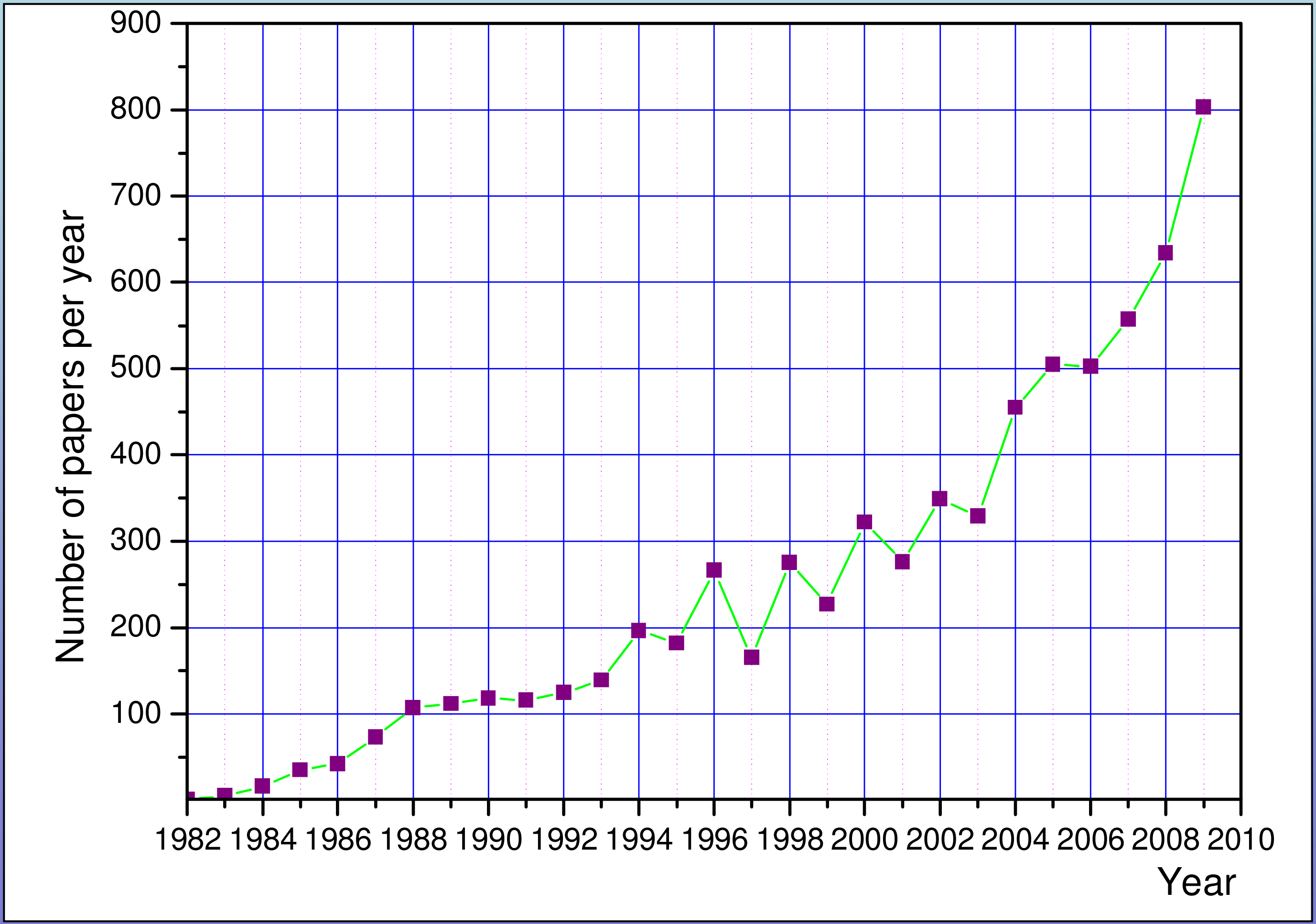
Techniques and Results for the Direct Detection of Dark Matter

D. Akimov

ITEP, Moscow, Russian Federation

Growing interest for this subject

Annual distribution of DM papers (SLAC Spires database – FIND T DARK MATTER and DATE YYYY)



Content

- Physical motivations
  - Astrophysical evidences
  - Cosmological motivations
- Technique of WIMP detection
- DAMA/LIBRA and CDMS
- Noble-liquid WIMP detectors
  - Summary

Physical motivations

Nowadays the evidences in favor of DM are stronger than they have ever been!

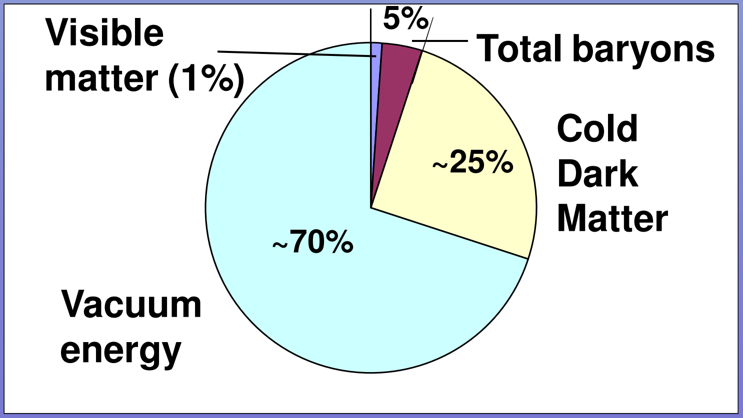
Astrophysical motivations

- Rotation curves of spiral galaxies
- Gravitational lensing for galaxy clusters

Cosmological motivations

- Large-scale structure of the Universe
- Anisotropy of cosmic microwave background (CMB)
- N-body simulations
- Brilliant agreement of the CMB and SN Ia data
- Nucleosynthesis theory

MODERN COSMOLOGICAL MODEL

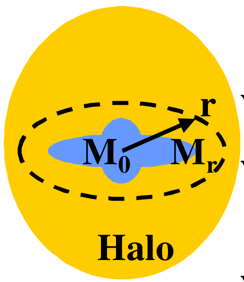


$\rho \approx \rho_{cr}$ =>

$\Omega = \rho / \rho_{cr} \approx 1$

Astrophysical evidences

The very exciting evidence is that rotation curves of numerous spiral galaxies are **FLAT**



M_r – mass inside r

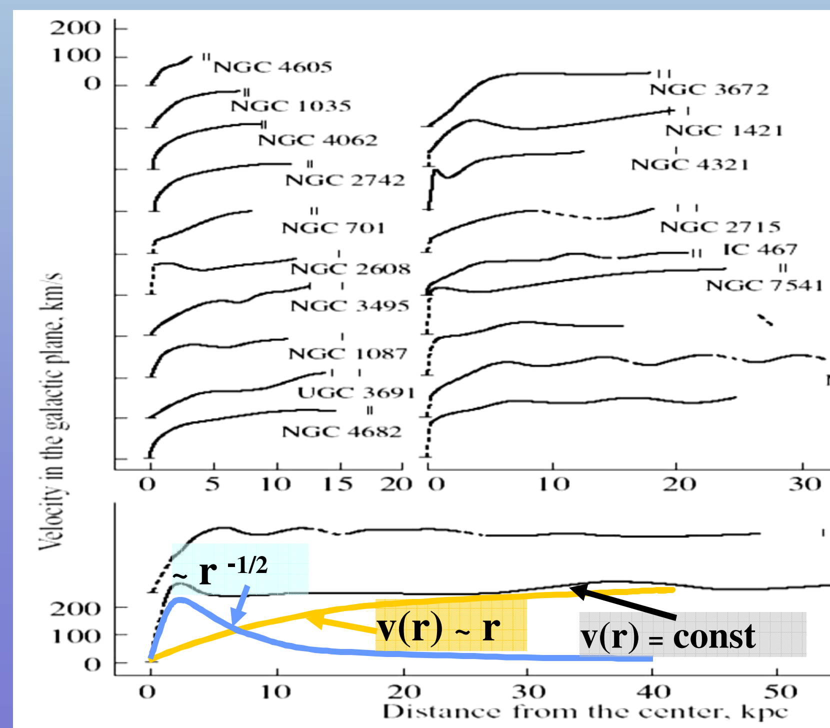
$v(r) \sim r^{-1/2}$ for the case of central mass M_0

$v(r) \sim r$ for the case of uniform mass distribution $(M_r \sim r^3)$

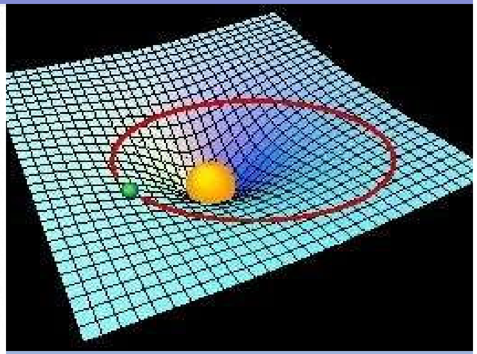
$v(r) = \text{const}$ for the case $M_r \sim r$

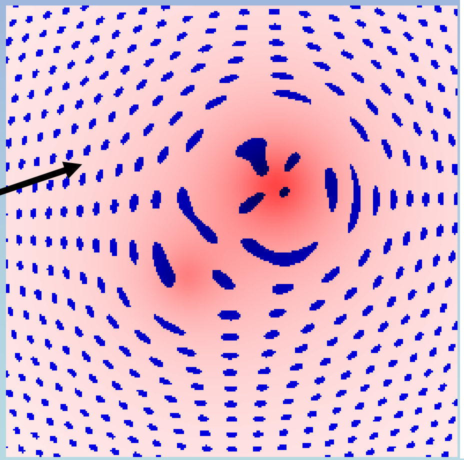
To explain this a massive (10:1) halo is required

2005: arXiv:astro-ph/0502312v1 astronomers discovered the galaxy VIRGOHI21 practically totally consisted of Dark Matter!
No stars, only 21 cm hydrogen-line emission ;
hydrogen is rotating and $M_H:M_{total} \sim 1:10^3$

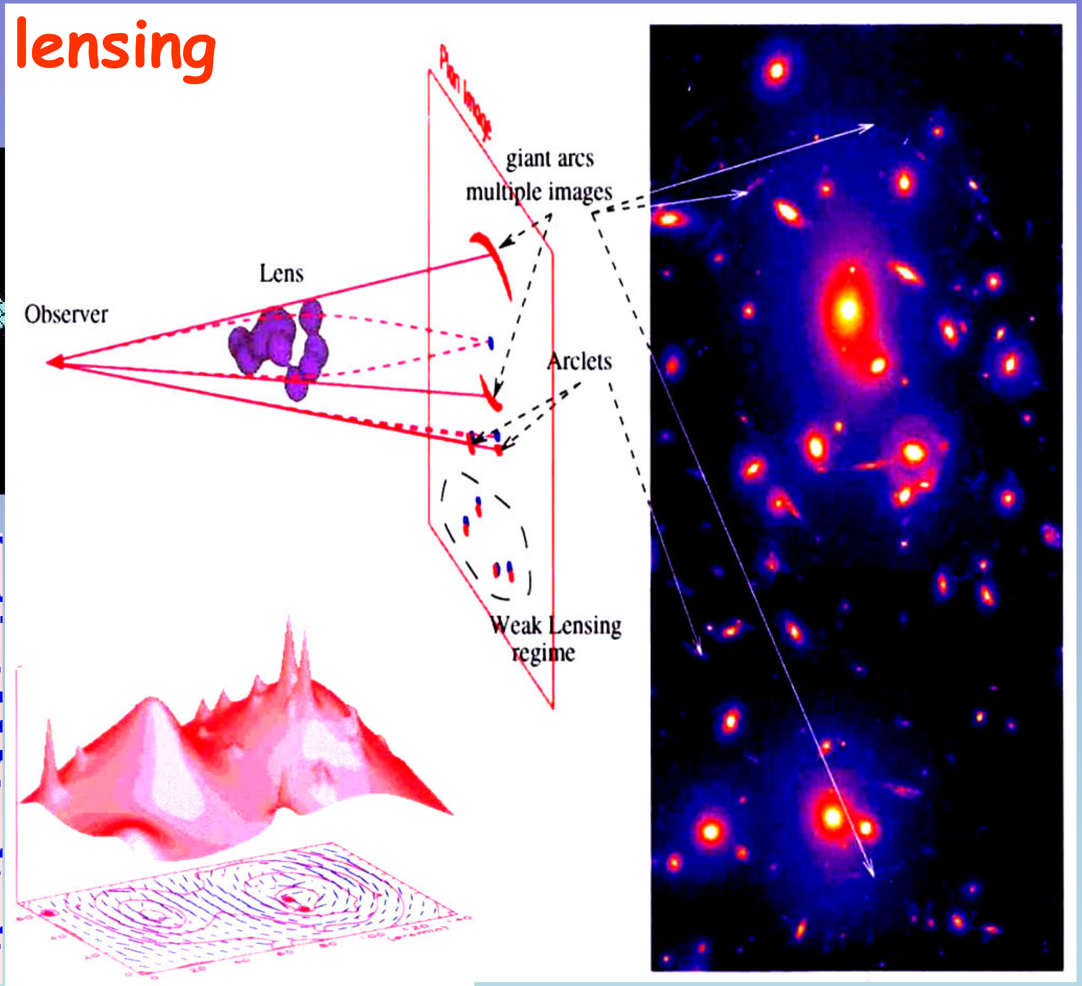


Gravitational lensing



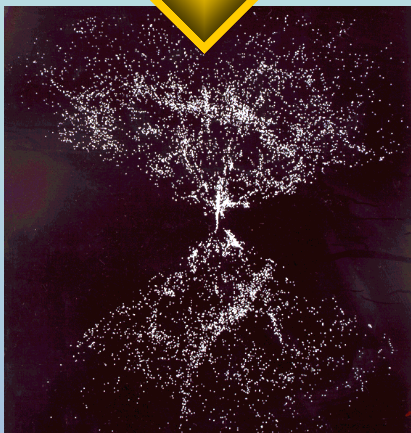


Distortion of the bckg object (regular pattern) by a distributed mass

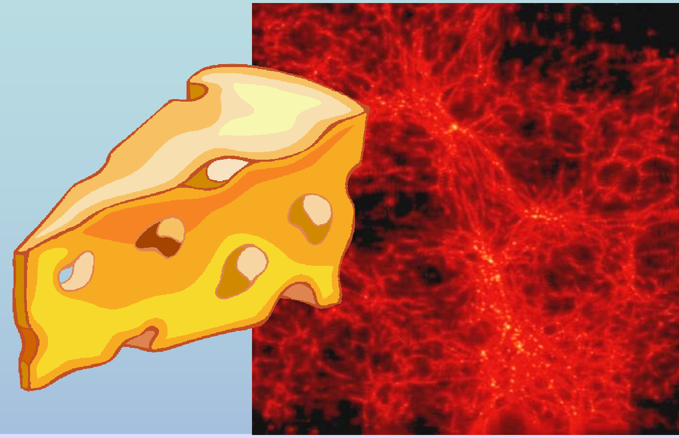


10 times greater mass is required to explain the effect

Cosmological motivation



Large-scale structure of the Universe, reconstructed from red-shift measurements



Result of N-body simulation, carried out with supercomputers

To explain such structure, a cold (nonrelativistic) substance is required. The most favorable hypothesis is Particle Dark Matter - elementary particles (relic from Big Bang) with a weak interaction only :

WIMPs - (Weakly Interacting Massive Particles)

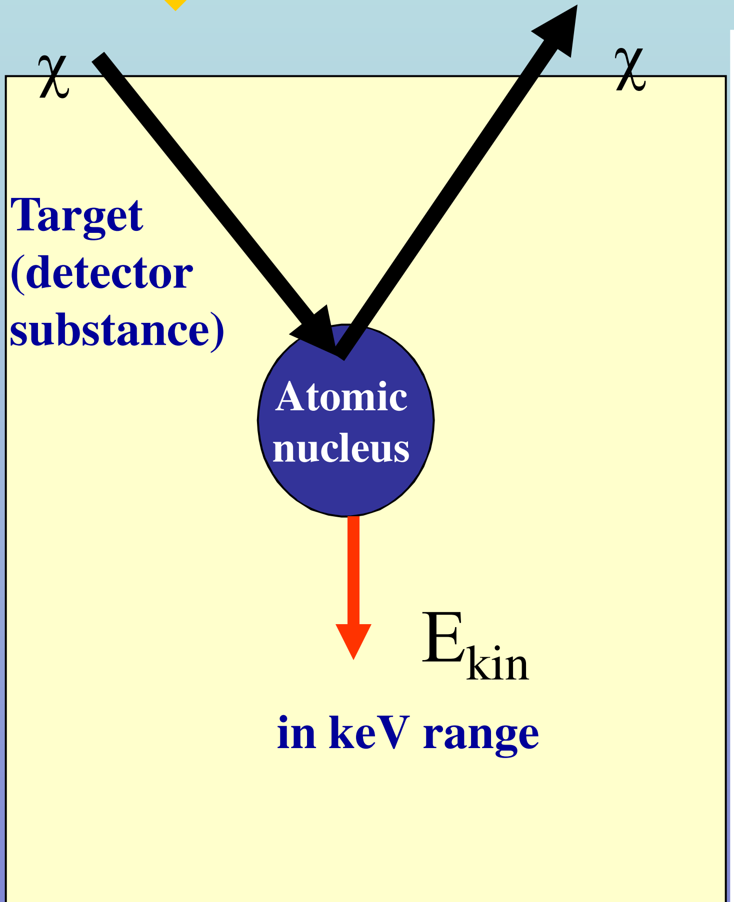
Local (Galactic) density is ~ 0.3 Gev/cm^3 ~few particles in a litre!

Neutralino predicted by SUSY theory is the most favourable candidate for WIMP

$$\chi = f_{11}B + f_{12}W^3 + f_{13}H_1 + f_{14}H_2$$

Mass scale – from tens to hundreds GeV

WIMP detection: direct detection



$\sigma \sim A^2$ - spin-independent (SI) interaction

$\sigma \sim J(J+1)$ - spin-dependent (SD) interaction

For the Quasi-Maxwellian distribution of WIMP speeds in the galaxy:

$$\frac{dN}{dE} = \frac{\rho}{M_\chi}\sigma N_N \frac{M_N c^2}{4 m_{\mathrm{red}}^2 v_0}\frac{g(\eta, E_{kin})}{\eta} F_N^2(E_{kin}))$$

$$g(\eta, E_{kin}) = \begin{cases} \mathrm{erf}(\xi+\eta) - \mathrm{erf}(\xi-\eta) - \frac{4}{\sqrt{\pi}}\eta e^{-z^2} & \xi \le z-\eta \\ \mathrm{erf}(z) - \mathrm{erf}(\xi-\eta) - \frac{2}{\sqrt{\pi}}(z+\eta-\xi)\eta e^{-z^2} & z-\eta \le \xi \le z+\eta \\ 0, & \xi \ge z+\eta, \end{cases}$$

M_χ, M_N и m^2_{red} – masses of WIMP and target nucleus, and their reduced mass, respectively;

$$\xi_i = \sqrt{\frac{M_i E_i}{2 m_{\mathrm{red}}^2 v_0^2}} \qquad \eta = \frac{v_{Earth}}{v_0} \qquad z = \frac{v_{escape}}{v_0}$$

v_{Earth} = 232 km/s – Earth velocity,

$v_0 = \sqrt{2/3}\, v_{r.m.s.}$ – Quasi-Maxwell distribution parameter,

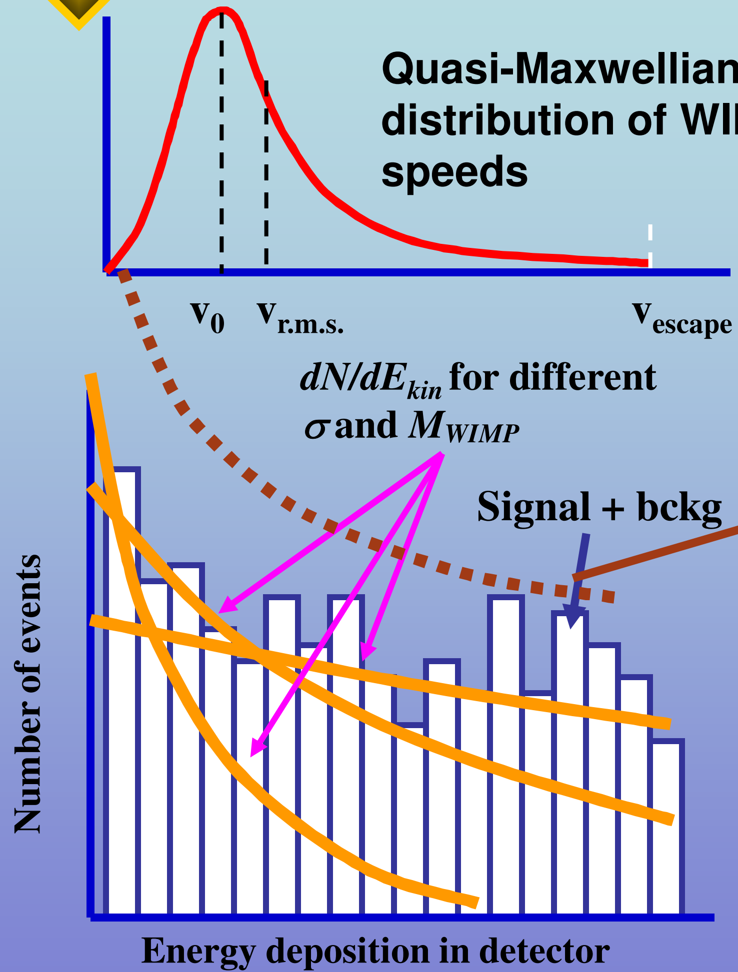
N_N – number of target nuclei,

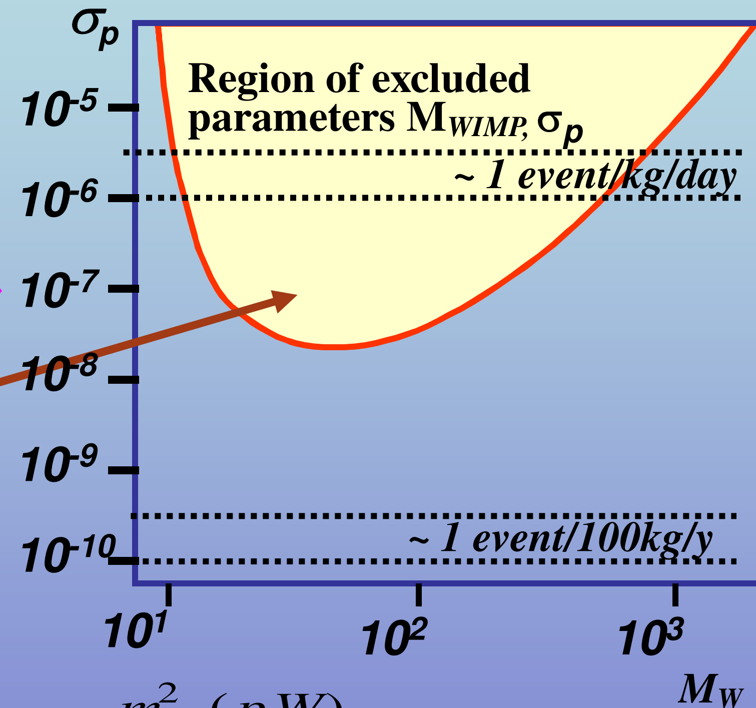
ρ = 0.3 GeV/cm^3 – WIMP density in Galactic halo,

σ – WIMP interaction cross-section,

$F_N^2(E_{kin})$ – nuclear form factor

WIMP detection: direct detection



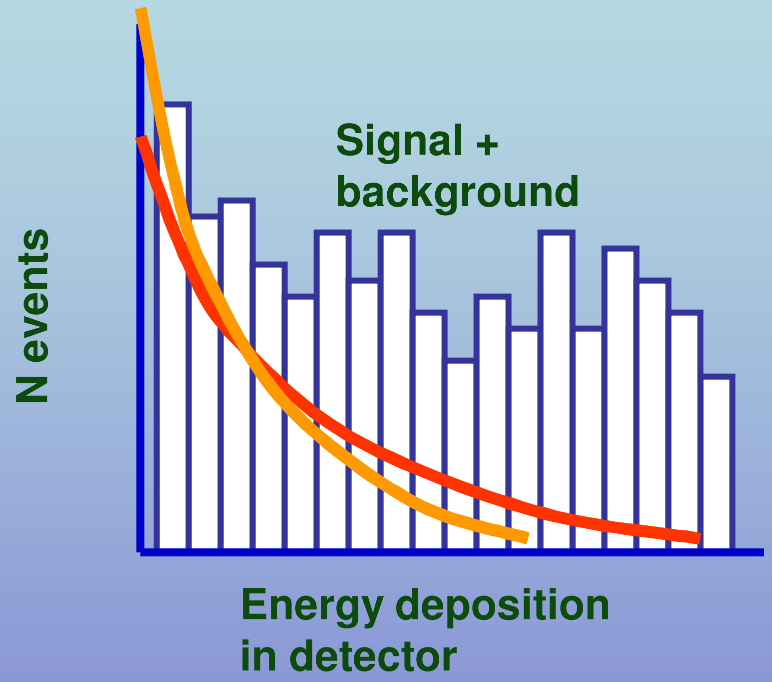


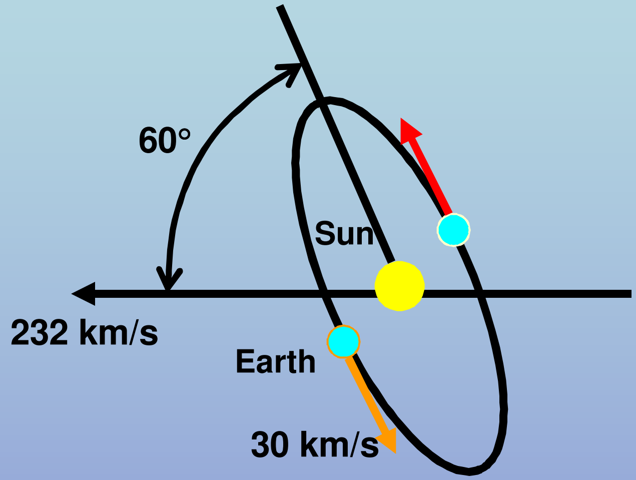
$$\sigma_p = \frac{m^2_{red}(p,W)}{C m^2_{red}(Nucl,W)} \sigma <\sim 10^{-7}\ pb$$

$C=A^2$

Exponential behavior is very similar to that of bckg of various origins.

WIMP detection: annual modulation



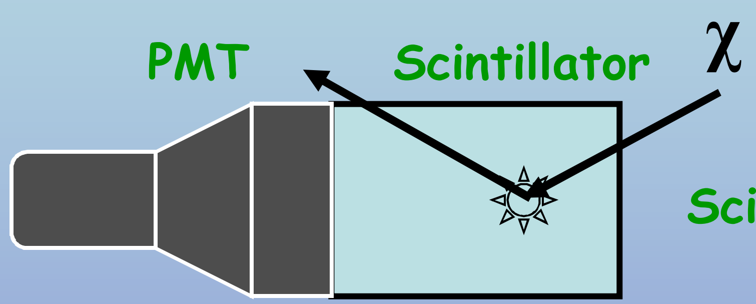


Expected variation of WIMP count rate ~ 5%

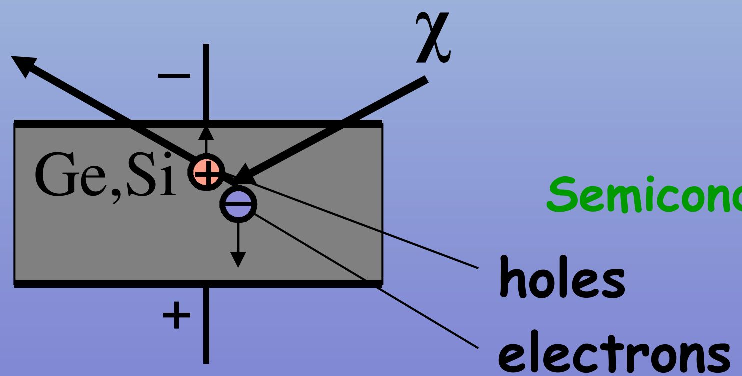
WIMP detection: how to detect?

Can use ordinary detectors for particles and radiations

used at the beginning in pioneer WIMP experiments:
COSME, IGEX, Heidelberg-Moscow, MIBETA ($\beta\beta$ decay experiments)



Scintillation detector



Semiconductor detector

The main disadvantage – single channel of energy deposition:

WIMP detection: how to detect?

or to develop special detectors for WIMPs

The main goal: to "switch off" background electromagnetic and strong interactions!

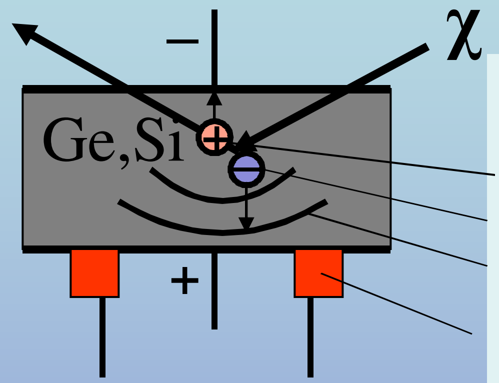
- By measurements of energy deposition in 2 or more channels => rejection of electron recoils

- Active neutron veto. For nuclear recoil events, by selection only single scatters in a central target => rejection of neutron scattering off atomic nuclei.

WIMP must scatter only once!

WIMP detection: how to detect?

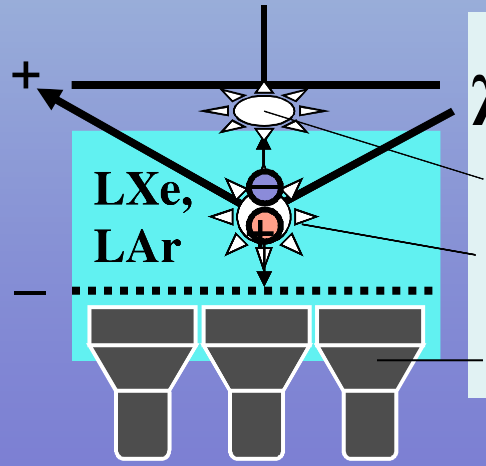
Two-channel measurement of energy deposition



Low-temperature bolometers

holes
electrons
phonons
thermistors

Particles produce ionisation and heat; heating up the crystal by ~10^{-6} K
Operate at T ~ tens mK



Two-phase noble gas detectors

electroluminescence EL
scintillation SC
PMTs

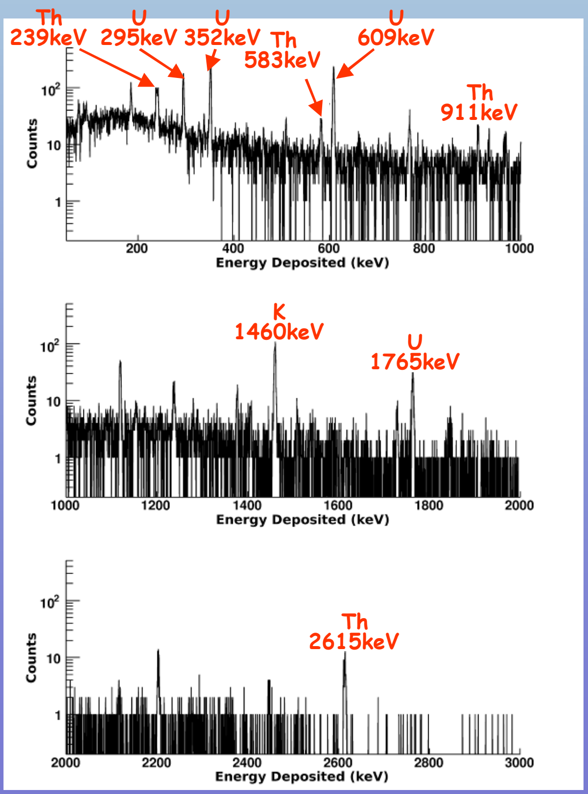
Particles produce scintillation and ionisation
Operate at T ~ 100 K

WIMP detection: background reduction

The use of low-radioactive materials ONLY !

Every component must be screened with Ge detector or MS or NAA!

The main contaminants are the isotopes of U/Th chains and ^{40}K



Construction materials:
Teflon U <0.7 10^{-9}, Th <2.3 10^{-9}, K<2.2 10^{-6}
Electrolytic copper - U<1.2 10^{-11}, Th<1.1 10^{-11}, K<5.6 10^{-9}

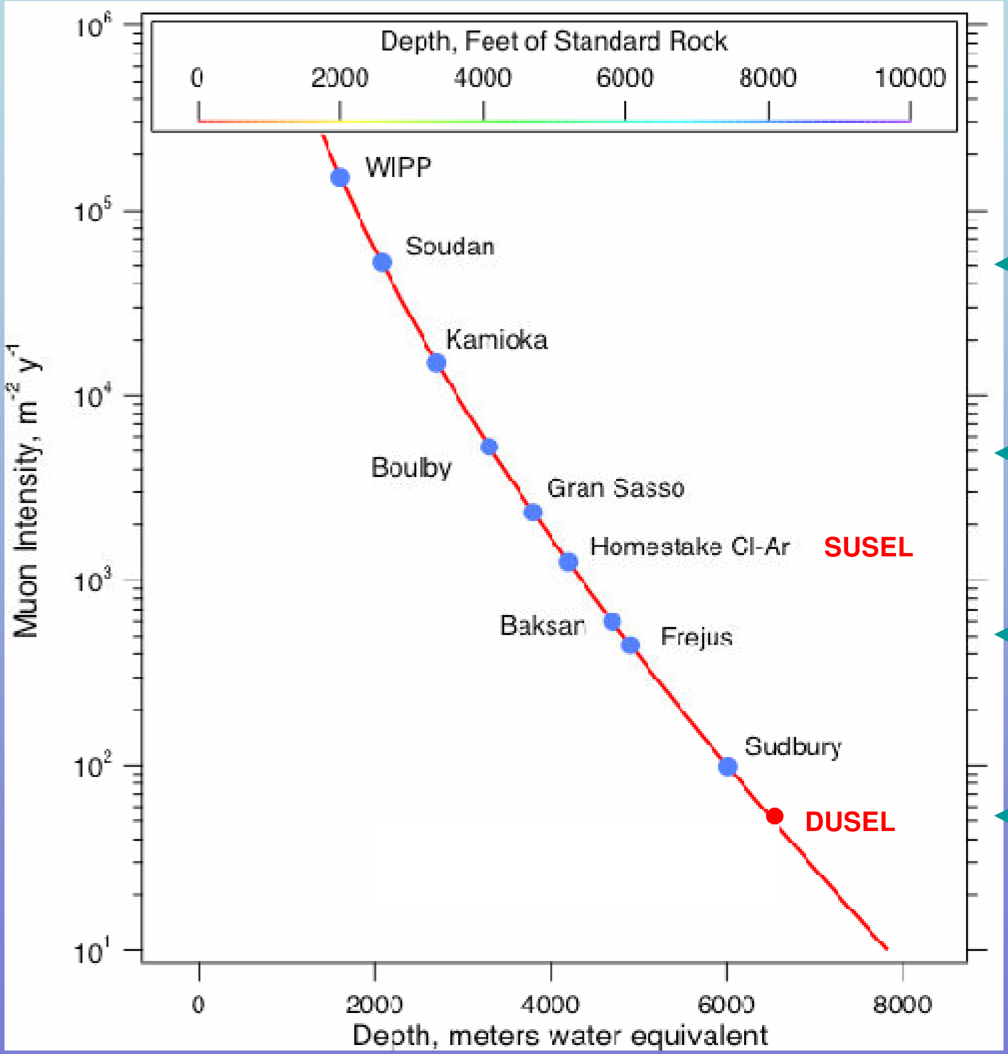
Detection media used for DM search:
Ge – U <10^{-14}, Th < 1.5 10^{-13}

LXe U/Th <~10^{-13} (XMASS)
technogenic ^{85}Kr (beta)
Can be removed : K. Abe et al., arXiv:0809.4413v3 [physics.ins-det] by distillation (XMASS)
A.I. Bolozdynya et al., NIM A, 579 (2007), p. 50 by chromatographic separation (Xenon, LUX)
LAr – cosmogenic ^{39}Ar (beta)
Depletion, Ar from underground reservoirs.

Rn – should be removed from the vicinity of setup: overpressuring by dry pure nitrogen.

WIMP detection: background reduction

The experiments are carried out in the underground labs



reduction of muon flux by:

10^5

10^6

10^7

10^8

Muon flux at sea level:

$\sim 1\ \mathrm{cm}^{-2}\ \mathrm{min}^{-1}$

=

$\sim 5 \cdot 10^9\ \mathrm{m}^{-2}\ \mathrm{y}^{-1}$

WIMP detection

Experiment	Target
ANAIS	NaI
DAMA/NaI	NaI
DAMA/LIBRA	NaI
DAMA/1 ton	NaI
NAIAD	NaI
HDMS	Ge
KIMS	CsI
Caf2-Kamioka	CaF2
DAMA/LXe	LXe
WARP	LAr
XENON 10	LXe
Zeplin II	LXe
Zeplin III	LXe
ArDM	LAr
LUX	LXe
LZS/LZD	LXe
XAX	LXe/LAr
CLEAN	LNe
DEAP	LAr
XMASS	LXe
CDMS	Ge
CRESST	CaWO4
EDELWEISS	Ge
ROSEBUD	Ge, sap,tung
COUPP	FSH
PICASSO	FSH
SIMPLE	FSH
Drift	CS2 gas
MIMAC	^{3}He gas

Experiments

DAMA/LIBRA

CDMS

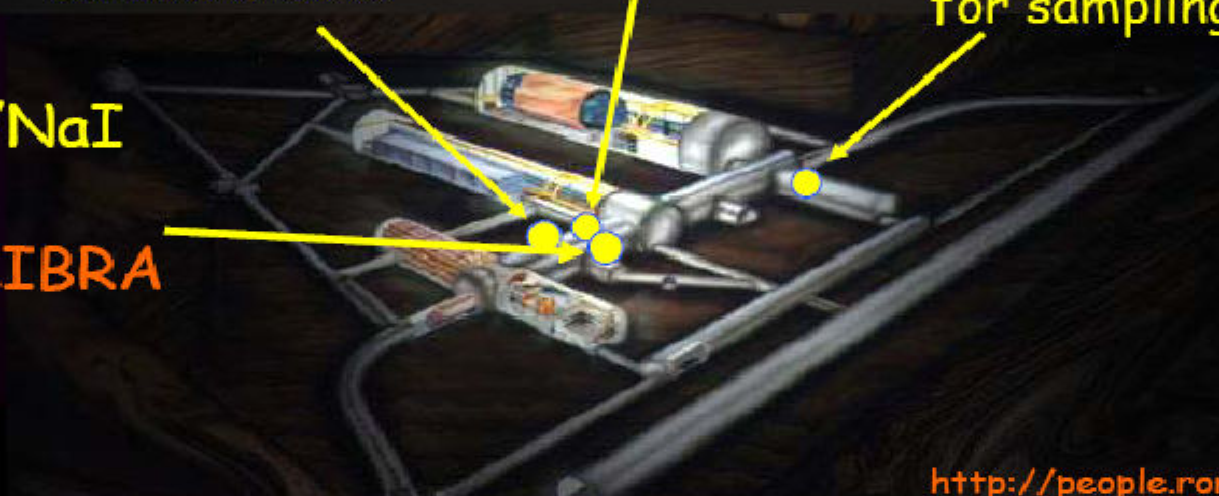
Xenon

ZEPLIN

Experiments: DAMA/LIBRA

Roma2,Roma1,LNGS,IHEP/Beijing

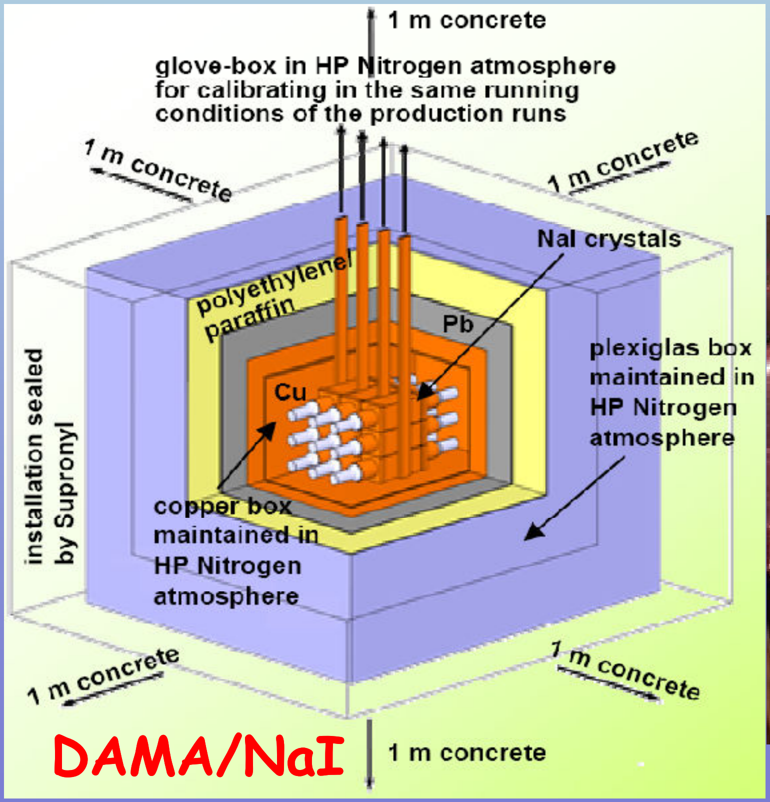
DAMA: an observatory for rare processes @LNGS



http://people.roma2.infn.it/dama

Experiments: DAMA/LIBRA

9 crystals NaI(Tl) 9,7 kg each, placed in a copper box, then lead, polyethylene, paraffin and enclosed in a plexiglas box filled with HP N2 to protect from Rn



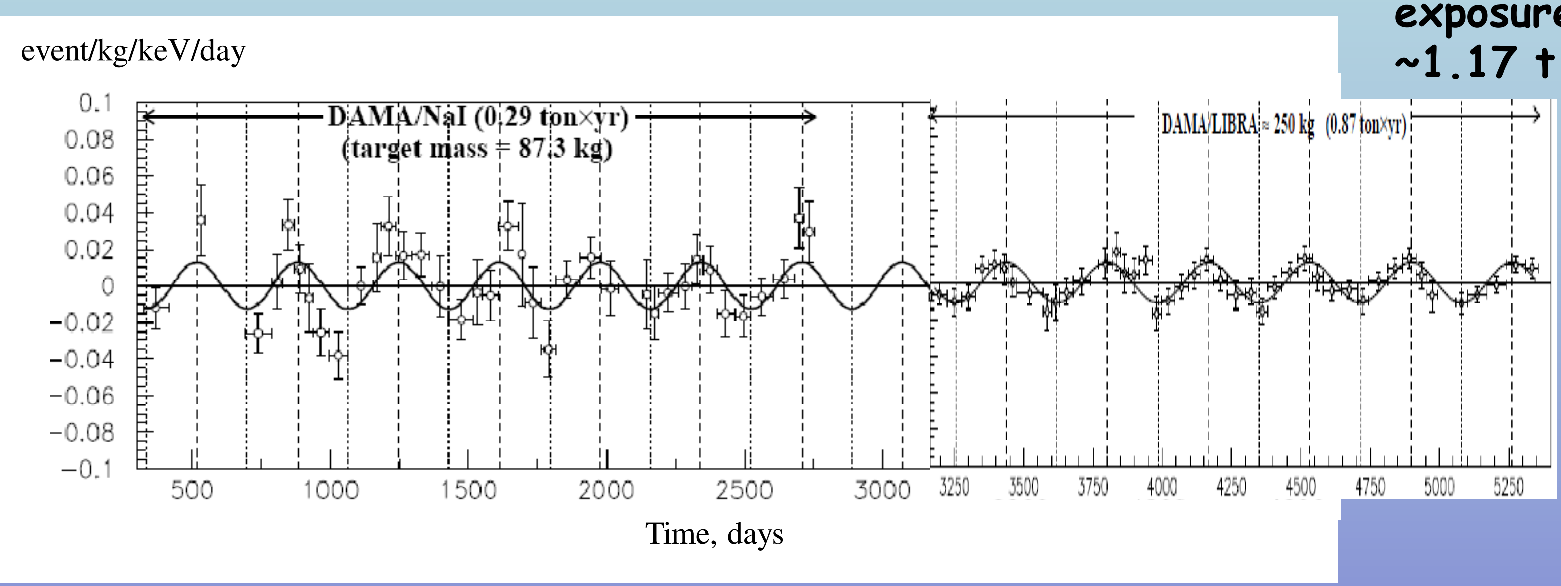
LIBRA- 25 of the same type in the same shield; 250 kg.
Data taking with LIBRA 2003 - 2008

Experiments: DAMA/LIBRA

Deviation of the count rate from the mean value (2 – 6 keV only) during the whole exposure time on both setups DAMA and LIBRA

arXiv:1002.1028v1 [astro-ph.GA]

Total exposure ~1.17 t·y

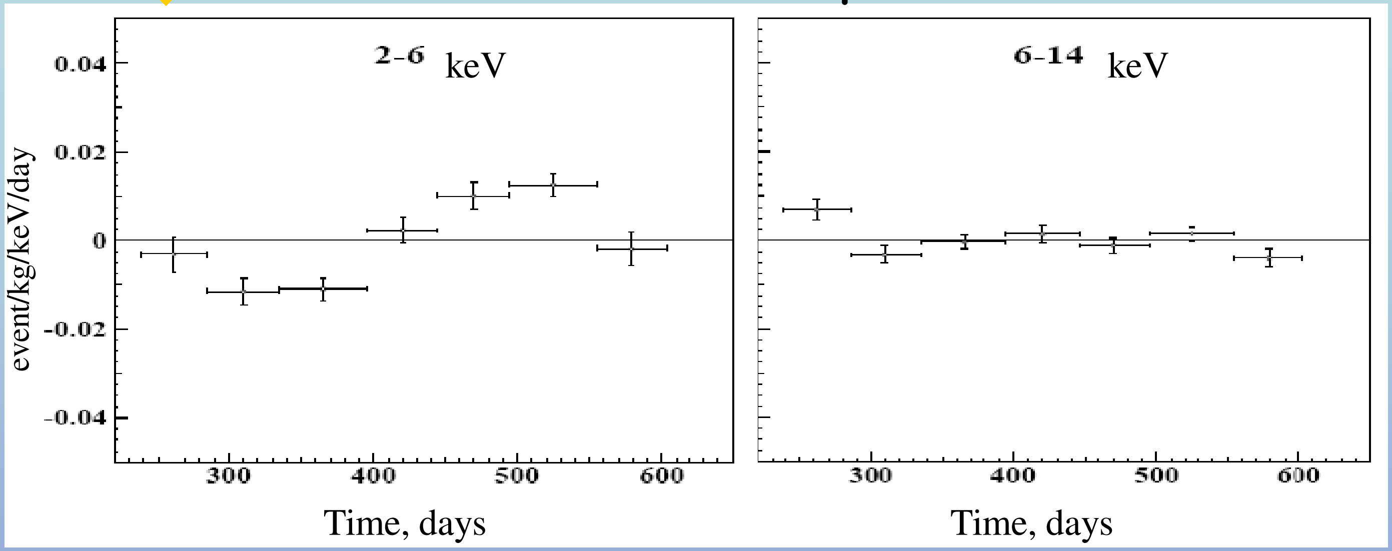


$A \cdot \cos \omega(t - t_0)$ with a period $T = 2\pi/\omega = 0.999 \pm 0.002$ y,
and a phase $t_0 = 146 \pm 7$ day, which is very close to the expected: 152,5 days (2 June)

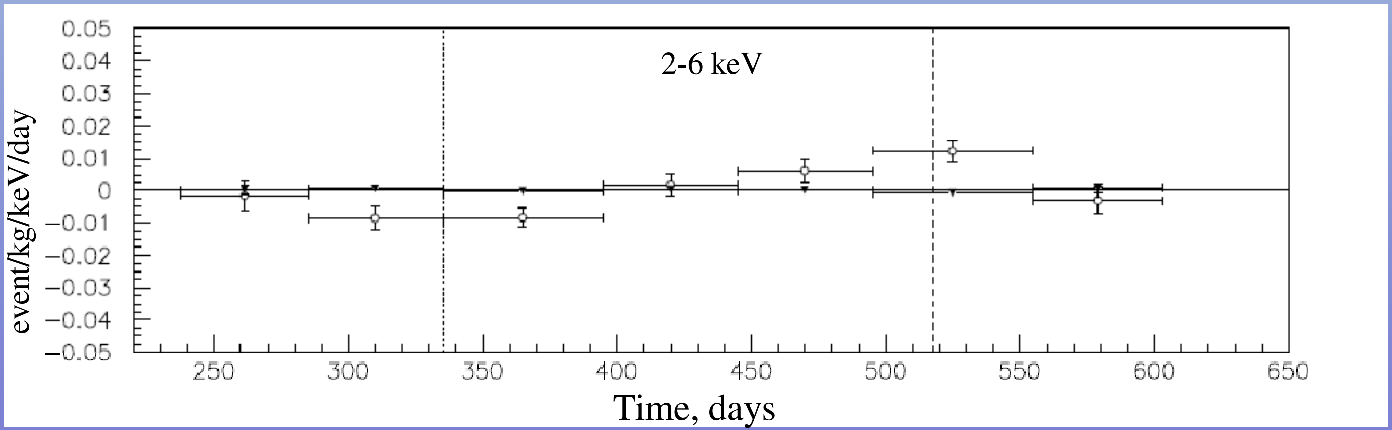
$A=(0.0114 \pm 0.0013)$ event/kg/keV/day, C.L. = 8.8σ

Experiments: DAMA/LIBRA

Data reduced to one period:

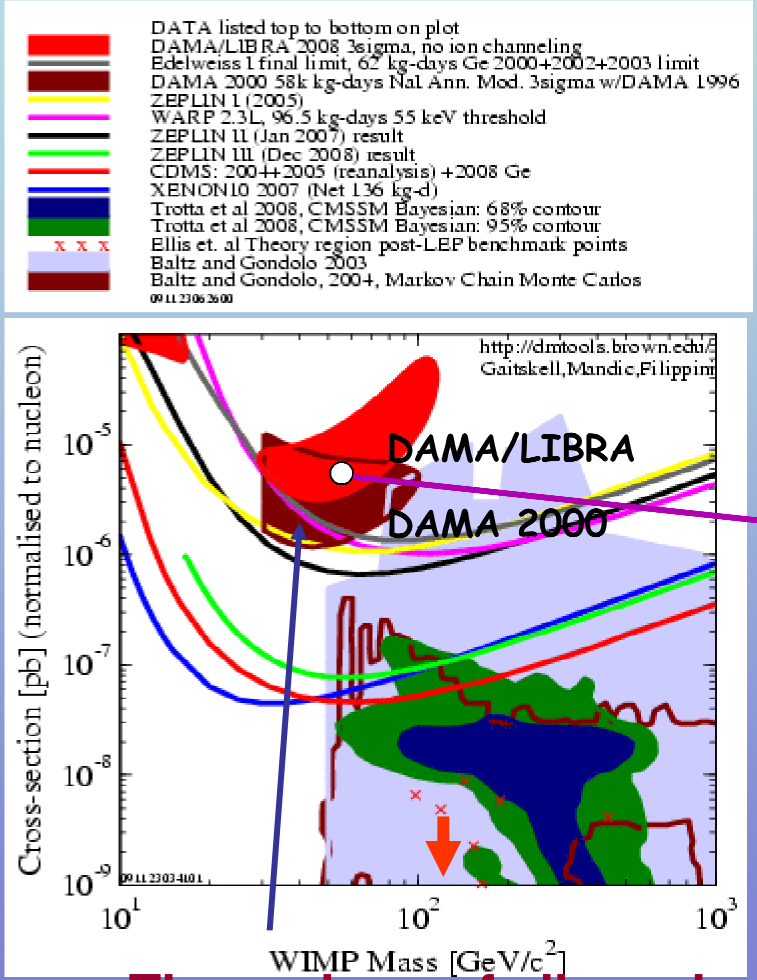


The effect takes place **only in 2-6-keV interval**



The effect takes place **only for single "hits"!**

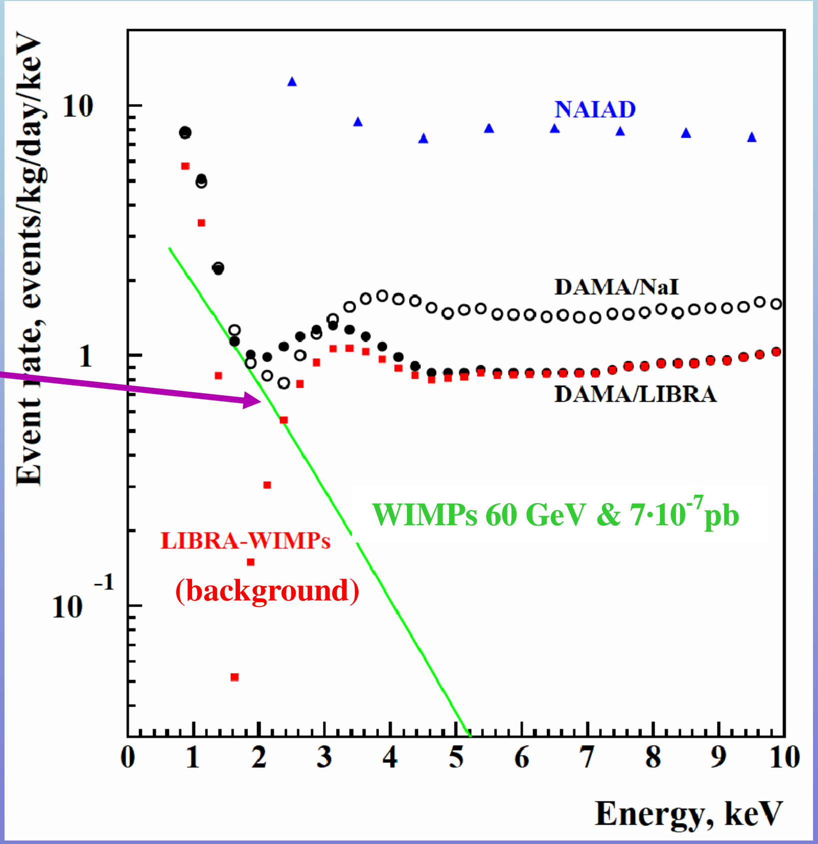
Experiments: DAMA/LIBRA



The regions of allowed σ_p, M_w

But there is a significant discrepancy!

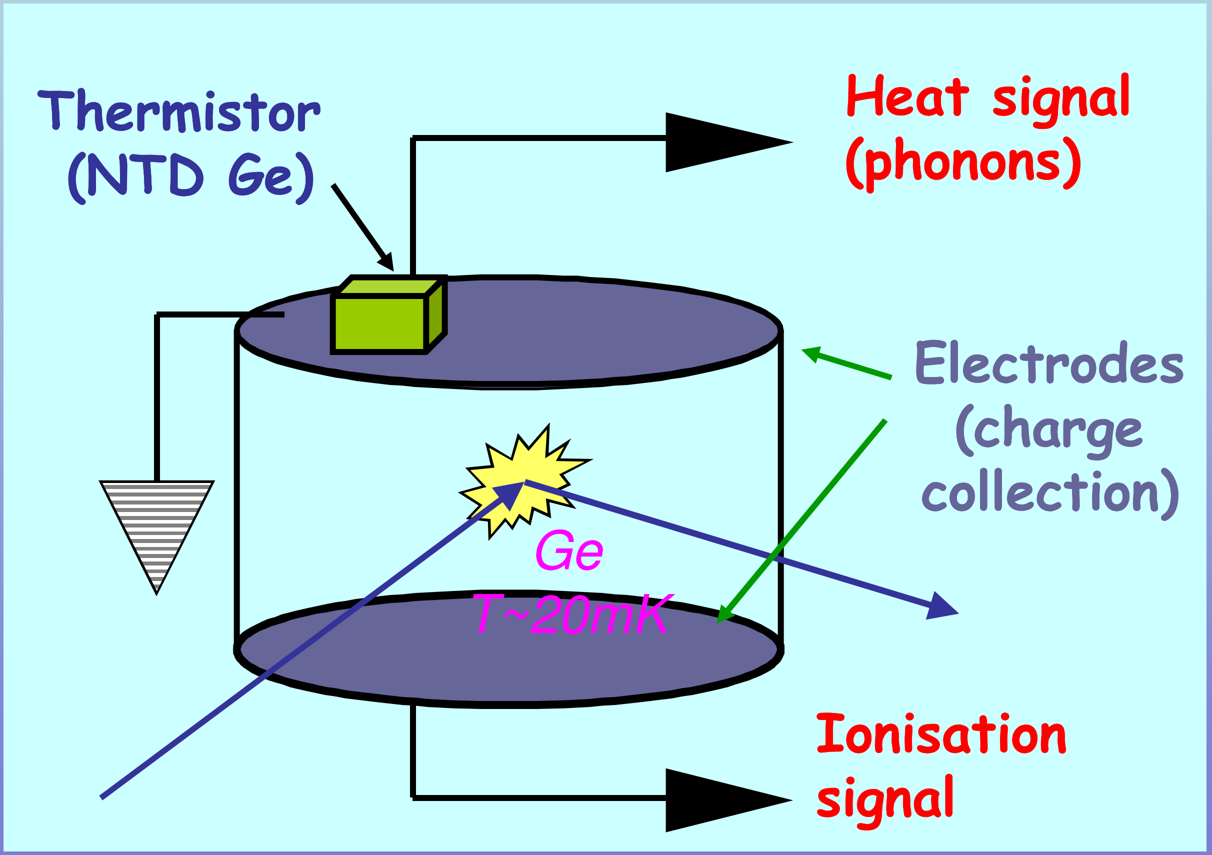
arXiv:0912.2983v1 [hep-ex]



Experiments: CDMS

Cryogenic Dark Matter Search (USA)

Detection with low-temperature bolometers



At the low temperature, the specific heat capacity becomes very small. According to the Debye model:

$$C = \lambda_D \left(\frac{T}{\Theta_D}\right)^3,$$

λ_D=1944 J/mol/K,
T–temperature (K),
Θ_D–Debye temperature.

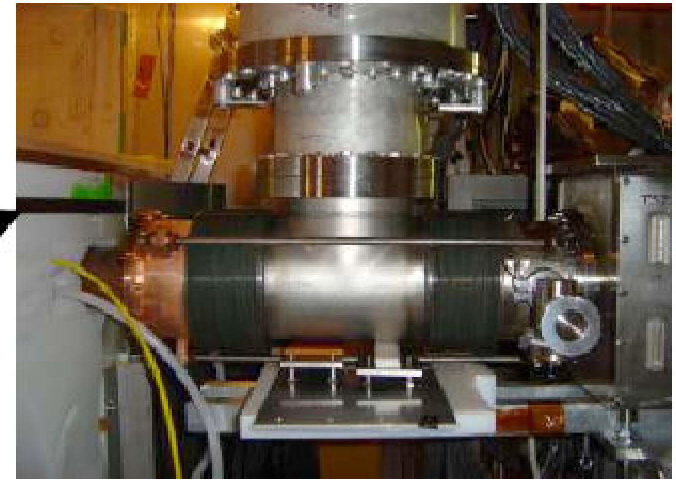
For Ge, Θ_D = 374K.
At T ~ 20 mK
C_{Ge} ~ 1 keV/mol/μK.

Experiments: CDMS

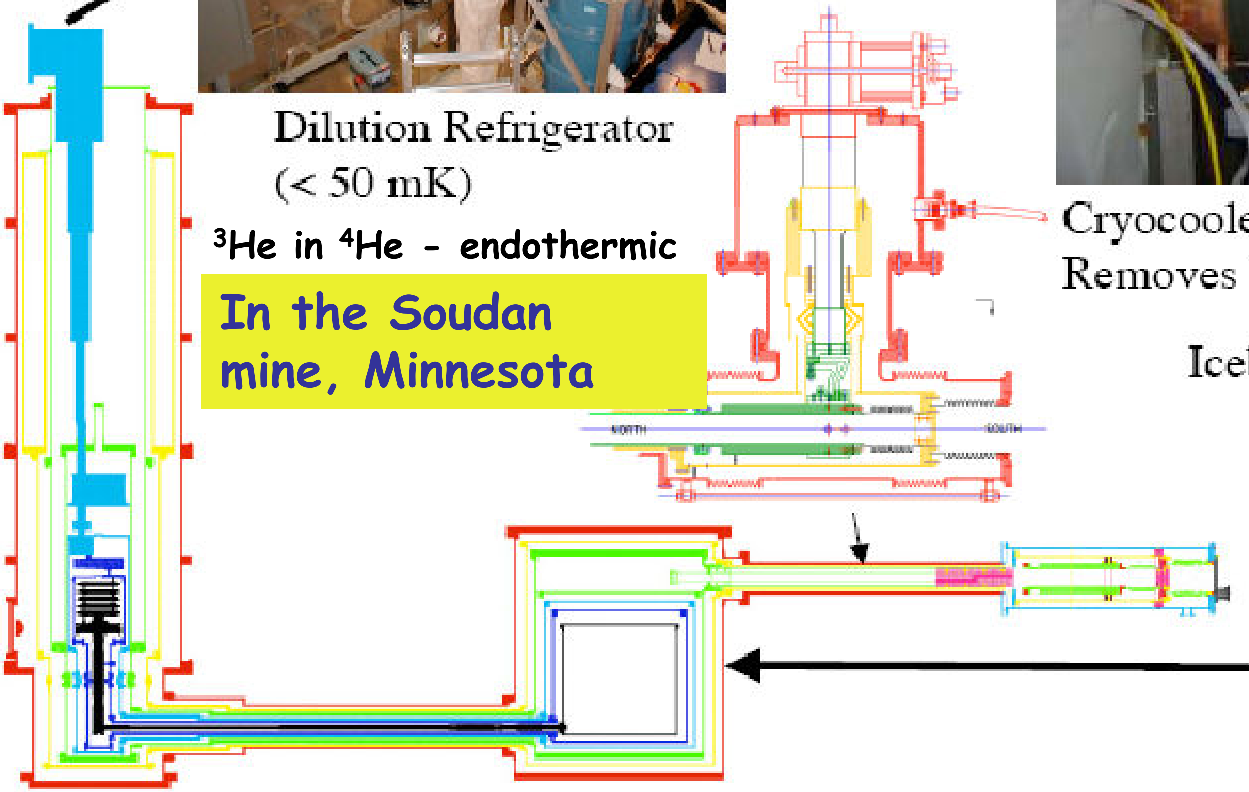
Dilution Refrigerator
(< 50 mK)

^{3}He in ^{4}He - endothermic

In the Soudan mine, Minnesota



Cryocooler (77K and 4K)
Removes heat load from signal cables.

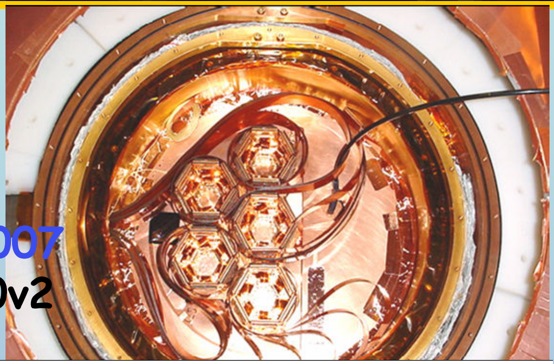


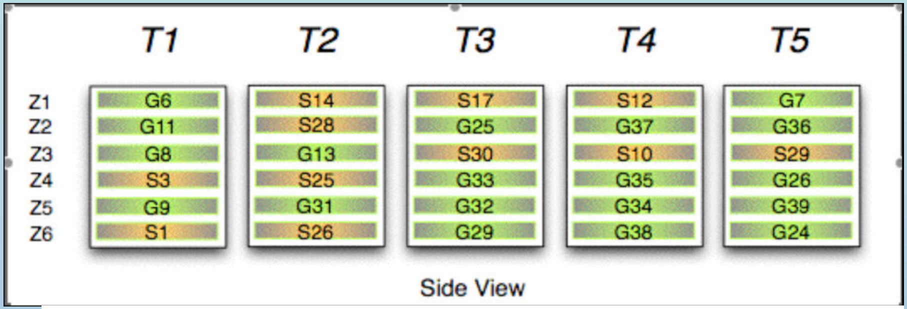
Icebox (Detector Cold Volume)

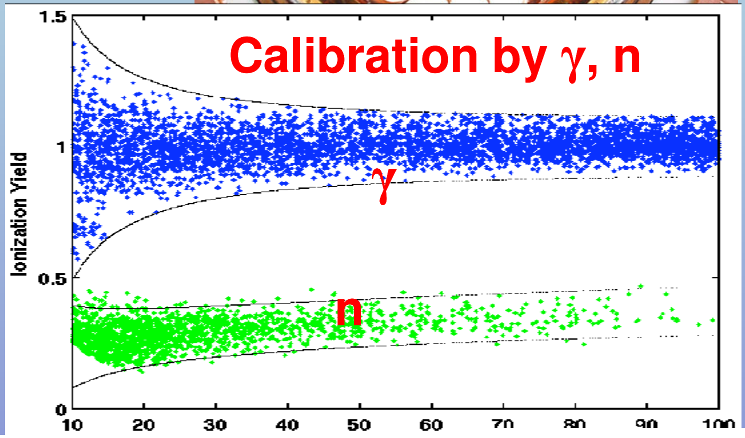
Experiments: CDMS

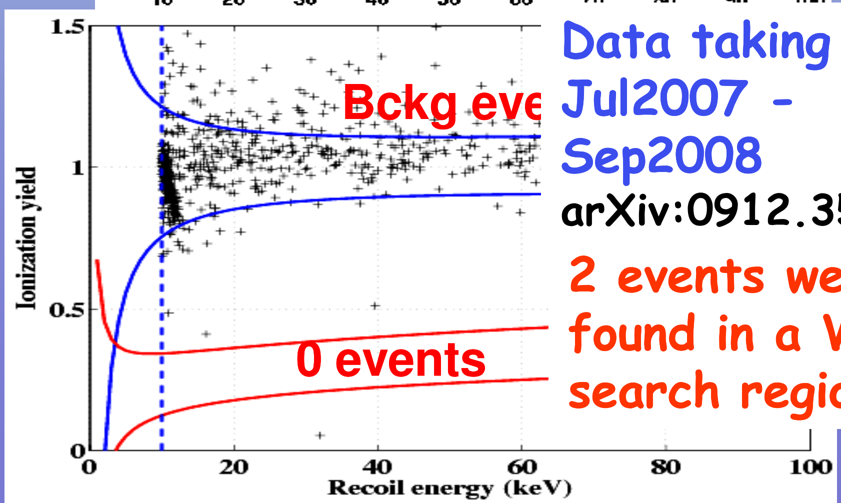
4.75 kg Ge,
1.1 kg Si

Data taking
Oct2006 - Jul2007
arXiv:0802.3530v2



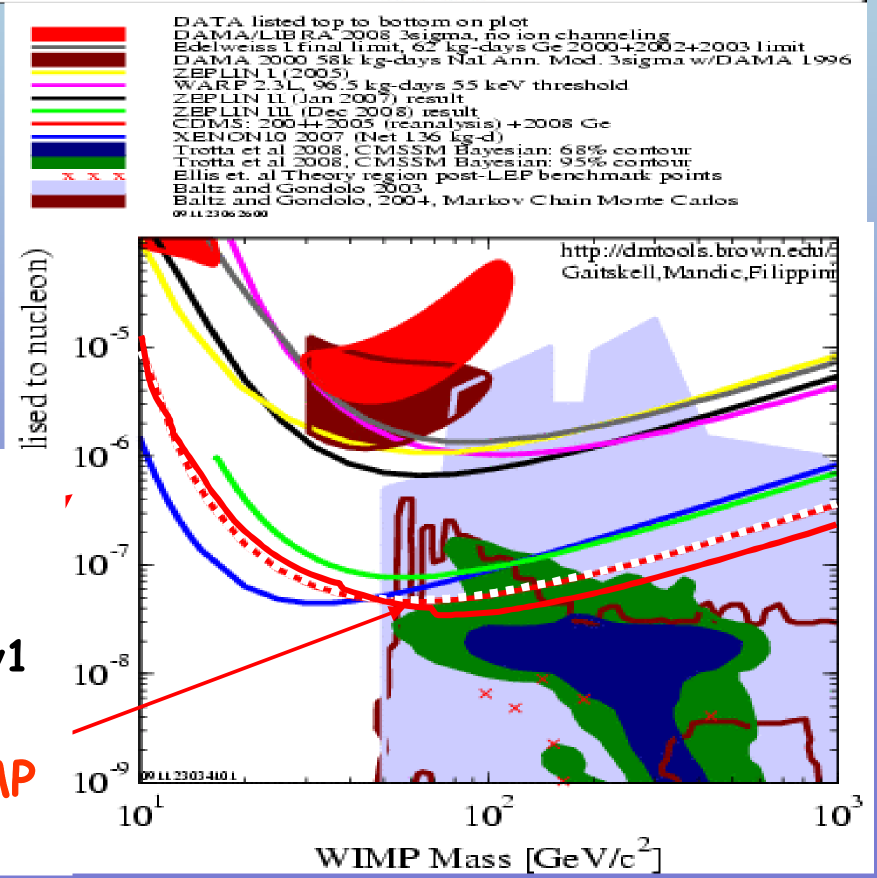






Data taking
Jul2007 -
Sep2008
arXiv:0912.3592v1

2 events were
found in a WIMP
search region



Experiments

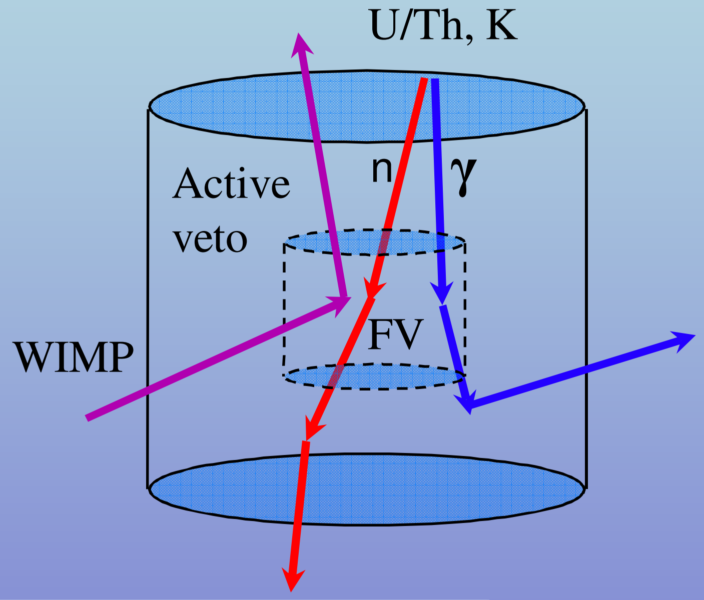
Liquid noble-gas detectors

~1/3 of experiments

Experiments: Liquid noble-gas detectors

Liquid noble gases are increasingly used as a detection medium for WIMPs

- very low contamination by U/Th, K (can be easily purified by filtering)
- possibility of discrimination by simultaneous measurements of scintillation and ionization signals in a two-phase mode
- possibility to build large and even very large (ton-scale) detectors
- 3D position sensitivity => "WALL-LESS" detector!!!



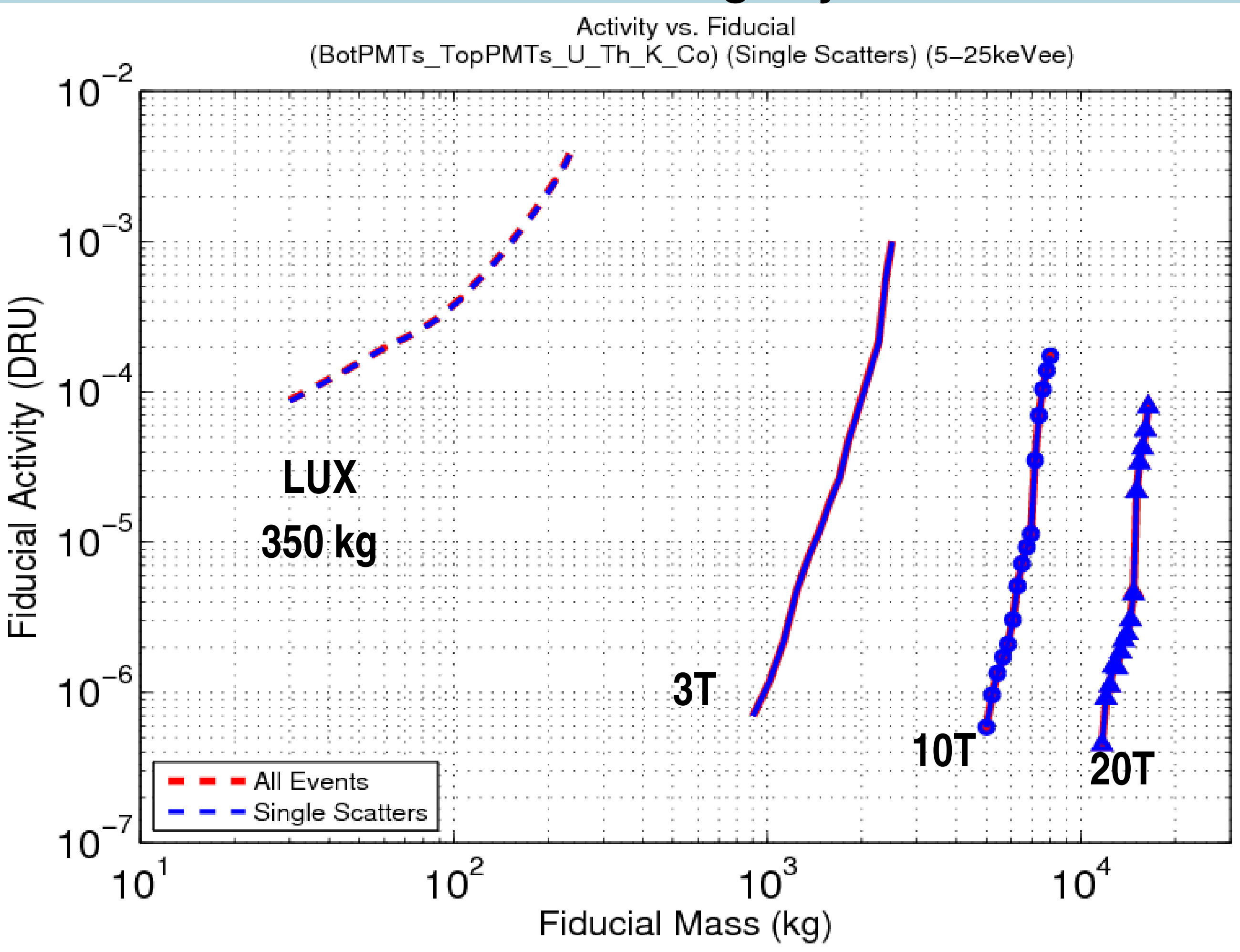
LAr, LXe: at the same mass LXe detectors have by an order of magnitude higher sensitivity:

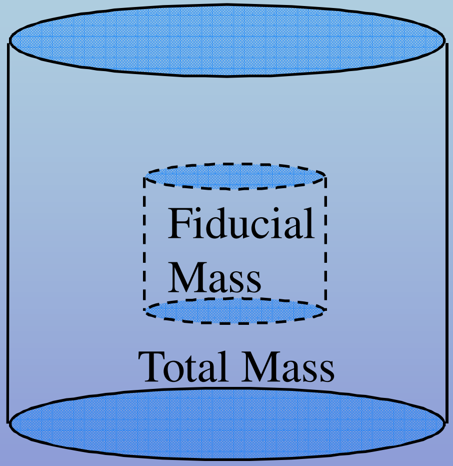
$\sigma_{SI} \sim A^2$, higher density and Z => better self-shielding

But to use different targets is very important!

Experiments: Liquid noble-gas detectors

Example of self-shielding effect. ***Simulation by LUX***
Single scatter events from PMTs gammas
DRU – event/keV/kg/day



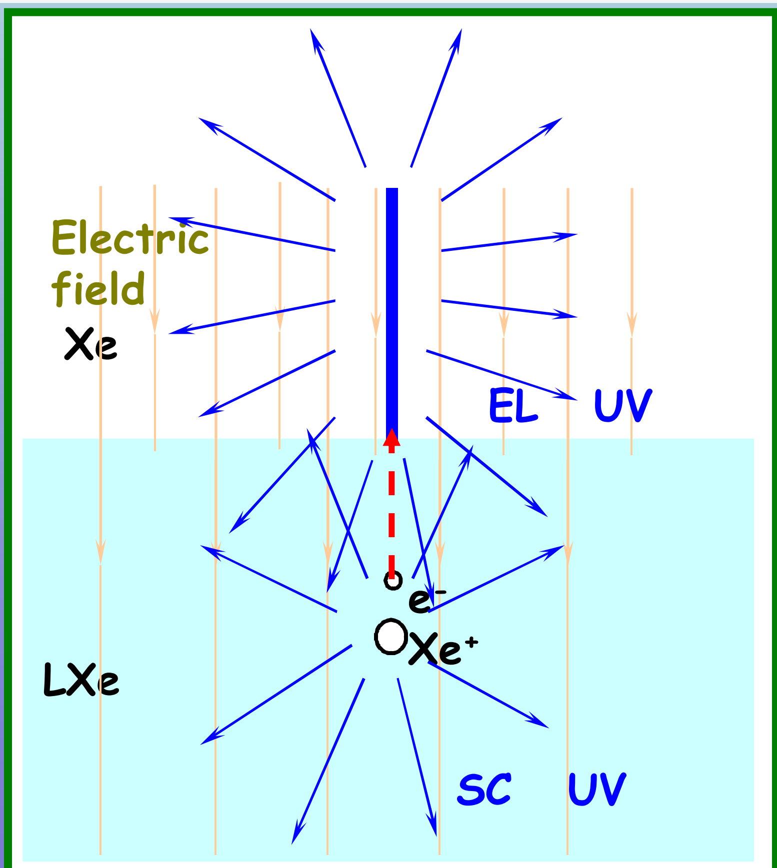


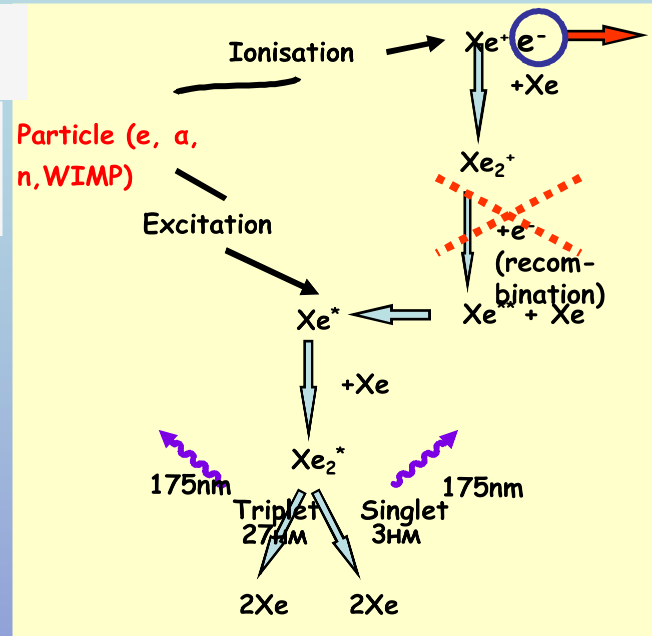
Experiments: LXe detectors

Discrimination of particles in a two-phase detector (Xe)

B.A. Dolgoshein, V.N. Lebedenko, B.U. Rodionov, JETF Letters (in Russian), 1970, v. 11, p. 513

For the Dark Matter search:
A.S. Barabash and A.I. Bolozdynya, JETF Letters (in Russian), 1989, v.49, p. 359

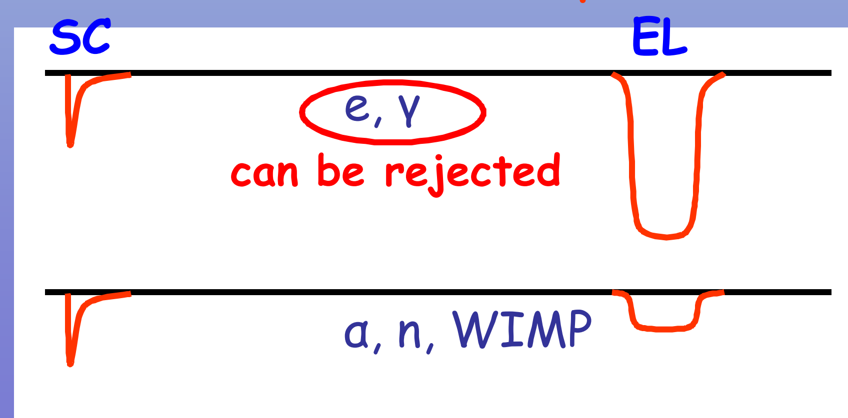




Electrons are partly extracted from the track: recombination is suppressed

Suppression depends on dE/dX

Ratio of SC/EL is different for different kind of particles

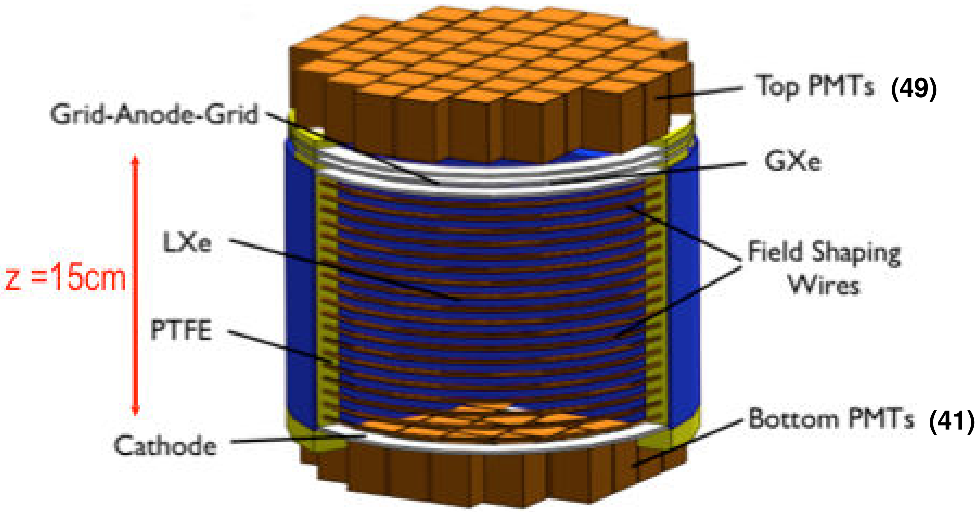


Xenon collaboration

- Columbia University
- Universität Zürich
- Brown University
- University of Coimbra
- CWRU
- Livermore National Laboratory
- Rice University
- Yale University
- Nazionali del Gran Sasso

Xenon10 - Gran Sasso

Experiments: Xenon10



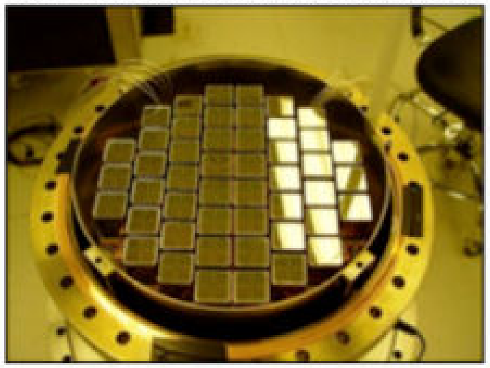
diam.~ 20 cm; drift gap= 15 cm
LXe - 25 kg (15 kg active)

Low Radioactive PMTs:

U	-	0.17±0.04 mBq/PMT
Th	-	0.20±0.09 mBq/PMT
K	-	10±1 mBq/PMT
Co	-	0.56±0.05 mBq/PMT

3.0 pe/keV at 122 keV gammas

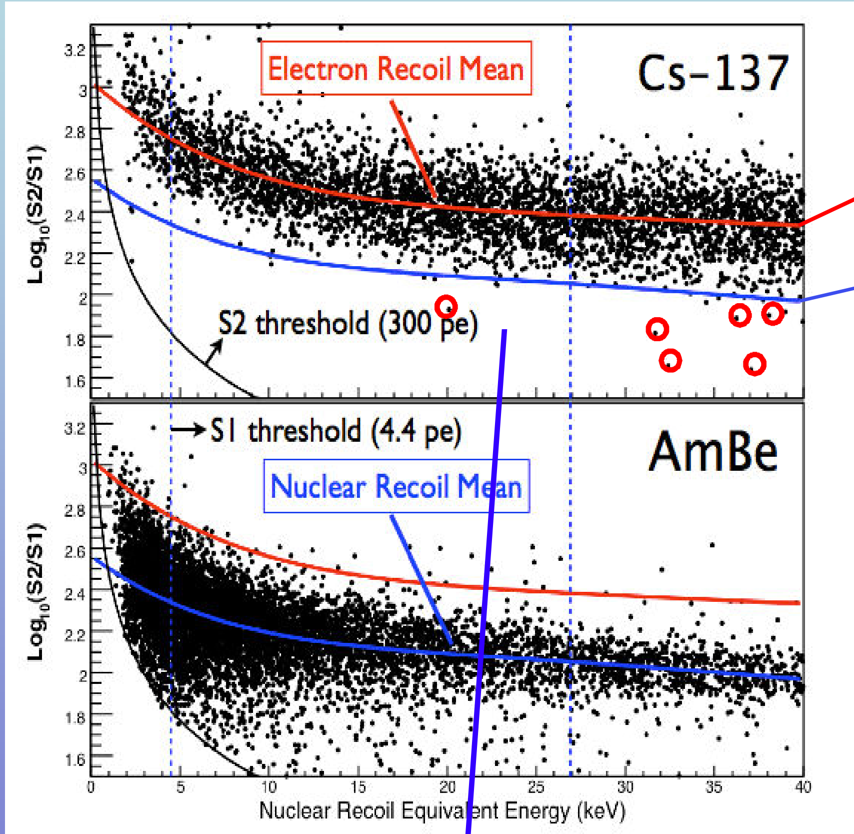
89 PMTs: Hamamatsu R8520-AL 2.5 cm square



Experiments: Xenon10

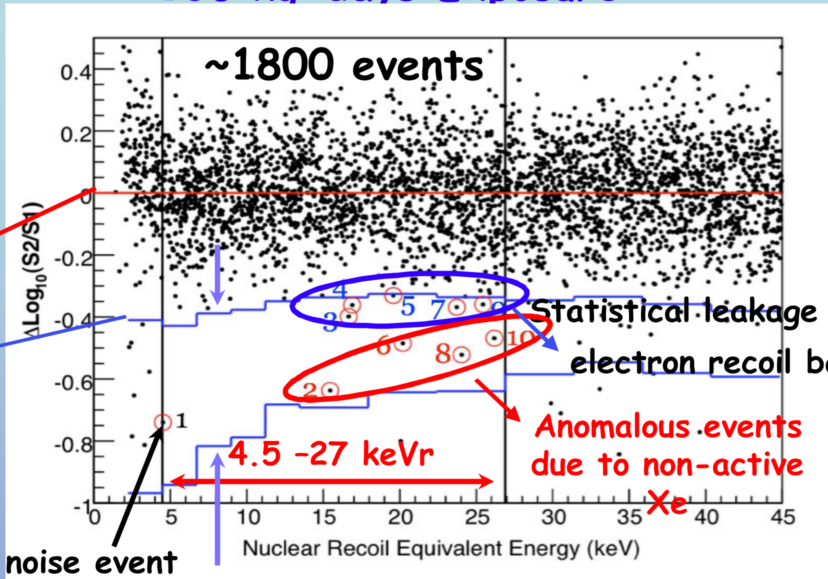
E.Aprile TAUP2007:

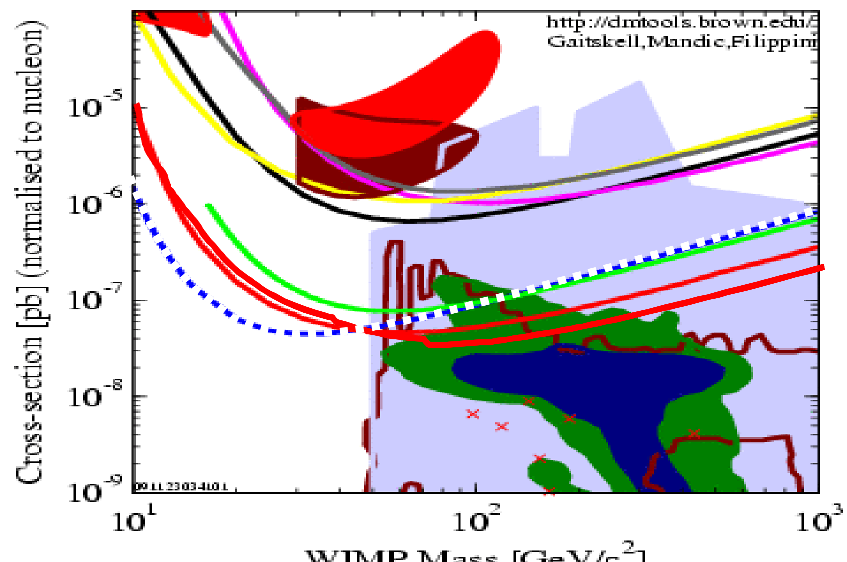
Gamma/Neutron calibration



~ 99.5 % gamma events are rejected below nuclear recoil mean

Blind Analysis
136 kg-days Exposure





ZEPLIN (UKDMC) collaboration

ZEPLIN I (single phase)

- CCLRC Rutherford Appleton Laboratory
- Imperial College London
- University of Sheffield
- University of London Queen Mary

ZEPLIN II (two-phase)

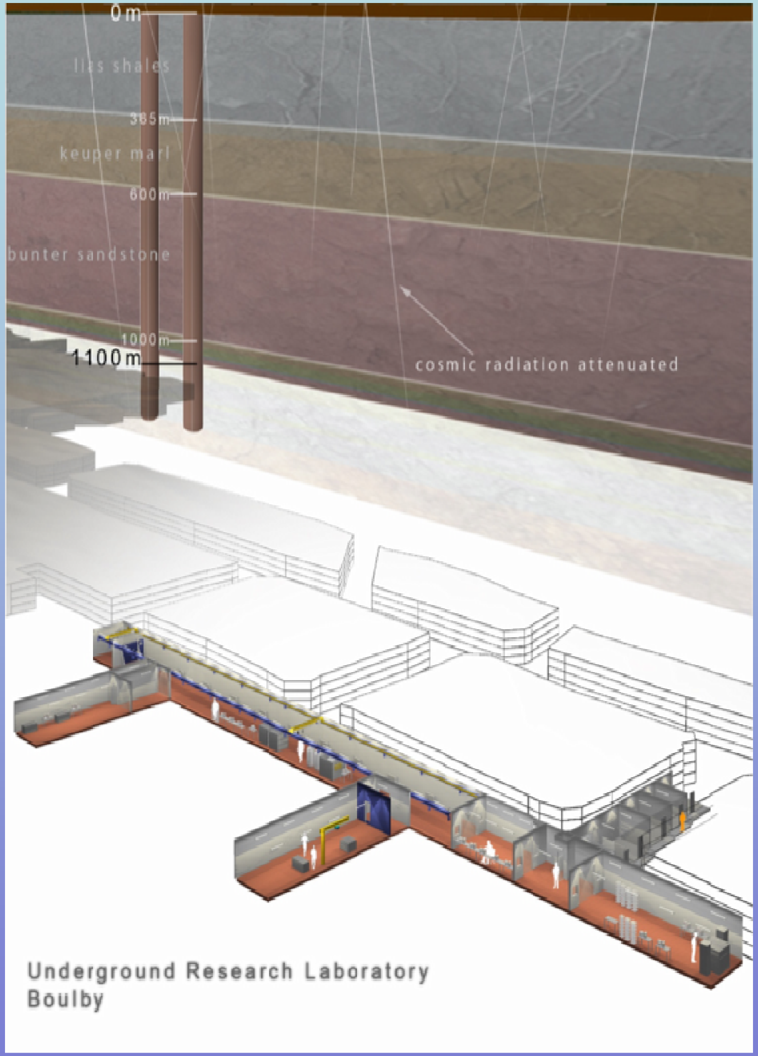
- CCLRC Rutherford Appleton Laboratory
- Imperial College London
- University of Sheffield
- University of Oxford
- University of Edinburgh
- University of California (UCLA)
- Texas A&M University
- University of Rochester
- LIP- Coimbra (Coimbra Univ.)
- INFN Pisa

ZEPLIN III (two-phase)

- CCLRC Rutherford Appleton Laboratory
- Imperial College London
- University of Edinburgh
- LIP- Coimbra (Coimbra Univ.)
- ITEP

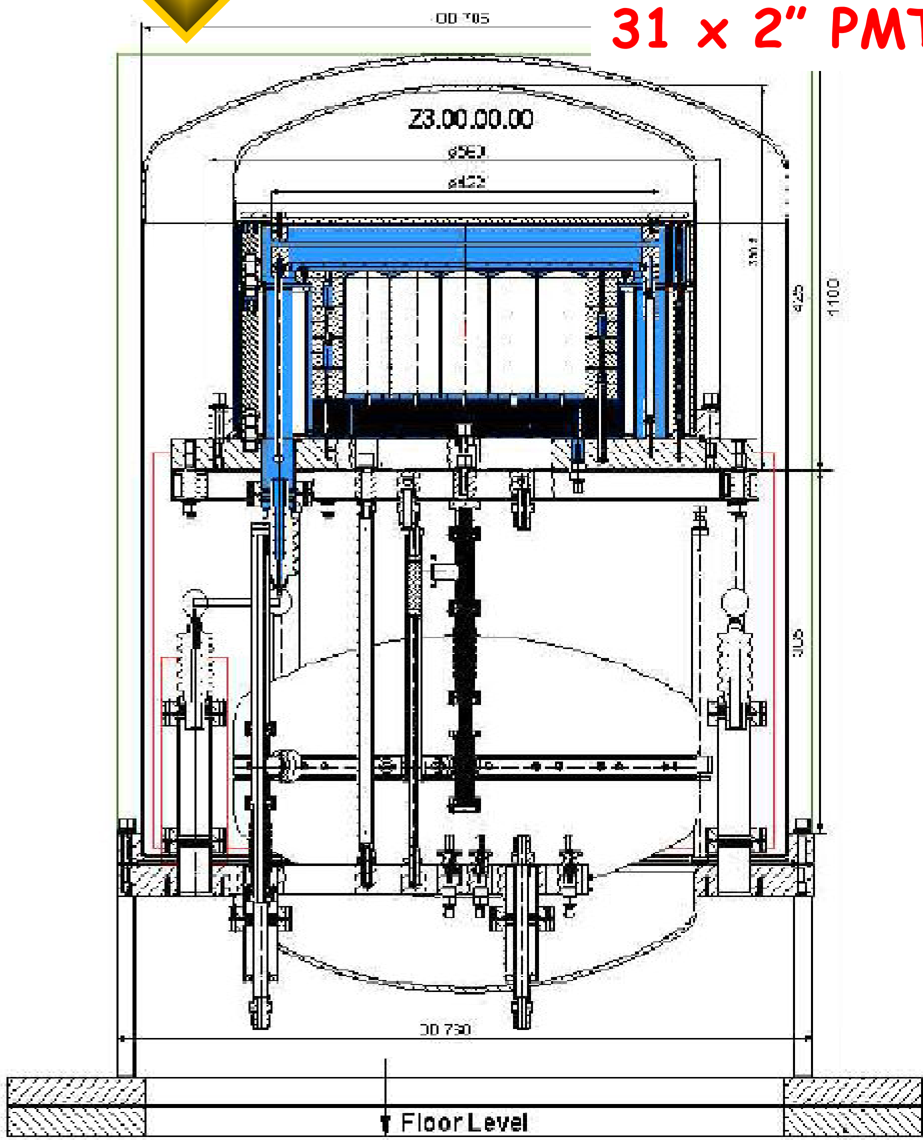
Experiments: ZEPLIN

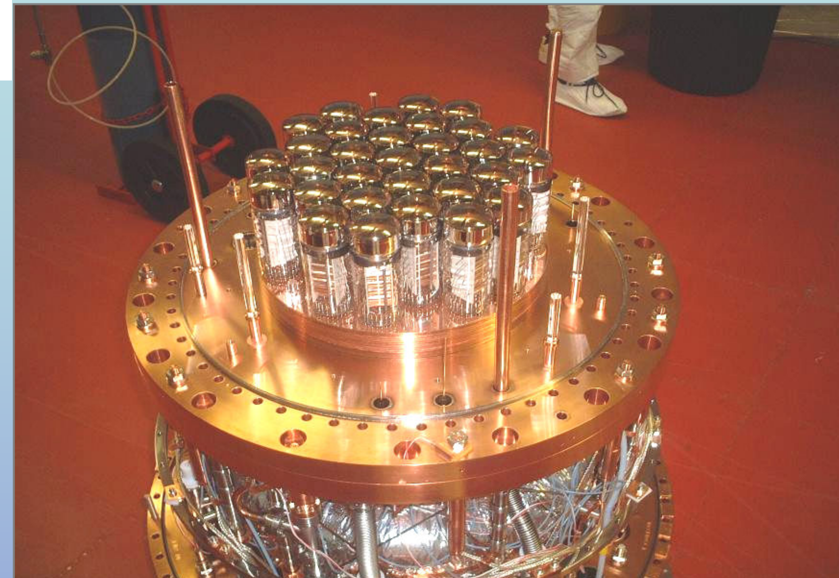
Boulby, U.K. site ('Palmer lab')
1100m, 2.8km water equiv.
10^6 reduction in muon flux



Experiments: ZEPLIN III

31 x 2" PMTs



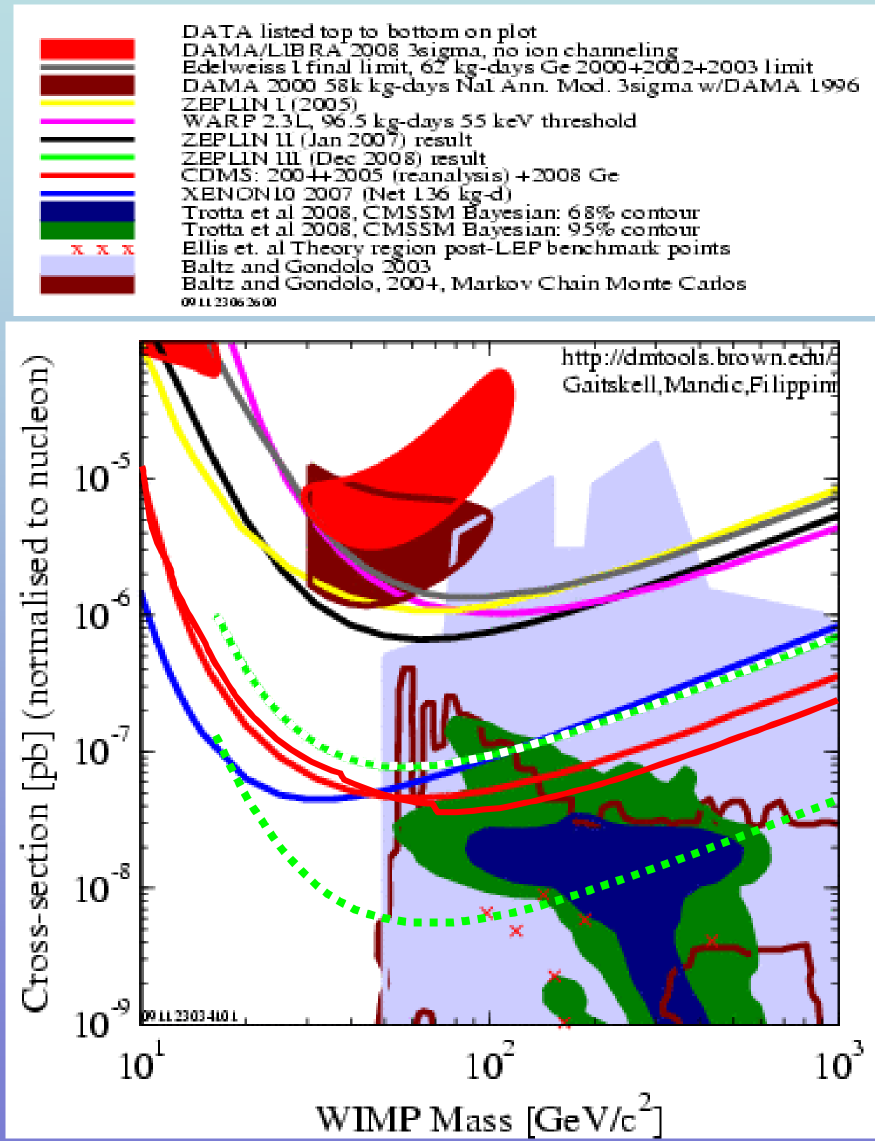


Experiments: ZEPLIN III

Phase 1
Completed
453.6 kg days
→ 8.1×10^{-8} pb
astro-ph:0812.1150

Phase 2
Upgrade completed:
- 30 times less radioactive PMTs
- Active neutron Veto

Collect 1 year of data
→ 5.6×10^{-9} pb



Future experiments

Future experiments will be large-scale

XMASS

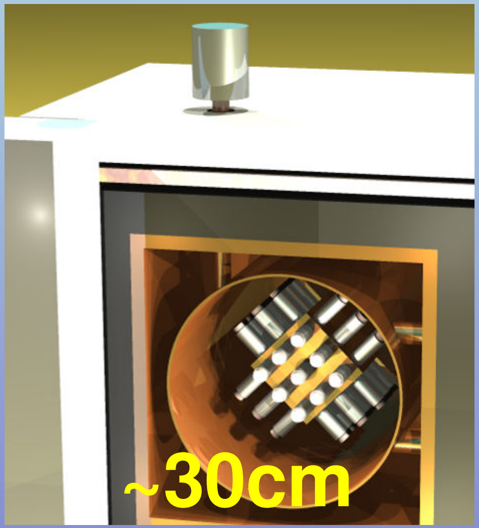
Xenon100

LUX

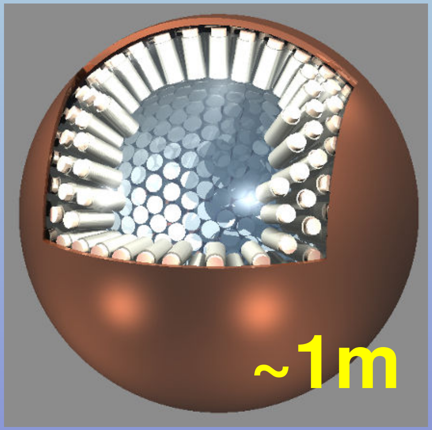
Future experiments: XMASS

XMASS – multipurpose detector

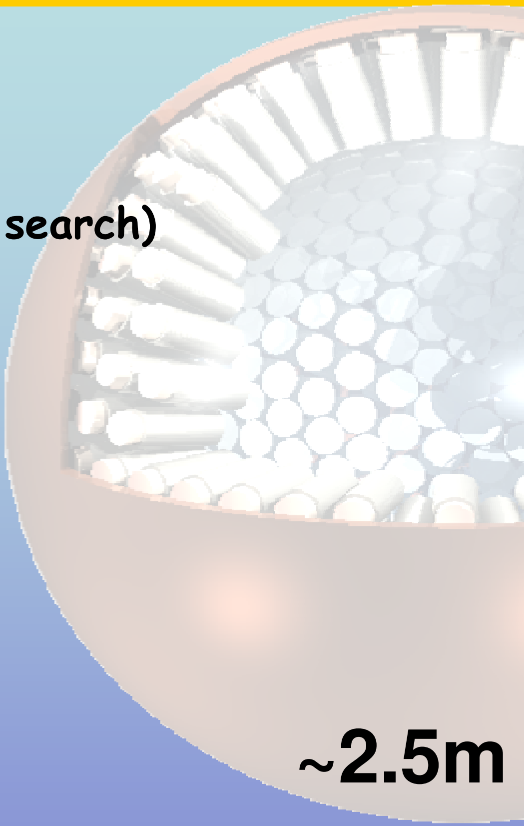
Xenon MASSive detector for Solar neutrino (pp/^{7}Be)
Xenon neutrino MASS detector (double beta decay)
Xenon detector for Weakly Interacting MASSive Particles (DM search)



Prototype detector (FV 3kg) R&D



~1 ton detector (FV 100kg)
Dark matter search



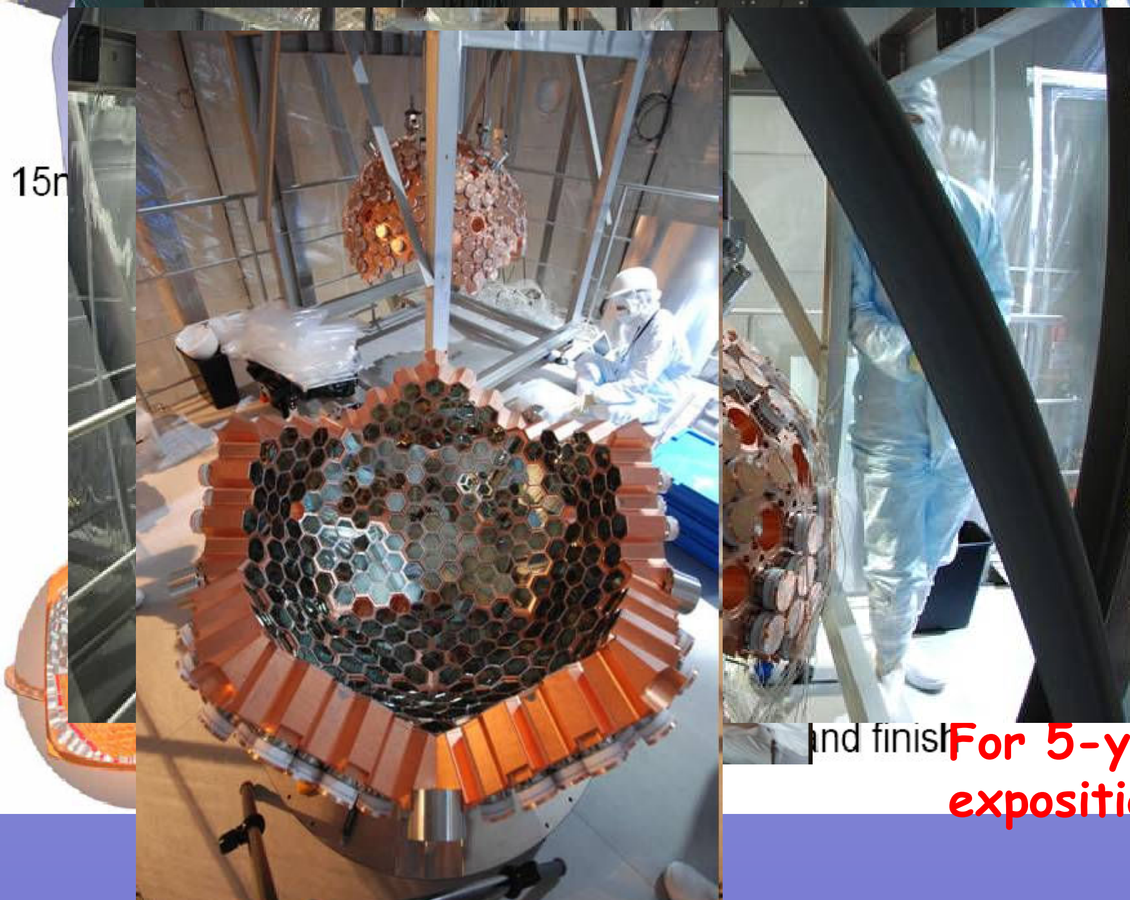
~20 ton detector (FV 10ton)
Solar neutrinos
Dark matter search

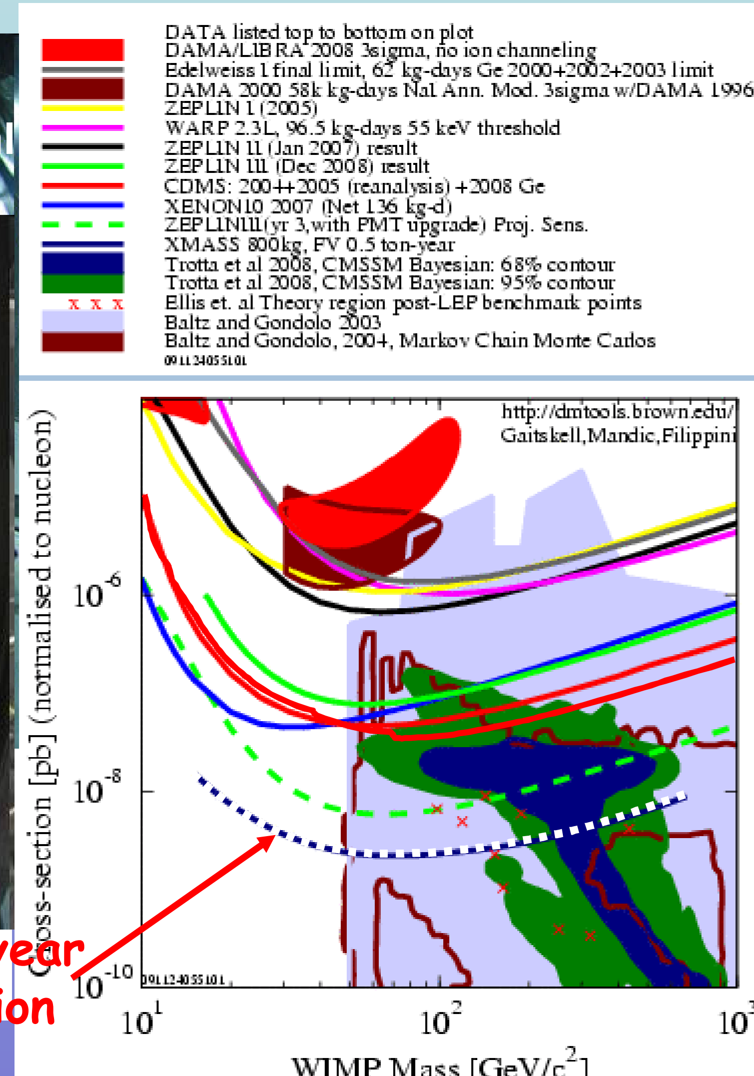
Confirmation of feasibilities of the ~1ton detector

Future experiments: XMASS

Assembling of XMASS can be tracked:

http://www-sk.icrr.u-tokyo.ac.jp/xmass/status-e.html

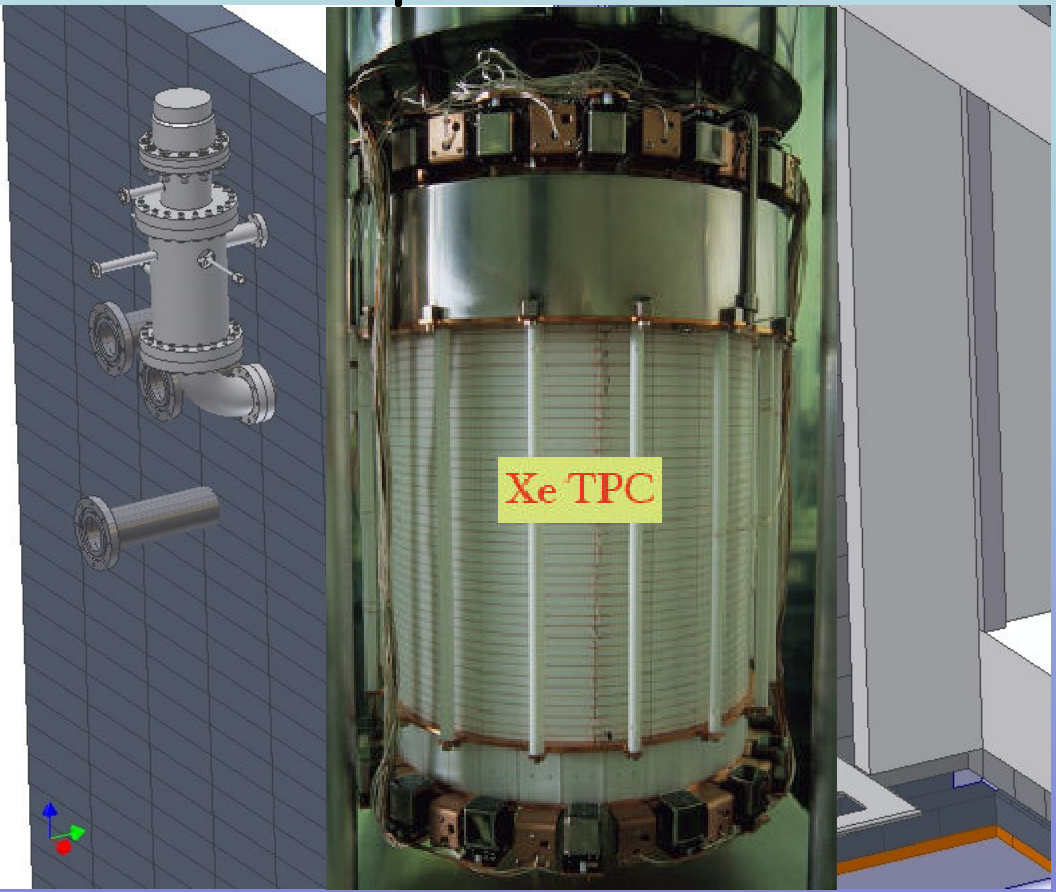


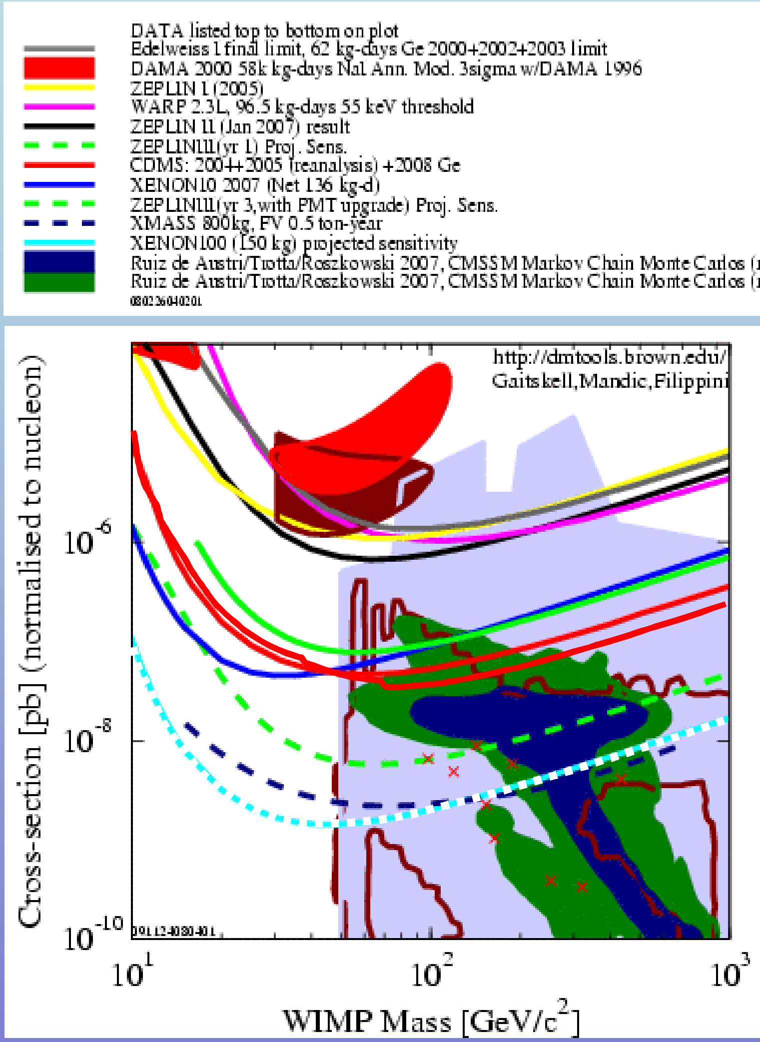


For 5-year exposition

Future experiments: Xenon100

Scaled-up Xenon10 detector





150 kg total (70 kg in target)

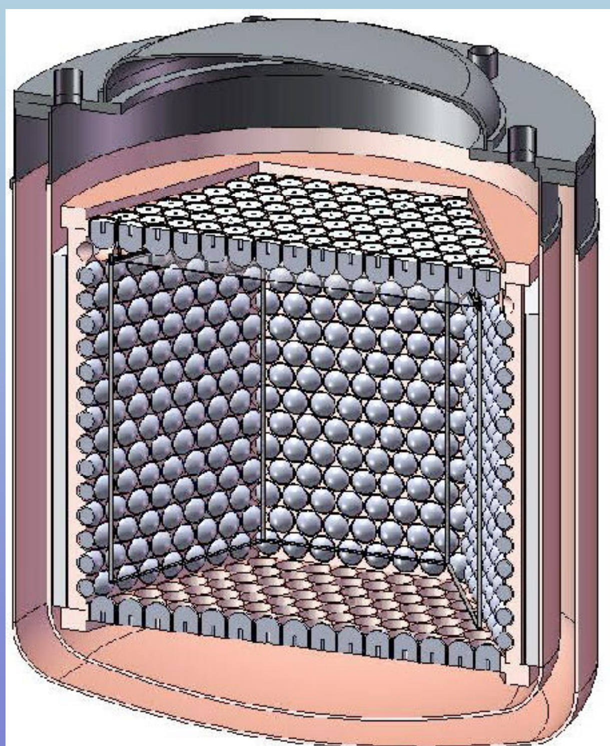
started data taking in mid Jan 2010

Projects: (Xenon 1t), MAX

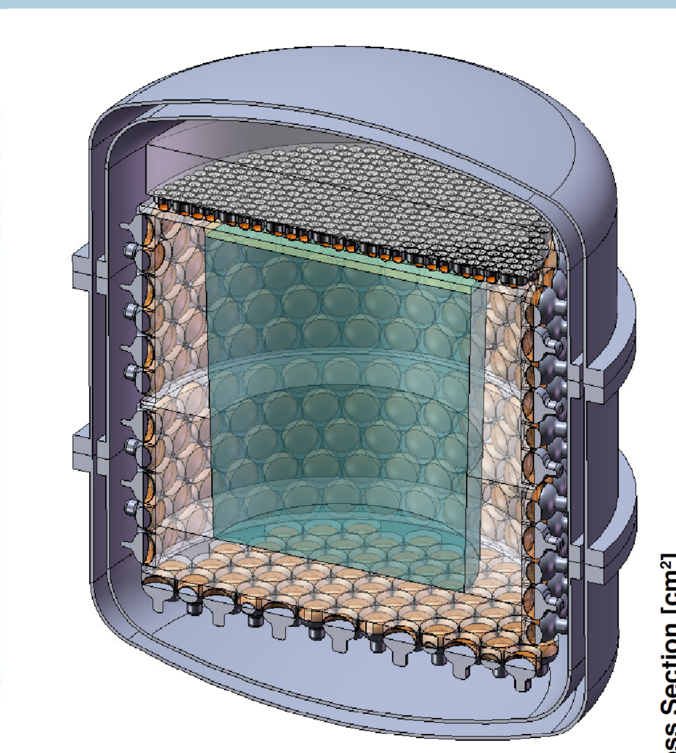
Xenon 1t for LNGS

MAX 2009 proposal for DUSEL http://www.fnal.gov/pub/max/index.html

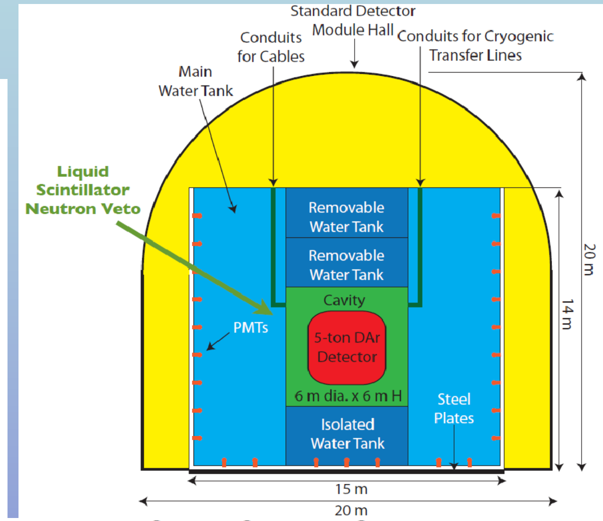
MAX collaboration - Multi-ton Argon & Xenon

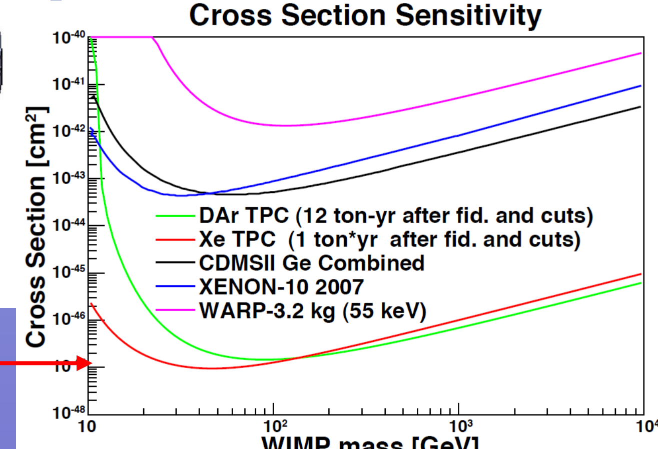


2.4 ton LXe



5 ton LAr





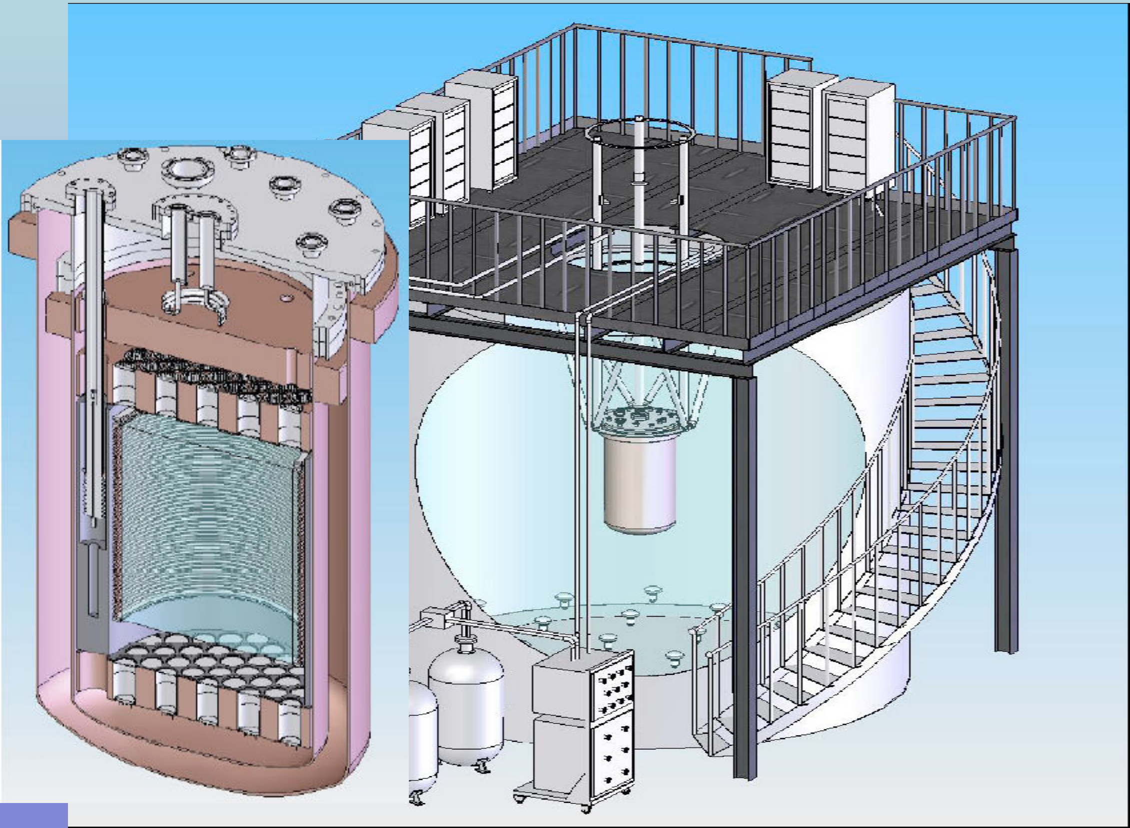
10^{-11} pb

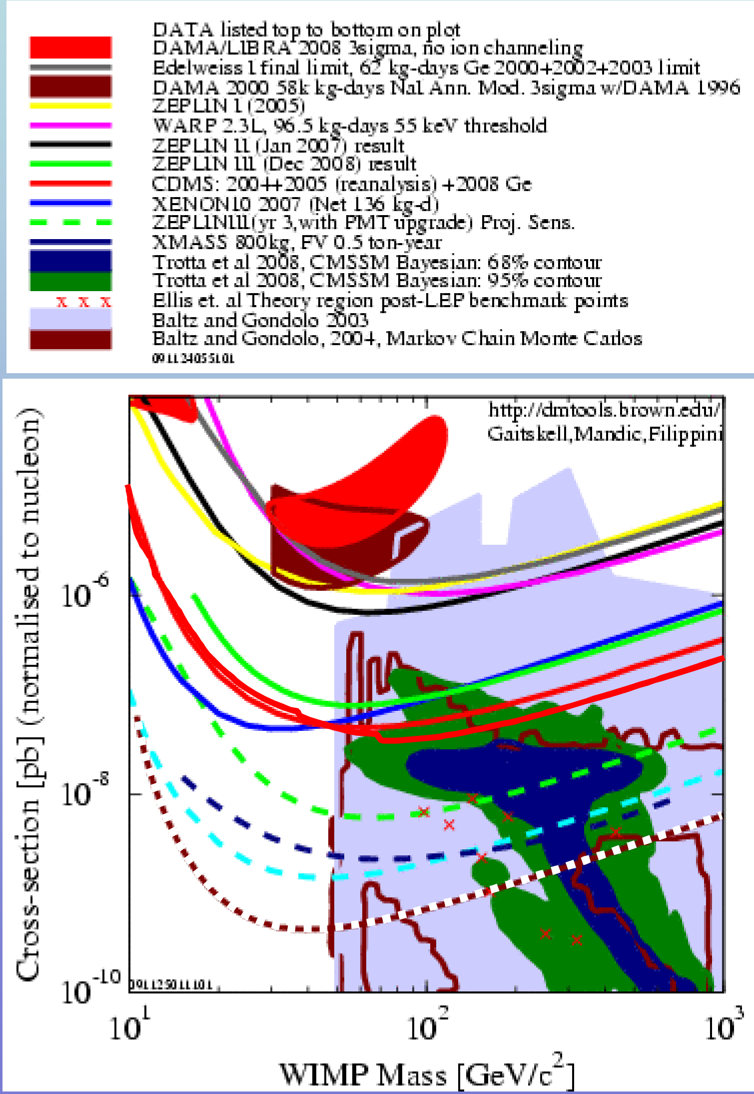
4π light collection

Future experiments: LUX

Large Underground Xenon detector

SUSEL – at Homestake; South Dakota



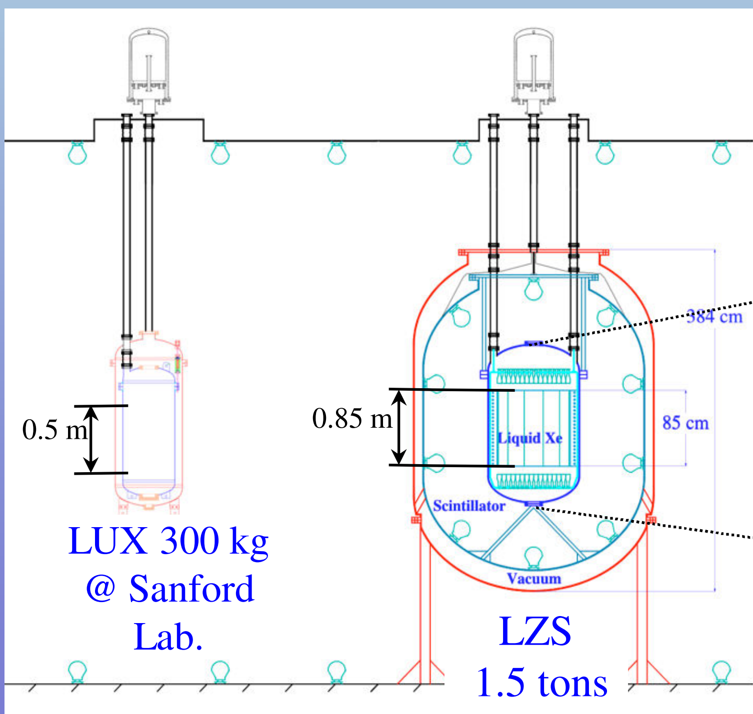


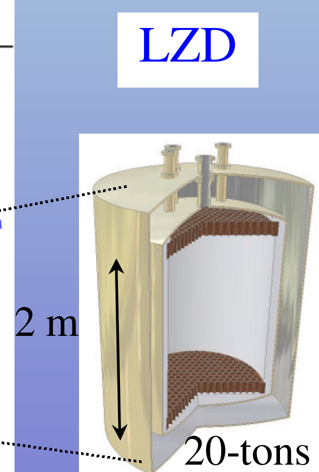
350 kg total (150 kg in target)

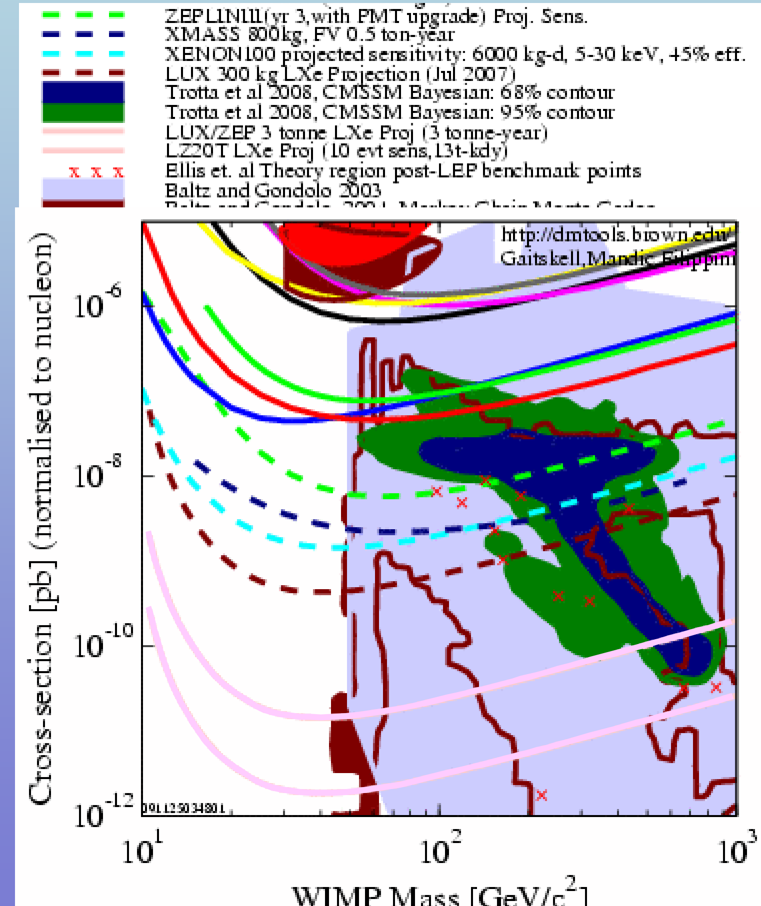
Large water shield Cherenkov readout - muon veto. 10-month exposition

Projects: LZ

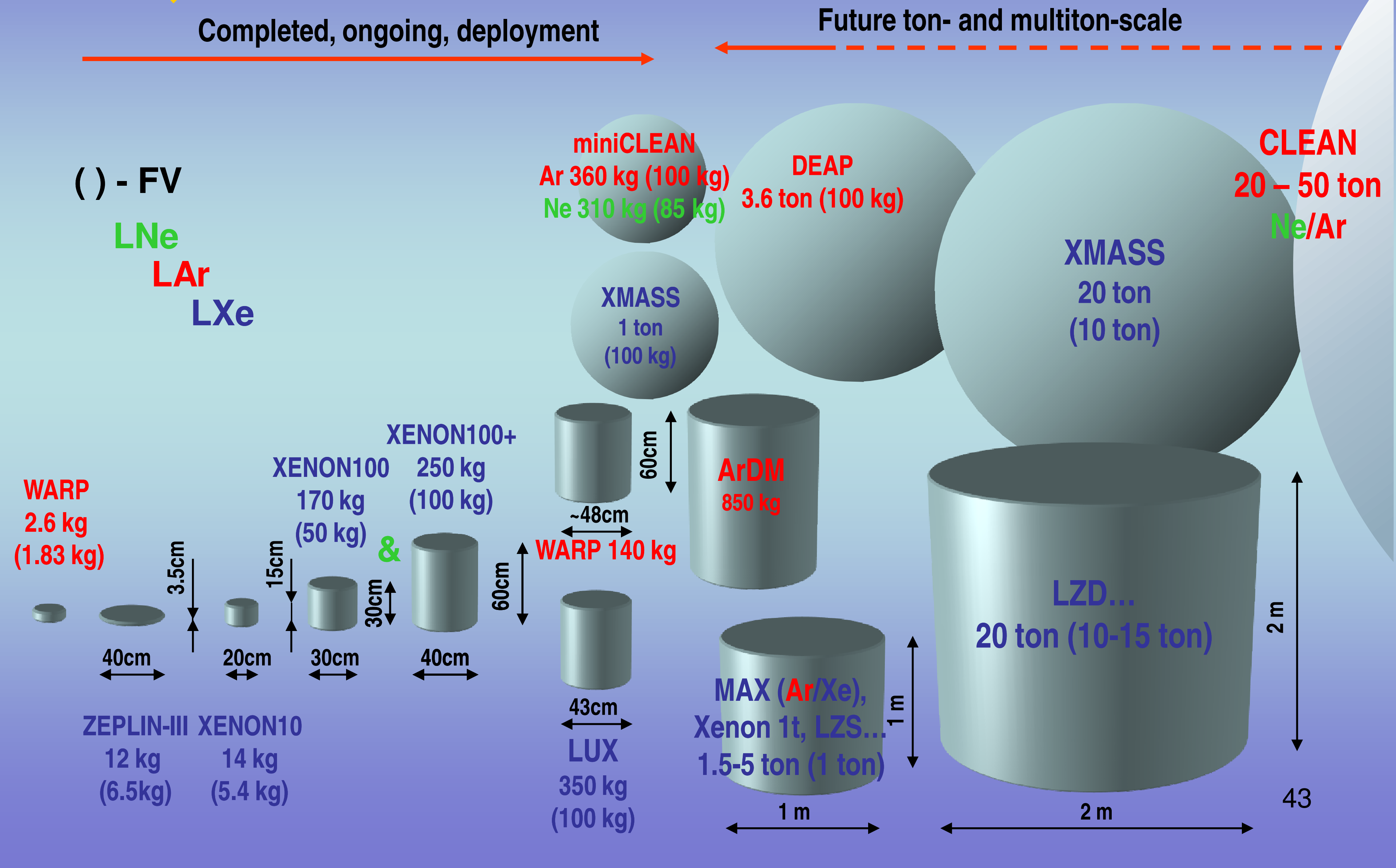
LZS@SUSEL – Sanford Underground Science and Engineering Lab. 4850 feet
LZD@DUSEL – Deep Underground Science and Engineering Lab. 8000 feet





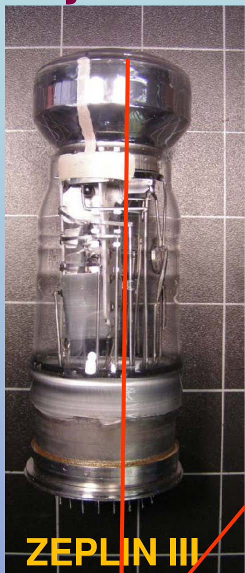


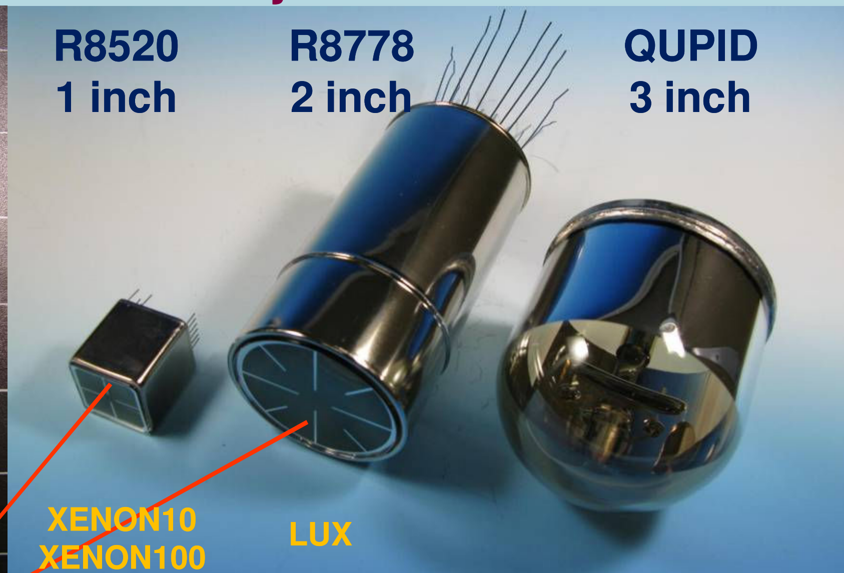
Family of noble-liquid DM detectors

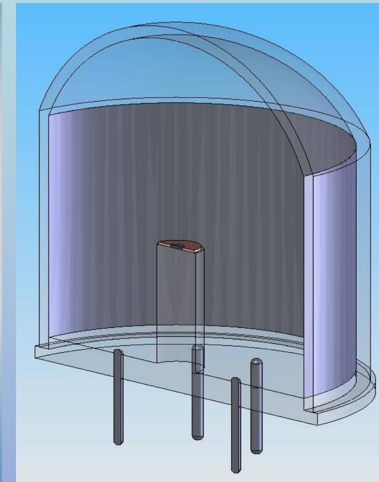


Special development: low-radioactive photodetectors

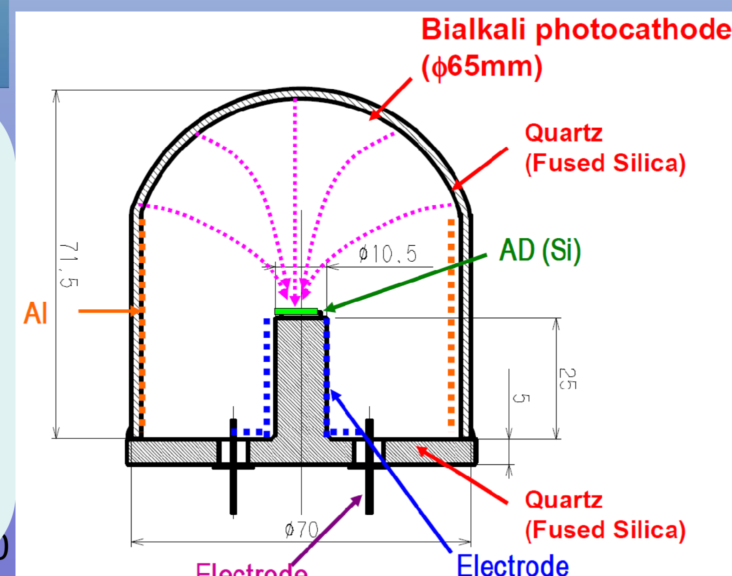
by ETL: **by Hamamatsu:**







A. Fukasawa et al., talk at TIPP 09



U - 0.17±0.04 mBq/PMT
Th - 0.20±0.09 mBq/PMT
K - 10±1 mBq/PMT

Metal strips to increase conductivity of photocathode at low temp.

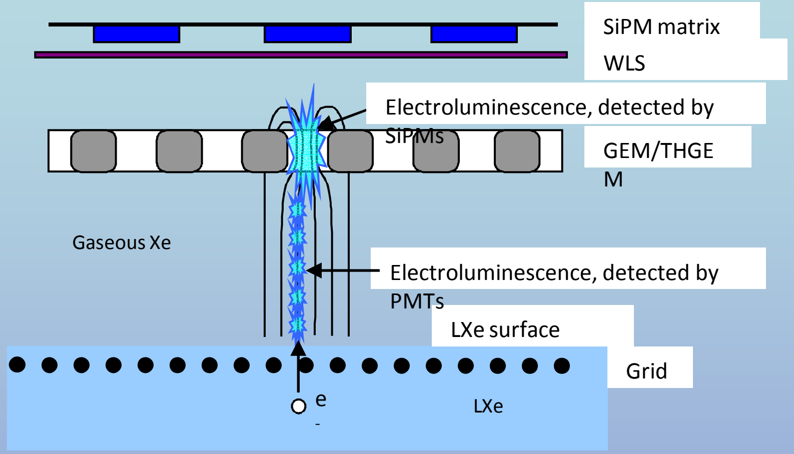
LUX (R8778):
U - 9 mBq/PMT
Th - 3 mBq/PMT

XMASS (R8778mod):
U - 1.8 mBq/PMT
Th - 0.7 mBq/PMT
K - 1.4 mBq/PMT

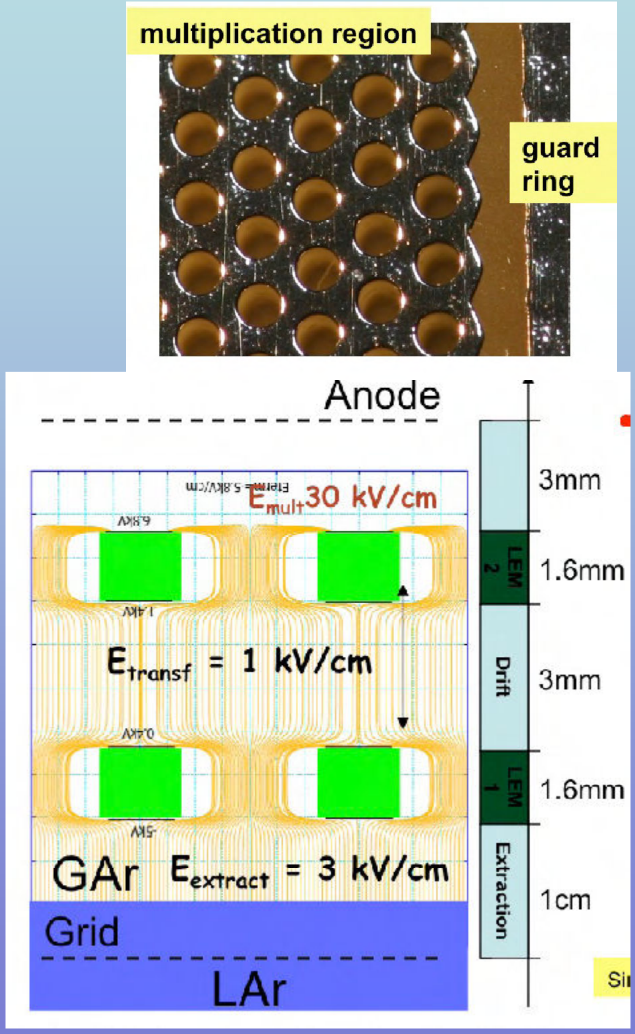
QUPID:
U - <0.3 mBq/PMT
Th - <0.3 mBq/PMT

Special development: charge readout with THGEM (LEM)

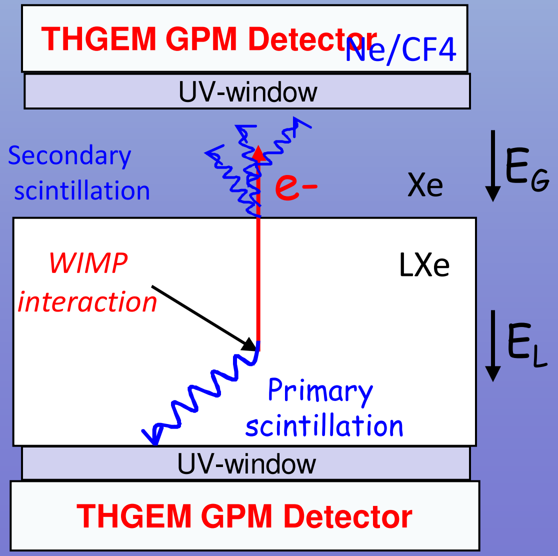
ITEP&INP



accepted as a base option for ArDM



RD51: Weizmann/Nantes/Coimbra



Summary

- The evidences of the existence of the Dark Matter in the Universe are very strong.
- The searches by direct detection of WIMPs (the new elementary particles predicted by SUSY) are in progress.

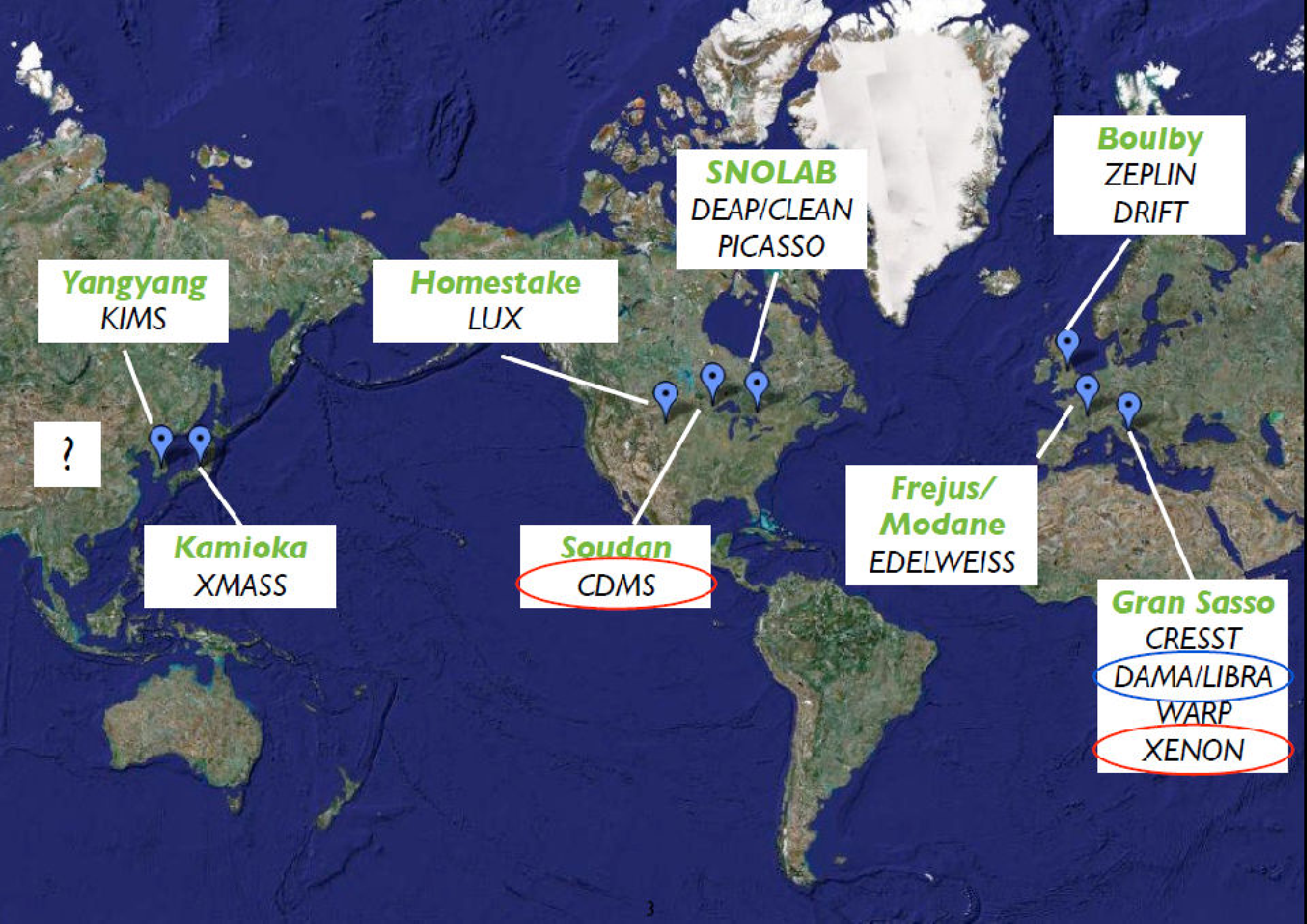
Such searches are complementary to indirect detection and collider experiments.

- Due to progress in development of DM detection technology, from the beginning till now – reduction of bckg by ~5 orders of magnitude!
- Ton-scale detectors based on liquid noble gases are coming.

Thanks to the Organising Committee of VCI2010 Conference for inviting me to give this talk!

Backup slides

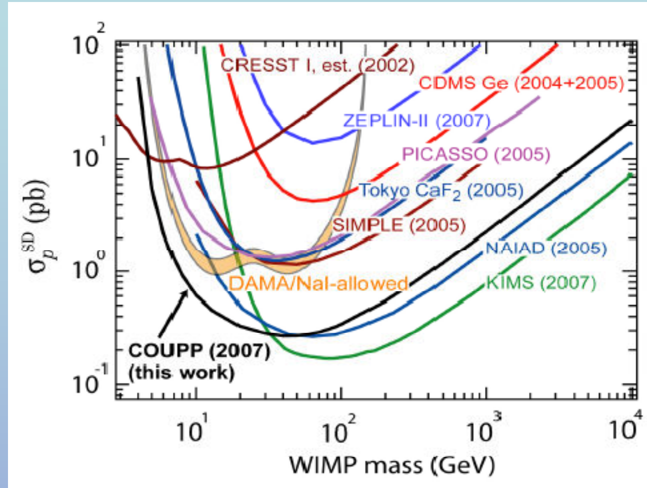
World Wide Dark Matter Searches

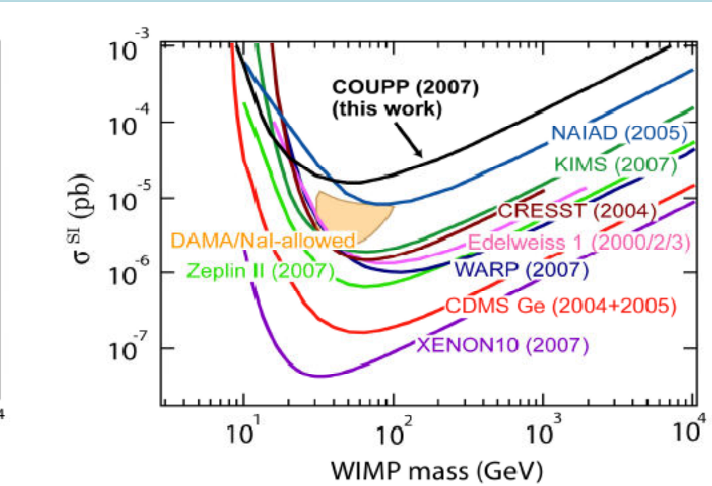


COUPP - Chicagoland Observatory for Underground Particle Physics

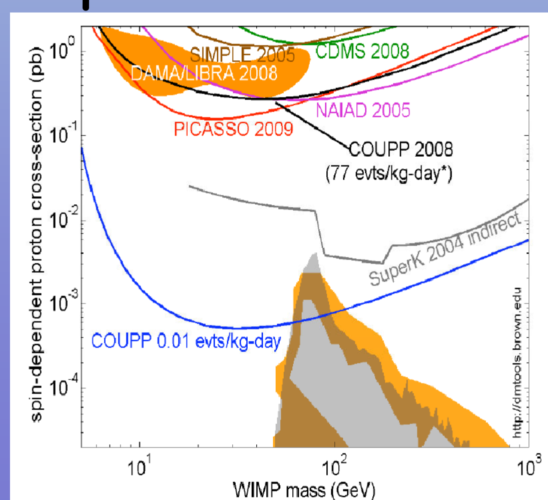
A bubble chamber; superheated CF_3I

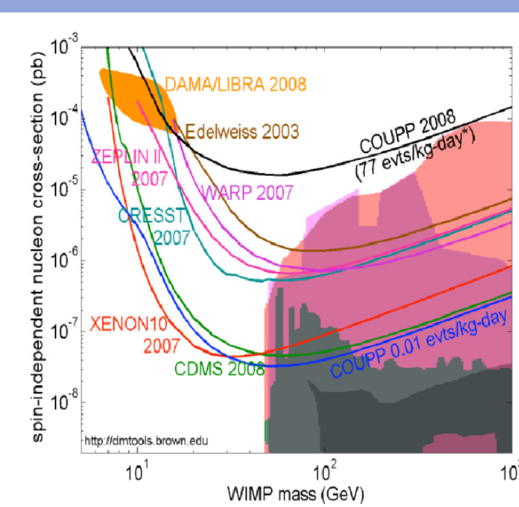
The limits obtained with 1.5-kg at Fermilab E. Behnke, *et al. Science* **319**, 933 (2008):





60kg chamber being commissioned at Fermilab
Proposed to SNOLAB



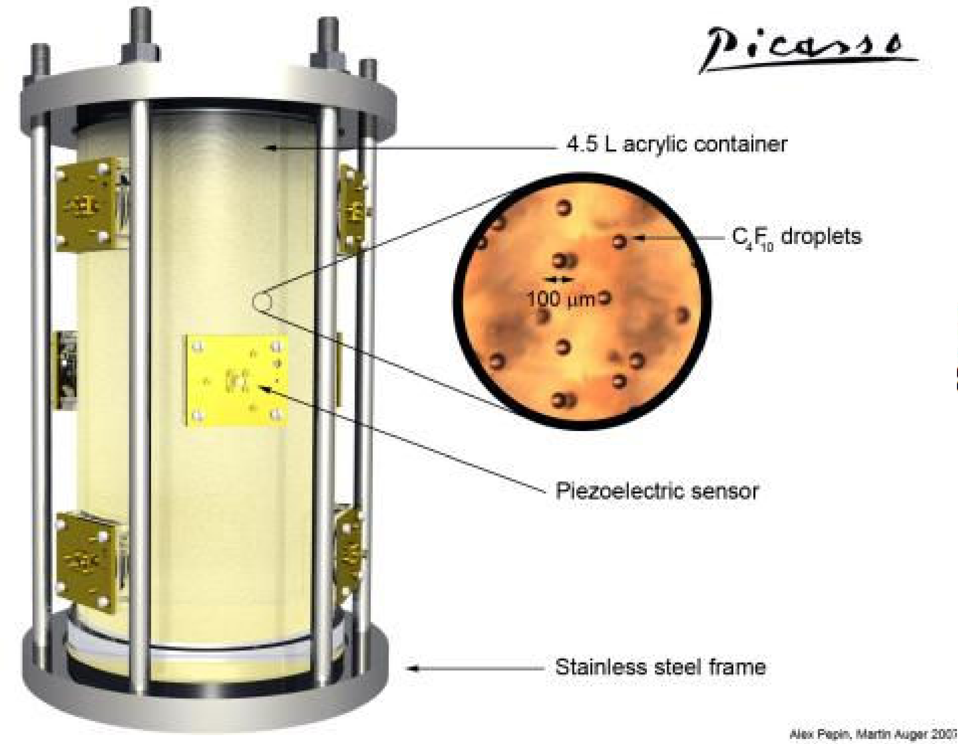


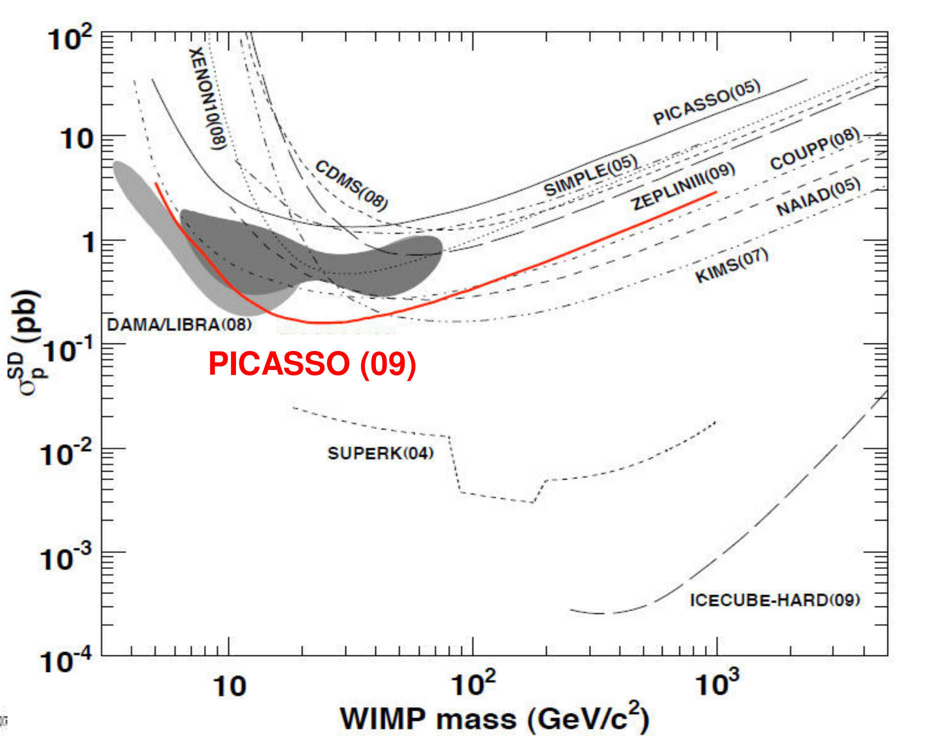
PICASSO

Experiment at SNOLAB

4.5l module with 80g of active mass of C4F10.
Superheated droplets are suspended in an elastic polymer
Signals are recorded by 9 piezo electric sensors. Events are localised by GPS-like triangulation.

Presently PICASSO is installing a new experiment with 32 detector modules as shown to the left and with an active mass of 2.6 kg.





Useful bibliography resources

- Internet recourses:
    - Dark Matter (DM) and DM related conferences: DM (http://www.physics.ucla.edu/hep/dm08/talks), idm, Dark, TAUP, NANP
    - Public pages of the DM experiments/collaborations: EDElWEISS, CDMS, ZEPLIN, Xenon, DAMA …
    - Wikipedia: http://en.wikipedia.org/wiki/Dark_matter and many related topics therein
    - For Russian-speaking: http://elementy.ru/lib/25560/25563 - very good video lecture of V.A. Rubakov
    - T.J. Sumner, Experimental Searches for Dark Matter – on-line review http://relativity.livingreviews.org/Articles/lrr-2002-4/
- Teilchenastrophysik (translated to Russian: Астрофизика элементарных частиц) H.V. Klapdor-Kleingrothaus, K. Zuber, published by Teubner B.G. GmbH (1997)
- D. Yu. Akimov, Experimental Methods for Particle Dark Matter Detection-Review, Instrum. Exp. Tech. 44 (2001) 575-617

The EURECA Collaboration

CRESST, EDELWEISS, ROSEBUD + CERN, others

United Kingdom

Oxford (H Kraus, coordinator)

Germany

MPI für Physik, Munich

Technische Universität München

Universität Tübingen

Universität Karlsruhe

Forschungszentrum Karlsruhe

International

JINR Dubna

CERN

France

CEA/IRFU Saclay

CEA/IRAMIS Saclay

CNRS/Neel Grenoble

CNRS/CSNSM Orsay

CNRS/IPNL Lyon

CNRS/IAS Orsay

Spain

Zaragoza

Ukraine

Kiev

EURECA in LSM

Timeline:

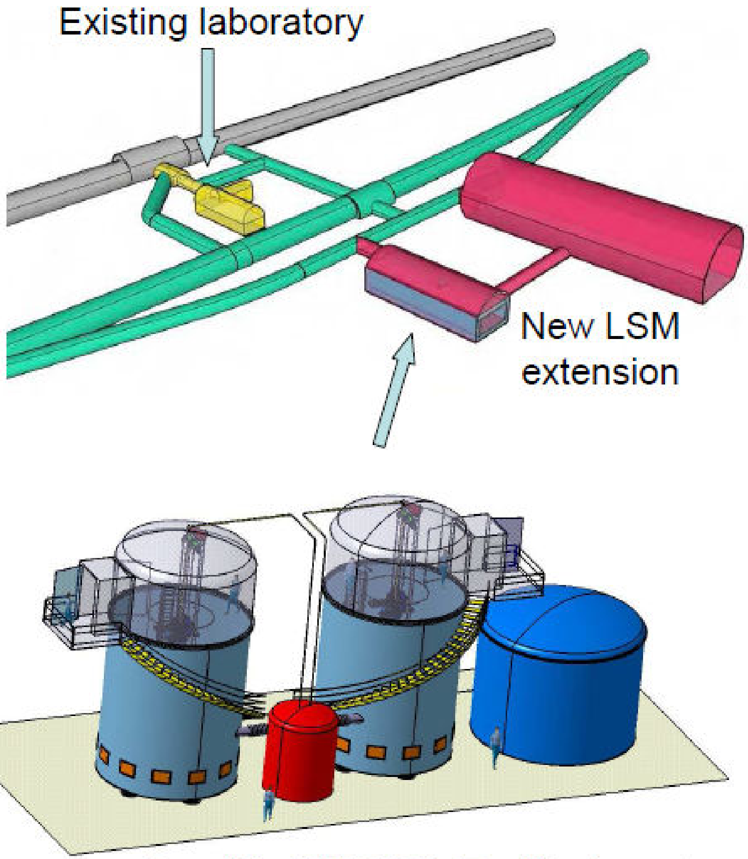
2009/10: Design Study → TDR

2011/12: Digging out of LSM extension begins. In parallel, begin construction of EURECA components away from LSM. Aim for ~100kg stage (10^{-9} pb).

2014: LSM extension ready to receive EURECA.

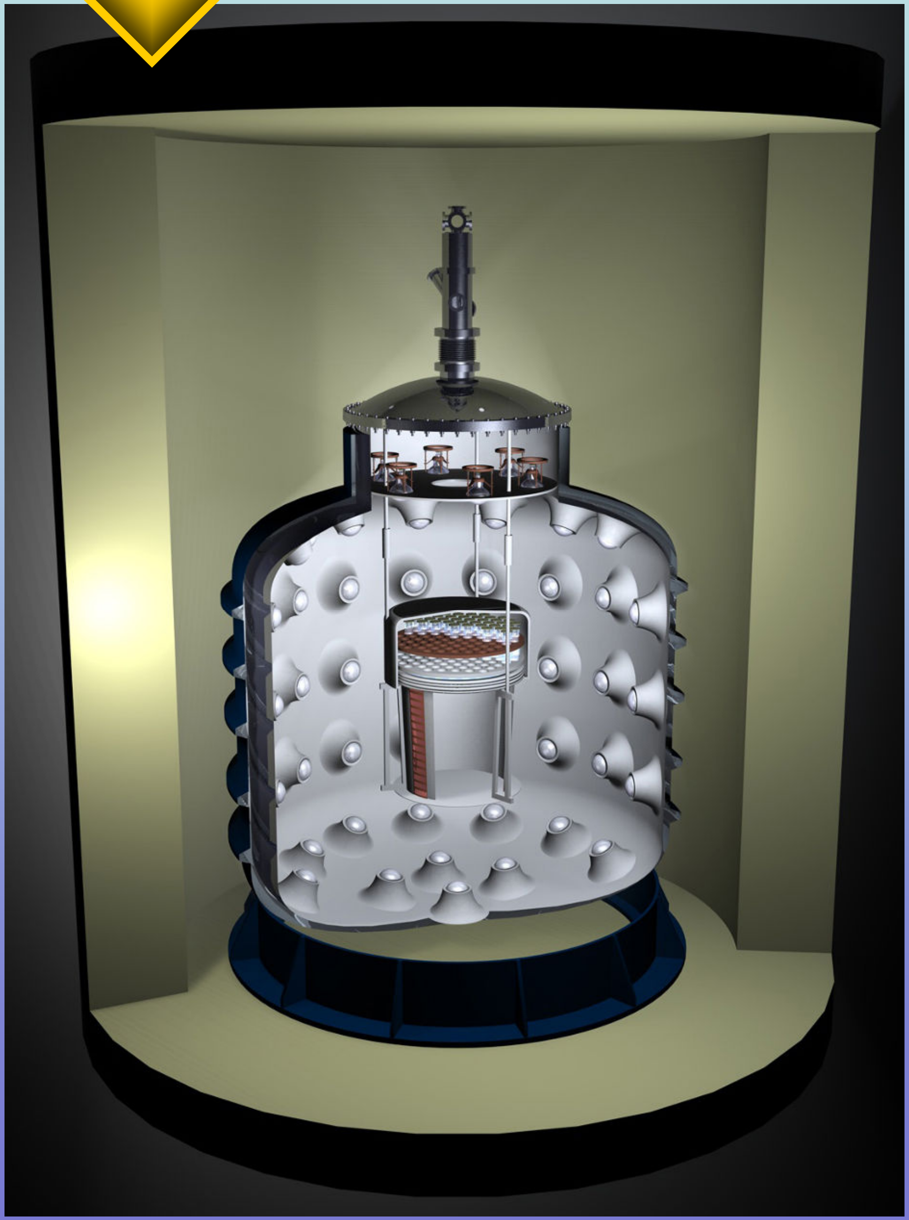
2015: Begin data taking and in parallel improve and upgrade.

2018: One tonne target installed.



Possible EURECA Facility Layout

WARP



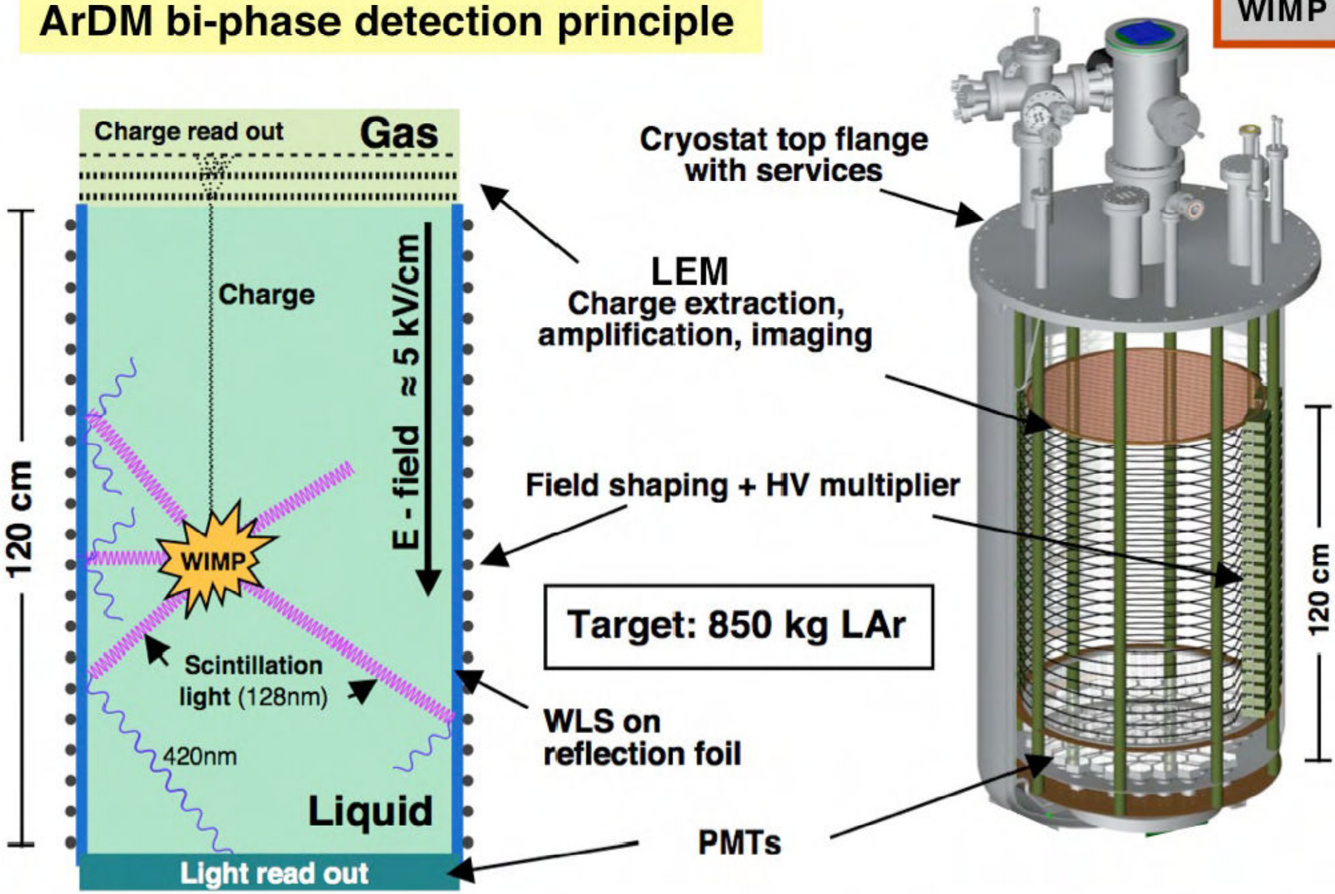
Experiment @ LNGS

- Exploit Ionization/Scintillation plus PSD for background reduction
- WArP @ LNGS: 140 kg active LAr volume (20 keVr threshold) surrounded by 8 ton LAr veto for beta/gamma and neutrons
- Veto designed for 1 ton scale detector
- Detector filled since May 09

ArDM

ArDM bi-phase detection principle

WIMP (rc. 30 keV) ≈ 400 VUV phot. + ≈ 3 e⁻



- Drift length ≈ 120 cm
- 850 kg target
- Drift field: 1...4 kV/cm
- LEM on top: gain ≈ 10^4

  res ≈ [mm]
- PMTs at bottom:

  L_{det} eff. ≈ 2% ($1e_{ph}$/keV)
- Trigger rate < 1kHz
- DAQ: FADCs,

  buffer length ≈ 1ms

A.Rubbia (Zurich, ETH)
J.Phys.Conf.Ser.39:129-132,2006.

Directional Experiments

Directional detectors with low pressure gas (large volume)
Challenge is to measure 3D tracks of low energy recoils

- DRIFT-II @ Boulby mine: 1 m3 MWPCs with 40 torr CS2 (167 g)
- DM-TPC @ MIT: 2x 10-2 m3 with 50 torr CF4 (PMTs + CCD readout for 3D + E)
- NEWAGE @ Kamioka: 23 x 28 x 30 cm3 TPC with 150 torr CF4 and microwell readout
- MIMAC @ Saclay : 3 He & CF4 TPC modules (3 x 3 cm Micromegas with pixellized anode)