THE XENON DARK MATTER PROGRAM

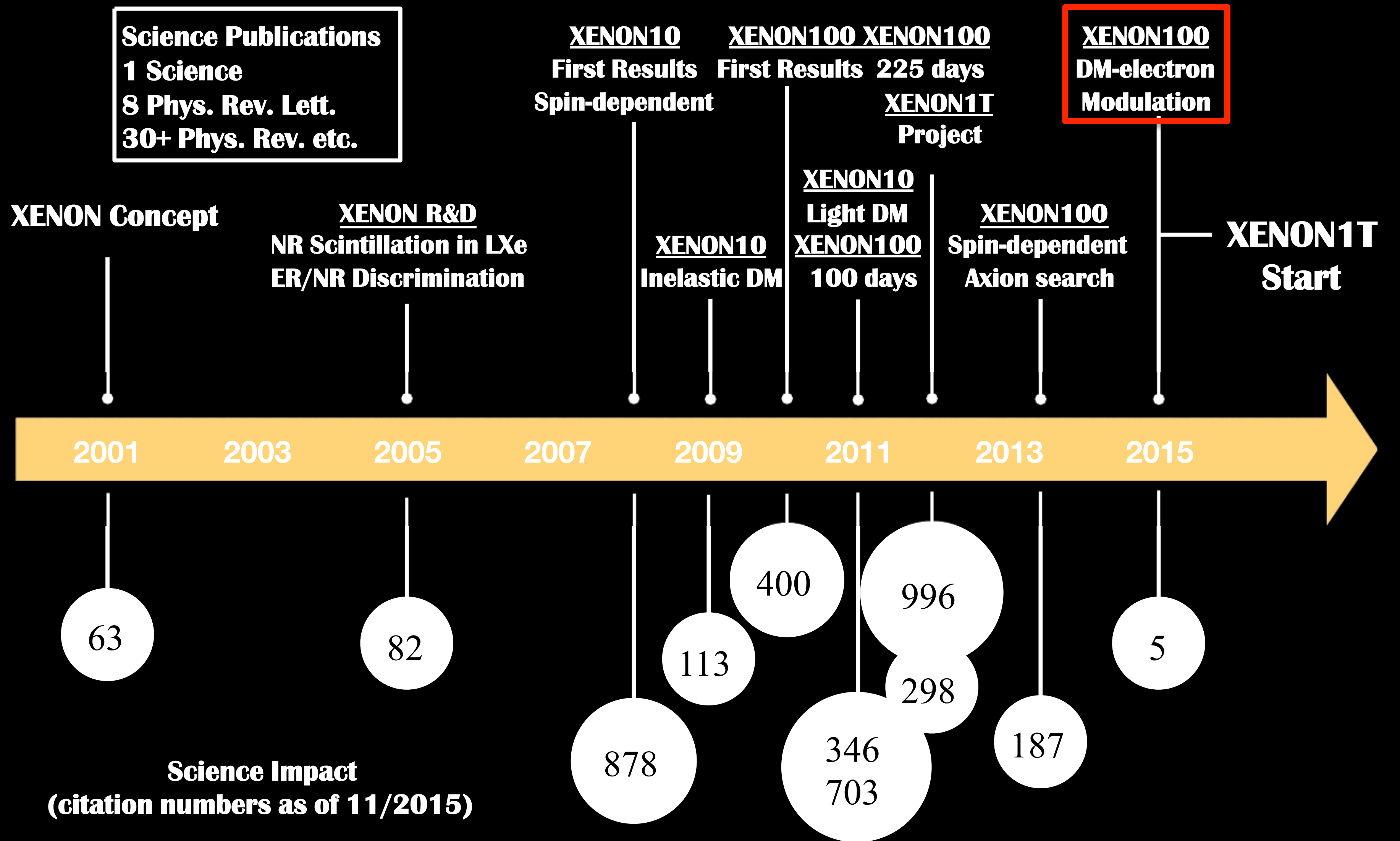
XENON10	XENON100	XENON1T	XENONnT
			
2005	2009 still in operation	2015 Science data by spring 2016	2018+
25 kg	161 kg	3500 kg	~7000 kg
$<8.8 \times 10^{-44}$ cm^2	$<2 \times 10^{-45}$ cm^2	$\sim<2 \times 10^{-47}$ cm^2	$\sim<2 \times 10^{-48}$ cm^2

Time

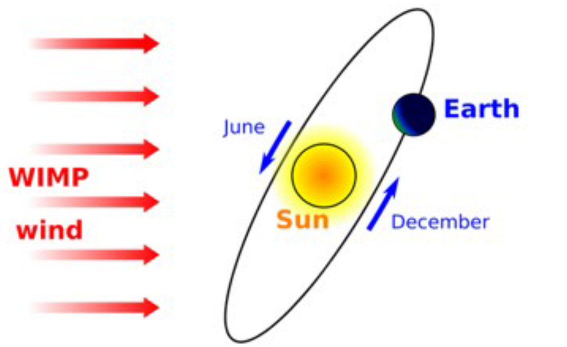
Total Xe mass

WIMP-nucleon cross section

The XENON Dark Matter Program

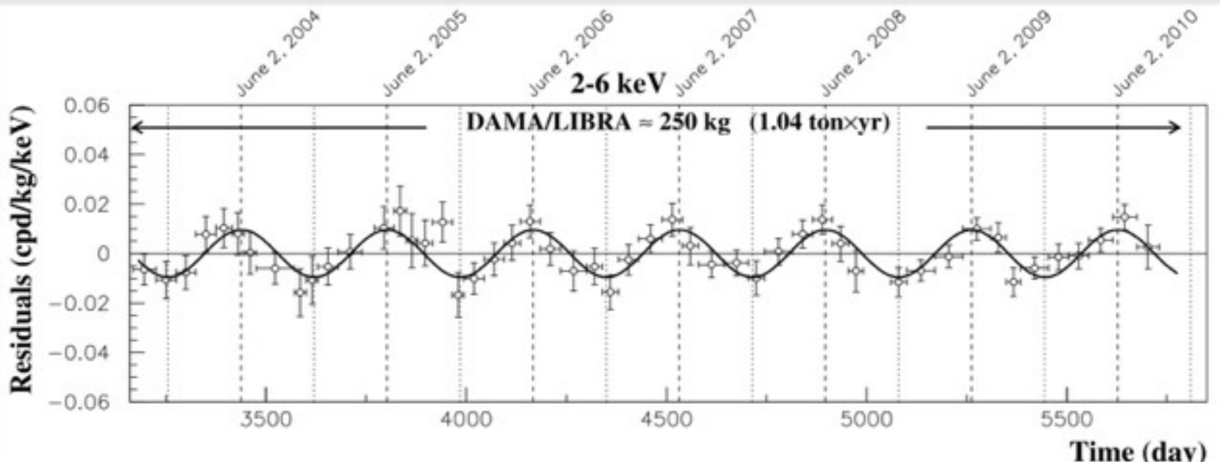


Probing the DAMA/LIBRA Anomaly with XENON100



Freese et al., Rev. Mod. Phys. 85, 1561 (2013)

DM signal rate is expected to be annually modulating
Peak phase 152 days (June 1)



9.3 σ significance only for single hit phase (144 +- 7) days
No signal above 6 keV, No ER/NR discrimination

Bernabei et al., Eur. Phys. J. C 73, 12 (2013)

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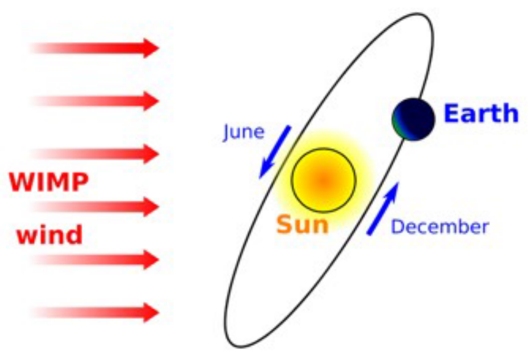

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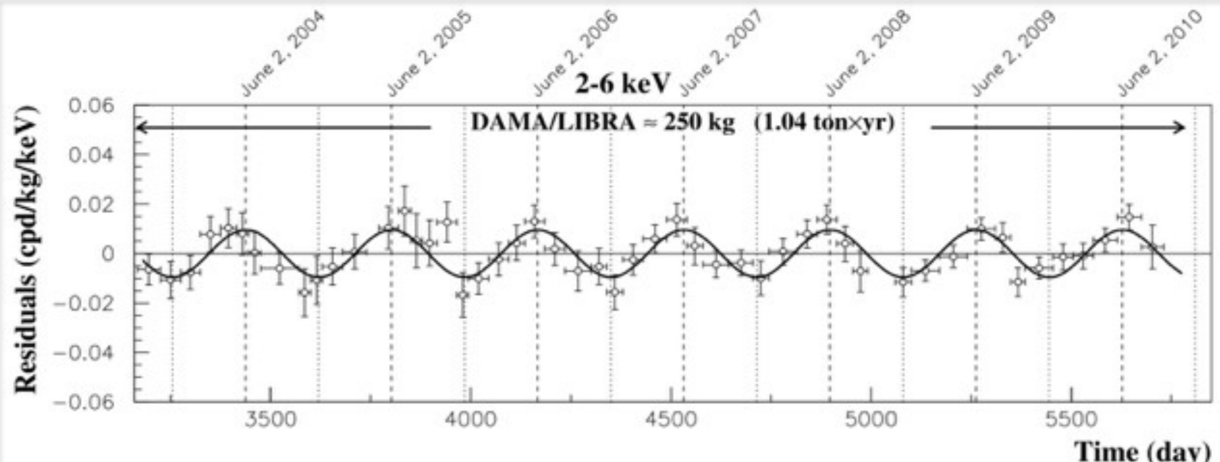

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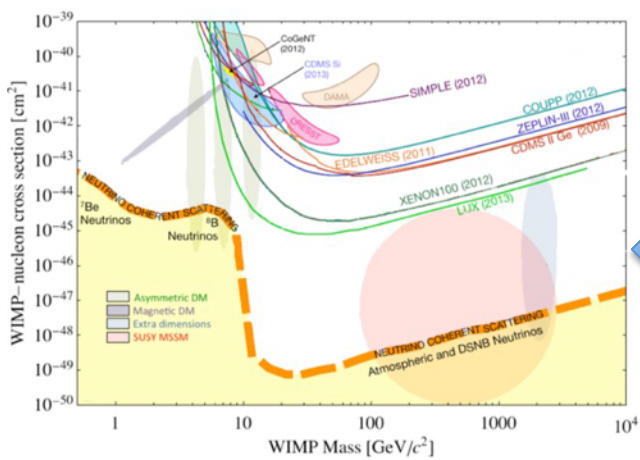

Seems to be convincing evidence, HOWEVER…

… *Null results* from many experiments *more sensitive* than DAMA/LIBRA

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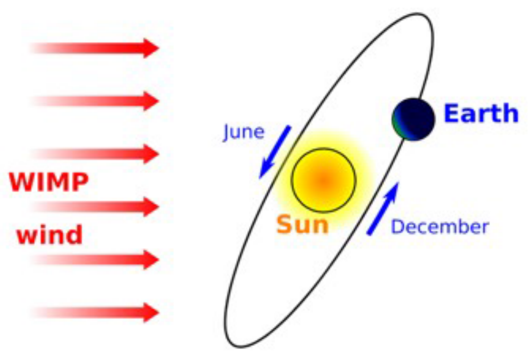

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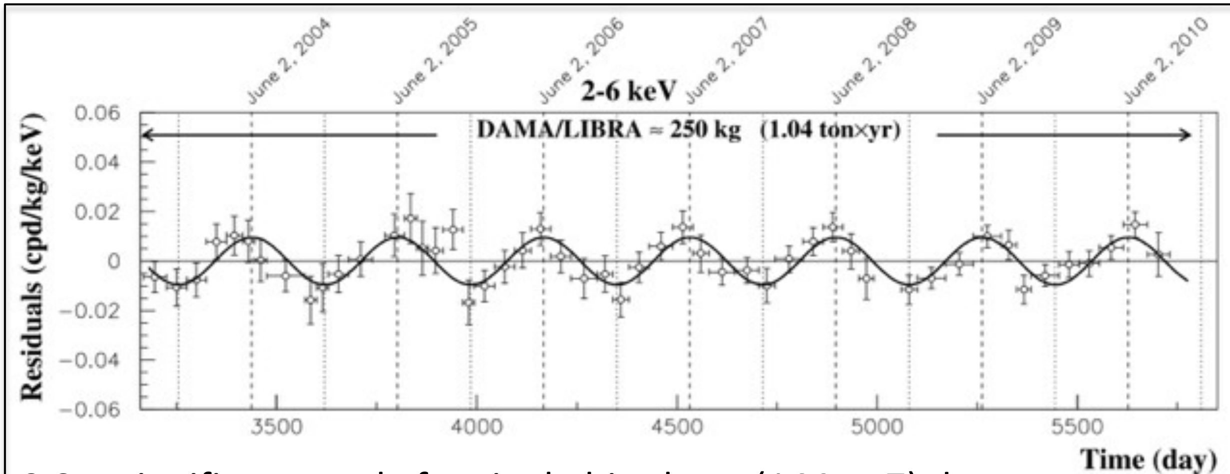

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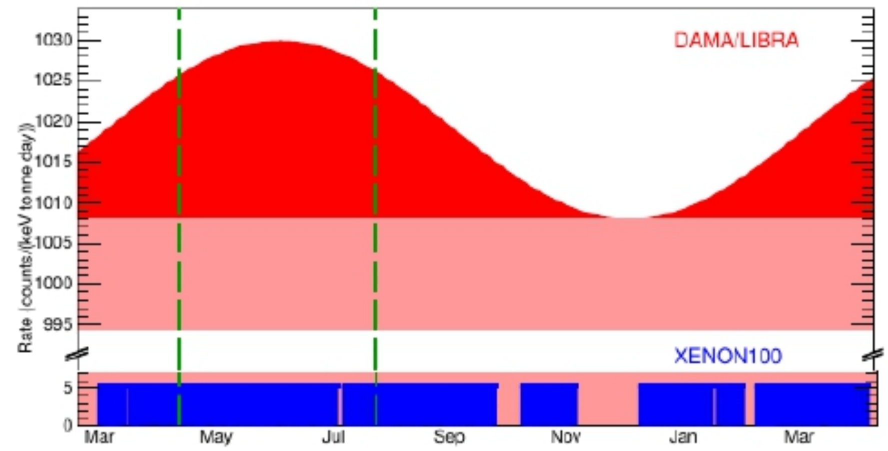
Xenon100 studies

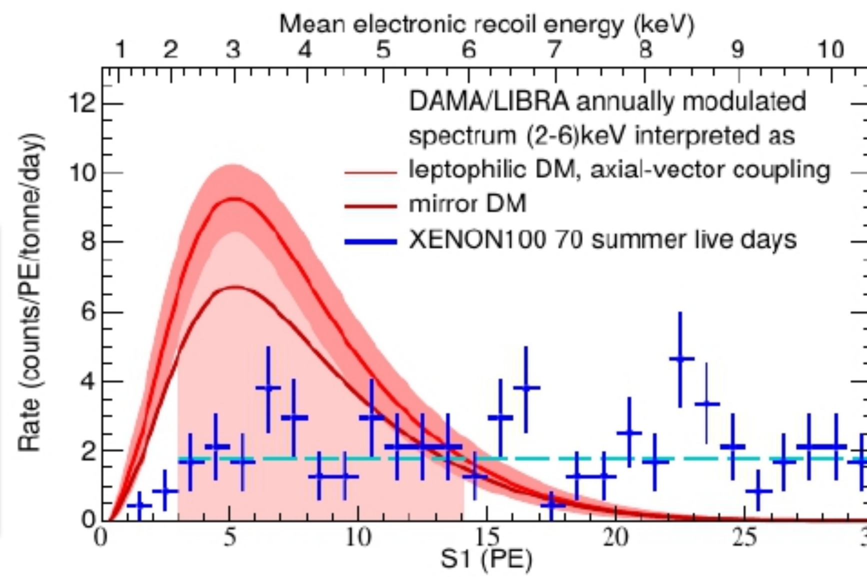
- From overall ER Rate:
  Exclusion of leptophilic DM
  Science 349, 851 (2015)
- From ER periodic variations:
  Search for Event Rate Modulation
  Phys. Rev. Let. 115, 091302

Reconcile DAMA/LIBRA with the null-results from other experiments assuming leptophilic dark matter?
→ DAMA/LIBRA might see electronic recoils ?

Exclusion of leptophilic Dark Matter

- DAMA/LIBRA experiment observes annual *modulation interpretable with leptophilic DM* Eur.Phys.J. C73, 2648
- Convert DAMA/LIBRA modulation spectrum to Xe
- Assume some model of WIMP coupling to e^- to estimate expected signal in XENON100
- XENON100 steady background level lower than DAMA/LIBRA modulation signal





Exclusion of several types of DM models as the cause of the annual modulation

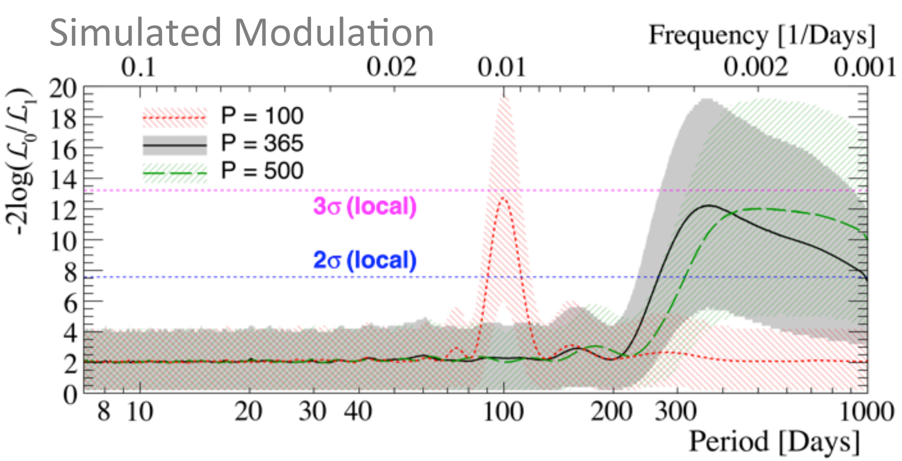
Kinematically mixed Mirror DM:	3.6σ Exclusion
Luminous DM:	4.6σ Exclusion
Axial-vector coupling:	4.4σ Exclusion

Science 349, 851 (2015)

Search for Event Rate Modulation

- The first LXe TPC with more than one year of stable running conditions
- Temporal evolution of relevant detector parameters studied (02/2011-03/2012) → no significant correlation with event rate observed

Discovery potential



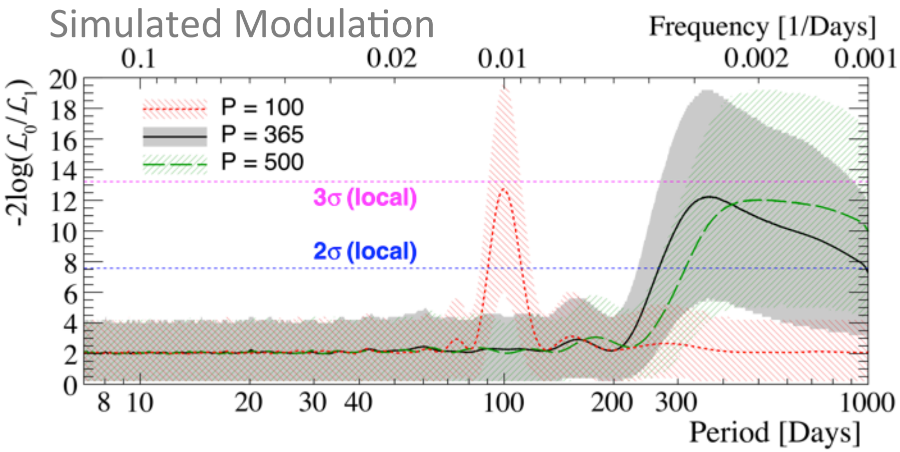
Phys. Rev. Let. 115, 091302

Search for Event Rate Modulation

- The first LXe TPC with more than one year of stable running conditions
- Temporal evolution of relevant detector parameters studied (02/2011-03/2012) → no significant correlation with event rate observed
- No evident peak crossing the 1σ global significance threshold!

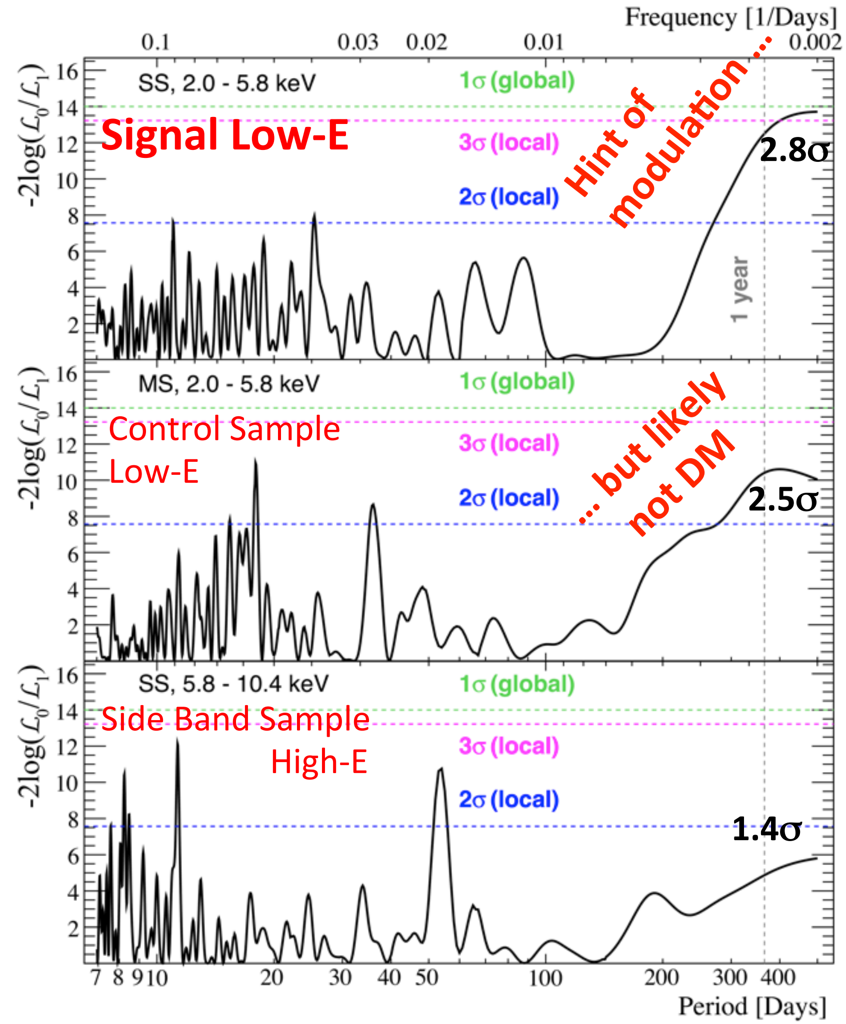
Discovery potential

Simulated Modulation



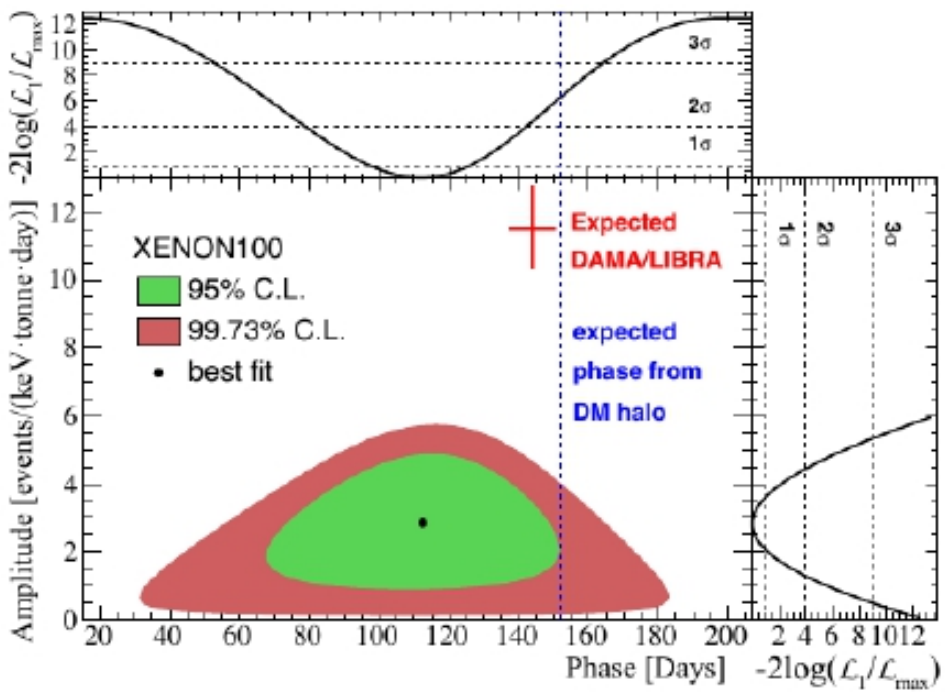
Phys. Rev. Let. 115, 091302

Compare periodic signal hypothesis to null hypothesis



Search for Event Rate Modulation

- The phase (112+-15) days (April 22) is not consistent with the standard halo model (June 2) at 2.5σ
- The amplitude is too small (only~25%) compared with the expected DAMA/LIBRA modulation signal in XENON100
- Interpretation of DAMA/LIBRA signal as electron recoils (axial-vector coupling) excluded at 4.8σ



Exclusion DAMA/Libra annual modulation: 4.8σ
Disfavor of modulation due to standard Dark Matter halo: 2.5σ

Phys. Rev. Let. 115, 091302

XENON1T

In Hall B of the Gran Sasso National Laboratory

XENON1T

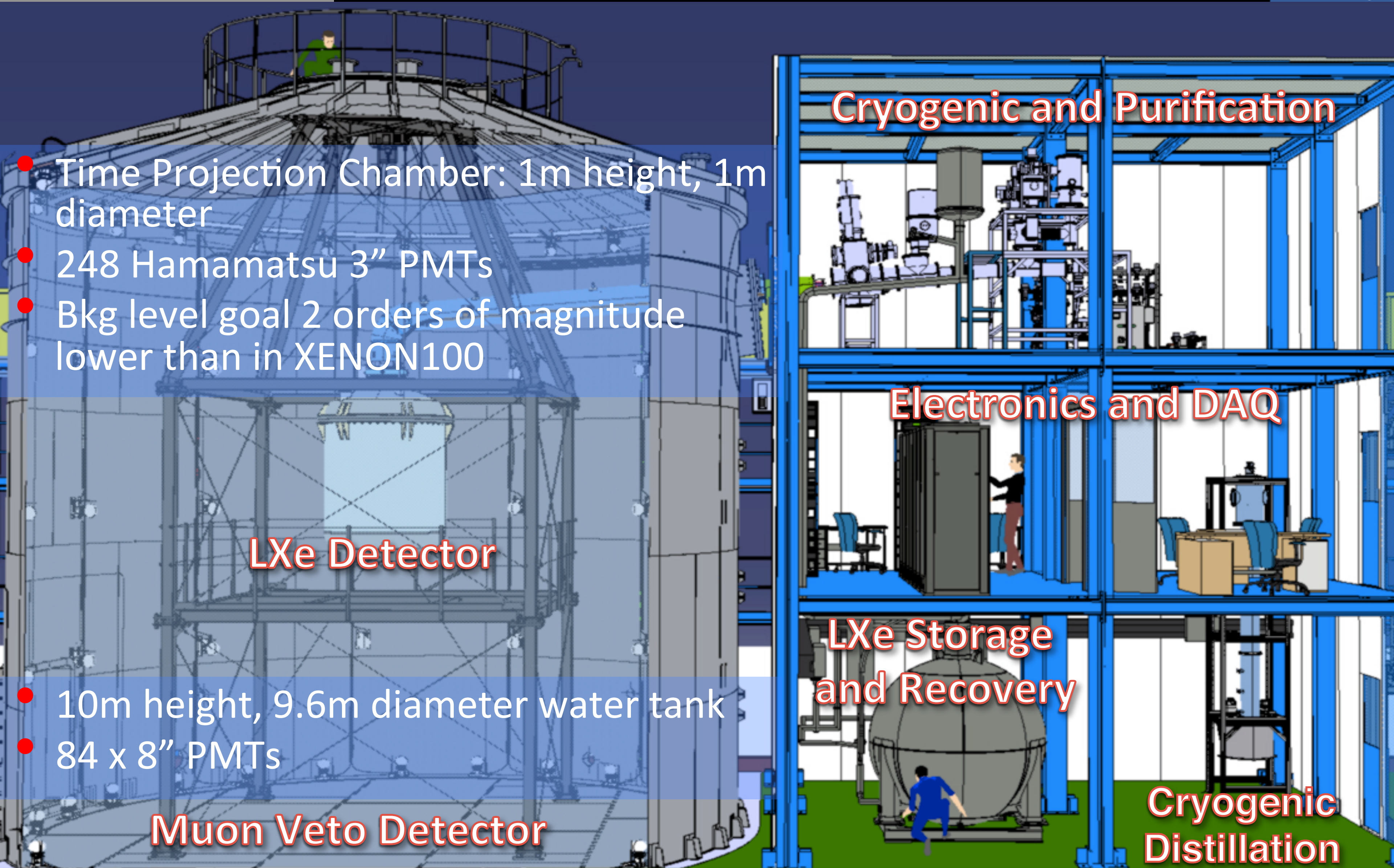
Hall B in July 2013

Two years later… Hall B in November 2015

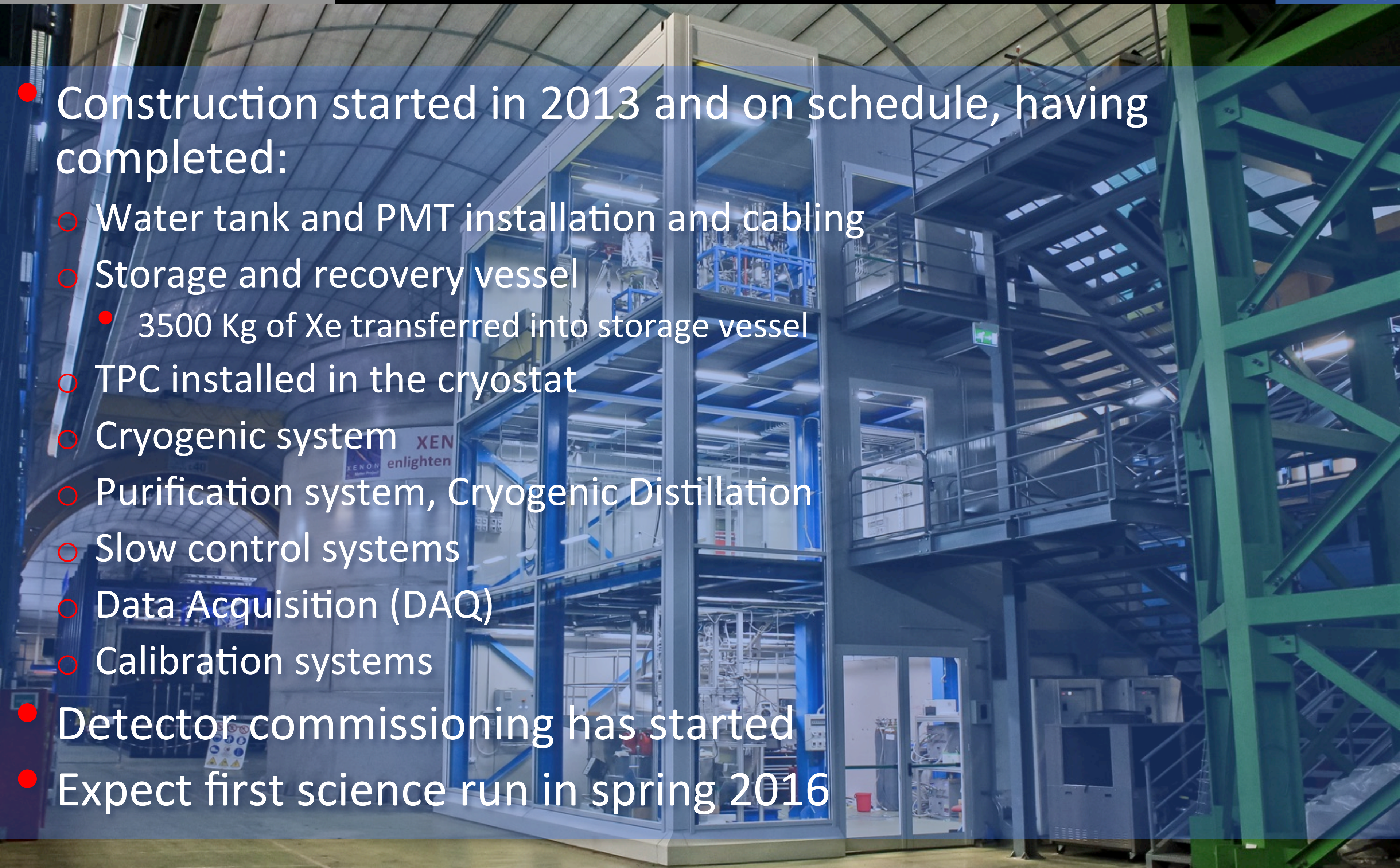
XENON1T SUBSYSTEMS

- Time Projection Chamber: 1m height, 1m diameter
- 248 Hamamatsu 3” PMTs
- Bkg level goal 2 orders of magnitude lower than in XENON100

- 10m height, 9.6m diameter water tank
- 84 x 8” PMTs



XENON 1T STATUS



- Construction started in 2013 and on schedule, having completed:
  - Water tank and PMT installation and cabling
  - Storage and recovery vessel
    - 3500 Kg of Xe transferred into storage vessel
  - TPC installed in the cryostat
  - Cryogenic system
  - Purification system, Cryogenic Distillation
  - Slow control systems
  - Data Acquisition (DAQ)
  - Calibration systems
- Detector commissioning has started
- Expect first science run in spring 2016

WATER SYSTEM AND CHERENKOV MUON VETO

Water System

Water Cherenkov Muon Veto

Goals

- Provide a “house” and clean water for an active shield around the LXe detector
- Provide access points and feedthroughs for water purification, calibration sources and detector leveling

Goal

Identify cosmic ray muons reaching the detector and their induced neutrons that are a source of background for XENON1T

Principle: detection of the passage of the muon or its secondary charged particles through the Cherenkov light they produce in a mass of pure water surrounding the cryostat

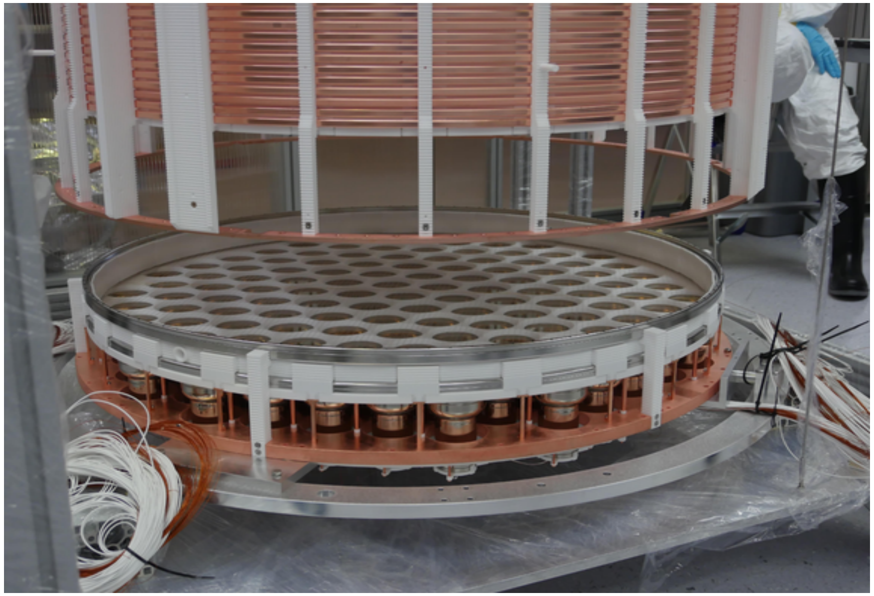
E. Aprile et al. (XENON Collaboration), JINST 9, P11006 (2014)

TIME PROJECTION CHAMBER

Goal

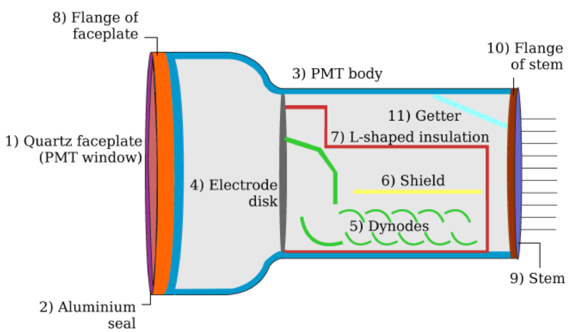
build a ultra-low-background two-phase XeTPC with the best performance for WIMP detection

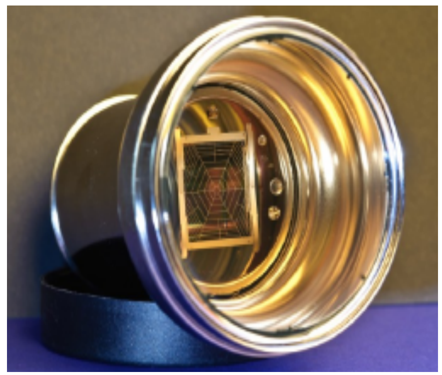
Design: The XENON1T TPC has the longest drift (~1 m) and largest active mass of LXe (~2000 kg) of any TPC built to-date

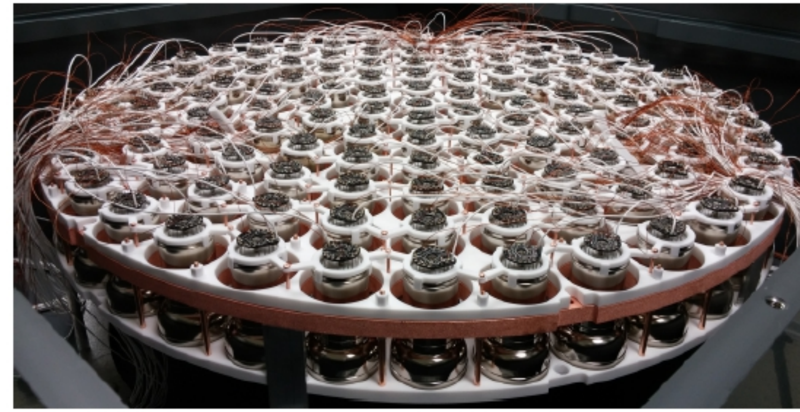


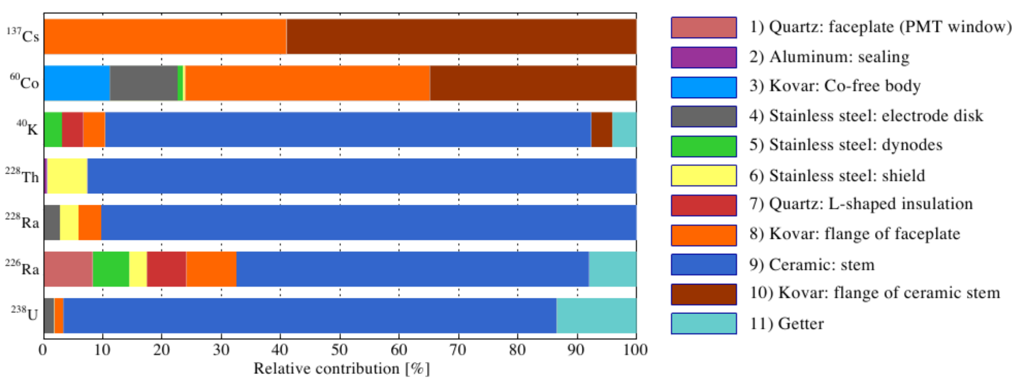
Goal

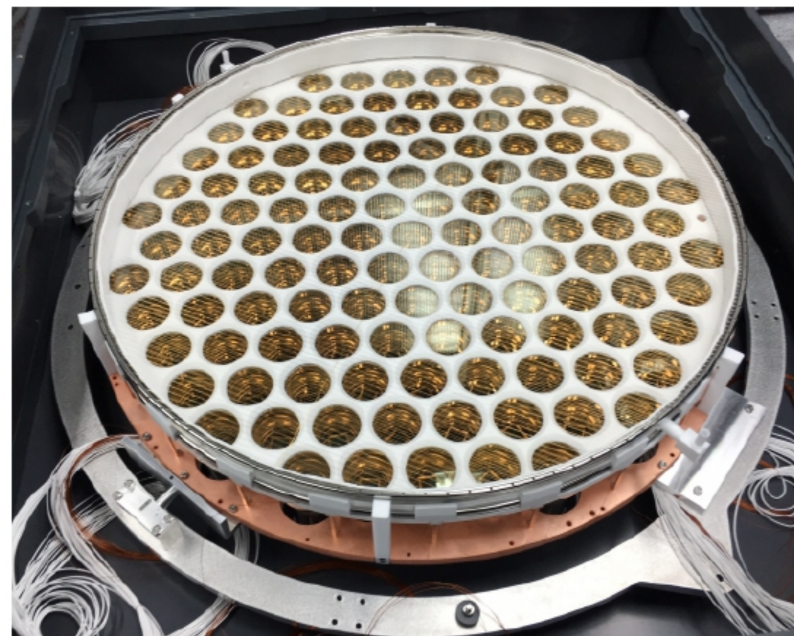
compact, low-radioactivity, high QE photomultipliers (Hamamatus R11410-21)









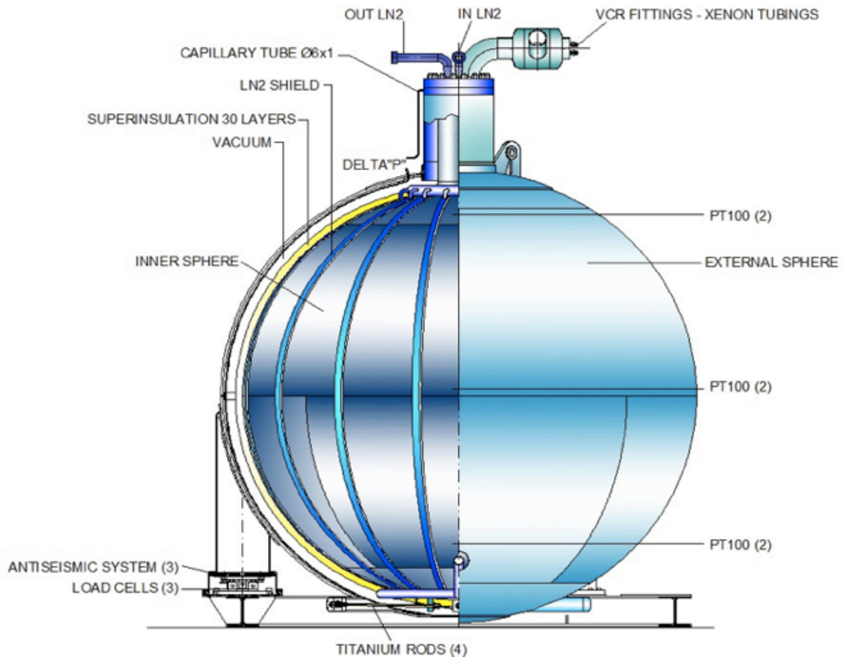


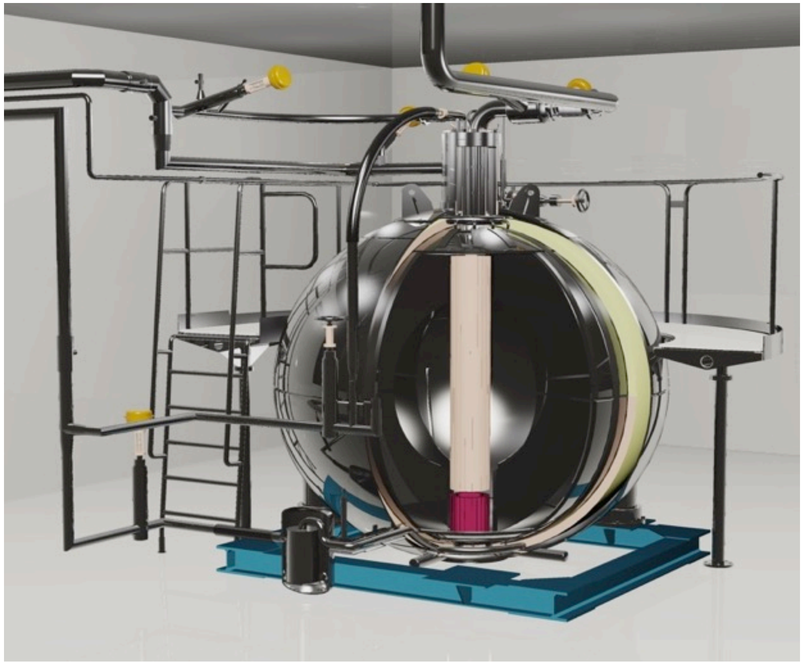
The overall background goal of XENON1T is < 1 event for an exposure of 2 ton per year

E. Aprile et al. (XENON), Eur. Phys. J. C75 (2015) 11, 546
arXiv:1503.07698

Goals

- Store up to 7600 kg of Xe in gaseous or liquid/solid phase under high purity conditions
- Fill Xe in ultra-high-purity conditions into detector vessel
- Recover all the Xe from the detector: in case of emergency all Xe can be safely recovered in a few hours



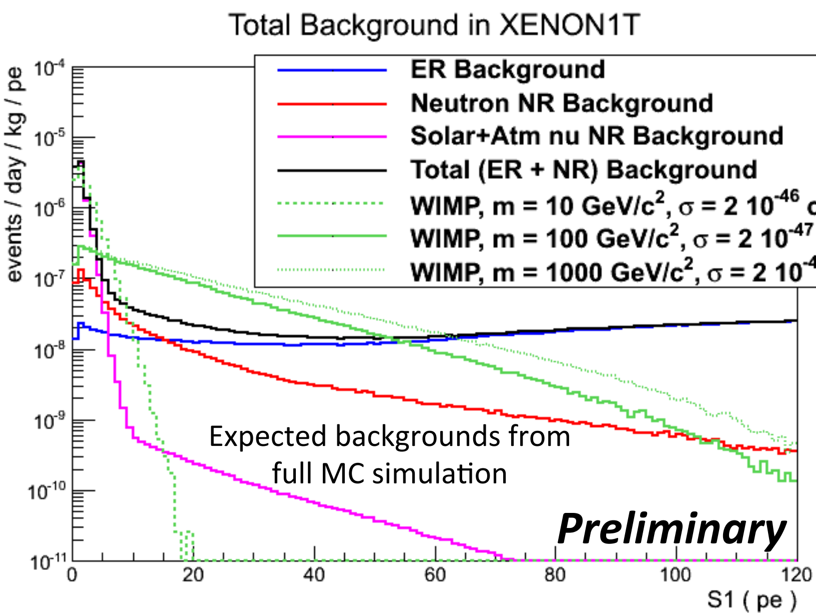


ReStoX Construction Phases

MONTE CARLO SIMULATION

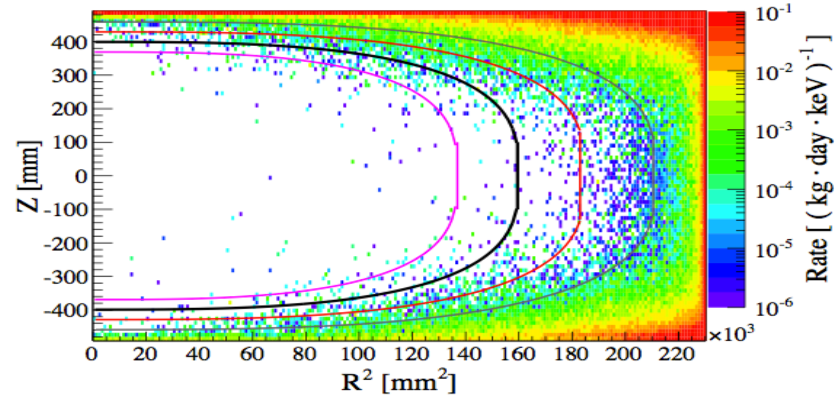
Goal

Reproduce via software the performance of the XENON1T detector, and predict the sensitivity of the experiment



1 ton fiducial volume
S1 in [3,70] PE
ER discrimination 99.75%
NR acceptance 40%

Position of the ER background from the materials ← they are negligible inside the 1 ton fiducial volume

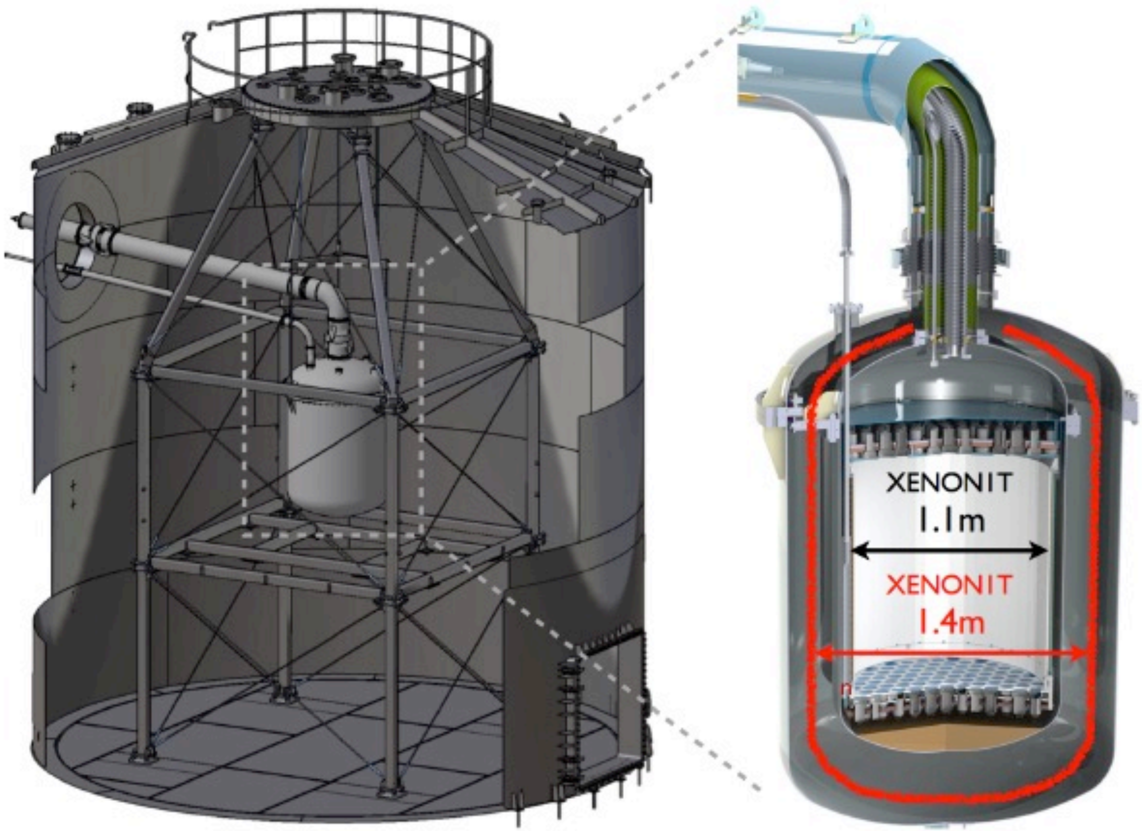


Method:

- Input from screening campaign by all detector components
- Monte Carlo simulation with GEANT4
- Statistical treatment

Source	Bkg (evts/ton/year)
ER (materials + intrinsic + solar ν)	0.32
NR from radiogenic neutrons	0.22
NR from ν coherent scattering	0.21
Total	0.75

XENON1T infrastructure already designed to host XENONnT

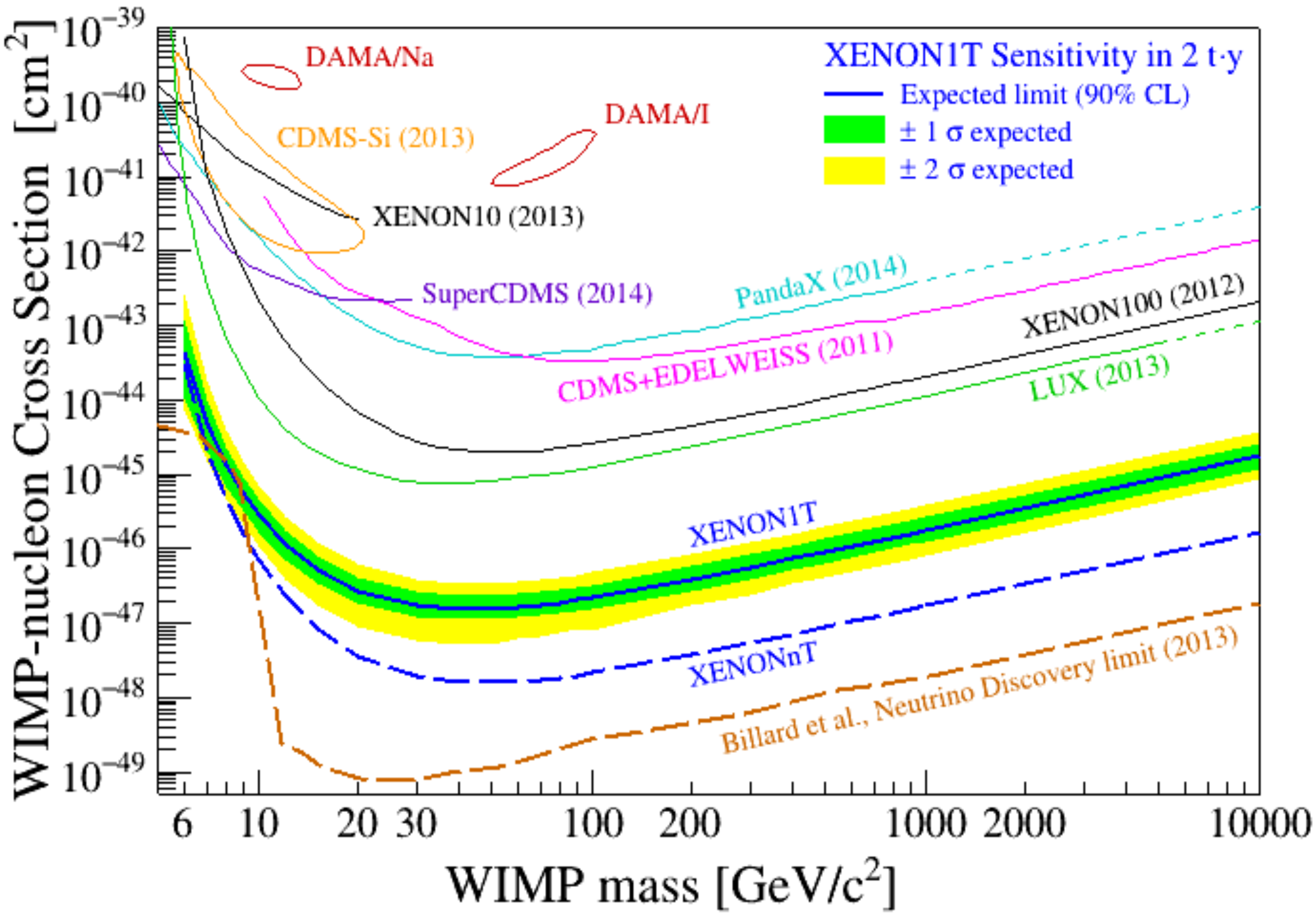


- Larger TPC and inner vessel
- ~ 200 additional PMTs
- 4 extra tons of LXe
  (7.5 t in total)

Projected to start in **2018**

Sensitivity:
$\sigma < 2 \cdot 10^{-48}$ **cm²**
for a 50 GeV WIMP

XENON1T- nT SENSITIVITY



XENON1T: Design sensitivity after 2 years of data taking → minimum x-sec: **$\sigma = 1.6 \times 10^{-47}$ cm^2** @ m = 50 GeV/c^2

XENONnT: improvement by one order of magnitude with 20 ton x year exposure

CONCLUSIONS

- The hypothesis that the **Dark Matter** is made of a new, heavy, neutral, stable and weakly interacting particle is well motivated by the expectation of new physics at the weak scale
- **Direct detection** plays a unique role in the search for WIMPs and is highly complementary to accelerator and indirect searches
- **Liquid Xenon** based experiments offer great sensitivity over a wide range of masses
- **XENON100** has reached its design sensitivity for medium-heavy WIMPs, and it probes other type of interactions
- ***XENON1T*** *is under commissioning* at LNGS & first science data for spring 2016→ if WIMPs are out there, XENON1T will be the first in line to discover them
- ***XENONnT*** *is proposed as a fast upgrade* to XENON1T, with a factor of 10 increase in sensitivity: observe an initial XENON1T signal with higher statistics, constrain WIMP properties

Xe
XENON
Dark Matter Project

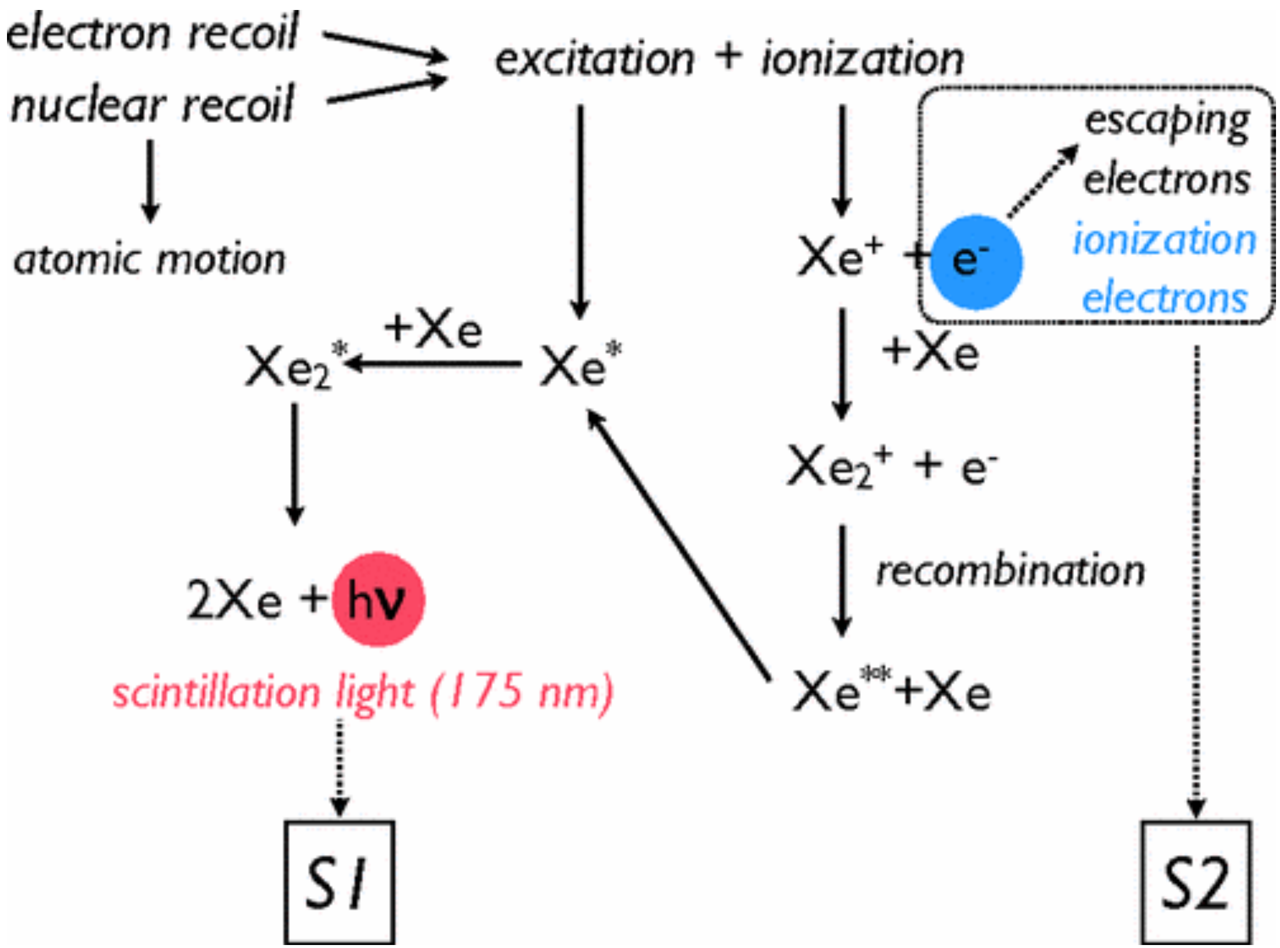
Thank you !

Subatech

Région PAYS de la LOIRE

BACKUP

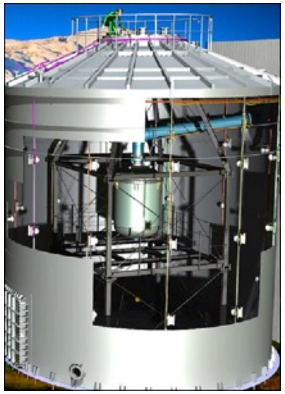
DOUBLE PHASE TIME PROJECTION CHAMBER



The number of free electrons liberated by a nuclear recoil is very small, because the bulk of the ionization electrons recombine within picoseconds.
Thus, under a high electric field, a nuclear recoil will yield a very small charge signal and a much larger light signal, compared to an electron recoil of the same energy.

The XENON Dark Matter Program

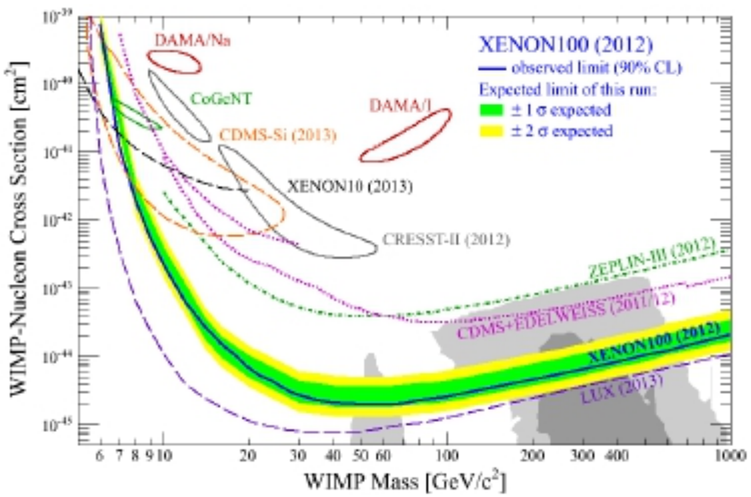
	XENON10	XENON100	XENON1T
total Xe mass	25 kg	161 kg	3.5 ton
TPC size	D=20cm, H=15 cm	D=30 cm, H=30 cm	D=100cm, H=100 cm
PMT	89, 1" PMTs	242, 1" PMTs	248, 3" PMTs
Kr/Xe	5 ppb	20 ppt	0.2 ppt
Rn/Xe	60 μBq/kg	65 μBq/kg	10 μBq/kg
ER bkg @ FV	~1 /keV/kg/day	5.3×10^{-3} /keV/kg/day	3.5×10^{-5} /keV/kg/day
LY @122keV,w/ E-field	3.0 PE/keV	2.3 PE/keV	4.6 PE/keV
σ_{SI} limit (cm^2)	4.5×10^{-44} @ 30 GeV Phys.Rev.Lett.100,021303 (2008)	2.0×10^{-45} @ 55 GeV Phys.Rev.Lett.109,181301(2012)	1.6×10^{-47} @ 50 GeV Projected (2017)



XENON100 DM SEARCH BENCHMARKS

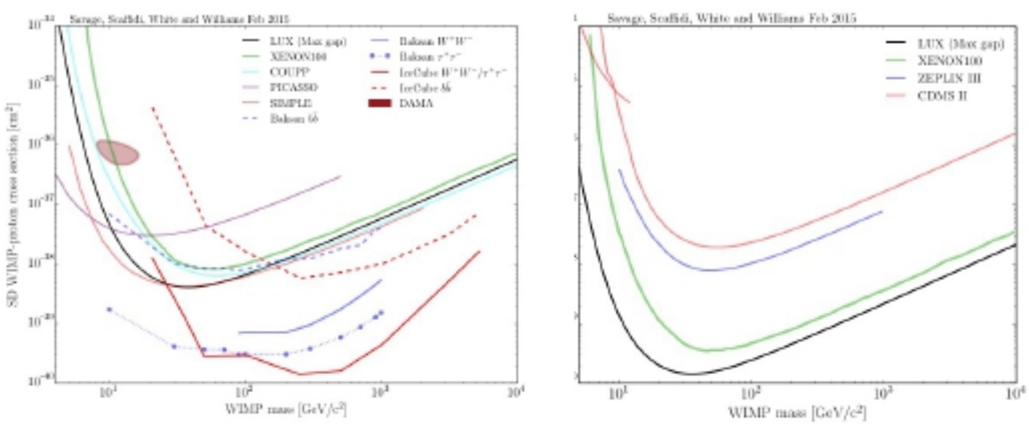
Spin-independent WIMP-nucleon coupling

Phys. Rev. Lett. 109, 181301 (2012)



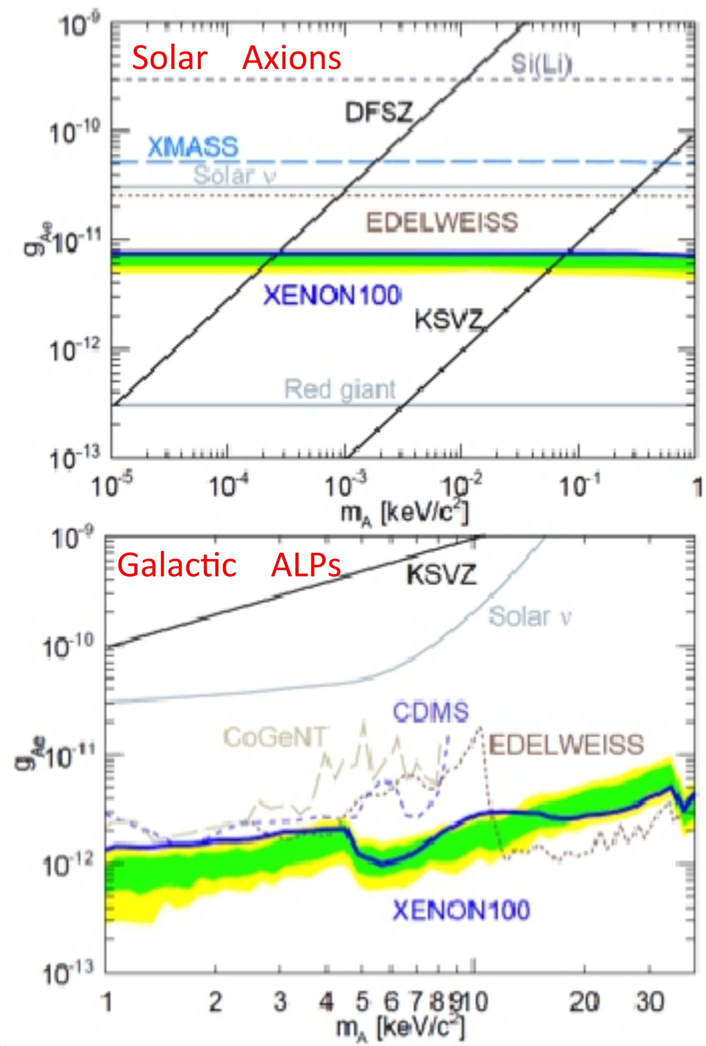
Spin-dependent WIMP-nucleon coupling

Phys. Rev. Lett. 111, 021301 (2013)



Axions and Axion-like Particles

Phys. Rev. D 90, 062009 (2014)



Search for Event Rate Modulation

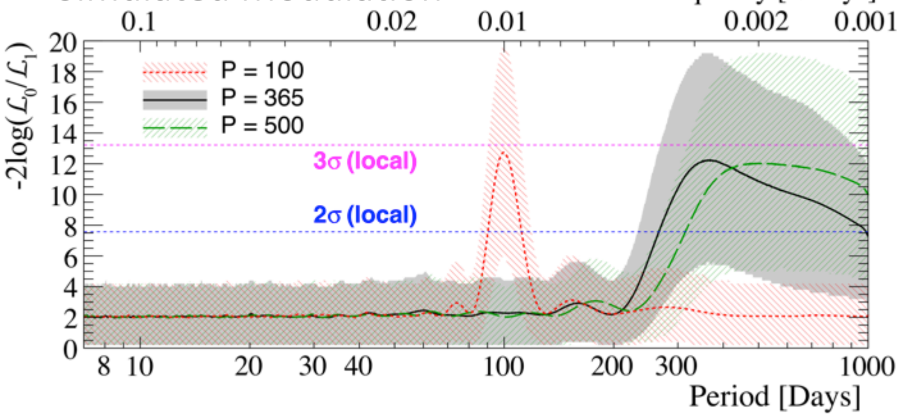
Event Rate ↓ — Acceptance ↘ — Bkg from known air leak ↙ — Modulation ↙

$$f(t) = \epsilon(t)\left(C + Kt + A\cos\left(2\pi\frac{(t-\phi)}{P}\right)\right)$$

$$\mathcal{L} = \left(\prod_{i=1}^{n}\tilde{f}(t_i)\right)\mathrm{Poiss}\left(n|N_{\mathrm{exp}}(E)\right)\mathcal{L}_\epsilon\mathcal{L}_K\mathcal{L}_E$$

Total observed events ↗ — Constraint terms

Simulated Modulation



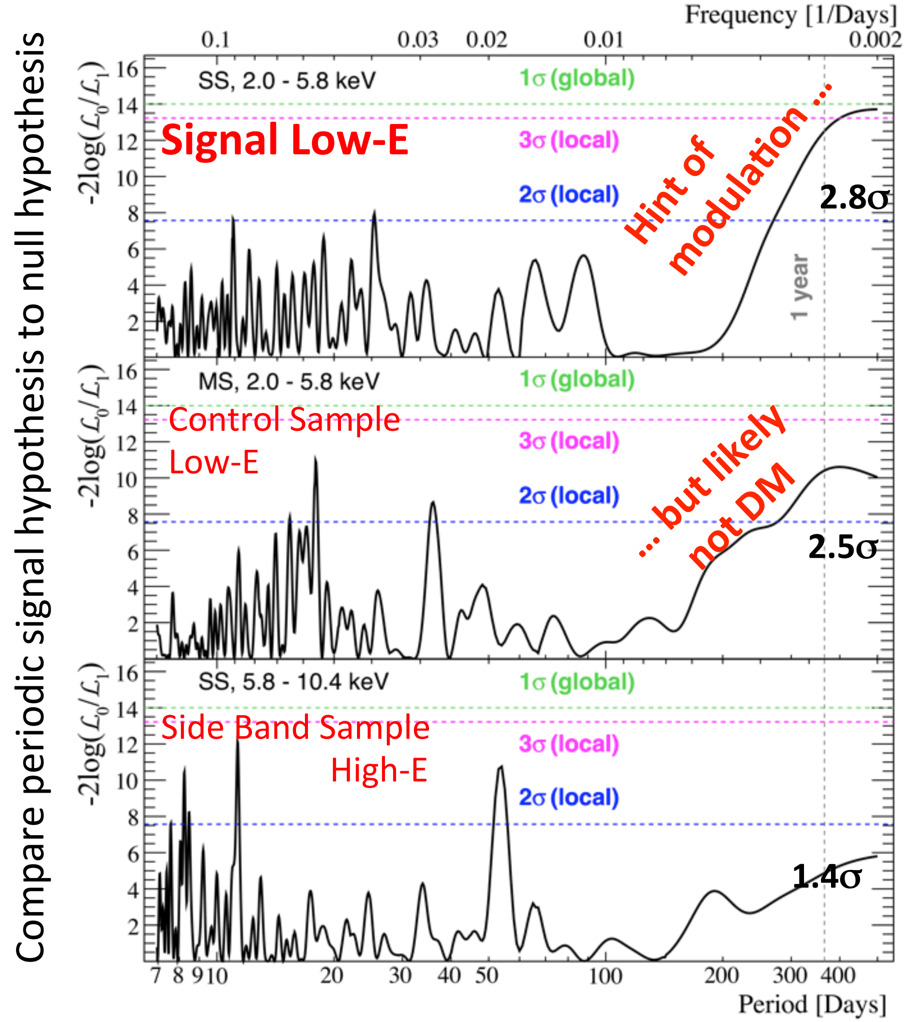
C_0 = 6.0 events/(keV tonne day)

C_1 = 5.5 events/(keV tonne day)

K = 2.54 x 10^{-3} events/(keV tonne day)/day

A = 2.7 events/(keV tonne day)

ϕ = 112 +-15 days

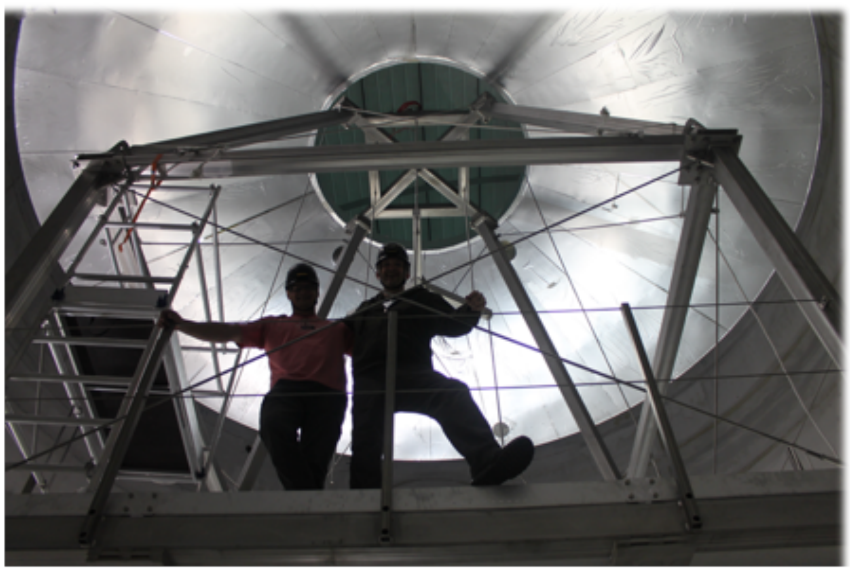


Phys. Rev. Let. 115, 091302

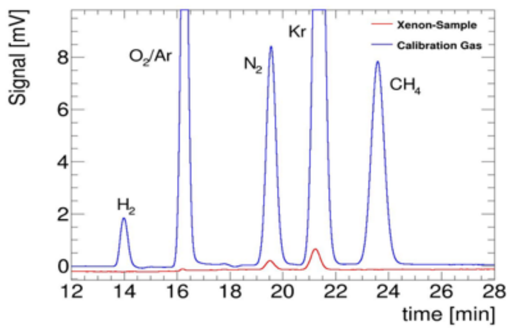
CRYOSTAT AND CRYOSTAT SUPPORT

Goal

a ultra-high-vacuum, thermally insulated system made of low-radioactivity material, to contain the detector with 3.5 tons of LXe at -95 °C and 2 bar pressure and to couple it to the cryogenics system outside the water shield



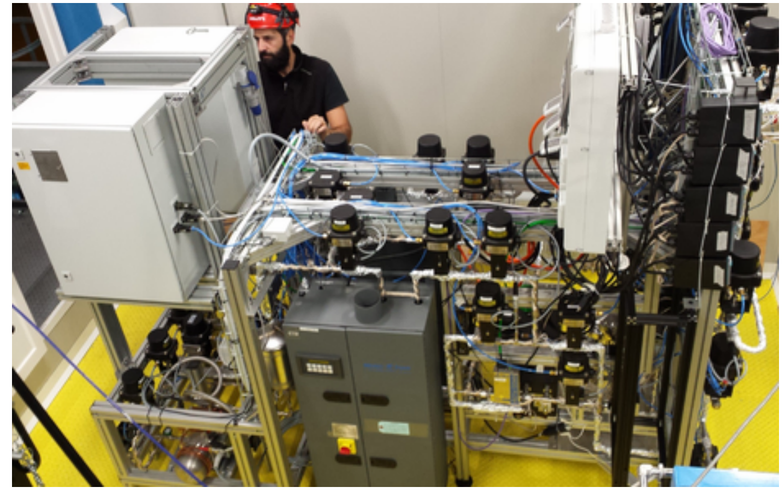
Gas handling and Impurity control



Goal

Measure impurities level of each cylinder of Xe gas prior to transferring into storage vessel (ReStoX) using a dedicated Gas Chromatograph

Purification system



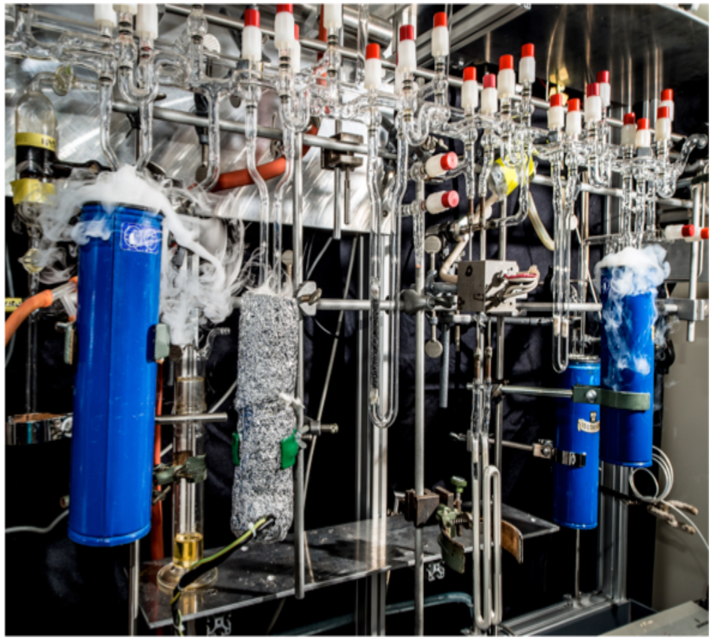
Goal

clean Xe from electronegative impurities via continuous circulation of gas through heated getters

Method: implement a high flow rate purification system (100 SLPM) with two parallel custom-developed pumps and two high capacity purifiers

RADON CONTROL AND MEASUREMENT AND DETECTOR CALIBRATION

Radon control measurement



Goals

- Select construction materials with low radon (^{222}Rn) emanation rate
- Implement measures to further reduce ^{222}Rn (alternative materials, surface cleaning procedures, etc.)
- Quantify and locate remaining ^{222}Rn sources

Detector Calibration

Goal

Accurately calibrate the detector response to electron and nuclear recoils

New (respect to XENON100)
usage of internal sources and a neutron generator

CRYOGENIC SYSTEM AND DISTILLATION COLUMN

Cryogenic system

Goals

liquefy 3500 Kg of Xe and maintain the Xenon in the cryostat in liquid form, at a constant temperature and pressure, and so for years without interruption

Cryogenic Distillation Column

Goal

Active removal of Kr contamination in Xe

Principle: cryogenic distillation based on improved package column uses the 10 times higher vapor pressure of Kr w.r.t. Xe at -95°C to reach $^{Nat}Kr/Xe < 0.2$ ppt for XENON1T

First results:

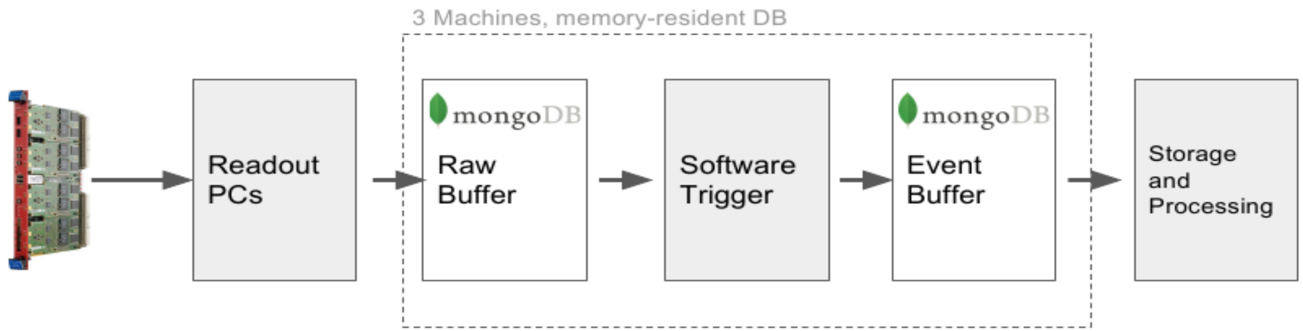
Purified liquid out:

$^{Nat}Kr/Xe < 0.026$ ppt (90% c.l.)

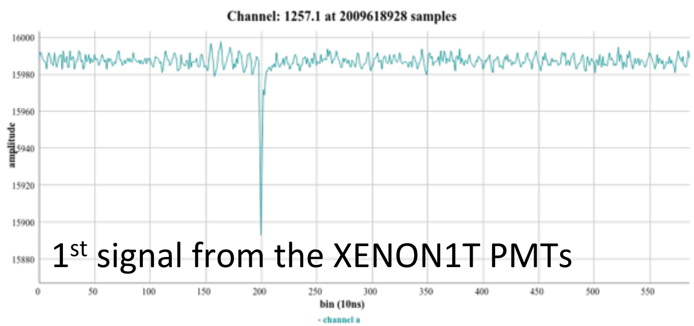
A factor ~10 better than required for XENON1T!

S. Rosendahl et al., JINST 9 (2014) P10010
E. Brown et al., JINST 8 (2013) P02011
S. Rosendahl et al., Rev. Sci. Instr. 86 (2014) 115104

Data Acquisition (DAQ) and Computing System



Data Acquisition



Goals

- lowest possible threshold
  →achieved by a trigger-less readout combined with a computer-based online trigger
- high data throughput (1200 MB/s)
  →achieved through parallelization and an online veto system

Computing system

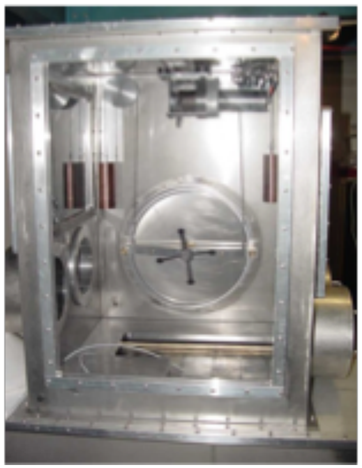
Goals

- Providing enough computing facilities to process raw data and to allow data analysis by all Collaboration members
- Development and use of sharing resources

Material screening and selection

Goal

Improve radio purity of all materials used in XENON1T detector by screening and selection: all relevant components of the cryostat and the TPC have been measured



GeMPI-1, LNGS

GeMPI-4, LNGS

GIOVE, MPIK

GATOR at LNGS

LNGS screening facility

Method

- multiple facilities available to Collaboration
- 200 samples measured with gamma spectroscopy and ~40 samples with mass spectroscopy

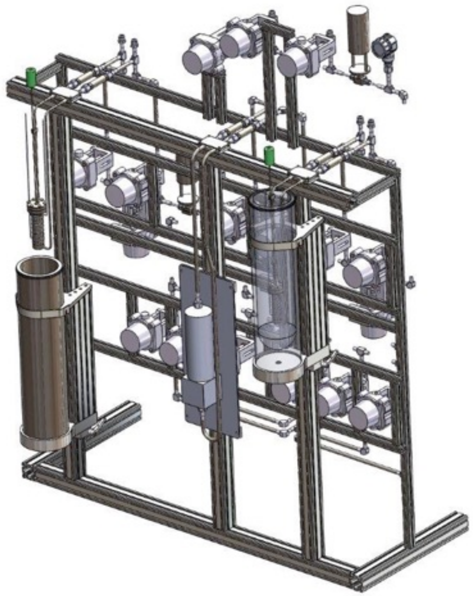
How do we increase sensitivity?

Lower the backgrounds!

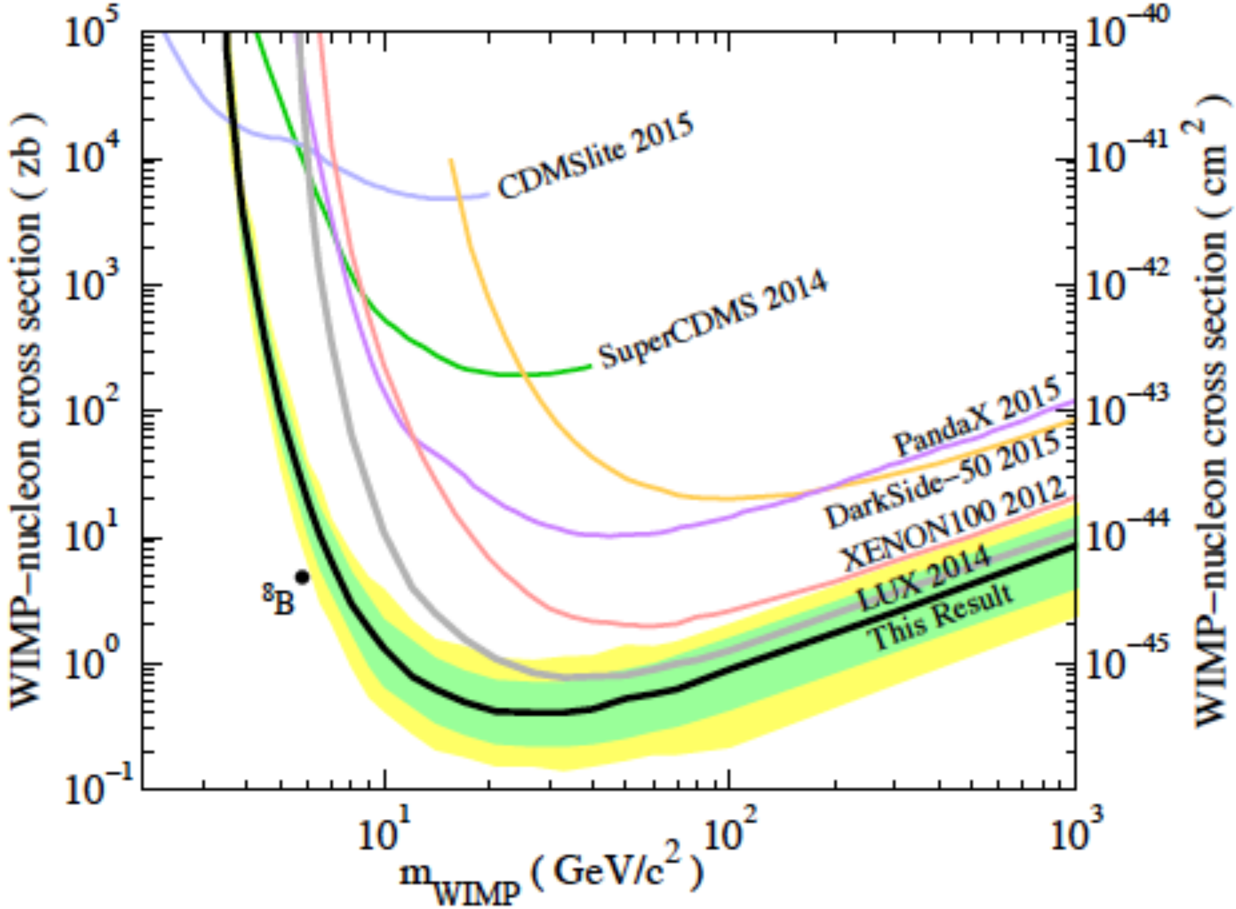
- **less radon** (Rn/Xe separation; Rn slowed down in adsorber and decays; boil-off purification -> lower vapour pressure of Rn compared to Xe)
- **increased exposure** and the larget detector (better self shielding)
- **less krypton** (use XENON1T krypton purification column)
- **lower radioactivity of materials** (use world's best HPGe detectors for screening/ selection)

Direct measurement of emanated 222Rn

- sensitivity 30 μBq
- automated system
- high sample throughput
- increased reproducibility
- systematic investigation of 222Rn sources
- system under construction at MPIK
- Commissioning Feb 2016



MOST RECENT LUX RESULTS



arXiv:1512.03506v1