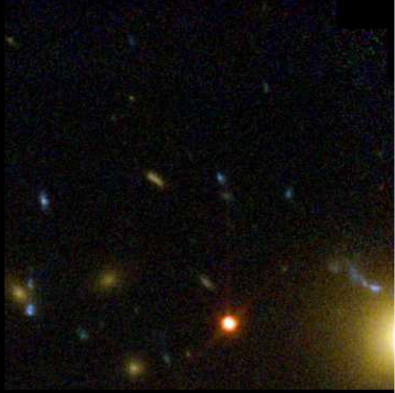
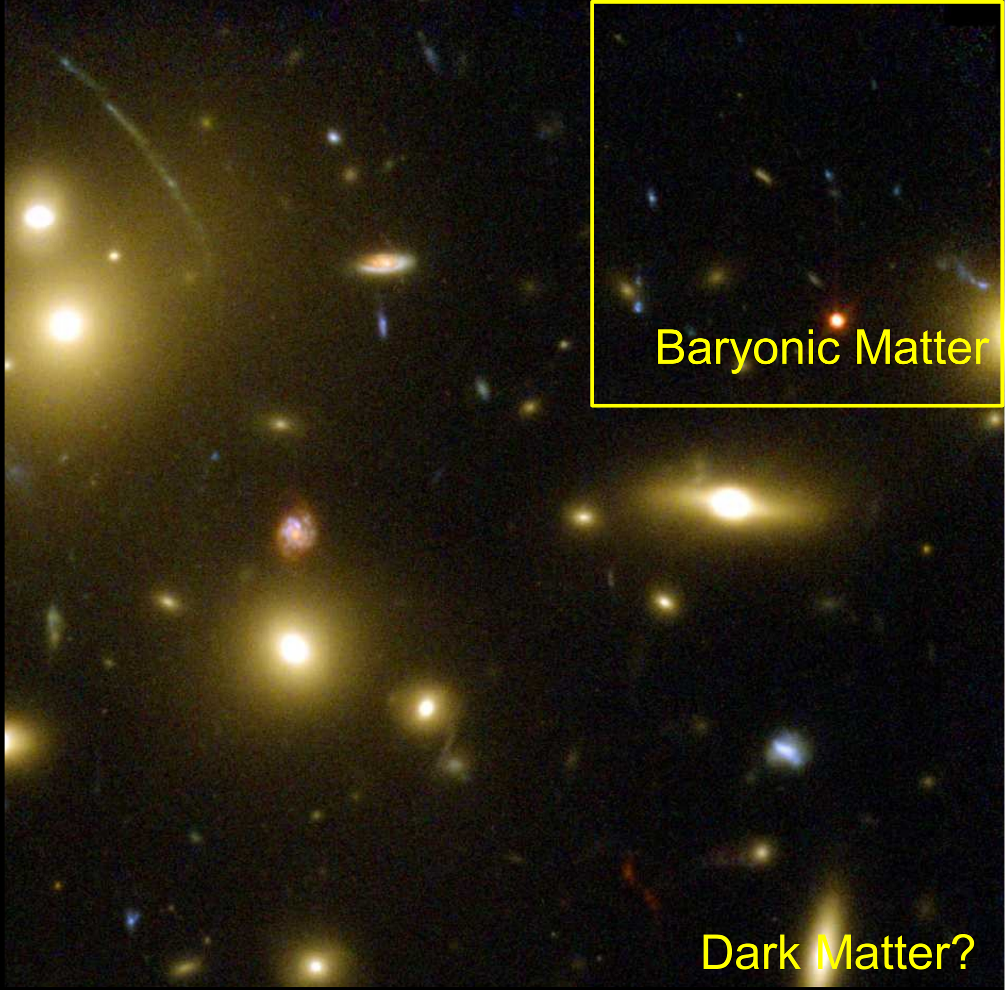
Dark Matter Search with XENON

Marc Schumann *Physik Institut, Universität Zürich*

Universität Mainz, Seminar, May 2, 2012

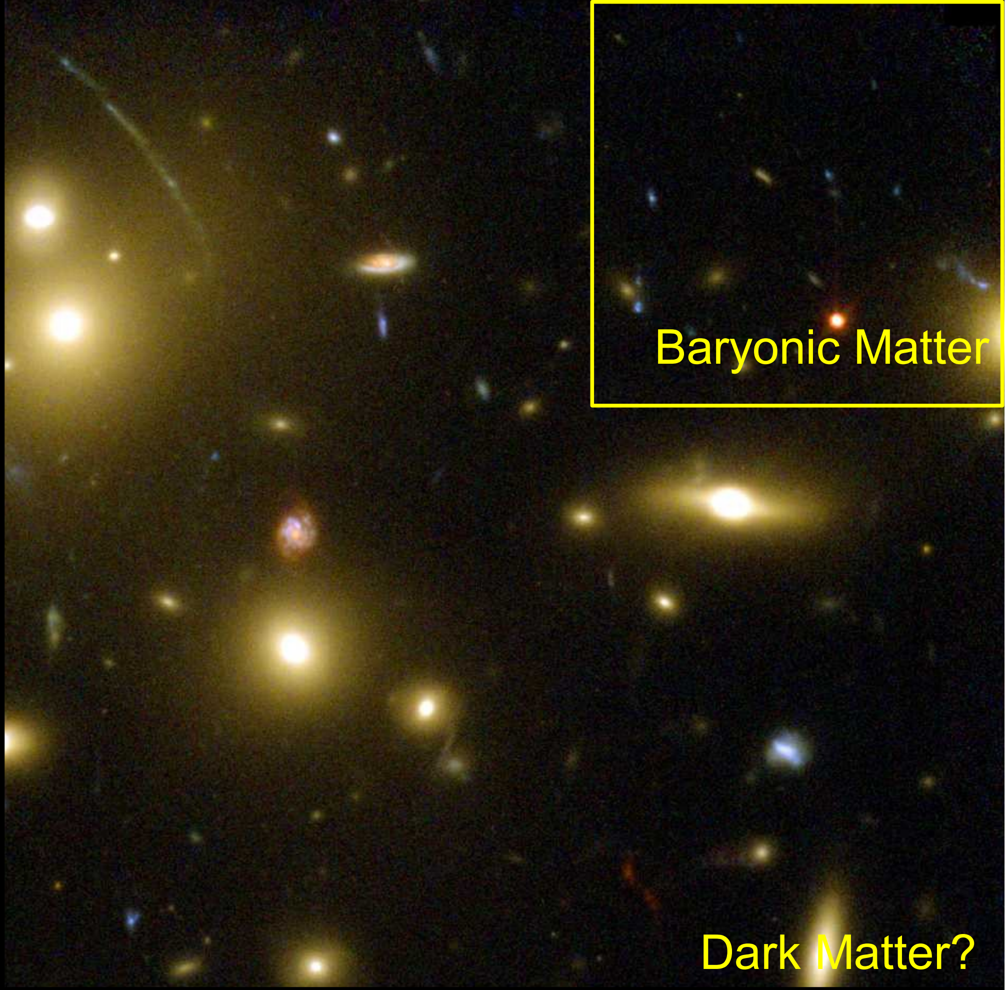
www.physik.uzh.ch/groups/groupbaudis/xenon/





Dark Energy????

95% of the Universe is dark!



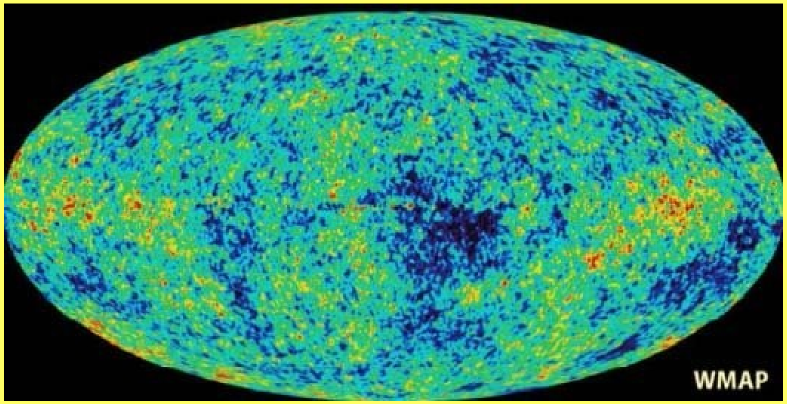
Dark Energy????

2 colliding galaxy clusters

separation of Dark and Light (baryonic) matter

→ Dark Matter and not modified gravity

Cosmic Microwave Background



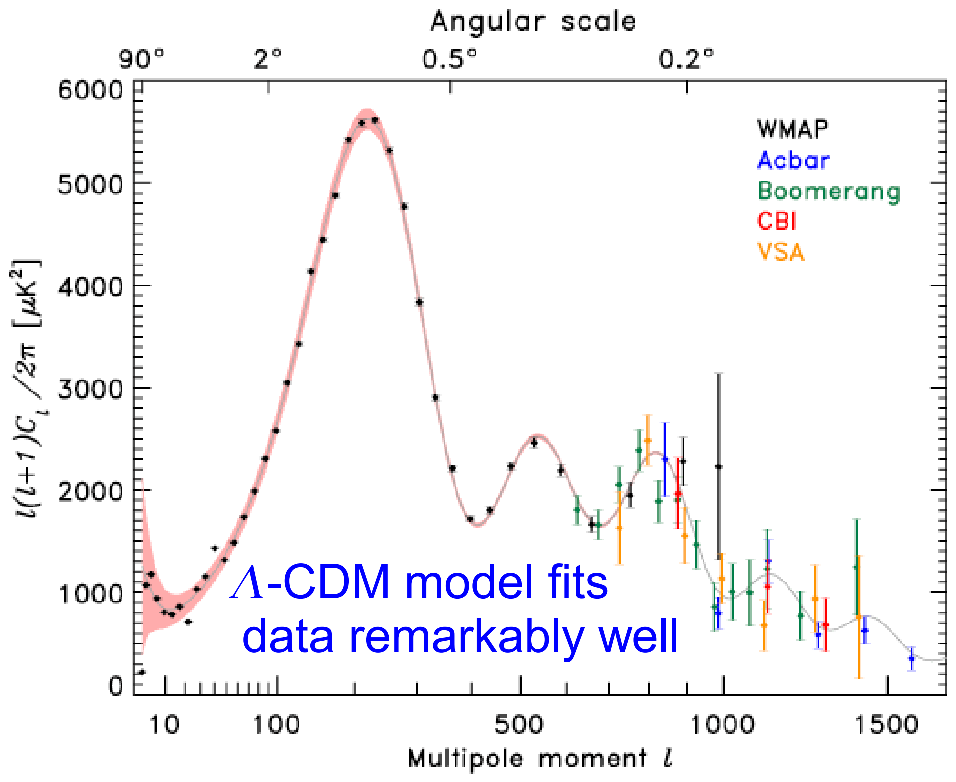
generated when radiation and matter decouple and photons can propagate freely

get information about structures in early universe

→ **Cold Dark Matter:**
- invisible
- cold ($v < 10^{-8}\ c$)
- collisionless
- stable
- from „new physics“

power spectrum of ΔT

„typical variation at typical distance“



$\Omega = \rho/\rho_{crit} = 1.02(2)$ $\quad \Omega_\Lambda = 0.73(4)$

$H = 71(4)$ km/s/Mpc $\quad \Omega_B = 0.044(4)$

$t_0 = 13.7(2)$ Gyr $\quad \Omega_m = 0.27(4)$

The WIMP Miracle

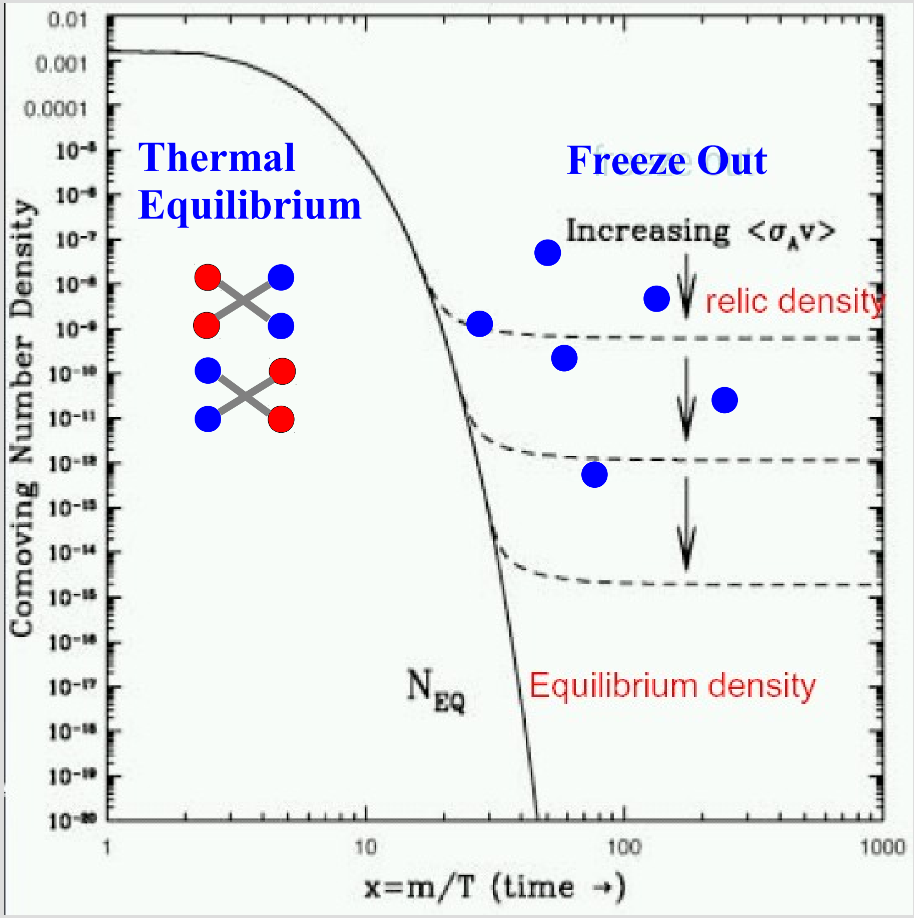
In early Universe:
WIMPs in thermal equilibrium
creation ↔ annihilation

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

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:

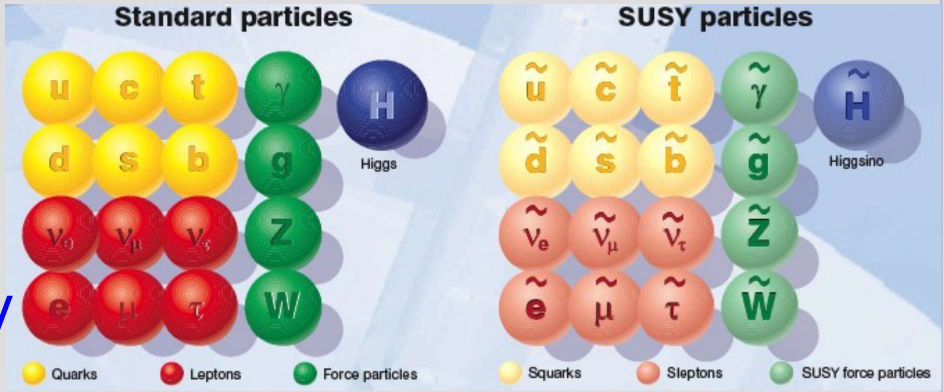
$$\Omega_\chi h^2 \approx \text{const.}\frac{T_0^3}{M_{Pl}^3 \langle\sigma_A v\rangle} \approx \frac{0.1\text{pb}}{\langle\sigma_A\ v/c\rangle}$$

O(1) when $\sigma_A \sim 10^{-36}$ cm² → weak scale

SUSY and the WIMP

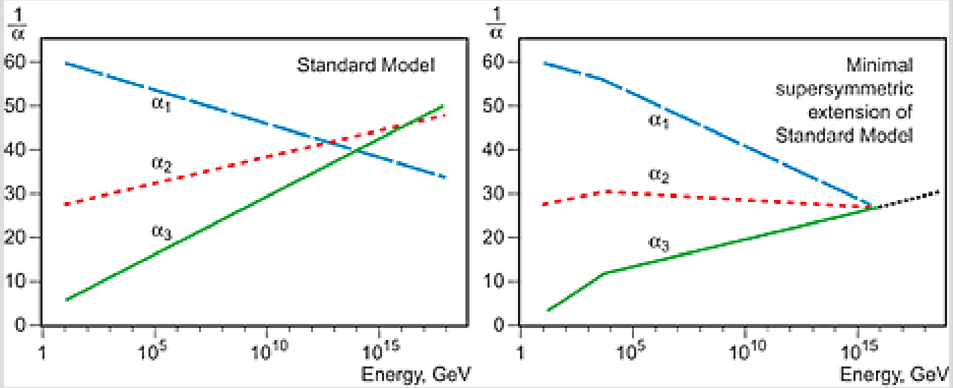
SUSY was introduced to solve Standard Model problems
(i.e. hierarchy problem, Higgs mass)

New fundamental space-time symmetry between fermions and bosons

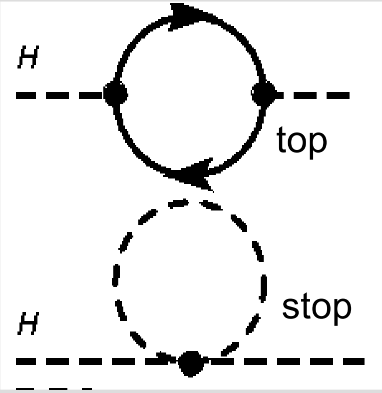


R-parity avoids B/L number violation:

$$R = (-1)^{(3B+L+2S)}$$



→ lightest supersymmetric particle (LSP) is stable → cold DM candidate:
WIMP = weakly interacting massive particle



Neutralino: $\tilde{\chi}^0_1 = N_{11}\tilde{B}^0 + N_{12}\tilde{W}^0_3 + N_{13}\tilde{H}^0_d + N_{14}\tilde{H}^0_u$

Outline

Motivation: Dark Matter ✓

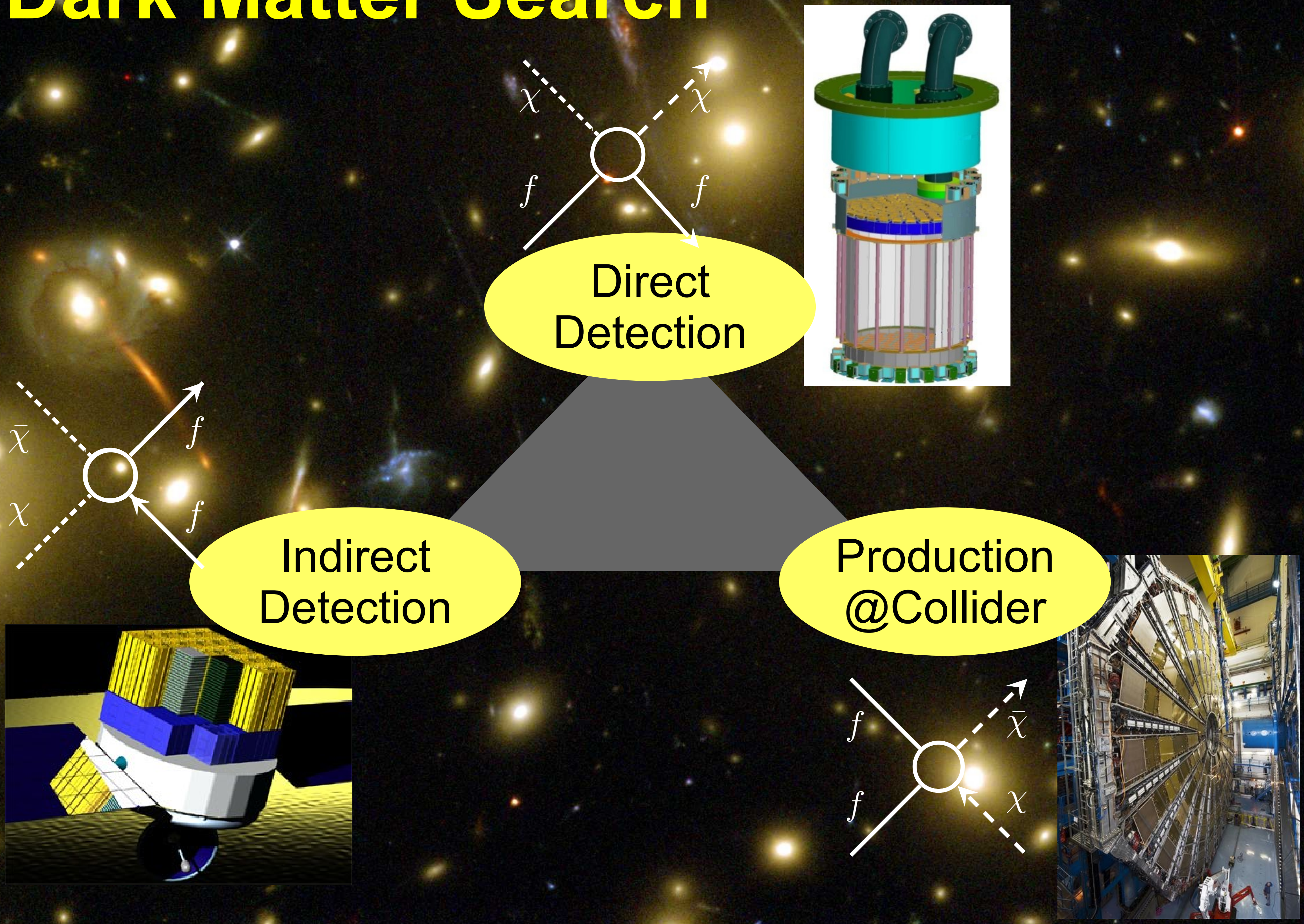
Direct WIMP Search

XENON100

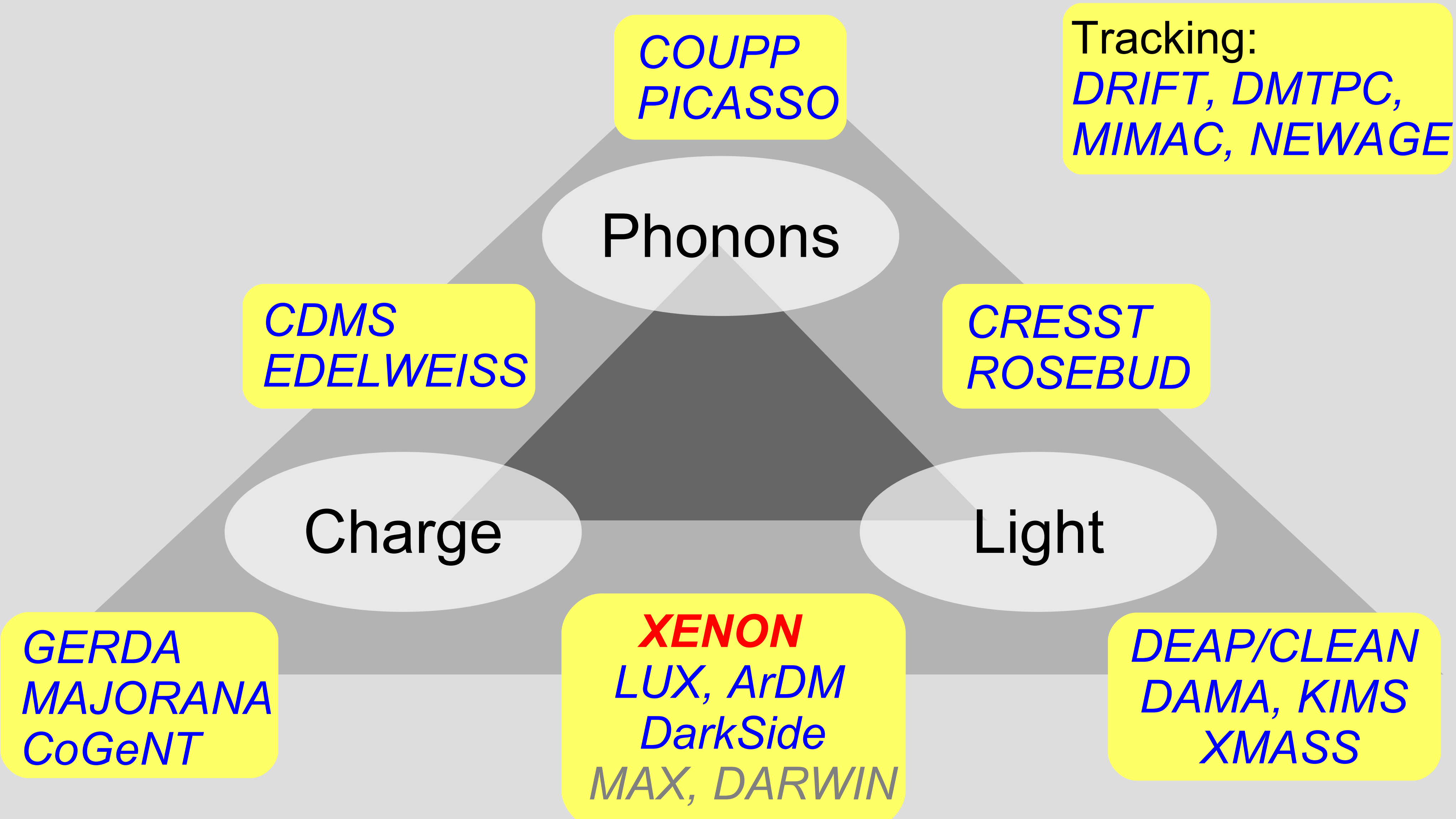
The latest Results

The Future

Dark Matter Search

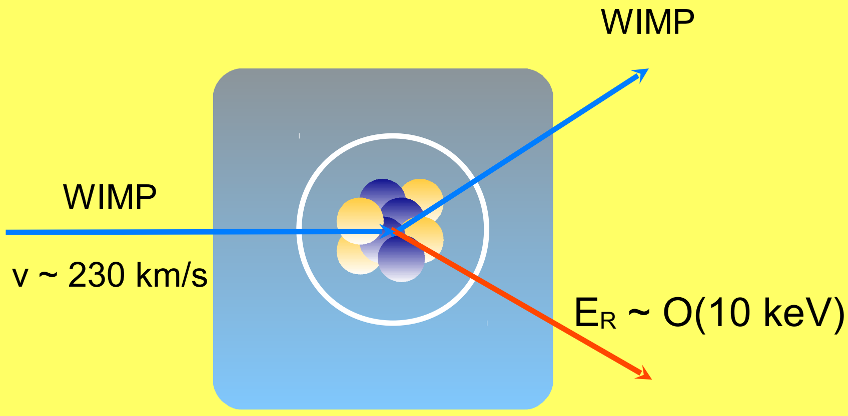


Direct WIMP Detection



Direct WIMP Search

Elastic Scattering of WIMPs off target nuclei
➞ nuclear recoil



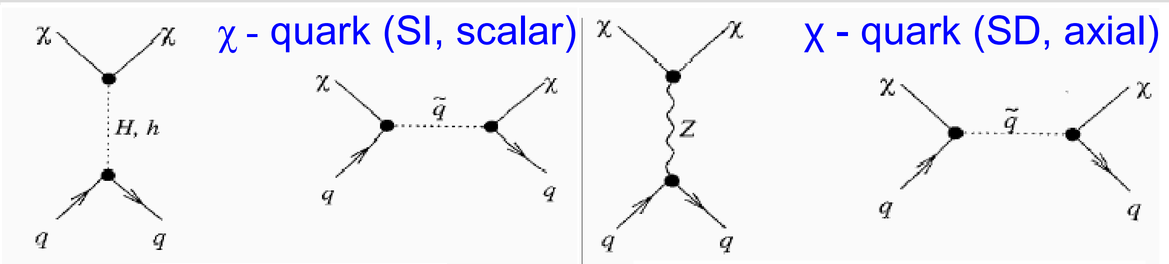
Recoil Energy: $$E_r = \frac{|\vec{q}|^2}{2m_N} = \frac{\mu^2 v^2}{m_N}(1-\cos\theta) \sim \mathcal{O}(10\text{ keV})$$

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



$\mathcal{L}_S \sim \tilde{\chi}\chi\bar{q}q \quad \propto A^2$ $\quad$ $\mathcal{L}_A \sim \tilde{\chi}\gamma_\mu\gamma_5\chi\bar{q}\gamma^\mu\gamma_5 q \quad \propto J(J+1)$

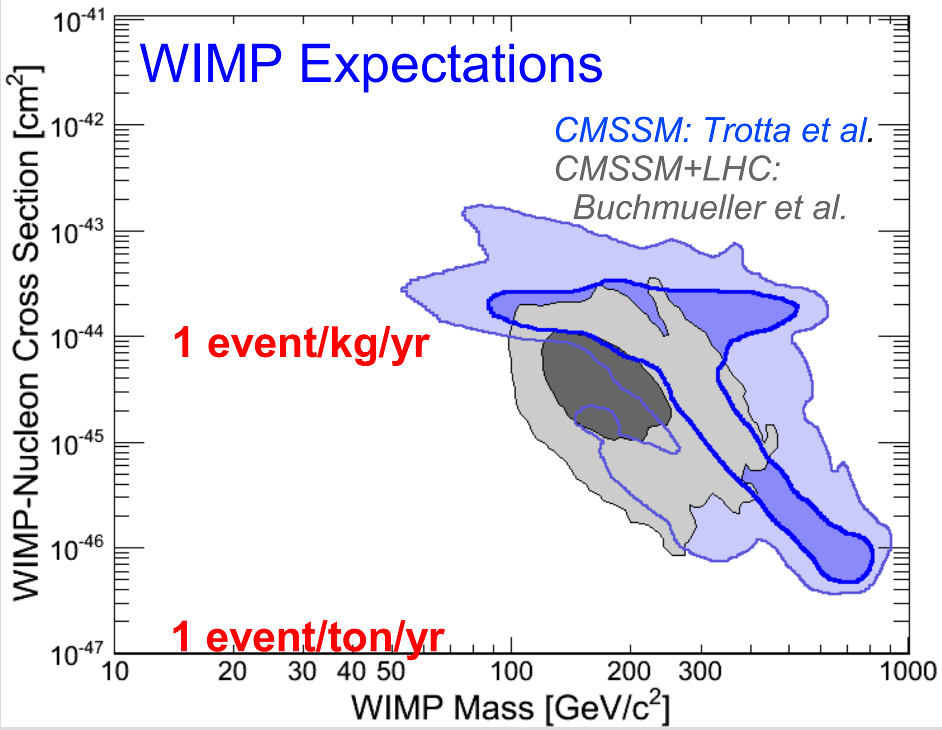
Jungmann et al. '96 Phys.Rep.

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?



WIMP Interactions
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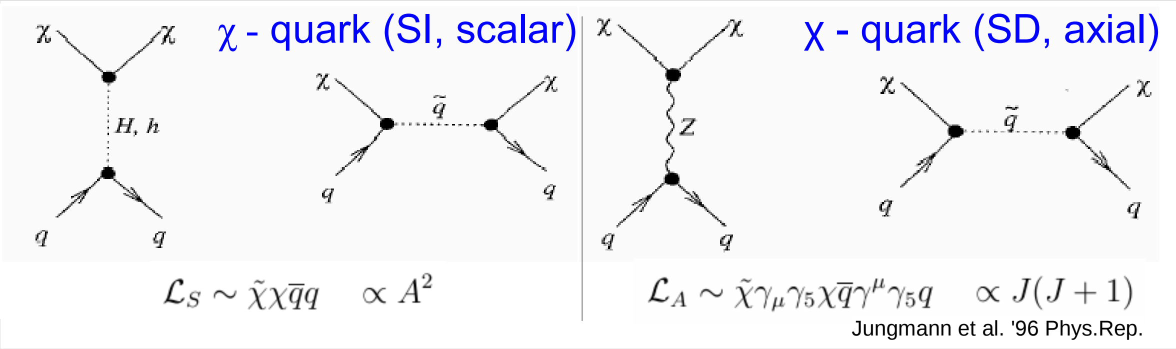

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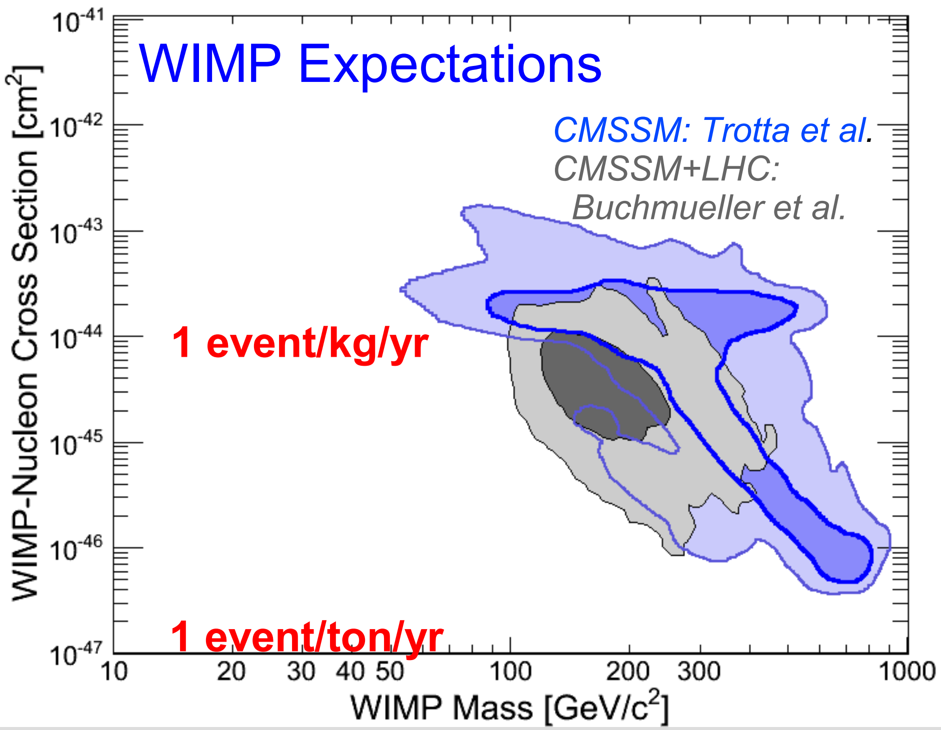
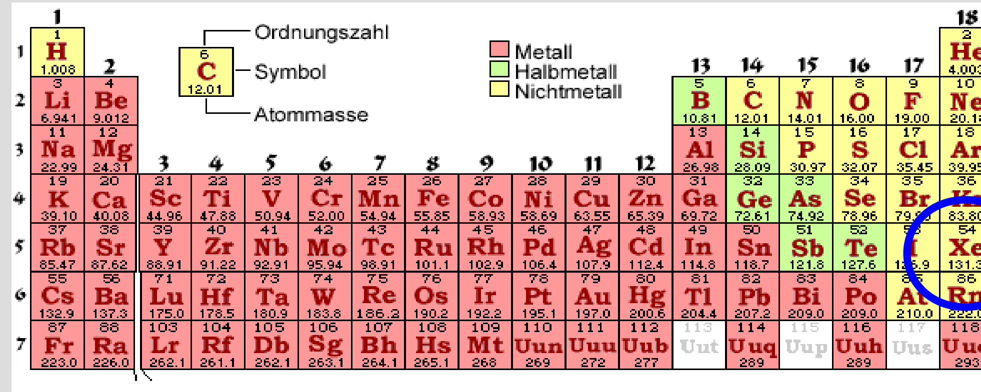
How to build a WIMP detector?

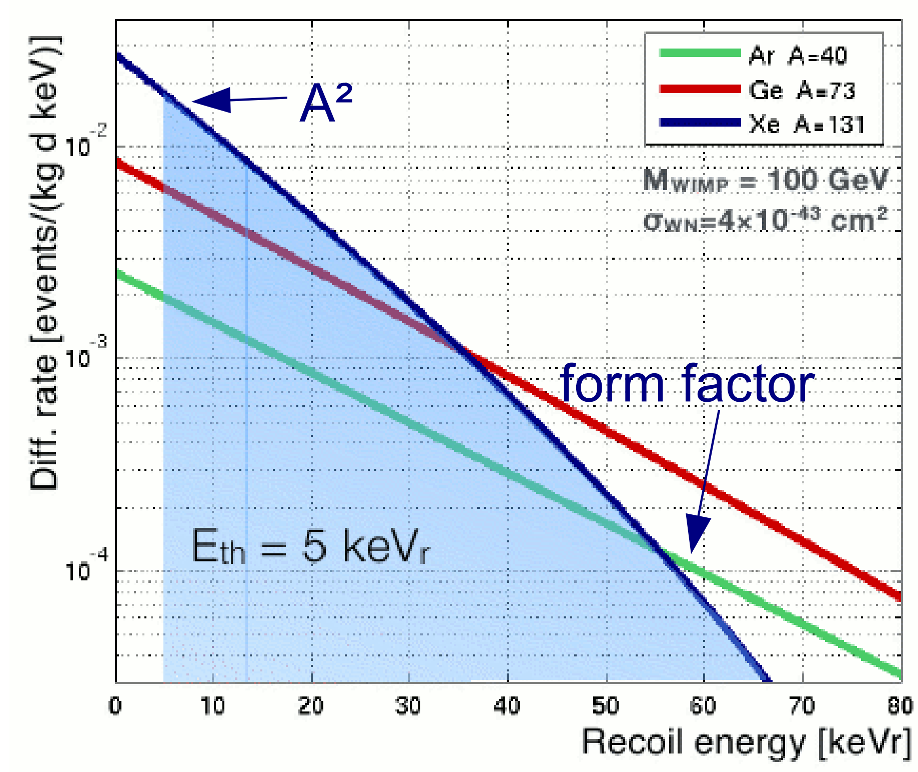
- large total mass, high *A*
- low energy threshold
- ultra low background
- good background discrimination



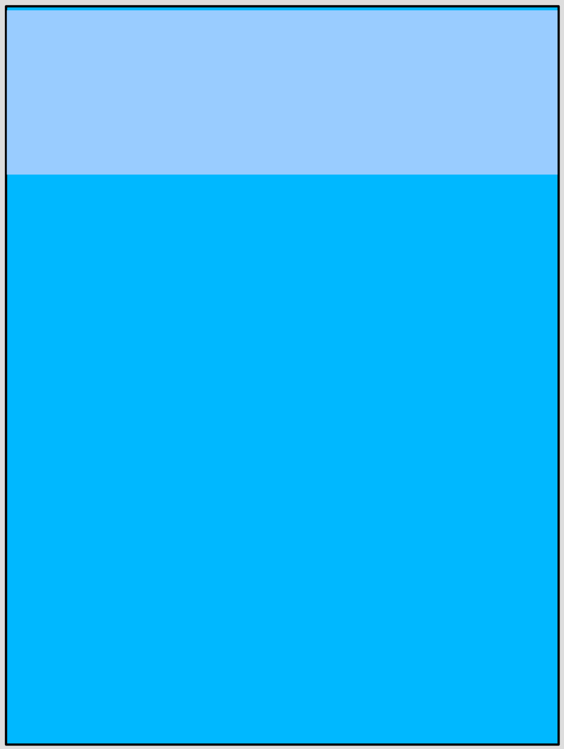
Why WIMP Search with Xenon?

- 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
- 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



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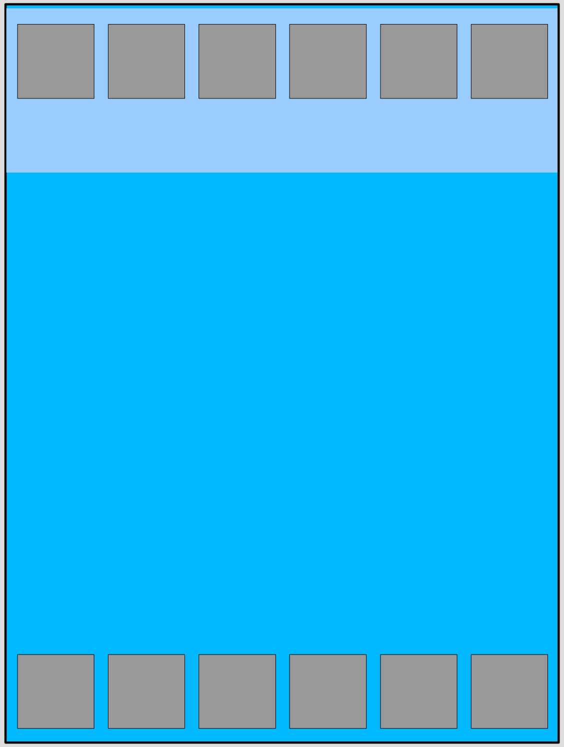

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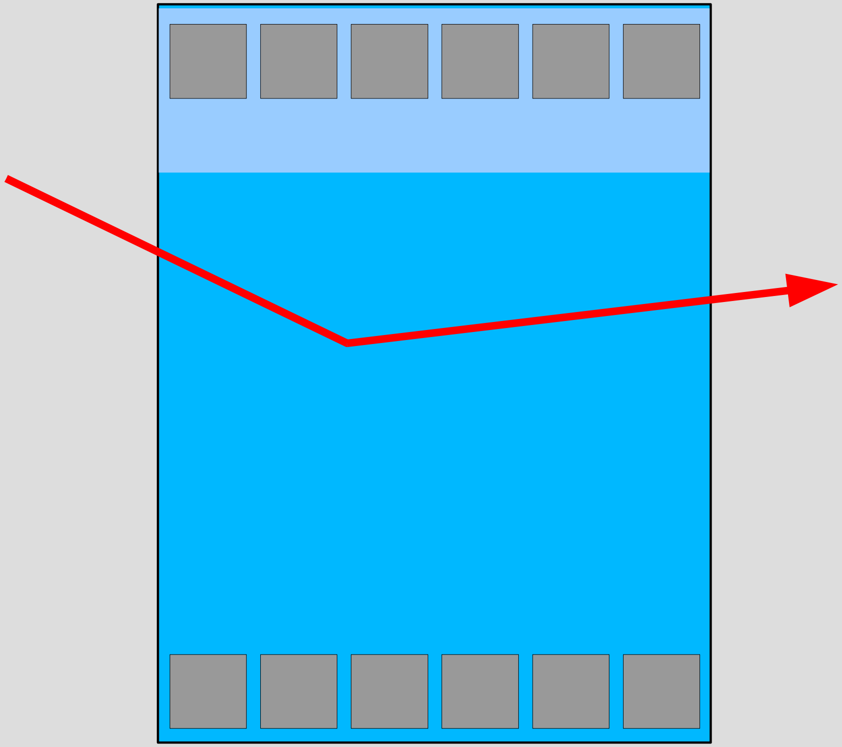

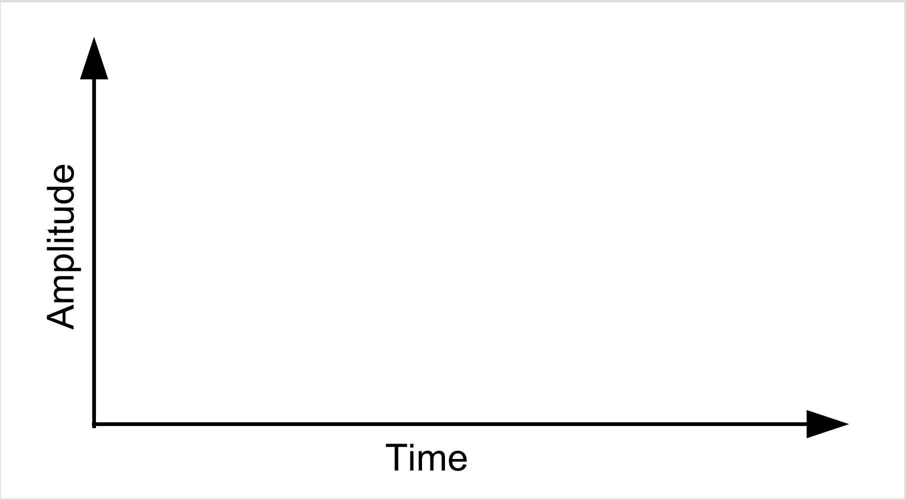

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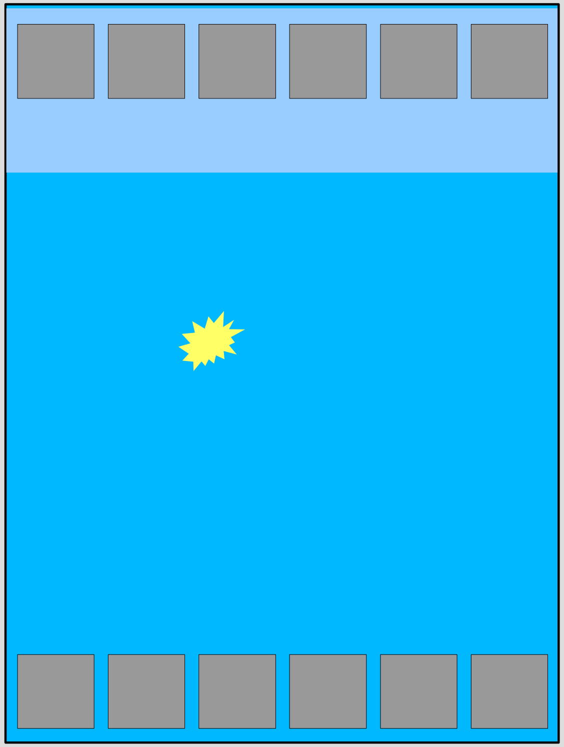

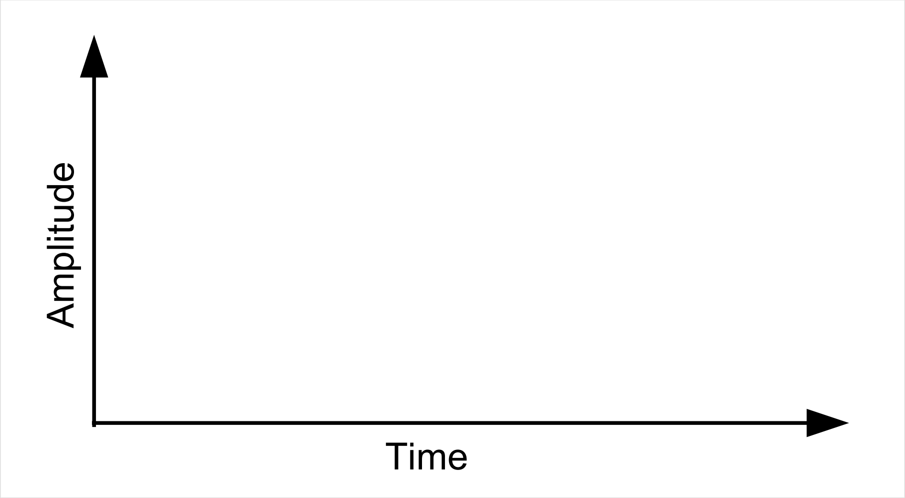

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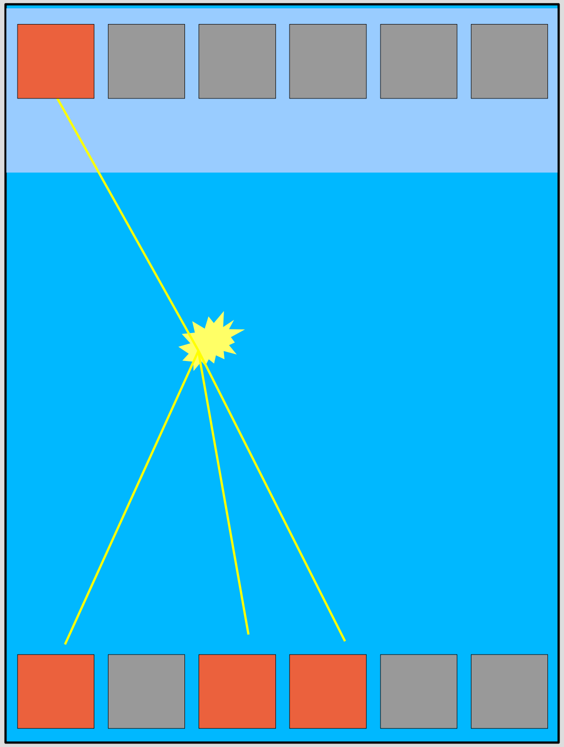

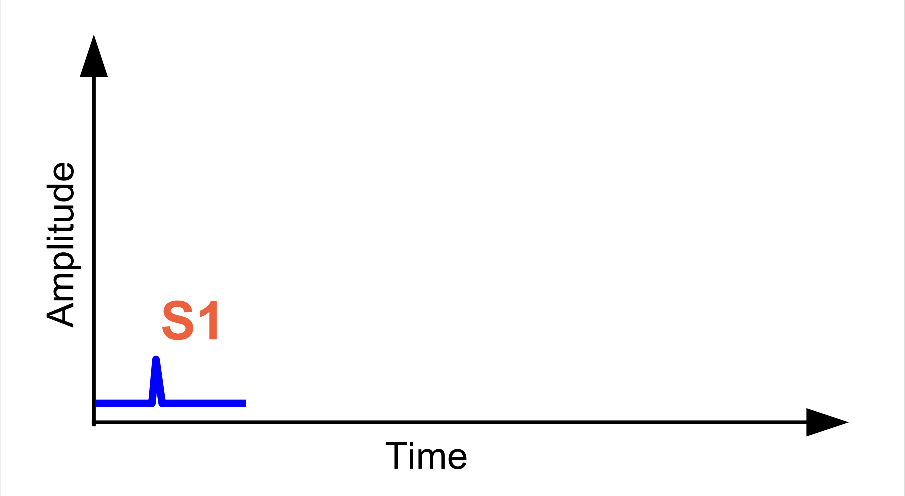

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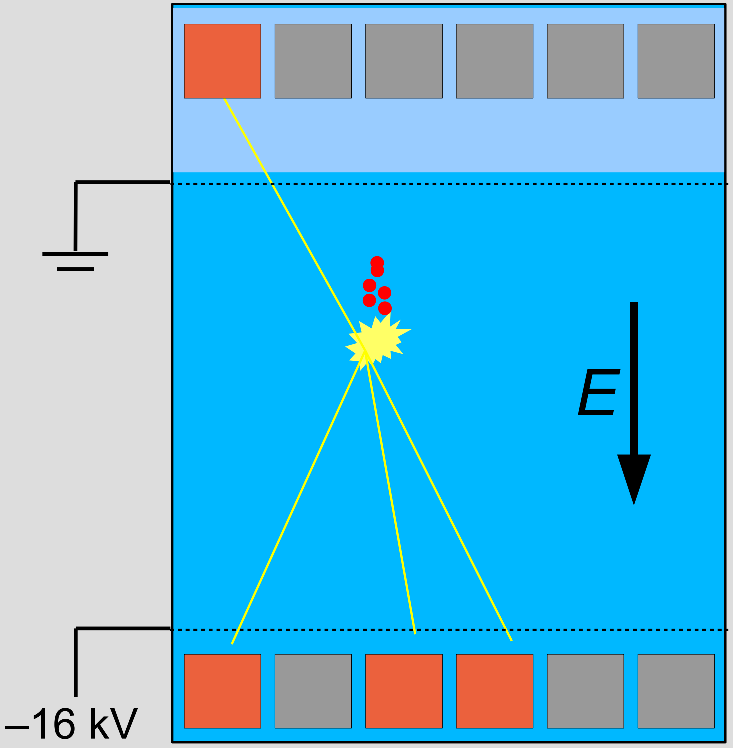

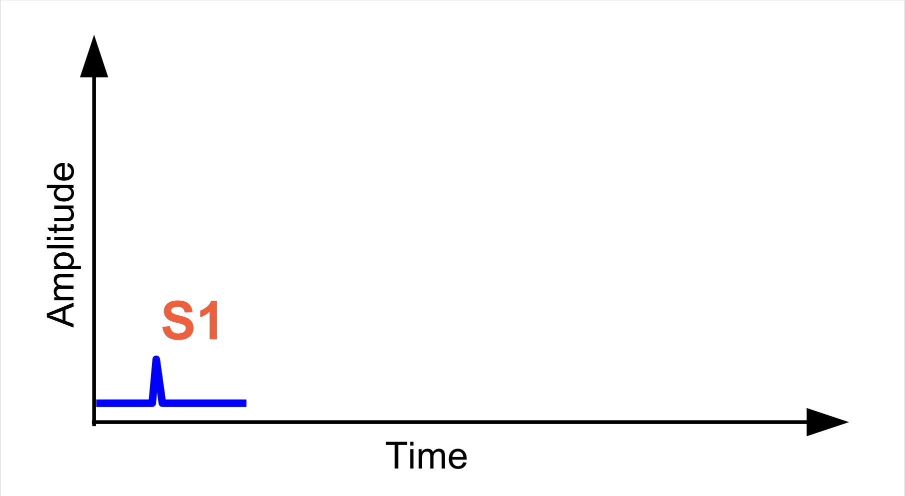

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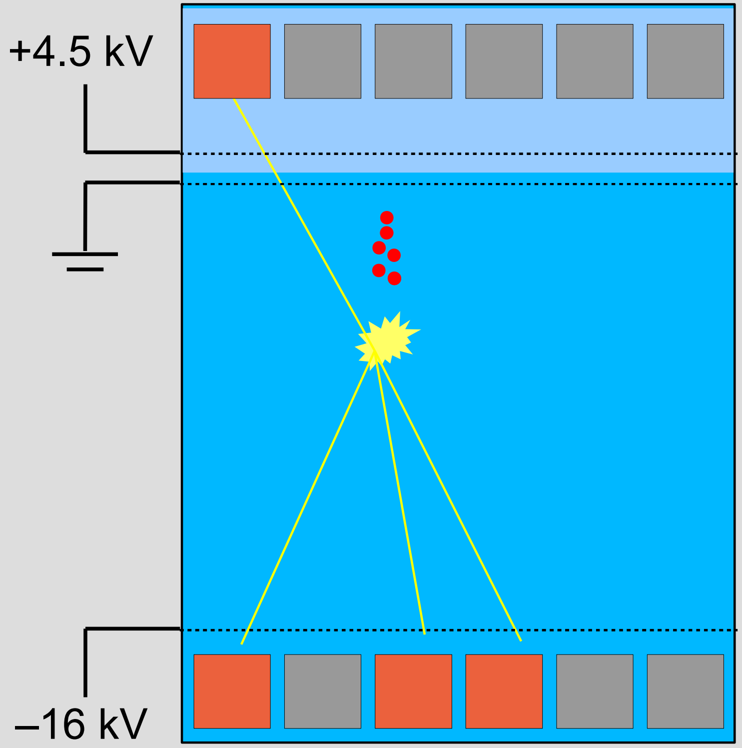

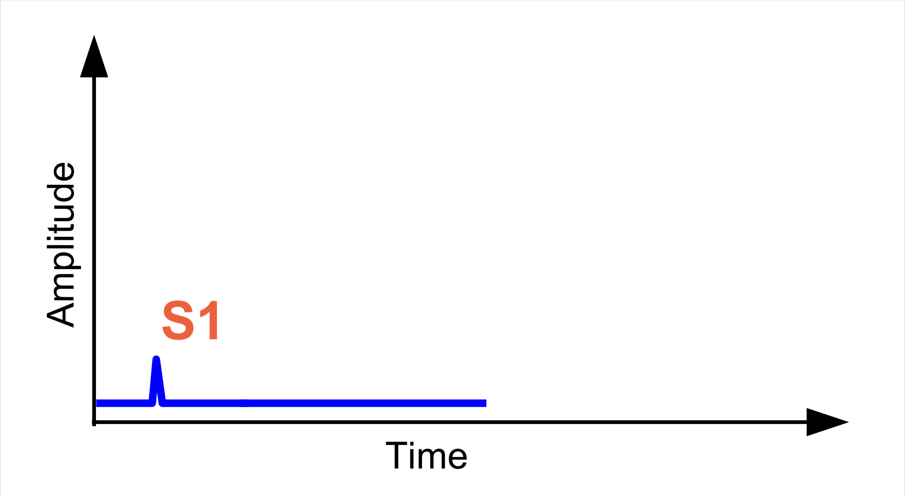

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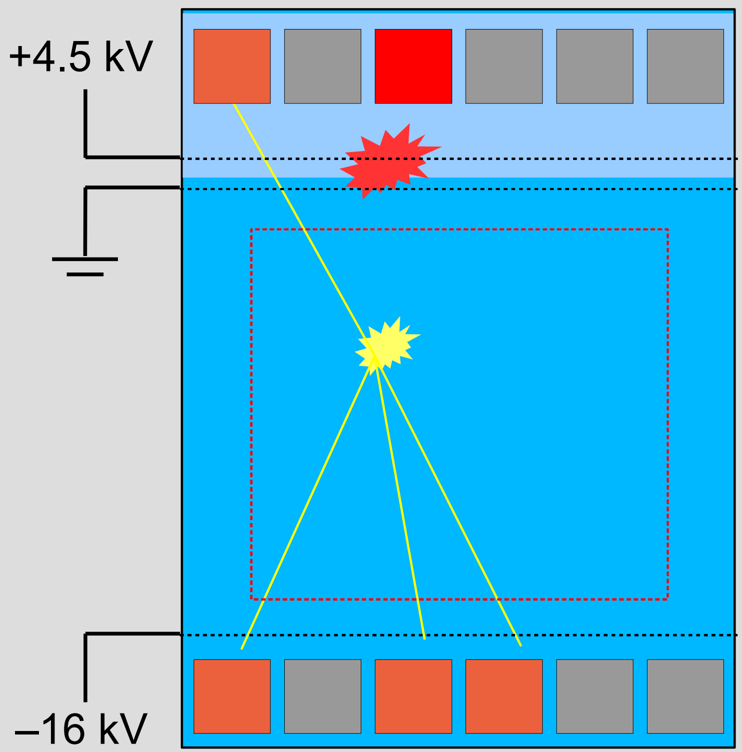

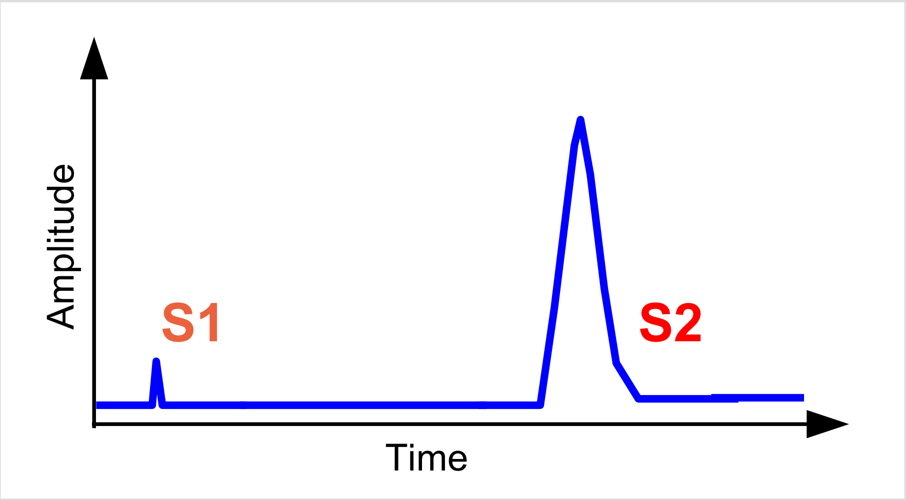

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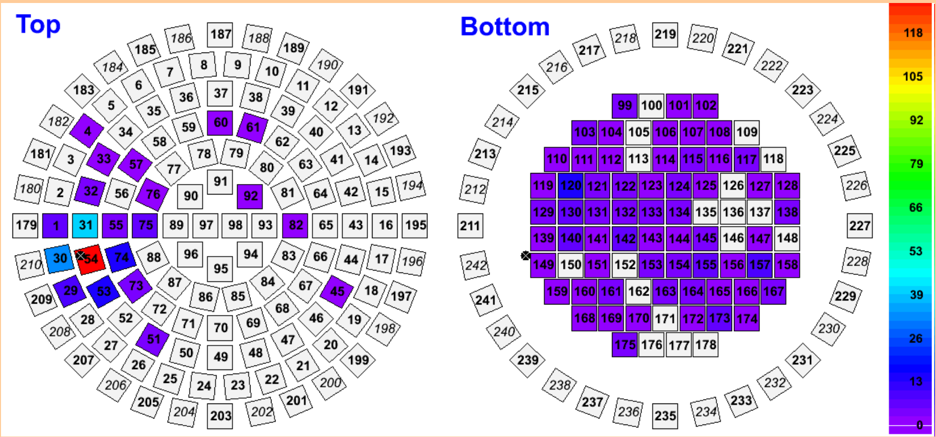
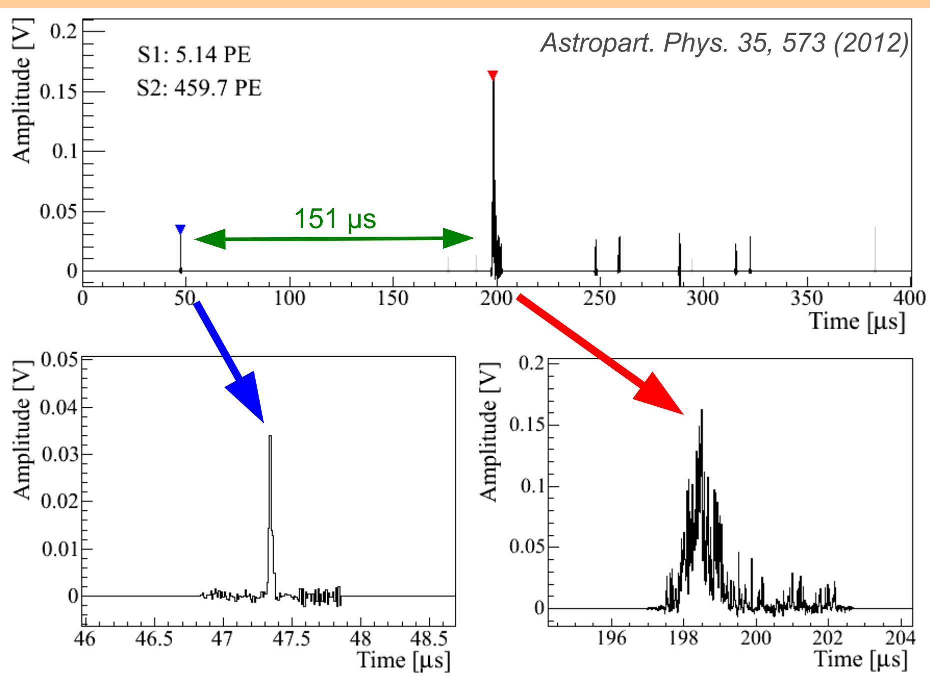
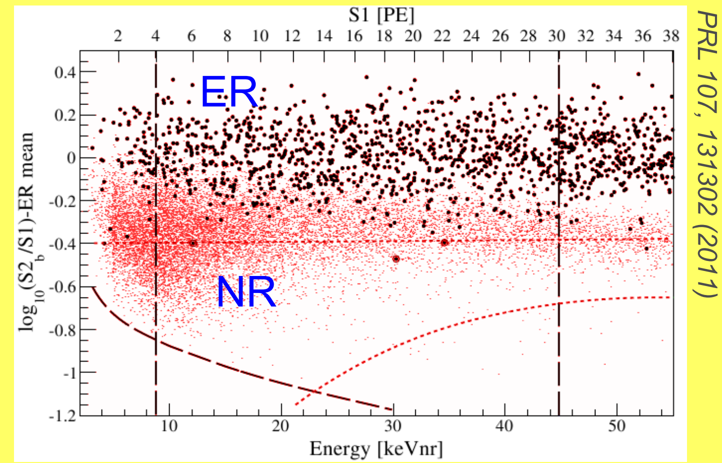
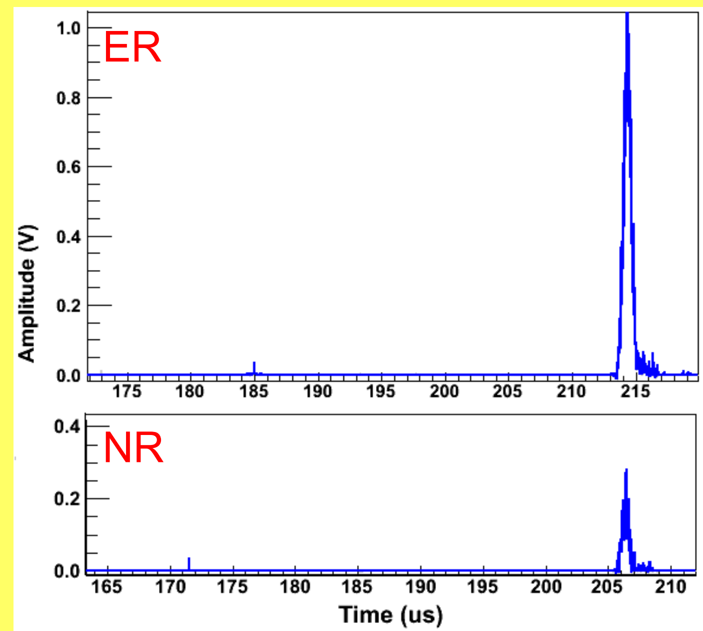








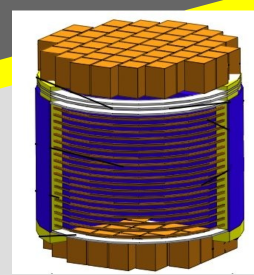
Figures from XENON100

The XENON program

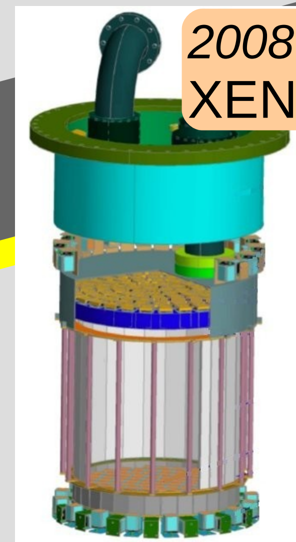
XENON: A phased WIMP search program

XENON R&D

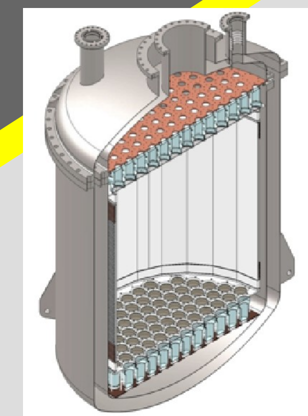
2005-2007: XENON10



2008-2012: XENON100



2010-2015: XENON1T



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

Bologna *MPIK* *NIKHEF* *Purdue* *Subatech* *Münster* *WIS*

XENON Collaboration

XENON Collaboration Meeting, LNGS, April 2012

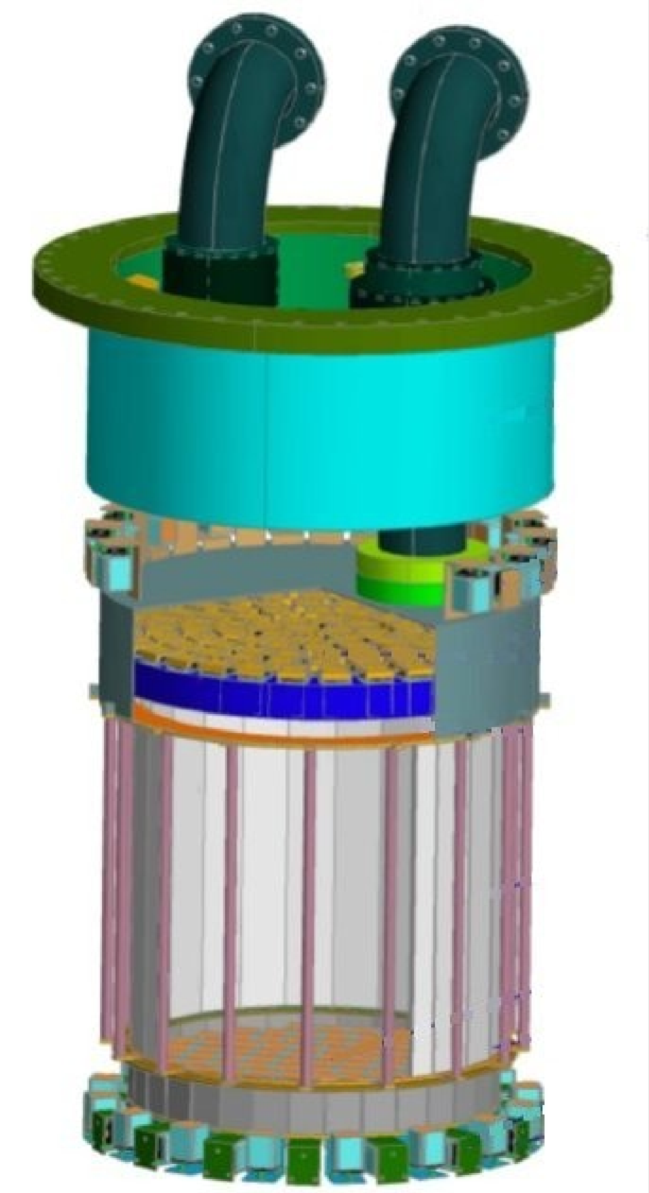
XENON100

Astropart. Phys. 35, 573 (2012)

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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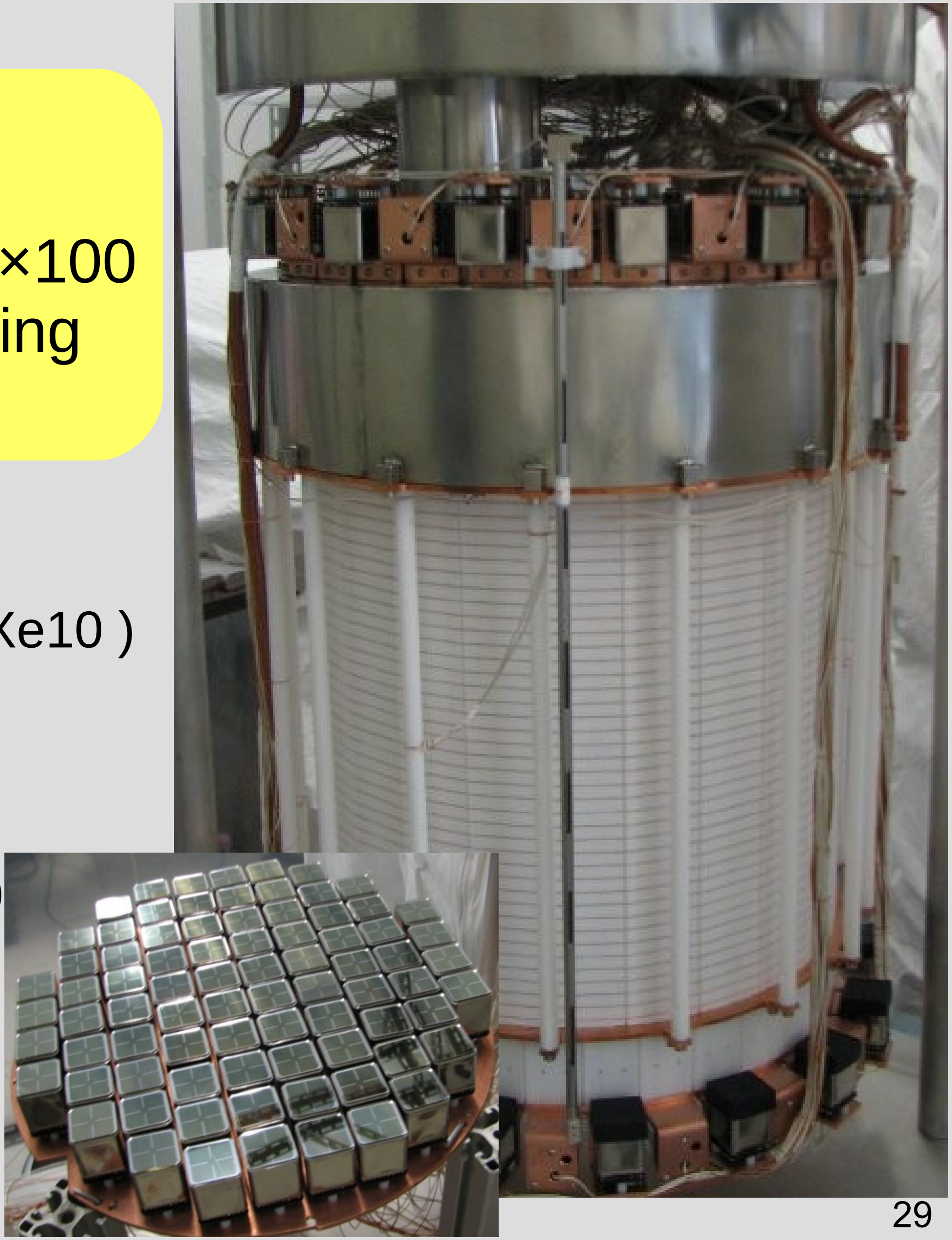

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Backgrounds

XENON Dark Matter Project

Experimental Sensitivity

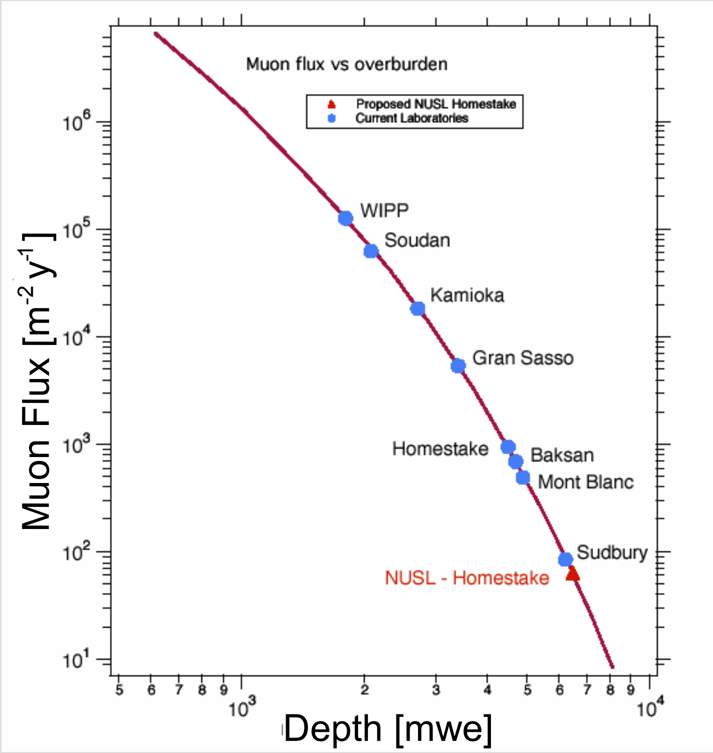
without background: $\propto (mt)^{-1}$
with background: $\propto (mt)^{-1/2}$

Background Sources

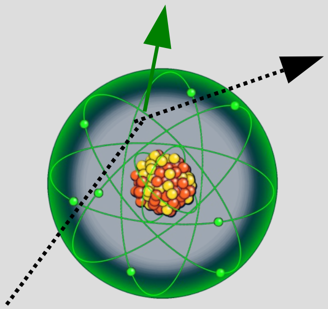
environment: U, Th chains, K

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

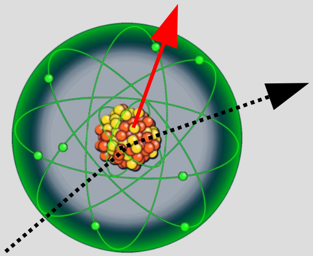
$$^{232}Th \xrightarrow[\alpha]{} {}^{228}Ra \xrightarrow[\beta]{} {}^{228m}Ac \xrightarrow[\beta]{} {}^{228}Th \xrightarrow[\alpha]{} {}^{224}Ra \xrightarrow[\alpha]{} {}^{220}Rn \xrightarrow[\alpha]{} {}^{216}Po \ldots$$



- γ and β Decays (electronic recoil)
  → „intrinsic“ bg most dangerous (Kr85, Ar39, Rn)
- neutrons from (α,n) and sf in rocks and detector parts
- neutrons from cosmic ray muons
- alphas irrelevant for noble liquids



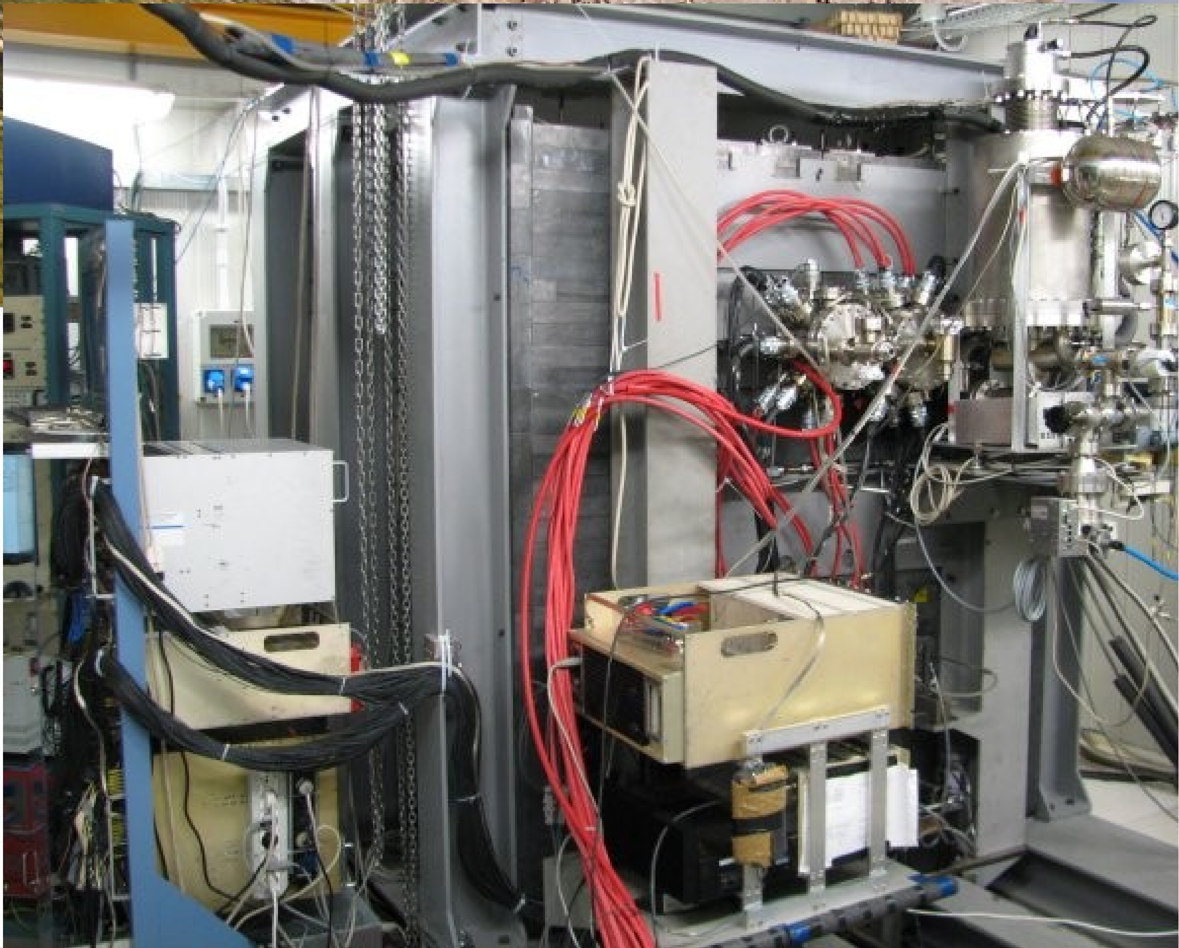
Electronic Recoils
(gamma, beta)



Nuclear Recoils
(neutron, WIMPs)

Laboratori Nazionali del Gran Sasso

Laboratori Nazionali del Gran Sasso



Background Suppression

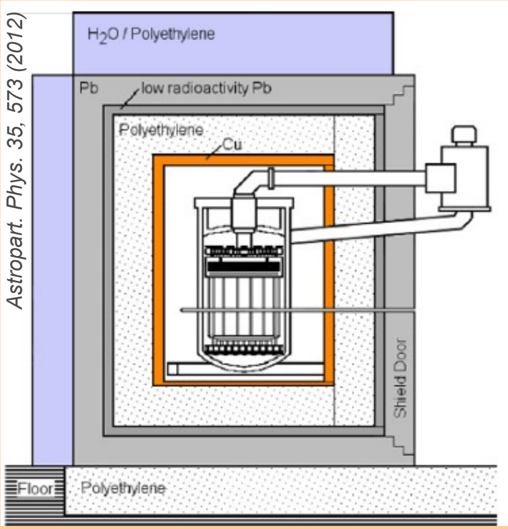
A Avoid Backgrounds

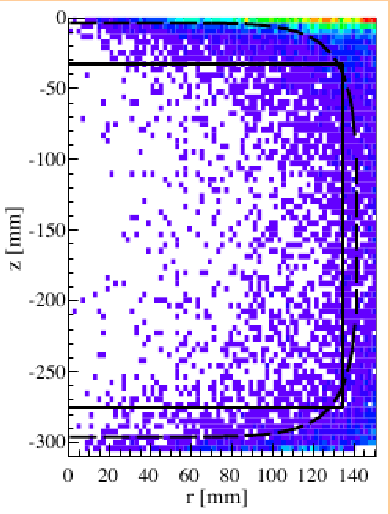
Shielding

deep underground location
large shield (Pb, water, poly)
active veto (μ, γ coincidence)

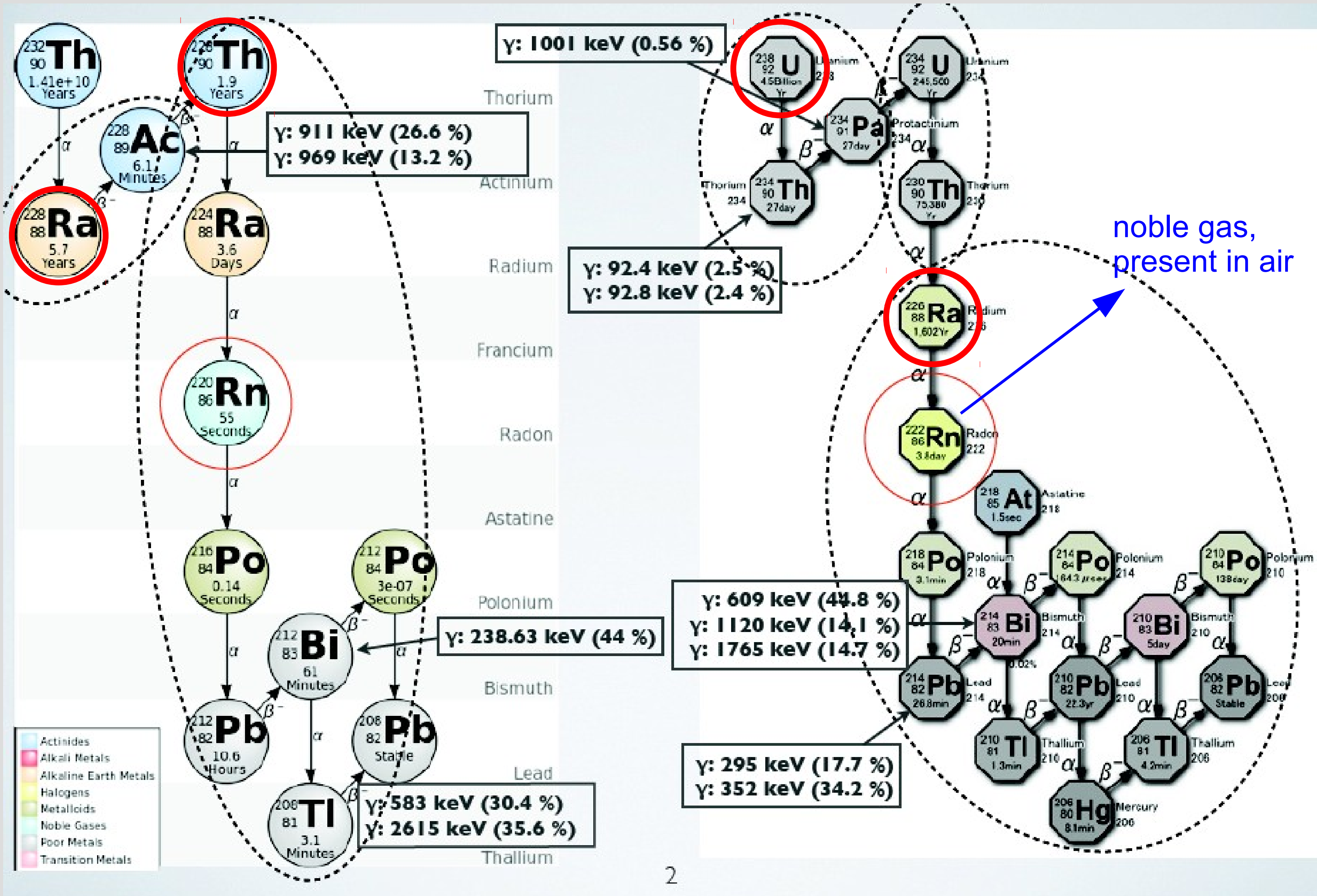
self Shielding → fiducialization

Use of radiopure materials

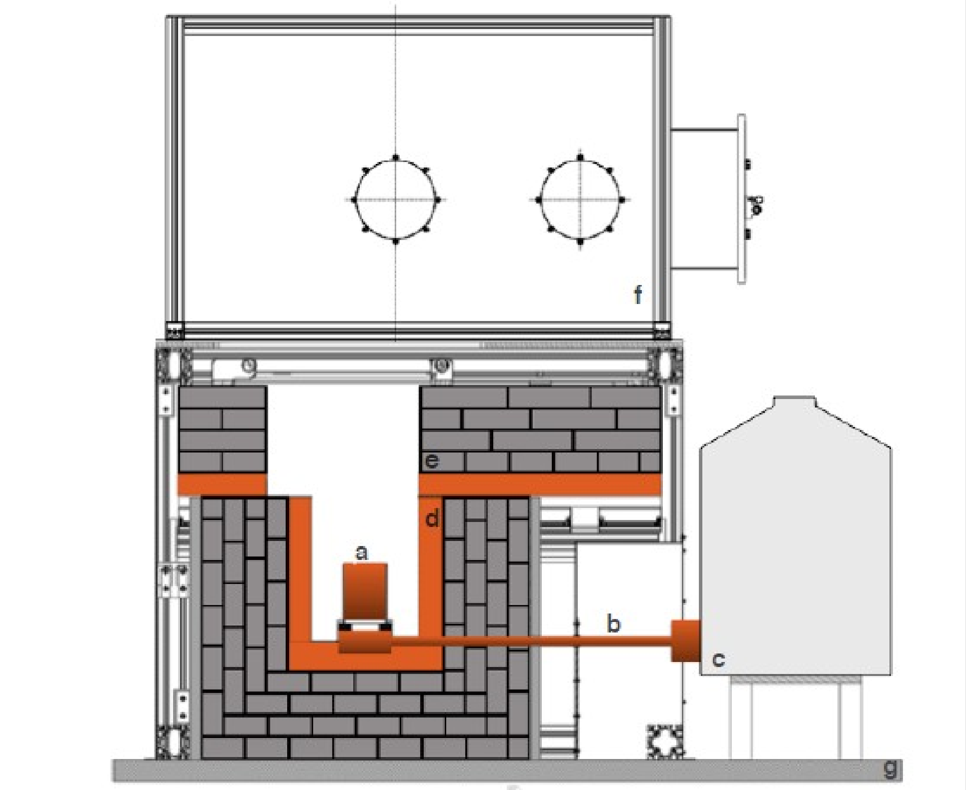


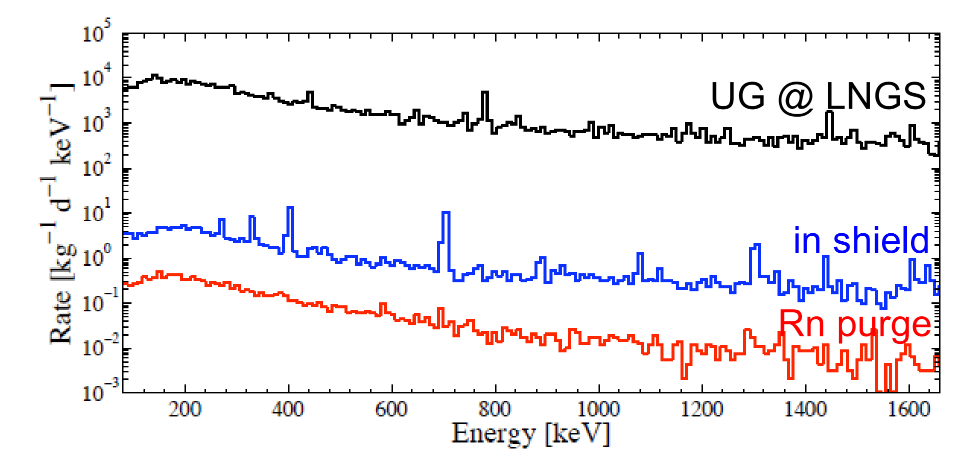


The U and Th Chains



Gamma Ray Screening



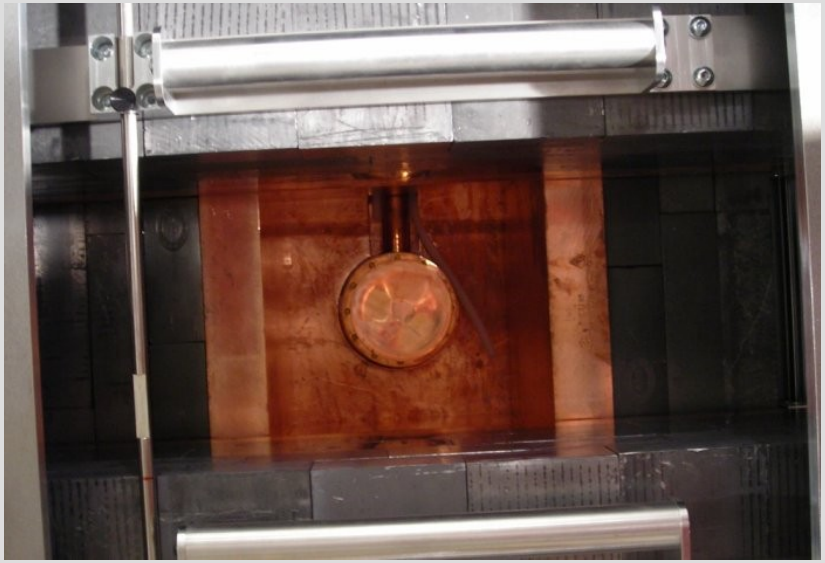


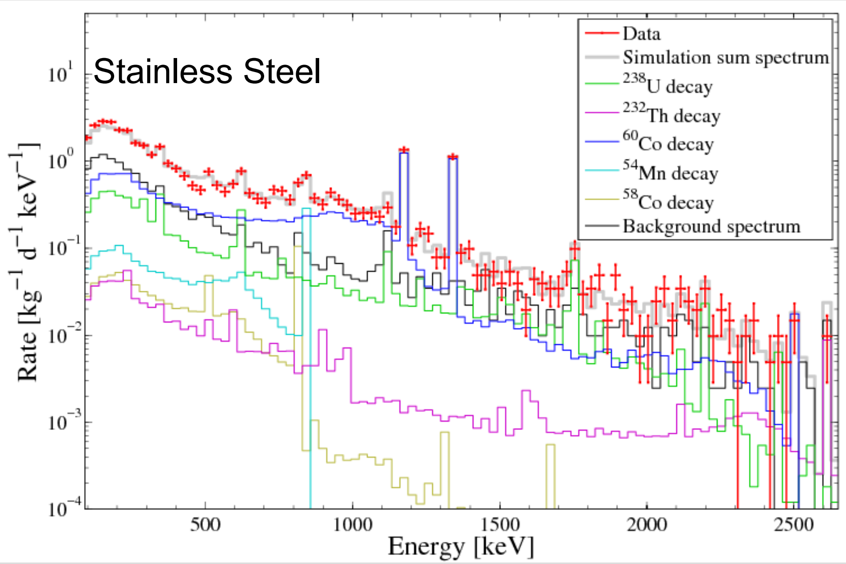
Gator 2.2kg high purity Ge detector operated by UZH @ LNGS

JINST 6, P08010 (2011)

Gamma Ray Screening

JINST 6, P08010 (2011)





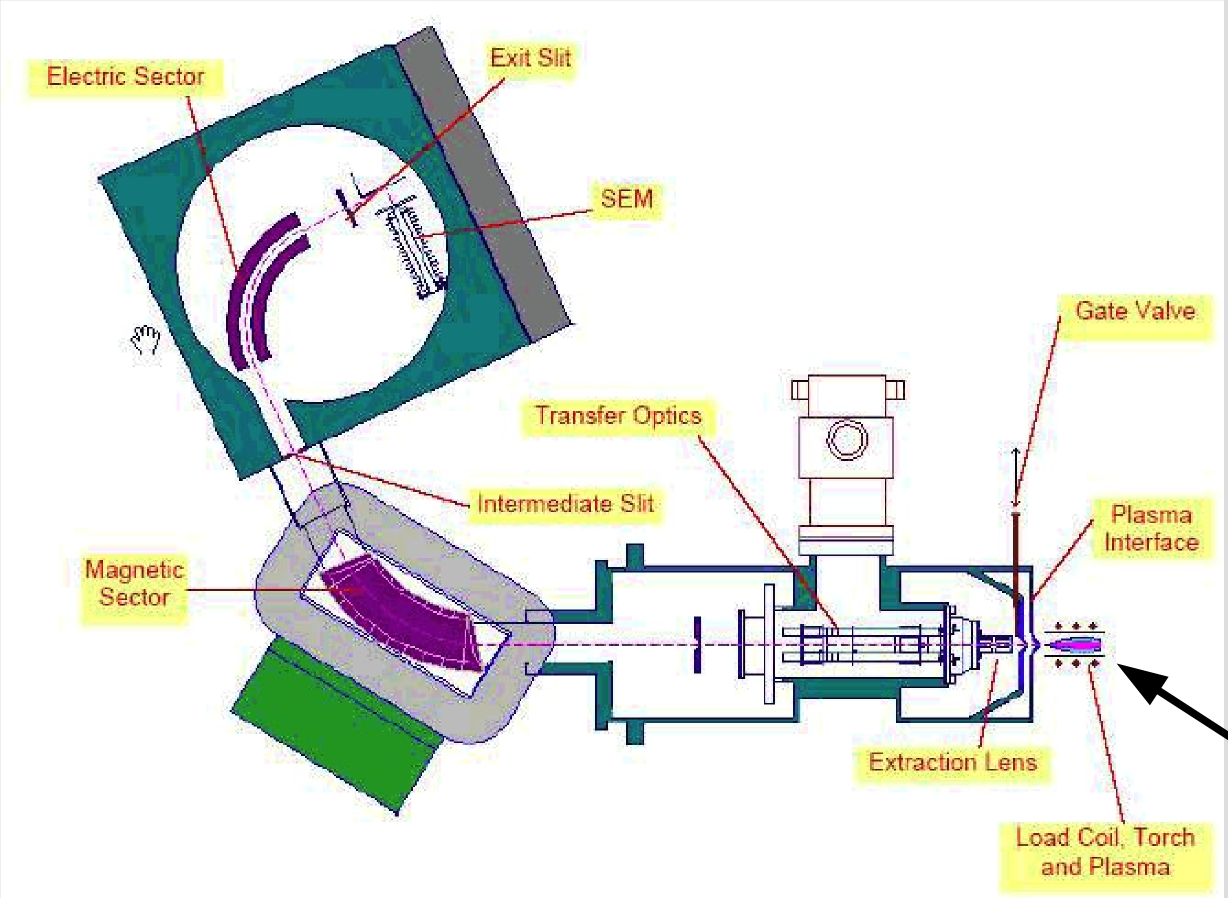
Component	Amount	Total radioactive contamination in materials [mBq/amount]				
		^{238}U / ^{226}Ra	^{232}Th	^{60}Co	^{40}K	other nuclides
Cryostat and 'diving bell' (316Ti SS)	73.61 kg	121.46	147.23	404.87	662.52	
Support bars (316Ti SS)	49.68 kg	64.58	144.07	69.55	352.73	
Detector PTFE	11.86 kg	0.71	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: *Astro. Part. Phys. 35, 43 (2011)*

use results for Monte Carlo Simulations

ICP-MS

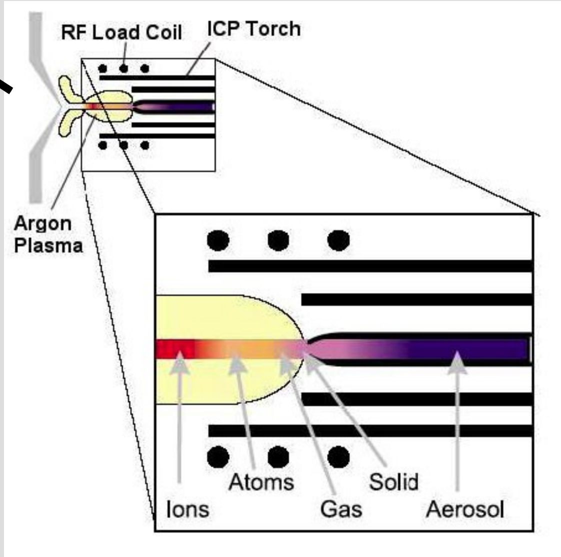
Inductively Coupled Plasma Mass Spectrometry



Produce ions in an inductively coupled plasma

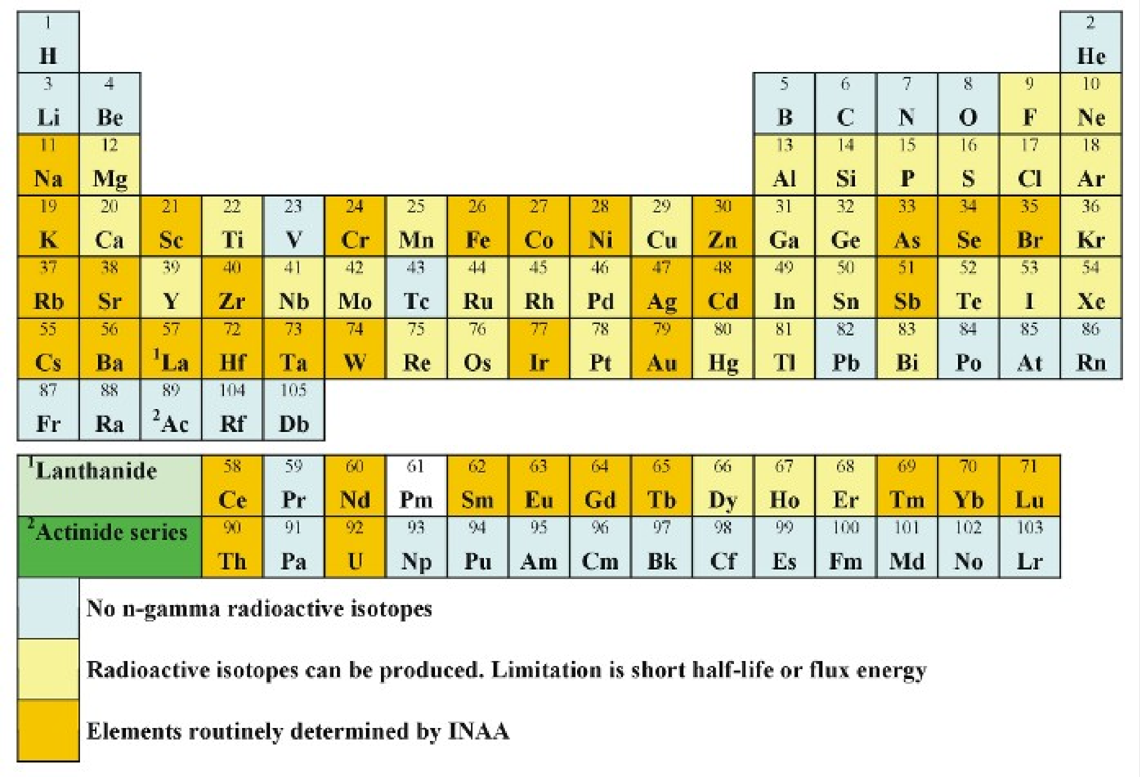
Separate and detect ions in a mass spectrometer

Sensitivity down to
0.1 mBq/kg for U and Th and
1 mBq/kg for K



XENON100's ICP-MS measurements were done at the Chemistry Lab at LNGS

Neutron Activation Analysis

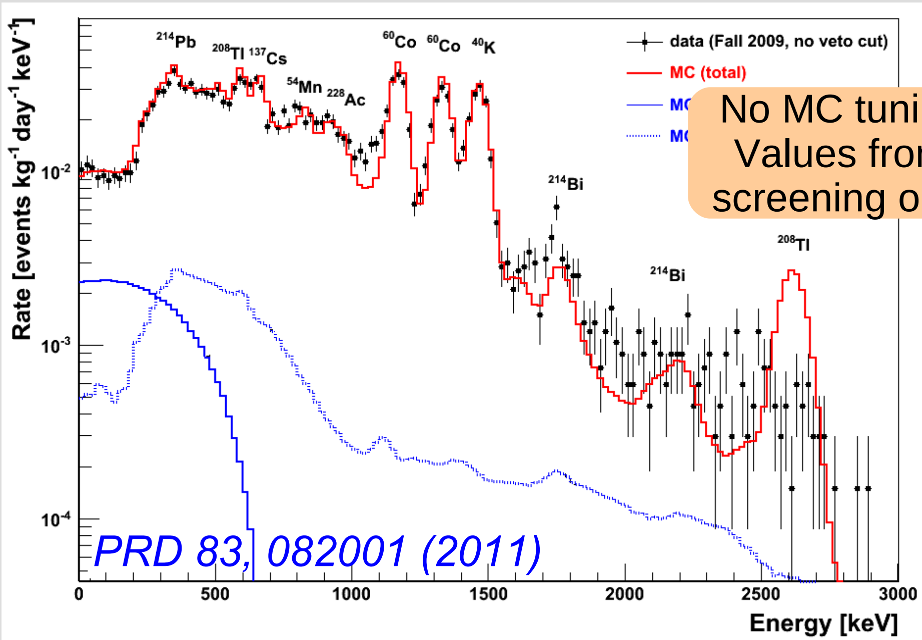


3 XENON Samples (2x Ti, PTFE) activated @ Mainz in Dec 2011

Analysis by C. Stieghorst (Mainz)

PTFE Maagtechnic				μBq/kg							
Detector	Pcs	Mass [kg]	Time	238U	226Ra	228Ra	228Th	235U	40K	60Co	137Cs
Gator	12	23.4	47.37d	<3000	<60	<160	<100	<130	<750	<30	<70
ICP-MS	1	0.0044	few h	50±10	–	200±60	–	–	590±10	–	–
NAA-Mainz	1	~0.005	few h	<670	–	<540	–	–	–	–	–

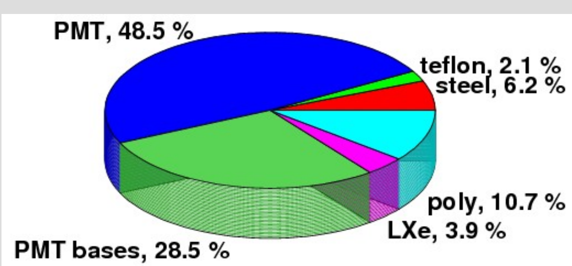
XENON100 Background



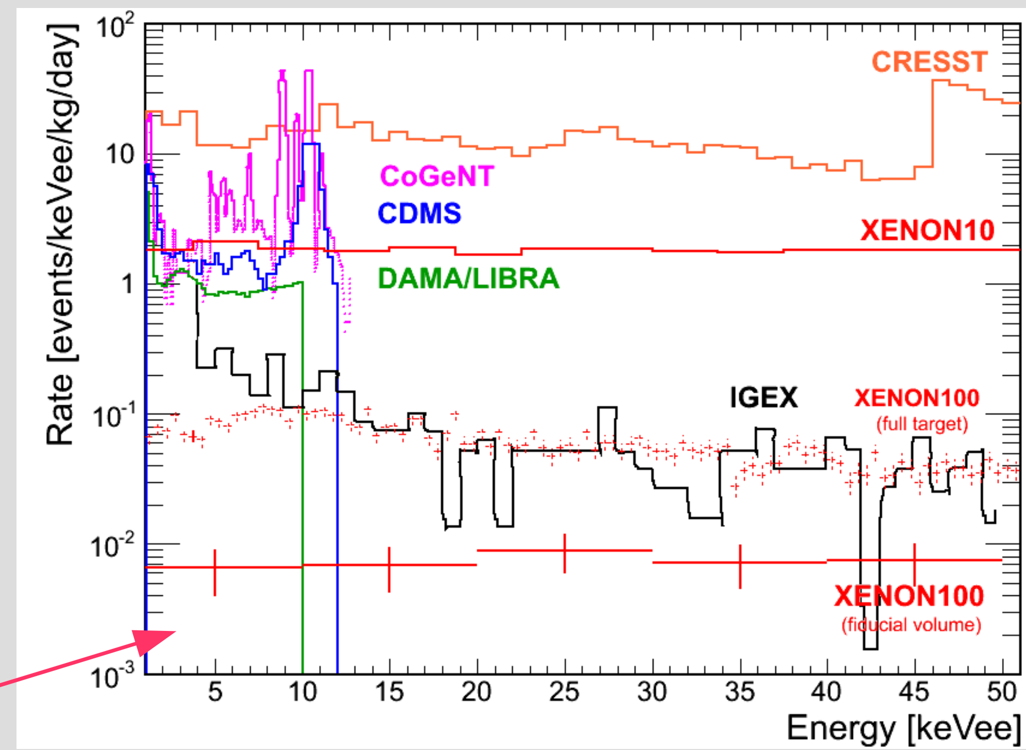
Measured Background in good agreement with MC prediction.

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

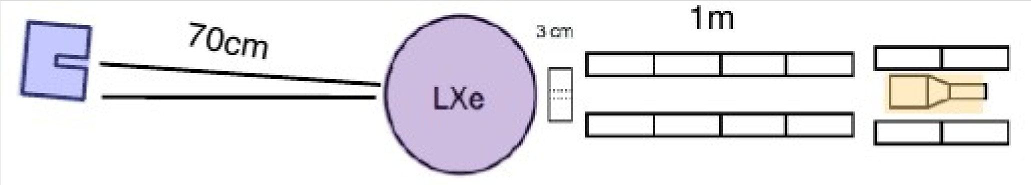
- 30 kg fiducial mass
- active LXe veto not used for this plot
- exploit anti-correlation between light and charge for better ER-energy scale

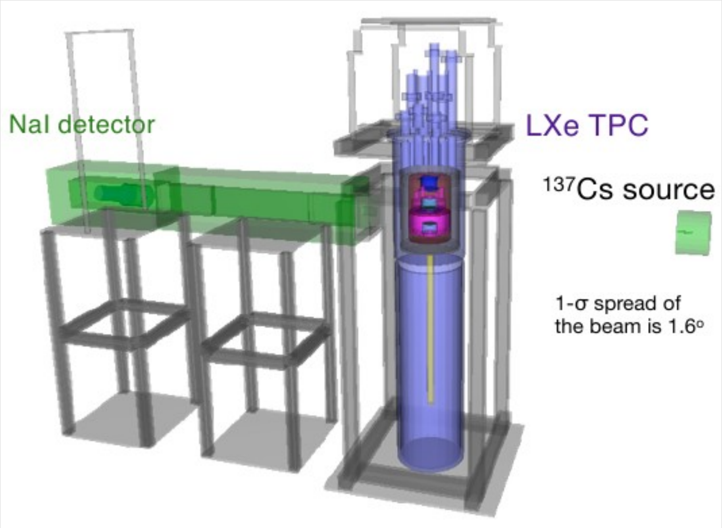


Xenon keVee-Scale not precisely known below 9 keVee

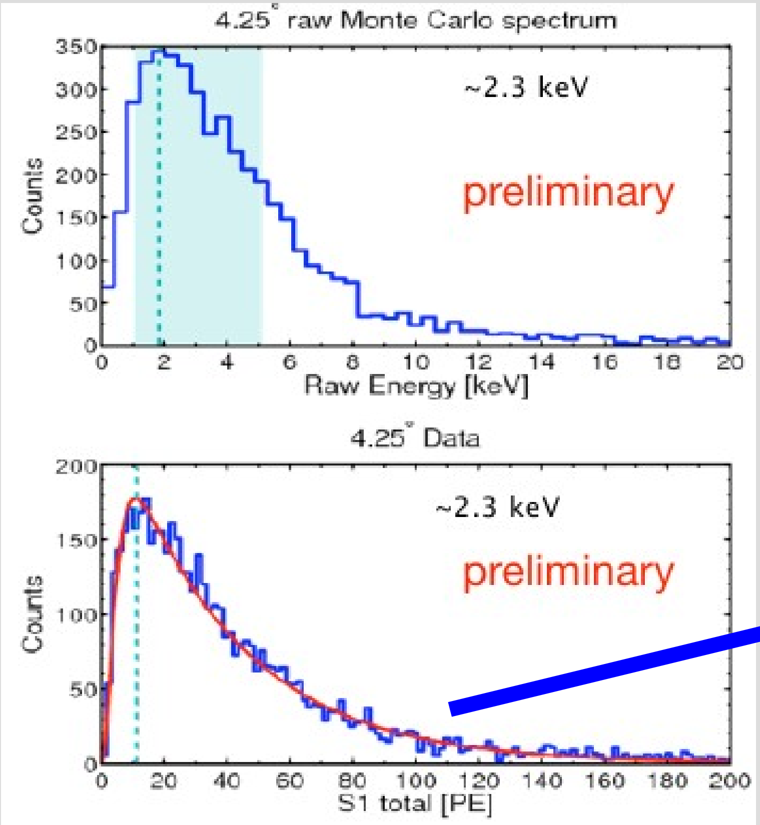


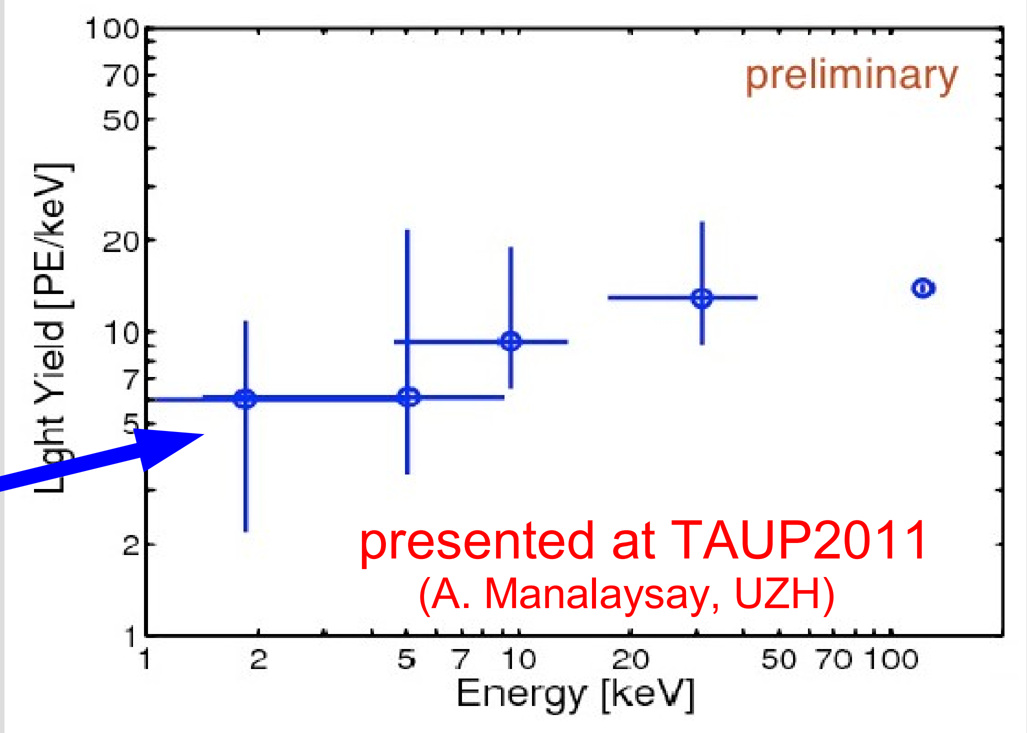
Low Energy Response to ER





Compton Scatter Measurement in Zürich indicates that LXe „sees“ electronic recoil interactions around ~2.3 keV (at zero-field)





Background Suppression

XENON Dark Matter Project

A Avoid Backgrounds

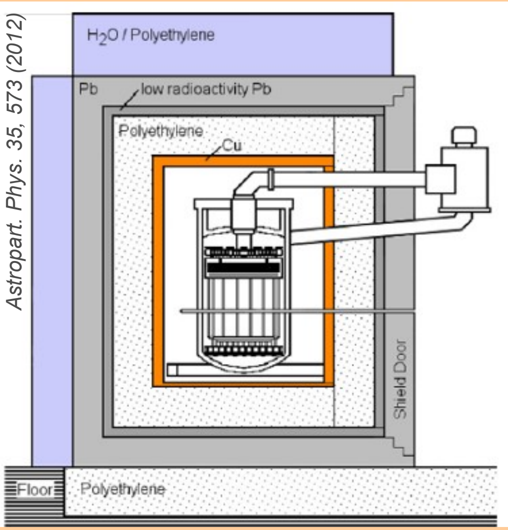
Shielding

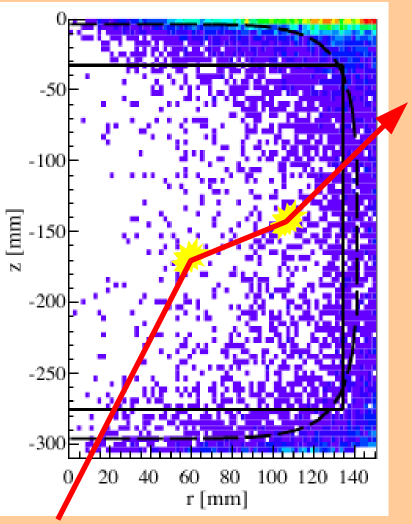
- deep underground location
- large shield (Pb, water, poly)
- active veto (µ, γ coincidence)

- self Shielding → fiducialization

Use of radiopure materials

Astropart. Phys. 35, 573 (2012)





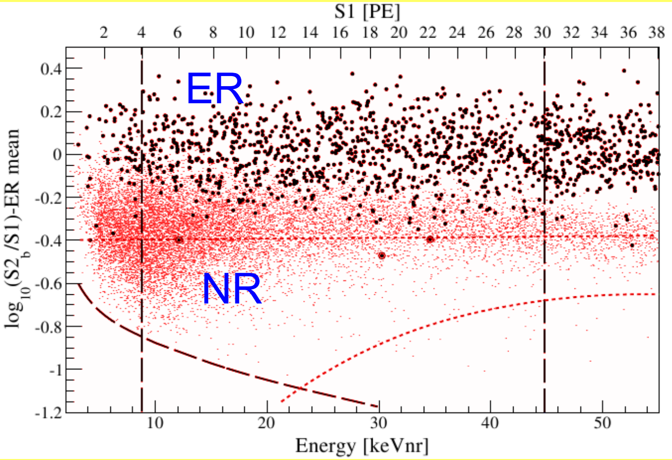
B Use knowledge about expected WIMP signal

WIMPs interact only once

- → single scatter selection
- require some position resolution

WIMPs interact with target nuclei

- → nuclear recoils
- exploit different dE/dx from signal and background



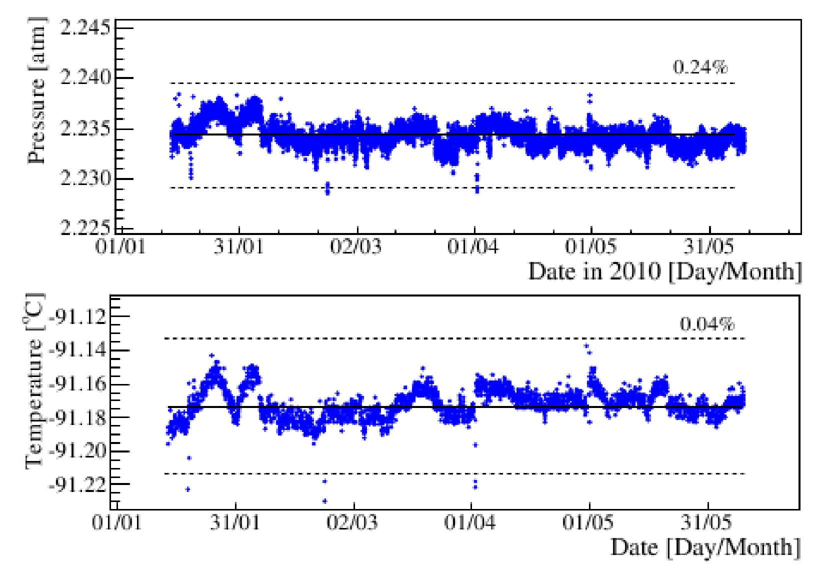
PRL 107, 131302 (2011)

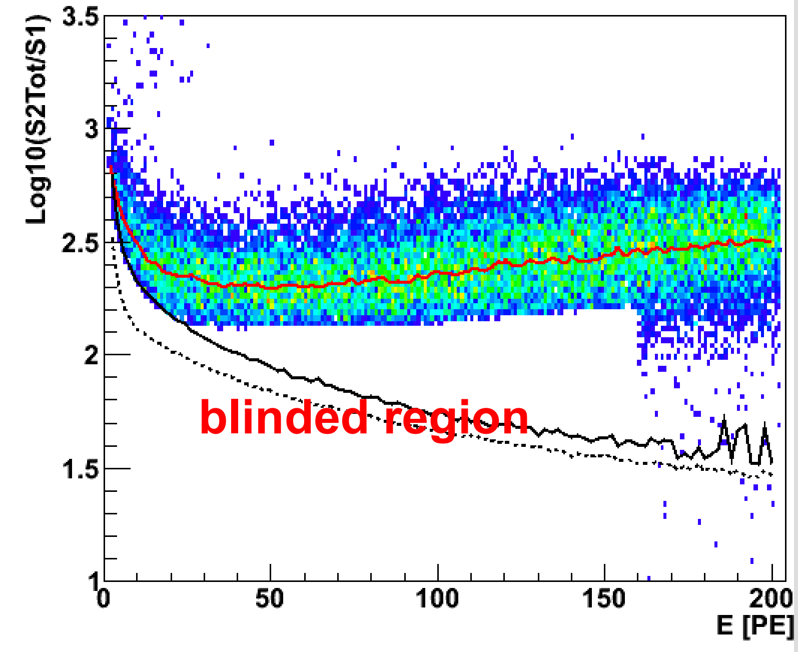
Outline

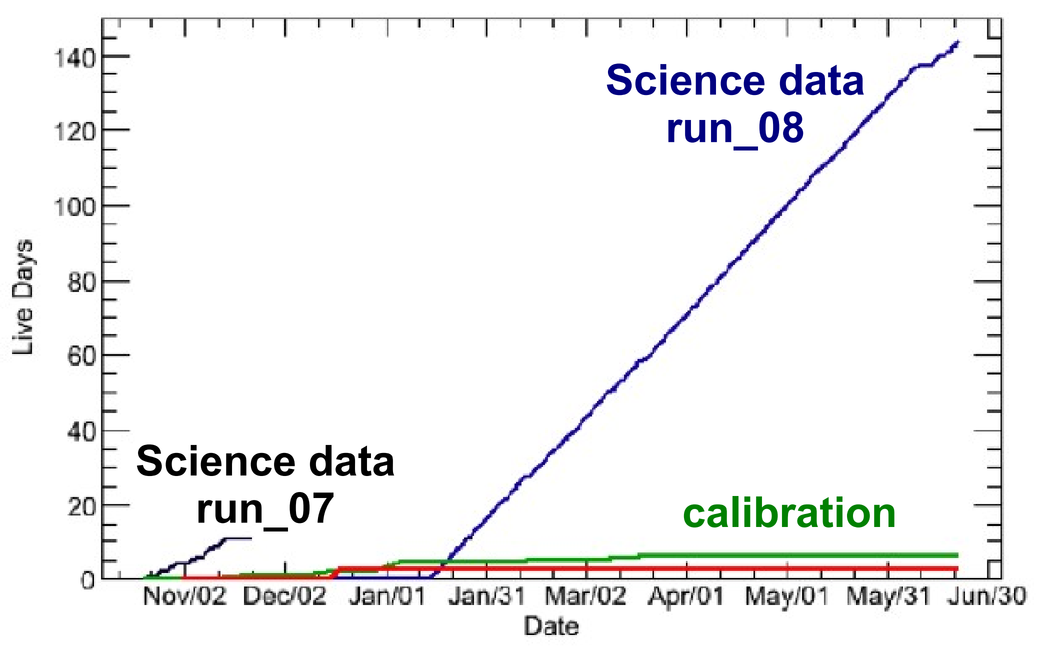
- Motivation: Dark Matter ✓
- Direct WIMP Search ✓
- XENON100 ✓
- **The latest Results**
- The Future

The new XENON100 Data

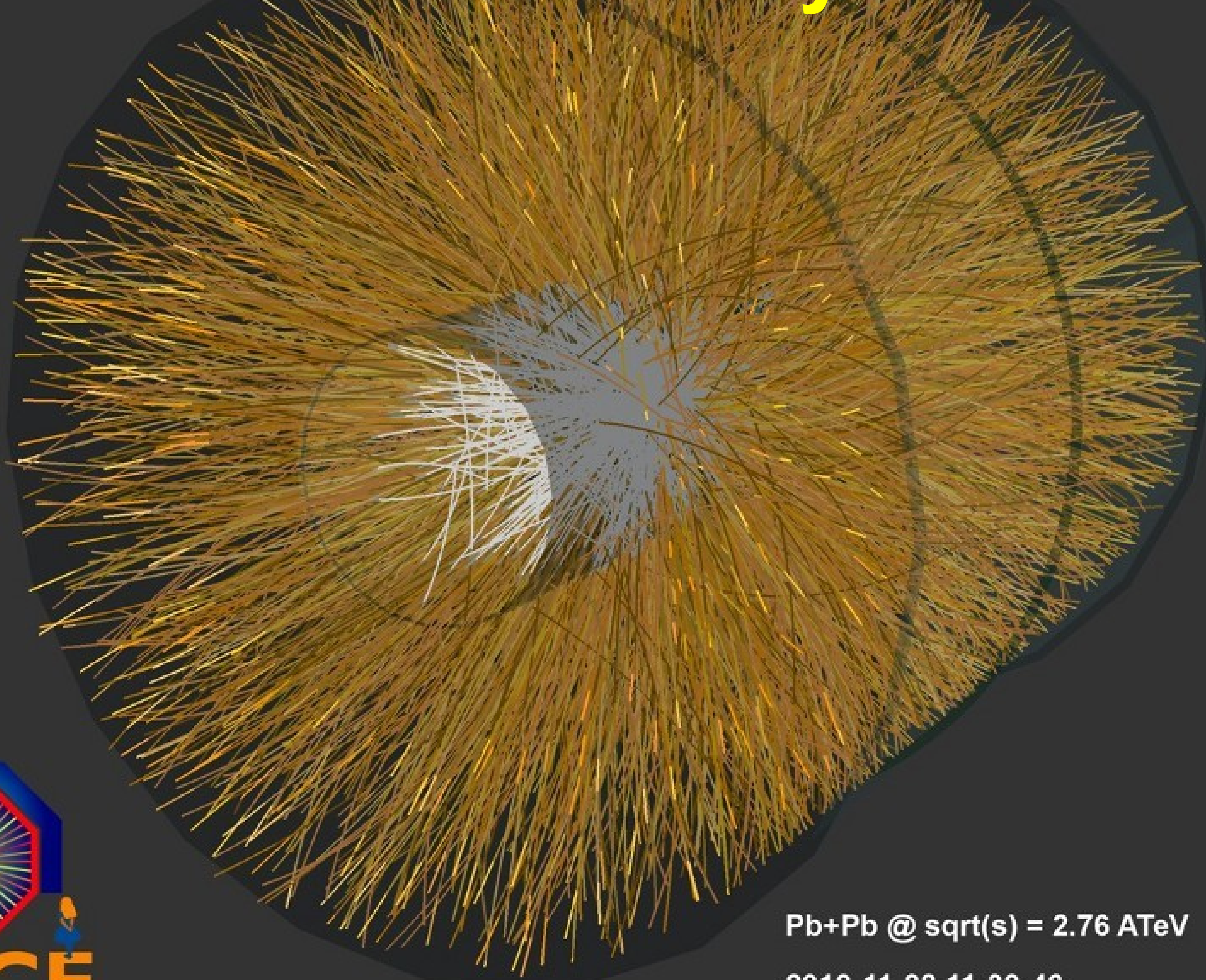
- data taken in first half of 2010
- 100.9 life days
- data blinded in ROI
- analysis and results in:
  PRL 107, 131302 (2011)







Find a needle in a haystack!



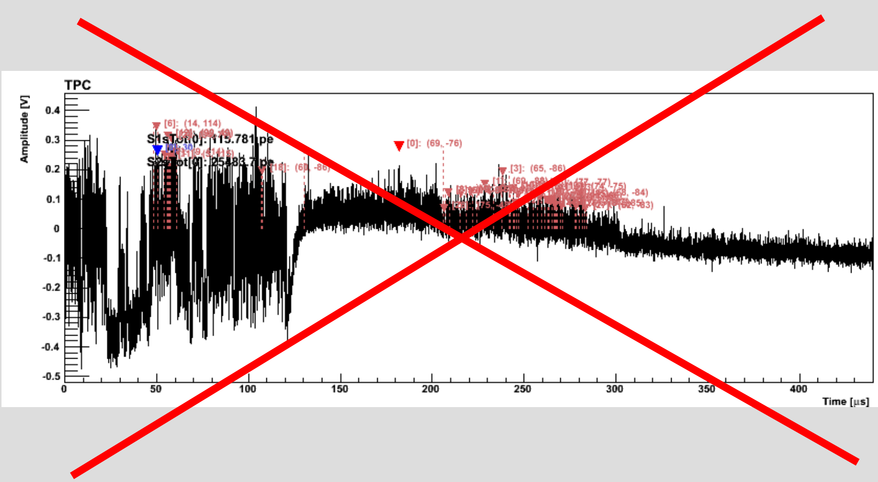
Pb+Pb @ sqrt(s) = 2.76 ATeV

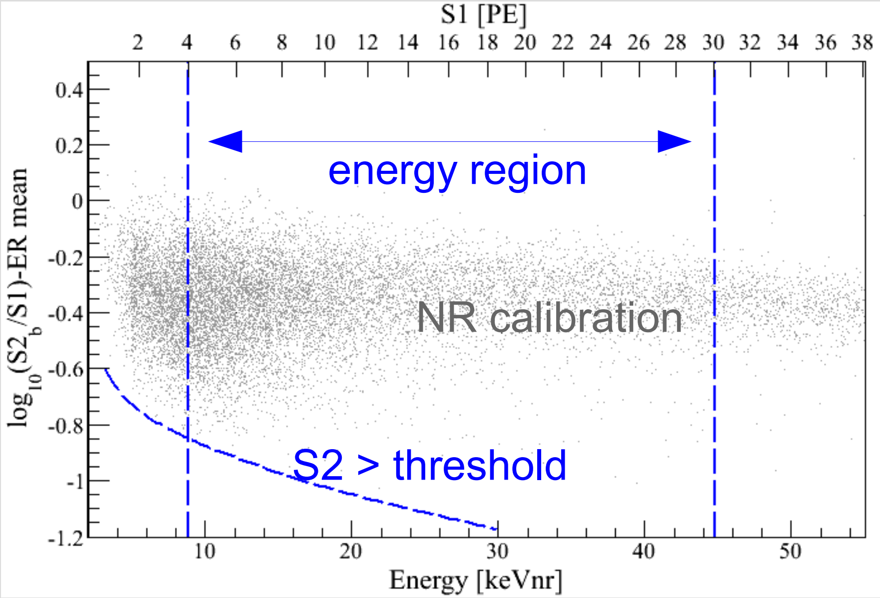
2010-11-08 11:30:46

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)





Data Analysis

Basic Data Quality Cuts
- reject non useable waveforms (muons, micro-discharges, …)
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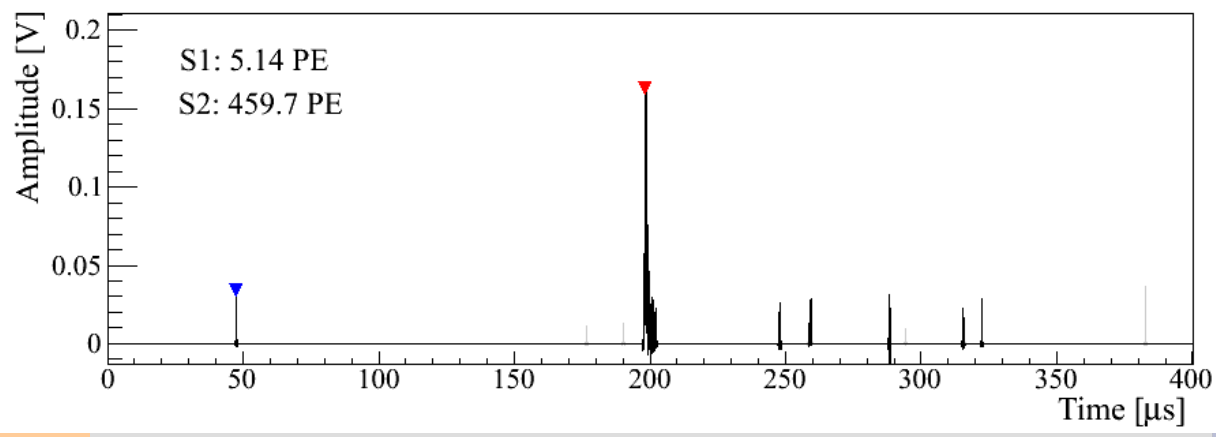
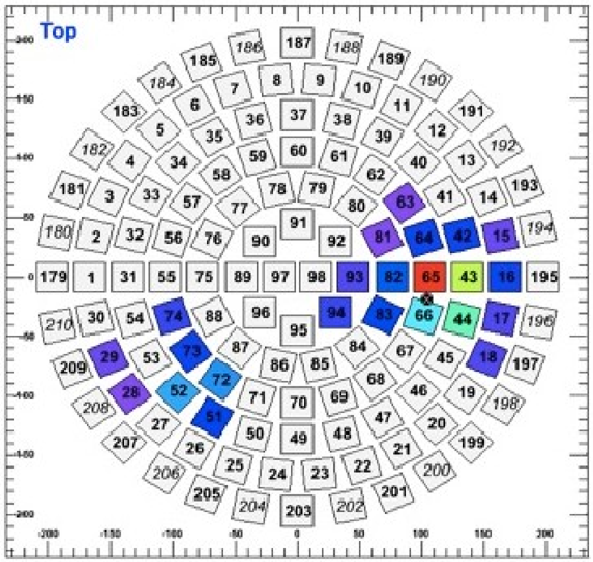
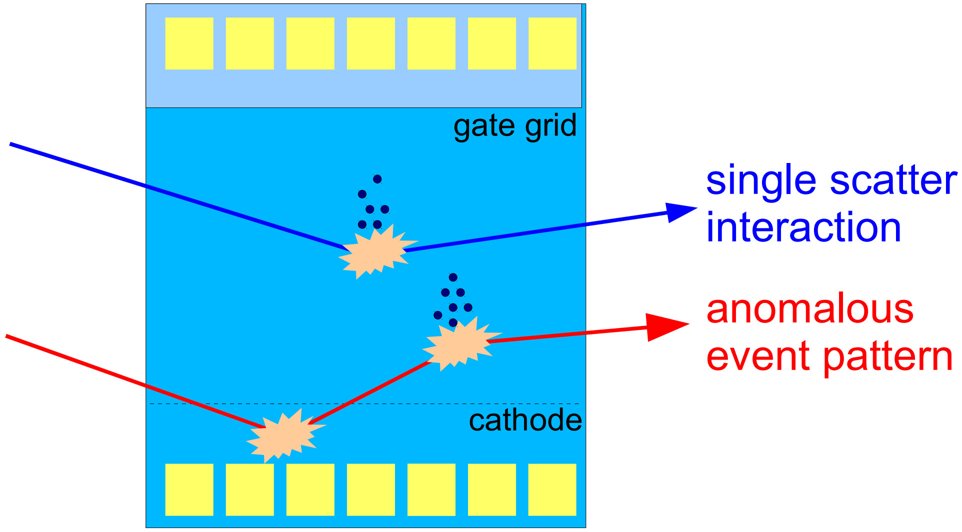
Energy Cuts
- low E region (S1)
- S2 software threshold
- require 2x S1 coincidence (against PMT dark current, noise)

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







Energy Cuts

- low E region (S1)
- S2 software threshold
- 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

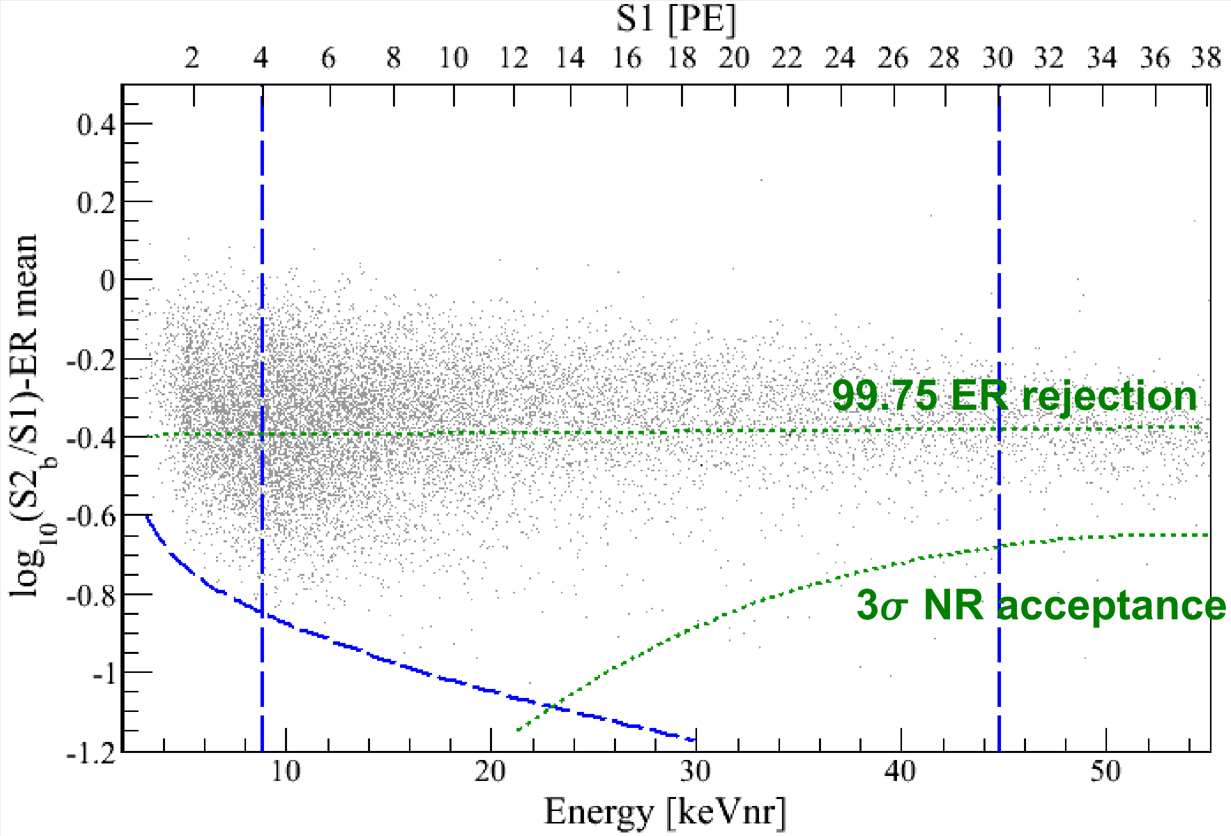
- 48 kg fiducial mass
- 100.9 live days
- 99.75% ER rejection

Gaussian Leakage:
1.14 ± 0.48

Anomalous Leakage:
0 .56 ± 0.25

Neutron Background:
0.11 ± 0.08

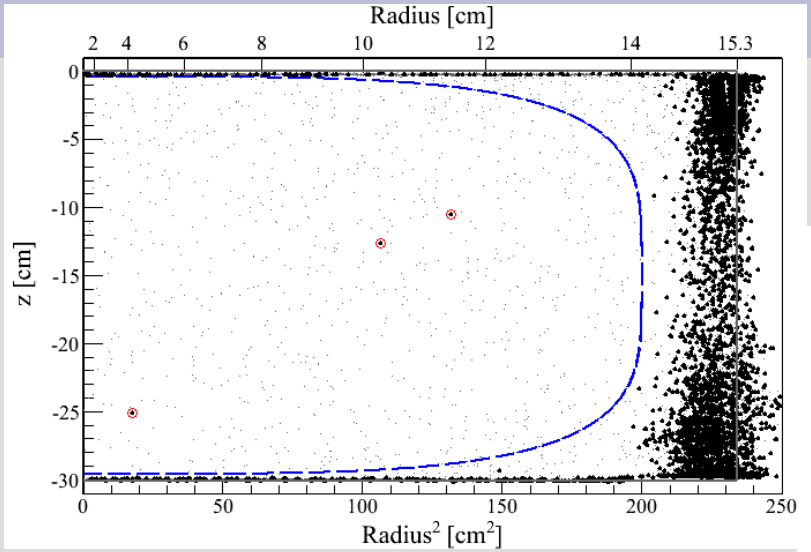
1.8 ± 0.6 events

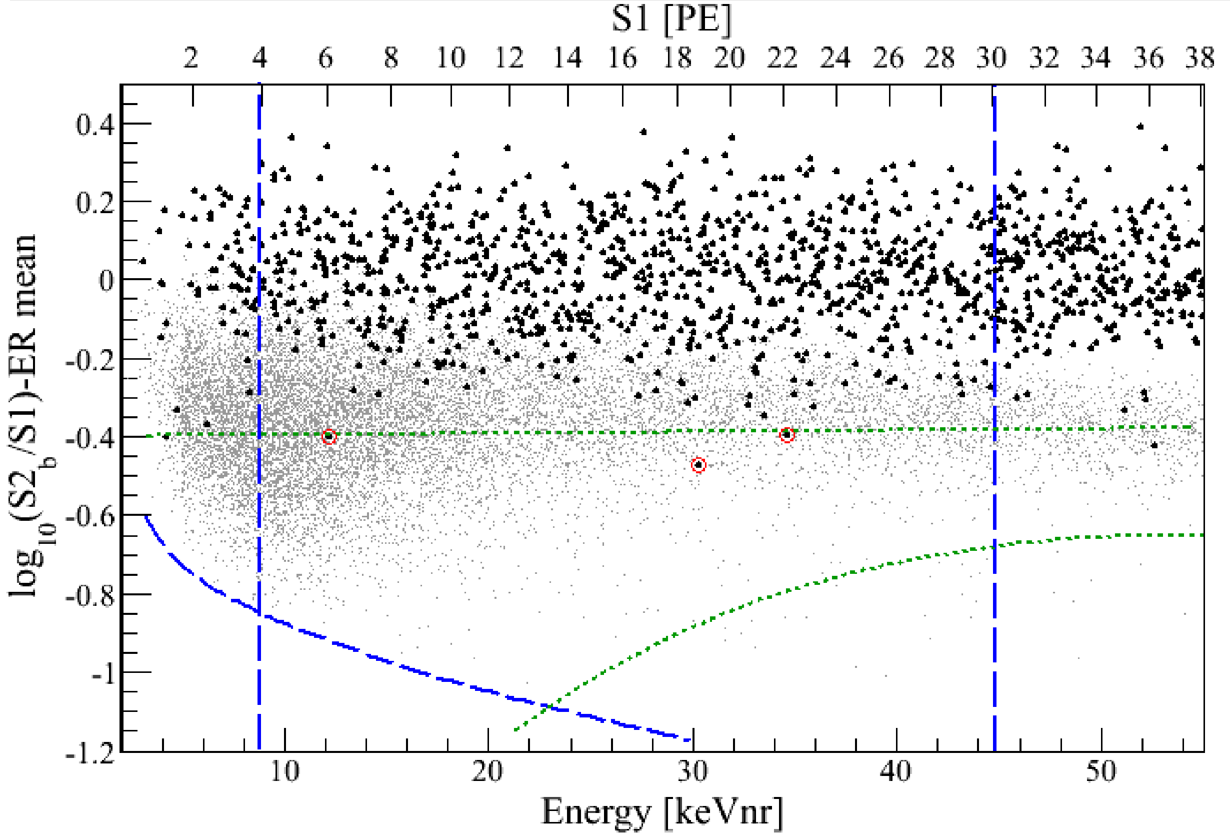


➡ prediction based on data and MC

➡ prediction verified on high *E* sideband

Result





Gaussian Leakage:
1.14 ± 0.48

Anomalous Leakage:
0.56 ± 0.25

Neutron Background:
0.11 ± 0.08

1.8 ± 0.6 events

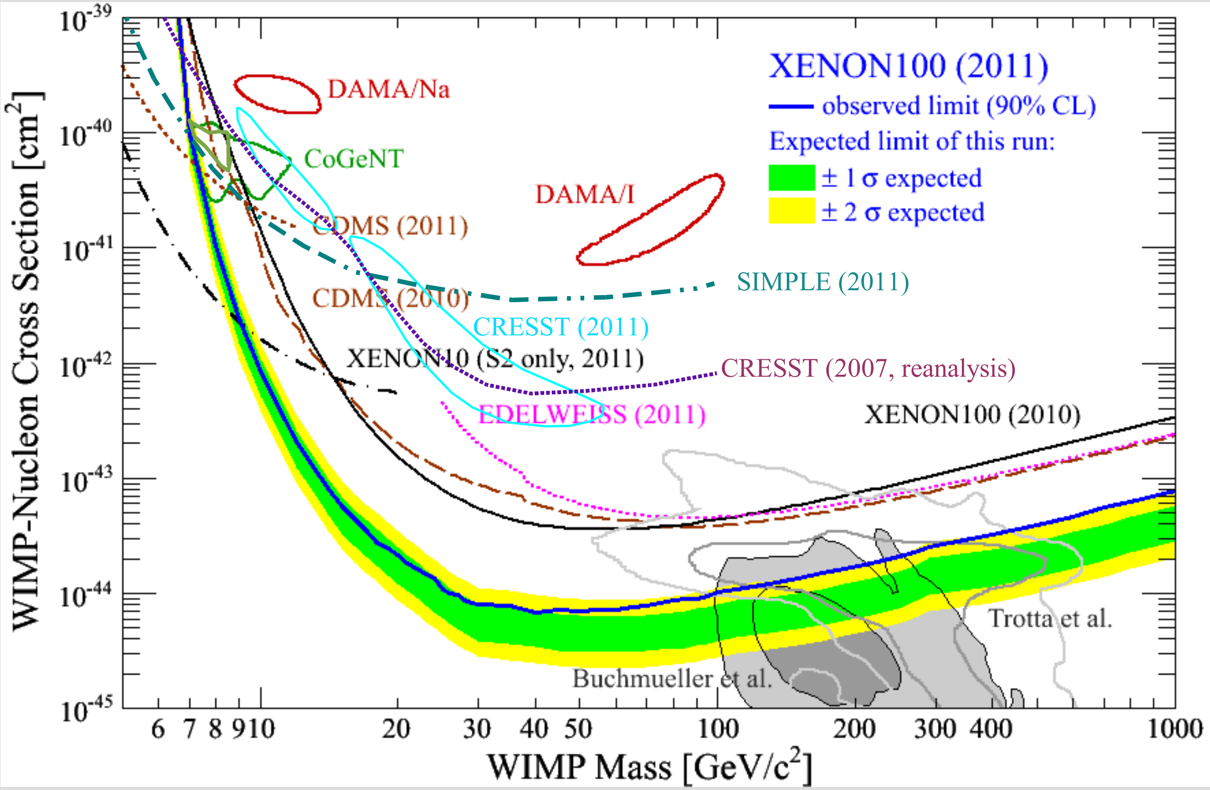
Observe 3 events

➡ likelihood for 3 or more events is 28%

➡ Profile Likelihood analysis does not yield significant signal ➡ calculate limit

(spin-independent) WIMP Limit

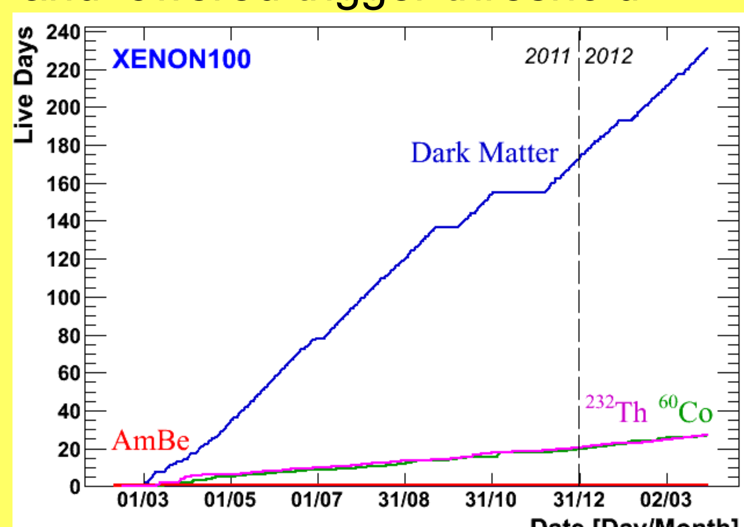
XENON Dark Matter Project



PRL 107, 131302 (2011)

Limit derived with
Profile Likelihood method
PRD 84, 052003 (2011)

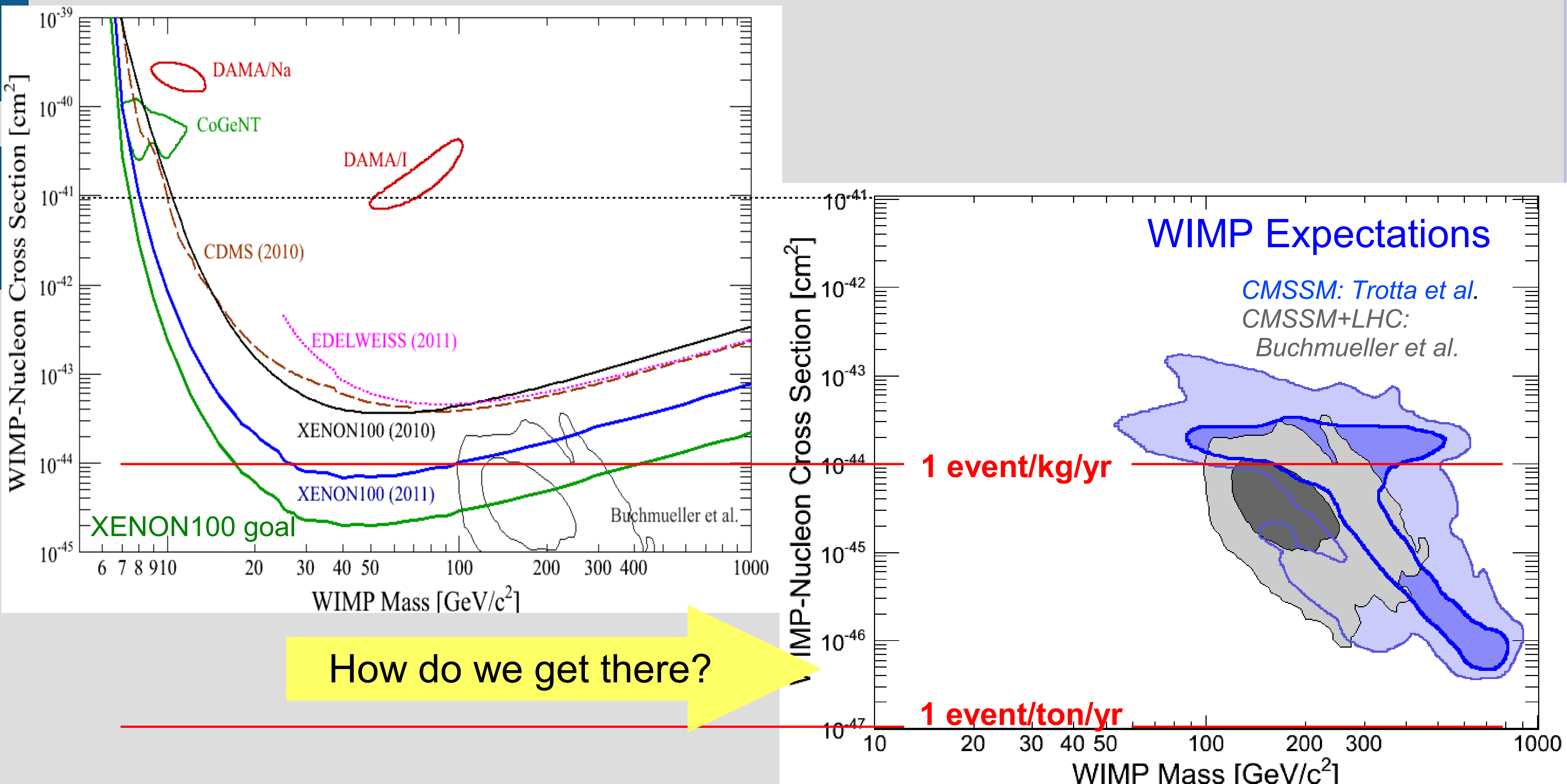
Detector is operational
with lower background level
and lowered trigger threshold



XENON100 sets the most sensitive
limit over a large WIMP mass range

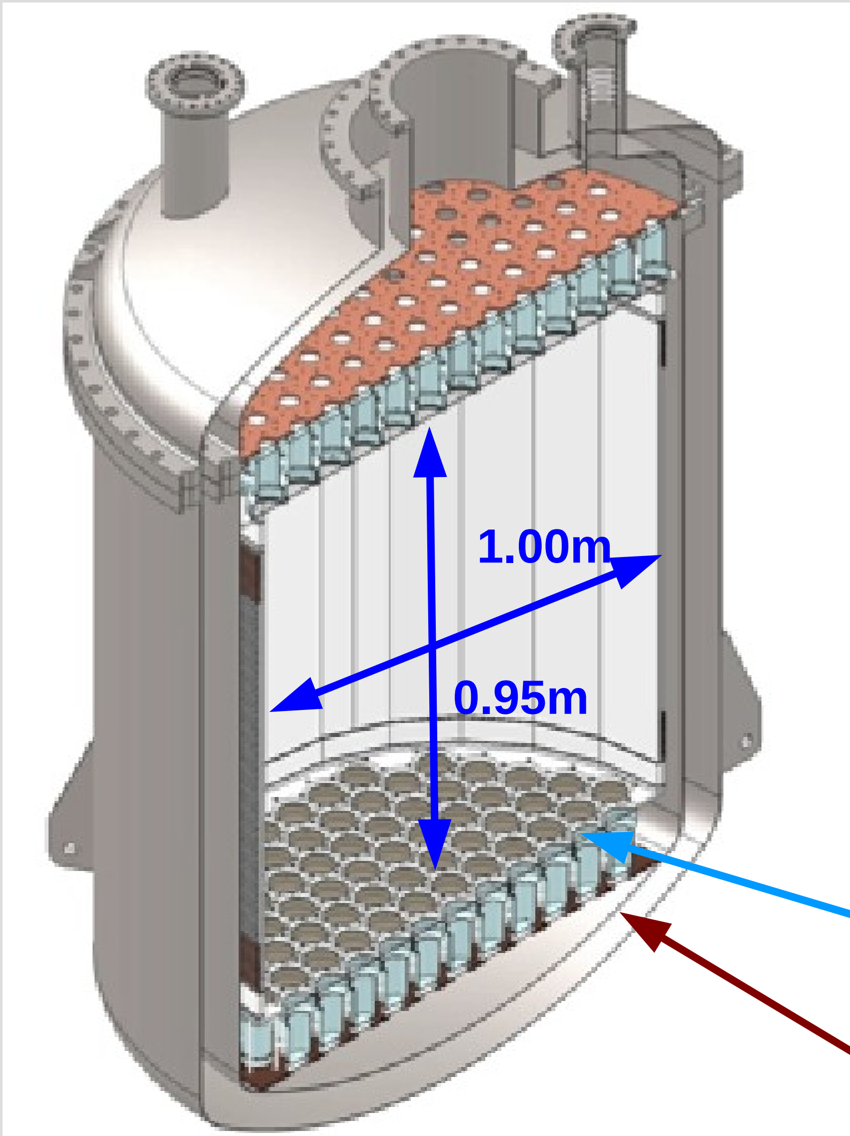
Challenges the CoGeNT, DAMA, CRESST-II
signals as being due to light mass WIMPs

XENON100: Sensitivity



The next step: XENON1T

1.9m

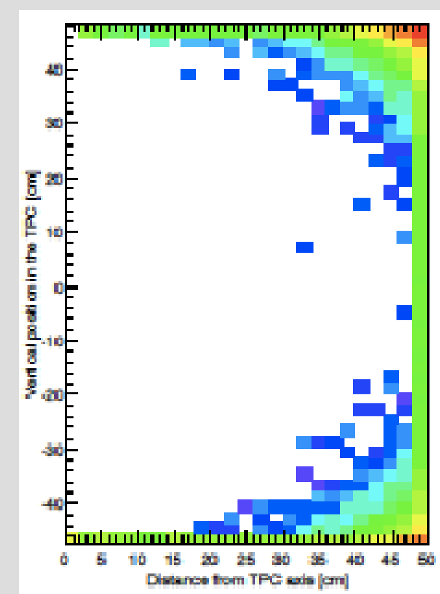


1.3m

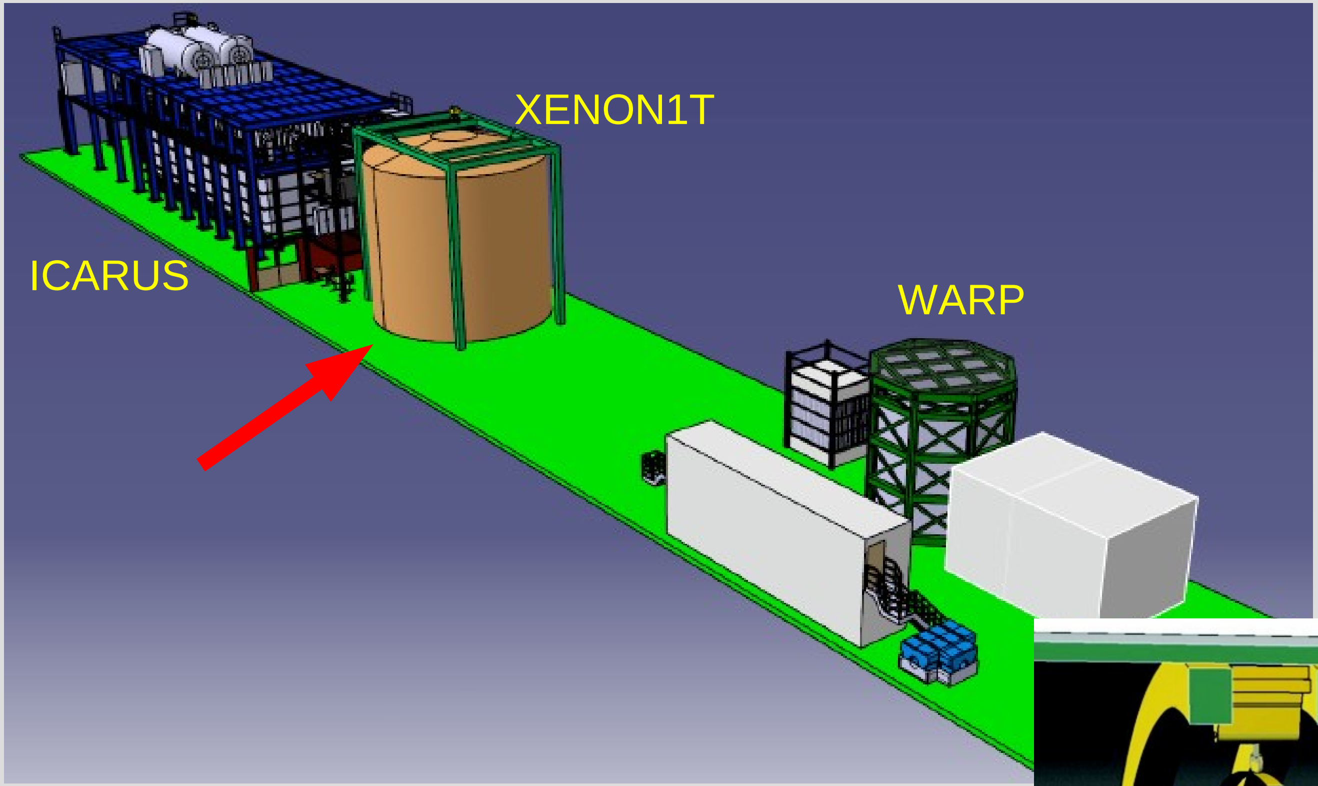
- 2.6t LXe ("1m³ detector")
  1t fiducial mass
- 100x lower background
  (10 cm self shielding,
  low radioactivity components)
- Timeline: 2010 – 2015
- start construction in 2012

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

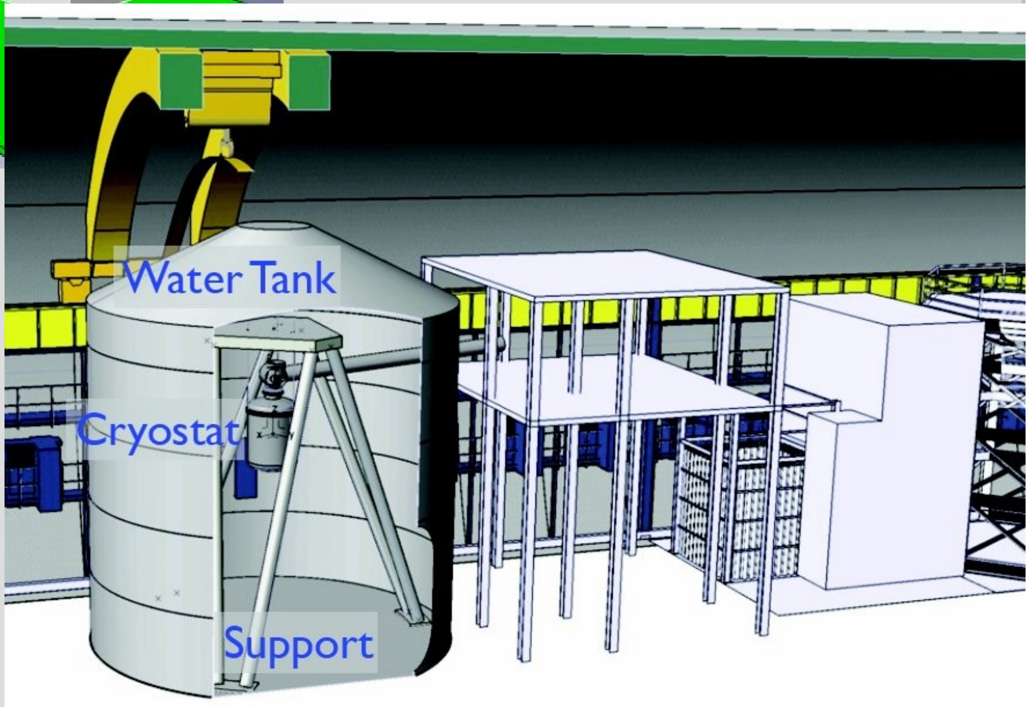
Ti Cryostat
(or low rad. stainless steel)



XENON1T @ LNGS

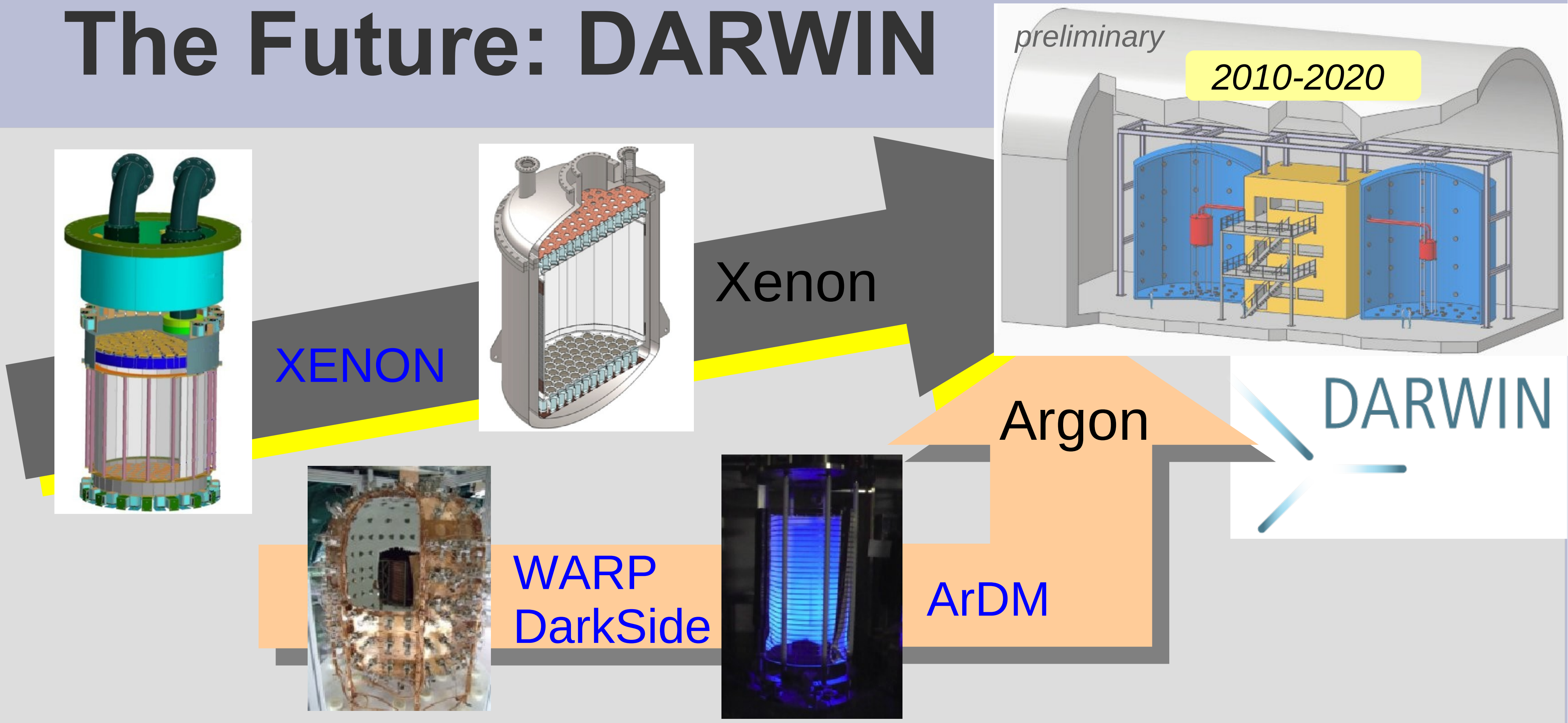


XENON1T
@ LNGS (Hall B)
➞ 4.8 m water shield
acting as active muon veto



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

The Future: DARWIN

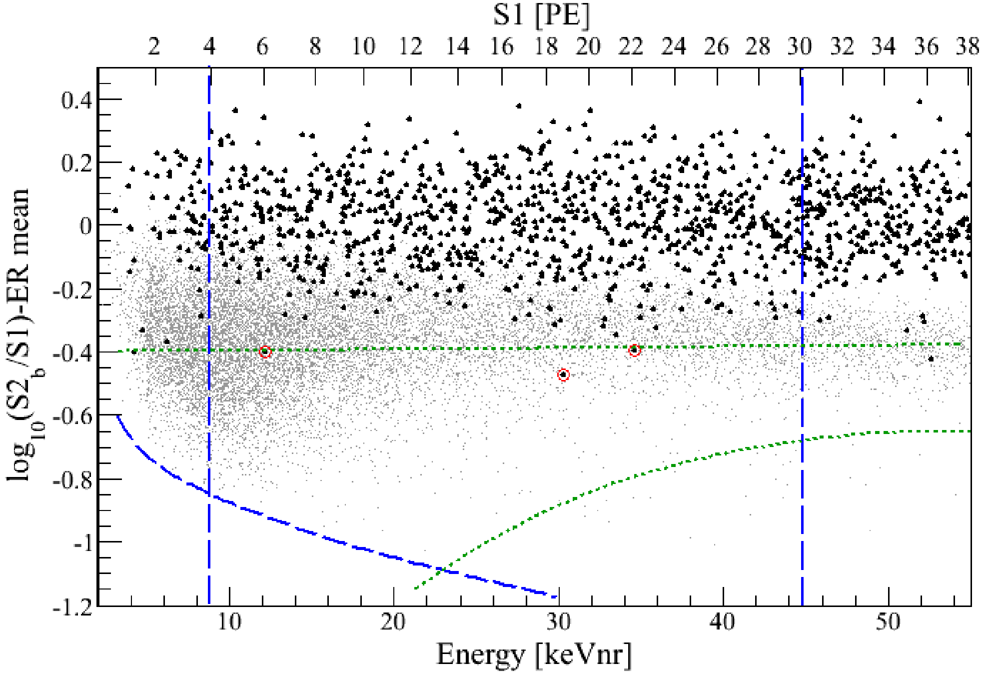


DARWIN – Dark Matter WIMP Search with Noble Liquids

- *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 using one or both targets
- Physics goal: $\sigma < 10^{-47}$ cm²

http://darwin.physik.uzh.ch

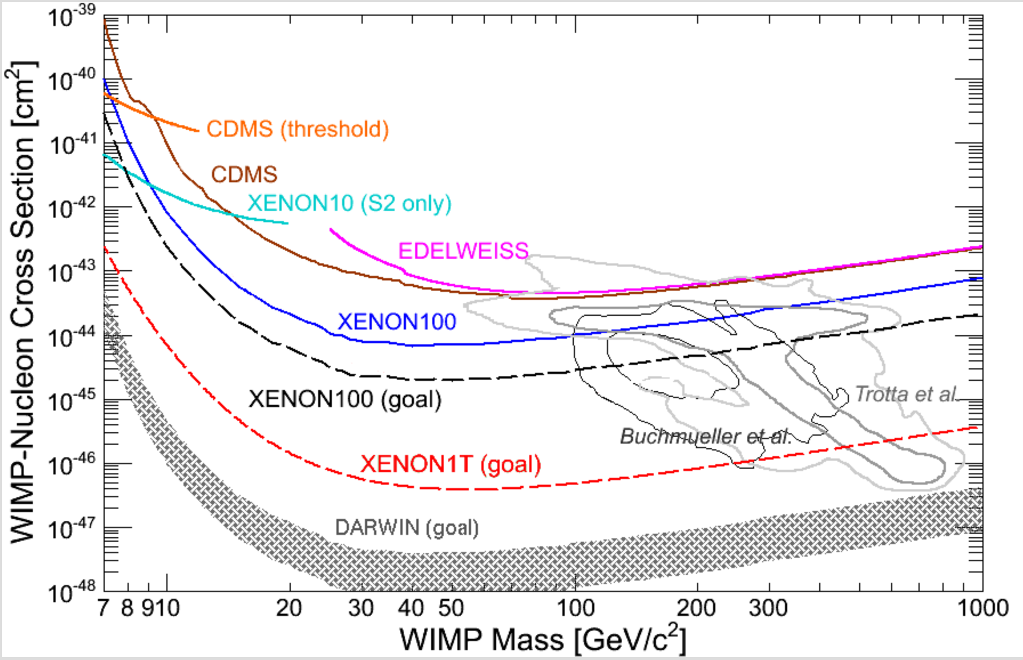
Summary



- Dark Matter: One of the big unsolved puzzles
- **XENON100**
  62 kg dual-phase LXe TPC
- extremely low background
- latest results from 100d data:
  PRL 107, 131302 (2011)

Two new projects upcoming:

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



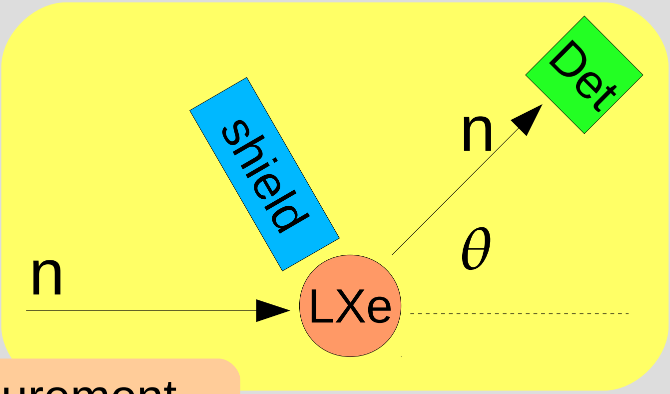
Backup

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 $\mathcal{L}_{eff}$:

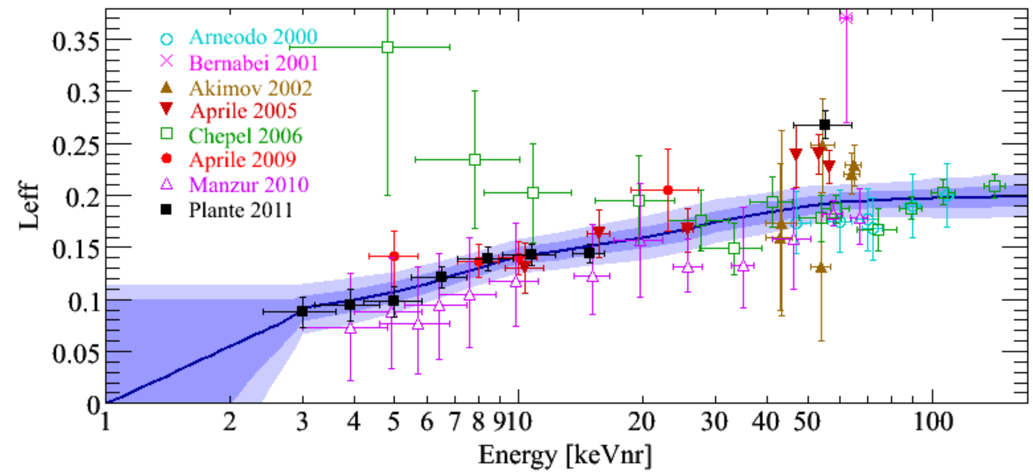
$$\mathcal{L}_{\rm eff}(E_{\rm nr}) = \frac{\mathrm{LY}(E_{\rm nr})}{\mathrm{LY}(E_{\rm ee} = 122\ \mathrm{keV})}$$

measurement principle:



New measurement
in preparation in Zürich

average over all direct measurements

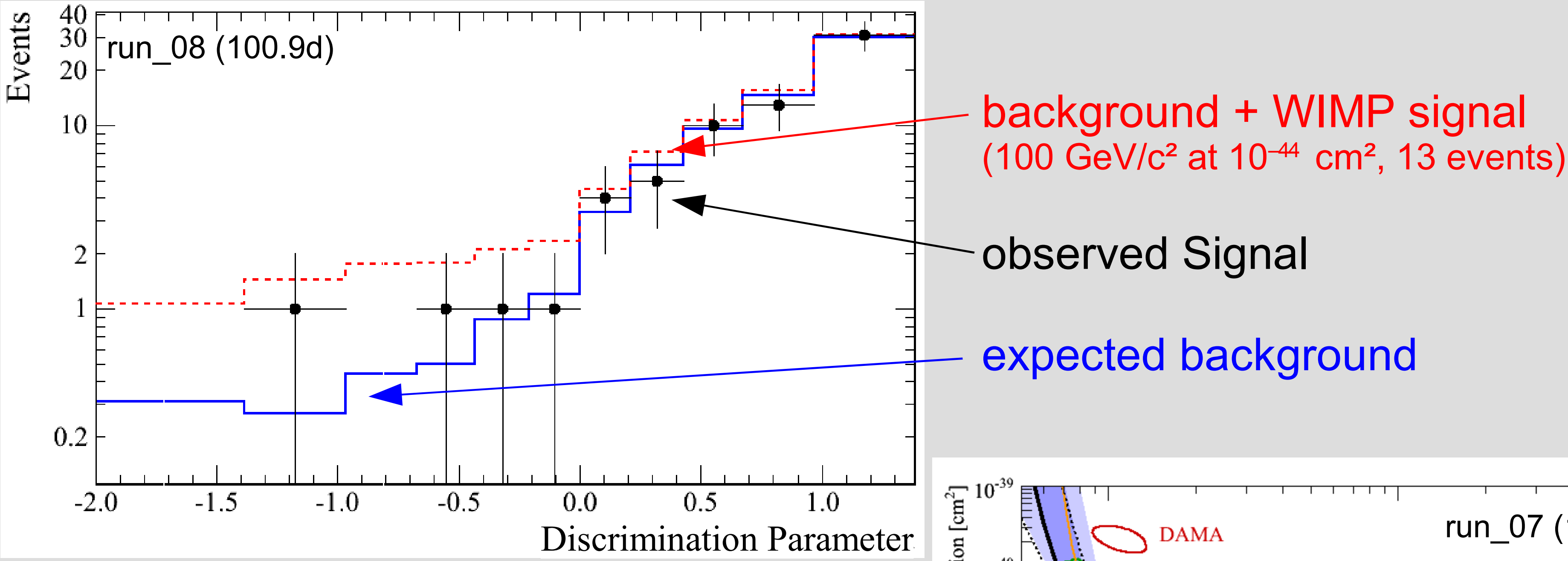


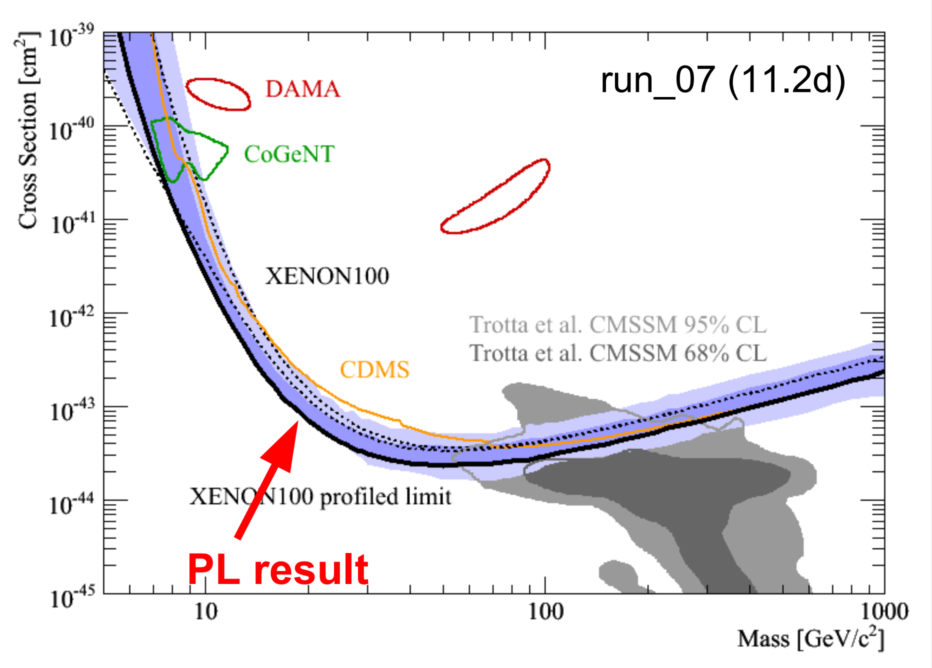
most recent measurements:
■ *Plante et al., PRC 84, 045805 (2011)*
△ *Manzur et al., PRC 81, 025808 (2010)*

for discussion of possible systematic errors see
A. Manalaysay, arXiv:1007.3746

Profile Likelihood Method

PRD 84, 052003 (2011)





need good understanding of background („background model")

➡ but this is required by any low background experiment (regardless of the type of analysis)