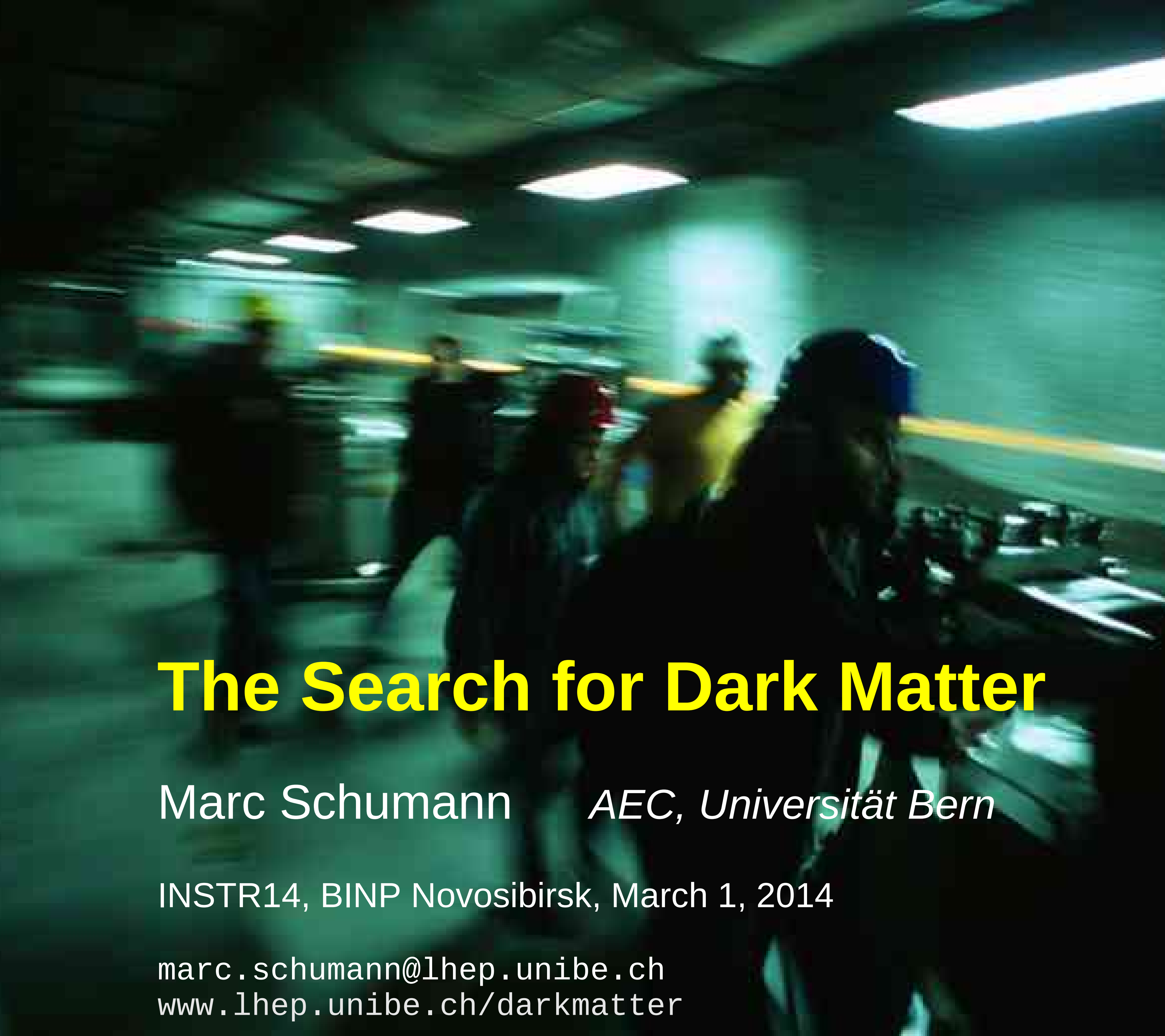

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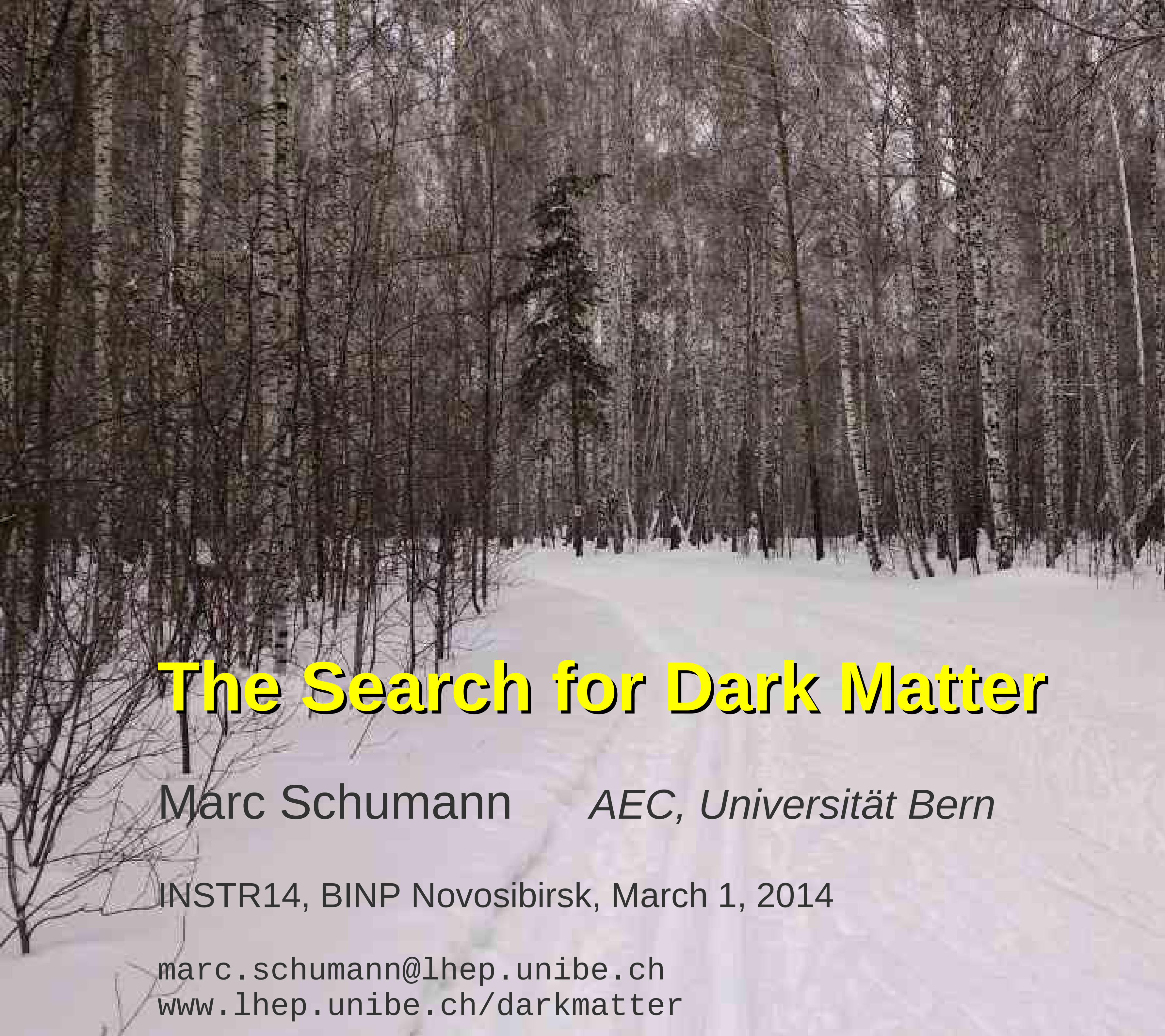
The Search for Dark Matter

Marc Schumann *AEC, Universität Bern*

INSTR14, BINP Novosibirsk, March 1, 2014

marc.schumann@lhep.unibe.ch
www.lhep.unibe.ch/darkmatter



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The Search for Dark Matter with XENON

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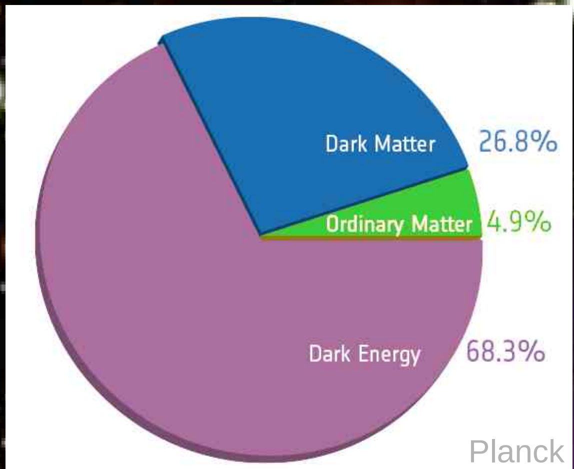
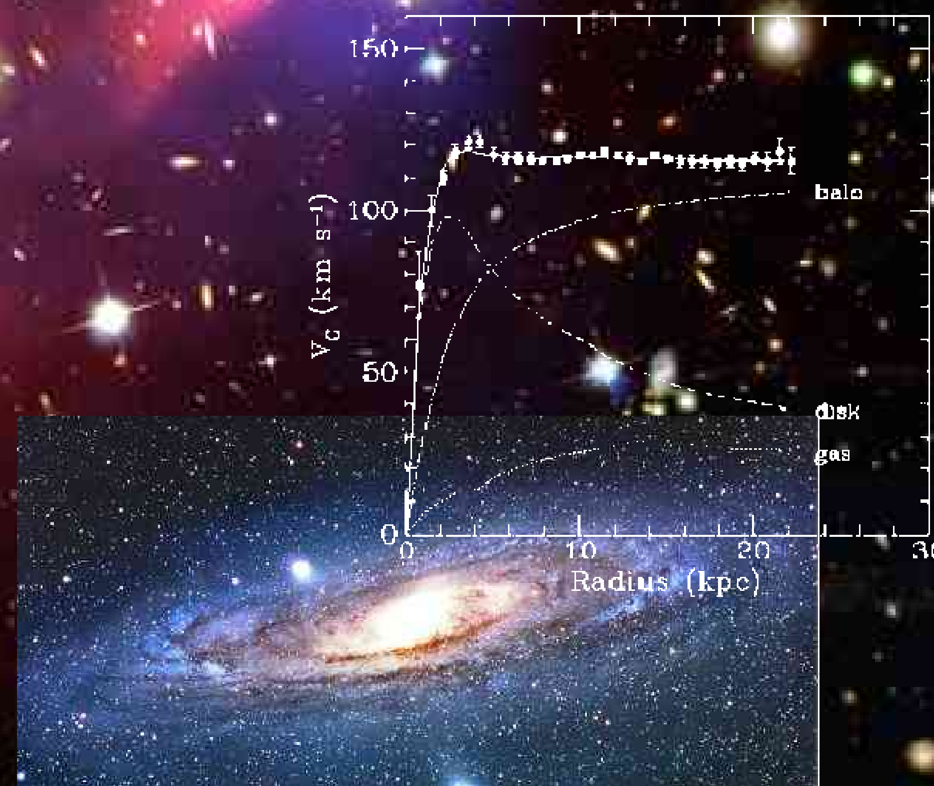
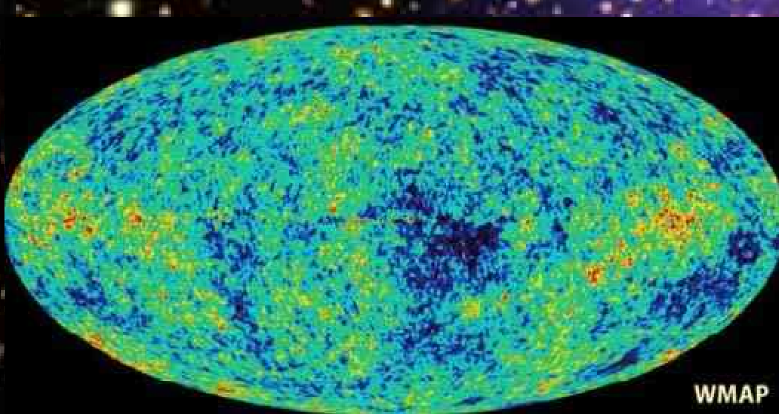
XENON Dark Matter Project

Dark Matter: (indirect) **Evidence**



Particle Dark Matter Candidates:
- WIMP → *„WIMP miracle“*
- Axion
- SuperWIMPs
- sterile neutrinos
- WIMPless dark matter
- Gravitino
- ...





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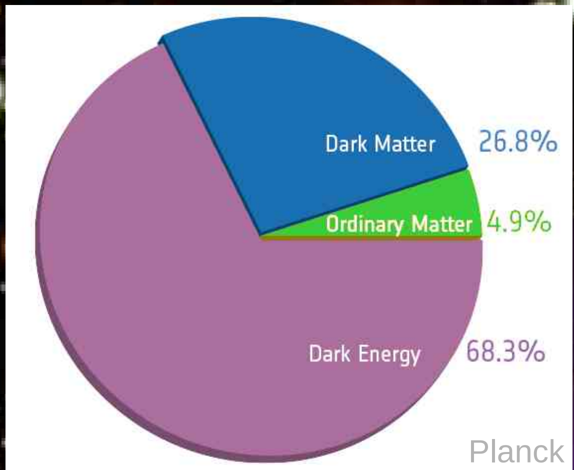
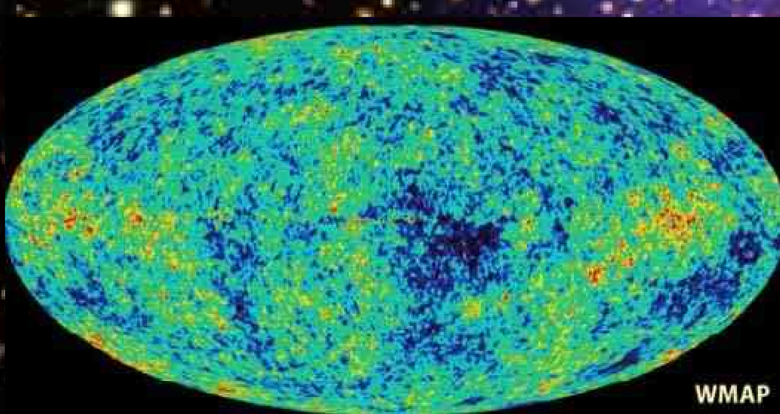
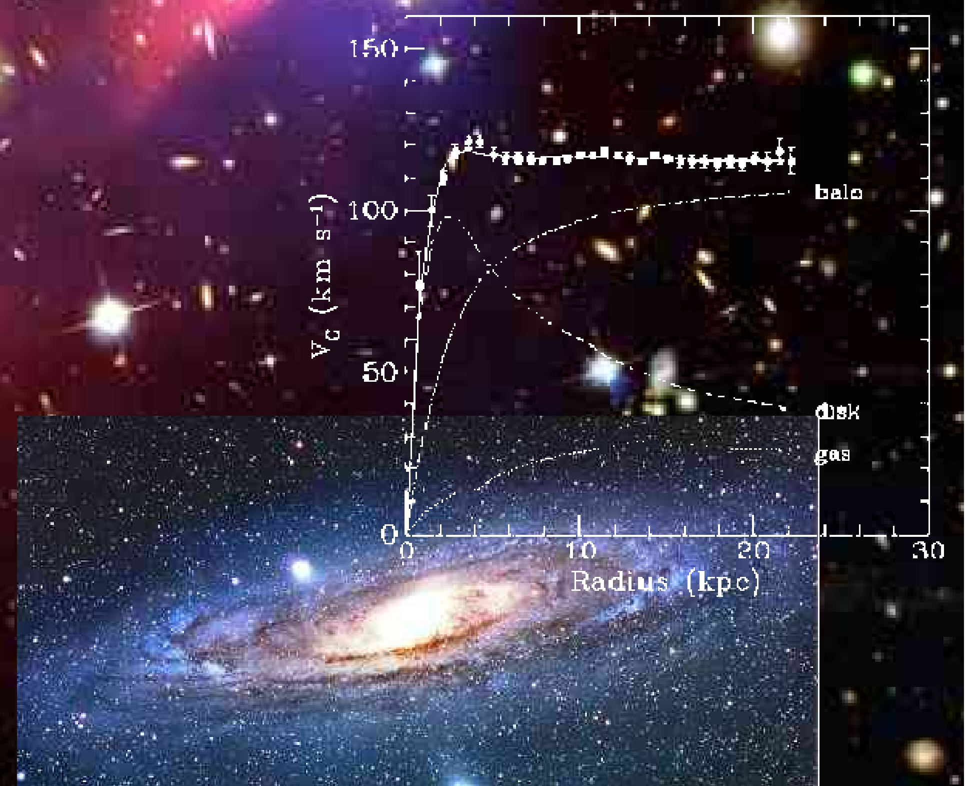


Particle Dark Matter Candidates:
- WIMP → *„WIMP miracle“*
- Axion
- SuperWIMPs
- sterile neutrinos
- WIMPless dark matter
- Gravitino
- ...

The indirect evidence of the existence of dark matter is a clear indication for physics beyond the standard model





Direct WIMP Search

Elastic Scattering of WIMPs off target nuclei

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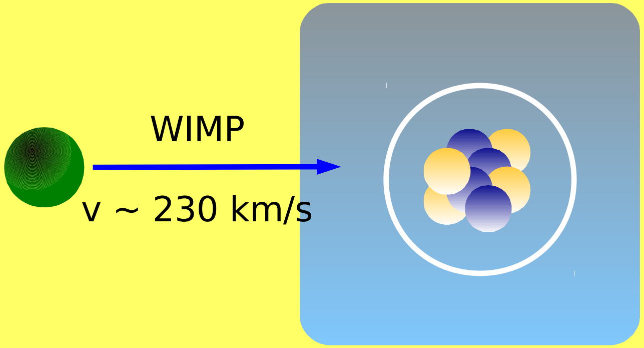

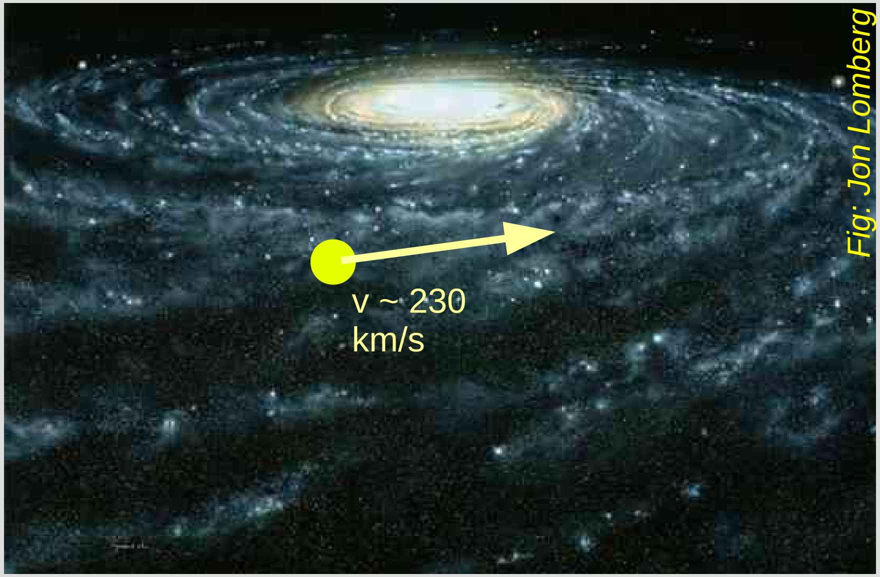

Direct WIMP Search

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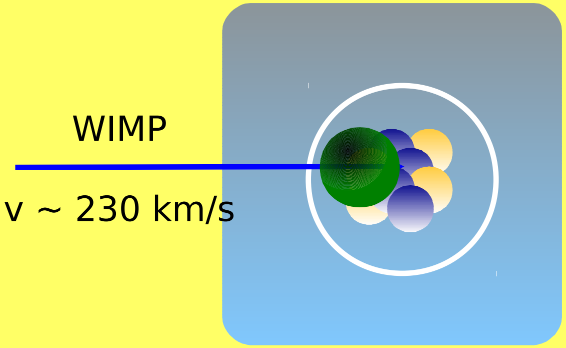
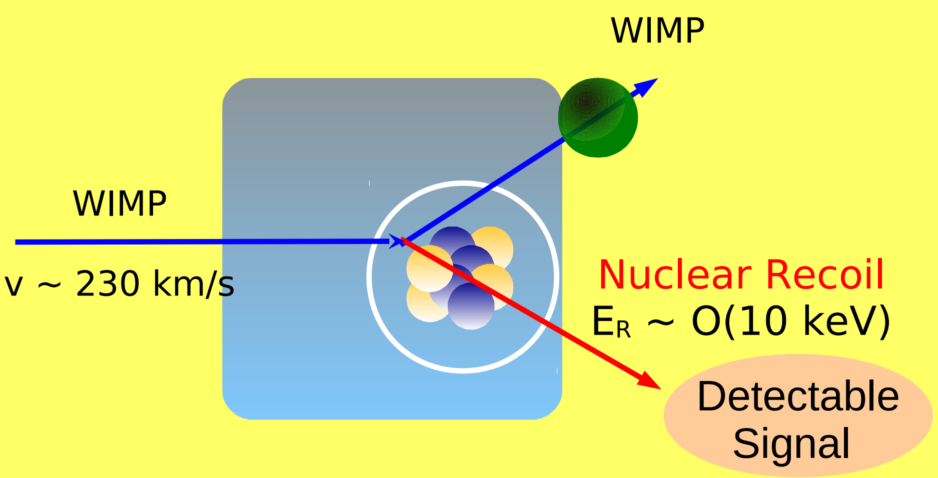


Direct WIMP Search

Elastic Scattering of WIMPs off target nuclei
➡ nuclear recoil



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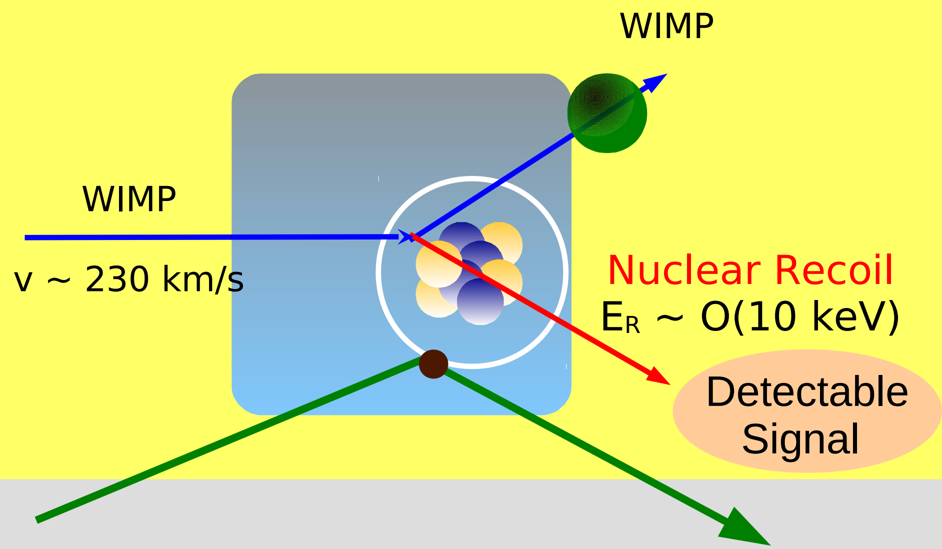
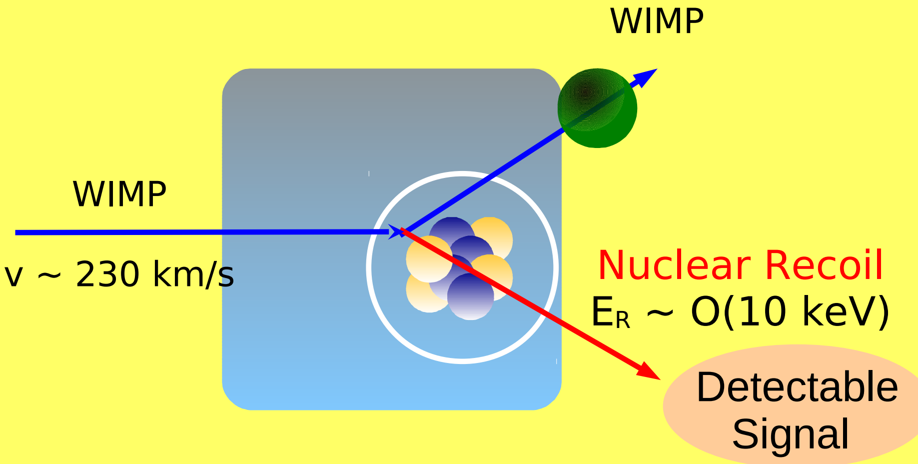


gamma- and beta-particles
(background) interact with the
atomic electrons
→ **electronic recoil**

Direct WIMP Search

Elastic Scattering of WIMPs off target nuclei
➡ nuclear recoil



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

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

Detector (N)
Local DM Density (ρ_χ/m_χ)
Physics ($\langle \sigma_{\chi-N} \rangle$)

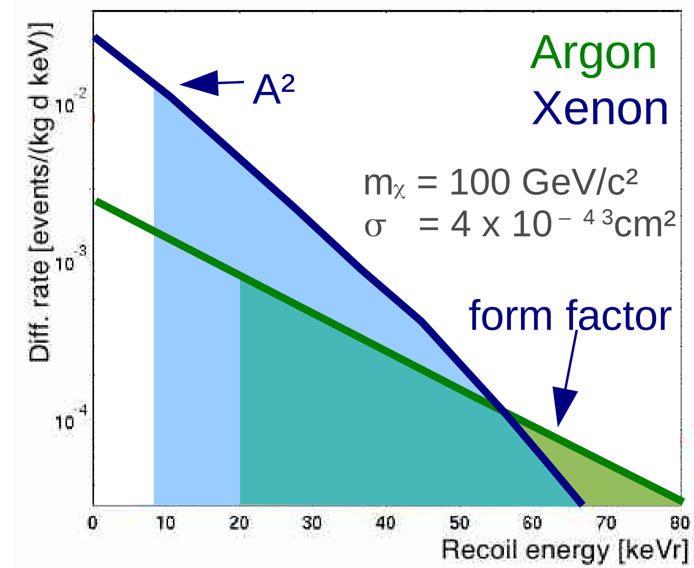
ρ_χ~0.3 GeV/c²

Direct WIMP Search

Summary: Tiny Rates

$R < 0.01$ evt/kg/day

$E_R < 100$ keV



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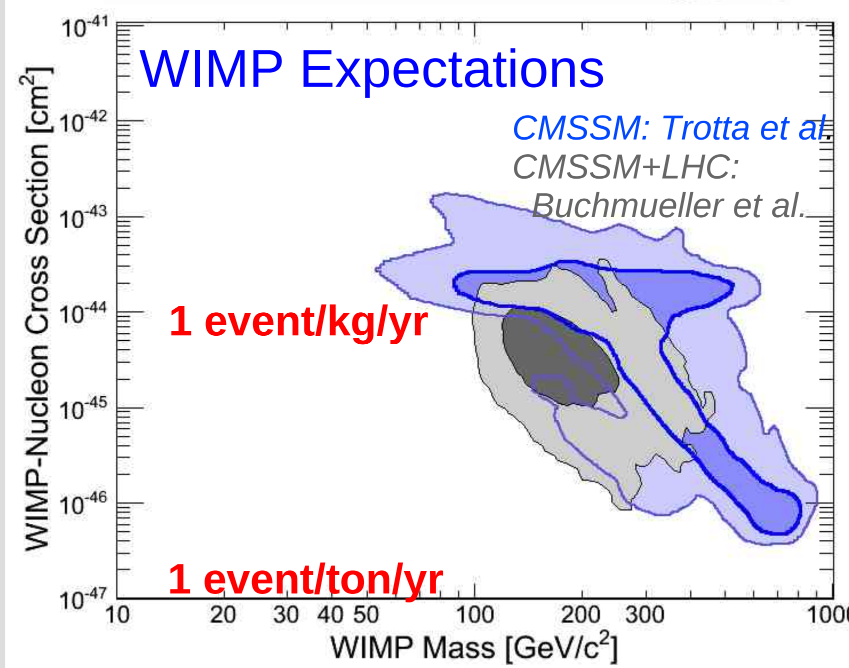
Detector

Local DM Density

Physics

$\rho_\chi \sim 0.3$ GeV/c^2



Direct WIMP Search

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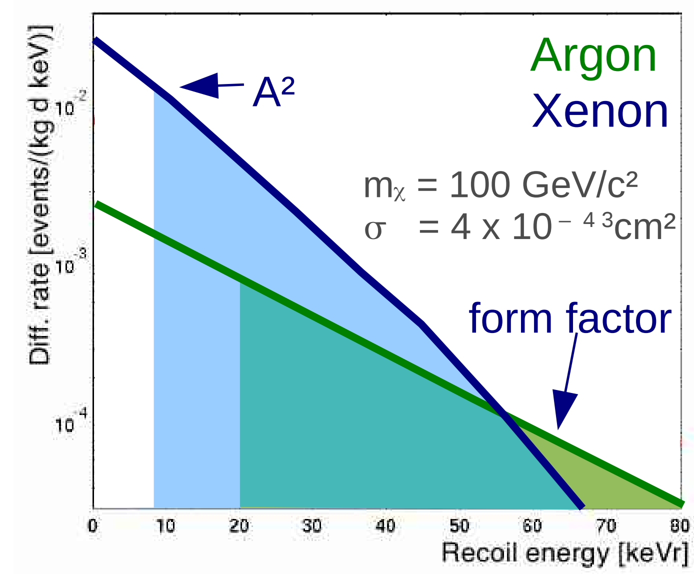
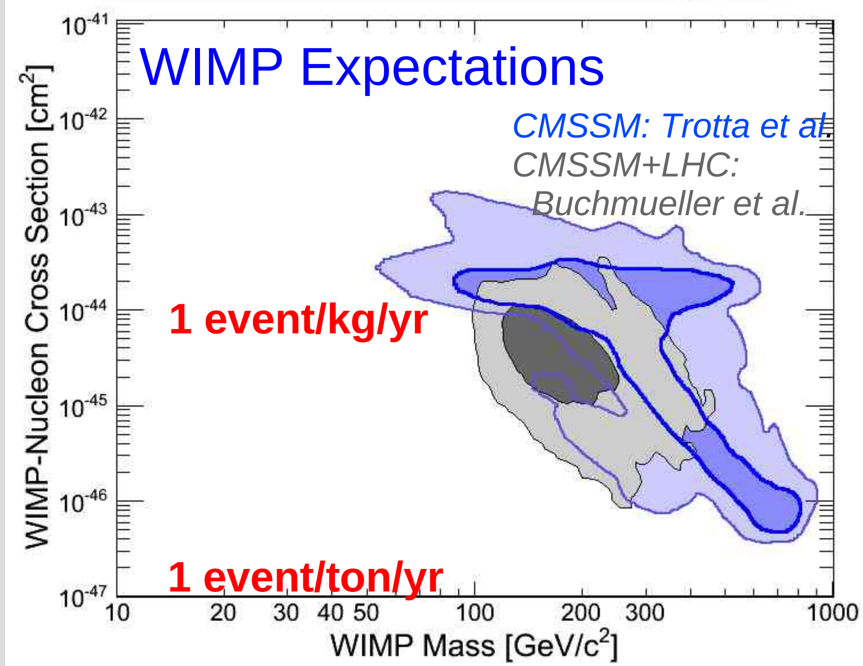
How to build a WIMP detector?

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





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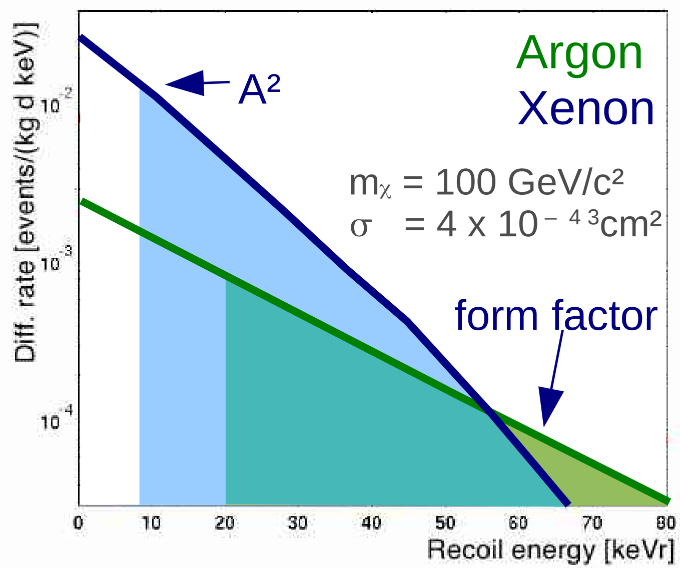
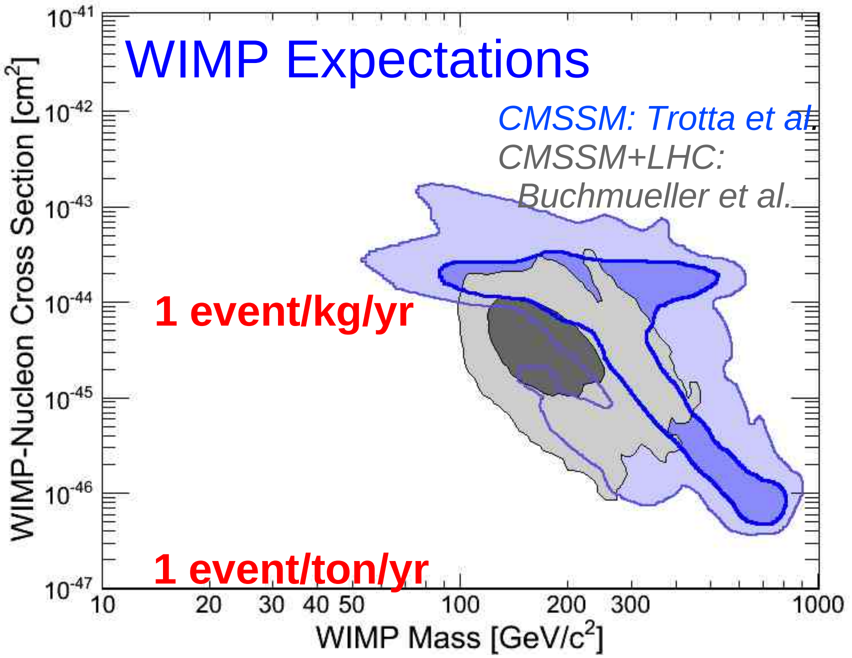
How to build a WIMP detector?

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

for liquid xenon dual phase detectors





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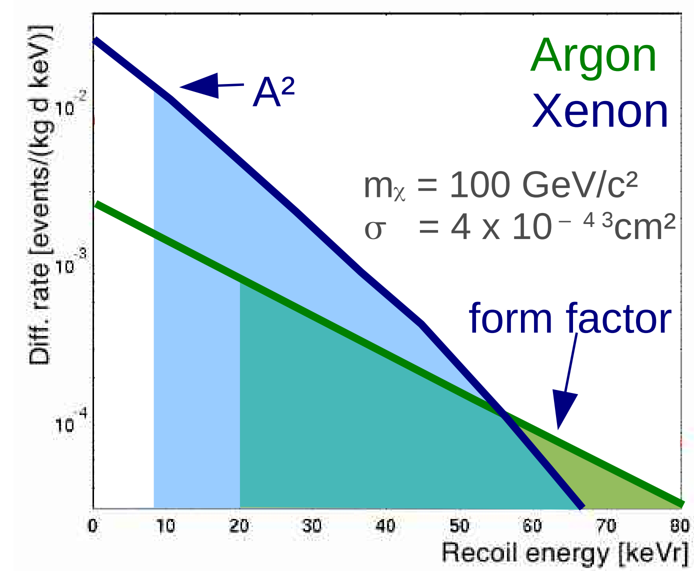
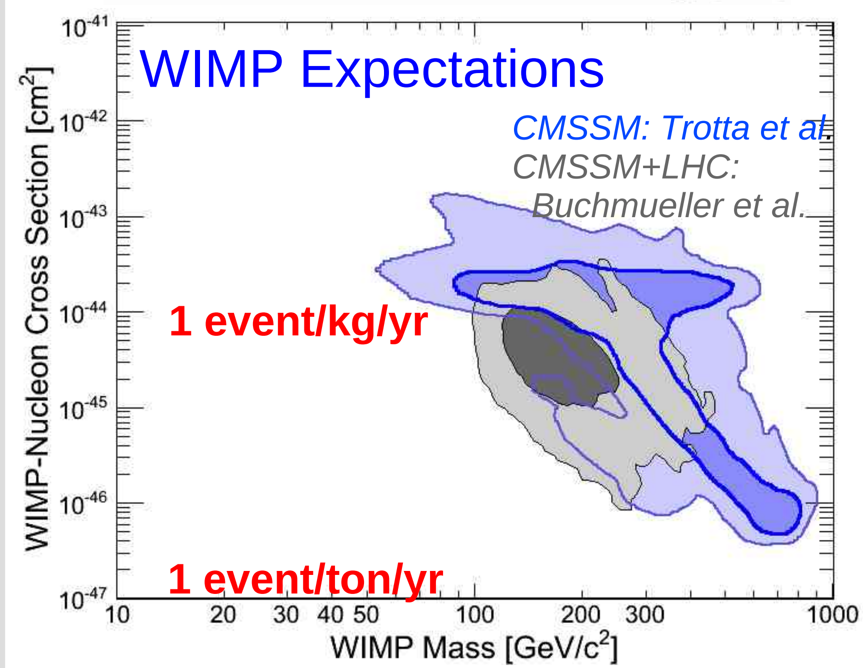
- low energy threshold ✔
- ultra low background ✔
- good background discrimination ✔

for liquid xenon dual phase detectors

We are dealing with
- extremely **low rates** (1 – 1000 Hz)
- extremely **low thresholds** (2 keV)
- extremely **low radioactive** backgrounds





Backgrounds

Experimental Sensitivity

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

Background Sources

environment: U, Th chains, K

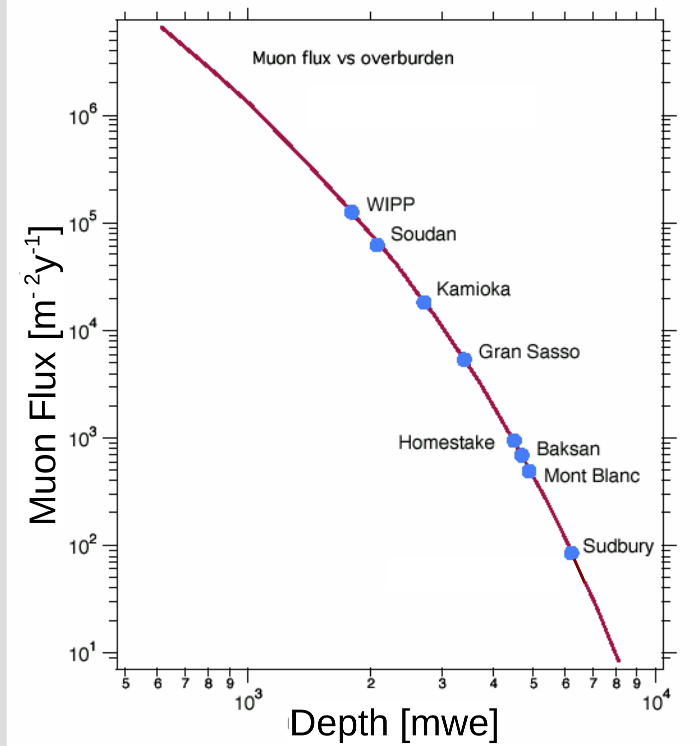
$^{238}U \xrightarrow{\alpha} {}^{234}Th \xrightarrow{\beta} {}^{234m}Pa \xrightarrow{\beta} {}^{234}U \xrightarrow{\alpha} {}^{230}Th \xrightarrow{\alpha} {}^{226}Ra \xrightarrow{\alpha} {}^{222}Rn \xrightarrow{\alpha} {}^{218}Po \ldots$

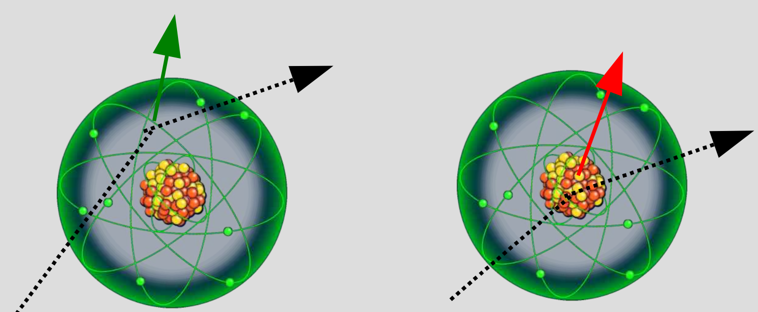
$^{232}Th \xrightarrow{\alpha} {}^{228}Ra \xrightarrow{\beta} {}^{228m}Ac \xrightarrow{\beta} {}^{228}Th \xrightarrow{\alpha} {}^{224}Ra \xrightarrow{\alpha} {}^{220}Rn \xrightarrow{\alpha} {}^{216}Po \ldots$

- γ and β Decays (electronic recoil)
  → „intrinsic“ bg most dangerous (Kr85, Rn222)

- neutrons from (α,n) and sf in rocks and detector parts
- neutrons from cosmic ray muons

Muon reduction in underground laboratory





Electronic Recoils (gamma, beta) **Nuclear Recoils** (neutron, WIMPs)

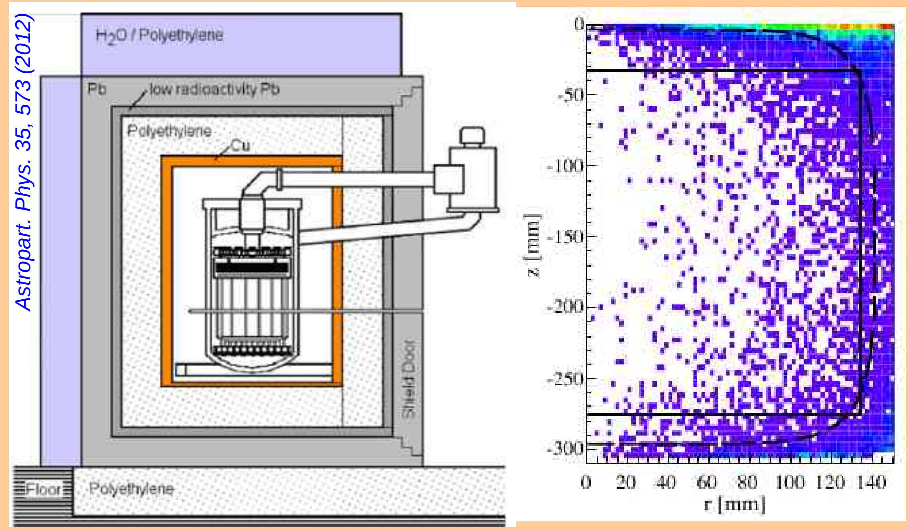
Background Suppression

A Avoid Backgrounds

Use of radiopure materials

Shielding

- deep underground location
- large shield (Pb, water, PE)
- active veto (μ, γ coincidence)
- self shielding → fiducialization



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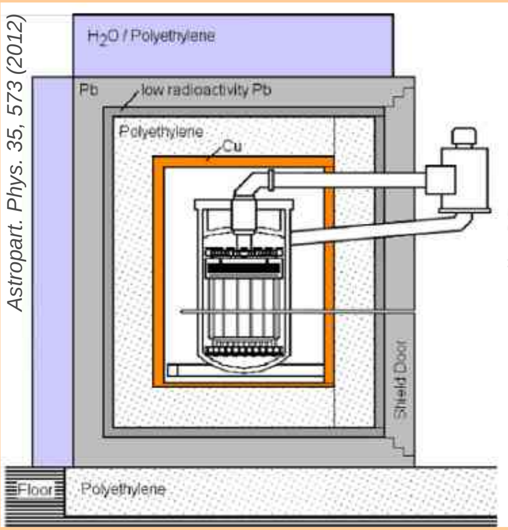
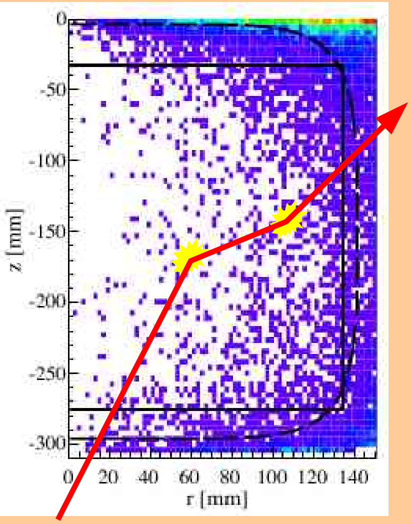




B Use knowledge about expected WIMP signal

WIMPs interact only once

→ single scatter selection
requires some vertexing capability

WIMPs interact with target nuclei

→ nuclear recoils
exploit different d*E*/d*x* from
signal and background

Direct WIMP Detection

Crystals (NaI, Ge)
Cryogenic Detectors
Liquid Noble Gases

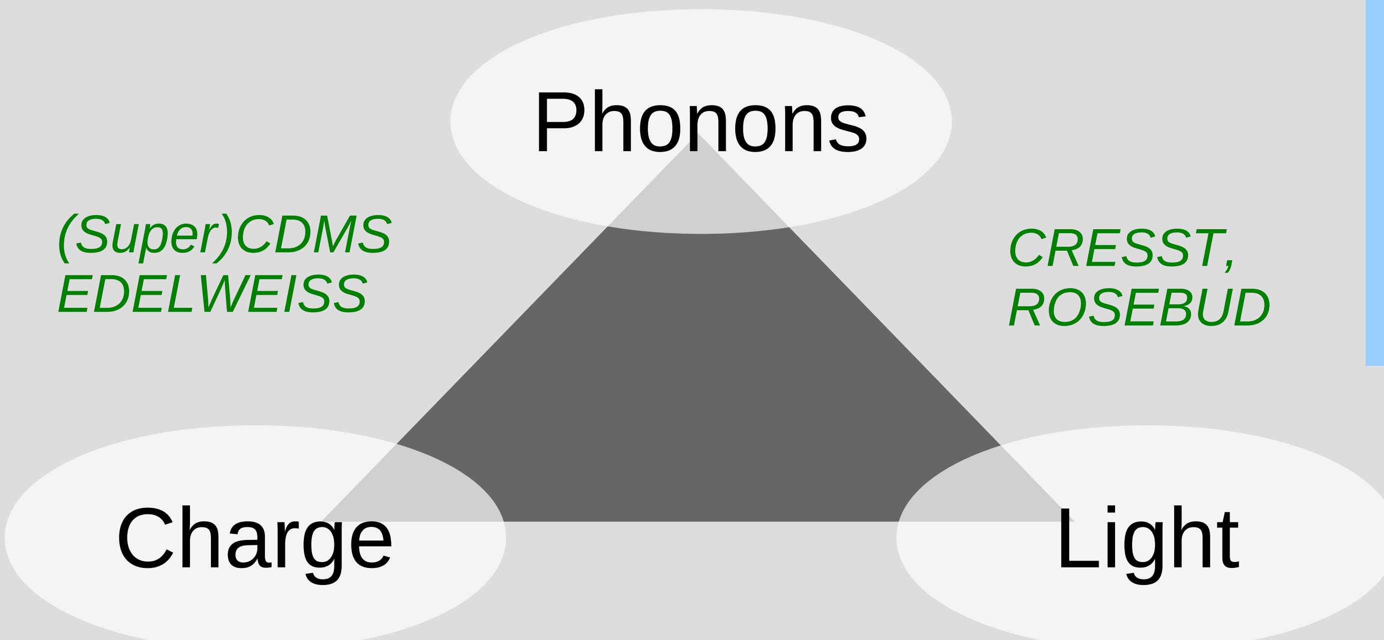
Tracking:
DRIFT, DMTPC
MIMAC,
NEWAGE

Superheated Liquids:
COUPP
PICASSO
SIMPLE

CRESST-I
CUORE

(Super)CDMS
EDELWEISS

CRESST,
ROSEBUD



CoGeNT
CDEX
Texono
Malbek

XENON, LUX
ArDM, Panda-X
ZEPLIN, Darkside

DEAP/CLEAN
DAMA, KIMS
XMASS, DM-Ice

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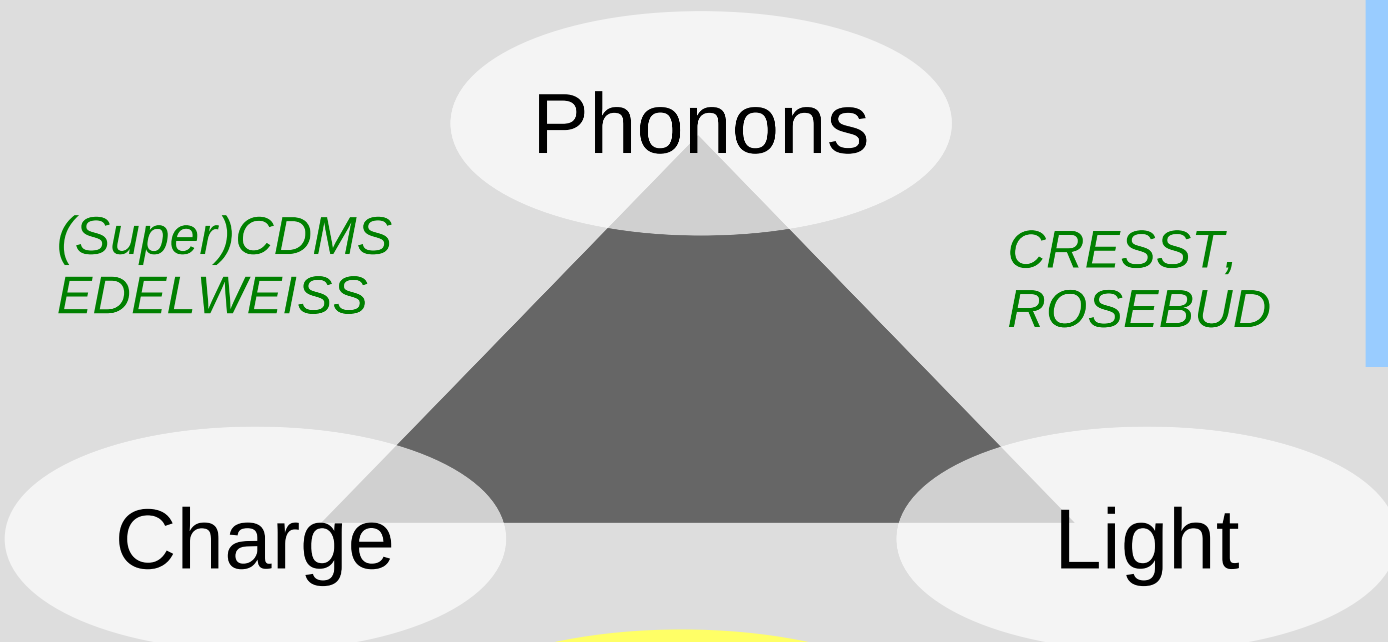

(Super)CDMS
EDELWEISS

CRESST,
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CoGeNT
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XENON, LUX
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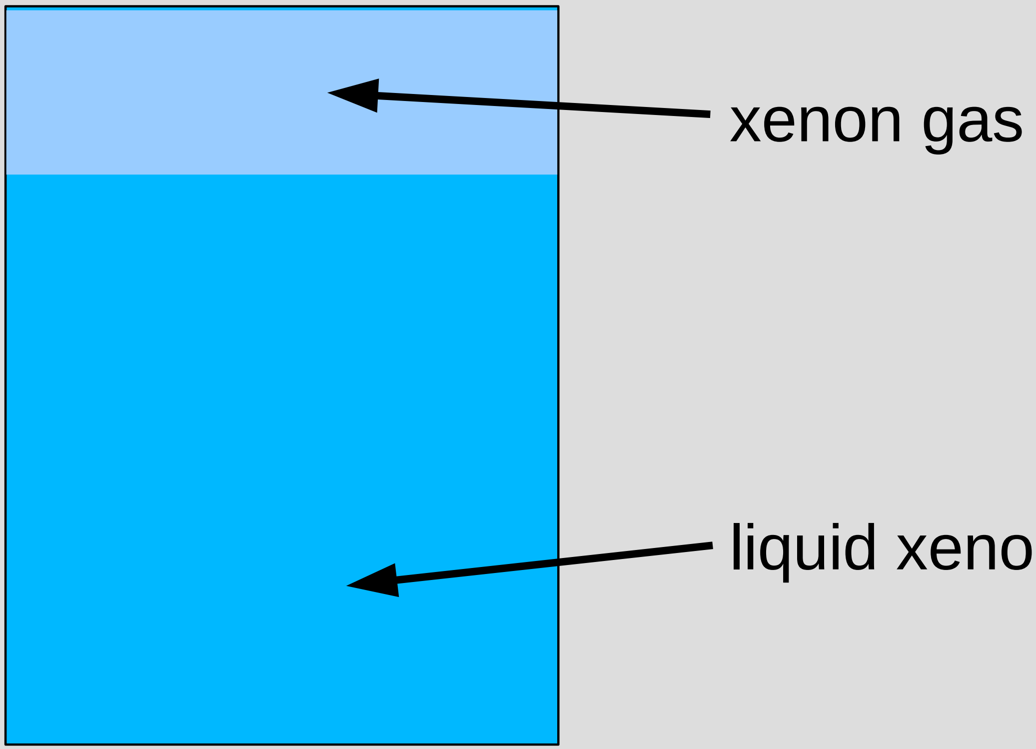
Dual-phase TPCs

DEAP/CLEAN
DAMA, KIMS
XMASS, DM-Ice

Dual Phase TPC

Dolgoshein, Lebedenko, Rodionov, JETP Lett. 11, 513 (1970)

TPC = time projection chamber



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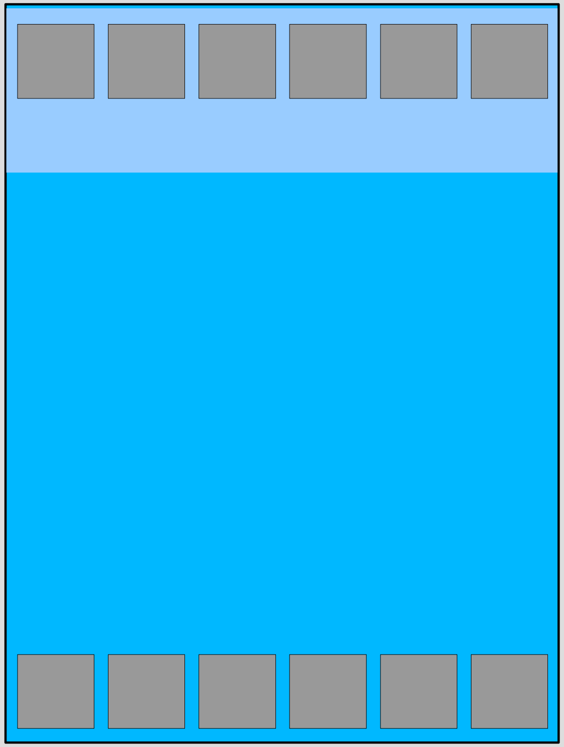

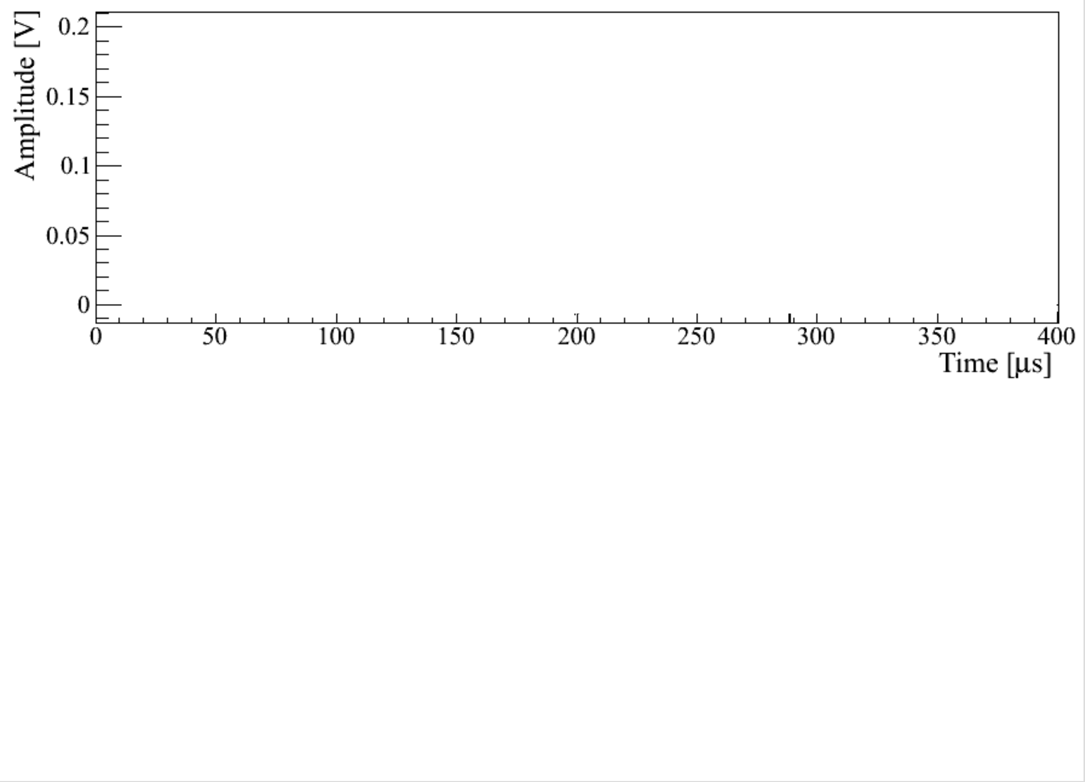

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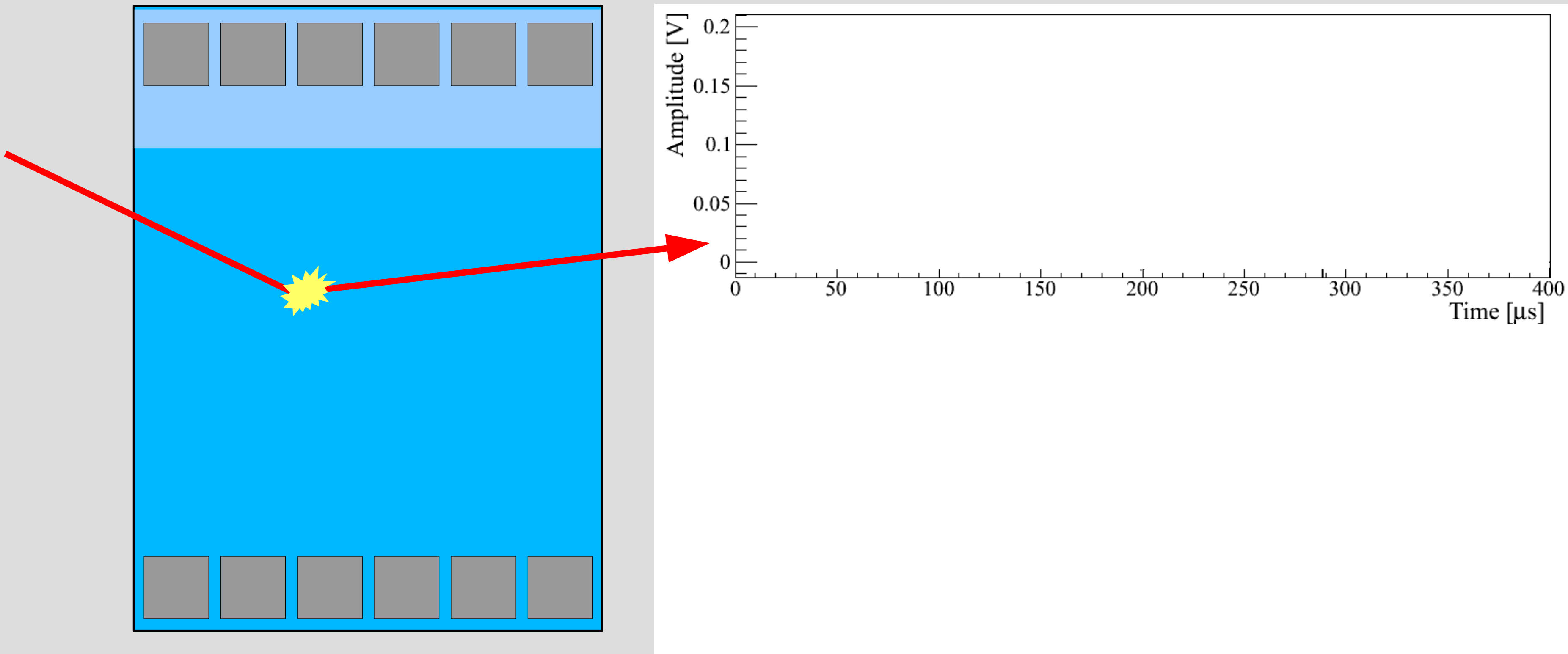

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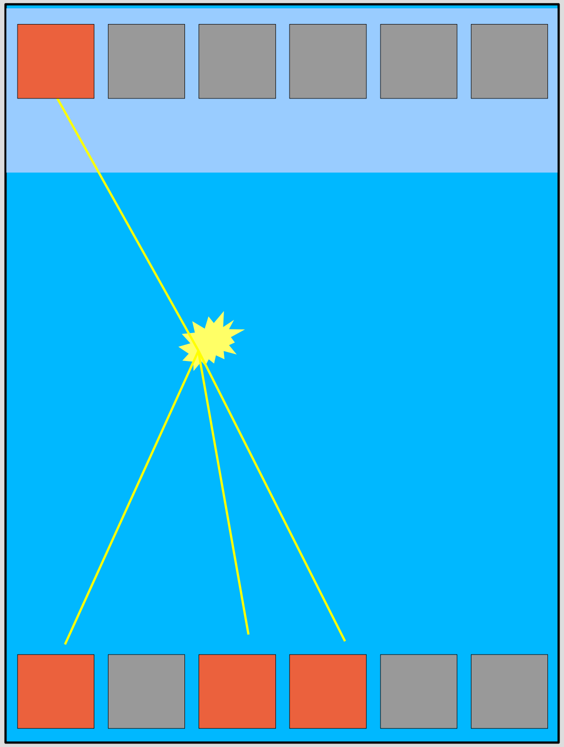

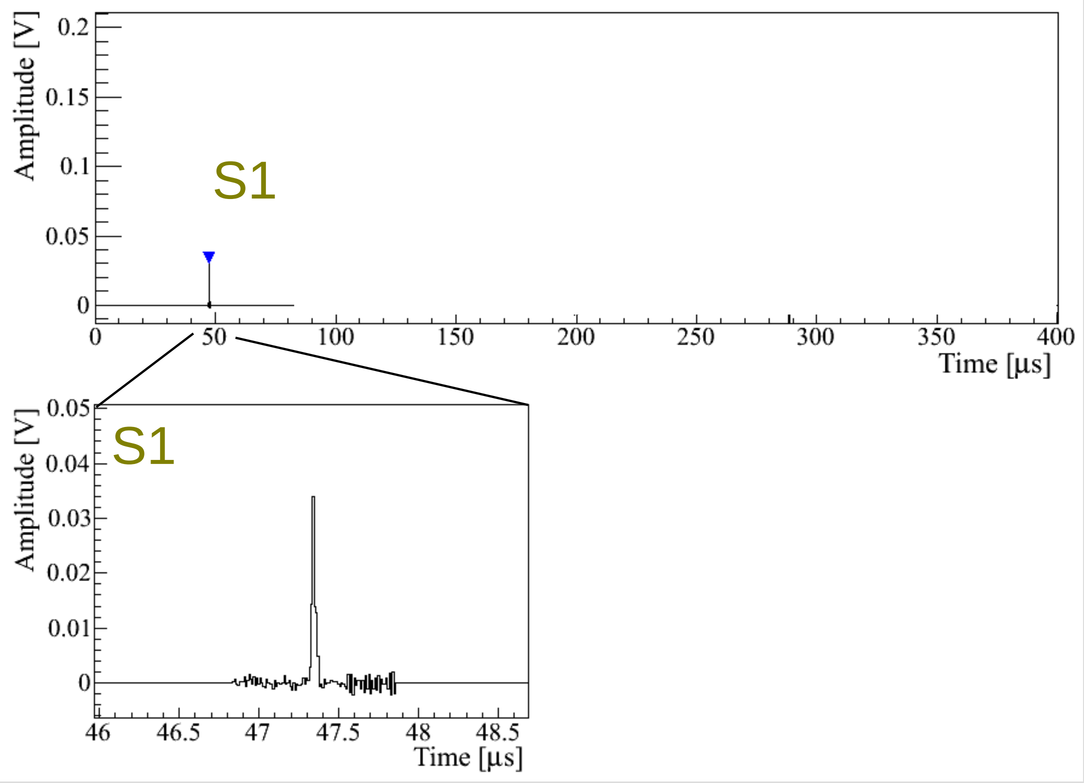

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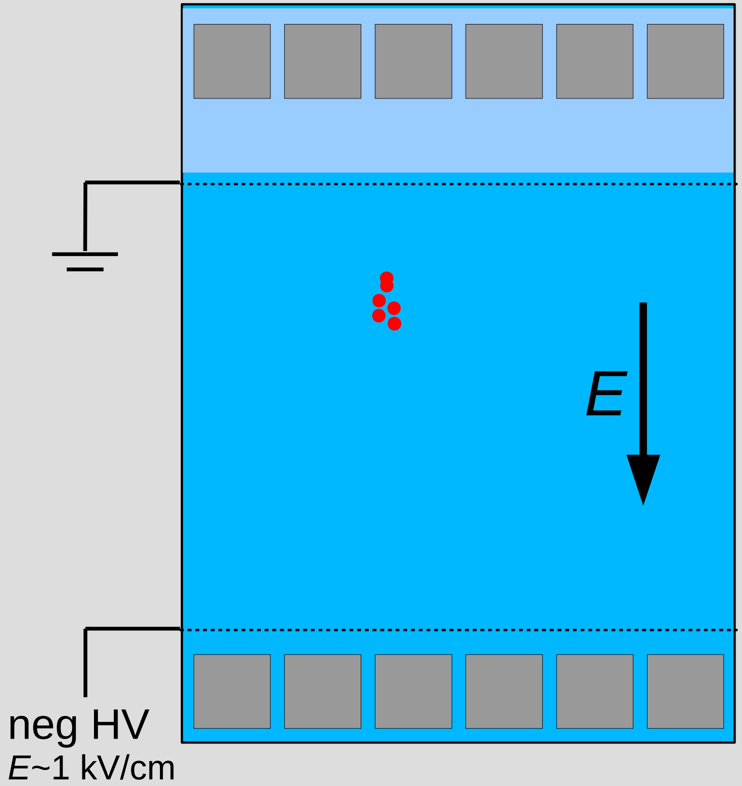

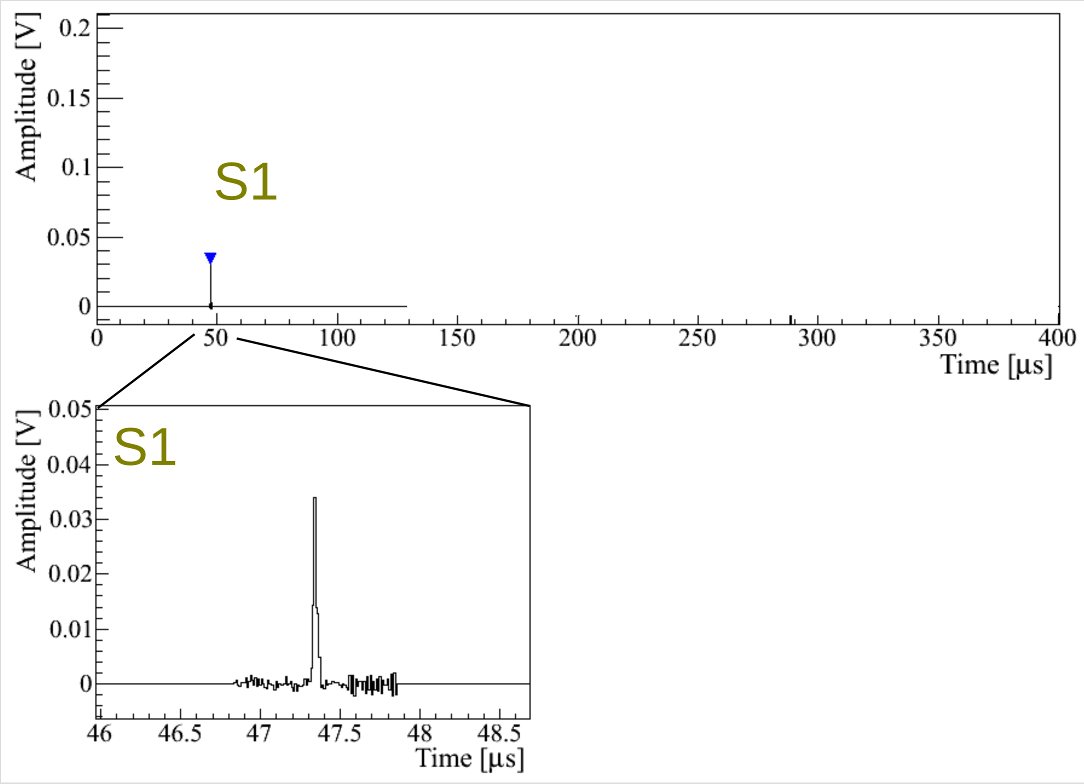

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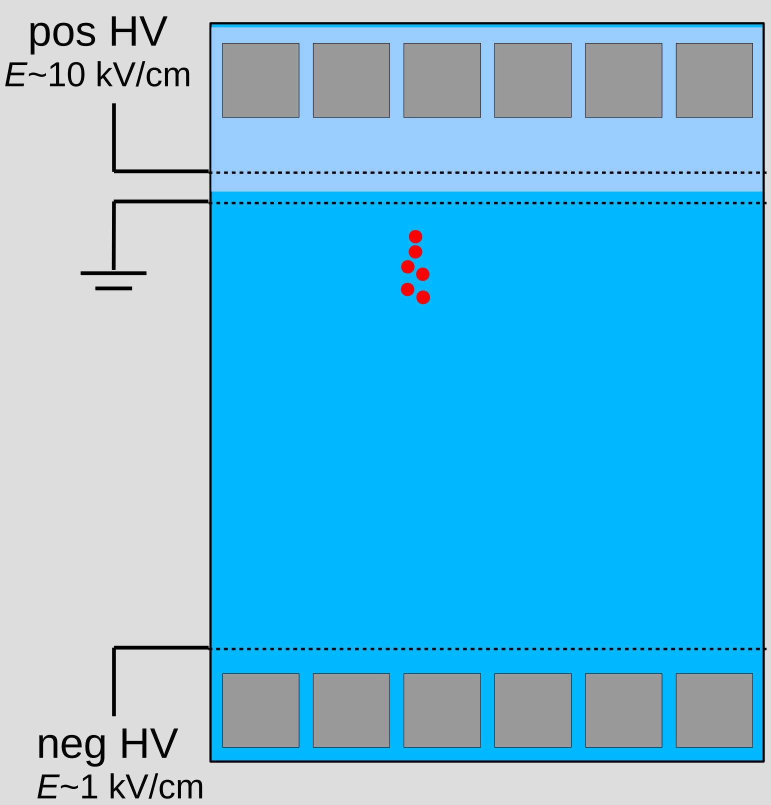

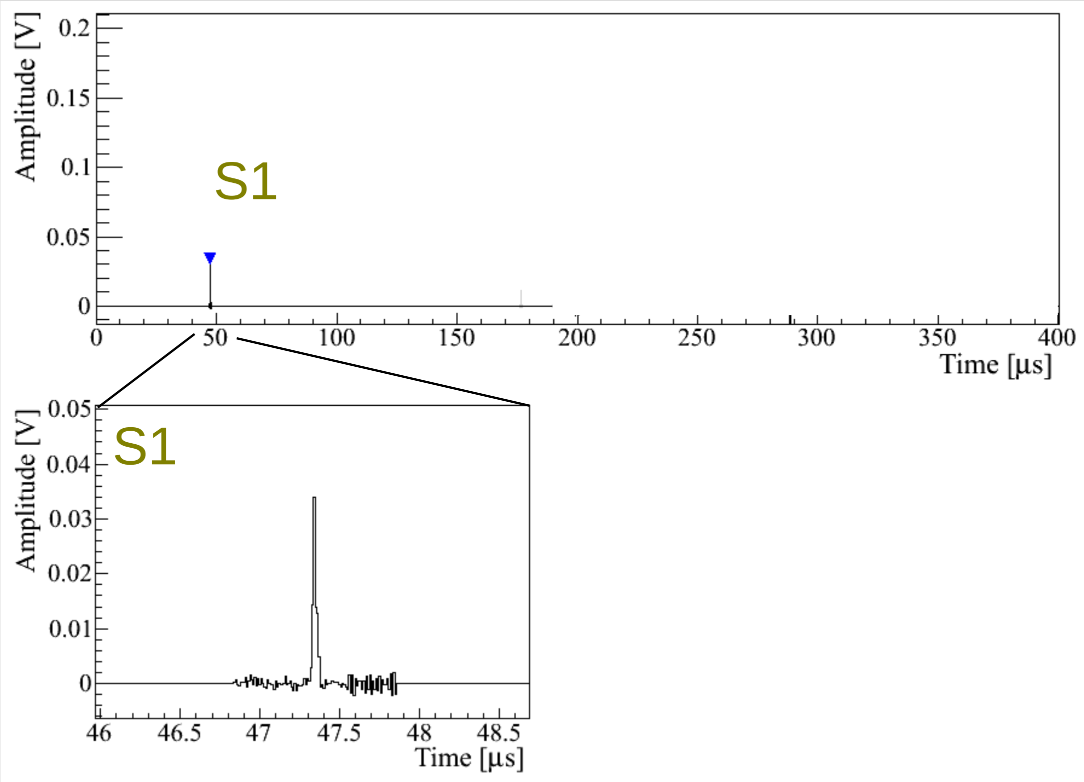

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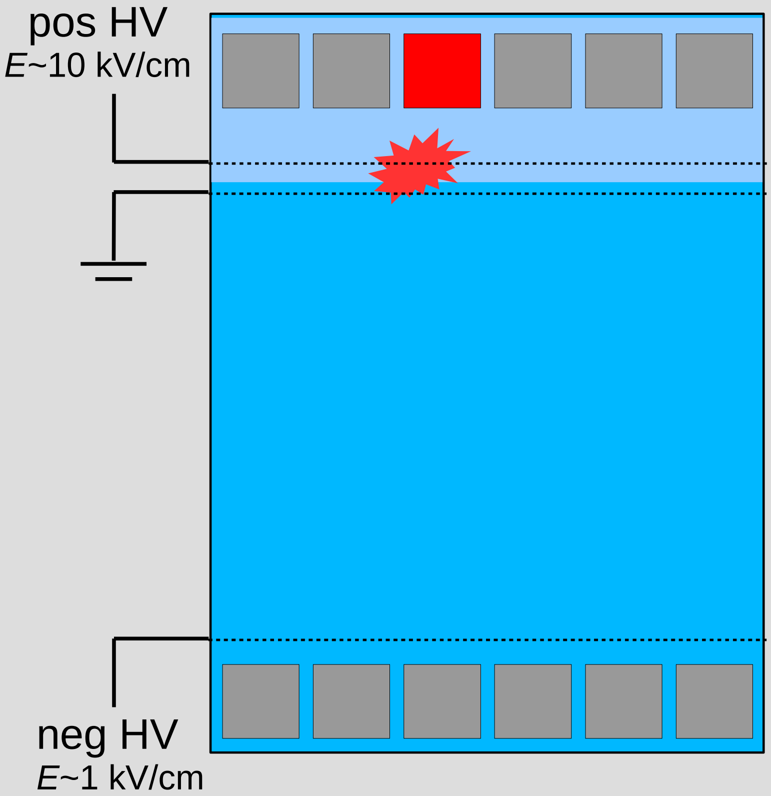
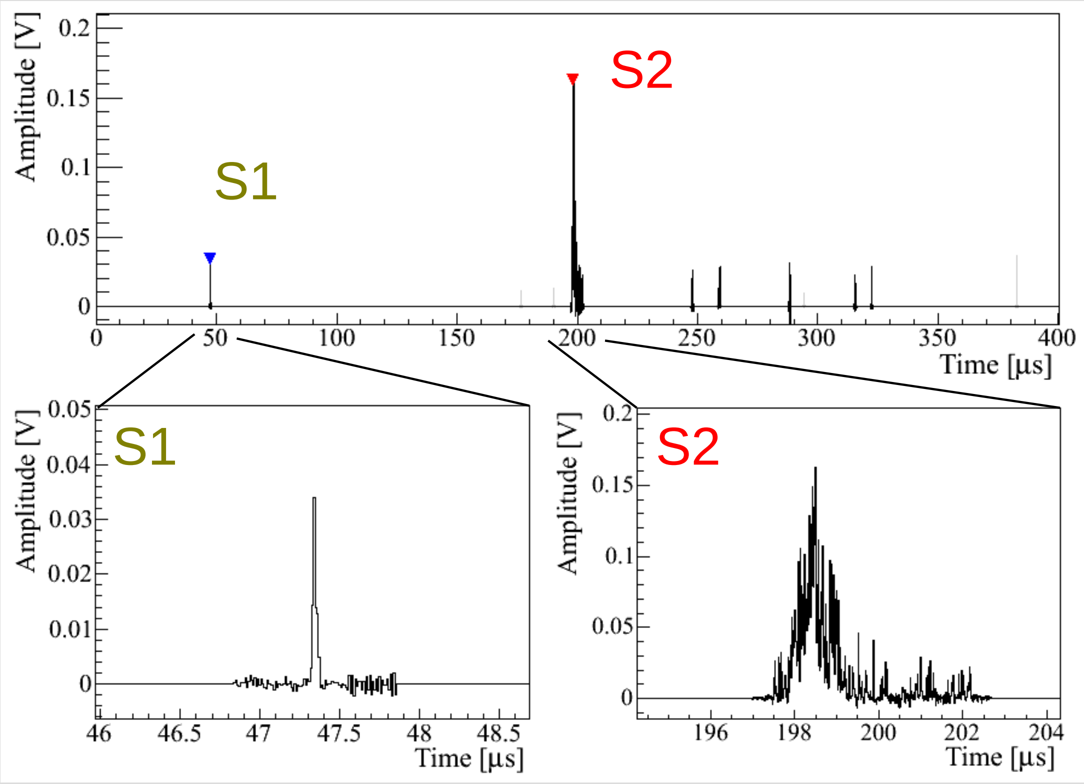
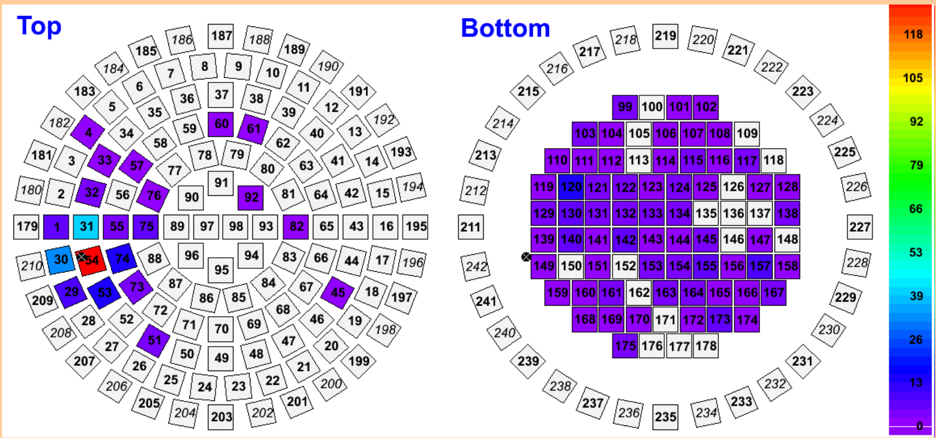
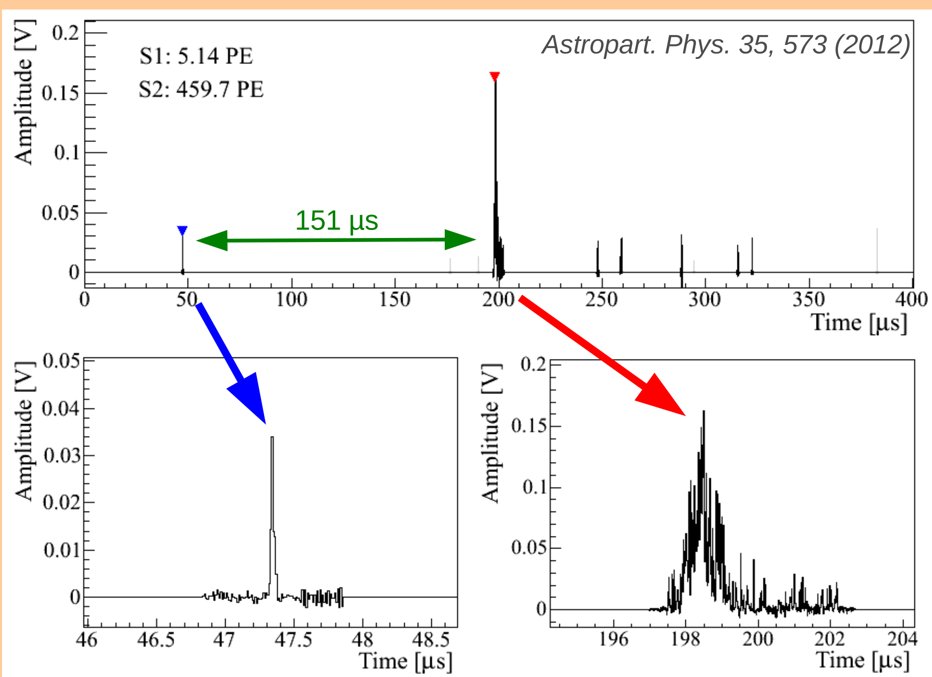




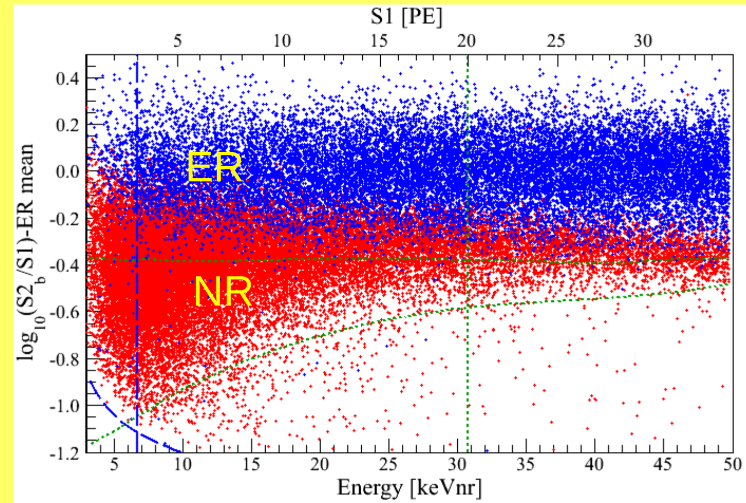
Dual Phase TPC

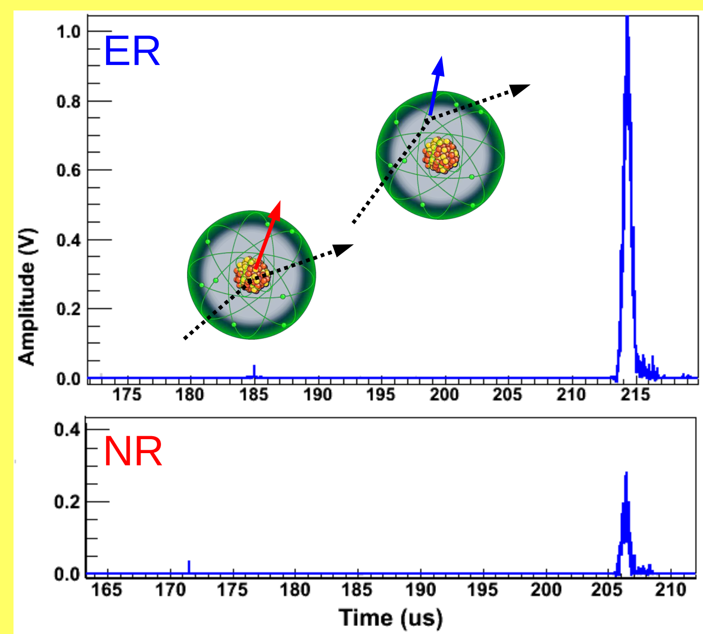
3d Vertex Reconstruction





Signal/Background Discrimination





Figures from XENON100

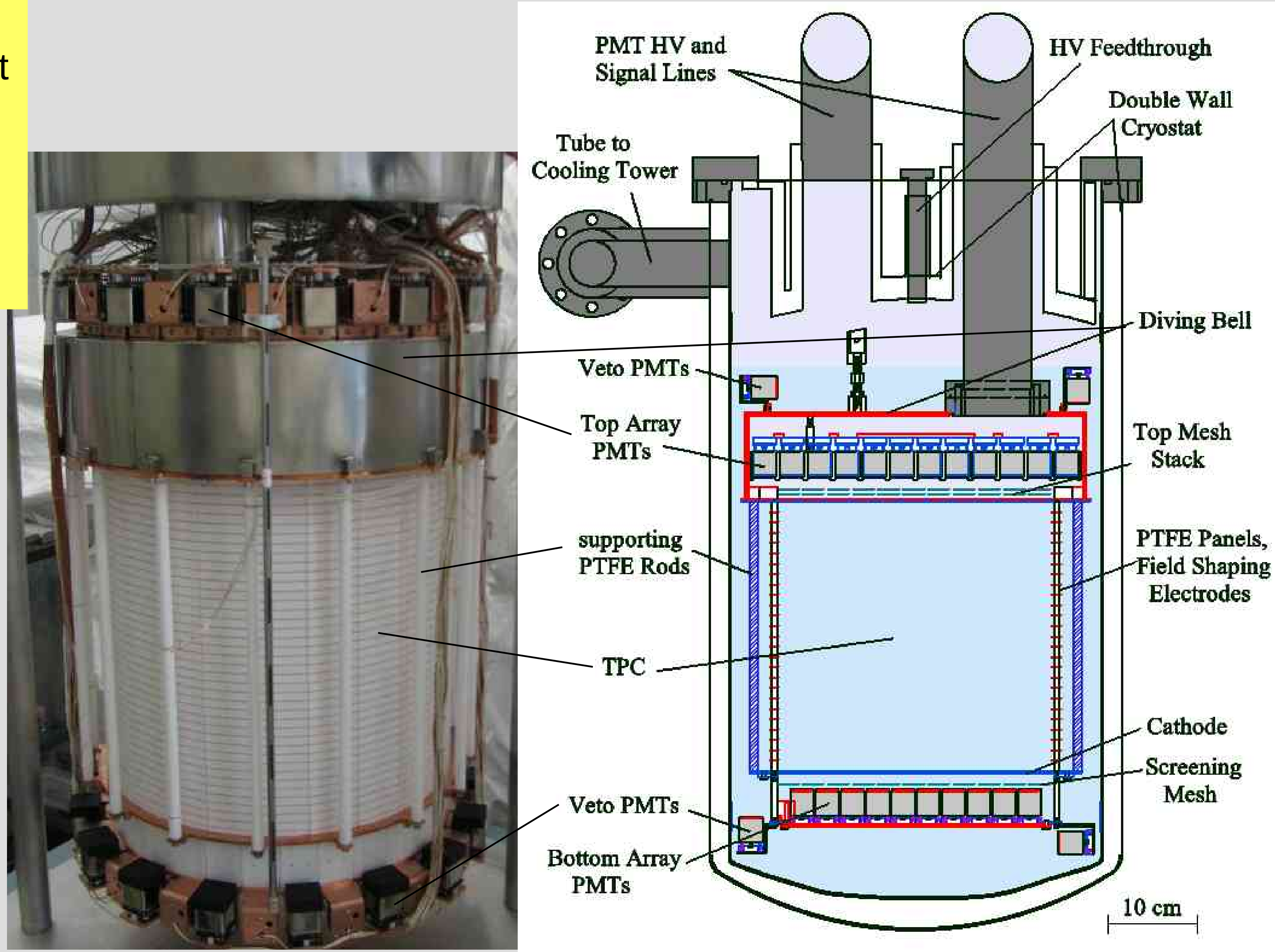

LNGS
Xe
XENON
Dark Matter Project


Xe
XENON
Dark Matter Project

The XENON100 Detector

Astropart. Phys. 35, 573 (2012)

Quick Facts
- 62 kg **LXe** target
- dual phase TPC
- active LXe veto
- 242 PMTs
- running
  @ LNGS (IT)



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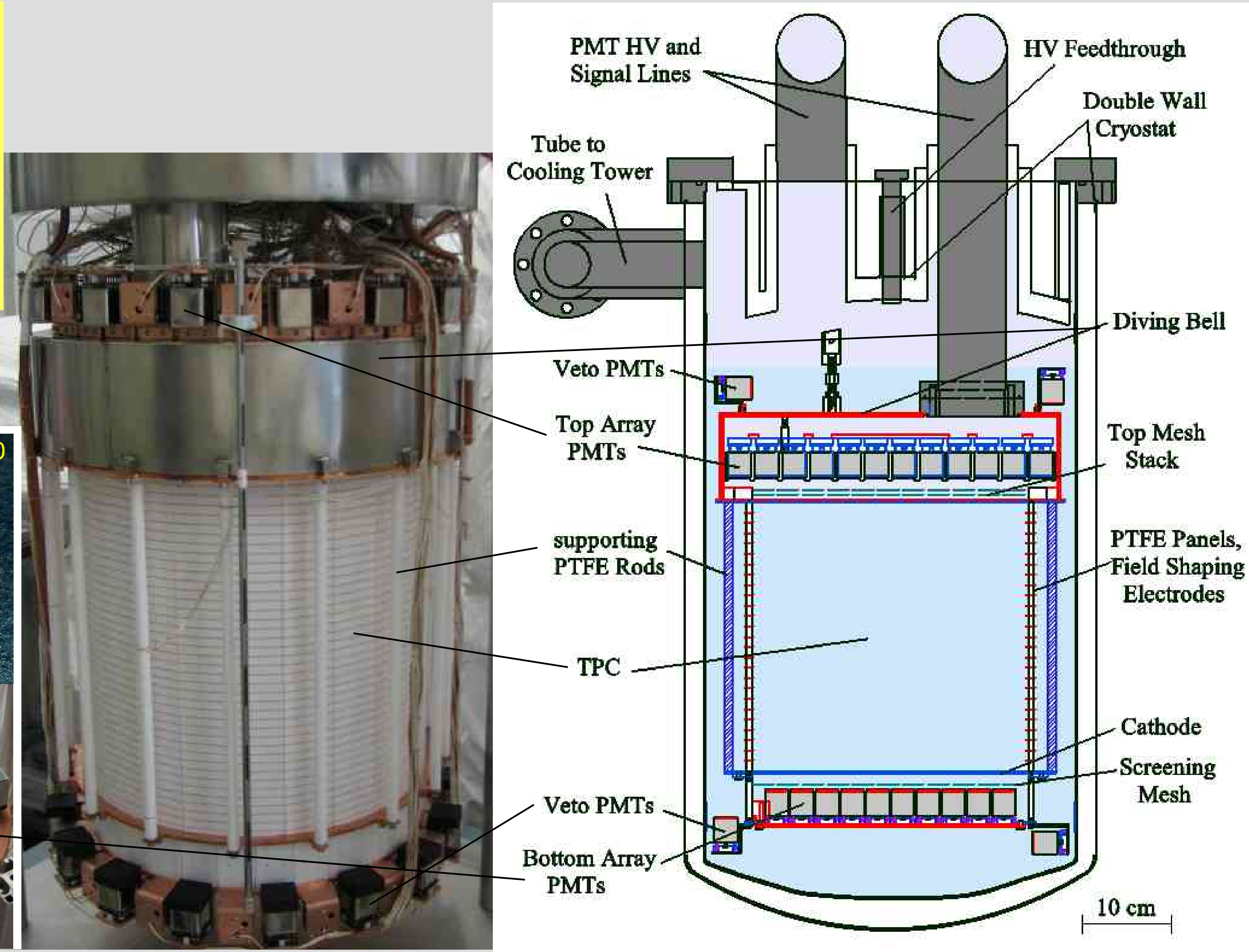
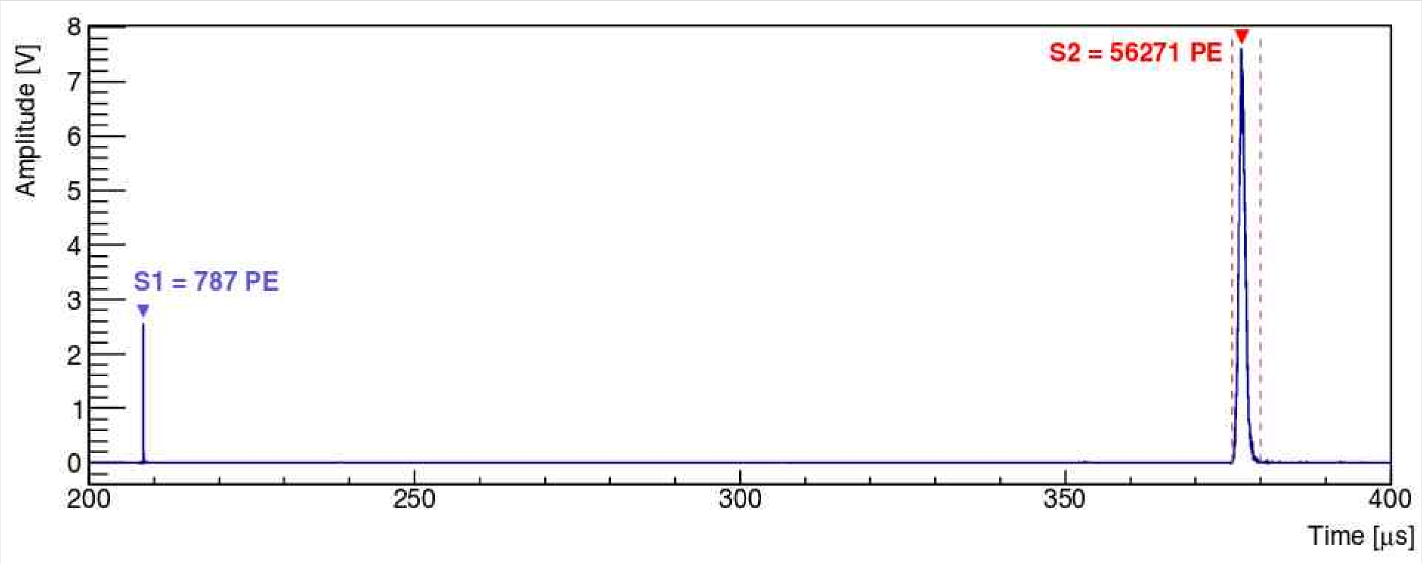


Single electron sensitivity

J. Phys. G 41, 035201 (2014)



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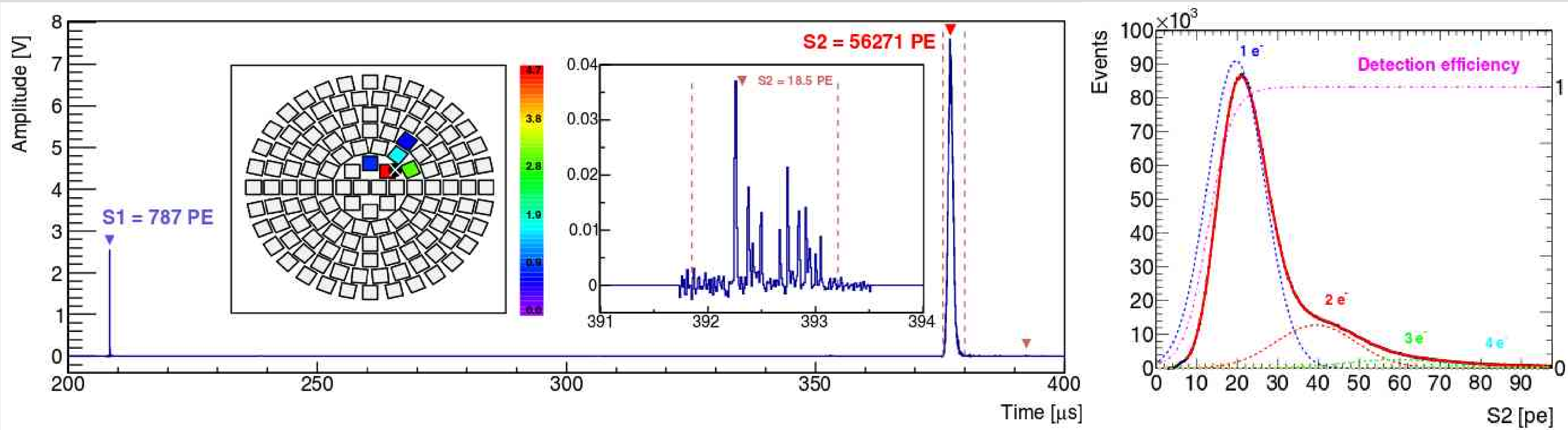

Single electron signals

- the path towards an extremely low threshold
  → XENON10 low-mass limit *PRL 110, 249901 (2013)*

Single electron sensitivity

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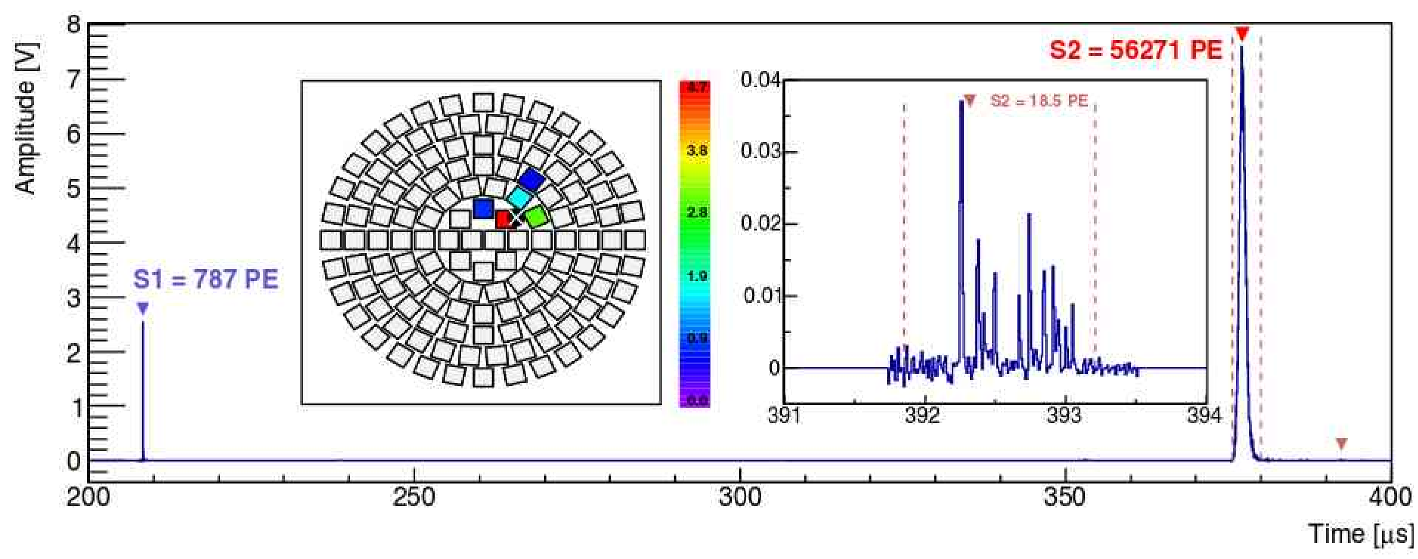
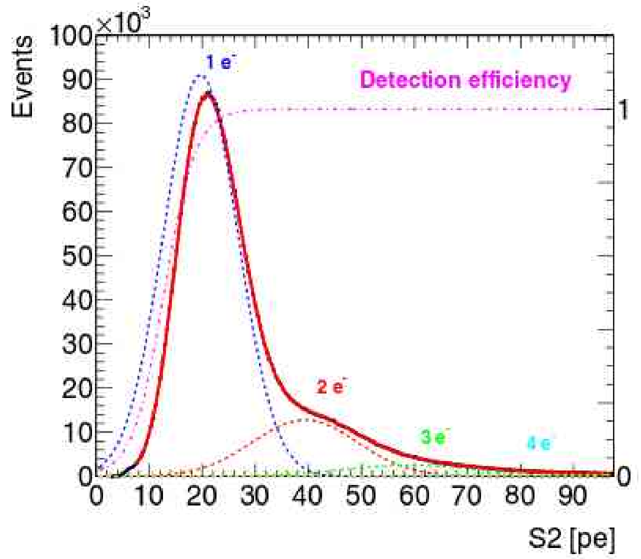


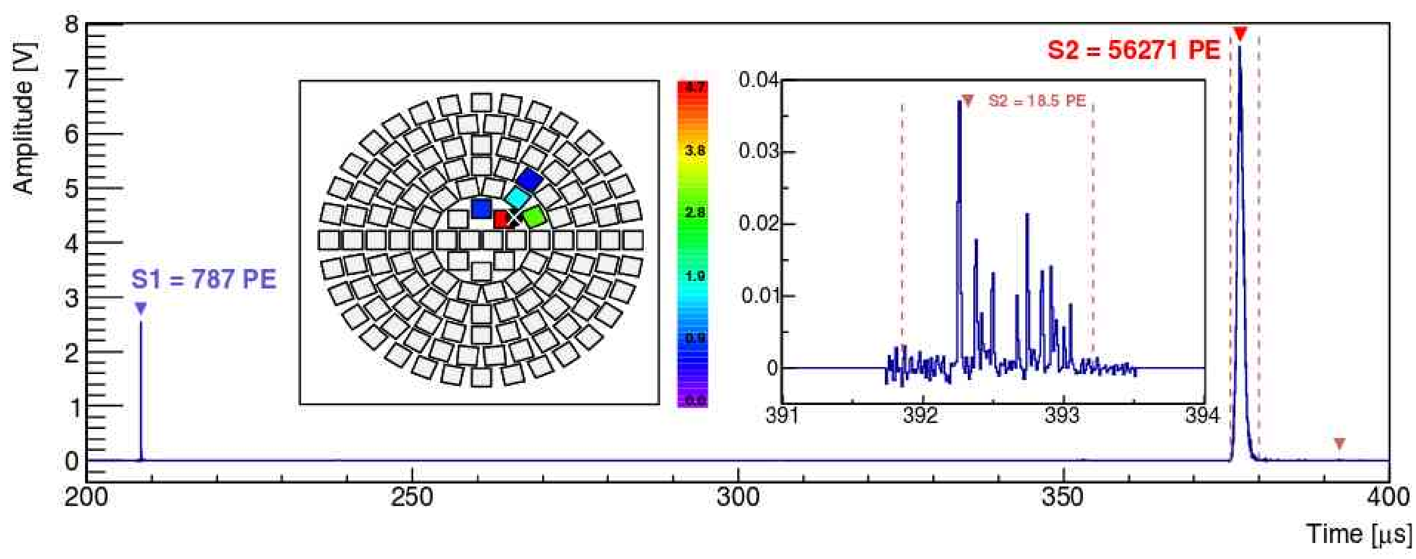


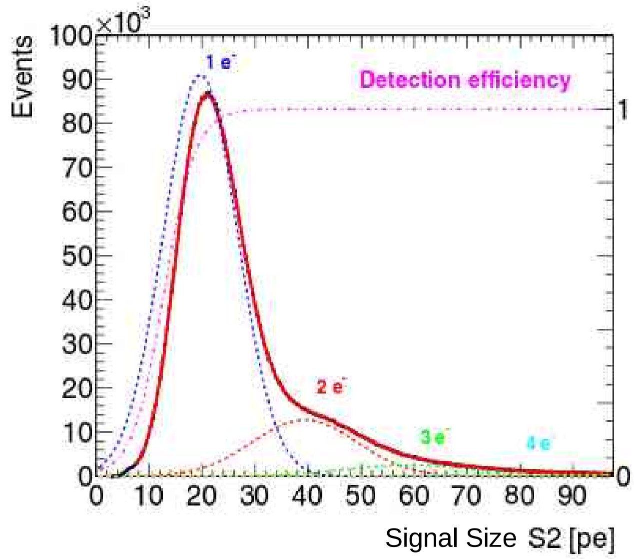
Single electron signals

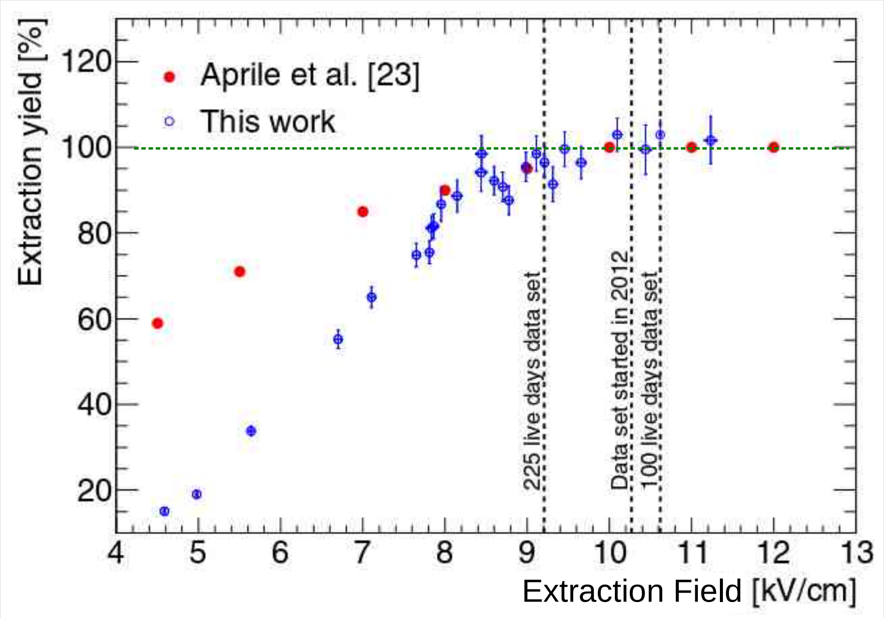
- the path towards an extremely low threshold
  → XENON10 low-mass limit *PRL 110, 249901 (2013)*
- observed signals are mainly from photo-ionization of surfaces and impurities
  → depends on LXe purity
  → rate correlated to large S2 signal
  → few e⁻ signals are accidental coincidences

Single electron sensitivity

J. Phys. G 41, 035201 (2014)







Single electron signals

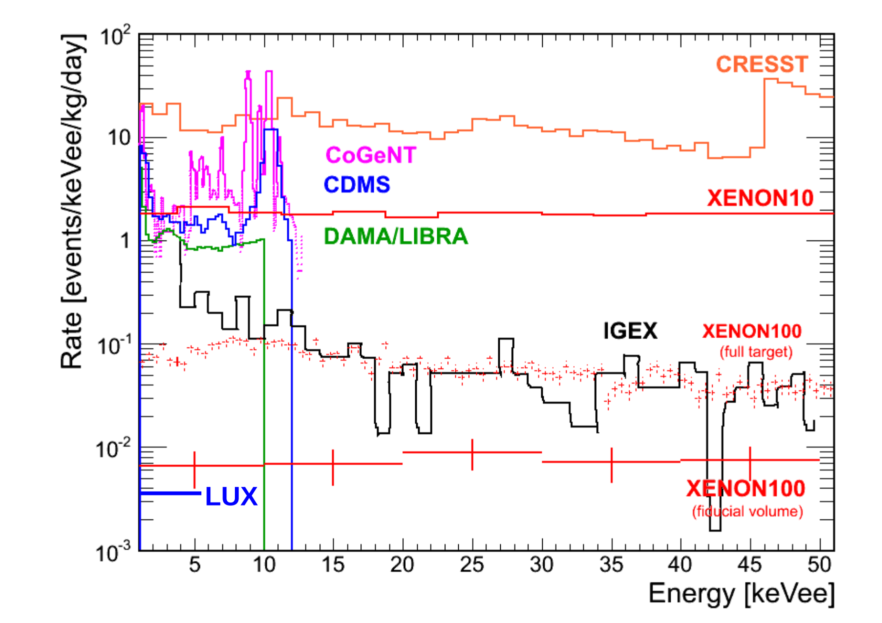
- the path towards an extremely low threshold
  - → XENON10 low-mass limit *PRL 110, 249901 (2013)*
- observed signals are mainly from photo-ionization of surfaces and impurities
  - → depends on LXe purity
  - → rate correlated to large S2 signal
  - → few e⁻ signals are accidental coincidences
- high stats sample to monitor detector stability
- allows for measurement of instrument parameters

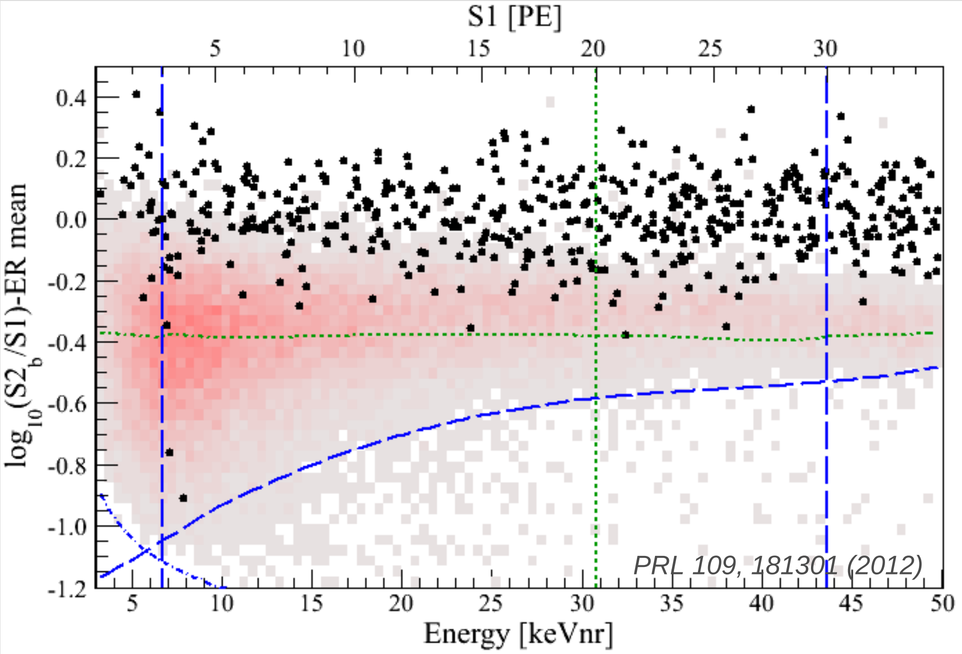
XENON100 Results

Background
among the lowest of all DM experiments

electronic recoils („background like")
rate = 0.0053 evts/keV$_{ee}$/kg/day *(in FV)*
PRD 83, 082001 (2011)

nuclear recoils („signal like")
rate = 0.000003 evts/keV$_{ee}$/kg/day *(in FV)*
J. Phys G 40, 115201 (2013)



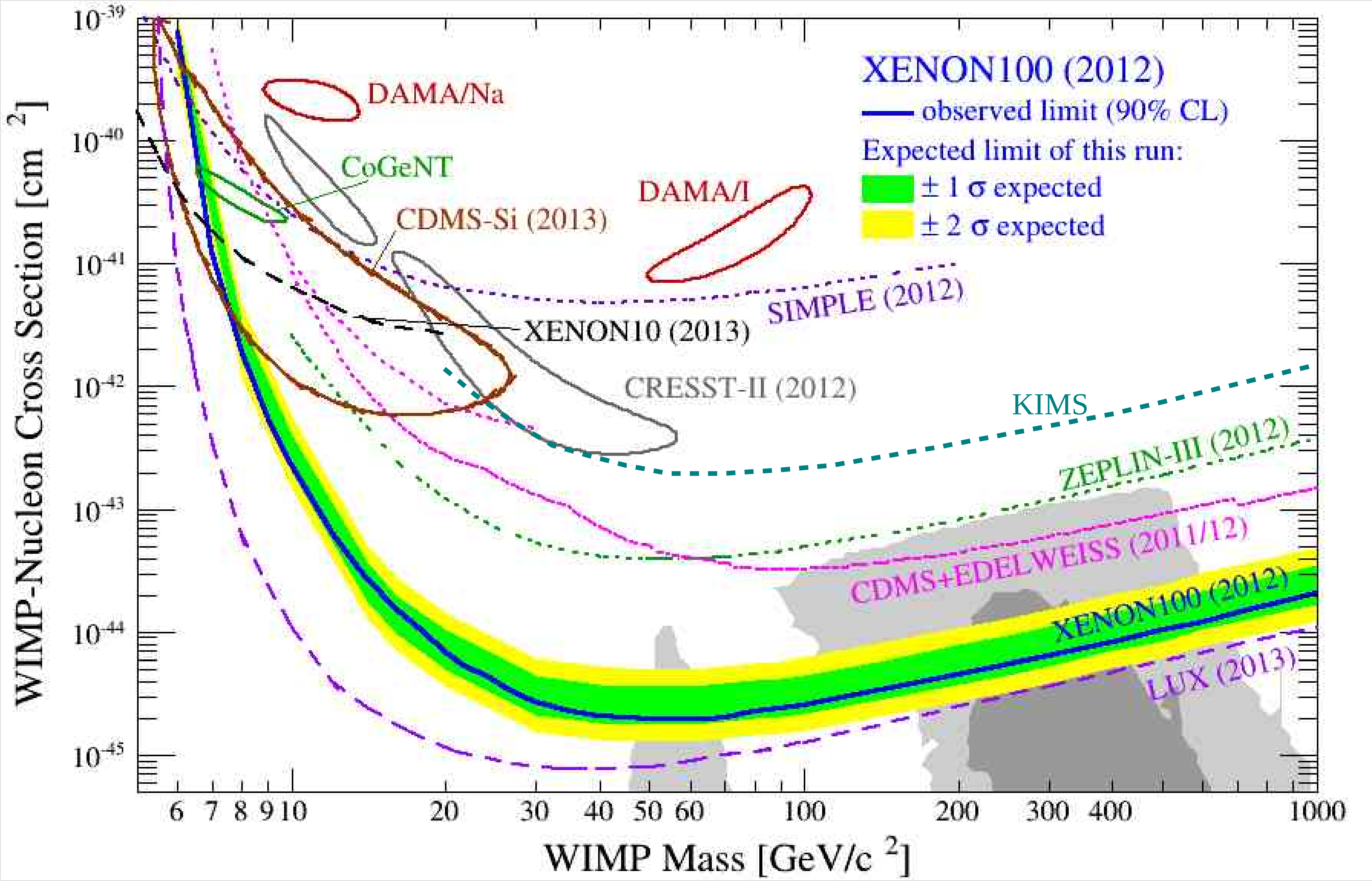


Last science run *PRL 109, 181301 (2012)*

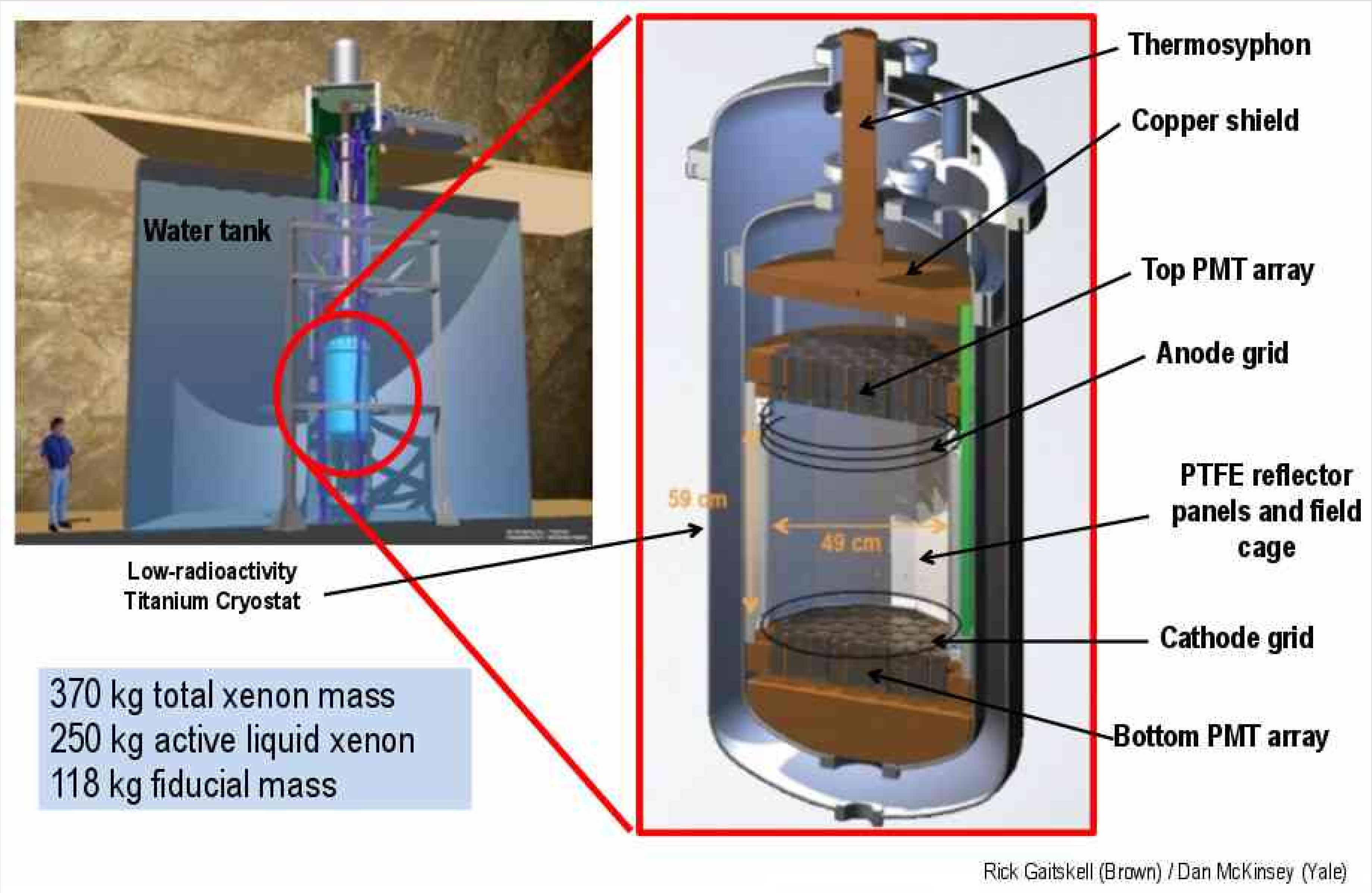
7636 kg x d raw exposure
2324 kg x d acpt. corrected (100 GeV/c²)

2 events observed
→ compatible with background expectation of (1.0±0.2) evt
→ best WIMP limit over large mass range (at time of publication)

The current WIMP Landscape



LUX

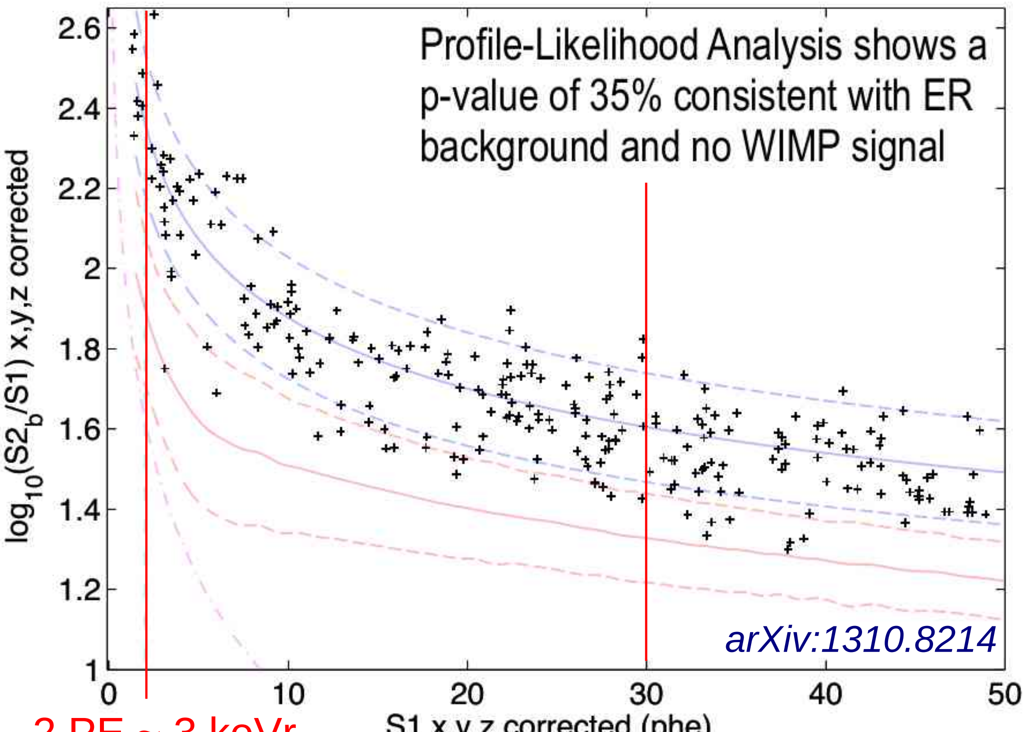


370 kg total xenon mass
250 kg active liquid xenon
118 kg fiducial mass

LUX @ SURF

Raw exposure: 118 kg x 85.3 d = 10065 kg d
(XENON100): 34 kg x 224.6 d = 7636 kg d

Non-blind analysis, only a few cuts
High light yield, rather low E-field (0.18 kV/cm)



2 PE ~ 3 keVr

LUX @ SURF

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(XENON100): 34 kg x 224.6 d = 7636 kg d

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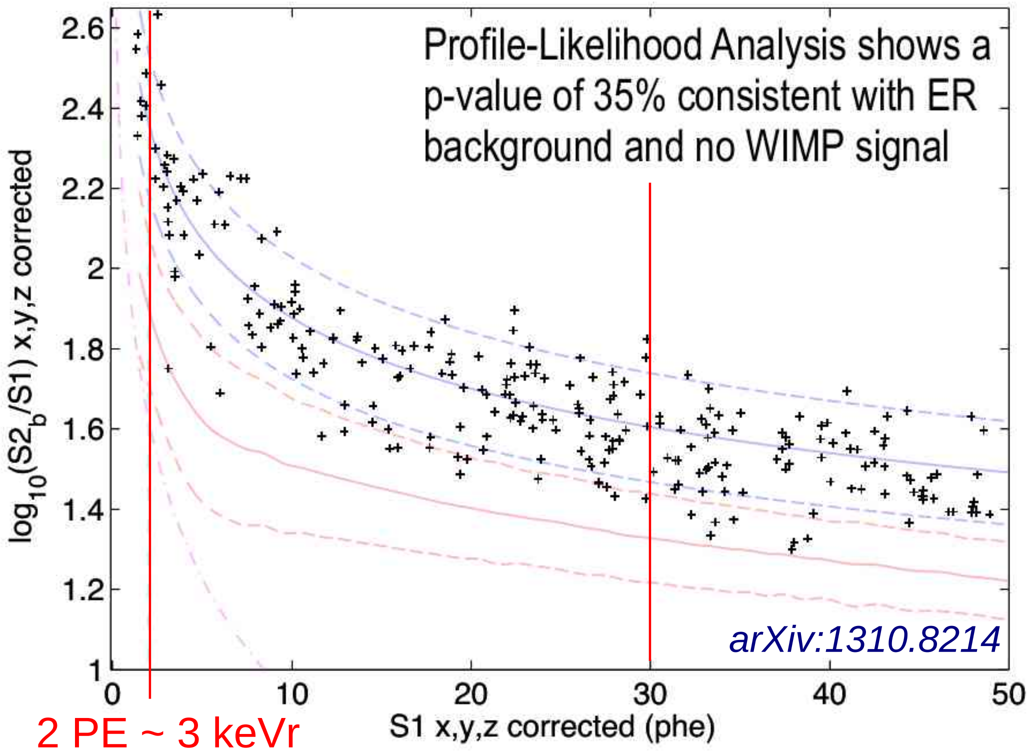
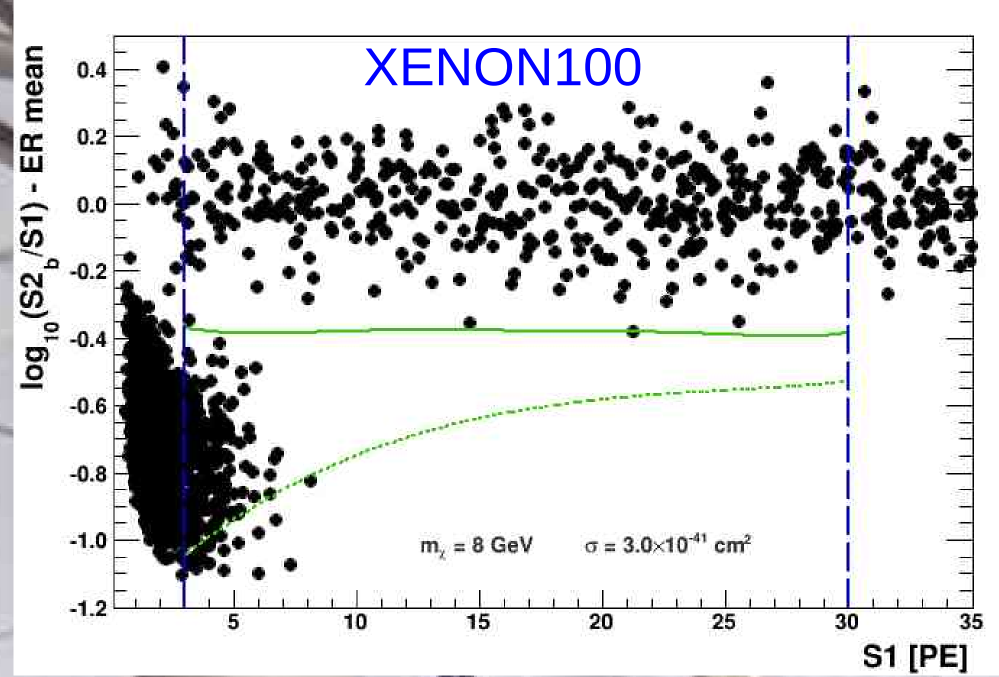
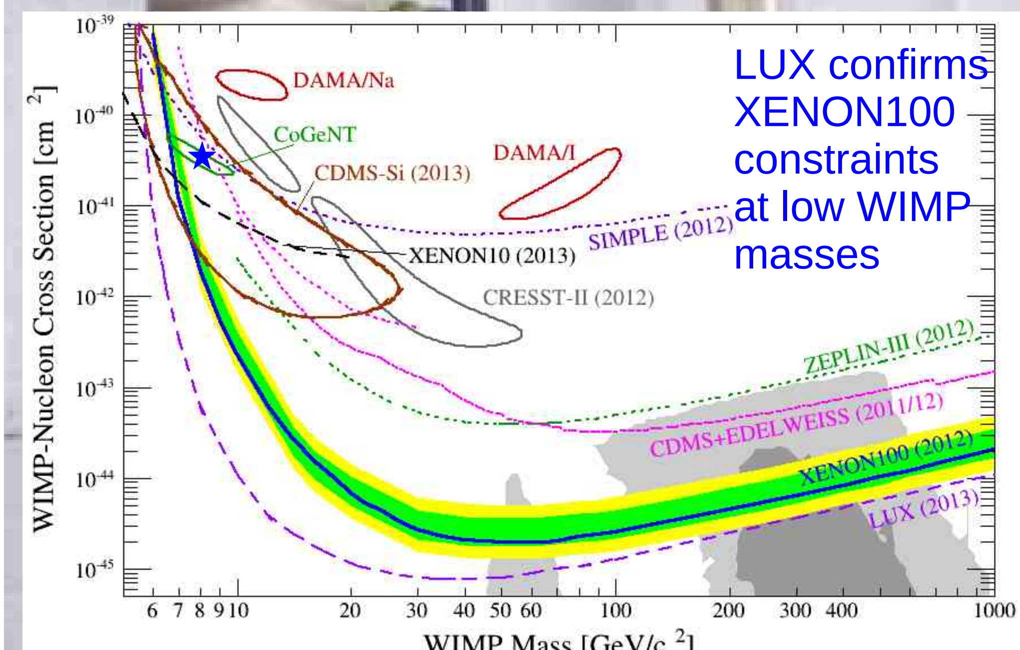
High light yield, rather low E-field (0.18 kV/cm)





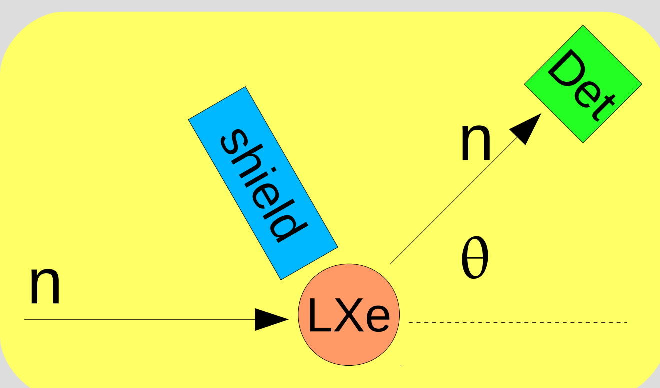


Nuclear Recoil Energy Scale

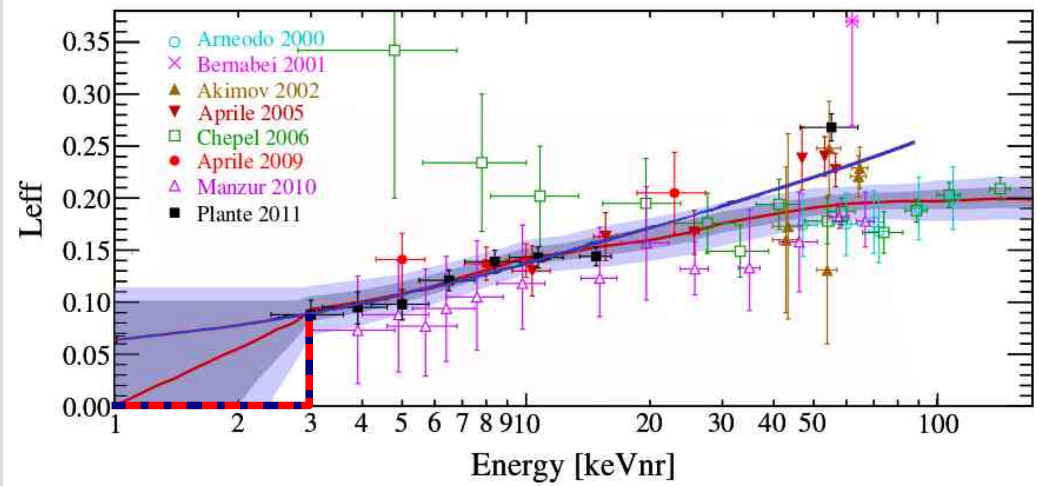
- WIMPs interact with Xe nucleus
  ➞ nuclear recoil (*nr*) scintillation (β and γ's produce electronic recoils)
- absolute measurement of *nr* scintillation yield is difficult
  ➞ measure relative to ^{57}Co (122keV)
- relative scintillation efficiency *L*eff:

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

measurement principle:



average over all direct measurements

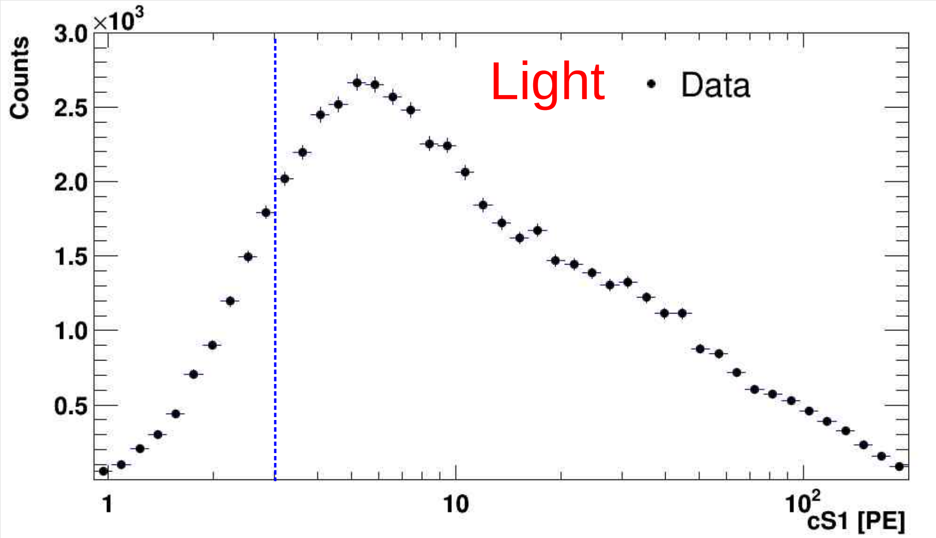


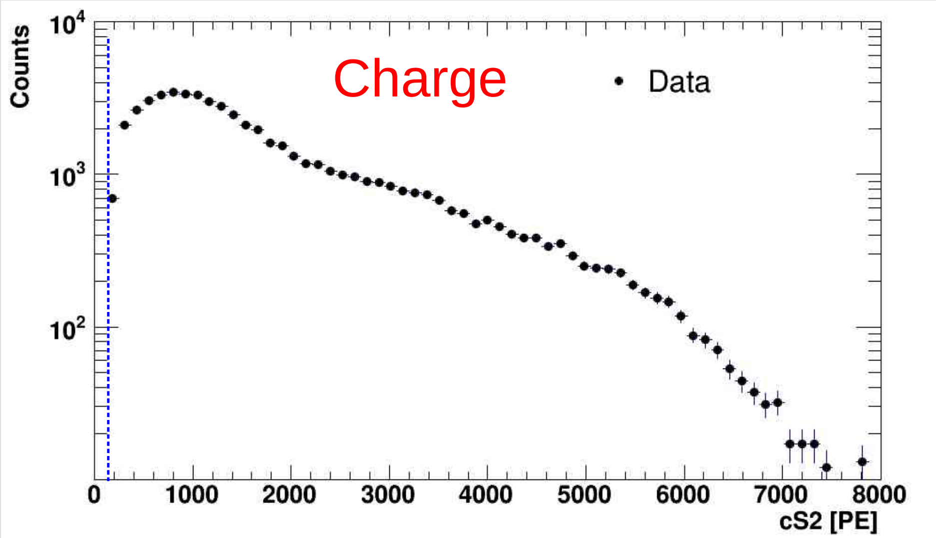
most recent measurements:
■ *Plante et al., PRC 84, 045805 (2011)*
△ *Manzur et al., PRC 81, 025808 (2010)*

– *parametrization used by XENON*
– *parametrization used by LUX*

XENON100: Low *E* response

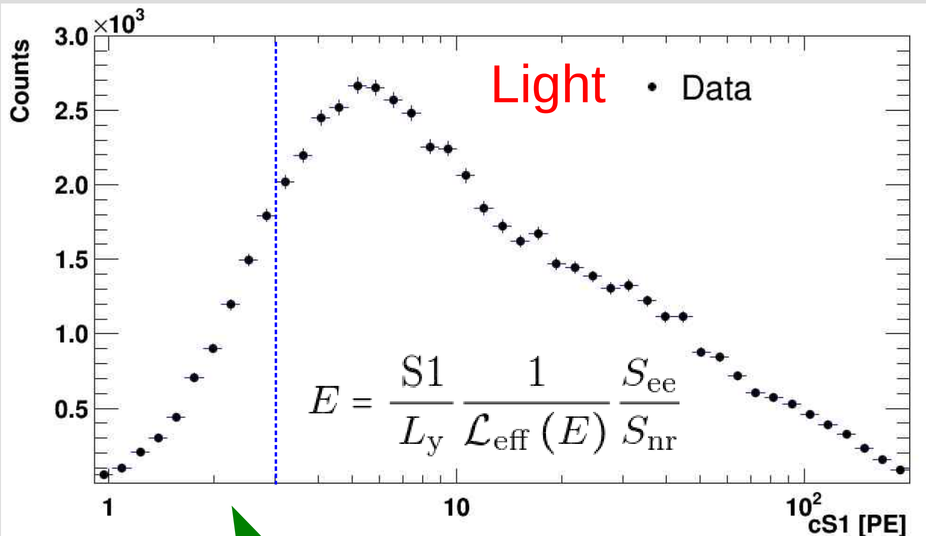
PRD 88, 012006 (2013)

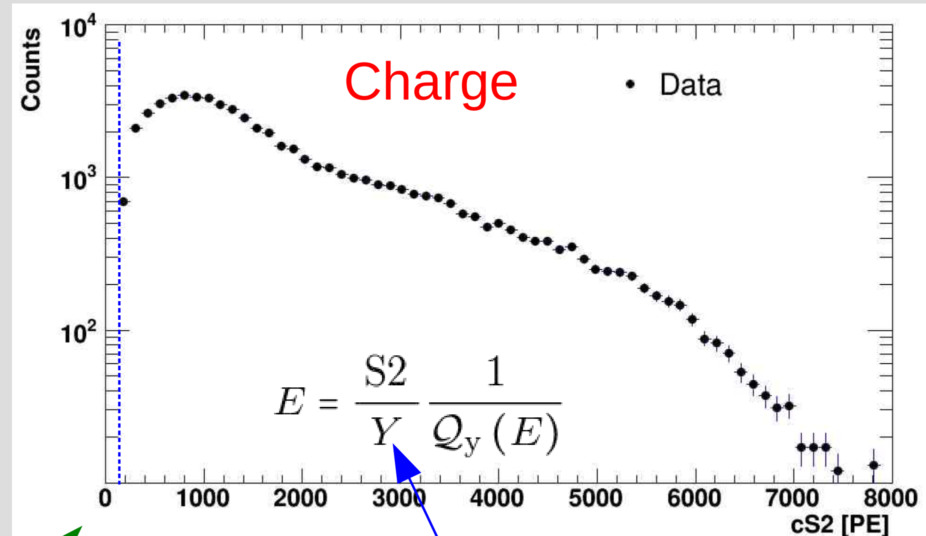


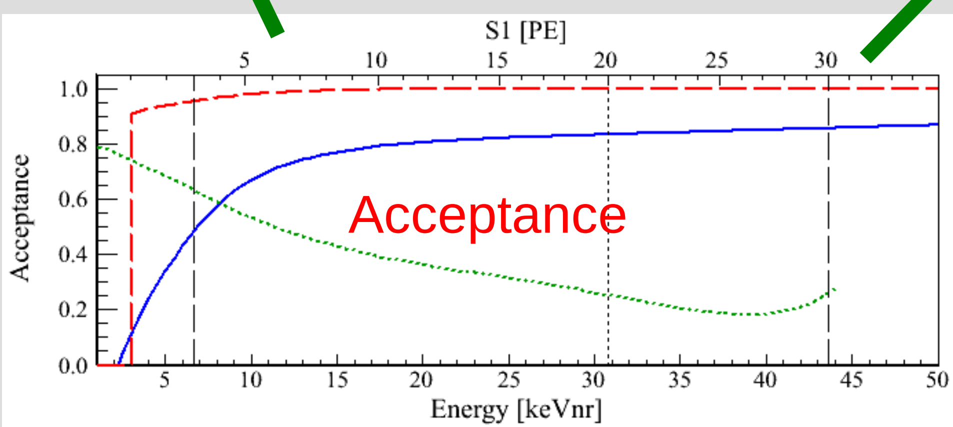


XENON100: Low *E* response

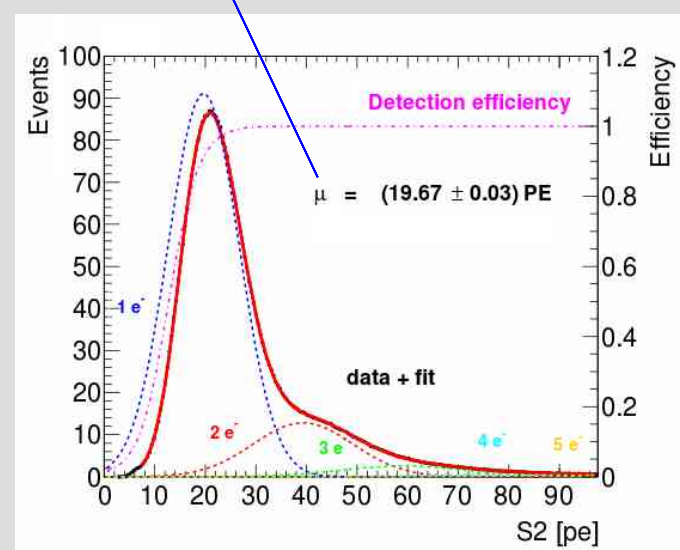
PRD 88, 012006 (2013)







PRL 109, 181301 (2012)

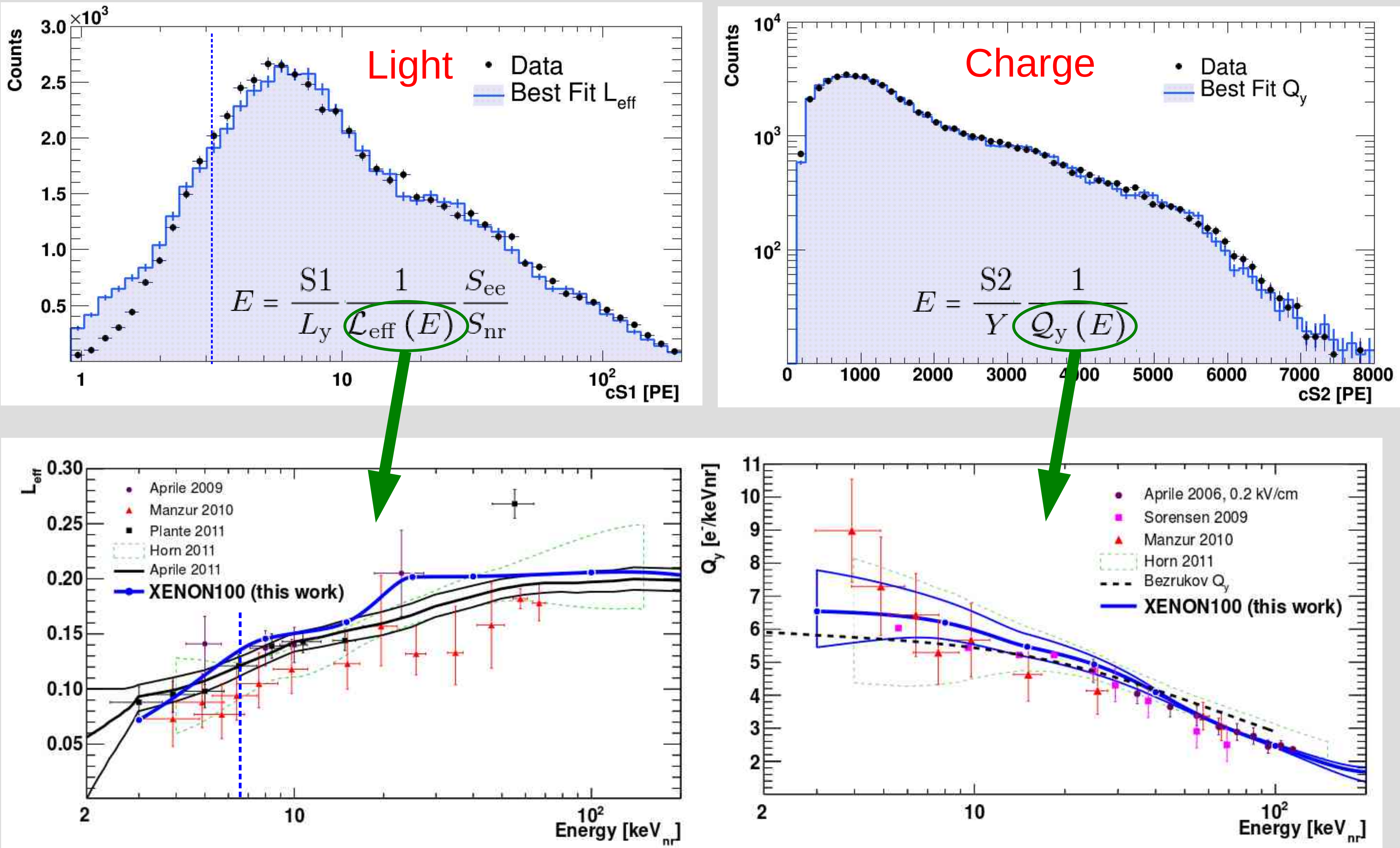


J. Phys. G 41, 035201 (2014)

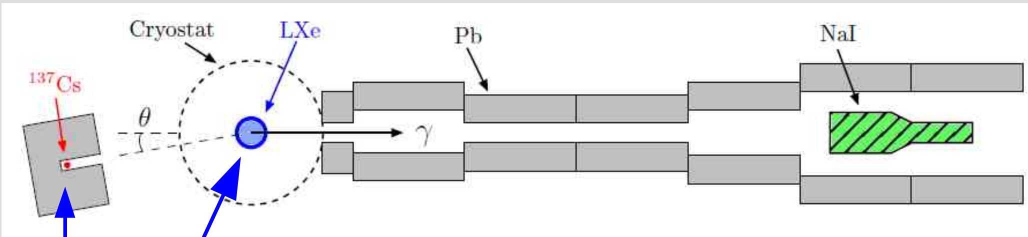
XENON100: Low *E* response

PRD 88, 012006 (2013)

→ successful absolute neutron data/MC matching down to ~3 keVr



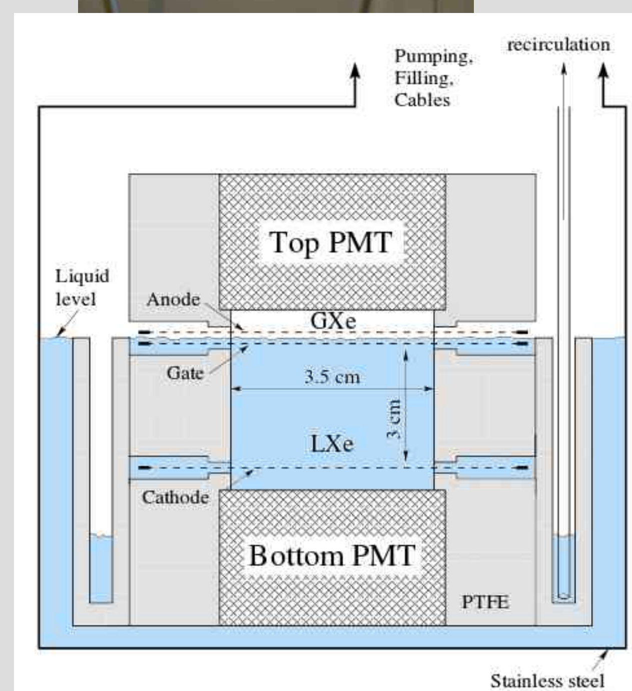
LXe Response to electronic recoils



$$E'_e(\phi) = E_\nu \left(1 - \frac{1}{1 + \frac{E_\nu}{m_e c^2}(1 - \cos(\phi))}\right)$$

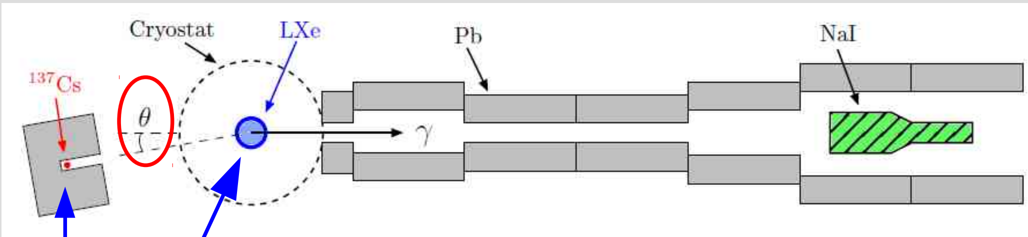
PRD 87, 115015 (2013)

Measure response of LXe to ERs of known energy in Compton scattering experiment



Rev. Sci. Instrum. 81, 073303 (2010)

LXe Response to electronic recoils



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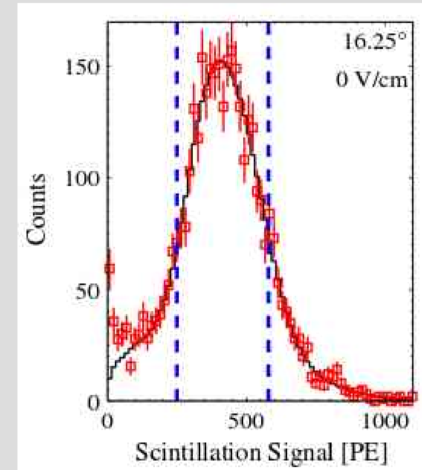
PRD 87, 115015 (2013)



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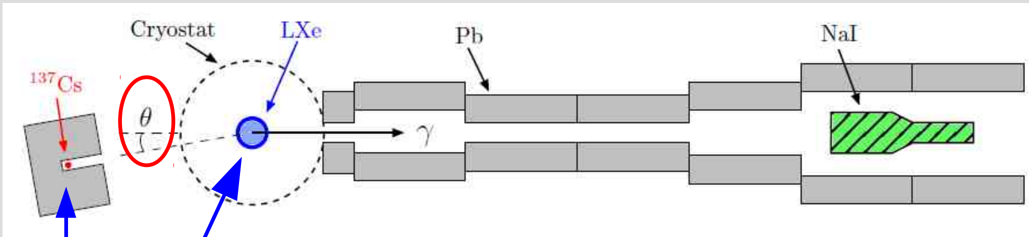

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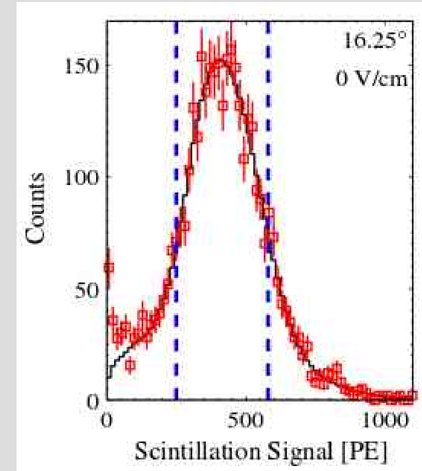
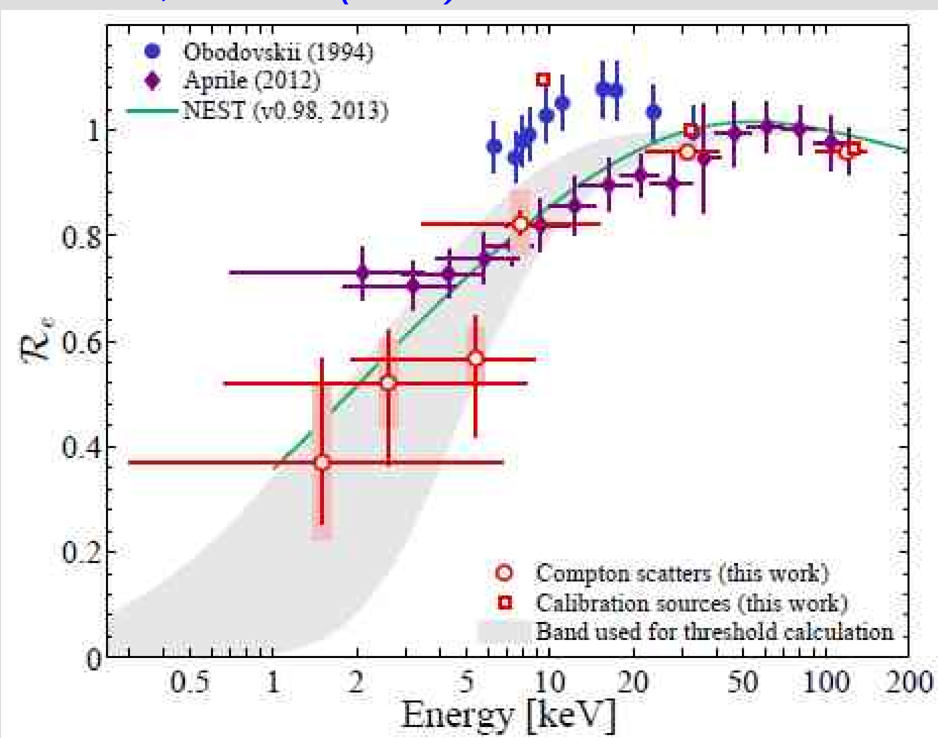
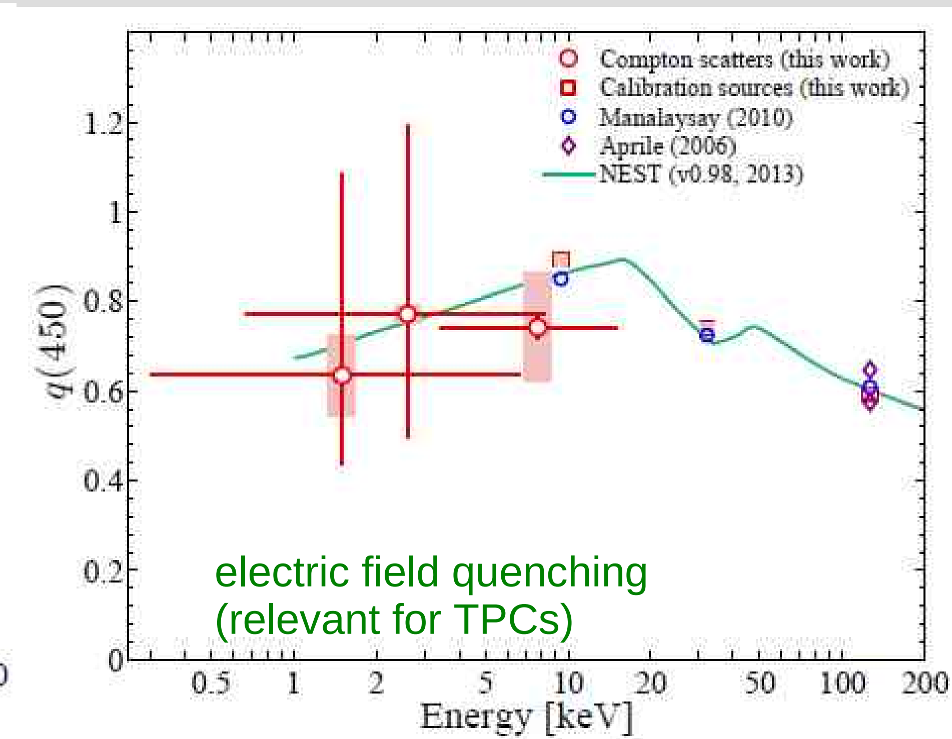
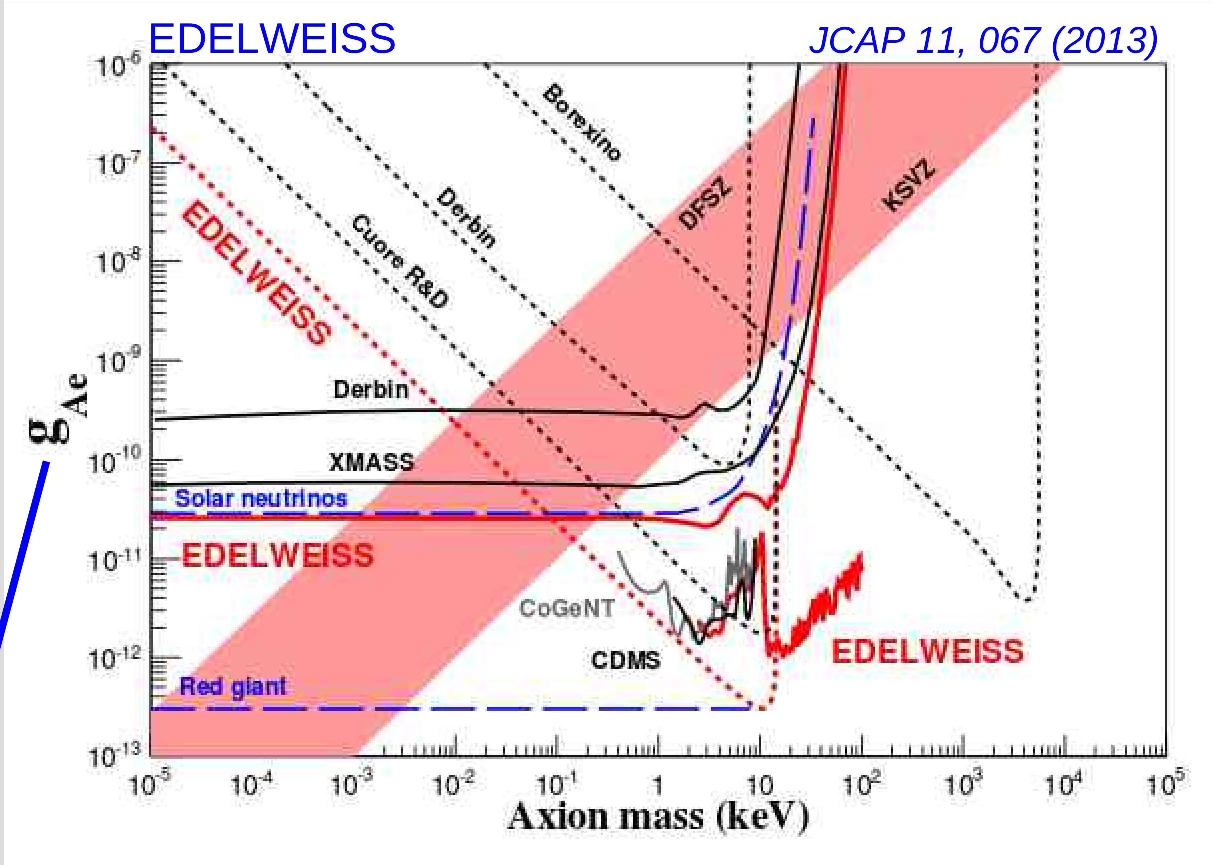


PRD 87, 115015 (2013)

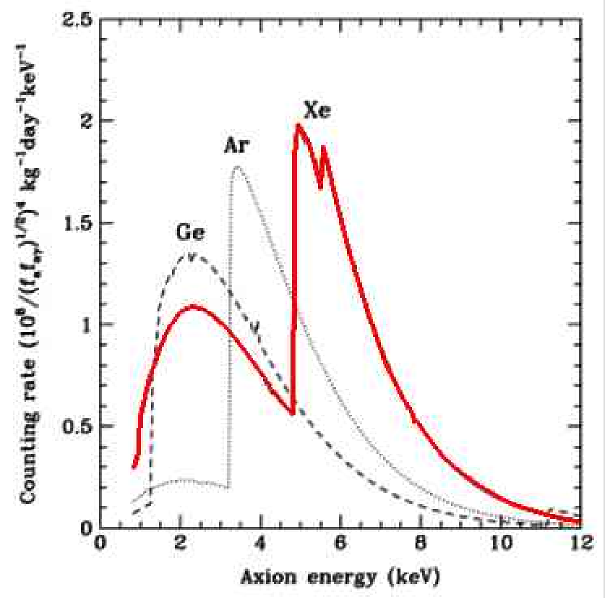




Axion-like Particles (ALPs)



Derevianko et al., PRD 82, 065006 (2010)

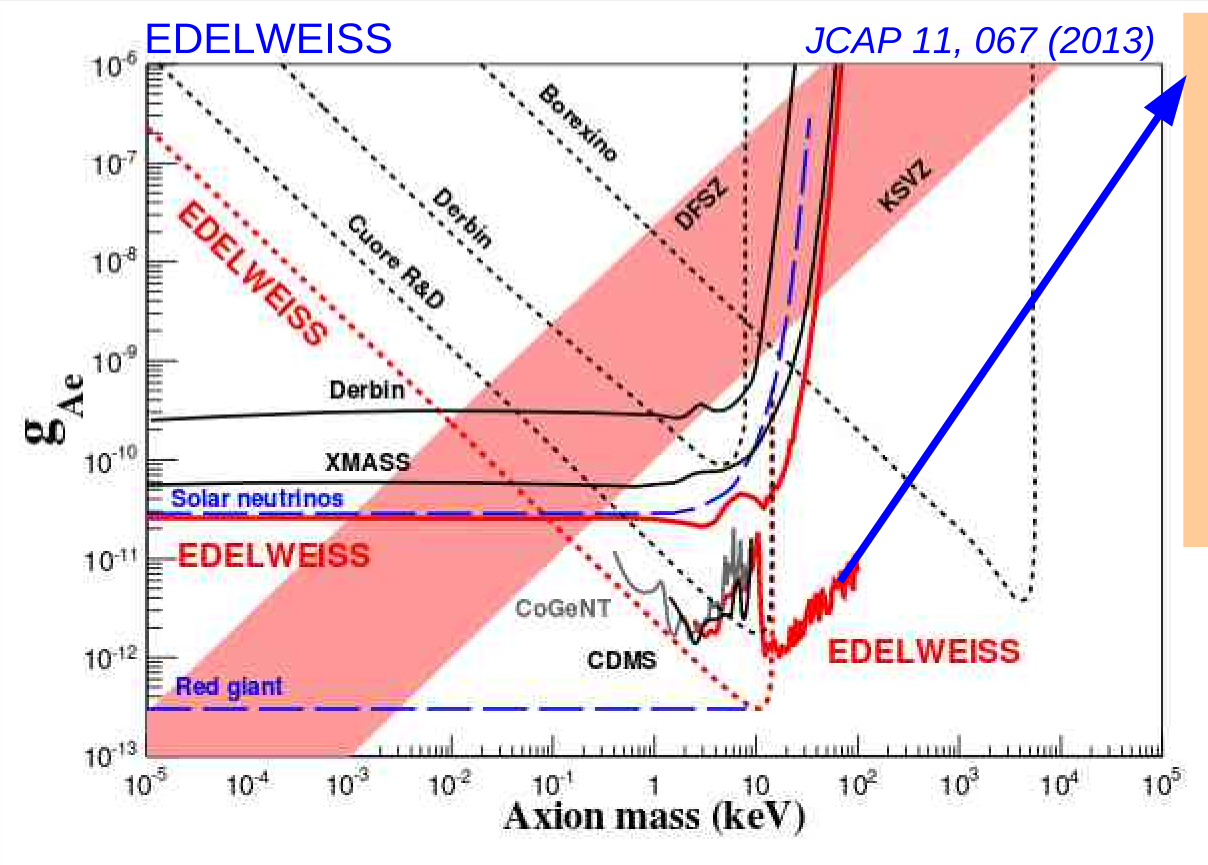


Axions and ALPs couple to xenon
via **axio-electric-effect**

$$\sigma_{Ae}(E_A) = \sigma_{pe}(E_A)\frac{g_{Ae}{}^2}{\beta_A}\frac{3E_A{}^2}{16\pi\,\alpha\,m_e{}^2}\left(1-\frac{\beta_A}{3}\right)$$

→ axion ionizes a Xe atom → produces an electronic recoil signal

Axion-like Particles (ALPs)



Galactic ALPs
assume that all local DM is made of ALPs.
ALPs created in early Universe

$$\Phi^{DM} = 9.0 \times 10^{15} \frac{\text{keV}}{m_A} \beta_m$$

$$\frac{dR^{DM}}{dm_A} = \sigma_A \Phi^{DM} = \left(\frac{1.29 \times 10^{19}}{A}\right) g_{Ae}^2 \, m_A \sigma_{pe}$$

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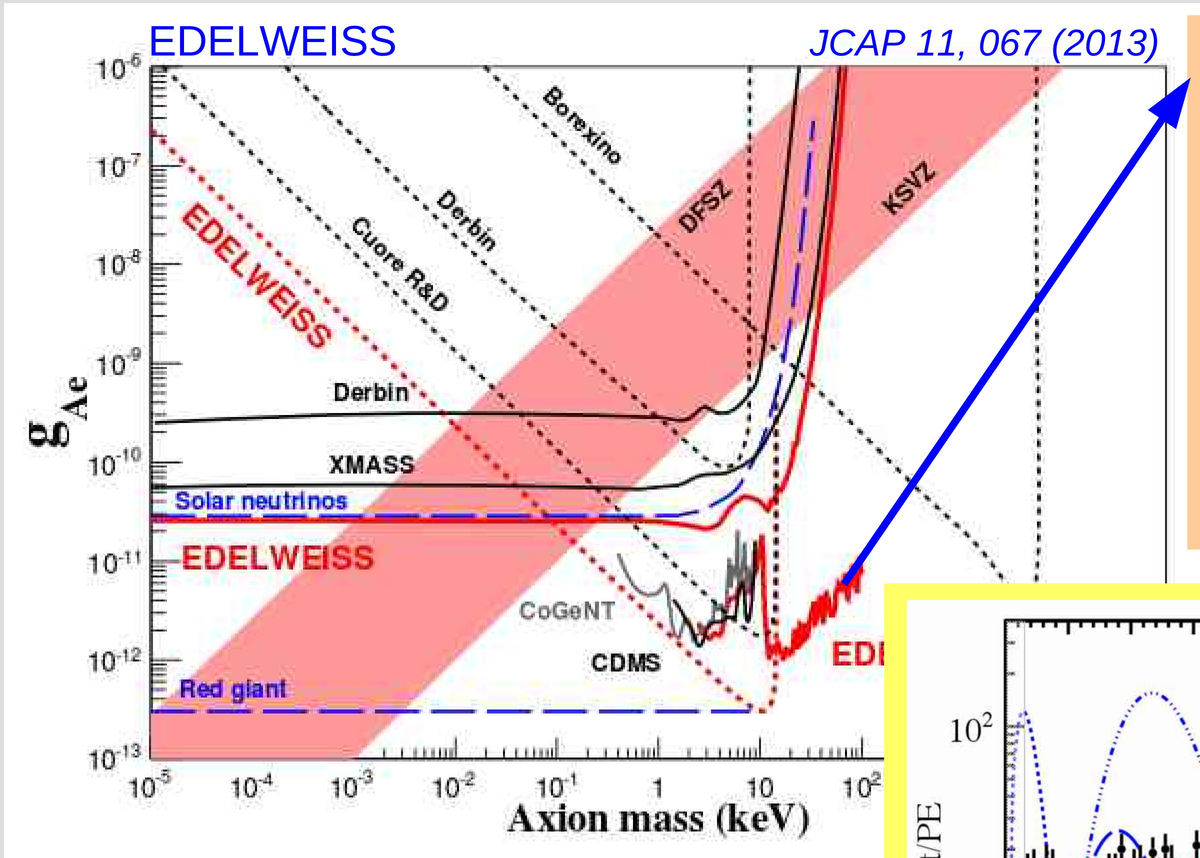

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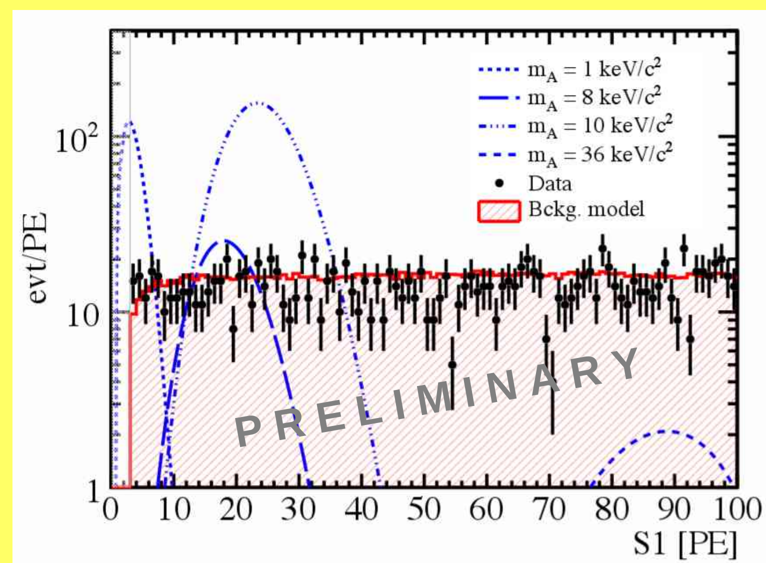


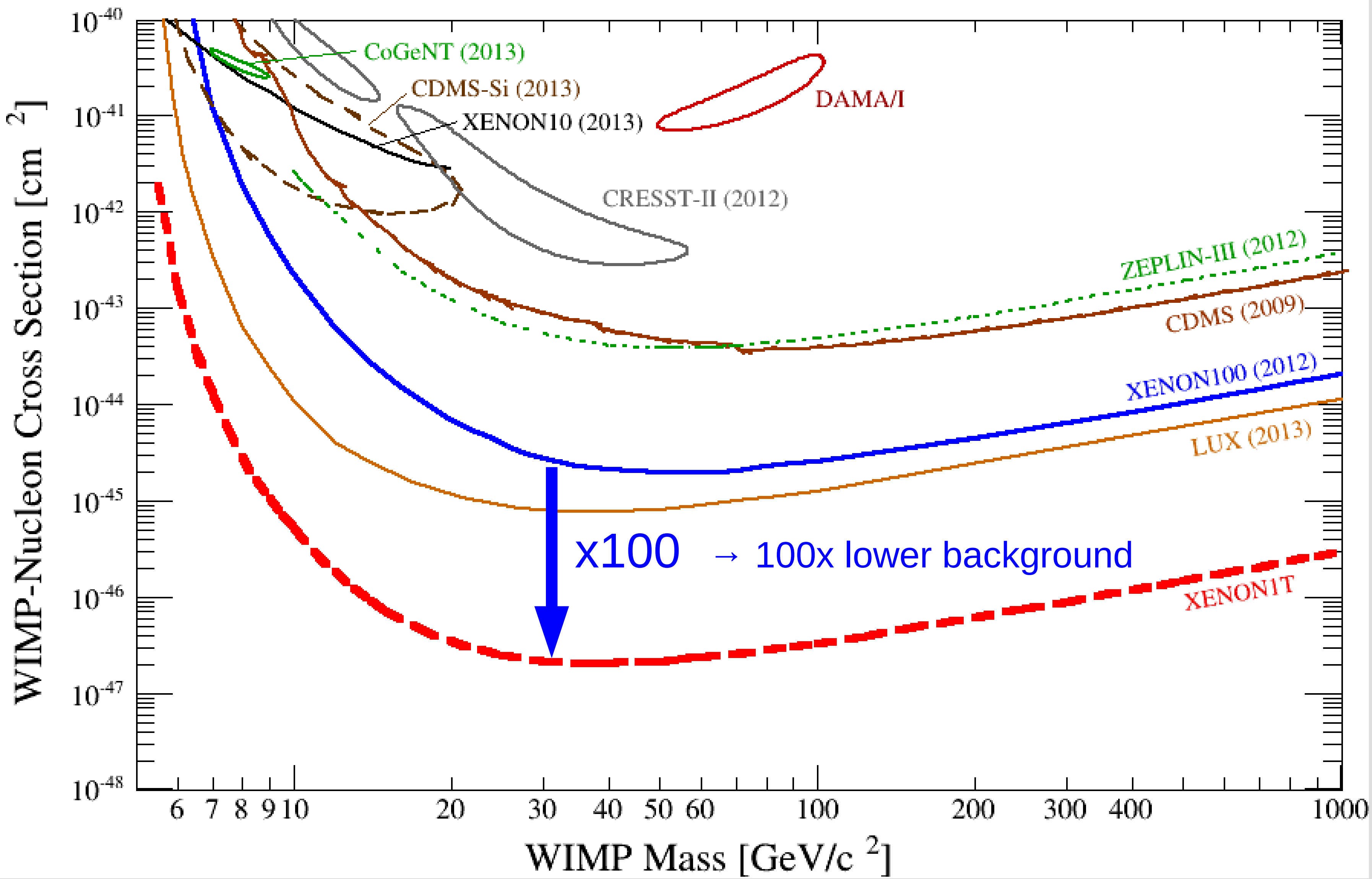
XENON100 analysis ongoing...

Axions and ALPs couple to xenon via **axio-electric-effect**

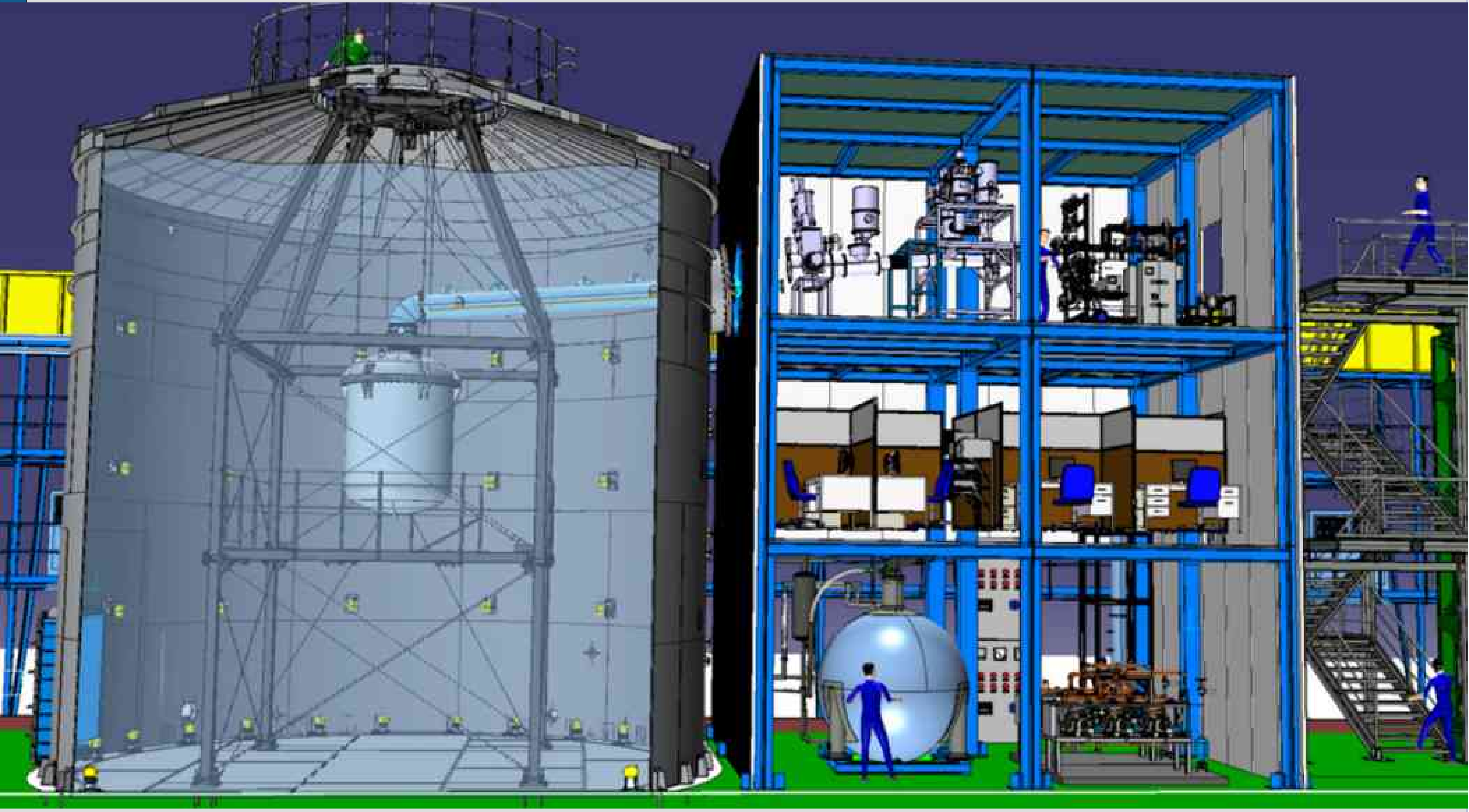
$$\sigma_{Ae}(E_A) = \sigma_{pe}(E_A) \frac{{g_{Ae}}^2}{\beta_A} \frac{3{E_A}^2}{16\pi\,\alpha\,{m_e}^2} \left(1 - \frac{\beta_A}{3}\right)$$

→ axion ionizes a Xe atom

The XENON Future



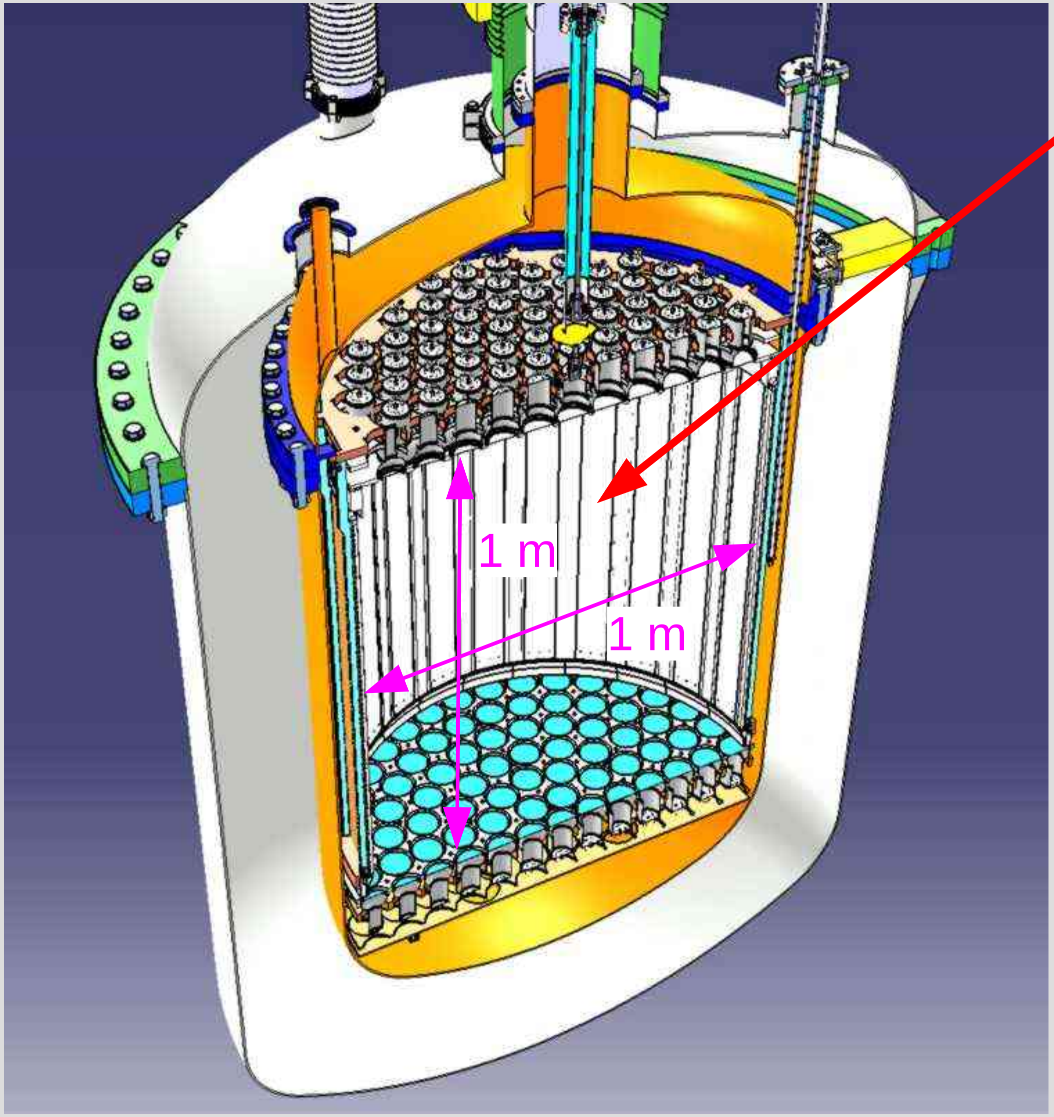
XENON1T in Hall B @ LNGS



XENON1T in Hall B @ LNGS

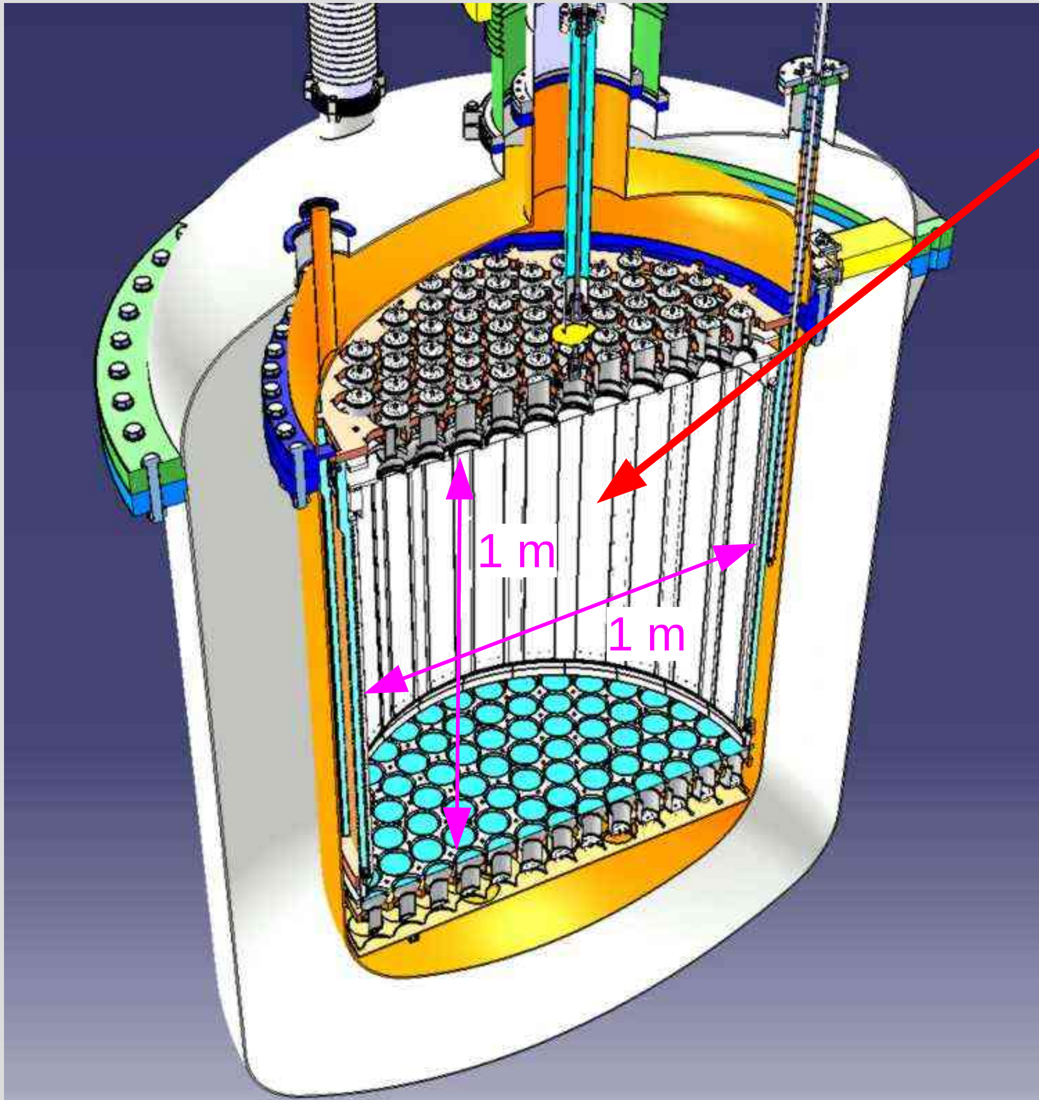
project approved and funded,
construction ongoing

XENON1T



dual-phase LXe TPC
- total mass ~3 t
- active mass ~2.2 t
- fiducial mass: ~1 t

XENON1T



dual-phase LXe TPC
- total mass ~3 t
- active mass ~2.2 t
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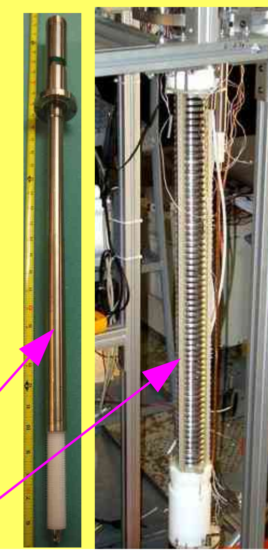
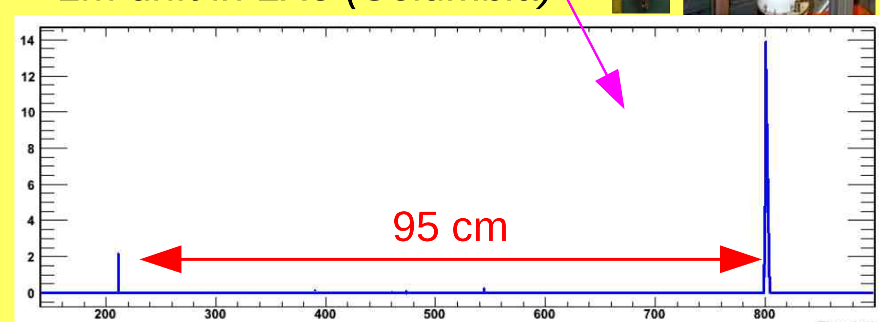
Some challenges
- high voltage: ~100 kV
- long electron drift
  → LXe purification

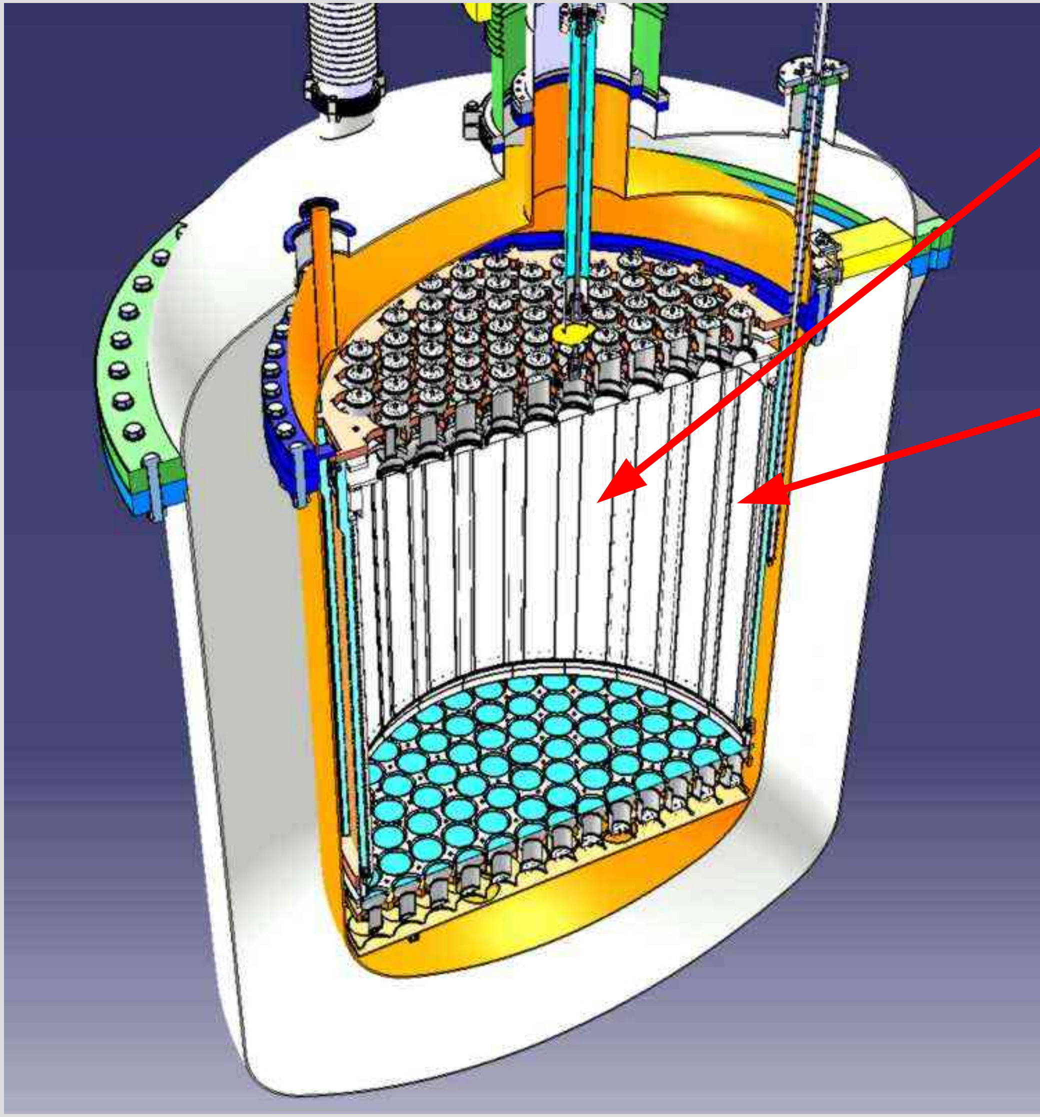


HV Feedthrough (UCLA)

1m drift in LXe (Columbia)



XENON1T



dual-phase LXe TPC
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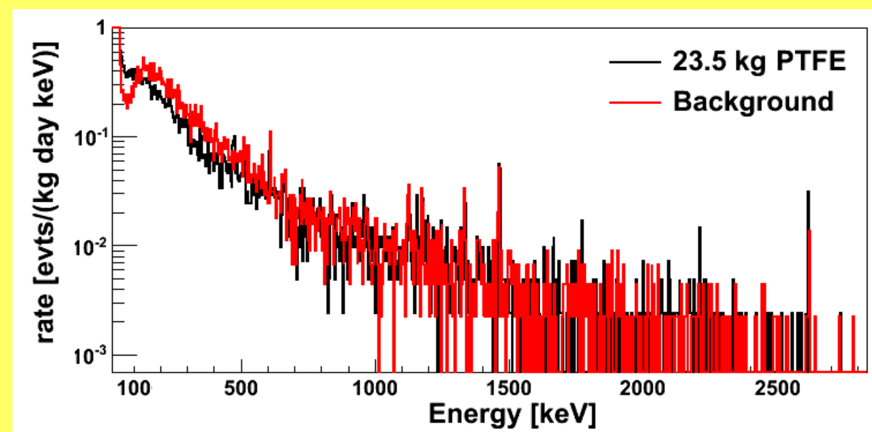
TPC made from OFHC and PTFE

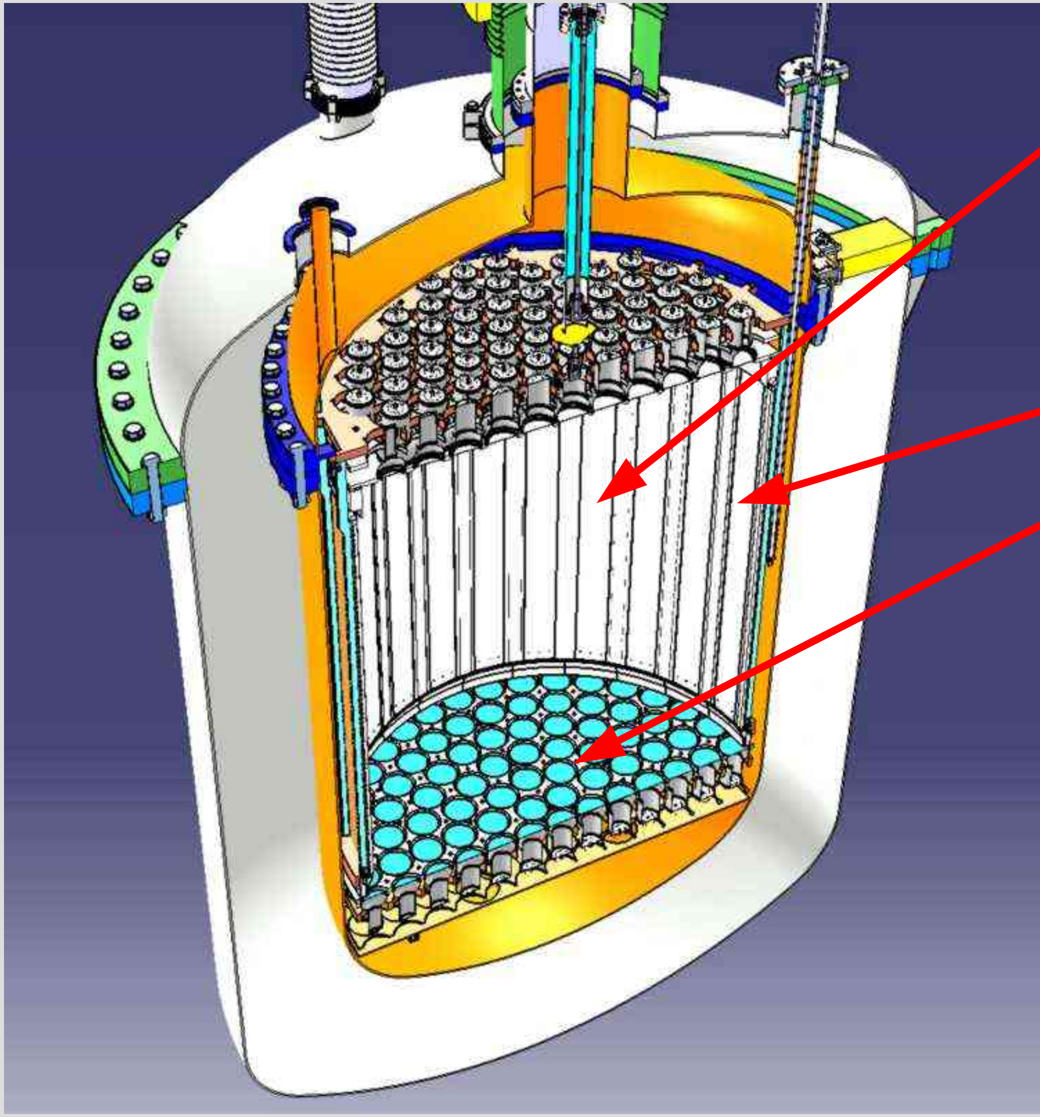
Material selection mandatory



Astropart. Phys. 35, 43 (2011)

→ process still ongoing

XENON1T



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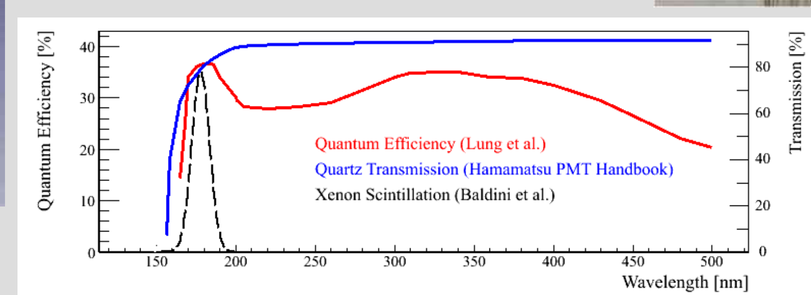
TPC made from OFHC and PTFE

248 photomultipliers
- Hamamatsu R11410-21
- low background
- high QE (36% @ 178nm)
- extensive testing in cryogenic environments *JINST 8, P04026 (2013)*

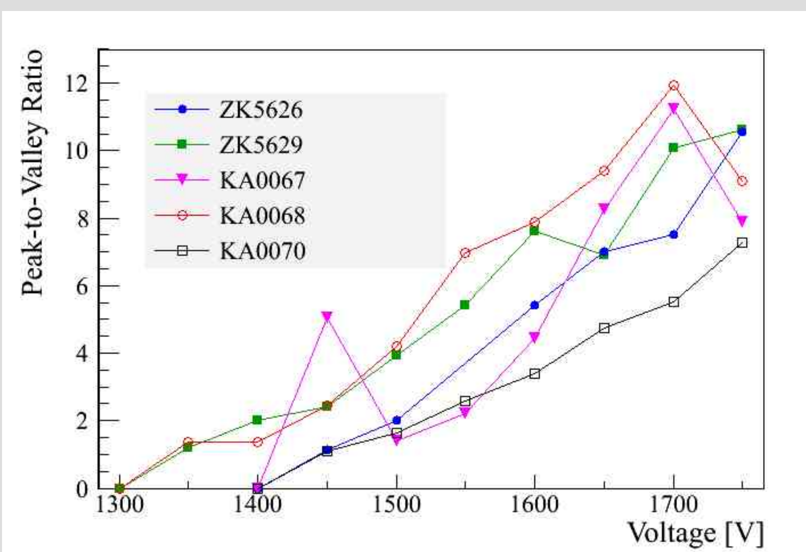


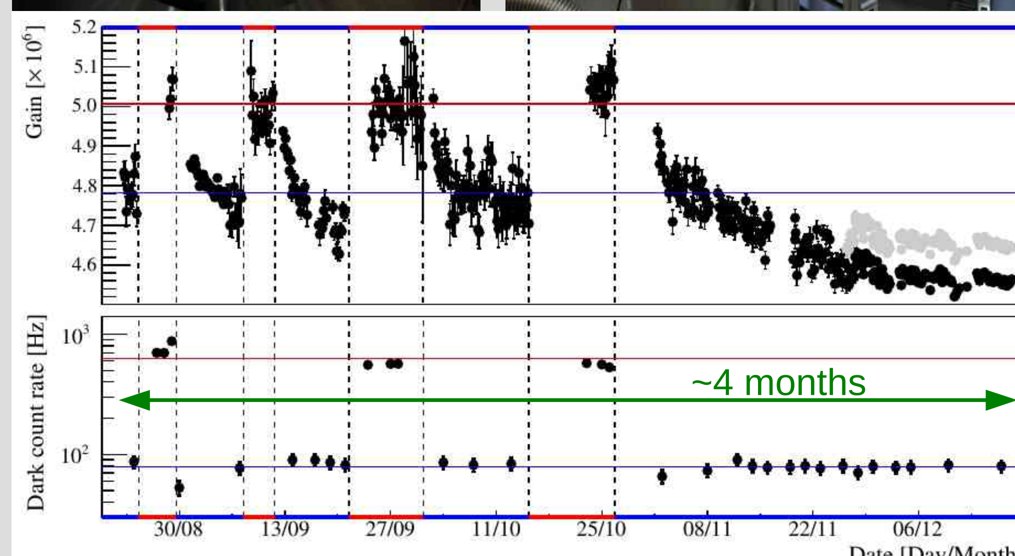
Low-background PMT: Tests

JINST 8, P04026 (2013)

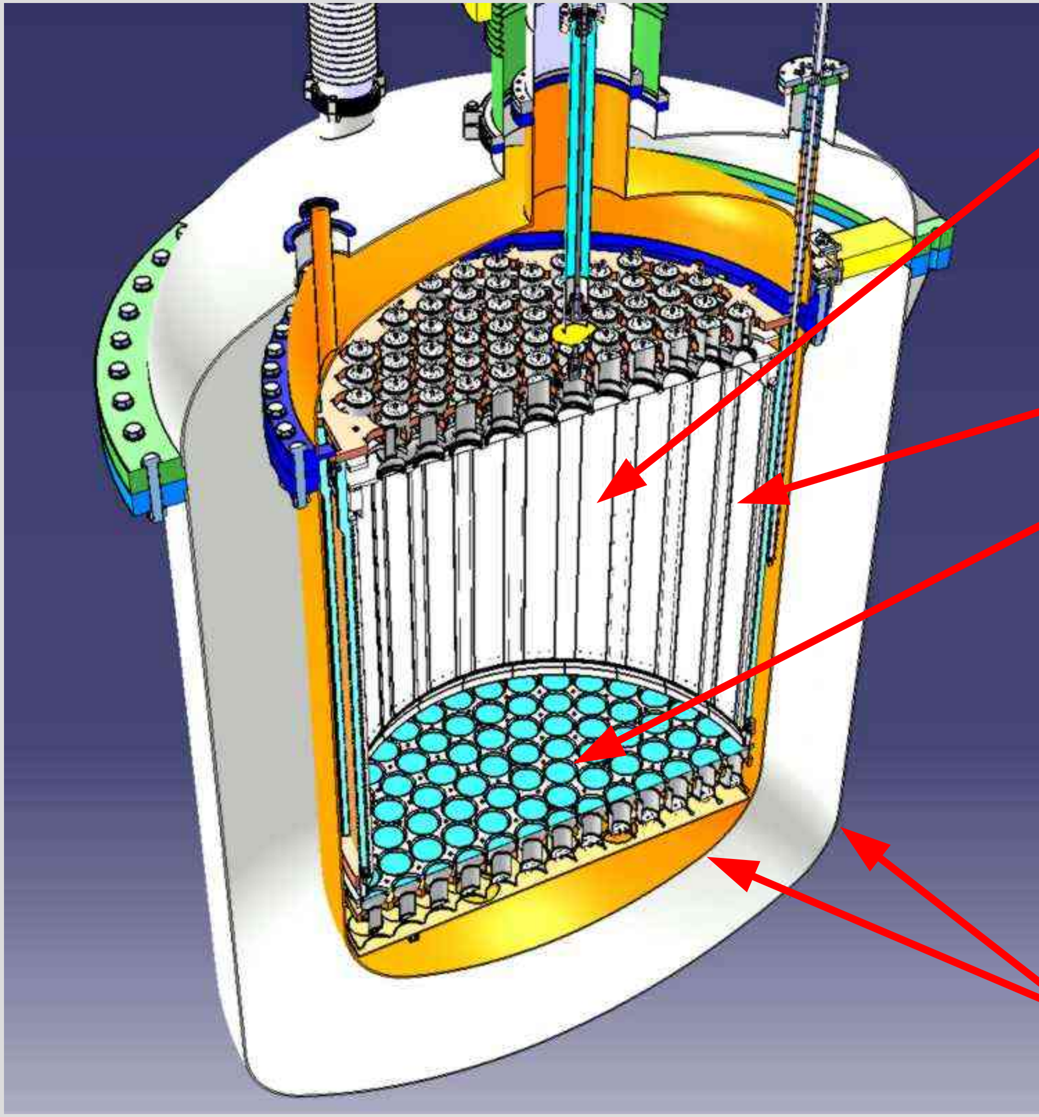
Hamamatsu R11410

- 3“ low-background PMT
- extensive laboratory tests:
  - general response
    - (gain, P/V, DC, afterpulses)
  - performance in LXe
  - performance in electric fields
  - intrinsic radioactive contamination





XENON1T



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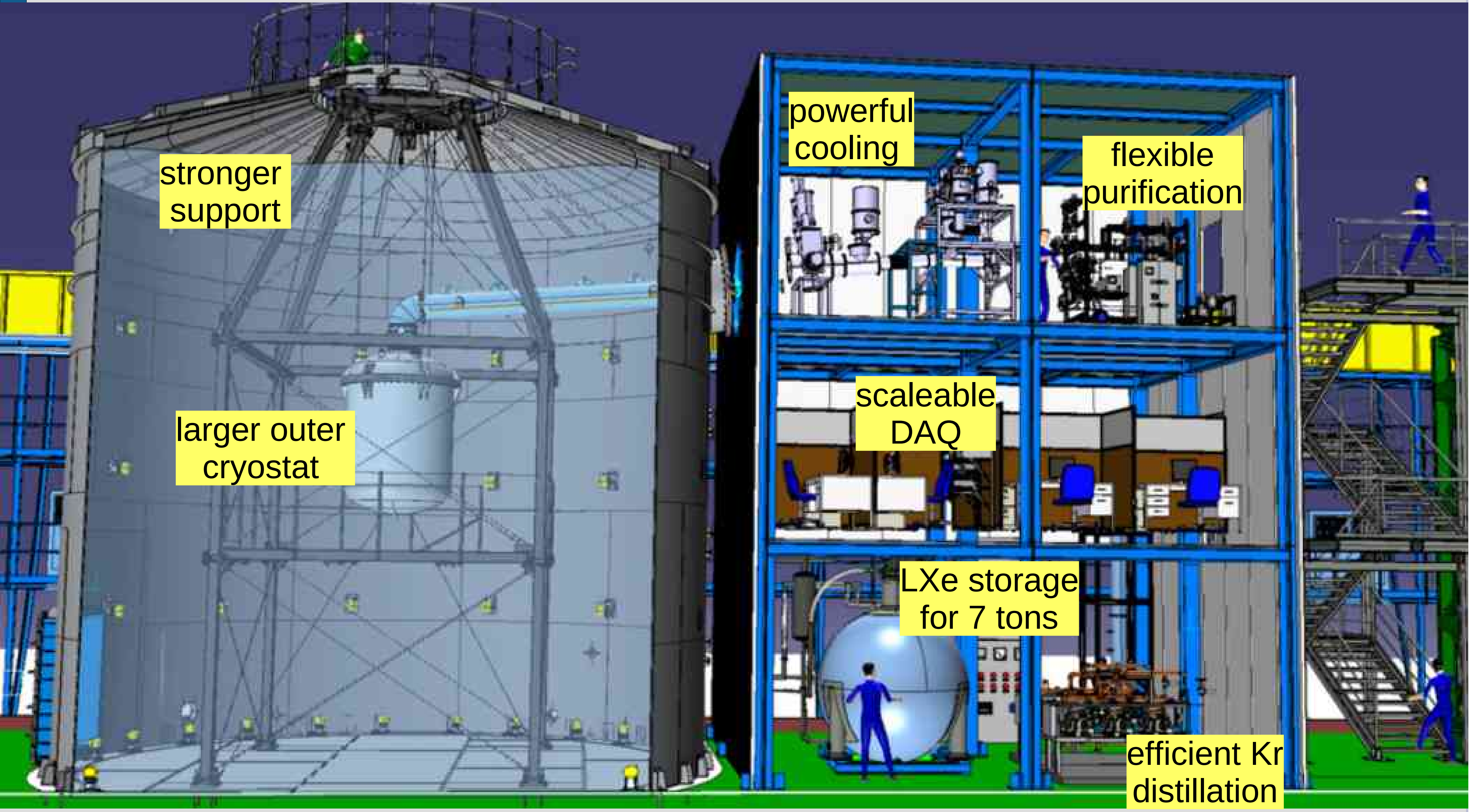
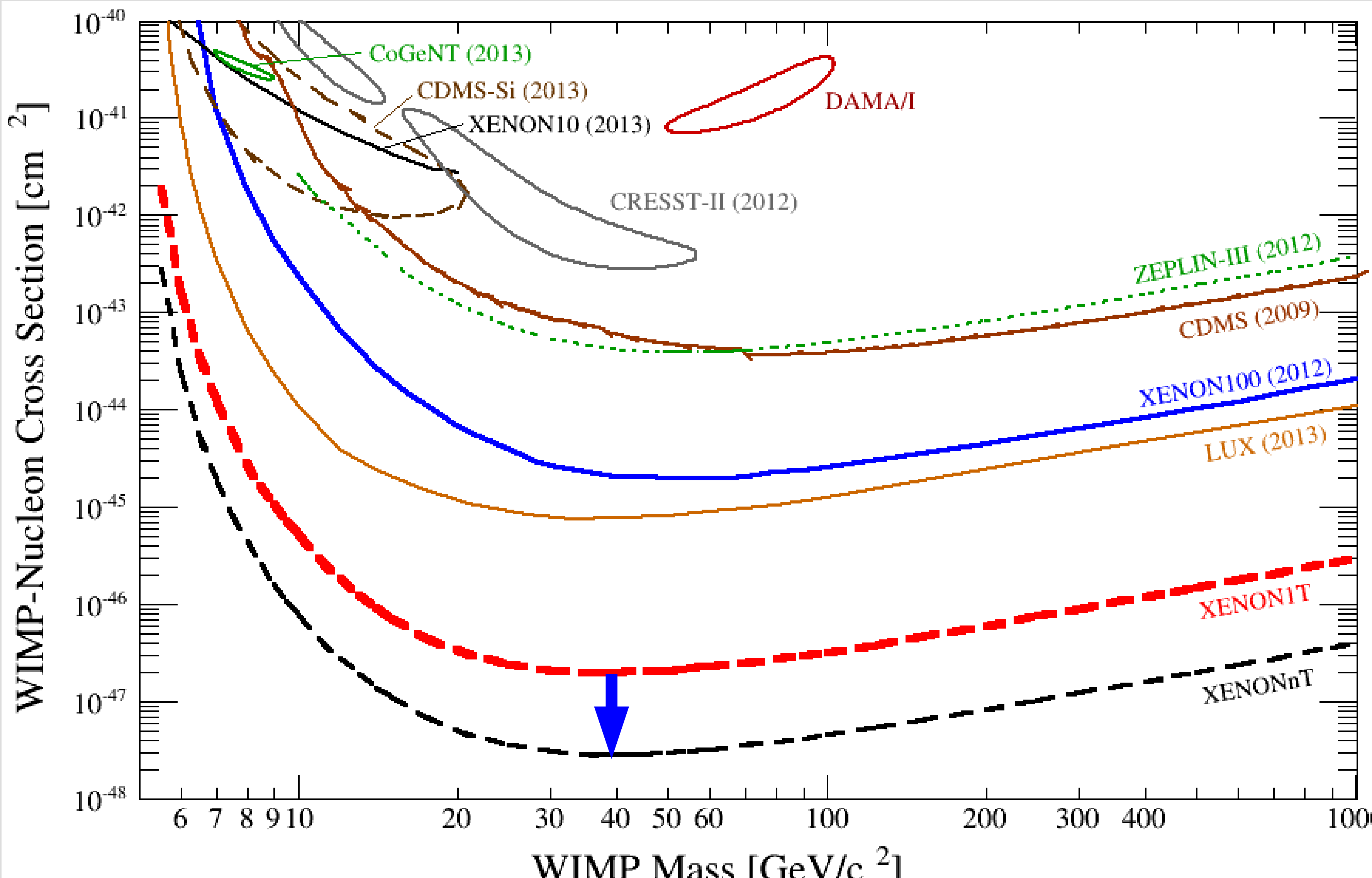
Low-background stainless steel cryostats

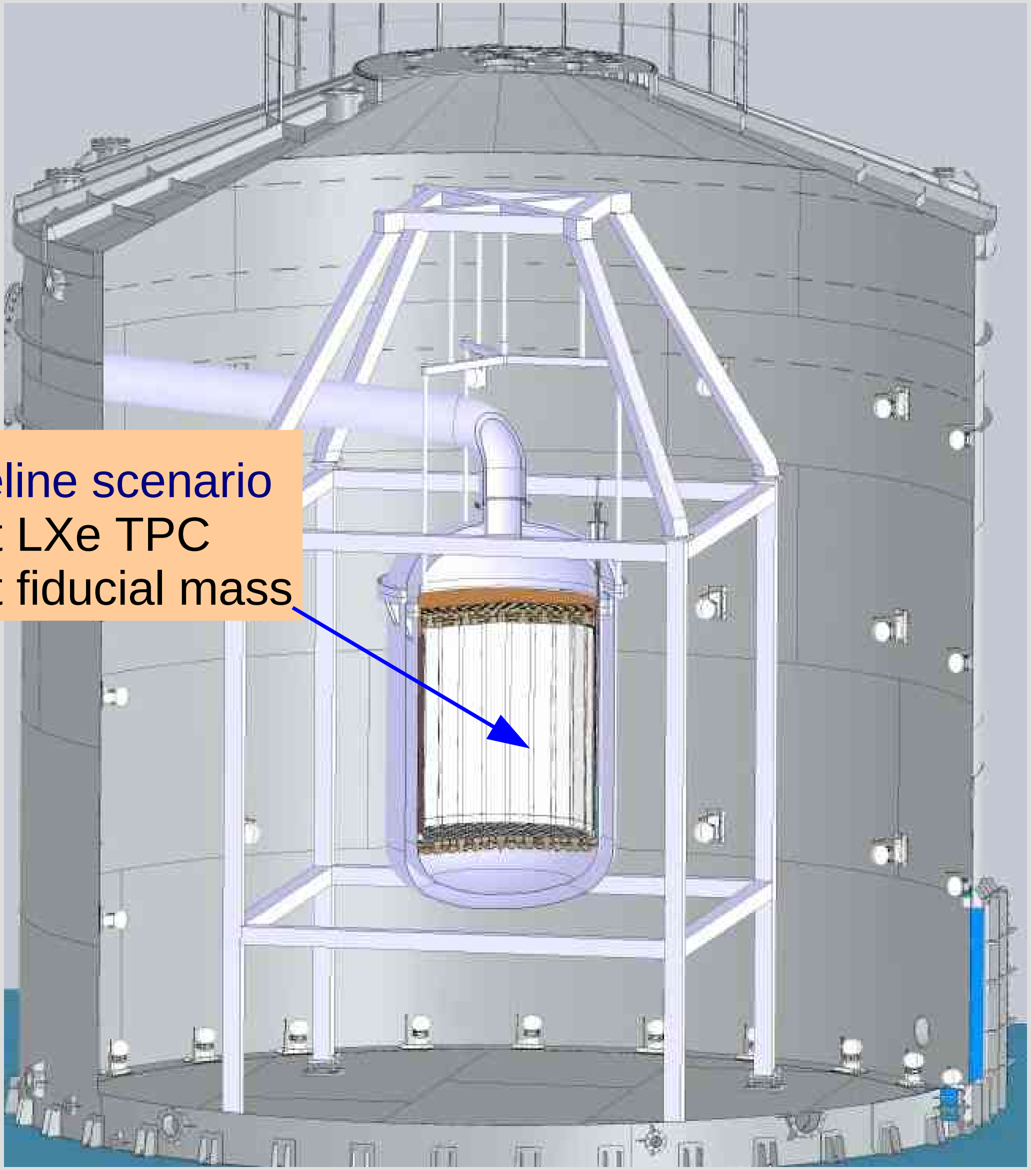
XENONnT in Hall B @ LNGS



The XENON Future



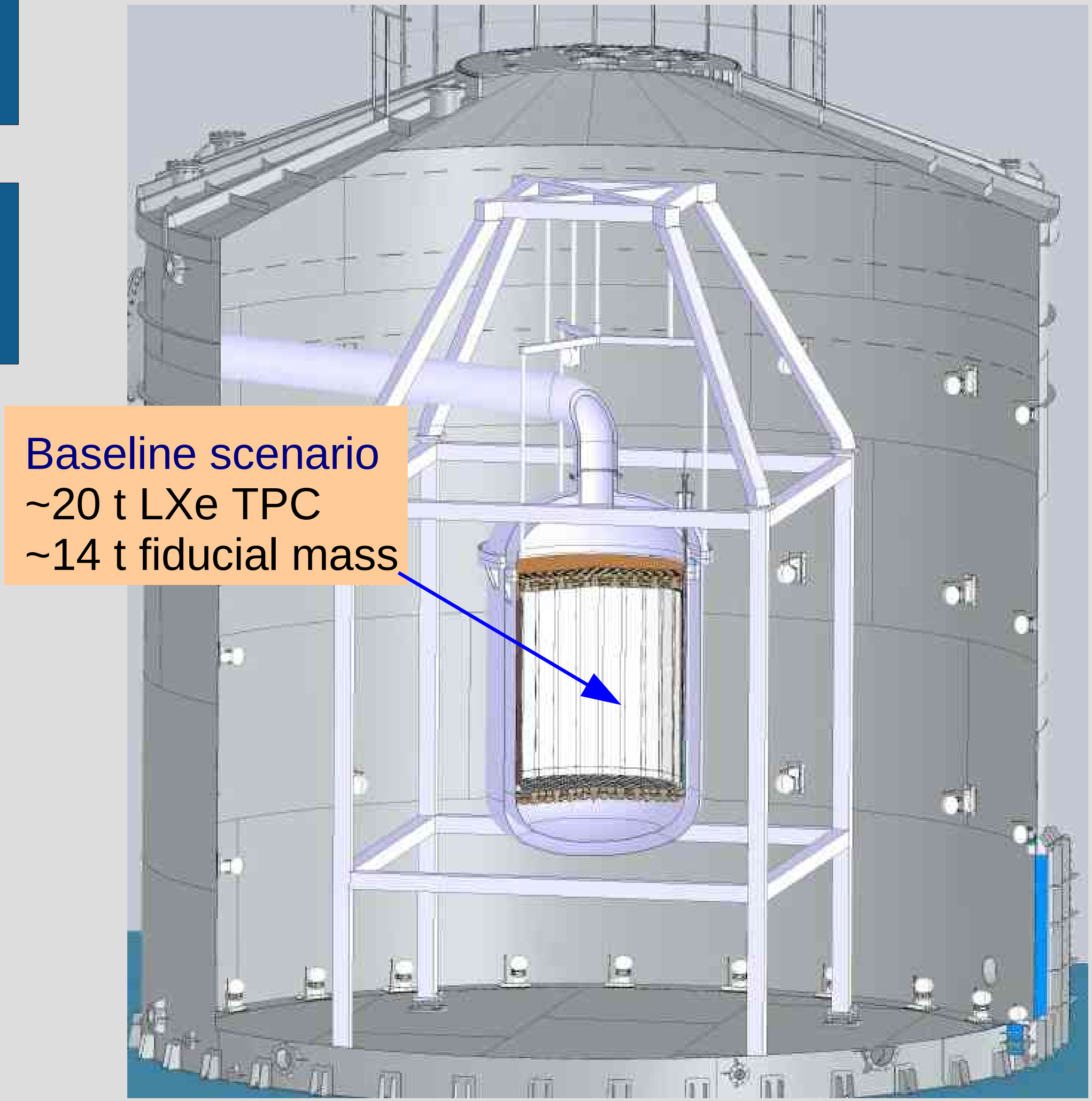
DARWIN The ultimate WIMP Detector



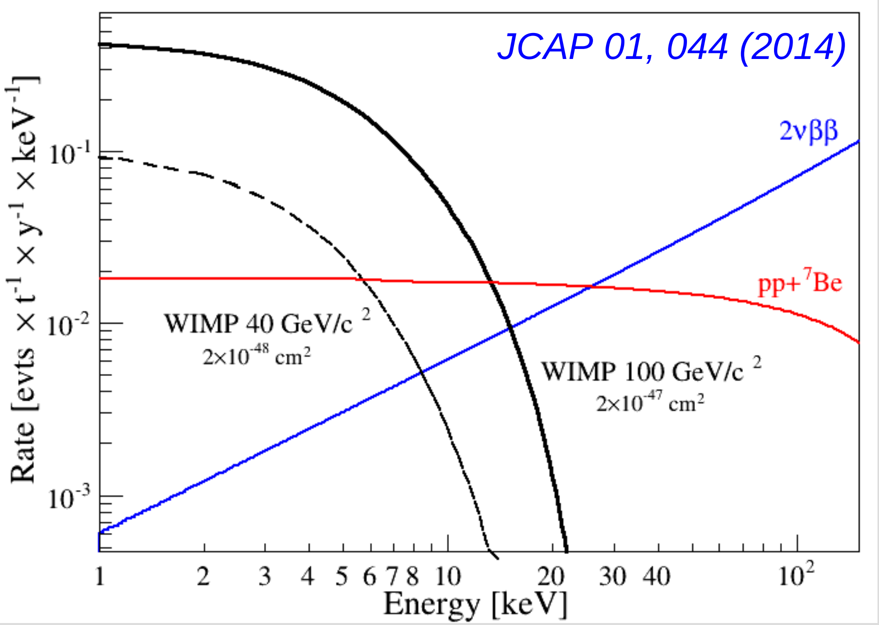
Baseline scenario
~20 t LXe TPC
~14 t fiducial mass

- aim at sensitivity below 10^{-48} cm², limited by irreducible ν-backgrounds

DARWIN The ultimate WIMP Detector



- aim at sensitivity below 10^{-48} cm², limited by irreducible ν-backgrounds
- Low energy solar neutrinos (pp+^{7}Be) → reduction by discrimination possible



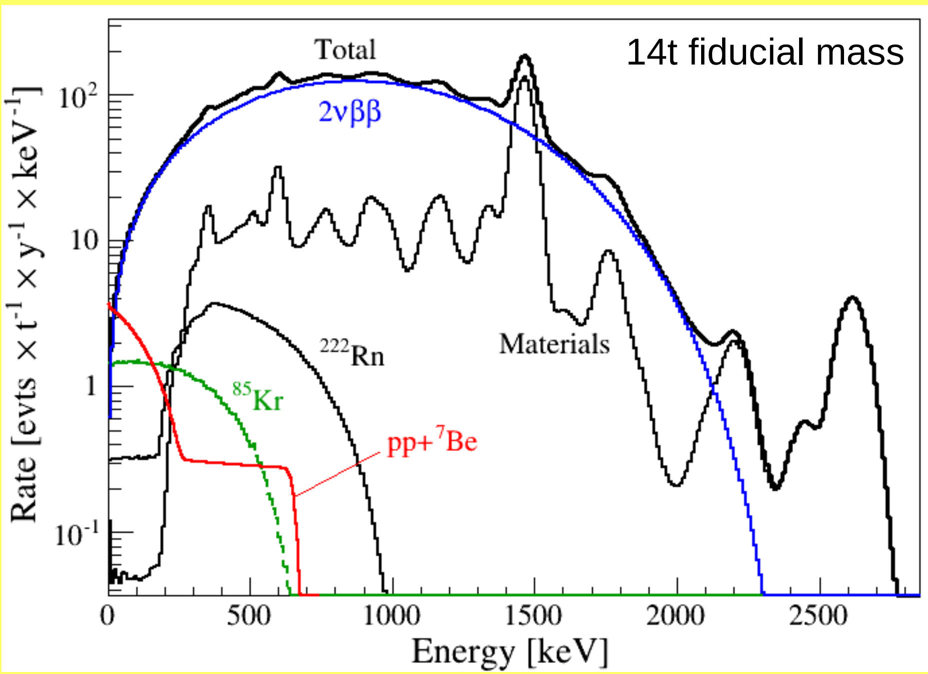
- Coherent neutrino-nucleus scattering → nuclear recoil signal, indistinguishable from WIMPs

DARWIN: Neutrino Physics

Results of a detailed DARWIN background study

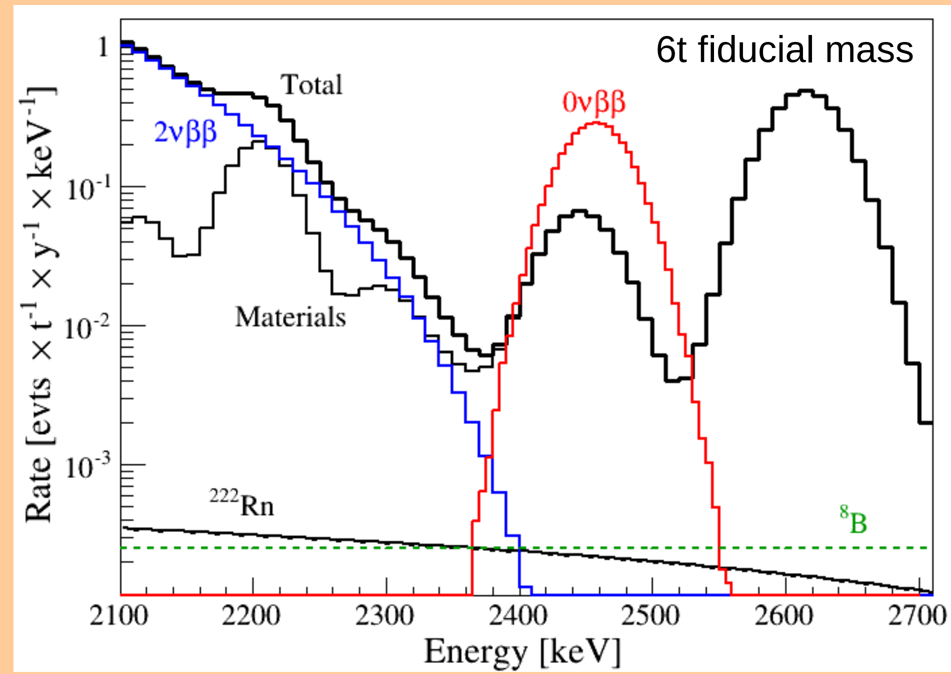
JCAP 01, 044 (2014)

Low-energy solar Neutrinos: pp, ^{7}Be



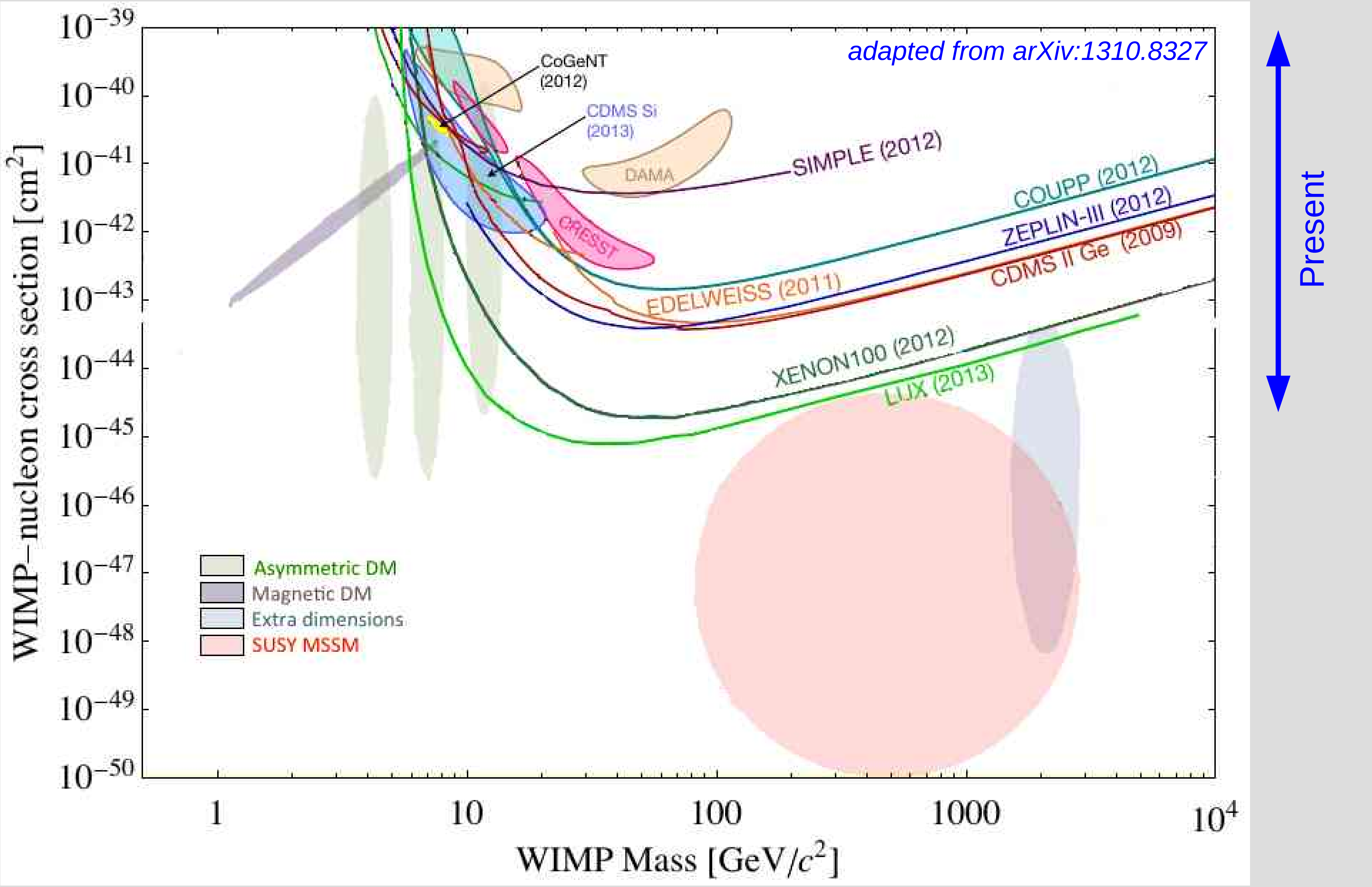
- realistic detector design (~20t LXe) , all relevant backgrounds included
- 1180 pp-ν/year in [2,30] keV interval
- flux-measurement at 1% precision in 5y

Neutrinoless double-beta decay



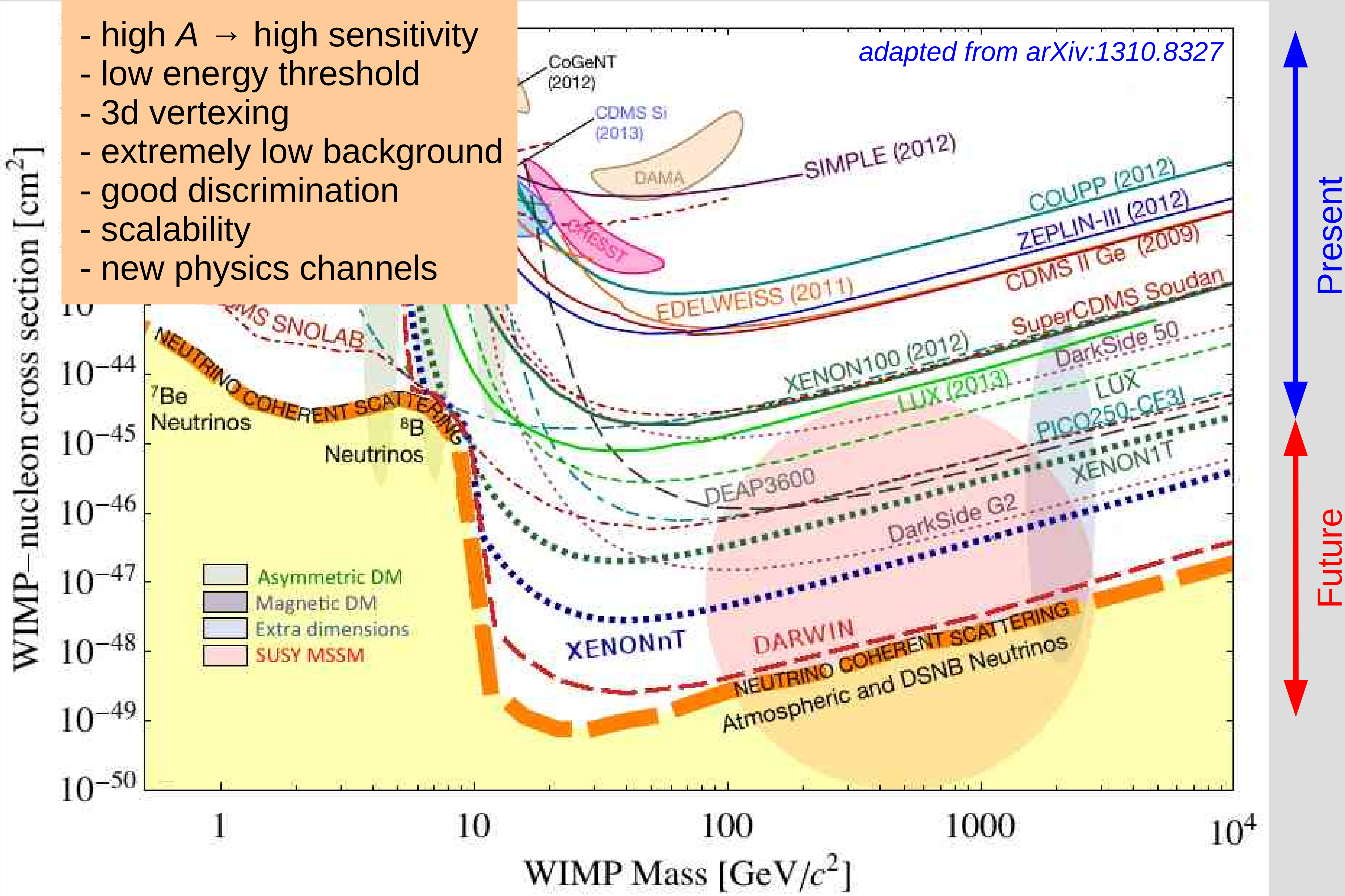
- natural Xe, no isotopic enrichment!
- signal in plot assumes $T_{1/2}$=1.6 x 10^{25} y
- ultimate sensitivity (limited by intrinsic bg): $T_{1/2}$=8.5 x 10^{27} y (95% CL) with 14t x 10y

The WIMP Landscape



Dark Matter Future will be driven by dual-phase LXe TPCs

- high *A* → high sensitivity
- low energy threshold
- 3d vertexing
- extremely low background
- good discrimination
- scalability
- new physics channels

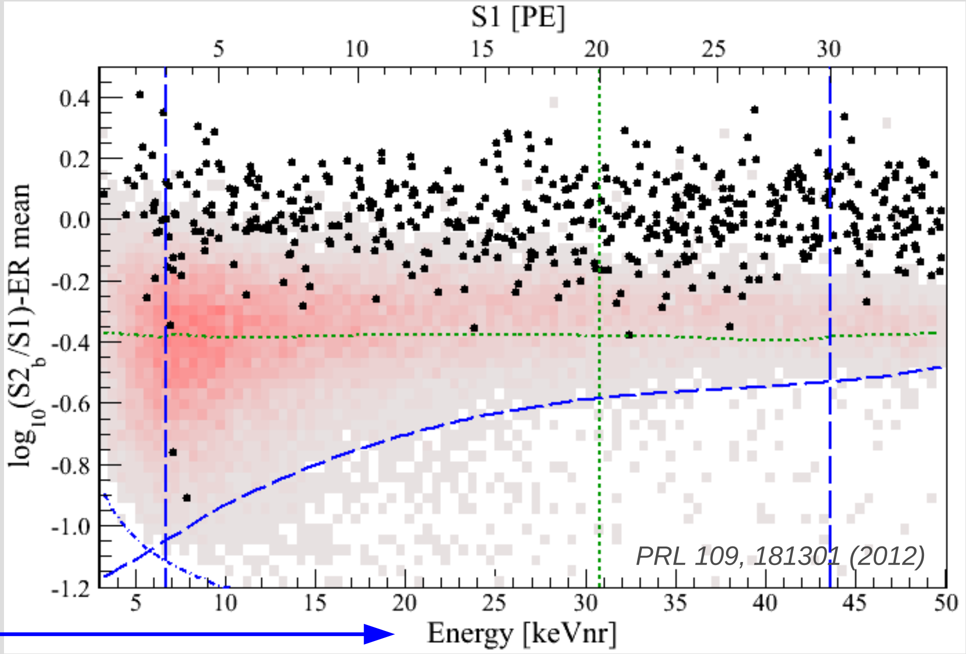


Backup

Field-quenching of S1 Light?

energy in keVr

$$E = \frac{S1}{L_y} \frac{1}{\mathcal{L}_{\rm eff}(E)} \frac{S_{\rm ee}}{S_{\rm nr}}$$



What is needed to derive the energy scale based on the scintillation light S1?

Field-quenching of S1 Light?

$$E = \frac{\mathrm{S1}}{L_{\mathrm{y}}} \frac{1}{\mathcal{L}_{\mathrm{eff}}(E)} \frac{S_{\mathrm{ee}}}{S_{\mathrm{nr}}}$$

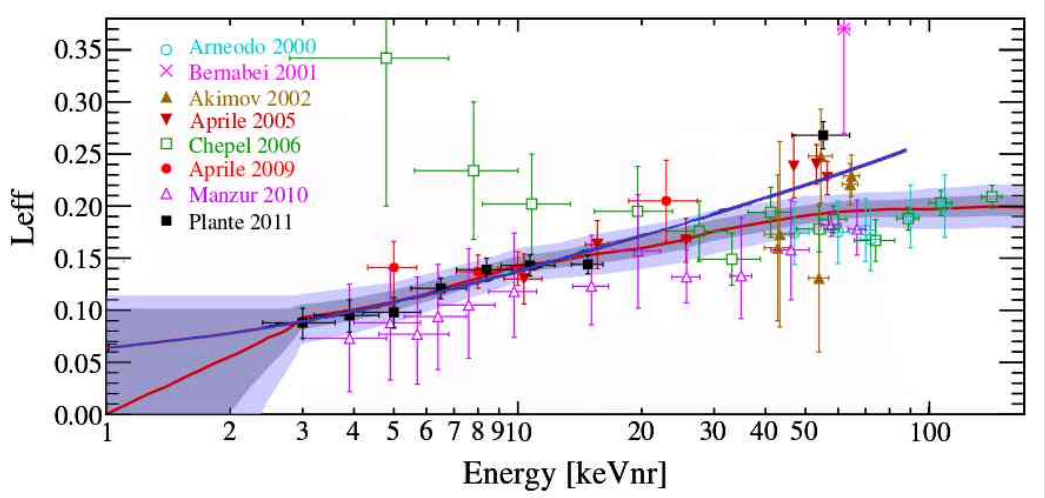
energy in keVr

light yield @ 122 keVee
→ measured in situ
(depends on detector)

relative scintillation efficiency
→ dedicated measurements

field quenching of 122 keVee
→ very well measured (simple)

field quenching of NRs
→ we use S_{nr}=0.95



Field-quenching of S1 Light?

$$E = \frac{S1}{L_y} \frac{1}{\mathcal{L}_{\text{eff}}(E)} \frac{S_{\text{ee}}}{S_{\text{nr}}}$$

energy in keVr

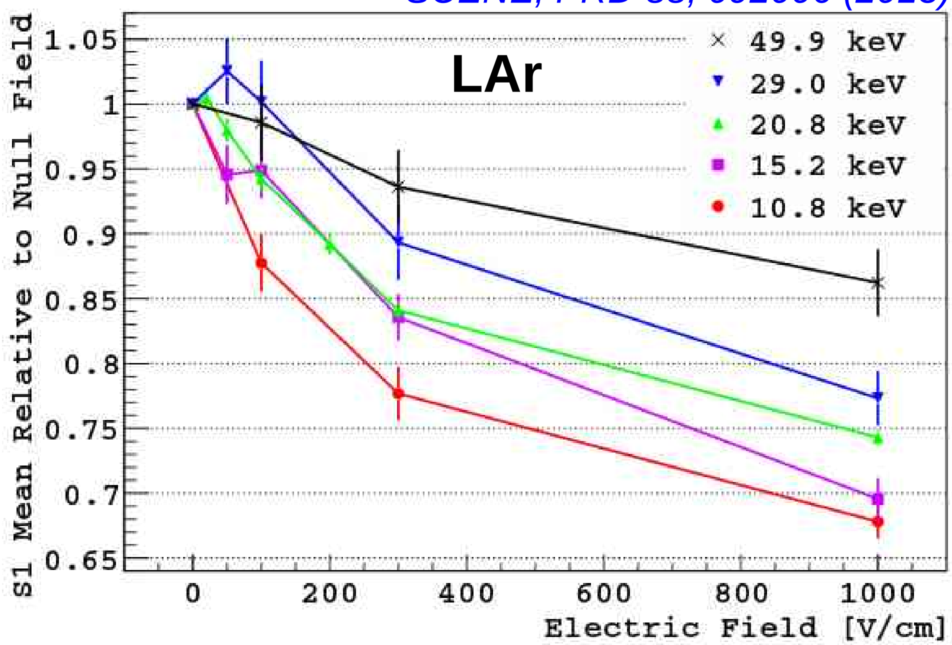
field quenching of 122 keVee
→ very well measured (simple)

light yield @ 122 keVee
→ measured in situ
(depends on detector)

relative scintillation efficiency
→ dedicated measurements

field quenching of NRs, $S_{nr}(E)$?
→ we use S_{nr}=0.95
→ recent measurements in LAr found strong E dependence
→ not seen in LXe so far

SCENE, PRD 88, 092006 (2013)



data: Manzur et al., PRC 81, 025808 (2010)