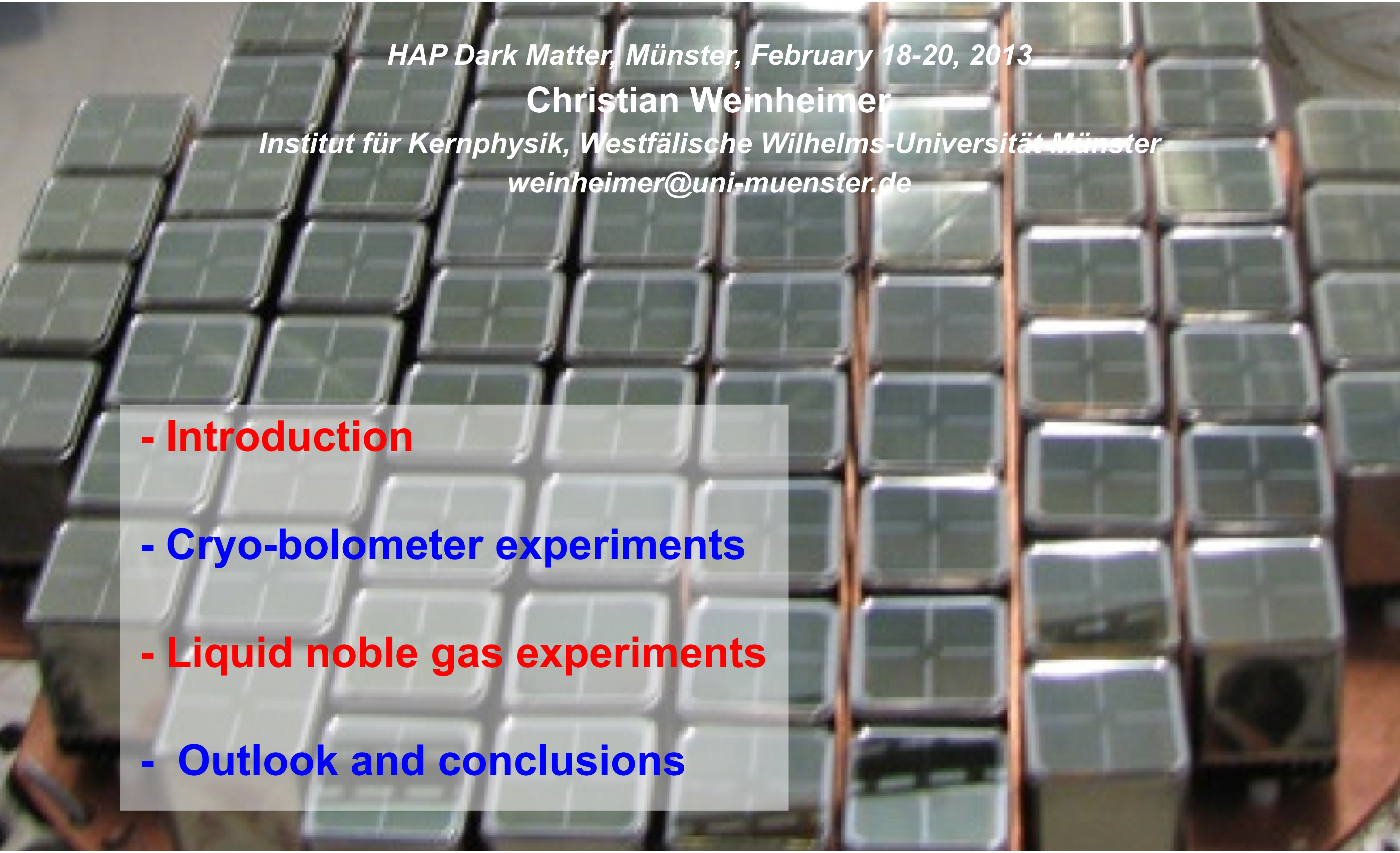
Westfälische Wilhelms-Universität Münster

Direct Search for Dark Matter



HAP Dark Matter, Münster, February 18-20, 2013

Christian Weinheimer

Institut für Kernphysik, Westfälische Wilhelms-Universität Münster

weinheimer@uni-muenster.de

- Introduction

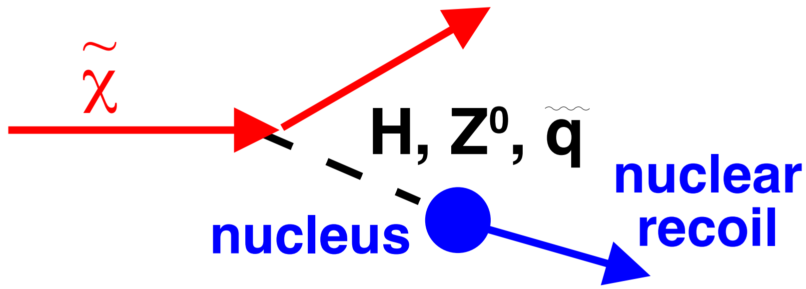
- Cryo-bolometer experiments

- Liquid noble gas experiments

- Outlook and conclusions

Experimental search for WIMPs

c) Direct WIMP detection – search for nuclear recoil:



Signature:
energy transfer to nucleus
by invisible particle

Recoil energy

$$E_R = \frac{\mu^2}{M_N^2} \cdot v^2 \cdot (1 - \theta_{CMS}) \approx 10 \text{ keV} \qquad \text{for} M_N = m_\chi = 50 \text{ GeV}$$

with reduced mass

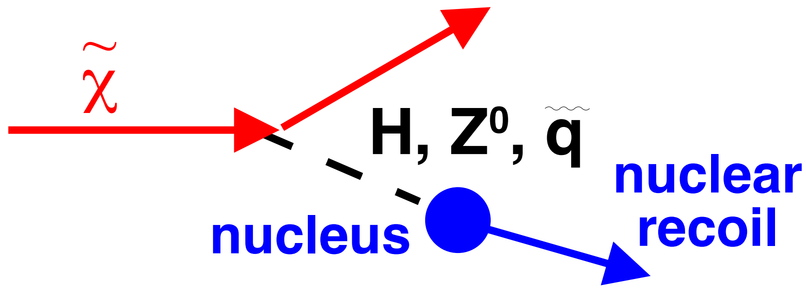
$$\mu = \frac{M_N \cdot m_\chi}{M_N + m_\chi}$$

Simple estimate of weak interaction rate:

$$R \propto N_N \cdot j \cdot \sigma = N_N \cdot n_\chi \cdot \langle v \cdot \sigma \rangle = N_N \cdot \frac{\rho_\chi}{m_\chi} \cdot \langle v \cdot \sigma \rangle$$

Experimental search for WIMPs

c) Direct WIMP detection – search for nuclear recoil:



Signature: energy transfer to nucleus by invisible particle

Differential cross section

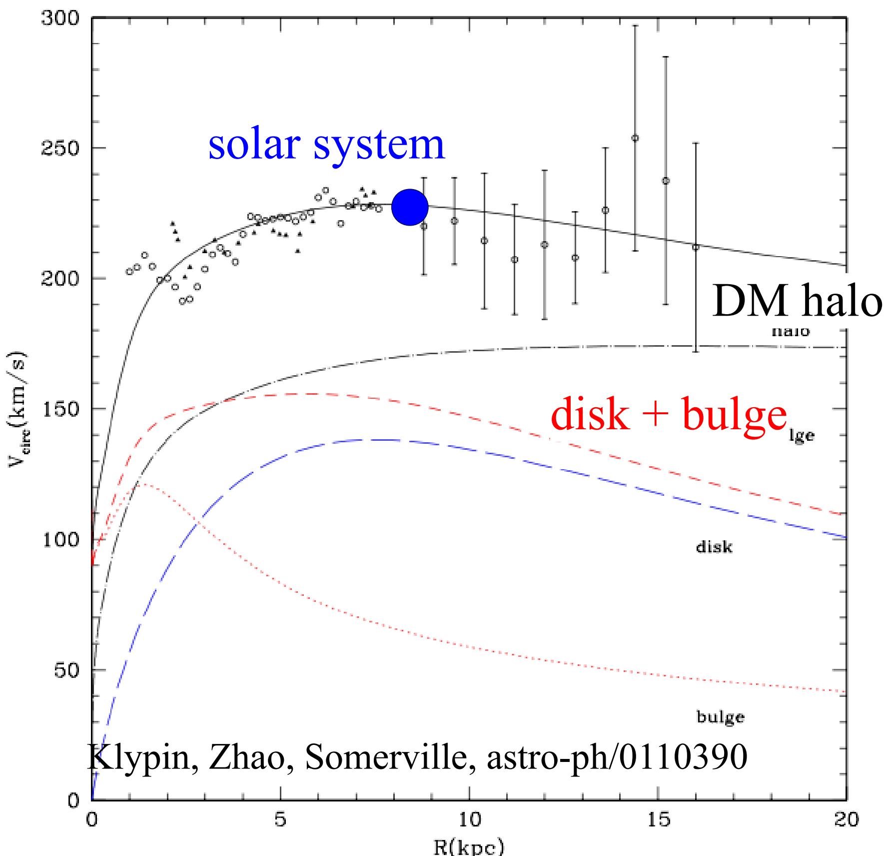
$$\frac{d\sigma}{dE_R} = \frac{M_N}{2 \cdot \mu^2 \cdot v^2} \cdot \left(\sigma_{SI} \cdot |F_{SI}(E_R)|^2 + \sigma_{SD} \cdot |F_{SD}(E_R)|^2 \right)$$

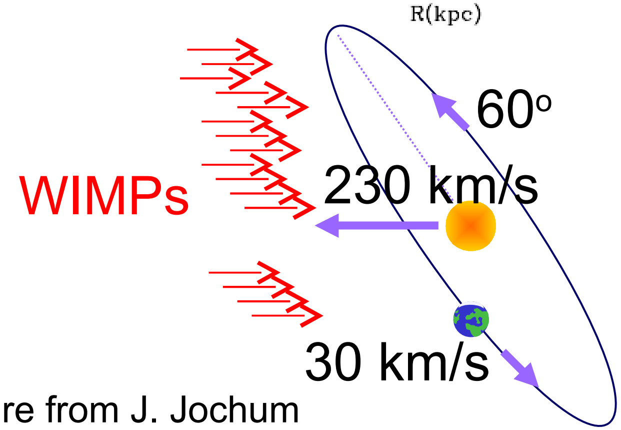
with WIMP-nucleus spin-indepedent (SI) and spin-dependent (SD) cross sections

$$\sigma_{SI} = \frac{4\mu^2}{\pi} \cdot (Z \cdot f_p + (A - Z) \cdot f_n)^2 \propto A^2$$

$$\sigma_{SD} = \frac{32\mu^2}{\pi} \cdot \frac{J+1}{J} \cdot (a_p \cdot \langle S_p \rangle + a_n \cdot \langle S_n \rangle)^2$$

Interaction with WIMPs from our DM halo





picture from J. Jochum

local density (PDG2009):

$$\rho(r_E) = 0.3^{+0.3}_{-0.15}\ \mathrm{GeV/cm^3}$$

halo distribution (NFW APJ490 (1997) 493):

$$\rho(r) = \frac{\rho_0}{\frac{r}{R_s}\cdot\left(1+\frac{r}{R_s}\right)^2}$$

local velocity distribution (Maxwell):

$$f(\vec{v}-\vec{v}_E) = \exp(-(\vec{v}+\vec{v}_E)^2/v_0^2)$$

$$v_0 = 220\ \mathrm{km/s}$$

velocity of earth:

$$v_E = 215_{2.\ \mathrm{Dec.}} - 245_{2.\ \mathrm{June}}\ \mathrm{km/s}$$

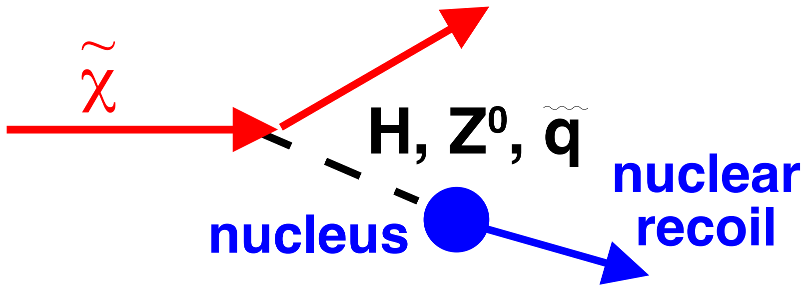
⇒ annual modulation

recoil spectrum:

$$\frac{dR}{dE_R} = N_N\cdot\frac{\rho_\chi}{m_\chi}\cdot\langle v\cdot\frac{d\sigma}{dE_R}\rangle = N_N\cdot\frac{\rho_\chi}{m_\chi}\cdot\int_{v_{min}(E_R)}^{v_{max}}\cdot f(\vec{v}-\vec{v}_E)\cdot v\frac{d\sigma}{dE_R}d^3v$$

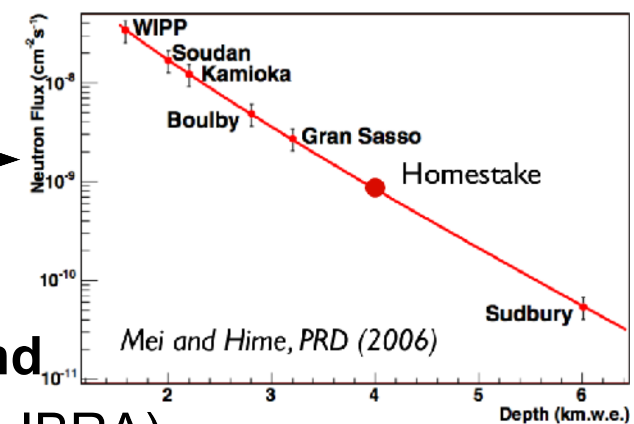
$$\frac{dR}{dE_R} \approx \exp\left(-\frac{E_R}{E_0}\right)$$

Difficulties to search for WIMPs



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

⇒ **go underground to reduce μ`s and μ-induced n`s**
& shielding, very clean materials, ..

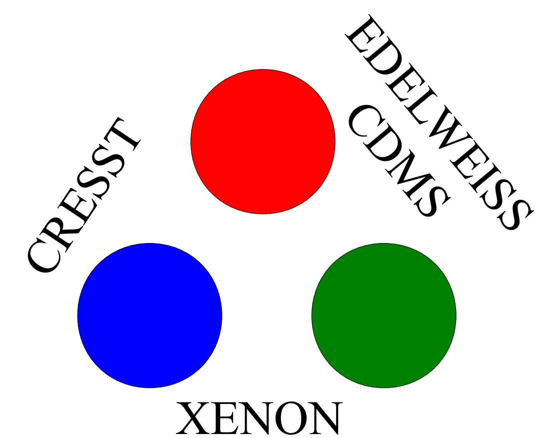


⇒ **very special techniques to suppress γ, e, α background**

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

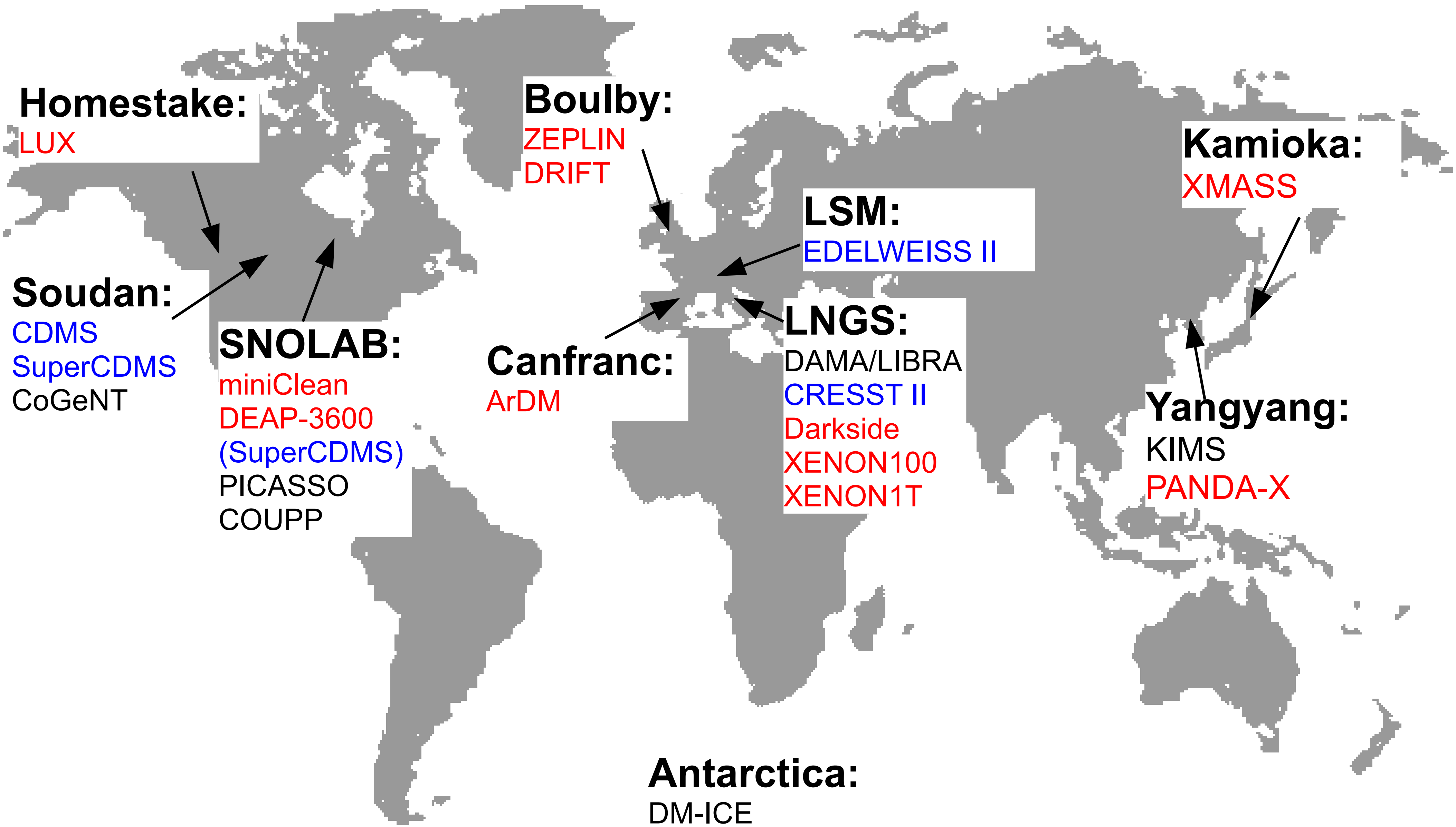
b) double read-out to distinguish nuclear recoil from others

- cryobolometers:
  heat + ionsiation or heat + light
- liquid noble gas detectors:
  light + ionisation

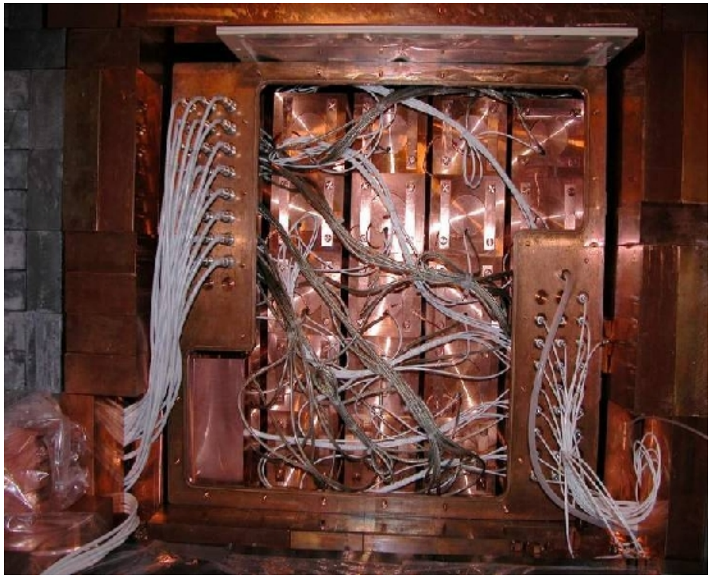


c) directional (but not enough target mass)

Direct Cold Dark Matter (WIMP) searches
cryo bolometer / liquid noble gases / others

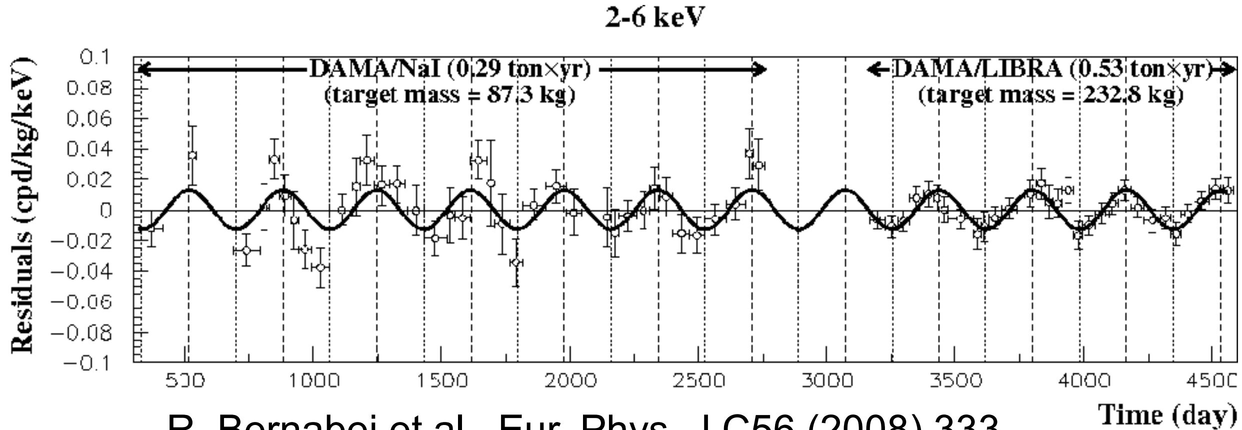


DAMA/LIBRA experiment: signal for Dark Matter ?

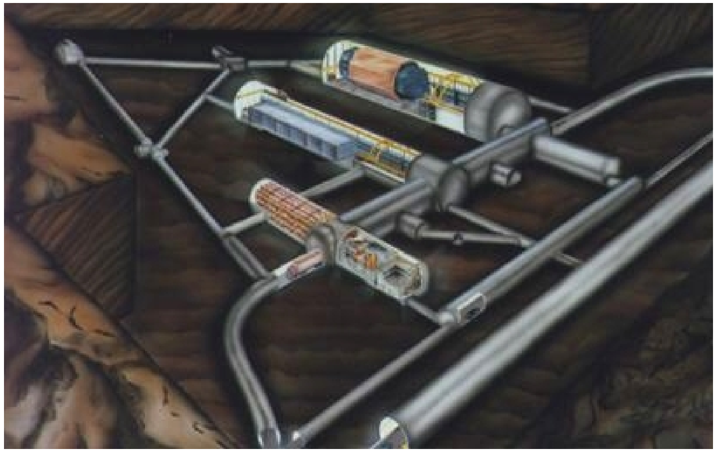


at LNGS / Italy
250 kg NaI crystals
detection of scintillation light

clear annual modulation signal



R. Bernabei et al., Eur. Phys. J C56 (2008) 333



Are these really WIMPs ?

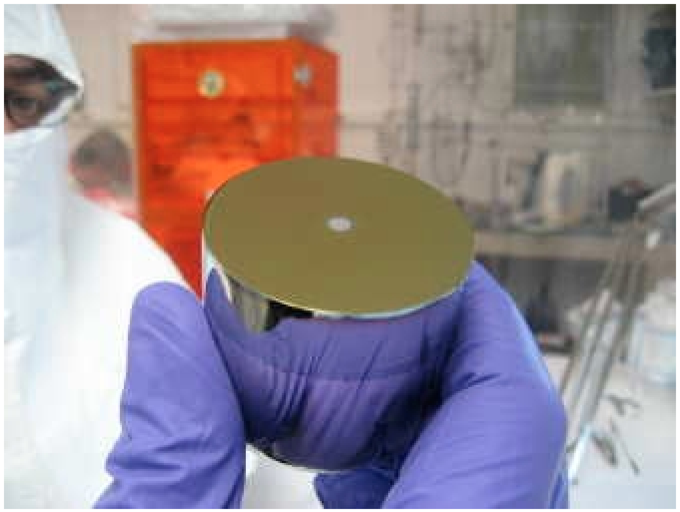
Not seen by any other experiment

KIMS (CsI) sees no oscillation at the DAMA amplitude: a < 0.0119 cts /(d kg keV) (90% C.L.)

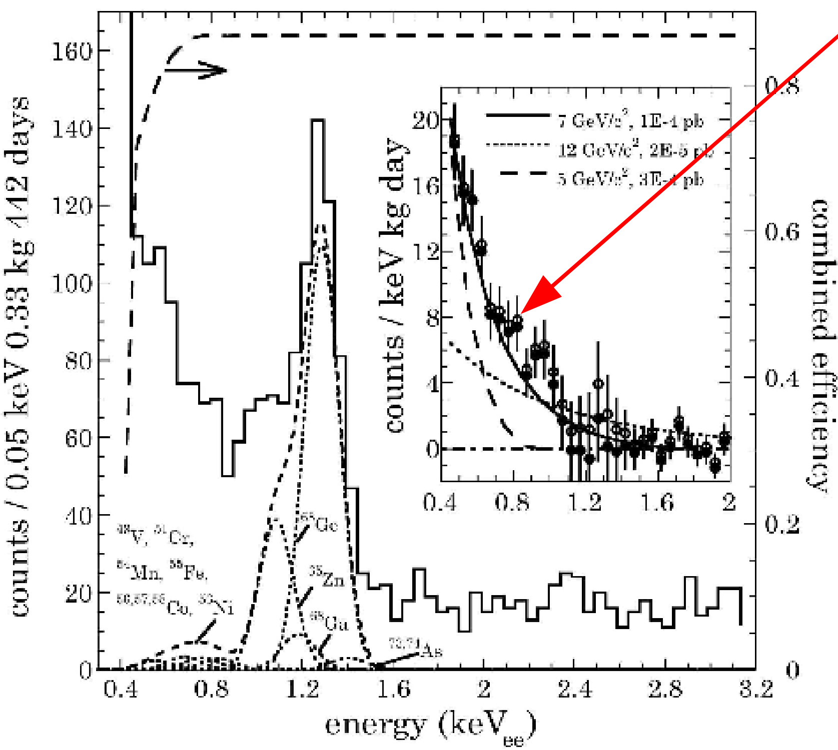
⇒ non-understood detector feature of DAMA/LIBRA
or something very interesting and unexpected ?

CoGeNT at Soudan mine

excess and anual modulation: low mass WIMPs ?

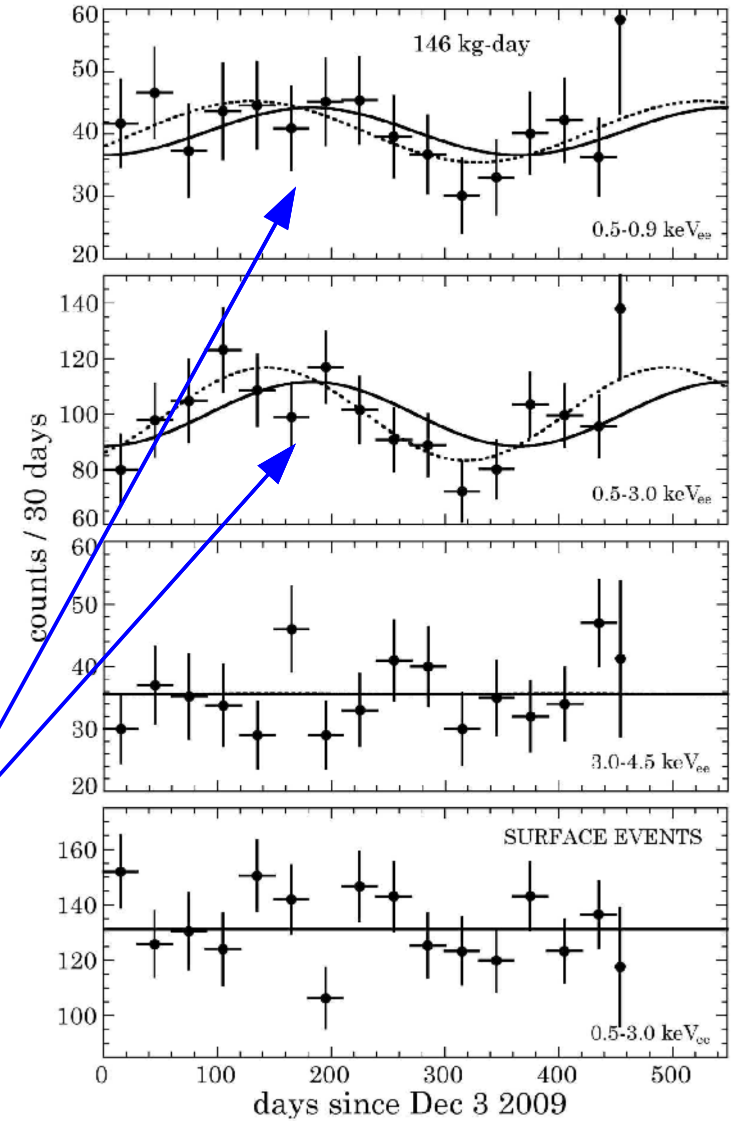


p-type point contact germanium detector
→ ultra-low threshold
at Soudan mine



"irreducible background"
after subtraction of lines and flat background
→ WIMP-signal ?

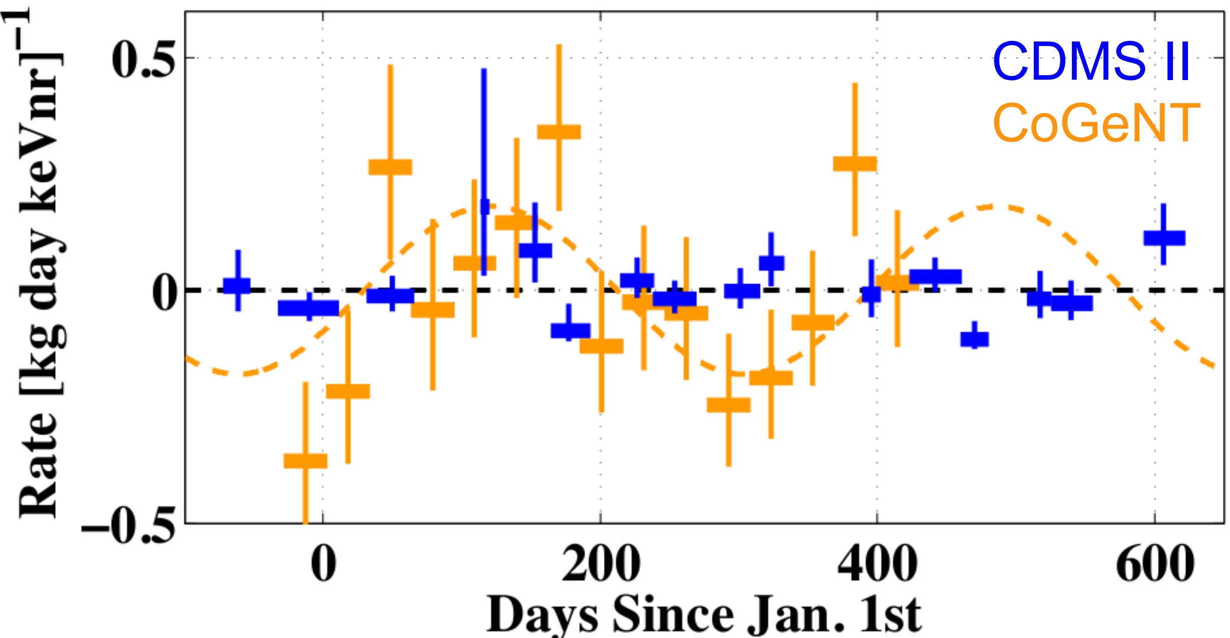
2.8 σ annual modulation in low energy part, but large amplitude (> 10%)

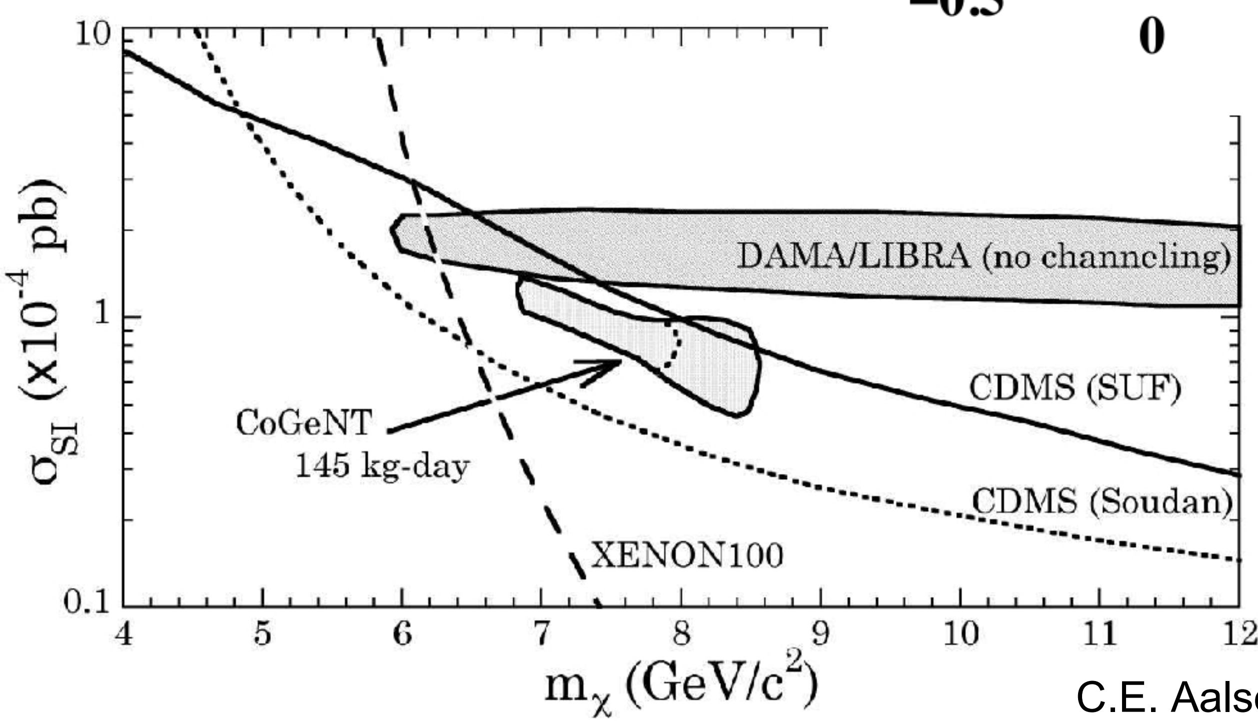


C.E. Aalseth et al., arXiv:1106:0650

CoGeNT at Soudan mine
do low mass WIMPs fit with other experiments ?

Z. Ahmed et al., (CDMS II)
arXiv:1203.1309v1





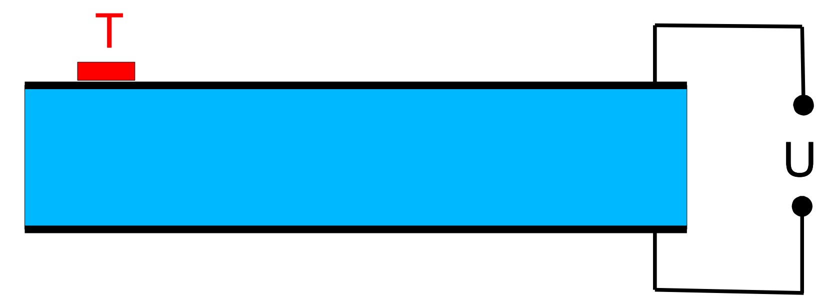
Similar to CoGeNT:
Majorana demonstrator

C.E. Aalseth et al., arXiv:1106:0650

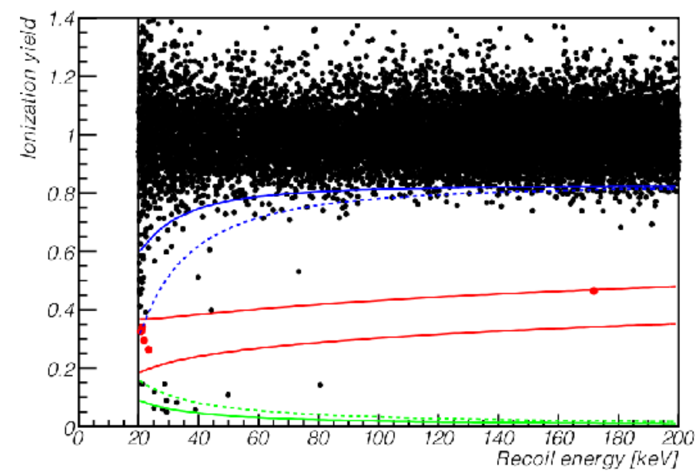
Cryo bolometers for WIMP search

Dual read-out:

heat (thermal + athermal phonons)
+ ionisation
Super-CDMS, EDELWEISS, ...



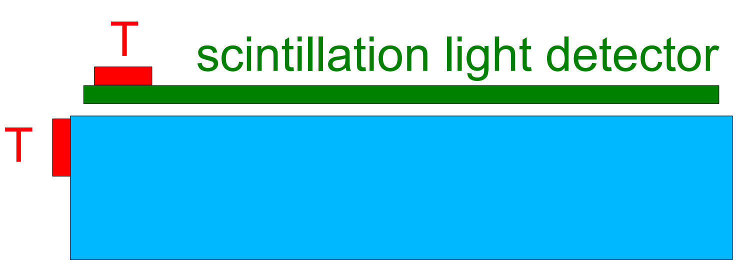
Nuclear recoil – electronic recoil separation:

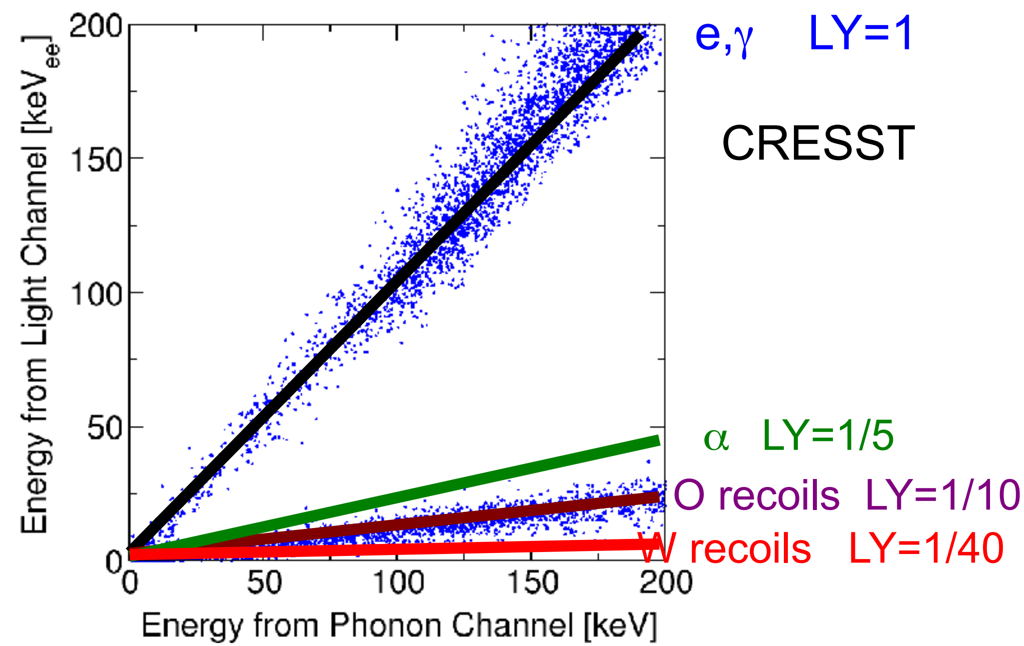


EDELWEISS

Dual read-out:

heat (thermal + athermal phonons)
+ scintillation light
CRESST, AMORE, ...





CRESST

CRESST II

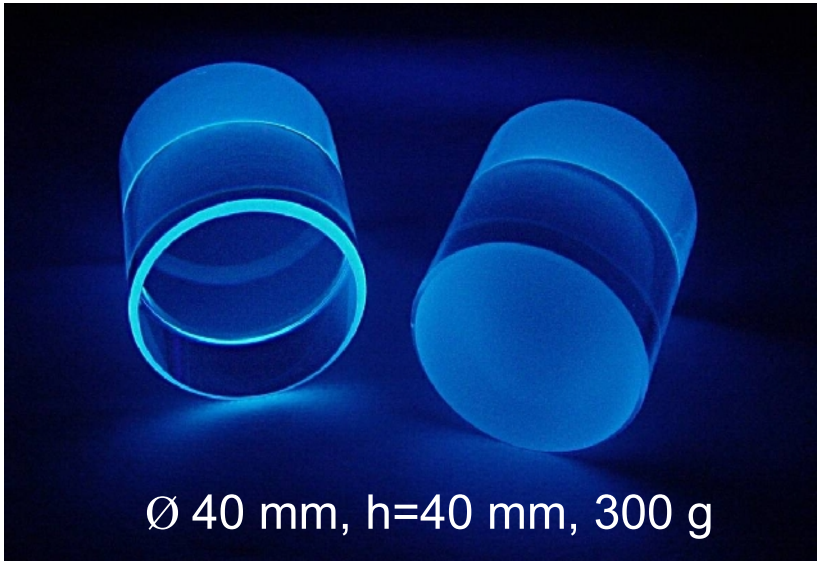
Collaboration: MPIPH Munich, TU Munich, U Tübingen, (U Oxford/UK), LNGS/Italy

located in Gran Sasso underground laboratory LNGS

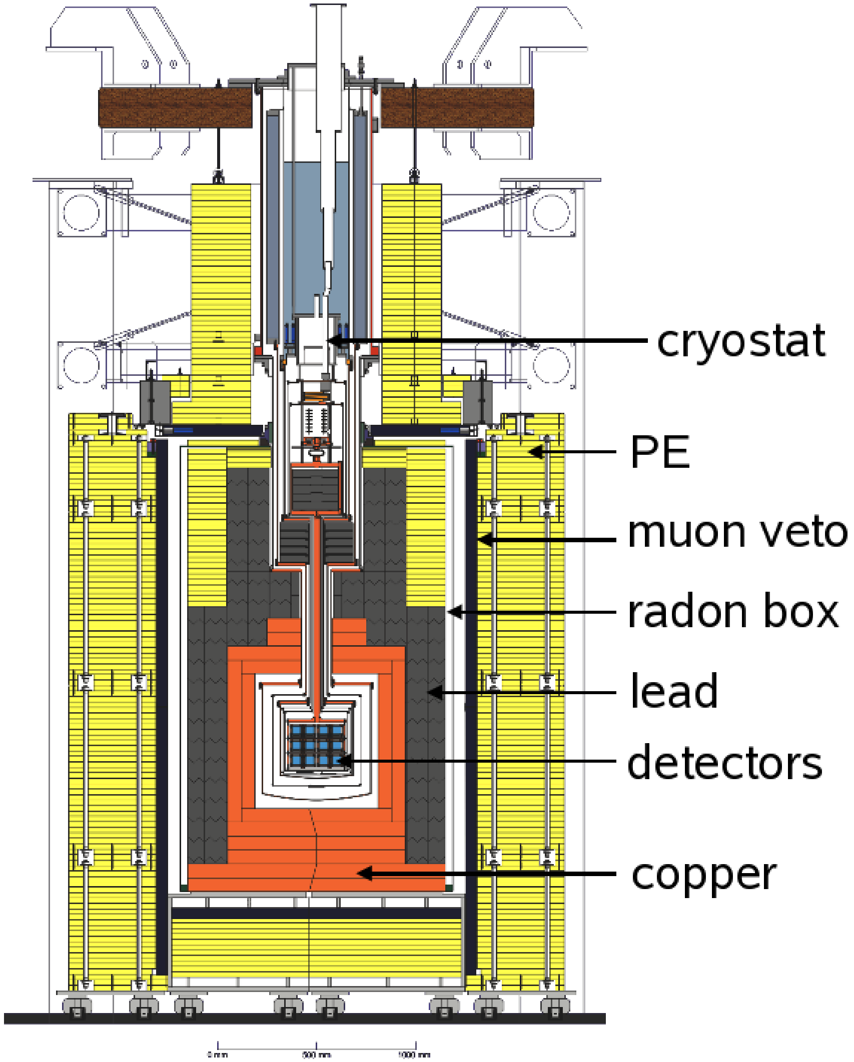
Detectors: 10 cryobolometers $CaWO_4$ of 400g

(shielded cryostat can house 33)

with heat (thermal phonons) and light readout



J. Schmaler, LTD Stanford, July 2009



CRESST II – excess of events low mass WIMPs ?

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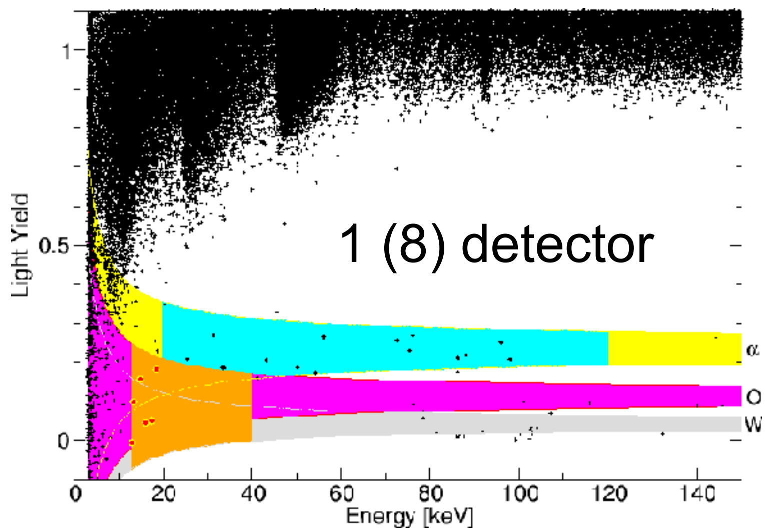
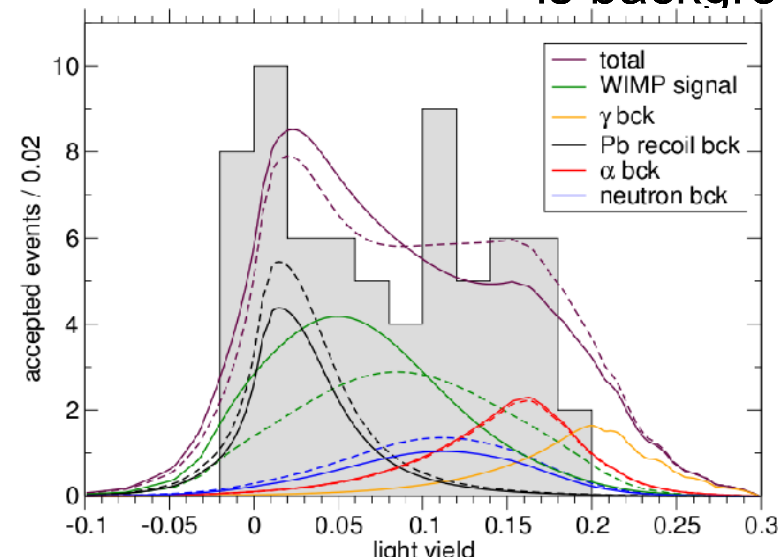
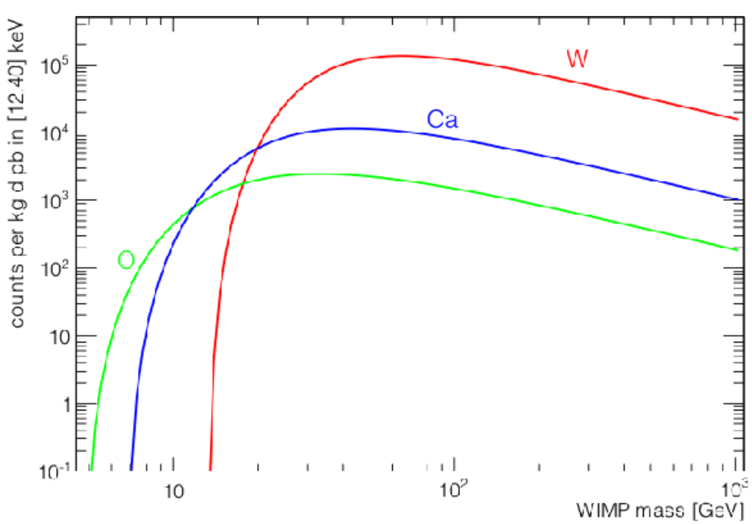
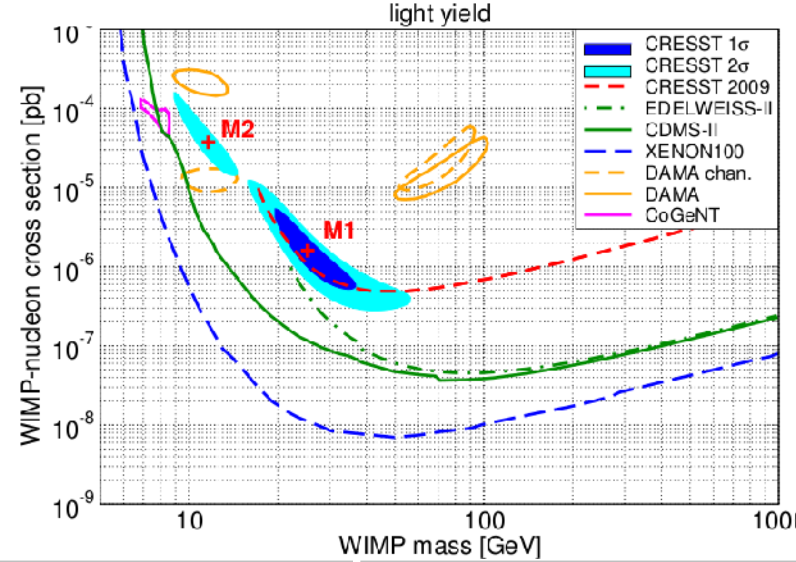
8 detectors, in total 730 kg d: 67 events in signal region
→ background is leaking into the signal region → max likelihood fit → ½ of candidates is background

G. Angloher et al., arXiv:1109.0702









EDELWEISS II

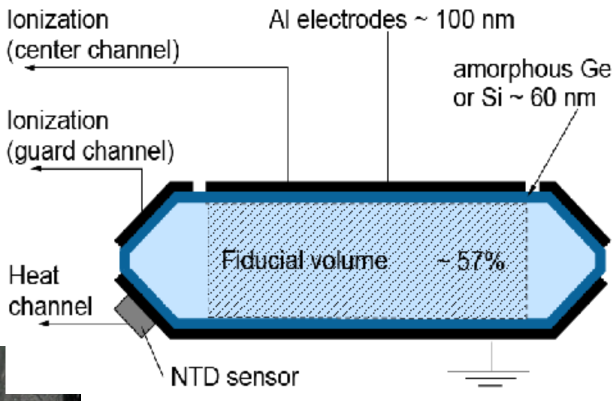
Collaboration: 5 institutions from France, JINR/Russia, U Oxford/UK, KIT

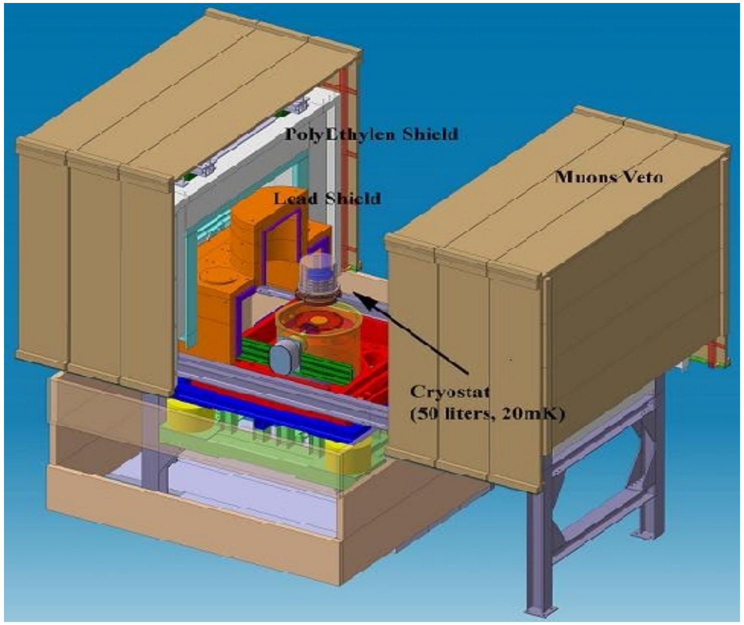
located in Modane underground laboratory LSM

Detectors: 10 cryobolometers Ge of 400g (166g fiducial)

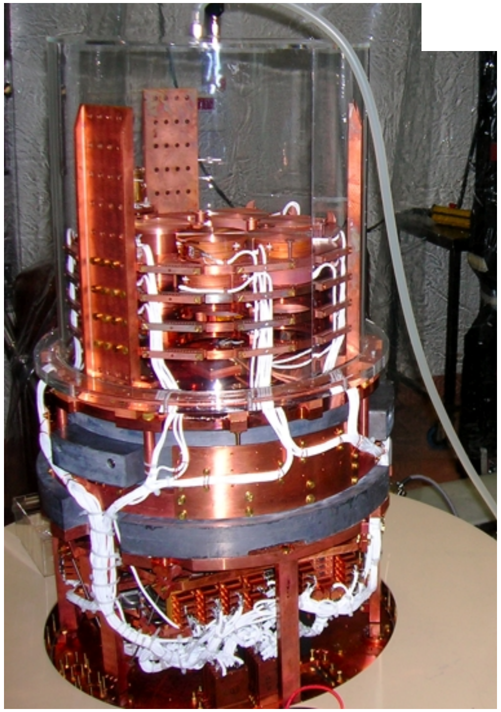
with heat (NTD sensor) and ionisation readout

shielded cryostat with active μ-veto





E. Armengaud, Colliquium APC, Feb 2010

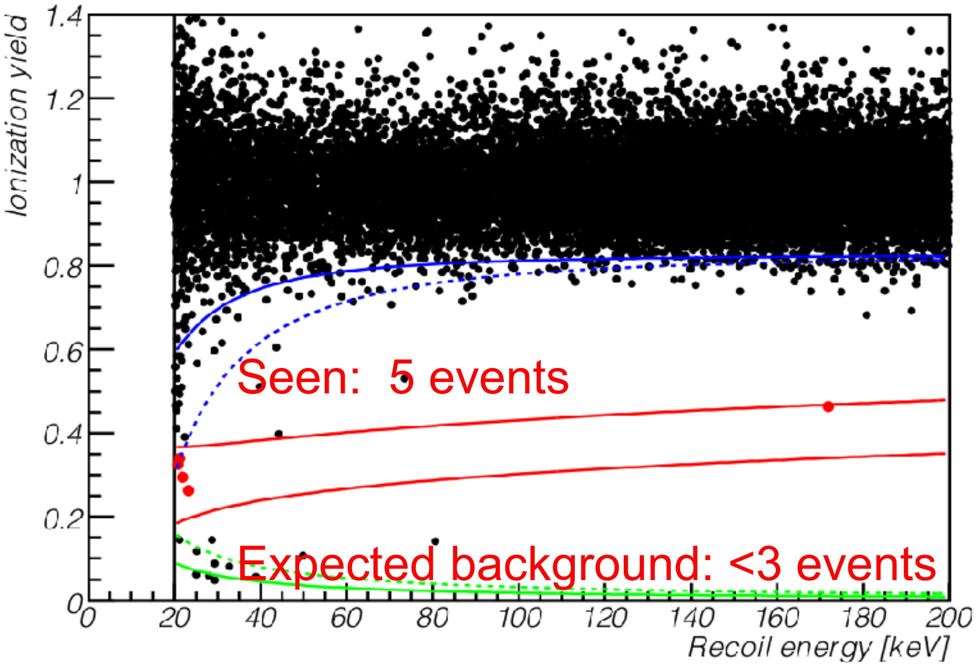


Idea: measure ioniszation and heat: temperature rise ΔT caused by energy release ΔE:

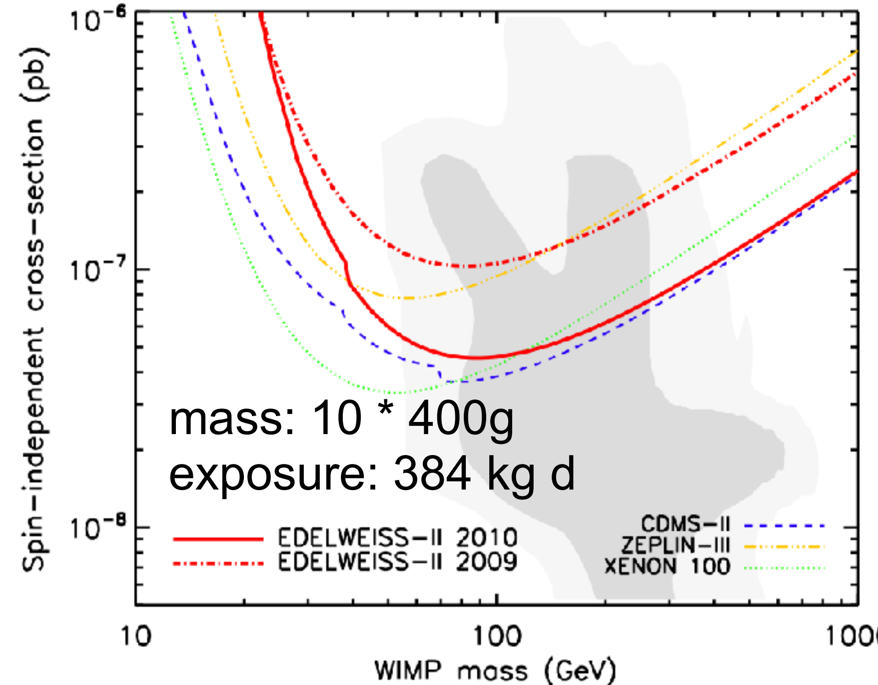
$\Delta T = \Delta E / C$

→ require small $C \sim (T/\Theta_D)^3$

EDELWEISS II: results

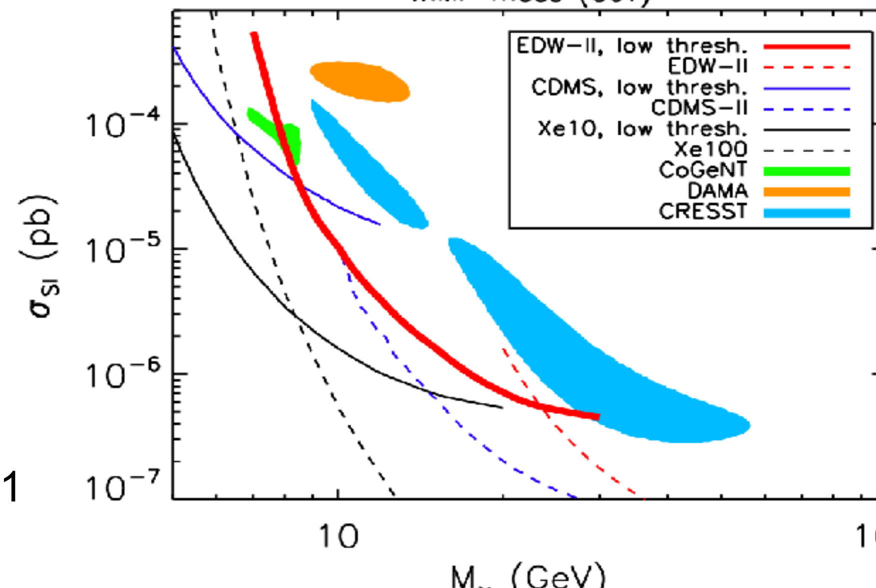


E. Armengaud et al.,
Phys.Lett. B702 (2011) 329



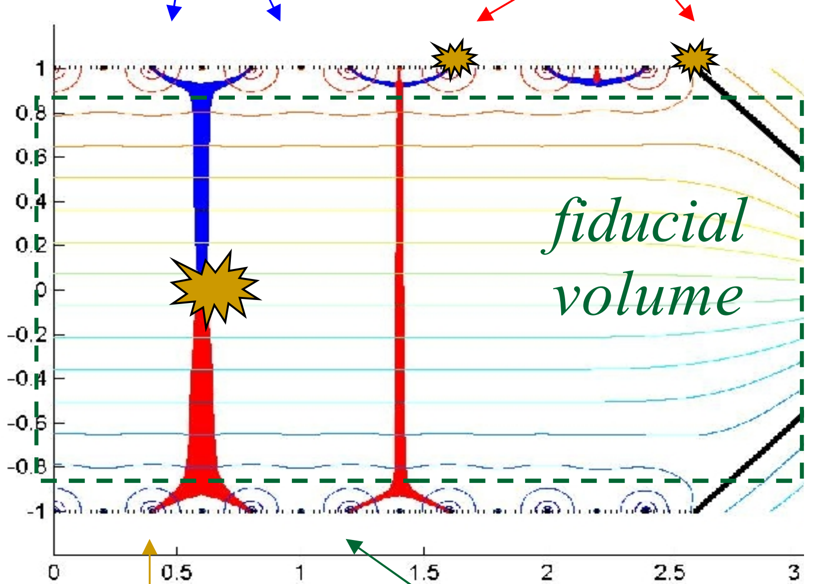
EDELWEISS II low threshold:

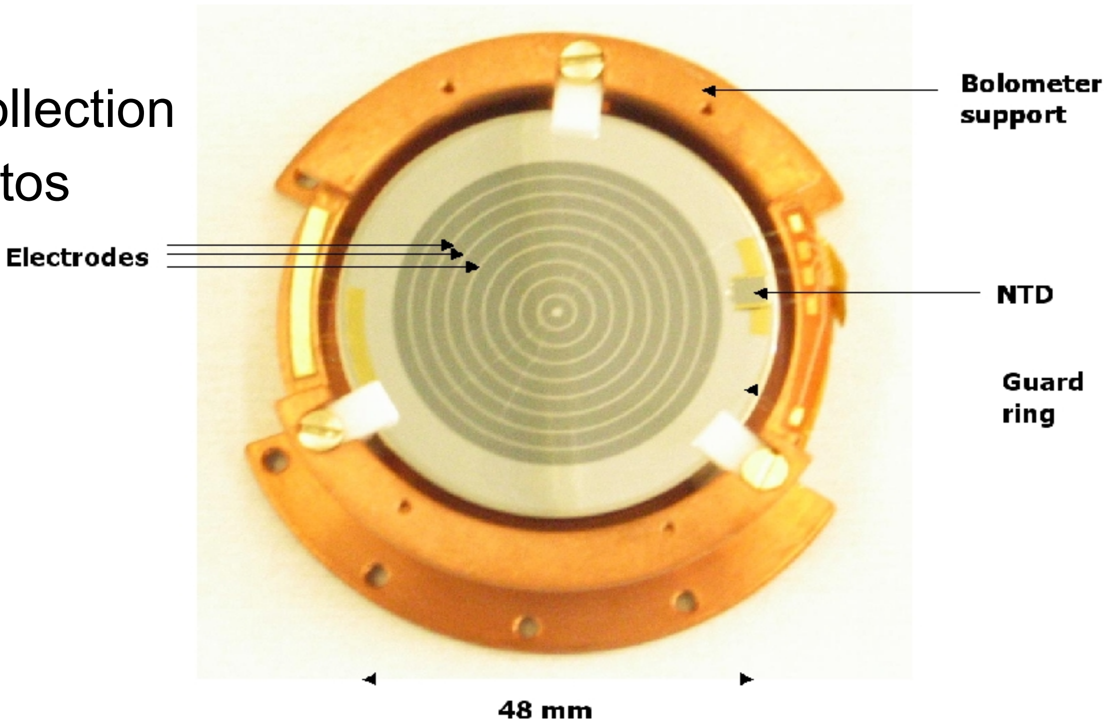
E. Armengaud et al.,
Phys.Rev. D86 (2012) 051



Rejecting surface events with interleaved electrodes

Near surfaces:
Transversal E field to suppress charge collection to other side, use 'b' and 'd' signals as vetos without changing bulk field

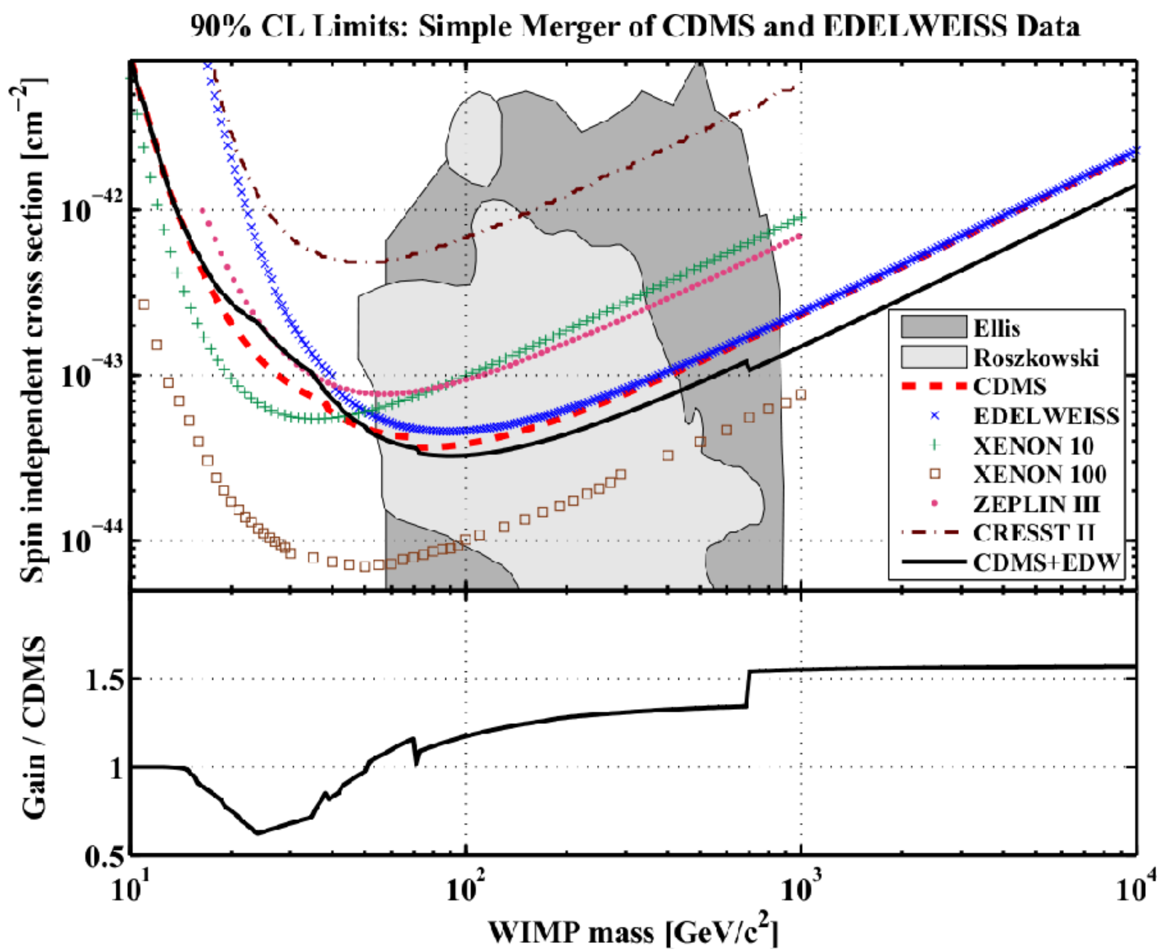




First detector built 2007
1x200g + 3x400g tested in 2008
10x400g running since beginning 2009

E. Armengaud, Colliquium APC, Feb 2010

Common exclusion plot from CDMS and EDELWEISS



Z. Ahmed et al., Phys.Rev. D84 (2011) 011102

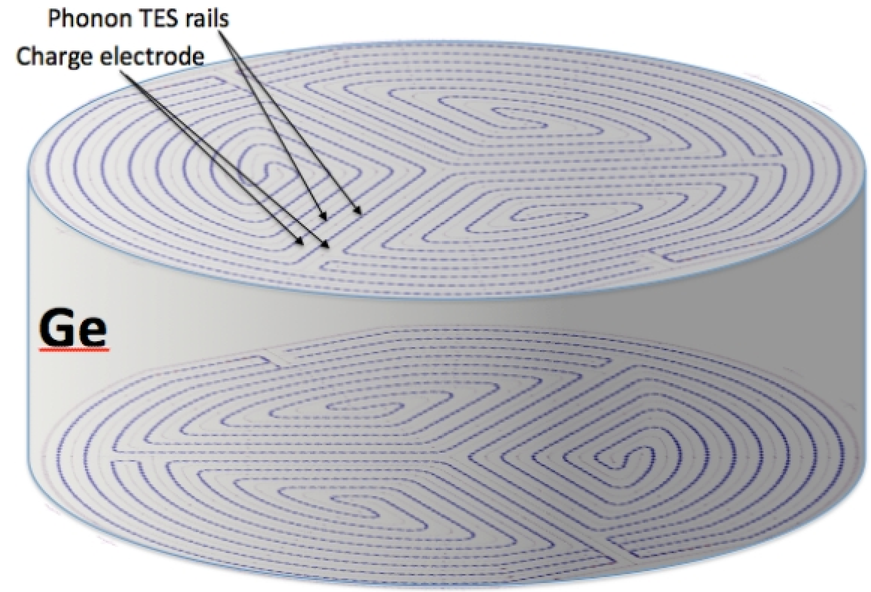
EDELWEISS 3: 14 FIDs in Febuary 2013
40 FIDs in summer/automn 2013
→ 3000 kg days in winter 2013/14

WESTFÄLISCHE WILHELMS-UNIVERSITÄT MÜNSTER

Super-CDMS

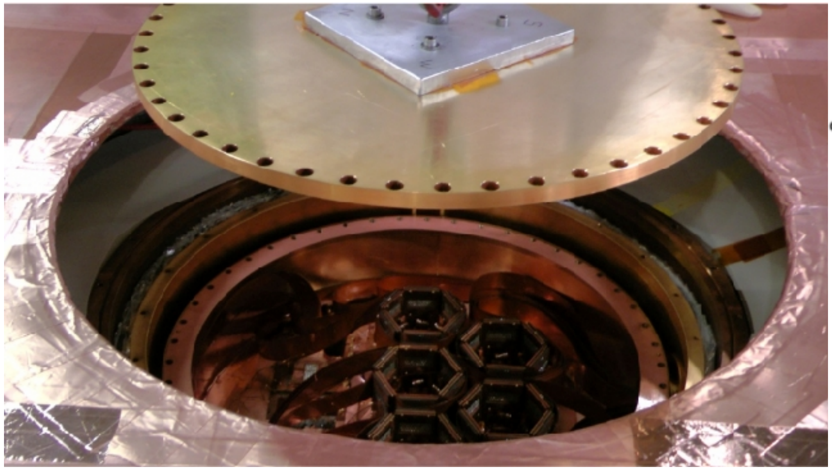
located in Soudan underground mine

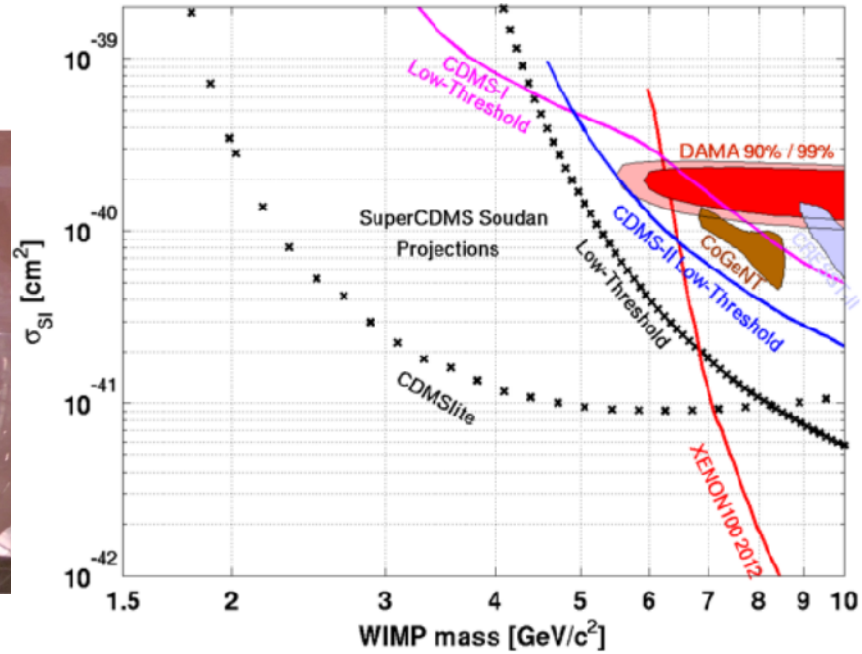
- 15 iZIP-detectors, 10 kg in total:
  differentiate bulk signal from surface bg
- 170 live days collected
- aim: sensitivity $\sigma_{SI} = 2\ 10^{-45}\ cm^2$



New technology for very low mass WIMPs:

- Neganov-Luke-amplification:
  phonon due to charge propagation



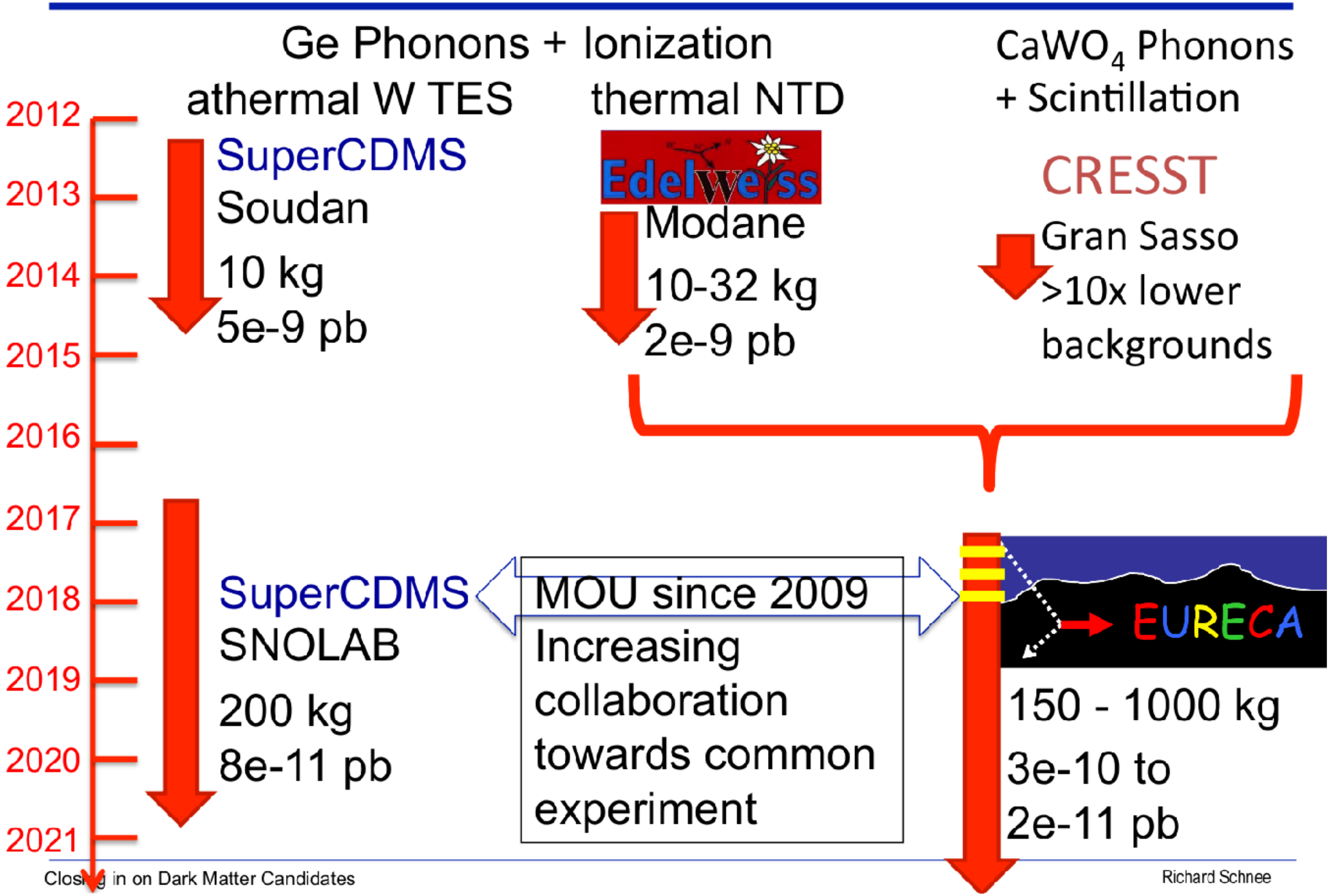


Future plans:

- 200 kg in SNOLab
- $\sigma_{SI} = 8\ 10^{-47}\ cm^2$

Future of cryo-bolometers in direct dark matter search

Phonons and Ionization or Scintillation



Liquid noble gas detectors

	Liquid density (g/cc)	Boiling point at 1 bar (K)	Electron mobility (cm^2/Vs)	Scintillation wavelength (nm)	Scintillation yield (photons/MeV)	Long-lived radioactive isotopes	Triplet molecule lifetime (μs)
LHe	0.145	4.2	low	80	19,000	none	13,000,000
LNe	1.2	27.1	low	78	30,000	none	15
LAr	1.4	87.3	400	125	40,000	^{39}Ar (269 y), ^{42}Ar	1.6
LKr	2.4	120	1200	150	25,000	^{81}Kr, ^{85}Kr	0.09
LXe	3.0	165	2200	175	42,000	^{136}Xe ($2\ 10^{21}$ y)	0.03

Scintillation by forming excited dimers
→ noble gas is transparent for scintillation light

Different live times of singlet and triplet states
→ discrimination between nuclear recoil and electron recoil possible for Argon detectors

Charge vs light (charge quenching)
→ discrimination between nuclear recoil and electron recoil possible

$$Xe^* + Xe + Xe \rightarrow Xe_2^* + Xe,$$
$$Xe_2^* \rightarrow 2Xe + h\nu,$$
$$Xe^+ + Xe \rightarrow Xe_2^+,$$
$$Xe_2^+ + e^- \rightarrow Xe^{**} + Xe,$$
$$Xe^{**} \rightarrow Xe^* + \text{heat},$$
$$Xe^* + Xe + Xe \rightarrow Xe_2^* + Xe,$$
$$Xe_2^* \rightarrow 2Xe + h\nu.$$

Arguments for a Xenon detector

Heavy nucleus (A~131):
→ good for spin-indenpendent interaction
(coherent scattering off all nucleons)
SD sensitivity too (~50% odd isotopes)

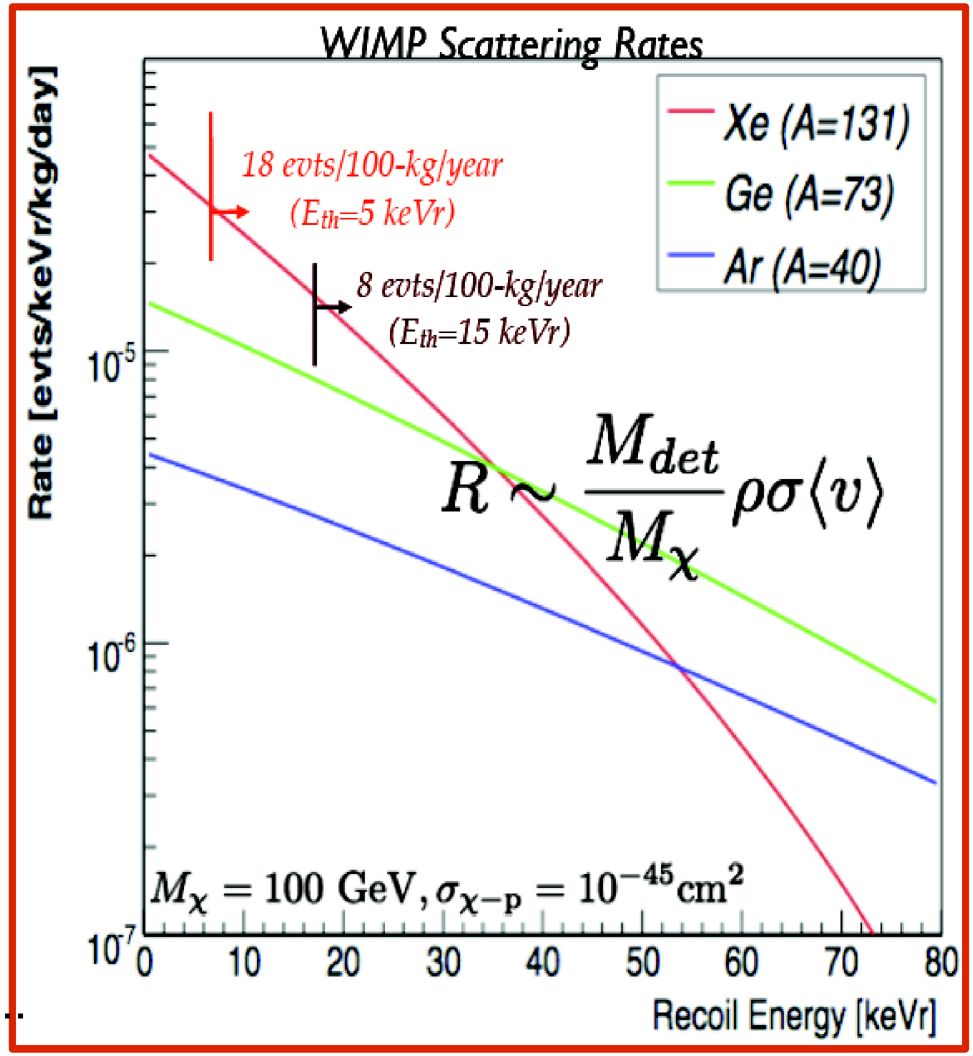
High nuclear charge (Z=54)
→ very good self-shielding

Ultraclean material
liquid noble gases are among the most clean materials
no long-lived isotope except
^{136}Xe: $t_{1/2}$ = 2 10^{21} yr, 8.9% nat. abund.

Very high charge & light yield:
42,000 γ / MeV at 178nm (PMTs exist)

Proven XENON technology with
high efficiency & low energy threshold,
background rejection methods, fiducialisation, ...

Moderate cost (<1k$/kg),
effort scales with surface not volume

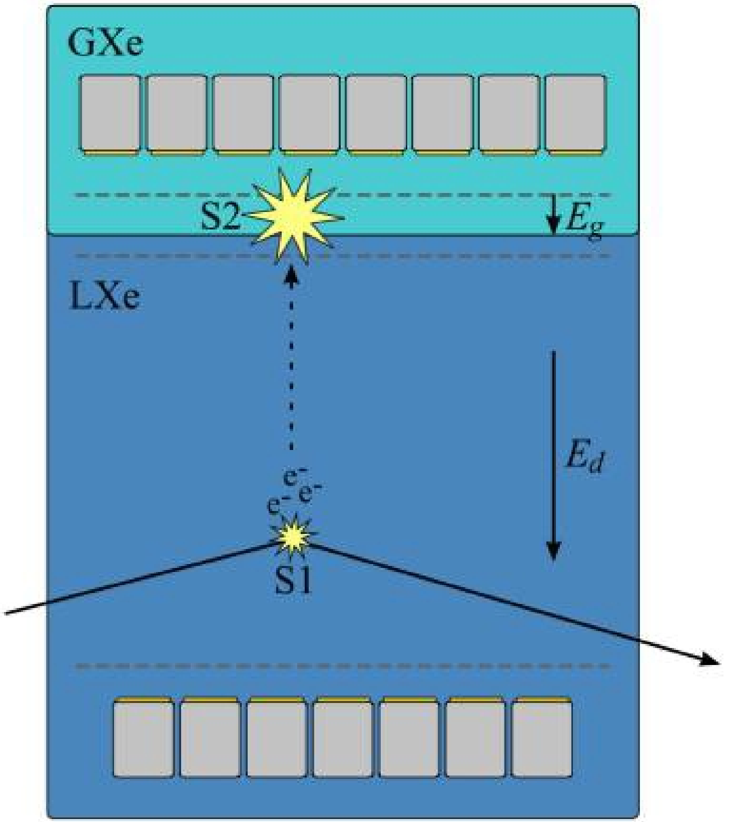


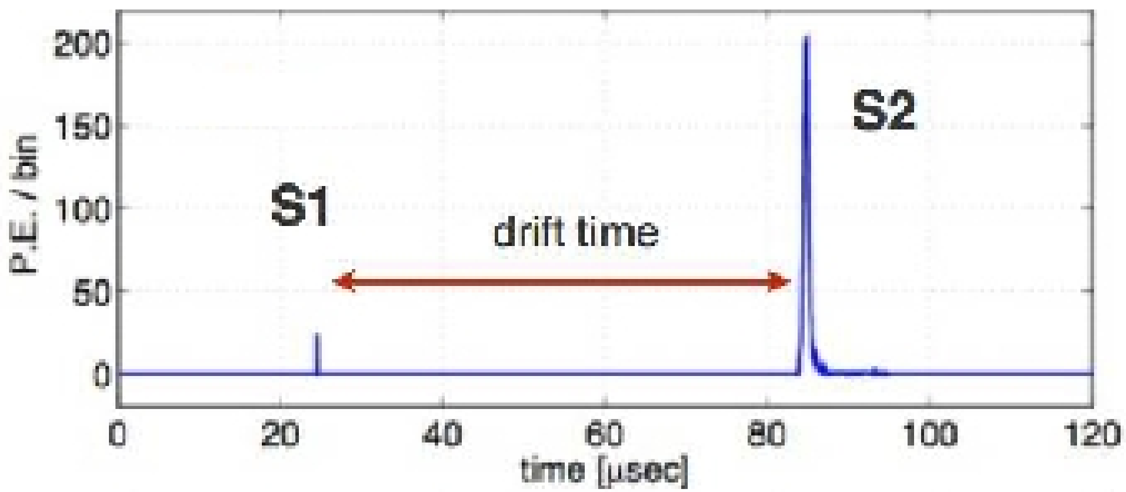
(for details see E. Aprile, T. Doke, Rev. Mod. Phys. 82 (2010) 2053)

XENON technology: basic principle

Detector: liquid xenon time projection chamber (-91 °C)
 in passive shield (γ and neutron shield)

WIMP interaction
 ⇒ prompt scintillating light S1
 electrons drifted into gas phase
 by drift field in LXe (0.5-1 kV/cm)
 ⇒ proportional light (S2) by electro-luminescense
 in GXE (10kV/cm)



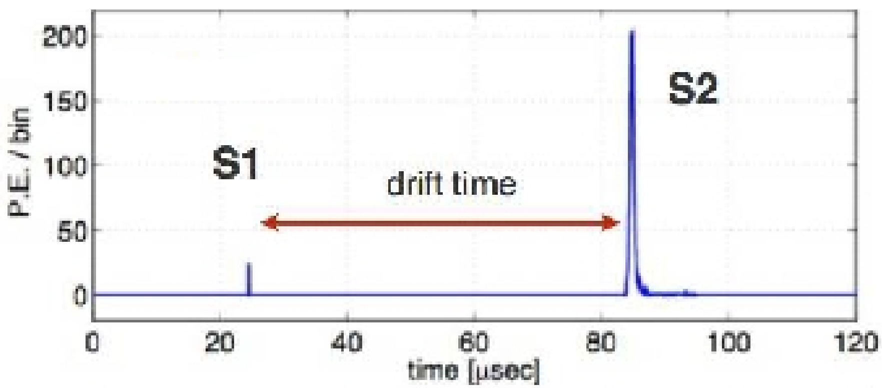


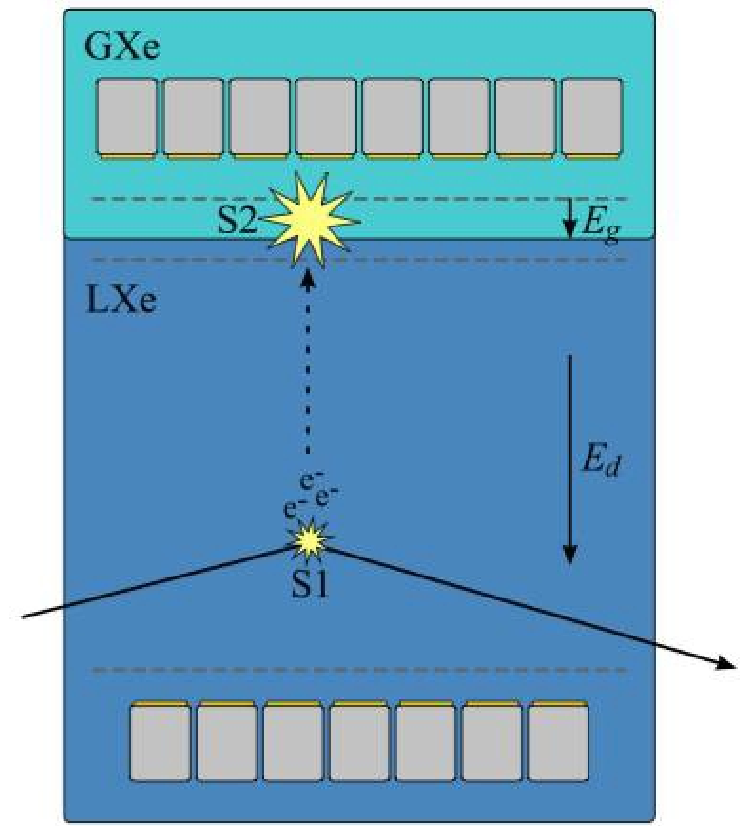
XENON technology: position reconstruction

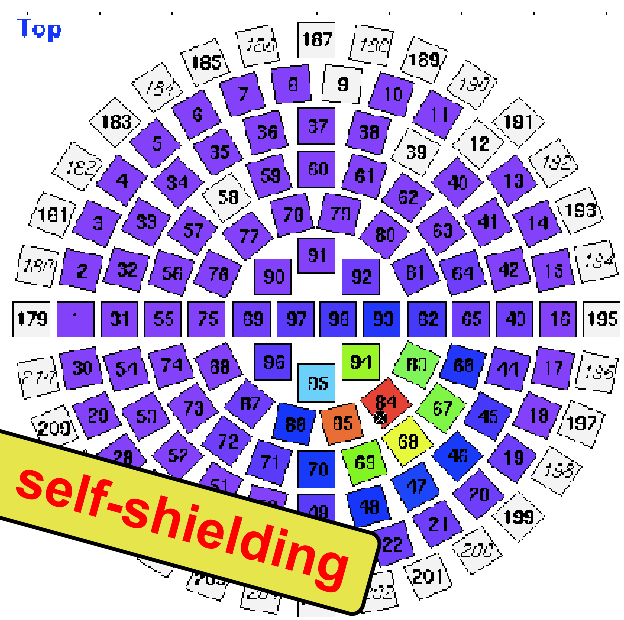
Drift time of charge to liquid / gas interface = Dt(S1-S2):

in LXe: 0.53 kV/cm: v_d = 1.7 mm/μs

→ vertical position precision: Δz = 0.3 mm







⇒ fiducialisation & self-shielding

Electroluminescence in GXe

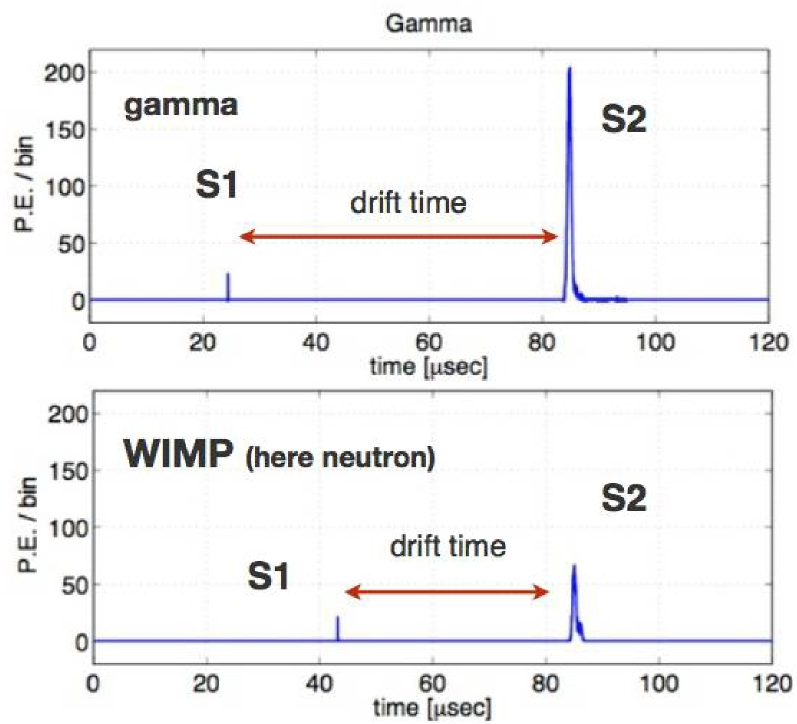
→ light pattern on top PMT array

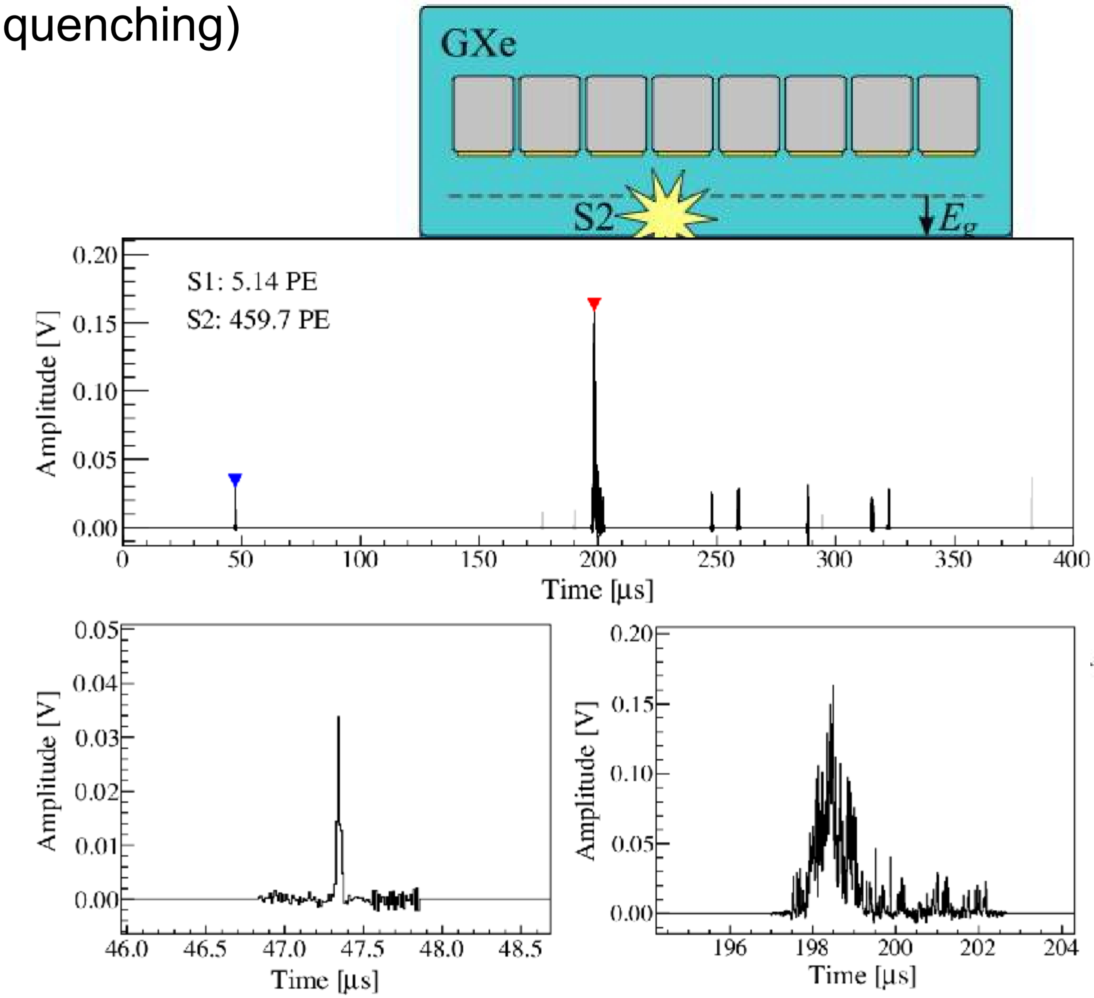
provides horizontal position

with Δx = 3 mm = Δy precision

XENON technology: nuclear recoil and e-/γ separation

Distinguish nuclear recoil (WIMP, n → charge quenching)
from electronic recoil (background)
using S2/S1 ratio

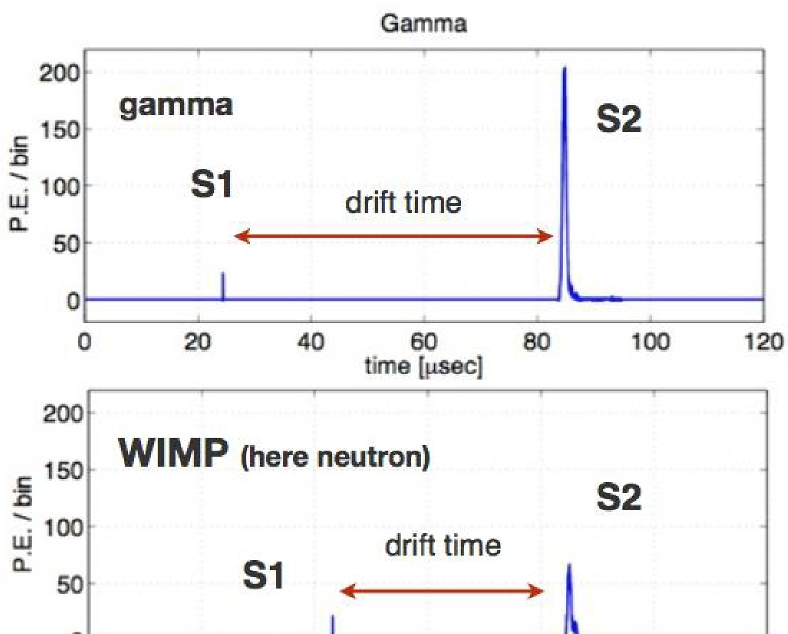


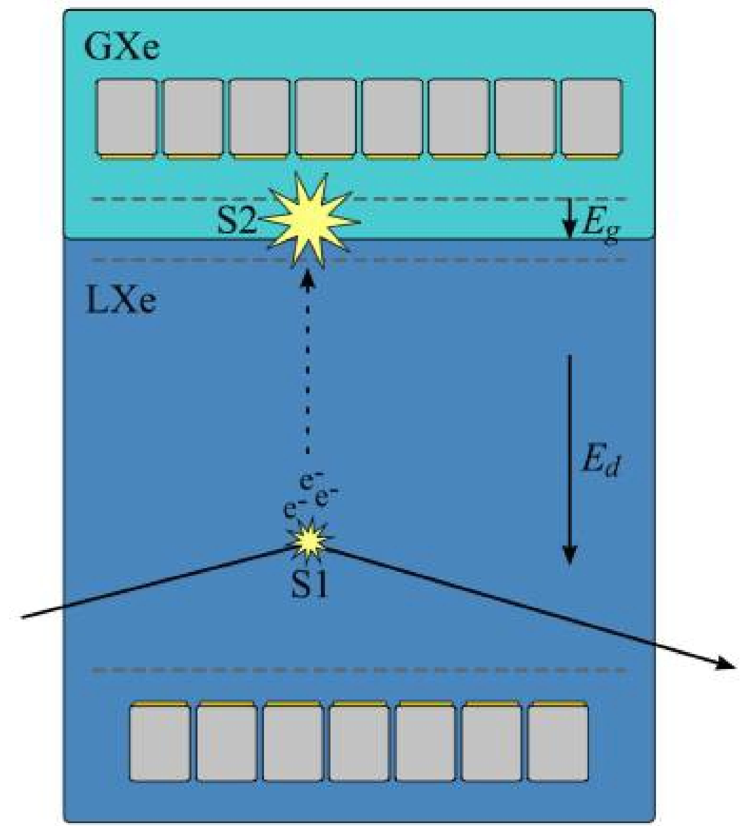


⇒ 99.5% background rejection at 50% nuclear recoil acceptance

XENON technology: challenges

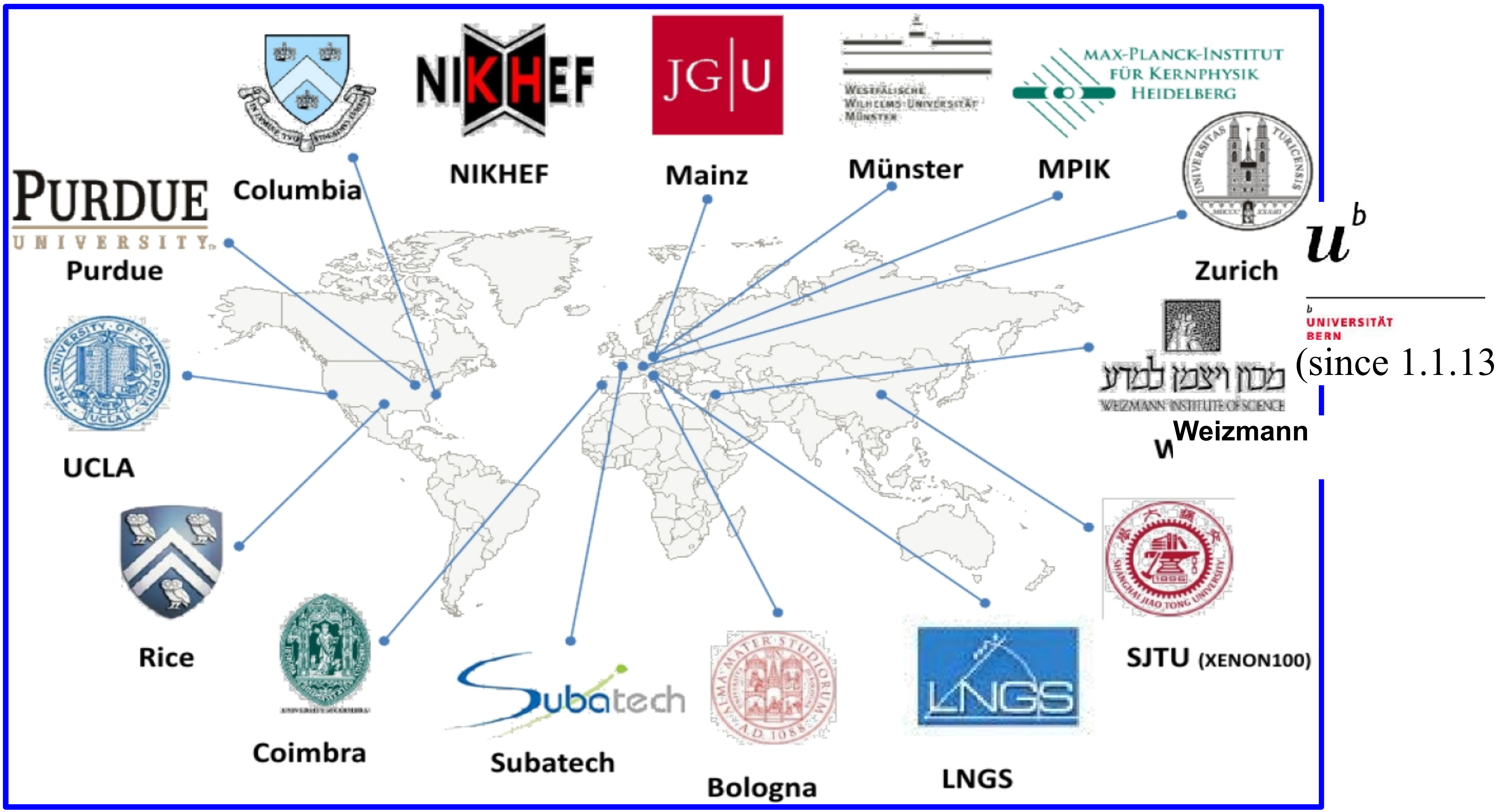
Distinguish nuclear recoil (WIMP, n → charge quenching)
from electronic recoil (background)
using S2/S1 ratio





Challenges: ultra-pure LXe (<1ppb O_2)
efficient charge extraction
high E-field (0.5-1kV/cm in LXe, 10kV/cm in GXe)
efficient light collection @178nm

The XENON collaboration



XENON100

TPC:

161 kg two phase GXe & LXe TPC

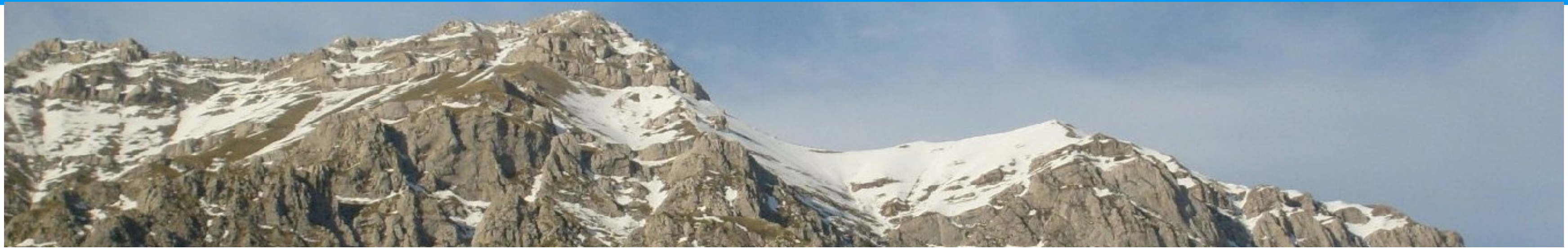
TPC: 30.5 cm diameter
30.6 cm height
→ 62 kg active target
99 kg LXe veto (> 4 cm)

98 + 80 (+64) 1" x 1" R8520-AL PMTs

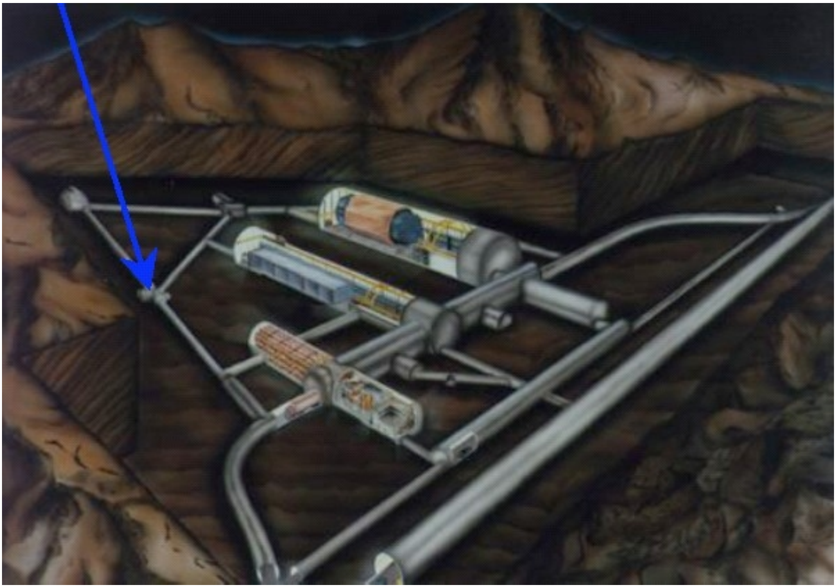
Xe purified by distillation to ≈ 20 ppt Kr

E. Aprile et al., Astropart. Phys. 35 (2012) 573

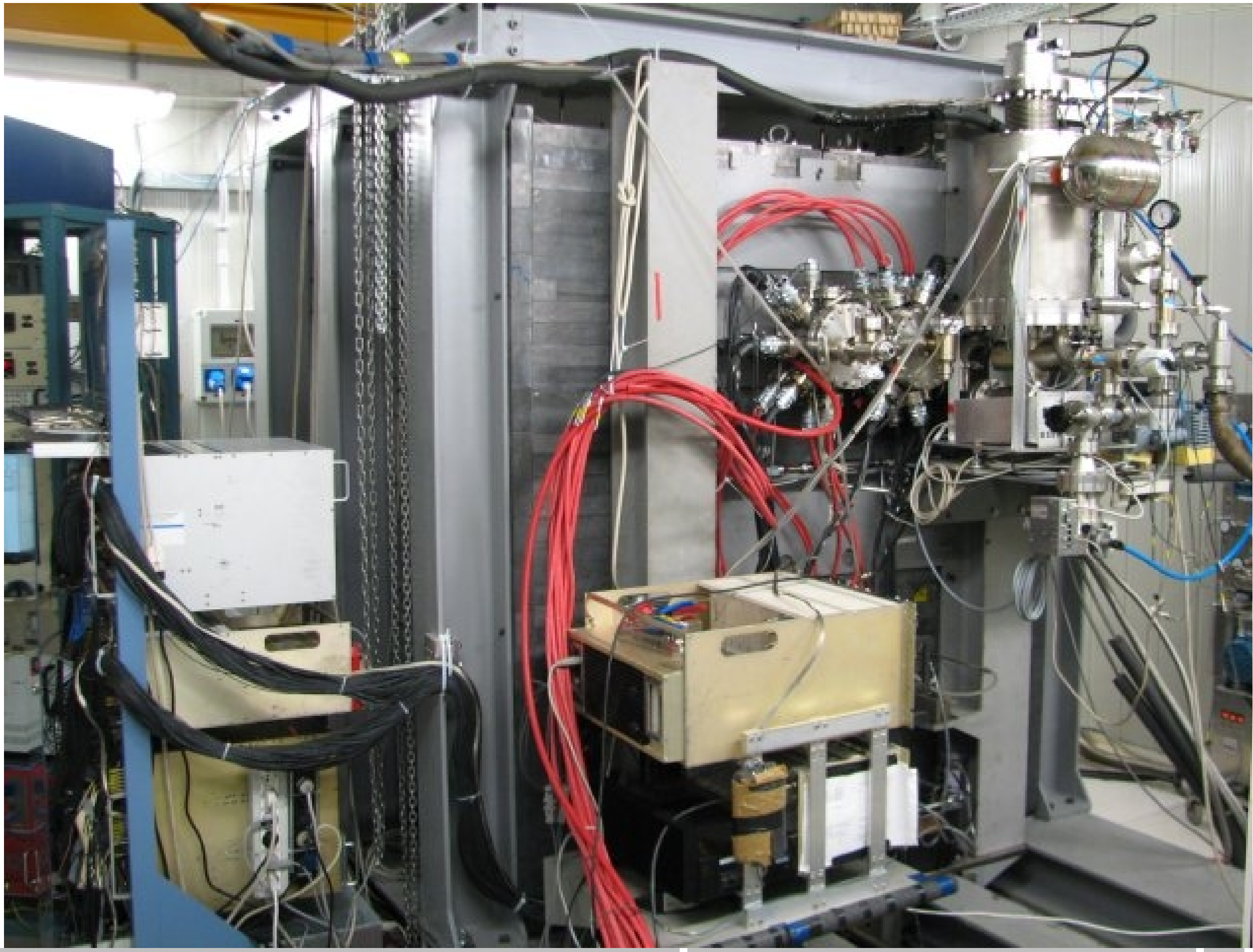
XENON100 @ LNGS



LNGS: 1.4km rock
(3700 mwe)

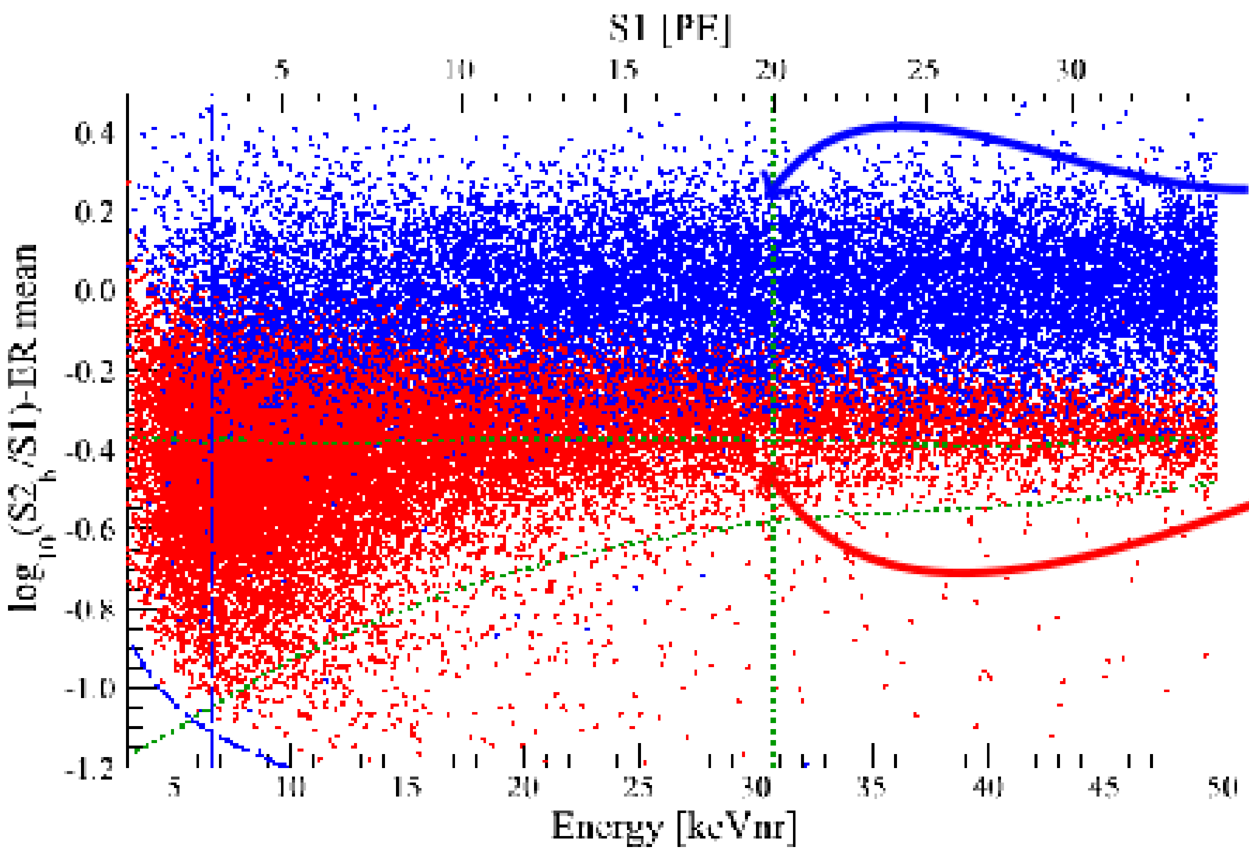


passive shield: H_20, lead, polyethylene, copper



Calibration nuclear recoils versus electron recoils

~1% accuracy of S1,S2 position corrections using various γ lines.



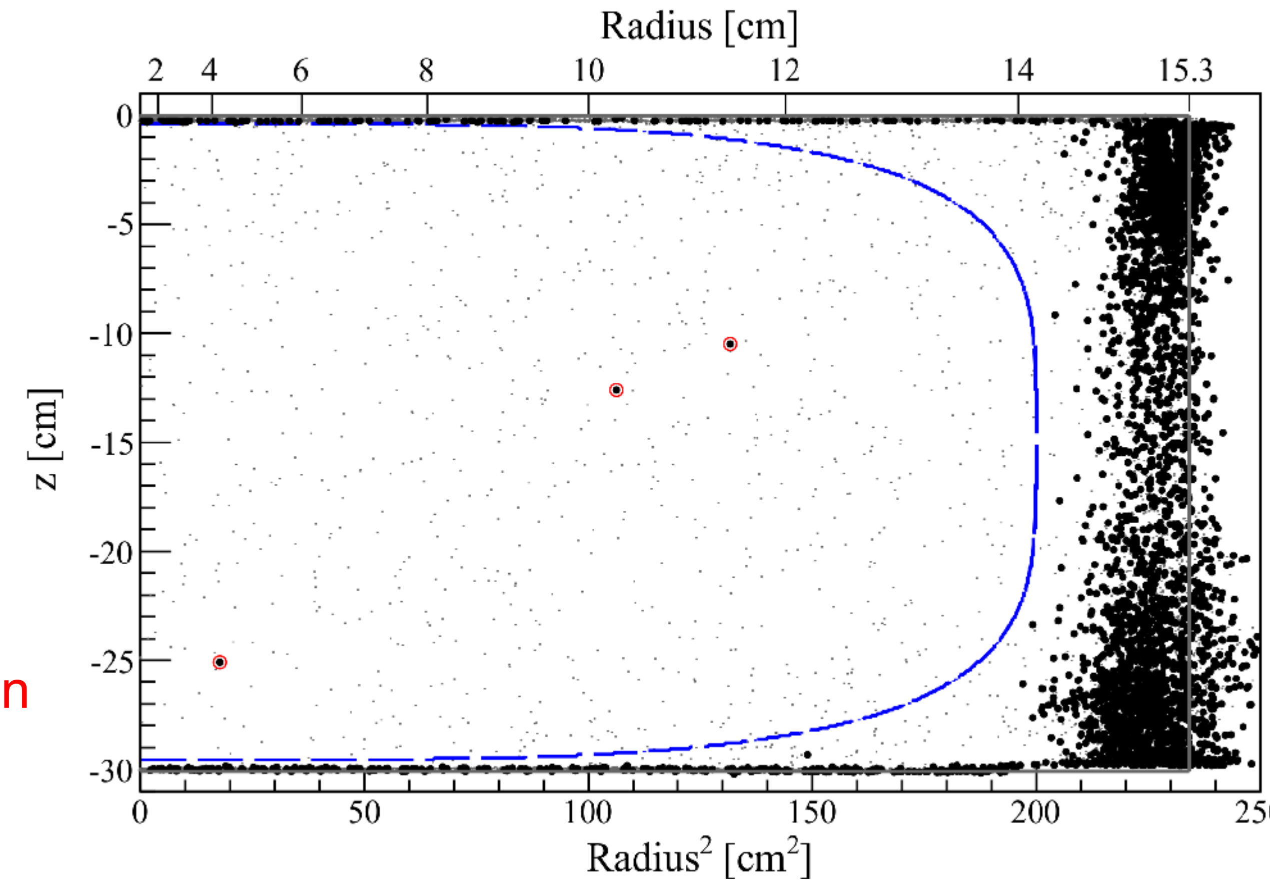
ER calibration data
^{60}Co and new ^{232}Th source
35× science data

NR calibration data
AmBe source
beginning and end of run

~99.5% ER rejection @ 50% NR acceptance

E. Pantic, Aspen 2013

XENON100 run 8: 100d data of 2010

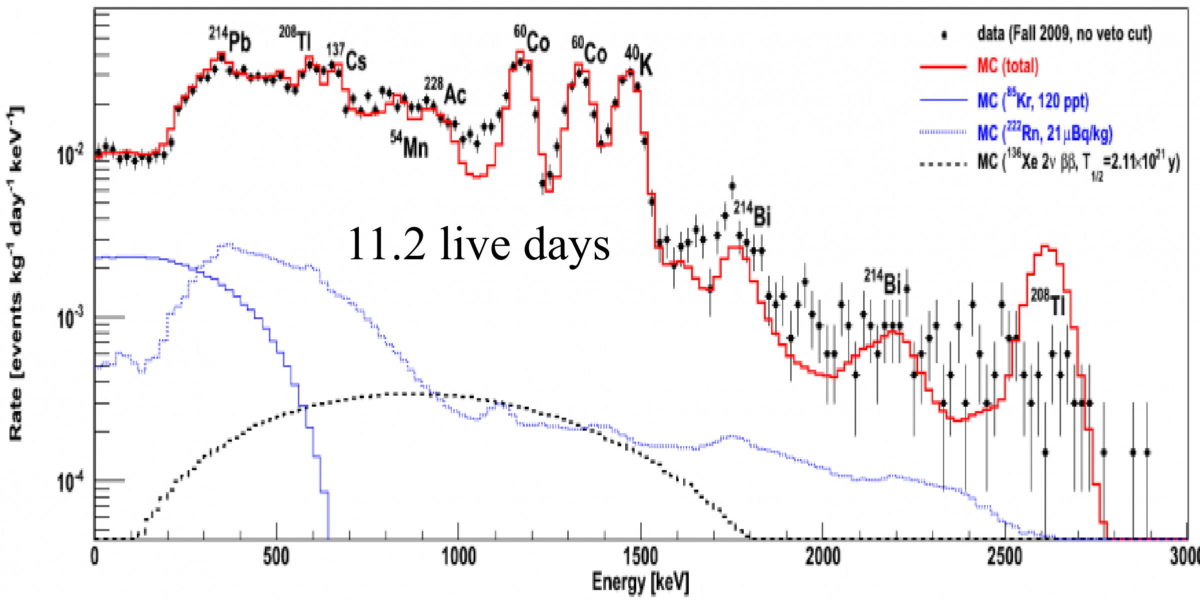


3 events in benchmark region
1.8 +/- 0.6 events expected

⇒ **fiducialisation & self-shielding is working**

E. Aprile et al., Phys. Rev. Lett. 107 (2011) 131302

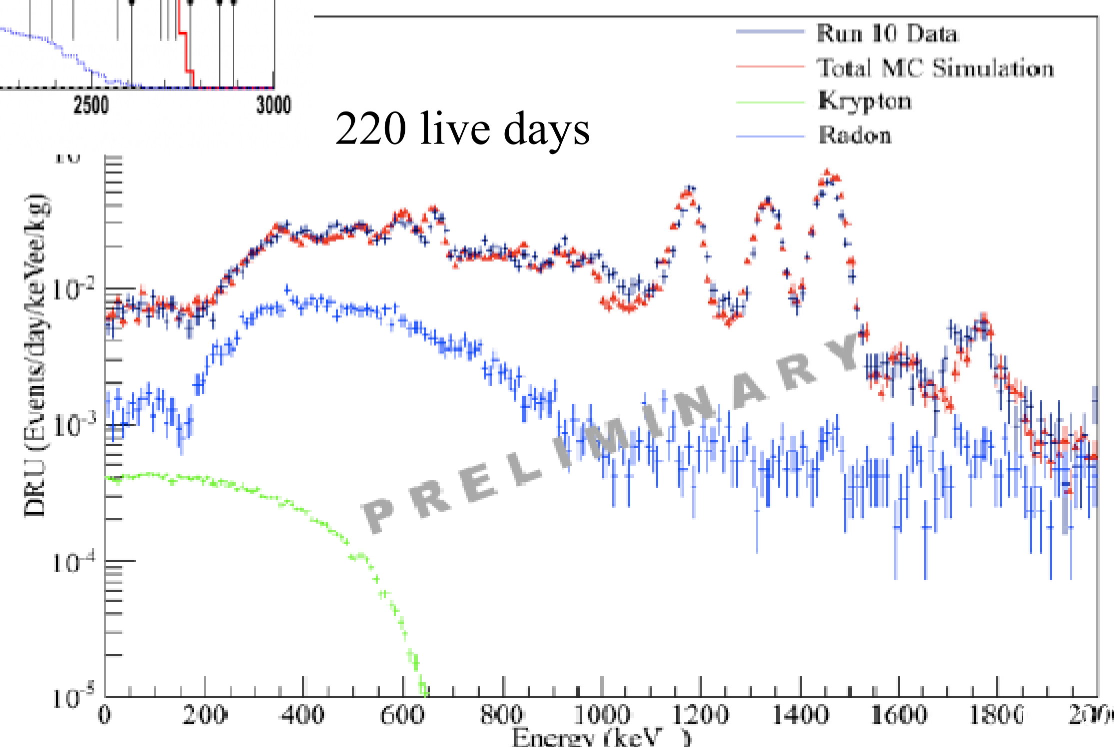
XENON100 Dark Matter run 10: improved background at low energies



E. Aprile et al. Phys.Rev.D83 (2011) 082001

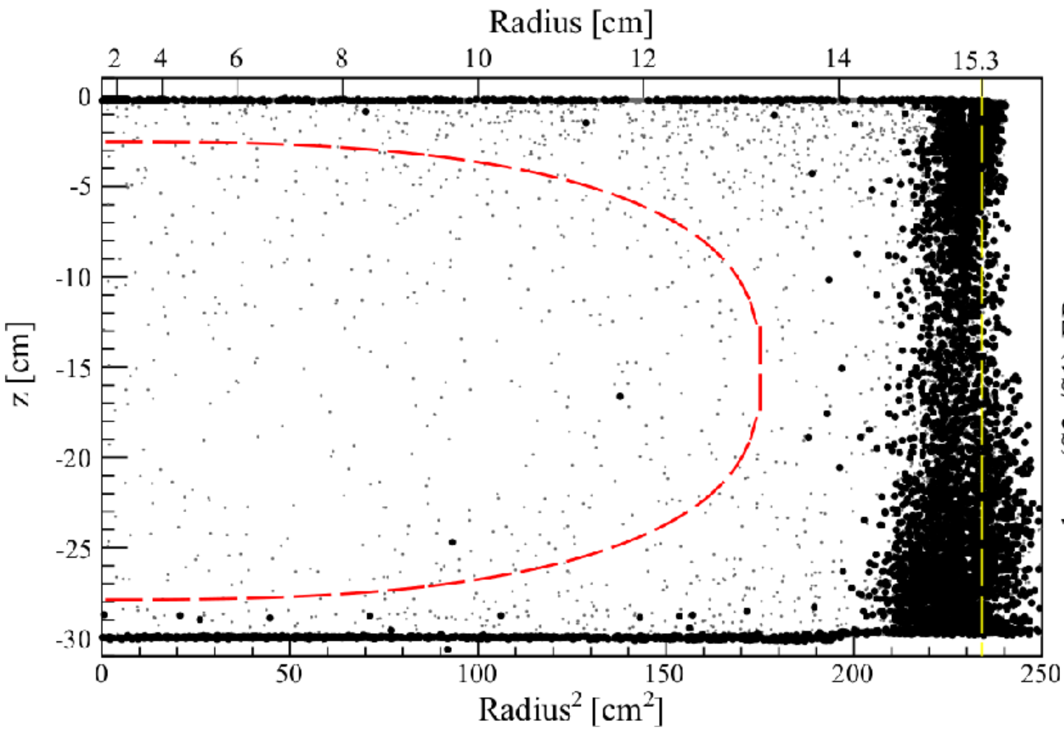
Excellent agreement
No fine tuning required
Radioactivities taken from measurements

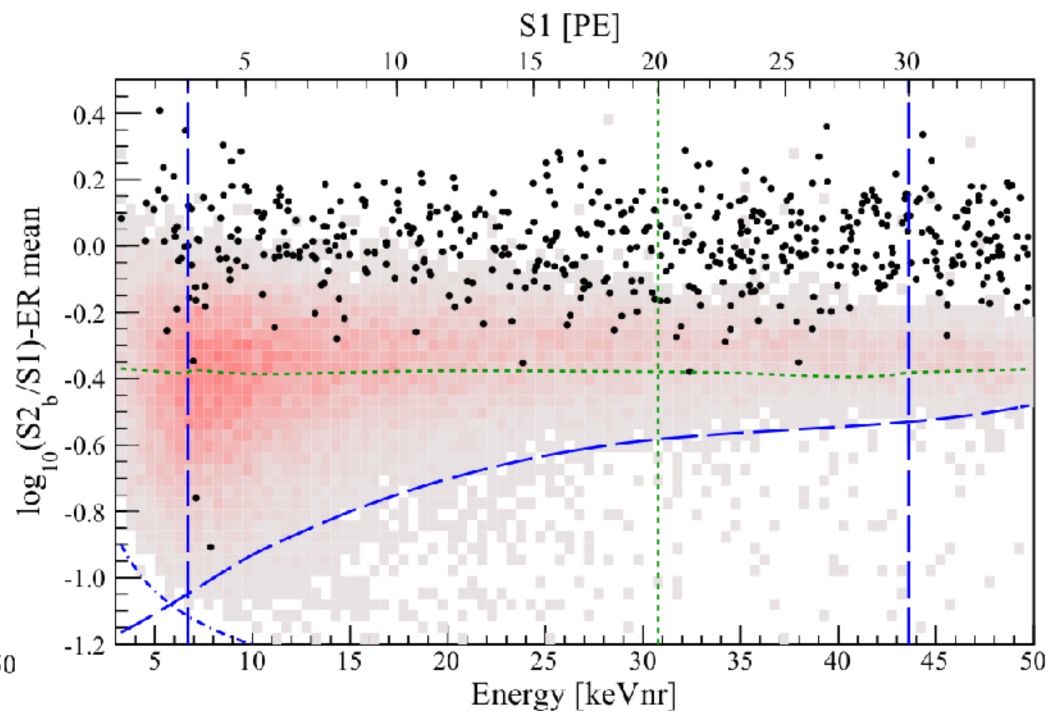
Rate below 100 keV significantly reduced
Kr reduced to 19 ± 1 ppt in run10 as measured by rare gas mass spectrometry



Run 10: 225 live days in 2011/2012

E. Aprile et al., Phys. Rev. Lett. 109 (2012) 181301

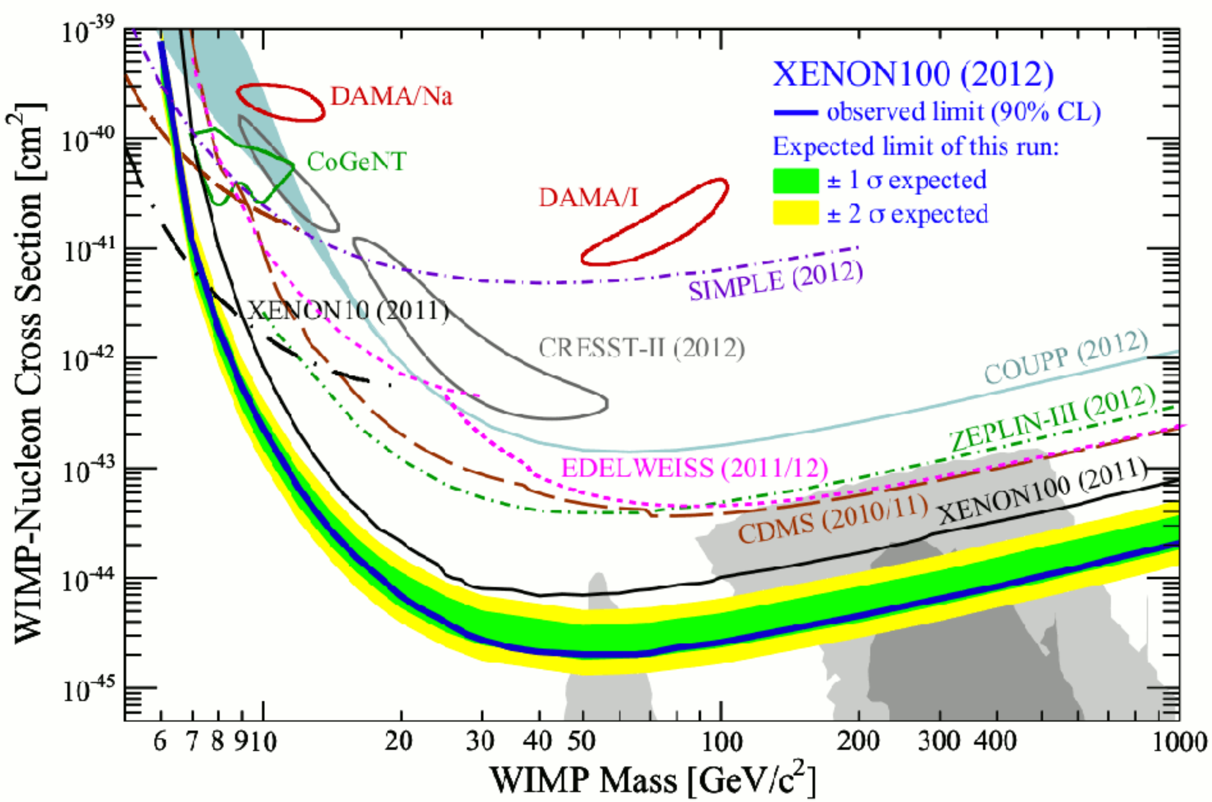




blind analysis, use 34 kg fiducial mass
cut-based analysis:
expected background: 1 event, measured: 2 events
→ statistical consistent with no signal
→ no dark matter found, only upper limit

XENON100 run 10: 225d data of 2011/2012

E. Aprile et al., Phys. Rev. Lett. 109 (2012) 181301



Profile Likelihood Analysis:

- all observed events
- full energy information,
  no discrimination
- incorporate calibration informations
- include systematic uncertainties
  (v_{esc}, L_{eff}, …)
- method makes smooth transition
  between rejection/discovery

→ calculate only one true 90%CL limit

Details of the profile likelihood analysis:

E. Aprile et al.,
Phys. Rev. D 84 (2011) 052003

World´s best sensitivity on WIMPs
but nothing found yet !

disfavours DAMA & CoGeNT (& CRESST) possible signal regions
(also IDM@DAMA ruled out, E. Aprile et al, Phys. Rev. D 84 (2011) 061101)

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XENON100 Dark Matter run 10: Limits on spin-dependent interaction

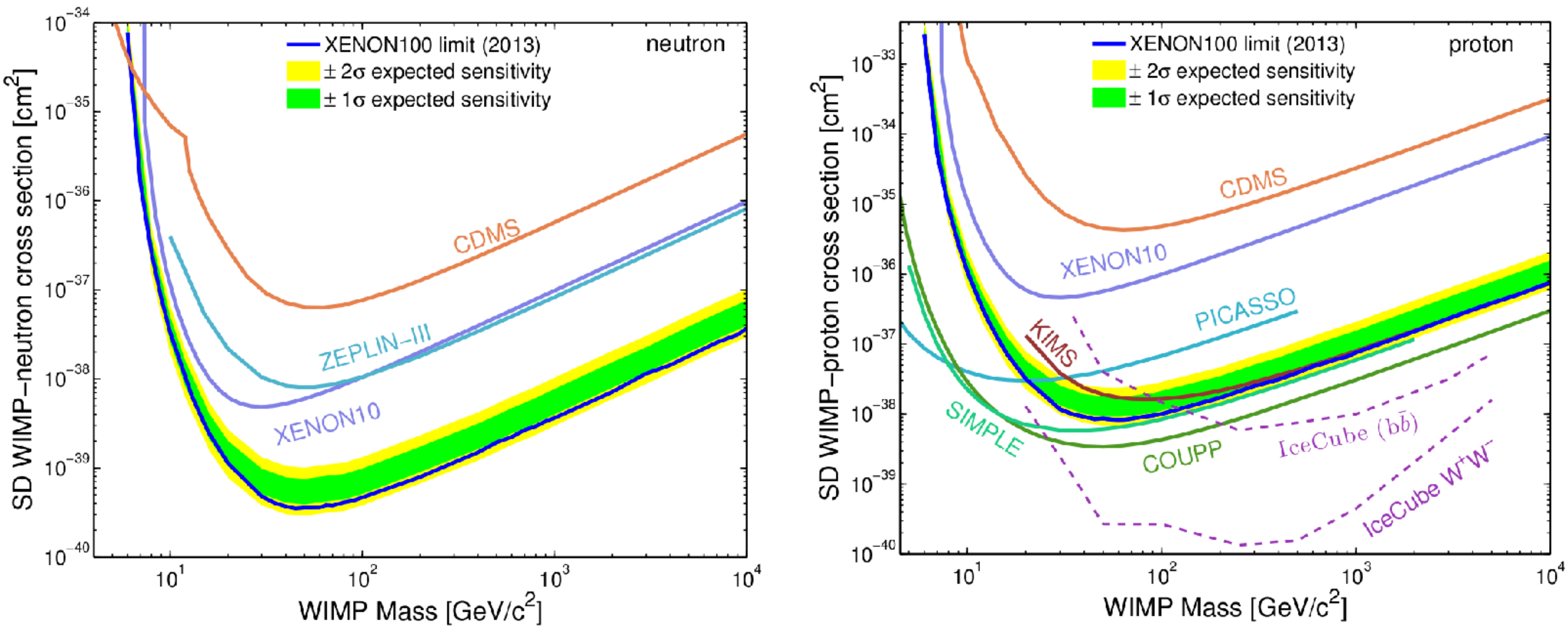
XENON Dark Matter Project

Some data selection and analysis as 225 days run 10 analysis (PRL 109 (2012) 181301)

Sensitivity to SD interaction by odd isotopes ^{129}Xe (J=1/2, 26.4%) and ^{131}Xe (J=3/2, 21.2%)

Single particle cross section limits

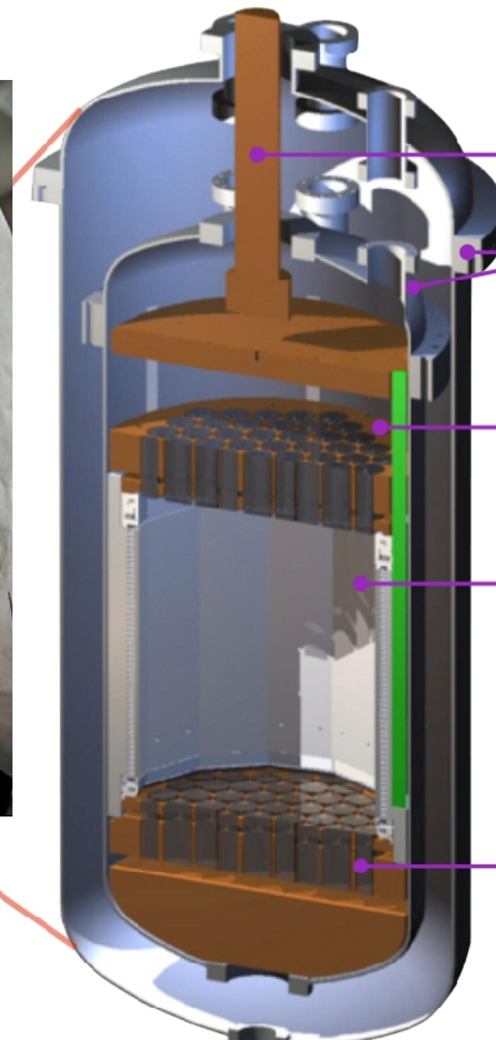
$$\sigma_{p,n}(q) = \frac{3}{4}\frac{\mu_{p,n}^2}{\mu_A^2}\frac{2J+1}{\pi}\frac{\sigma_{SD}(q)}{S_A^{a_0=\pm a_1}(q)}$$

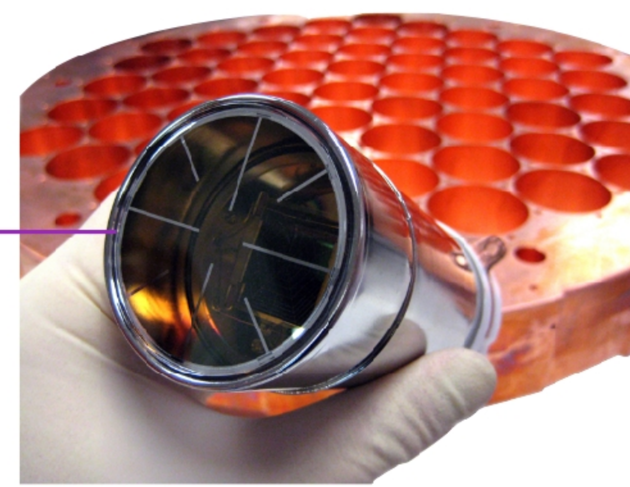


E. Aprile et al., arXiv:1301.6620

LUX: 2-phase Xe, commissioning started in Homestake mine, aim: $\sigma = 2\ 10^{-46}\ \mathrm{cm}^2$

from R. Gaitskell, Aspen 2013





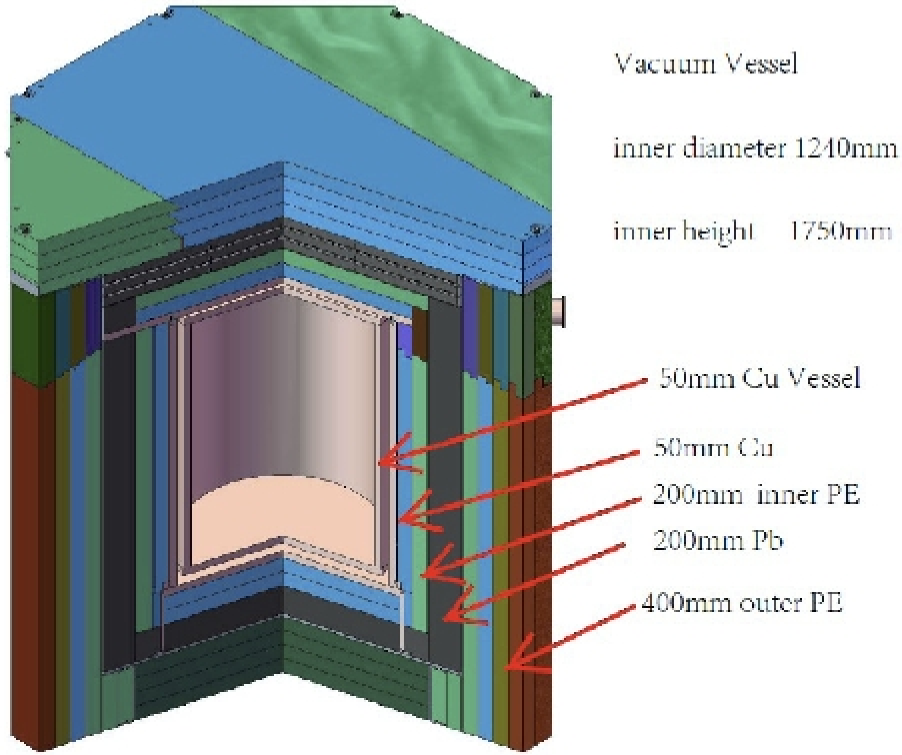
2" Hamamatsu R8778 Photomultiplier Tubes (PMTs)

- 370 kg (300 kg active) LXe
- 122 PMTs (2" round)
- Low-background Ti cryostat
- PTFE reflector cage
- Thermosyphon used for cooling (>1 kW)

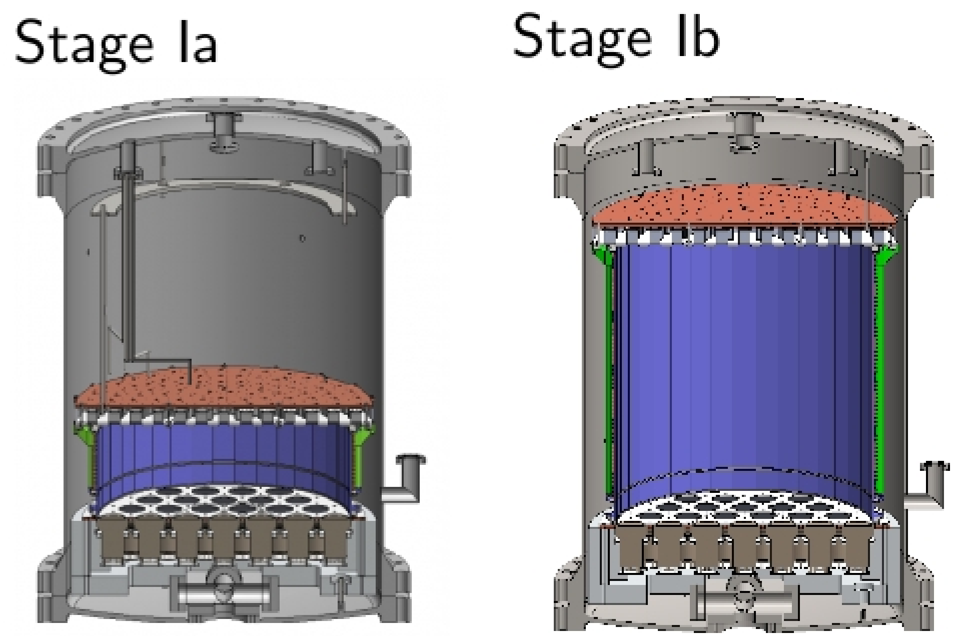
PANDA-X: 2-phase Xe, start in 2013 with stage 1a: low mass WIMP search

from S. Stephenson, Aspen 2013

in JinPing underground laboratory, China



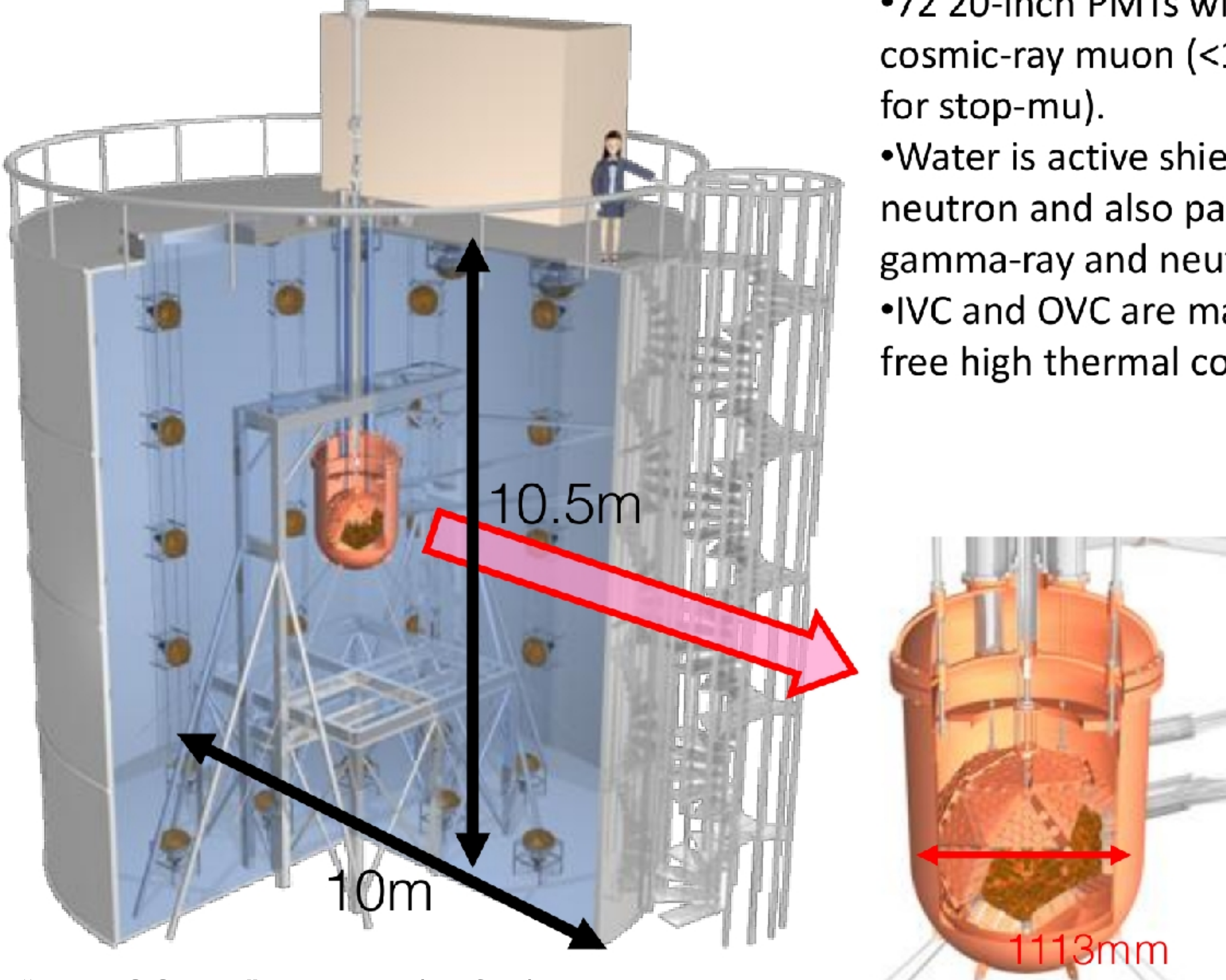
- Low Z (PE) to attentuate n's
- High Z (Pb,Cu) for γ's



- Same inner vessel for Ia/Ib
- PandaX Ia - 15x60cm 'Pancake'
- PandaX Ib - 60x60cm (300 kg fid.)

XMASS: 1-phase LXe in Kamioka mine restart in 2013 after refurbishment

from K. Kobayashi, Aspen 2013



- 72 20-inch PMTs will be installed to veto cosmic-ray muon ($<10^{-6}$ for thr-mu, 10^{-4} for stop-mu).
- Water is active shield for muon induced neutron and also passive shield for gamma-ray and neutron from rock/wall.
- IVC and OVC are made of OFHC (Oxygen-free high thermal conductivity) copper

OVC

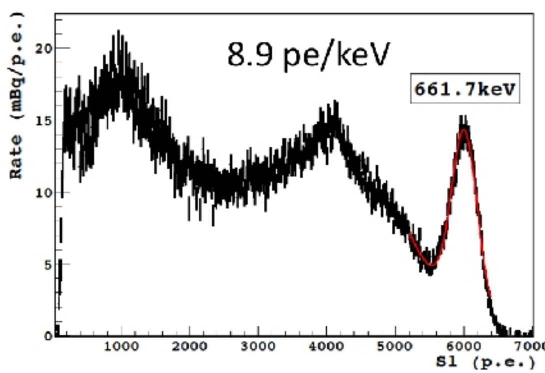
IVC

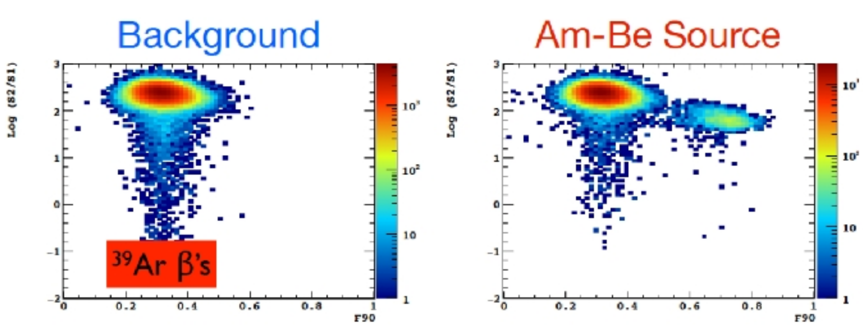
Future “XMASS 1.5”: 5t LXe (1t fid.)

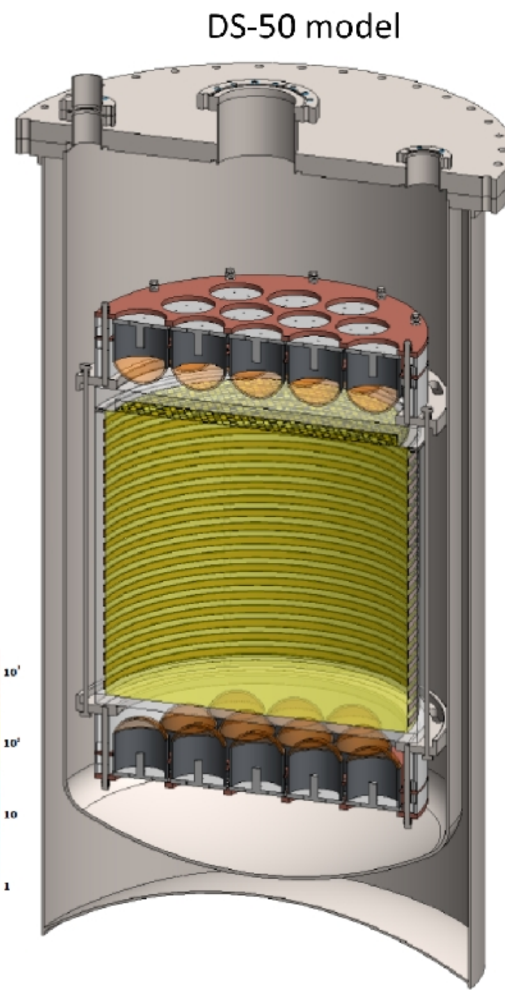
Darkside-50: 2-phase Ar in LNGS depleted in ^{39}Ar, aim: $\sigma = 2\ 10^{-46}$ cm^2

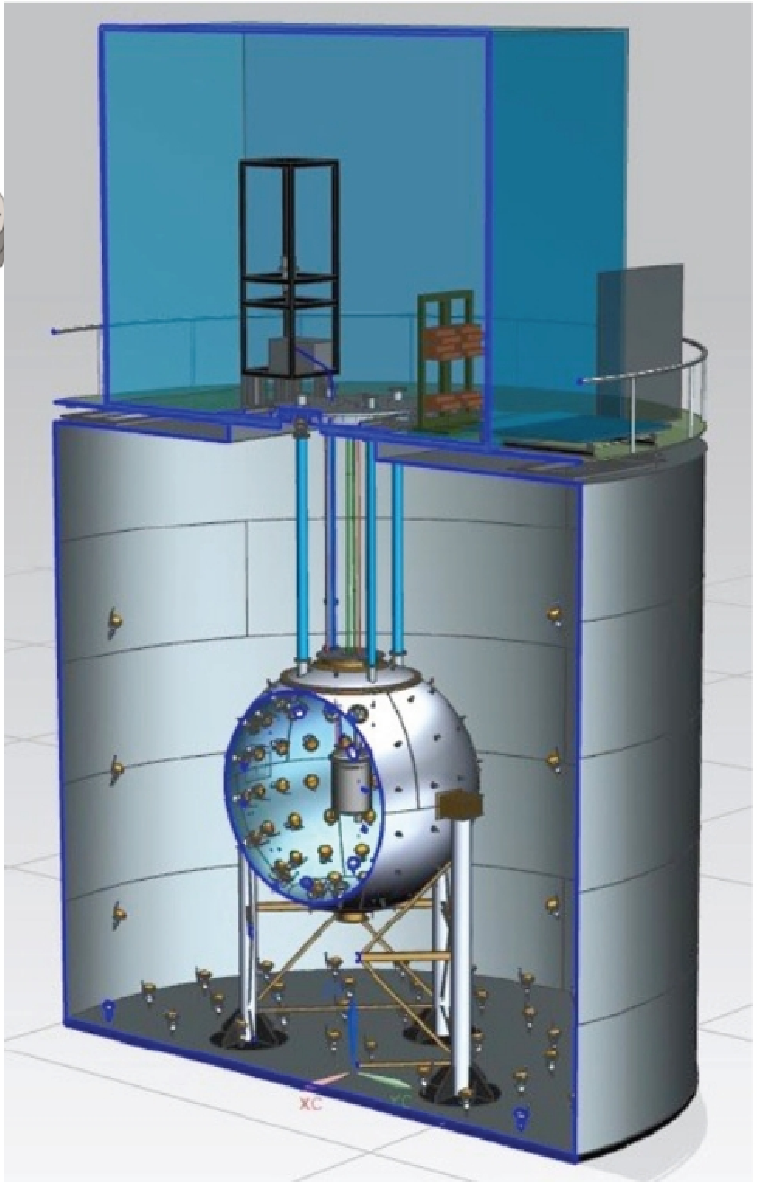
from D. McKinsey, Aspen 2013

Darkside G2: 5t Ar, aim: $\sigma = 10^{-47}$ cm^2





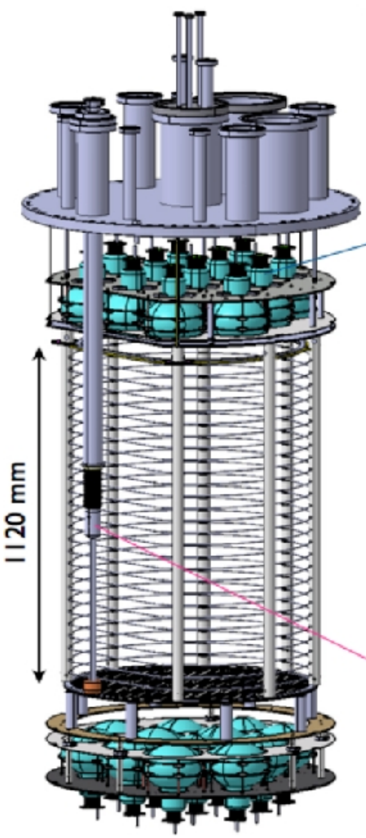




Other Ar detectors: ArDM in Canfranc, Deap/Clean in SNOLab

from D. McKinsey, Aspen 2013

ArDM



Fully PMT-based readout
(initial configuration)

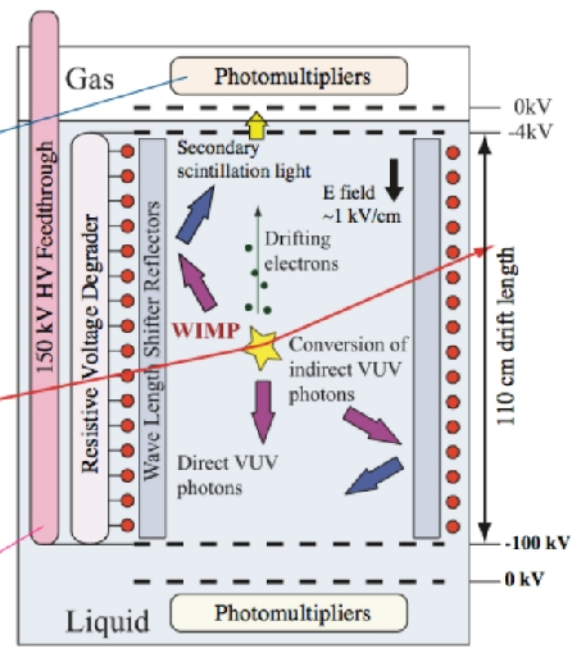
Top PMT array in gas phase
and bottom array in liquid,
both will be newly built :

- new PMT supporting structure
- new layout with 12 PMTs
- fresh coating with wave-length shifting TPB

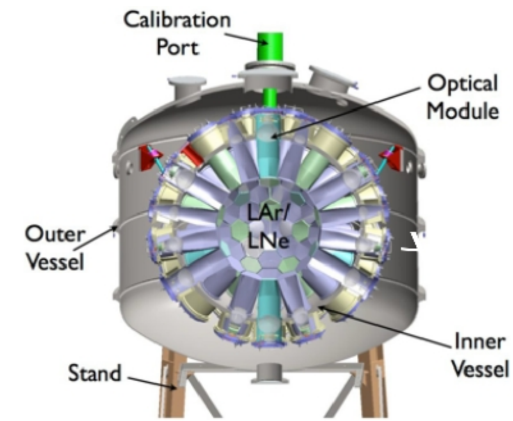
HV feedthrough for drift field

Modified field cage

Slide from A. Rubbia



miniClean: 500 kg LAr
commissiong in 2013
^{39}Ar spiking for PSD tests



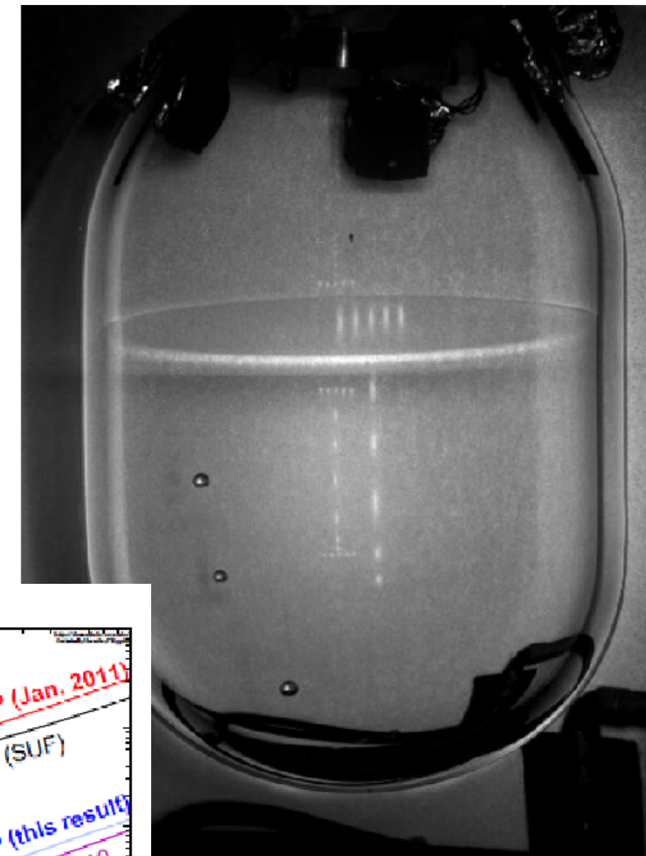
Steel Shell

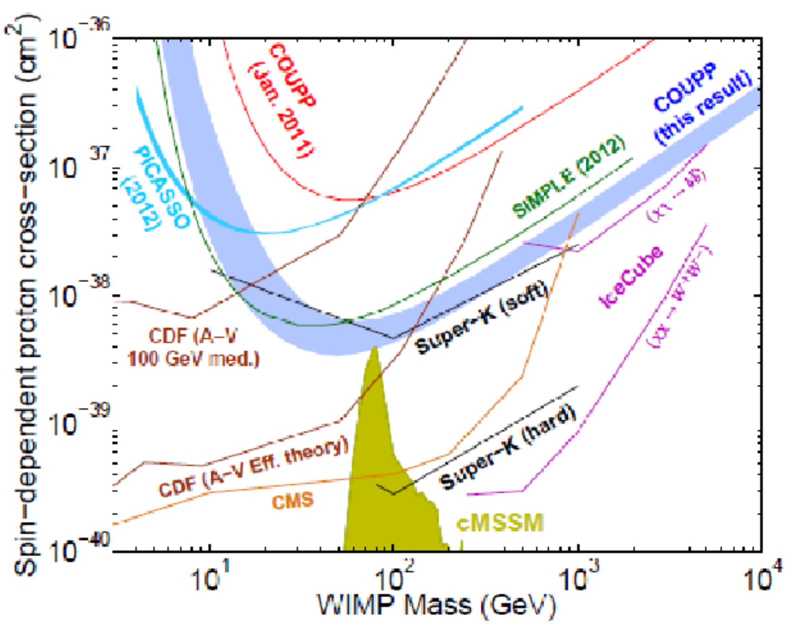
Deep-3600: 3.6 t LAr
commissiong in 2014

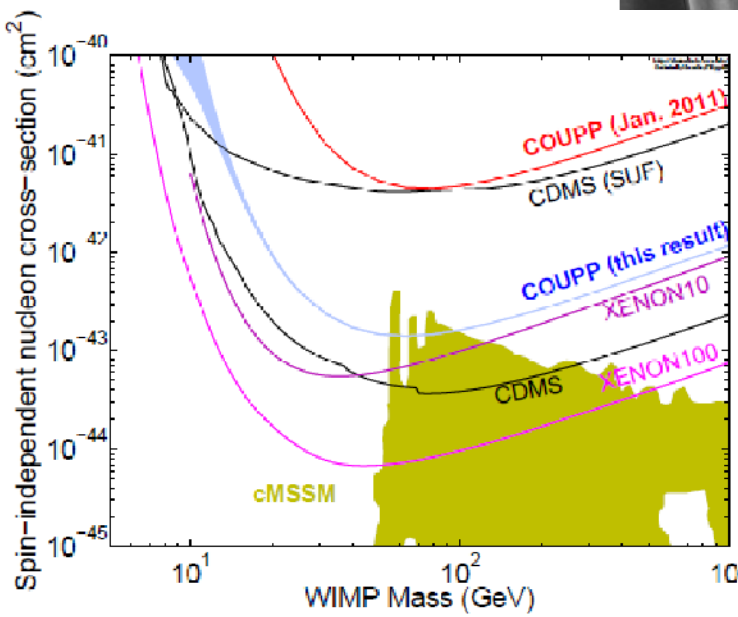
Some different detector technology: COUPP bubble chamber in SNOLab

from R. Neilson, Aspen 2013 (see also PICASSO@SNOLAB)

- Superheated fluid CF_3I
  - F for spin dependent
  - I for spin independent
- Observe bubbles with two cameras and piezo-acoustic sensors.







XENON1T at LNGS

- 1 m drift TPC with 2.4 ton (1 ton fiducial) LXe
- 10 m water shield as Cherenkov Muon Veto
- 100 x less background than XENON100
- Approved by INFN for installation at LNGS
- Fully funded
- construction start in LNGS Hall B in 2012
- Science Data projected to start in 2015
- Sensitivity: 2 x 10^{-47} cm^2 after 2 years of data

XENON1T infrastructure meeting at MS/Jan. 2013

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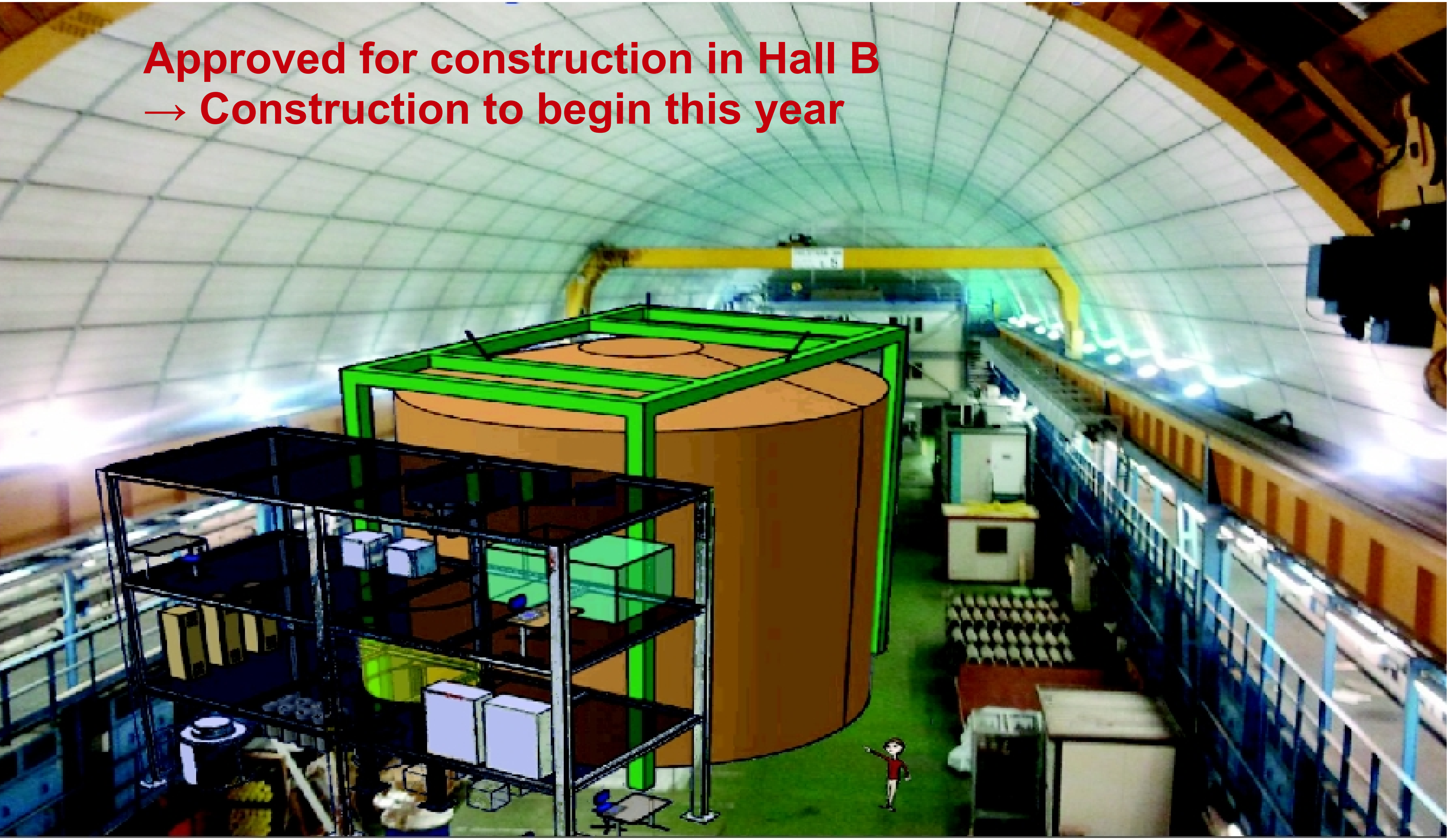
XENON1T at LNGS

Xe XENON Dark Matter Project



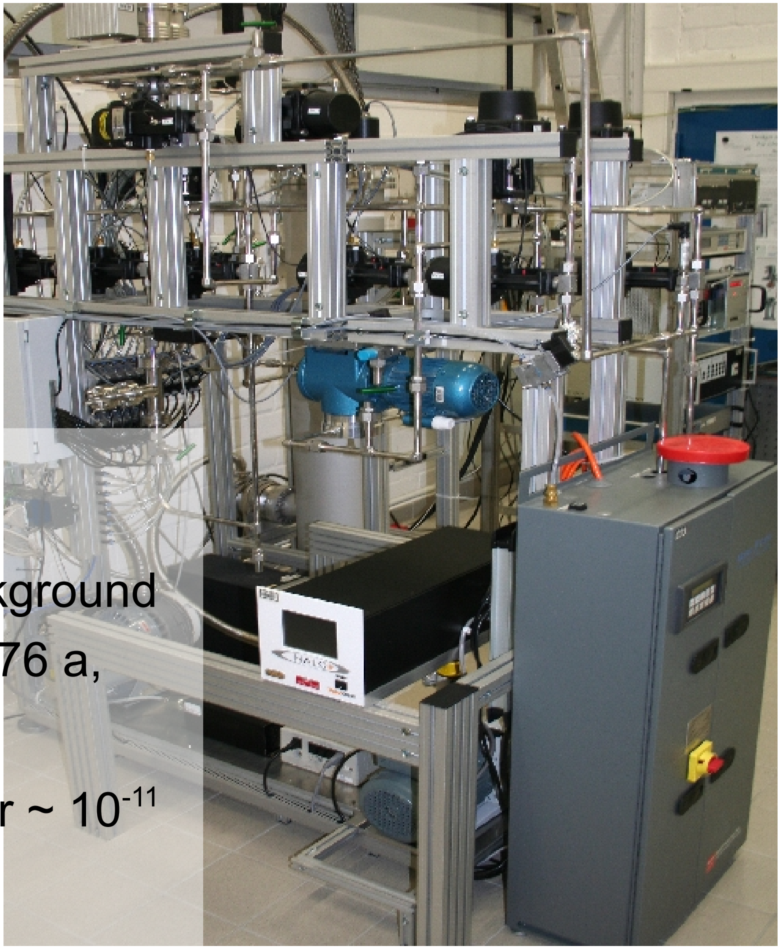
Purification requirements for the XENON1T experiment

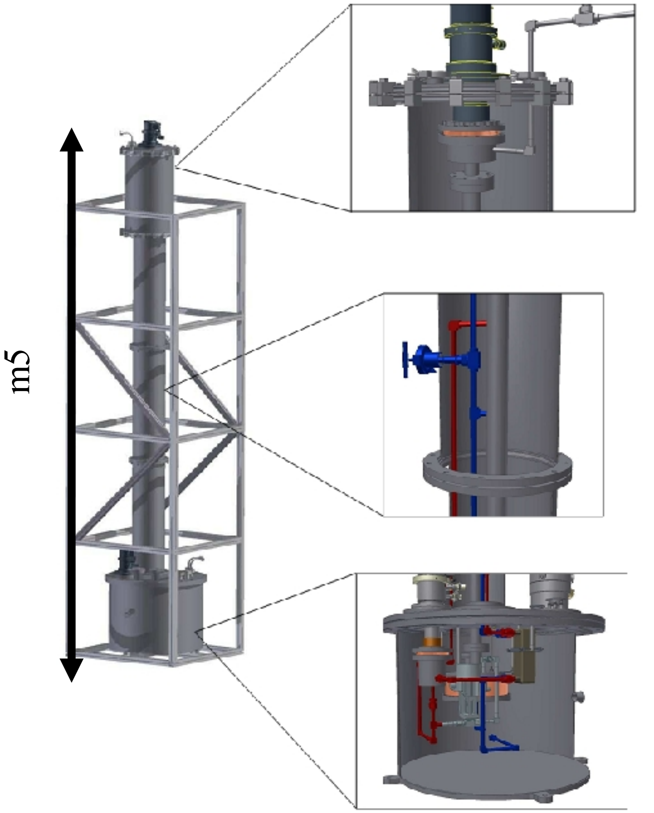
- Purification for electronegative elements (e.g. oxygen, water) < 1ppb using hot zirconium oxide Getter

  Aim for fast circulation up to 100 (200) SLPM

  → Increase of light yield

  → Increase of electron drift lifetime





- Purification for Kr/Xe < 1ppt using cryogenic distillation
  → ^{85}Kr is one source of background (Q_β = 687 keV, $t_{1/2}$ = 10.76 a, 99.57% BR)
  → natural abundance ^{85}Kr/Kr ~ 10^{-11}

- Purification for Radon

Status of the new distillation column as of Christmas 2012

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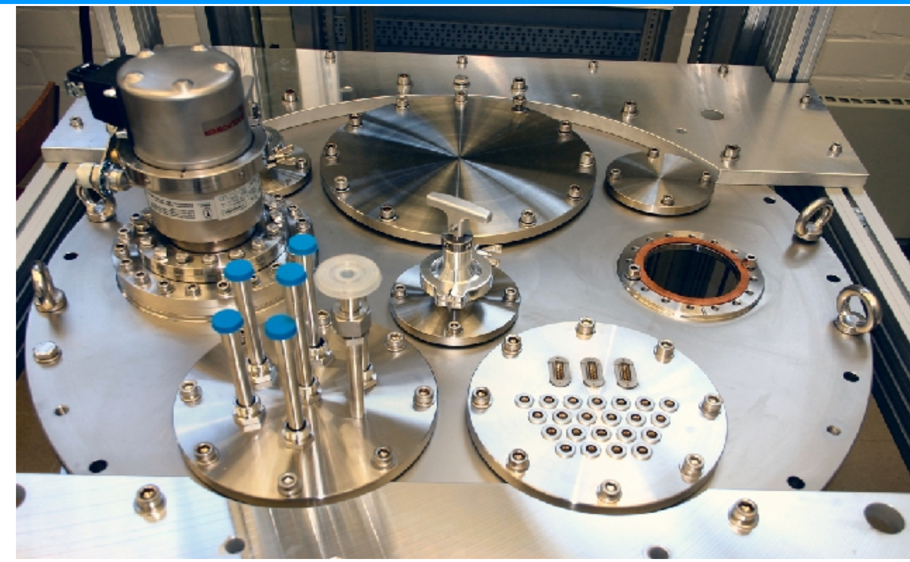
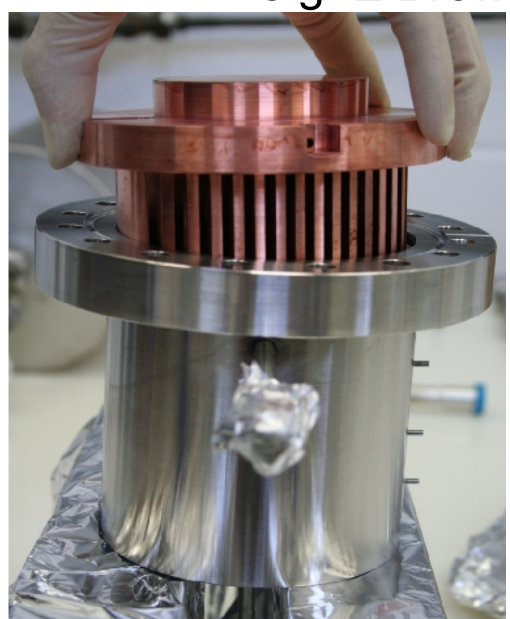
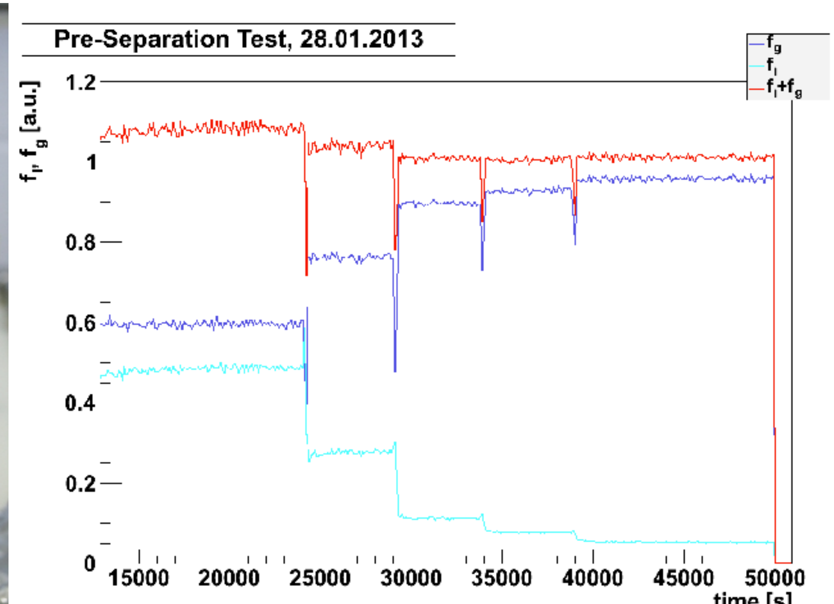
Xe XENON Dark Matter Project

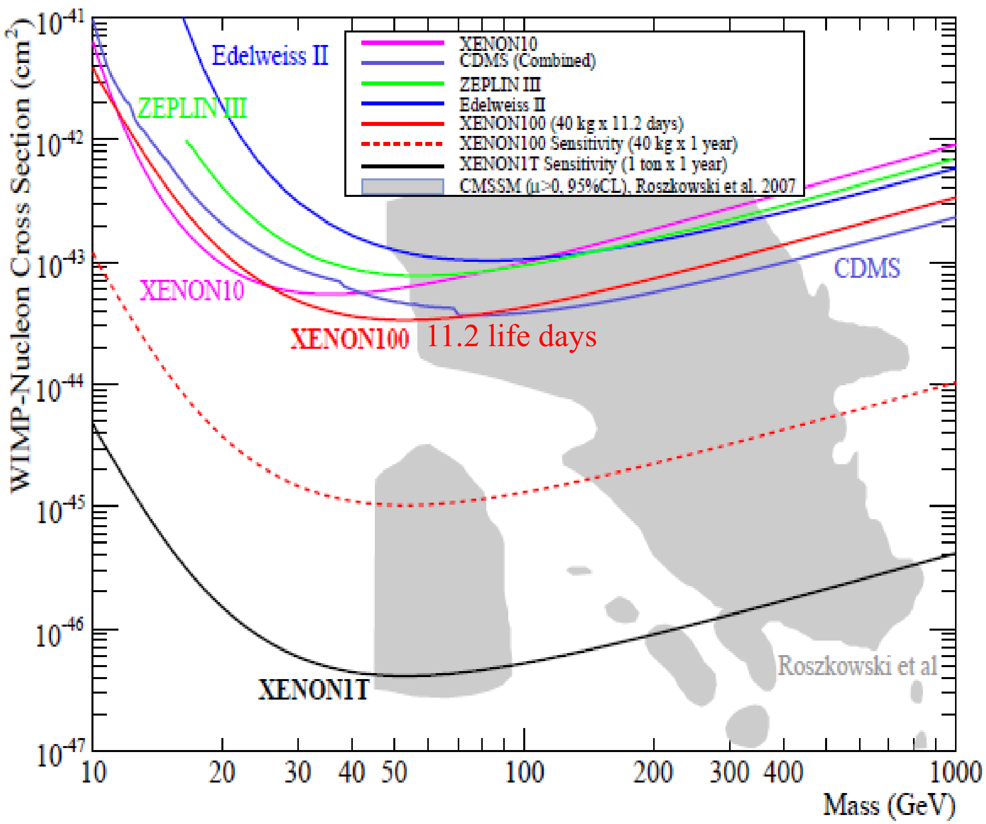


2 new kinds of Kr in Xe diagnostics developed,
e.g. E Brown et al 2013 JINST 8 P02011

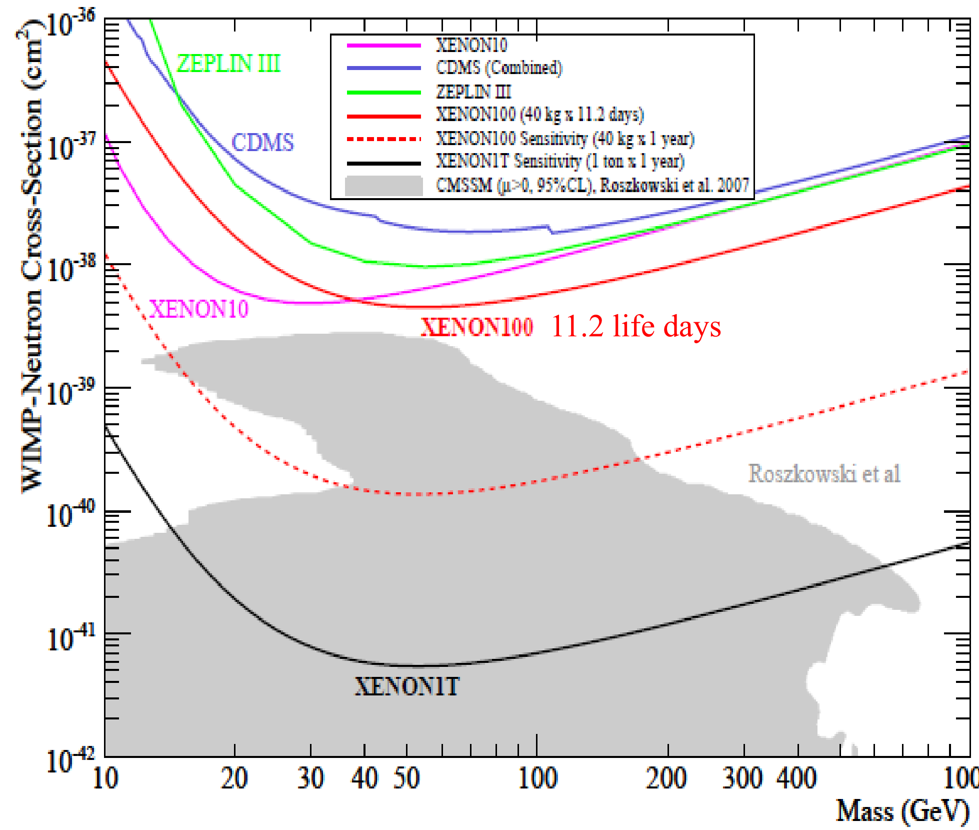




XENON1T sensitivity



Spin Independent



Spin Dependent

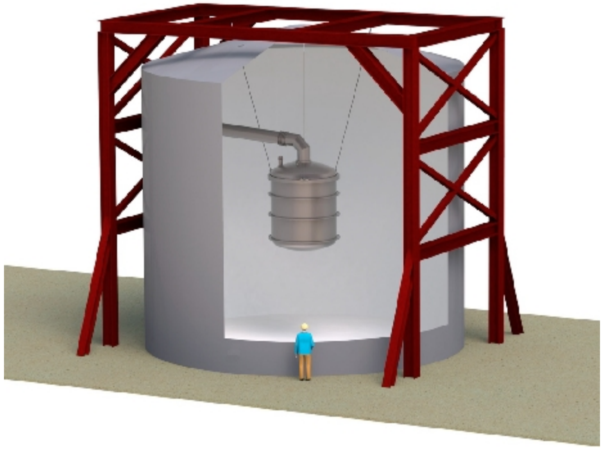
Future of direct cold Dark Matter (WIMP) search

Could go on until limit by intrinsic background (e.g. solar neutrinos, double β decay)

Further possible improvements:

- ultra-clean materials and Xenon
- full coverage of surface by photo-sensors (Problem of high electric potential)
- advanced photo-sensors (QUPID, GPMTs, ..)
- advanced methods for background suppression:
  - n-tagging by tagging multple scatters
  - differentiate NR from ER by pulse shape analysis of fast scintillation light
- ....

DARWIN: 20t LXe or LAr



And: Xe TPCs could be used in medical imaging, e.g. GridPix technolgy

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Conclusion

Dark Matter

cosmological and astrophysical evidence for exotic Dark Matter

LSP would help particle physics

Direct Dark Matter experiments

Very active field with many experiments, two major technologies:

cryogenic bolometers & liquid noble gases

some indications for low mass WIMPs, but they do not fit together

in tension with / excluded by XENON100 results

XENON100

62 kg dual-phase Xe TPC @ LNGS

extremely low background

world best limit on WIMPs

Outlook

XMASS (started), LUX (started commissioning), XENON1T (approved & funded),
Super-CDMS (running), DarkSide, PANDA-X, DEAP-3600, miniCLEAN, EDELWEISS-III, EURECA, DARWIN, ...

Funding of Dark Matter activities at Münster: Deutsche Forschungsgemeinschaft DFG; Westfälische Wilhelms-Universität Münster; bmbf - Förderschwerpunkt Astroteilchenphysik, Großgeräte der physikalischen Grundlagenforschung; Helmholtz Association, Alliance for Astroparticle Physics