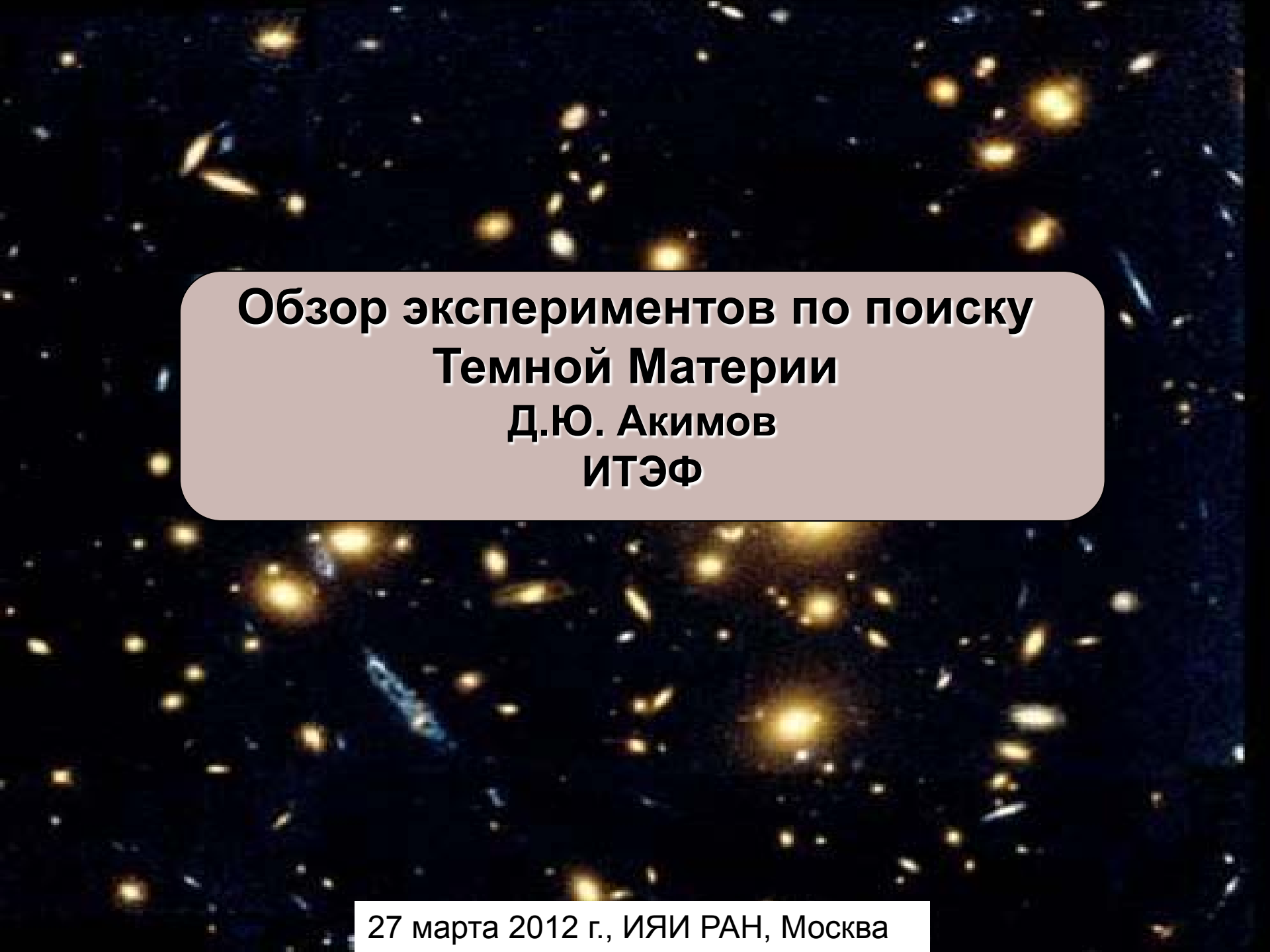


Обзор экспериментов по поиску Темной Материи

Д.Ю. Акимов
ИТЭФ

27 марта 2012 г., ИЯИ РАН, Москва

Содержание доклада

- Мотивация поиска Темной Материи
- Регистрация WIMP
- Эксперименты:

  DAMA/LIBRA; DM-Ice; CoGeNT; CRESST; COUPP

  Детекторы на жидких благородных газах:

  ZEPLIN-III; Xenon100; LUX; Darkside-50; XMASS; LZ; MAX; РЭД

Мотивация

Сегодня свидетельства в пользу существования Темной Материи намного сильнее, чем когда-либо!

Астрофизическая мотивация

Кривые вращения спиральных галактик

Гравитационное линзирование скоплениями галактик

Космологическая мотивация

Крупномасштабная структура Вселенной

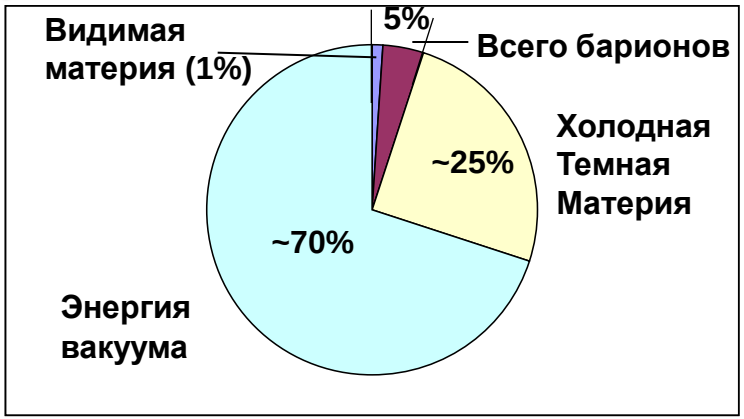
Анизотропия реликтового излучения (CMB)

N-body симуляция

Замечательное согласие выводов по CMB and SN Ia

Теория нуклеосинтеза

Современная космологическая модель

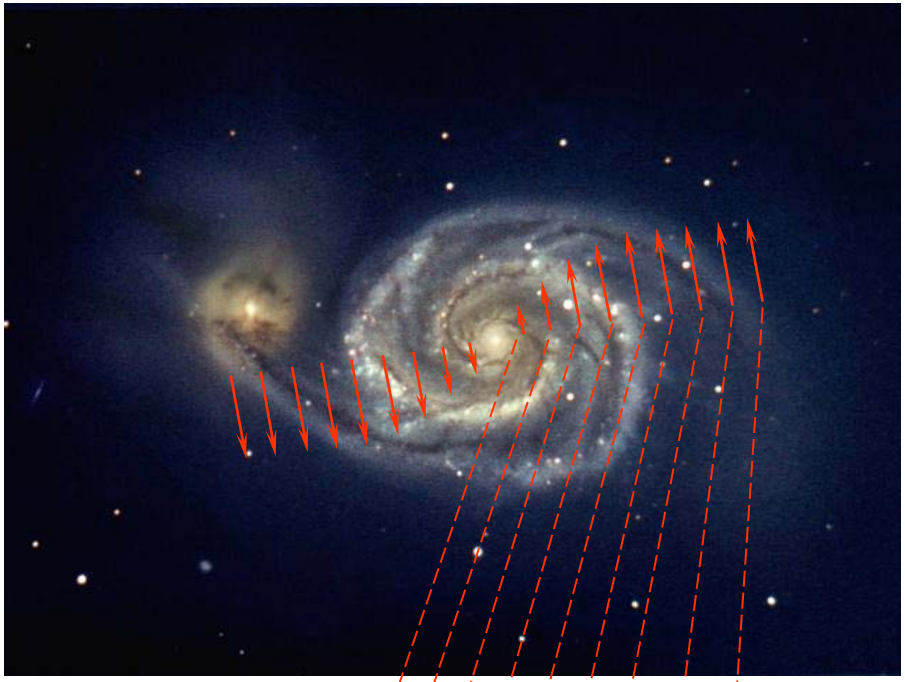


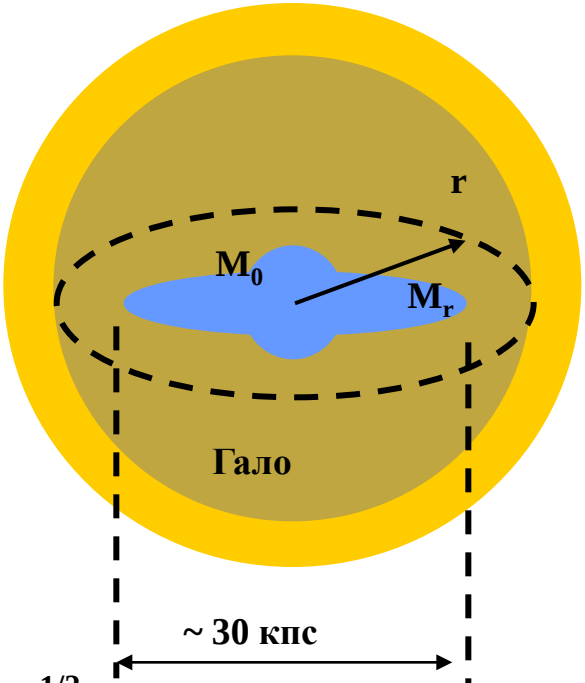
$\rho \approx \rho_{cr} \Rightarrow$

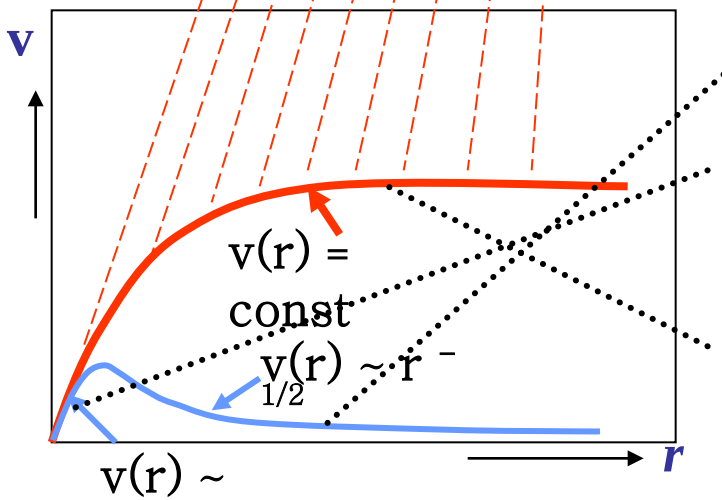
$\Omega = \rho / \rho_{cr} \approx 1$

Астрофизические свидетельства

Что же наблюдается на галактических масштабах?







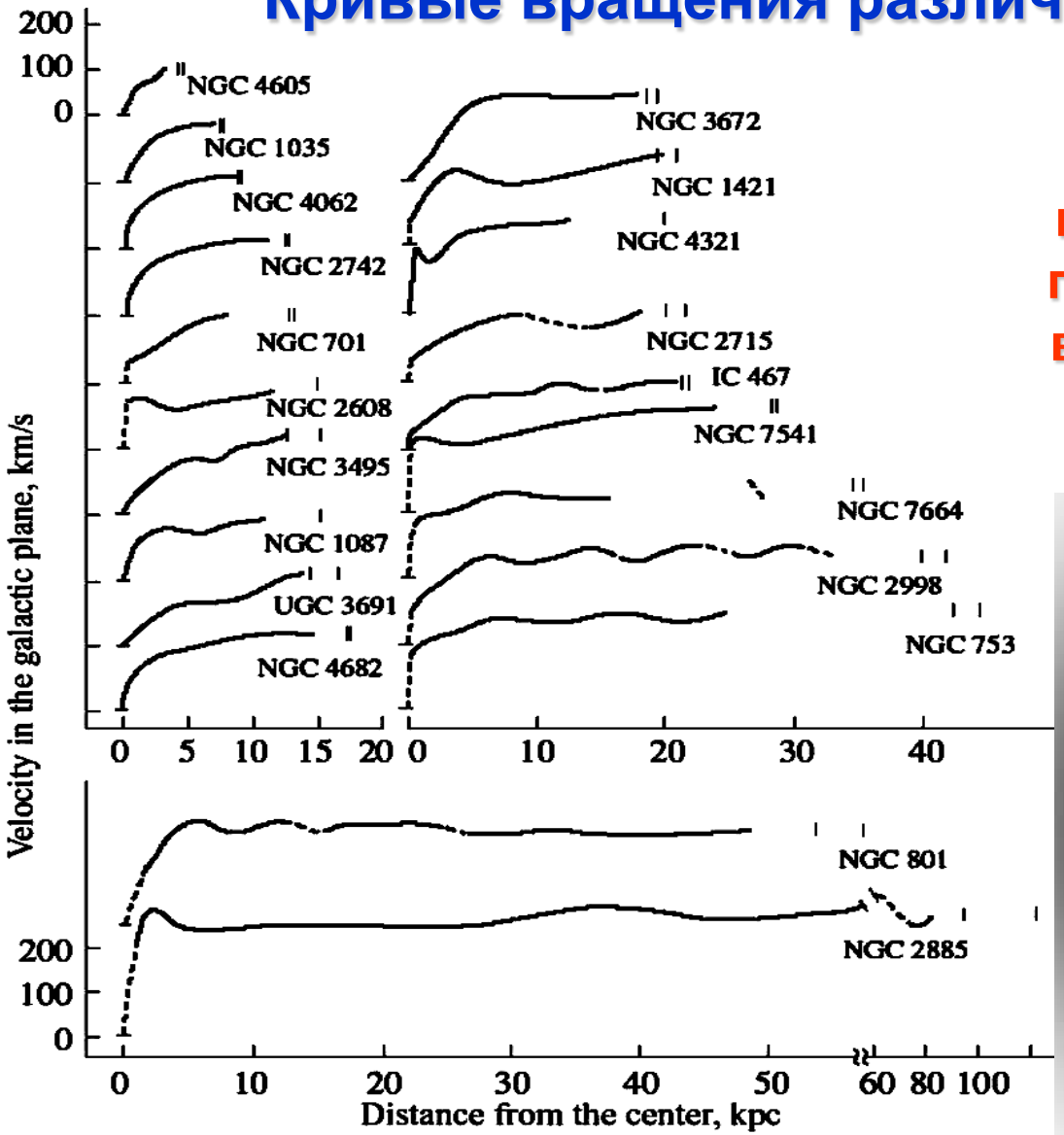
$v(r) \sim r^{-1/2}$ для случая центральной массы M_0

$v(r) \sim r$ для случая равномерного распределения массы ($M_r \sim r^3$)

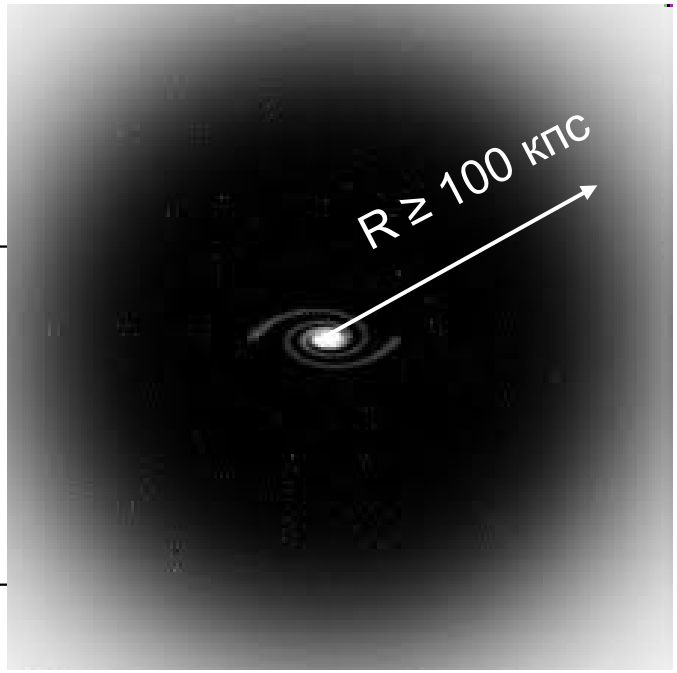
$v(r) = const$ для случая $M_r \sim r$

Астрофизические свидетельства

Кривые вращения различных галактик

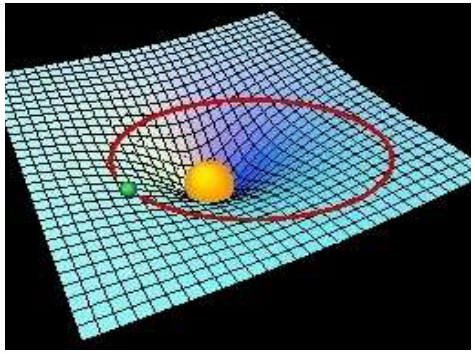


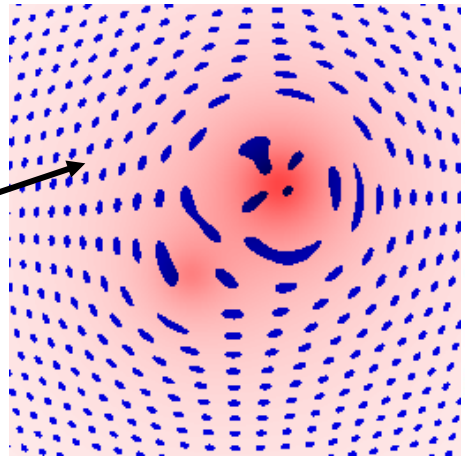
Для объяснения такого поведения кривых необходимо количество гравитирующей материи в ~10 раз превышающее количество видимой!



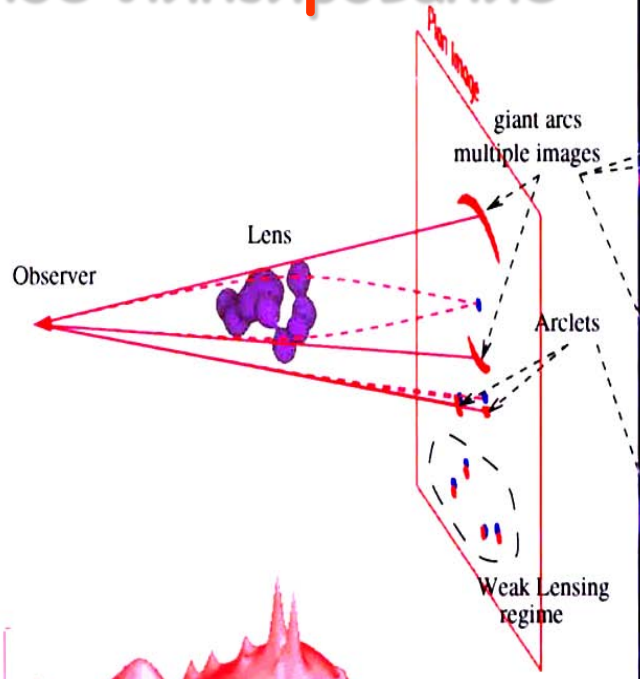
Астрофизические свидетельства

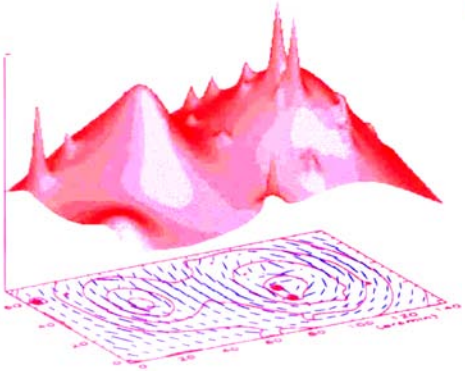
Гравитационное линзирование

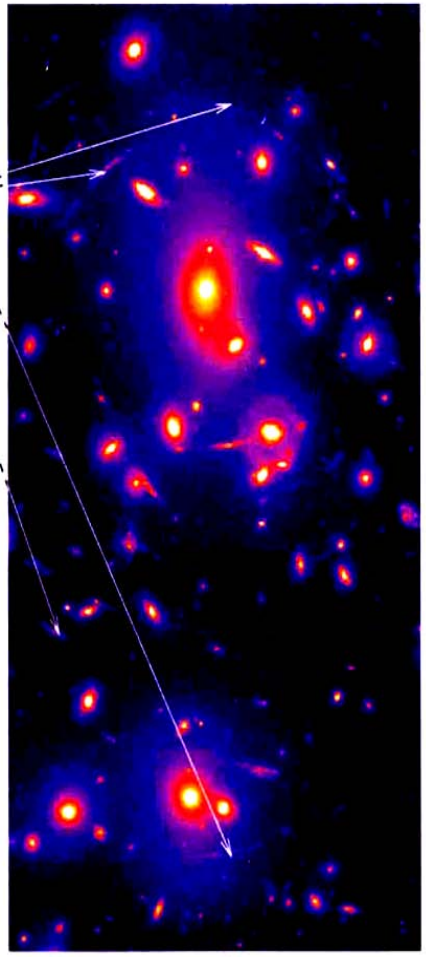




Так выглядел бы регулярный паттерн, находящийся за "размазанным" массивным объектом

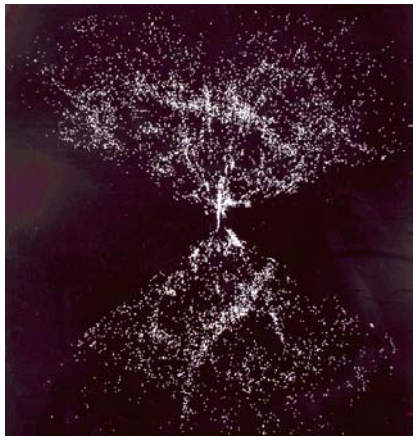




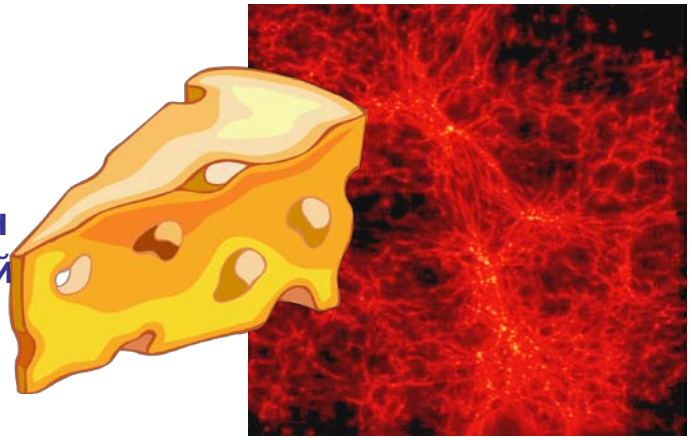


Также требуется на порядок величины большая масса

Космологическая мотивация



Крупномасштабная структура Вселенной, реконструированная из измерений красного смещения объектов



Результат N-body симуляции, проведенный на суперкомпьютерах

Главный результат симуляции – Темная Материя должна быть холодной (нерелятивистской)

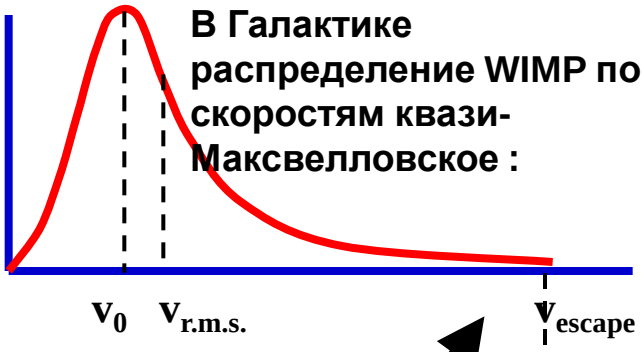
Теория Суперсимметрии SUSY предоставляет нам новый класс частиц.

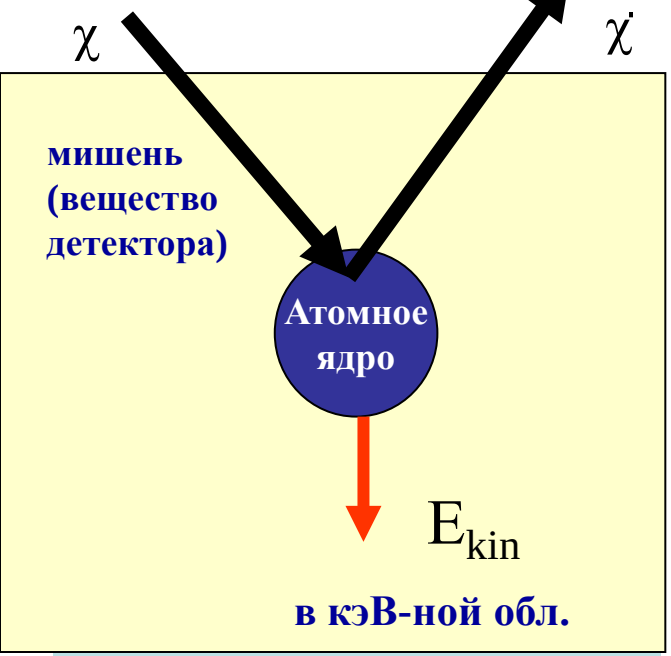
Нейтралино – наиболее вероятный кандидат в WIMP - (Weakly Interacting Massive Particles)

Диапазон масс от неск. дес. до неск. сотен ГэВ

Местная галактическая плотность ~ 0.3 ГэВ/см^3 ~неск. частиц в литре!

Прямое детектирование





$\sigma \sim A^2$	- spin-independent (SI) interaction
$\sigma \sim J(J+1)$	- spin-dependent (SD) interaction

$$\frac{dn_w}{dv} = 4\pi\left(\frac{1}{\pi v_0^2}\right)^{3/2} v^2 \exp\left(-\frac{v^2}{v_0^2}\right)$$

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

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

M_χ, M_N и m_{red} – masses of WIMP and target nucleus, and their reduced mass, respectively;

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

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

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

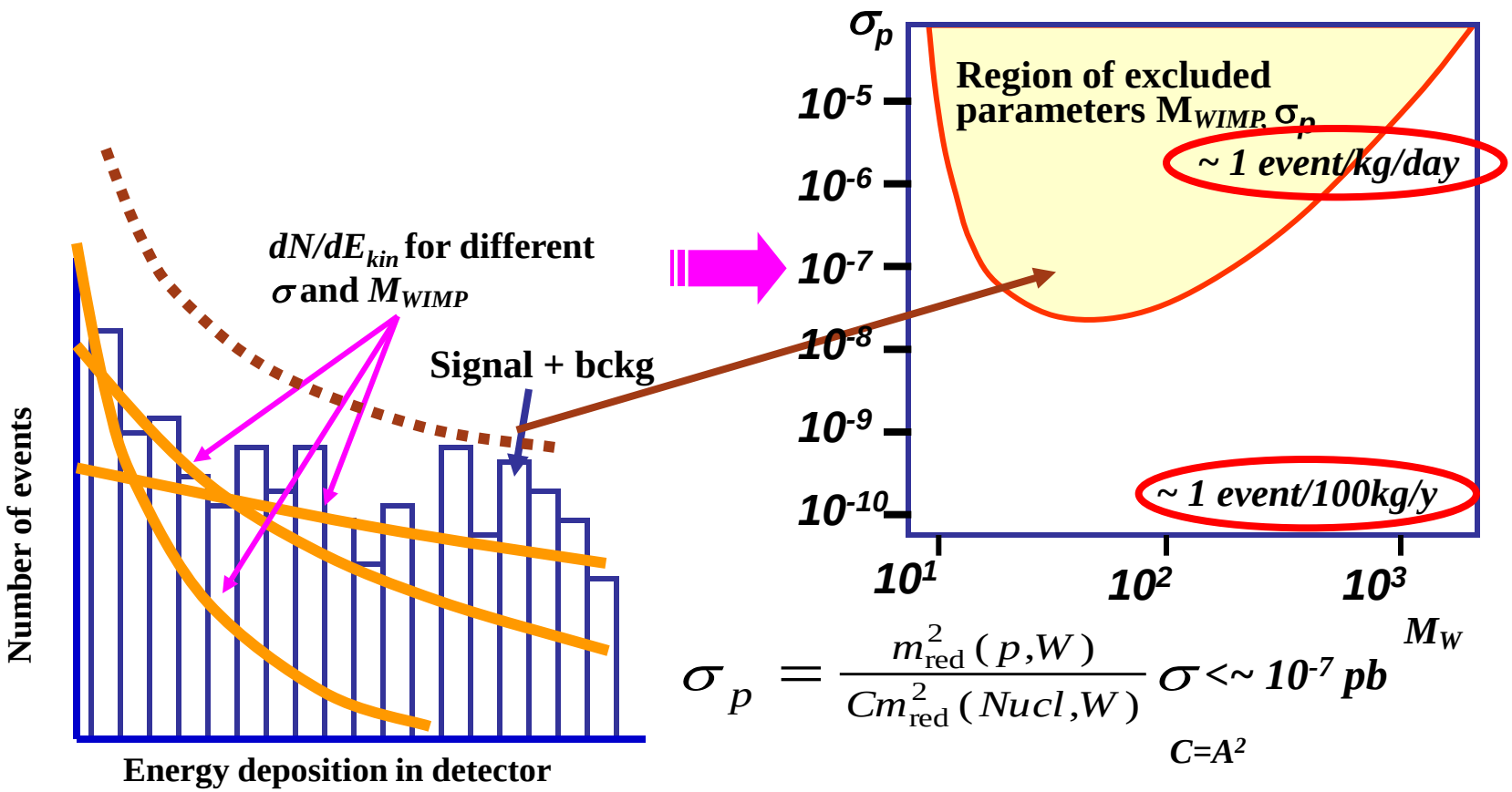
N_N – number of target nuclei,

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

σ – WIMP interaction cross-section,

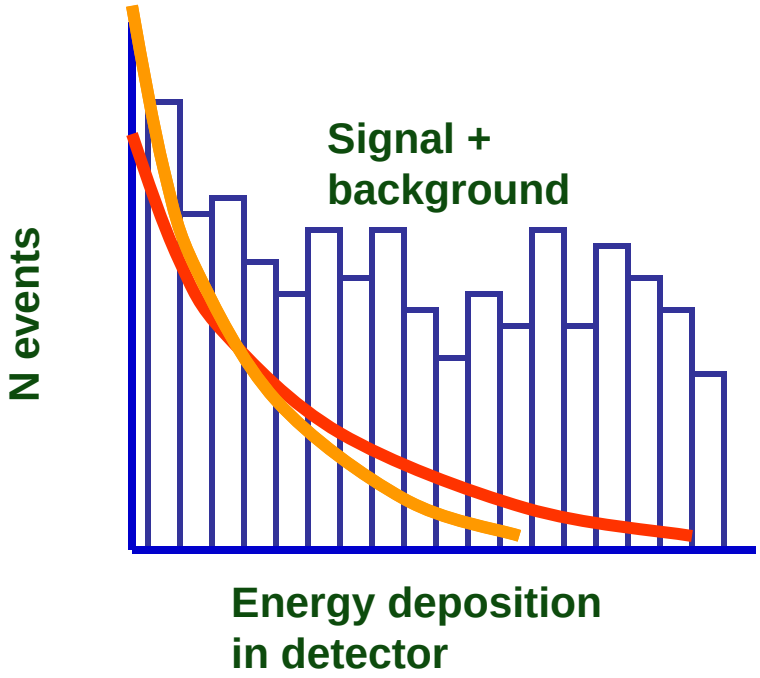
$F_N^2(E)$ – nuclear form factor

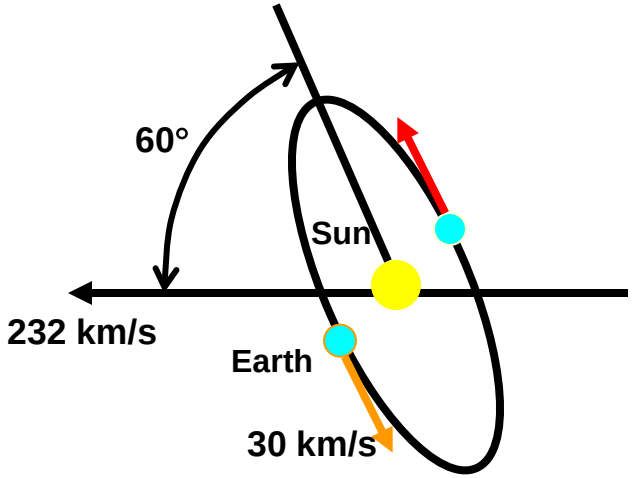
Прямое детектирование



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

Годичная модуляция





Ожидаемая вариация темпа счета WIMP ~ 5%

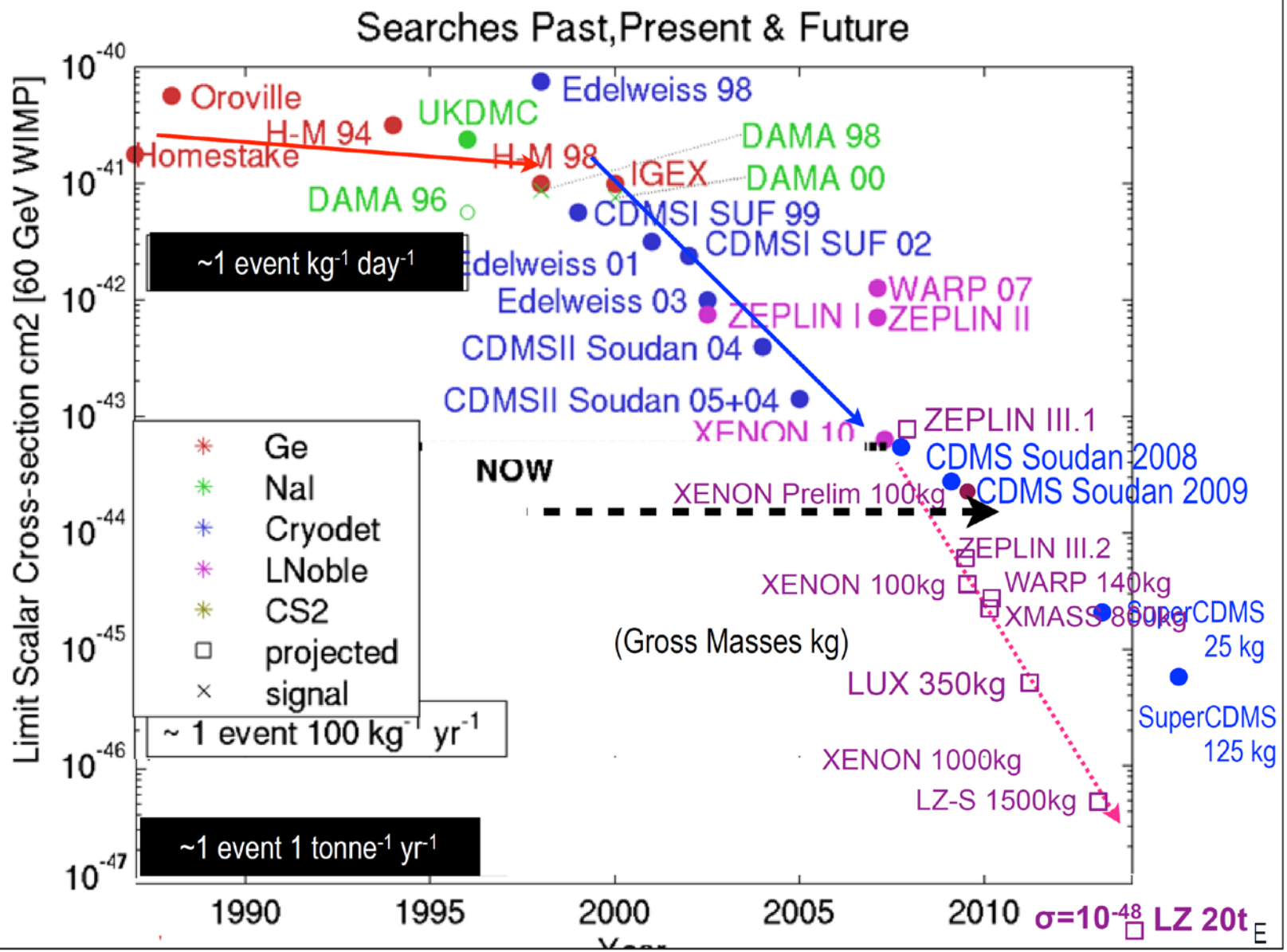
(с максимумом 2 го июня)

Эксперименты

Experiment	Target
ANAIS	NaI
DAMA/NaI	NaI
DAMA/LIBRA	NaI
DAMA/1 ton	NaI
NAIAD	NaI
HDMS	Ge
KIMS	CsI
Caf2-Kamioka	CaF2
CDMS	Ge
CRESST	CaWO4
EDELWEISS	Ge
EURECA	Ge
CoGeNT	Ge
ROSEBUD	Ge, sapphire
COUPP	FSH
PICASSO	FSH
SIMPLE	FSH
NEWAGE	CF4
DM-TPC	CF4
Drift	CS2
MIMAC	3He gas

Experiment	Target
DAMA/LXe	LXe
WARP	LAr
XENON 10	LXe
XENON 100	LXe
Zeplin I	LXe
Zeplin II	LXe
Zeplin III	LXe
ArDM	LAr
LUX	LXe
LZS/LZD	LXe
MAX	LXe/LAr
CLEAN	LNe
DEAP	LAr
XMASS	LXe
MIMAC	3He gas

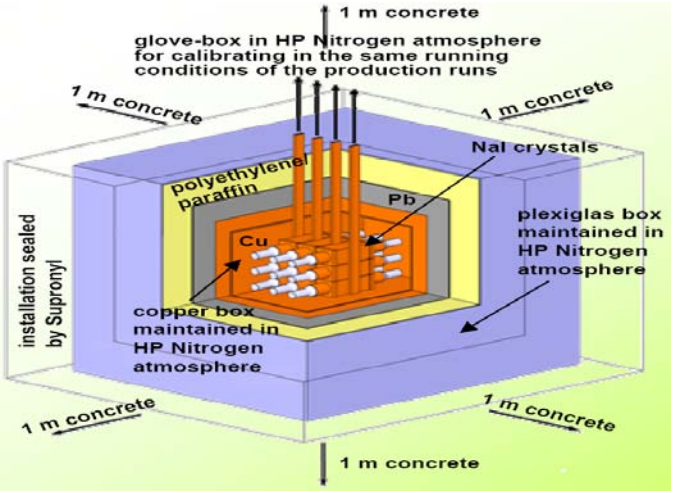
DM Direct Search Progress Over Time (2011/12)



Dark Matt

from R.Gaitskell

DAMA/LIBRA

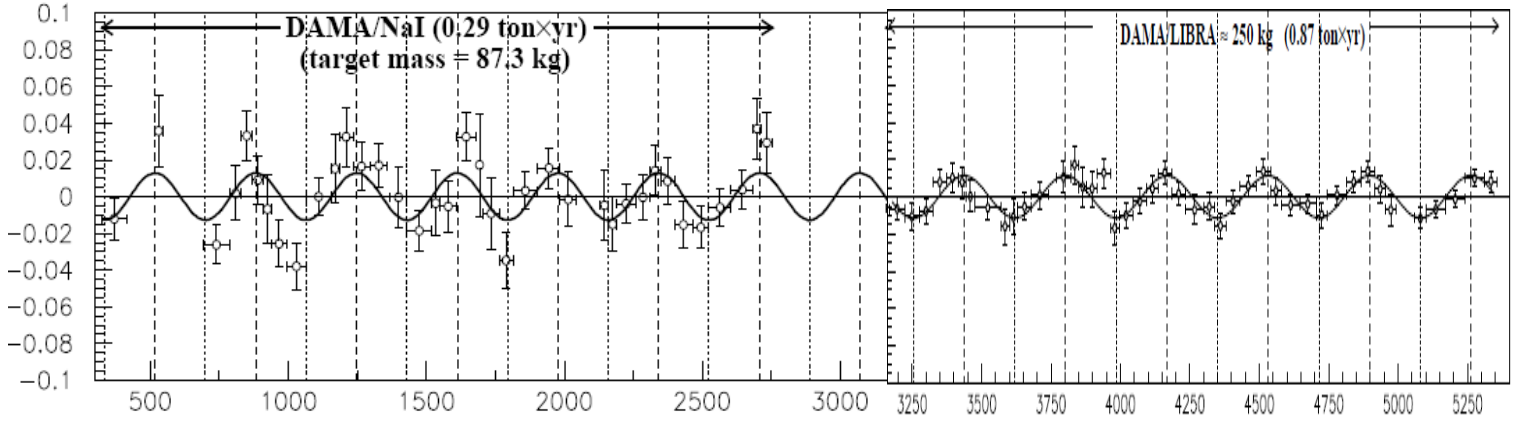


Total exposure ~1.17 t·y

arXiv:1002.1028v1 [astro-ph.GA]

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

event/kg/keV/day

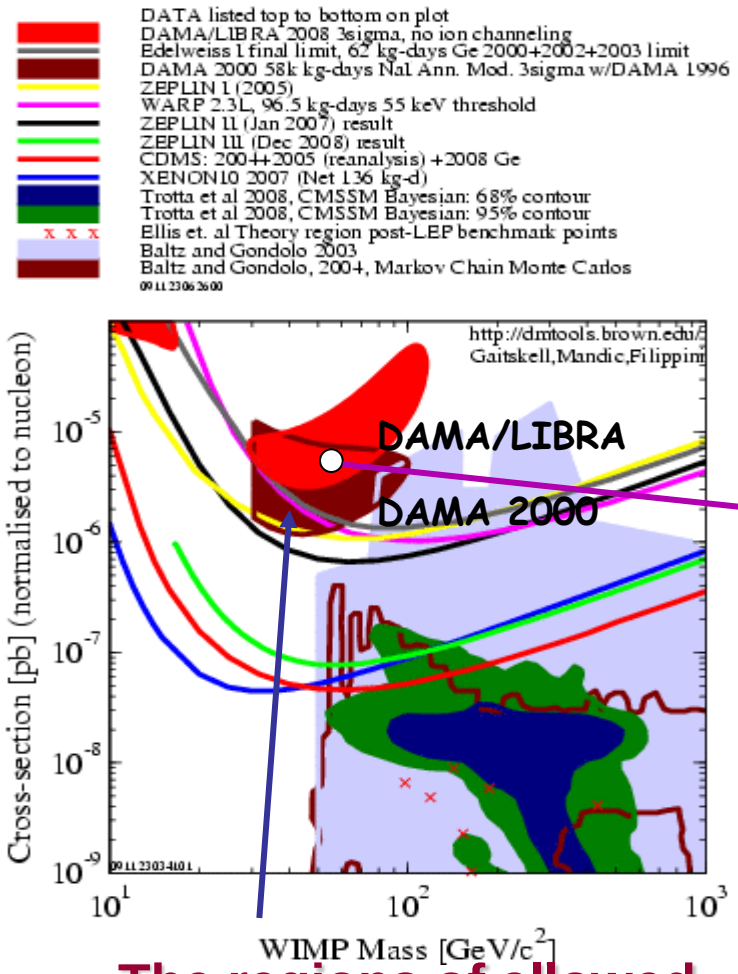


Time, days

$A \cdot \cos \omega(t - t_0)$ 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

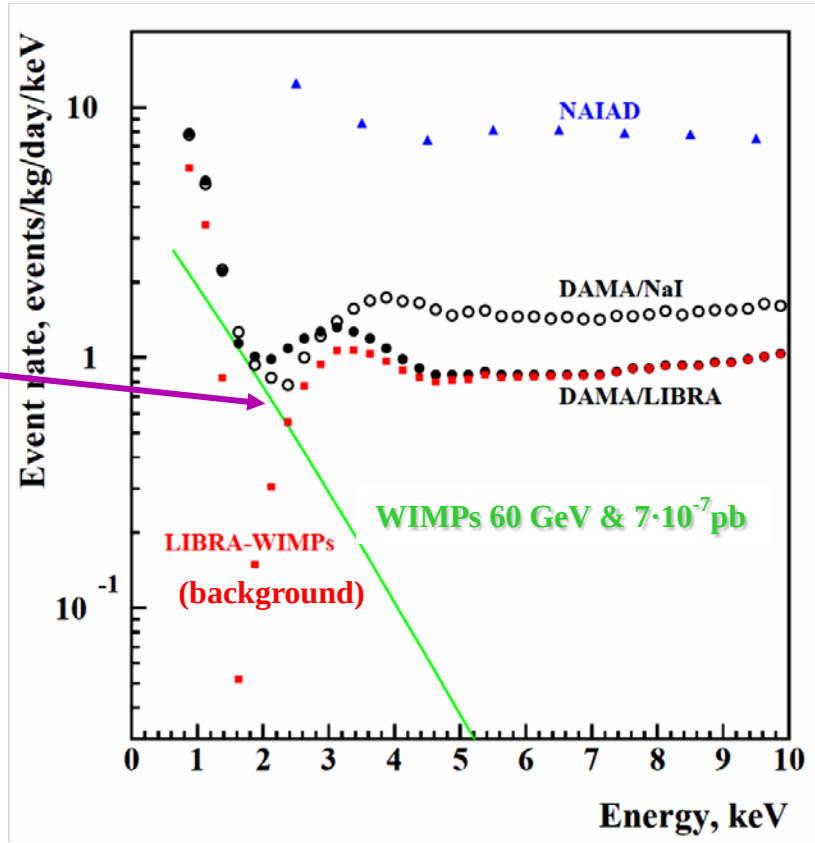
DAMA/LIBRA



The regions of allowed σ_p, M_w

But there is a significant discrepancy!

arXiv:0912.2983v1 [hep-ex]



DM-Ice

250 – 500 kg NaI(Tl)

DM-Ice-17: First Step

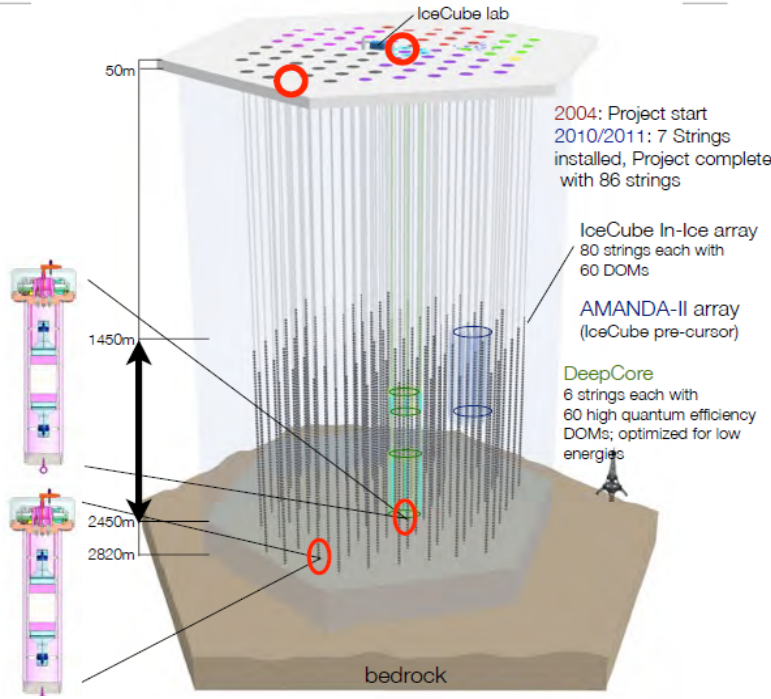
Detectors:

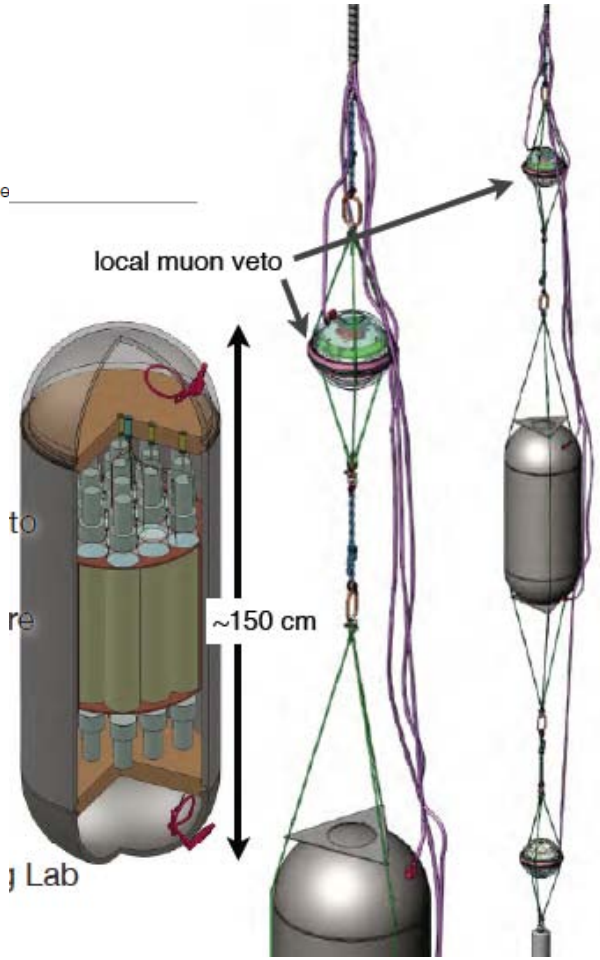
- Two 8.5 kg NaI detectors from NAIAD (17 kg total)

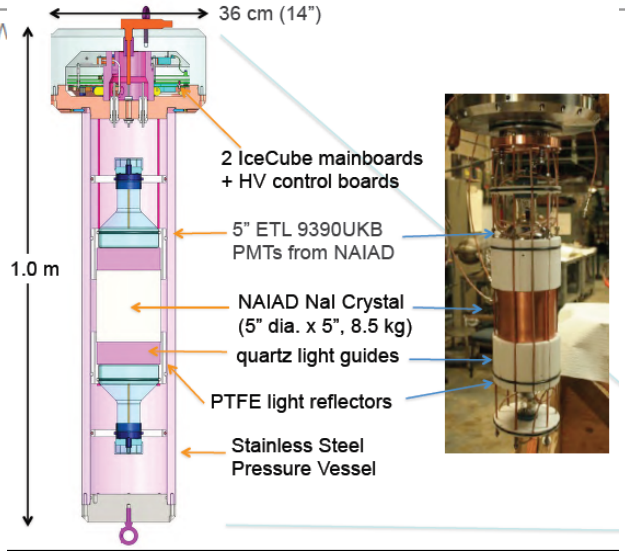
Goals:

- Assess the feasibility of deploying NaI(Tl) crystals in the Antarctic Ice for a dark matter detector
- Establish the radiopurity of the antarctic ice / hole ice
- Explore the capability of IceCube to veto muons

Installed Dec. 2010

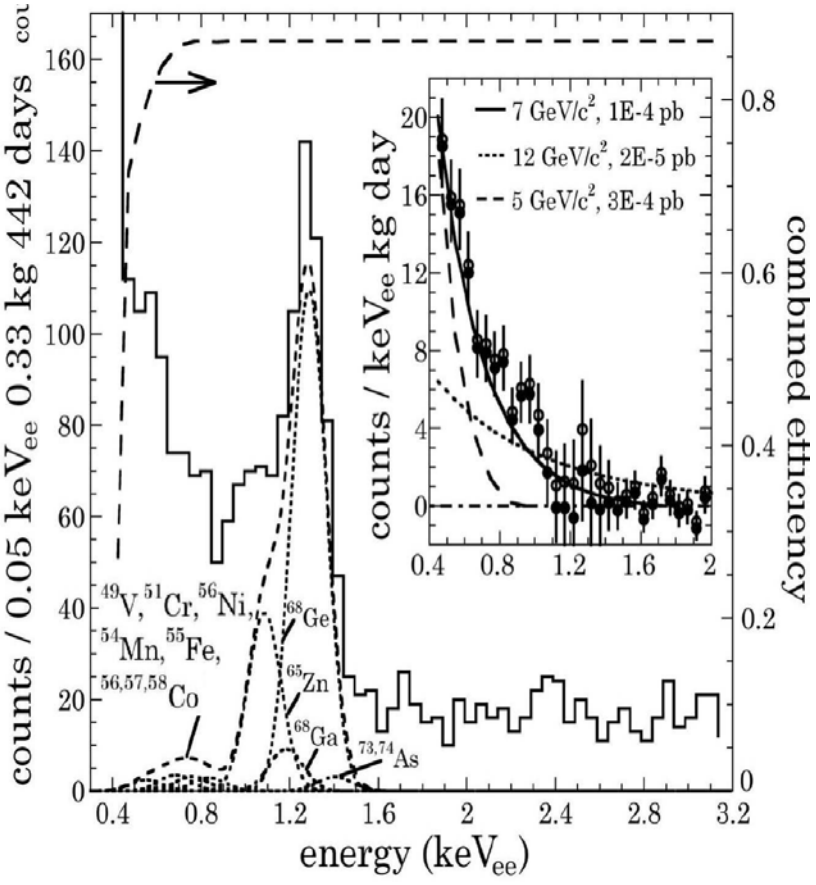


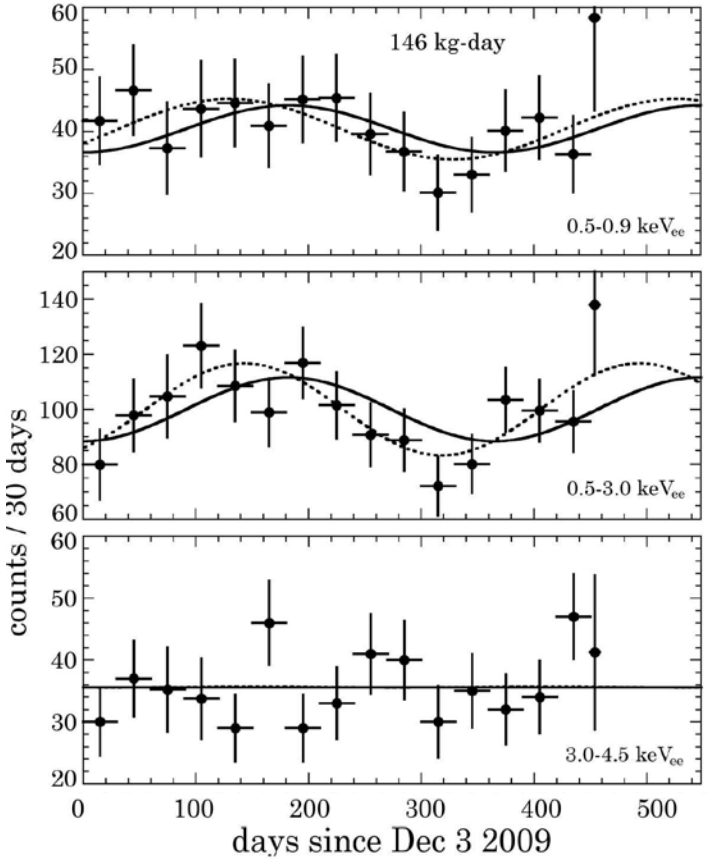




CoGeNT

In Soudan mine 2,100 m.w.e.,
Dark Matter run:

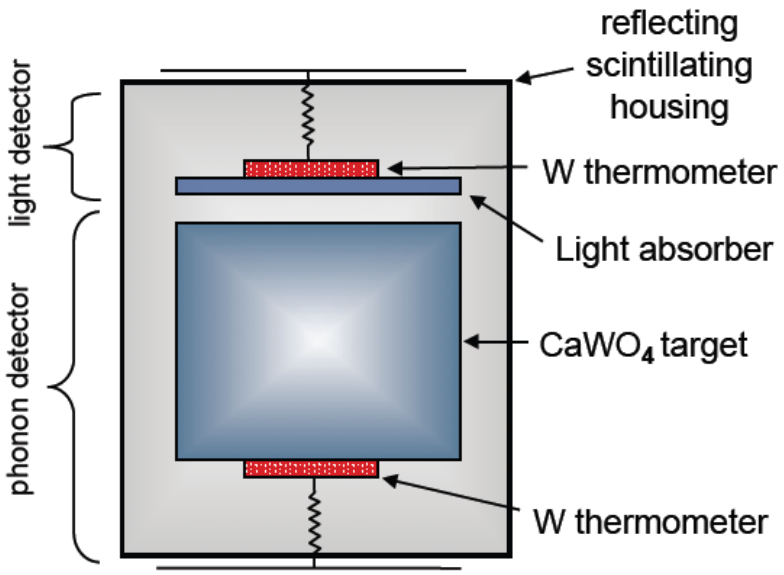


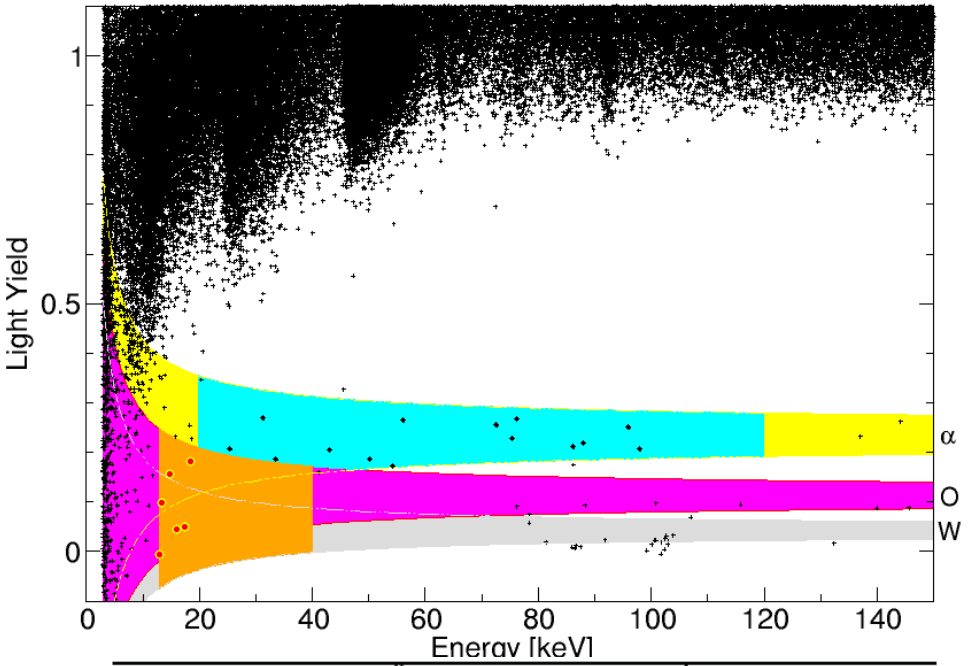


"Search for an Annual Modulation in a P-type Point Contact Germanium Dark Matter Detector"

arXiv:1106.0650 [astro-ph.CO]

CRESST



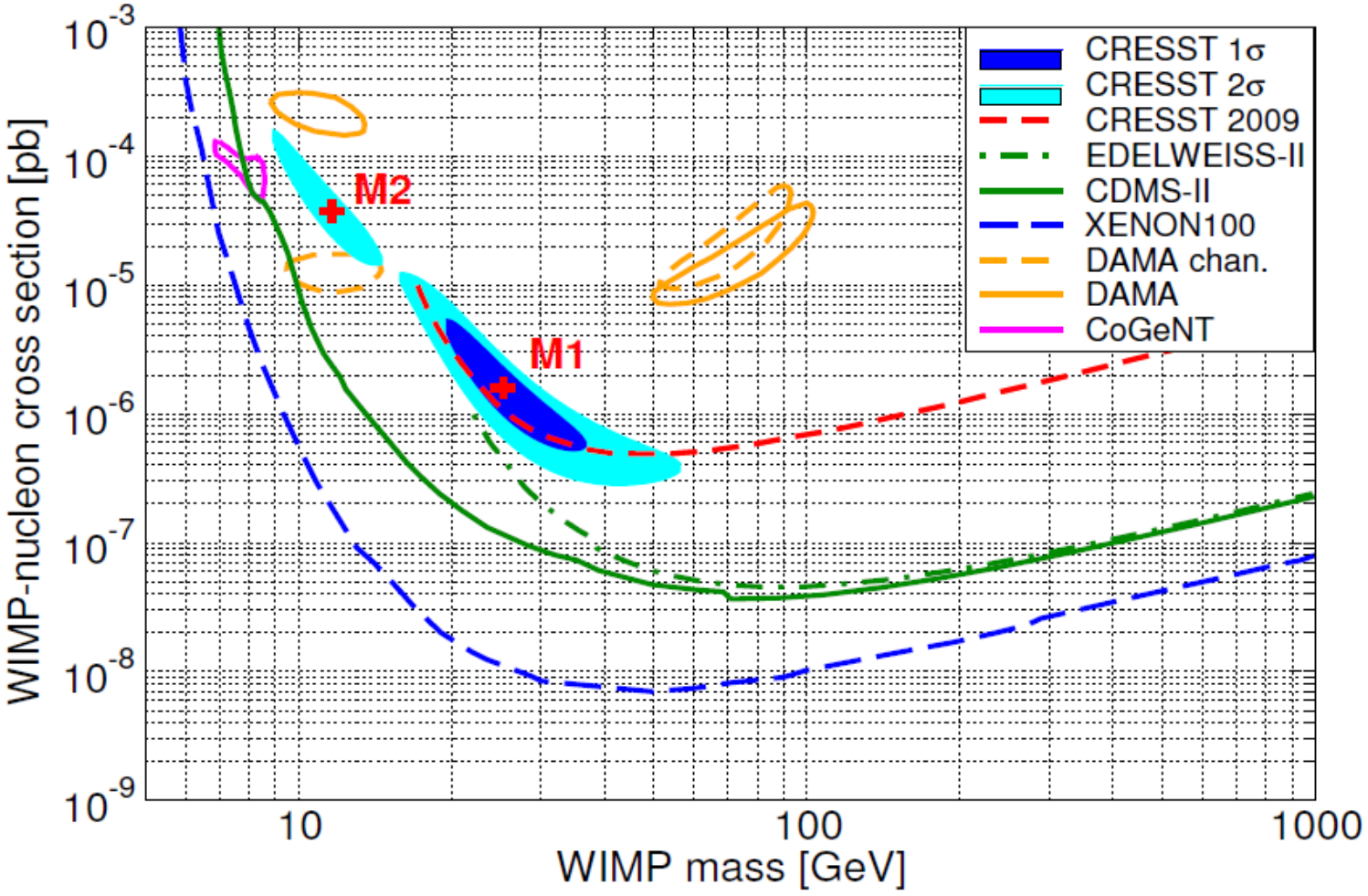


	M1	M2
e/γ events	8.00 ± 0.05	8.00 ± 0.05
α events	$11.5^{+2.6}_{-2.3}$	$11.2^{+2.5}_{-2.3}$
neutron events	$7.5^{+6.3}_{-5.5}$	$9.7^{+6.1}_{-5.1}$
Pb recoils	$15.0^{+5.2}_{-5.1}$	$18.7^{+4.9}_{-4.7}$
signal events	$29.4^{+8.6}_{-7.7}$	$24.2^{+8.1}_{-7.2}$
m_χ [GeV]	25.3	11.6
σ_{WN} [pb]	$1.6 \cdot 10^{-6}$	$3.7 \cdot 10^{-5}$

18 modules

analysis from 8 modules

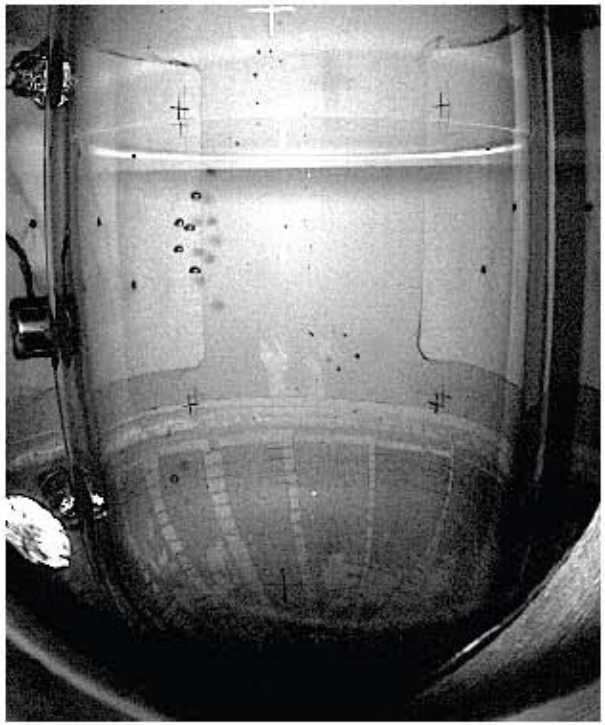
CRESST


CRESST 1σ
CRESST 2σ
CRESST 2009
EDELWEISS-II
CDMS-II
XENON100
DAMA chan.
DAMA
CoGeNT
M1
M2
WIMP-nucleon cross section [pb]
WIMP mass [GeV]
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
10
100
1000

The COUPP program

- COUPP-4: A 2-liter chamber - shallow site in 2009, at SNOLAB since September, 2010
- COUPP-60: A 30-liter chamber commissioning at Fermilab, goal is to move to SNOLAB within a year

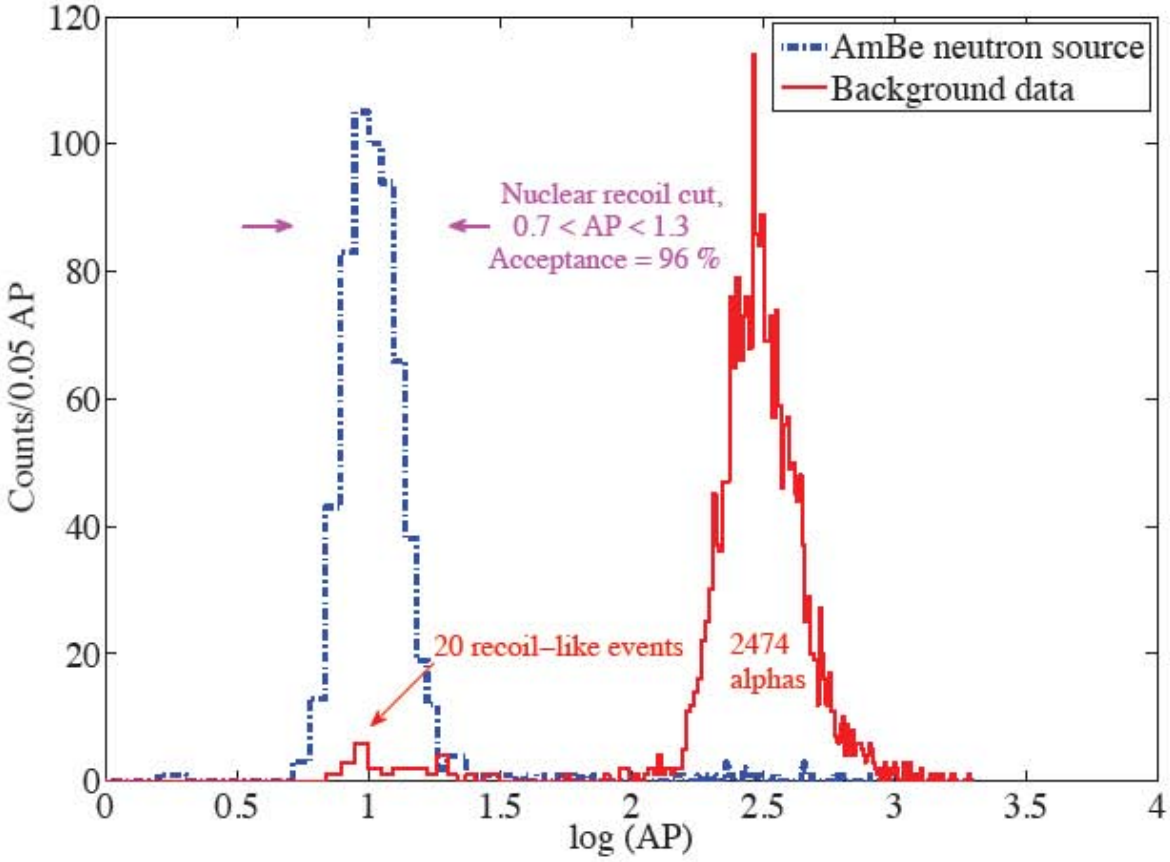
COUPP-4



COUPP-60

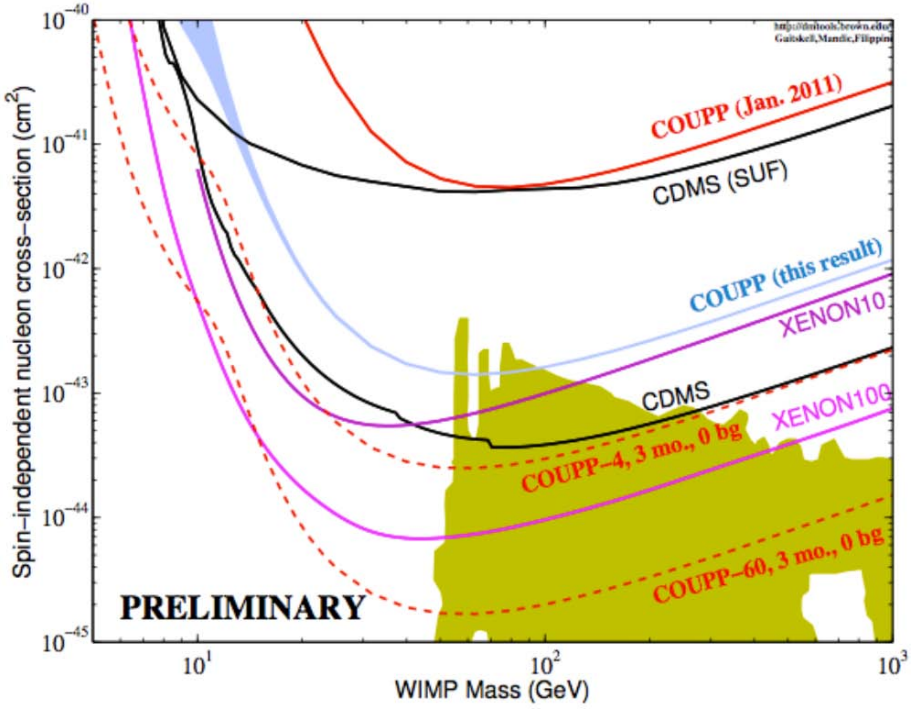
COUPP2L SNOLAB Results

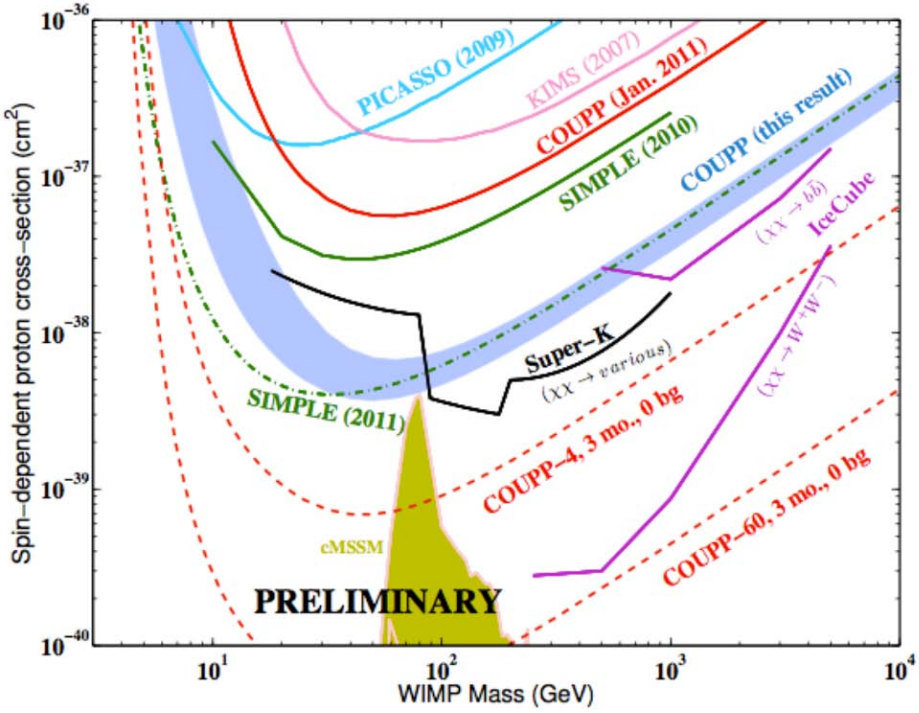
- >99.3% alpha rejection (15 keV threshold)
- 20 WIMP candidates
  - (0.11,0.09,0.03) ev/kg/day above (8, 11, 16) keV
  - Expect ~0.01 ev/kg/day from identified neutron sources



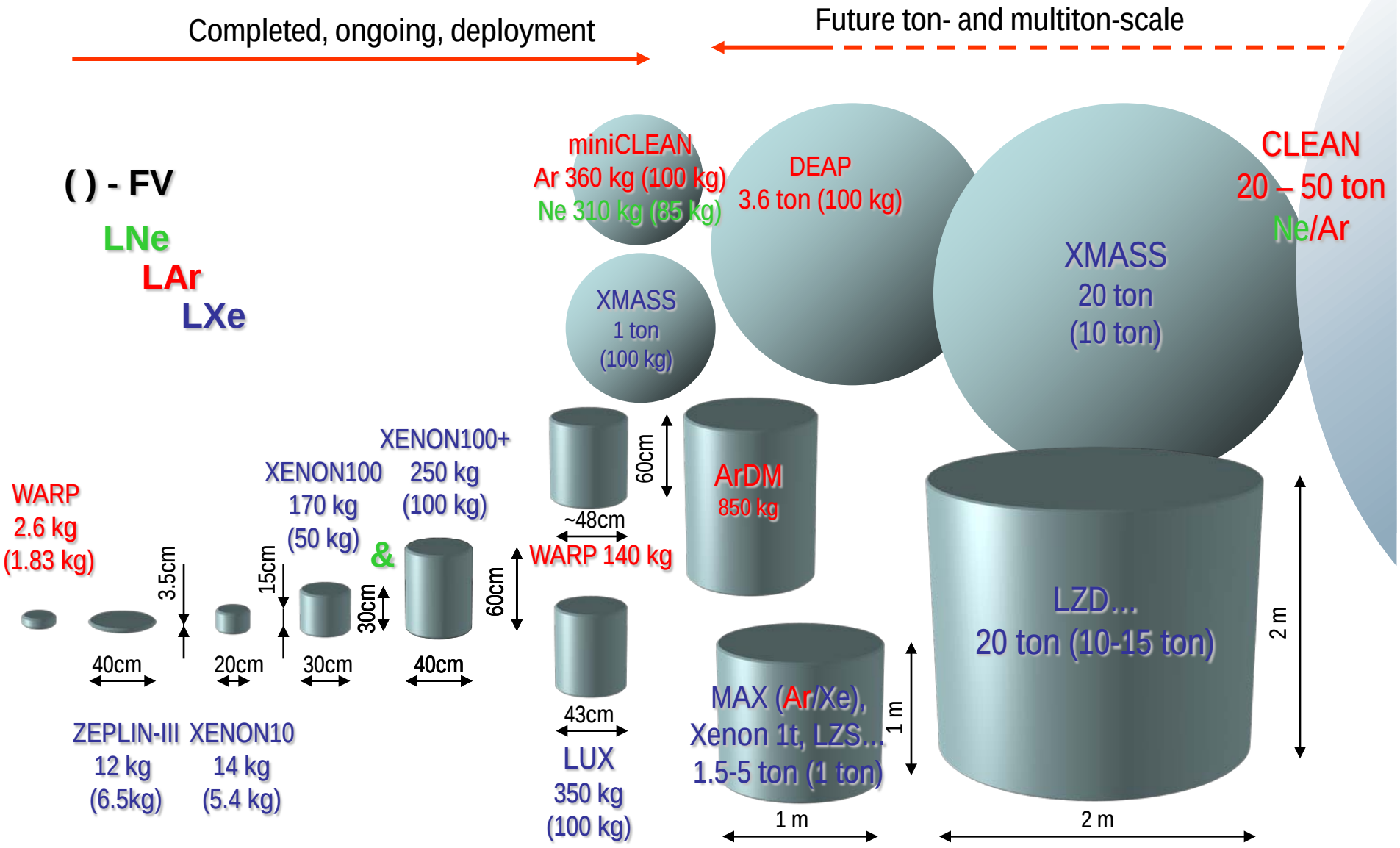
$$AP = A(T)\sum_{j} G_j \sum_{n} C_n(x) \sum_{f} f \times psd_f^j$$

- **AP** is a measure of acoustic energy
- **A(T)** temperature correction
- G_j gain correction for j^{th} acoustic sensor
- $C_n(x)$ position correction for n^{th} frequency range
- **psd** power spectral density with bin center frequency **f**


COUPP (Jan. 2011)
CDMS (SUF)
COUPP (this result)
XENON10
CDMS
XENON100
COUPP–4, 3 mo., 0 bg
COUPP–60, 3 mo., 0 bg
PRELIMINARY
Spin–independent nucleon cross–section (cm^2)
WIMP Mass (GeV)


PICASSO (2009)
KIMS (2007)
COUPP (Jan. 2011)
SIMPLE (2010)
COUPP (this result)
$(\chi\chi \to b\bar{b})$
IceCube
Super–K
$(\chi\chi \to various)$
$(\chi\chi \to W^+W^-)$
SIMPLE (2011)
COUPP–4, 3 mo., 0 bg
COUPP–60, 3 mo., 0 bg
cMSSM
PRELIMINARY
Spin–dependent proton cross–section (cm^2)
WIMP Mass (GeV)

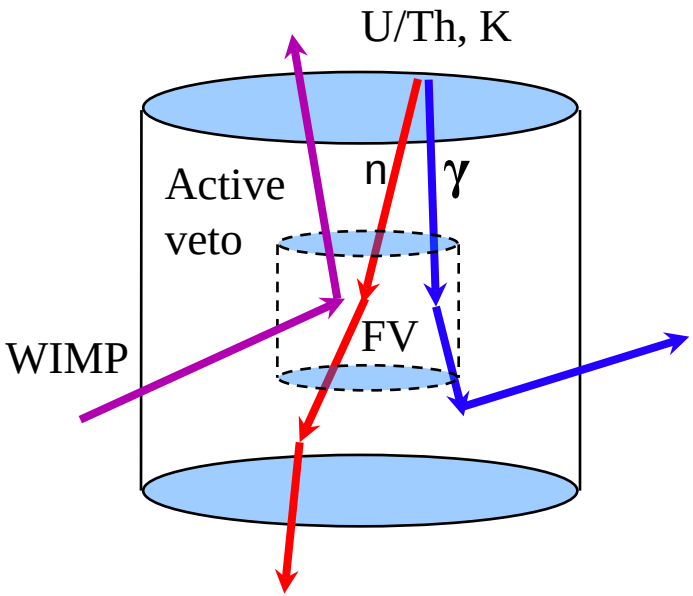
Детекторы на жидких благородных газах



Детекторы на жидких благородных газах

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!!!



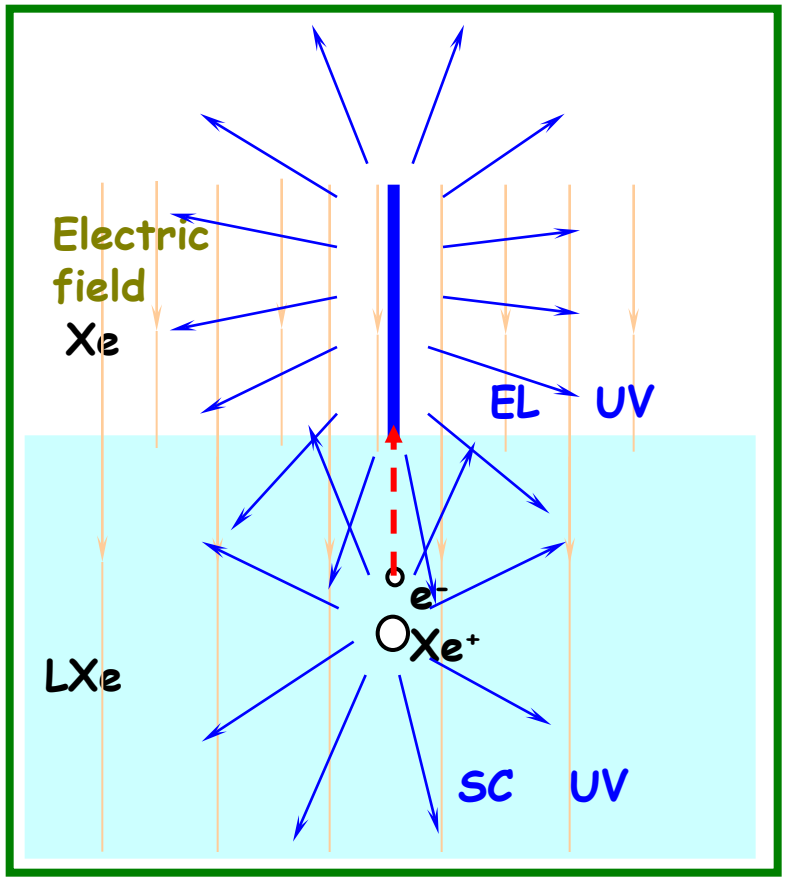
For total mass of >3t, reduction of bckg > 10^3

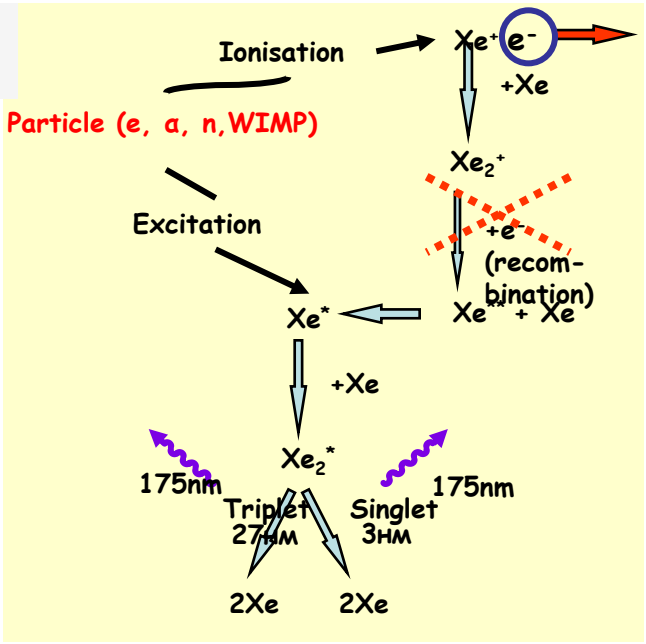
Детекторы на жидких благородных газах

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

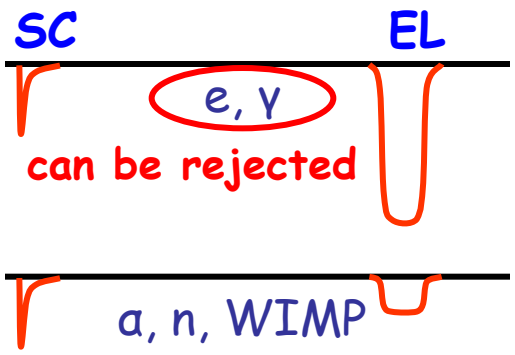


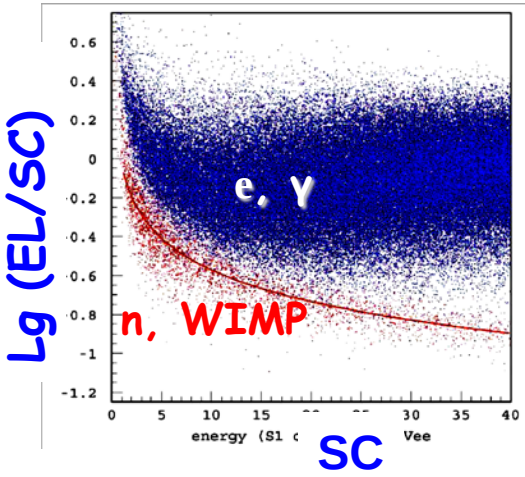


Electrons are partly extracted from the track: recombination is suppressed

Suppression depends on dE/dX

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



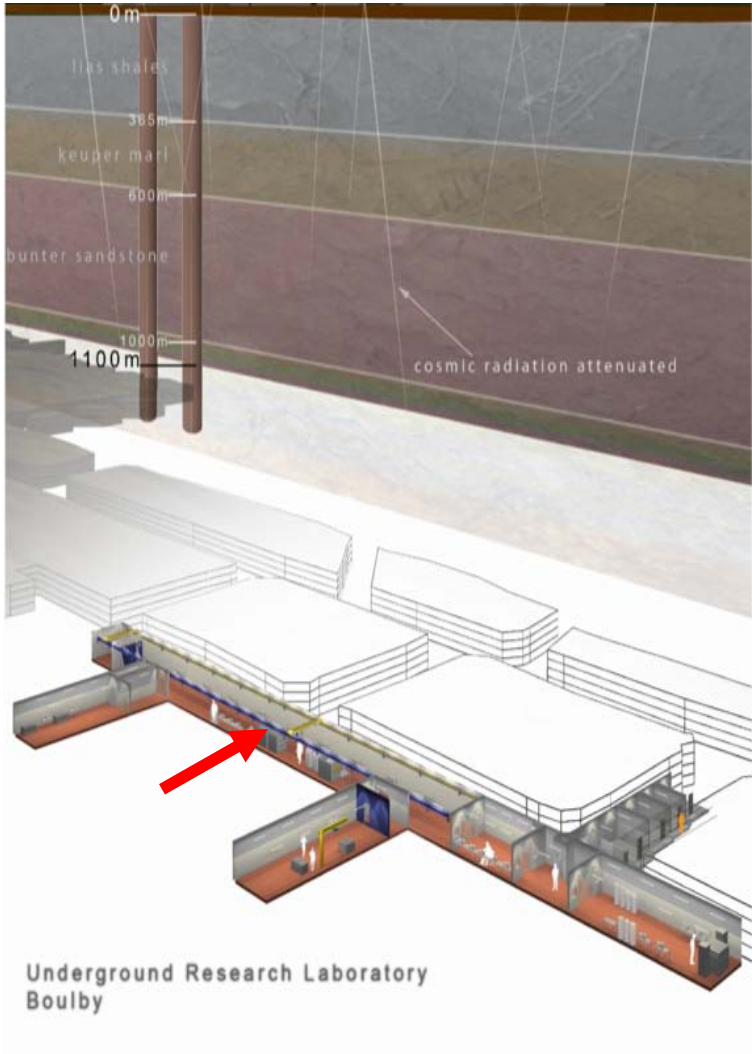


ZEPLIN

ZEPLIN III (two-phase)

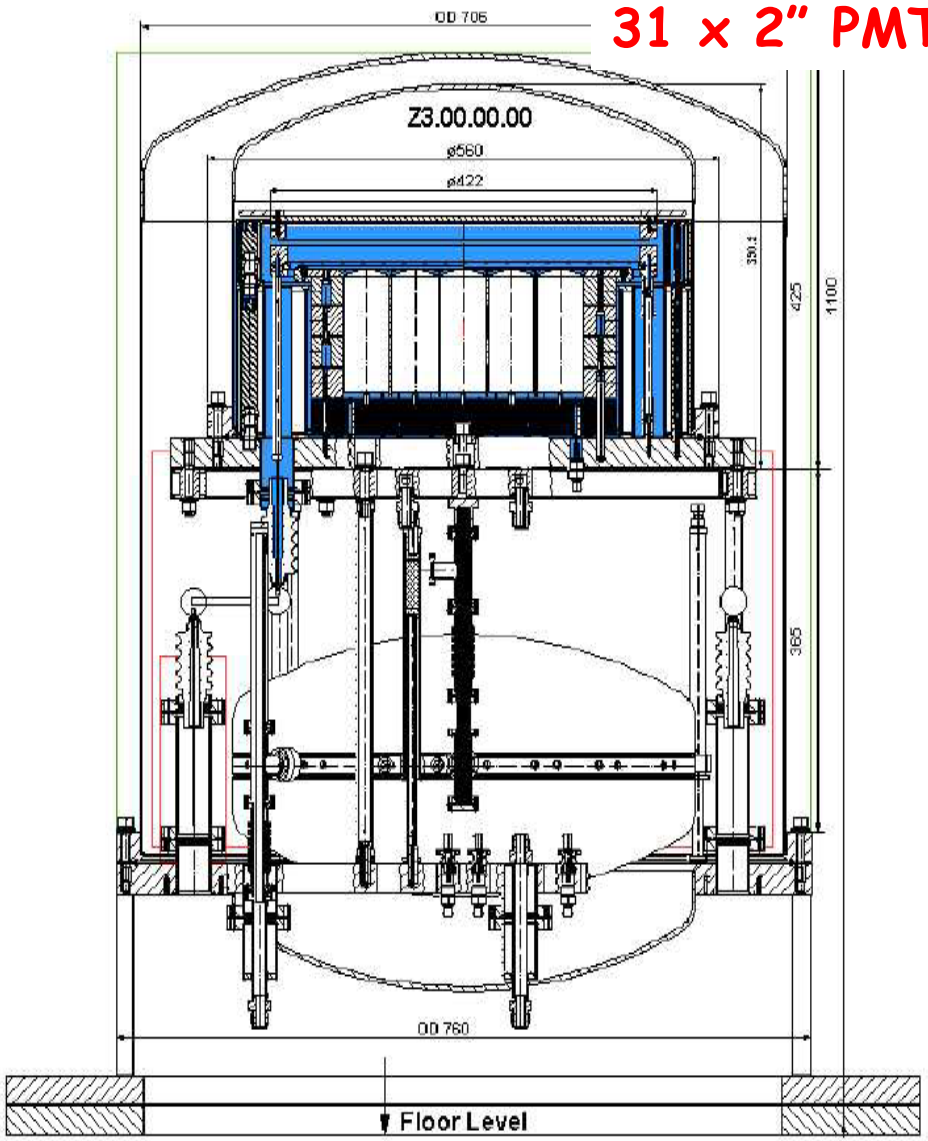
- CCLRC Rutherford Appleton Laboratory
- Imperial College London
- University of Edinburgh
- LIP- Coimbra (Coimbra Univ.)
- ITEP

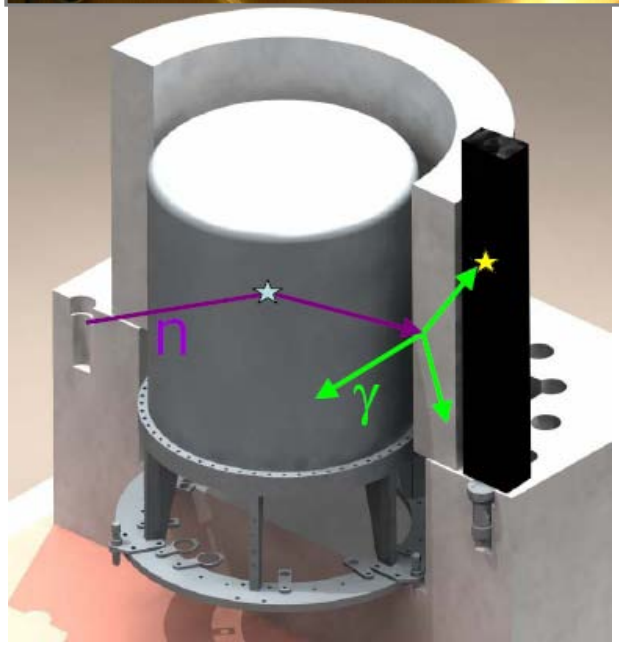
Boulby, U.K. site ('Palmer lab')
1100m, 2.8km water equiv.
10^6 reduction in muon flux



ZEPLIN III

31 x 2" PMTs





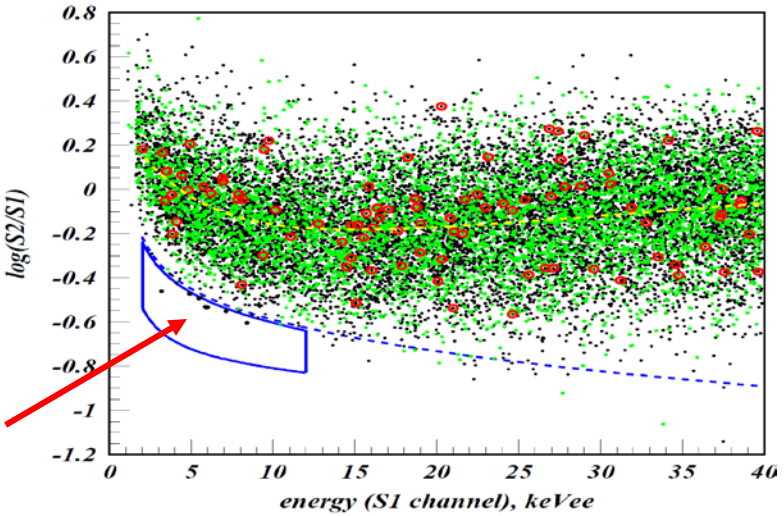
Дизайн разработан в ИТЭФ

ZEPLIN III

Phase 1 (FSR)

Completed in 2008
453.6 kg days
→8.1 x10^{-8} pb
astro-ph:0812.1150

8 events in WIMP search region



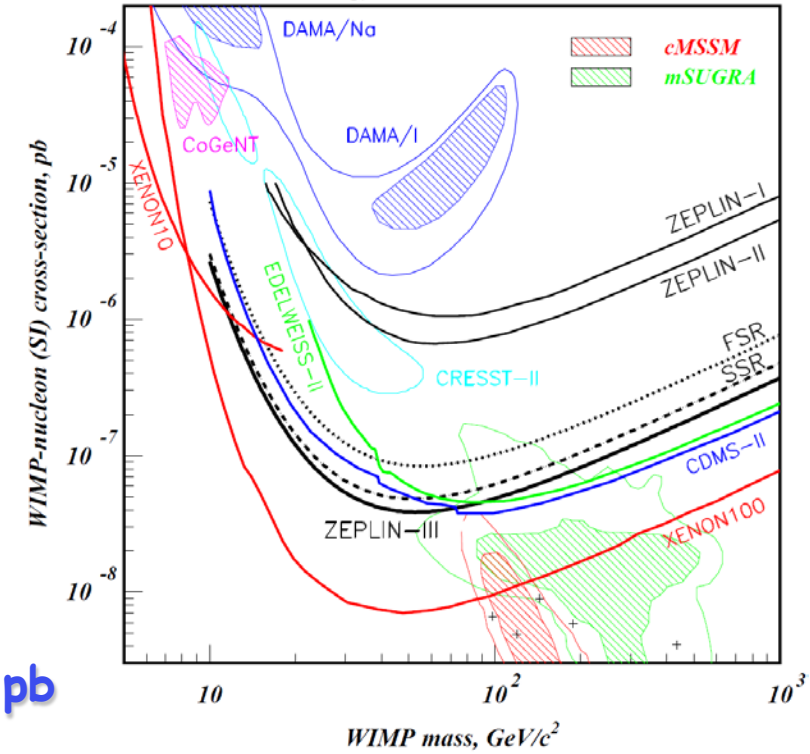
Phase 2 (SSR)

Upgrade:
• 30 times less radioactive PMTs
•Active neutron Veto

Data collected during 319 days

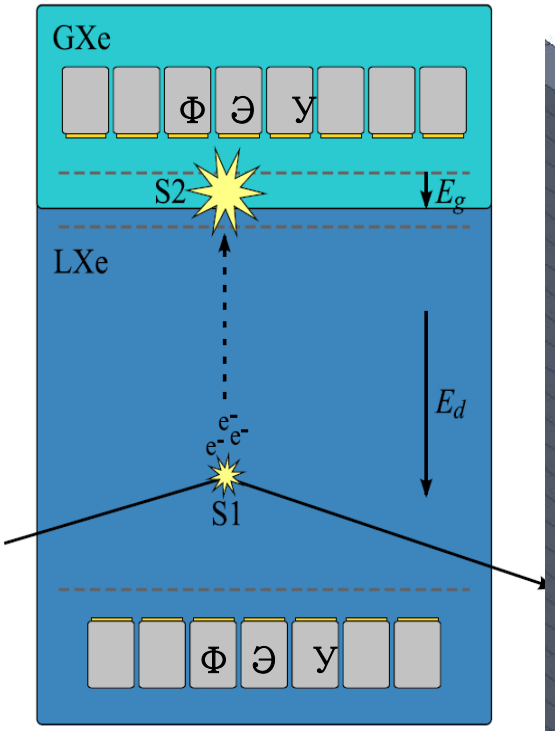
1344 kg·days in FV

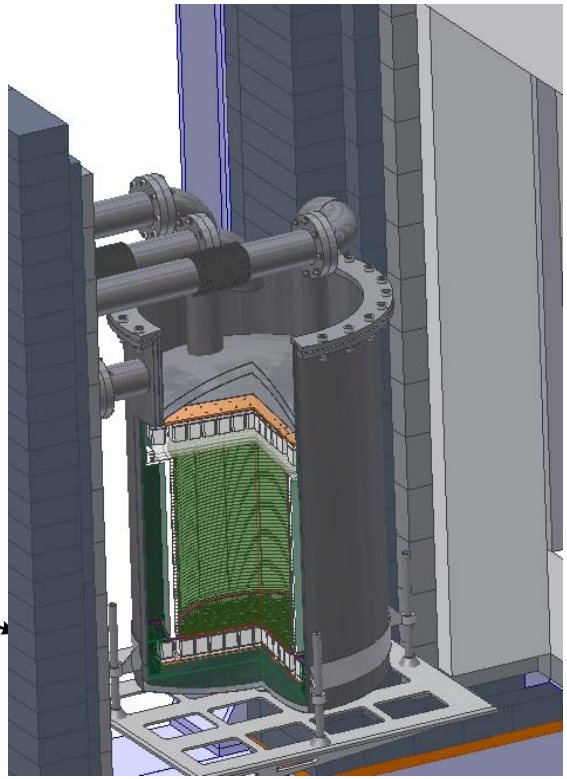
$\sigma_{p\ SI}$ =3.9 x10^{-8} pb

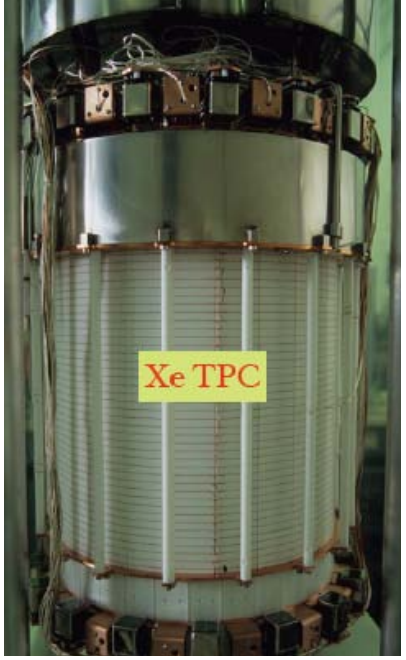


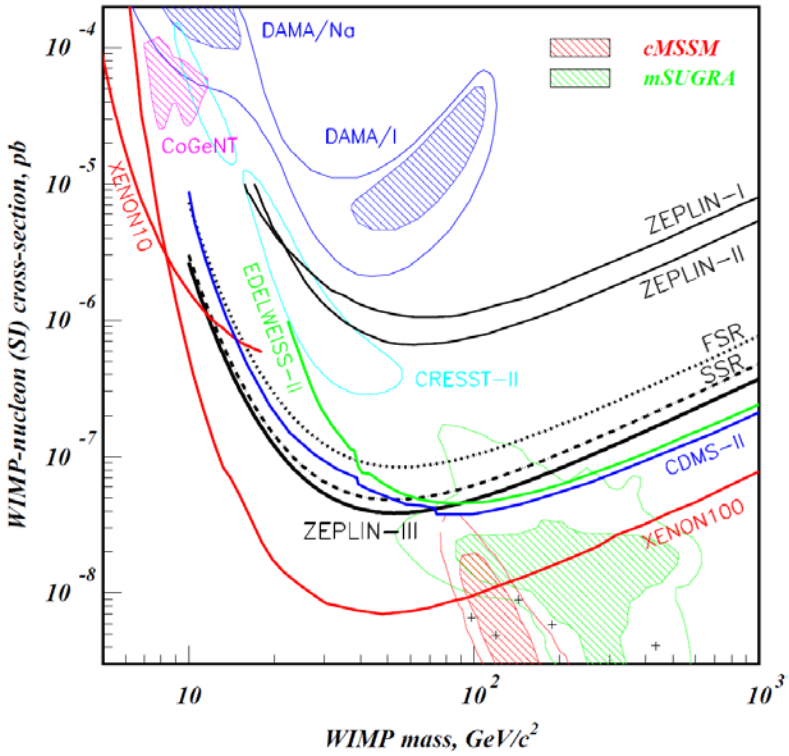
Xenon100

150 kg total (70 kg in target)









Dark Matter Results from 100 Live Days of XENON100 Data.

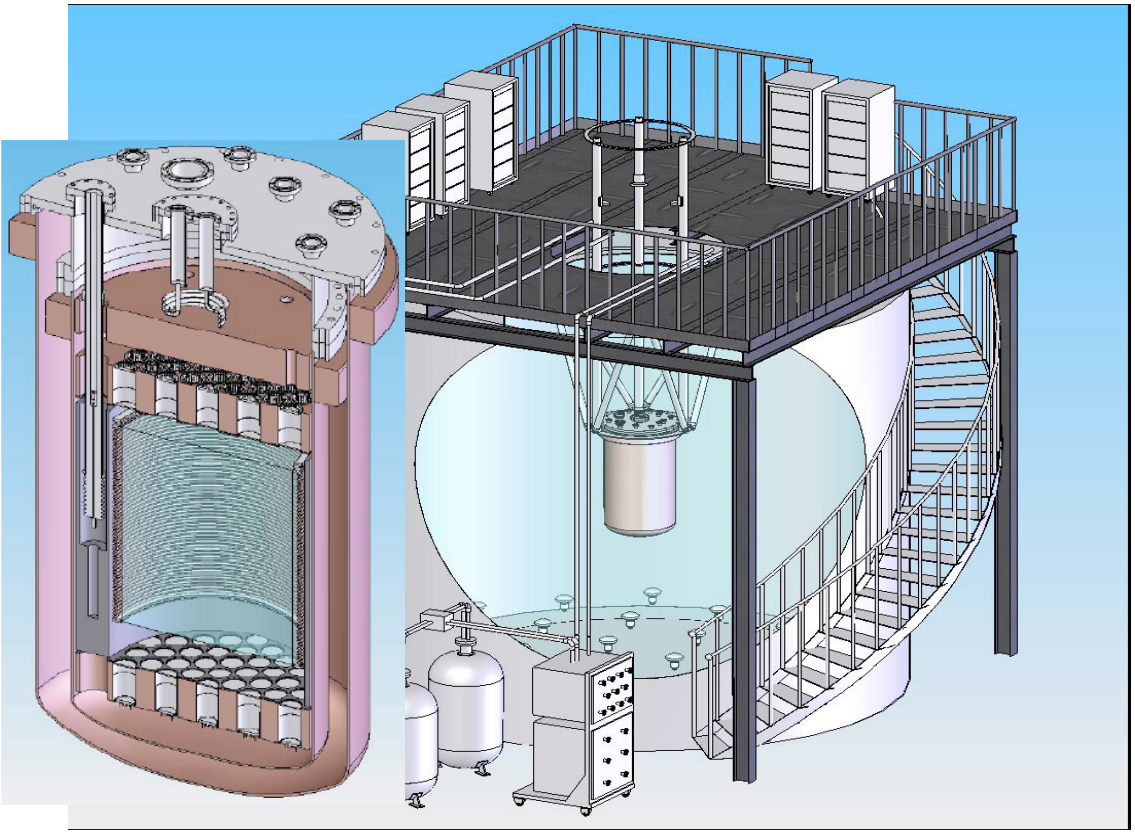
Phys.Rev.Lett.107:131302,2011.

e-Print: **arXiv:1104.2549** [astro-ph.CO]

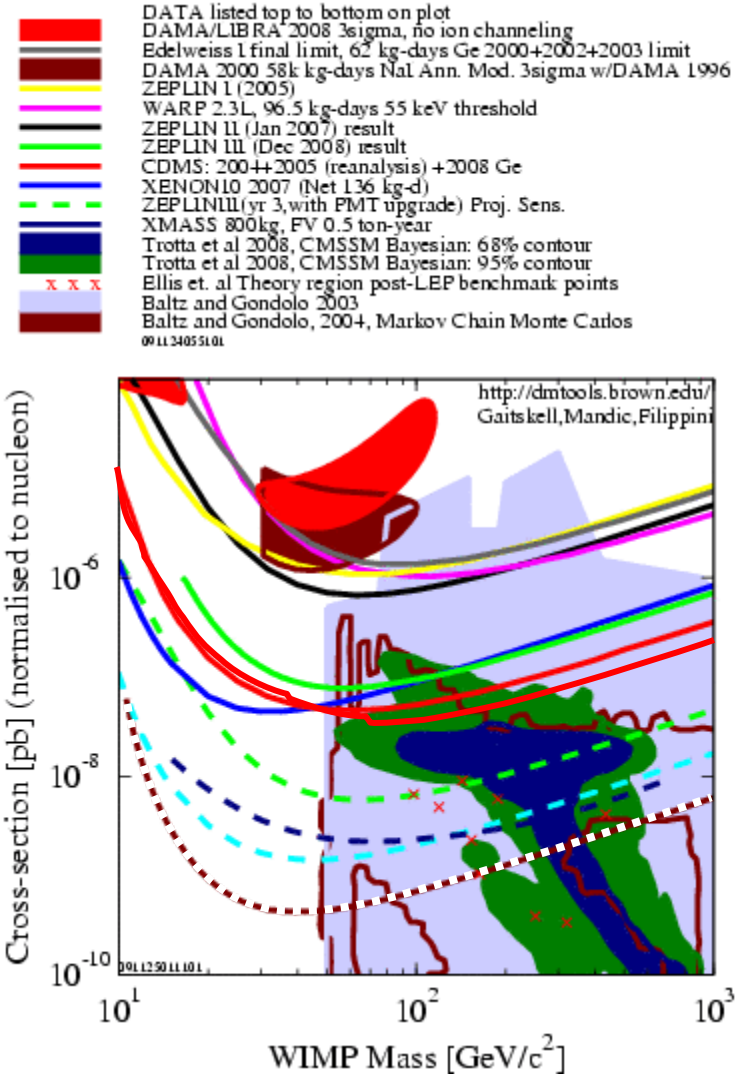
LUX

Large **U**nderground **X**enon detector

SUSEL – at Homestake; South Dakota

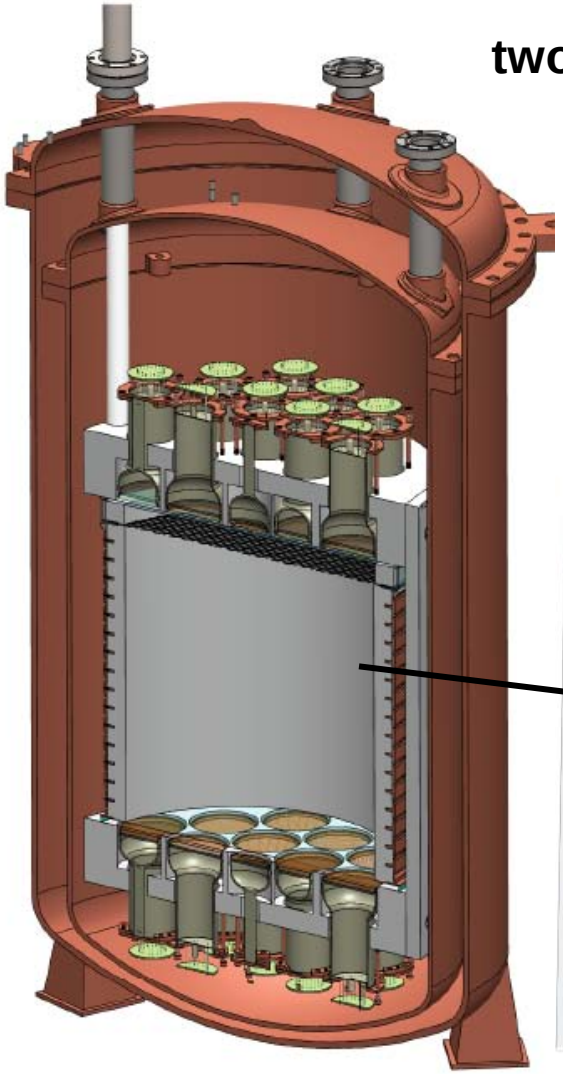


350 kg total (150 kg in target)
Large water shield Cherenkov readout - muon veto. 10-month exposition



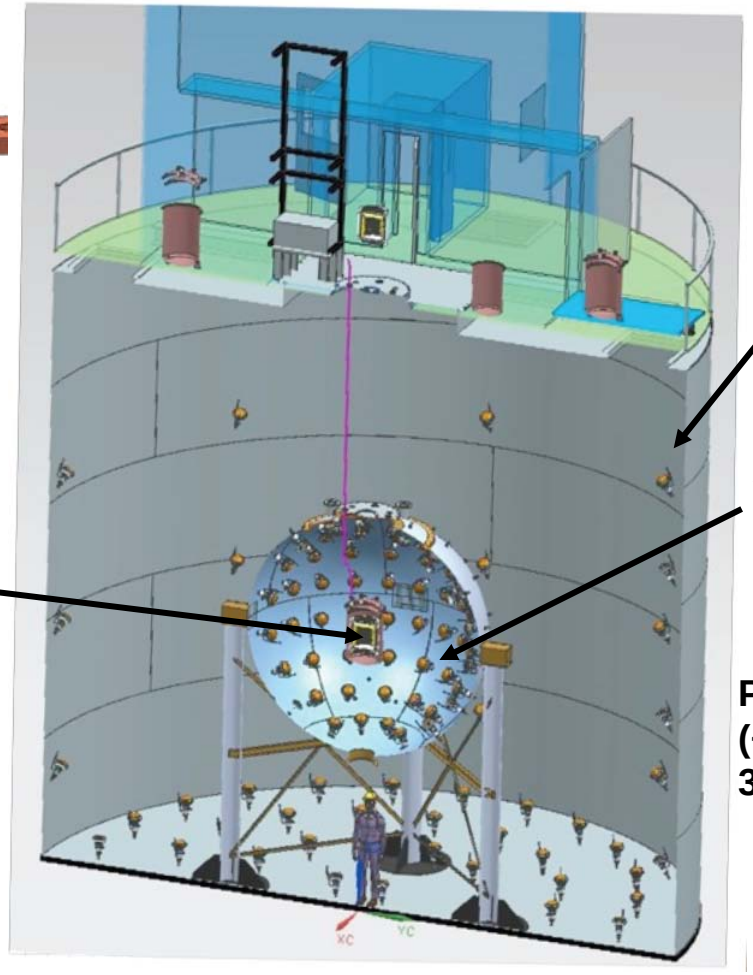
Darkside-50 @ LNGS

Depleted Argon Cryostat for Scintillation and Ionization Detection



two-phase Argon TPC

Will use Ar depleted with ^{39}Ar (1%)



Existing Borexino CTF Water Tank

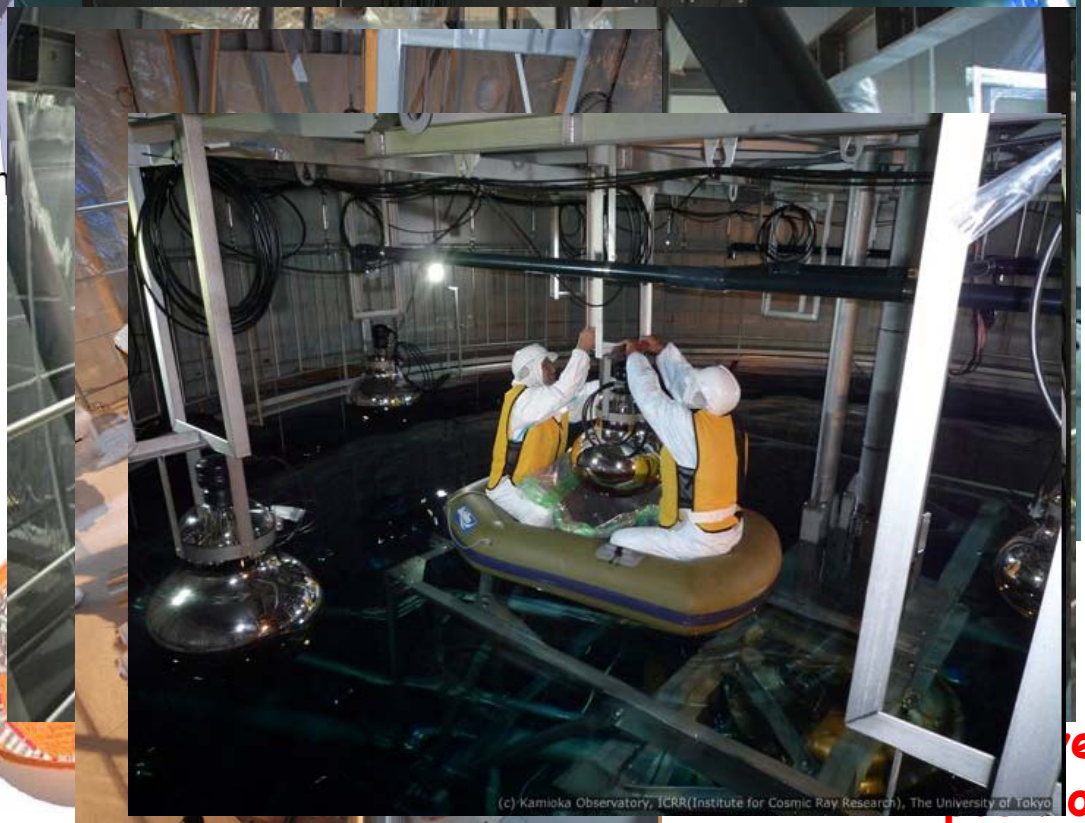
Liquid scintillator (PC) loaded with tri-methyl borate (TMB) with natural 20% ^{10}B

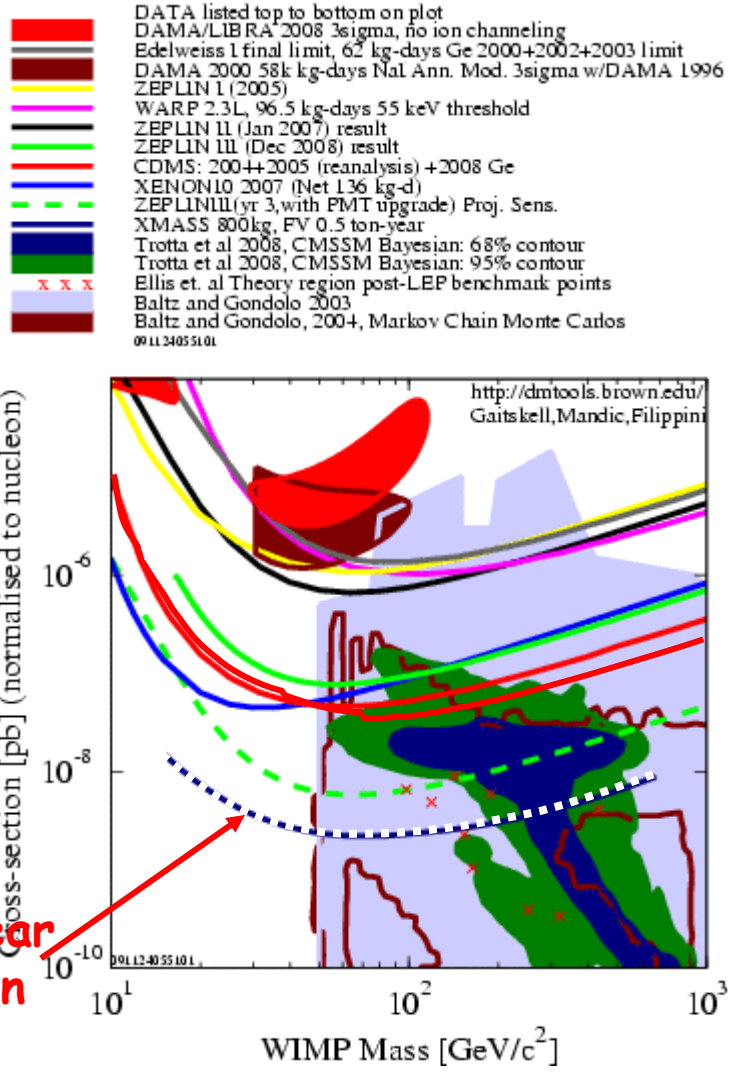
Projected sensitivity (~20 keV$_{rec}$ threshold) ~1·10^{-45} cm^2 3 yr background-free exposure

Experiments: XMASS

Assembling of XMASS can be tracked:

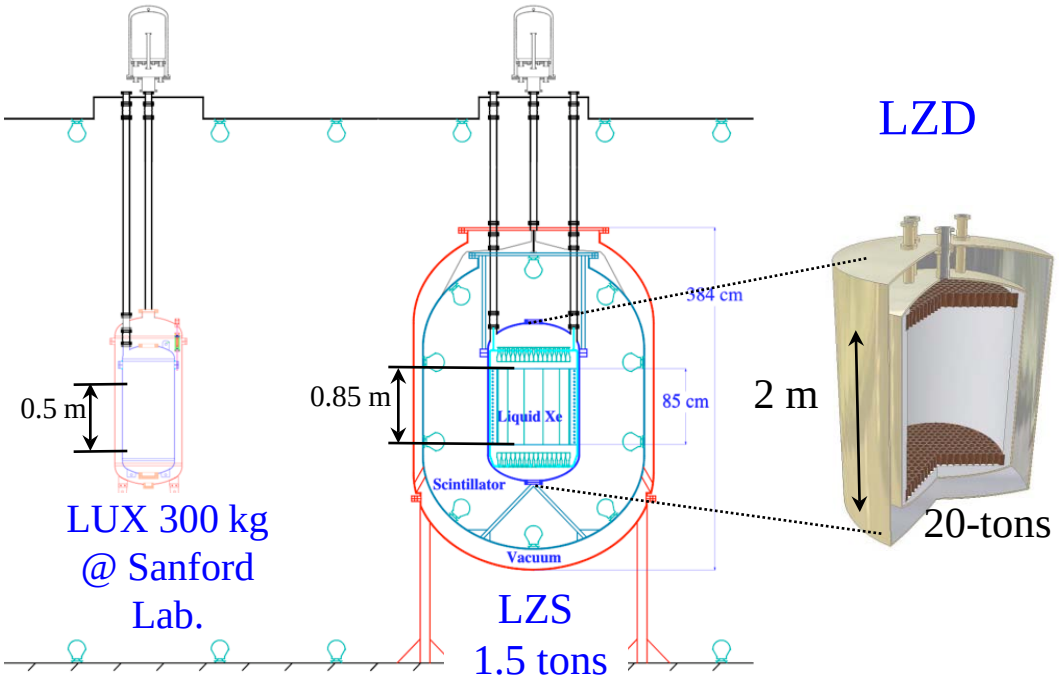
http://www-sk.icrr.u-tokyo.ac.jp/xmass/status-e.html

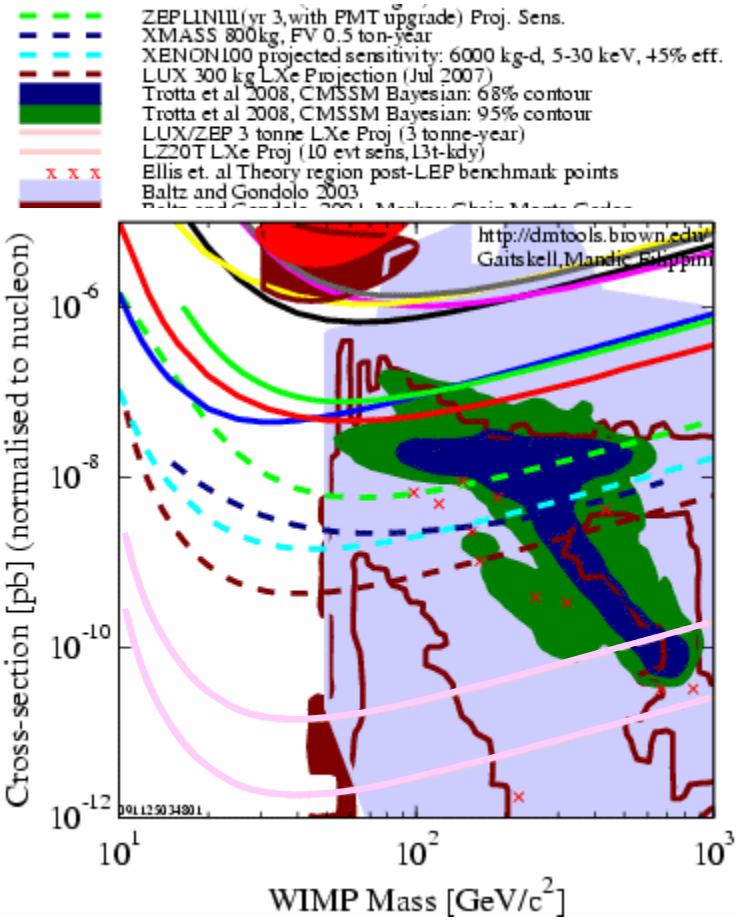




LZ

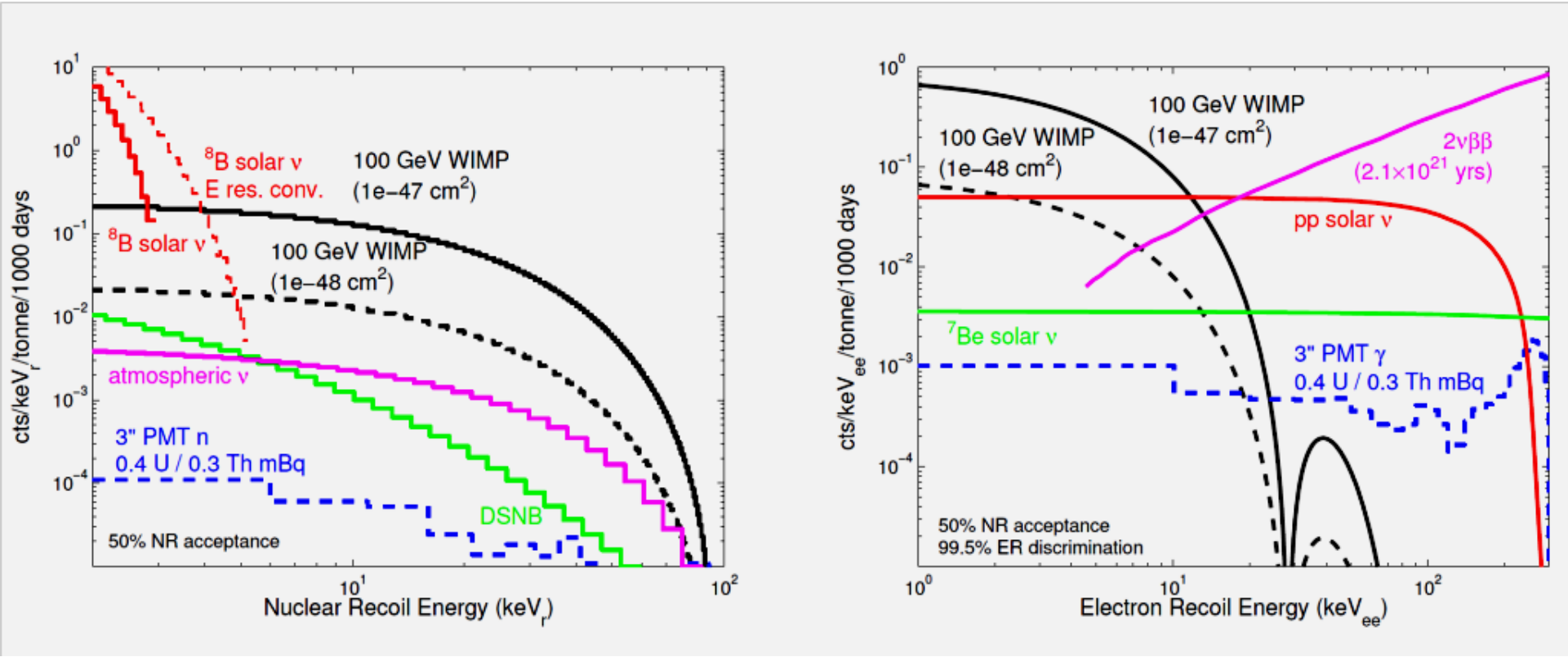
LZS@SUSEL – Sanford Underground Science and Engineering Lab. 4850 feet
LZD@DUSEL – Deep Underground Science and Engineering Lab. 8000 feet





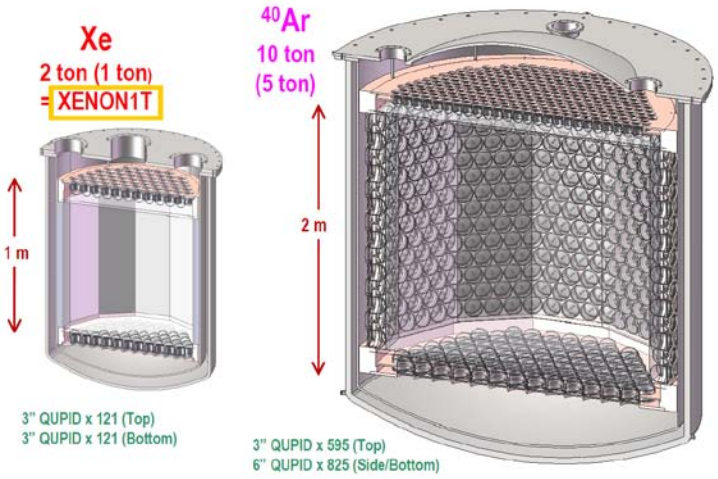
LZ

After multi-hit cut and S2/S1 cut

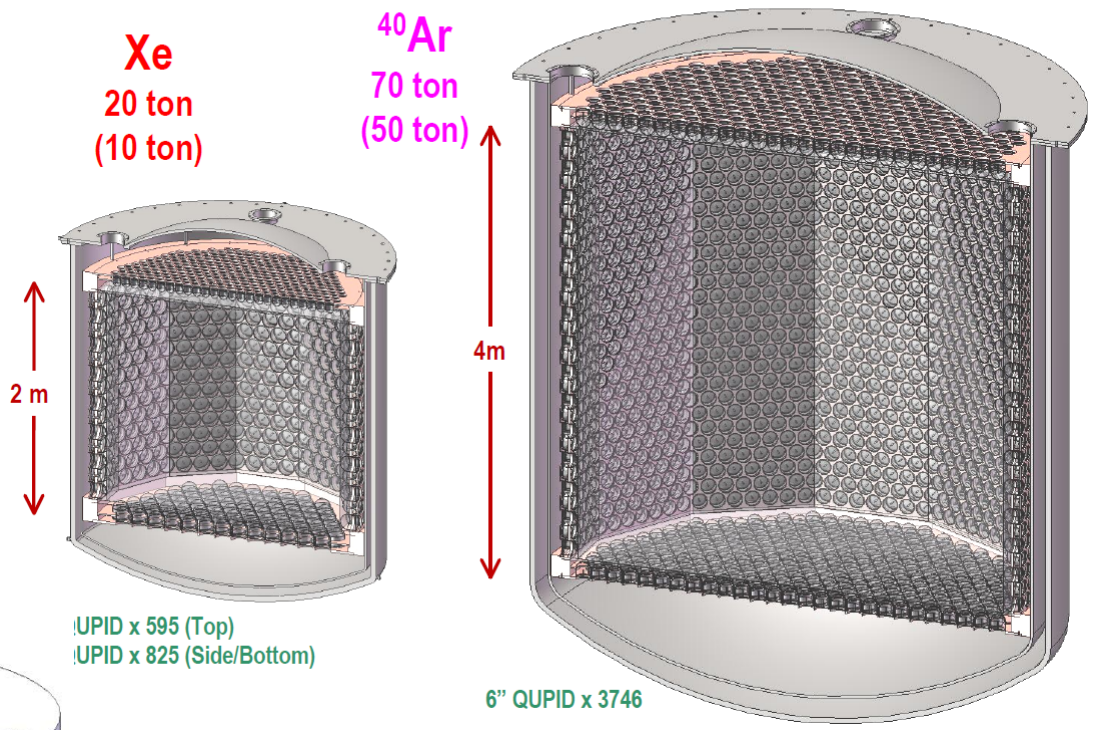


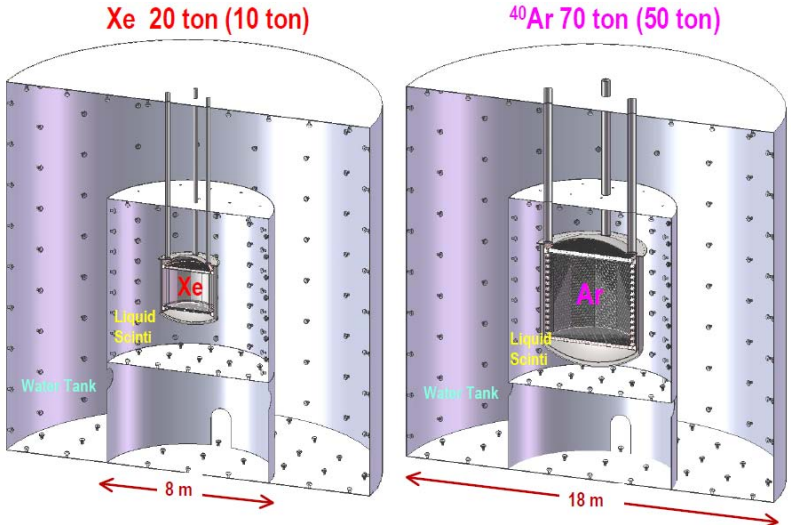
MAX

MAX – G2 Detector



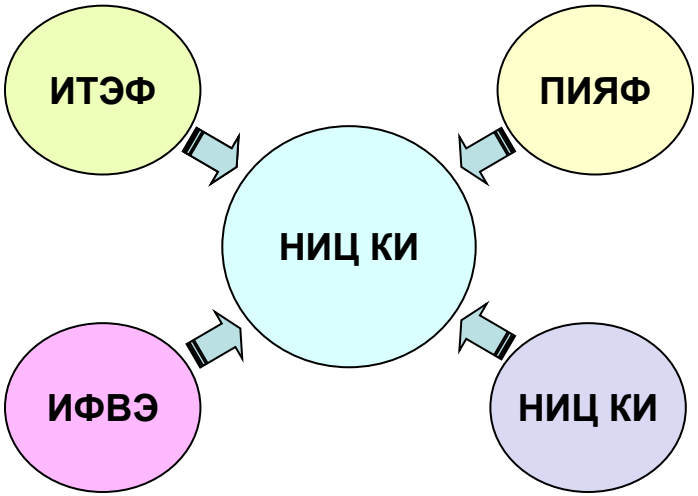
MAX – G3 Detector





DUSEL –
Deep Underground Science and Engineering Laboratory
8000 feet ≈ 2500 м!
Южная Дакота, США

РЭД



РЭД

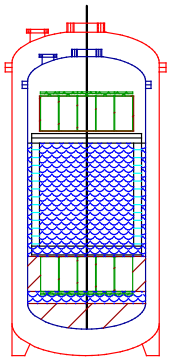
РОССИЙСКИЙ ЭМИССИОННЫЙ ДЕТЕКТОР

Коллаборация РЭД:
ИТЭФ, ПИЯФ, НИЦ КИ – НИЦ КИ
МИФИ, ИЯФ, НИИЯФ МГУ

В настоящее время идет разработка детекторов

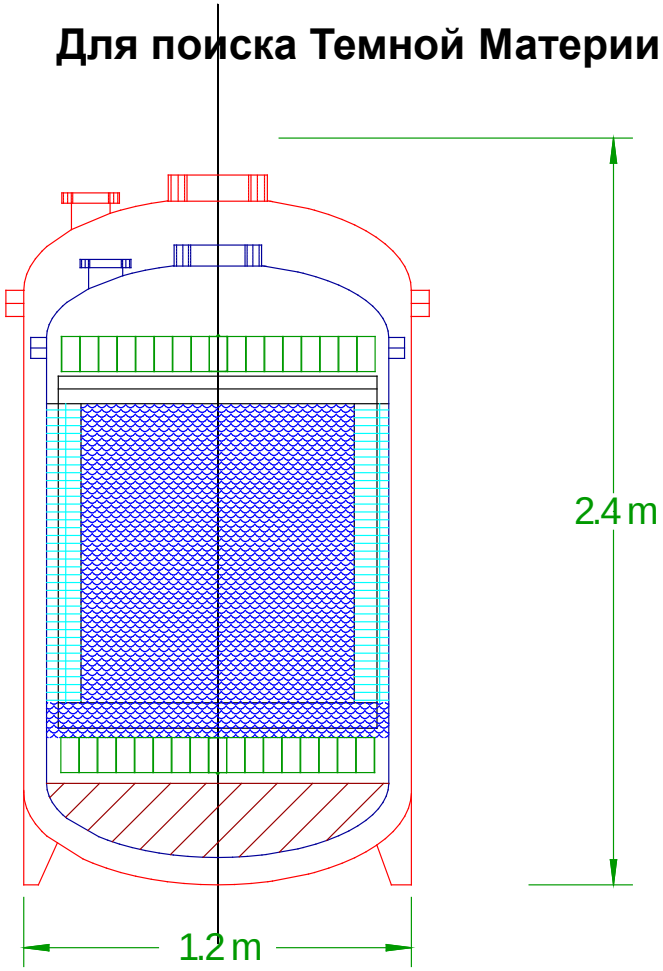
Для поиска ν-N когерентного рассеяния

RED-100



RED-3000

Для поиска Темной Материи



Заключение

- Имеются очень сильные свидетельства существования Темной Материи.
- Эксперименты по прямому детектированию идут полным ходом.
- Благодаря прогрессу в технологиях, с начала экспериментов по настоящее время фон в установках уменьшен почти на 6 порядков величины!
- Супердетекторы (с массой более тонны) пройдут практически весь диапазон предсказаний SUSY.