Searching for Dark Matter: new results from the XENON project

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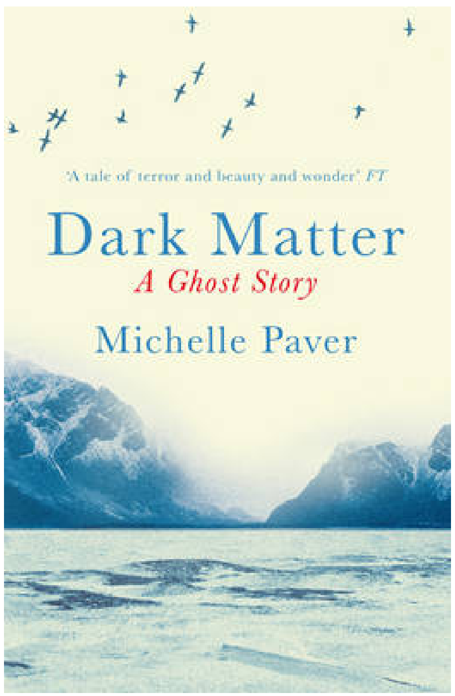
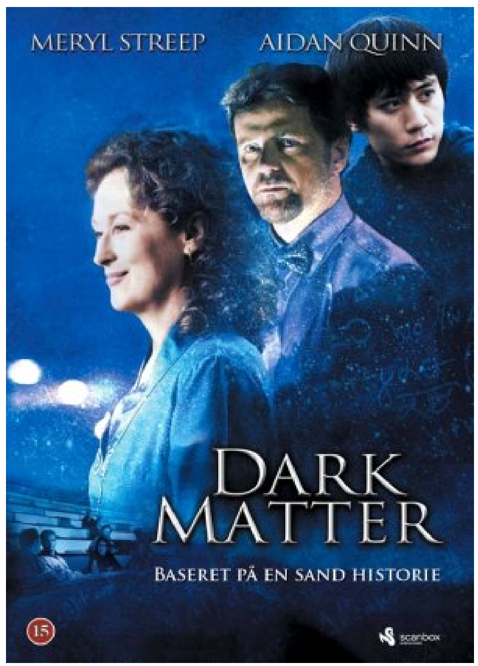
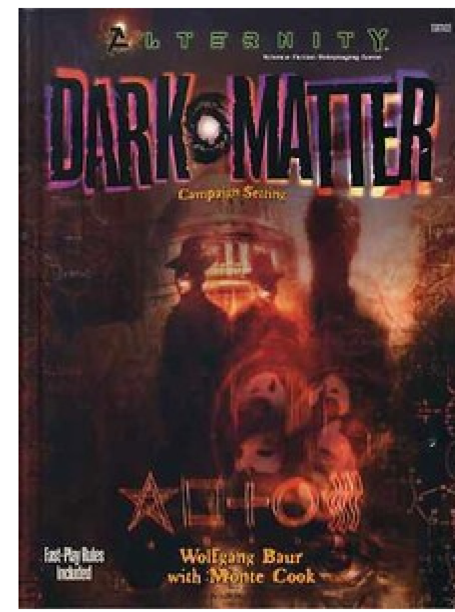
What is **not** Dark Matter?

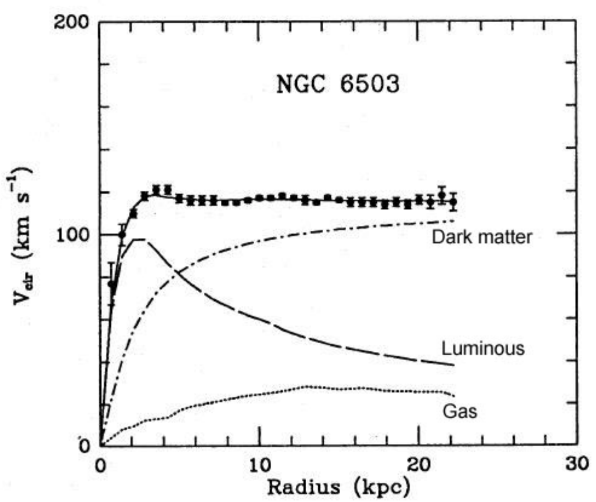
It's not a scary book, not a dramatic movie, not a progressive music, not a role playing game . . .



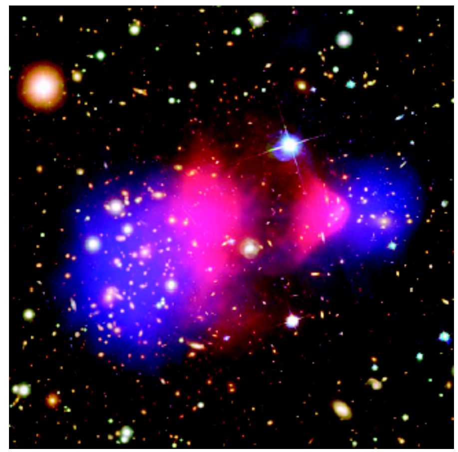




Many indirect evidences from the space



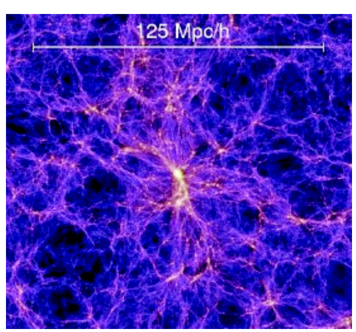
Flat velocity of stars
beyond visible disk size
implies the existence
of an unseen mass distribution



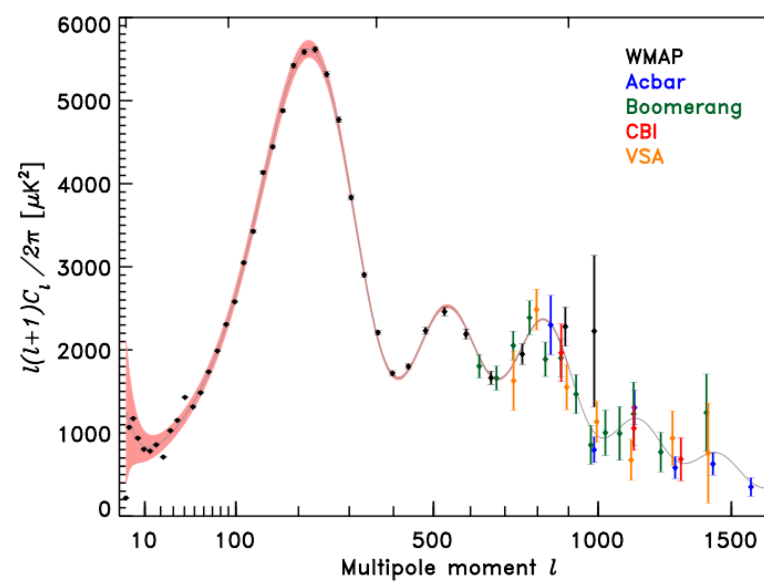
Baryonic matter
from X-ray observation (red),
does not coincide with
mass distribution from
gravitational lensing (blue)

Existence
of **dwarf galaxies**
can be understood
if there is enough
mass around
which is not seen

Cold dark matter
to be consistent
with formation of
large scale structures



Anisotropies in CMB
allow a measurement
of dark matter density



Dark Matter wind

Dark Matter is required to be:

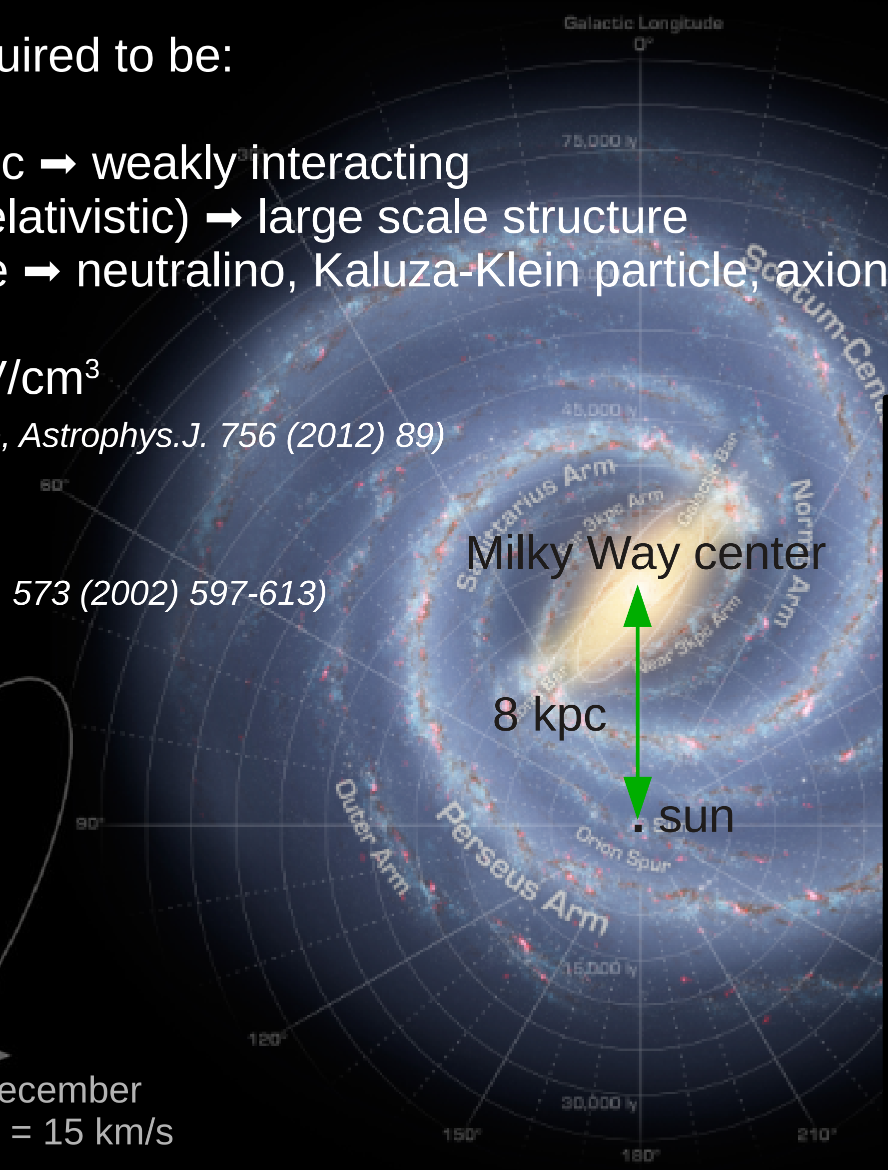
- Neutral
- Non-baryonic ➡ weakly interacting
- Cold (non-relativistic) ➡ large scale structure
- New Particle ➡ neutralino, Kaluza-Klein particle, axion, gravitino …

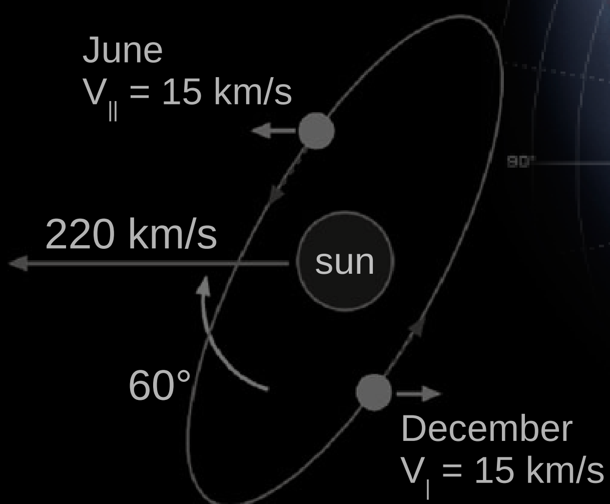
$\rho_\chi = 0.3 \pm 0.1$ GeV/cm^3

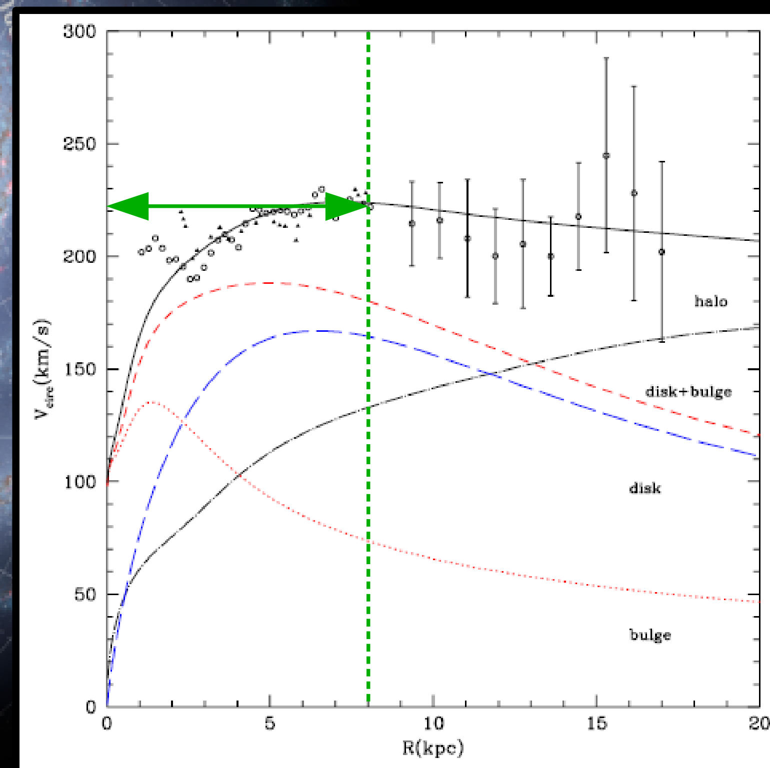
(J. Bovy and S. Tramaine, Astrophys.J. 756 (2012) 89)

$V_{sun} \sim 220$ km/s

(Klypin et al. Astrophys.J. 573 (2002) 597-613)







The WIMP miracle

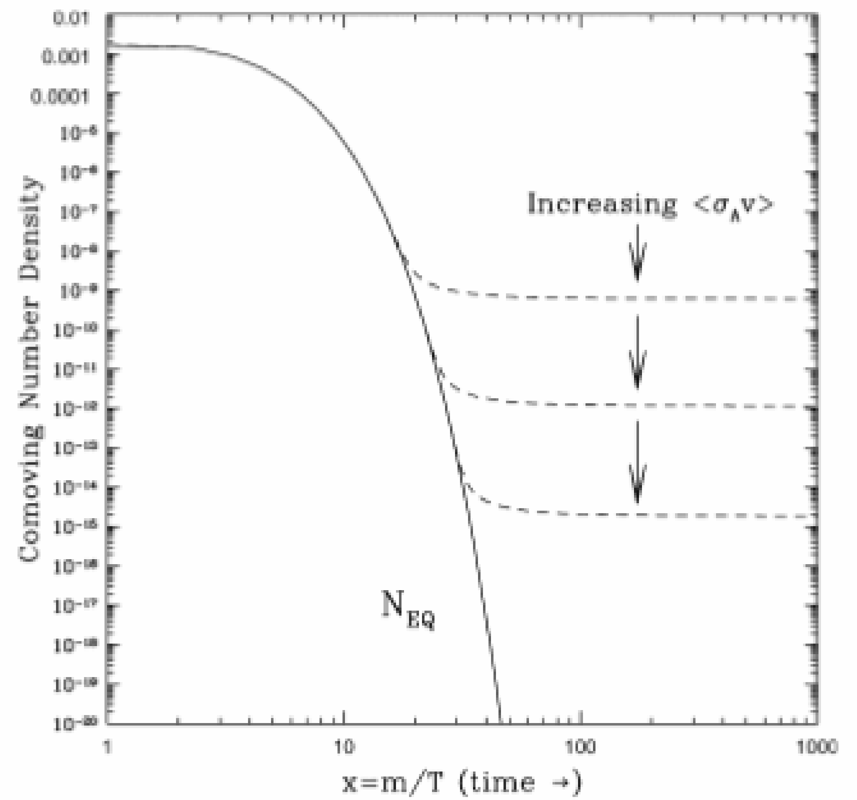
I interact, therefore I am...

The abundance of a particle is related to its cross section: $\Omega_{DM} \sim < \sigma_A v >^{-1}$

The Weakly Interacting Massive Particle (WIMP) is the most popular candidate:

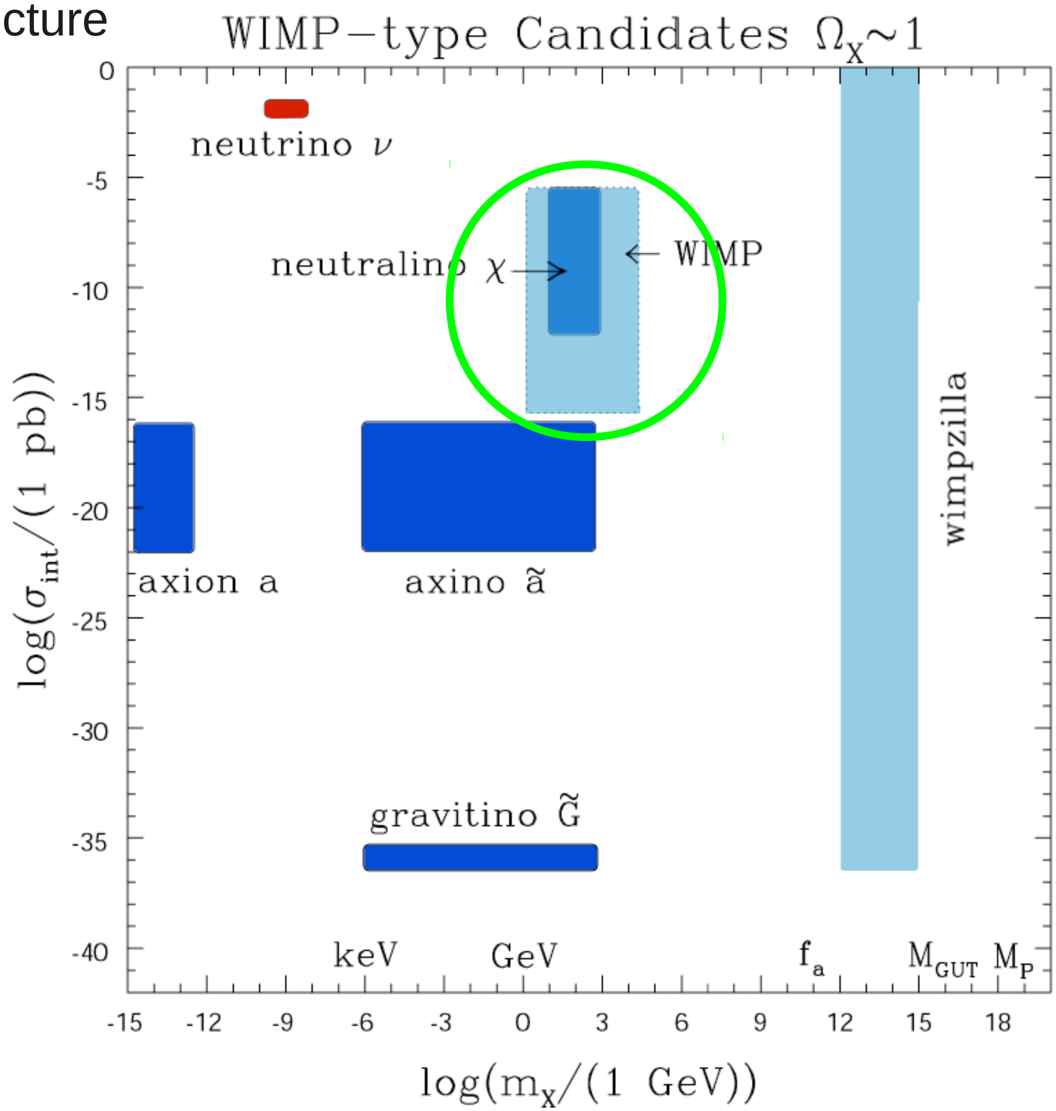
- weak scale cross section
- non-relativistic particle
- mass 100 GeV – 1 TeV

$$\frac{dn_\chi}{dt} = -\langle\sigma_a v\rangle \left[(n_\chi)^2 - \left(n_\chi^{eq}\right)^2\right] - 3Hn_\chi$$



Dark Matter candidates

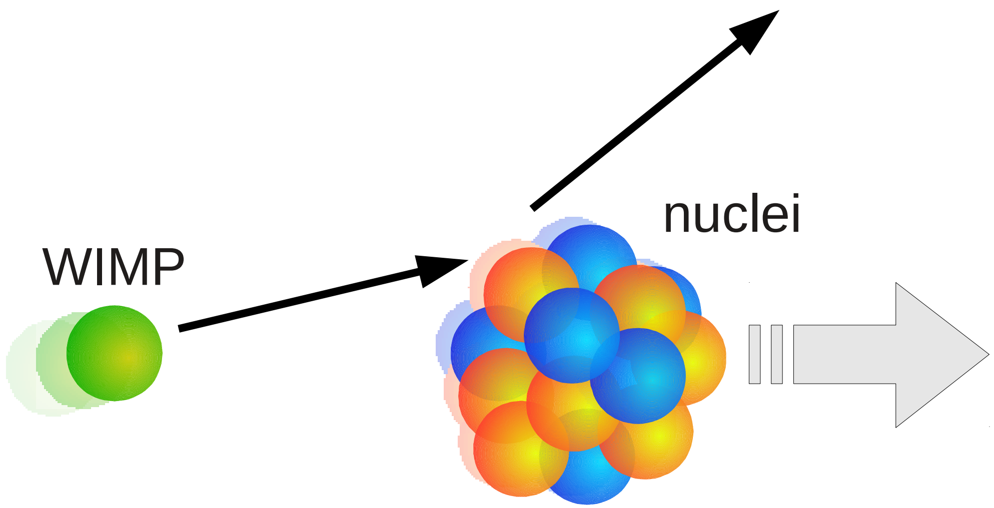
Quite old but still quite valid picture to see where to look for . . .



L. Roszkowski, 2004

The direct detection principle

WIMPs elastically scatter off nuclei in targets, producing nuclear recoils



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

$E_{recoil} \lesssim 100$ 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: $E_0 = \frac{1}{2} M_\chi v_0^2$ ~ 30 keV

Differential rate

WIMP-nucleus cross section (model dependent, spin)

0.3 GeV/cm³

Nuclear form factor (depends on atomic nuclei)

Expected spectrum: $$\frac{dN}{dE_R}(t) = \frac{\rho_\chi}{m_\chi} \frac{\sigma_p |F(q)|^2 A^2}{2\mu_p^2} \int_{v_{\min}(E_R)}^{v_{\max}} d^3v \frac{f_\oplus(\vec{v},t)}{v}$$

WIMP-nucleus reduced mass

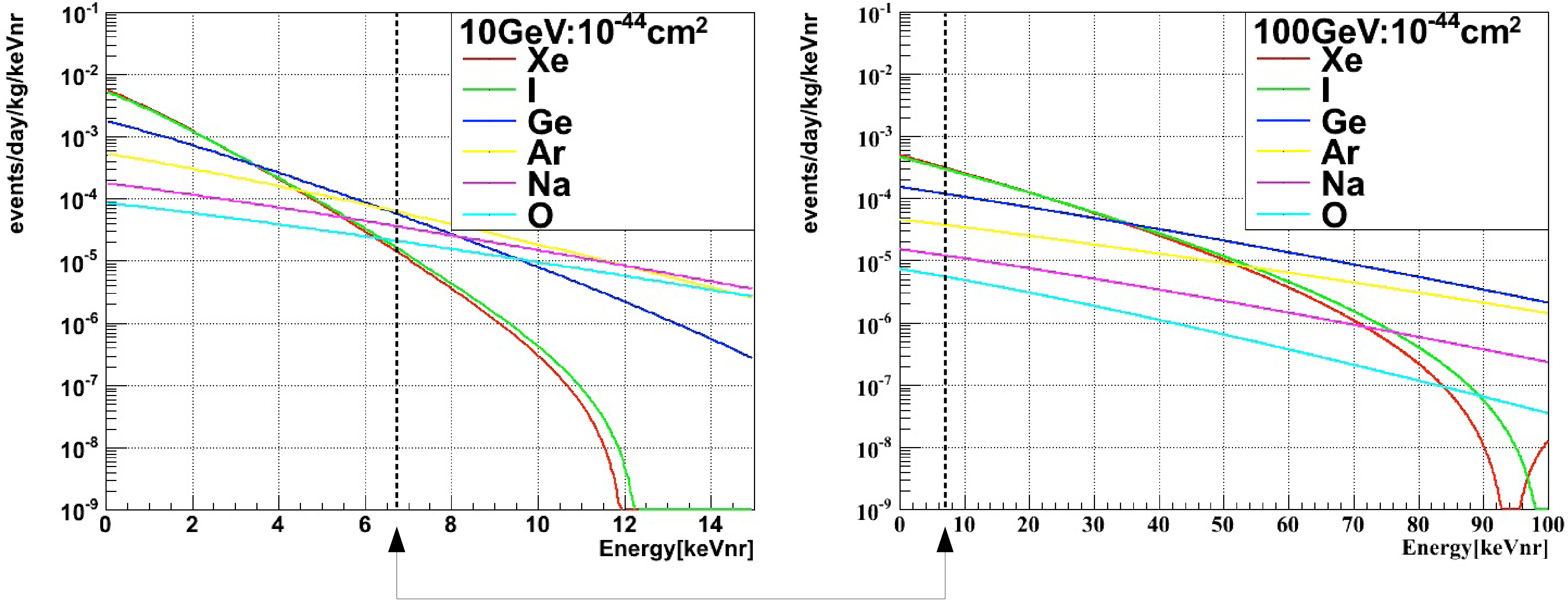
$$v_{\min} \approx \frac{\sqrt{ME_R/2}}{m_\chi}$$

Motion dynamics
- Maxwellian distribution for DM velocity is assumed
- v = velocity on target
- v_{min} = minimum required to produce recoil energy
- v_{max} = galactic escape velocity (~ 500 – 650 km/s)

Differential rate (spin-independent)

Low mass WIMP:
energy threshold is important

High mass WIMP:
detector mass is important

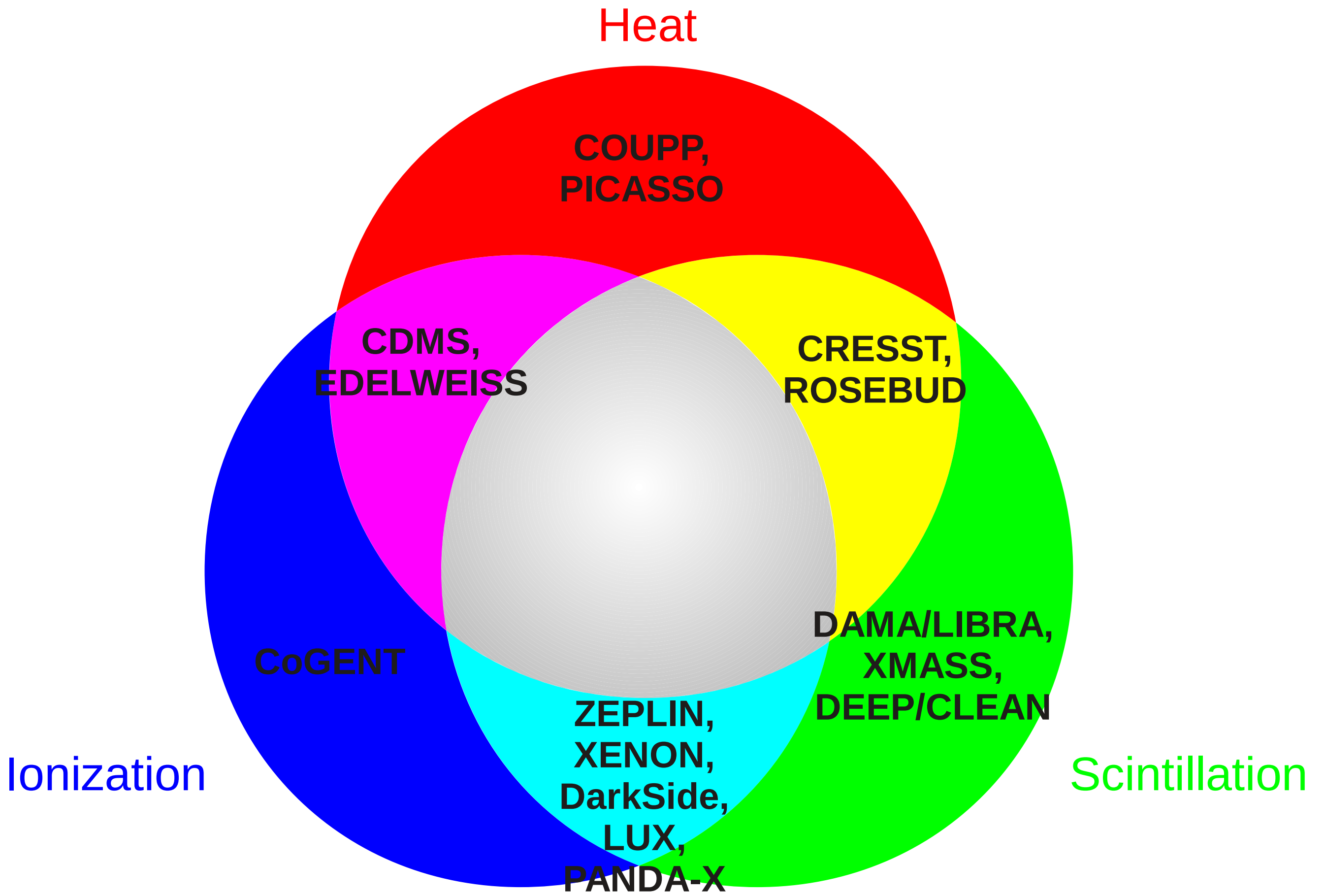


XENON100 energy threshold: 6.6 keV$_{nr}$

Plots from Yamashita, Blois2012

Detection techniques

Various targets are used (Ge, Xe, Ar, Ne, . . .)
Energy recoil is transferred to three possible phenomena: **scintillation**, **ionization**, **heat**
One (or two) among these three signals are used for particle detection.



Direct Dark Matter Search in the world

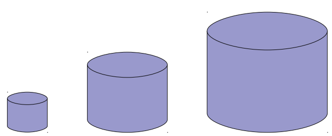
Direct Dark Matter Search in the world

Using xenon

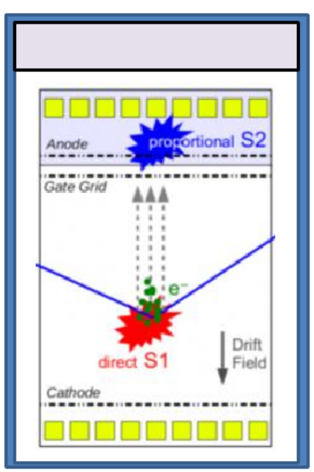
French participation

The XENON program

Science Objective : Explore WIMP Dark Matter with a sensitivity to Spin Independent cross section < $2 \cdot 10^{-47}$ cm^2 at 50 GeV/c^2 by 2017



Strategy : Phased program with detectors of increasing target mass (from O(10), to O(100), to O(1000) kg) and parallel studies on increasing light detection sensitivity and decreasing the overall background

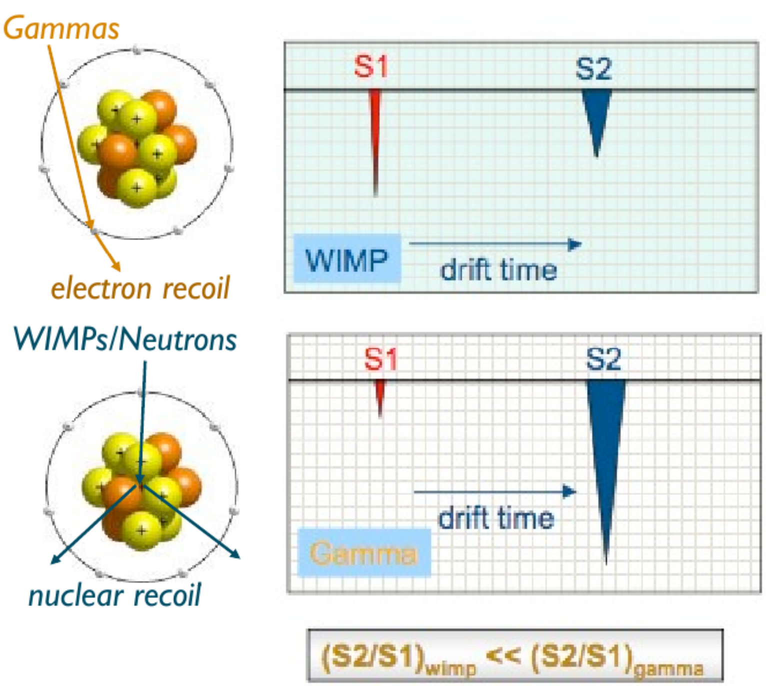


Detection technique : LXe (sensitive to both scalar and axial coupling) two-phase LXe TPC with simultaneous charge and light detection via PMTs with low radioactivity and QE > 30% at 178 nm

Background Reduction and Signal Discrimination : LXe self-shielding; fiducial volume selection thanks to 3D reconstruction; ER/NR distinguished via charge/light ratio; multi-scatter rejection

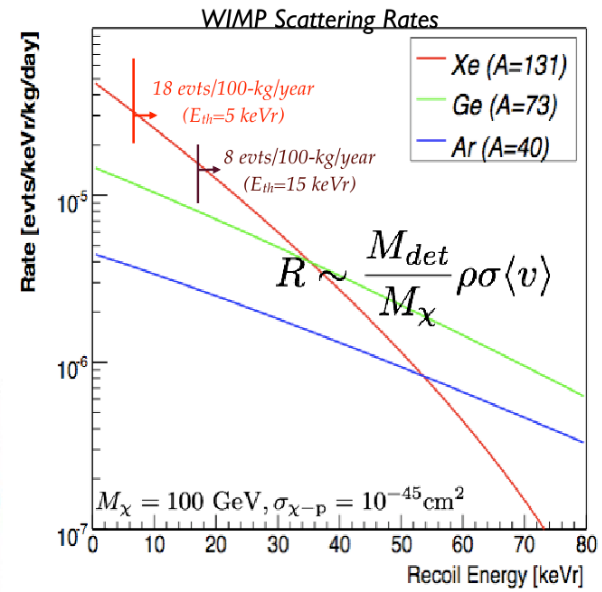
Advantages of two-phase xenon TPC principle

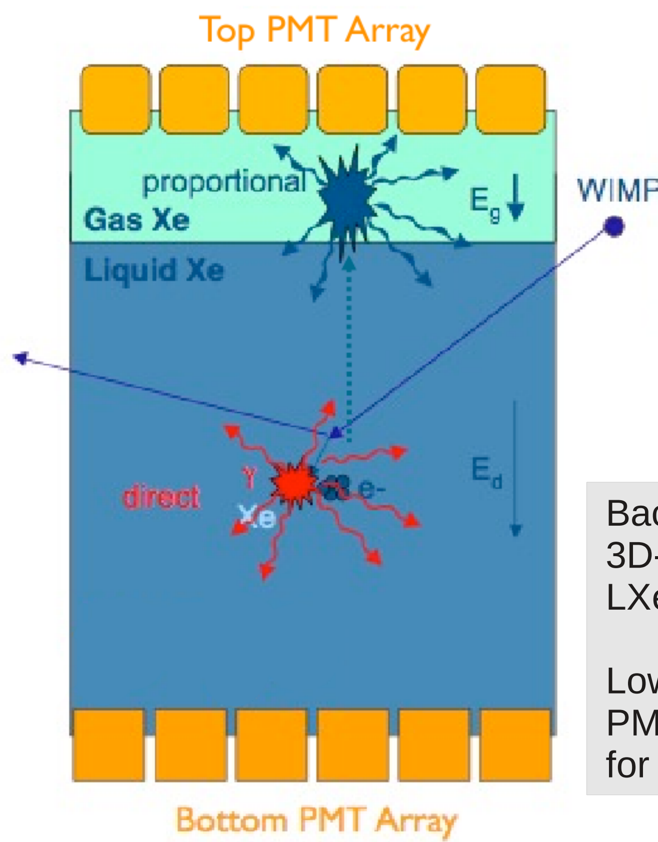
Background rejection: charge-to-light ratio



Charge & Light: highest yield among noble liquids and best self-shielding

Big nucleus (A~131): good for SI + SD sensitivity





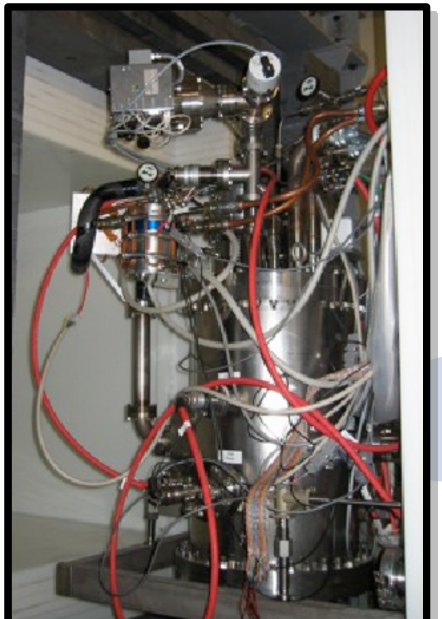
Scalability: massive target at modest cost

Intrinsically pure: no long-lived radioactive isotopes

Background rejection: 3D-event imaging, LXe self-shielding

Low energy threshold: PMTs within liquid for efficient light detection

The XENON program roadmap: growing in target size...



XENON10

Achieved (2007)

σ_{SI} = 8.8 · 10^{-44} cm^2 @ 100 GeV/c^2

Phys.Rev.Lett. 100 (2008) 021303

Light DM:

σ_{SI} = 7 · 10^{-42} cm^2 @ 7 GeV/c^2

Phys.Rev.Lett. 107 (2011) 051301

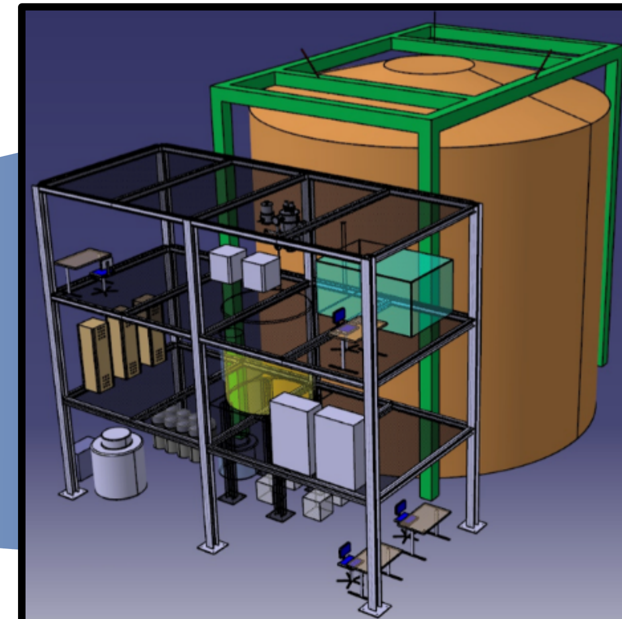
XENON100

Achieved (2012)

σ_{SI} = 2.0 · 10^{-45} cm^2 @ 55 GeV/c^2

Accepted by PRL:
E. Aprile et al. (XENON100),
arXiv:1207.5988

In operation since 2009



XENON1T

Projected (2017)

σ_{SI} = ~ 10^{-47} cm^2

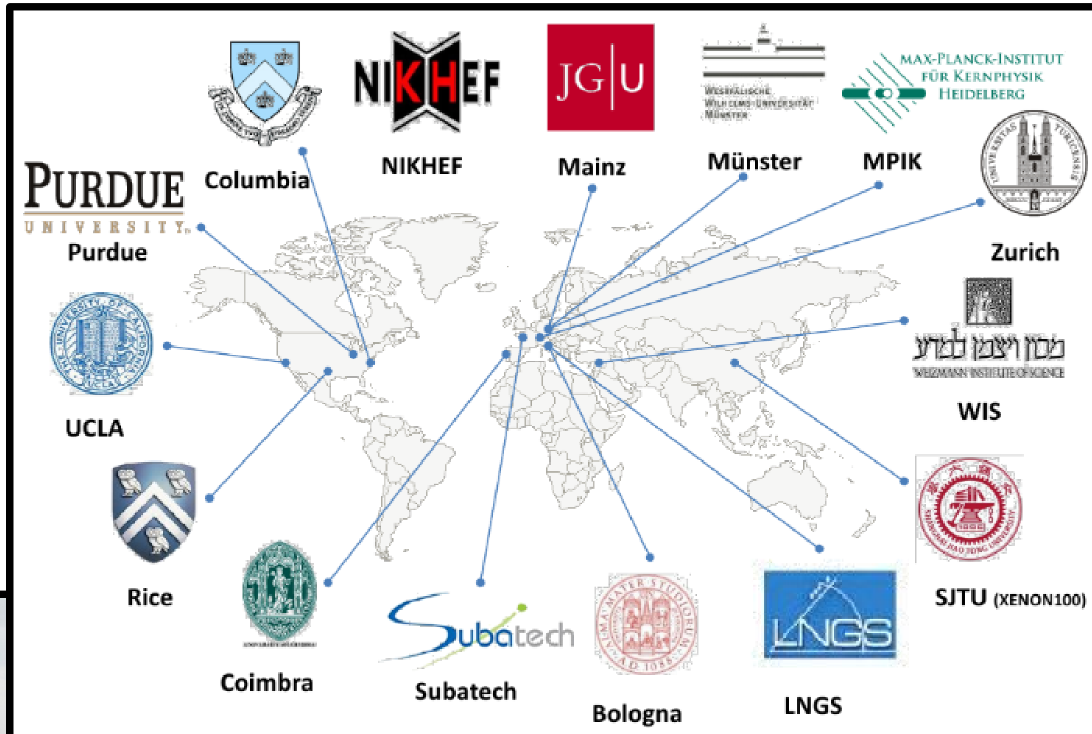
In advanced design phase
Construction in March 2013

Xe XENON Dark Matter Project

… and people

The XENON Collaboration

15 Institutes
~100 members

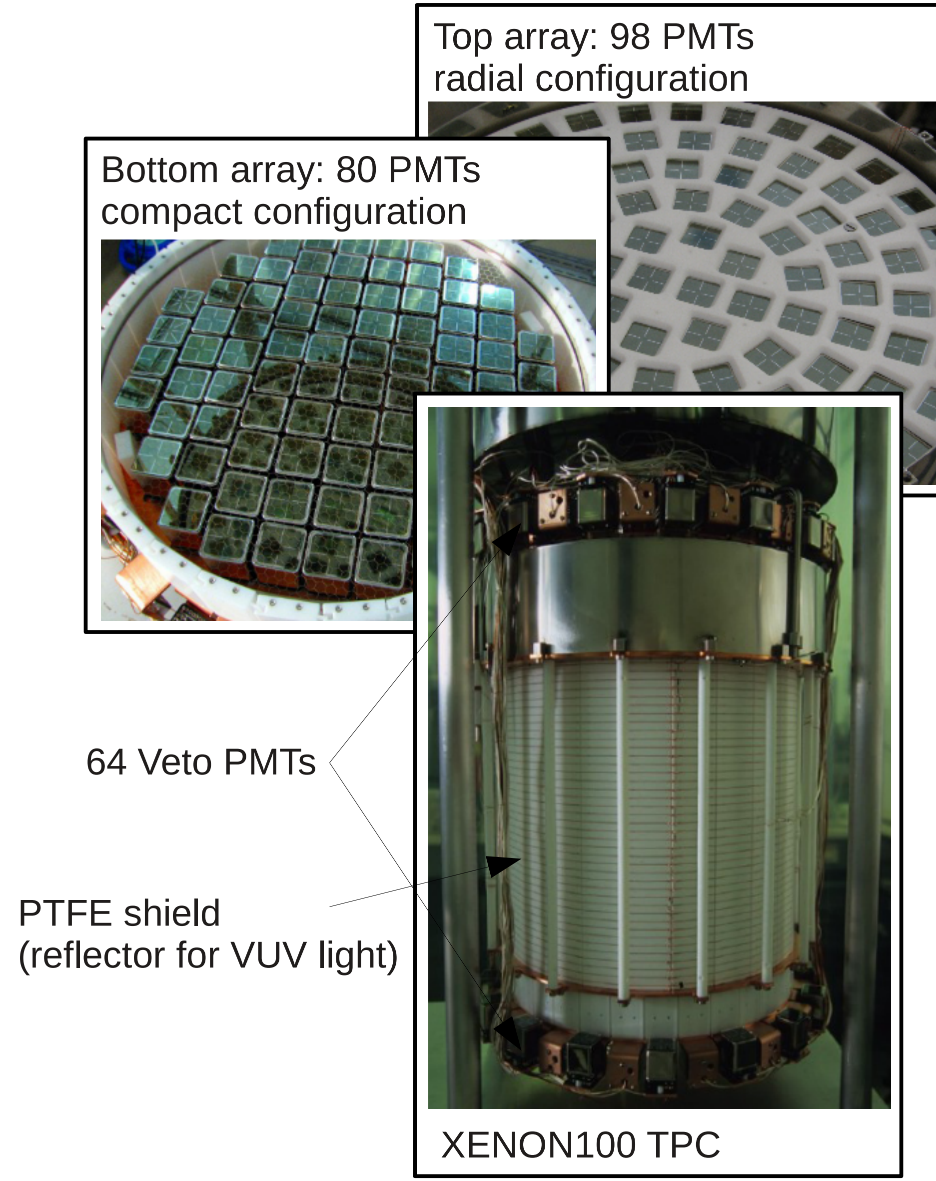


XENON100 detector

- 161 kg in total, 62 as target, 34 kg of which used as fiducial volume
  - → 10x more than XENON10
- Self-shielding properties
  - → 100x less background than XENON10
- TPC 30 cm drift x 30 cm diameter
- 1” square PMTs with ~1 mBq (U/Th)
- 242 PMTs are used in total
  - Measuring light and charge with PMTs
  - PMTs used also as active veto
- Improved passive shield system
- Dedicated Kr distillation column
- Electric drift field ~ 0.53 kV/cm
- Materials selected for low radioactivity

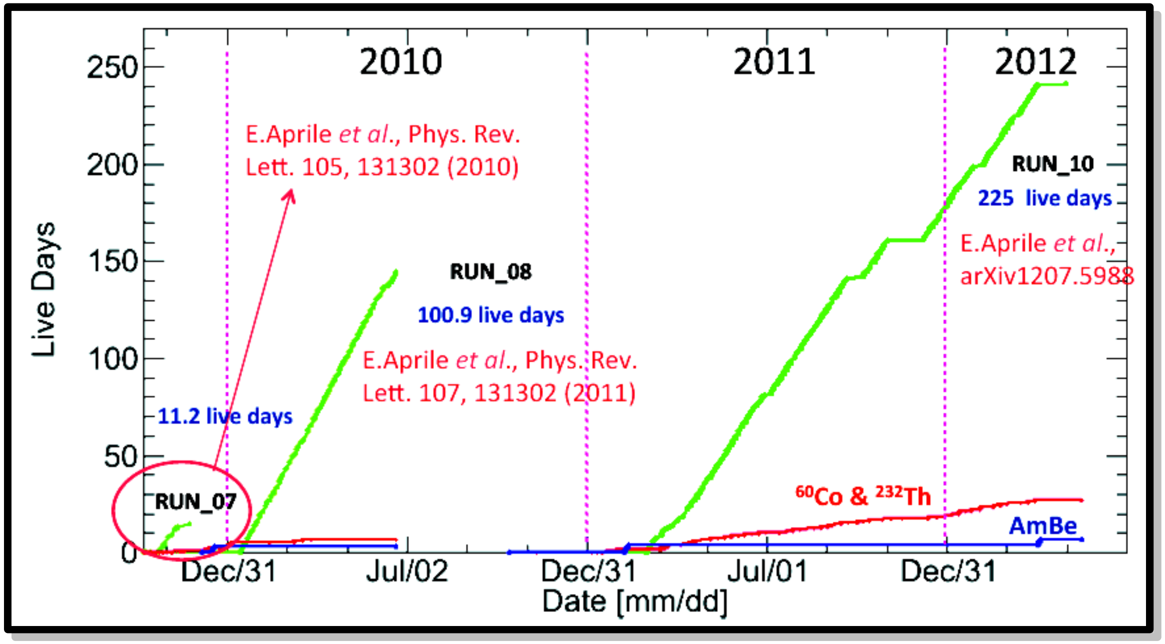
Scintillation signal (S1) detected by top and bottom arrays

Secondary scintillation (S2, from ionization signal) detected by top array



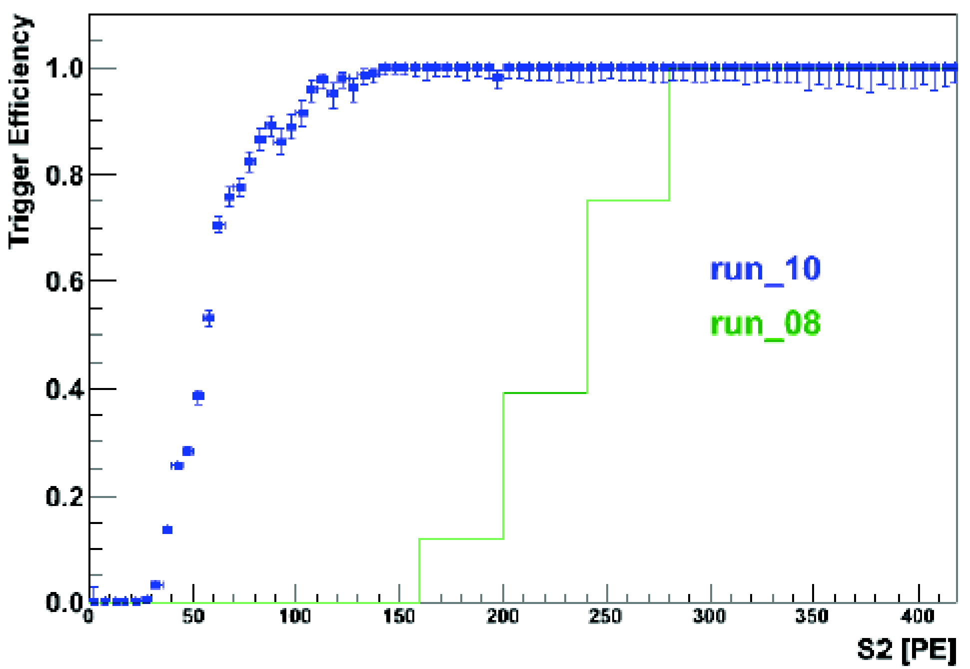
New data taken in 2011 - 2012

- **New data taking** for Dark Matter search is from March 1st 2011 up to May 22nd 2012. **More than one year** of continuous operation!
- A total of **224.6 live days** of data collected
- Excellent Detector Performance and Stability
- **Kr** in Xe reduced by a factor 20 by cryogenic distillation
- Increased **Gamma** calibration statistics
- Increased **Neutron** calibration statistics (two exposure campaigns: at beginning and at about the end of the run)
- Improved S2 **trigger efficiency**
- Lowered S1 **threshold**

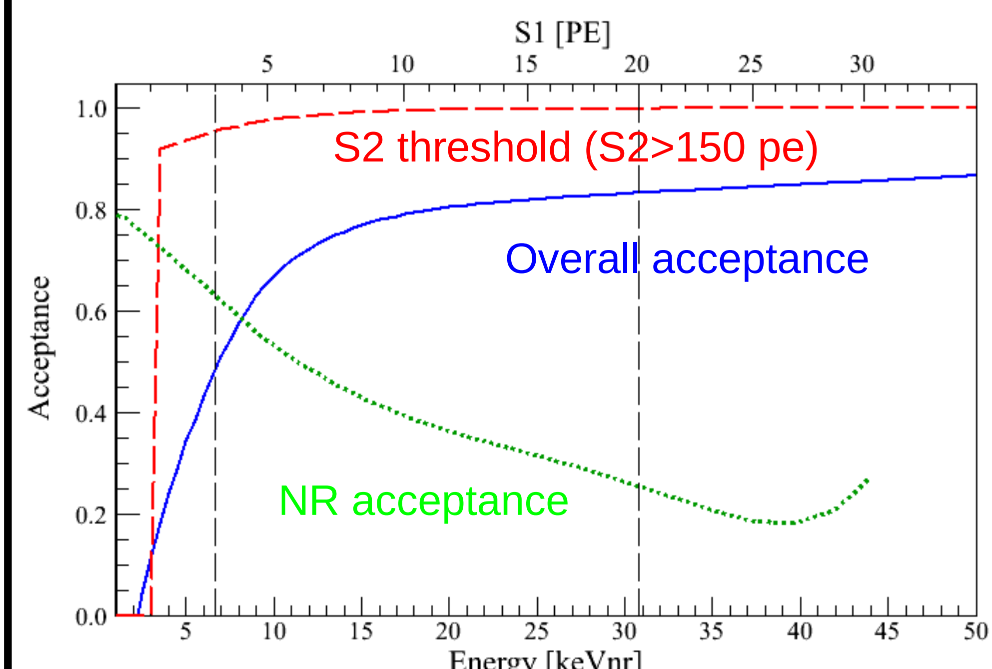


Improved S2 trigger efficiency and lowered S1 threshold

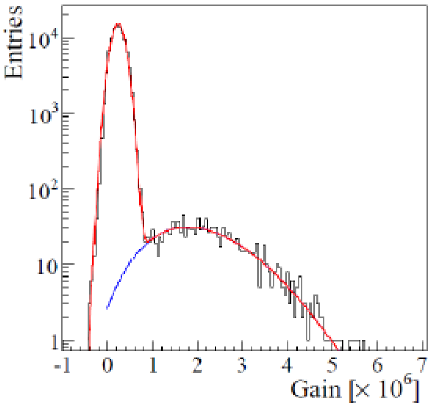
- 100% efficiency above S2 = 150 photoelectrons (~10 electrons!)
- ability to trigger on smaller signals



- S1 energy threshold lowered from 4 pe (8.7 keVr) to 3 pe (6.6 keVr)



Calibrations

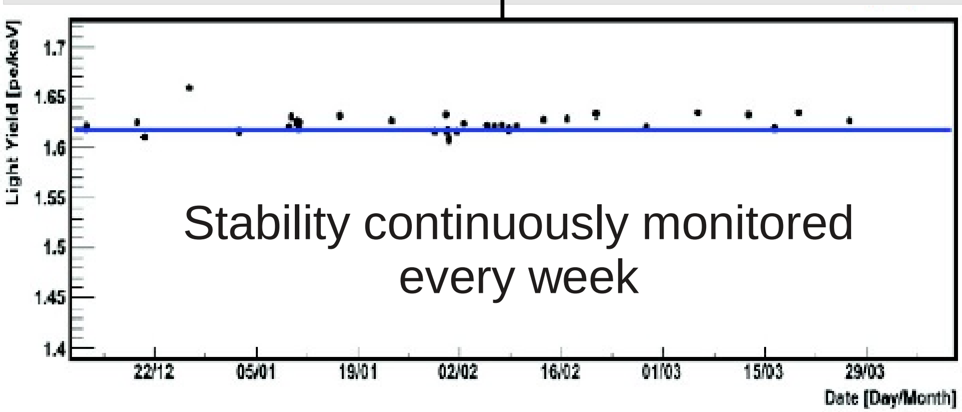


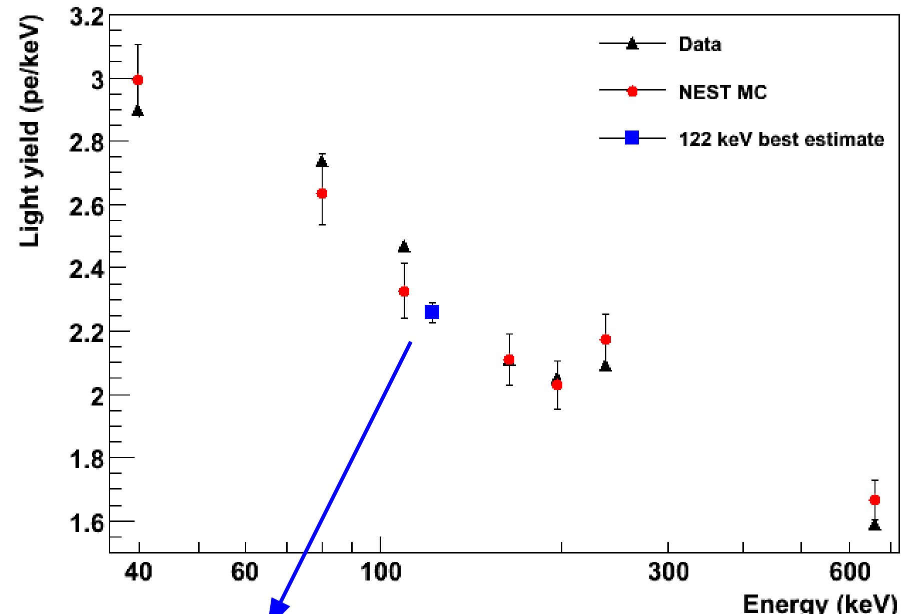
PMT gain calibration

- Equalized to a mean gain of ~2.6 x 10^6 by adjusting the PMT HV
- Determined by stimulating single PE emission by using a blue LED (λ = 470 nm, ν = 100 Hz)
- Optical fibers used to transport the light in the TPC
- A calibration of all 242 PMTs **every week**
- Average gain stable during physics run **stable within 2%**

Gamma calibrations for the yield of primary light

- 40 keV (^{129}Xe (n,n'γ)^{129}Xe), by ^{241}AmBe
- 80 keV (^{131}Xe (n,n'γ)^{131}Xe), by ^{241}AmBe
- 164 keV (^{131m}Xe), by ^{241}AmBe
- 236 keV (^{129m}Xe), by ^{241}AmBe
- 662 keV (^{137}Cs)





input for L_{eff} :

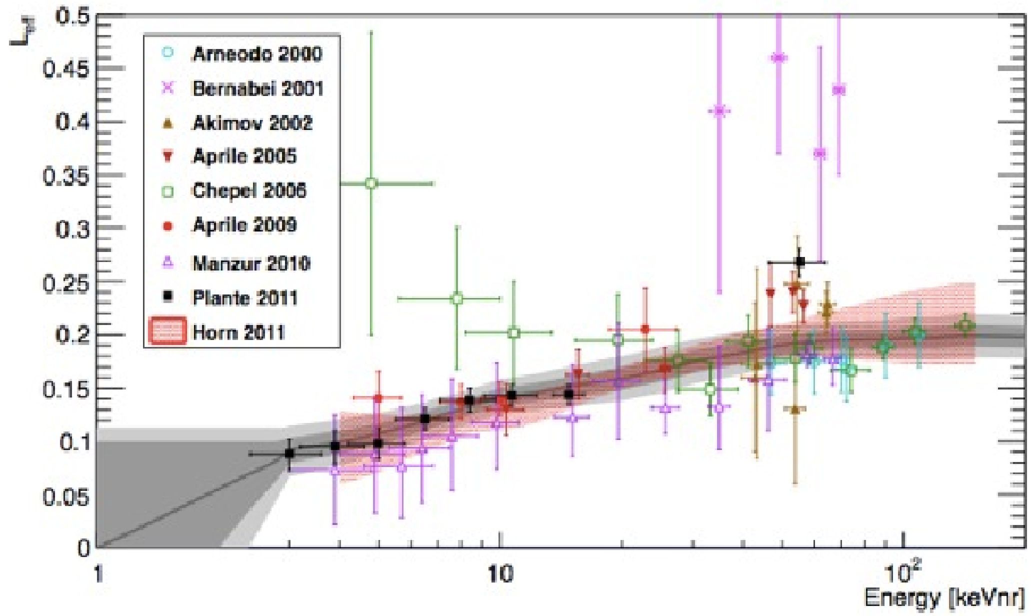
2.28±0.04 pe/keVee with field

Scintillation efficiency for Nuclear Recoils

- Energy scale is set by using scintillation signal (*S*1): $E_{\rm nr} = \frac{S1}{L_{y,\rm er}} \frac{1}{\mathcal{L}_{\rm eff}(E_{\rm nr})} \frac{S_{\rm er}}{S_{\rm nr}}$

- $L_{y,er}$ is the light yield for electron recoils of 122 keV_{ee}
- S_{nr} and S_{er} are the quenching factors due to drift field
- L_{eff} is the relative scintillation efficiency and it is given by:

$$\mathcal{L}_{\rm eff}(E_{\rm nr}) = \frac{L_{y,\rm er}(E_{\rm nr})}{L_{y,\rm er}(E_{\rm ee} = 122\ \rm keV)}$$

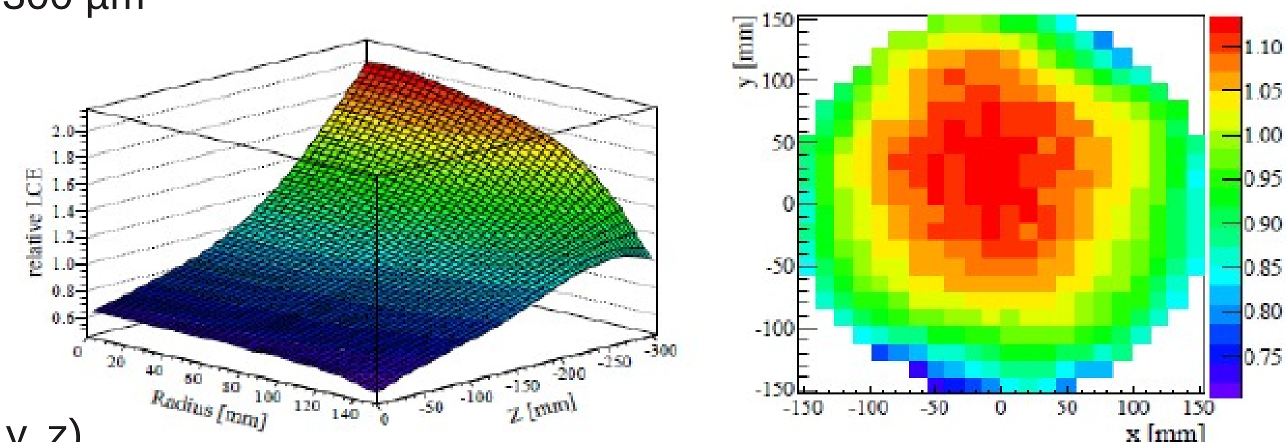


Plante et al., Phys. Rev. C 84, 045805, 2011

Data reconstruction and corrections

3D position reconstruction

- X,Y from the light on the Top PMTs
- Z from the measured drift time (dt = $t_{S2} - t_{S1}$, v_{drift} ~1.74 mm/μs @ 533 V/cm)
- Three different algorithms studied: Neural Network (used), Support Vector Machine, χ^2
- Achieved resolution: δr < 3 mm, δZ < 300 μm



E. Aprile et al. (XENON100), Astropart. Phys. 35:573-590,2012

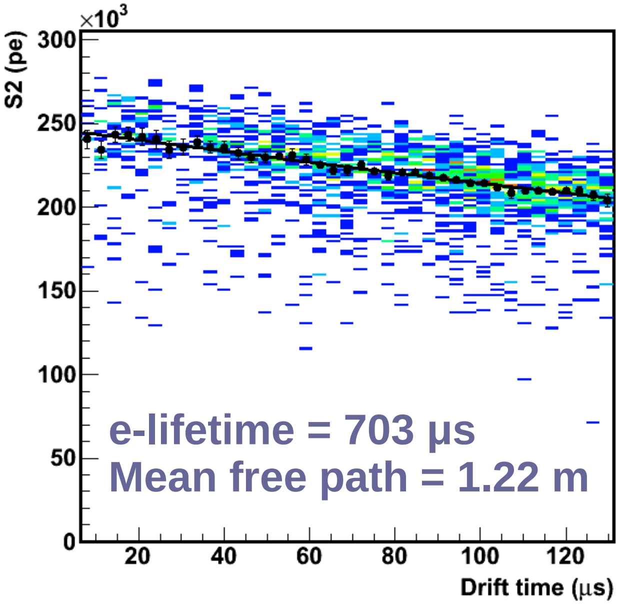
3D corrections

- S1 Response
    - Light collection efficiency map (x,y,,z)
    - LY @ 122 keVee

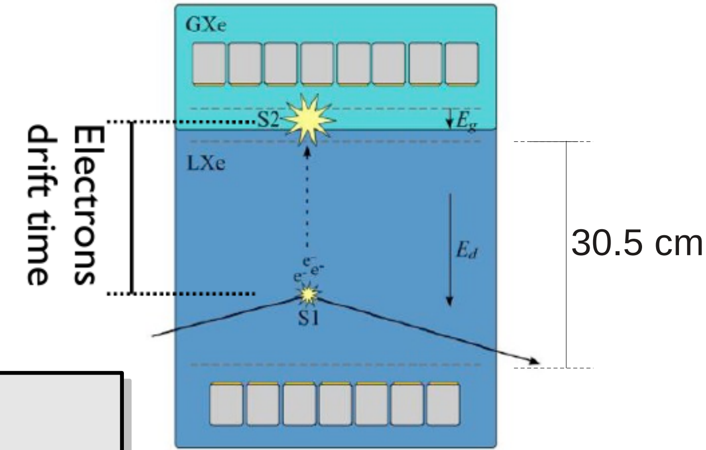
- S2 Response
    - Electron attachment by impurities in LXe (z)
    - Variation of the S2 light collection efficiency (x,y)

- Corrections obtained with ^{137}Cs and AmBe (40 keV inelastic) ^{131m}Xe (164 keV) with an agreement better than 3%.

Electron Lifetime during 2011-2012 Dark Matter search

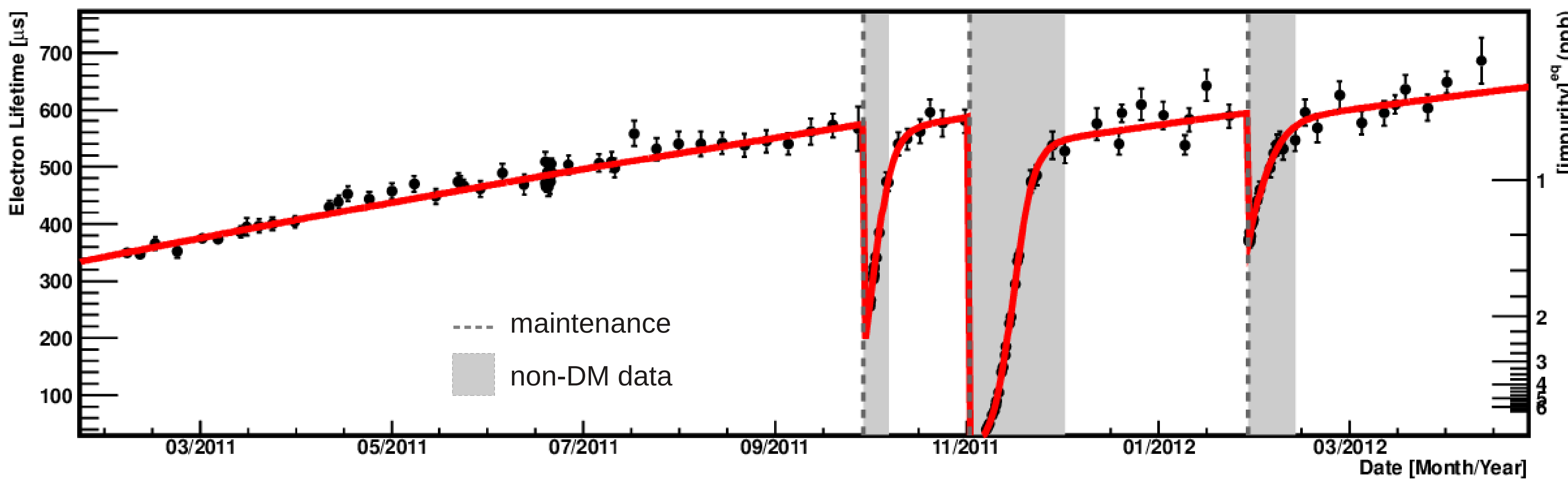


Amplitude of S2 signal vs Drift Time



Ultra high purity liquid xenon!

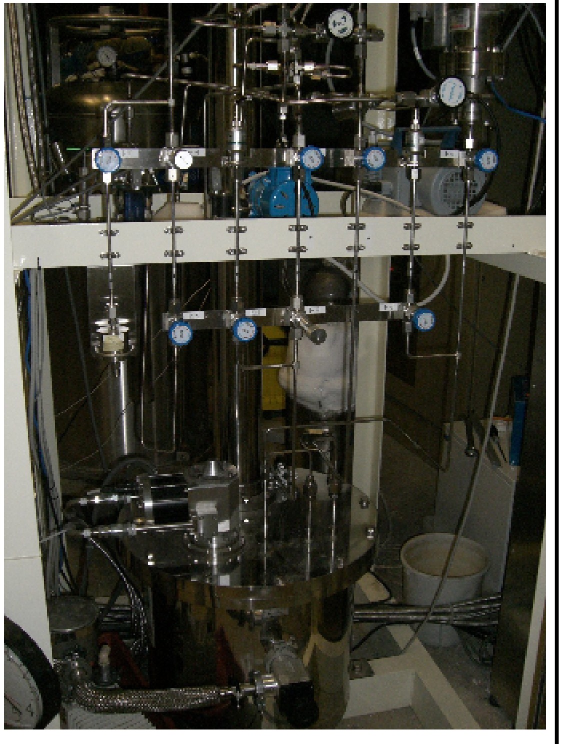
We reached 0.7 ppb O_2 - equivalent



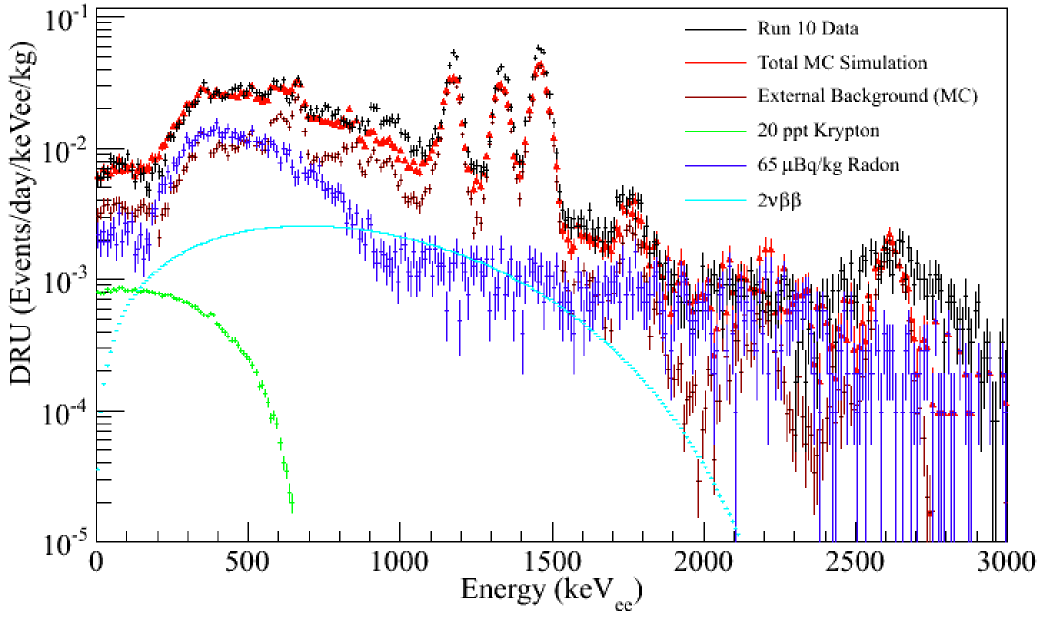
Significantly reduced background

- Kr85 is an internal background, cannot be removed by self-shielding
- Long-lived β^- emitter (99.6%), E_{max} = 687 keV β^- decays indistinguishable from gamma background
- Sensitivity of published data (PRL107, 2011) limited by high Kr/Xe level from accidental leak

- In Fall 2010, Kr removed by distillation of the Xe with on-site distillation column
- Kr/Xe reduced significantly! Dedicated measurement with RGMS gives for current search a Kr/Xe level of (19±1) ppt
- Similar value from delayed coincidence analysis



Kr distillation in XENON100



- In WIMP search region background is around 5 x 10^{-5} evts/kg/keV/day after S2/S1 discrimination
- Factor 100 less than XENON10 and than other DM experiments (see PRD 83, 2011)

Background expectation

Electronic recoil background

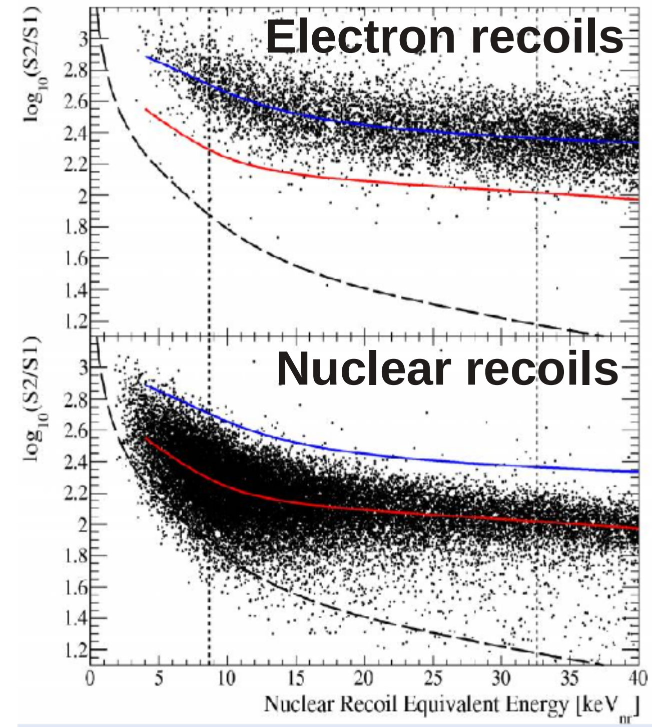
- Electronic recoil estimation done with ^{60}Co and ^{232}Th
- Data collected all the time for a total of 40 effective days
- 35 times more statistics than in data used for Dark Matter search
- Expected events in a benchmark region : **0.79±0.16**

Neutron recoil background

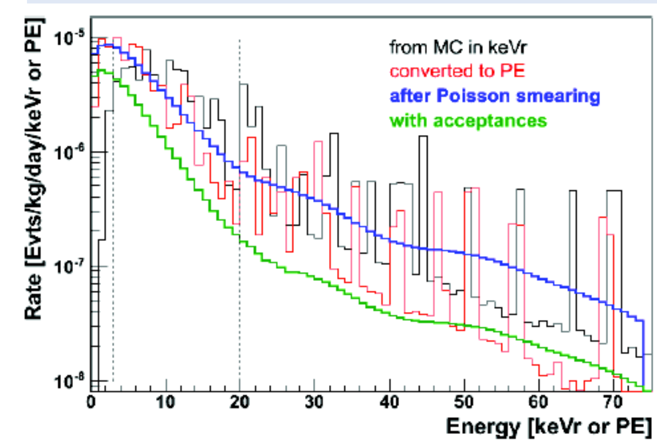
- Calibration done with ^{241}AmBe exposure
  Two exposure campaigns:
  one at beginning and one at the end of run
- Nuclear recoil estimation done with Geant4 simulation
- Expected events in a benchmark region : **$0.17^{+0.12}_{-0.07}$**

Total background

In the benchmark region we expect in **total 1.0±0.2 events**



E. Aprile et al., Phys. Rev. Lett 105, 131302 (2010)

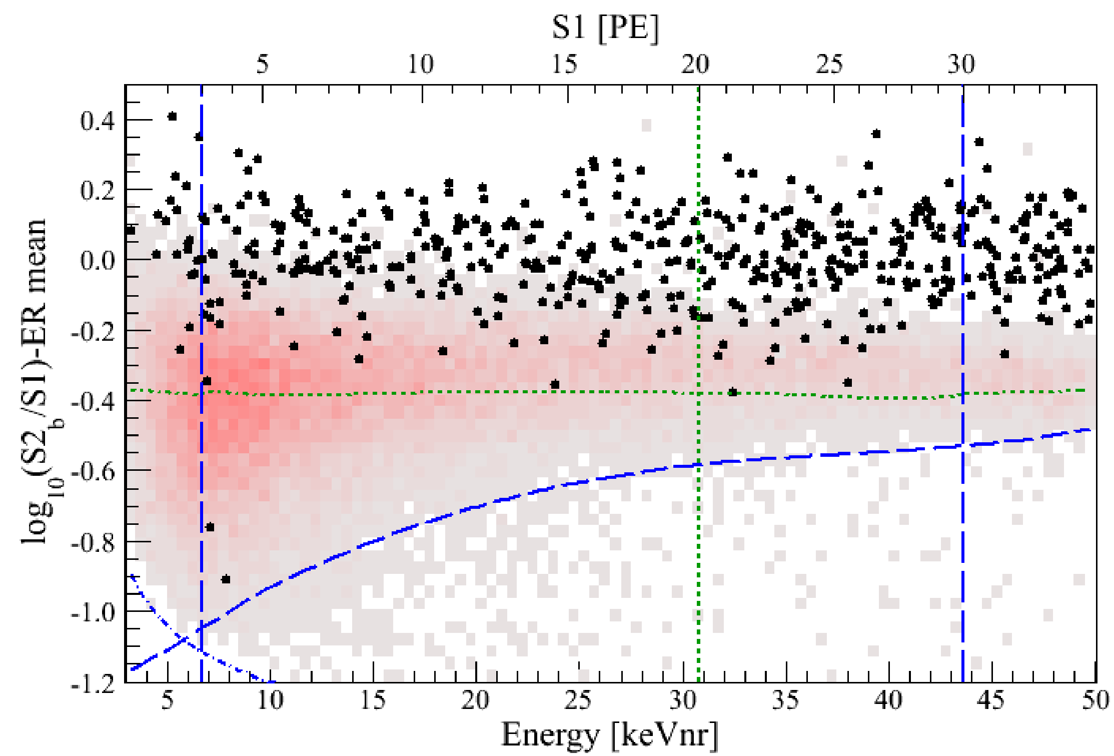


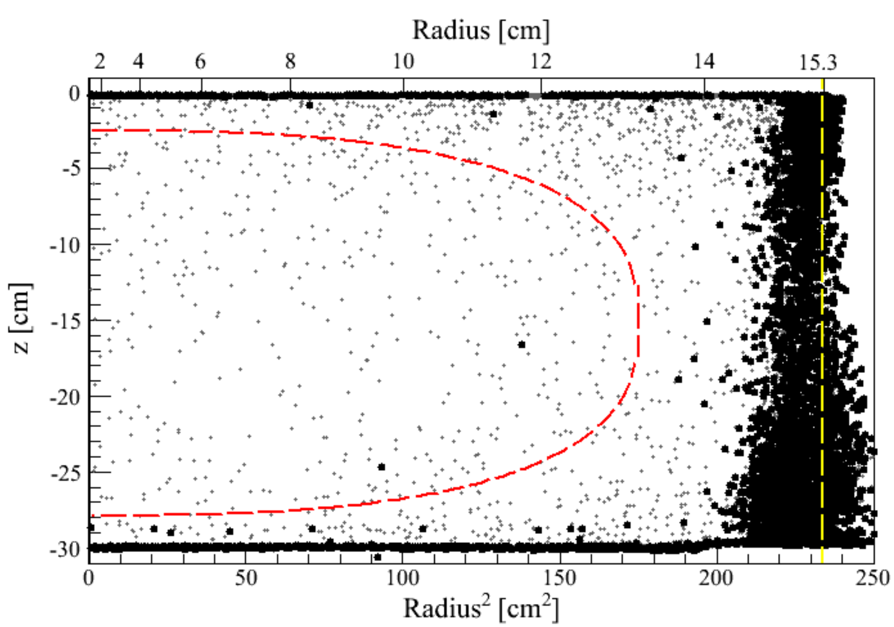
Blind analysis

XENON100 did a blind analysis

Event discrimination by S2/S1 separation

Defined WIMP searching region:
- S1 with benchmark region (3 - 30 pe)
- S2 threshold cut (S2 > 150 pe)
- 99.75 % ER rejection line





Event rejection by defining a 34kg super-ellipse

Double scatters excluded

Absence of WIMP signal

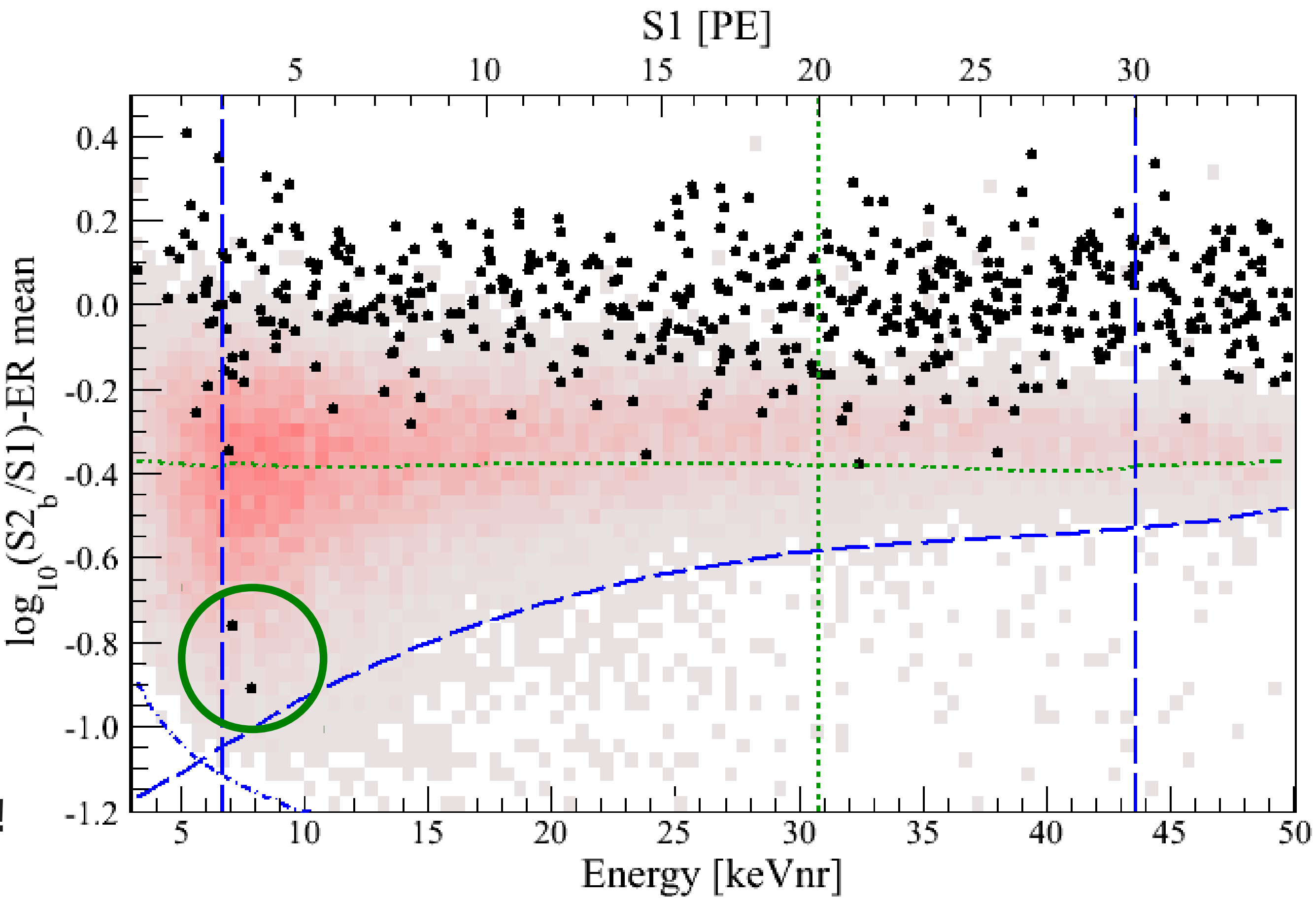
Profile Likelihood analysis:
- S1 range from 3 – 30 pe
- Signal region above 97% NR quantile

Crosscheck: analysis using benchmark region
- S1 range from 3 – 20 pe
- Signal region above 97% NR quantile
- Signal region below 99.75 % rejection line (ER)

After unblinding,
2 events are found
in the benchmark
WIMP search region!

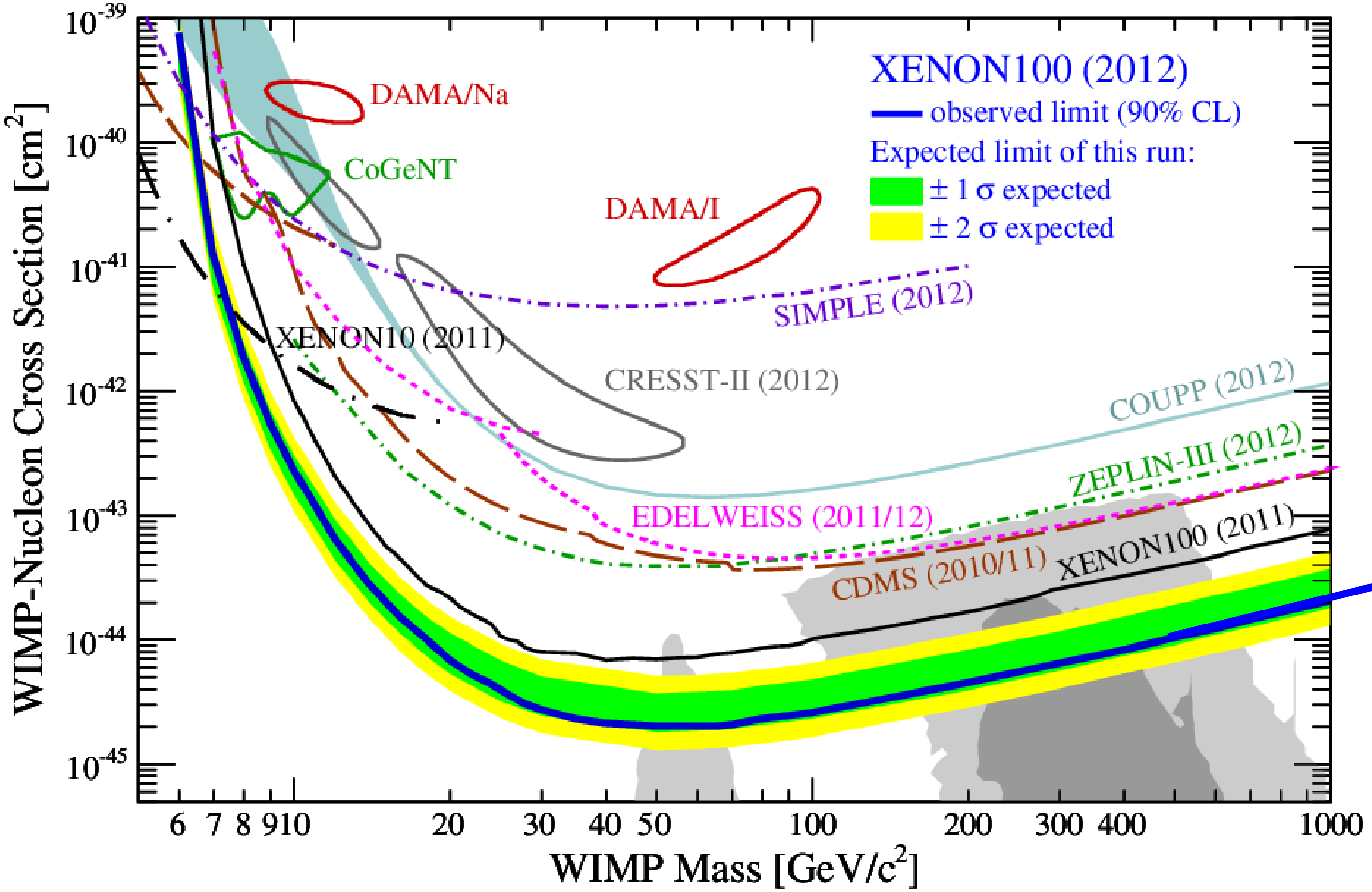
- Both events are located between 3 pe to 4 pe
- Waveforms are of high quality
- Both events at the lower edge of the NR band
- Probability that 2 events fluctuate over the background expectation is 26.4%

No WIMP signal !!!



Latest SI limit from XENON100

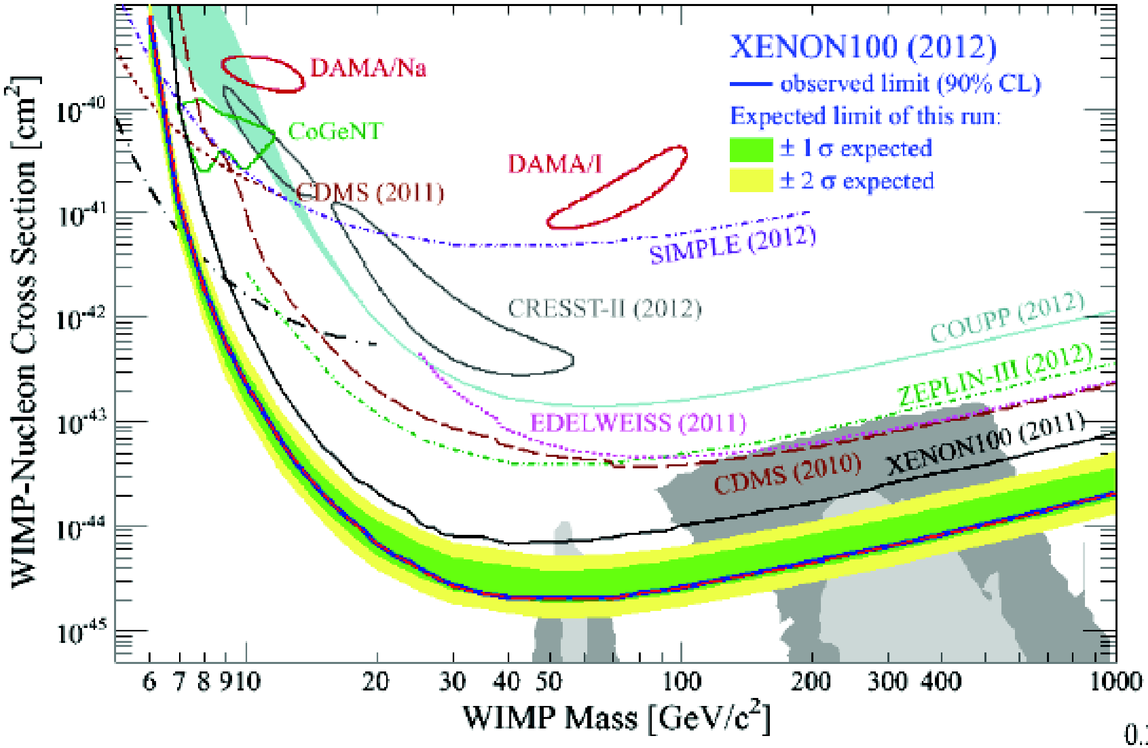
Accepted by PRL : E. Aprile et al. (XENON100), arXiv:1207.5988

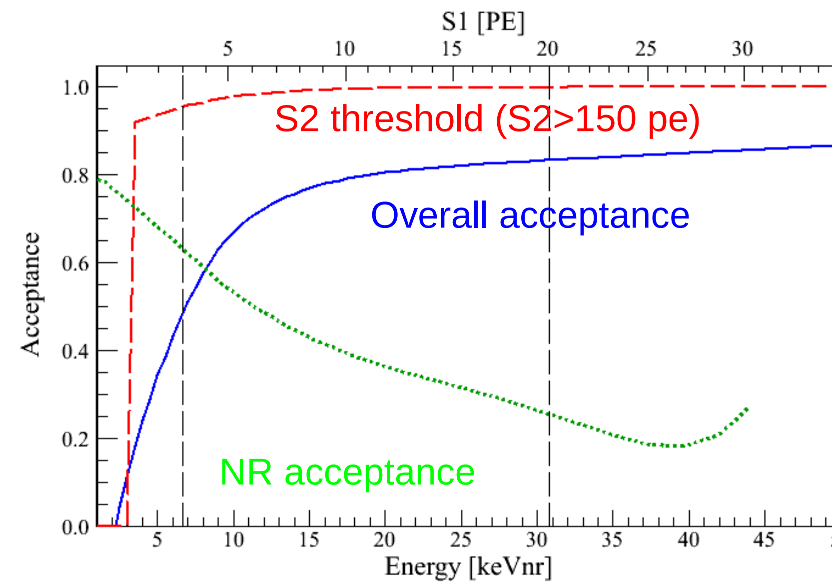


Spin-independent WIMP-nucleon cross-section

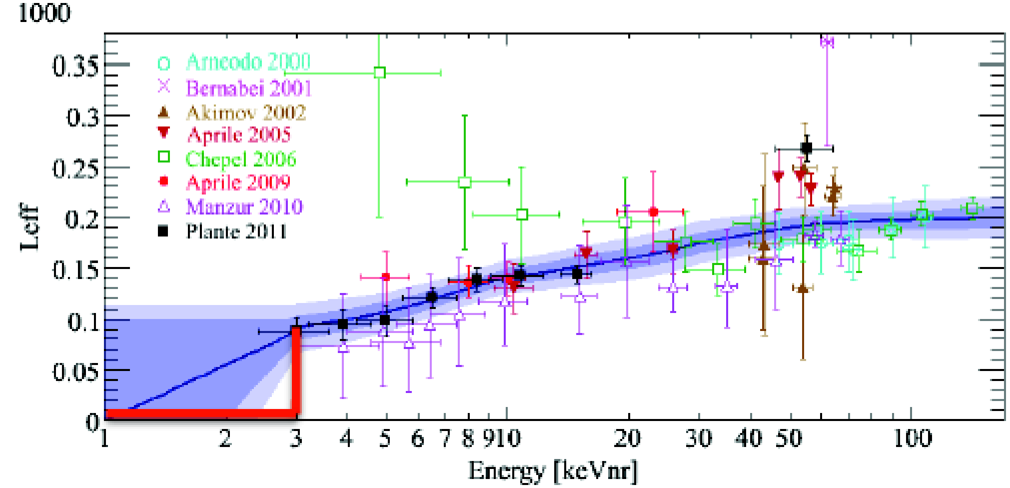
Limit at M_χ = 55 GeV/c²:
2.0 x 10^{-45} cm² (90% C.L.)

The dependency in L_{eff}

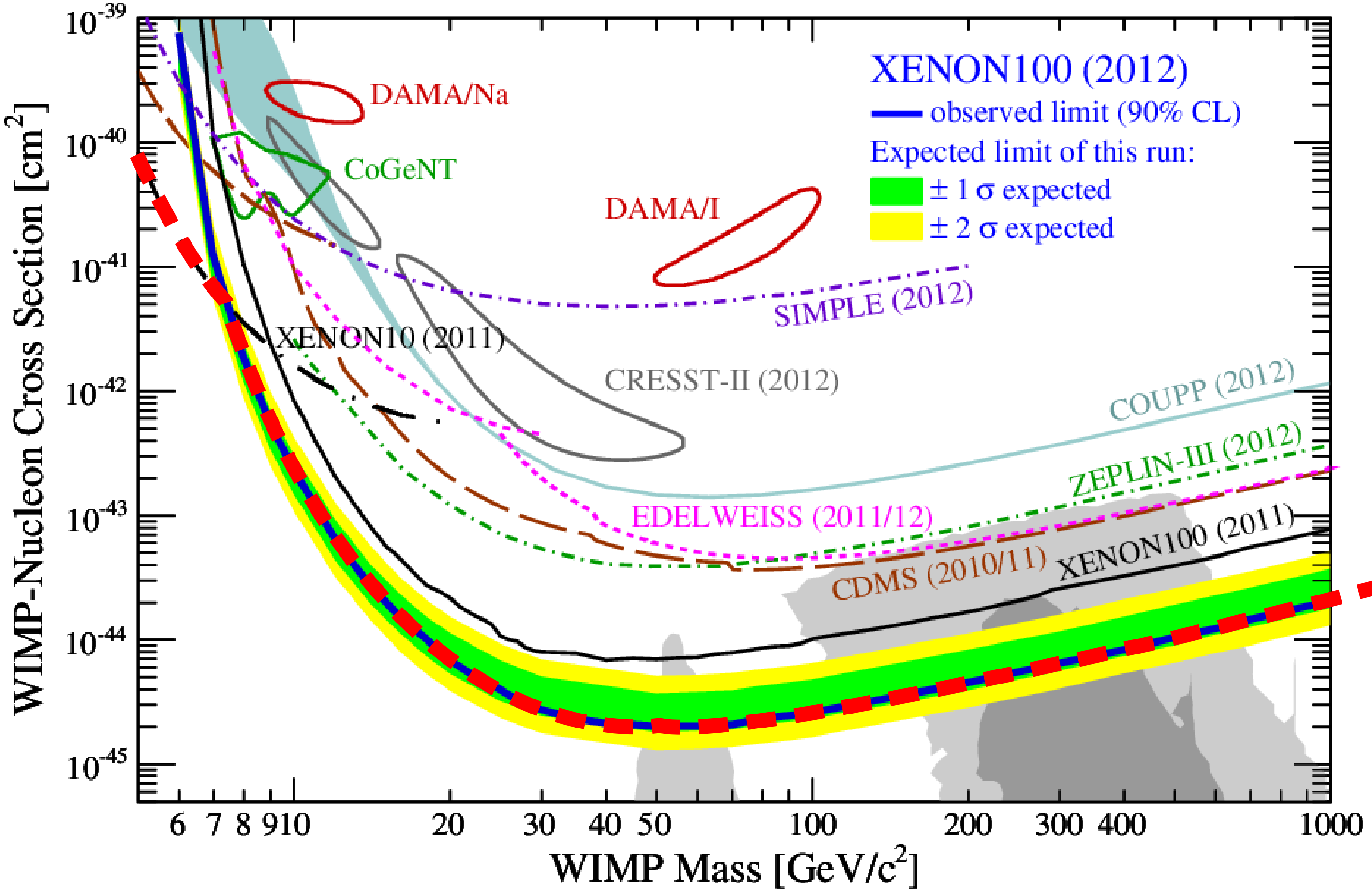




The impact of uncertainty in L_{eff} on the limit is very small (<5%)



Direct Dark Matter Search from Xe-based experiments



Spin-independent WIMP-nucleon cross-section

Low-mass (XENON10):

Limit at M_χ = 7 GeV/c²: 7 x 10^{-42} cm² (90% C.L.)

High-mass (XENON100):

Limit at M_χ = 55 GeV/c²: 2.0 x 10^{-45} cm² (90% C.L.)

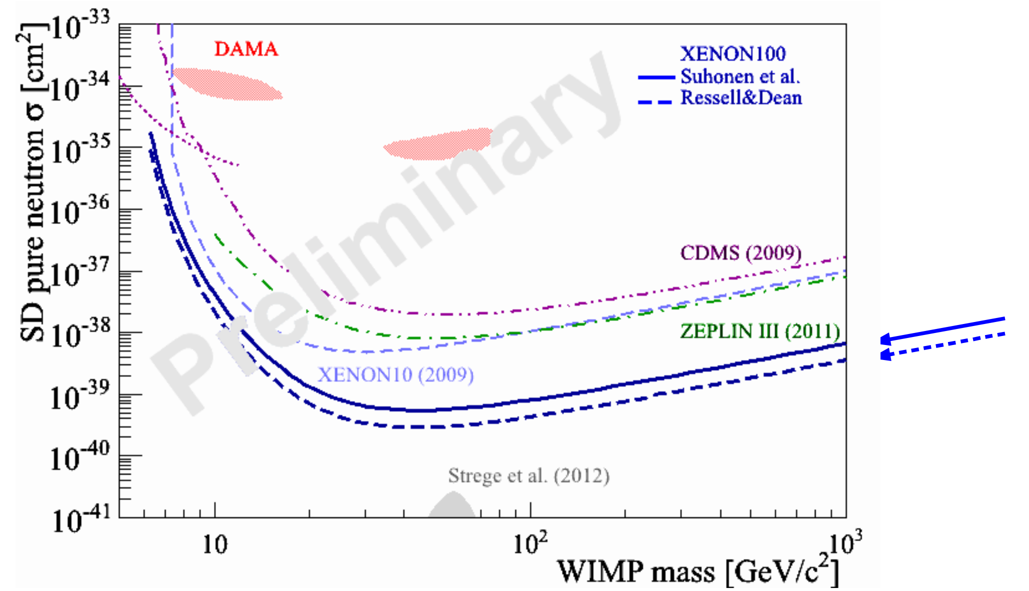
Xe XENON Dark Matter Project

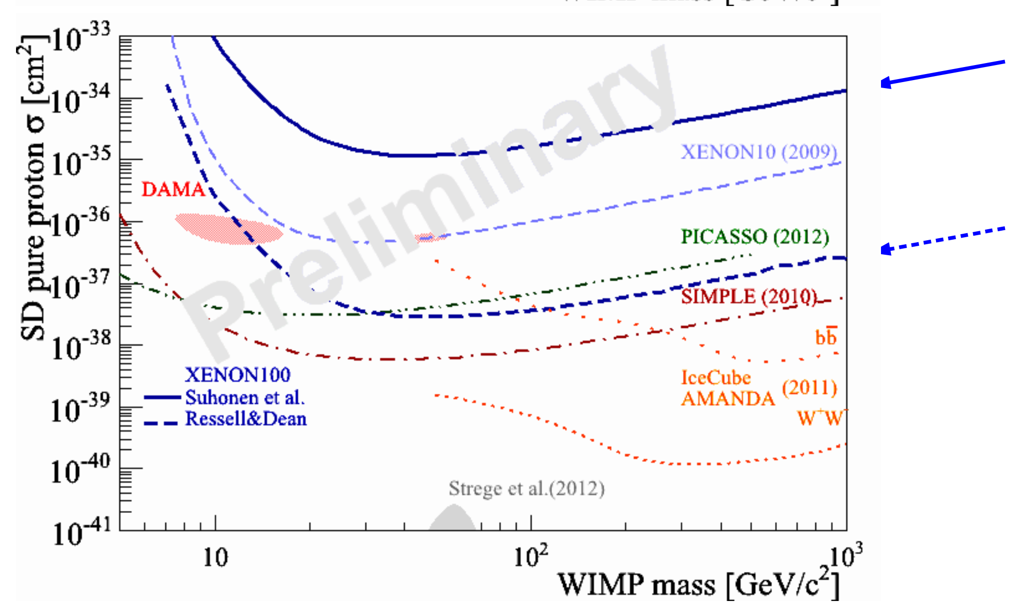
Forthcoming papers: new XENON100 Spin Dependent Limit

Analysis for SD coupling of WIMPs to ^{129}Xe (26.2%) and ^{131}Xe (21.8%) (unpaired n)

- Paper in internal referee phase
- So far, analysis **only from 2010 data taking** and event selection as for SI analysis
- Profile Likelihood analysis used: Phys. Rev. D 84, 052003 (2011)
- So far, results by using 2 nuclear models:
  - Suhonen et al. (——)
  - Ressell&Dean (-------)

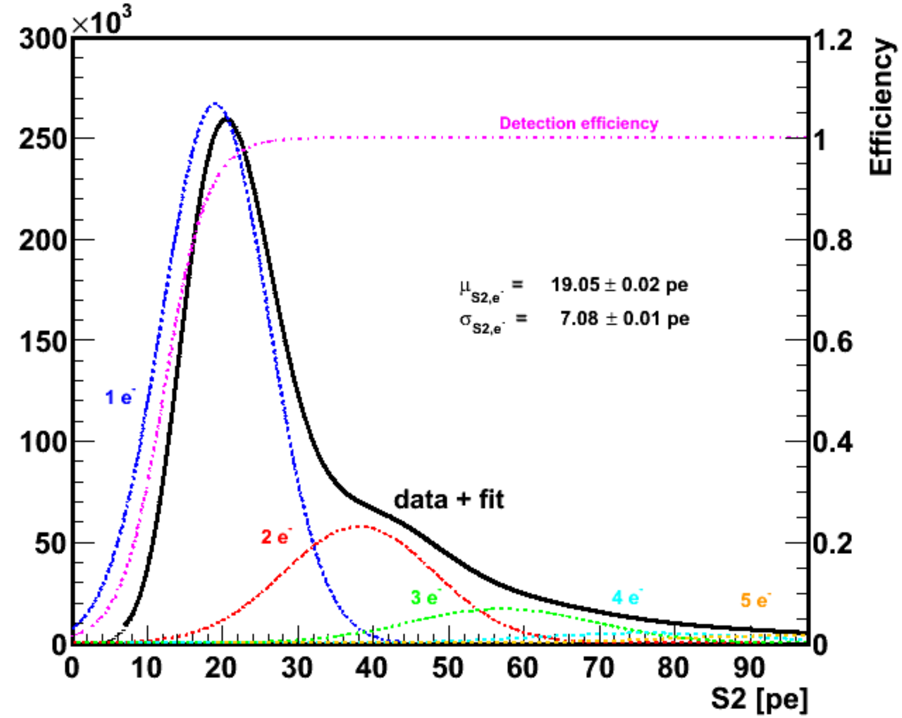
  The new model from Mendez at al. will be used (arXiv:1208.1094), not yet showed
- New best limits for pure neutron coupling (relatively small impact of nuclear model)
- Pure proton coupling (strong dependence on nuclear model used)





Forthcoming physics papers

- Single electron signal study



- Gamma background "annual modulation" analysis

- And much more...

XENON100 status

Analysis from 2010 data (**run 8**): limit down to **7.0×10^{-45} cm^2 (90% C.L.)**

E. Aprile et al. (XENON100), Phys. Rev. Lett. 107, 131302 (2011) 410 citations to-date

Analysis from 2011-2012 data (**run 10**): limit down to **2.0×10^{-45} cm^2 (90% C.L.)**

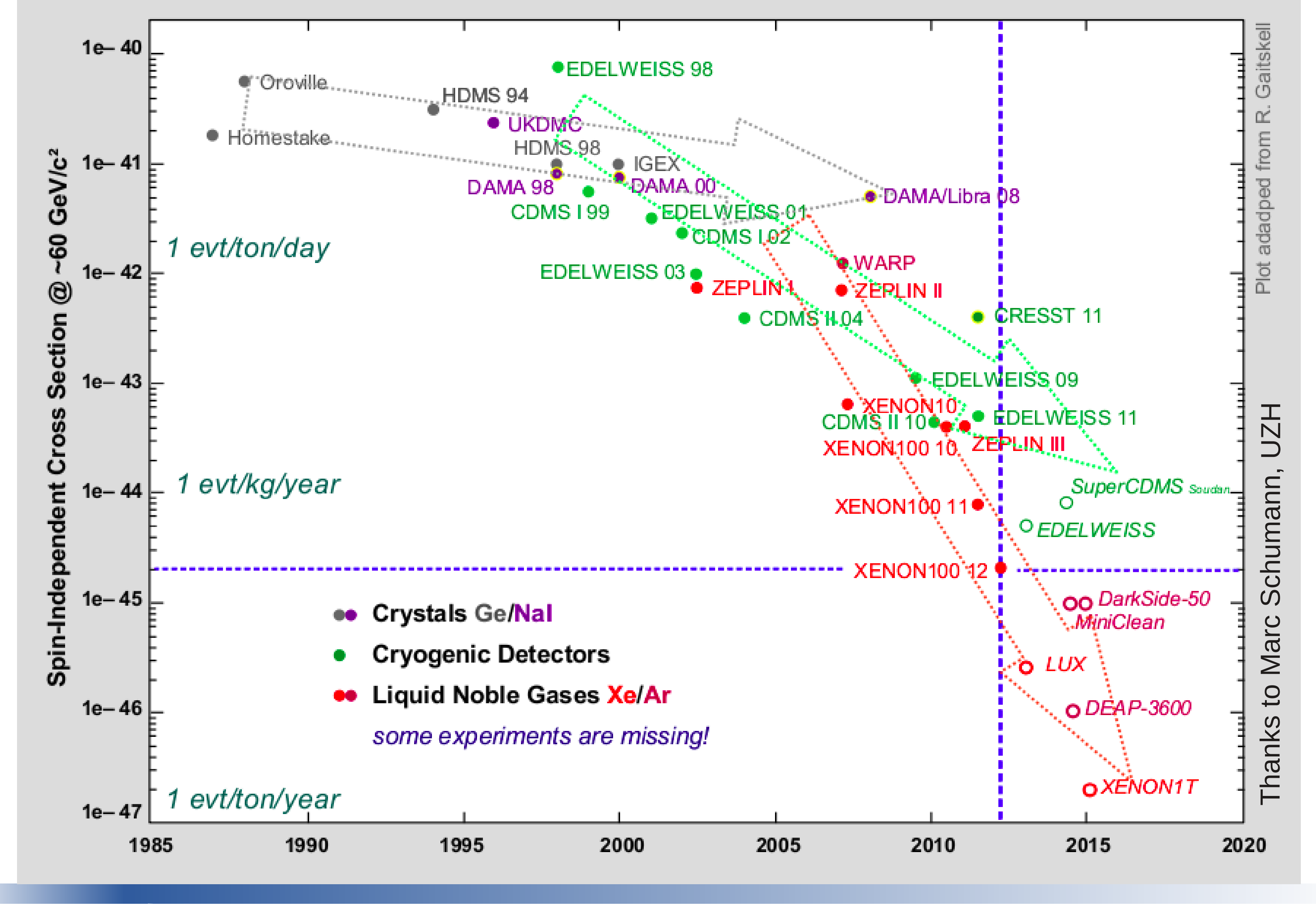
Accepted by PRL: E. Aprile et al. (XENON100), arXiv:1207.5988

Many interesting physics analysis are under way with the already existing data

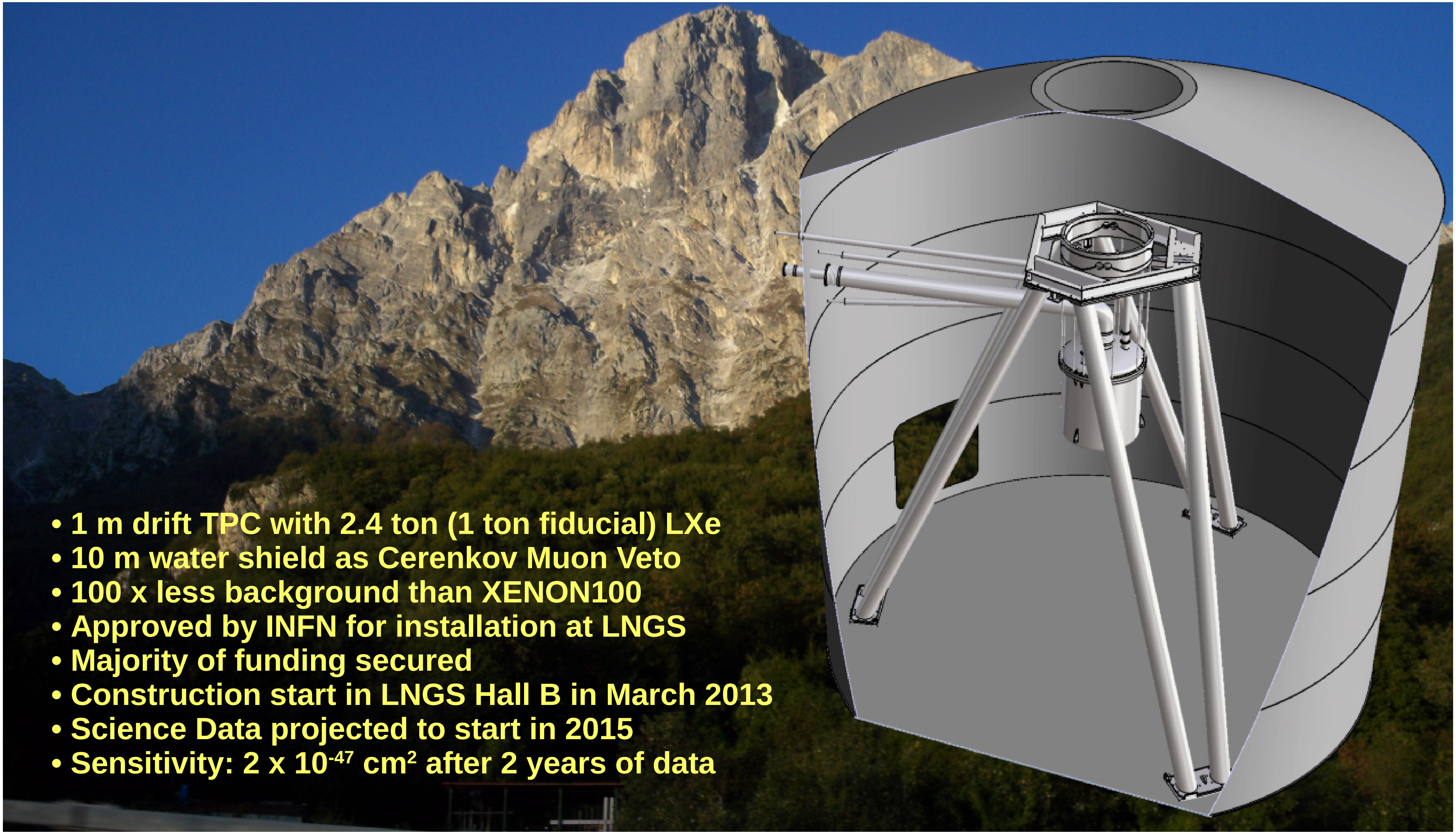
After run 10:

- Measured Rn emanation from empty detector and from gas system
- Cryogenics system maintenance: restored 200 W cooling power
- New Xe gas distillation to further reduce Kr/Xe

The performances of detectors using liquid noble gases

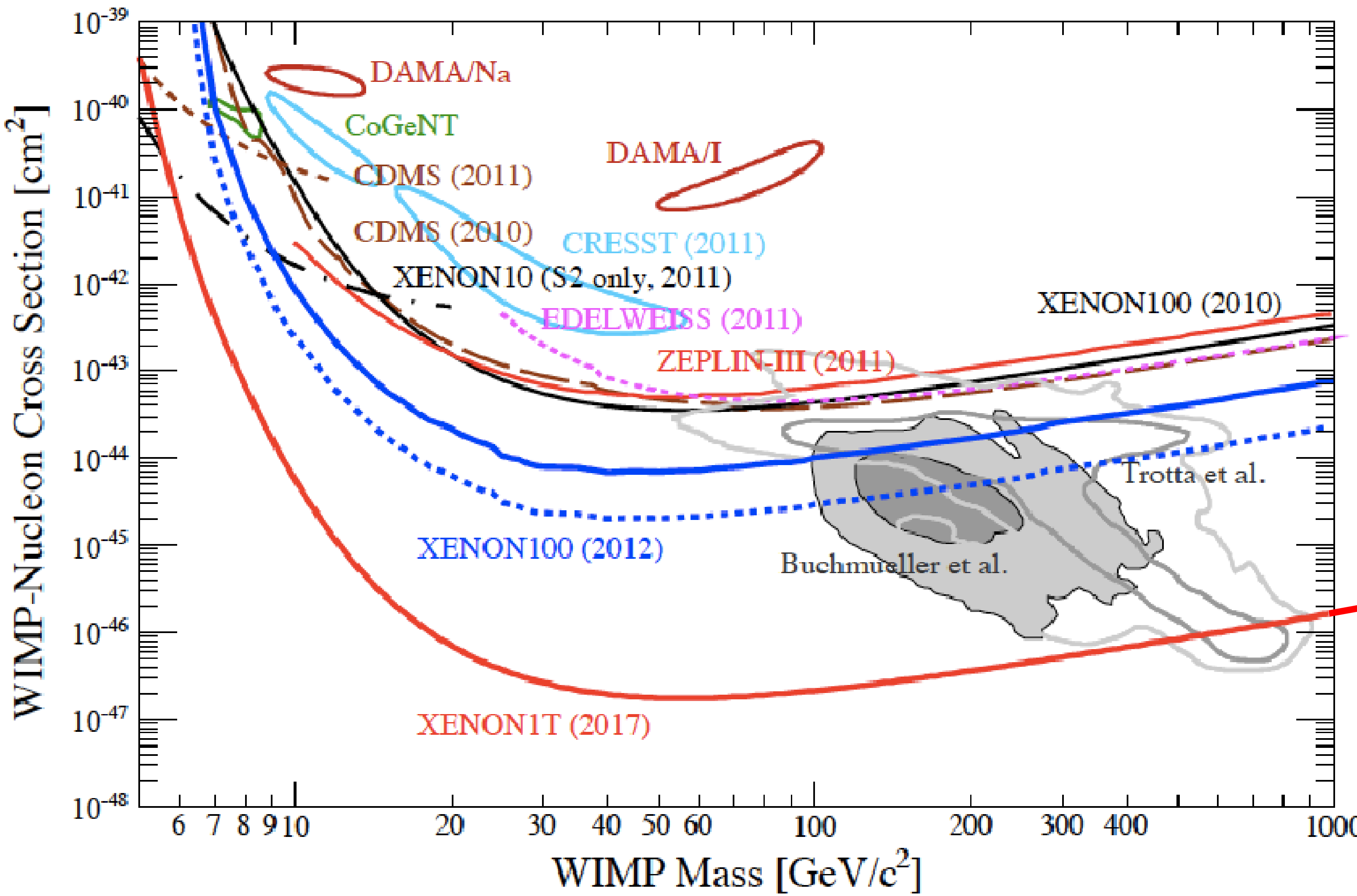


The next generation: XENON1T



- 1 m drift TPC with 2.4 ton (1 ton fiducial) LXe
- 10 m water shield as Cerenkov Muon Veto
- 100 x less background than XENON100
- Approved by INFN for installation at LNGS
- Majority of funding secured
- Construction start in LNGS Hall B in March 2013
- Science Data projected to start in 2015
- Sensitivity: 2 x 10^{-47} cm^2 after 2 years of data

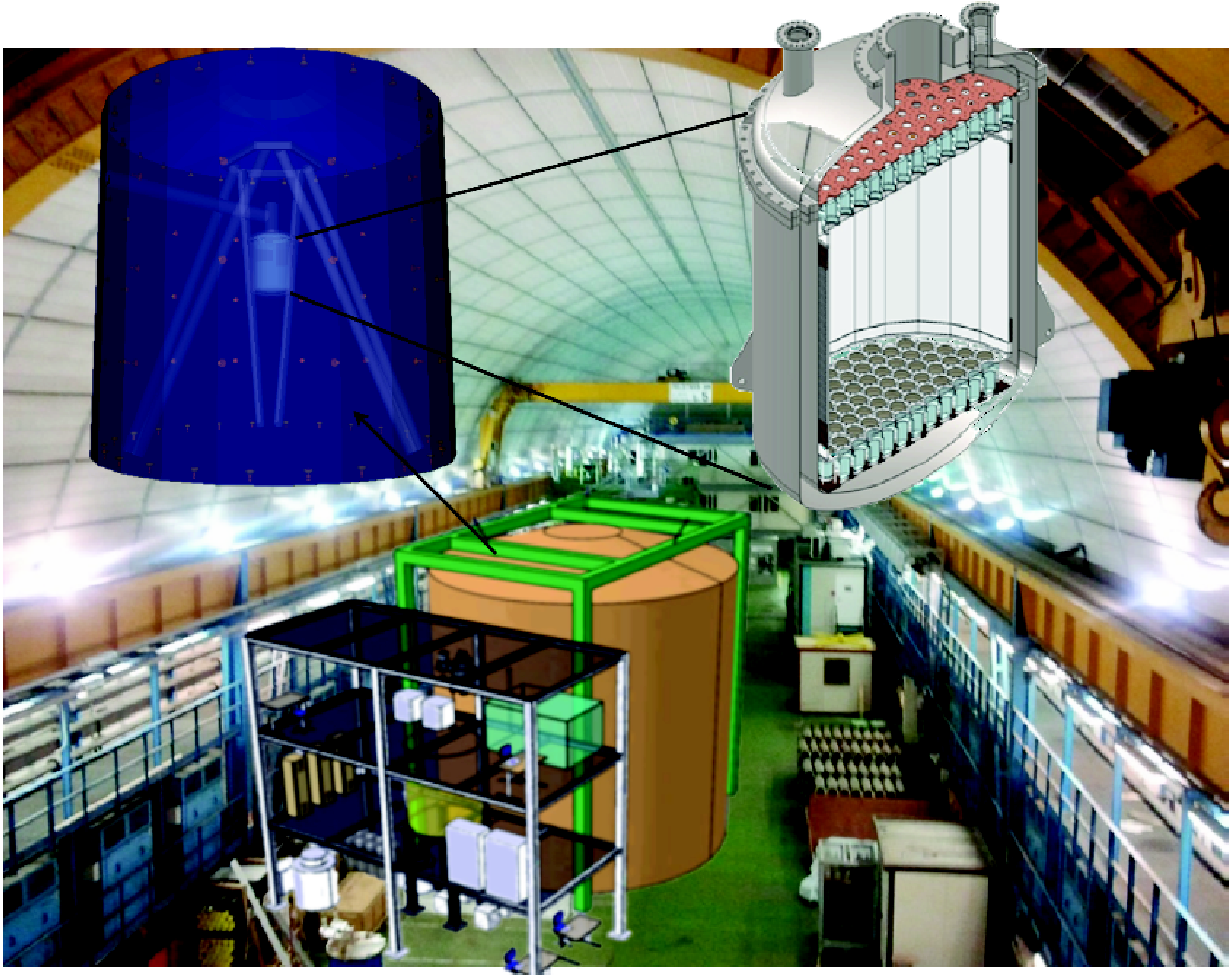
XENON1T expected sensitivity



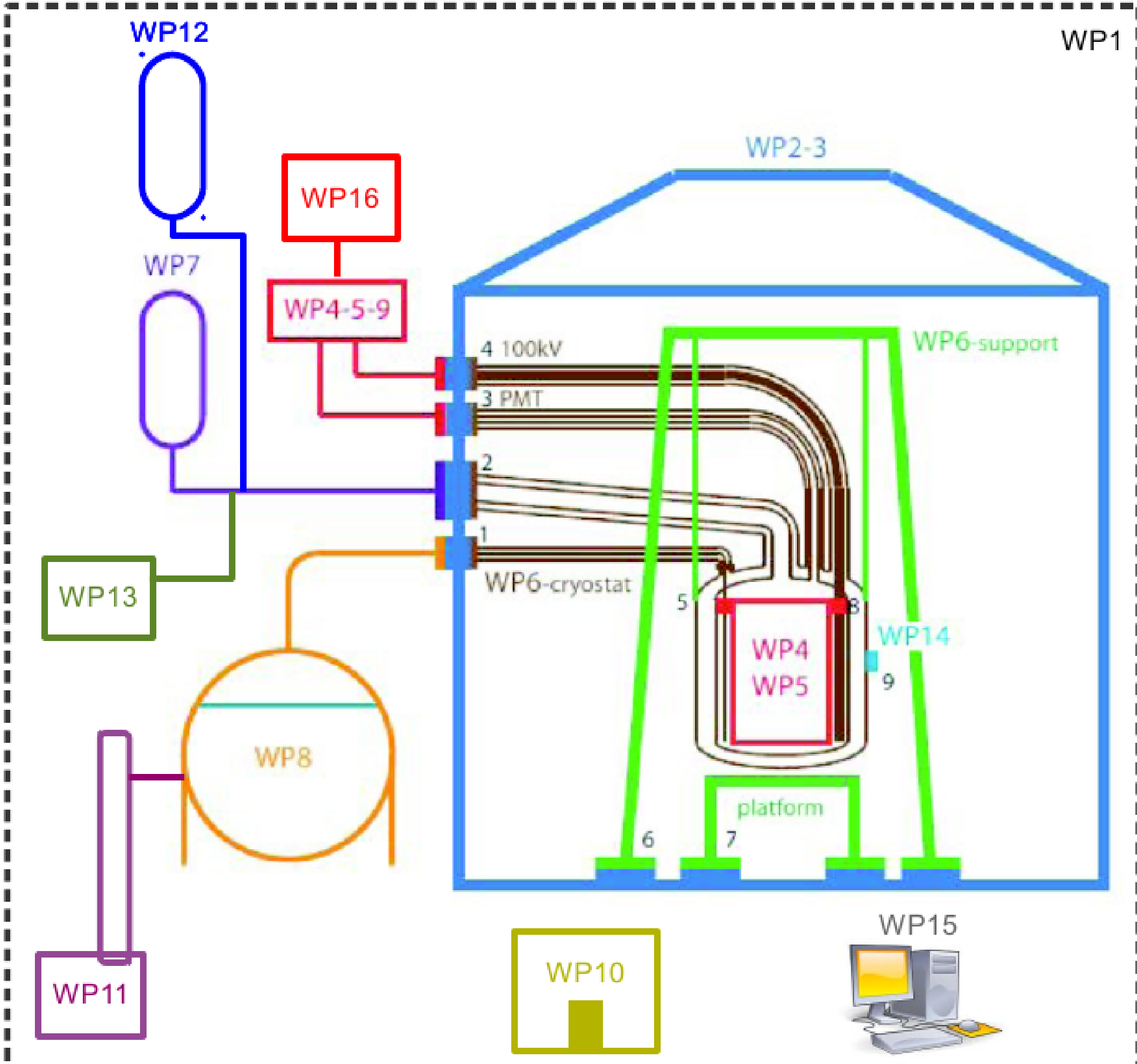
New XENON100 limit

XENON1T already in advanced design study. Construction in March 2013

XENON1T in LNGS Hall B



Work divided in many Working Groups



1. **Infrastructure**
   F. Arneodo (LNGS)
2. **Muon veto**
   W. Fulgione (INFN-Torino), S. Fattori (Mainz)
3. **Water tank**
   H. Landsman (WIS)
4. **Detector: TPC, Grids, HV**
   M. Messina (Columbia), M. Schumann (UZH)
5. **PMTs**
   K.Arisaka (UCLA), T. Marrodan (MPIK)
6. **Cryostat & Support Platform)**
   G. Tajiri (Columbia), A. Colijn (Nikhef)
7. **Cryogenics**
   G. Plante, R. Budnik (Columbia)
8. **Cryogenic storage vessel**
   L. Scotto Lavina (Subatech)
9. **Slow control**
   J. Cardoso (Coimbra), L. Levenson (WIS)
10. **Material screening and selection**
    A.D. Ferella (LNGS), J.Schreider (MPIK)
11. **Distillation column**
    C. Weinheimer (Munster)
12. **Xe Purification**
    E. Brown (Munster), A. Malgarejo (Columbia)
13. **Gas purity and analytics**
    H. Simgen (MPKI)
14. **Calibration**
    A. Kish (Zurich), R. Lang (Purdue)
15. **Monte Carlo simulation**
    M. Selvi (Bologna), A. Kish (UZH)
16. **DAQ and Trigger**
    M.Schumann (UZH), P.Decowski (Nikhef)

Big detectors require new solutions...

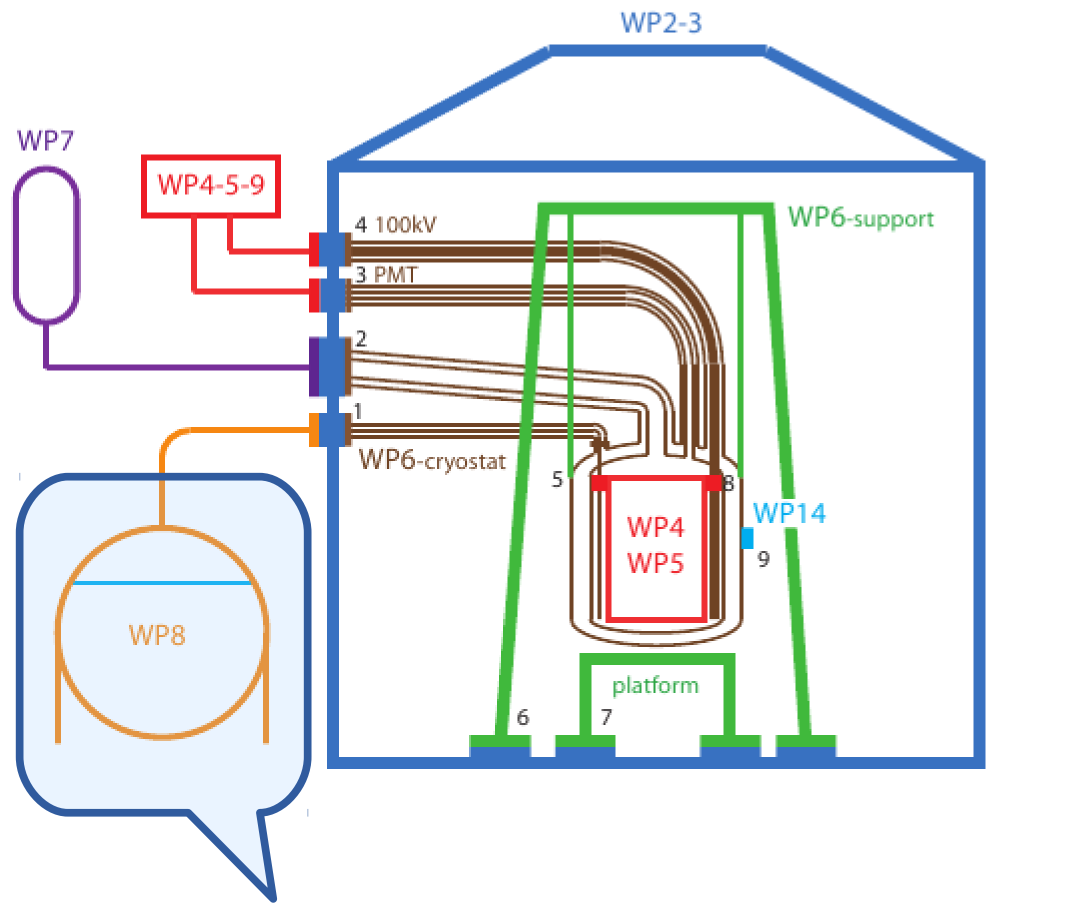
XENON1T must handle 3.6 tons of liquid xenon and detect electrons after long drift lengths (impurities <100 ppt O_2 eq.)

- XENON1T must be filled with an already purified and liquefied xenon

- We need a fast procedure to fill and recover it

- Krypton and Radon contamination during xenon operations must be minimized

Solution: a new concept of storage and recovery system



WP8 : The XENON1T storage and recovery system

The **Re**covering and **Sto**rage system of **X**ENON1T: ReStoX

Subatech (France)

Very compact station,
(L x l x H) = 2.7 m x 3.2 m x 3.3 m
for a 3 ton storage capacity

Temperature ranges from
room temperature (GXe at 65 bar)
down to -108 °C (LXe)

Able to keep high purity
all the time

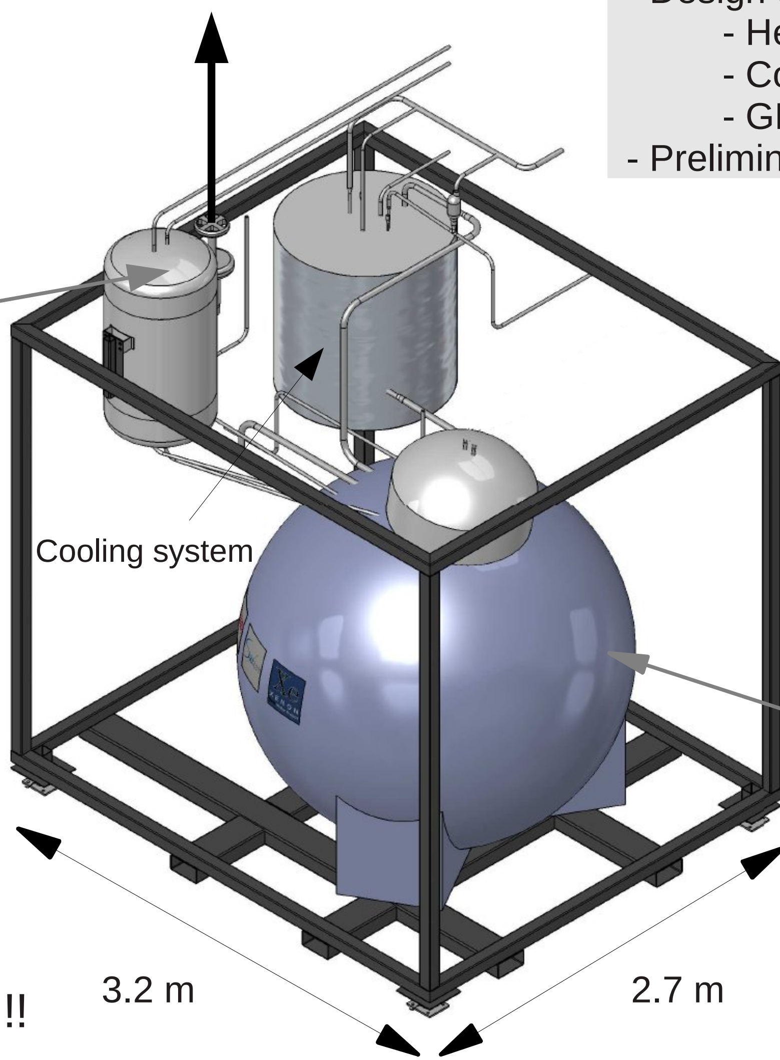
Developed in partnership with

AIR LIQUIDE
ADVANCED TECHNOLOGIES

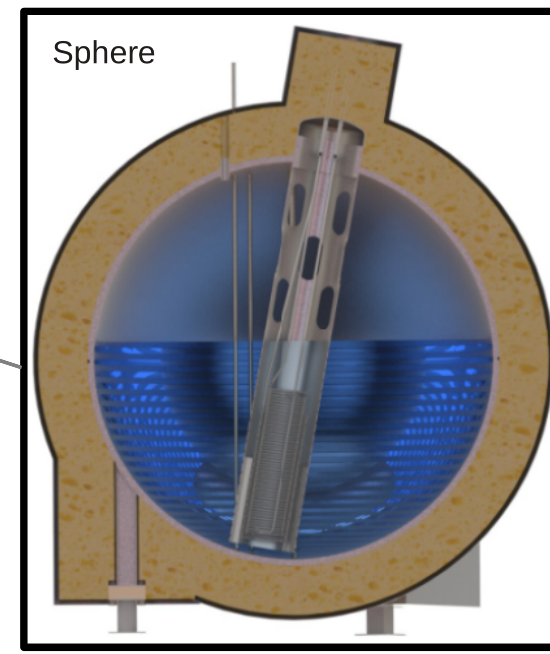
Subatech

The **Re**covering and **Sto**rage system of **X**ENON1T: **ReStoX**

Subatech (France)



- R&D in Subatech laboratory
- Design (with P&ID) and thermal calculations of
  - Heat exchanger toward the purification system
  - Cooling system (aluminum block)
  - GN2 pressurizer
- Preliminary slow control schema designed

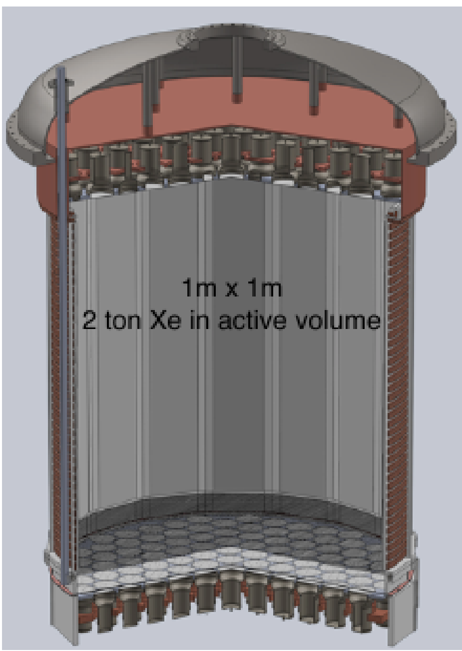


Must be ready before all others equipments !!!

Detector

TPC, grids, HV

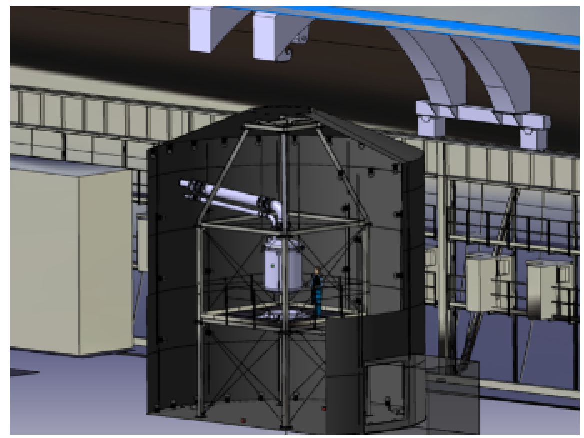
Columbia/RICE/UCLA (USA), UZH (Switzerland)



Goal: 1kV/cm field

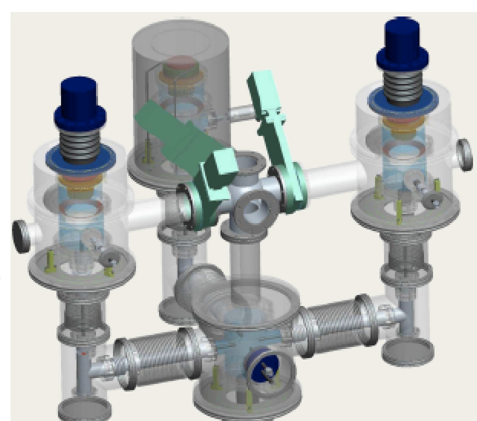
Cryostat and support

Columbia(USA), Nikhef (Netherland)



Cryogenics

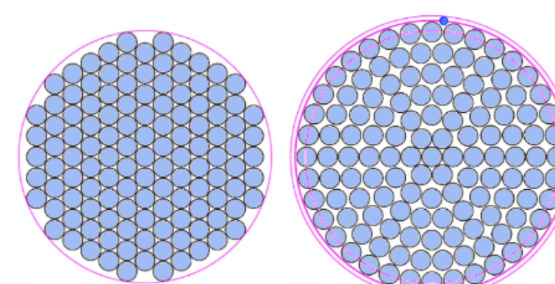
Columbia(USA)



PMTs

UCLA (USA), UZH (Switzerland), MPIK (Germany)

Hamamatsu R11410-21 chosen for XENON1T. QE > 28% ; average of 300 tubes = 32.5%



Water Cherenkov Muon Veto

Water Tank

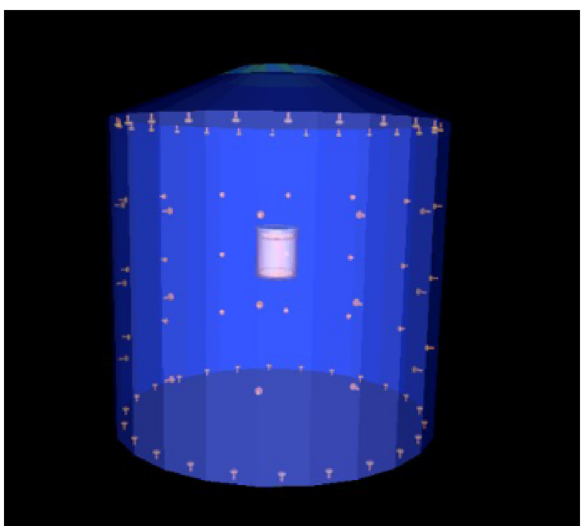
Weizmann (Israel)

Water purification plant

LNGS (Italy)

Muon veto

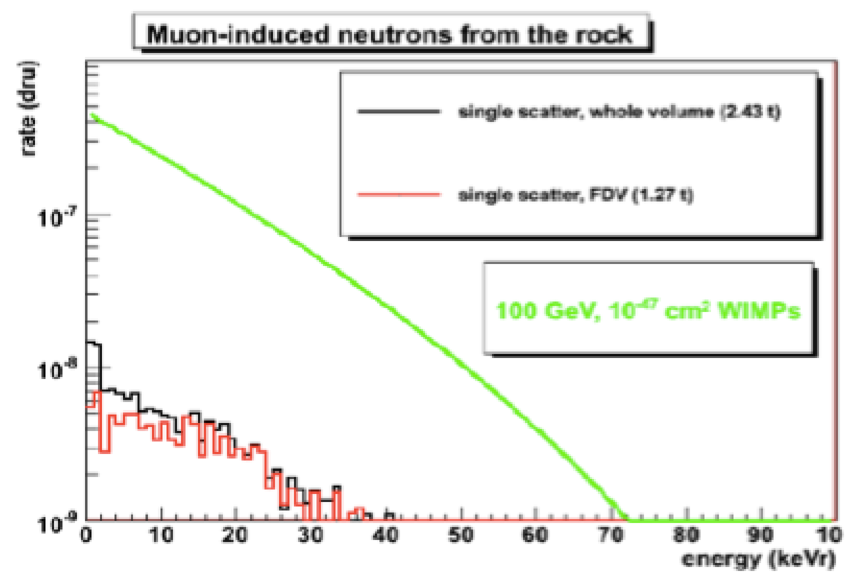
Bologna/Torino (Italy), Mainz (Germany)



Muon-induced neutrons
are the dominant external background

650 m^3 water tank instrumented
with 84 high QE 8´´ PMTs as Active Veto

With ~85% efficiency for tagging neutrons entering the water tank, we expect a rate of 0.01 neutrons/year in LXe fiducial volume, well below the signal rate from 100 GeV WIMP with 10^{-47} cm^2

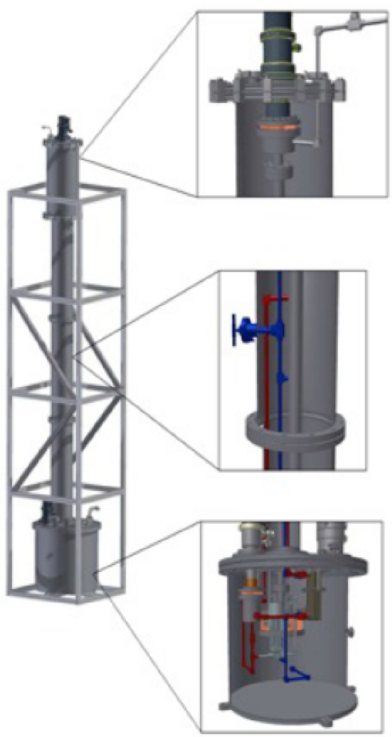


Purification

Kr distillation column

Muenster (Germany)

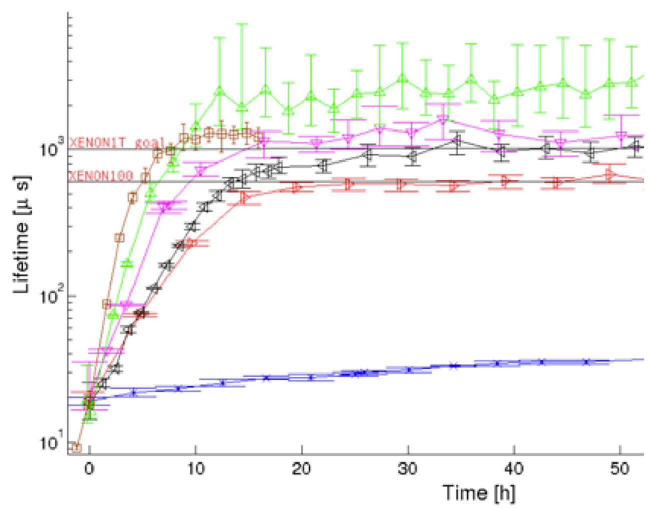
Aim: sub-ppt concentration of Kr in Xe. Design values: 3 kg/h, factor 10000 separation



Purification from Electronegative impurities

Columbia (USA), Muenster (Germany)

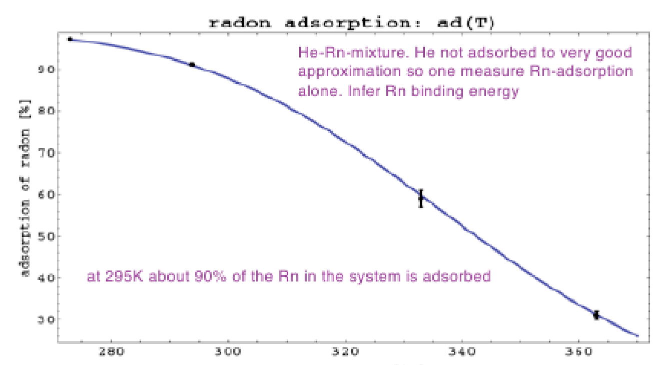
XENON1T Demonstrator Facility and 30 cm drift TPC. Measured electron lifetime as a function of purification speed



^{222}Rd removal column

MPIK (Germany)

Goal: a few µBq/kg (very challenging - strategy will be to avoid and/or minimize sources of Rn)
Principle: cryogenic adsorption of Rn on charcoal. Slow down Rn sufficiently to decay



Materials screening

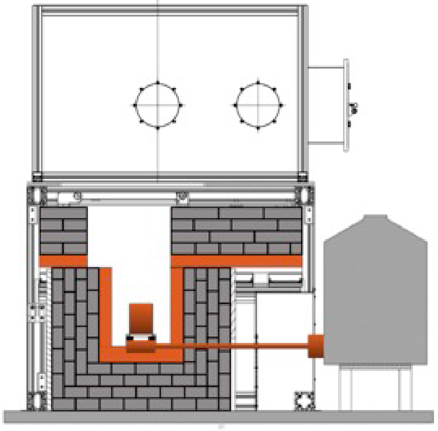
UZH (Switzerland), MPIK (Germany)

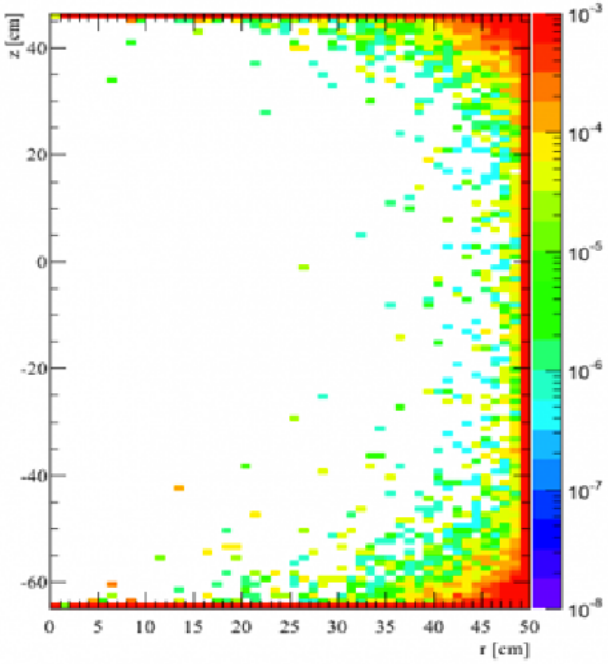
Gamma-ray screening with ~10 μBq/kg sensitivity (GeMPIs, GATOR, etc. @LNGS and MPIK)

222Rn emanation measurement with a few atom sensitivity (Gas counting systems @ LNGS and @ MPIK)
Ultra-low background miniaturized proportional counter @MPIK

ICPMS (Inductively Coupled Plasma Mass Spectrometry) @LNGS and UCLA

Neutron Activation Analysis@PSI, Mainz



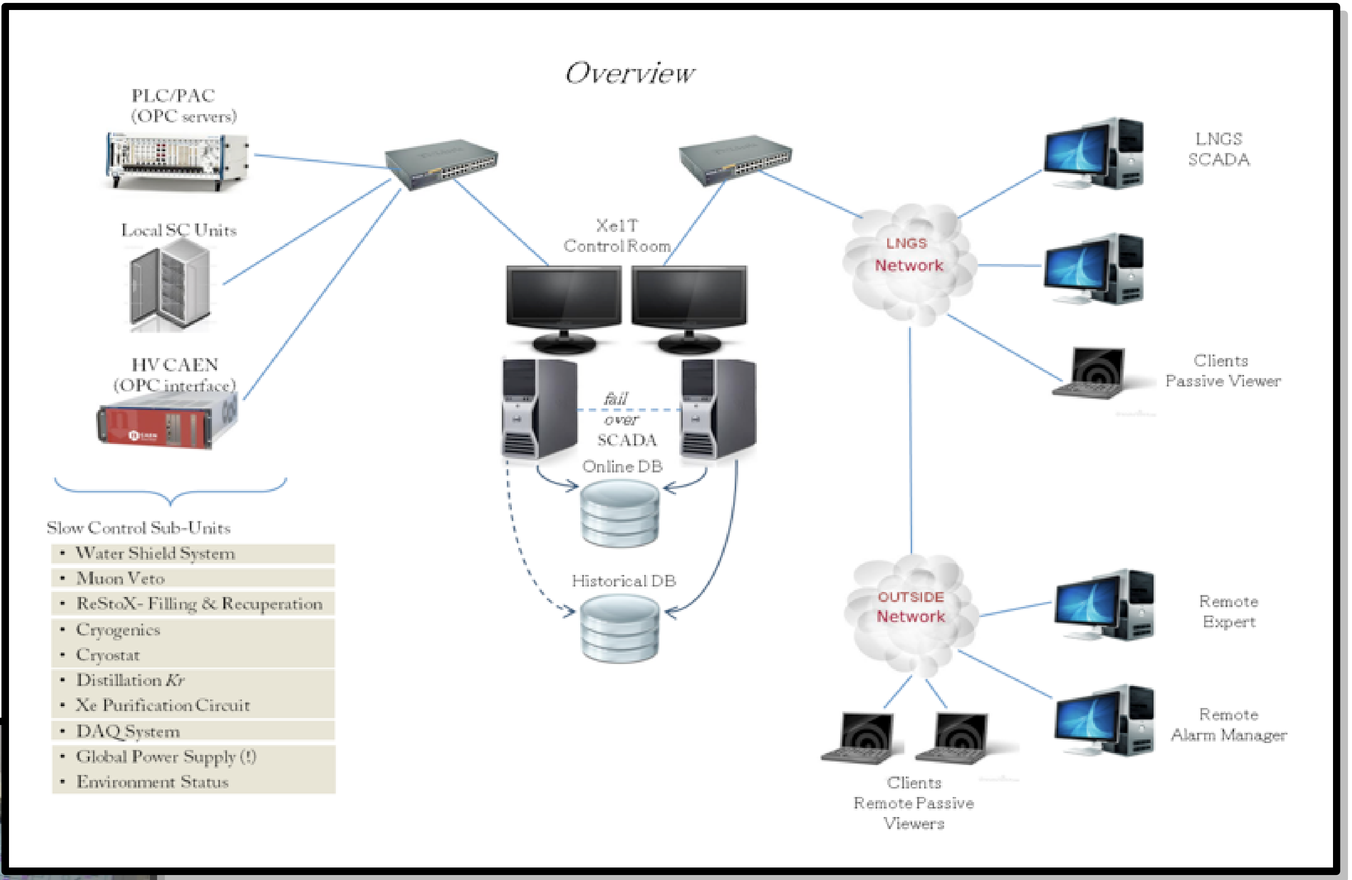


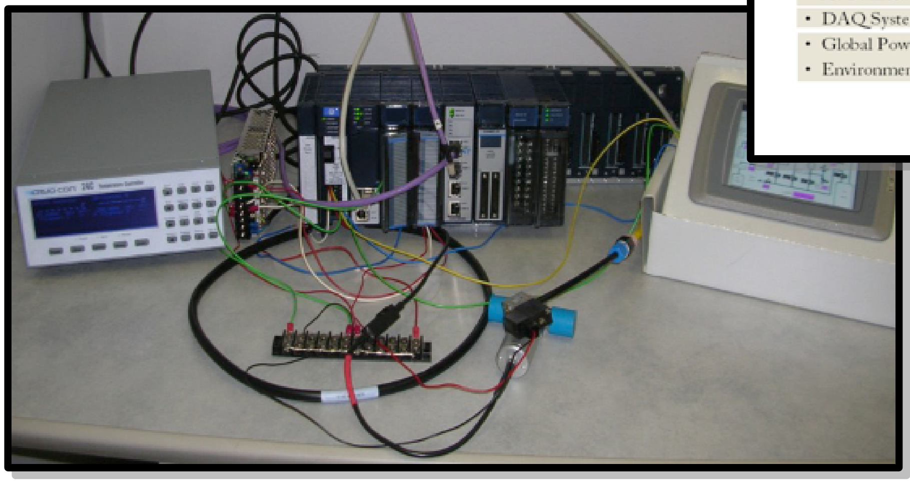
Monte Carlo simulations

Bologna (Italy), UZH (Switzerland)

Full Monte Carlo simulation in GEANT4 of the Water Tank, Support structure, Cryostat, TPC, PMTs.

Coimbra (Portugal), Weizmann (Israel)





Conclusions

XENON100 set again a new record with a limit of SI cross section down to **2.0×10^{-45} cm^2 (90% C.L.)**

New papers under work

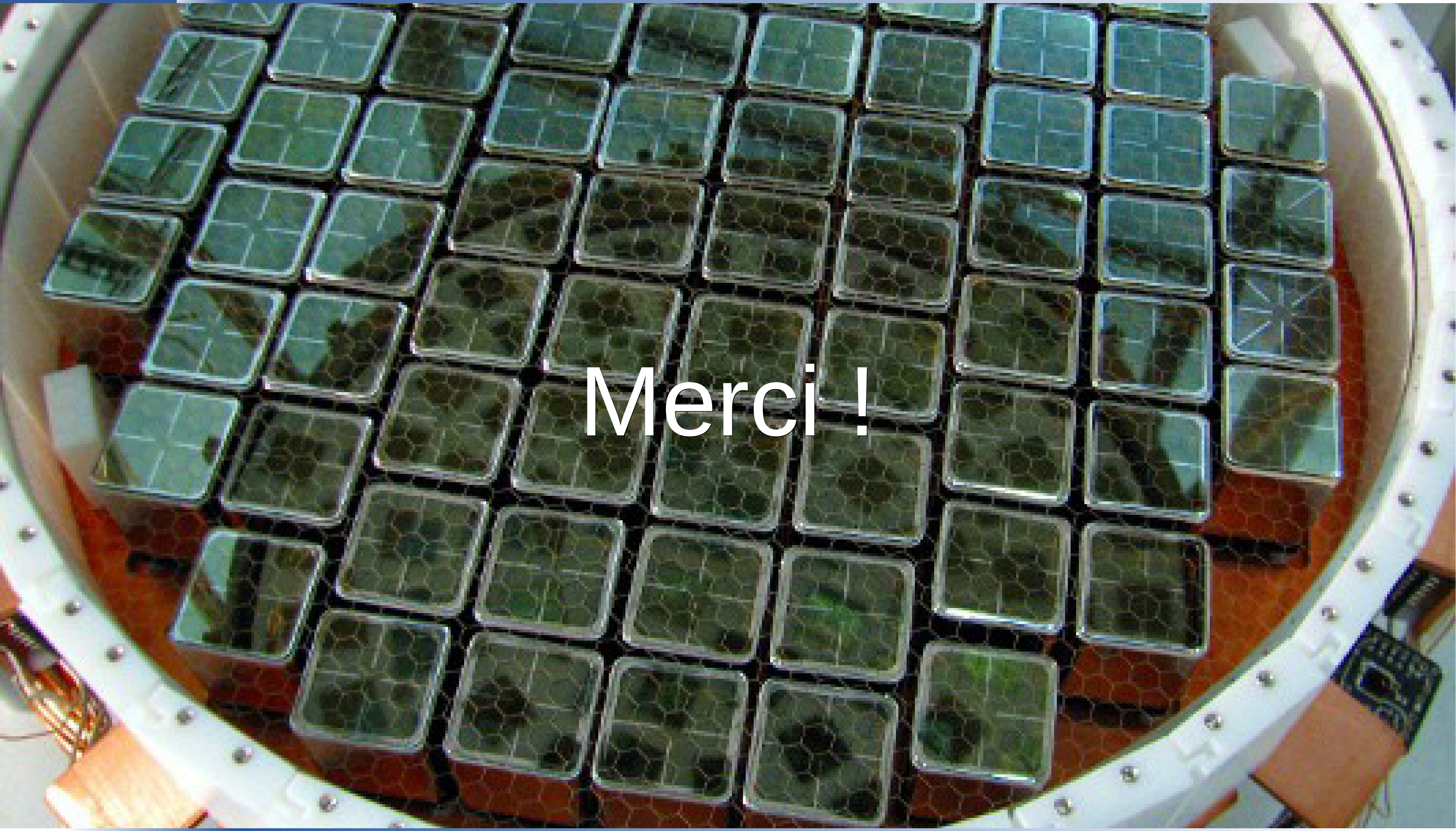
XENON Collaboration is now engaged in the construction of **XENON1T**, aiming to be 100 times more sensitive than its predecessor.

Stay tuned in 2015 for first data !!!

French participation consists only in **Subatech Laboratory** (Nantes), involving about 6 people.

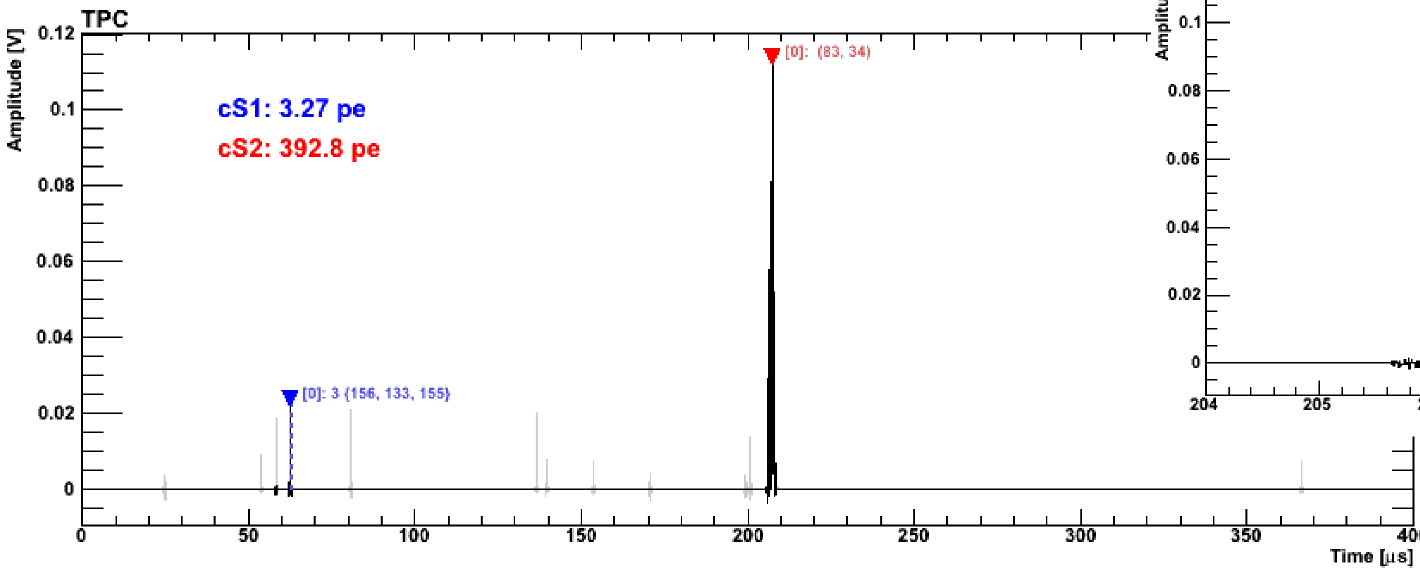
Some amusement . . .

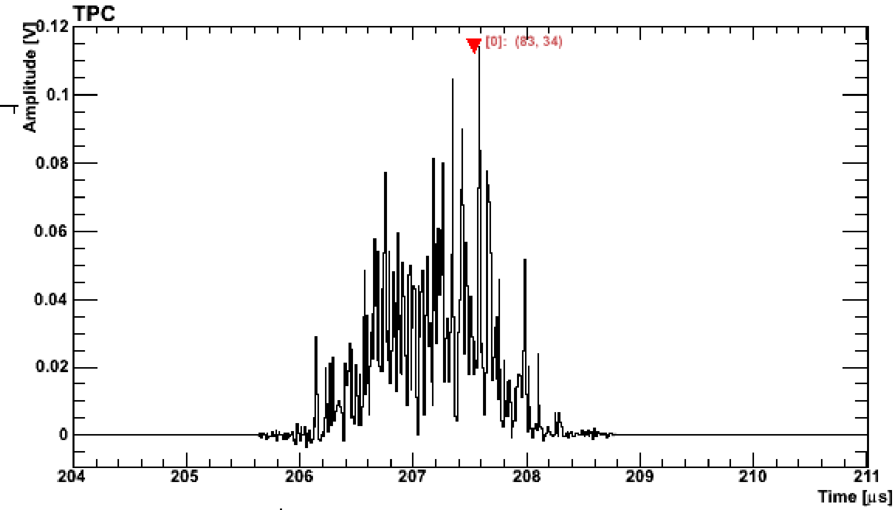
Un documentaire de Cécile Denjean (2012, 55min)
Coproduction : ARTE France, CNRS Images, CEA, Scientifilms
Ce documentaire sera diffusé sur ARTE, jeudi 13 décembre 2012 à 22.45

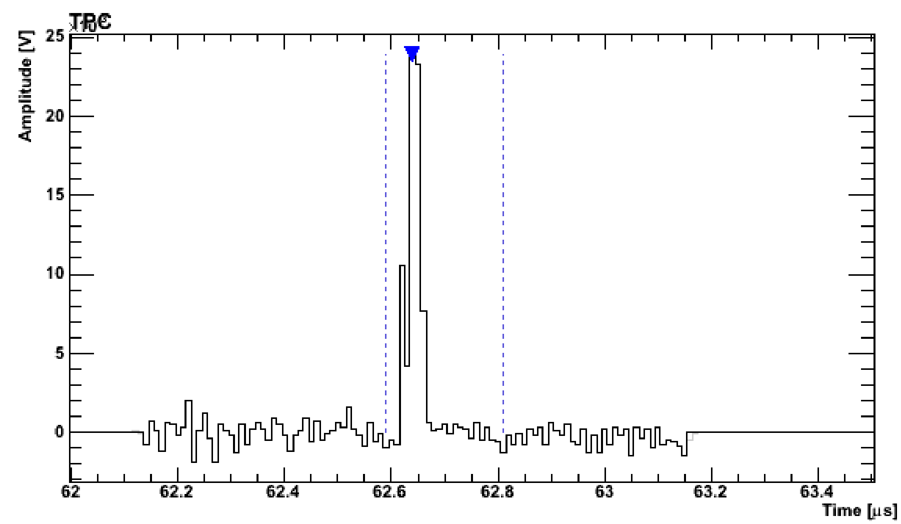

Merci !

Backup...

XENON100: run 10 observed event #1







XENON100: run 10 observed event #2