Westfälische Wilhelms-Universität Münster

The XENON Project for direct Dark Matter search

XENON Dark Matter Project

Int. School on Nuclear Physics – September 16 – 24, 2010, Erice / Italy

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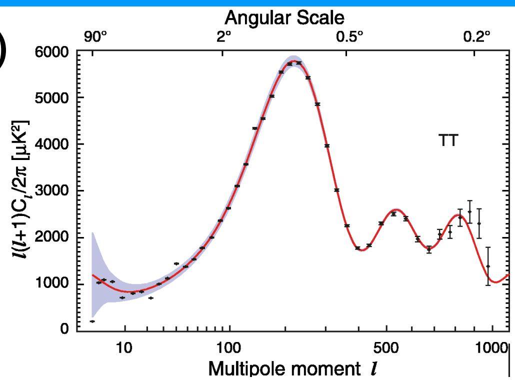
- Introduction
- XENON100 detector and first results
- Outlook to XENON1t
- Conclusion

Cosmological Concordance Model

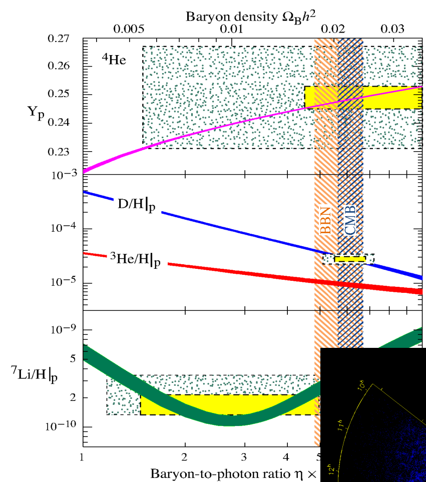
- CMB (WMAP)

$\Rightarrow \Omega_{tot} = 1$



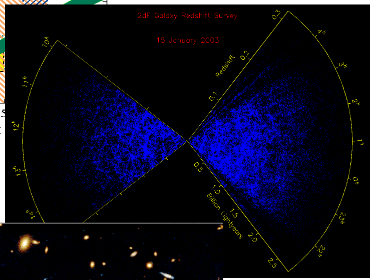
- CMB, BBN

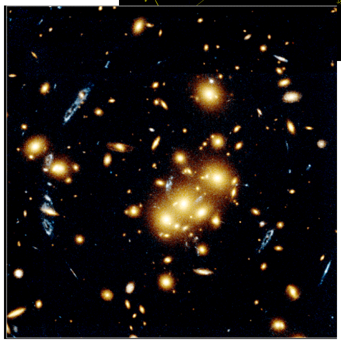
$\Rightarrow \Omega_B = 0.045$



- Lensing,
  large scale structure,
  rotation curves

$\Rightarrow \Omega_M = 0.27$





- SN Ia + ... $\Rightarrow \Omega_\Lambda = 0.74$

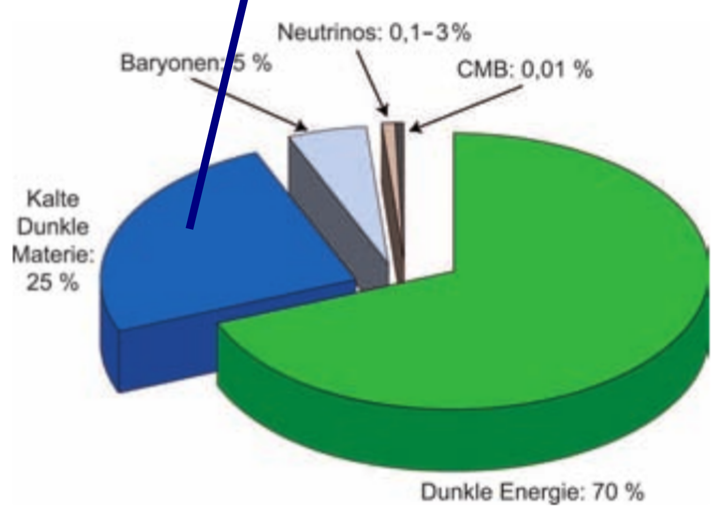
ΛCDM model

with

cosmological constant $\Lambda \neq 0$

& non-baryonic Cold Dark Matter

$\Omega_{DM} \approx 0.23$



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Candidates for Dark Matter: particle dark matter

XENON Dark Matter Project

a) Neutrinos: only known dark matter, but small fraction & „hot dark matter“

b) Axions: only small parameter range open, some search

c) Axinos: supersymmetric partner of axions

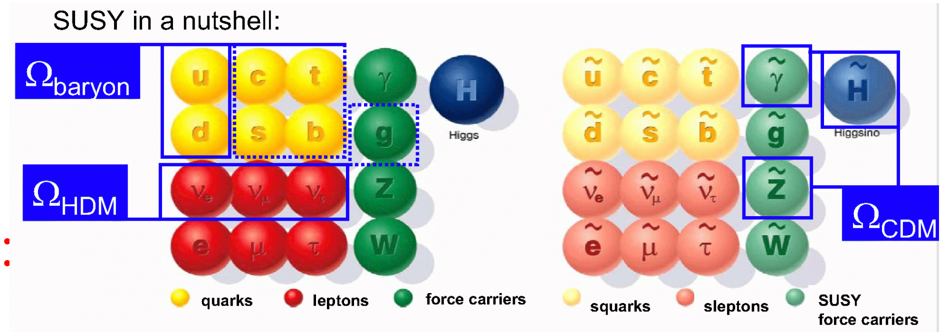
d) Gravitinos: supersymmetric partner of graviton

e) Weakly Interacting Massive Particles (WIMPs):

„The natural cold dark matter candidate“:

Supersymmetry is a nice way to avoid divergences of the SM at high energies

Supersymmetry provides a natural candiate: LSP (lightest supersymmetric particle)



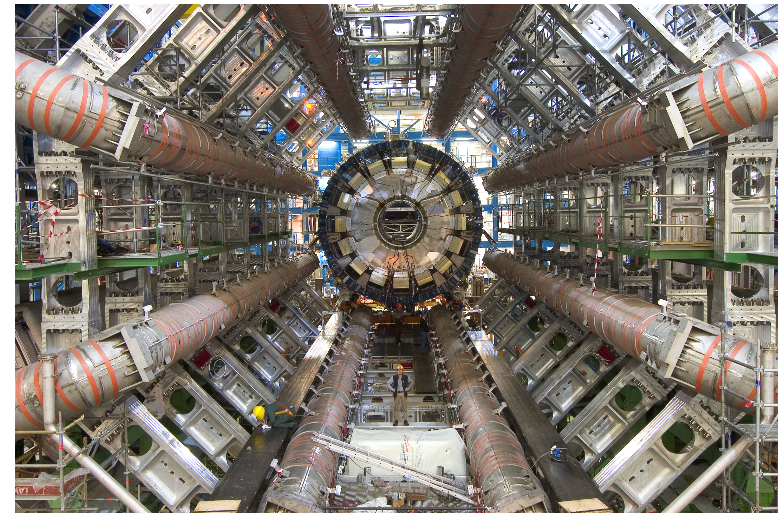
LSP has about the right relic abundance

WIMP/LSP/Neutralino: $\tilde{\chi}^0 = a_1 \tilde{\gamma} + a_2 \tilde{Z}^0 + a_3 \tilde{H}^0_1 + a_4 \tilde{H}^0_2$

Experimental search for WIMPs

a) At accelerators:

$$p + p \to ..... \to ... + \tilde{a} + \tilde{\chi}$$

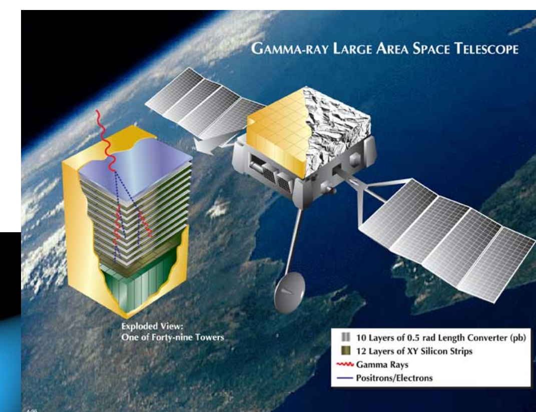


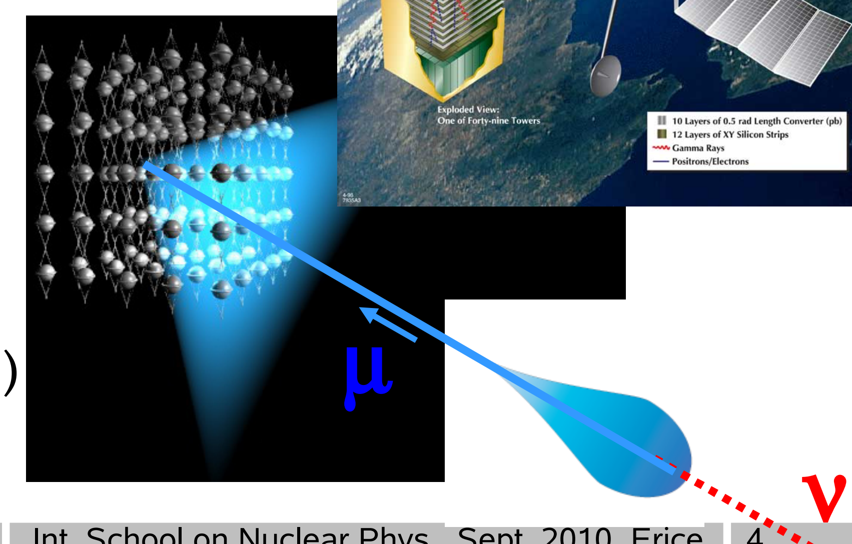
Indirect detection by missing mass+momentum
Not really a proof of WIMPs being the Dark Matter of the universe

b) WIMP annihilation in the universe:

$$\tilde{\chi} + \tilde{\chi} \to ..... \to ... + \nu + \bar{\nu}$$

$$..... \to ... + \gamma + \gamma$$



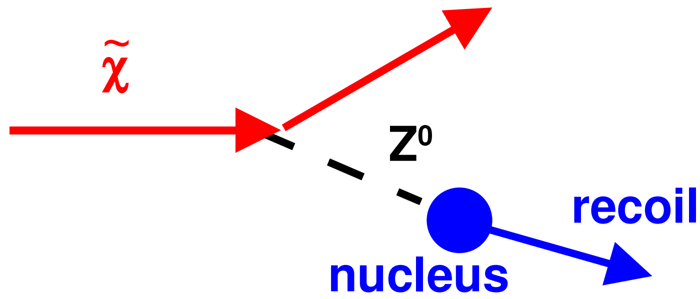


Search for neutrinos or gammas from large mass accumulations (center of galaxy, sun, ..)

Experimental search for WIMPs

c) Direct WIMP detection – search for nuclear recoil:

e.g. via
Z exchange



Signature:
energy transfer to nucleus
by invisible particle

Cross section:

$$\sigma \;\propto\; G_F^{\,2} \cdot \mu^2 \cdot \begin{cases} (f_p \cdot Z + f_n \cdot (A-Z))^2 & \text{for spin-independent coupling (coherent)} \\ (J+1)/J & \text{for spin-dependent coupling} \end{cases}$$

with reduced mass $\mu = \dfrac{M_N * m_\chi}{M_N + m_\chi}$

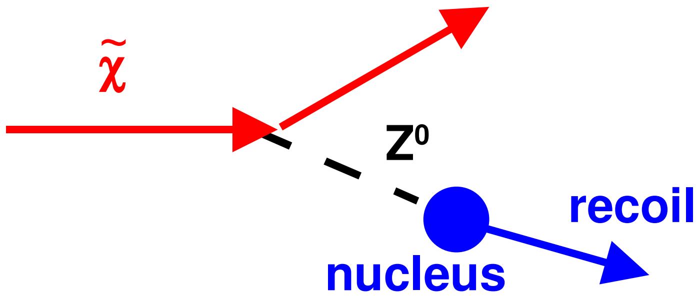
Recoil energy:

$$E_R = \mu^2 / M_N \cdot v^2 \cdot (1 - \cos\theta_{CMS}) = O(10\text{ keV}) \qquad (\text{for } M_N = m_\chi = 100\text{ GeV})$$

After convoluting with the velocity distribution of WIMPs from the halo:

$$E_R \approx a \cdot \exp(-E_R/E_0)$$

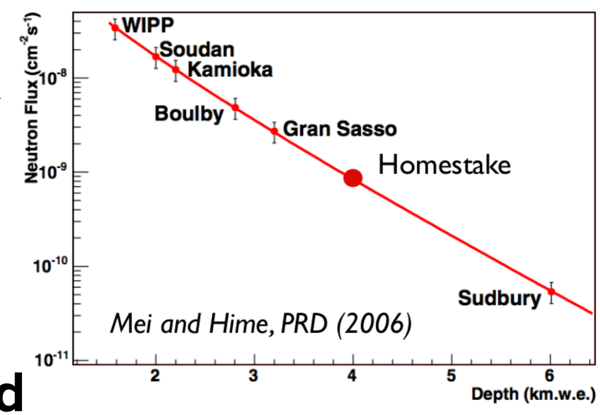
Difficulties to search for WIMPs



2 generic problems:
- **very low rate**
- **very low recoil energy**

⇒ **go underground to reduce μ`s and μ-induced n`s**

& very clean materials, shielding, ..



⇒ **very special techniques to suppress γ, e, α background**

a) large detector mass to see annual modulation (DAMA/LIBRA)

b) double read-out to distinguish nuclear recoil from others

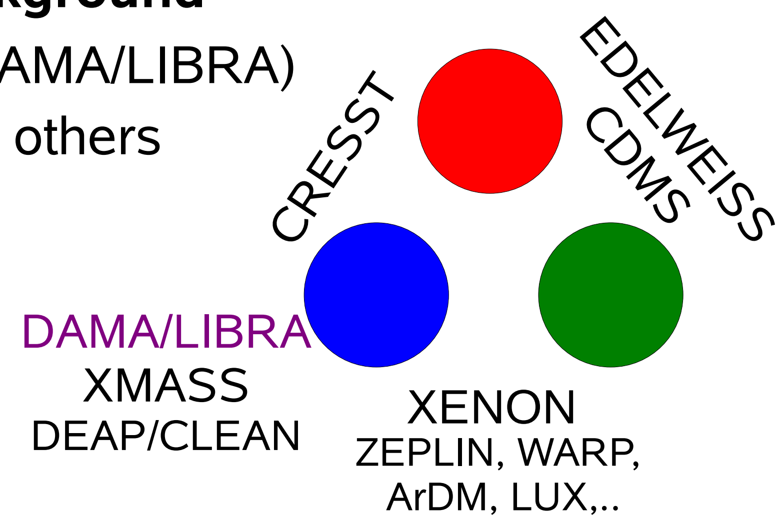
- cryo bolometers:

  heat + ionsiation or heat + light

- liquid noble gas detectors:

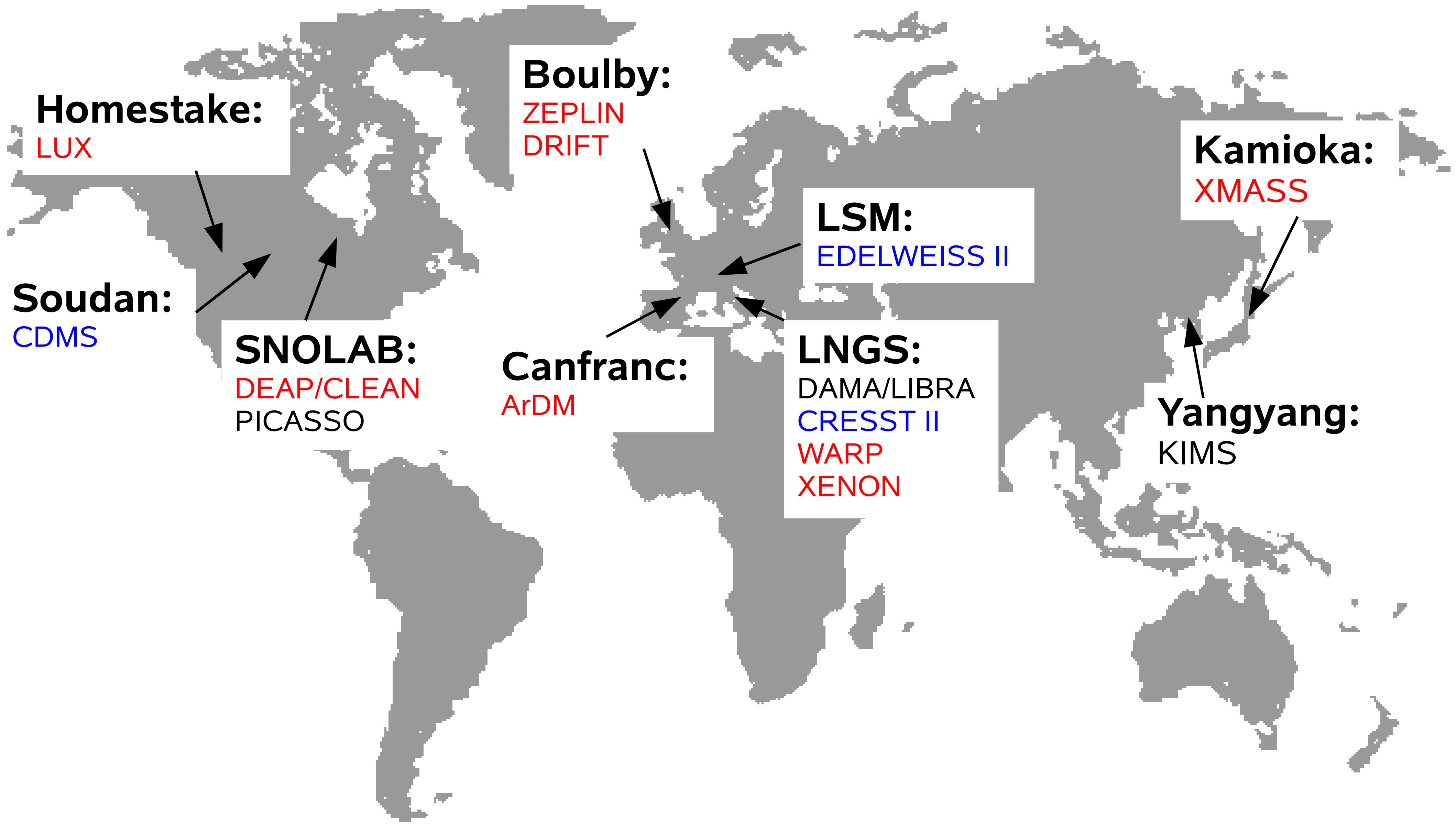
  light + ionisation

c) directional (but not enough target mass)



Direct WIMP searches

cryo bolometer / liquid noble gases / others



Why Xenon for WIMP search ?

Signal rate:

high mass number A~131:

→ spin independent: high WIMP rate @ low thresh.

50% odd isotopes

→ sensitive to spin-dependent couplings

Background rate:

noble gases can be made extremely clean

no long-lived Xe isotopes (except DBD of ^{136}Xe)

^{85}Kr can be removed to ppt level

high atomic number Z=54 → good self-shielding

in 2-phase TPC: good background discrimination

Detector:

efficient (42000 photons/MeV), fast scintillator:

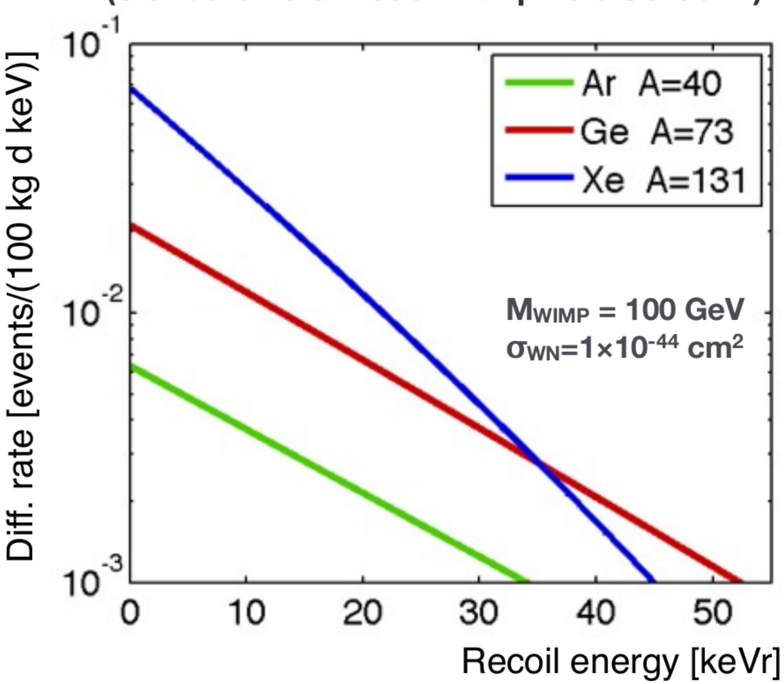
λ=178nm → no WLS

high density (~3kg/l) → compact detector

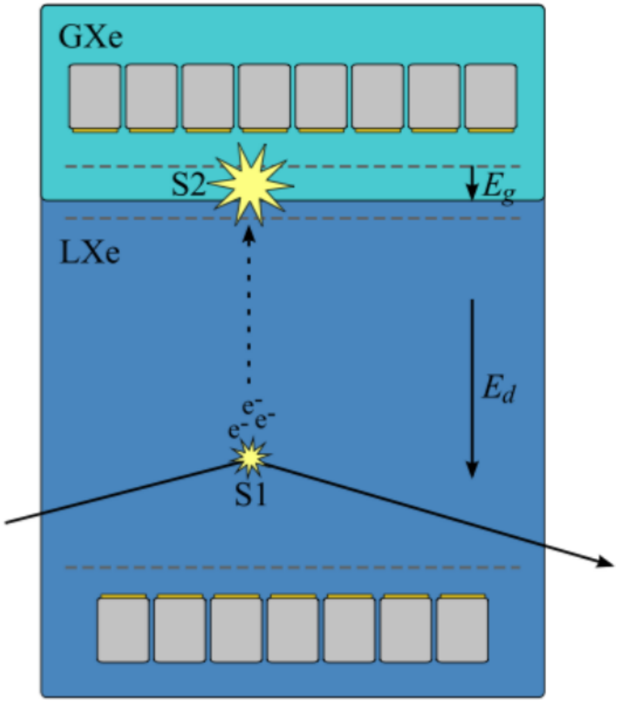
"easy" cryogenics @ −100°C → scalability to larger detectors

Differential rates (per 100 kg and day) for different targets (Ar, Ge, Xe)

(Standard halo model with ρ= 0.3 GeV/cm³)



Dual Phase TPC



interaction in LXe

→ primary scintillation light S1 & electrons/ions:

→ energy information from S1

electrons are drifted into the gas phase:

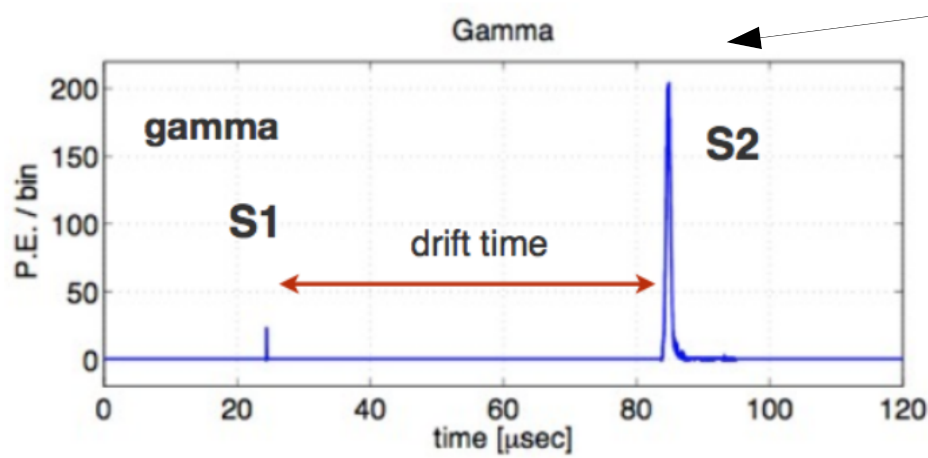
drift time → z-coordinate

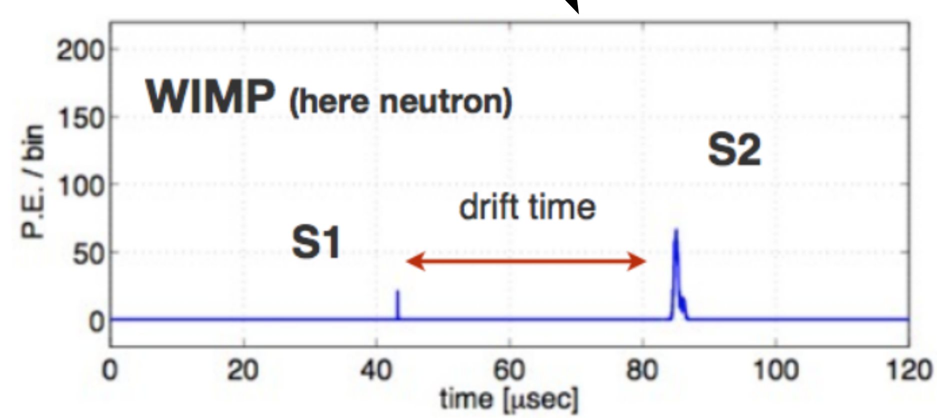
electrolumisnescence gives proportional light S2:

light distribution → x-, y-coordinates

electron recombination is stronger for nuclear recoils

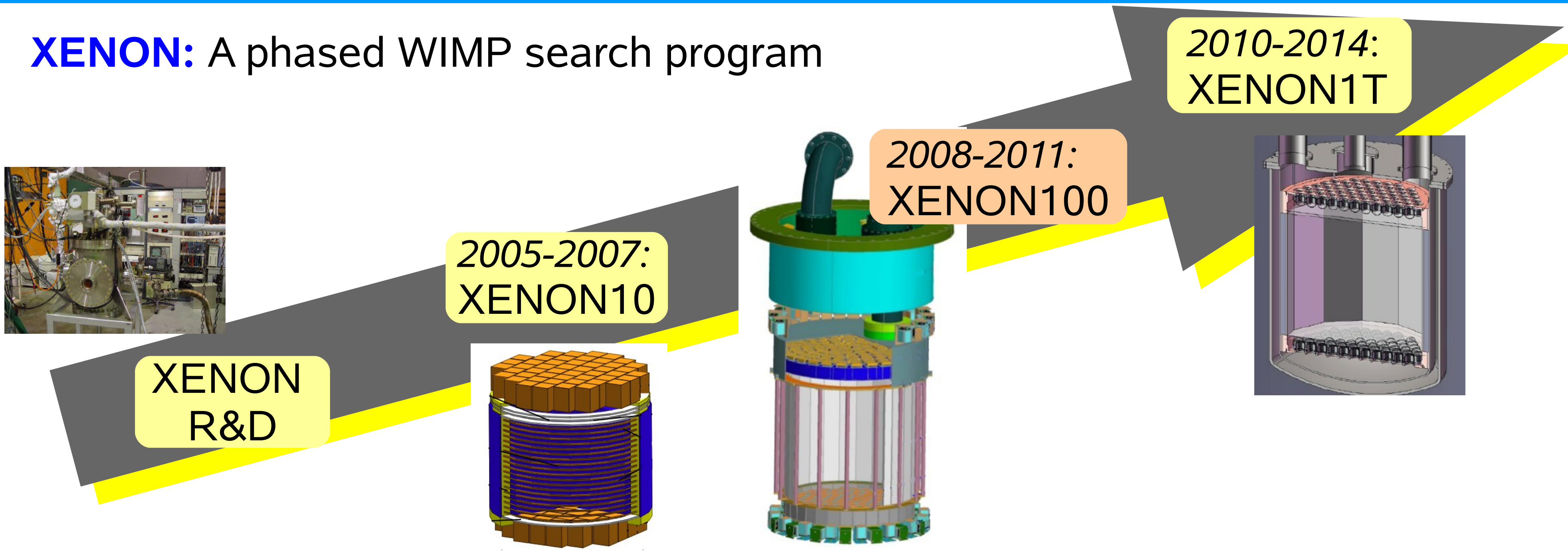
→ discrimination of electron/nuclear recoils





The XENON program

XENON: A phased WIMP search program



Columbia · Rice · UCLA · U Zürich · Coimbra · LNGS · SJTU

Bologna · MPIK · NIKHEF · Mainz · Subatech · Münster · WIS

XENON100

Goal (compared to XENON10):

increase target mass by 10

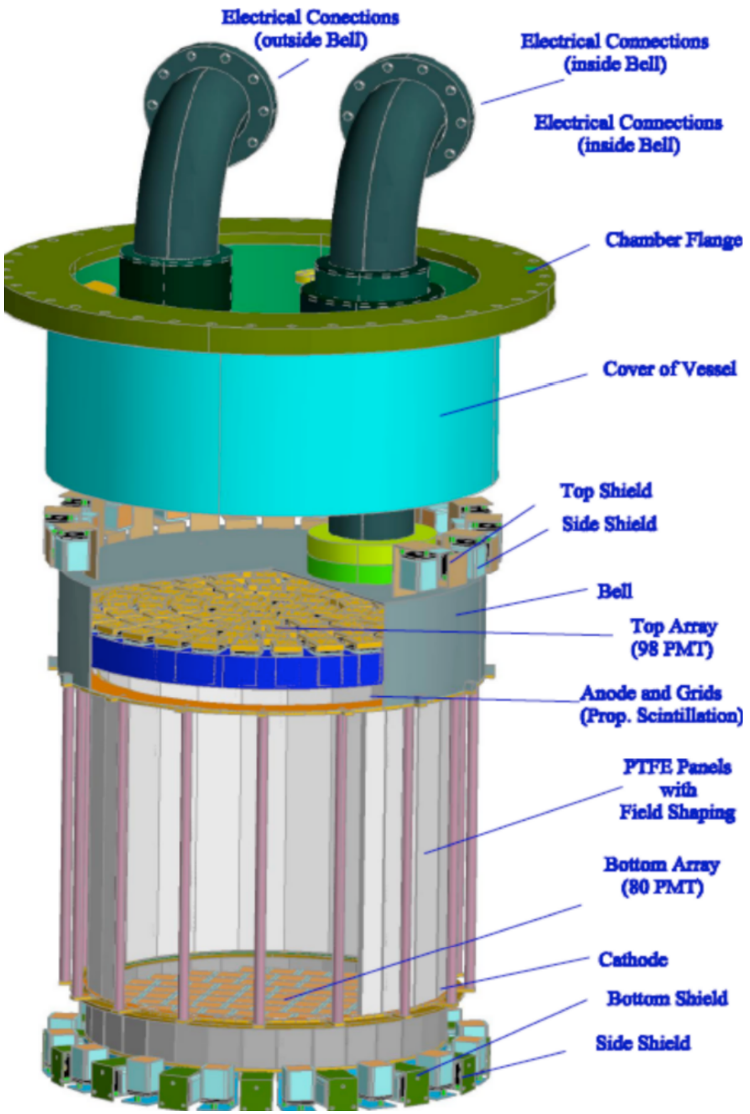
reduce gamma background by 100 by
- material selection & screening
- detector design

TPC:

161 kg two phase GXe & LXe TPC

TPC: 30.5 cm diameter
30.6 cm height
$\rightarrow$ 62 kg active target
99 kg LXe veto (> 4 cm)

Xe purified by distillation to ≈ 150 ppt Kr



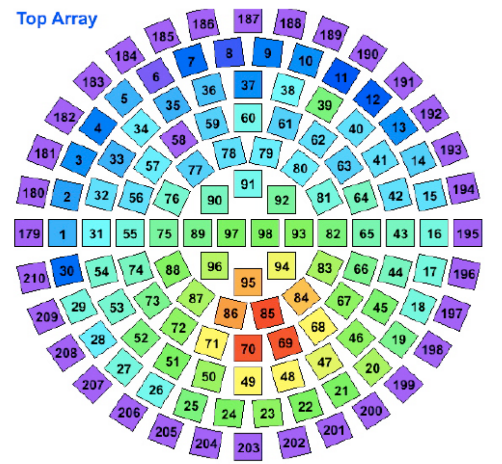
XENON100

Field cage:

polytetrafluoroethylene (PTFE)

→ good UV reflector

drift field: 530 V/cm



PMTs:

1“ x 1“ R8520-AL, appl. gain: $1.9 \cdot 10^6$

top array: 98 (QE ≈ 23%)

bottom array: 80 (QE ≈ 33%)

active veto: 64

DAQ:

fADC with 100 MS/s

XENON100

Cryogenics:

200 W pulse tube refrigerator

T = 182 K, p ≈ 2.2 bar

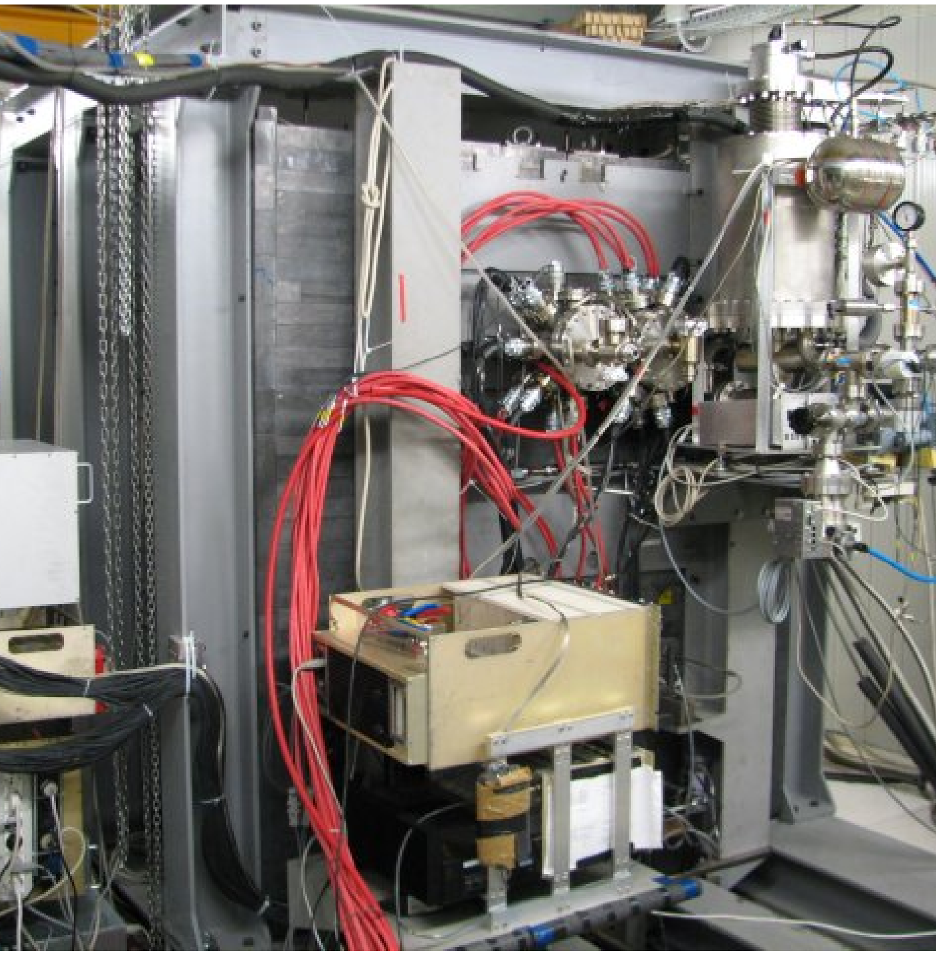
outside shield (different to XENON10)

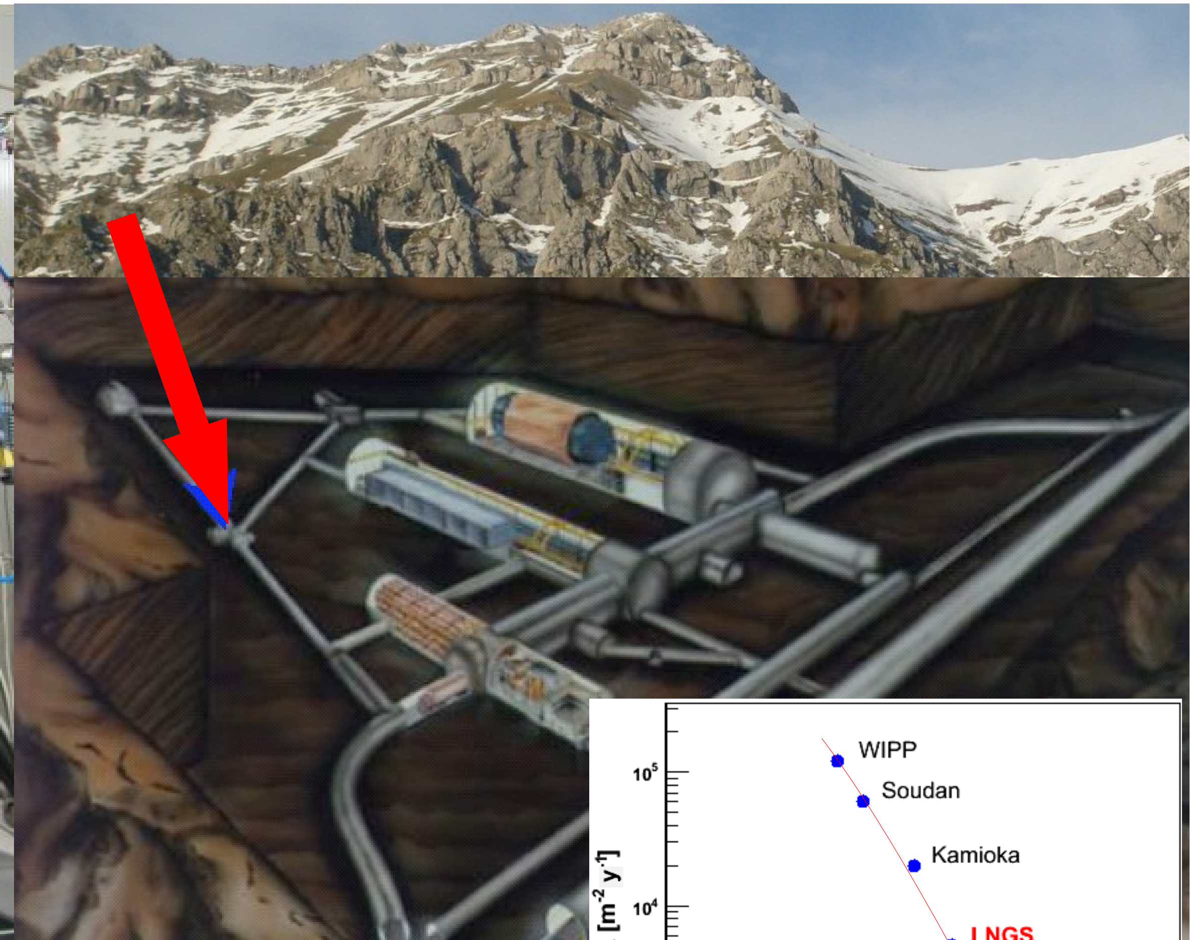
Passive shield:

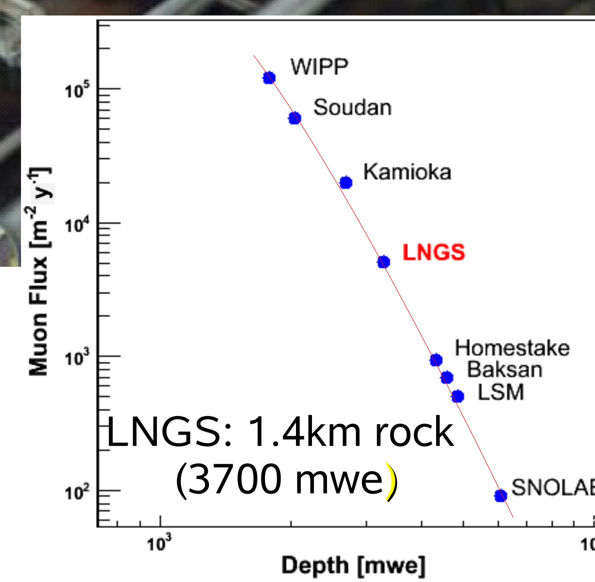
from outside to inside:

- 20 cm H_2O (not on all sides)
- 15 cm Pb
  - 5 cm French Pb
- 20 cm polyethylene
  - 5 cm Cu
- N_2 gas purging to lower Rn level

XENON100 @ LNGS

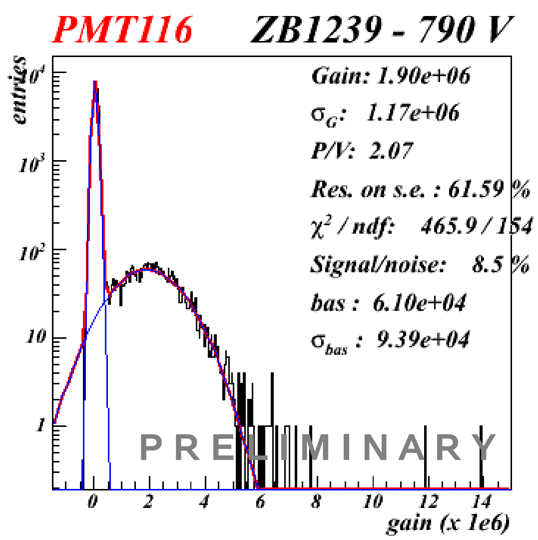


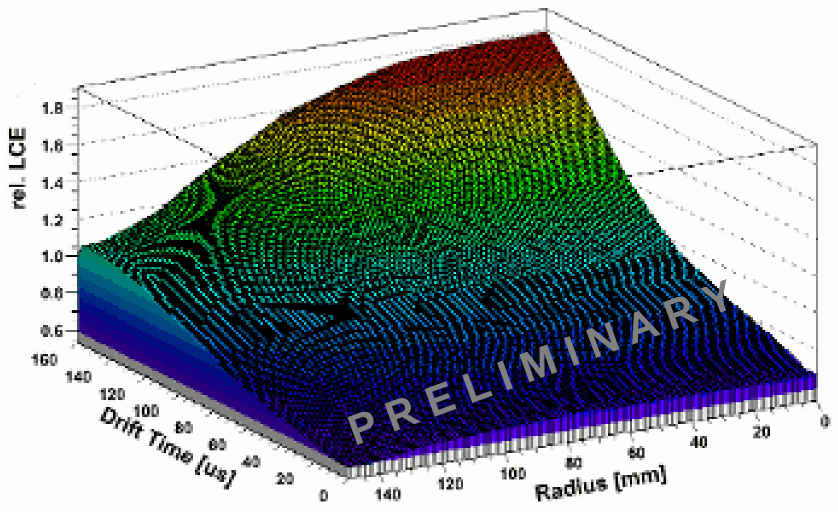




- underground since end of February 08
- first filled with Xe in mid May 08
- extensive calibrations, first science data

Calibration I





Gain calibration, gain stability:

blue LED (+ several optical fibers)

➡ gains stable within $\pm 2\%$ (σ/μ)

Average Light Yield, combined *E*-Scale:

γ-radiation:

662 keV (^{137}Cs), 1.17/1.33 MeV (^{60}Co)

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

➡ LY(122 keV$_{ee}$) = 2.20(9) PE/keV$_{ee}$

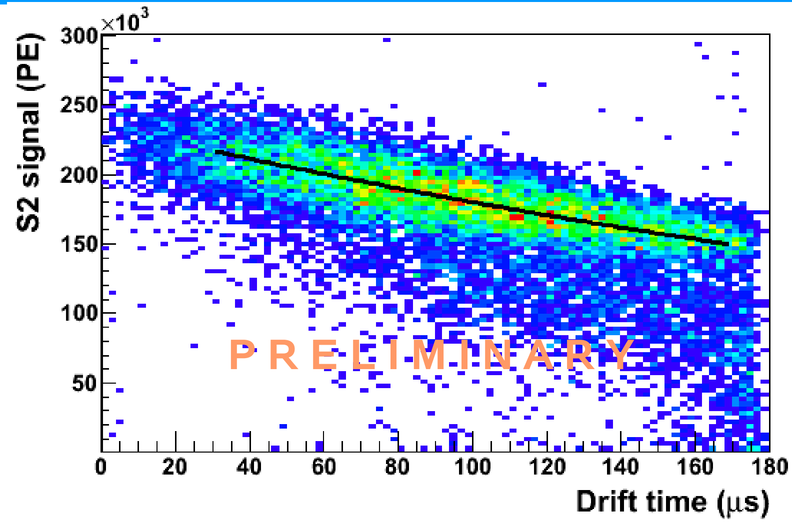
Position dependent Corrections:

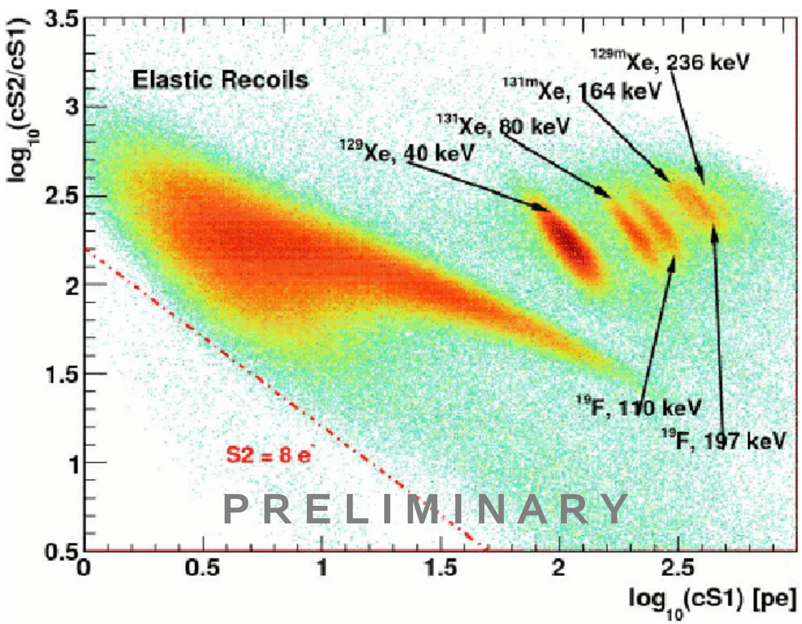
40 keV, 164 keV by ^{241}AmBe, ^{137}Cs

^{83m}Kr planned

➡ Agreement better than 3%

Calibration II





Electron Lifetime:
^{137}Cs

➡ ~200 μs (11.2d), up to 400 μs (run_08)

Position Reconstruction Tests:
^{57}Co (collimated), ^{137}Cs, + MC

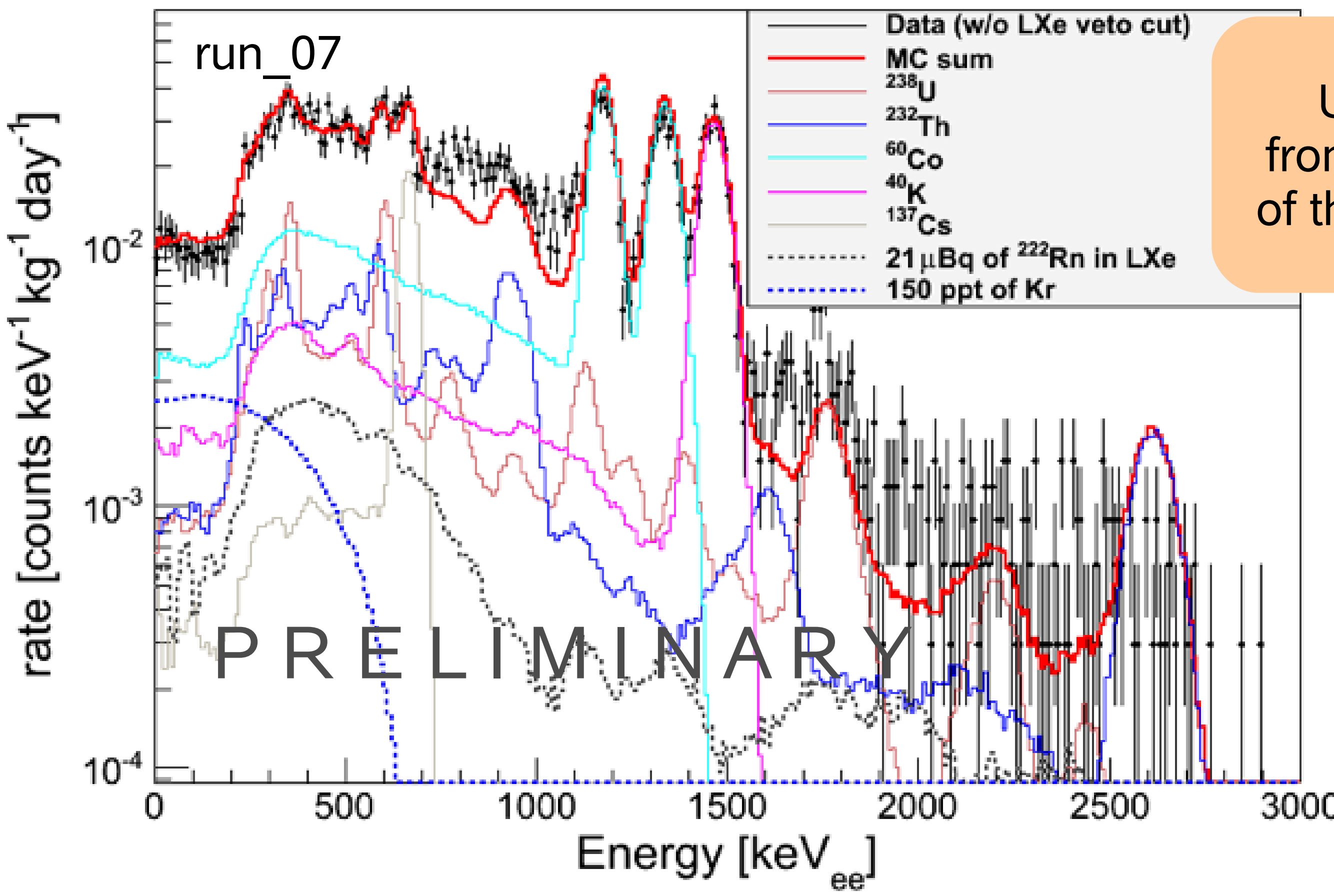
➡ 3 algorithms (NN, SVM, χ^2) available:
$\Delta r < 3$ mm, $\Delta z < 2$ mm

Electron Recoil Band (Background):
^{60}Co, ^{137}Cs, ^{228}Th

Nuclear Recoil Band (Signal):
Neutrons: AmBe

➡ definition of WIMP search region, discrimination

Background

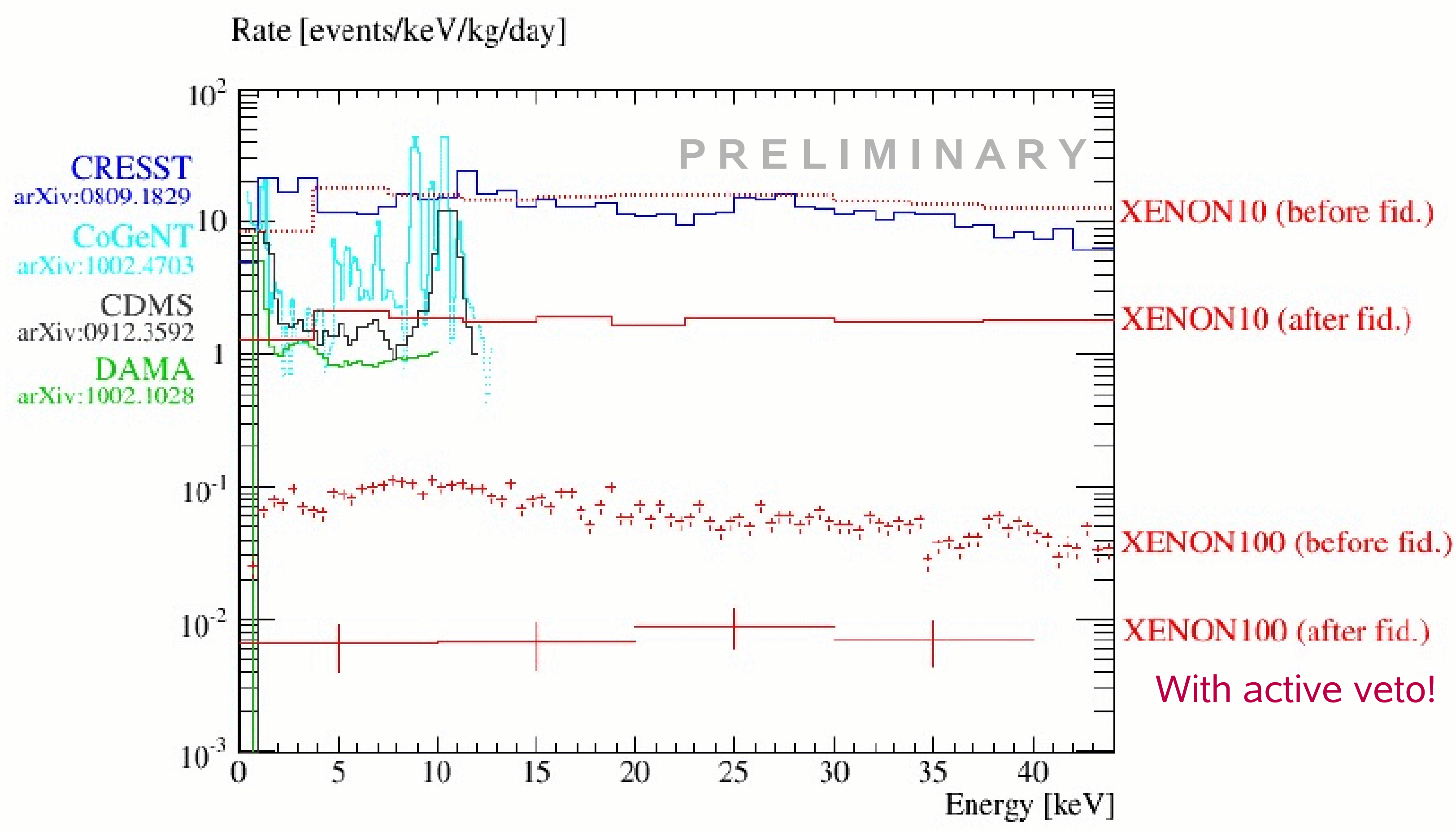


No MC tuning!
Using only values from the determination of the contamination of each material.

30 kg fiducial mass
active LXe veto not used for this plot
exploit anti-correlation between light and charge for better ER-energy scale

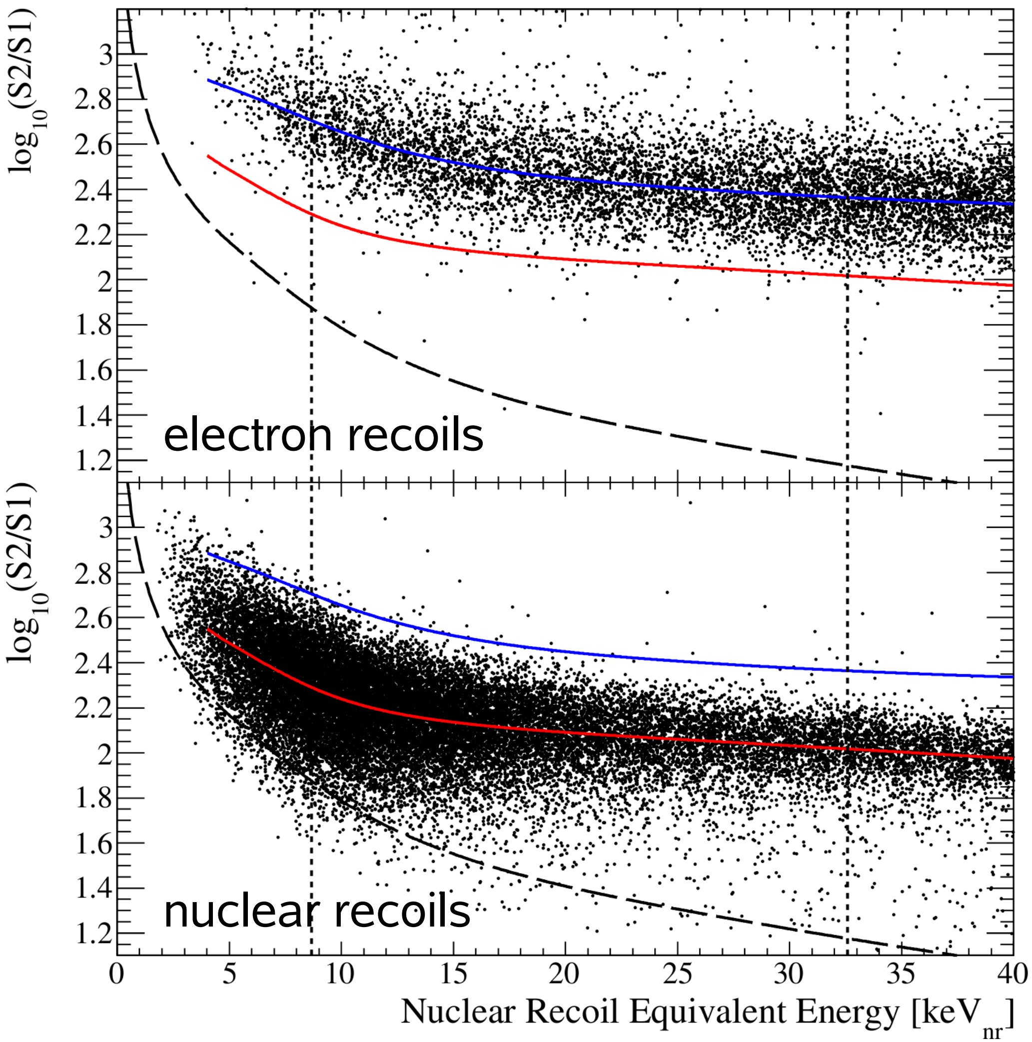
Measured Background in good agreement with Monte Carlo prediction.

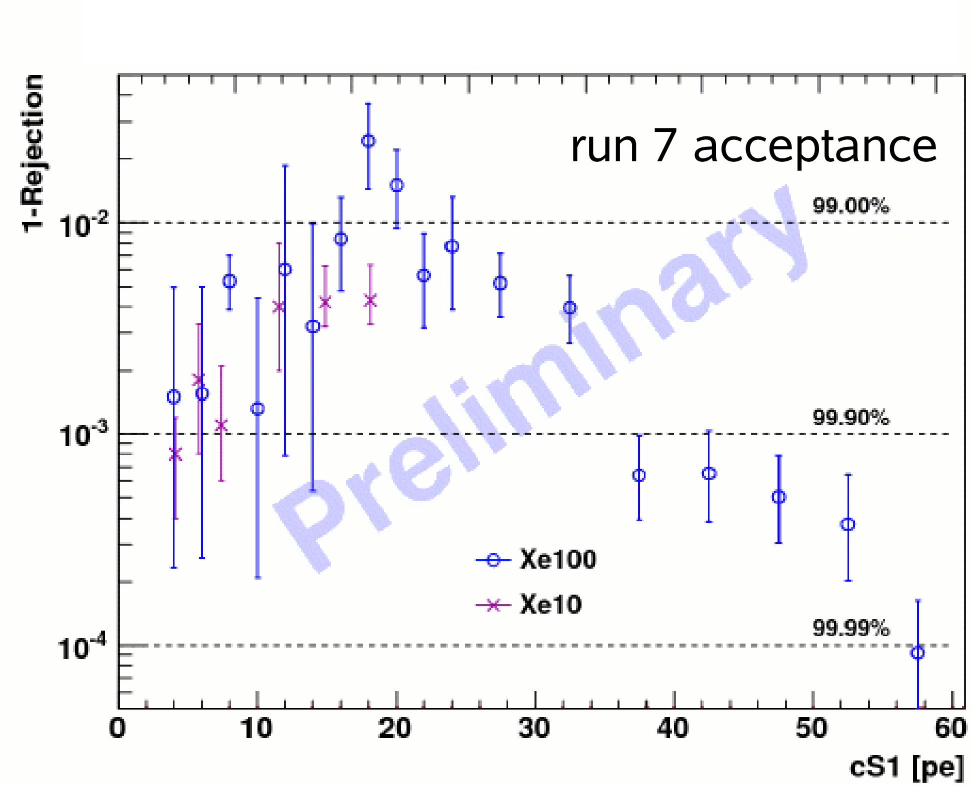
Background comparison



A factor 100 lower than XENON10
lower than any other DM experiment

Electron recoil / nuclear recoil discrimination via S2/S1 ratio





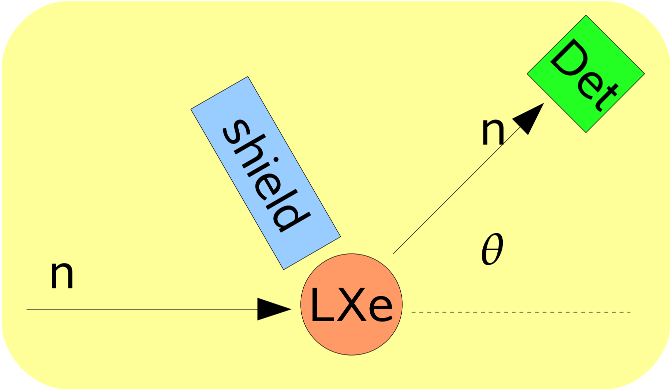
Discrimination efficiency similar to XENON10 (>99%)

Nuclear recoil energy calibration I

WIMPs interact with Xe nucleus

→ nuclear recoil (*nr*) scintillation

measurement principle:



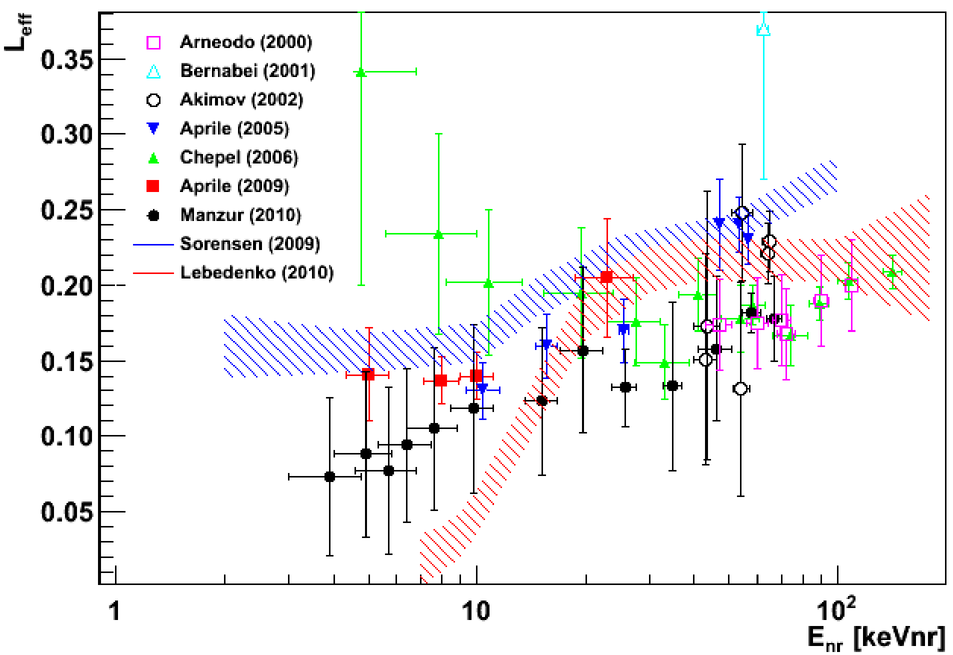
Absolute measurement of *nr* scintillation yield $L_Y(E_{nr})$ is difficult

→ measure $L_Y(E_{nr})$ relative to $L_Y(E_{ee}=122\text{keV})$ from ^{57}Co

in dedicated experiments (electric field $\mathrm{E} = 0$)

and define relative scintillation efficiency L_{eff}:

$$L_{eff}(E_{nr}) = \frac{L_Y(E_{nr})_{\mathrm{E}=0}}{L_Y(E_{ee}=122\text{ keV})_{\mathrm{E}=0}}$$



$$E_{nr} = \frac{S1}{L_Y(E_{nr})_{\mathrm{E}\neq 0}}$$

$$= \frac{S1}{L_Y(E_{nr})_{\mathrm{E}=0} \cdot S_{nr}} \cdot \frac{L_Y(E_{ee}=122\text{ keV})_{\mathrm{E}=0} \cdot S_{ee}}{L_Y(E_{ee}=122\text{ keV})_{\mathrm{E}\neq 0}}$$

$$= \frac{S1}{L_Y(E_{ee}=122\text{ keV})_{\mathrm{E}\neq 0}} \cdot \frac{1}{L_{eff}(E_{nr})} \cdot \frac{S_{ee}}{S_{nr}}$$

Nuclear recoil energy calibration II

difficult measurements

measurements differ systematically

large uncertainties

direct measurements vs. indirect determinations

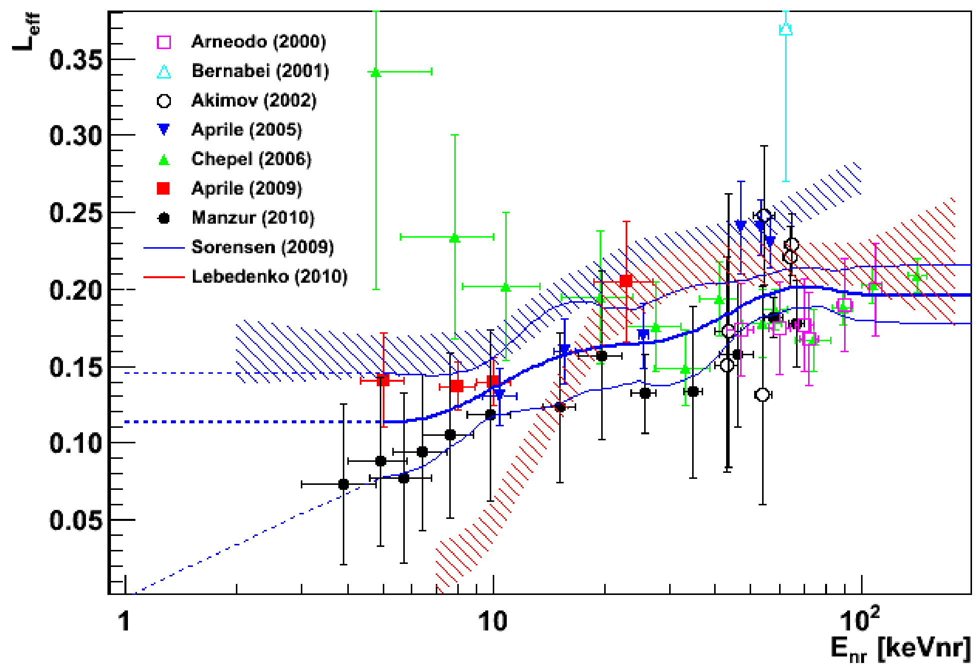
no proper theoretical model available

→ do not prefer single measurement (not even our own ones)

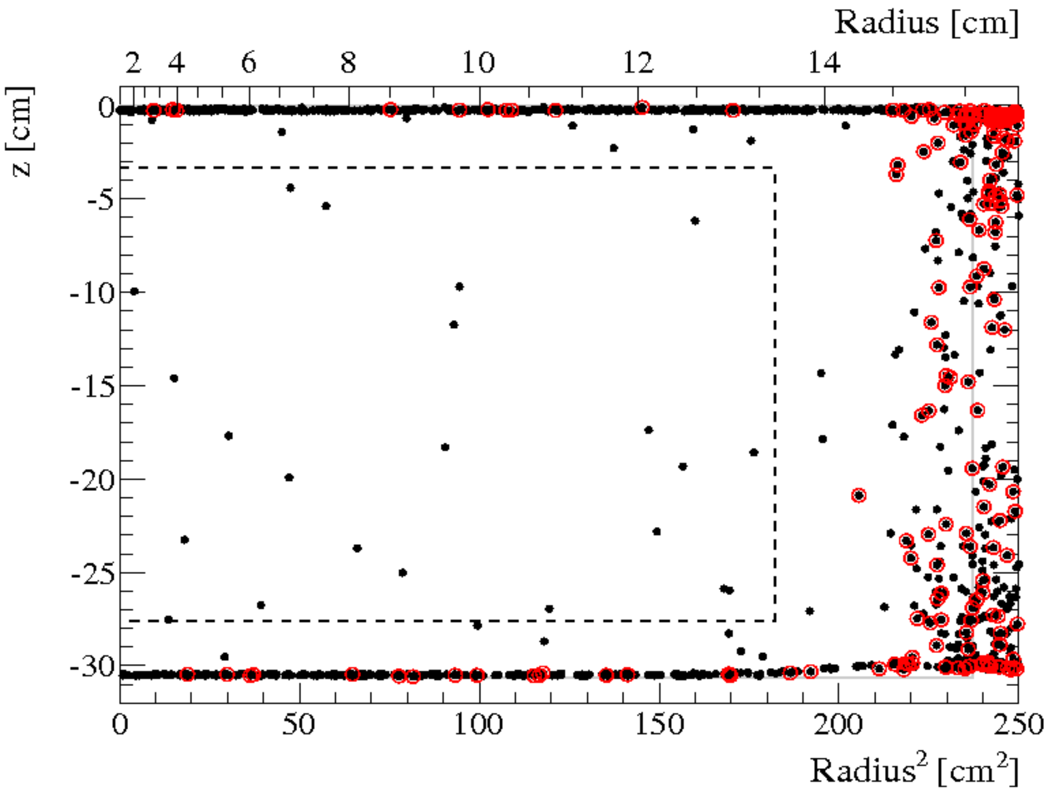
→ global fit to all direct measurements

→ get 90% CL from statistics

→ extrapolation to low energies motivated by available data



First XENON100 Data



Energy cut: <30 keV$_{nr}$

make use of excellent self-shielding capability of LXe

40 kg fiducial mass

Background data taken under stable conditions Oct-Nov 2009

11.2 life days

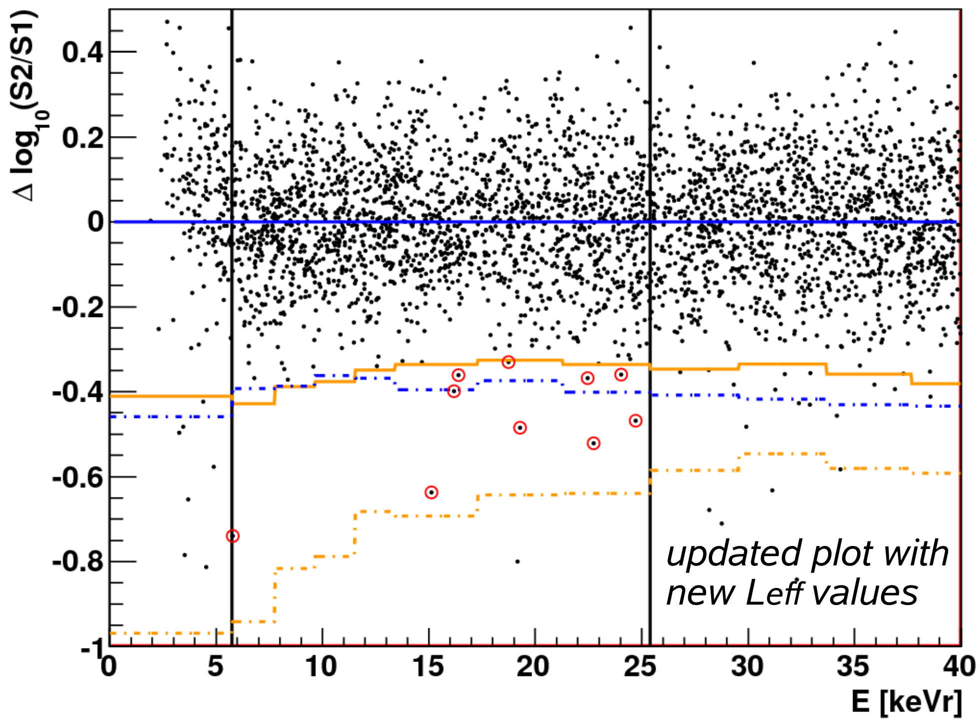
Data was not blinded

But: Cuts developed and optimized on calibration data only

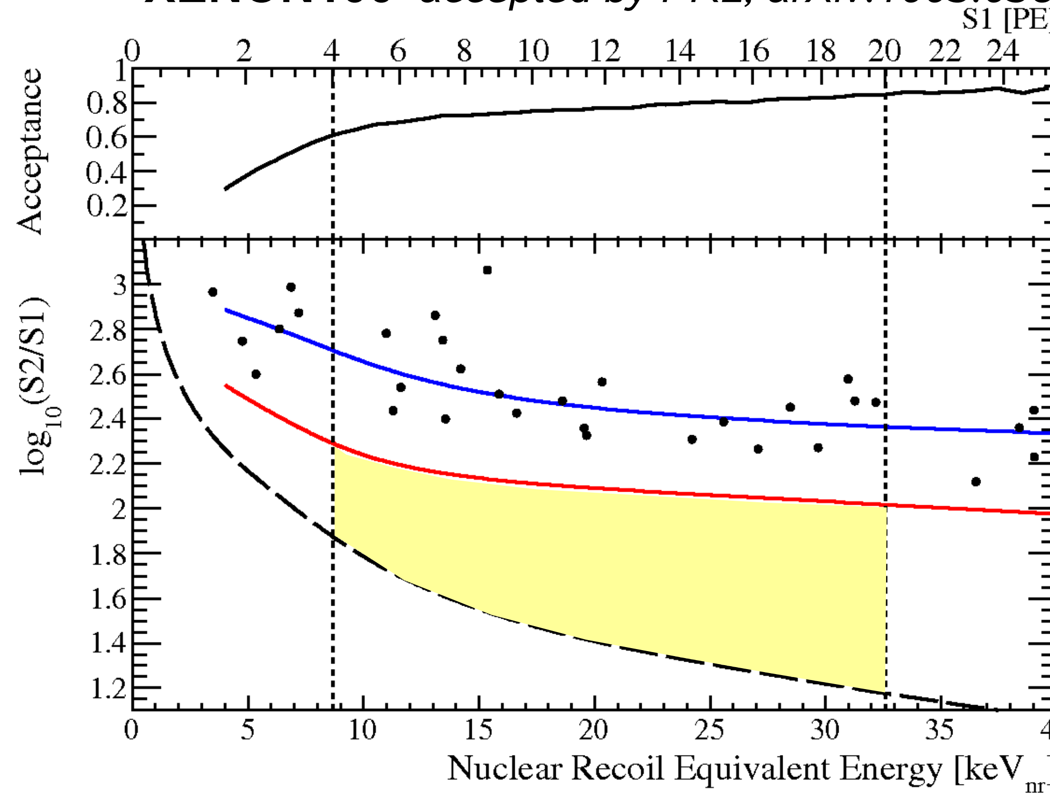
accepted by PRL *arXiv:1005.0380*

A Look at the Bands

XENON10 *PRL 100, 021303 (2008)*



XENON100 *accepted by PRL, arXiv:1005.0380*



Free of background in 11.2 days
after S2/S1 discimination

Both plots show similar exposure

NR acceptance = 50%
cut efficiency ~ 60-85 %

(conservative)
Background expectation $\ll 1$

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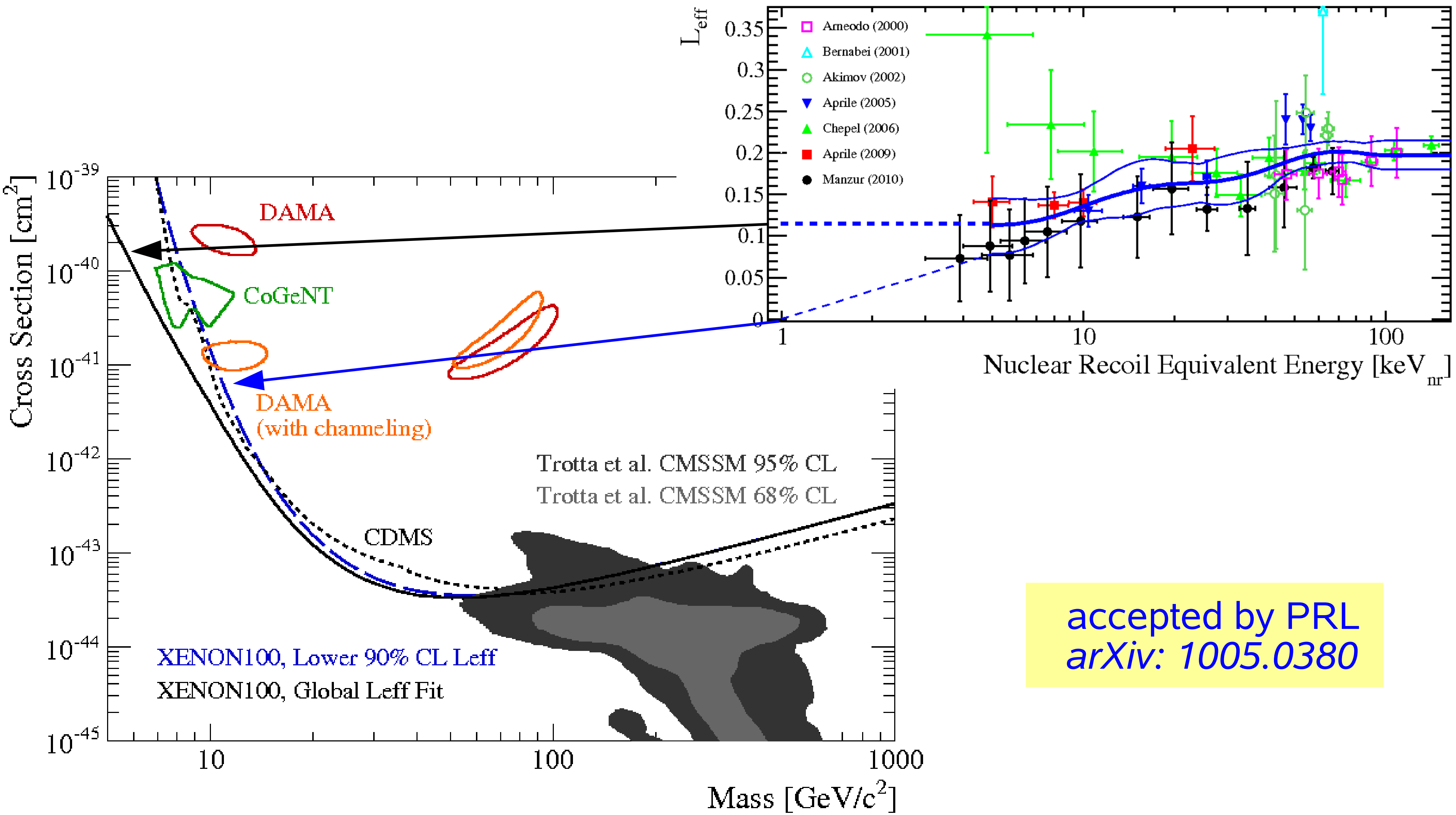
A first WIMP limit from XENON100

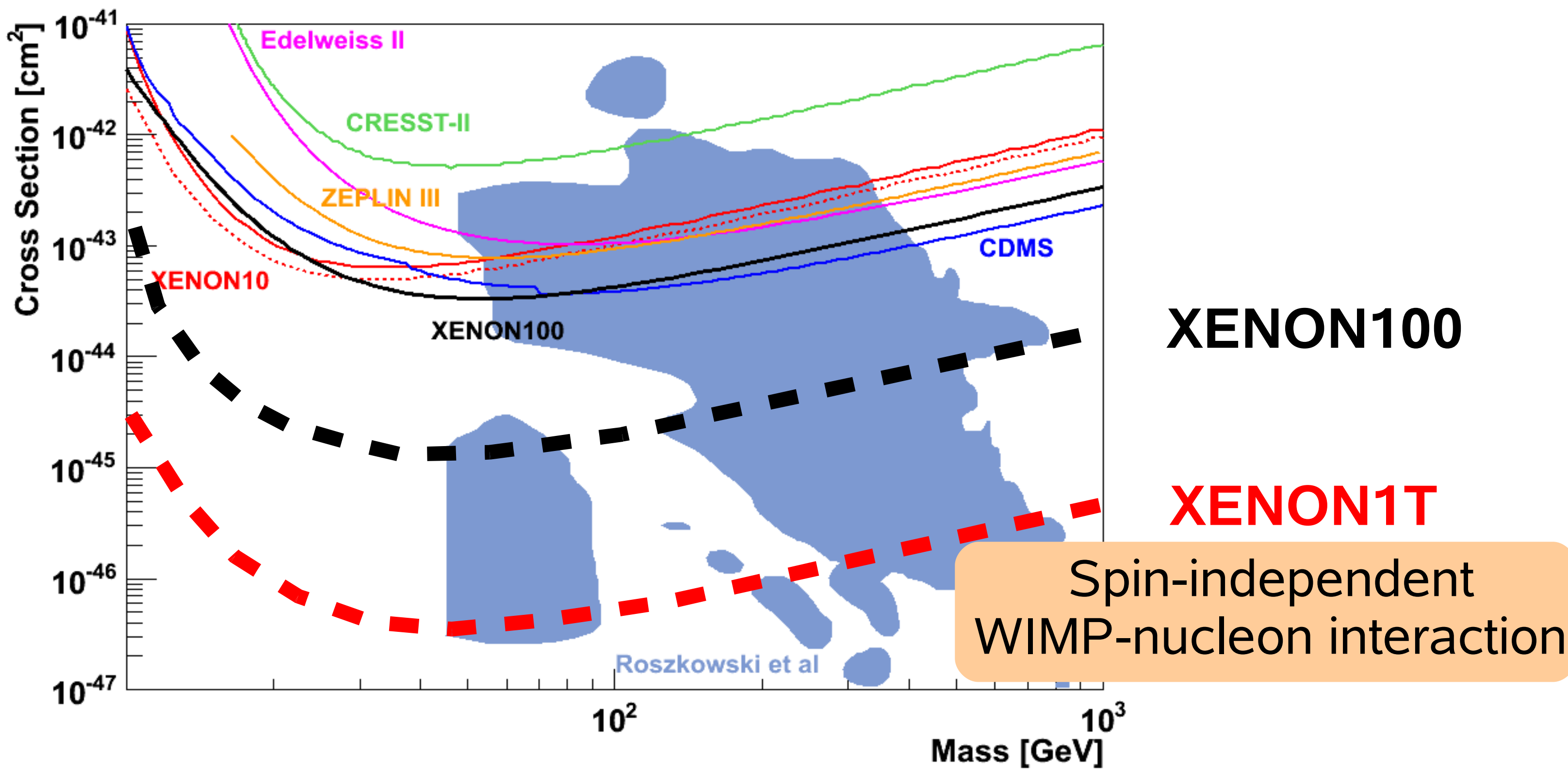


accepted by PRL
arXiv: 1005.0380

spectrum averaged exposure: 170 kg days

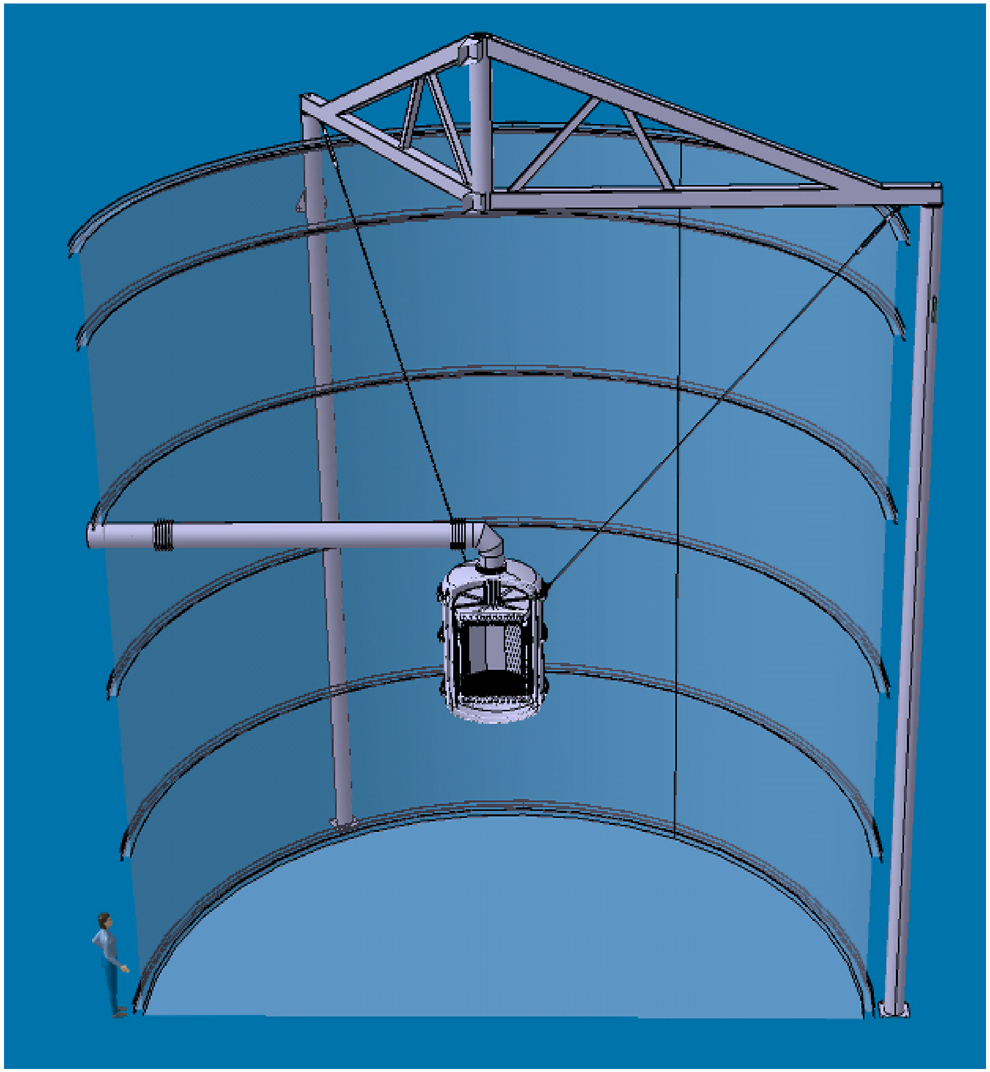
XENON100: Status and sensitivity

- 10 times more blinded data on harddisk from 2010: plan to unblind end of 2010
- maintainance of cryo system completed,
- at present filling of cryostat through destillation column for further Kr reduction
- restart science run soon



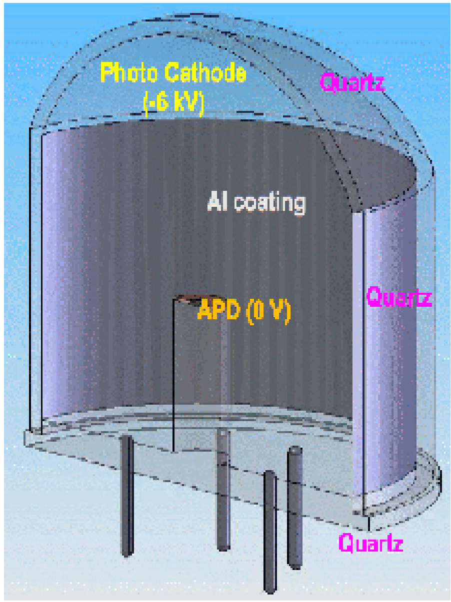
50 kg Target:	40 days	$\sigma = 6 \cdot 10^{-45}$ cm² (@ 100 GeV)
30 kg Target:	200 days	$\sigma = 2 \cdot 10^{-45}$ cm² (@ 100 GeV)

The next step: XENON1T



2.4t LXe ("1m³ detector")
    1.1t fiducial mass

100x lower background
    10 cm self shielding,
    QUPID
    active H_2O veto



in design phase

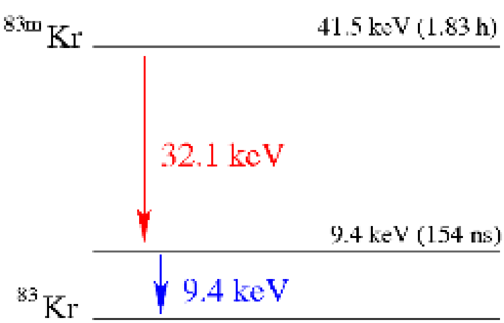
bigger collaboration

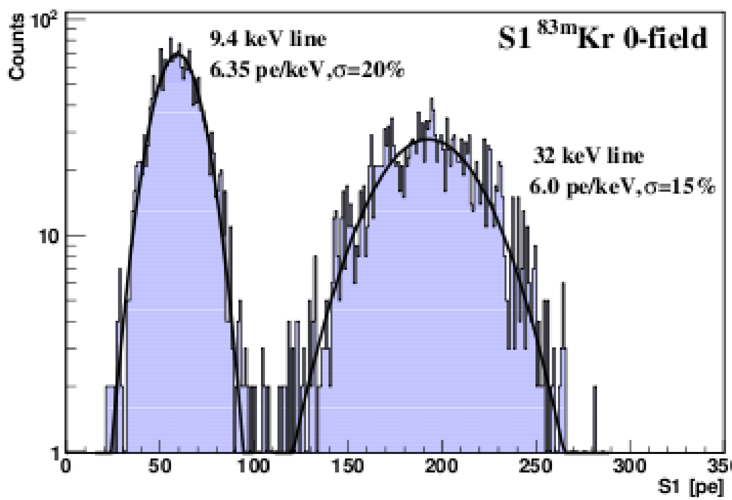
Two possible sites:
    LNGS / Modane

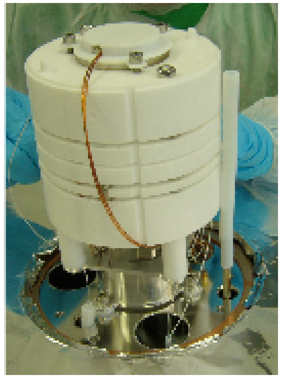
Timeline:
    2010 – 2014 ???

^{83m}Kr as internal calibration source

- ^{83m}Kr calibration source:
  - EC decay-product of ^{83}Rb
  - Lines at 9.4 and 32.1 keV
  - Uniform distribution

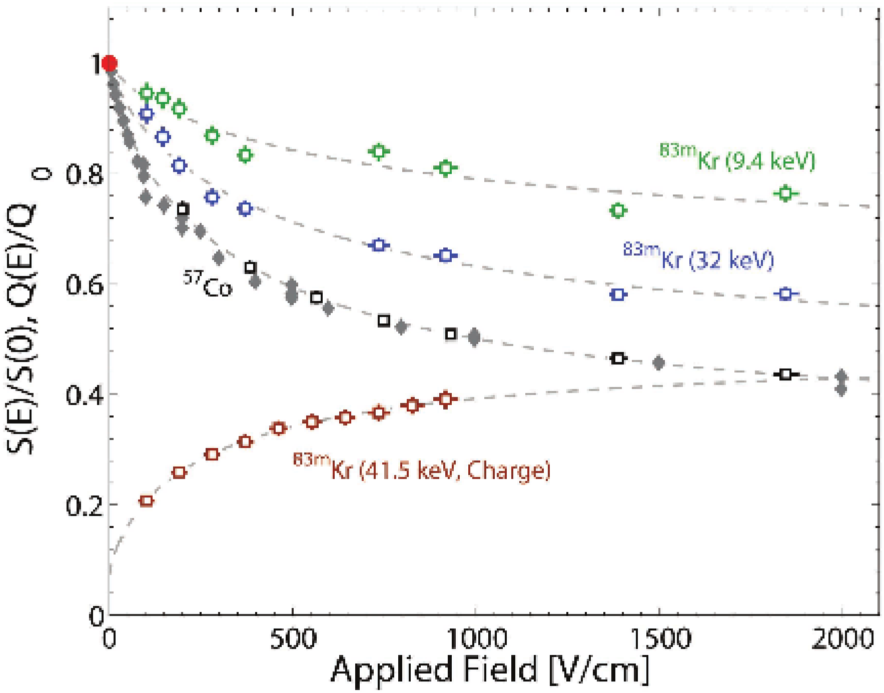






- Target mass: ~ 0.1 kg Xe
- Volume: 3 cm drift length and 3.5 cm diameter
- Two R9869 PMTs
- 6 pe/keV in double phase

→ at University of Zürich



→ ^{83m}Kr calibration planned in XENON100

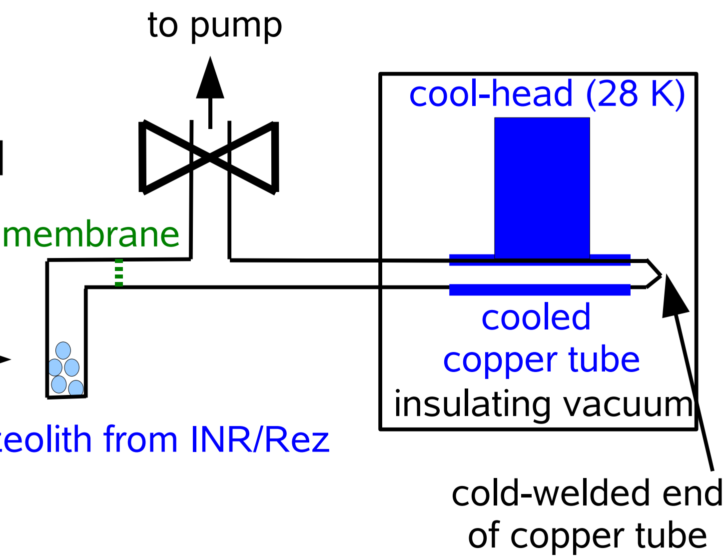
A. Manalaysay *et al*, Rev. Sci. Instrum. **81**, 073303 (2010)

Check Rb emanation out of ^{83}Rb source (^{83m}Kr generator)

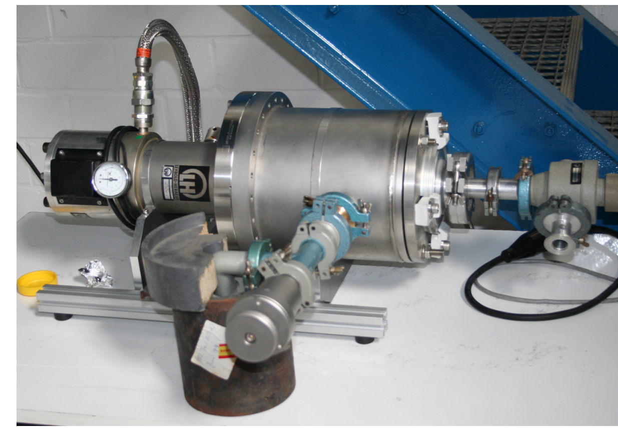
^{83}Rb emanation test:

trap possibly emanated

Rb in cryo trap over 10 d



^{83}Rb in zeolith from INR/Rez

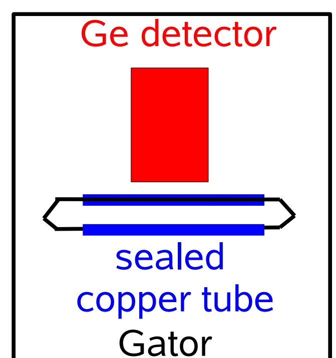


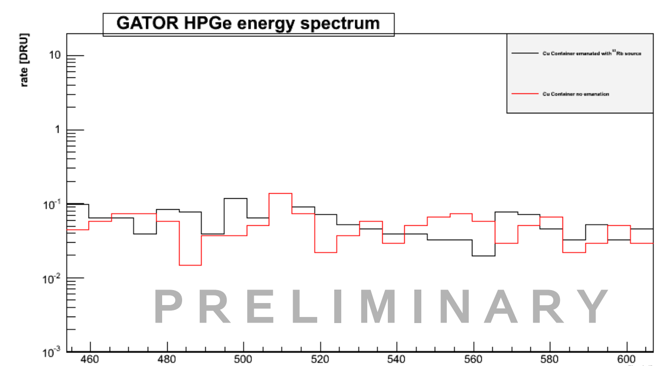
Cold-weld copper-tube on 2nd side and transport to LNGS

Search ^{83}Rb γ lines with underground

Germanium detector Gator at LNGS

none found after 16 d !

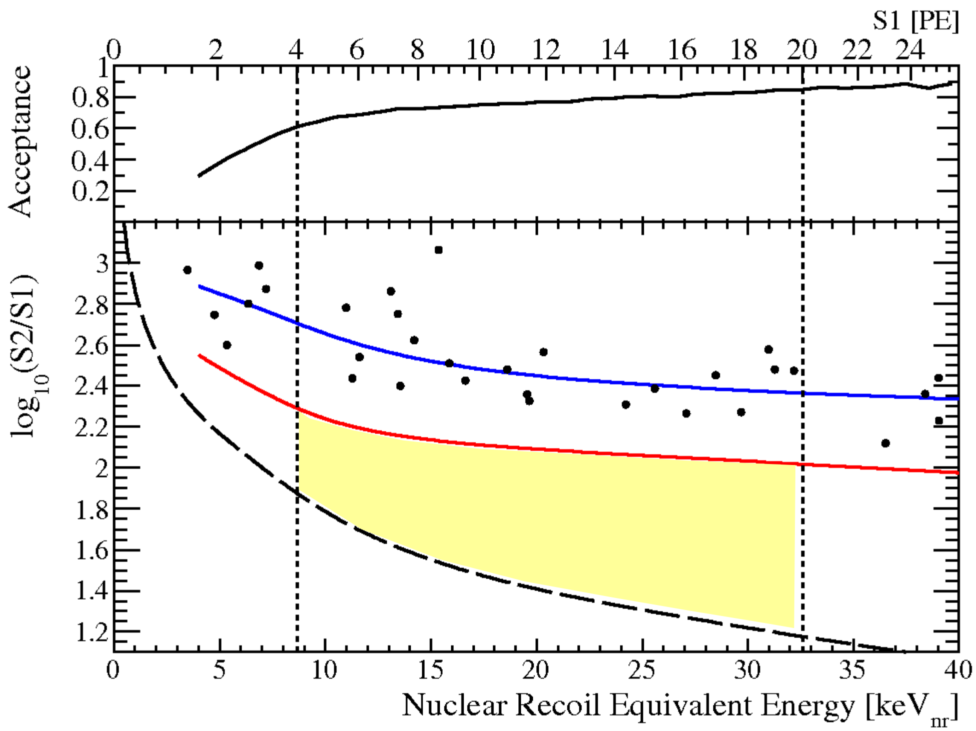




⇒ no danger of contaminating XENON by this ^{83}Rb source !

use as calibration source & tracer to measure distillation efficiency

Summary



XENON100

62 kg dual-phase Xe TPC @ LNGS

extremely low background

first results from 11.2d data:
accepted by PRL, *arXiv:1005.0380*

XENON1T

technical design is under way

Far future: DARWIN, MAX, ...