New Results from the XENON100 Dark Matter Experiment

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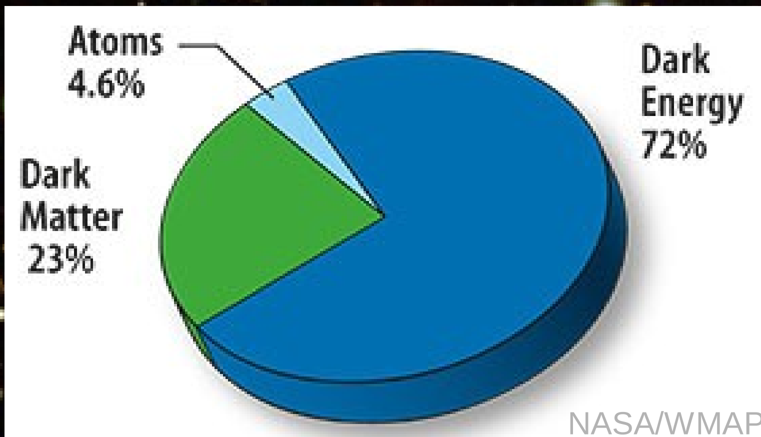
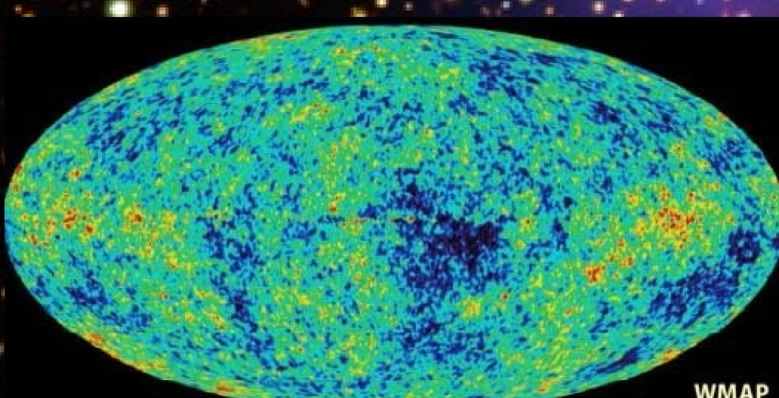
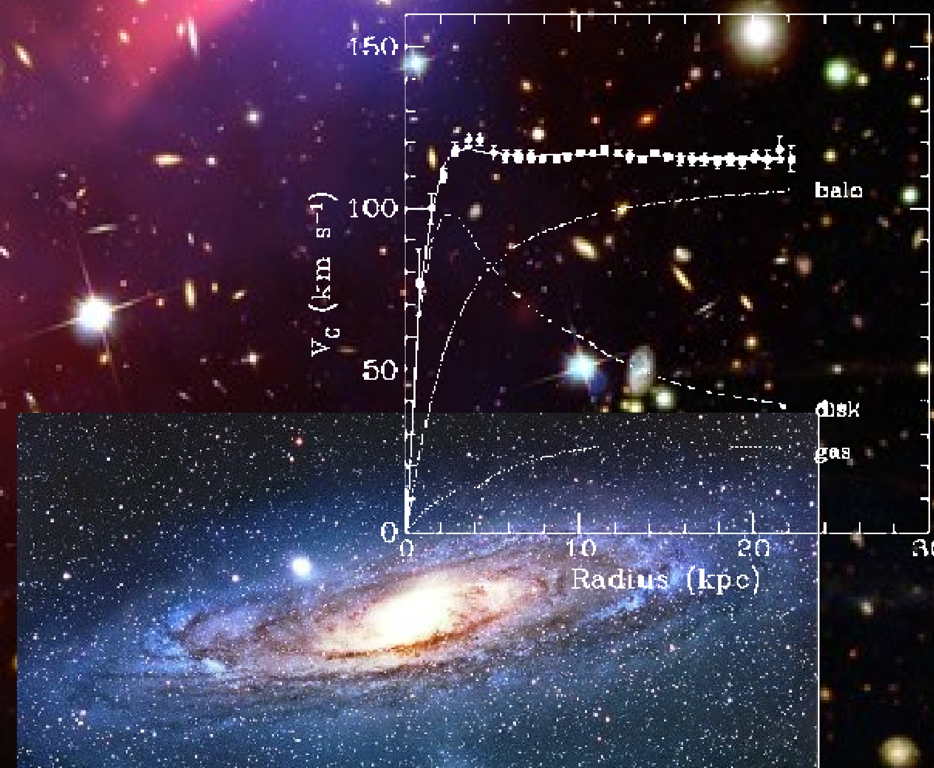
SPS Annual Meeting, Lausanne, June 17th, 2011

www.physik.uzh.ch/groups/groupbaudis/xenon/

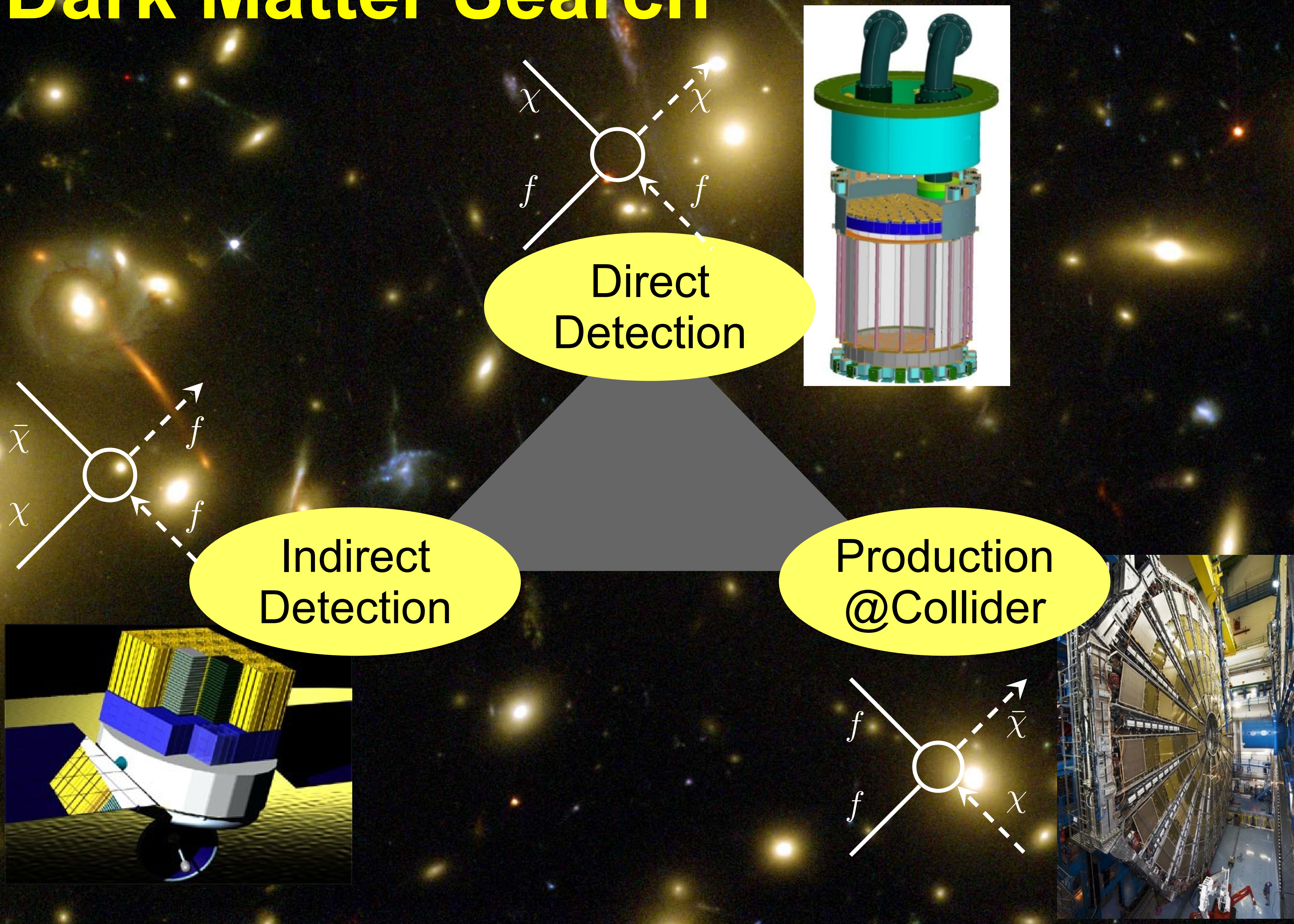
Dark Matter: (indirect) Evidence



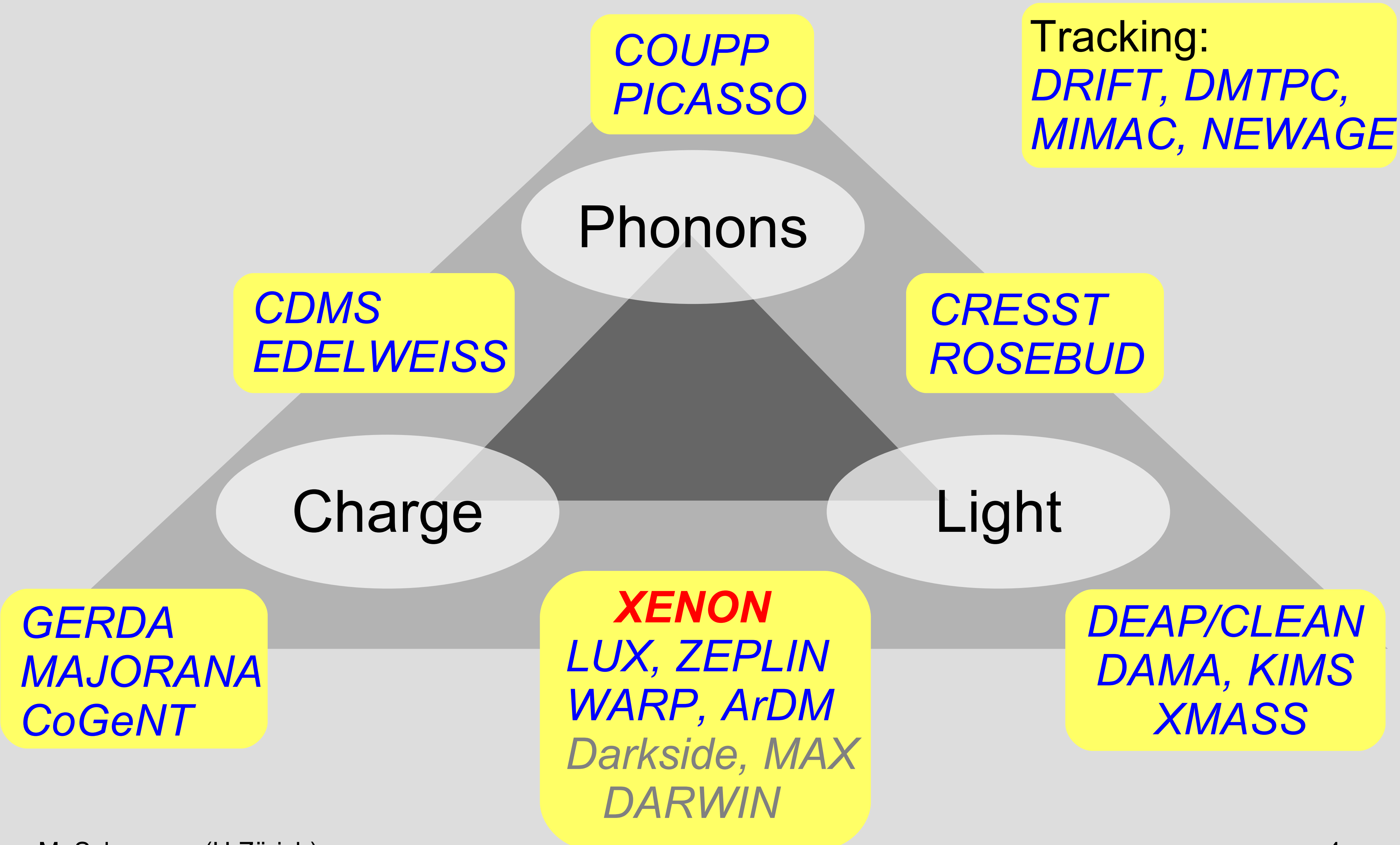




Dark Matter Search

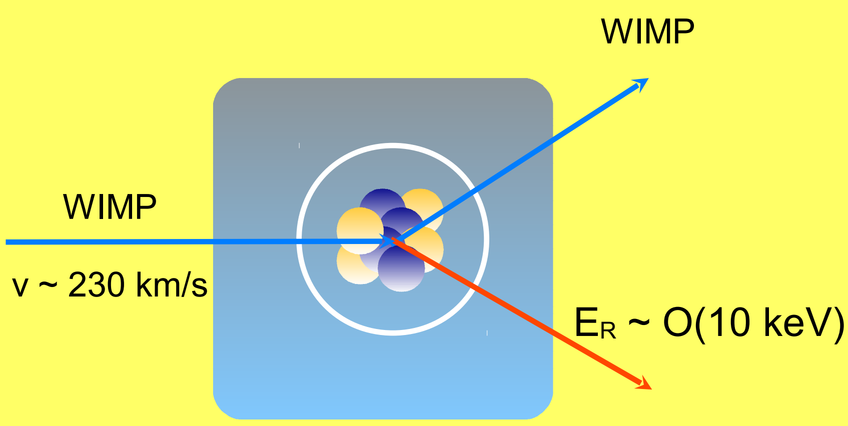


Direct WIMP Detection



Direct WIMP Search

Elastic Scattering of WIMPs off target nuclei
➞ nuclear recoil



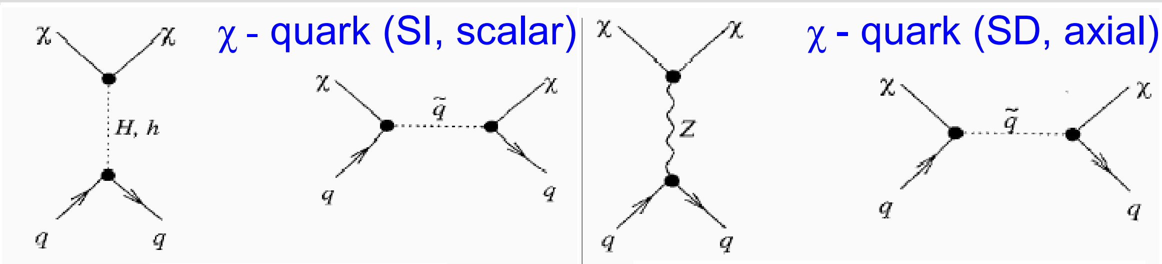
Recoil Energy: $$E_r = \frac{|\vec{q}|^2}{2m_N} = \frac{\mu^2 v^2}{m_N}(1 - \cos\theta) \sim \mathcal{O}(10 \text{ keV})$$

Event Rate: $$R \propto N \frac{\rho_\chi}{m_\chi} \langle \sigma_{\chi-N} \rangle$$

N	number of target nuclei
ρ_χ/m_χ	local WIMP density
$<\sigma>$	velocity-averaged scatt. X-section

➞ need information on halo and interaction to get rate

WIMP Interactions
Detector Requirements



$\mathcal{L}_S \sim \bar{\chi}\chi\bar{q}q \quad \propto A^2$

$\mathcal{L}_A \sim \bar{\chi}\gamma_\mu\gamma_5\chi\bar{q}\gamma^\mu\gamma_5 q \quad \propto J(J+1)$

Jungmann et al. '96 Phys.Rep.

Result: Tiny Rates

R < 0.01 evt/kg/day

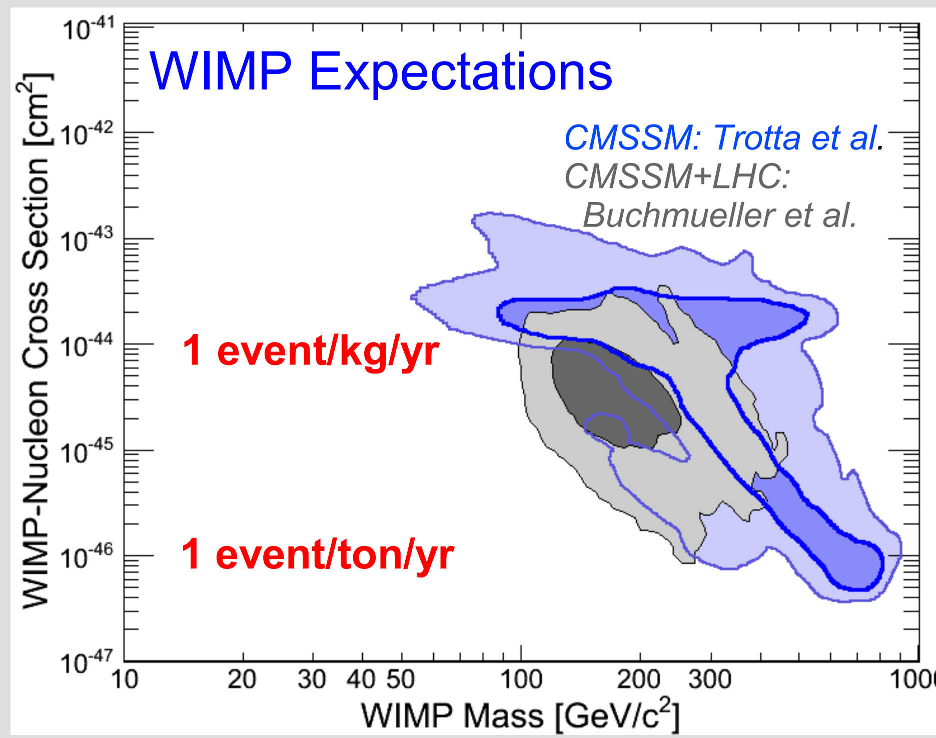
E_r < 100 keV

What do we look for?

- nuclear recoils, single scatters
- recoil spectrum falls with E
- dependence on A, spin?
- annual flux modulation?

How to build a WIMP detector?

- large total mass, high A
- low energy threshold
- ultra low background
- good background discrimination



Backgrounds

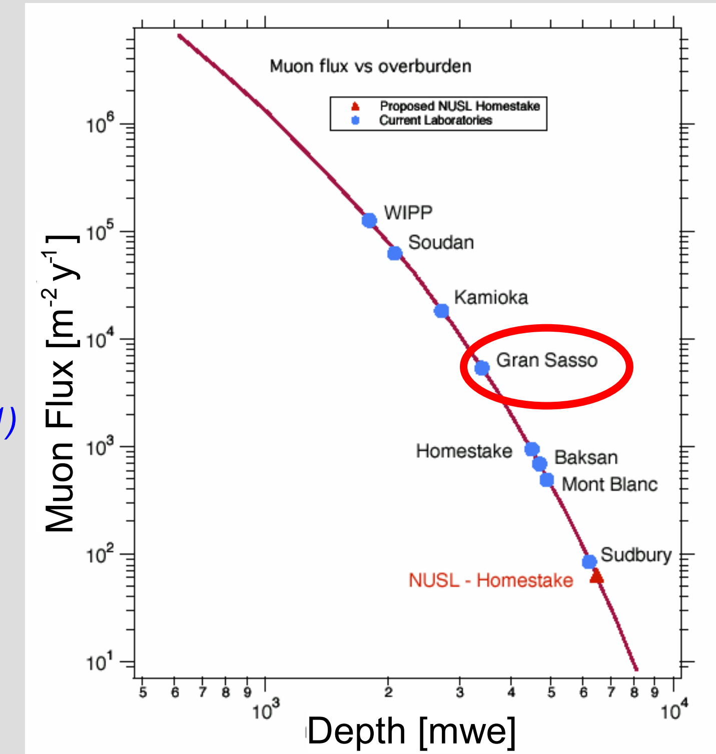
Experimental Sensitivity:
without background: $\propto (mt)^{-1}$
with background: $\propto (mt)^{-1/2}$

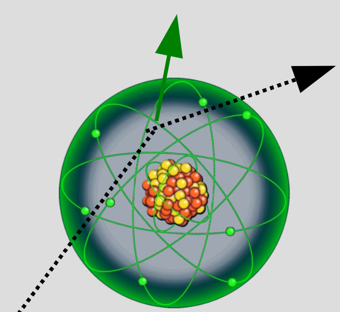
Background Sources:
environment: U, Th chains, K *NIM A 643, 36 (2011)*

$$^{238}U \xrightarrow[\alpha]{} {}^{234}Th \xrightarrow[\beta]{} {}^{234m}Pa \xrightarrow[\beta]{} {}^{234}U \xrightarrow[\alpha]{} {}^{230}Th \xrightarrow[\alpha]{} {}^{226}Ra \xrightarrow[\alpha]{} {}^{222}Rn \xrightarrow[\alpha]{} {}^{218}Po \ldots$$

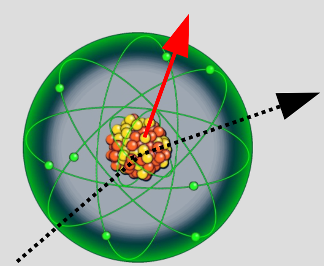
$$^{232}Th \xrightarrow[\alpha]{} {}^{228}Ra \xrightarrow[\beta]{} {}^{228m}Ac \xrightarrow[\beta]{} {}^{228}Th \xrightarrow[\alpha]{} {}^{224}Ra \xrightarrow[\alpha]{} {}^{220}Rn \xrightarrow[\alpha]{} {}^{216}Po \ldots$$

- γ and β Decays (electron recoil)
  careful material selection, discrimination, shielding (Pb, Cu, Xe, Ar, water)
- Neutrons from (α,n) in rocks
  neutron moderators (paraffin, poly, water)
- Neutrons from cosmic ray muons
  → go deep underground





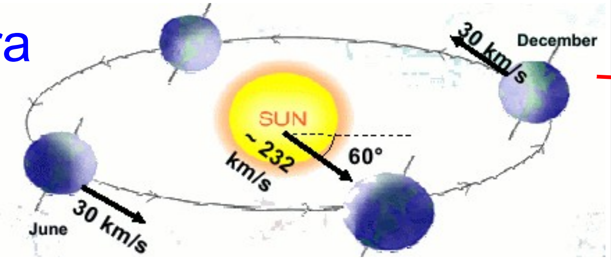
Electronic Recoils
(gamma, beta)



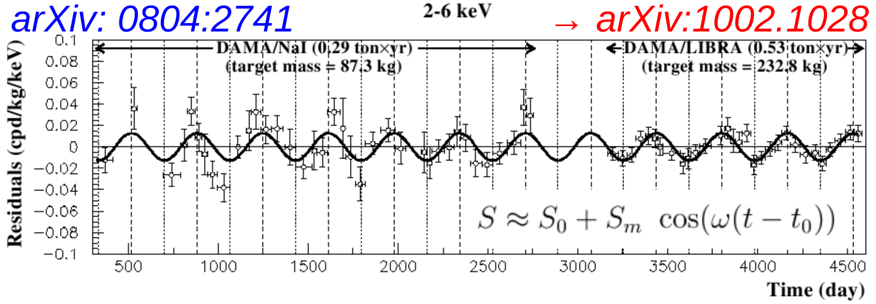
Nuclear Recoils
(neutron, WIMPs)

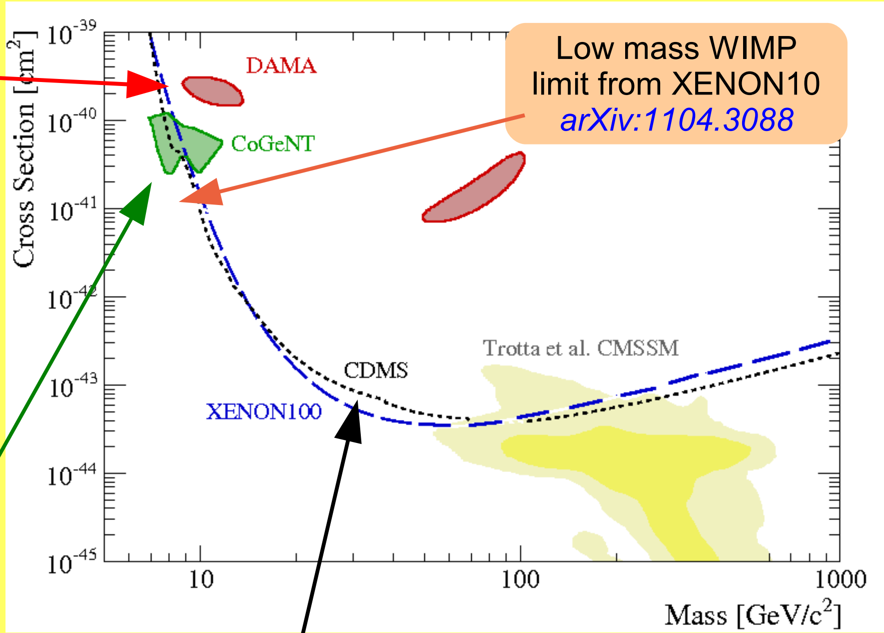
Three Experimental Results

DAMA/Libra
NaI(Tl)



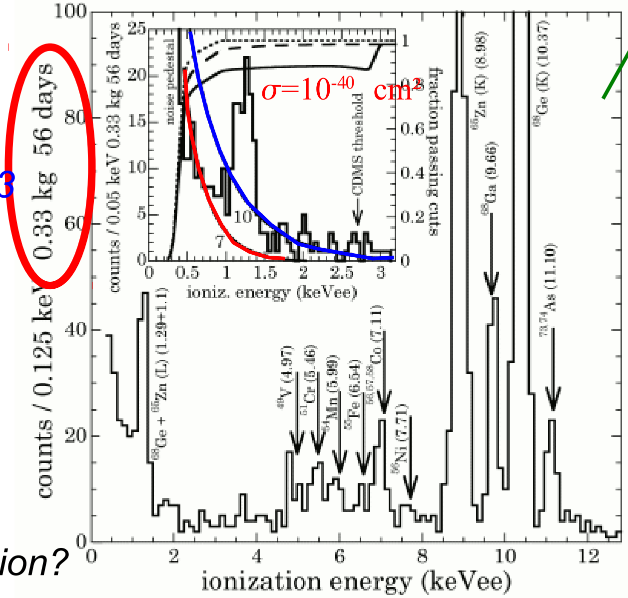
arXiv: 0804:2741 → arXiv:1002.1028





CoGeNT
p-type Ge

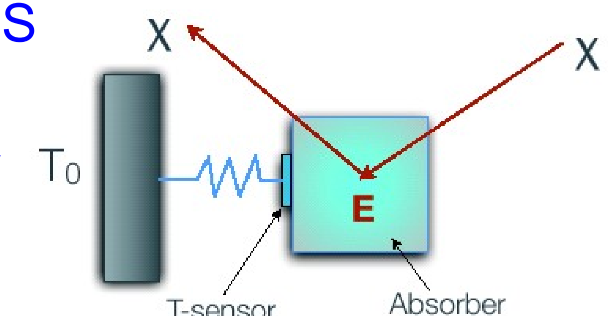
arXiv:1002.4703



New: claim of
annual modulation?

CDMS /
EDELWEISS
Ge

arXiv:1105.3377



- *excellent discrimination*
- *CDMS: low mass limits from Si and low threshold Ge data* arXiv:1011.2482

Outline

Motivation: Dark Matter ✓

Direct Dark Matter Detection ✓

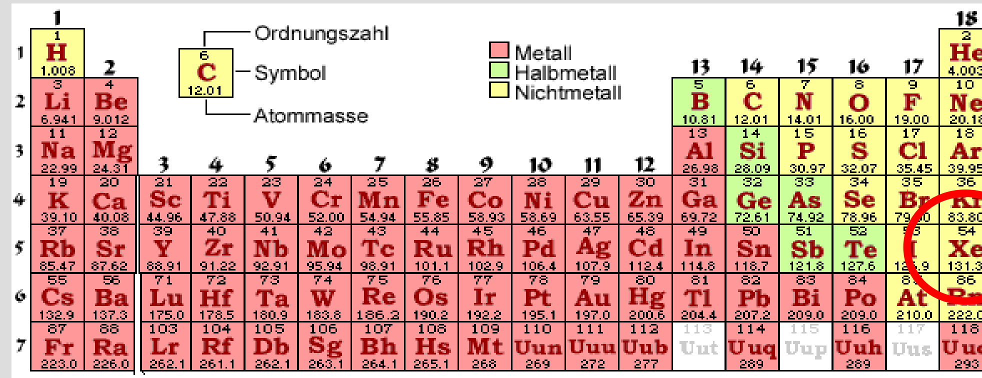
Xenon as a Detector Medium

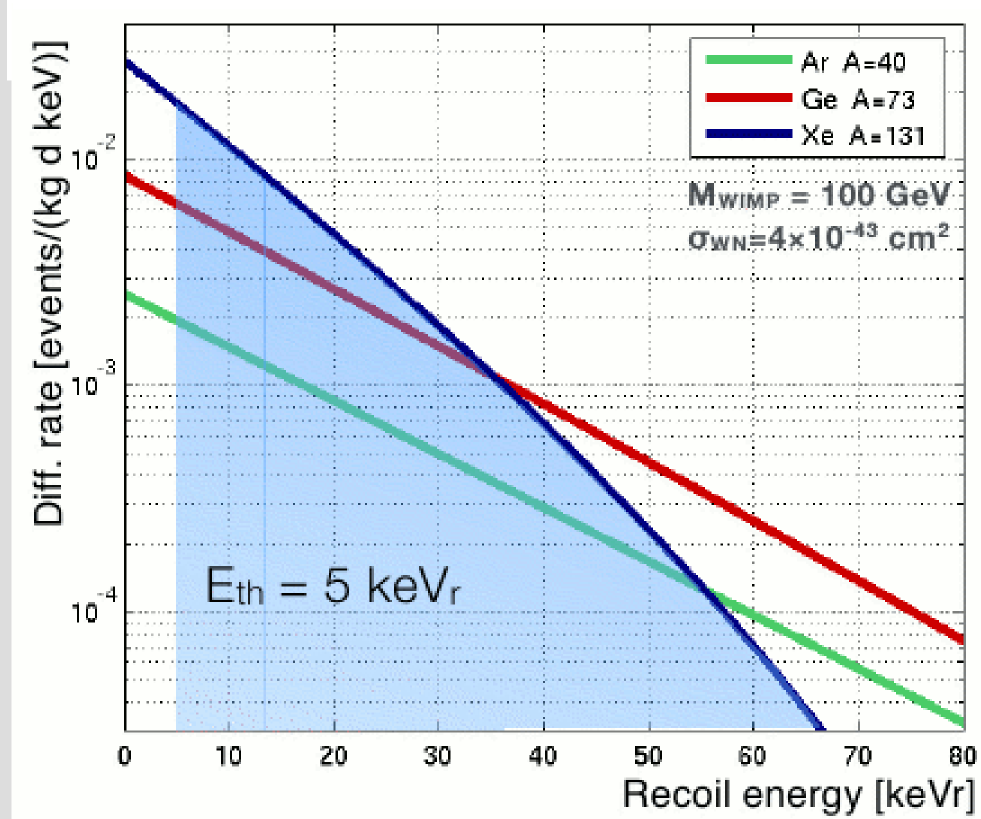
XENON100

The Future

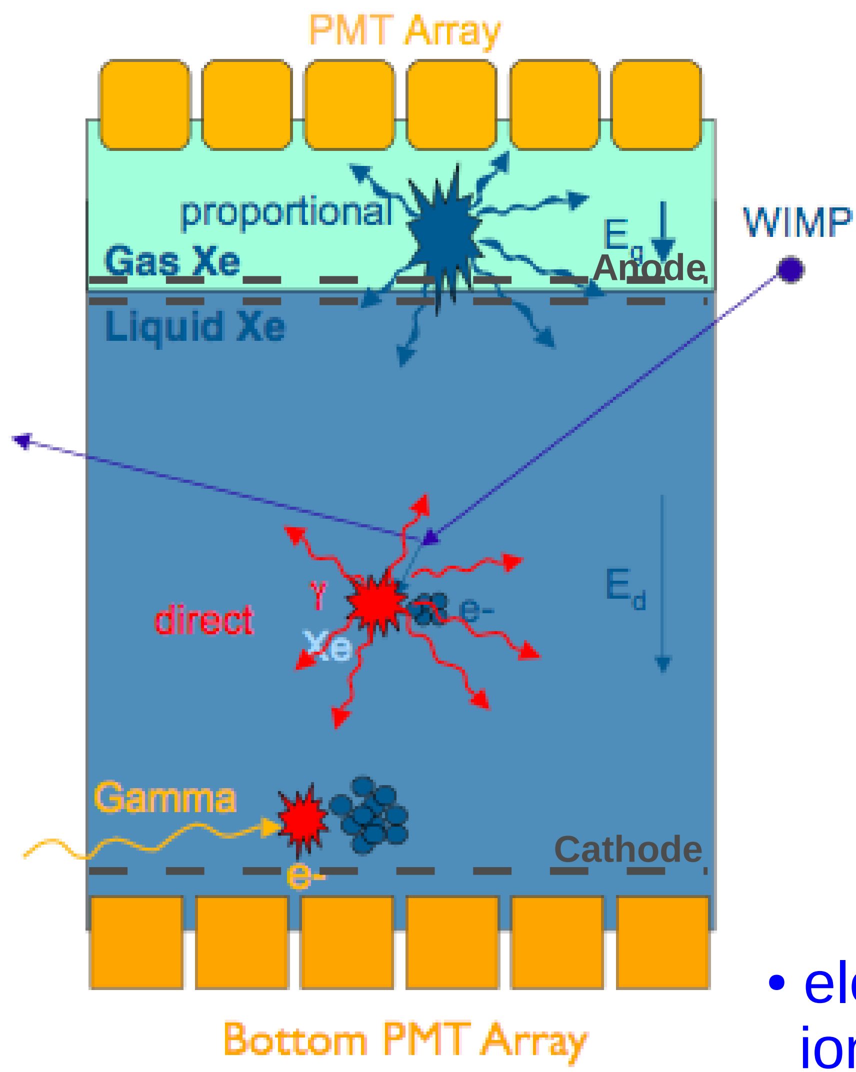
Why Xenon?

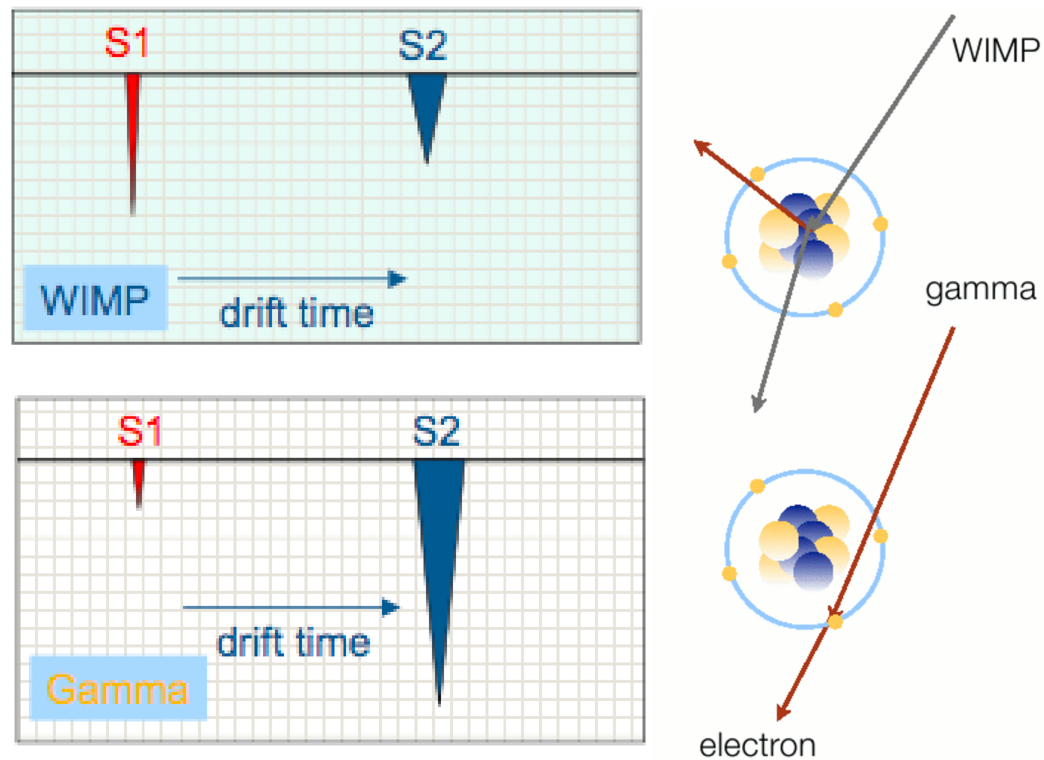
- efficient, fast scintillator (178nm)
- high mass number A~131:
  SI: high WIMP rate @ low threshold
- high Z=54, high ρ~3 kg/l:
  self shielding, compact detector
- SD: 50% odd isotopes
  allows further characterization after detection by testing only SI or SD
- no long lived Xe isotopes,
  Kr-85 can be removed to ppt
- "easy" cryogenics @ –100°C
- scalability to larger detectors
- in 2-phase TPC:
  good background discrimination





Dual Phase TPC

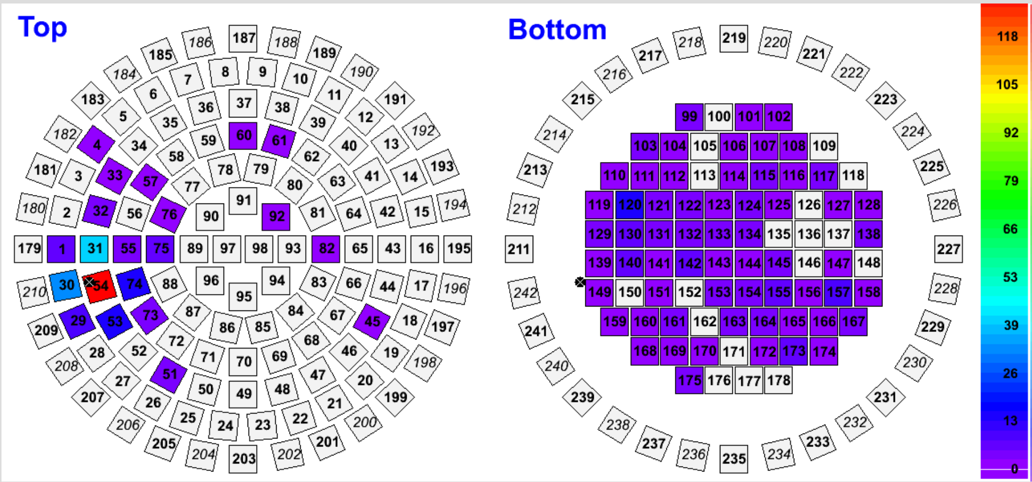


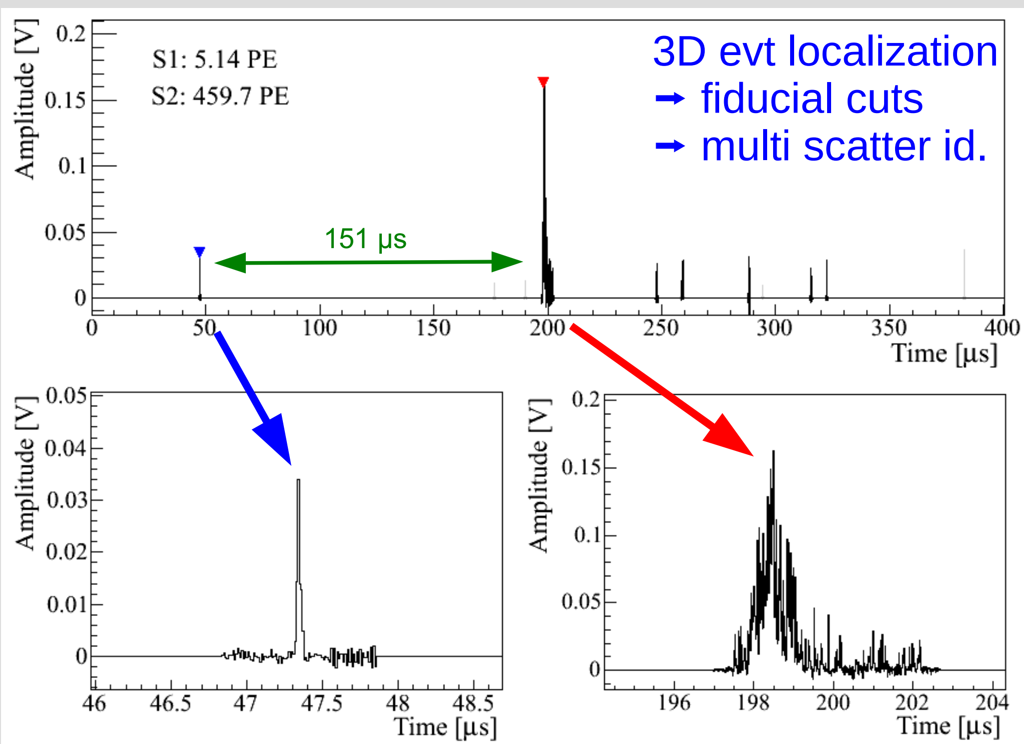


$(S2/S1)_{wimp} << (S2/S1)_{gamma}$

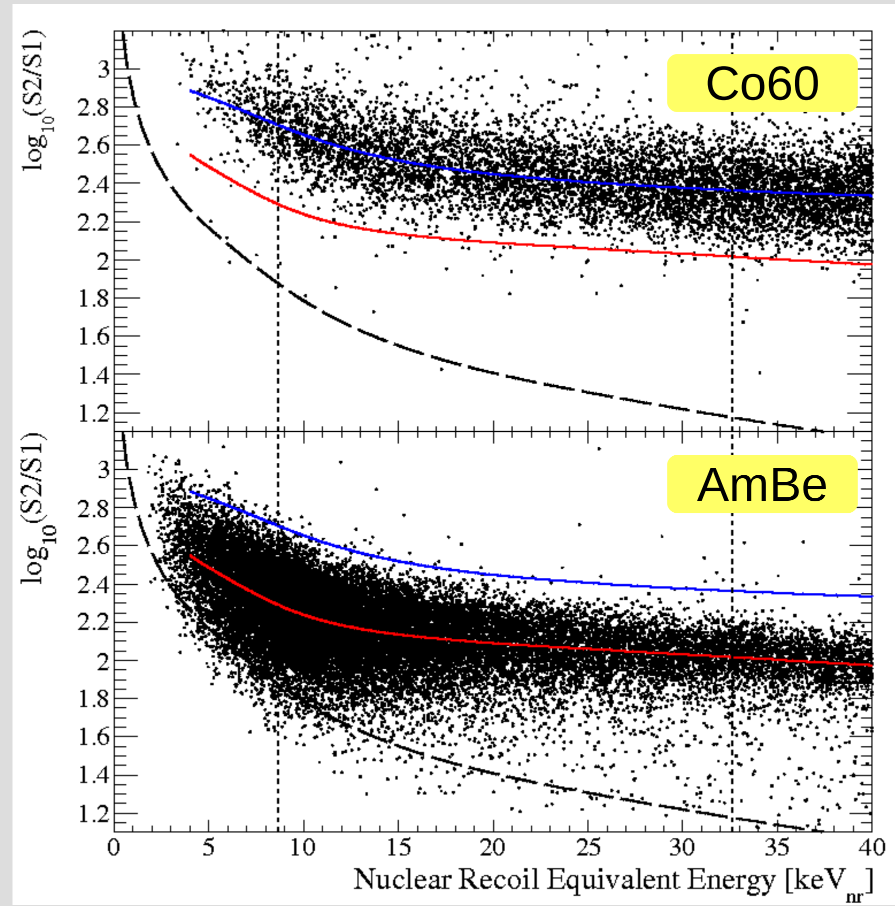
- electron recoil rejection to >99% via ionization/scintillation ratio (S2/S1)
- 3d position reconstruction in TPC
- multiple scatter rejection

Localization / Discrimination





Discrimination:



>99% rejection @ 50% acceptance

➡ definition of *WIMP search region*

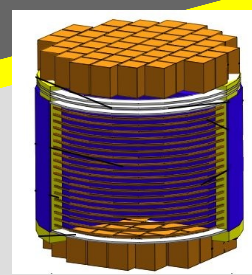
The XENON program

Xe XENON Dark Matter Project

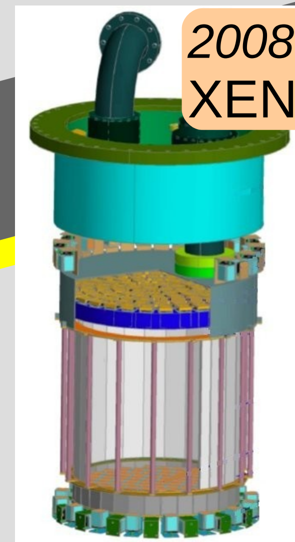
XENON: A phased WIMP search program

XENON R&D

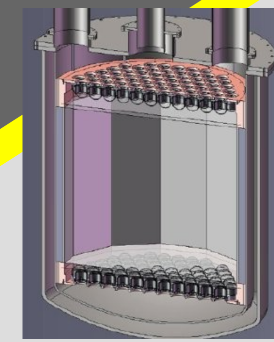
2005-2007: XENON10



2008-2011: XENON100



2010-2015: XENON1T



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

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

XENON Collaboration

XENON Collaboration Meeting, LNGS 2011

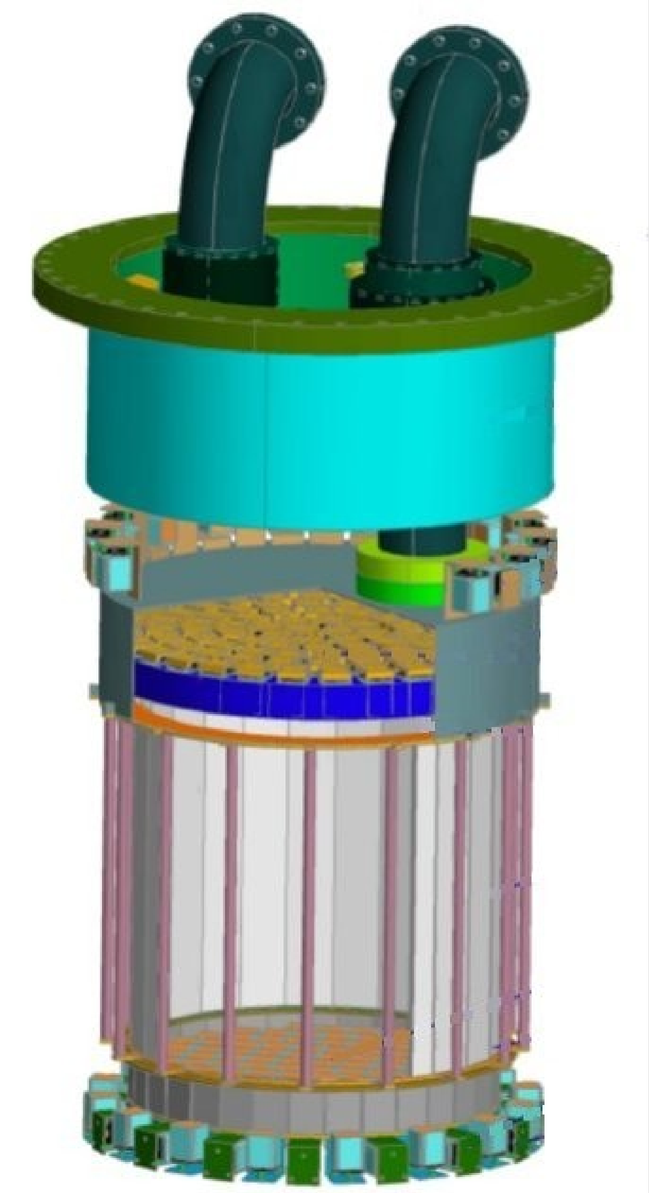
XENON100

Goal (compared to XENON10)**:**
- increase target ×10
- reduce gamma background ×100

➞ material selection & screening
➞ detector design

Quick Facts:

- 161 kg LXe TPC (mass: 10 × Xe10)
- 62 kg in target volume
- active LXe veto (≥4 cm)
- 242 PMTs
- passive shield
  (Pb, Poly, Cu, H_2O, N_2 purge)



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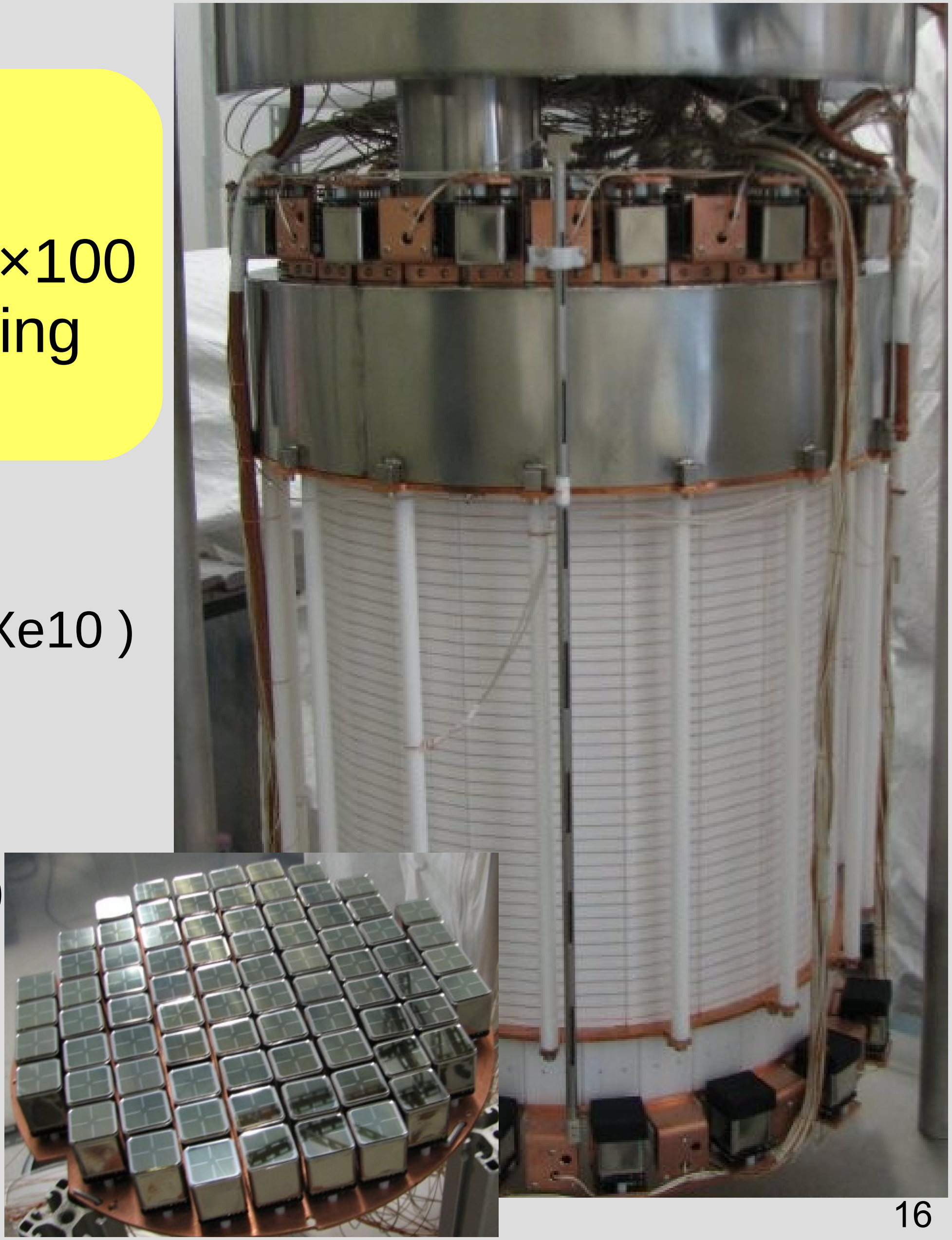

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Laboratori Nazionali del Gran Sasso

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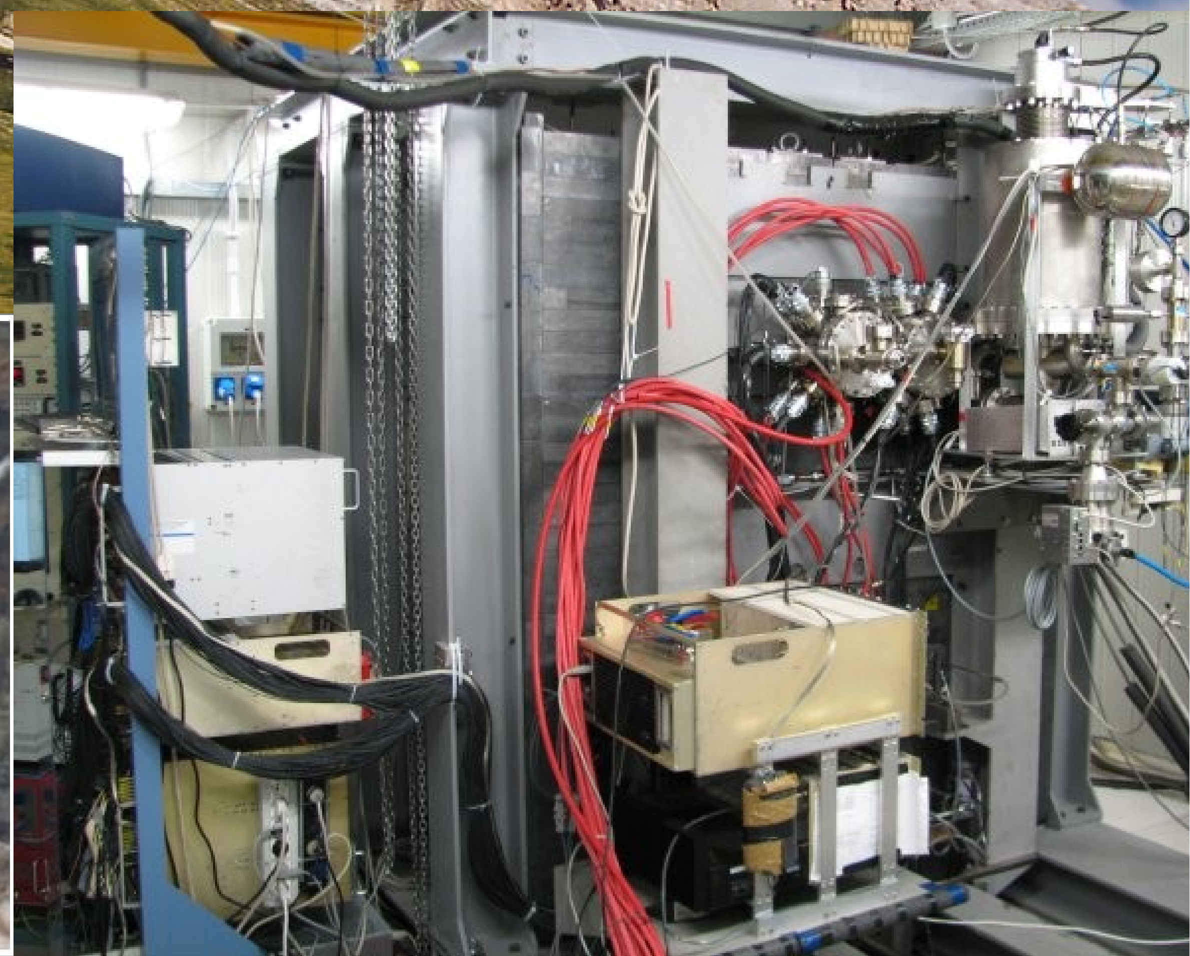
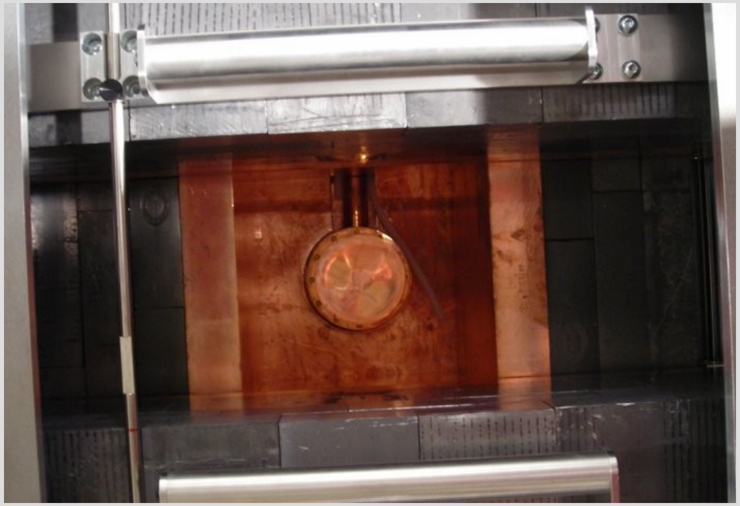
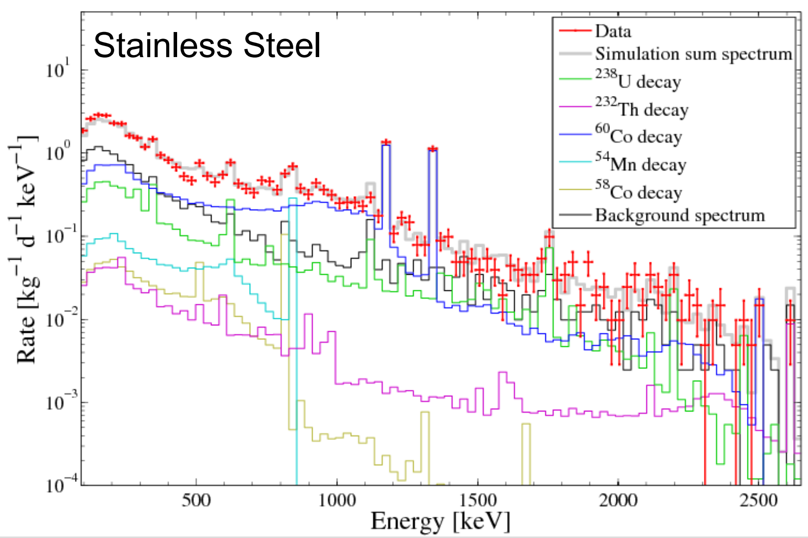


Material Screening

GATOR: 2.2kg high purity Ge detector operated by UZH @ LNGS

arXiv:1103.2125



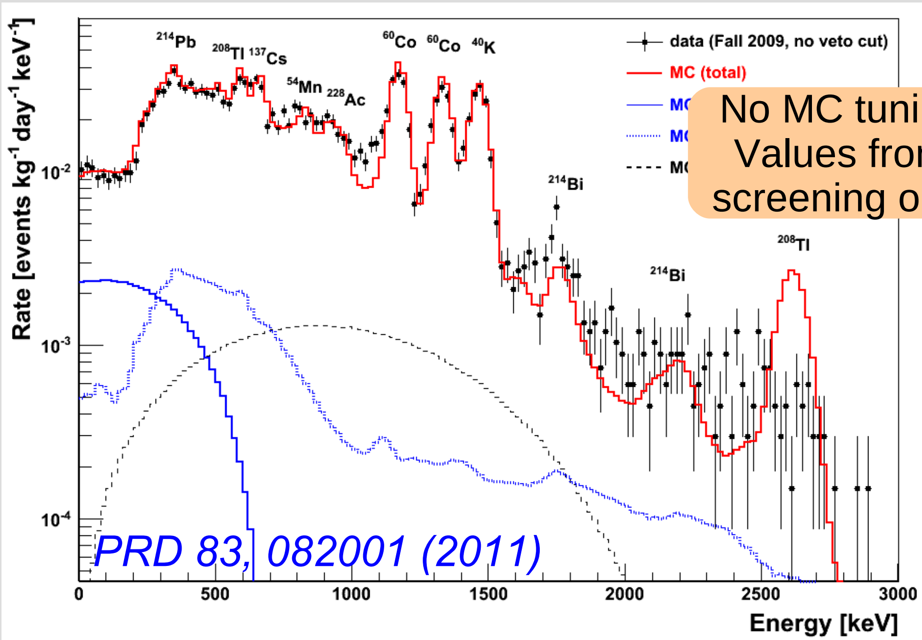


Component	Amount	Total radioactive contamination in materials [mBq/amount]				
		^{238}U / ^{226}Ra	^{232}Th	^{60}Co	^{40}K	other nuclides
Cryostat and 'diving bell' (316Ti SS)	73.61 kg	121.46	147.23	404.87	662.52	
Support bars (316Ti SS)	49.68 kg	64.58	144.07	69.55	352.73	
Detector PTFE	11.86 kg	0.71	1.19	0.36	8.89	
Detector copper	3.88 kg	0.85	0.62	5.21	0.78	
PMTs	242 pieces	60.50	111.32	181.50	1972.30	^{137}Cs: 41.14
PMT bases	242 pieces	38.72	16.94	2.42	38.72	
TPC resistor chain	1.5×10^{-3} kg	1.11	0.57	0.12	7.79	
Bottom electrodes (316Ti SS)	0.23 kg	0.43	0.45	2.14	2.36	
Top electrodes (316Ti SS)	0.24 kg	0.85	0.43	1.73	1.16	
PMT cables	1.80 kg	0.85	1.97	0.37	18.65	^{108m}Ag: 2.67
Copper shield	2.1×10^{3} kg	170.80	24.69	6.59	80.26	
Polyethylene shield	1.6×10^{3} kg	368.0	150.4	-	1120.0	
Lead shield (inner layer)	6.6×10^{3} kg	4.3×10^{3}	3.6×10^{3}	7.2×10^{2}	9.6×10^{3}	^{210}Pb: 1.7×10^{8}
Lead shield (outer layer)	27.2×10^{3} kg	1.1×10^{5}	1.4×10^{4}	2.9×10^{3}	3.8×10^{5}	^{210}Pb: 1.4×10^{10}

Screening results: *arXiv:1103.5831*

use results for Monte Carlo Simulations

XENON100 Background

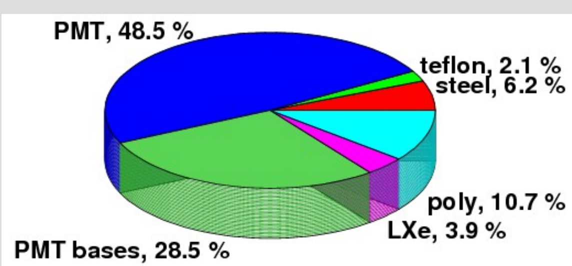


No MC tuning!
Values from
screening only.

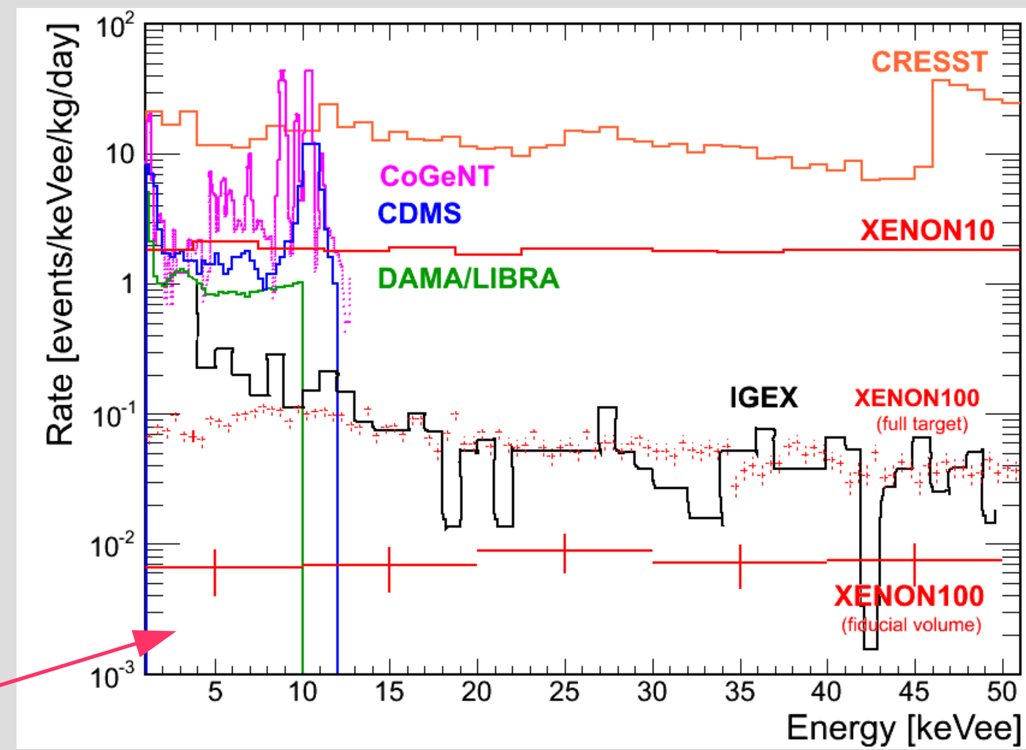
Measured Background in good agreement with MC prediction.

At low energies: Lowest background ever achieved in a Dark Matter Experiment!

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



Xenon
keVee-Scale
not precisely
known
below 9 keVee

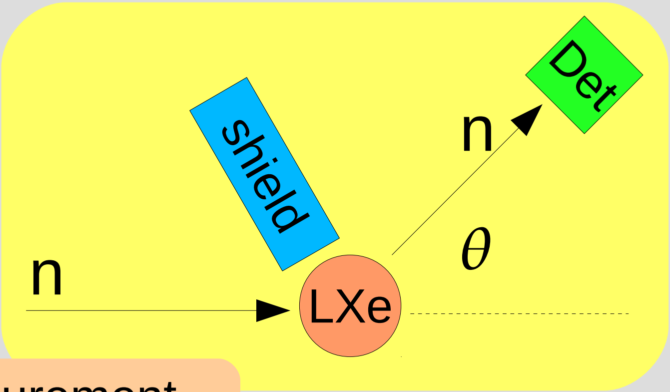


Nuclear Recoil Energy Scale

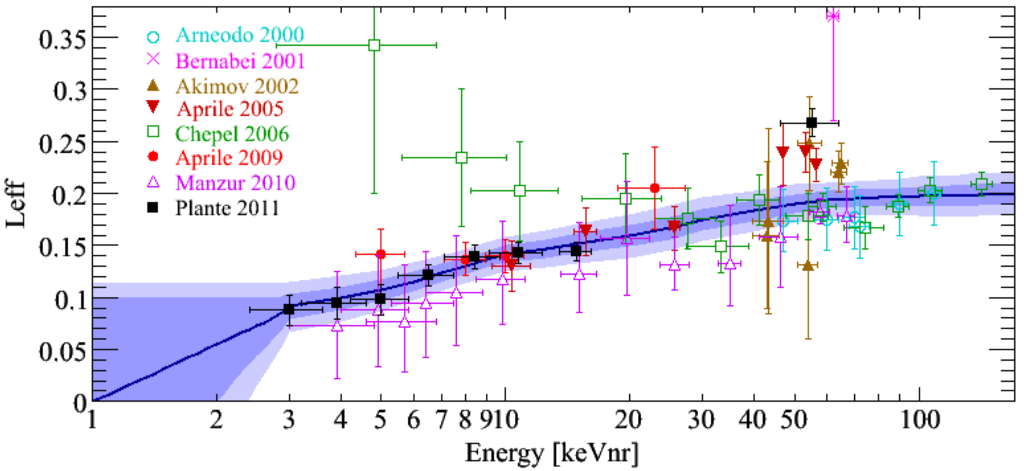
- WIMPs interact with Xe nucleus
  ➞ nuclear recoil (*nr*) scintillation (β and γ's produce electronic recoils)
- absolute measurement of *nr* scintillation yield is difficult
  ➞ measure relative to ^{57}Co (122keV)
- relative scintillation efficiency $\mathcal{L}_{eff}$:

$$\mathcal{L}_{\rm eff}(E_{\rm nr}) = \frac{{\rm LY}(E_{\rm nr})}{{\rm LY}(E_{\rm ee} = 122\ {\rm keV})}$$

measurement principle:



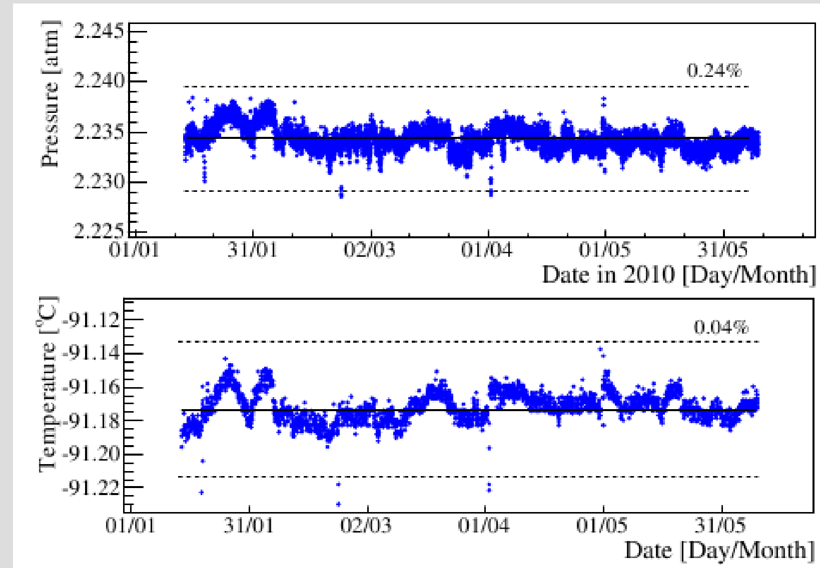
New measurement
in preparation in Zürich

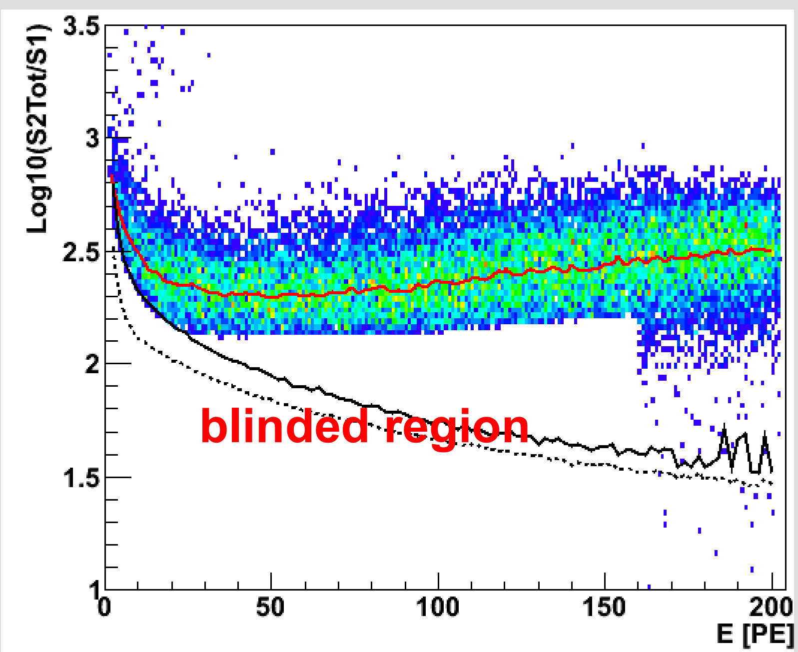


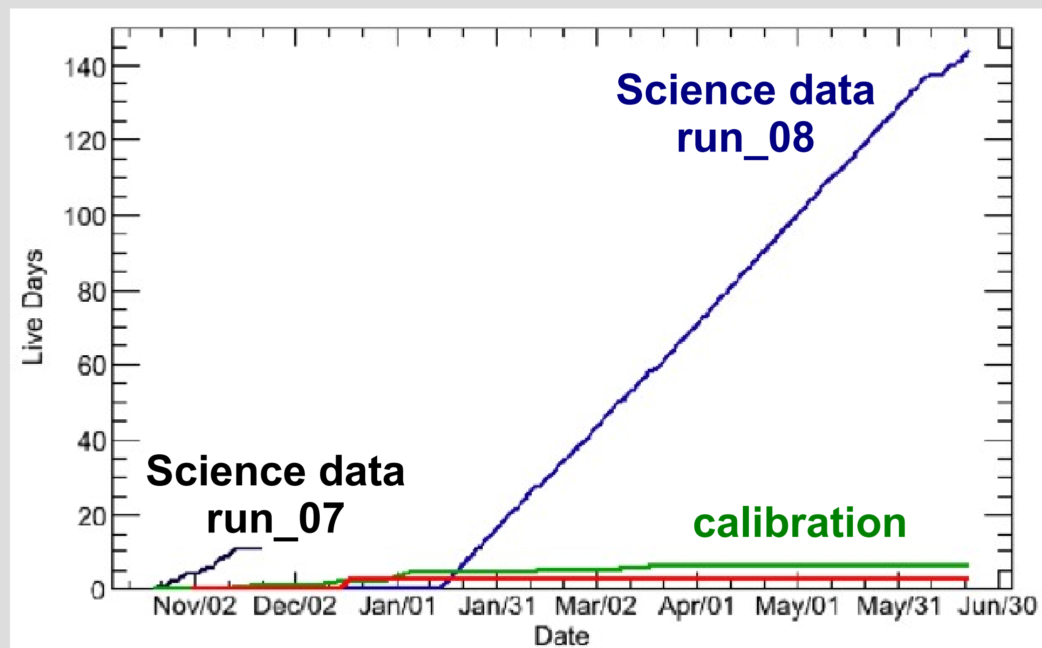
most recent measurements:
■ *Plante et al., arXiv:1104.2587 (2011)*
△ *Manzur et al., PRC 81, 025808 (2010)*
for discussion of possible systematic errors see
A. Manalaysay, arXiv:1007.3746

The new XENON100 Data

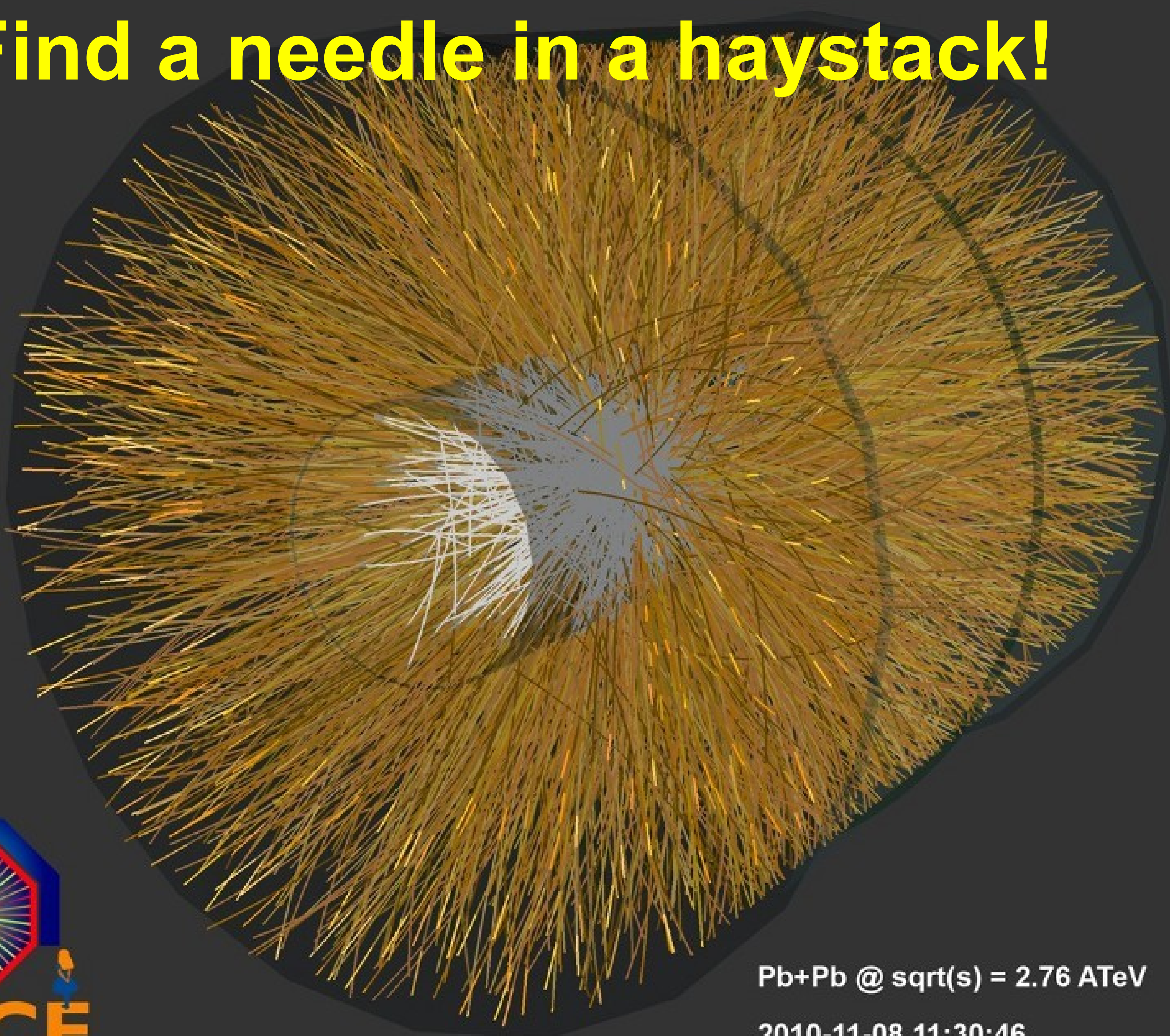
- data taken in first half of 2010
- 100.9 life days
- data blinded in ROI
- analysis and results in: *arXiv:1104.2549*







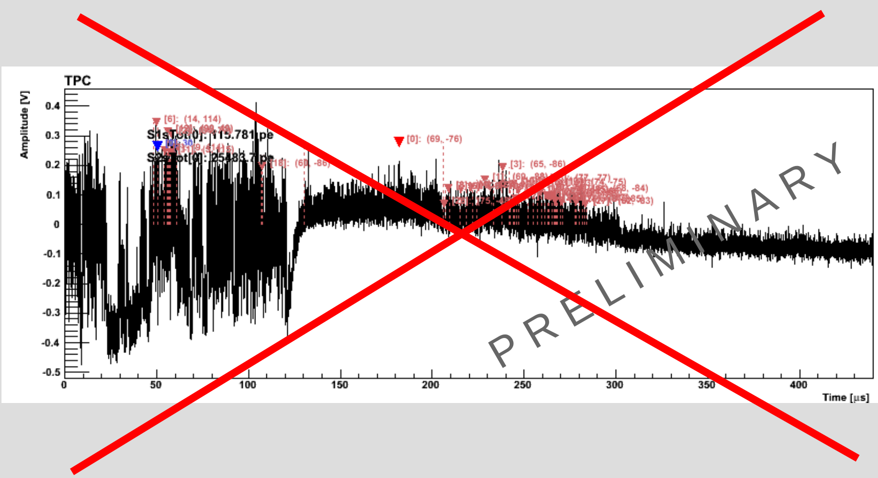
Find a needle in a haystack!

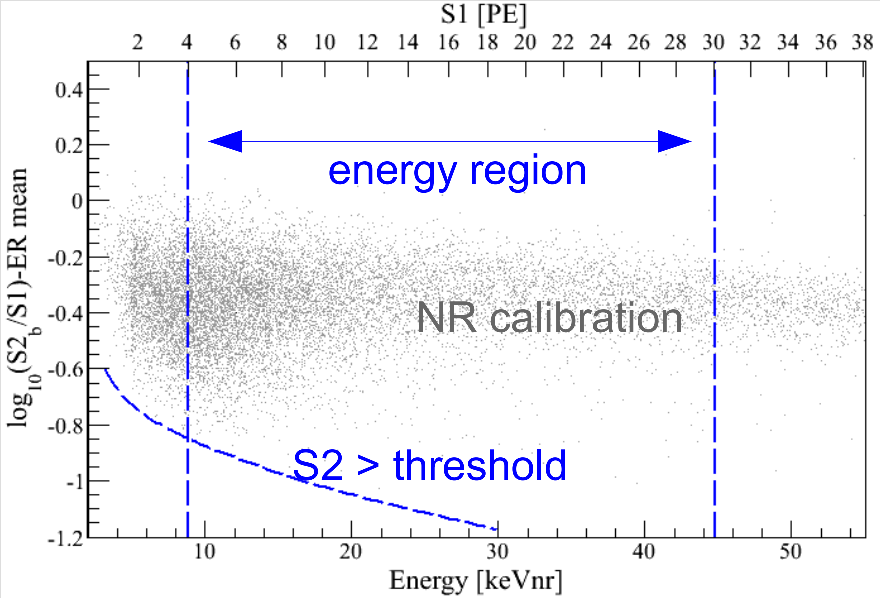


Data Analysis

Basic Data Quality Cuts
- reject non useable waveforms
  (muons, micro-discharges, …)
- hot spot cuts
- S1 noise cut

Energy Cuts
- low *E* region (S1)
- S2 software threshold
- require 2x S1 coincidence
  (against PMT dark current, noise)





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Energy Cuts
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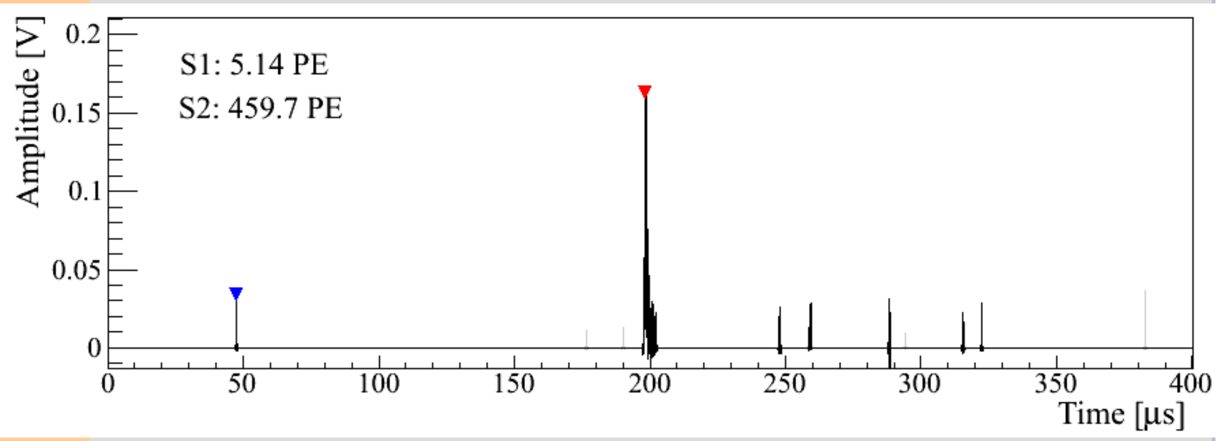
- require 2x S1 coincidence (against PMT dark current, noise)

Single Scatter Selection
(WIMPs interact only once!)
- only one S2 peak
- only one S1 peak
- active veto cut



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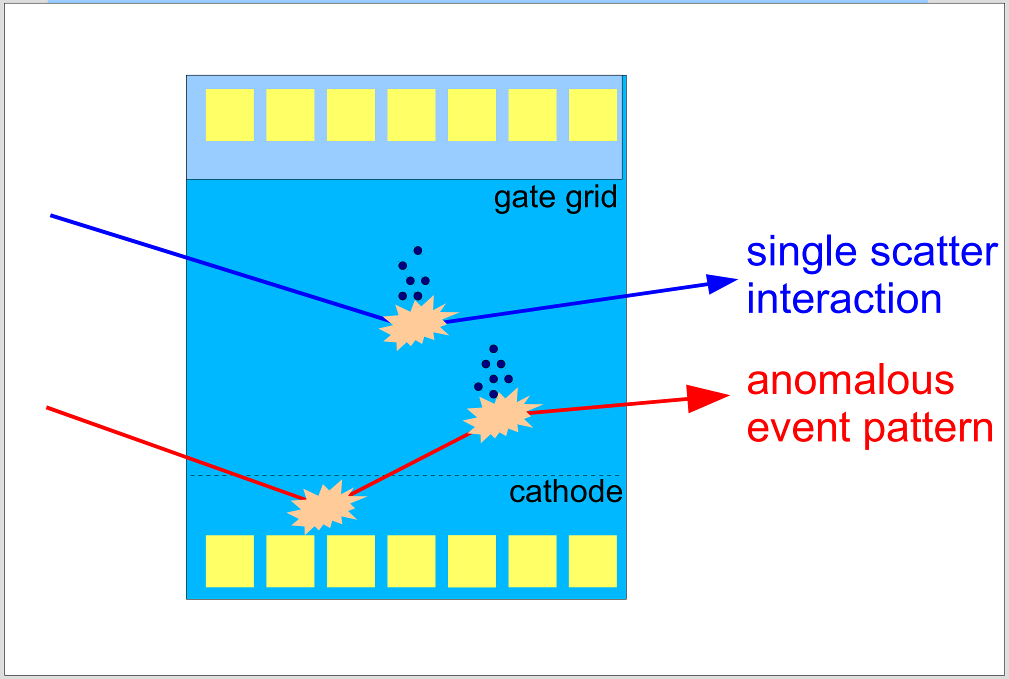

Energy Cuts
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- require 2x S1 coincidence
  (against PMT dark current, noise)

Consistency Cuts
- S2 width cut
  (drift time ok? gas events)
- position reconstruction
- anomalous event rejection

Data Analysis

Xe XENON Dark Matter Project

Basic Data Quality Cuts
- reject non useable waveforms (muons, micro-discharges, …)
- hot spot cuts
- S1 noise cut

Energy Cuts
- low E region (S1)
- S2 software threshold
- require 2x S1 coincidence (against PMT dark current, noise)

Fiducial volume cut

NR/ER discrimination
(strict only for classical analysis)

Single Scatter Selection
(WIMPs interact only once!)
- only one S2 peak
- only one S1 peak
- active veto cut

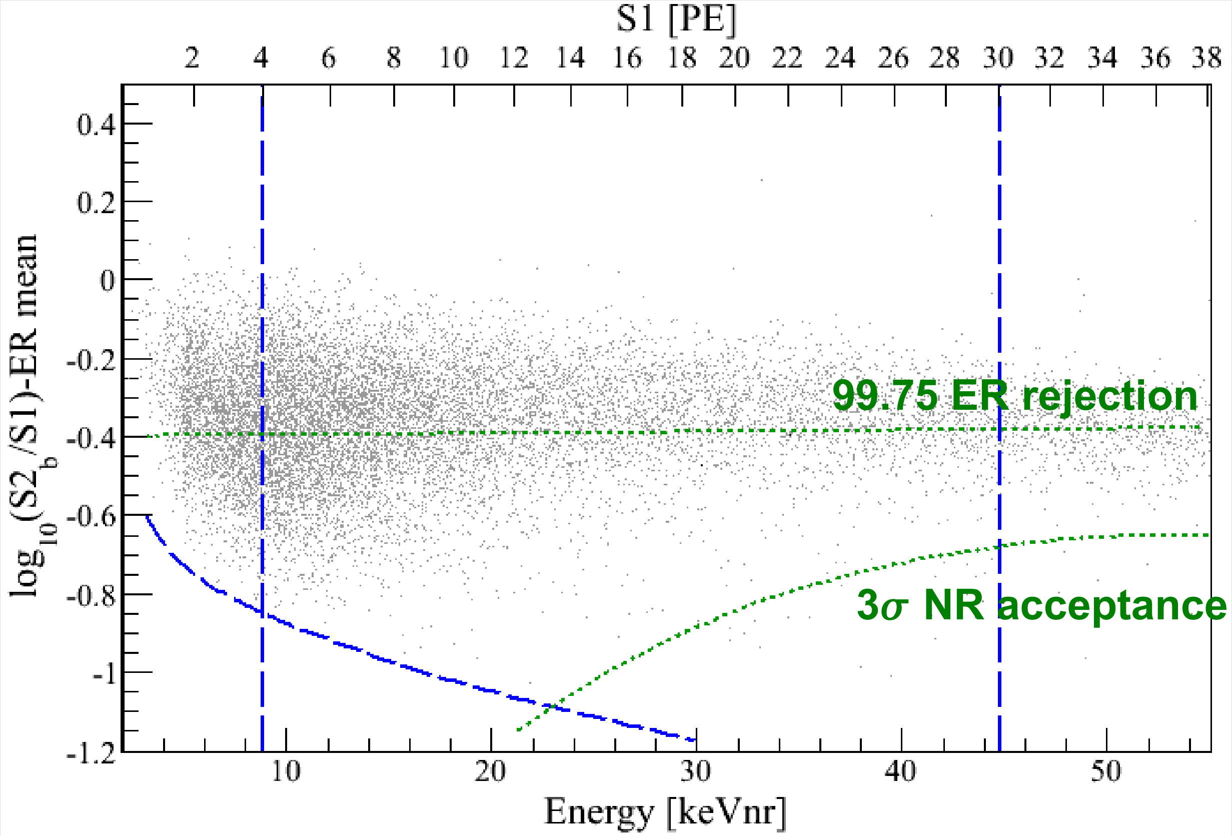
Consistency Cuts
- S2 width cut (drift time ok? gas events)
- position reconstruction
- anomalous event rejection

Background Prediction

Expected Background for
- 48 kg fiducial mass
- 100.9 live days
- 99.75% ER rejection

Gaussian Leakage:
1.14 ± 0.48
Anomalous Leakage:
0 .56± 0.25
Neutron Background:
0.11 ± 0.08

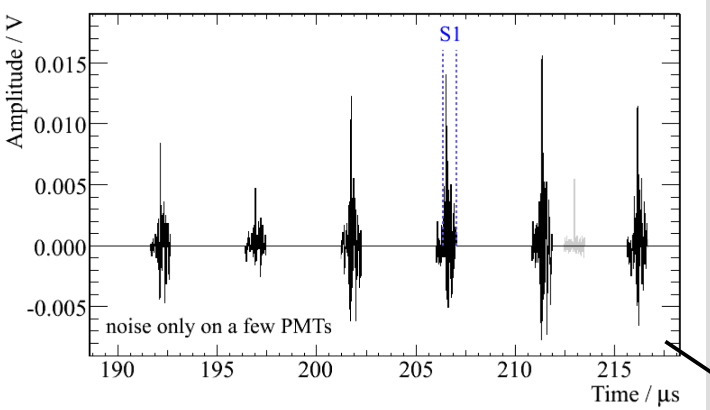
1.8 ± 0.6 events

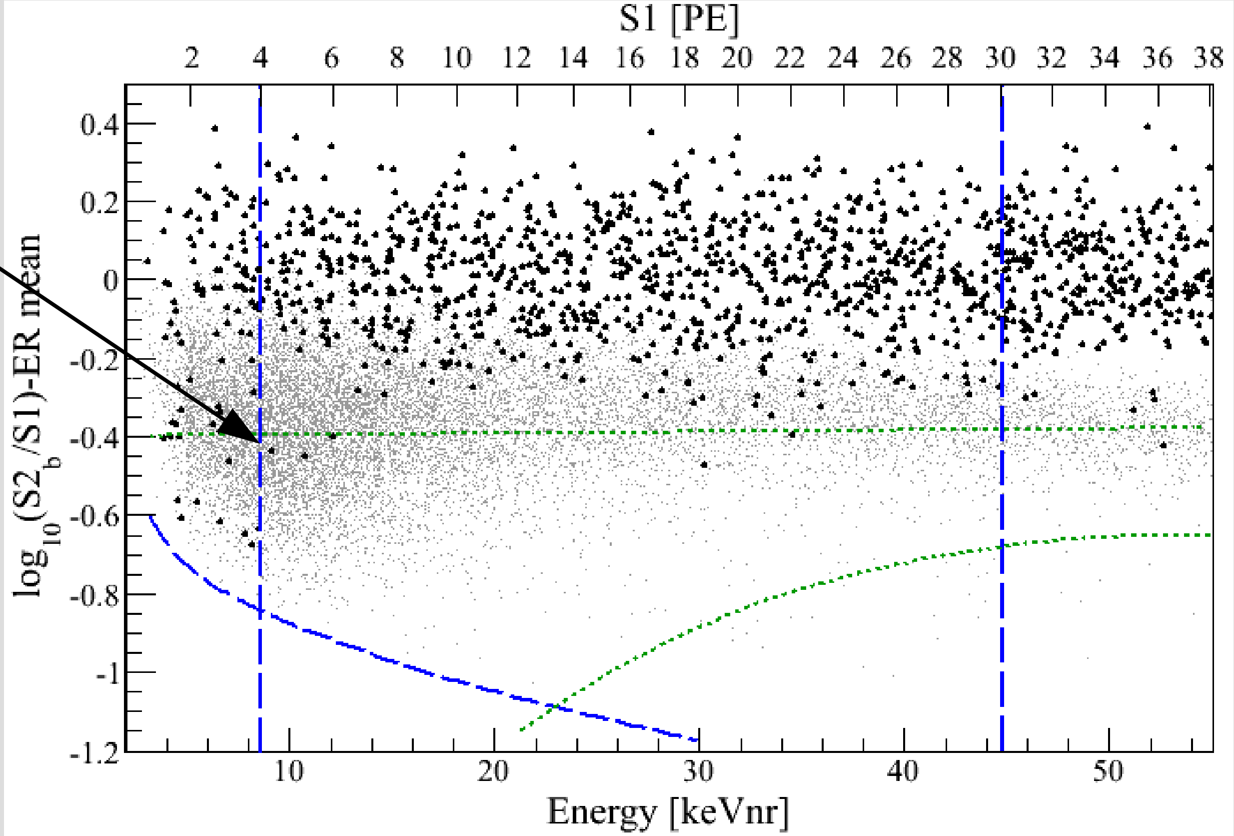


➡ prediction based on data and MC

➡ prediction verified on high *E* sideband

Unblinding





Gaussian Leakage:
1.14 ± 0.48

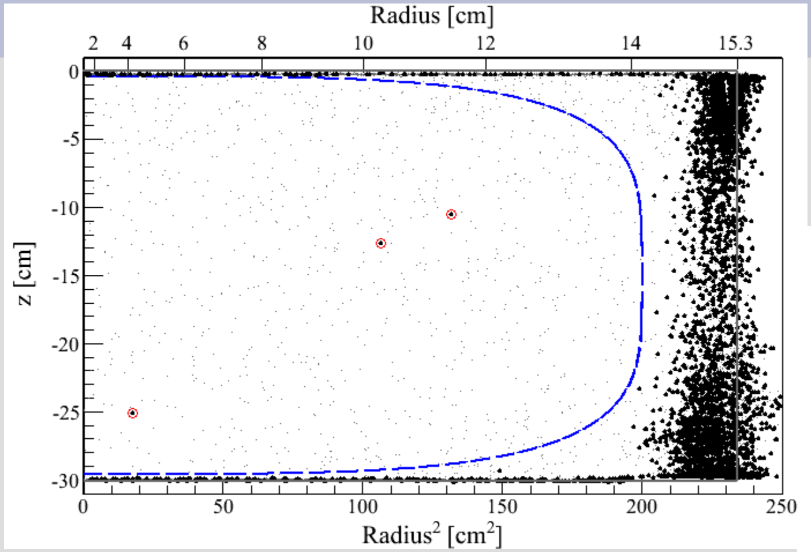
Anomalous Leakage:
0 .56± 0.25

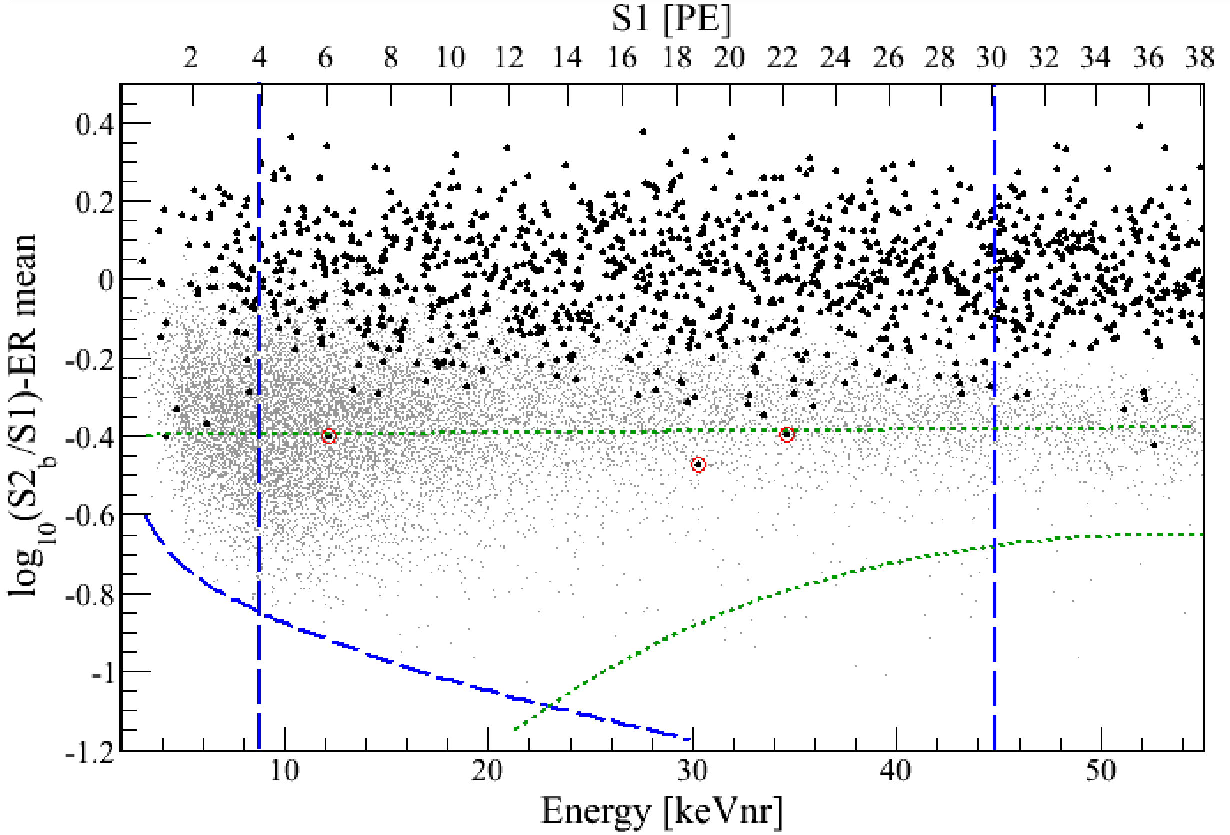
Neutron Background:
0.11 ± 0.08

1.8 ± 0.6 events

Population of noise events at threshold
➞ Some leak into WIMP search region
➞ Post-unblinding cut removes noise population

Result





Gaussian Leakage:
1.14 ± 0.48

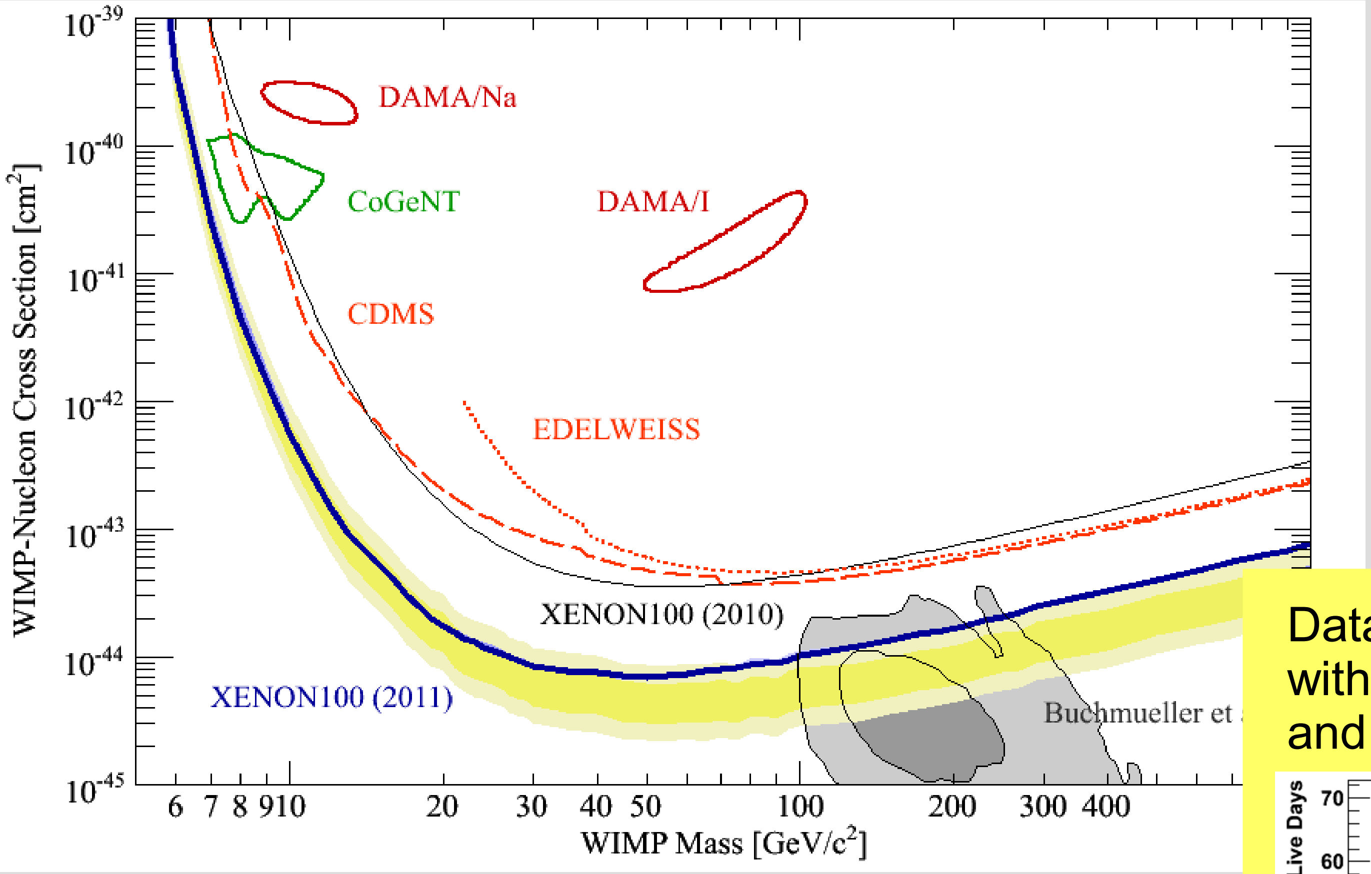
Anomalous Leakage:
0 .56± 0.25

Neutron Background:
0.11 ± 0.08

1.8 ± 0.6 events

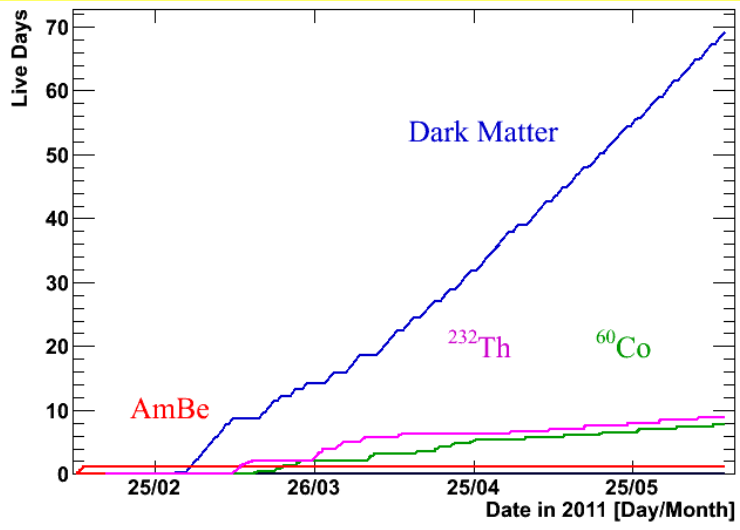
Observe 3 events
➡ likelihood for 3 or more events is 28%
➡ Profile Likelihood analysis also does not yield significant signal ➡ calculate limit

WIMP Limit



arXiv:1104.2549

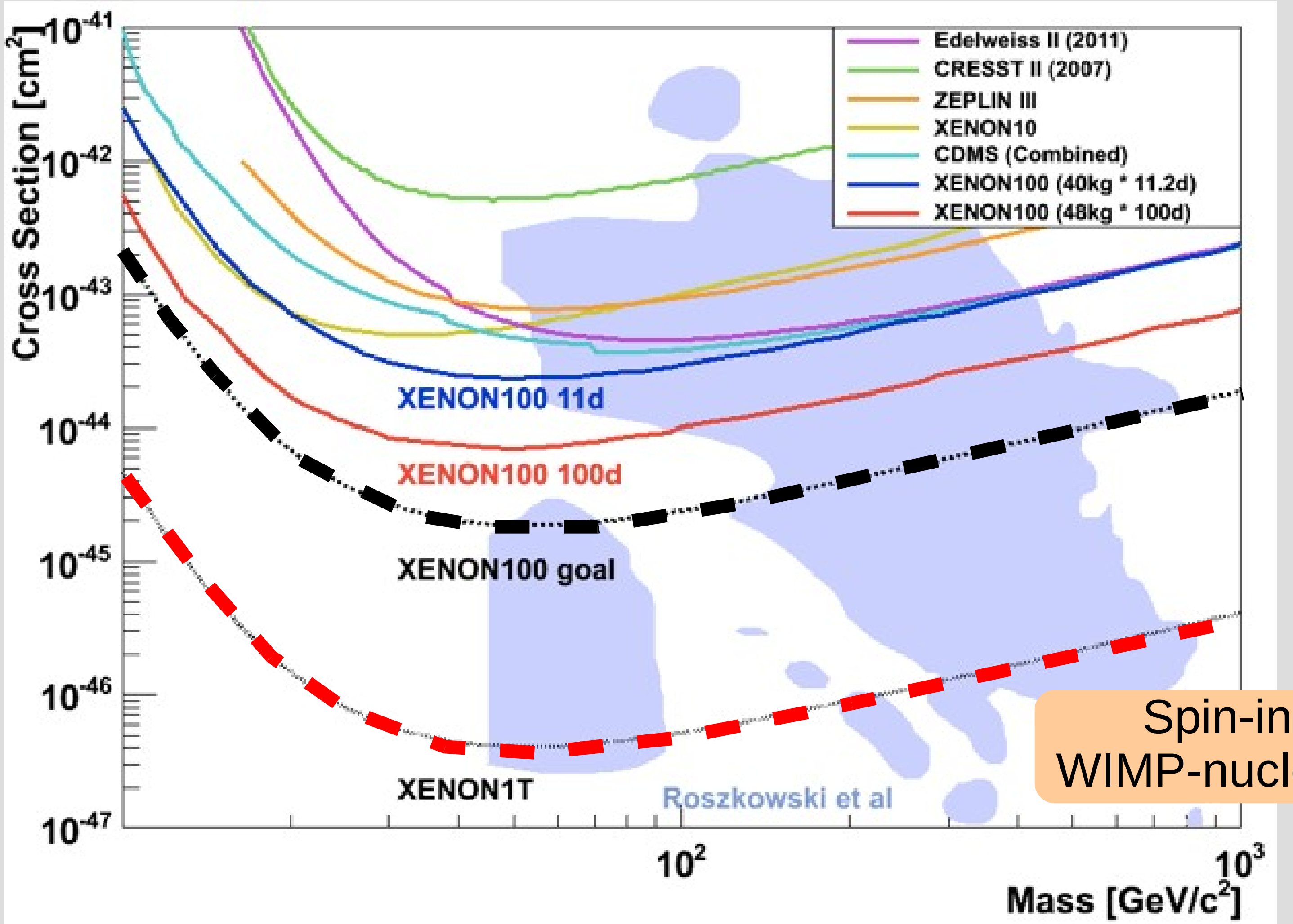
Data taking is ongoing with lower background level and lowered trigger threshold



XENON100 leads to the most sensitive limit over a large WIMP mass range

Challenges the CoGeNT, DAMA signals as being due to light mass WIMPs

XENON100: Sensitivity

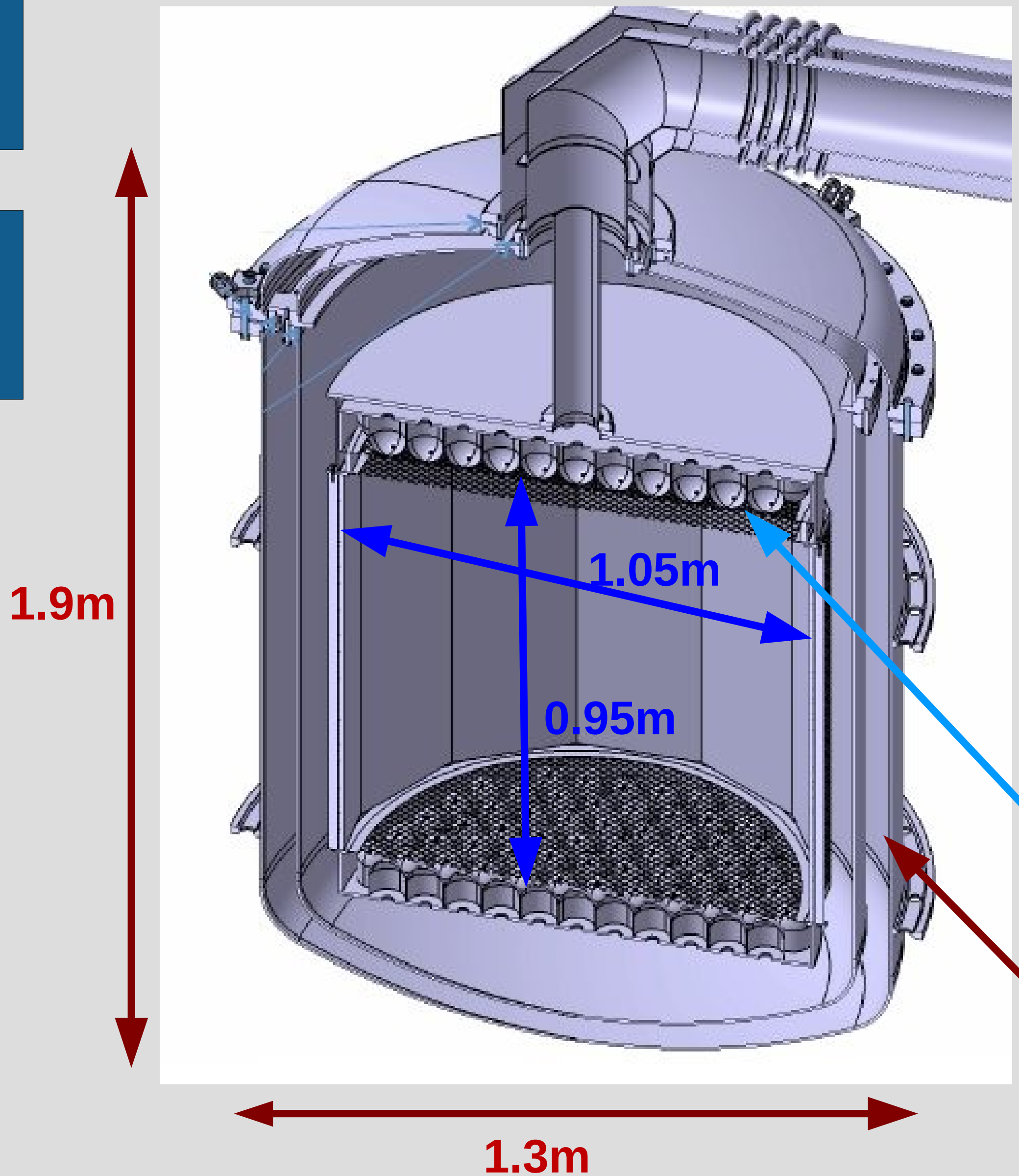


XENON100

XENON1T

Spin-independent
WIMP-nucleon interaction

The next step: XENON1T

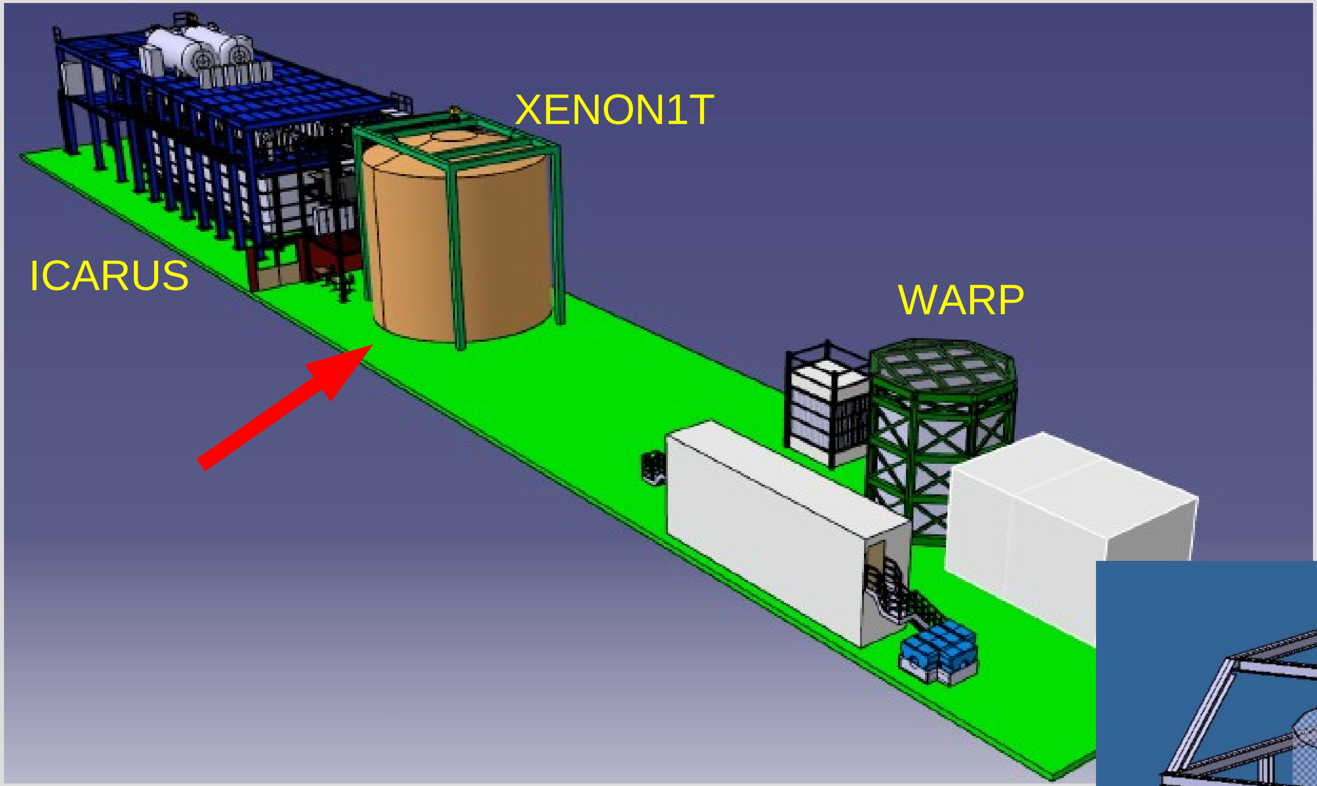


- 2.4t LXe ("1m³ detector")
  1t fiducial mass
- 100x lower background
  (10 cm self shielding, QUPID)
- Timeline: 2010 – 2015
- start construction end of 2011

Low Radioactivity Photon Detectors (3", Total ~250)

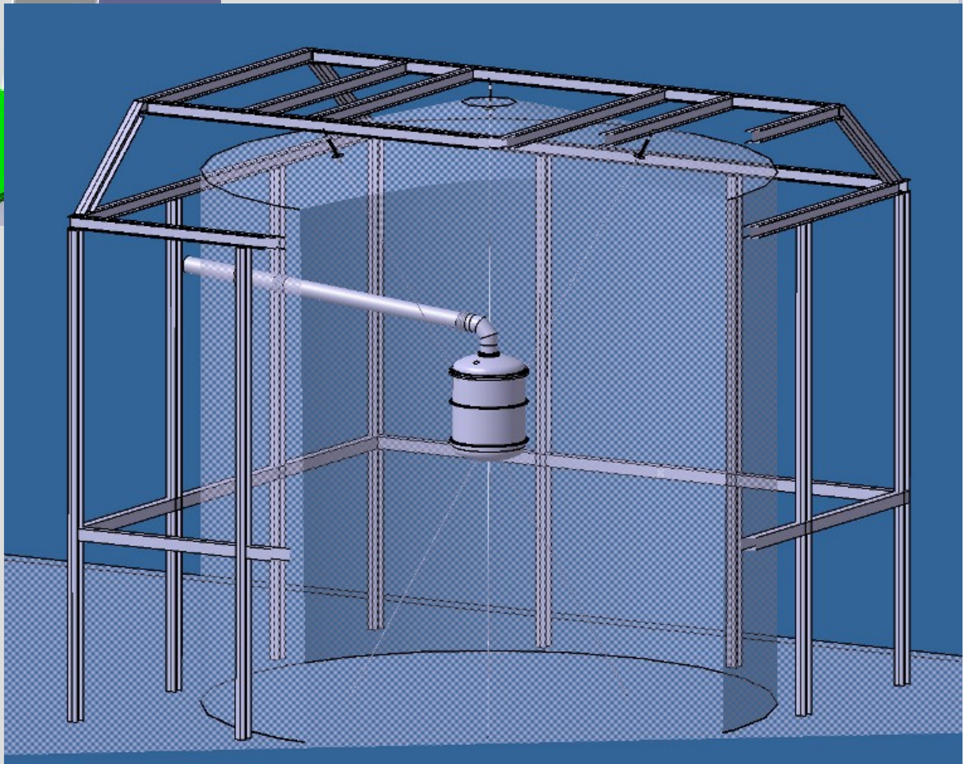
Ti Cryostat
(or low rad. stainless steel)

XENON1T @ LNGS



XENON1T
@ LNGS (Hall B)
➞ 5 m water shield acting as active muon veto

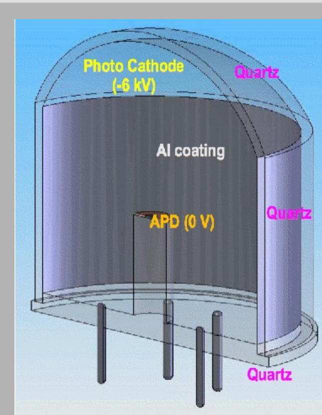
- Proposal and TDR submitted to LNGS
- Approved by INFN end of April 2011

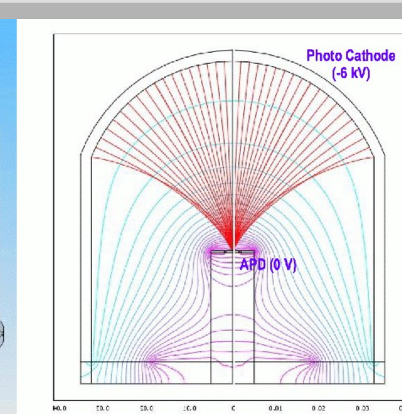


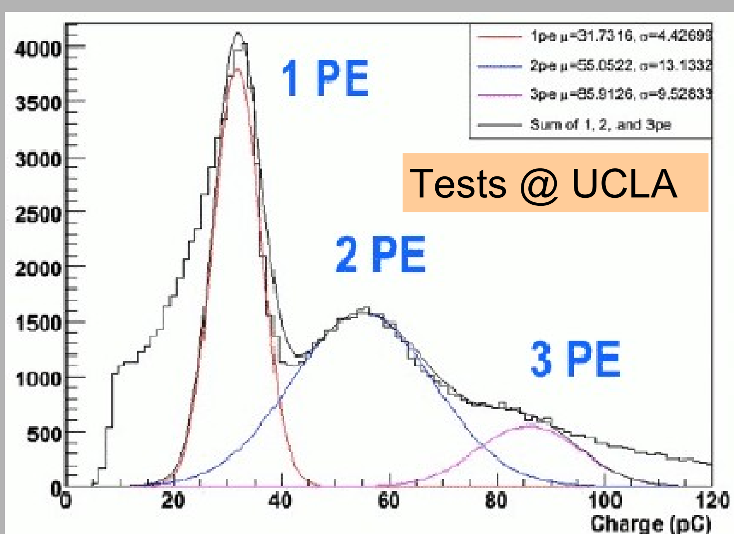
Photosensors

QUPID
Quartz Photon Intensifying Detector

- developed by UCLA group (Arisaka/Wang)
- very low radioactivity
  APD, quartz, no voltage divider
- ongoing tests and R&D at UCLA



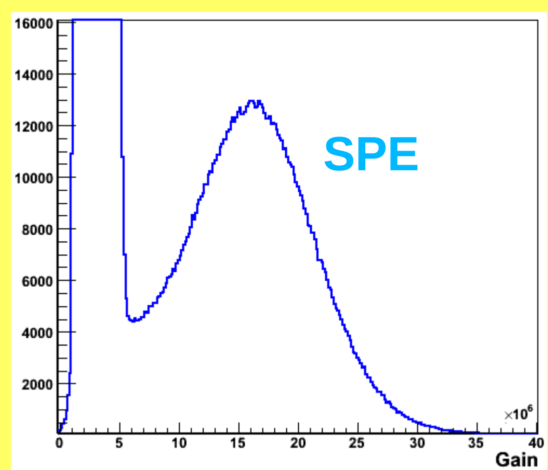




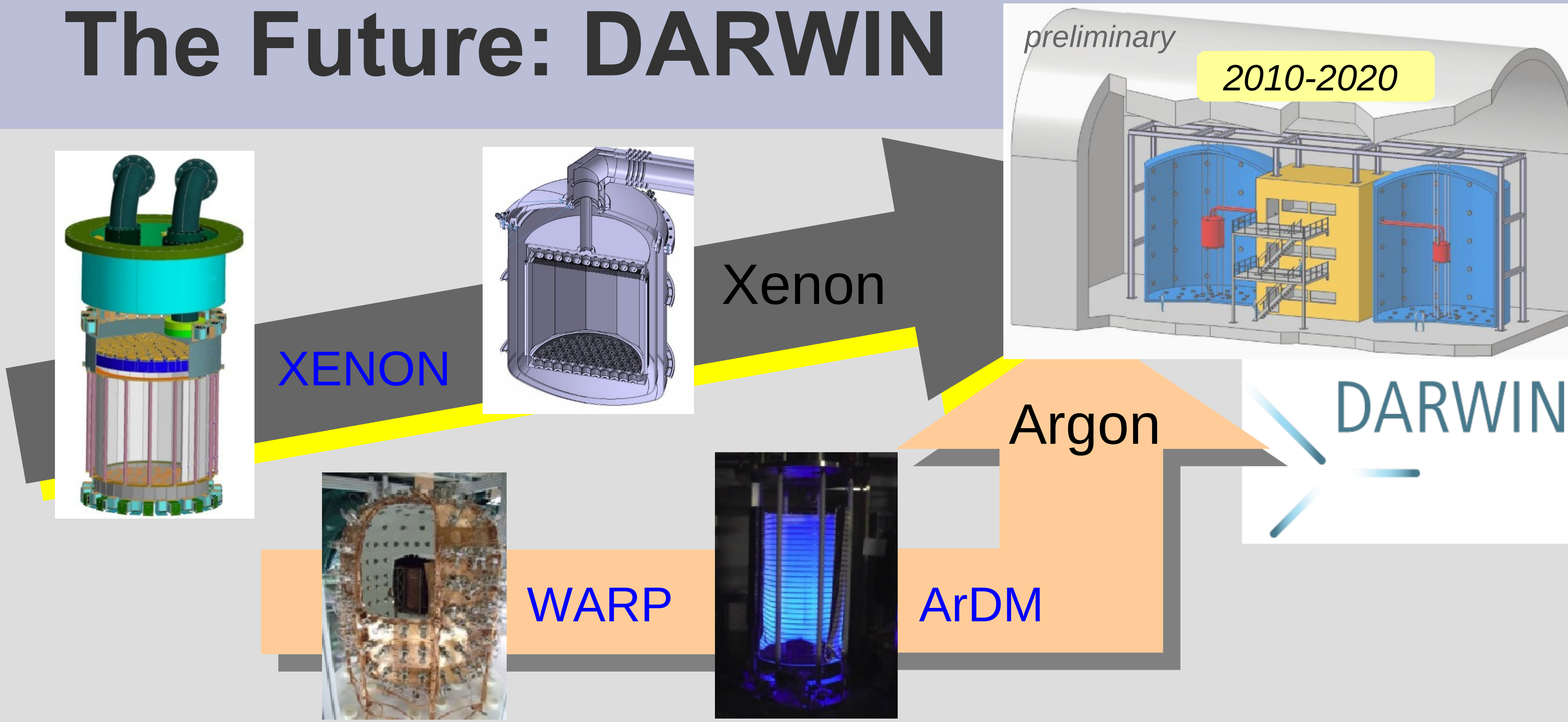
Alternative:
Hamamatsu R11410

Poster 3015
A. Behrens

3" PMT	high gain
LXe operation	low radioactivity



The Future: DARWIN

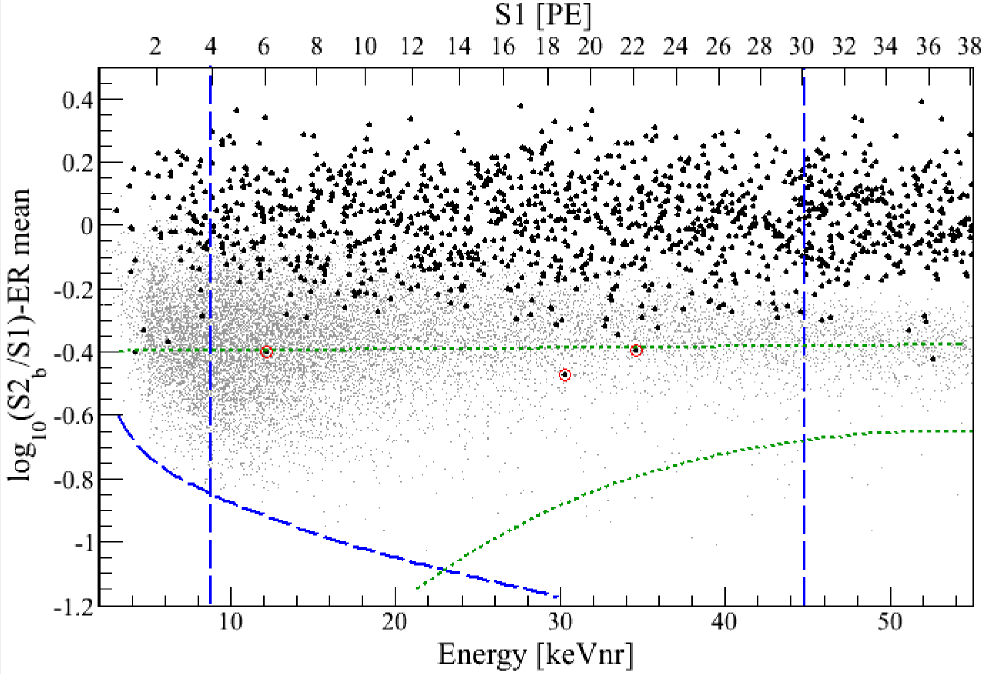


DARWIN – Dark Matter WIMP Search with Noble Liquids

- *R&D and Design Study* for a next generation noble liquid facility in Europe. Approved by ASPERA in late 2009
- Coordinate existing European activities in LXe and LAr towards a multi-ton dark matter facility
- Physics goal: $\sigma < 10^{-47}$ cm²

http://darwin.physik.uzh.ch

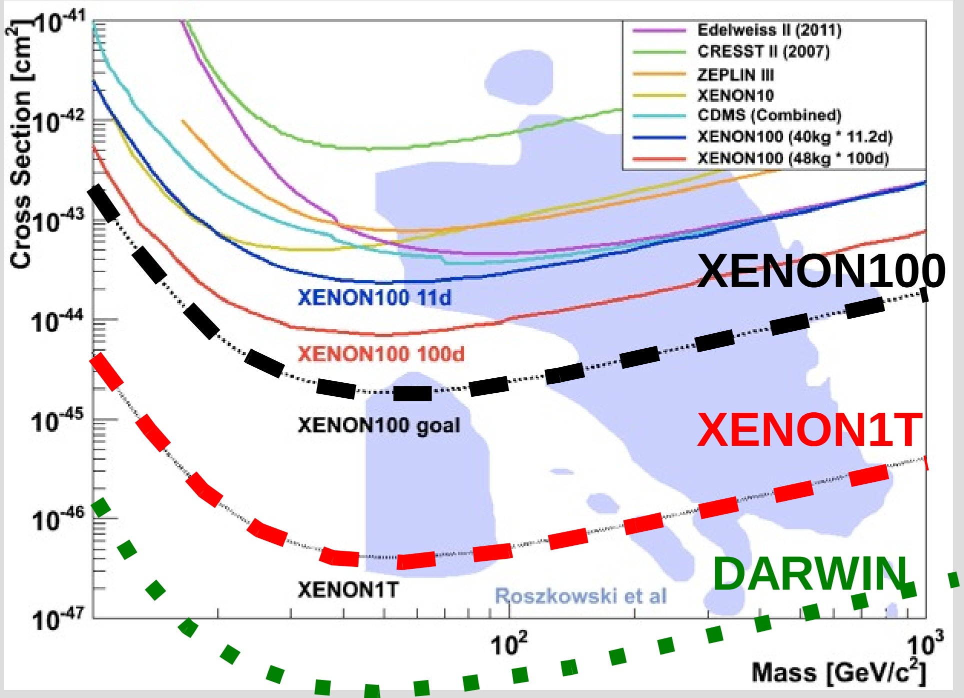
Summary



- Dark Matter: One of the big unsolved puzzles
- **XENON100**
  62 kg dual-phase LXe TPC
- extremely low background
- new results from 100d data: arXiv:1104.2549 *(2011)*

Two new projects upcoming:

- **XENON1T**
  1 ton LXe target mass
- **DARWIN**
  multiton LXe/LAr detector

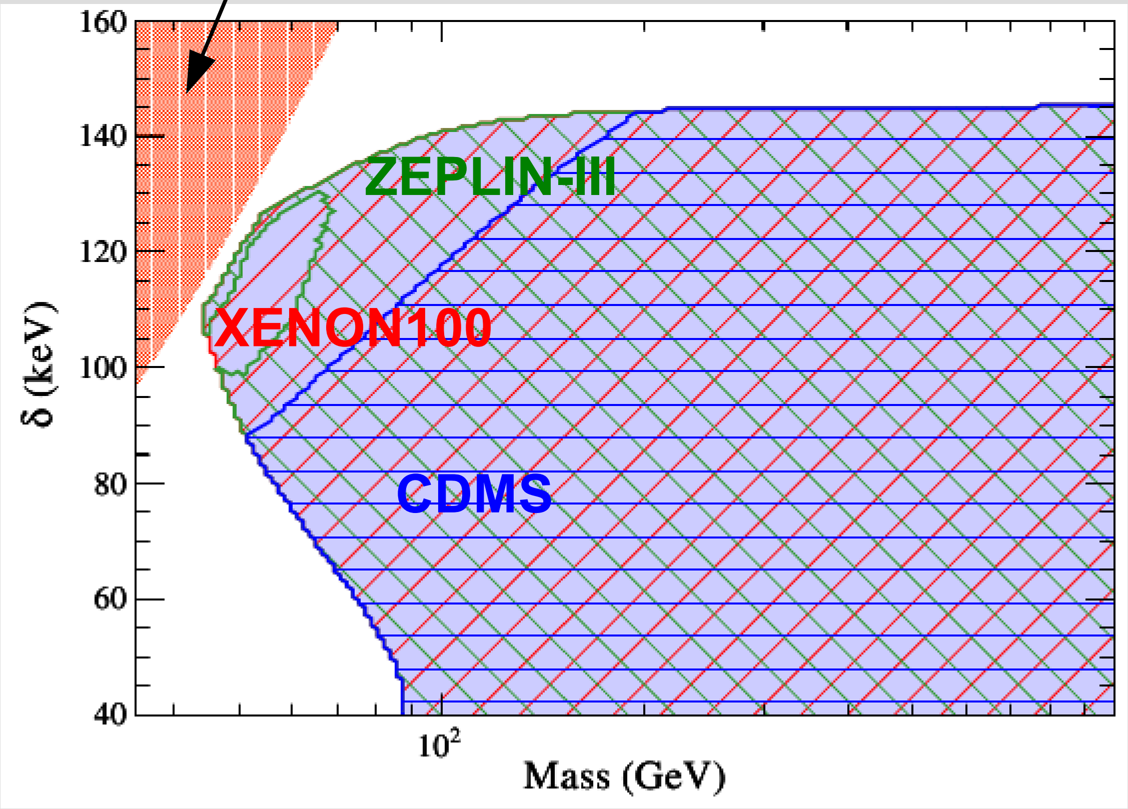


Backup

IDM Limit

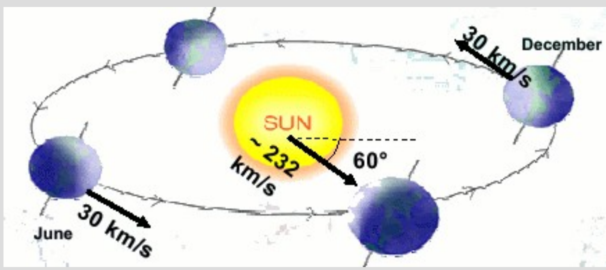
- Inelastic Dark Matter (IDM): tries to reconcile the result from DAMA with other expts
  Phys. Rev. D64, 043502 (2001)
- Dark Matter particle has an excited state, with an energy splitting δ
  WIMP-nucleon interactions excite the WIMP, elastic scattering forbidden
  ➞ rate peaks at higher *E*
- XENON100 excludes the IDM interpretation of the DAMA result at 90% CL
  arXiv:1104.3121

not accessible with LXe



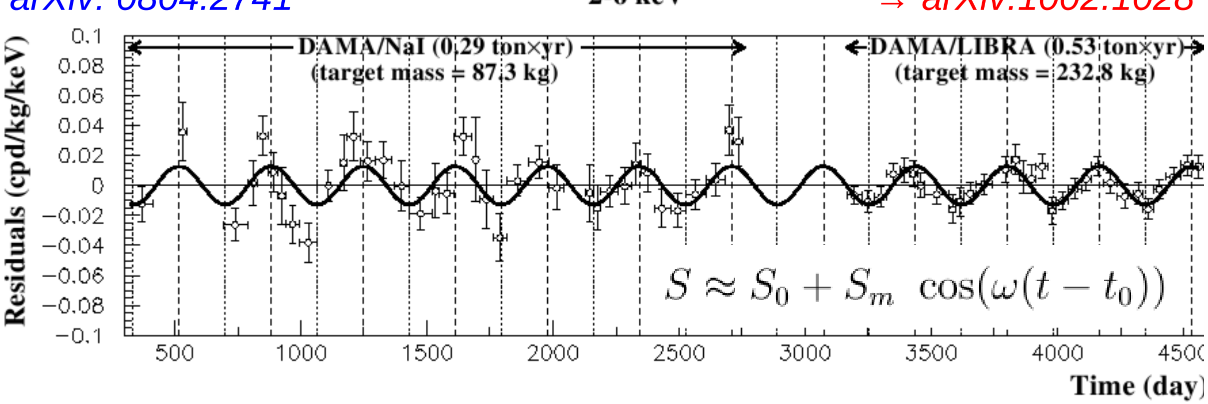
The DAMA Observation

- DAMA: PMTs coupled to NaI Scintillators
  ➞ extremely low background necessary
- looks for annual modulation @ LNGS
- large mass and exposure: 0.82 ton years

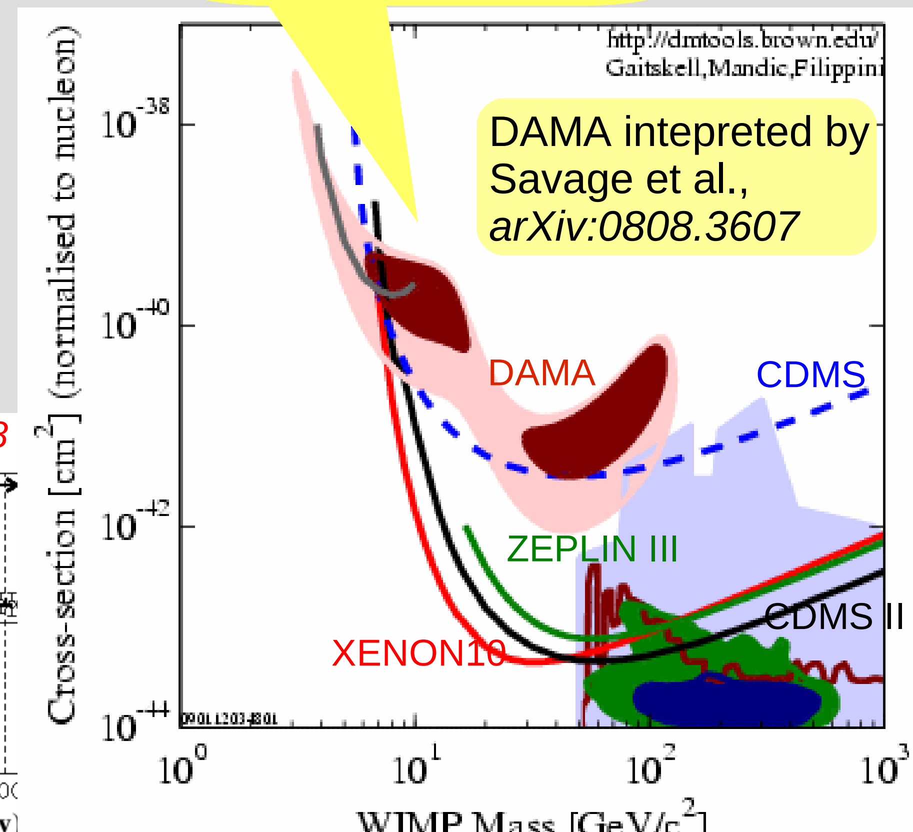


- DAMA finds annual modulation @ 8.9σ
- BUT: result cannot be explained with standard neutralinos or KK Dark Matter, result in conflict with other experiments

arXiv: 0804:2741 → arXiv:1002.1028

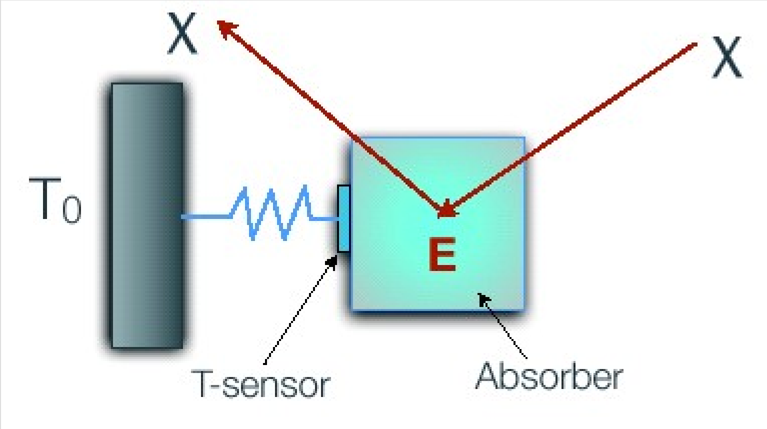


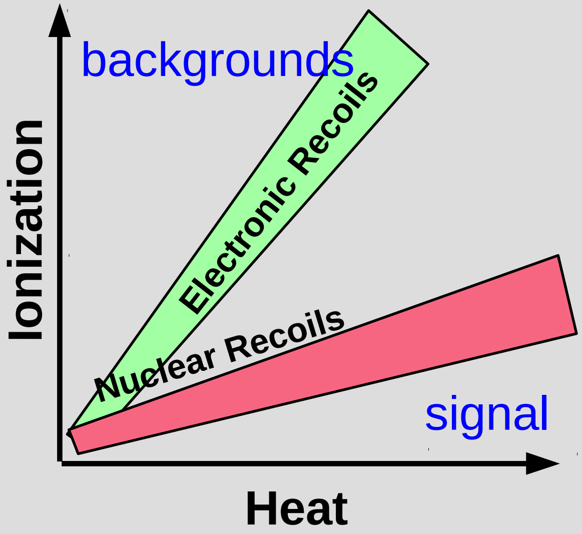
low mass WIMPs?

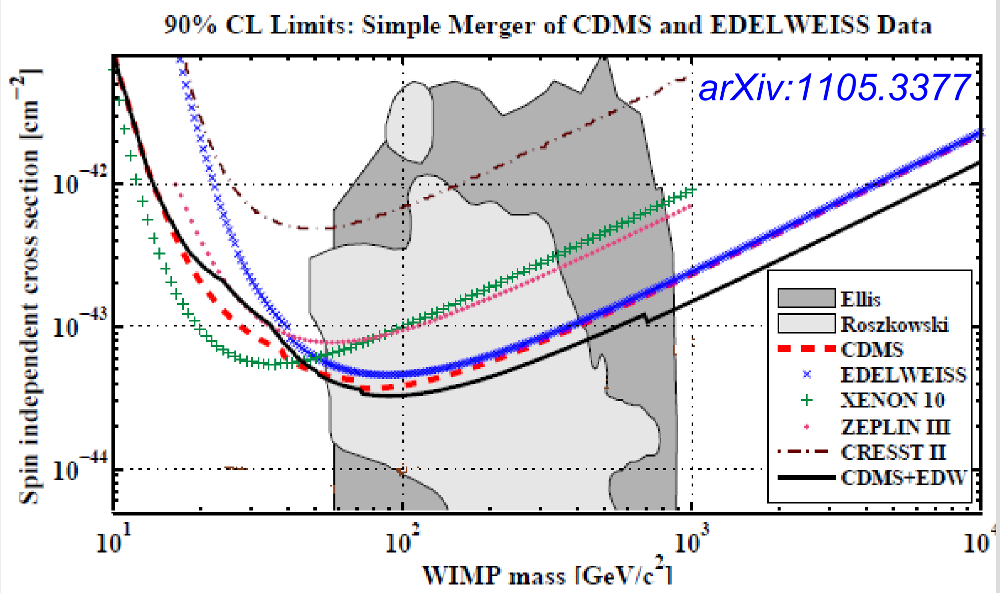


Soudan Mine, USA (CDMS); LSM, France (EDELWEISS)

Principle: measure charge and heat (phonons)
a deposited energy *E* produces temperature rise *ΔT*







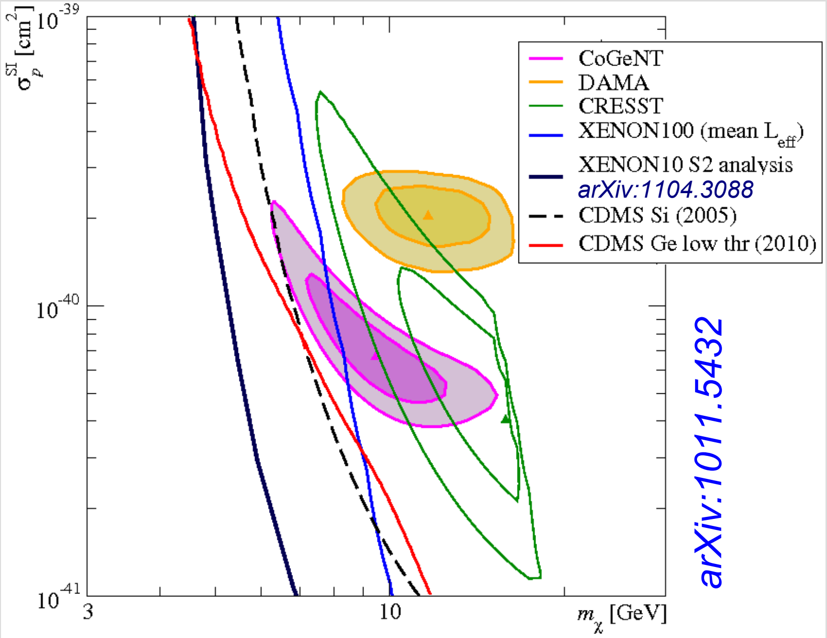
Crystals: Ge, Si cooled to few mK
➡ low heat capacity
➡ measurable μK temperature!

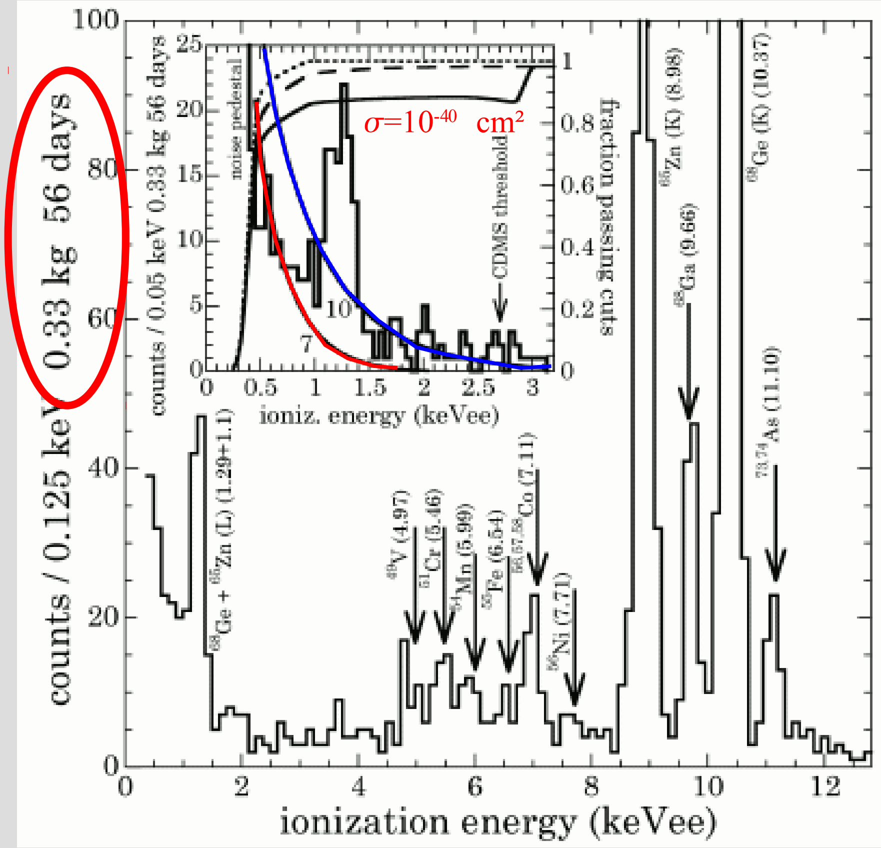
Good Discrimination
➡ reject surface events via PSA

CoGeNT

arXiv:1002.4703

- CoGeNT: p-type point contact Ge-detector, ultra low noise
- prototype for MAJORANA, operated underground at Soudan
- very low threshold: 0.4 keVee (electronic noise)
- only one observable (charge), some PSD against surface events
- Excess at lowest energies
  → light mass WIMP claim
  (BUT: null hypothesis has similar χ^2)





New: Claims of annual modulation?!?!

WIMP production

In early Universe:

WIMPs in thermal equilibrium
creation ↔ annihilation

$$p(E) \propto \exp\left(-\frac{E}{k_B T}\right)$$

expanding Universe: „freeze out“

WIMPs fall out of equilibrium, cannot annihilate anymore

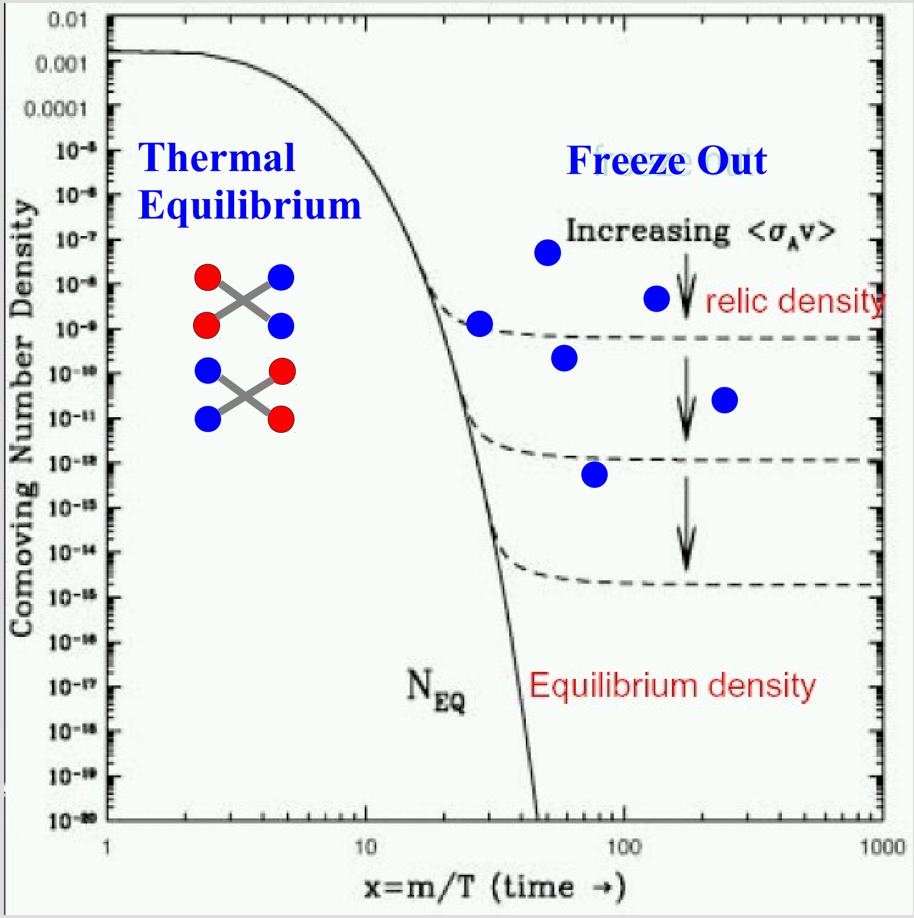
$$k_B T \sim \frac{m_\chi c^2}{20}$$

→ non relativistic when decoupling from thermal plasma
→ constant DM relic density
→ relic density depends on σ_A

WIMP relic density:

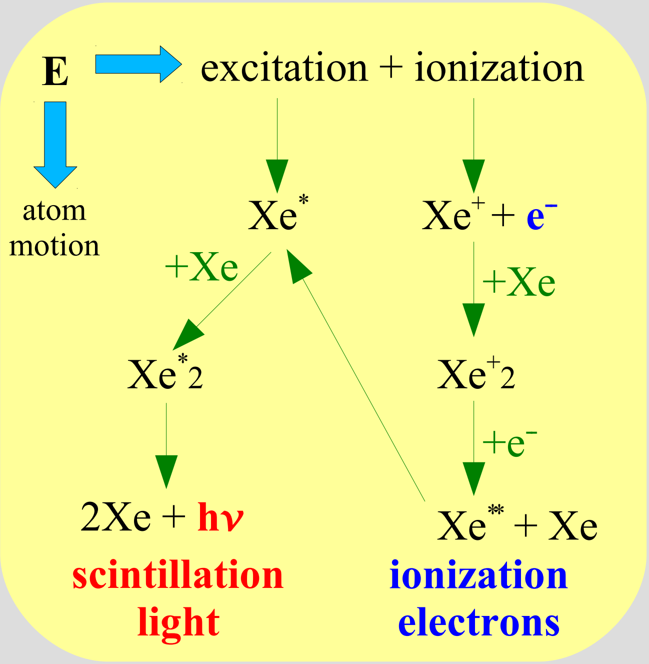
$$\Omega_\chi h^2 \approx \text{const.} \frac{T_0^3}{M_{Pl}^3 \langle \sigma_A v \rangle} \approx \frac{0.1\text{pb}}{\langle \sigma_A \, v/c \rangle}$$

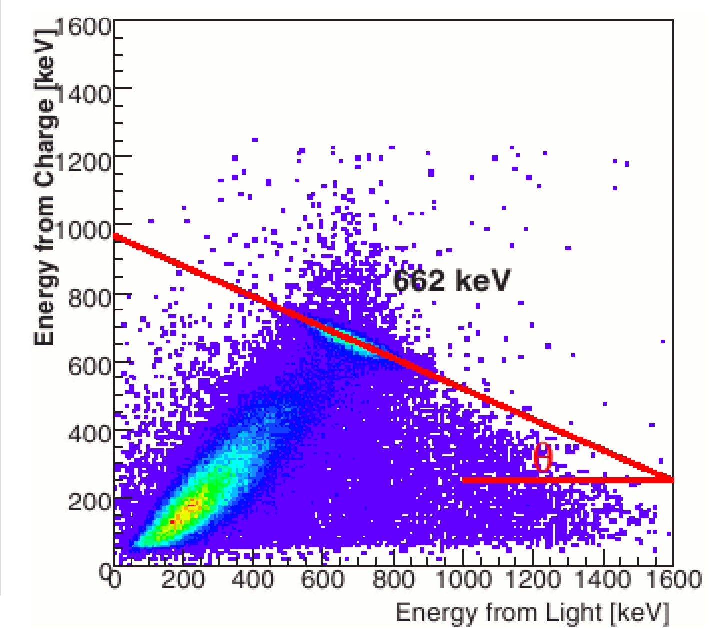
O(1) when σ_A~10^{-9} GeV → weak scale

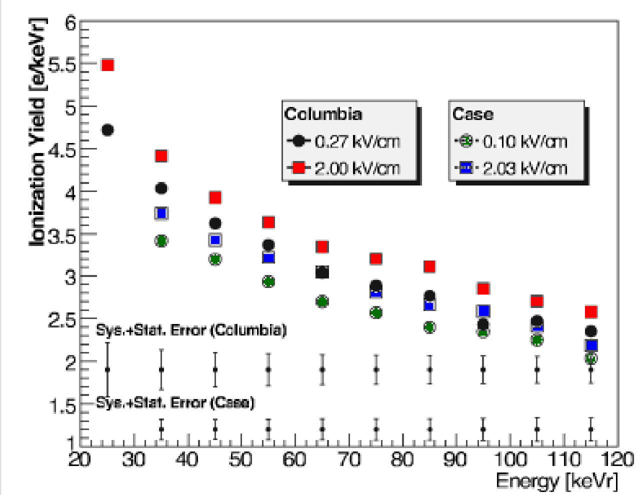


Xenon: Light and Charge

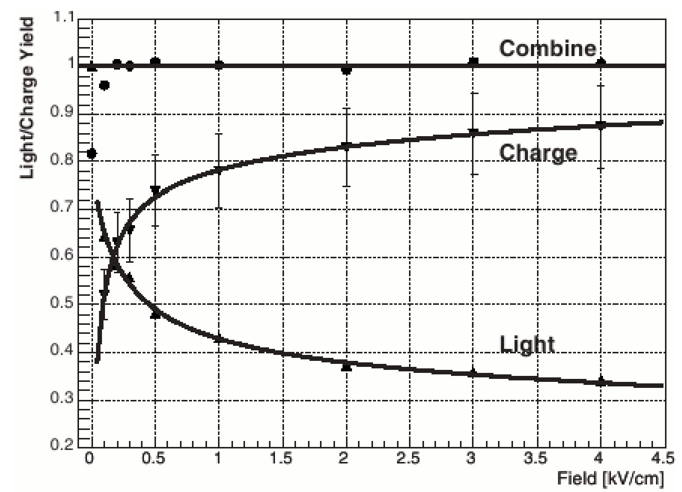
- energy deposited in LXe produces *electron-ion pairs* and *excited atom states*; both processes can lead to scintillation
- anti-correlation between charge and light
  ➡ improvement of energy resolution possible
- E-field dependence (field quenching)
- response also depends on particle energy





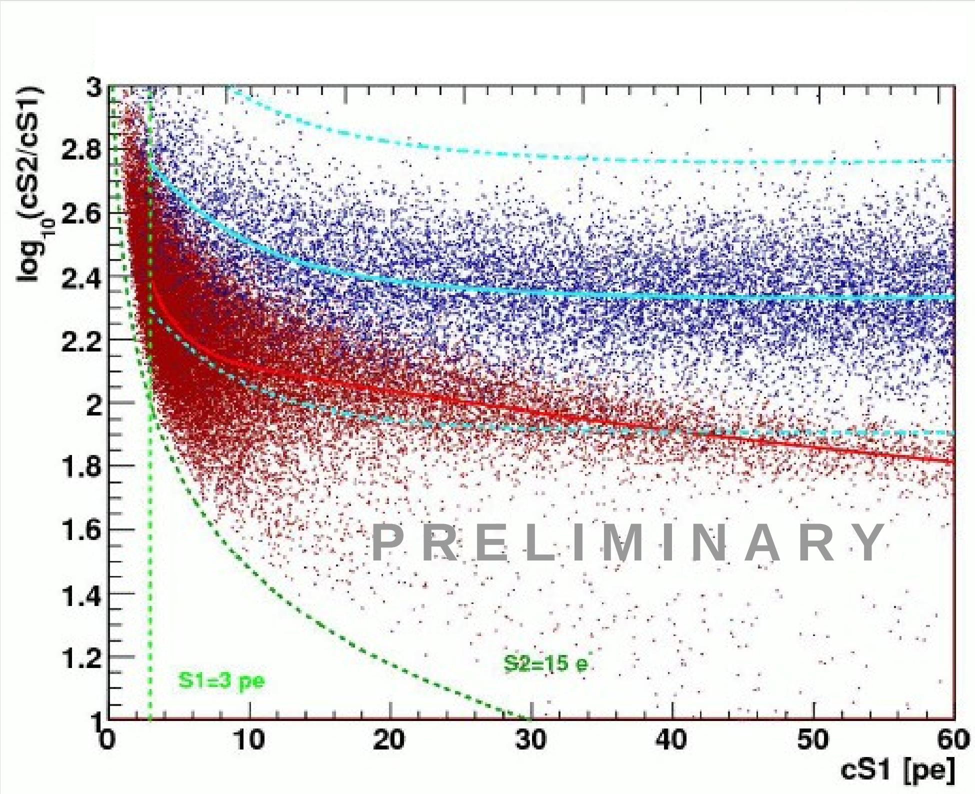


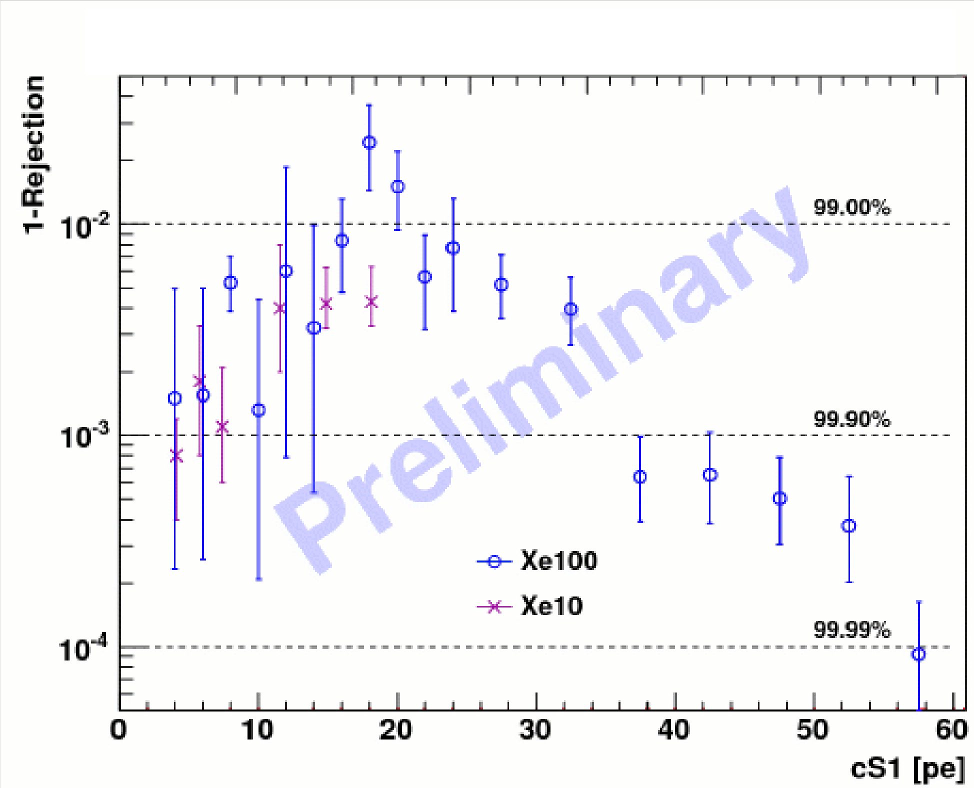
from: *Aprile et al., PRL 97, 081302 (2006)*



from: *Aprile et al., PRB 76, 014115 (2007)*

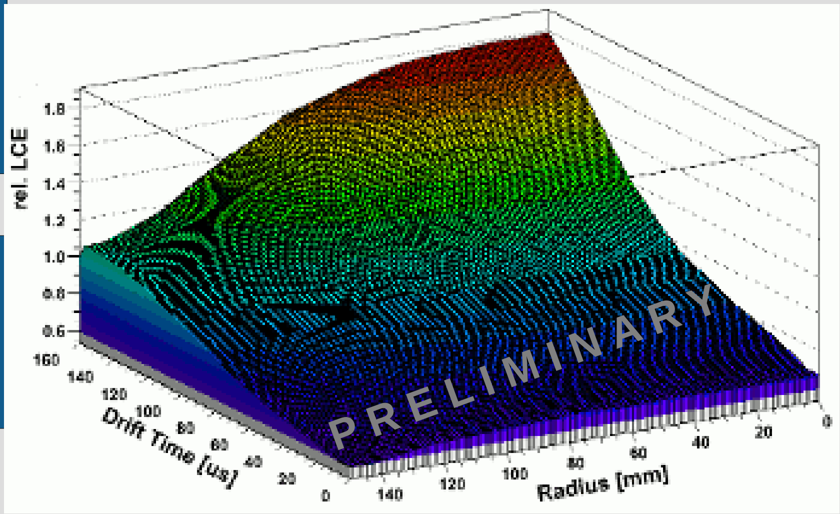
ER / NR Discrimination

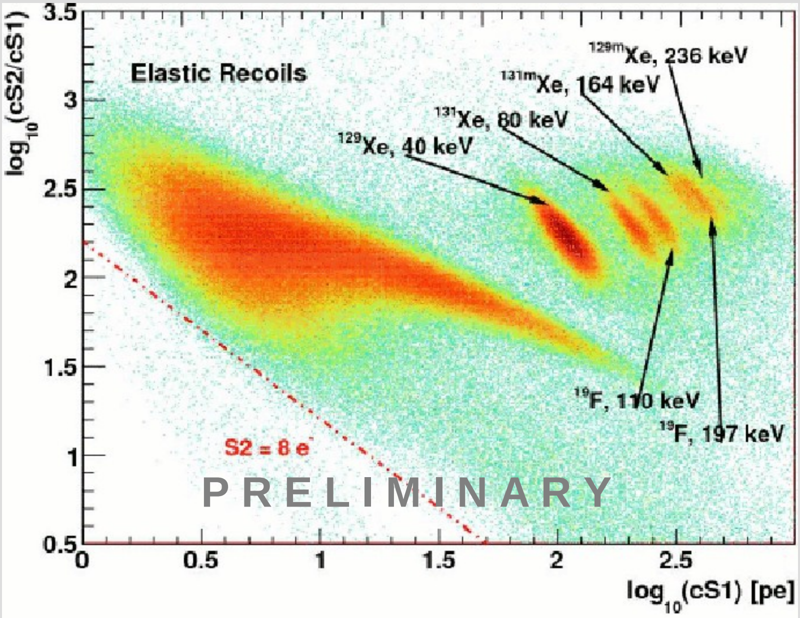




- ER/NR discrimination via S2/S1 ratio
- Discrimination efficiency similar to XENON10 (>99%)

Selected Calibrations





Position dependent Corrections:
Cs-137, AmBe inelastic (40 keV),
Xe* (164 keV)
Kr-83m (planned)

➡ Agreement better than 3%

Electron Lifetime:
Cs-137

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

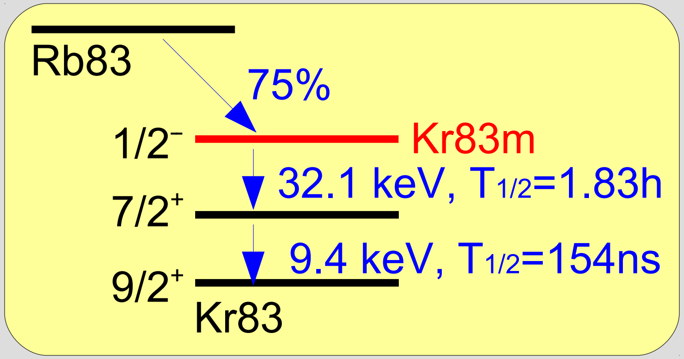
Electron Recoil Band (Background):
Co-60, Cs-137, Th-228

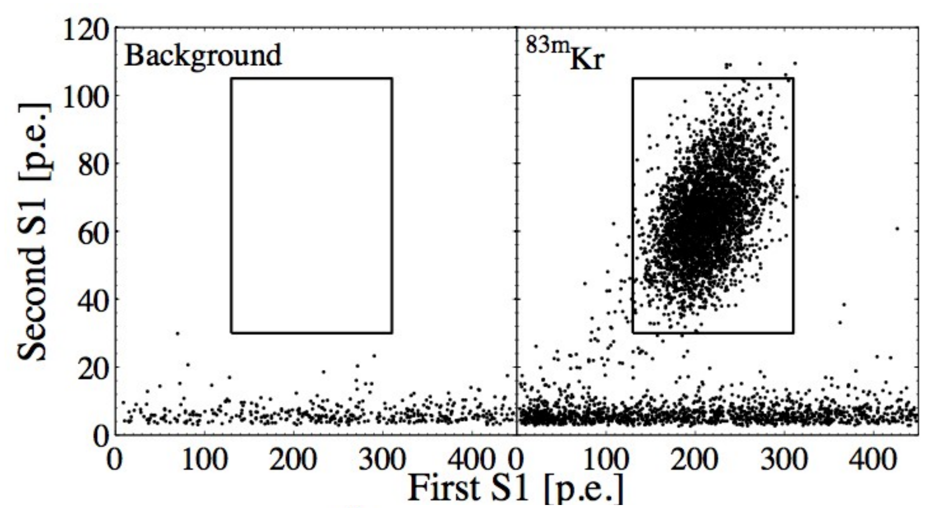
Nuclear Recoil Band (Signal):
Neutrons: AmBe

➡ definition of WIMP search region, discrimination

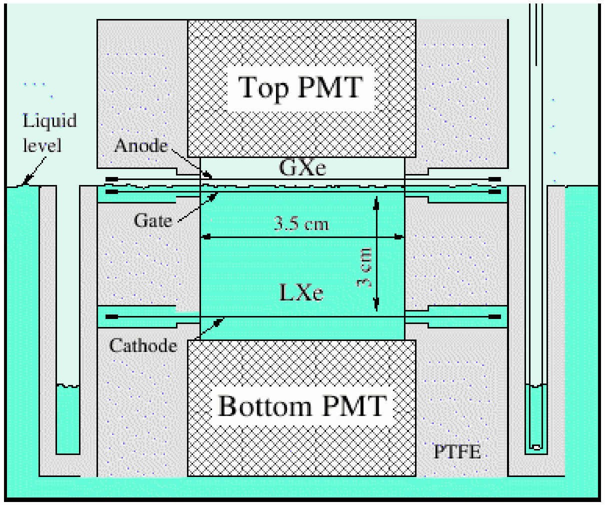
Calibration at low Energy

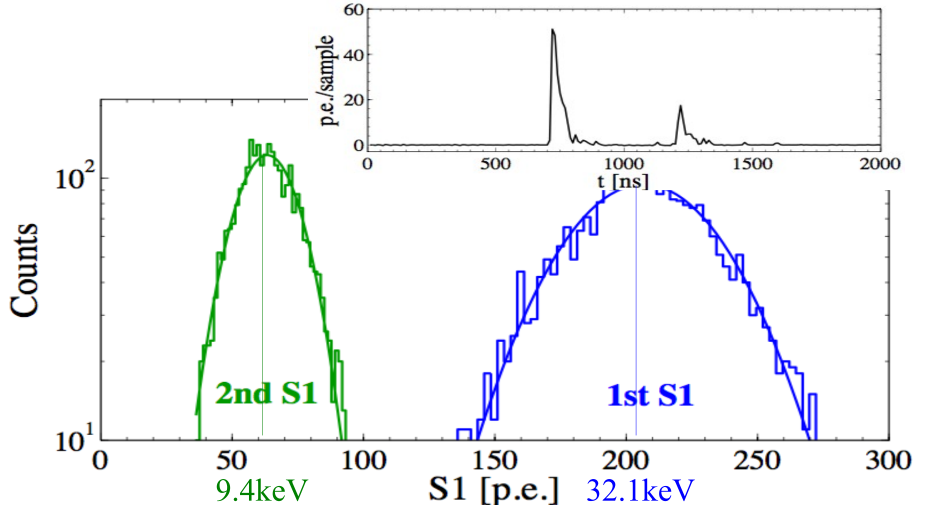
expect signal <40 keV (calibration from outside not possible)
⇨ n-activated Xe131, Xe129m
was used for Xe10, τ~O(10d)
⇨ Kr83m





R&D in Zürich:





Manalaysay et al., Rev.Sci.Instr. 81, 073303 (2010)

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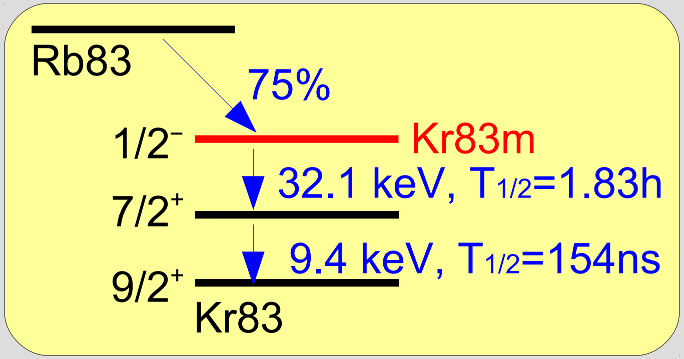

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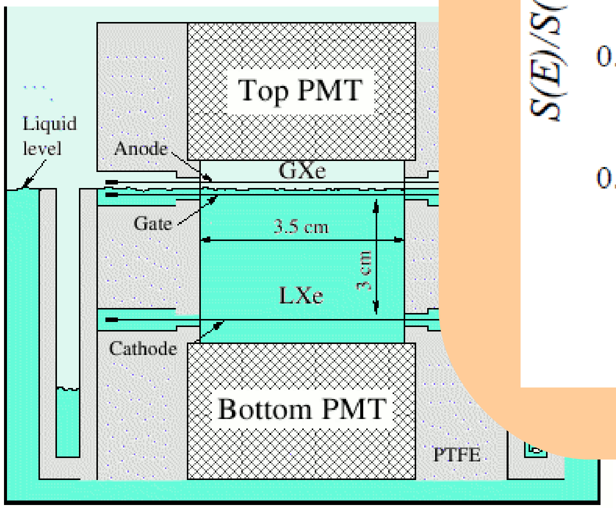
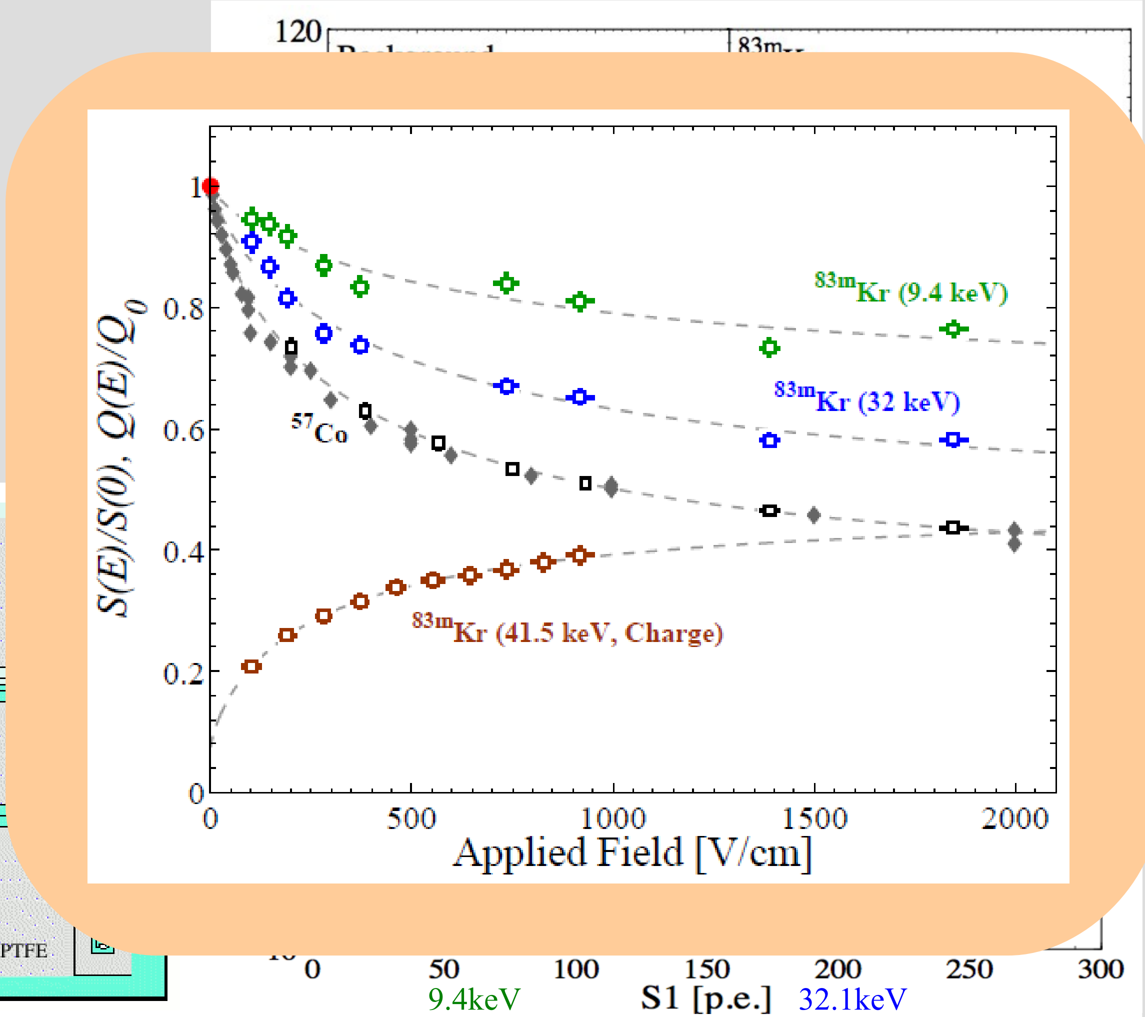




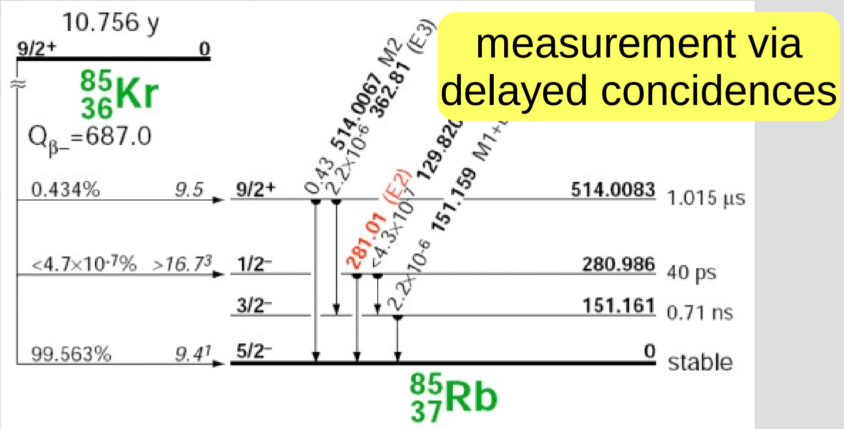
Manalaysay et al., Rev.Sci.Instr. 81, 073303 (2010)

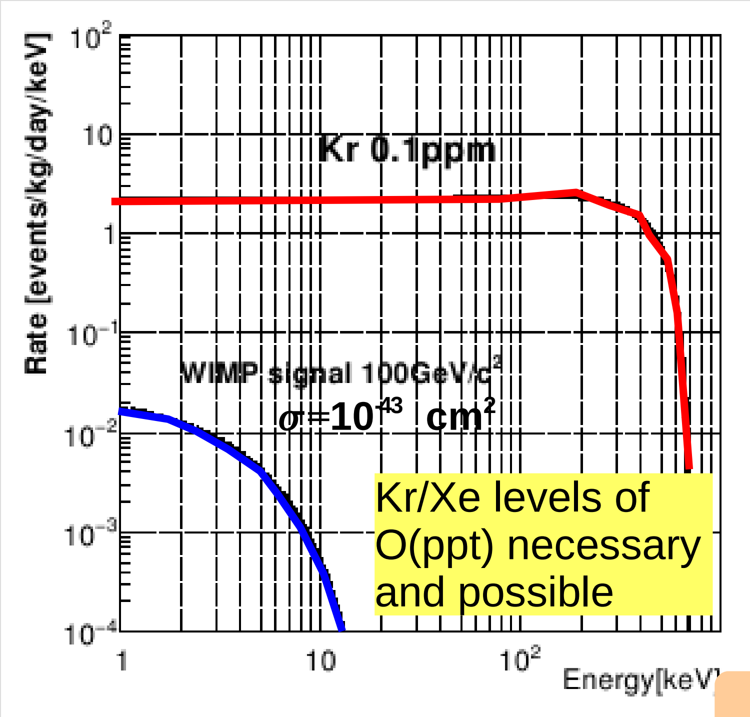
Kr-85-Removal

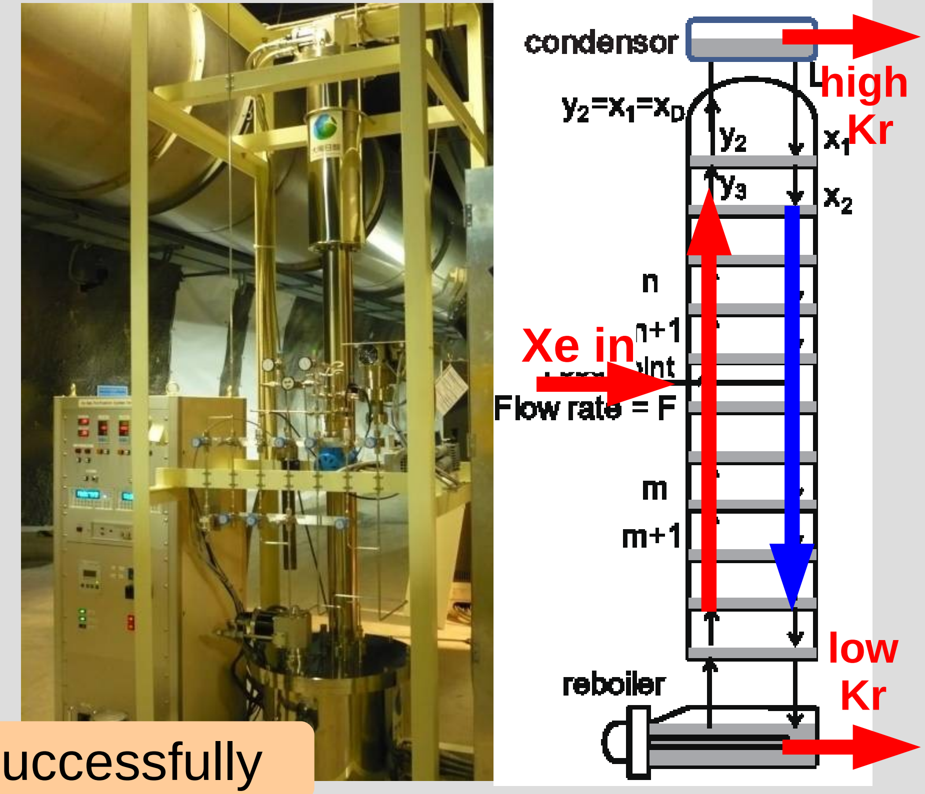
- Xe has no long lived radioactive isotope
- BUT: Xe contains Kr-85

in air:	Kr/Xe ~ 10
in Xe gas (commercial)	Kr/Xe ~ ppm-ppb
necessary (Xe100)	Kr/Xe ~ 100 ppt (<1 evt in 0.5 yr)

→ dedicated Kr-85 removal to ppt level





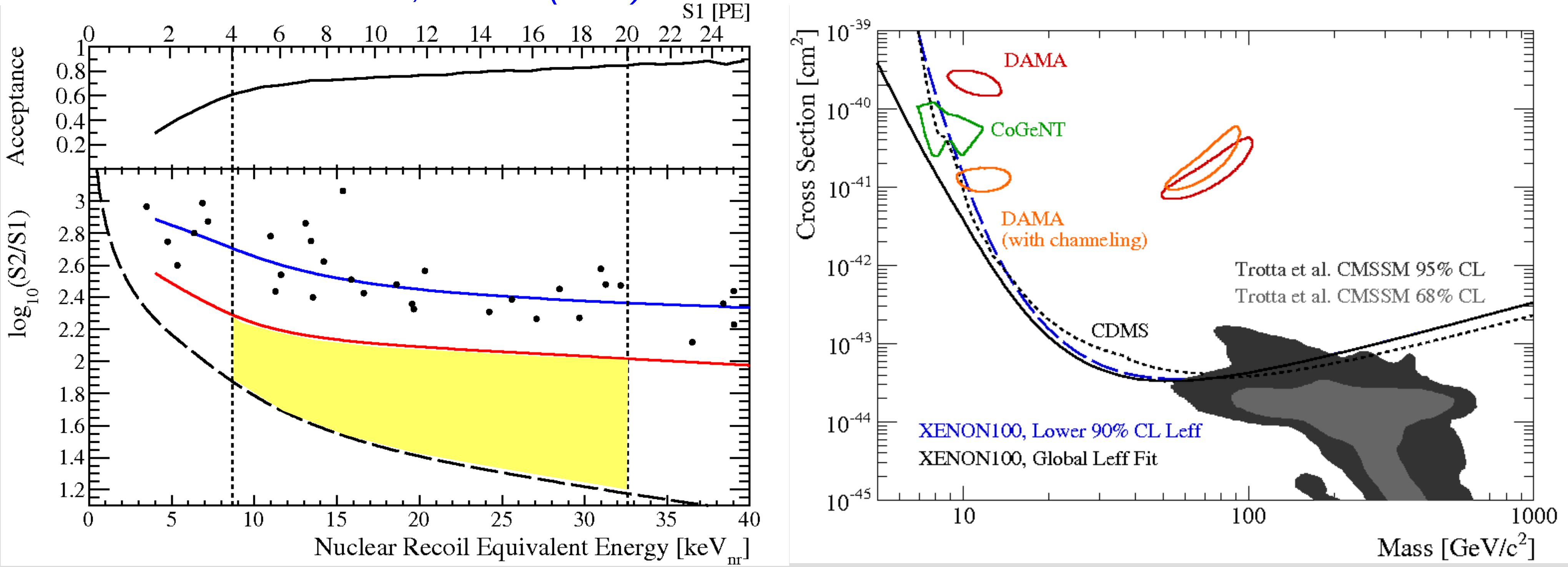


used successfully

XMASS, Astro.Part.Phys. 31 (2008)

First XENON100 Results

XENON100 *PRL 105, 131302 (2010)*

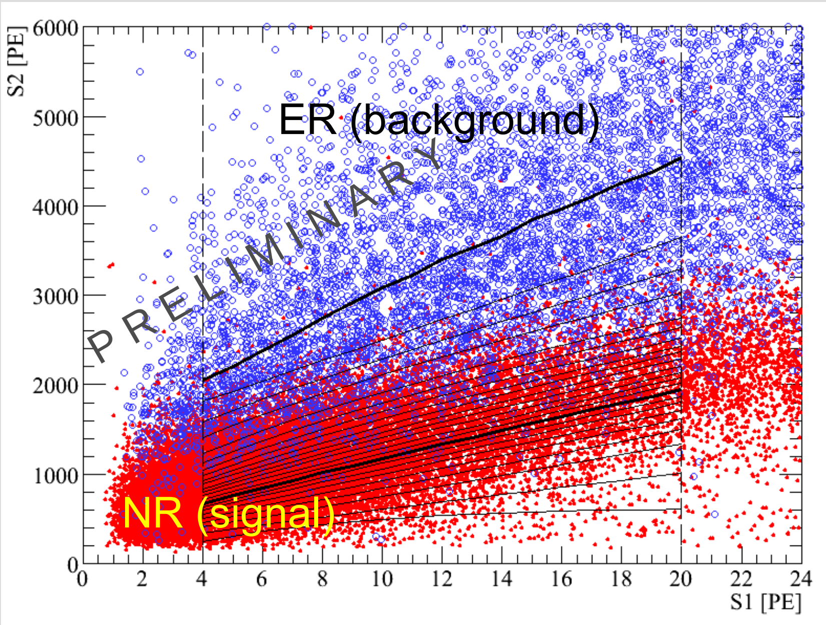


- Energy cut: <30 keVnr
- make use of excellent self-shielding capability of LXe
- 40 kg fiducial mass

- data from comissioning run Oct-Nov 2009
- 11.2 life days
- Data was not blinded
- But: Cuts developed on calibration data only

Profile Likelihood Method

arXiv:1103.0303



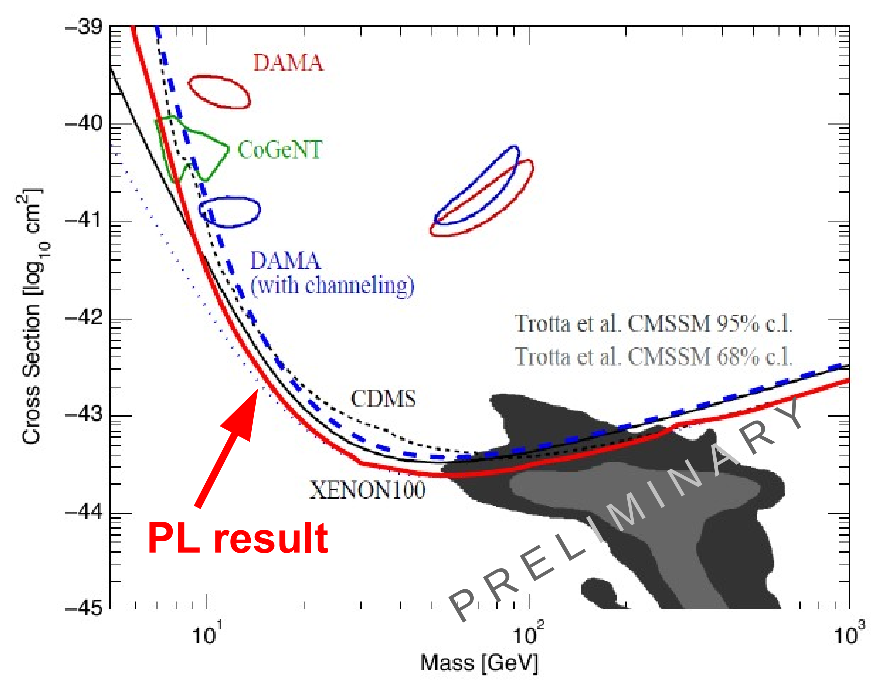
Construct Likelihood function:

$$\mathcal{L} = \mathcal{L}_1(\sigma, N_b, \epsilon_s, \epsilon_b, \mathcal{L}_{\text{eff}}, v_{\text{esc}}; m_\chi) \times \mathcal{L}_2(\epsilon_s) \times \mathcal{L}_3(\epsilon_b) \times \mathcal{L}_4(\mathcal{L}_{\text{eff}}) \times \mathcal{L}_5(v_{\text{esc}}).$$

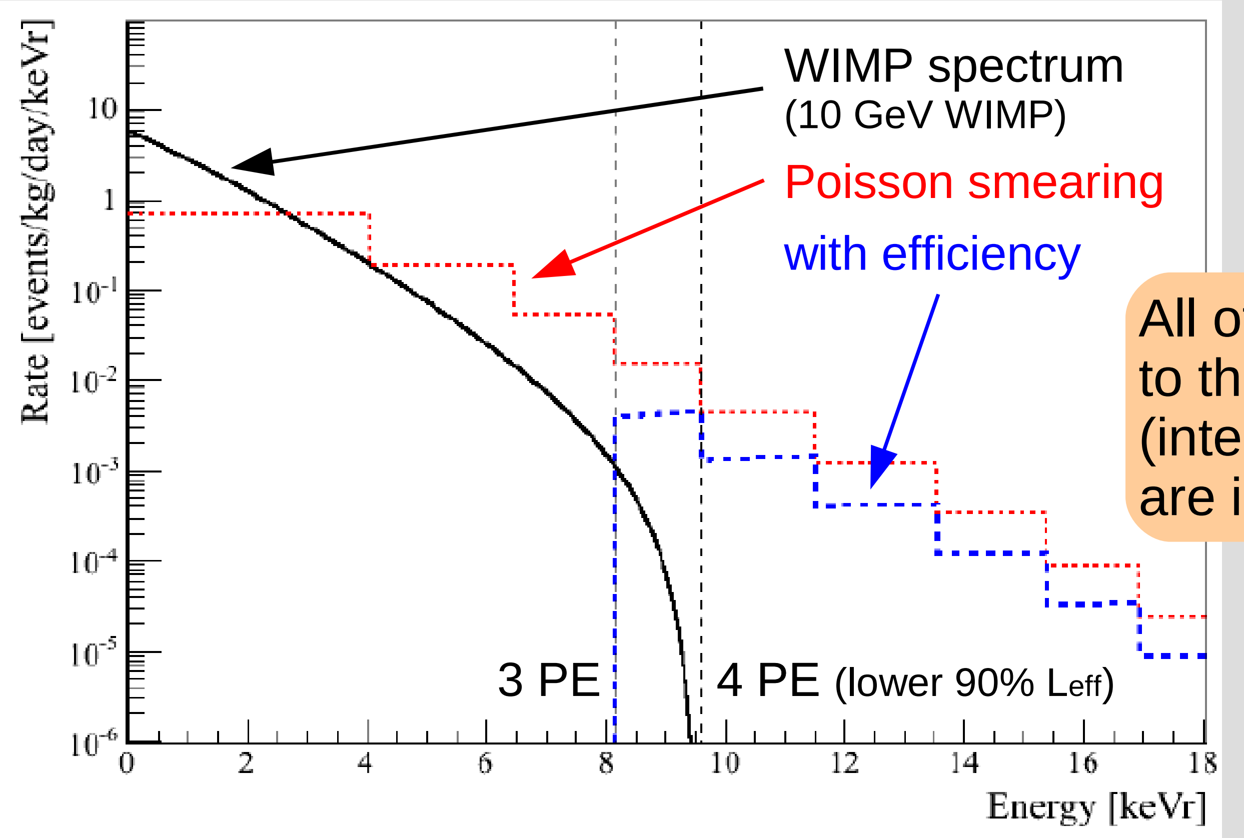
- $\mathcal{L}_1$: dark matter measurement
- $\mathcal{L}_2$: „NR like" sideband measurement
- $\mathcal{L}_3$: „ER like" sideband measurement
- $\mathcal{L}_4$: NR scale measurement
- $\mathcal{L}_5$: v_{esc} measurement

Profile Likelihood Method

- necessary to claim a detection
- account for systematic uncertainties
- uses full S2/S1 space
- hypothesis (signal/bg) based on profile likelihood ratio
- σ is the interesting parameter; other nuisance parameters are profiled out
- method described in *arXiv:1007.1727*



Poisson Smearing



All other contributions to the energy resolution (interaction in LXe etc.) are ignored here.

- Resolution at low *E* is dominated by Poisson counting statistics ➡ a few photoelectrons seen by PMTs
- WIMP spectrum is expeced to drop exponentially with *E* ➡ more events make it above threshold than vice versa