# Обзор экспериментов по поиску темной материи

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ФГБУ "ГНЦ РФ ИТЭФ", НИЯУ МИФИ

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# Содержание

- Мотивация поиска Темной Материи
- Поиск WIMPов прямым детектированием
- Фоны и основные принципы построения детекторов
- Эксперименты

**Many thanks to R. Gaitskell for permission to use some slides from his recent review talk at MEPhI !**

# Физическая 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

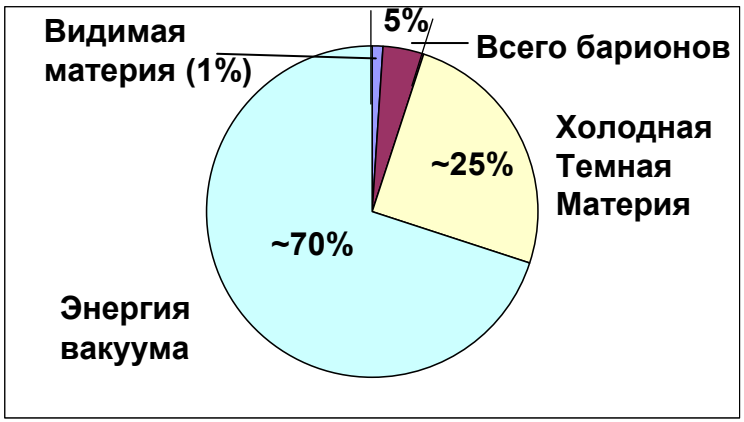
Анизотропия реликтового излучения (CMB)

N-body симуляция

Замечательное согласие выводов по CMB and SN Ia

Теория нуклеосинтеза

## Современная космологическая модель

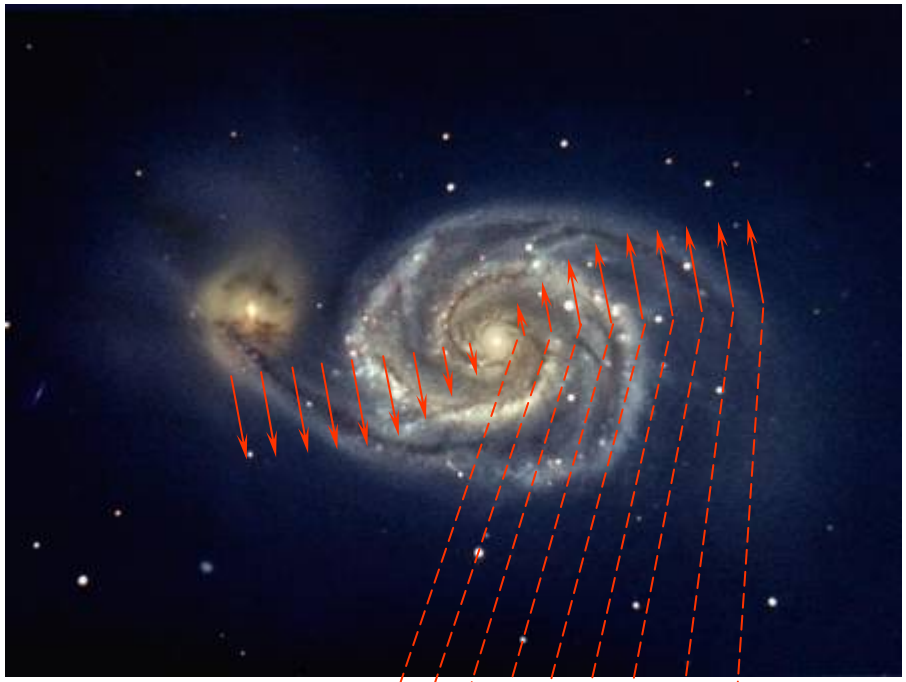


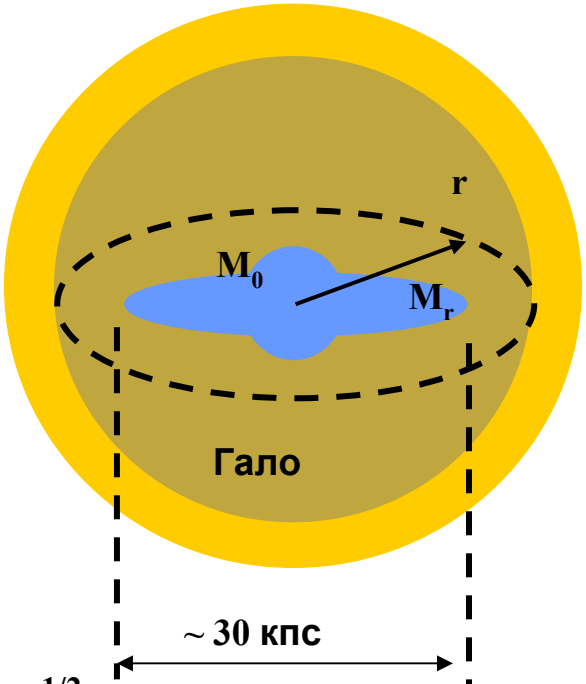

$\rho \approx \rho_{cr} \Rightarrow$

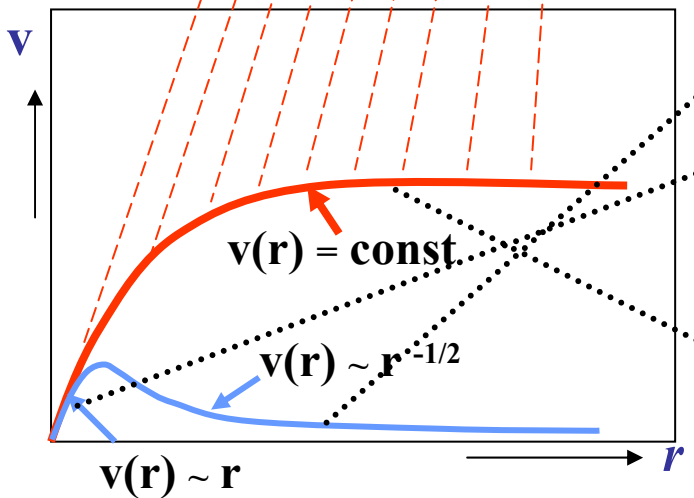
$\Omega = \rho / \rho_{cr} \approx 1$

# Астрофизические свидетельства

## Что же наблюдается на галактических масштабах?





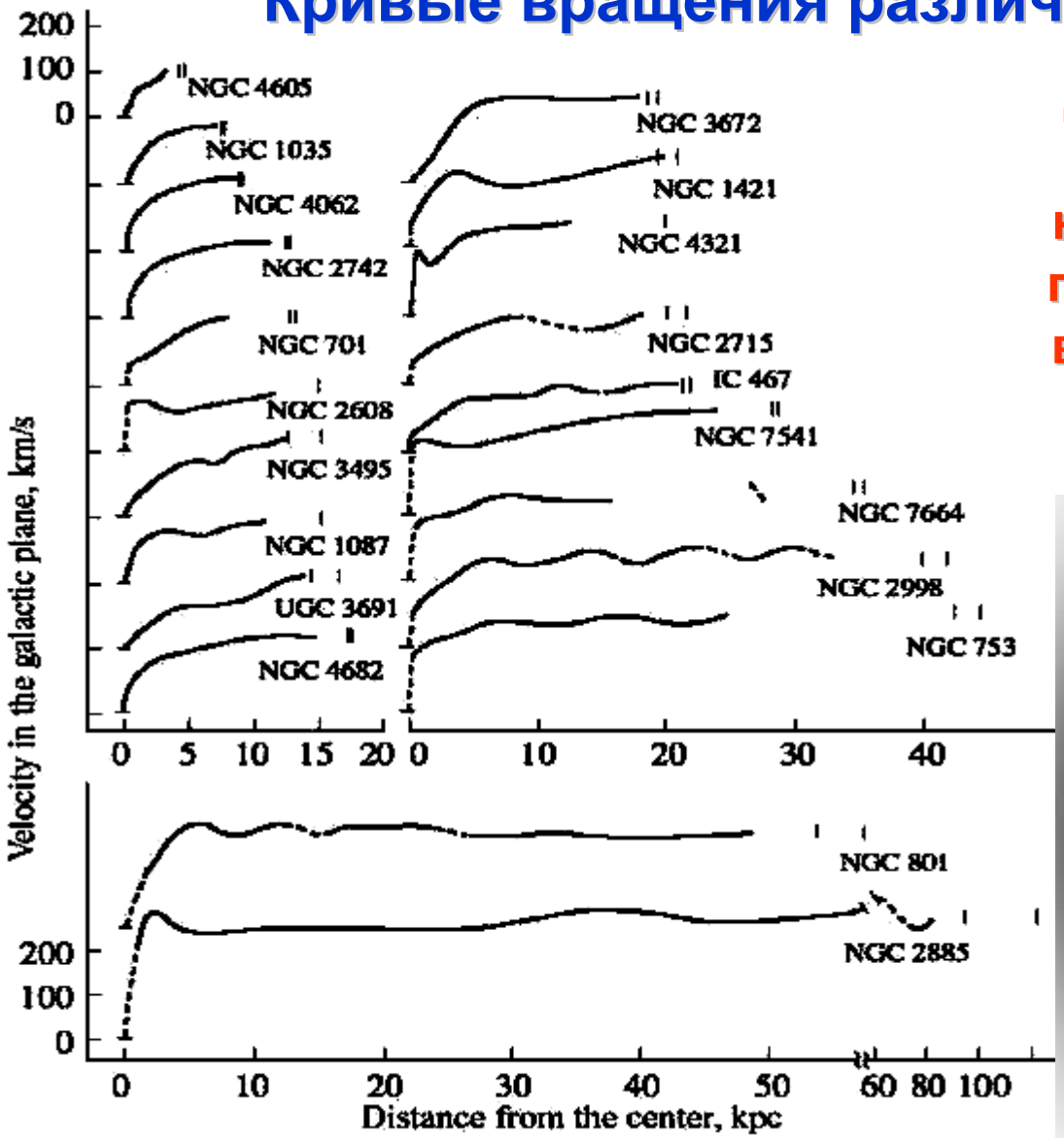

$v(r) \sim r^{-1/2}$ для случая центральной массы $M_0$

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

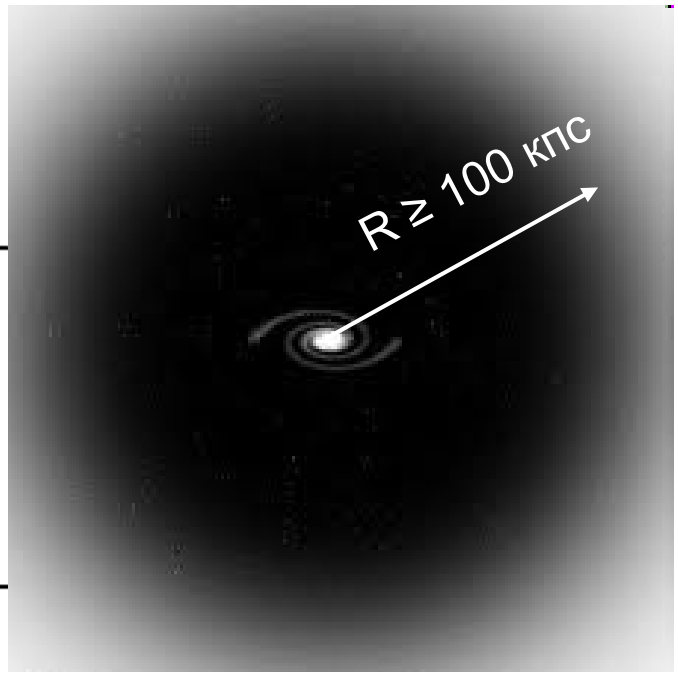
$v(r) = const$ для случая $M_r \sim r$

# Астрофизические свидетельства

## Кривые вращения различных галактик



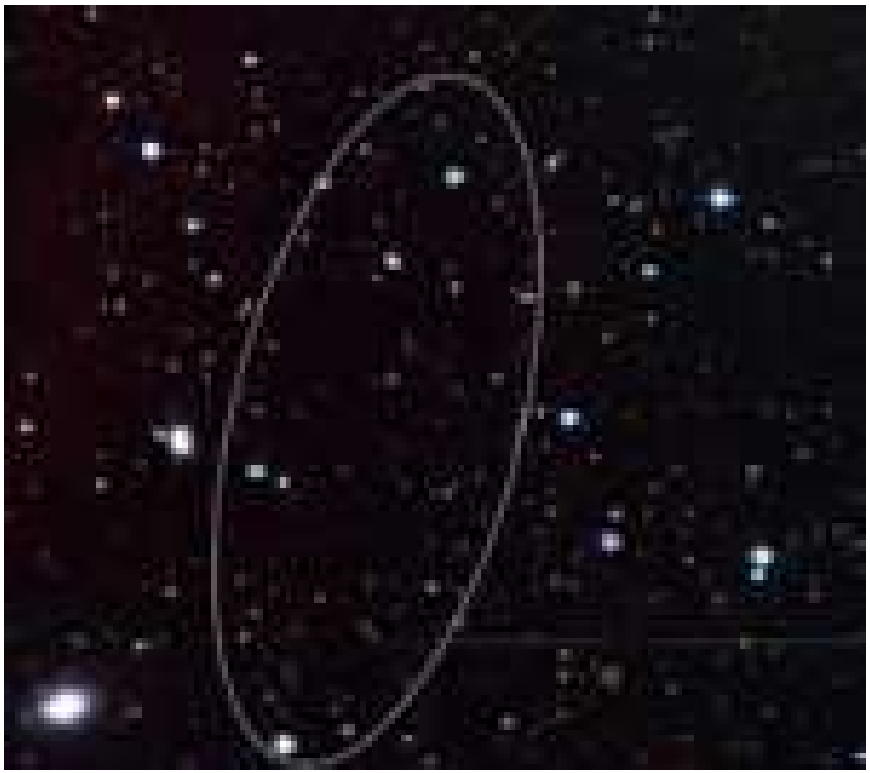

**Для объяснения такого поведения кривых необходимо количество гравитирующей материи в ~10 раз превышающее количество видимой!**



# Астрофизические свидетельства

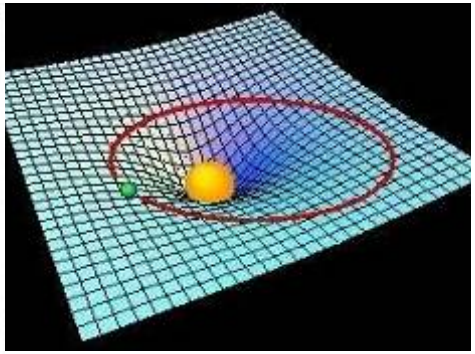
## Есть галактики, состоящие из Тёмной Материи!

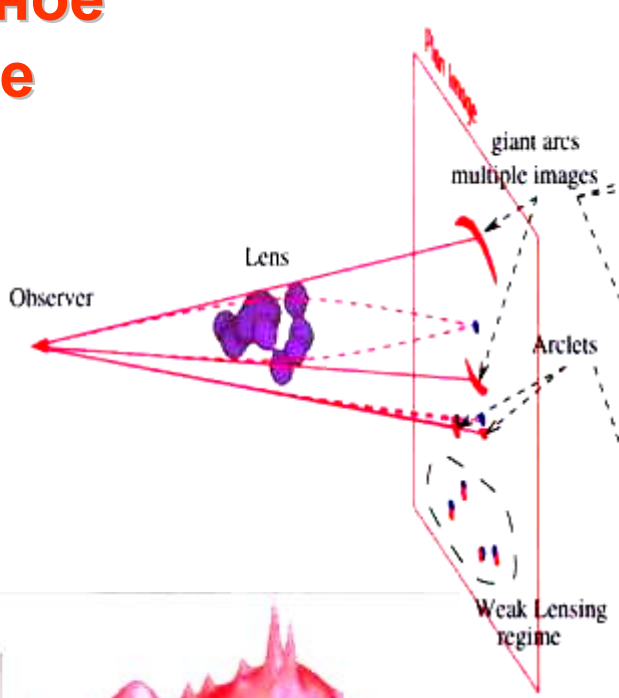
**В 2005 г. астрономы из Cardiff University открыли галактику VIRGOHI21 практически полностью состоящую из Тёмной Материи (arXiv:astro-ph/0502312)!**
**В ней нет звёзд, только один водород видимый в линии 21 см; водород вращается, и его скорость не убывает с расстоянием**
**$M_H$:$M_{total}$ = 1:1000**

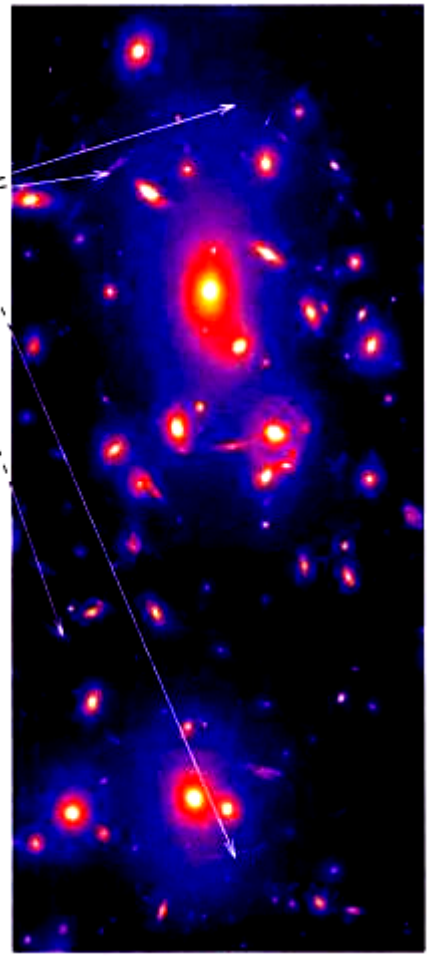


# Астрофизические свидетельства

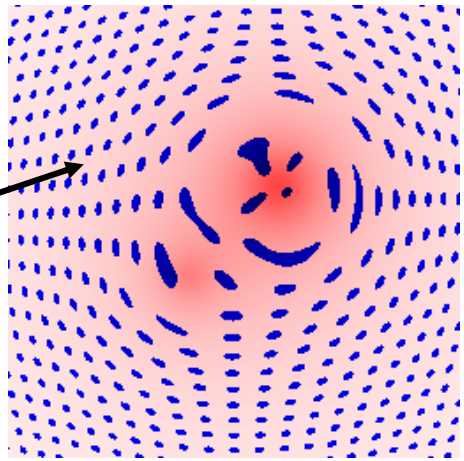
## Гравитационное линзирование

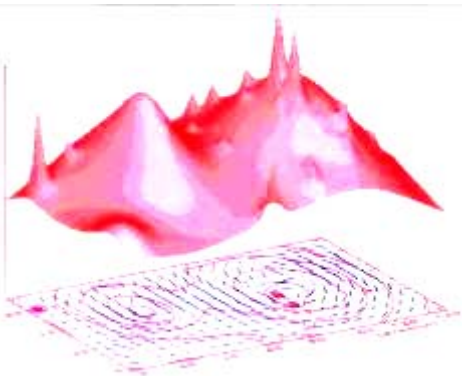




Так выглядел бы регулярный паттерн, находящийся за "размазанным" массивным объектом

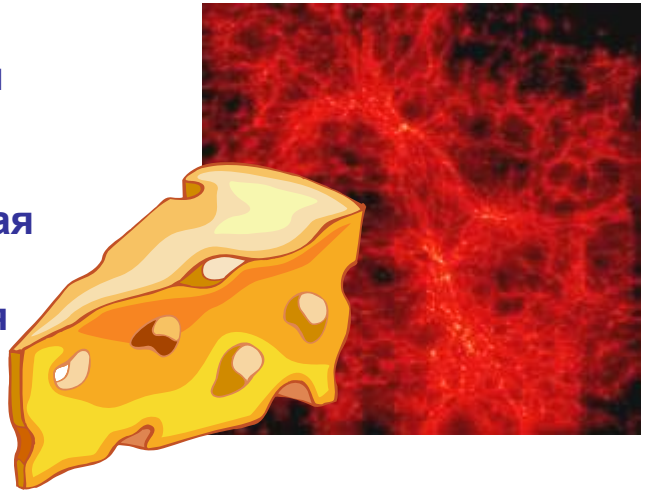




Также требуется в ~10 раз большая масса

# 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)**

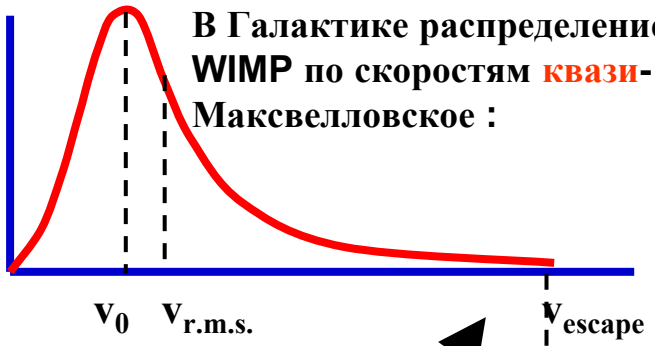
**Теория Суперсимметрии SUSY предоставляет нам новый класс частиц.**

***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!**

# Поиск WIMP: прямое детектирование

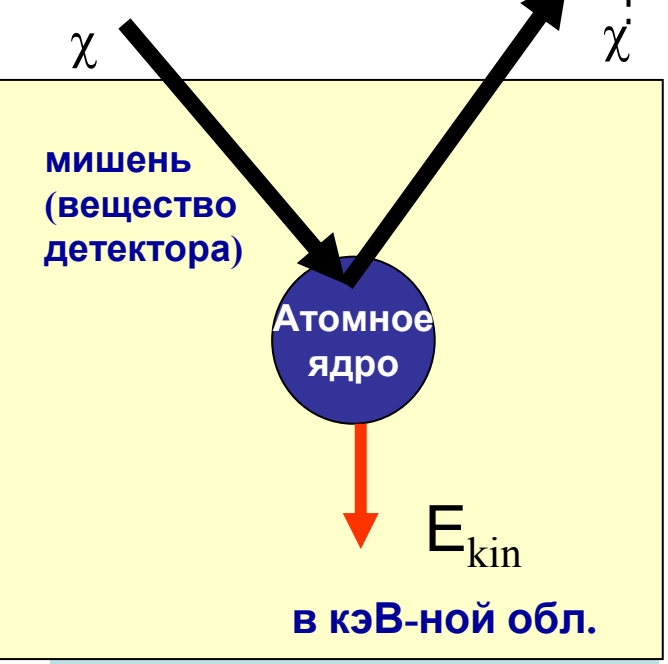



В Галактике распределение WIMP по скоростям квази-Максвелловское :

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

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

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




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

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

$M_\chi$, $M_N$ и $m_{red}$ – masses of WIMP and target nucleus, and their reduced mass, respectively;

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

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

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

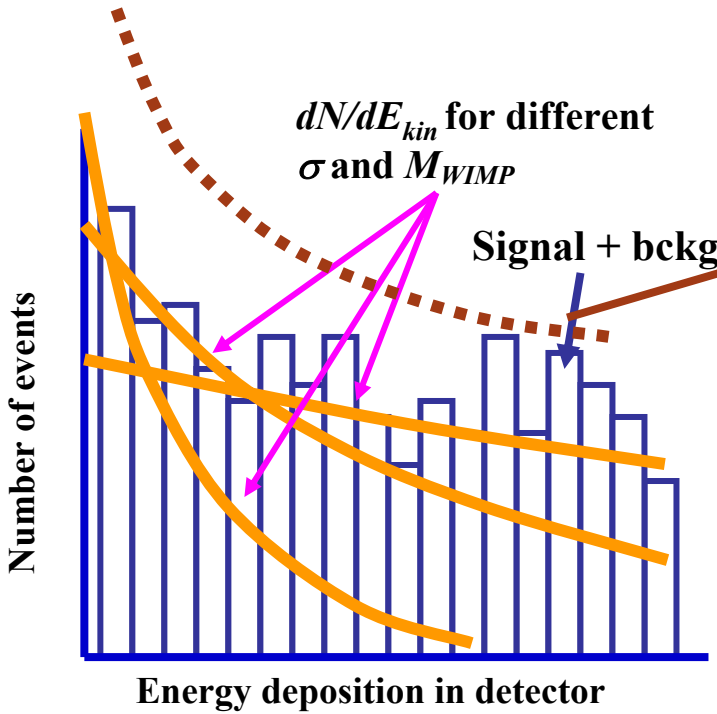
$N_N$ – number of target nuclei,

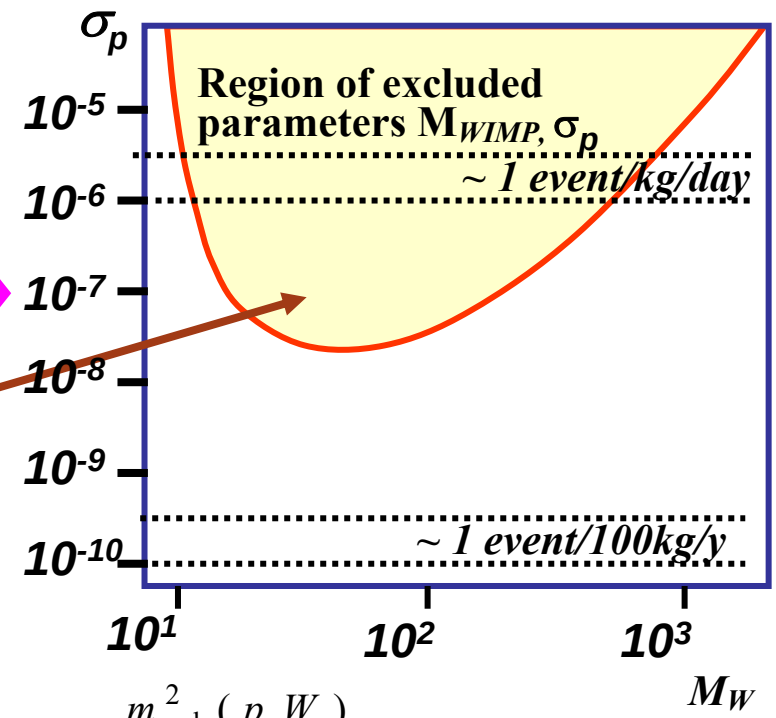
ρ = 0.3 GeV/cm³ – WIMP density in Galactic halo,

$\sigma$ – WIMP interaction cross-section,

$F_N^2(E)$ – nuclear form factor

# Регистрация WIMP: прямое детектирование



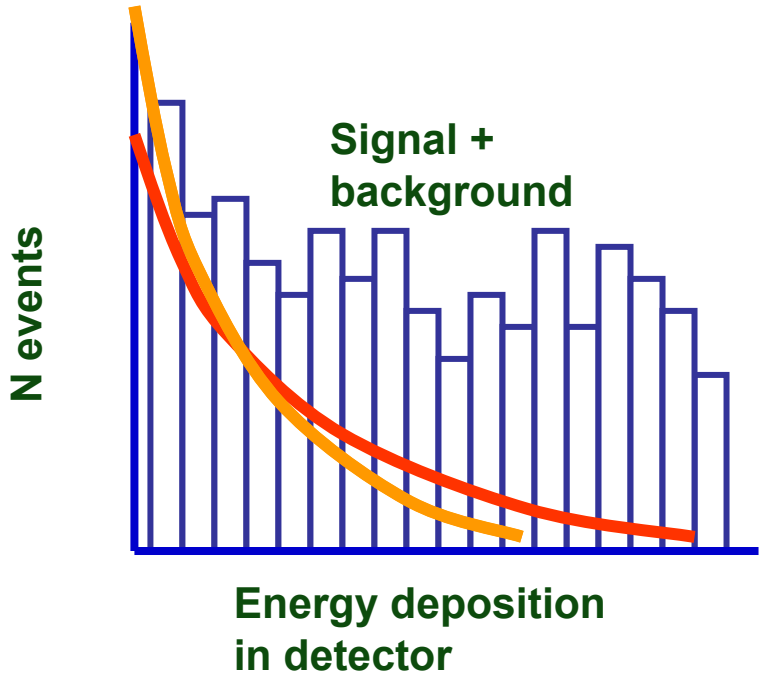



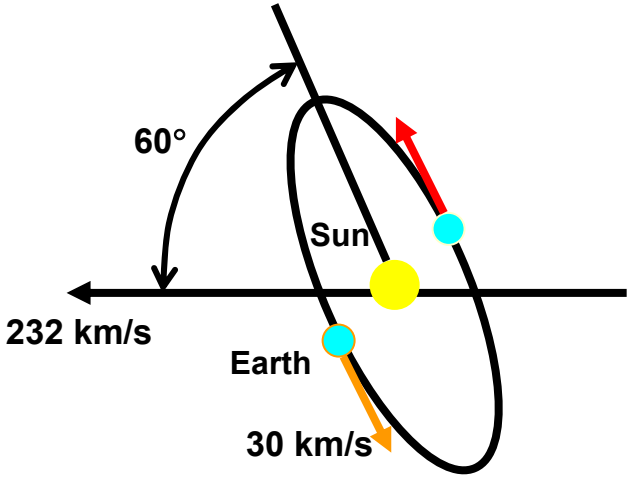

$$\sigma_p = \frac{m^2_{red}(p,W)}{Cm^2_{red}(Nucl,W)}\sigma <\sim 10^{-7}\,pb$$

$C=A^2$

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

# Поиск WIMP: годичная модуляция




**Ожидаемая вариация темпа счета WIMP ~ 5%**

**(с максимумом 2 го июня)**

# Первый эксперимент

**В 2012 г отмечался 25-летний юбилей:**
**http://www.pnnl.gov/physics/darkmattersymp.stm**

Volume 195, number 4 PHYSICS LETTERS B 17 September 1987

## LIMITS ON COLD DARK MATTER CANDIDATES FROM AN ULTRALOW BACKGROUND GERMANIUM SPECTROMETER

S.P. AHLEN [a], F.T. AVIGNONE III [b], R.L. BRODZINSKI [c], A.K. DRUKIER [d,e], G. GELMINI [f,g,1] and D.N. SPERGEL [d,h]

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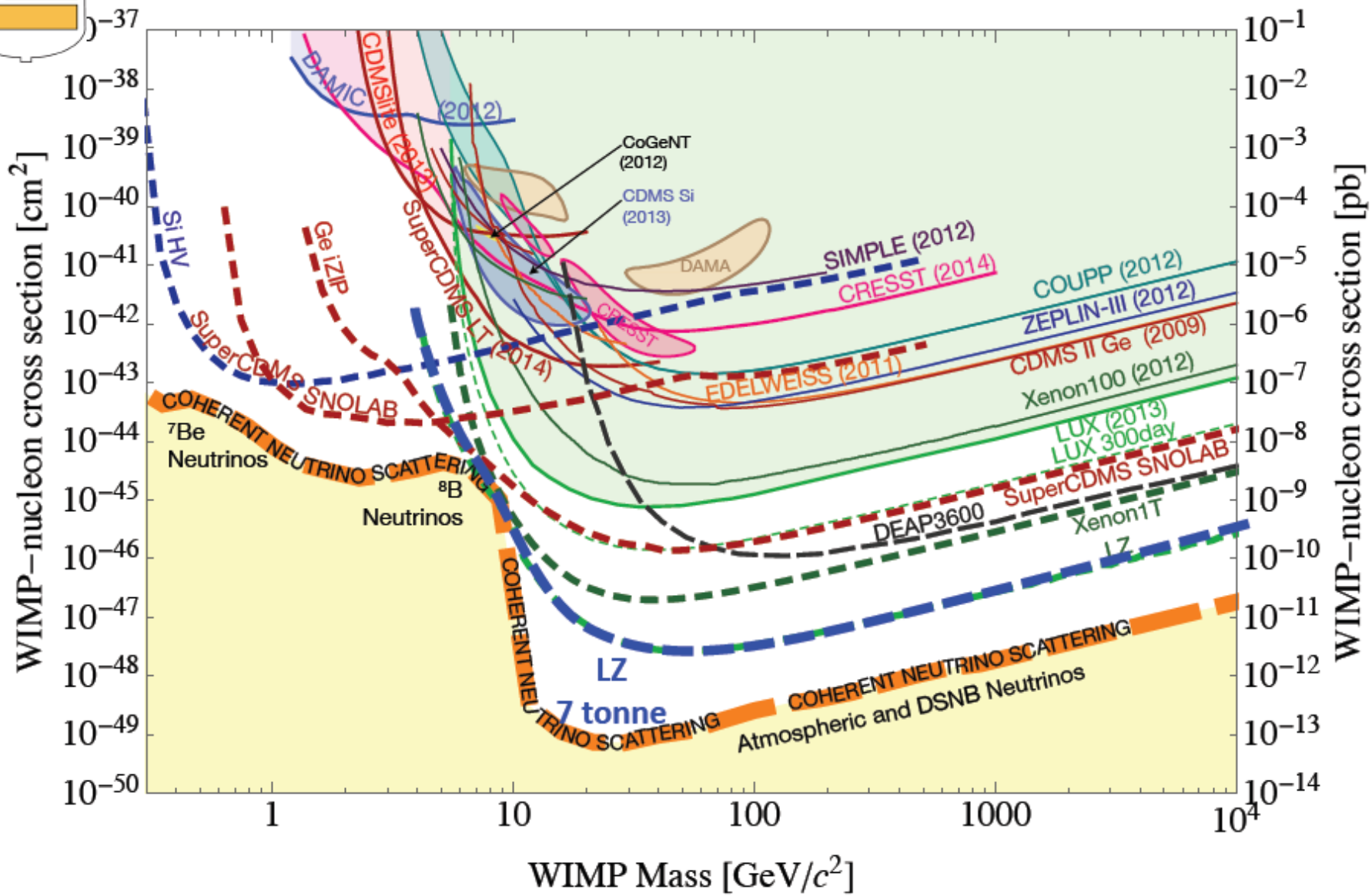
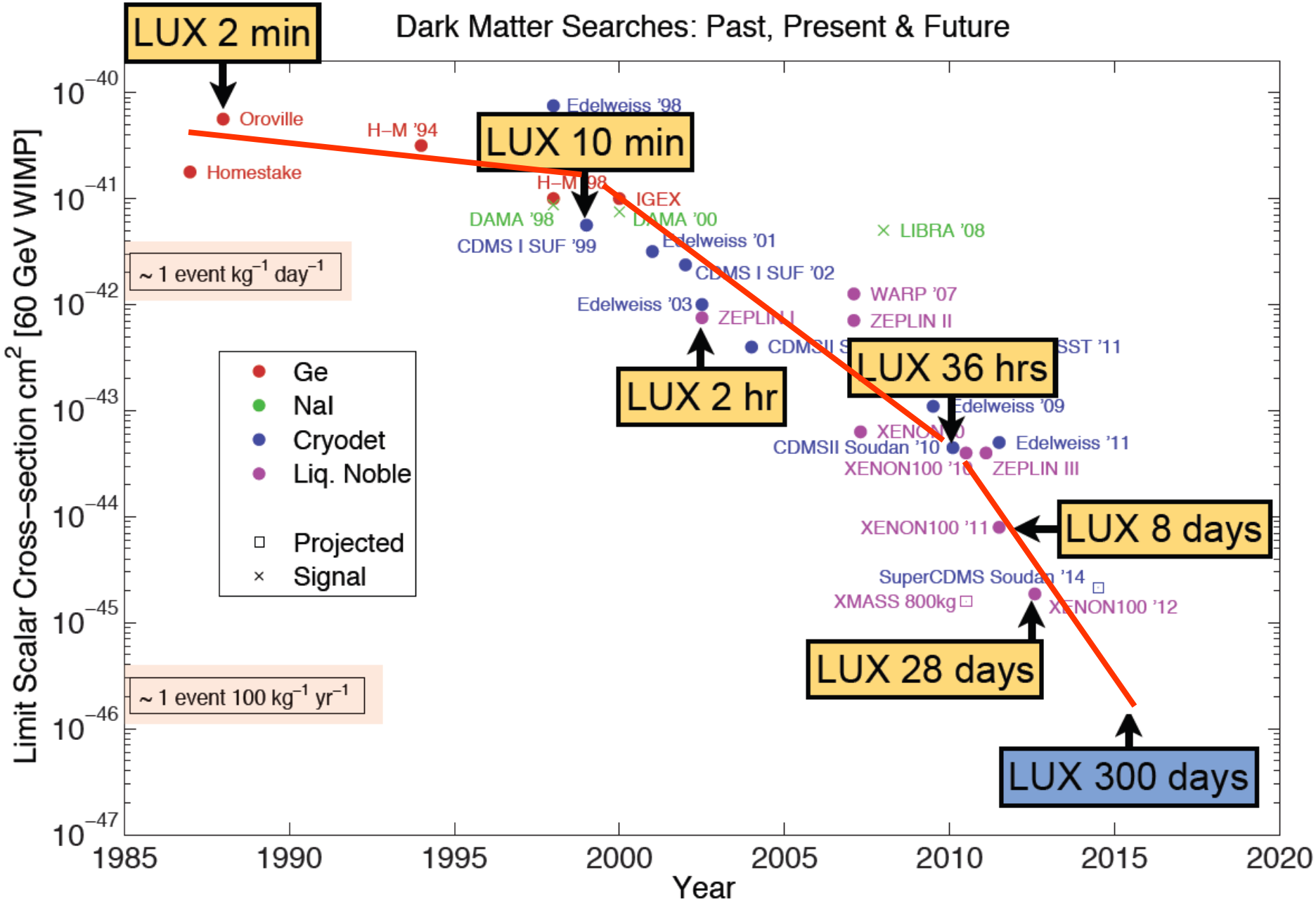
[d] *Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA*
[e] *Applied Research Corp., 8201 Corporate Dr , Landover MD 20785, USA*
[f] *Department of Physics, Harvard University, Cambridge, MA 02138, USA*
[g] *The Enrico Fermi Institute, University of Chicago, Chicago, IL 60637, USA*
[h] *Institute for Advanced Study, Princeton, NJ 08540, USA*

Received 5 May 1987

An ultralow background spectrometer is used as a detector of cold dark matter candidates from the halo of our galaxy Using a realistic model for the galactic halo, large regions of the mass–cross section space are excluded for important halo component particles. In particular, a halo dominated by heavy standard Dirac neutrinos (taken as an example of particles with spin-independent $Z^0$ exchange interactions) with masses between 20 GeV and 1 TeV is excluded. The local density of heavy standard Dirac neutrinos is $<0.4$ GeV/cm$^3$ for masses between 17.5 GeV and 2 5 TeV, at the 68% confidence level.

# Области исключения в пространстве $M_W$-σ



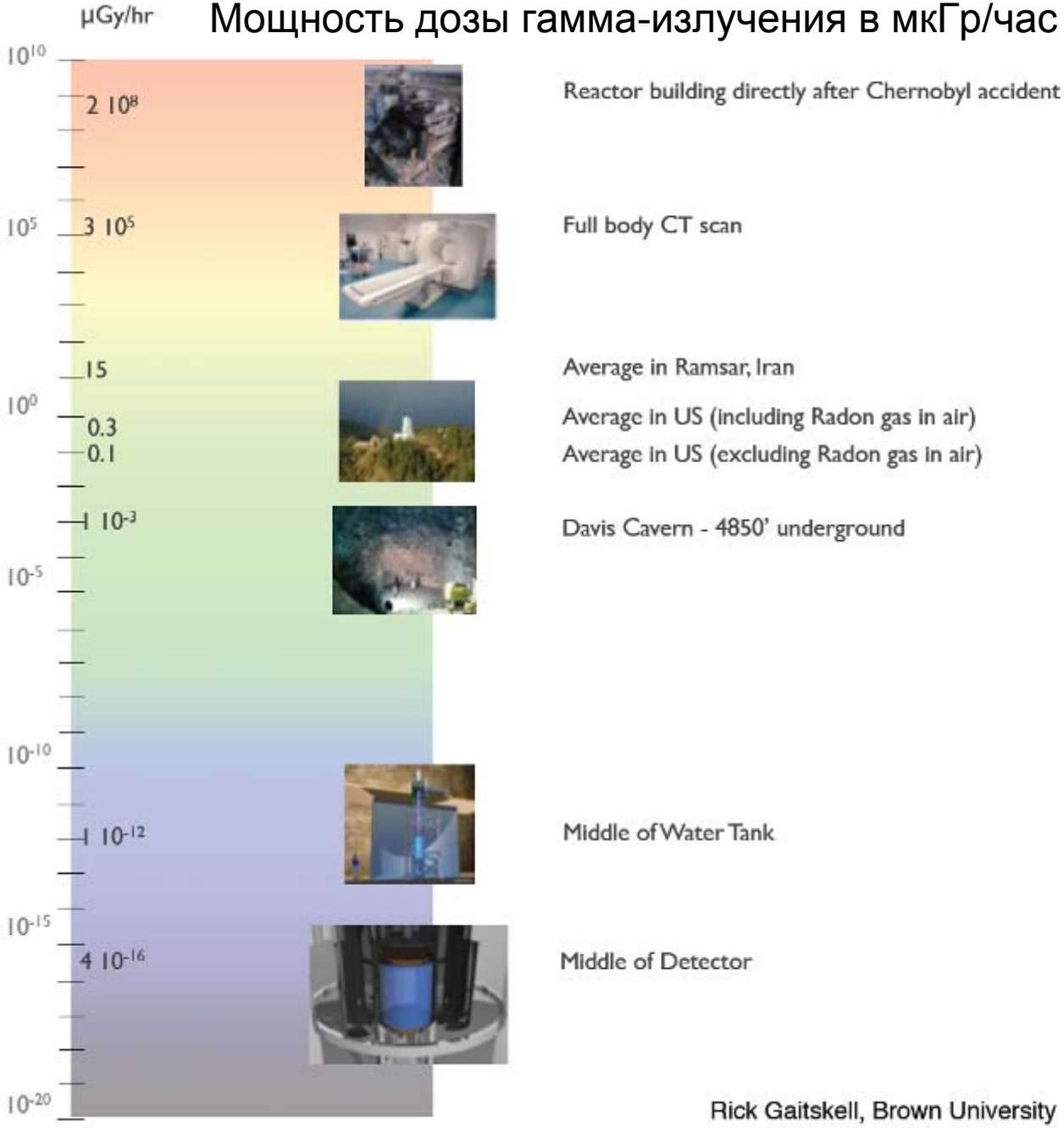



From R. Gaitskell

# География DM экспериментов

Picture from L. Baudis, 2012

# Мощность дозы гамма-излучения в мкГр/час в различных местах




Rick Gaitskell, Brown University

*1 Gy = 1 J/kg = 100 rad

# Радиоактивные загрязнения

## Обычные вещества

**Калиевая селитра -**

**до $10^4$ Бк/кг**

**Гранит -**

**до $10^3$ Бк/кг**

**Тело человека -**

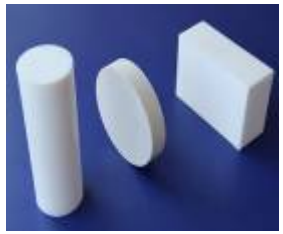
**~ $10^2$ Бк/кг**

**Бананы -**

**~ $10^2$ Бк/кг**

**~ 10 – 20 Бк/шт**

## Низкофоновые



**Тефлон**

**< 7 $10^{-5}$ Бк/кг**

**Электролитическая медь**

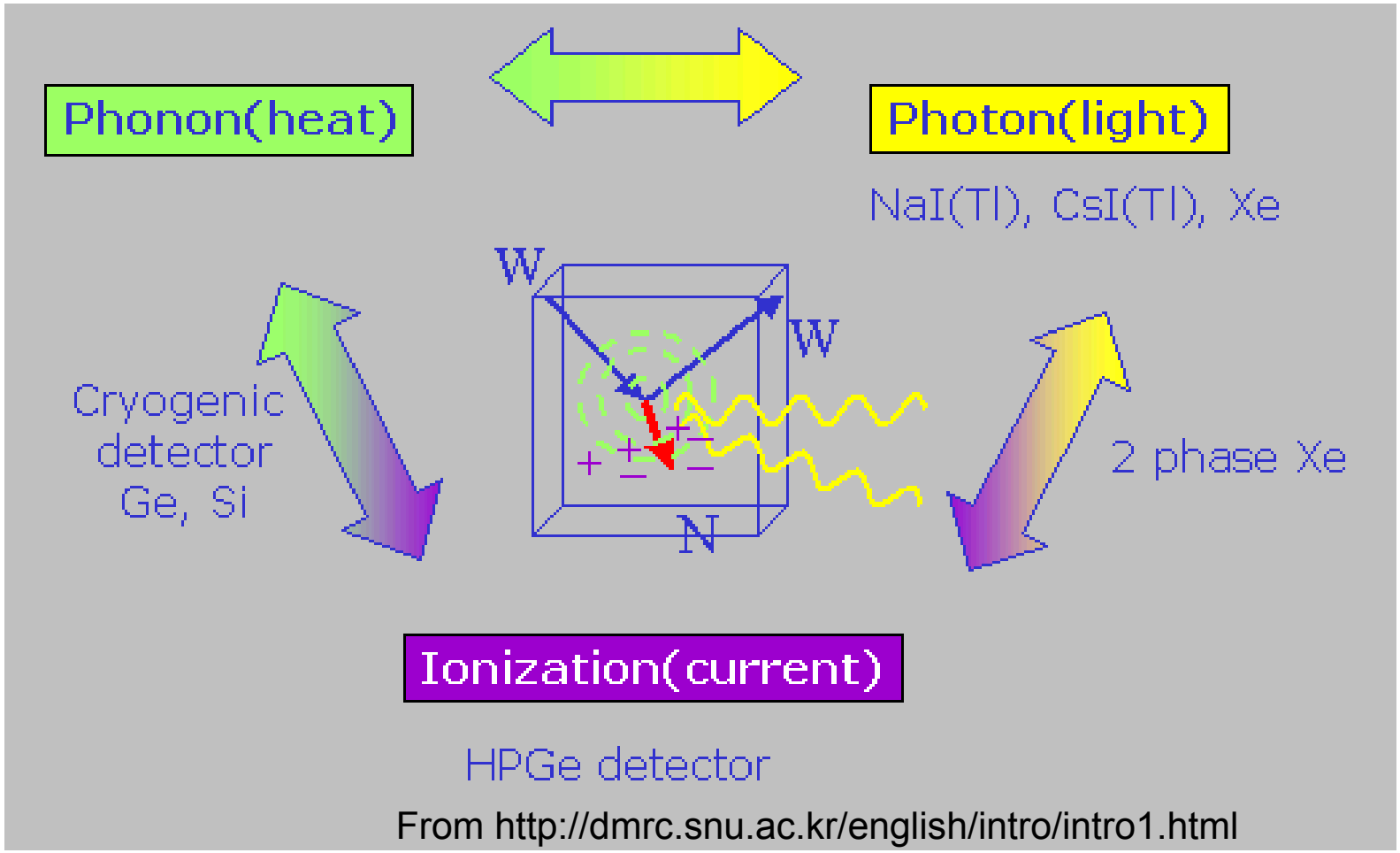
**< 1 $10^{-6}$ Бк/кг**

**Hamamatsu R11410-20**
**~ $10^{-2}$ Бк/шт.**

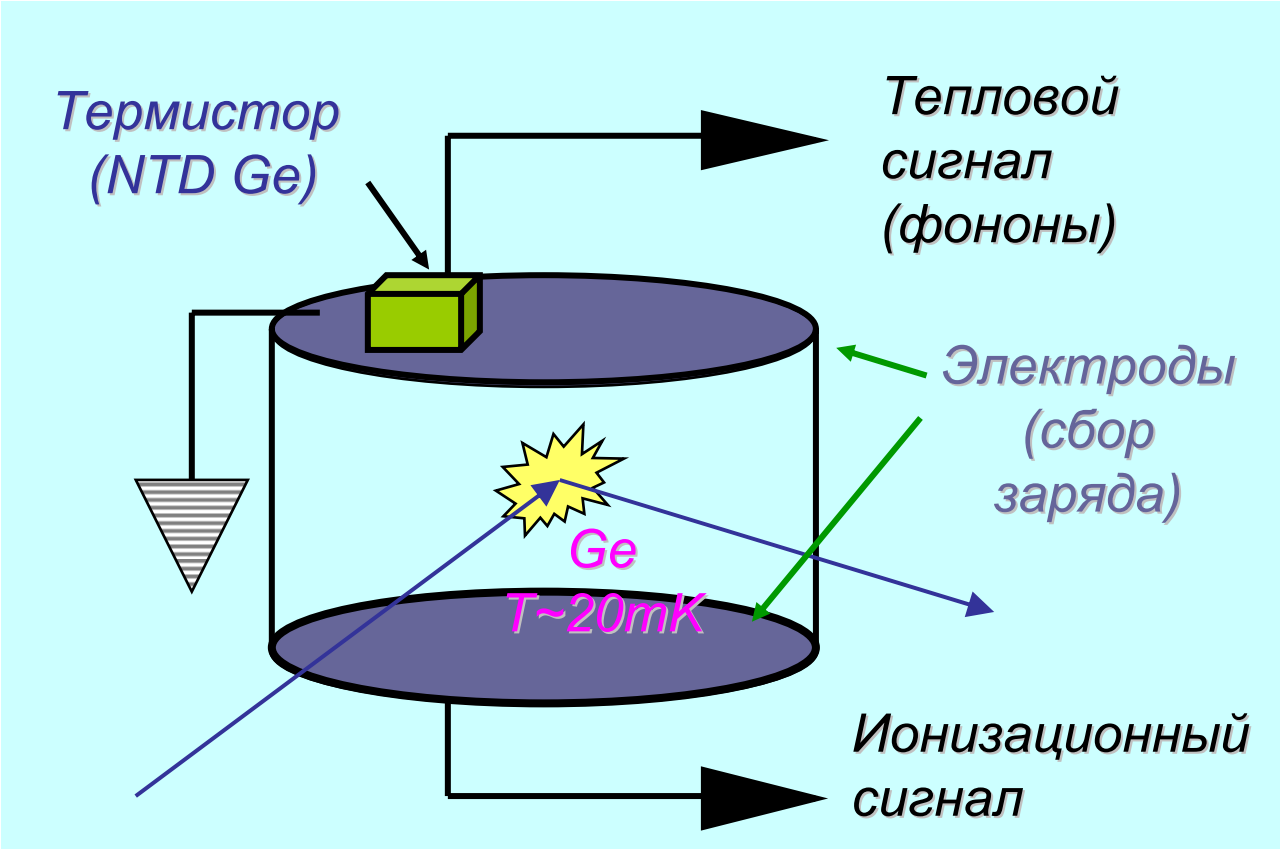
**QUPID**
**< 3 $10^{-4}$ Бк/шт.**

# Режекция гамма-фона и электронов

**Соотношение доли энергии, идущей по различным каналам энерговыделения, различно для NR и ER**



# Детектирование WIMP с помощью низкотемпературных болометров



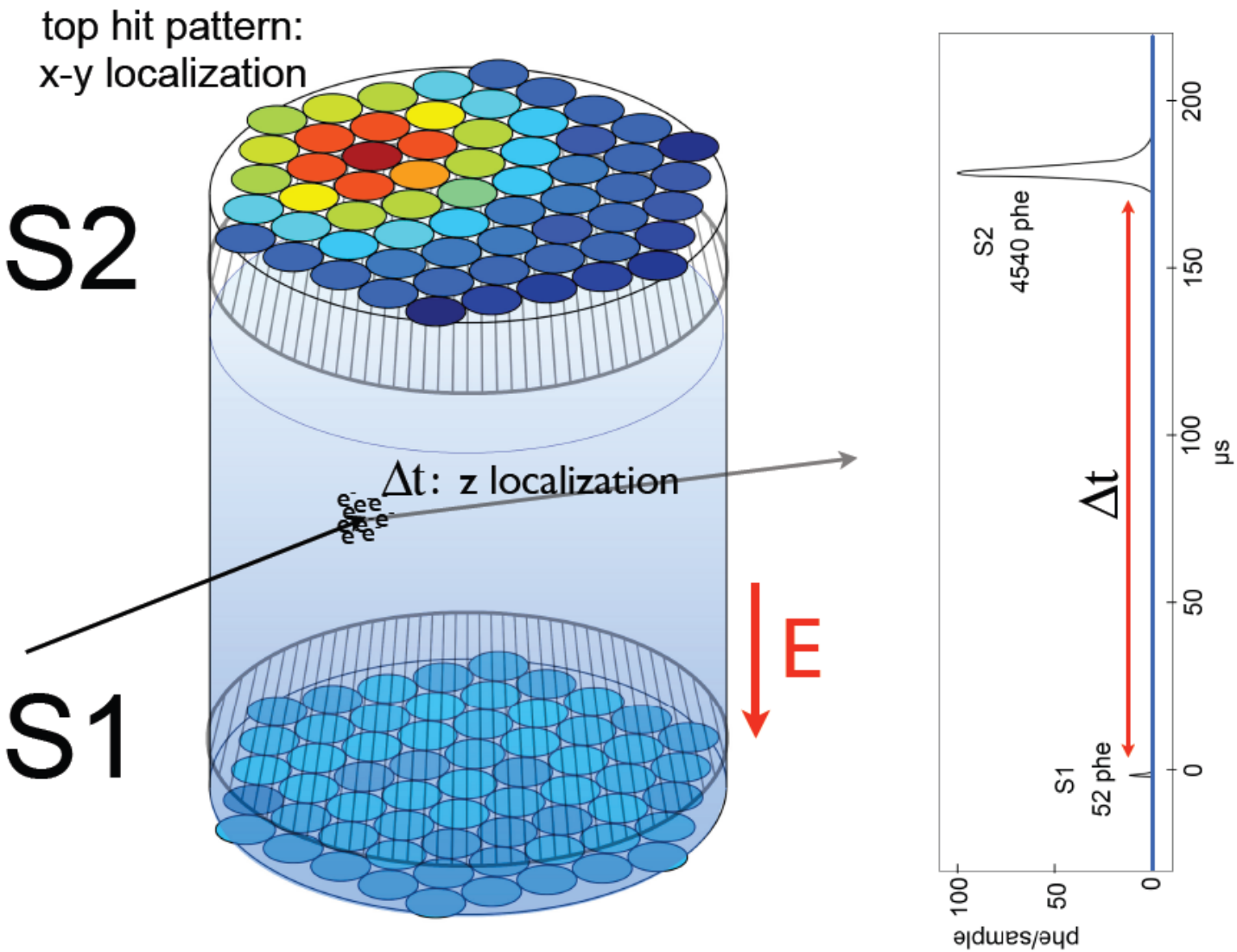

**Теплоёмкость диэлектрика определяется согласно закону Дебая:**

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

**где $\lambda_D$=1944 Дж/моль/К,**
**$T$ – температура (К),**
**$\Theta_D$ – температура Дебая.**

**Для Ge, например,**
**$\Theta_D$ равна 374К.**
**При $T$ ~ 20 мК**
**$C_{Ge}$ ~ 20 кэВ/моль/мкК.**

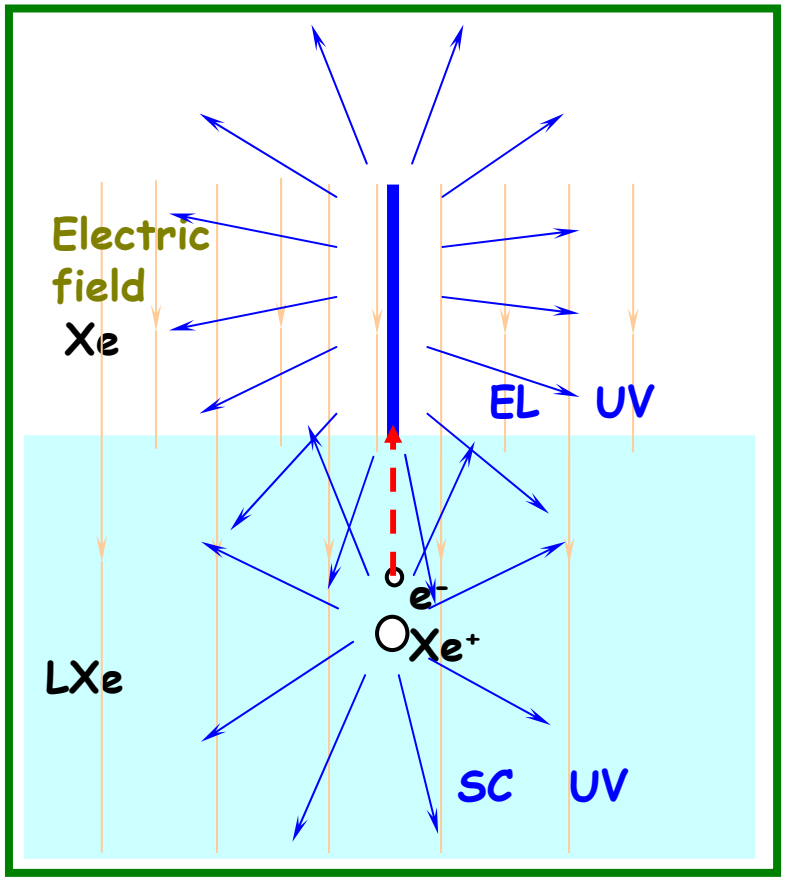
# Детектирование WIMP с помощью двухфазного эмиссионного детектора (LXe, LAr)

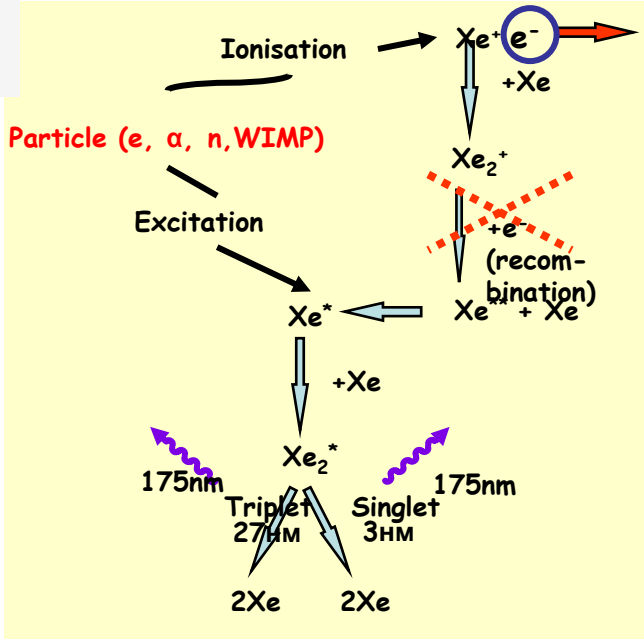


# Discrimination of particles in a two-phase detector (Xe)

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

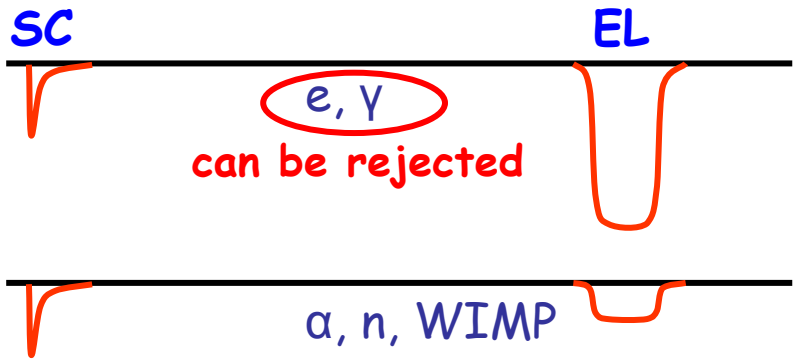



Electrons are partly extracted from the track: recombination is suppressed

Suppression depends on dE/dX

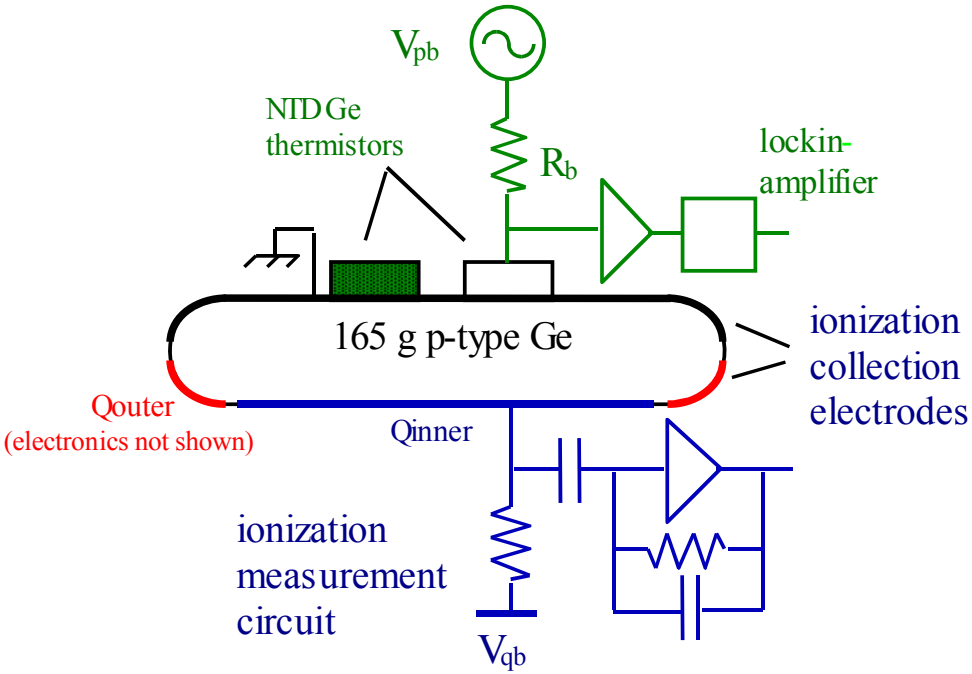
Ratio of SC/EL is different for different kind of particles

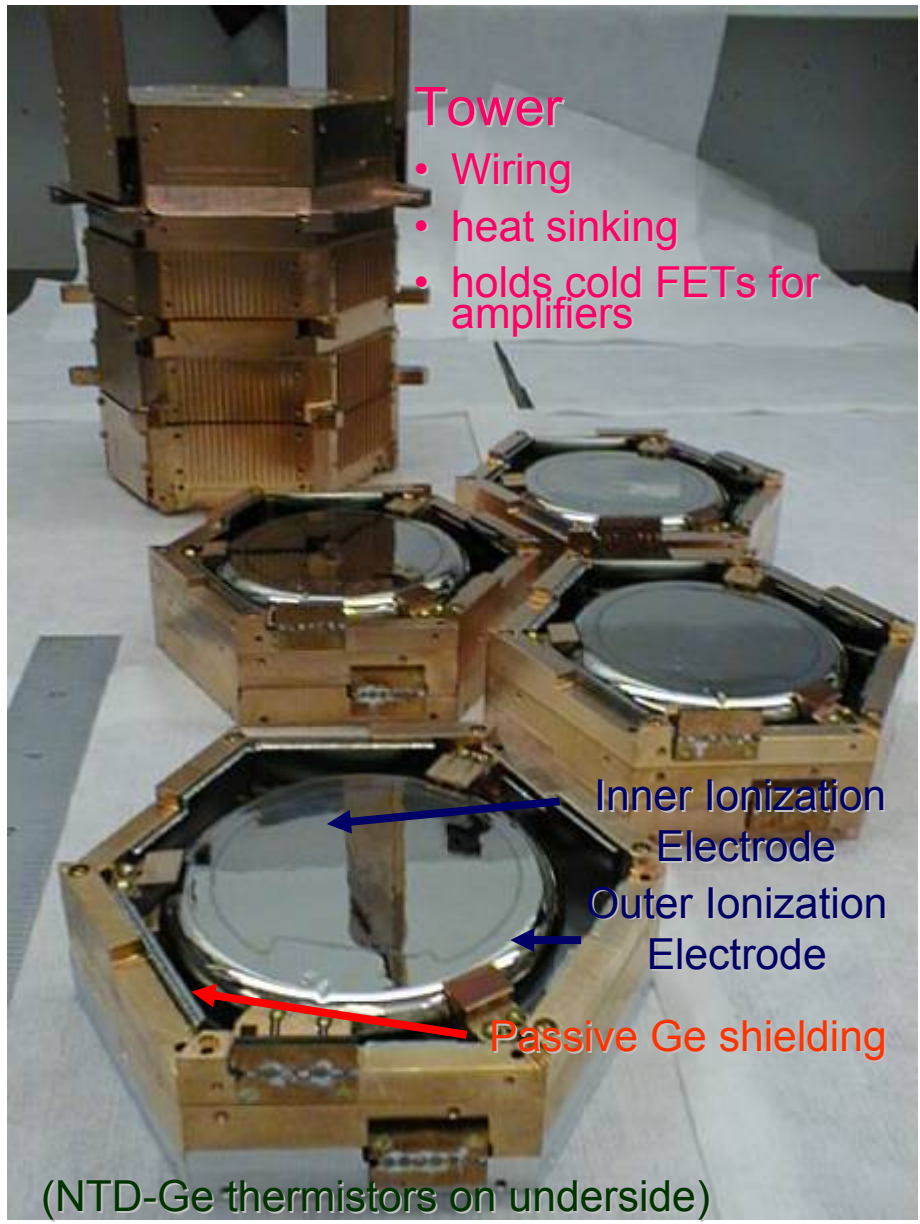


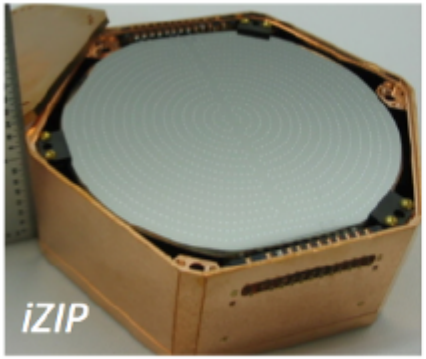
# Коллаборация по поиску Тёмной Материи CDMS – Cryogenic Dark Matter Search

## Ge BLIP Detectors

Berkeley Large Ionization- and Phonon-mediated Detectors

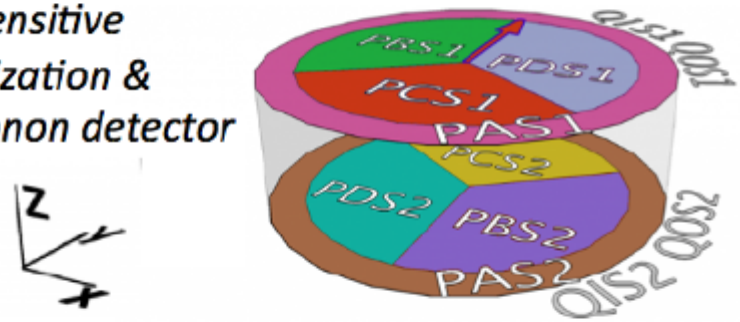


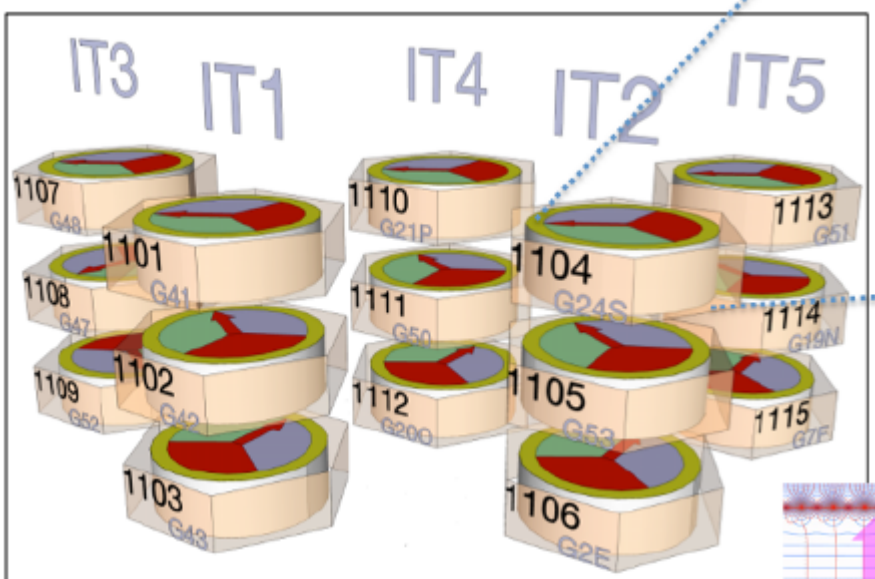






# SuperCDMS Soudan

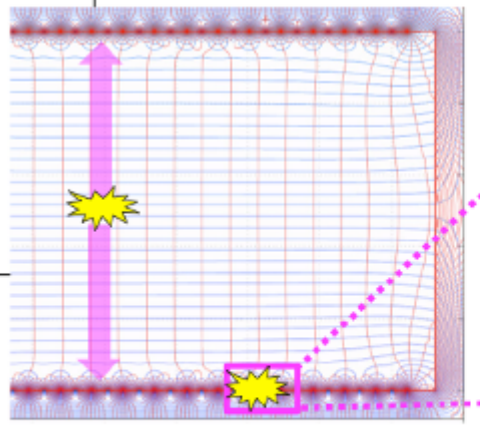
*interleaved*
*Z-sensitive*
*Ionization &*
*Phonon detector*



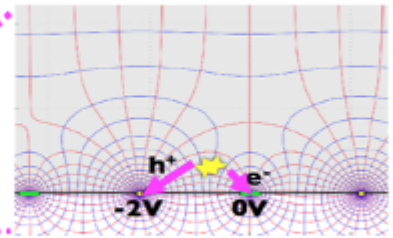




*15 germanium detectors*
*0.6 kg each*
*Operational since March of 2012*

*Improved fiducialization from measurement of z-symmetric ionization response*
*Phonon guard and z-symmetric phonon response helps too!*



*APL 103, 164105(2013)*

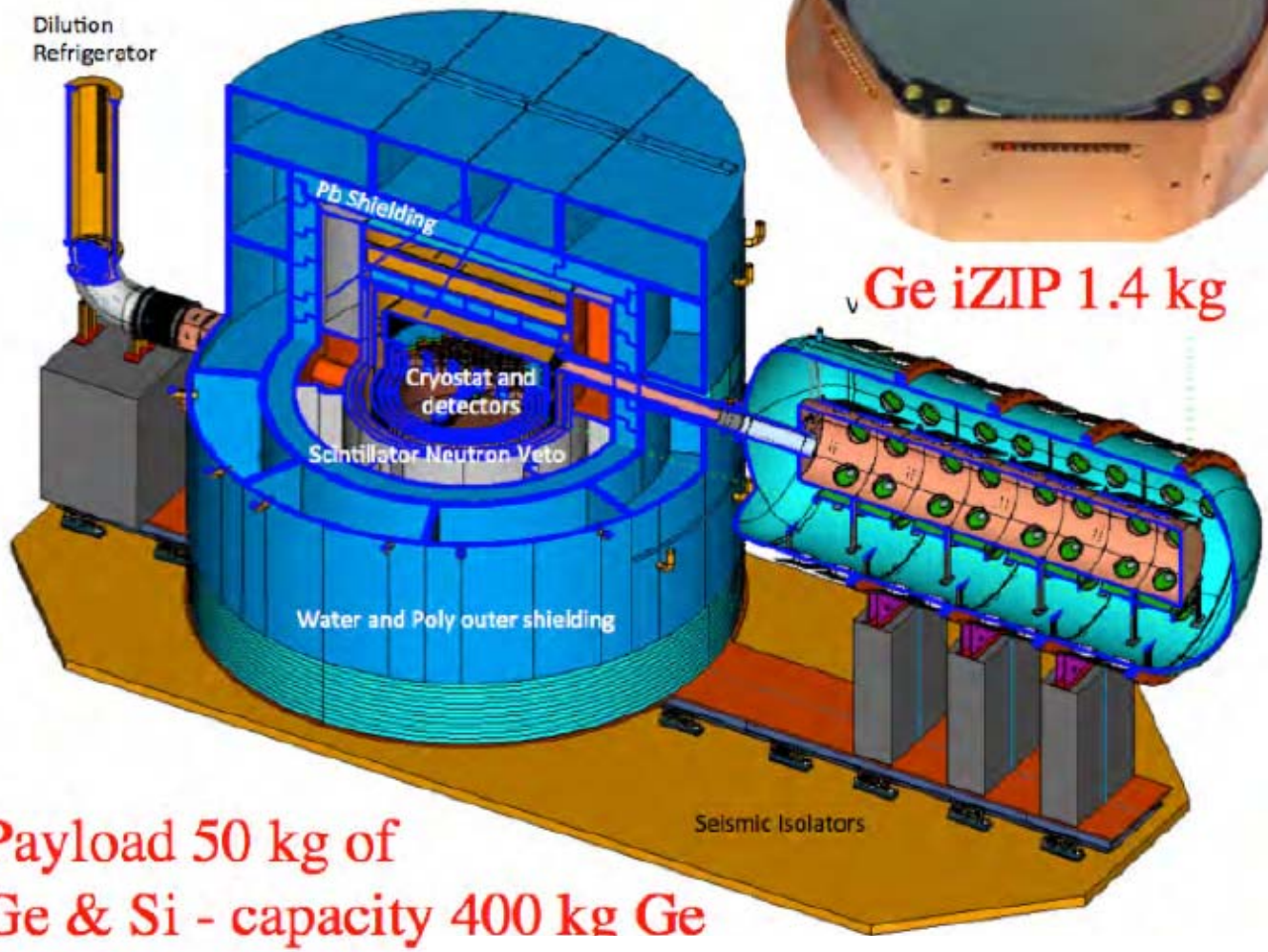



***Data for this analysis:*** *577 kg-days taken from Mar 2012 – July 2013*
*7 iZIPs w/ lowest trigger thresh*

2

# SuperCDMS SNOLAB Experiment

•SNOLAB 6010 mwe



Ge iZIP 1.4 kg

Payload 50 kg of
Ge & Si - capacity 400 kg Ge

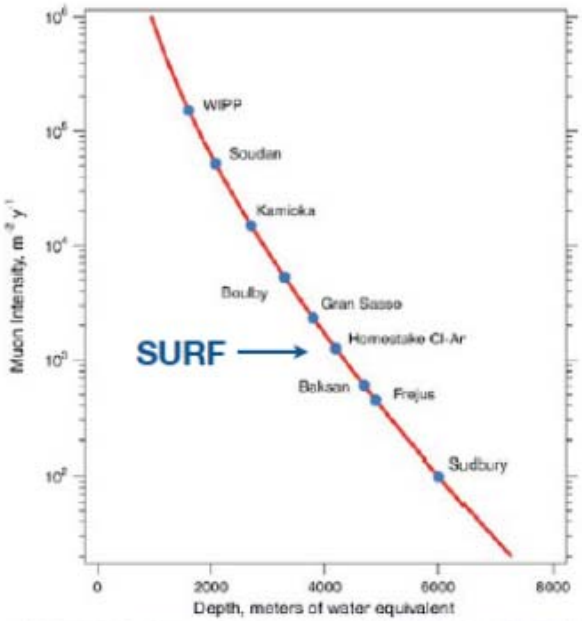
Ge Tower 8.4 kg

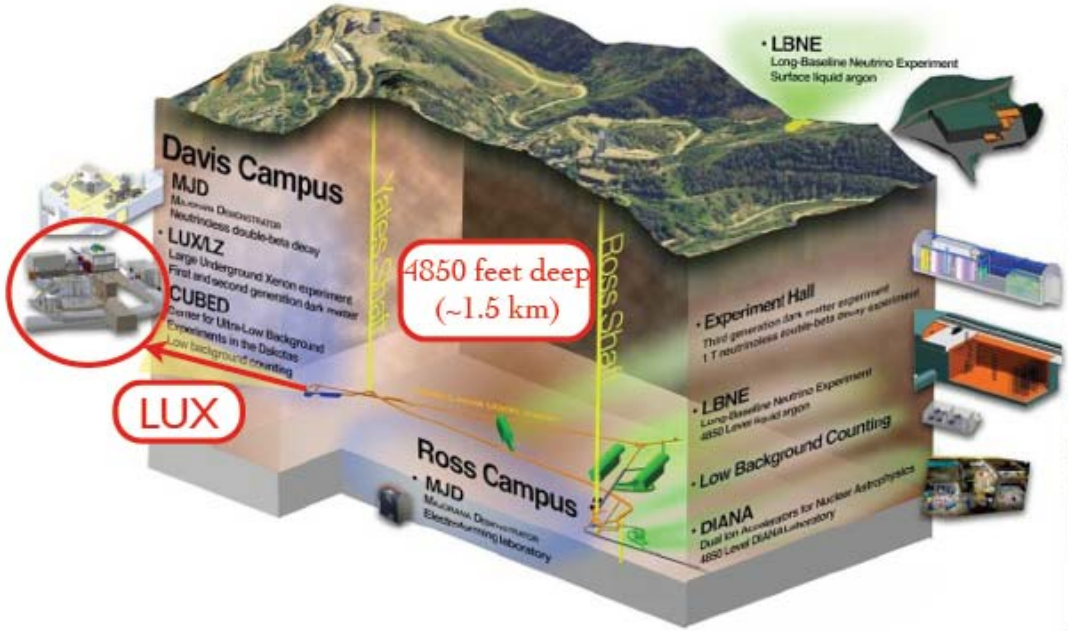


https://www.slac.stanford.edu/exp/cdms/

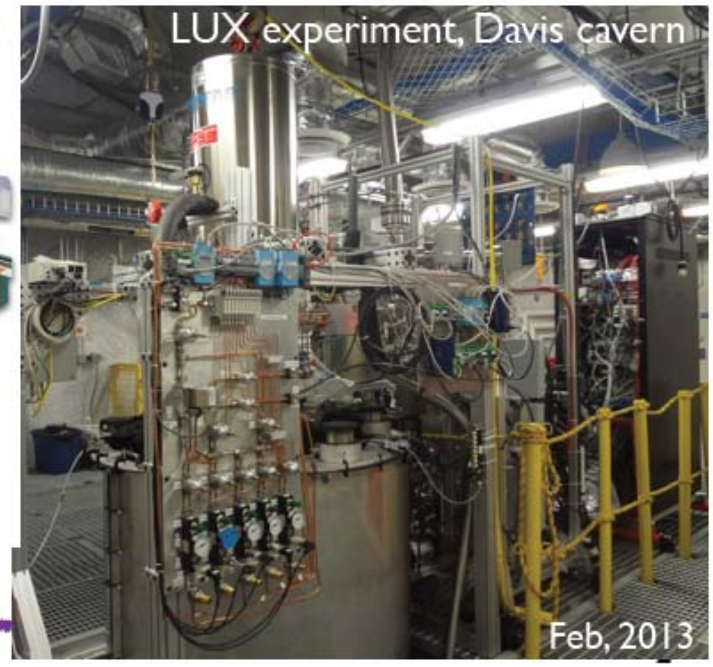
# Эксперимент LUX

## Sanford Underground Research Facility (SURF) in Lead, SD



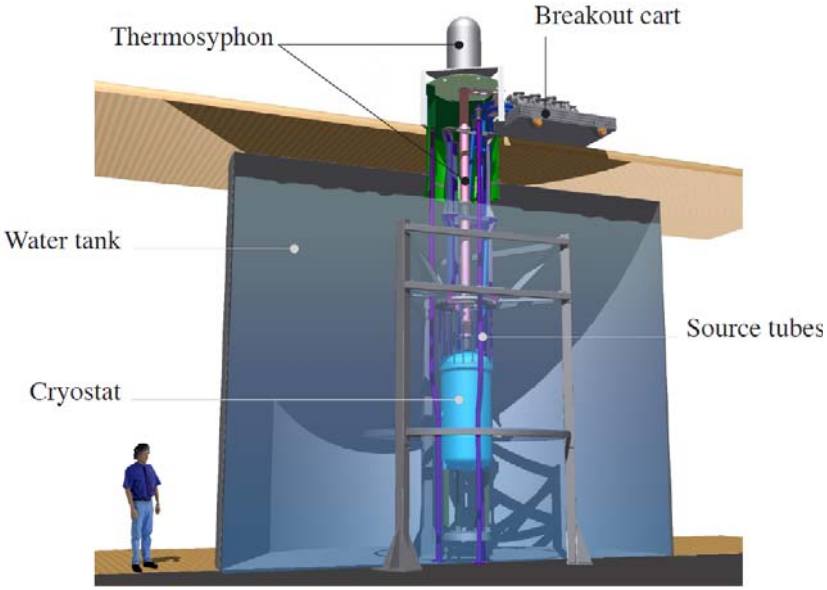



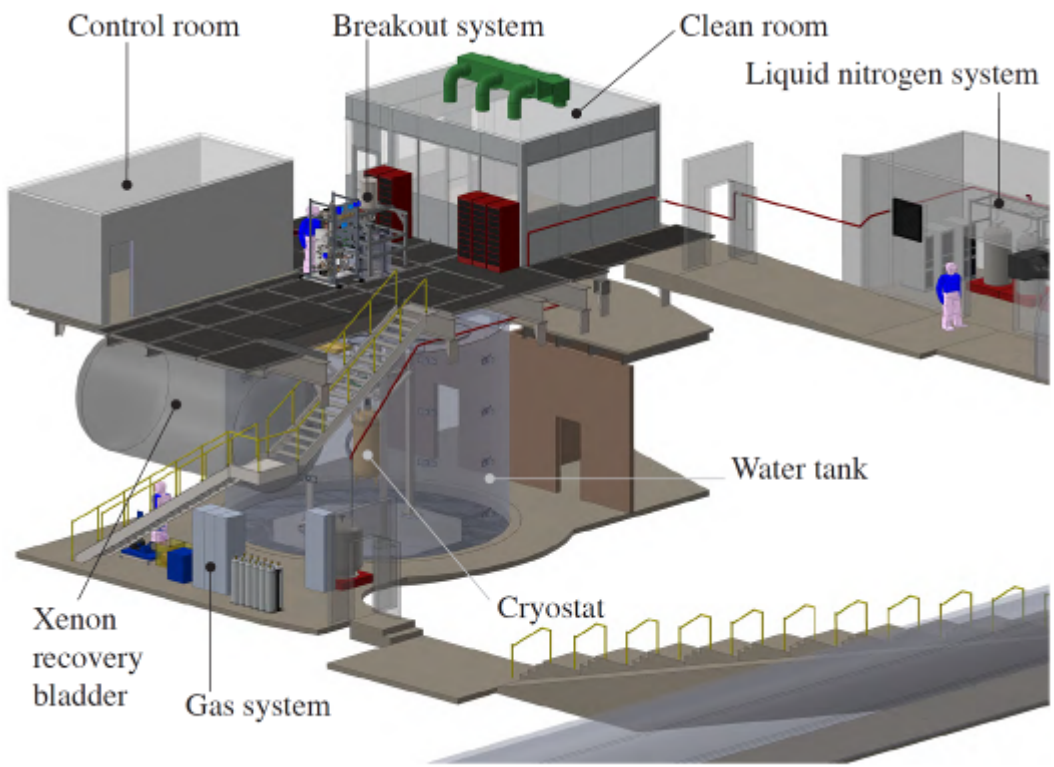

Muon flux reduced by $10^7$ (4.3 km.w.e)



# Эксперимент LUX

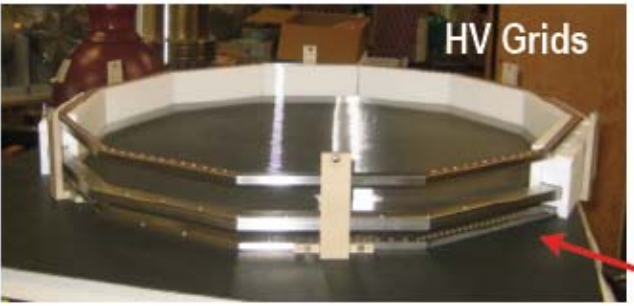
**Nucl. Instrum. Meth. A704 (2013) 111, arXiv:1211.3788 [physics.ins-det]**

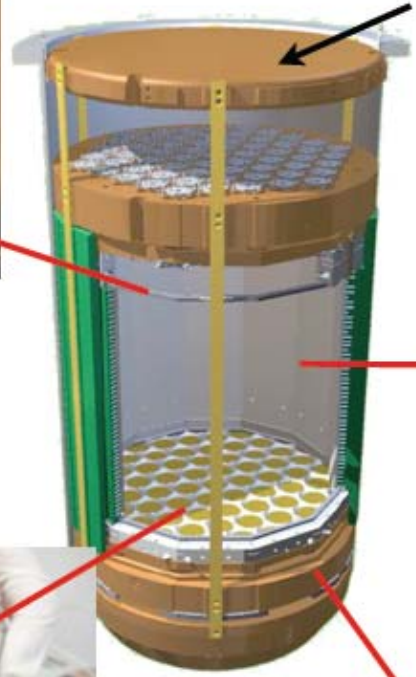


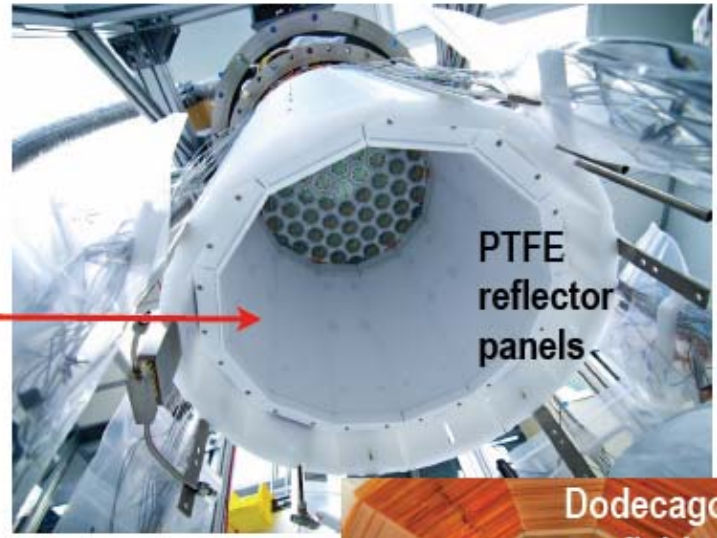



# Эксперимент LUX

# Эксперимент LUX

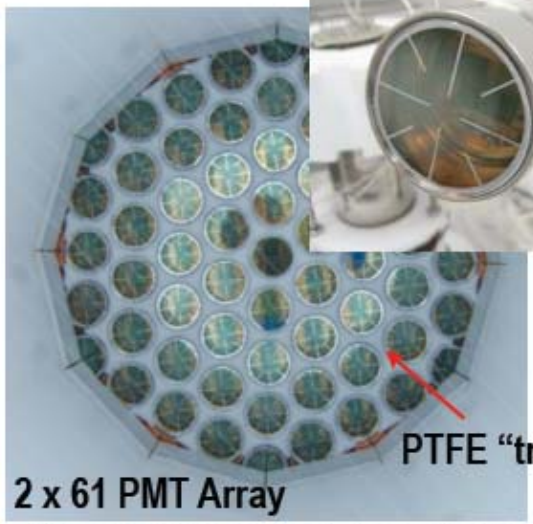


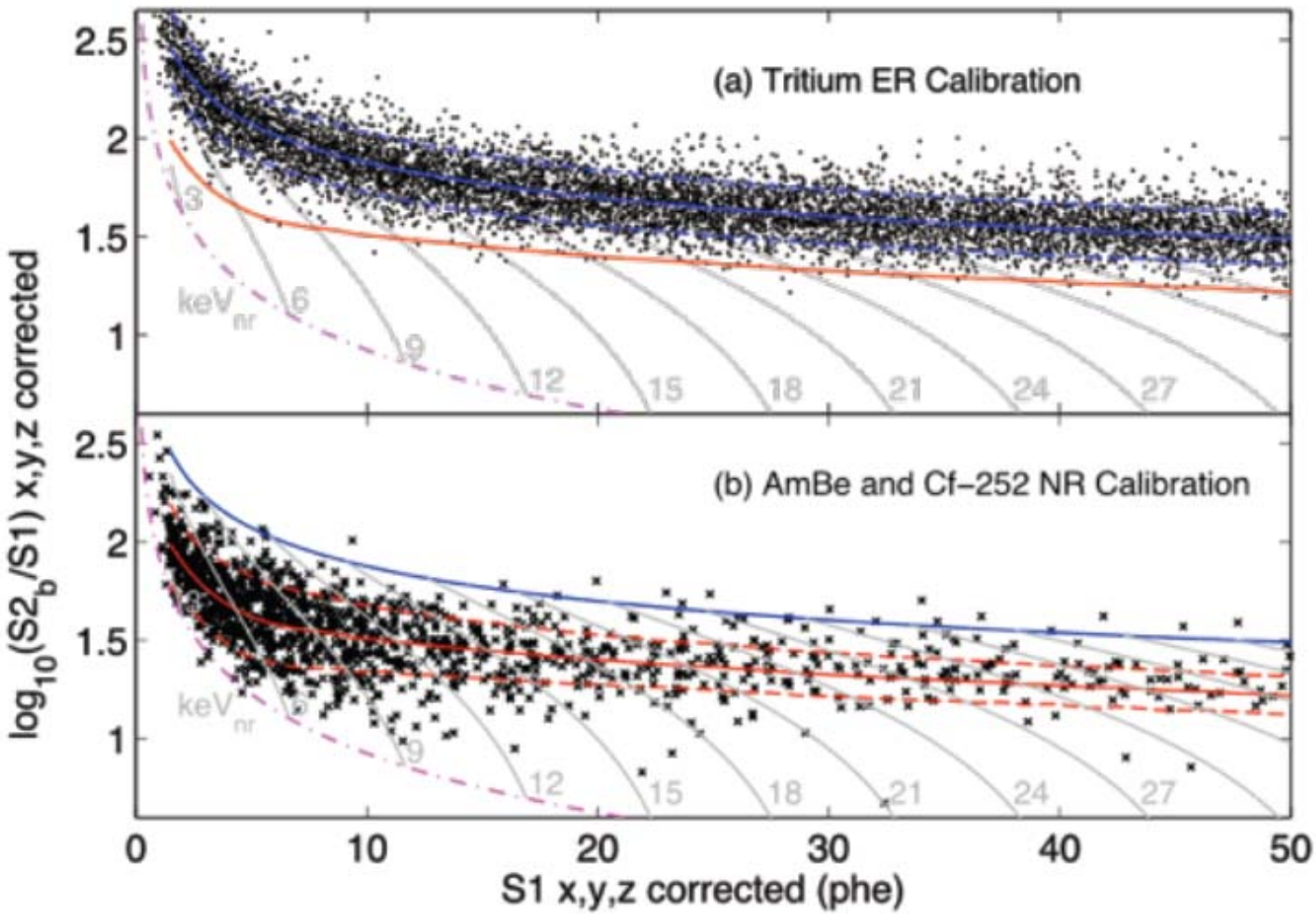

122 2" PMTs (Hamamatsu R8778)

- QE (175 nm) ~33%
- U/Th ~9/3 mBq/PMT



# LUX - Electron Recoil and Nuclear Recoil Bands

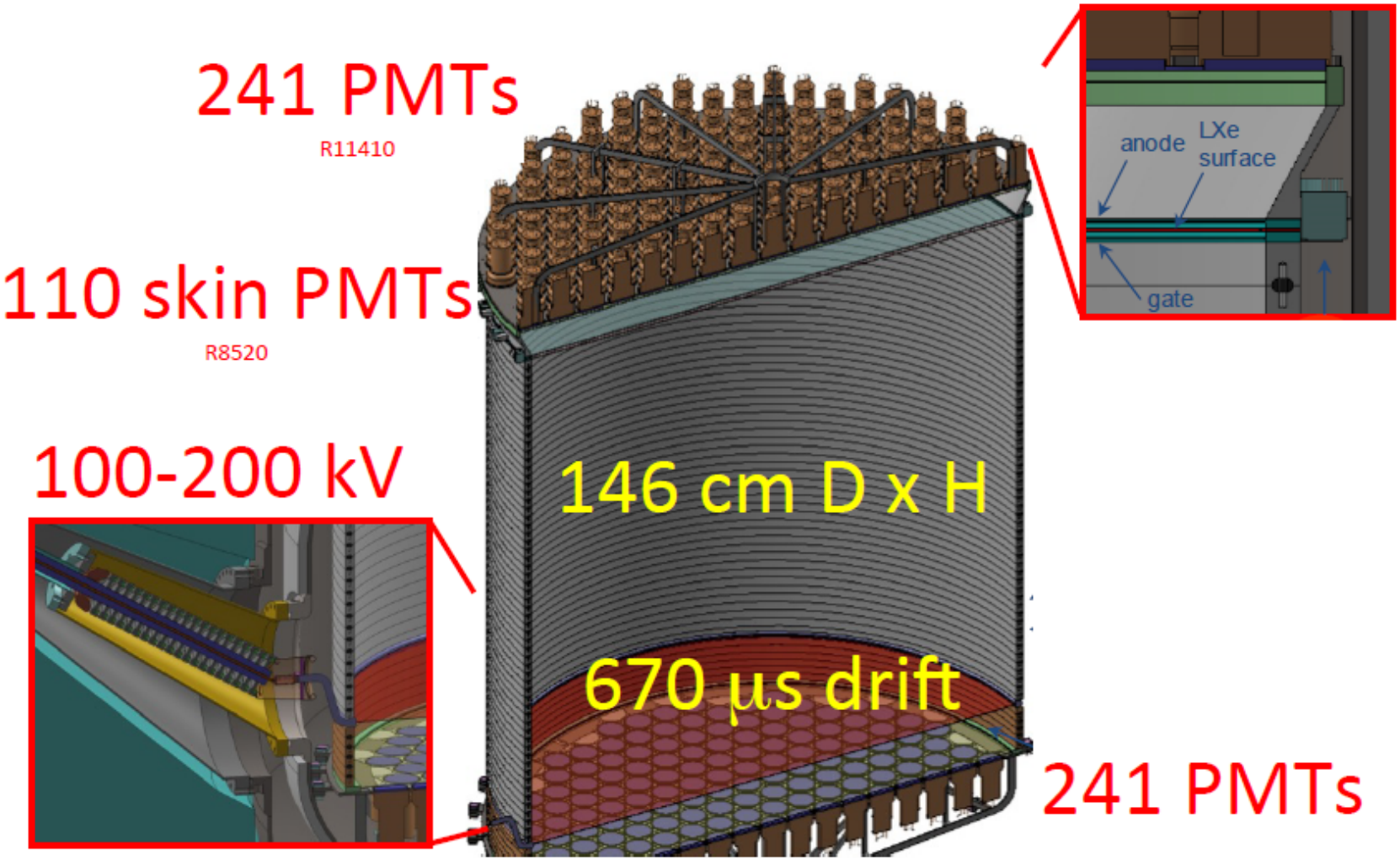
Tritium provides very high statistics electron recoil calibration (>>$10^3$ events/phe)
Neutron calibration is consistent with NEST + simulations



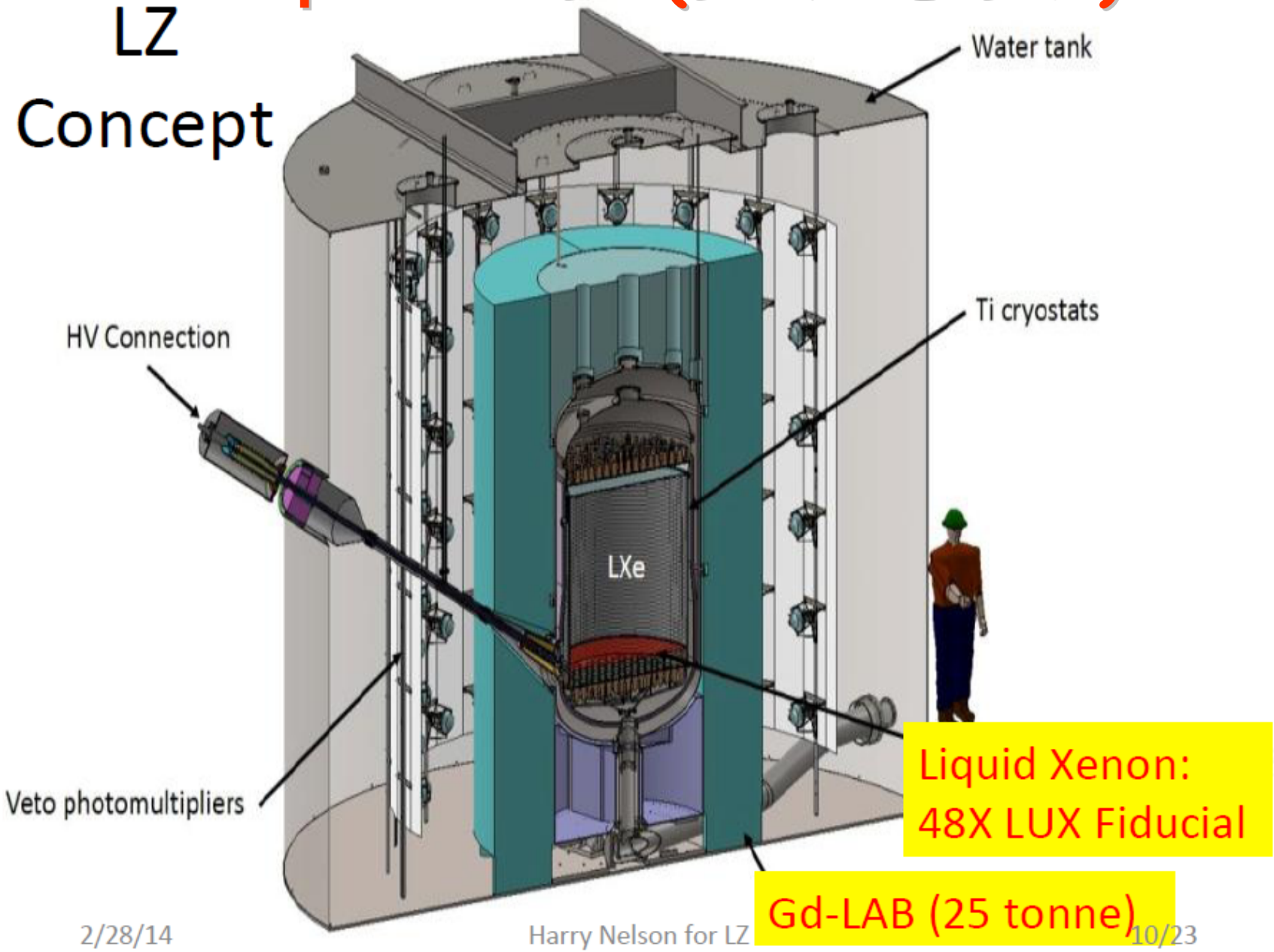

Gray contours indicate constant energies using a S1-S2 combined energy scale

# Эксперимент LZ (LUX-ZEPLIN)

## Central Xenon – 5600 kg Fiducial



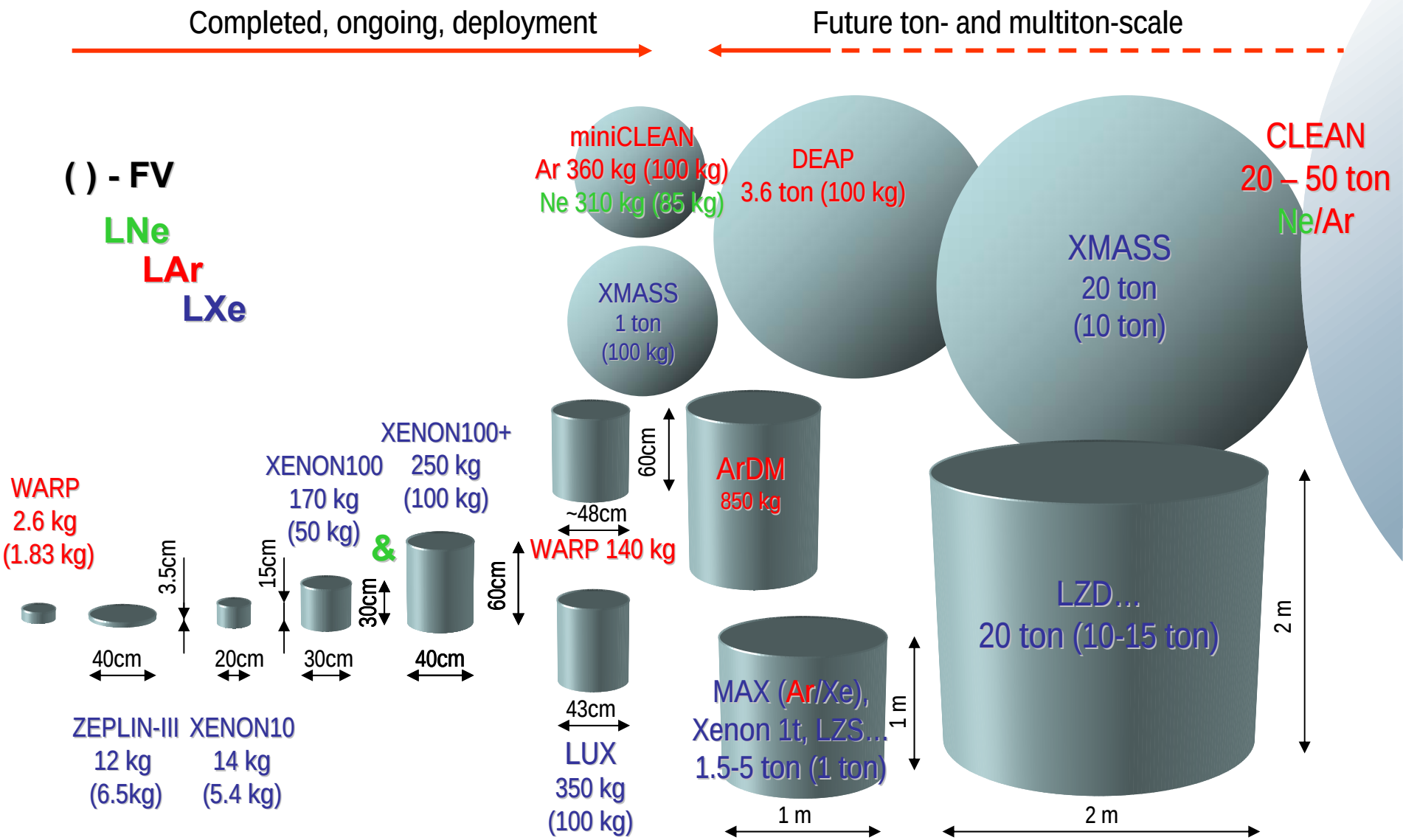
# Эксперимент LZ (LUX-ZEPLIN)



# Другие эксперименты с использованием жидких благородных газов

# Family of noble-liquid DM detectors

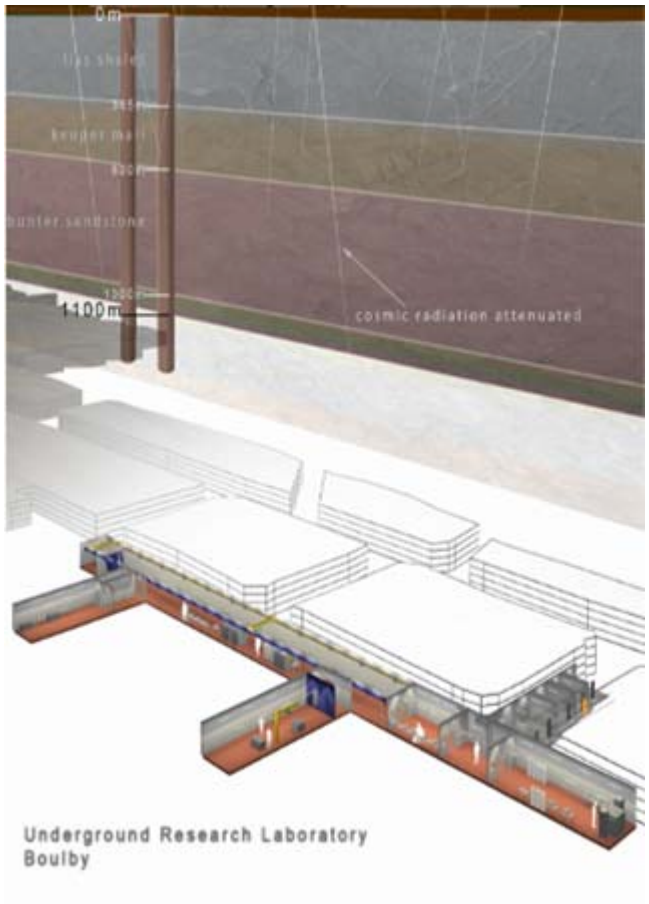
(**слайд** 2010 **года**)



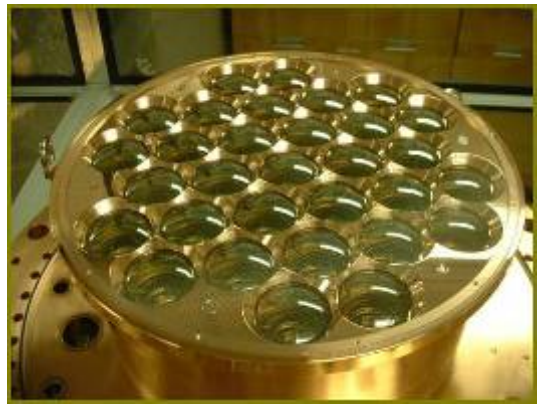
# Серия детекторов ZEPLIN

## ZEPLIN-I

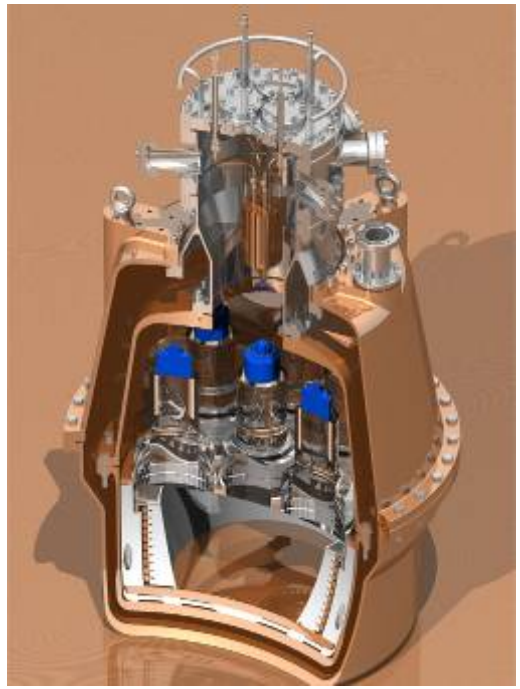
## Шахта Boulby, UK
## 1100 м

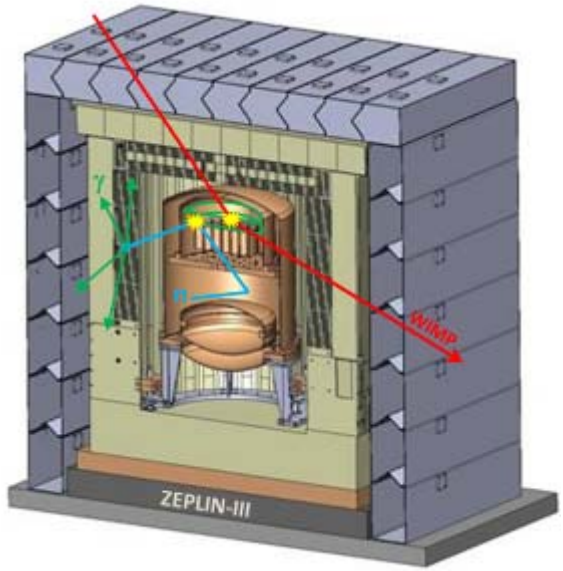



## ZEPLIN-III



## ZEPLIN-II

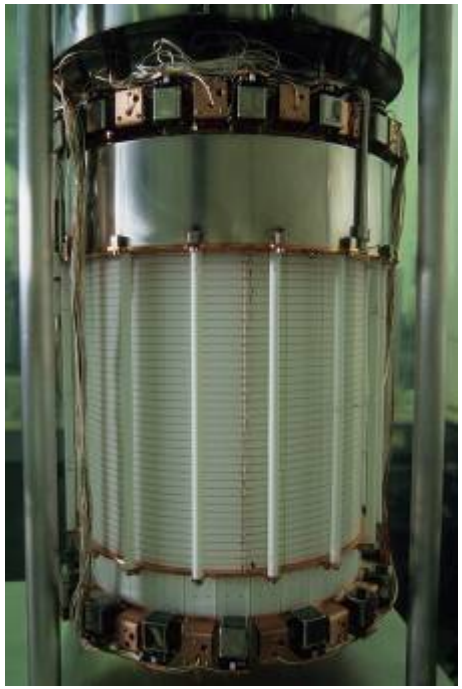




# Серия детекторов XENON

## XENON100

**161 kg**



2008-2015

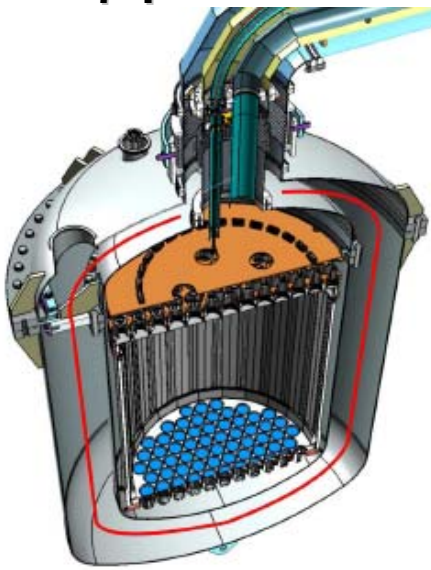
## XENON1T

**3.3 T**

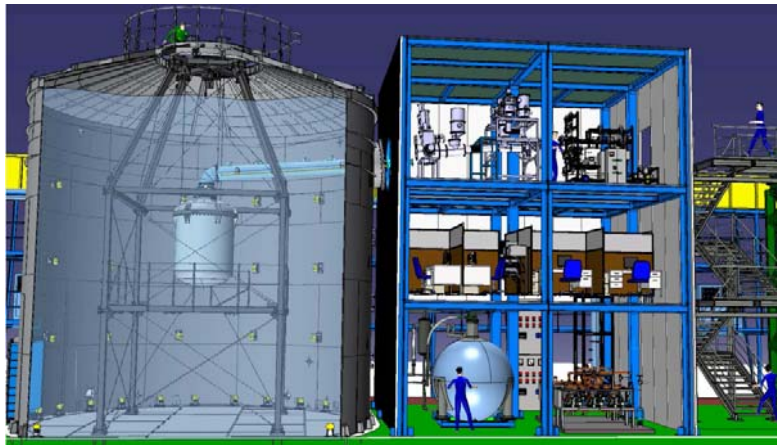
2012-2017

## XENONnT

**~ 7 T**

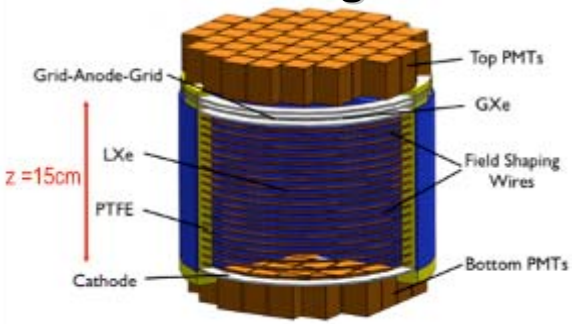


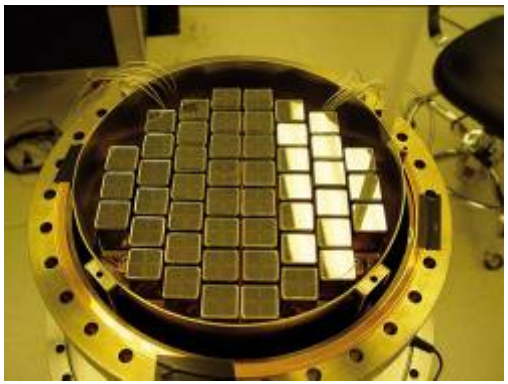
~2017-2022



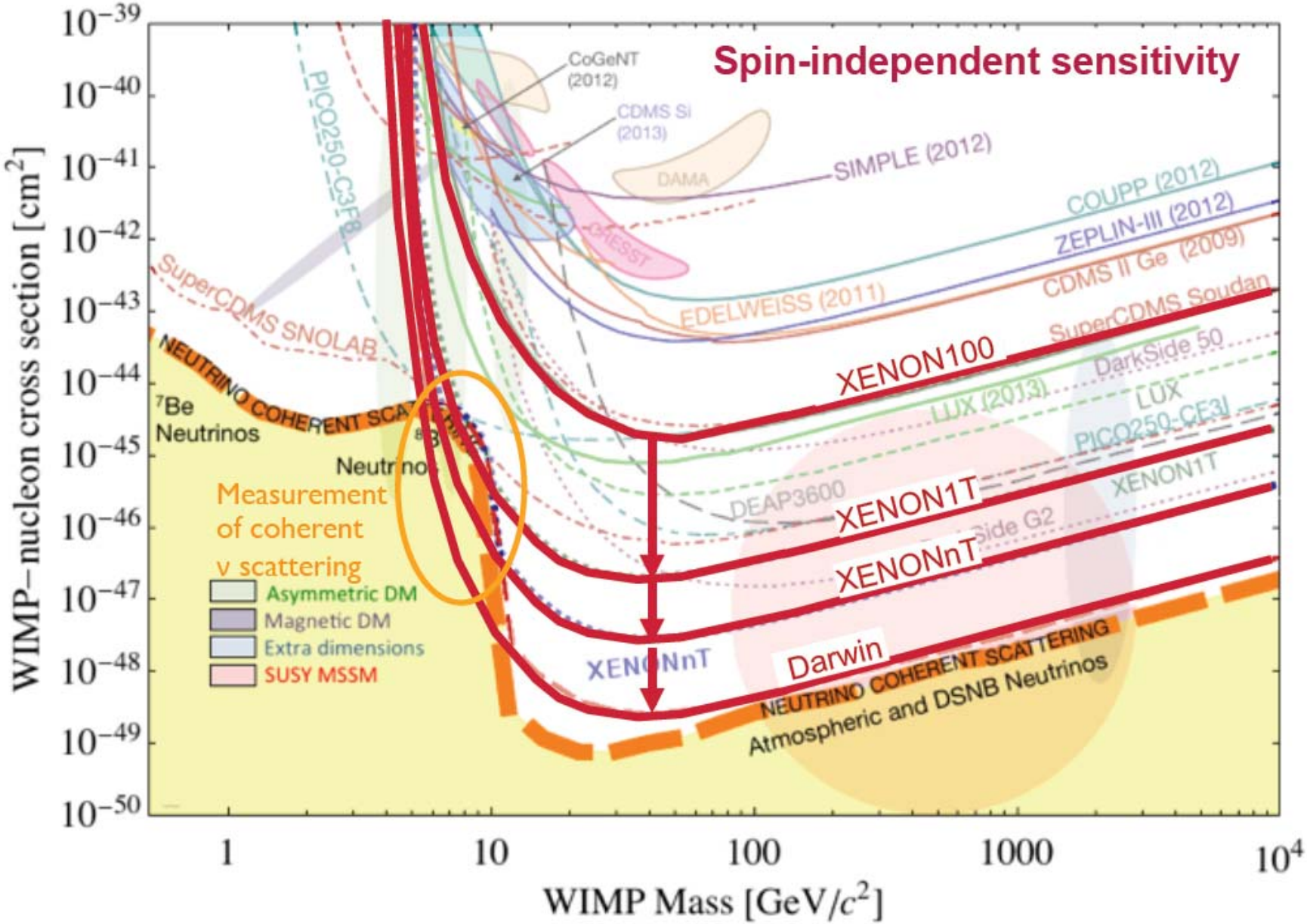
## XENON10

**25 kg**



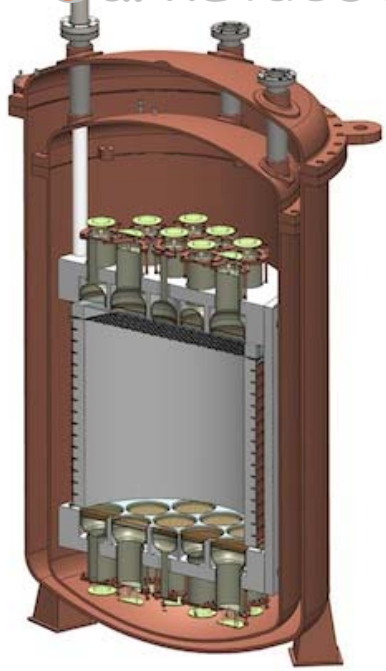



2005-2007

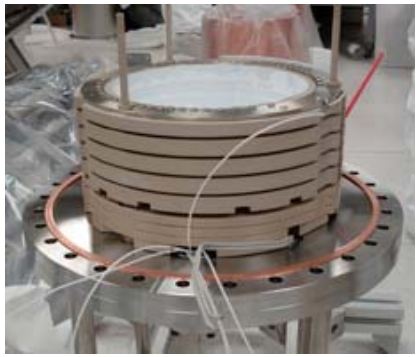

Spin-independent sensitivity
WIMP–nucleon cross section [cm$^2$]
WIMP Mass [GeV/$c^2$]
CoGeNT (2012)
CDMS Si (2013)
DAMA
CRESST
SIMPLE (2012)
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
SuperCDMS Soudan
PICO250-C3F8
SuperCDMS SNOLAB
NEUTRINO COHERENT SCATTERING
$^7$Be Neutrinos
$^8$B Neutrinos
Measurement of coherent ν scattering
Asymmetric DM
Magnetic DM
Extra dimensions
SUSY MSSM
XENON100
DarkSide 50
LUX (2013)
LUX
PICO250-CF3I
XENON1T
DEAP3600
XENON1T
DarkSide G2
XENONnT
XENONnT
Darwin
NEUTRINO COHERENT SCATTERING
Atmospheric and DSNB Neutrinos

# Серия детекторов на LAr

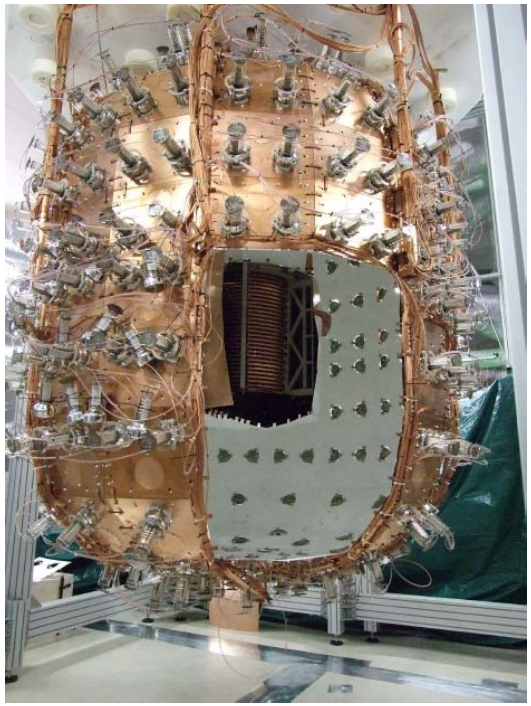
DarkSide50

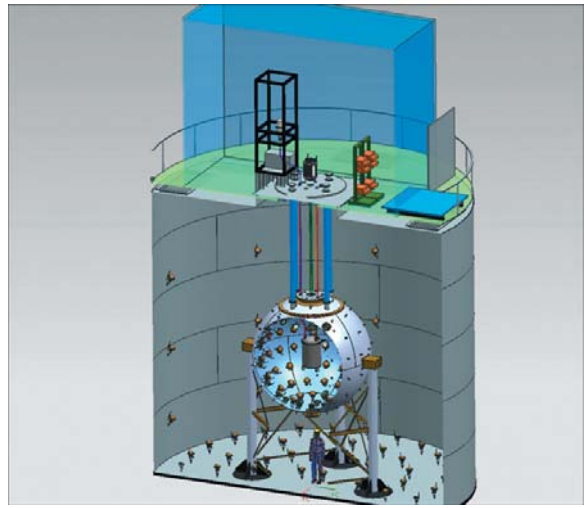


WARP 2.3 l

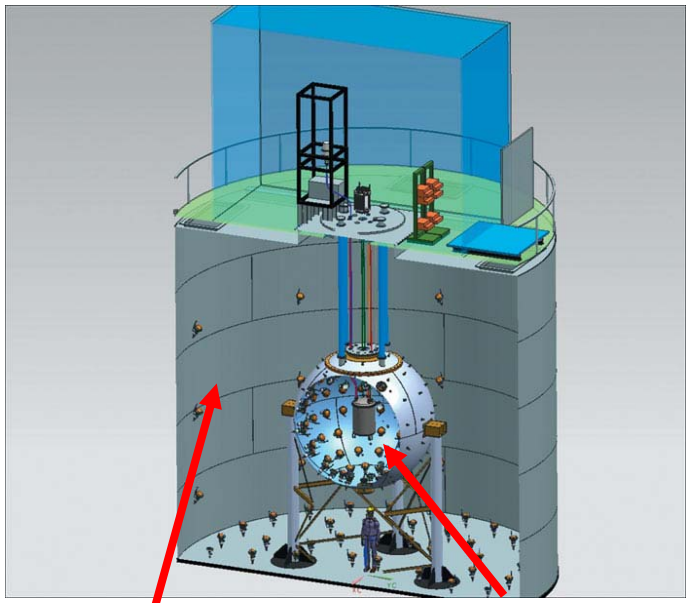


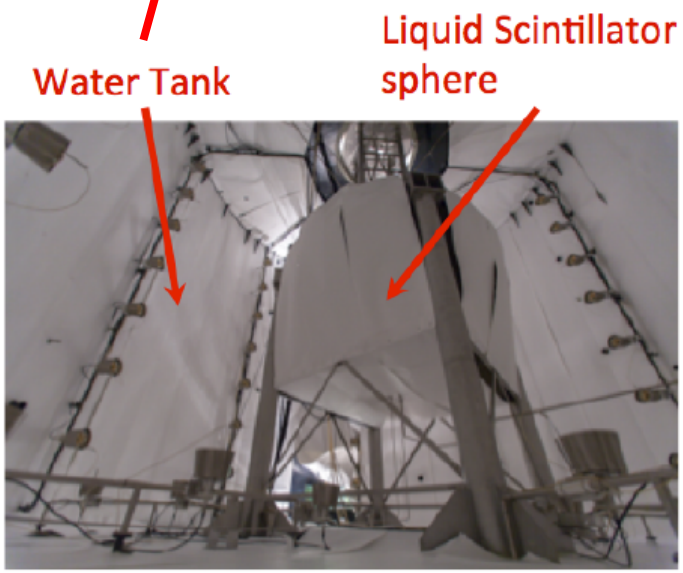
WARP 100 l





# DarkSide50



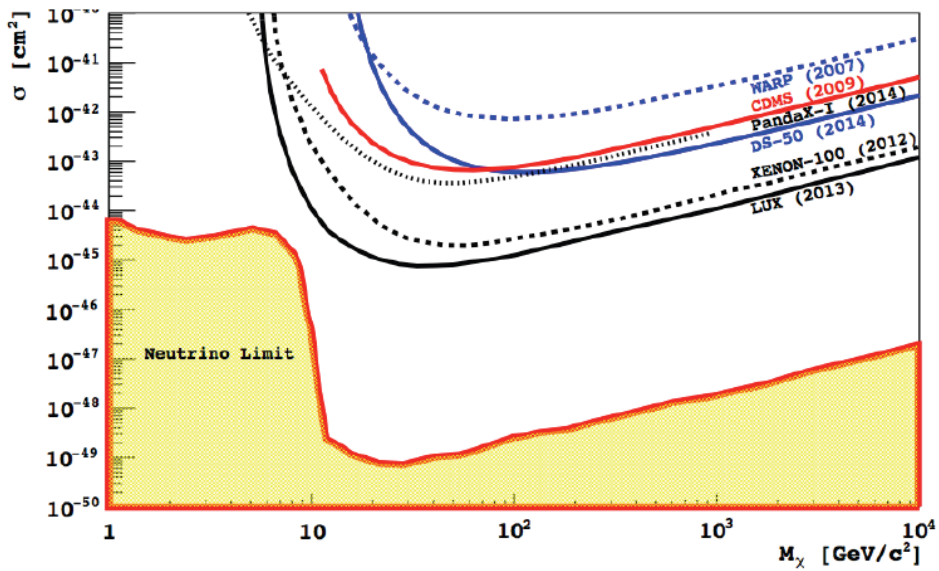



**В работе с октября 2013 г. с 3-мя заполненными детекторами**

**37/46 кg LAr FV/active, 30 t LS, 1kt $H_2O$**

**Заполнен "обычным" (атмосферным) аргоном**

**First Results from the DarkSide-50 Dark Matter Experiment at Laboratori Nazionali del Gran Sasso arXiv:1410.0653 [astro-ph.CO]**



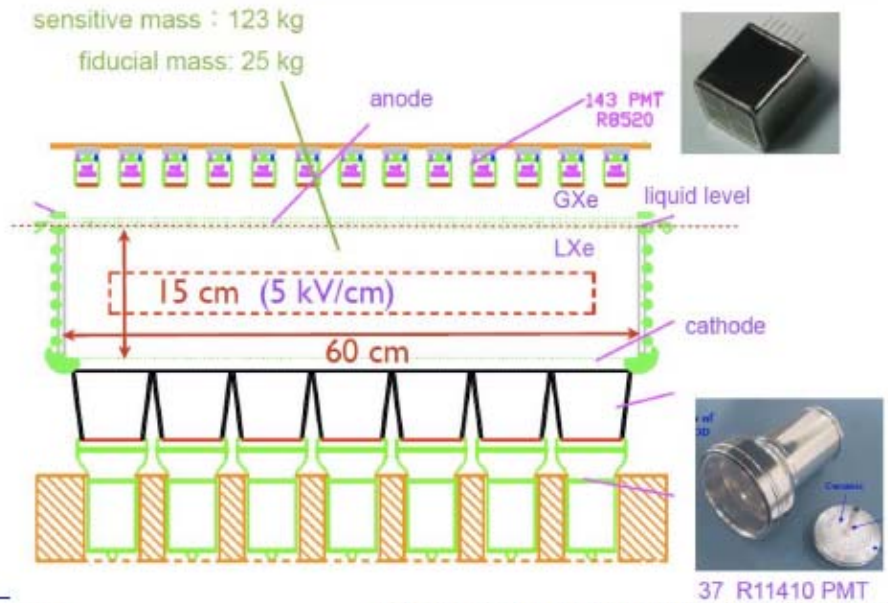
Thanks to Kaixuan Ni

# Panda-X

- Moved Panda-X equipment into Jinping Lab in Aug 2012
- Second test run (Aug-Oct,2013) of full assembly completed
  - 7 cm electron drift length, position reconstruction of 60Co events
- Dark Matter Search Runs
  - Phase Ia: 25 kg fiducial x 60 days (just reported)
  - Phase Ib: 300 kg fiducial x 180 days (start data taking in 2015)

**TPC assembly at CJPL**

***PANDAX: a LXe detector with high field & high light yield***



# Заключение

- Имеются очень сильные свидетельства в пользу существования Темной Материи.
- Эксперименты по прямому детектированию идут полным ходом.
- Благодаря прогрессу в технологиях, с начала экспериментов по настоящее время (за 27 лет) фон в установках уменьшен на 5 порядков величины!
- Супердетекторы (с массой несколько тонн) пройдут практически весь диапазон теоретических предсказаний и упрутся в непреодолимый нейтринный фон. В США гонку за G2 выиграли SupperCDMS и LZ.

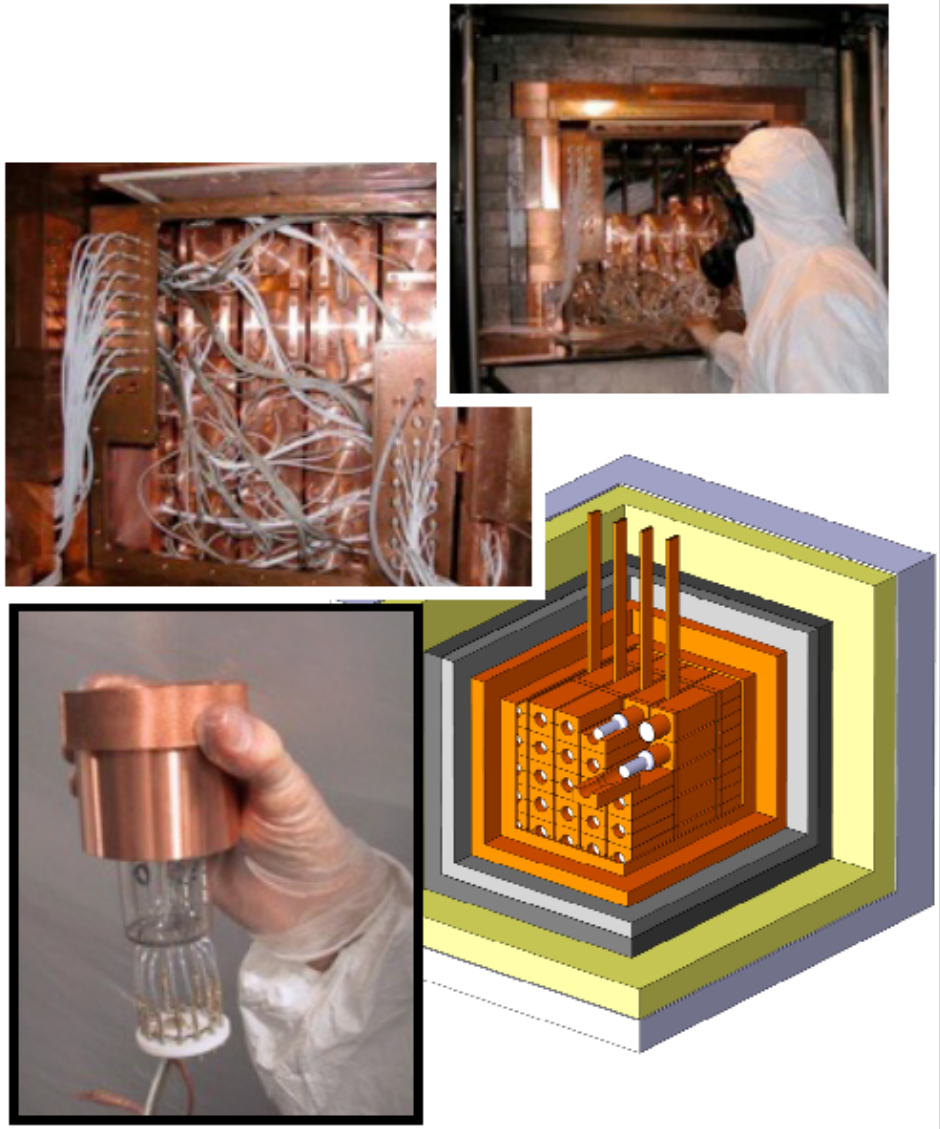
Эх!

Были бы потоки темной материи еще концентрированнее!

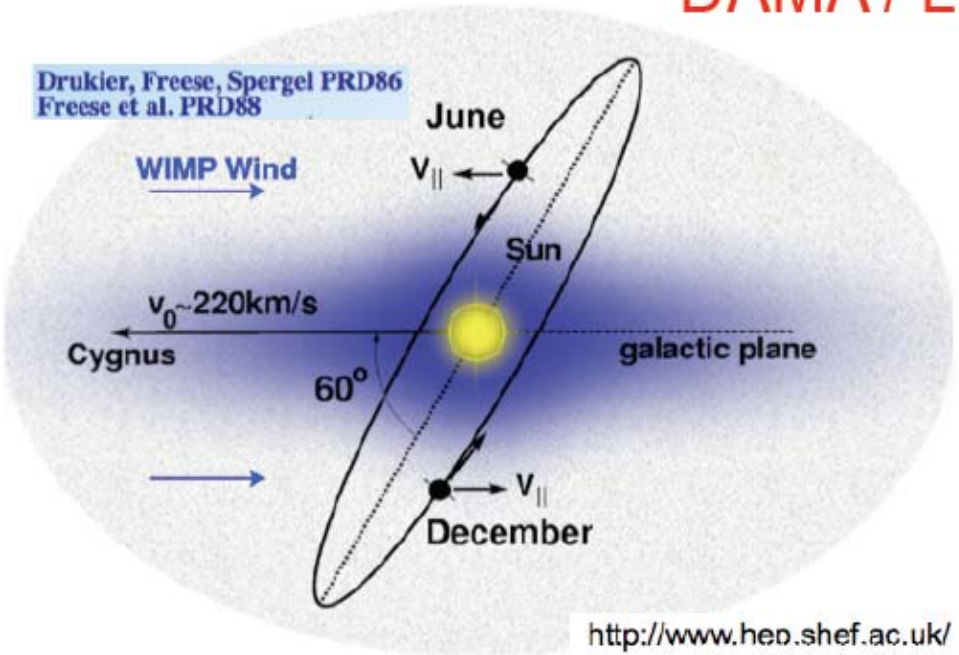
**Спасибо за внимание!**

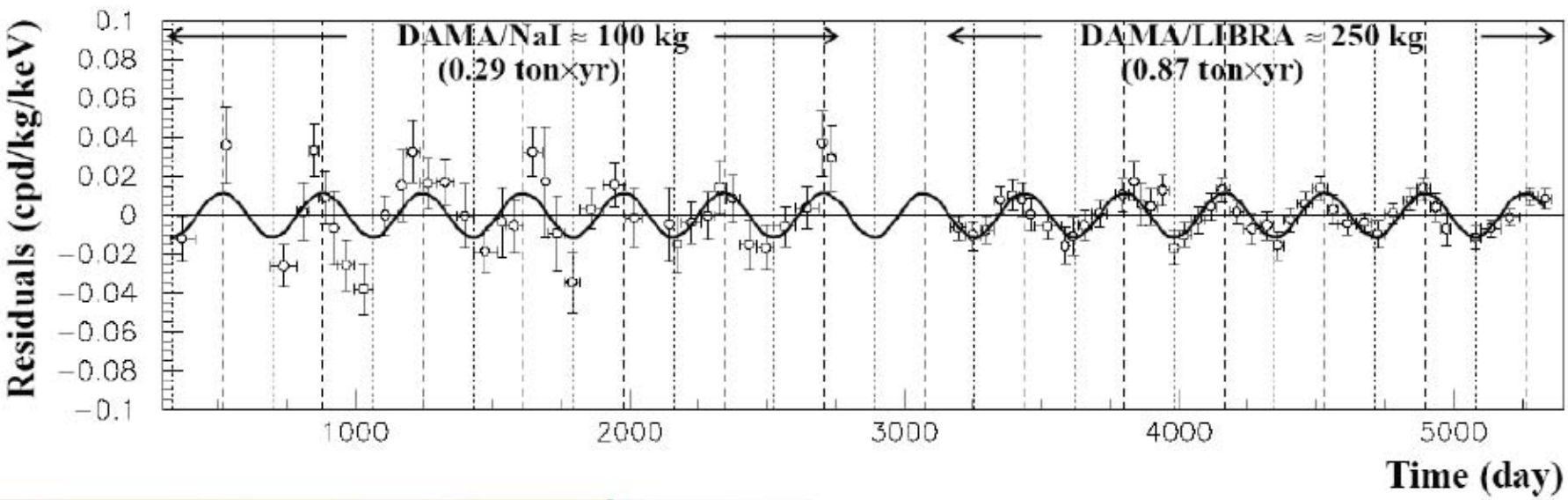
# DAMA (100 kg) → LIBRA (250 kg)

- DAMA
  - Original 100 kg NaI array, first reported positive results in 1989
- LIBRA
  - Large sodium Iodide Bulk for RAre processes
  - Operating since 2003 in LNGS
  - Modulation persists: total of 13 cycles



# DAMA / LIBRA




- Annual Modulation
  - Significance is 8.9σ
  - 1-2% effect in bin count rate
  - Appears in lowest energy bins
  - Can another experiment observe this effect?