Direct Dark Matter search with the XENON Project

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Università di Bologna
11/12/2015

[redacted]

Problem with the Projector?

No…

Simply the Universe is Dark!

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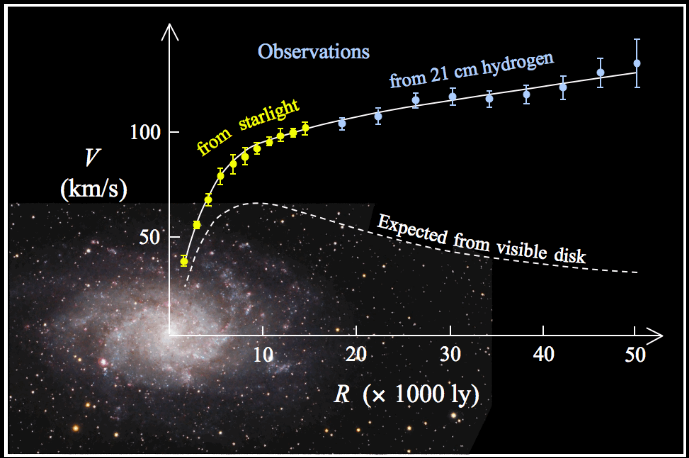
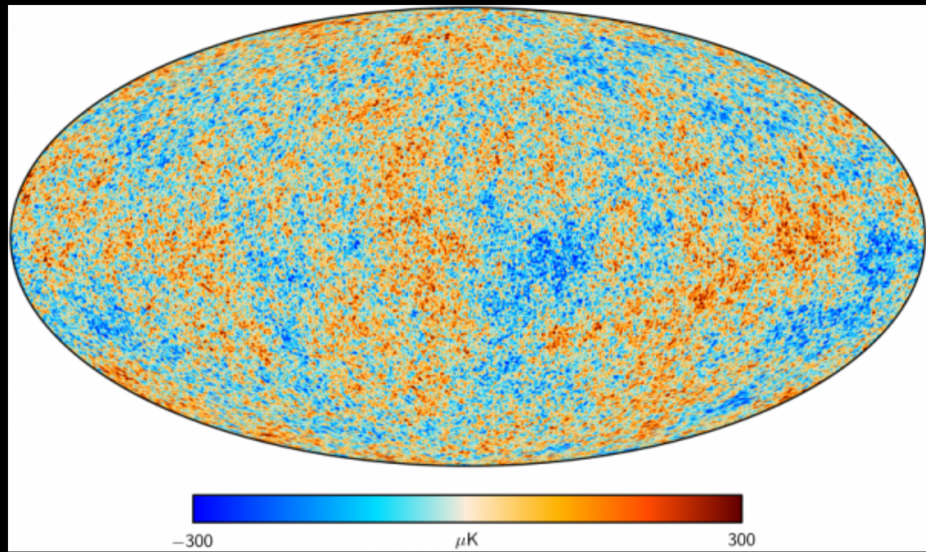
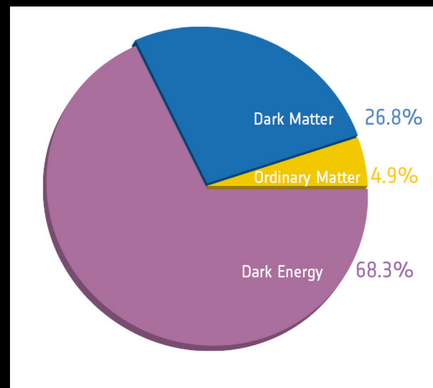
Simply the Universe is Dark!

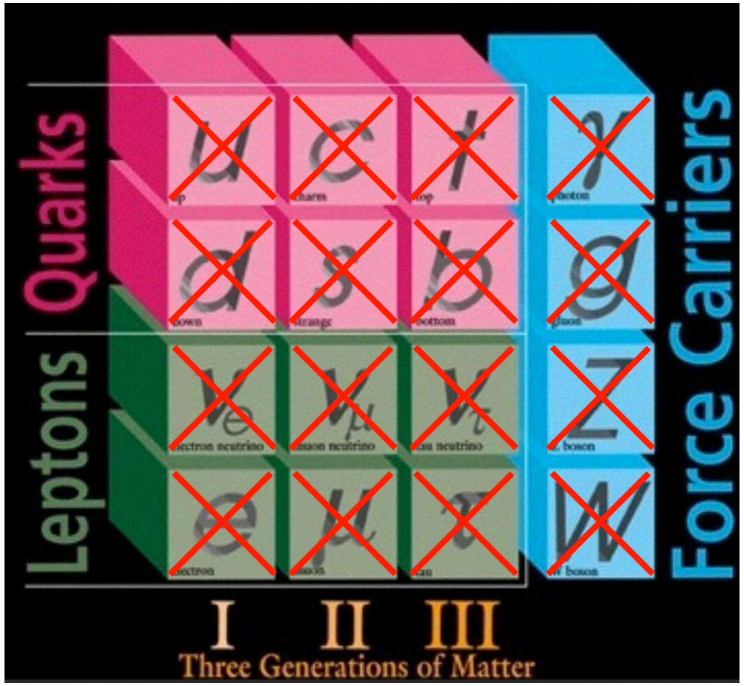




~90% of the matter of the Universe
is of unknown type



Dark Matter properties



Best evidence for new physics beyond Standard Model

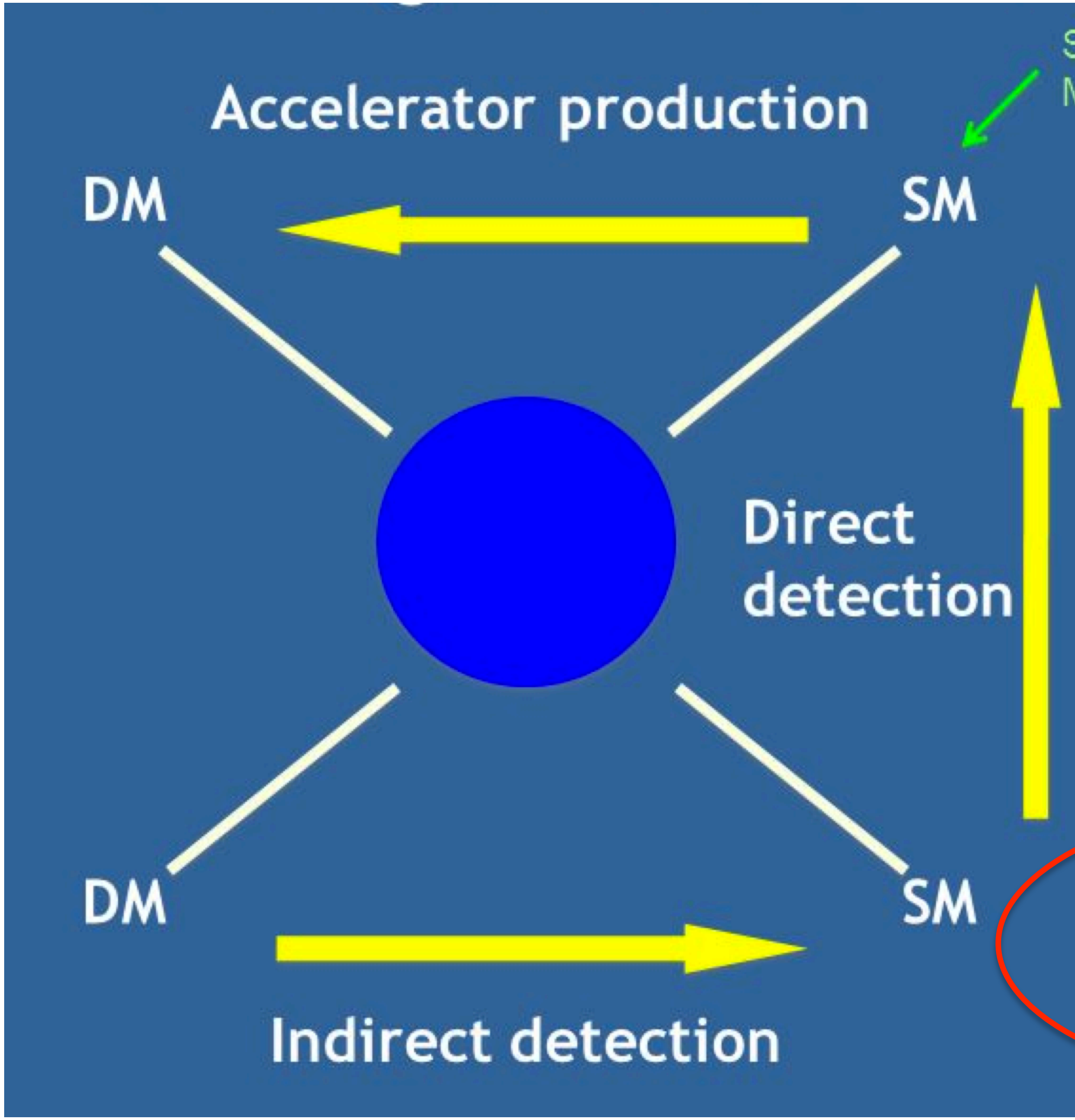
So far, we mostly have "negative"
Constraints from astrophysics and searches for new particles:

- No colour charge
- No electric charge
- No strong self-interaction
- Stable (or very long-lived)

Masses & interaction cross sections span an enormous range

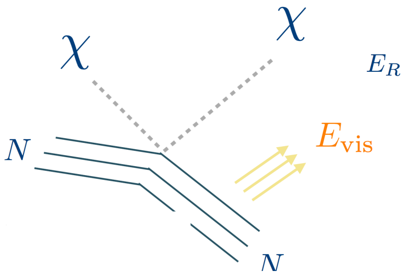
- Most dark matter experiments optimised to search for WIMPs
- However also searches for axions, ALPs

Dark Matter detection tecniques



- Production in accelarators (LHC)
- Indirect detection:
  - search for annihilation/decay products of χ's (self-antiparticle)
- Direct detection:
  - χ-nucleus elastic scattering

DM (WIMP) Direct Detection



$$\frac{dR}{dE_R} = N_N \frac{\rho_0}{m_W} \int_{\sqrt{(m_N E_{th})/(2\mu^2)}}^{v_{max}} dv\, f(v)\, v \frac{d\sigma}{dE_R}$$

Detector physics

N_N, E_{th}

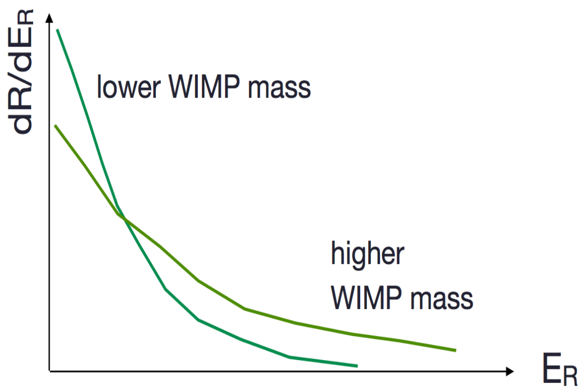
Particle/nuclear physics

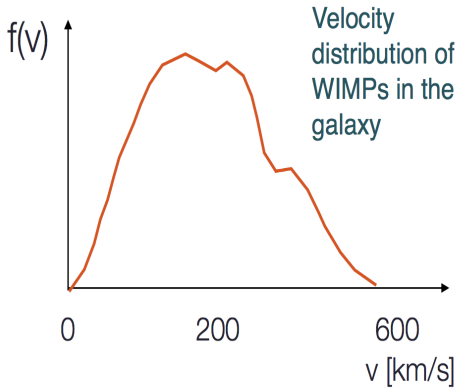
$m_W, d\sigma/dE_R$

Astrophysics

$\rho_0, f(v)$

$$\rho(R_0) = 0.2 - 0.56\,\mathrm{GeV\,cm^{-3}}$$





In general, interactions leading to WIMP-nucleus scattering are parameterized as:

- scalar interactions (Spin Independent)
- spin-spin interactions (Spin Dependent)

....other terms in the formulas

Expected interaction rates

- For a typical WIMP mass of 100 GeV/c^2, the expected WIMP flux on Earth (for the 'standard local density' value) is:

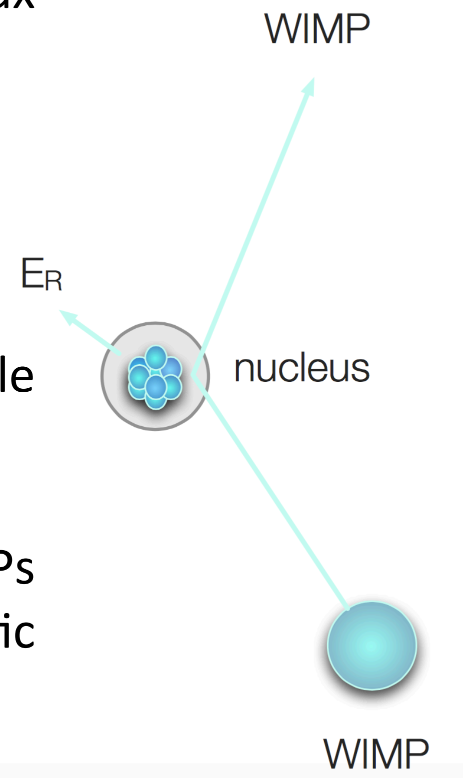
$$\phi_\chi = \frac{\rho_\chi}{m_\chi} \times \langle v \rangle = 6.6 \times 10^4\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

- Flux sufficiently large to have a small but potentially measurable fraction of elastic scatter in a detector

- Direct dark matter detection experiments aim to detect WIMPs via nuclear recoils which are caused by WIMP-nucleus elastic scattering

- Assuming a scattering cross section of 10^{-38} cm^2, the expected rate (for a nucleus with atomic mass A = 100) would be:

$$R = \frac{N_A}{A} \times \phi_\chi \times \sigma \sim 0.13\,\mathrm{events\,kg}^{-1}\mathrm{yr}^{-1}$$

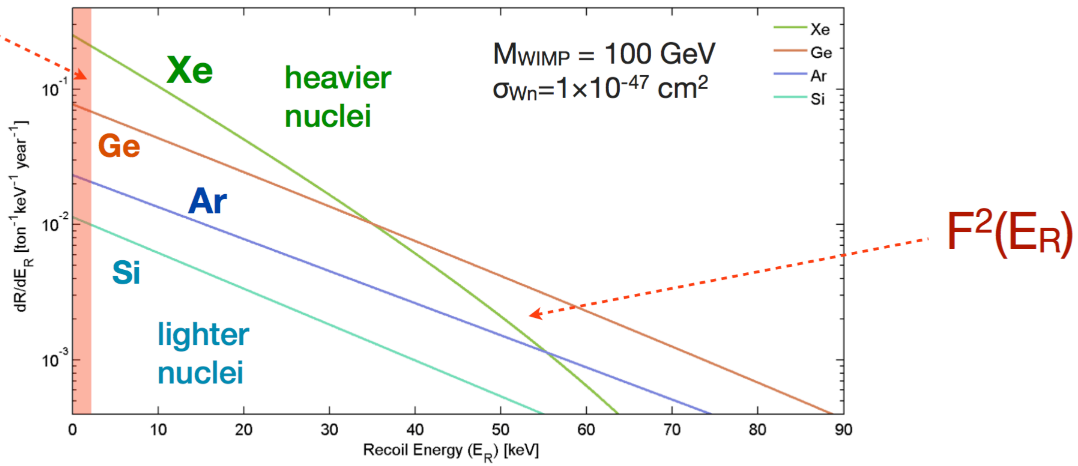


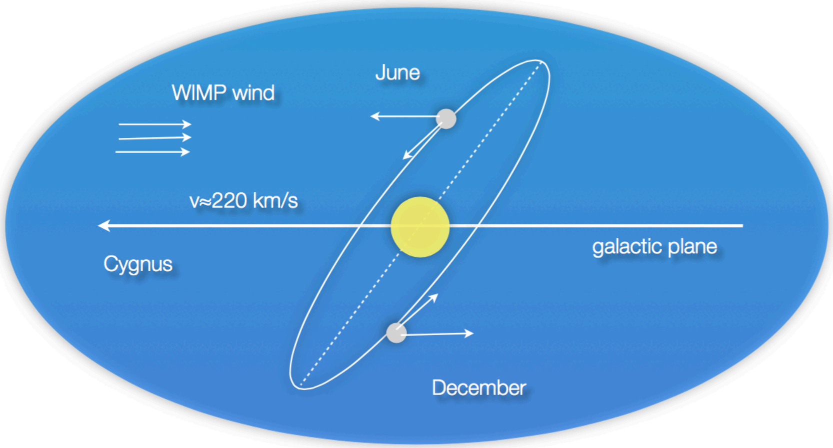
Expected interaction rates

$$R \sim 0.13 \frac{\text{events}}{\text{kg year}} \left[\frac{A}{100} \times \frac{\sigma_{WN}}{10^{-38}\,\text{cm}^2} \times \frac{\langle v \rangle}{220\,\text{km}\,\text{s}^{-1}} \times \frac{\rho_0}{0.3\,\text{GeV}\text{cm}^{-3}} \right]$$

$$v_{min} = \sqrt{\frac{m_N E_{th}}{2\mu^2}}$$

Rate and shape of recoil spectrum depend on target material





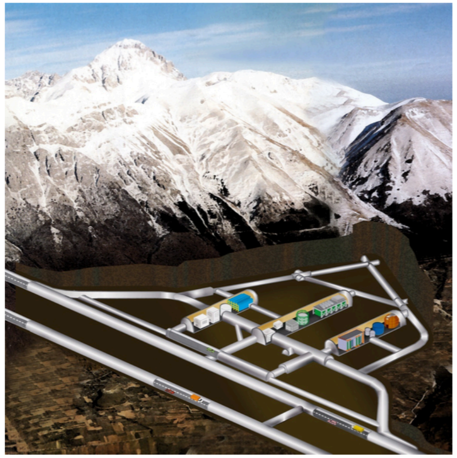
Possible signature:
Motion of the Earth causes annual event rate modulation: June – December asymmetry ~ 2-10%

Special care of backgrounds

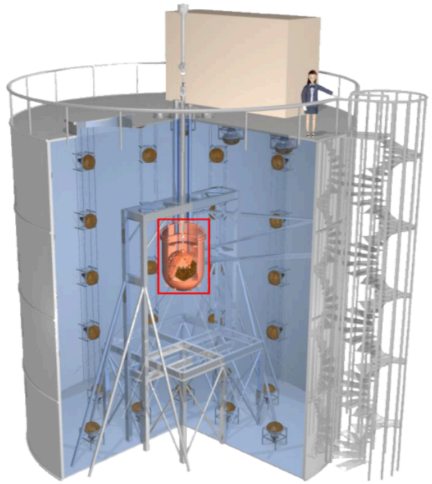
- Cosmic rays & cosmic activation of detector materials
- Natural (^{238}U, ^{232}Th, ^{40}K) & anthropogenic (^{85}Kr, ^{137}Cs) radioactivity: γ, e^-, n, α
- Ultimately: neutrino-nucleus scattering (solar, atm. and SN ν)

How to deal With backgrounds

- Go deep underground

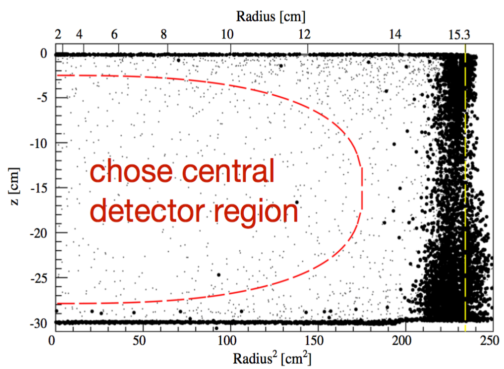


- Use active shields

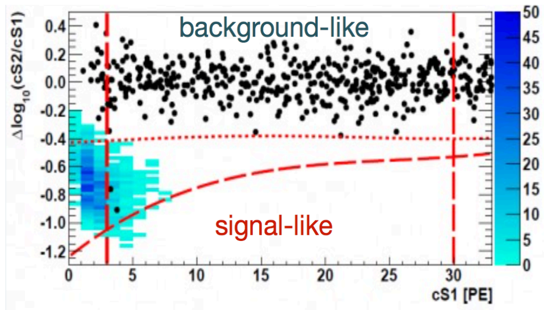


- HPGe material screening

- Fiducialization

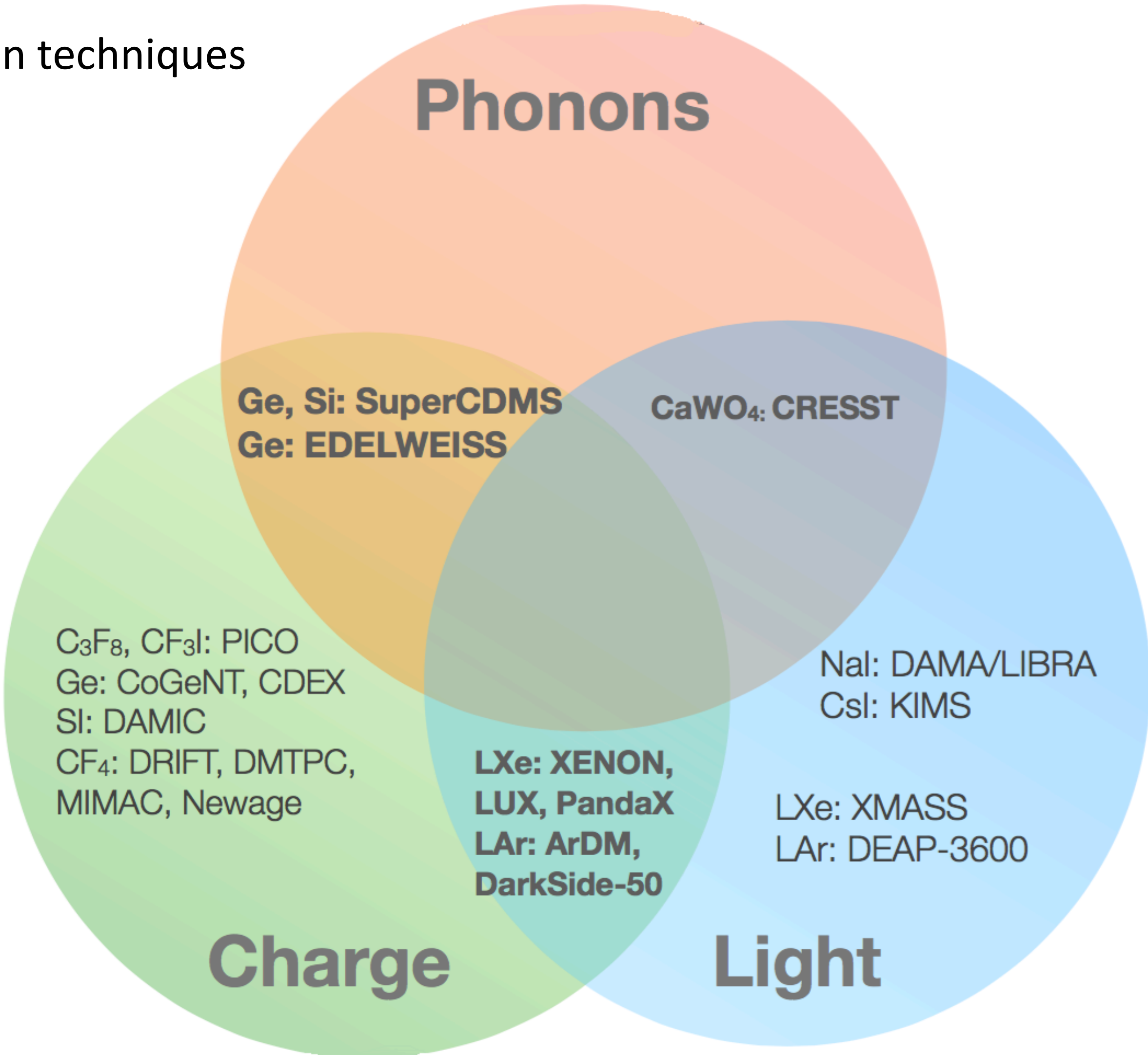


- Discrimination

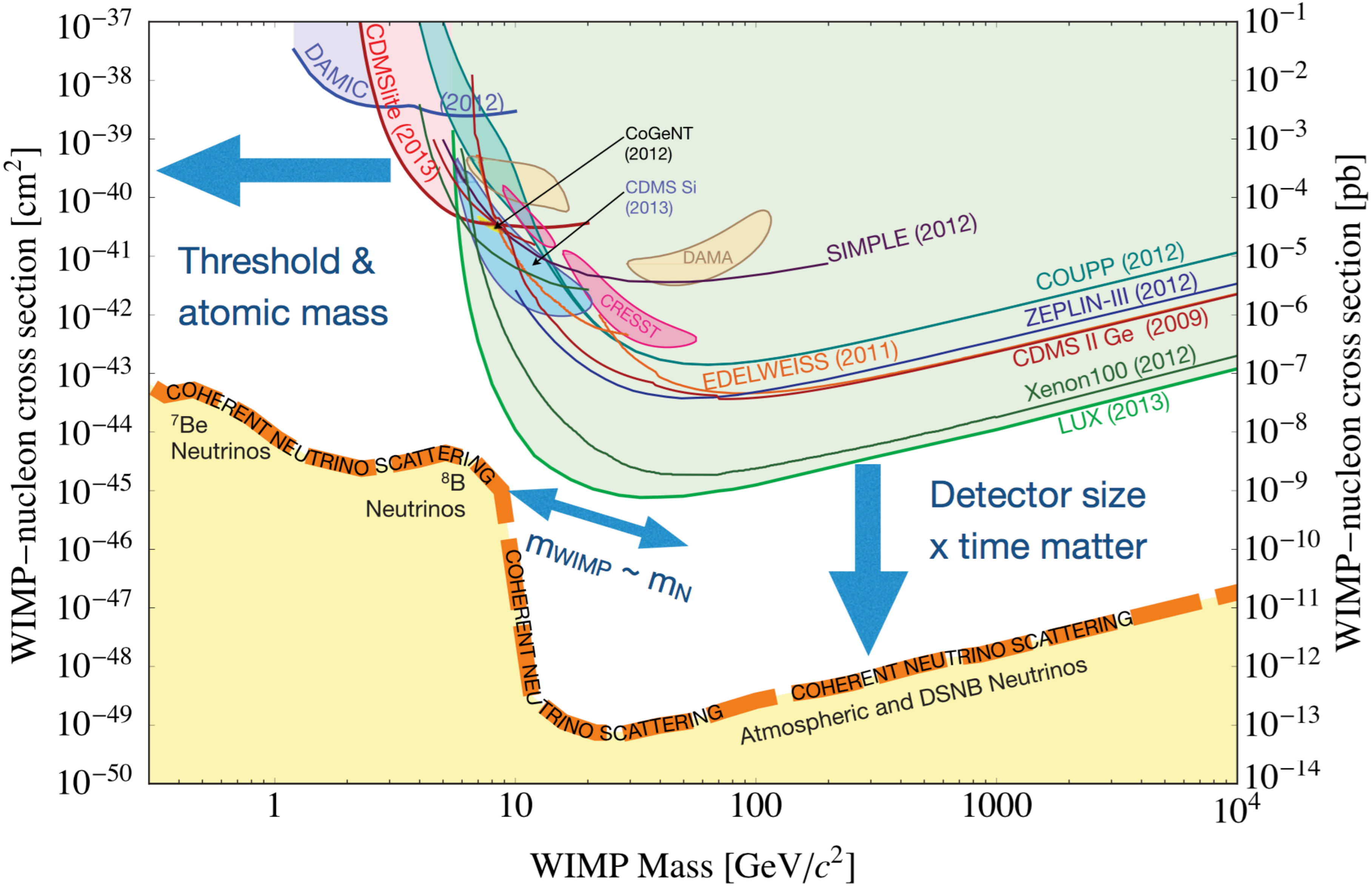


Dark Matter
direct detection techniques

Many Detection techniques



WIMP Landscape today



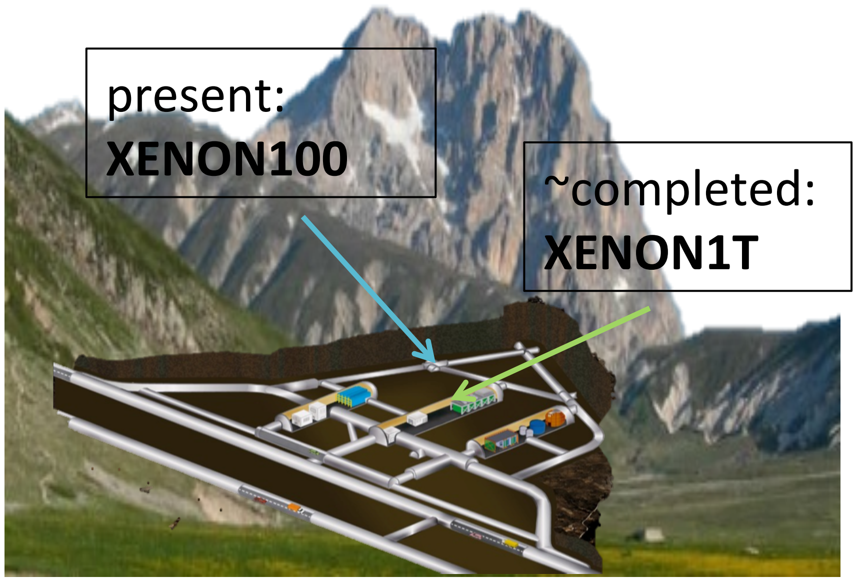
A direct DM search program:XENON

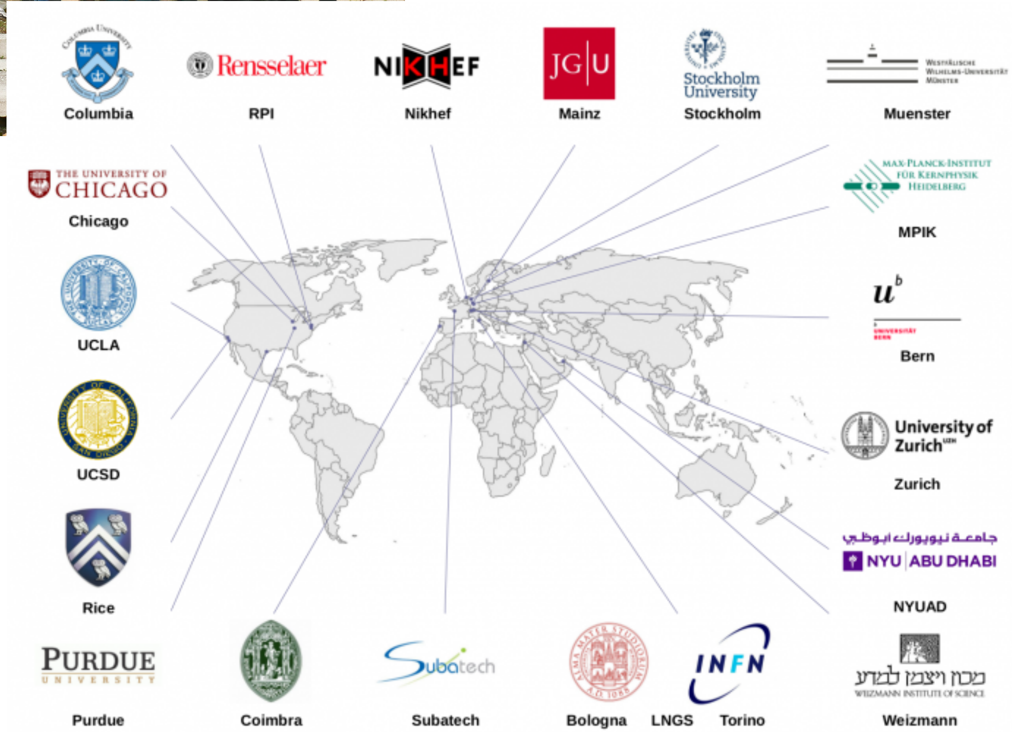
The XENON Collaboration

More than

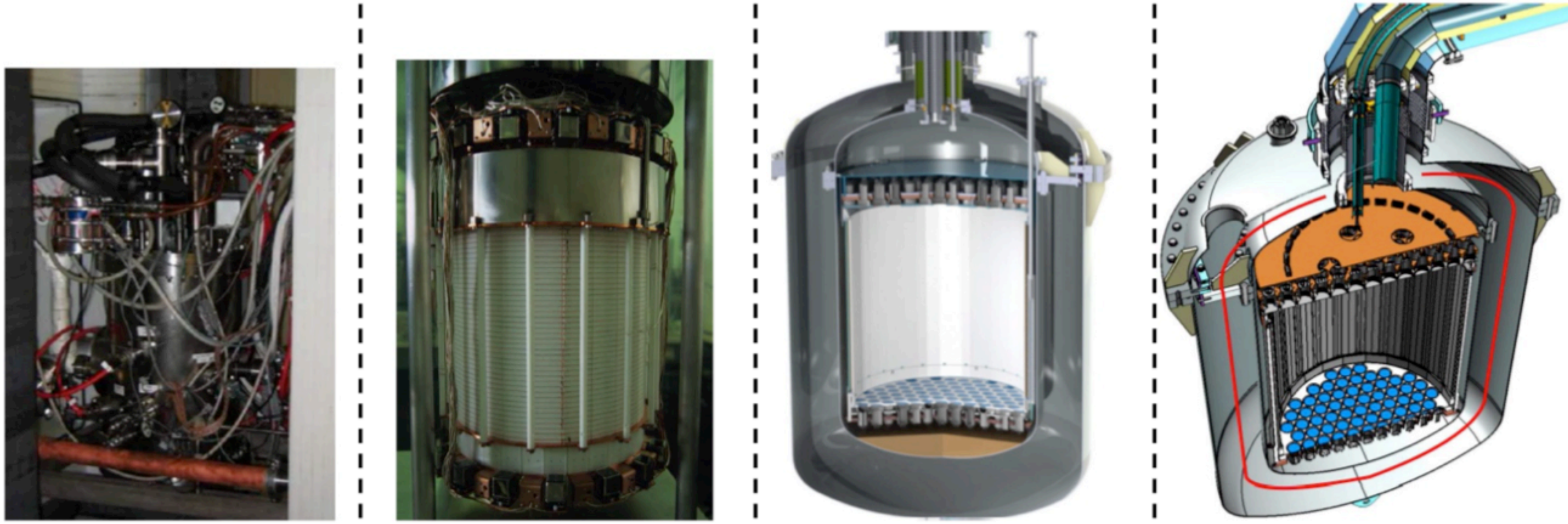
100 scientists

from 21 Institutions





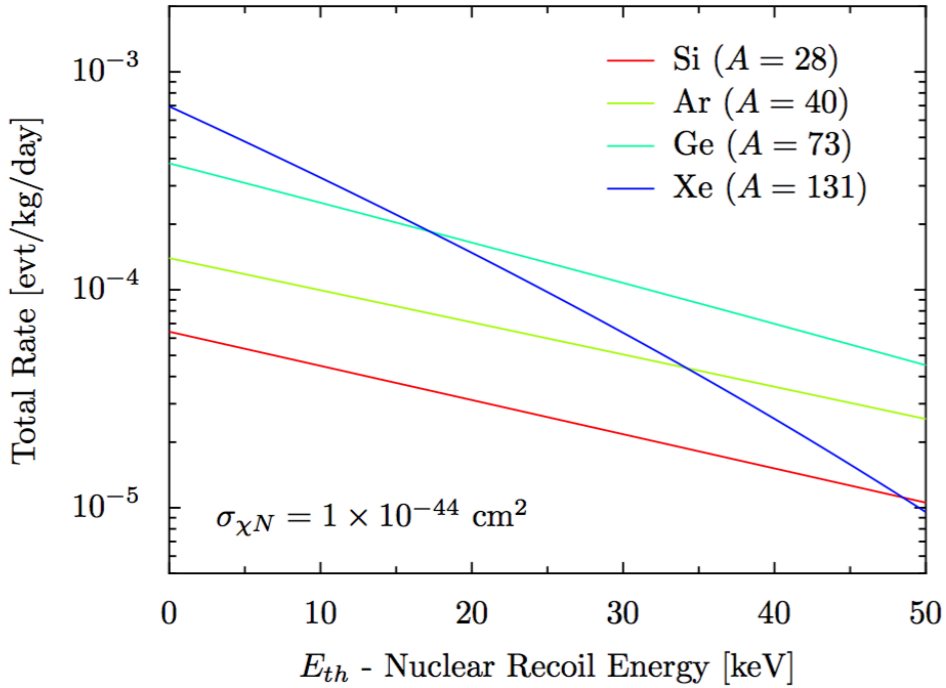
The XENON Program



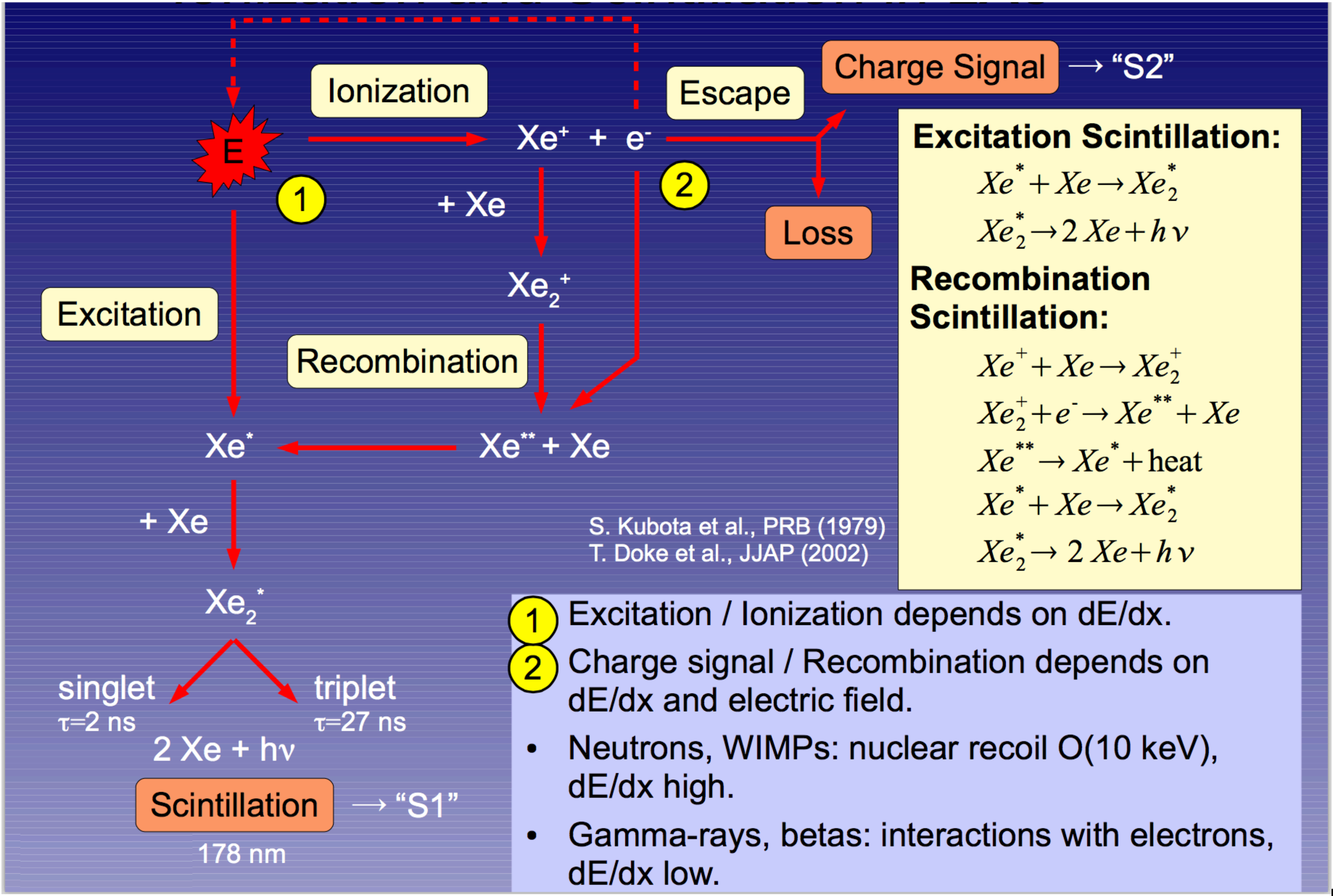
	XENON10	XENON100	XENON1T	XENONnT
Time	2005	2009	2015	2018+
Total mass	21 kg	161 kg	3300 kg	~7000 kg
WIMP-nucleon cross section [cm^2]	$<8.8 \times 10^{-44}$	$<2 \times 10^{-45}$	$\sim<2 \times 10^{-47}$	$\sim<2 \times 10^{-48}$

Why we use Xenon?

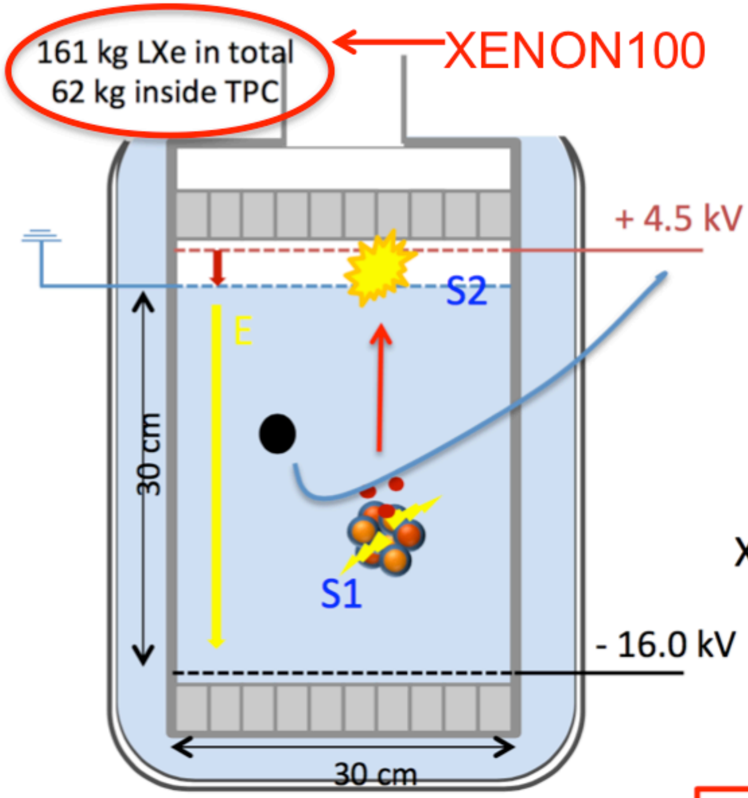
- *Large mass number A (131)*
- *50% odd isotopes (^{129}Xe, ^{131}Xe) for SD interactions*
- *No long-lived radioisotopes, Kr can be reduced to ppt levels*
- *High stopping power, i.e. active volume is self-shielding*
- *Efficient scintillator (178 nm)*
- *Scalable to large target masses*
- *Electronic recoil discrimination with simultaneous measurement of scintillation and ionization*



Light & Charge in Xenon

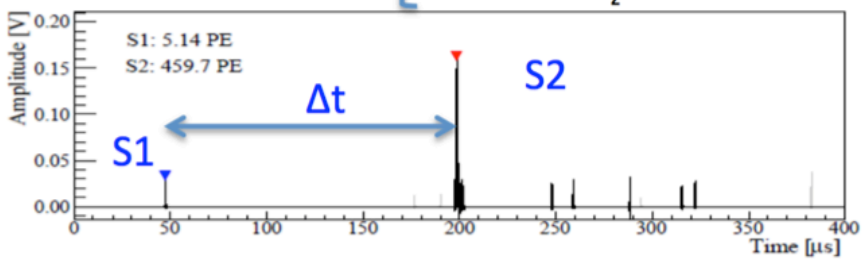


How we use it…



Z: $z(dt) = v_{drift} \times dt$; $v_{drift} \approx 1.74$ mm/μs

Resolution $\sigma_z < 0.3$ mm



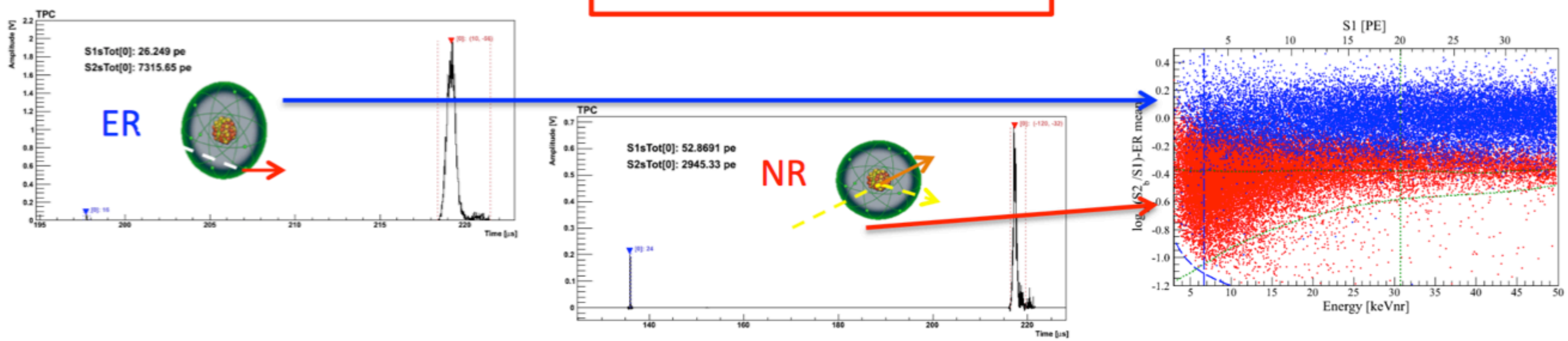
X-Y:

Computed and cross-checked by
- Neural network algorithm
- χ^2 minimization
- Support Vector Machine

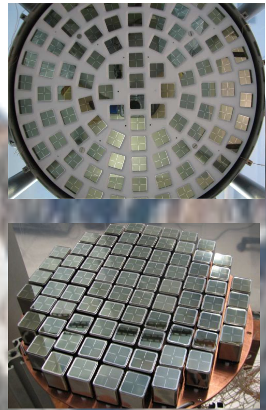
Resolution $\sigma_{X,Y} < 3$ mm

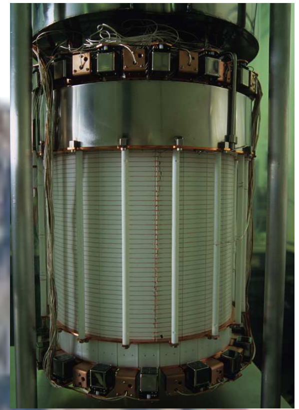
PMTs top array

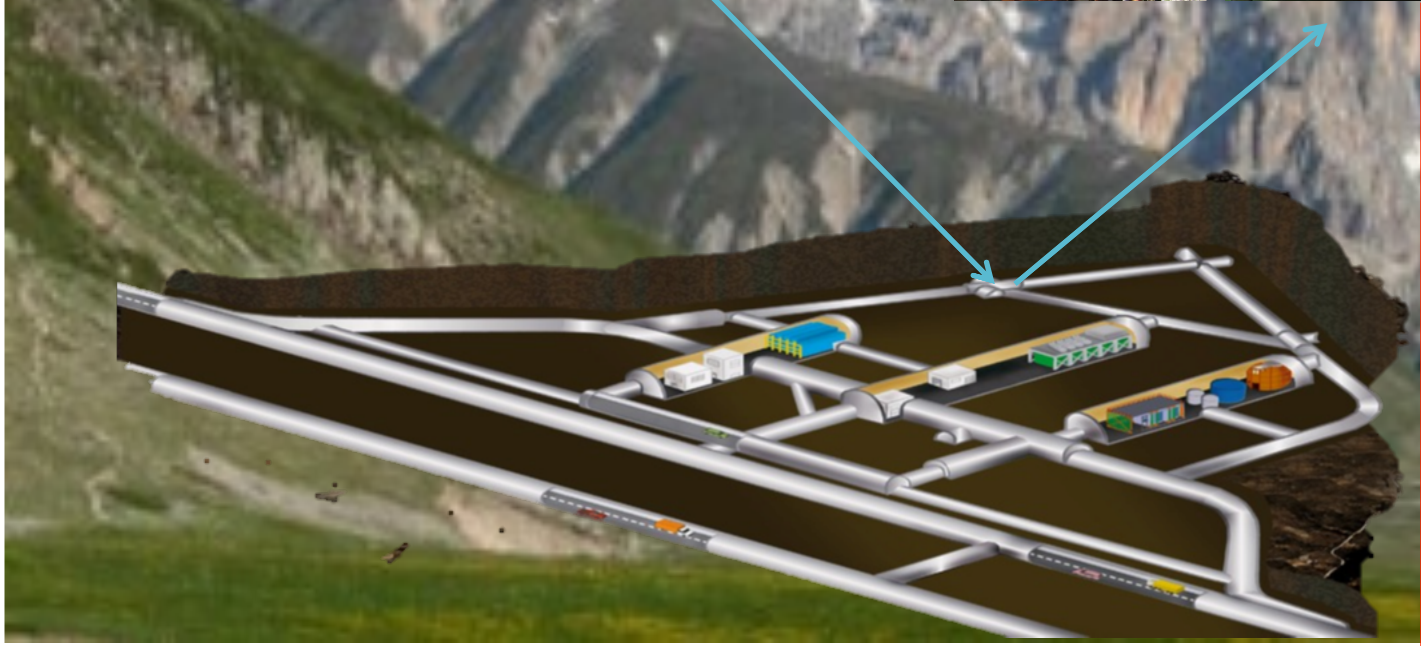
PARTICLE IDENTIFICATION



Still Running XENON100







- 161 kg LXe TPC

(62 kg target + 99 kg active veto)

- 30 cm height and 30 cmx\x diameter
- 242 1” square PMTs

Hamamatsu R8520 (low radioactivity
< 1mBq/PMT for U/Th)

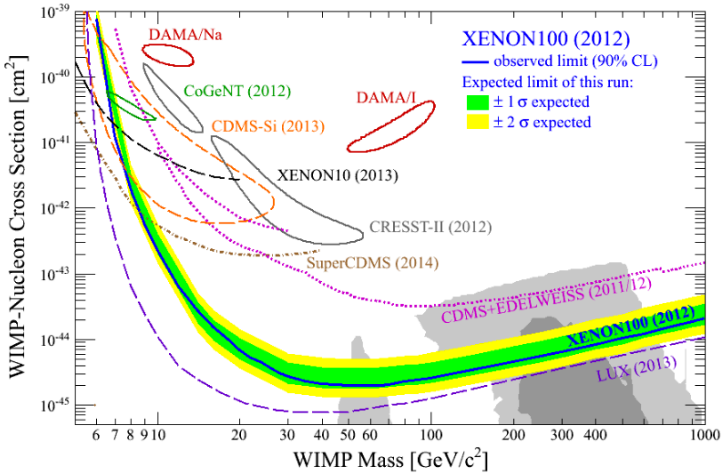
Low radioactive materials

Multilayer passive shield
(H_2O, Pb, Poly, Cu)

XENON100 Results on 225 live days

SI WIMP-nucleon Xsec limit

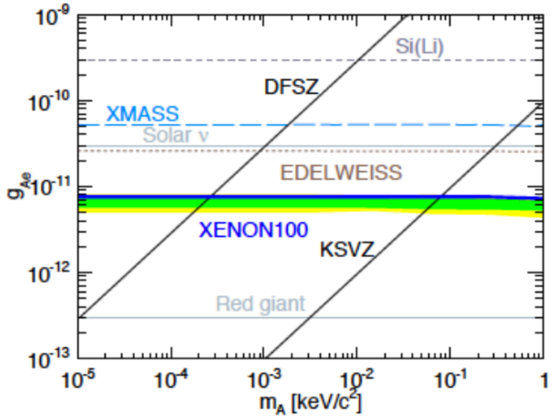
Phys.Rev.Lett.109.181301 (2012)



Axion-electron coupling limits

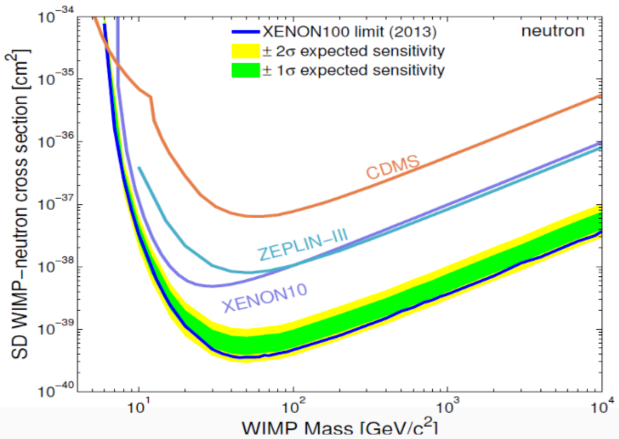
Phys.Rev.D90, 062009 (2014)

solar axion

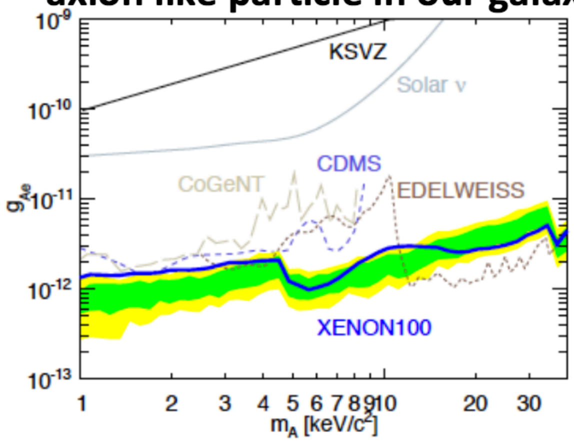


SD WIMP-neutron Xsec limit

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



axion-like particle in our galaxy



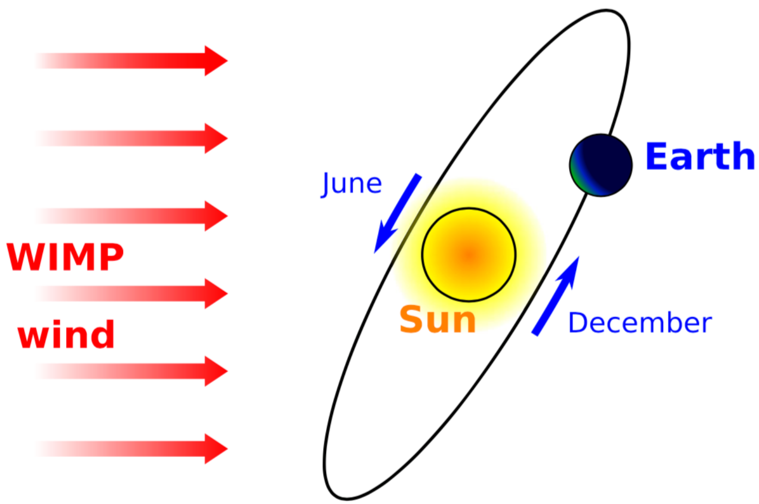
Reconciling with DAMA annual modulation signal

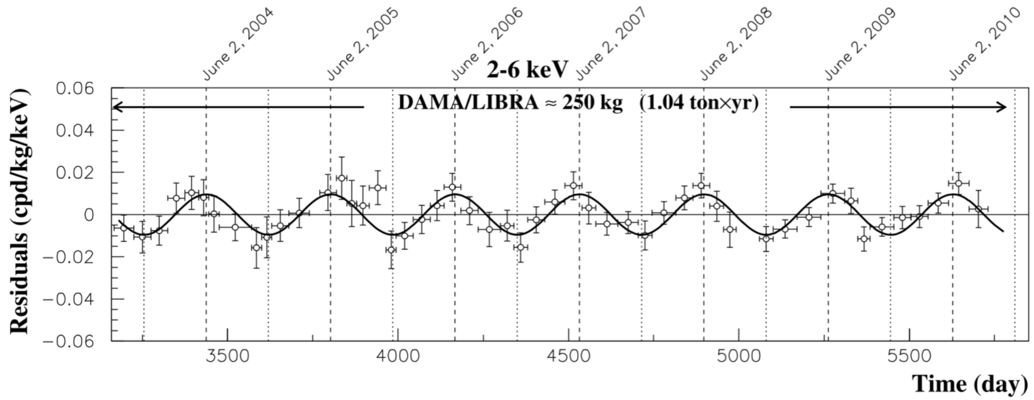
Period = 1 year, phase = June 2 ± 7 days; 9.3-sigma

- Results in tension with many WIMP searches
- Several experiments to *directly probe the modulation signal* with similar detectors (NaI, CsI):

SABRE, ANAIS, DM-Ice, KIMS

- “Leptophilic” models viable (until a few weeks ago...)





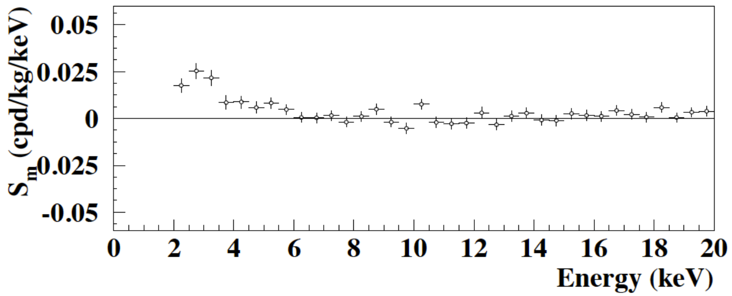


Figure 8: Energy distribution of the S_m variable for the total cumulative exposure 1.33 ton×yr. The energy bin is 0.5 keV. A clear modulation is present in the lowest energy region, while S_m values compatible with zero are present just above. In fact, the S_m values in the (6–20) keV energy interval have random fluctuations around zero with χ^2 equal to 35.8 for 28 degrees of freedom (upper tail probability of 15%).

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

DAMA/LIBRA:

9.3 sigma significance

only for single hit

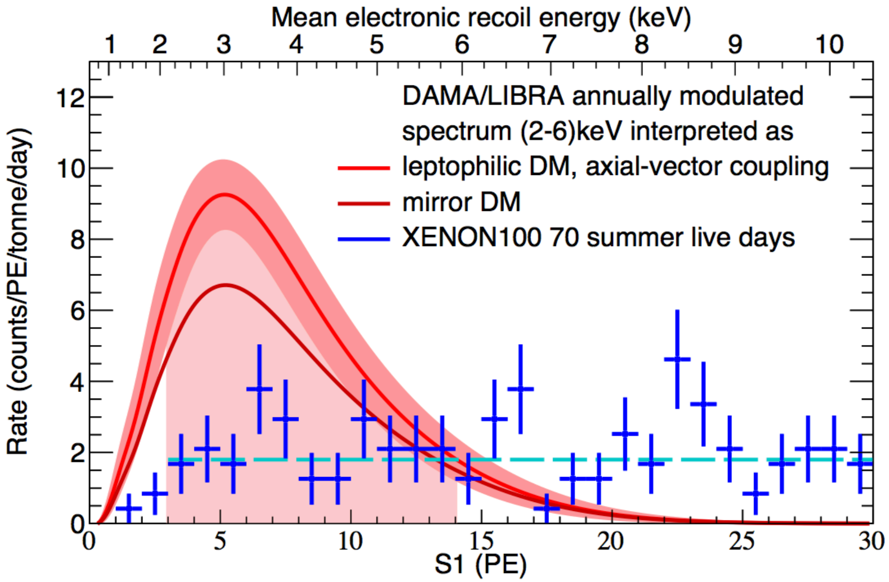
Phase (144 +- 7) days

No signal above 6 keV

A very strong model-independent signal,
let’s interpret it with a model.

Latest Analysis on Leptophilic DM

Use XENON100 225 live days Data to search for DM interacting with electrons
Reconcile the DAMA vs Null-results situation in case of Nuclear Recoils

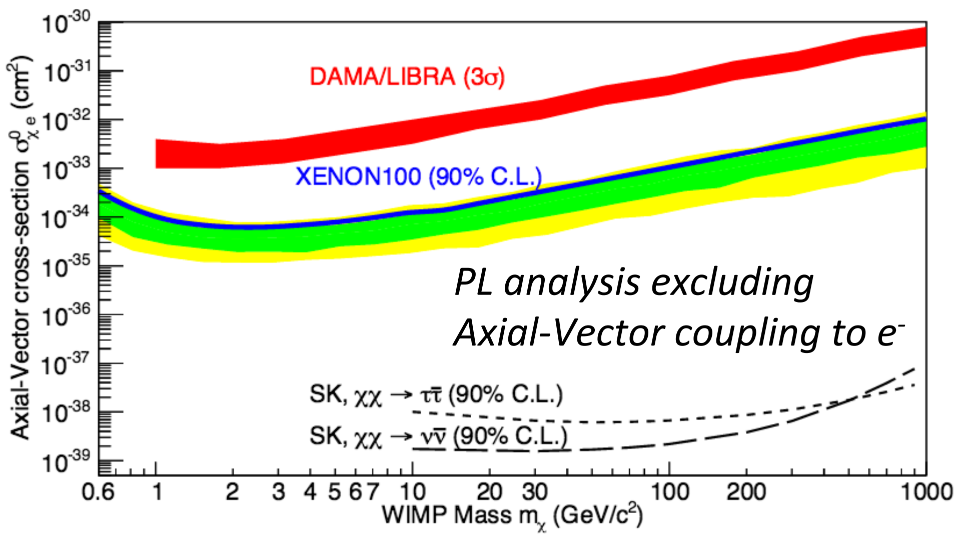


E. Aprile et al. (XENON Coll.), Science 349, 851 (2015)

We selected ER events around (70 days) the expected peak of modulation. Then, assuming 3 models on WIMP coupling to e⁻, we estimated the expected signal and derived exclusion curves.

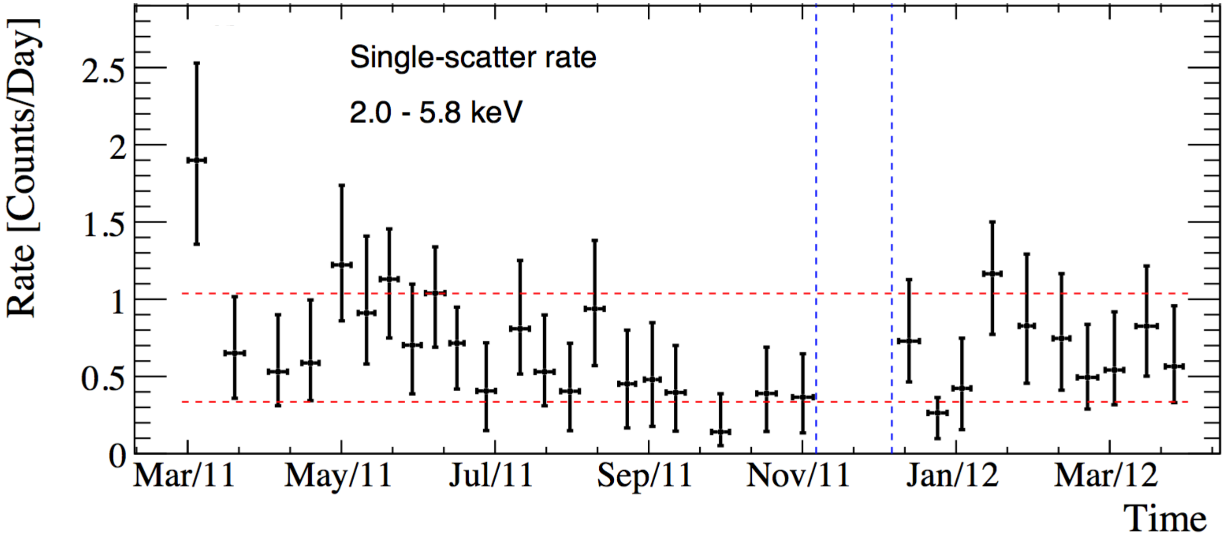
We exclude the DAMA signal as being induced by WIMPs interacting with e⁻ according to

- **Axial-Vector Coupling at 4.4 σ**
- **Mirror DM at 3.6 σ**
- **Luminous DM excluded at 4.6 σ**

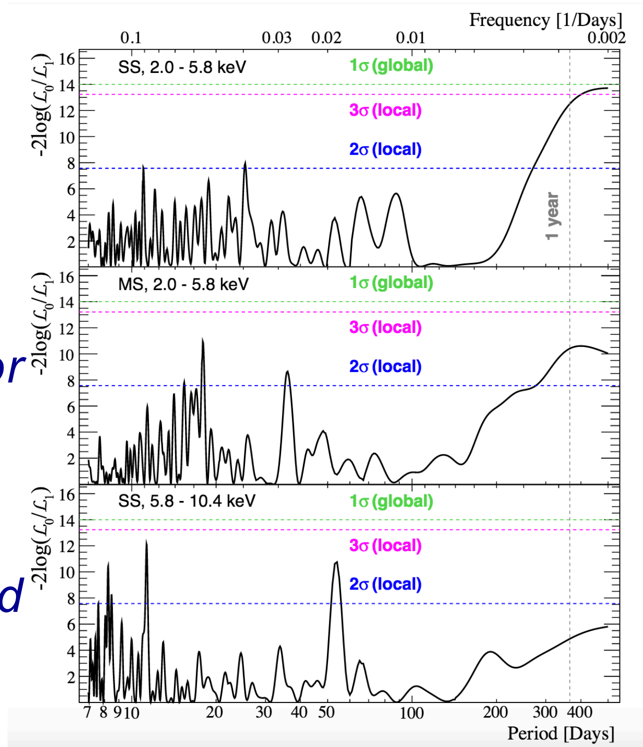


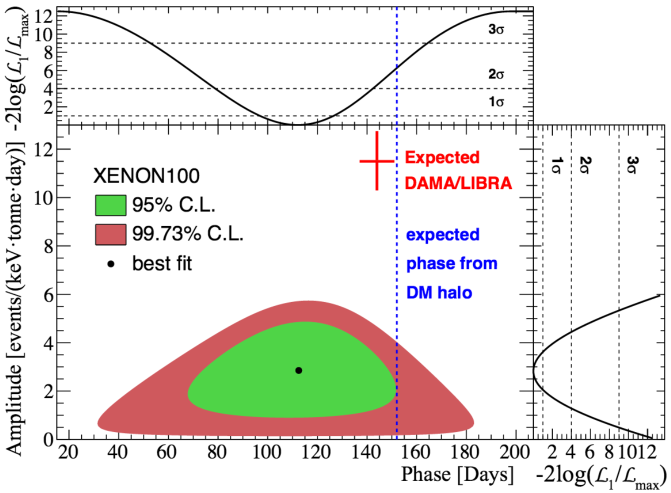
Latest Analysis on Annual Modulation

Use XENON100 225 live days Data to search for periodic variations of electronic recoil event rate→ **E. Aprile *et al.* (XENON Collaboration), Phys. Rev. Lett. 115, 091302 (2015)**



Compare periodic signal hypotesis to null hypotesis (no periodic signal)

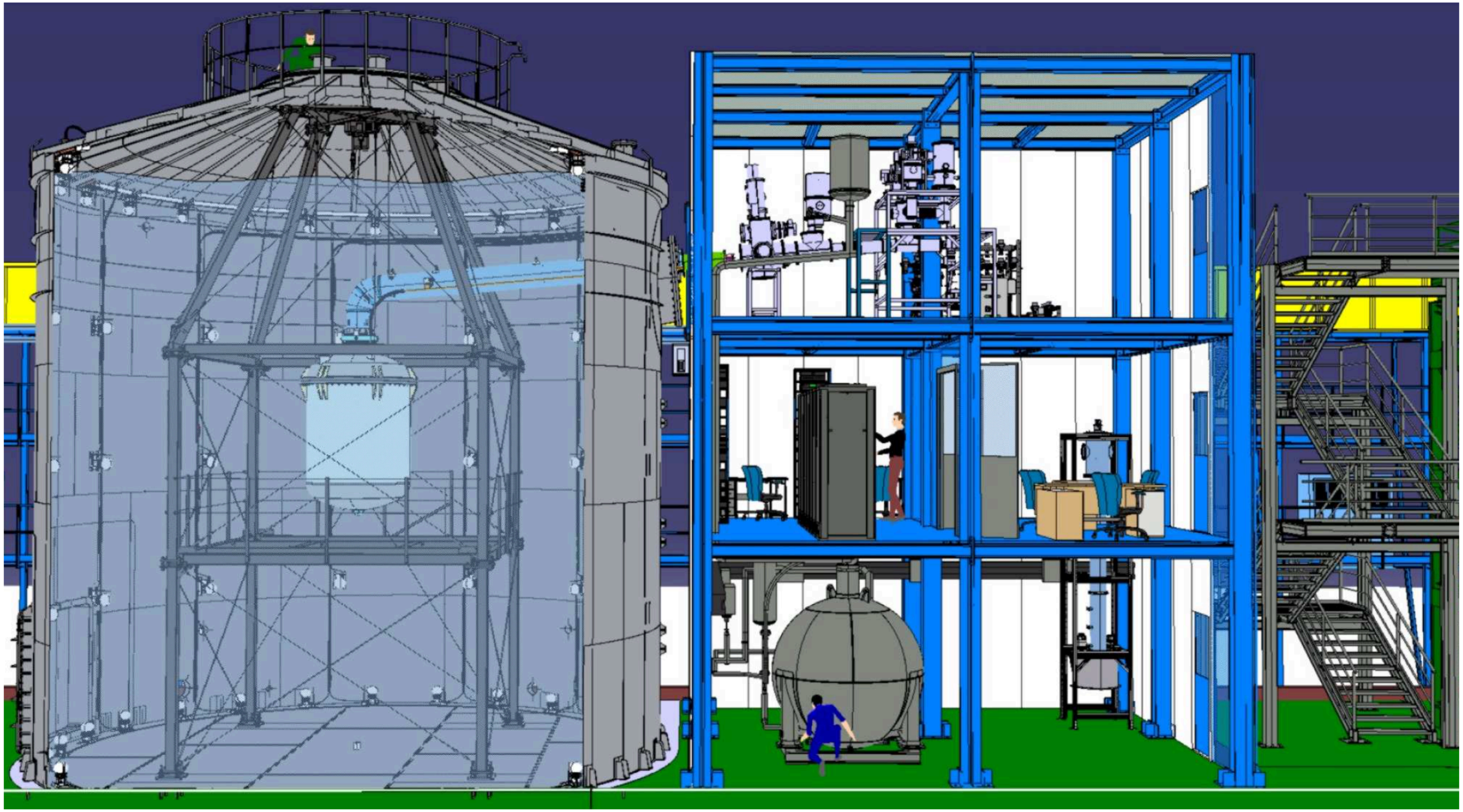




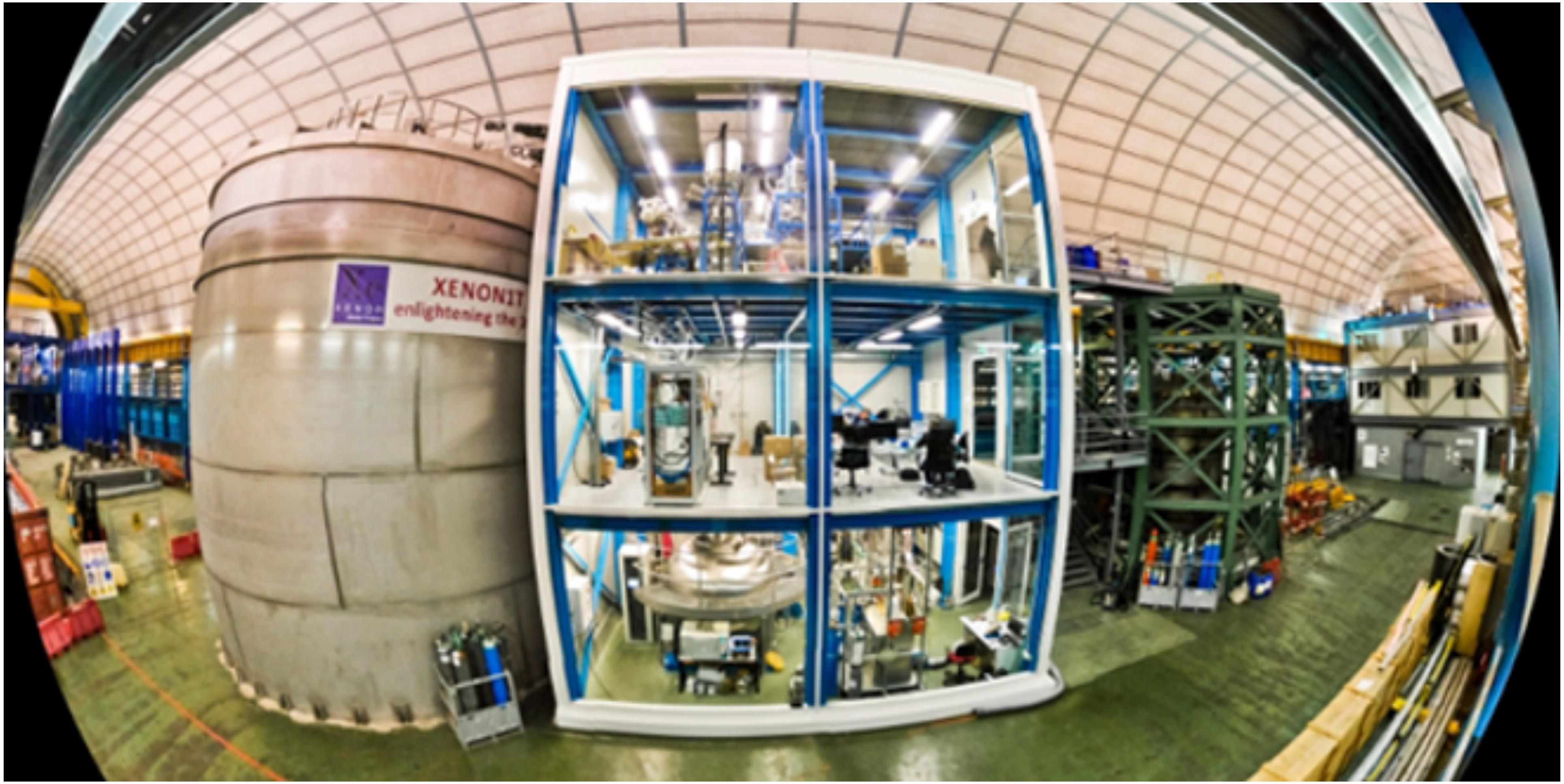
Assuming Axial-Vector coupling of WIMPs to electrons, DAMA/LIBRA annual modulation is excluded at 4.8σ

…Coming soon

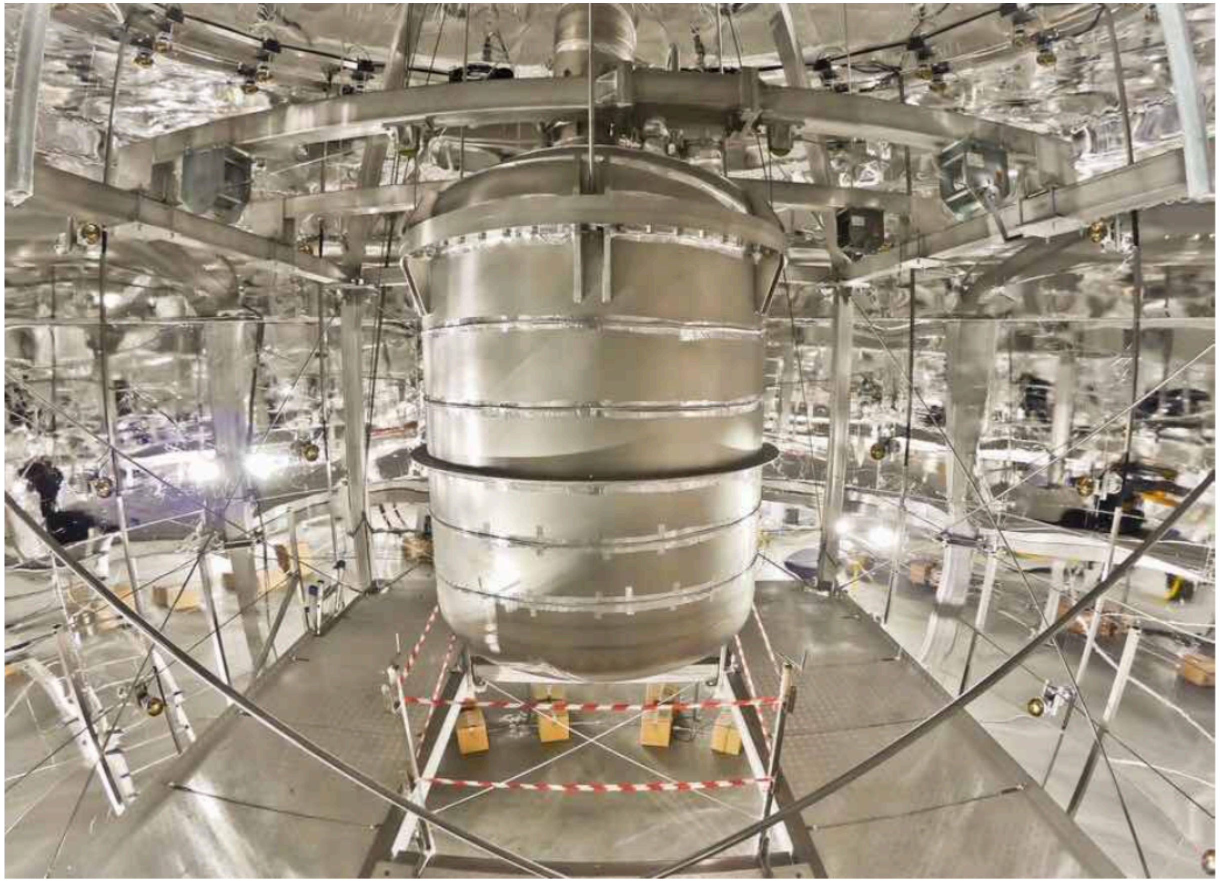
XENON1T: the design



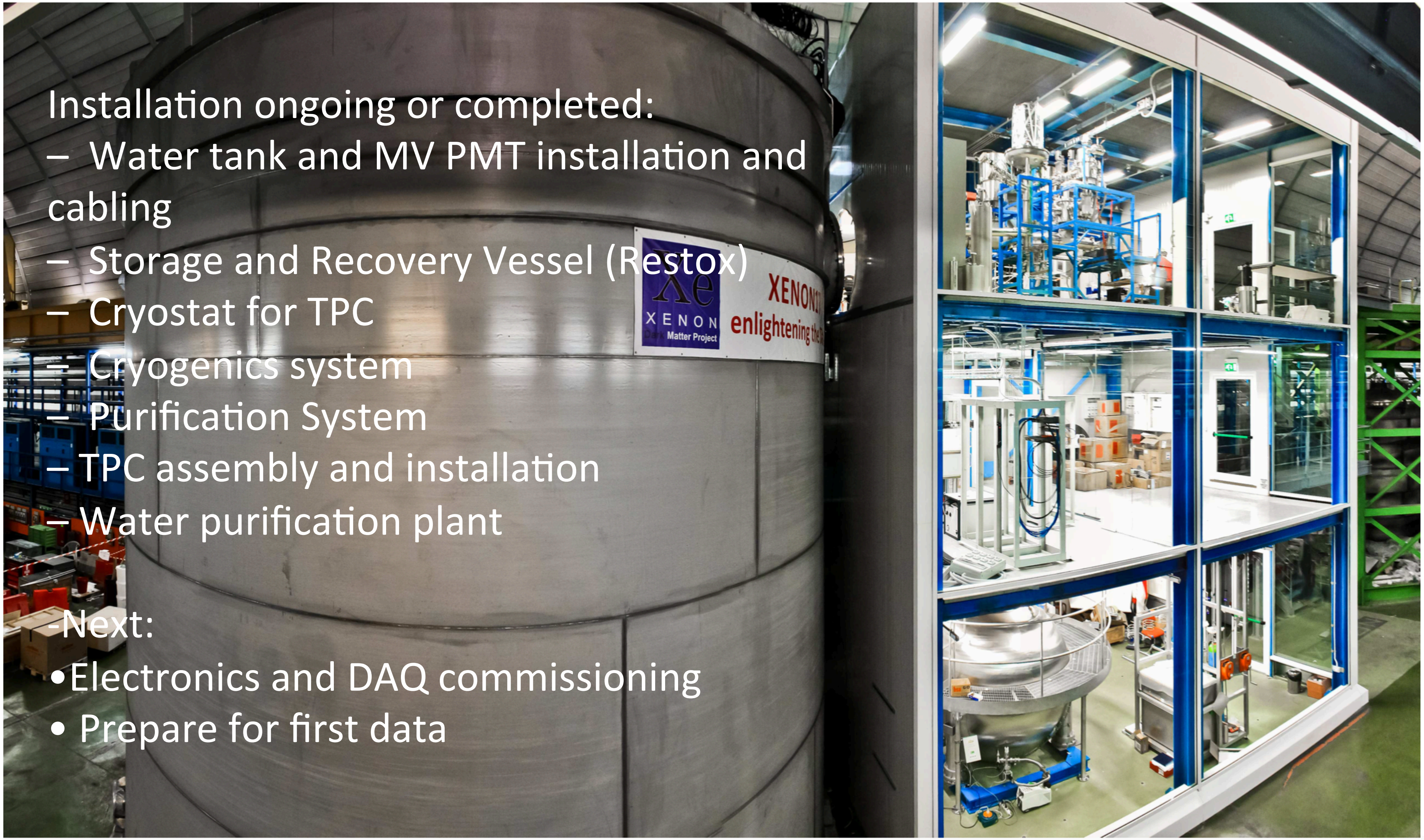
XENON1T: the reality



XENON1T: Inside the WT



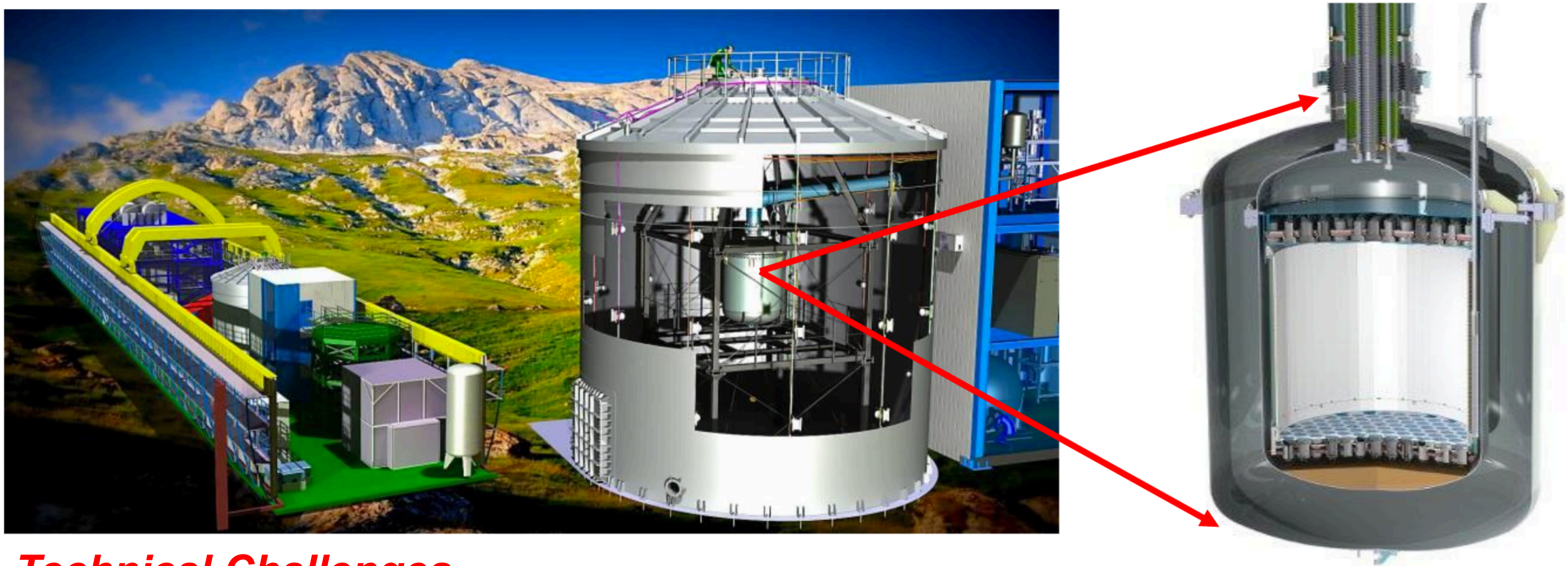
XENON1T: Status



Installation ongoing or completed:
– Water tank and MV PMT installation and cabling
– Storage and Recovery Vessel (Restox)
– Cryostat for TPC
– Cryogenics system
– Purification System
– TPC assembly and installation
– Water purification plant

-Next:
• Electronics and DAQ commissioning
• Prepare for first data

The Detector



Technical Challenges

<u>Low Background</u>
–Material selections
–Muon Veto
–Kr Removal

<u>Handling of >3 tons of Xe</u>
–Storage system
–Cryogenic System
–Purification system

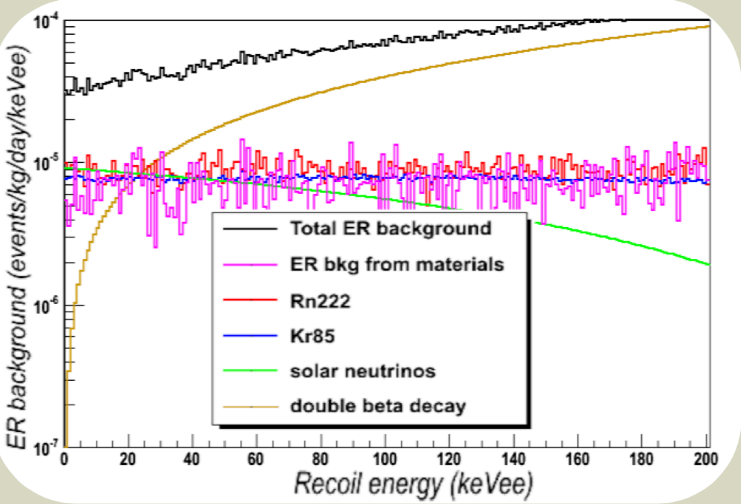
- Total LXe mass: ~3.3 tonnes
- Total LXe active volume: ~ 2 tonnes
- Fiducial volume: ~1 tonne
- 248 3” PMTs Hamamatsu R11410-21

Screening campaign was conducted to select materials with lowest radionuclide contamination level

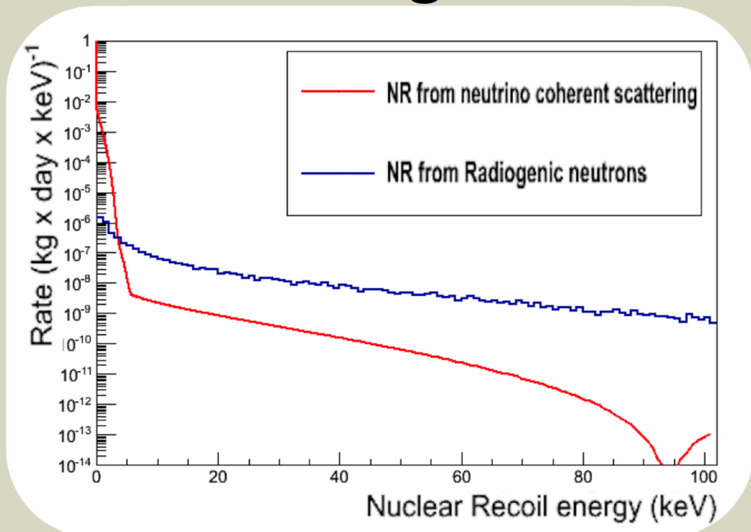
Reduce background of a factor 100 with respect to XENON100

Bologna activity:
Monte Carlo Sensitivity evaluation

ER background



NR background



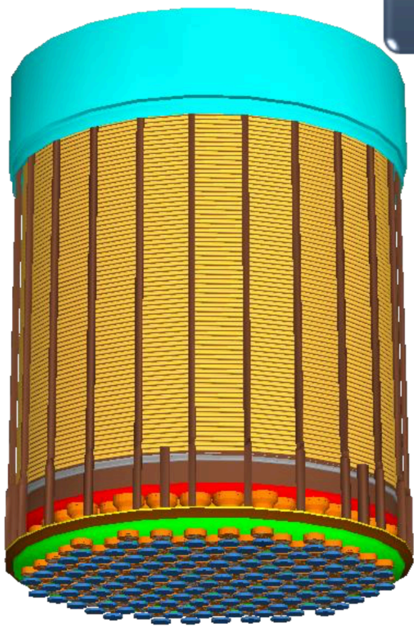
Electromagnetic background (ER)

- Material contaminations (^{60}Co, ^{40}K, ^{238}U, ^{232}Th)
- Intrinsic sources (^{85}Kr, ^{222}Rn, ^{136}Xe 2ν2β, solar neutrinos)

Nuclear background (NR)

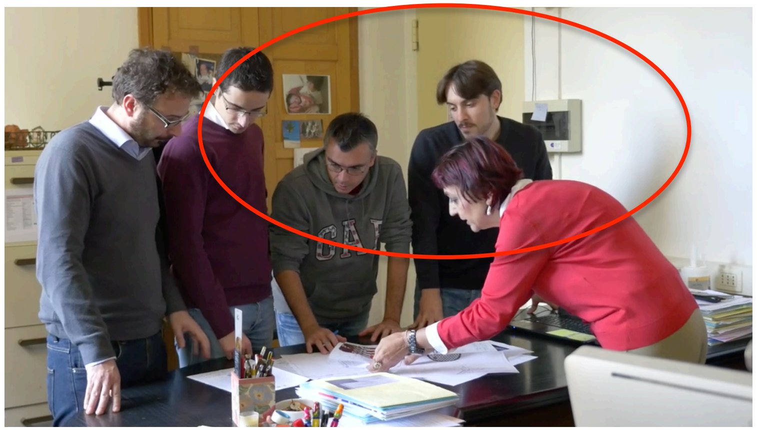
- Spontaneous fission (^{238}U)
- (α, n) reactions (^{238}U, ^{235}U, ^{232}Th)
- Muon-induced neutrons
- Neutrino coherent scatterings

MC implementation (GEANT4)

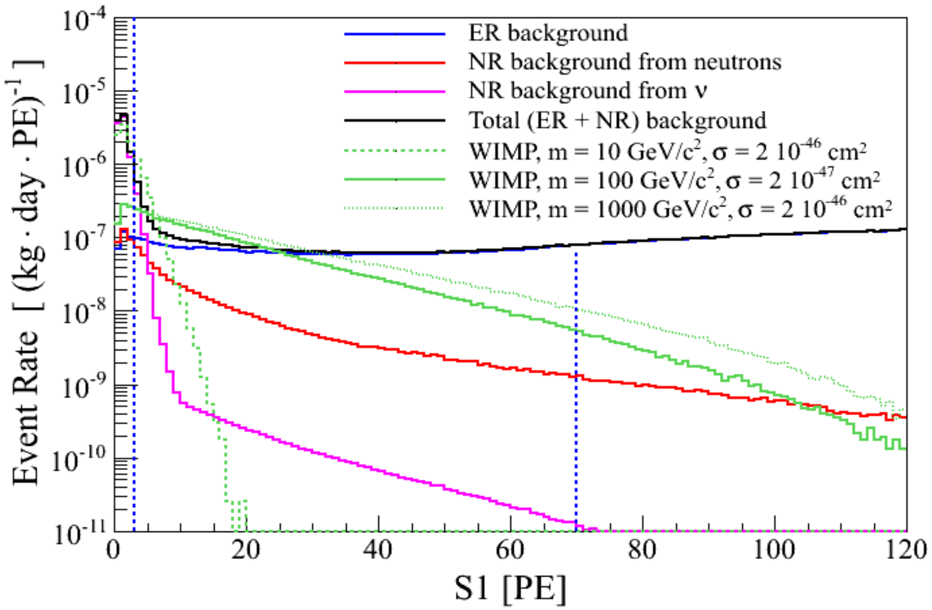


Full MC
Description
of the Detctor

Questions on this →Ask The Experts

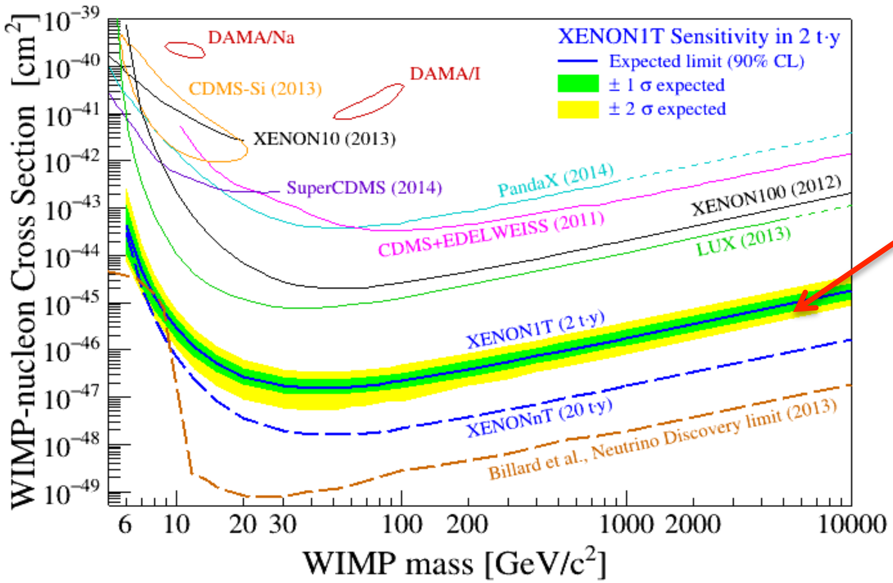


Expected Background and Sensitivity

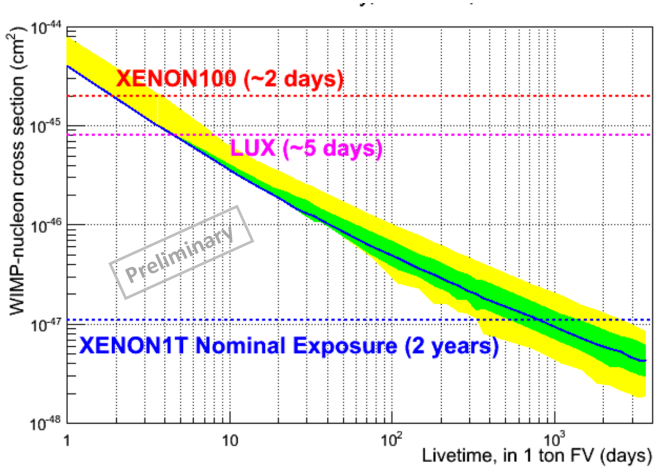


1 tonne fiducial volume, S1 in [3, 70] pe ([2, 12] keVee, [5, 50] keVr), *ER discrimination 99.75%, NR Acceptance 40%.*

ER (Material+ Intrinsic +solar ν)	1.63
NR from radiogenic neutrons	0.22
NR form neutrino Coherent Scattering	0.23
TOTAL	**2.08**

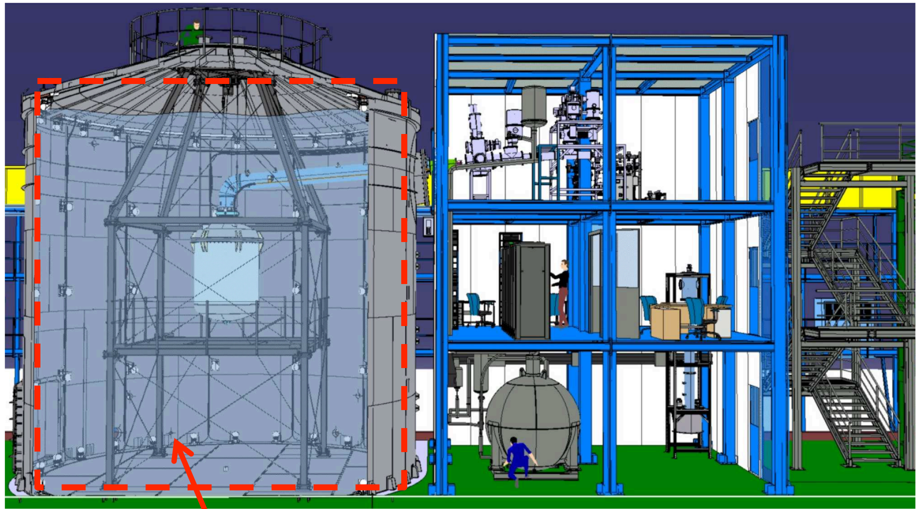


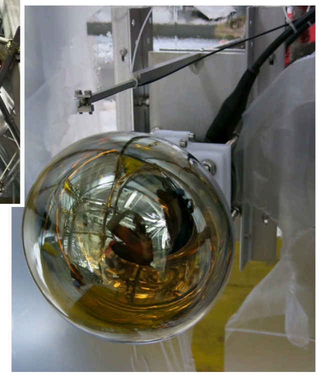
XENON1T design sensitivity after 2 years data taking



XENON1T: Systems Status

Muon Veto



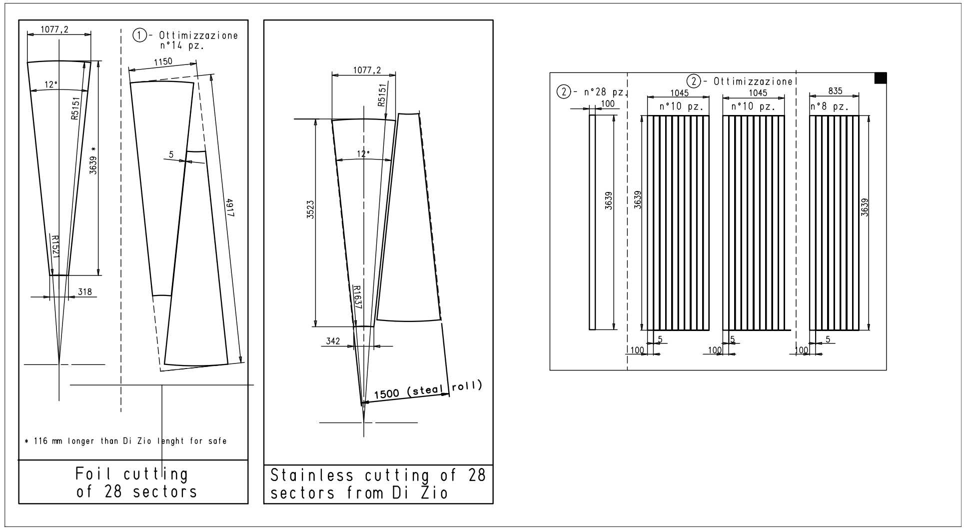


- 10 m height, 9.6 m diameter
- 84 high QE 8” PMTs (Hamamatsu R5912)
- Internal surface covered with reflective film foil
- Reject >99.5% of neutron with muon in water tank
- Reject >70% of neutron with muon outside water tank
- μ-induced neutron background < 0.01/(ton year)

Details in Aprile et al., JINST 9, P11006, 2014

Bologna activity & responsibility: Muon Veto

Other pictures

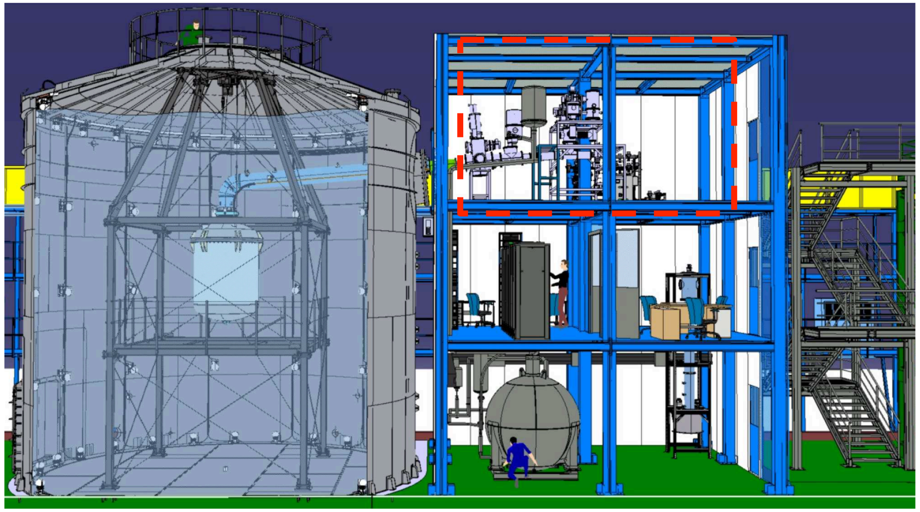


Cryogenic System

The design of the Cryogenic System is based on experience acquired by operating XENON10, XENON100, and XENON1T Demonstrator.

Purpose: keeping LXe temperature (~-100 °C) in reliable way

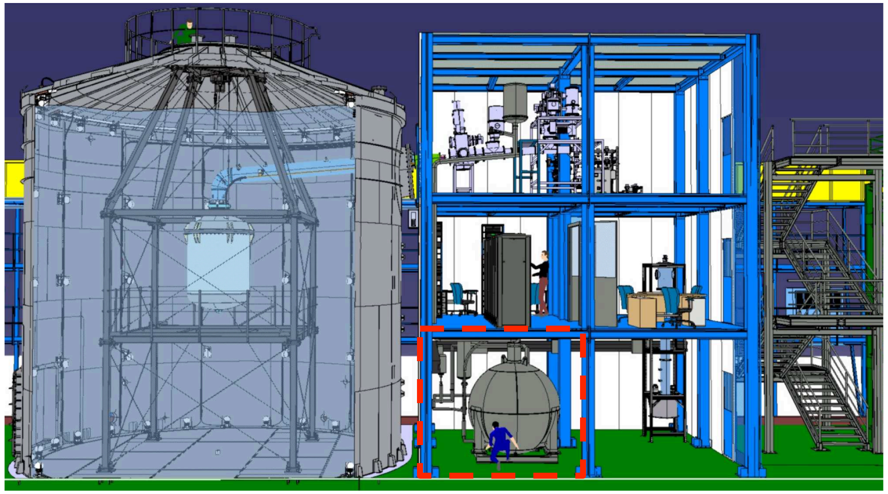
E Aprile et al. 2012 JINST **7** P10001, arXiv:1208.2001



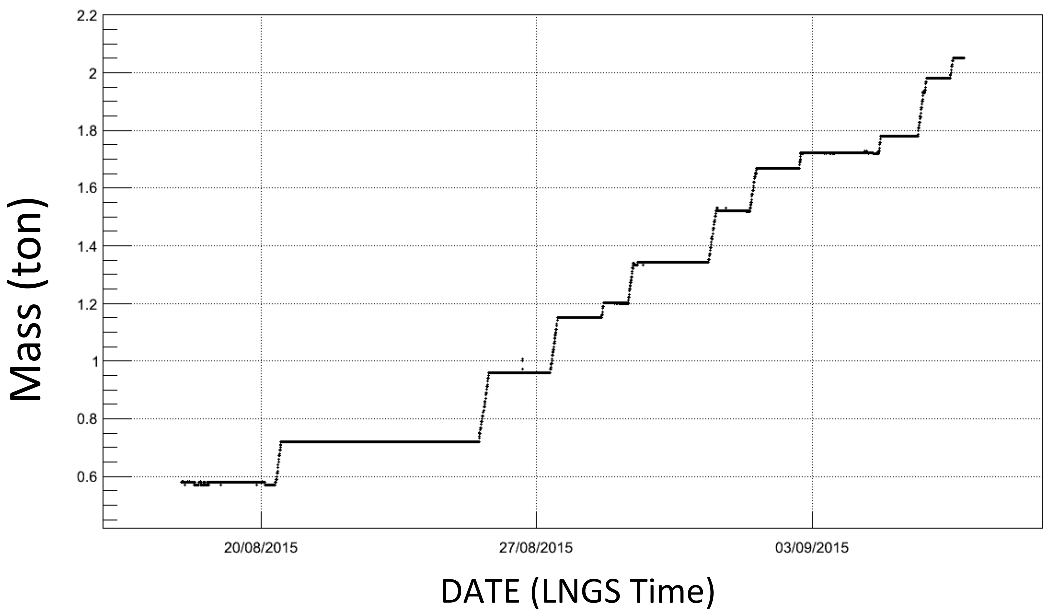
- 2 Redundant 200 W pulse tube Refrigerators
- One PTR can be serviced while the other is in operation
- Backup liquid nitrogen cooling
- Circulation at ~100 slpm through heat exchanger

The System has been fully validated and works as designed

Xenon Storage→RESTOX

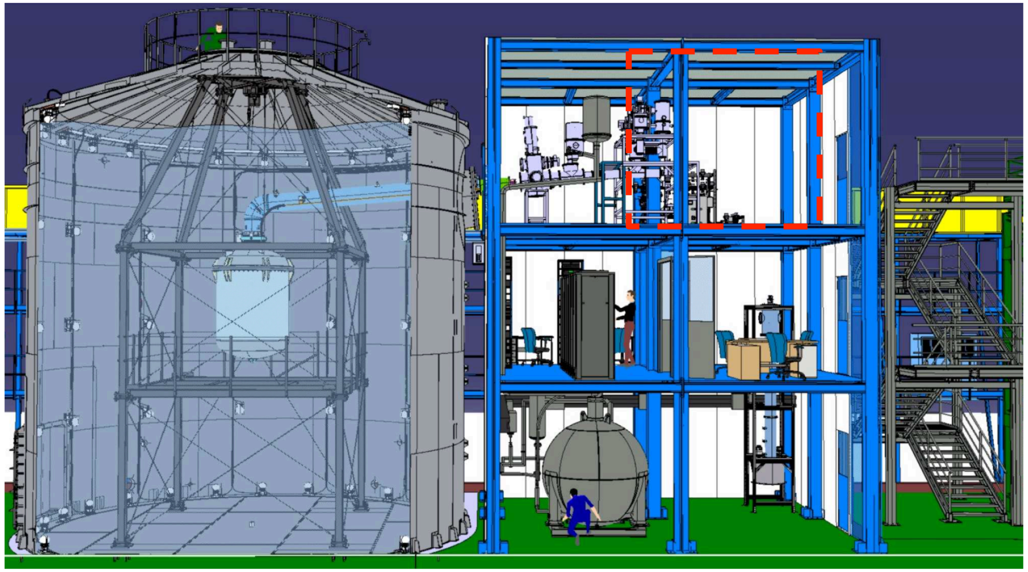


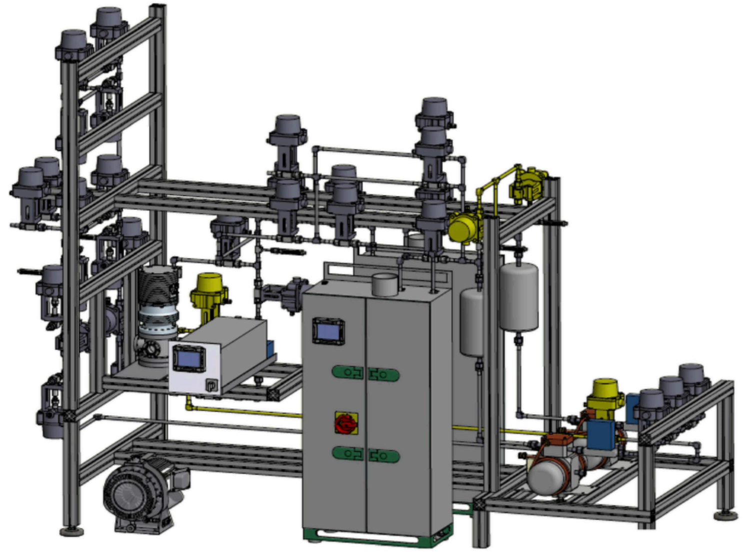
• Double-wall, high-pressure (70 atm), vacuum insulated, LN2 cooled sphere
• Designed to store ~7.6 tons of xenon,
in liquid form at −100° C or in gaseous form at room temperature
• Detector can be filled with liquid xenon directly instead of condensing xenon gas
• In case of emergency, liquid xenon from the detector can be recovered in a few hours



Currently filled with Xenon and works as expected

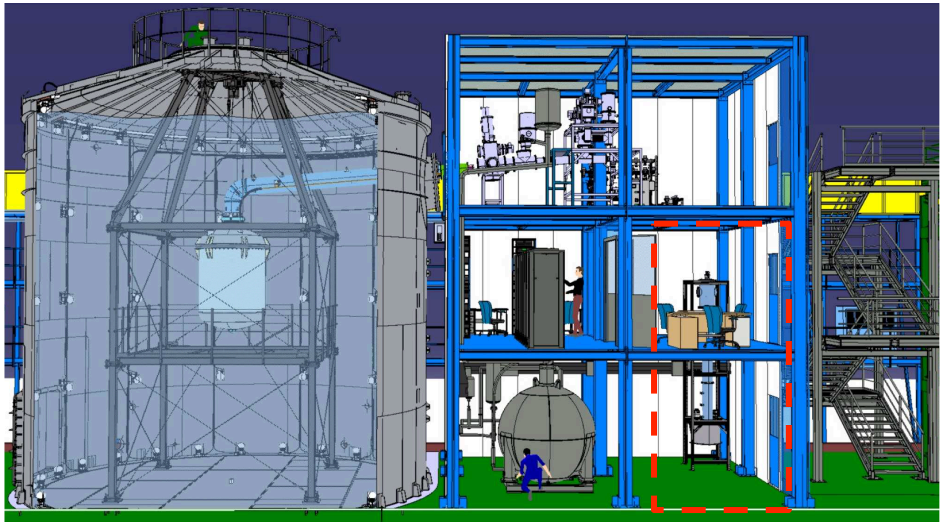
Purification System





- *Continuous GXe circulation at ~100 slpm*
- *Purification using high-flow heated getters*
- *Two parallel circulation pumps (QDrive) and purification circuits*
- *Continuous monitoring of impurity concentrations (e.g. H_2O)*

Distillation Column→Kr Removal

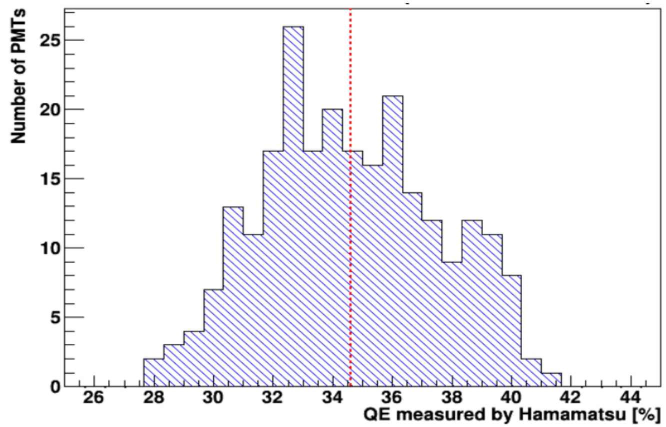


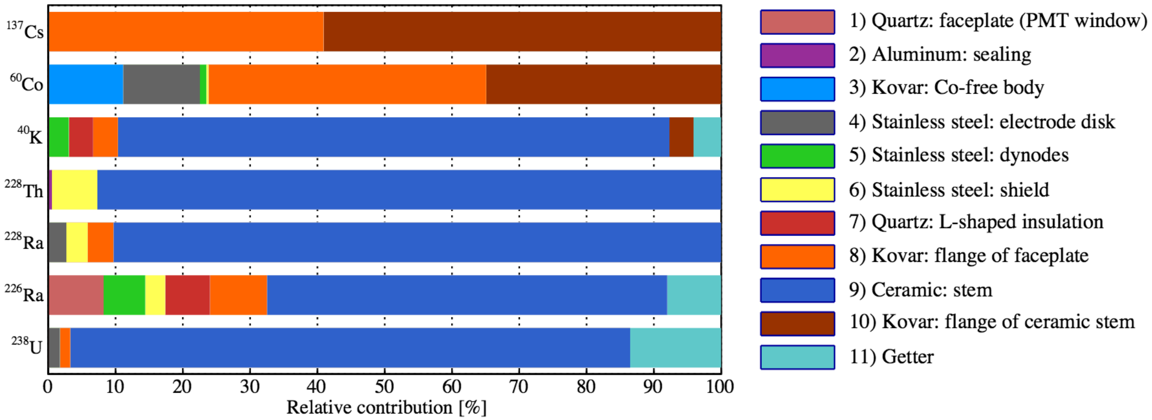
Custom designed cryogenic distillation column for Kr removal with the purpose of reducing ^{85}Kr internal beta-background.

- *XENON1T Kr/Xe concentration requirement is < 0.2ppt, aim at < 0.1ppt with the column*
- *High throughput, 3 kg/hr*
- *3.5 tons in ~1.8 months (single pass)*
- *Custom gas purity diagnostics (online, 83m Kr tracer, and offline, ATTA, RGMS, RGA+ cold trap)*
- *Very efficient purification: column between RESTOX and Cryostat*

The PMTs

- 248 3" PMTs (Hamamatsu R11410-21)
- Quartz window, bialkali photocathode, 12 dynode, Kovar enclosure
- Average QE ~35%
- Gain ~ 3.5×10^6 @ -1.5 kV
- All PMTs were screened before they get into the detector
- Test in cold (-100°C in N_2)
- Test in LXe



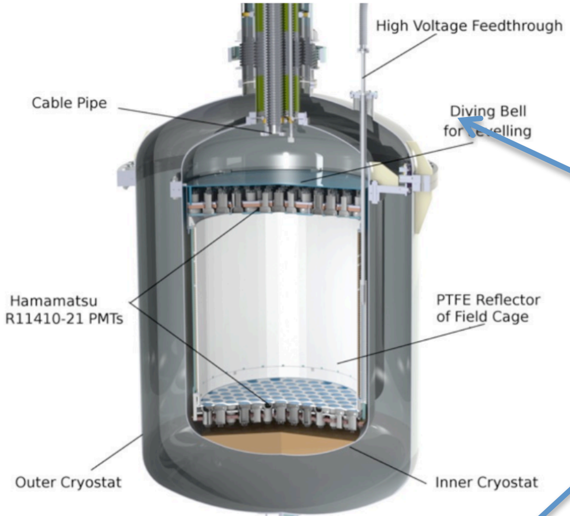


Component	Radioactivity
^{238}U	$<$ 10 mBq/PMT
^{228}Th	$\sim$ 0.5 mBq/PMT
^{226}Ra	$\sim$ 0.6 mBq/PMT
^{235}U	$\sim$ 0.3 mBq/PMT
^{60}Co	$\sim$ 0.8 mBq/PMT
^{40}K	$\sim$ 12 mBq/PMT

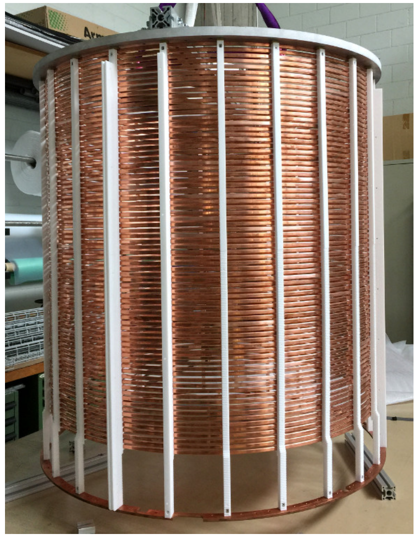
Lowering the radioactivity of the photomultiplier tubes for the XENON1T dark matter experiment→arXiv:1503.07698

The TPC

Under Construction

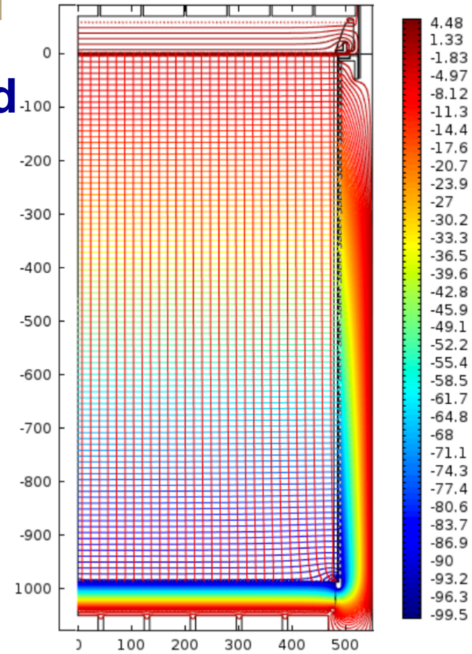


Custom cathode HV feedthrough tested up to -110 kV in LXe

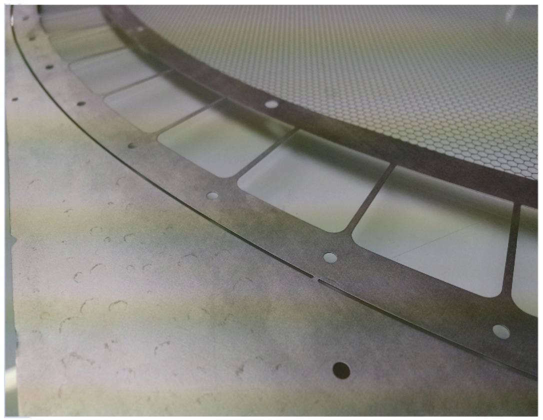


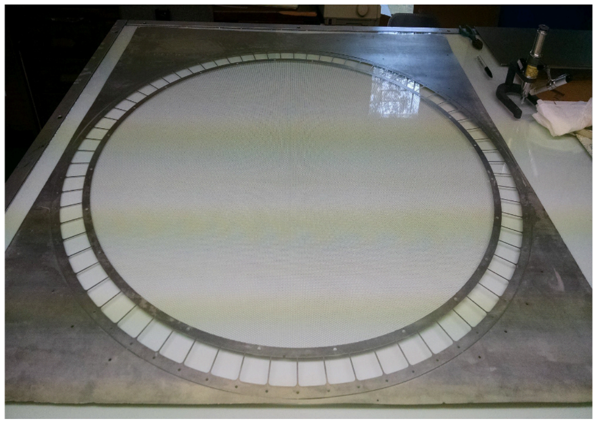
Height ~ 96 cm
Diameter ~ 96 cm
Active target mass
2 tonnes

Uniform Electric field (variation~ 1%)

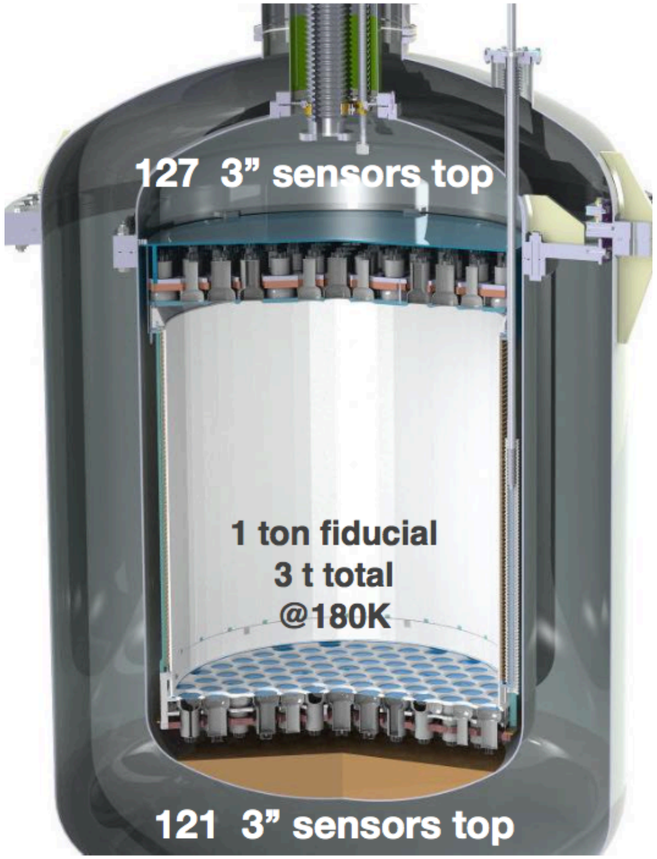


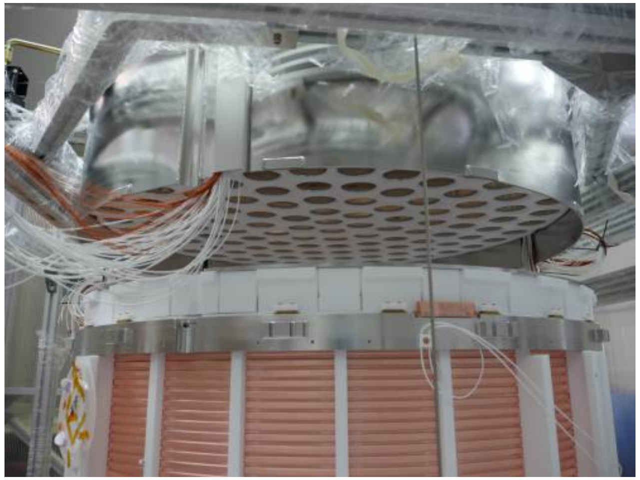
Anode Mesh





The TPC in place





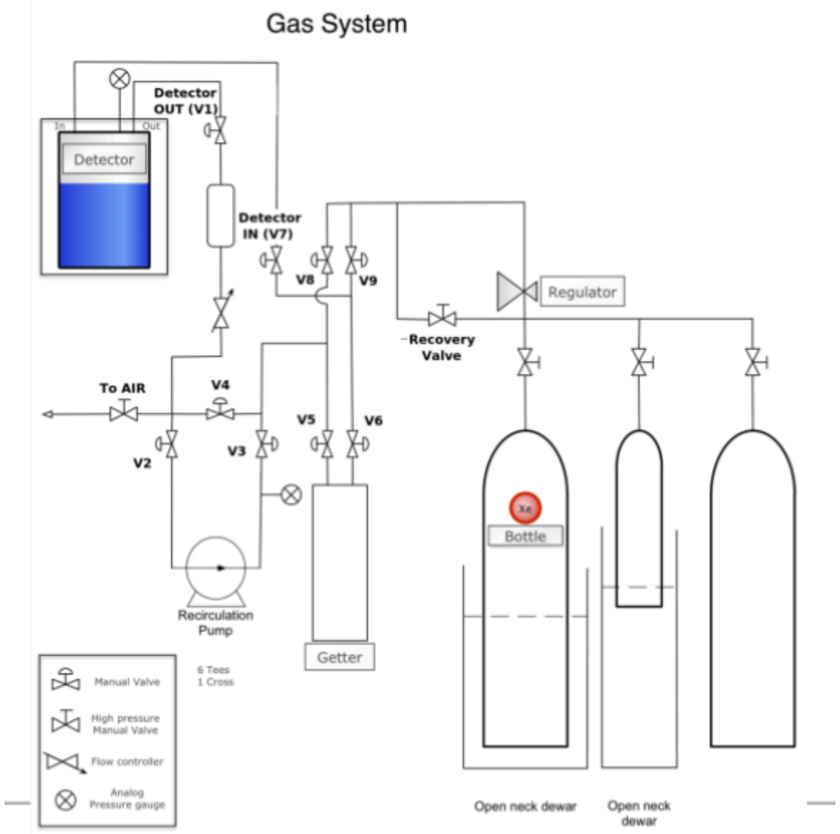
R&D in Bologna

- Study of new photosensors in LXe to:

- Increase light yield in LXe (using **MPPC**)
- Characterize MPPCs in air and in LXe
→Build a CryoLab
- Study the MPPC response in presence of electric fields

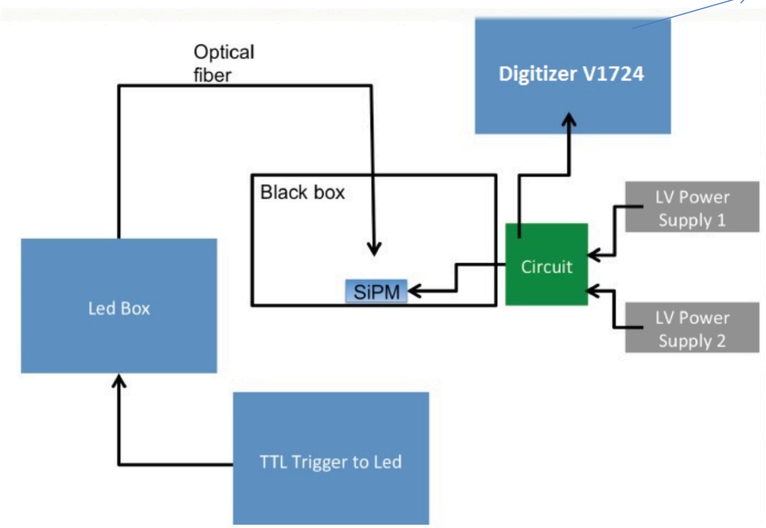
- Build a new TPC with MPPCs placed between the field shaping rings

- Measure the light yield and charge yield for ER and NR at very low recoil energies

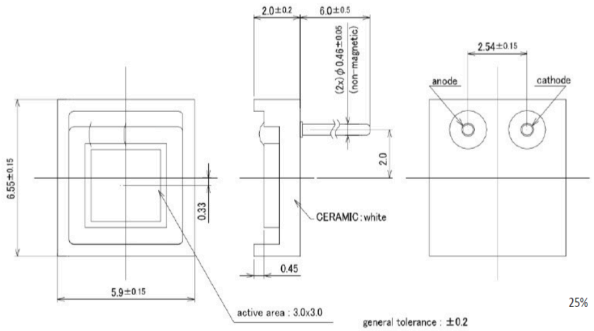


R&D in Bologna
MPPC characterization in air

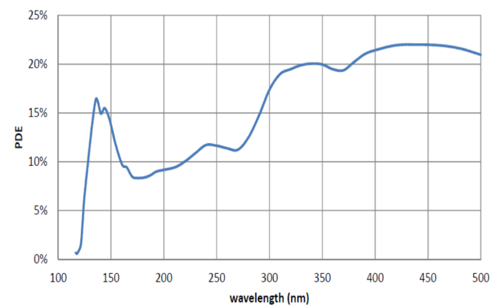
Programma DAQ

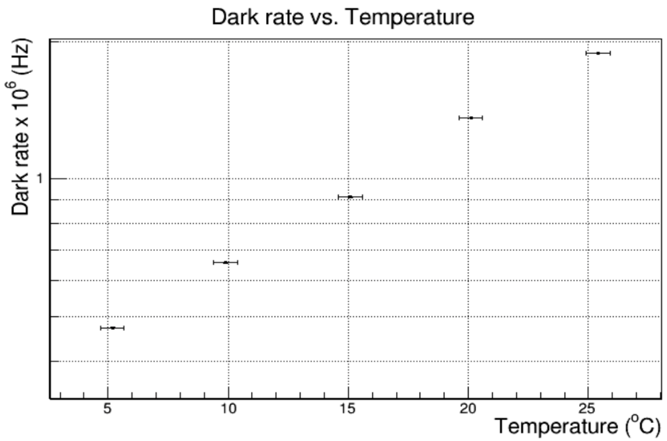


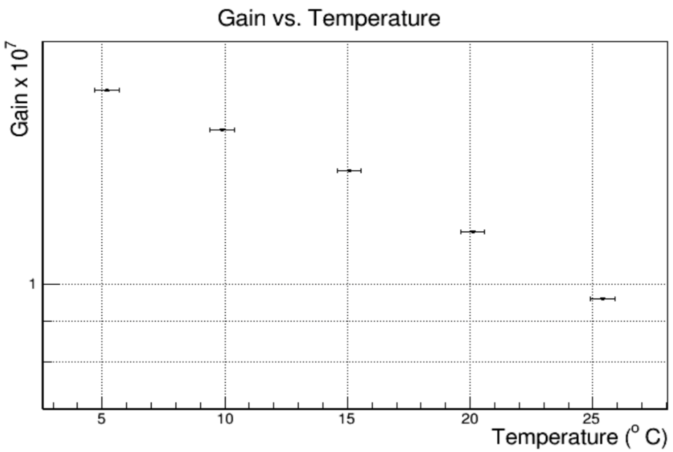
SiPM VUV3 Hamamatsu utilizzato:



- Dimensioni: 3 x 3 mm^2;
- Passo: 100 μm;
- Tensione nominale: 53.46 V.







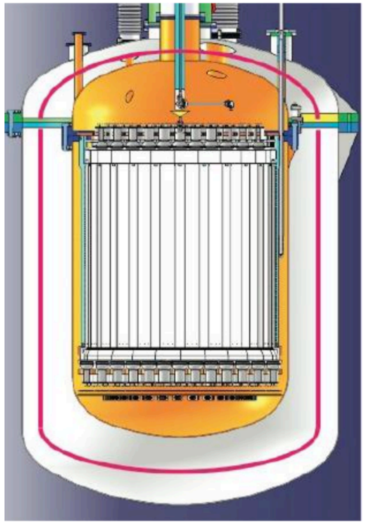
Summary

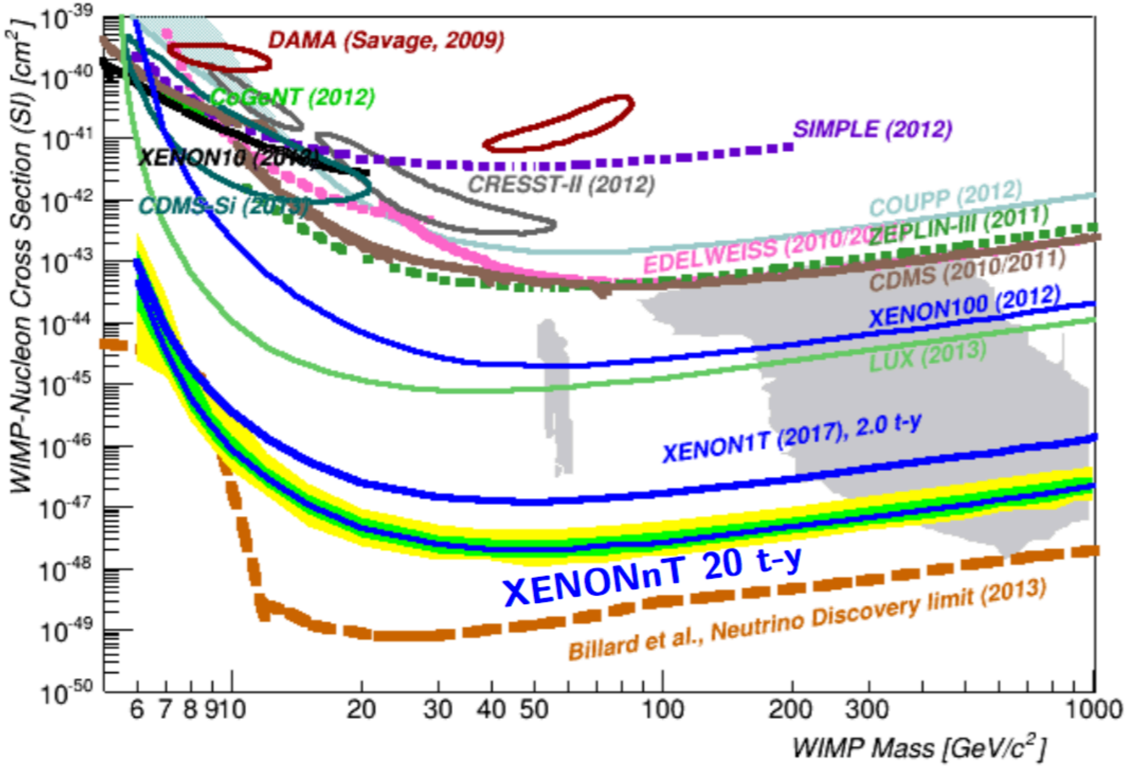
- *The XENON Program is continuing the search for the DM signal*
- *XENON100 still in operation is providing physics results and data analysis is still ongoing*
- *XENON1T is under commissioning. Cryogenic system, Restox, purification systems have been validated and work as expected*
- *Detector Assembly completed*
- *First data are expected by the end of the year*

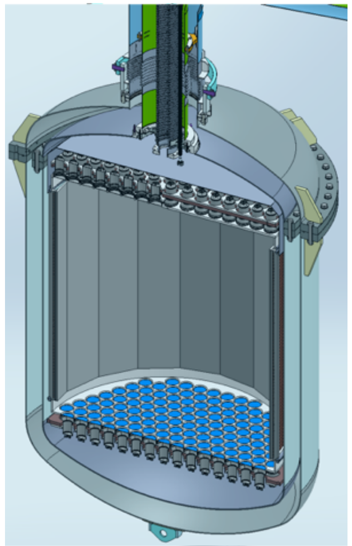
What Next?

XENONnT:2018-2022

The total mass of Xenon will be ~ 7000 kg.
The systems developed for XENON1T can be used to operate XENONnT:
Underground infrastructure, Cleanrooms, DAQ, Slow Control, Computing Infrastructure, Water Tank, Muon Veto, Outer Cryostat, Support Structure, Cryogenics and Purification systems, LXe storage and recovery system.
Only the inner cryostat, the number of PMTs (~ 200 more) and TPC will be upgraded.





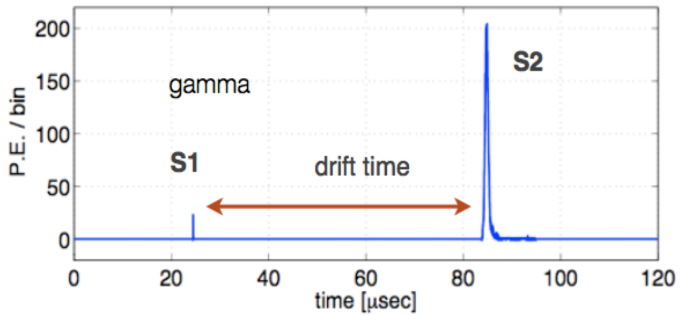


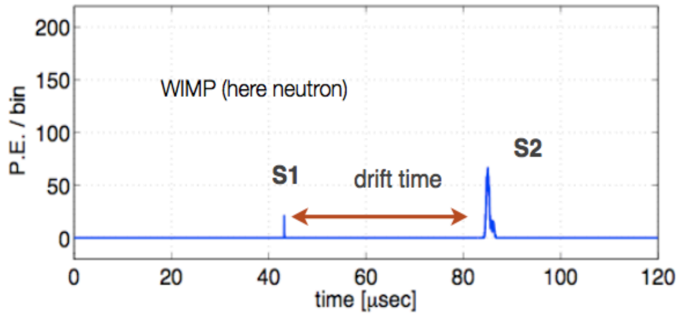
So…We will strongly try to enlighten the DARK

EXTRA

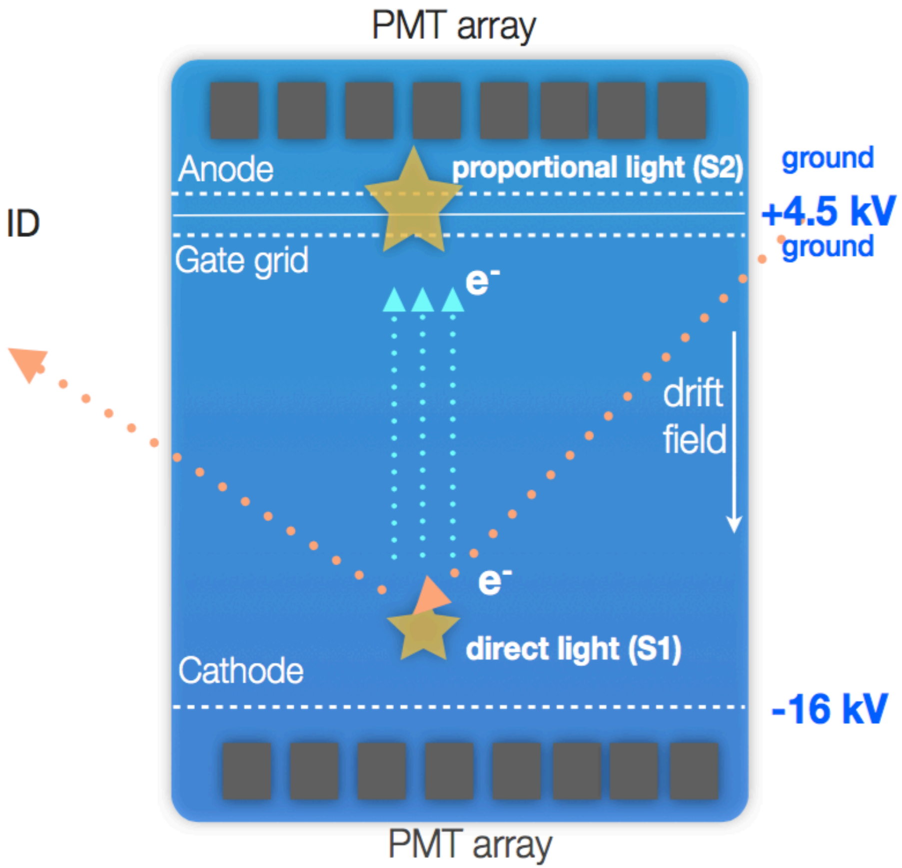
How we use it: the principles of dual phase Xe TPC

- Particle interaction in the active volume produces *prompt scintillation light (S1)* and ionization electrons
- Electrons drift to interface (E= 0.53 kV/cm) where they are extracted and amplified in the gas. Detected as *proportional scintillation light (S2)*
  - $(S2/S1)_{WIMP} << (S2/S1)_{Gamma}$
  - 3-D position sensitive detector with particle ID

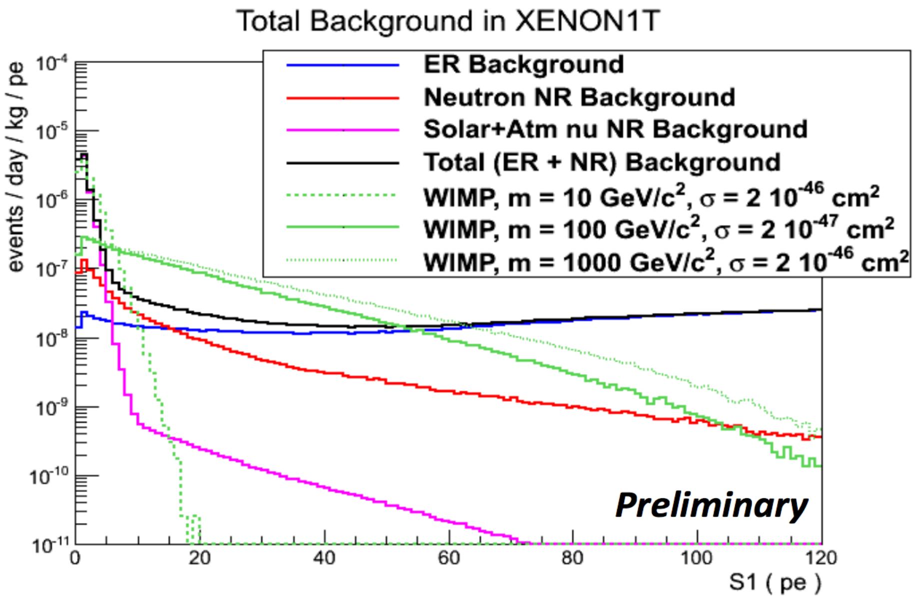




Xe (A=131); λ = 178 nm
position resolution:
<3mm in x-y; < 0.3 mm in z

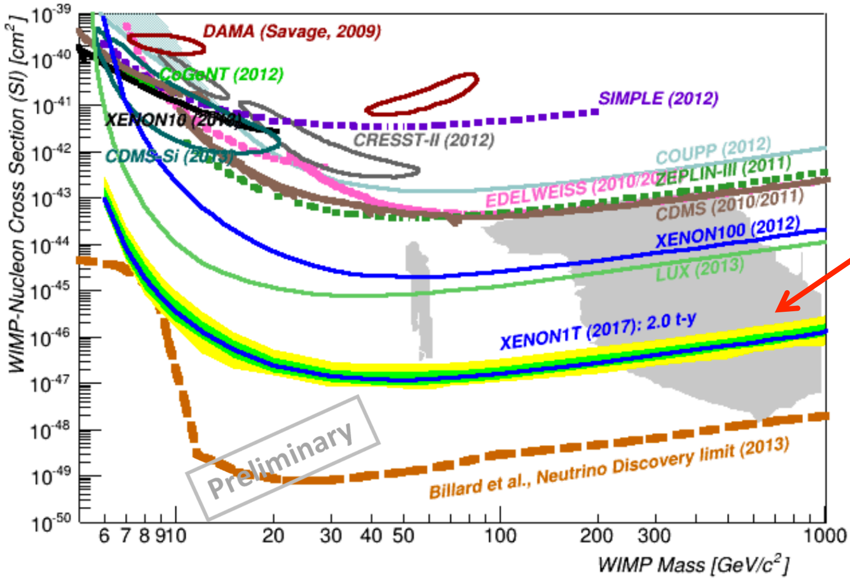


Expected Background and Sensitivity



1 tonne fiducial volume, S1 in [3, 70] pe ([2, 12] keVee, [5, 50] keVr), *ER discrimination 99.75%, NR Acceptance 40%.*

Source	Background (ev/y)
ER (Material+ Intrinsic +solar ν)	0.32
NR from radiogenic neutrons	0.22
NR form neutrino Coherent Scattering	0.21
TOTAL	**0.75**



XENON1T design sensitivity after 2 years data taking