Поиск темной материи

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Физическая мотивация

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

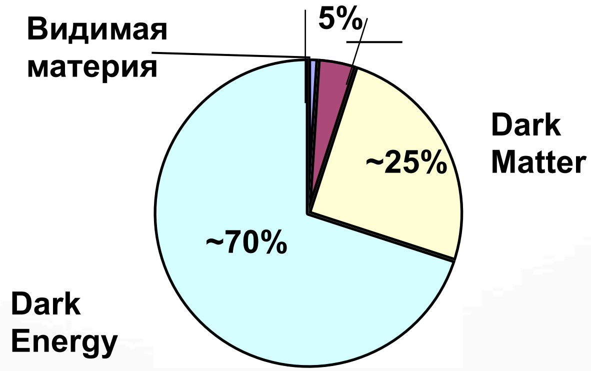
Астрофизическая мотивация

- Кривые вращения спиральных галактик
- Гравитационное линзирование скоплениями галактик

Космологическая мотивация

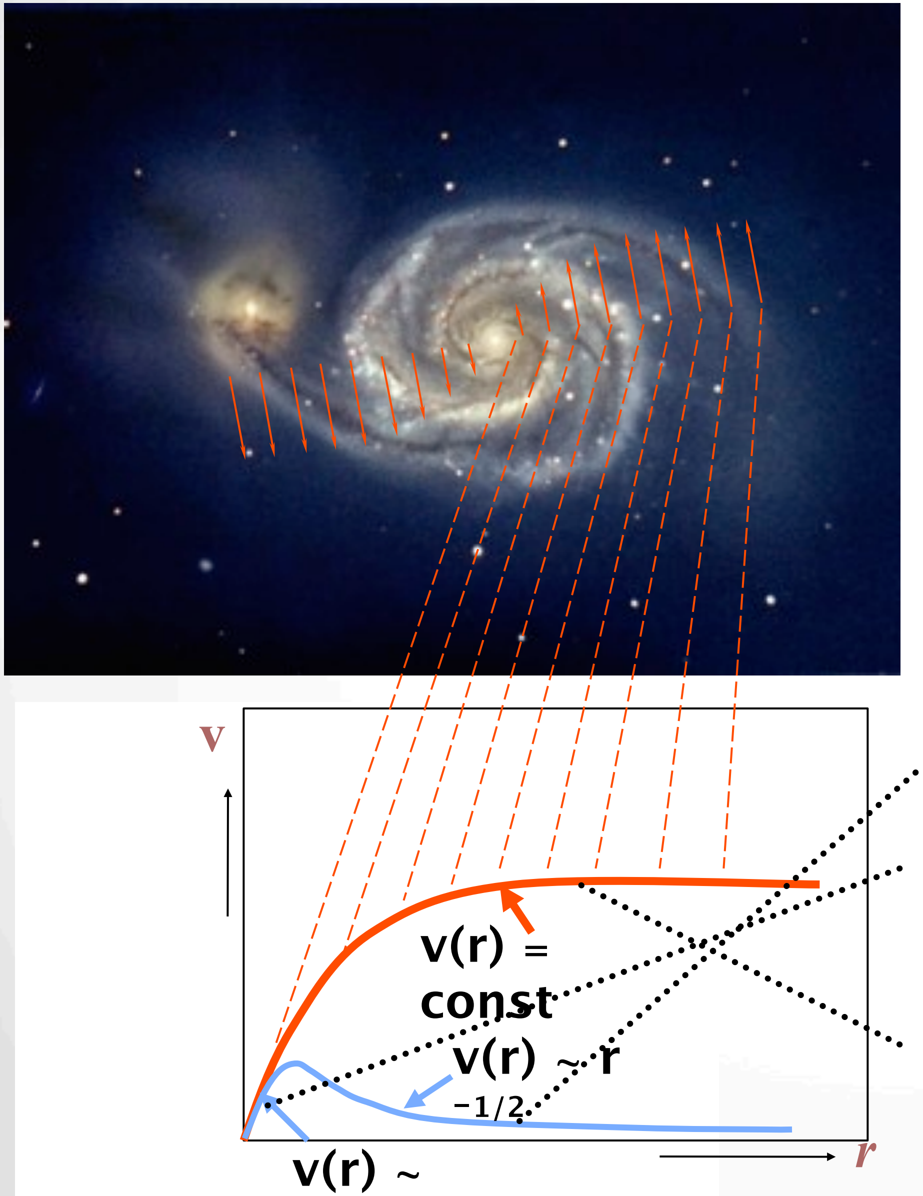
- Крупномасштабная структура Вселенной
- Анизотропия реликтового излучения (CMB)
- N-body симуляция
- Замечательное согласие выводов по CMB and SN Ia
- Теория нуклеосинтеза

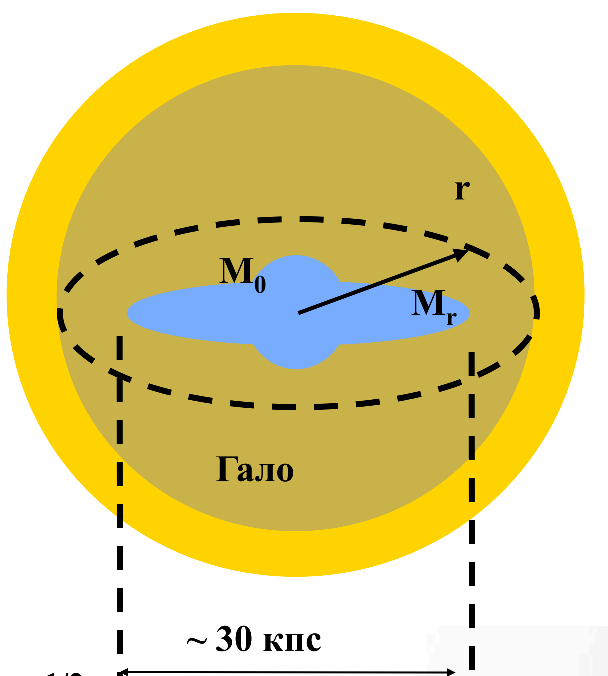
Современная космологическая модель



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 $M_r \sim r$

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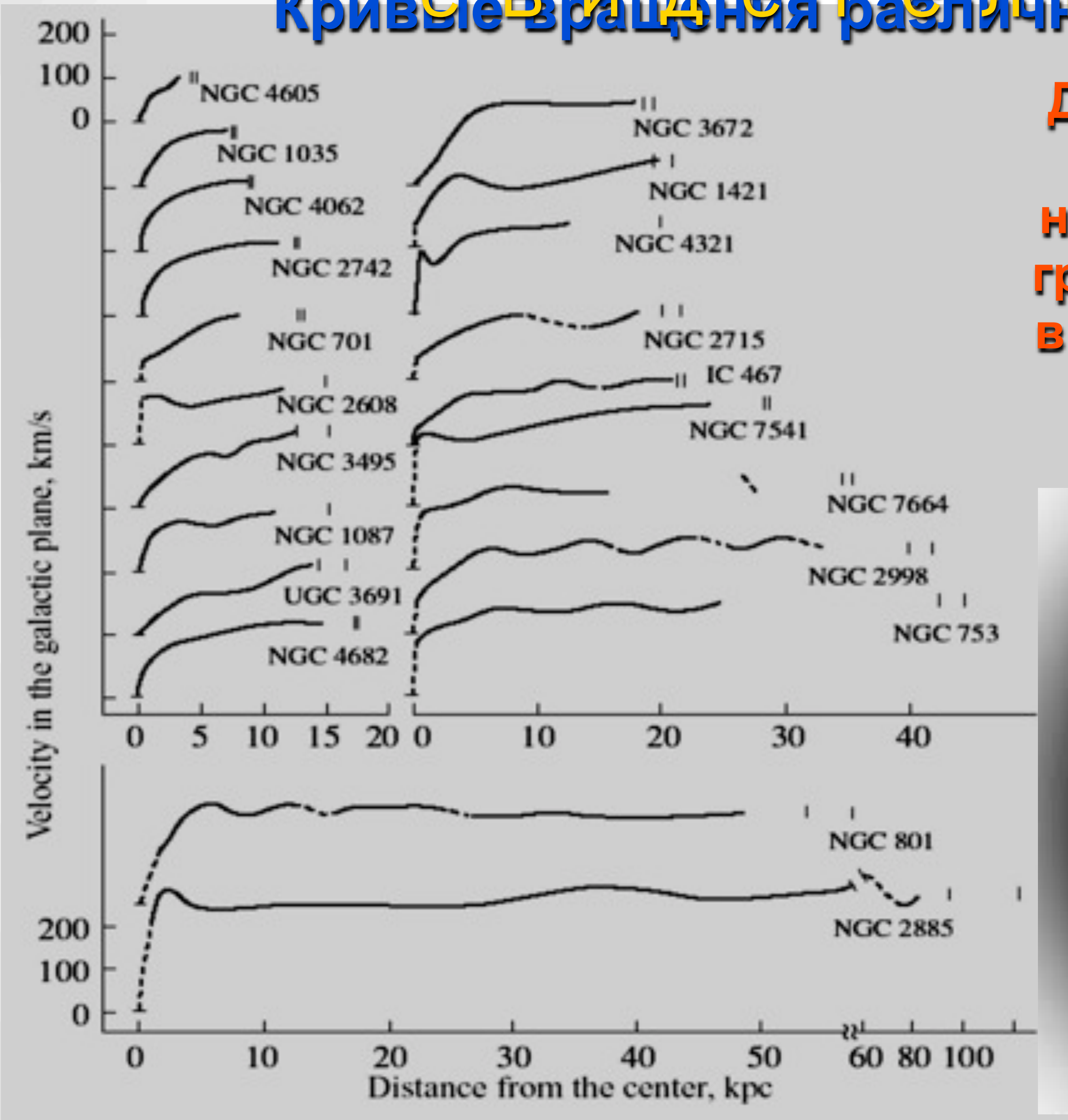
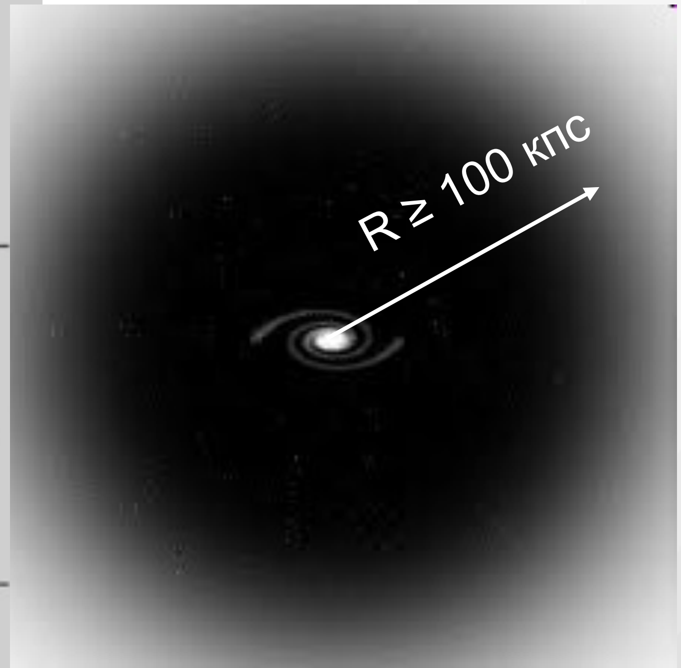
Кривые вращения различных галактик

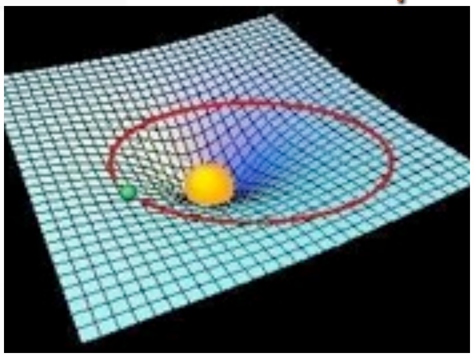


Для объяснения такого поведения кривых необходимо количество гравитирующей материи в ~10 раз превышающее количество видимой!

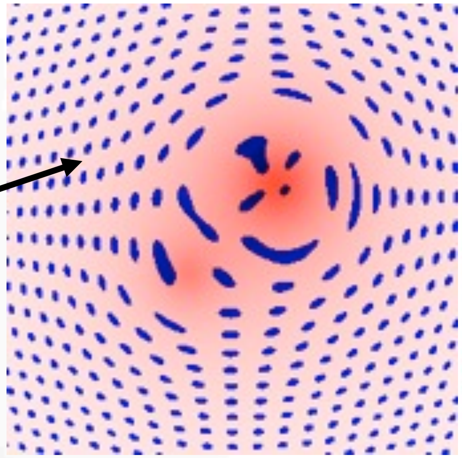


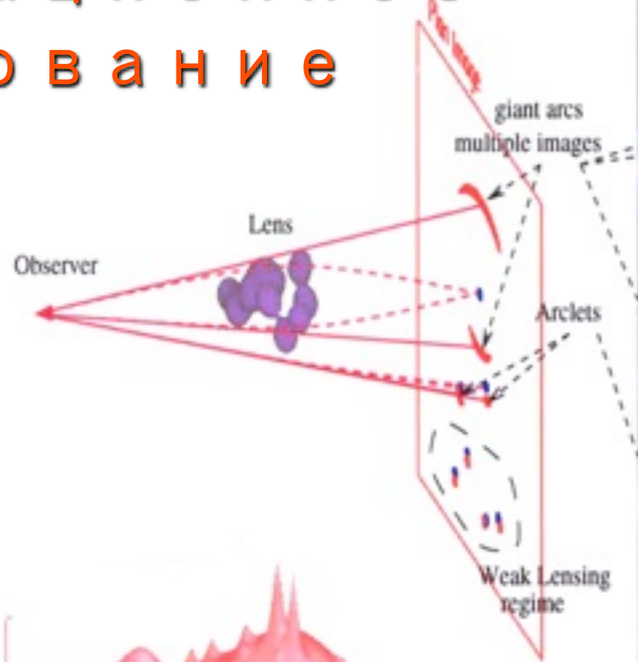
Астрофизические свидетельства

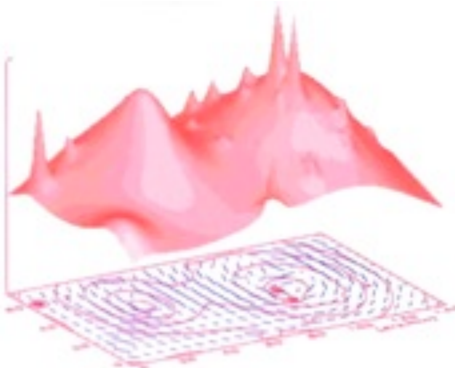
Гравитационное линзирование

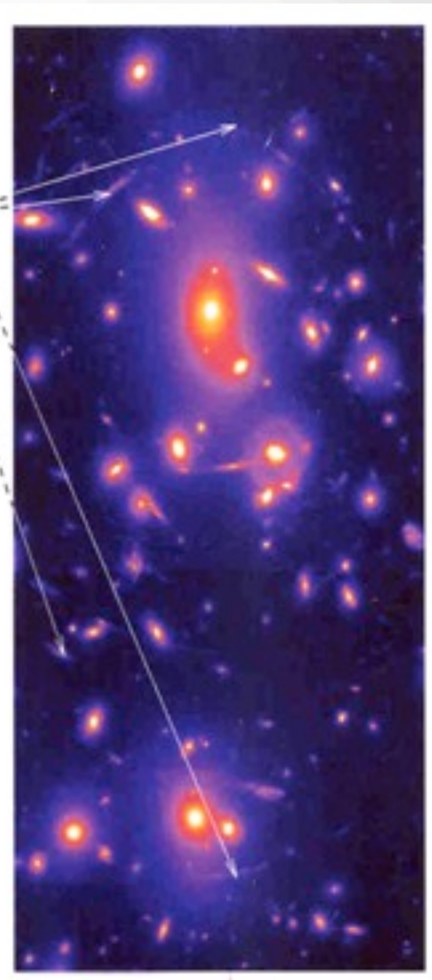


Так выглядел бы регулярный паттерн, находящийся за "размазанным" массивным



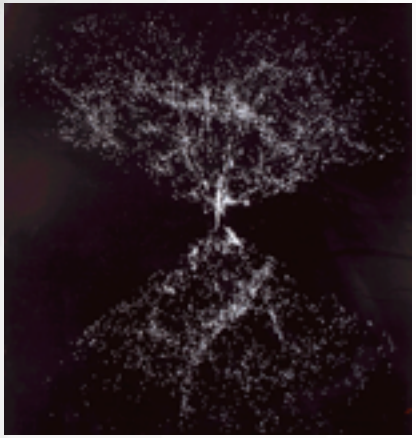




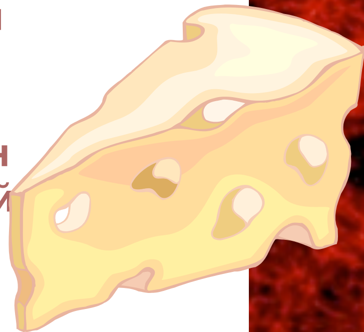


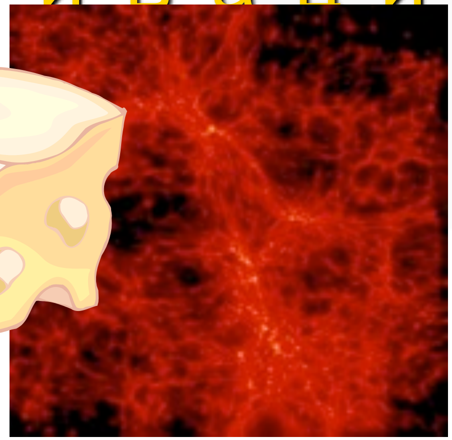
Также требуется в ~10 раз большая масса

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.

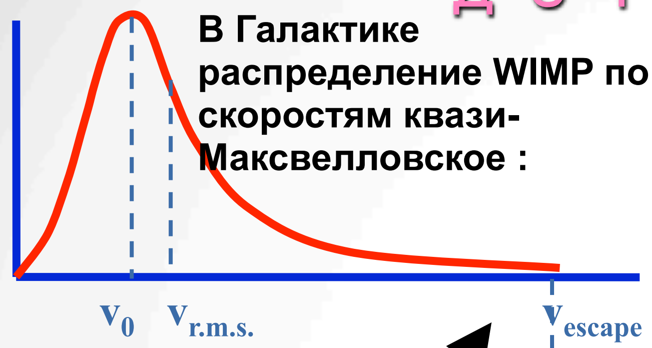
Нейтралино – наиболее вероятный кандидат в WIMP - (Weakly Interacting Massive Particles)

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

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

Регистрация WIMP: прямое детектирование

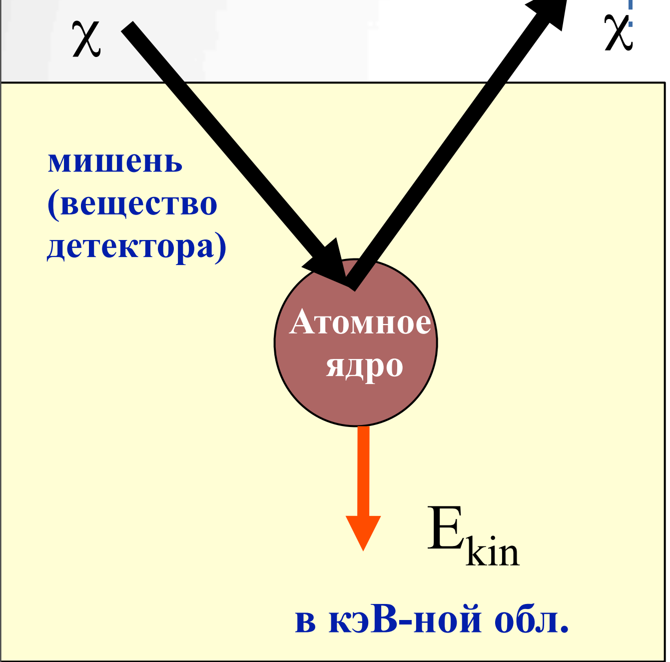
В Галактике распределение WIMP по скоростям квази-Максвелловское :



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

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

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



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

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

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,

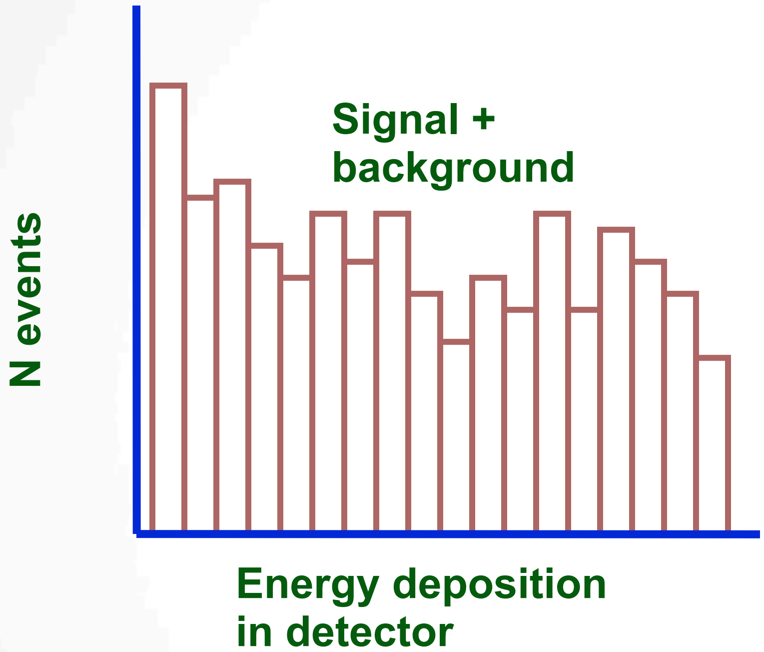
N_N – number of target nuclei,

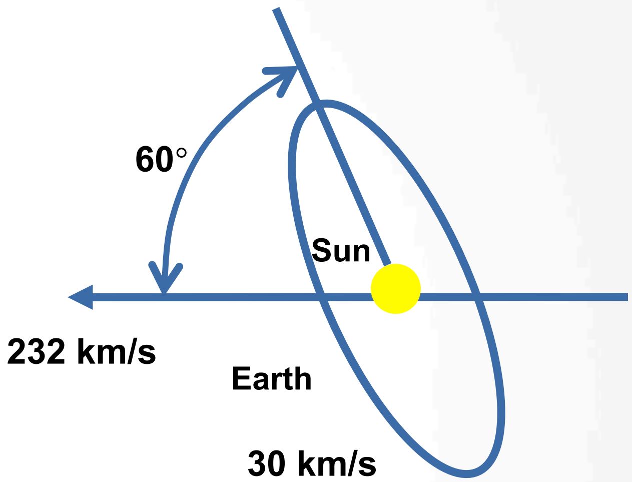
ρ = 0.3 GeV/cm^3 – WIMP density in Galactic halo,

σ – WIMP interaction cross-section,

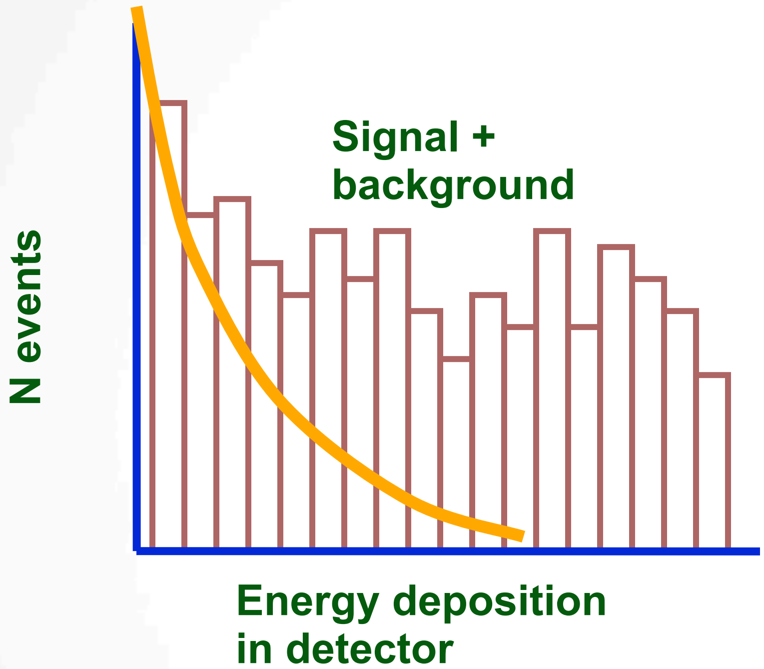
$F_N^2(E)$ – nuclear form factor

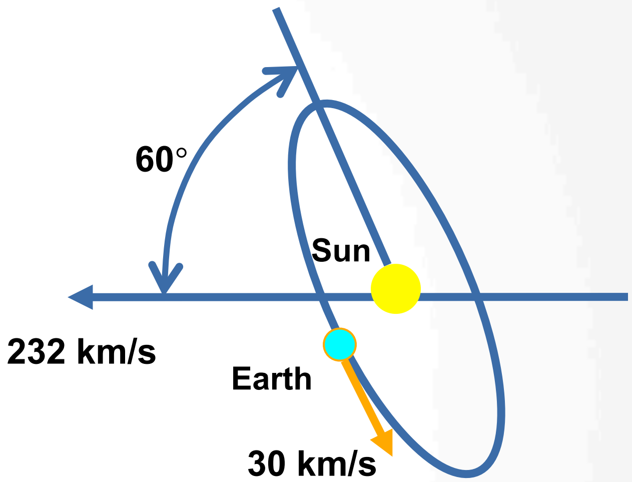
Регистрация WIMP: годичная модуляция



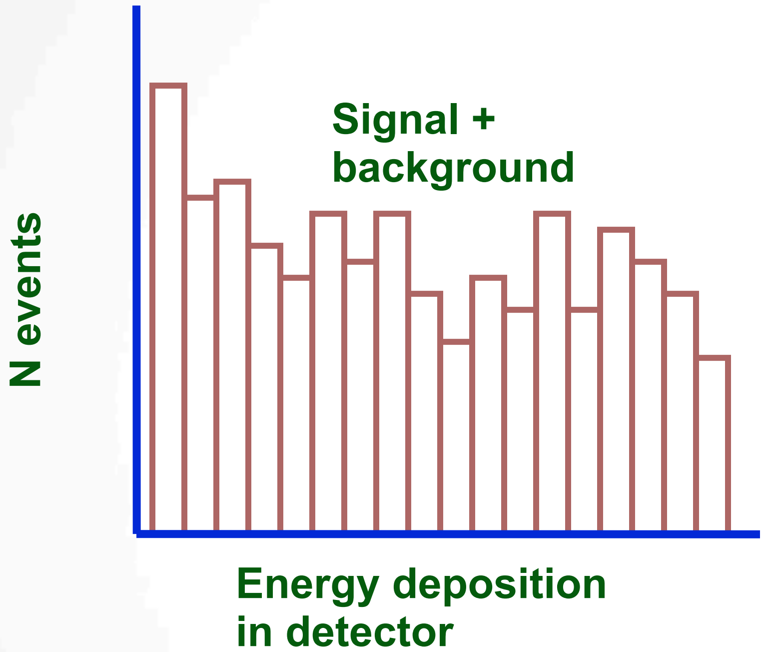


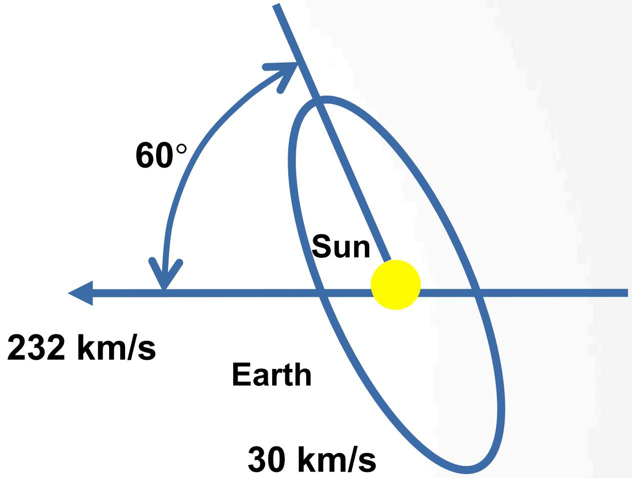
Регистрация WIMP: годичная модуляция



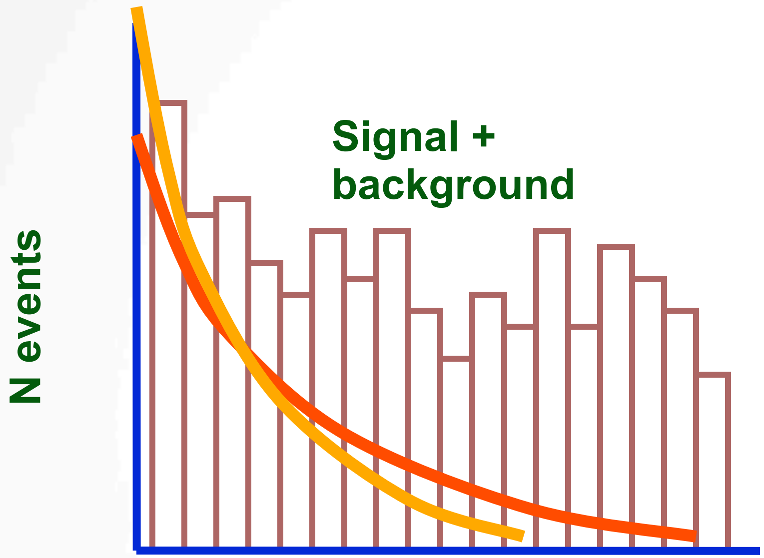


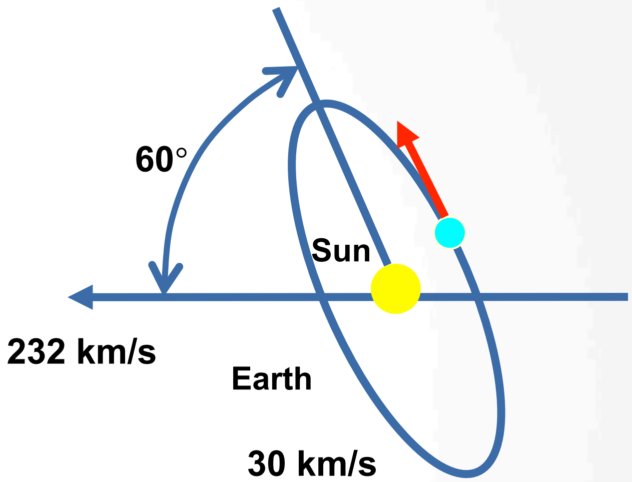
Регистрация WIMP: годичная модуляция



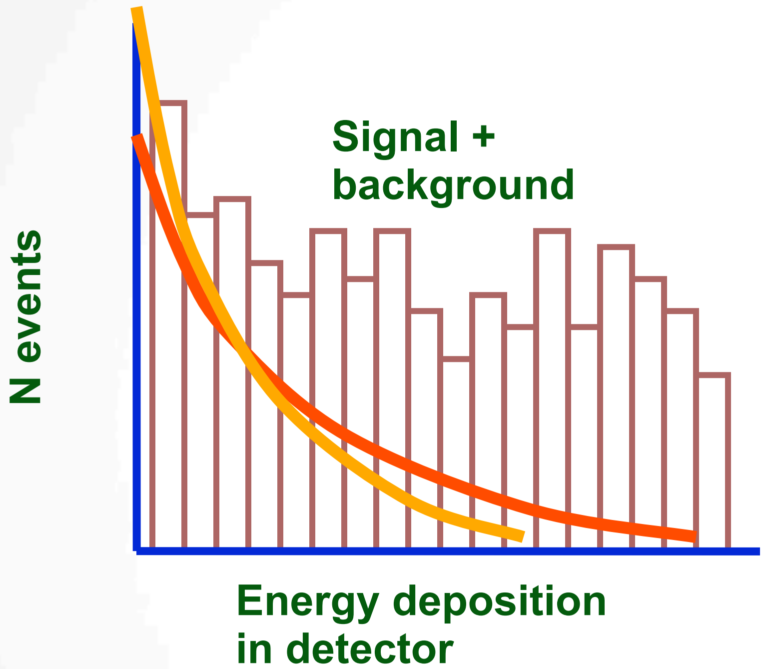


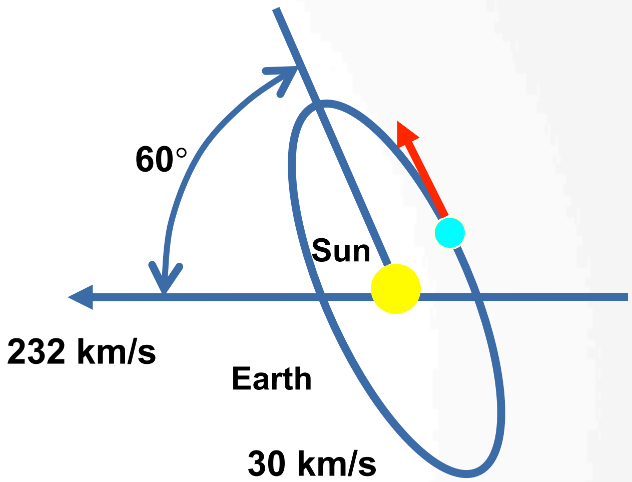
Регистрация WIMP: годичная модуляция





Регистрация WIMP: годичная модуляция





Ожидаемая вариация темпа счета WIMP ~ 5%

(с максимумом 2 го июня)

Experimental Ideas

$$\frac{dR}{dT}$$

DAMA
CDMS
EDELWEISS
ROSEBUD
XENON
XMASS
HDMS
ZEPLIN
CRESST
DEMOS
ELEGANTS

$$\frac{dR}{dT\ dcos}$$

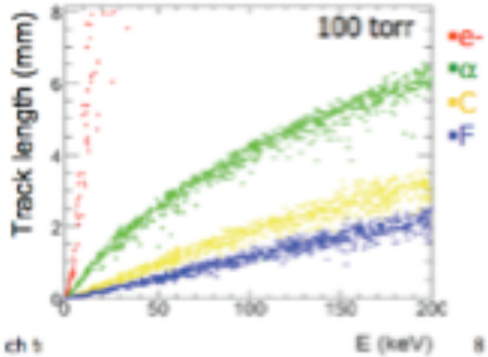
DRIFT

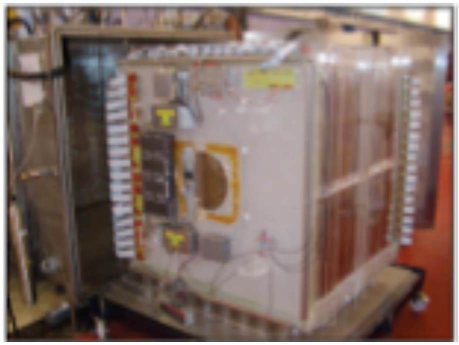
RDM –

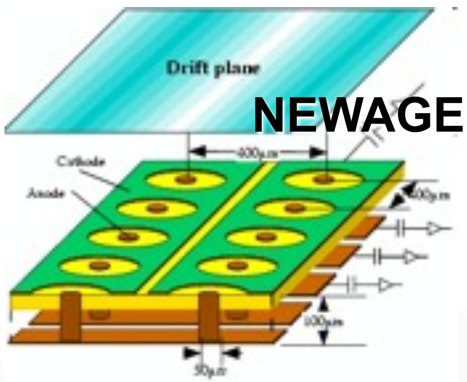
Directional Experiments

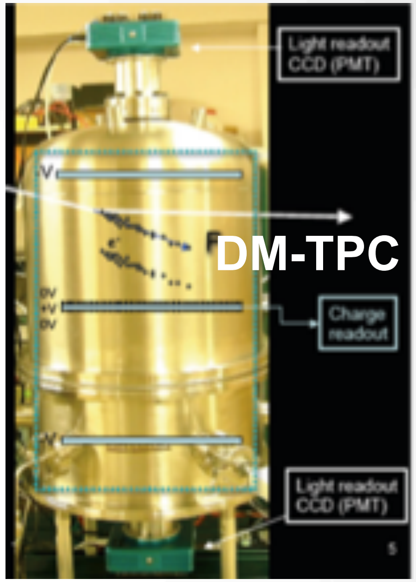
Directional detectors with low pressure gas (large volume)
Challenge is to measure 3D tracks of low energy recoils

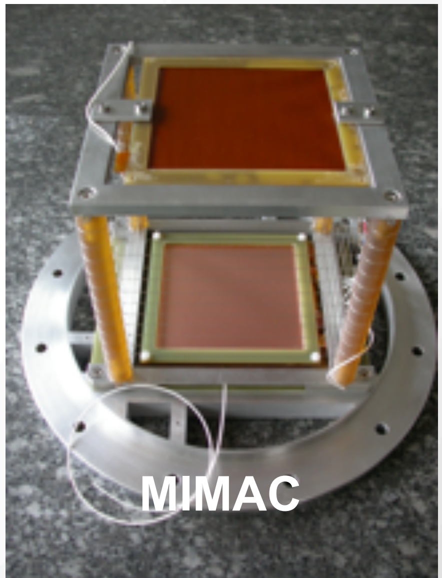
- DRIFT-II @ Boulby mine: 1 m3 MWPCs with 40 torr CS2 (167 g)
- DM-TPC @ MIT: 2x 10-2 m3 with 50 torr CF4 (PMTs + CCD readout for 3D + E)
- NEWAGE @ Kamioka: 23 x 28 x 30 cm3 TPC with 150 torr CF4 and microwell readout
- MIMAC @ Saclay : 3 He & CF4 TPC modules (3 x 3 cm





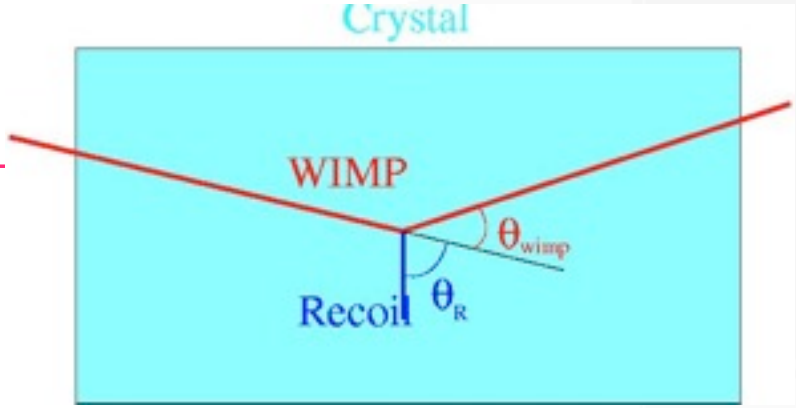


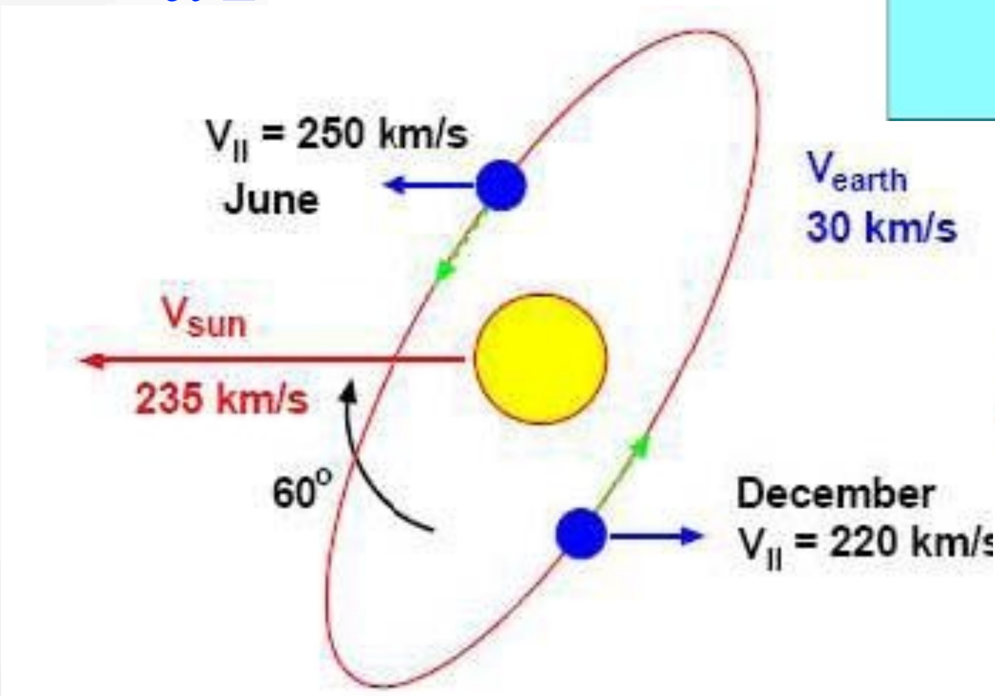


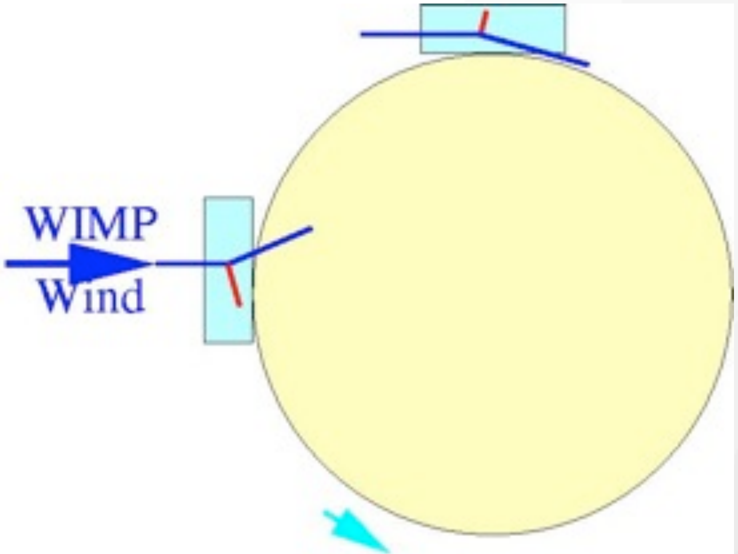


Dark matter Direct

$$\frac{d\sigma}{dT} \qquad \frac{d\sigma}{dTd\cos\theta_R}$$

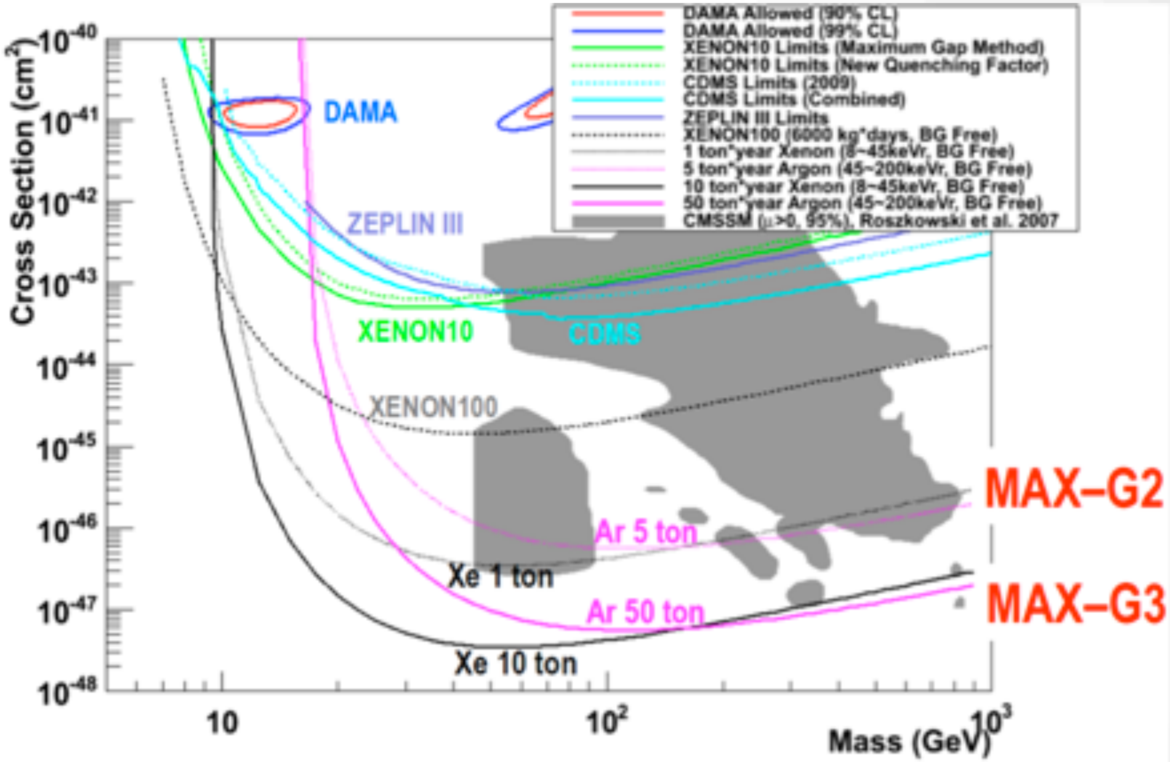






Status of direct WIMP searches

- DAMA (NaI)
- CDMS (Ge)
- EDELWEISS (Ge)
- CRESST (CaWO)
- ZEPLIN (Xe)
- New Experiments
- XENON
- XMASS
- DRIFT
- PICASSO

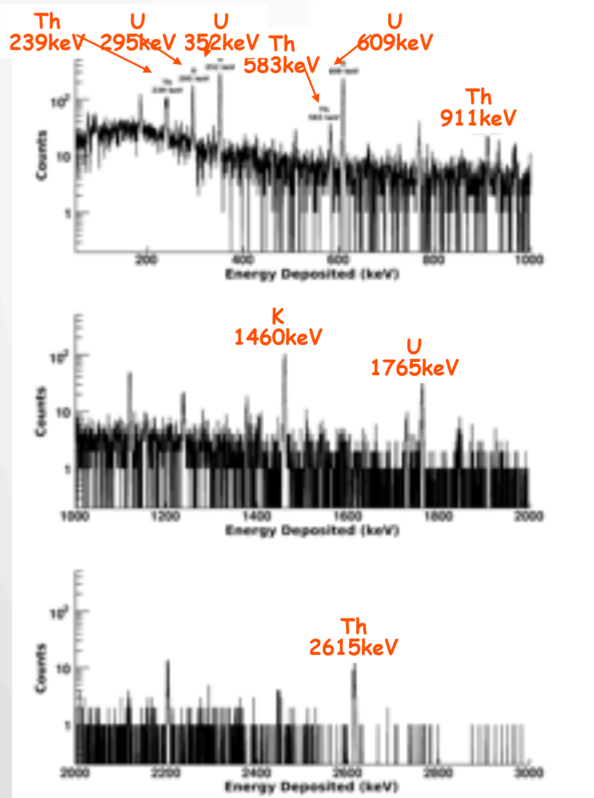


Регистрация WIMP: фоновые условия

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)

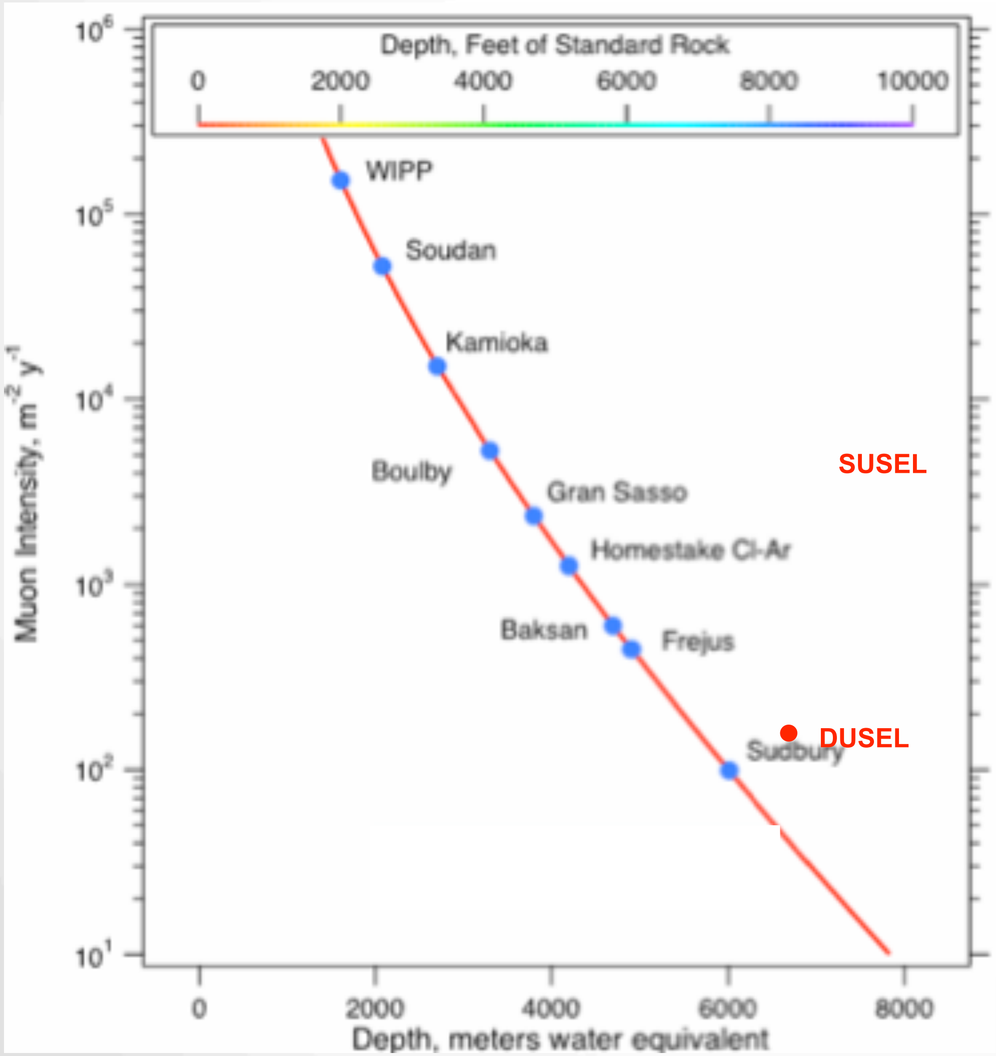
LAr – cosmogenic ^{39}Ar (beta)

Depletion, Ar from underground reservoirs.

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

Регистрация WIMP: фоновые условия

The experiments are carried out in the underground labs



reduction of muon flux by:

10^5

10^6

10^7

10^8

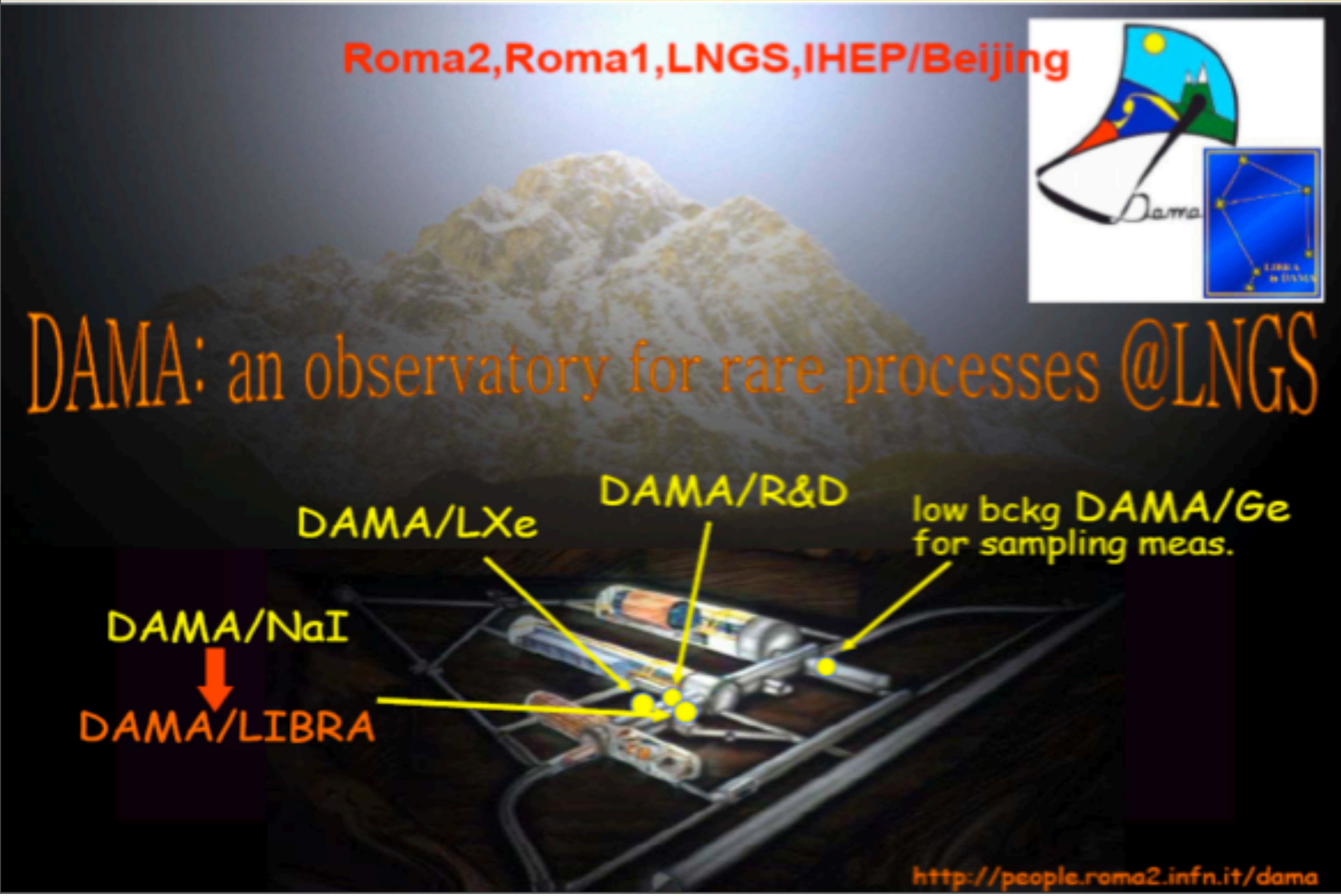
Muon flux at sea level:

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

=

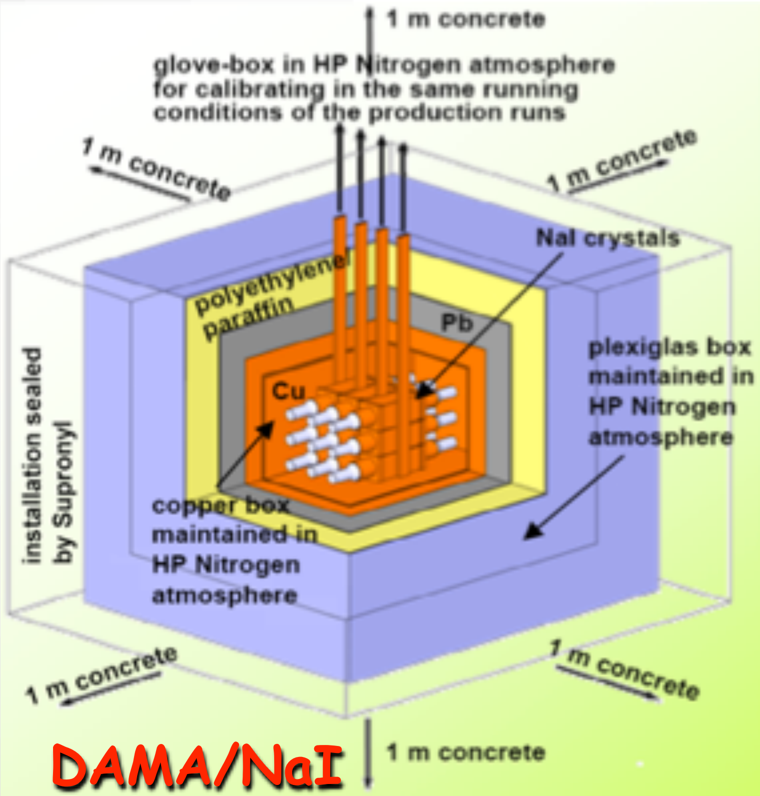
$\sim 5 \cdot 10^9\ m^{-2}\ y^{-1}$

Experiments: DAMA/LIBRA



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.

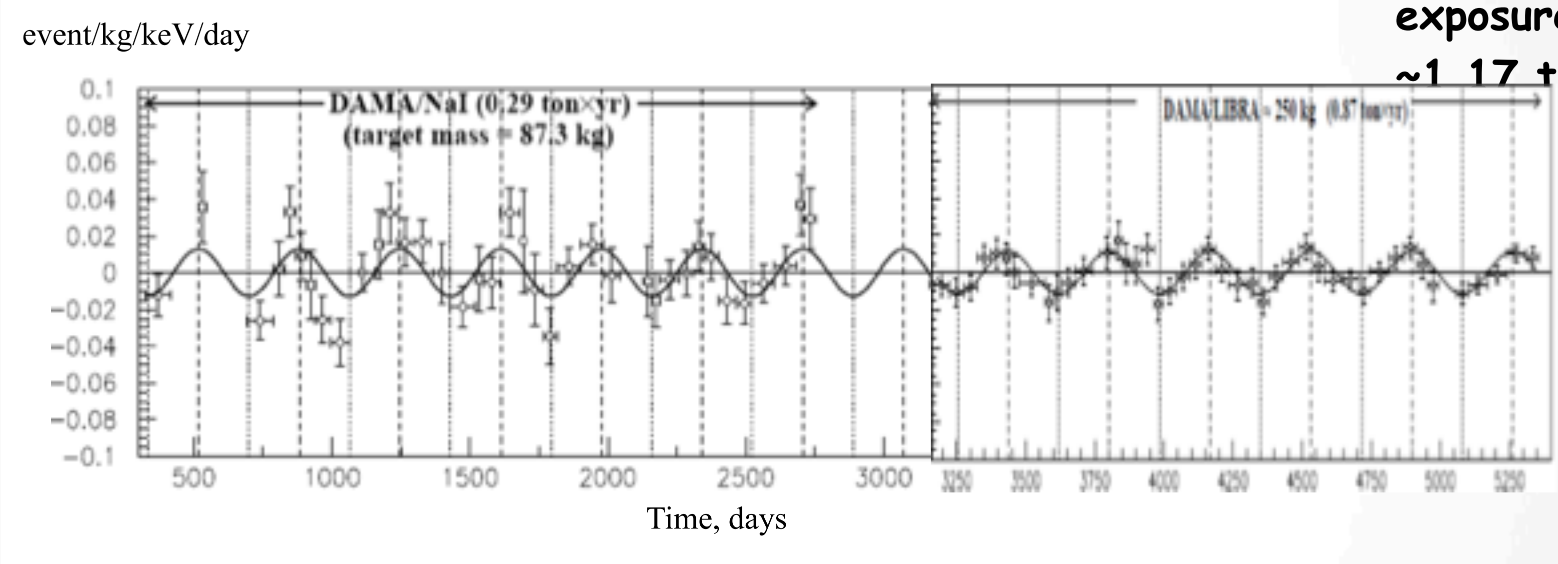
Data taking with LIBRA 2003 - 2008

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



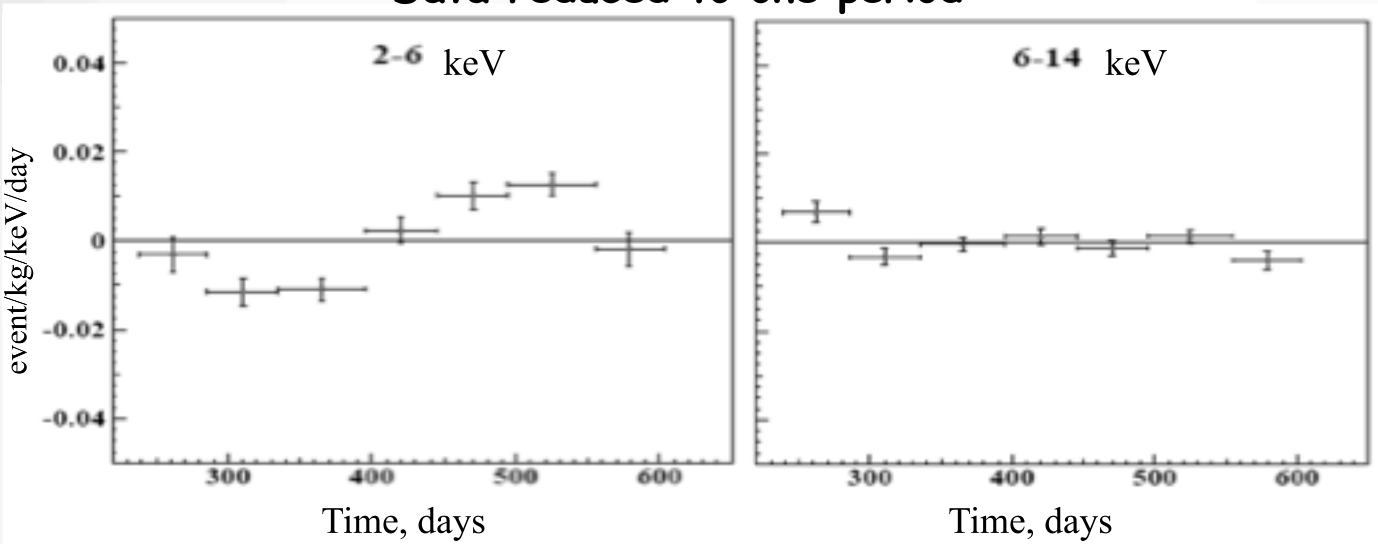
$A \cdot \cos\,\omega(t - t_0)$ with a period $T = 2\pi/\omega = 0.999 \pm 0.002$ y,

and a phase $t_0 = 146 \pm 7$ day, which is very close to the expected: 152,5 days (2 June)

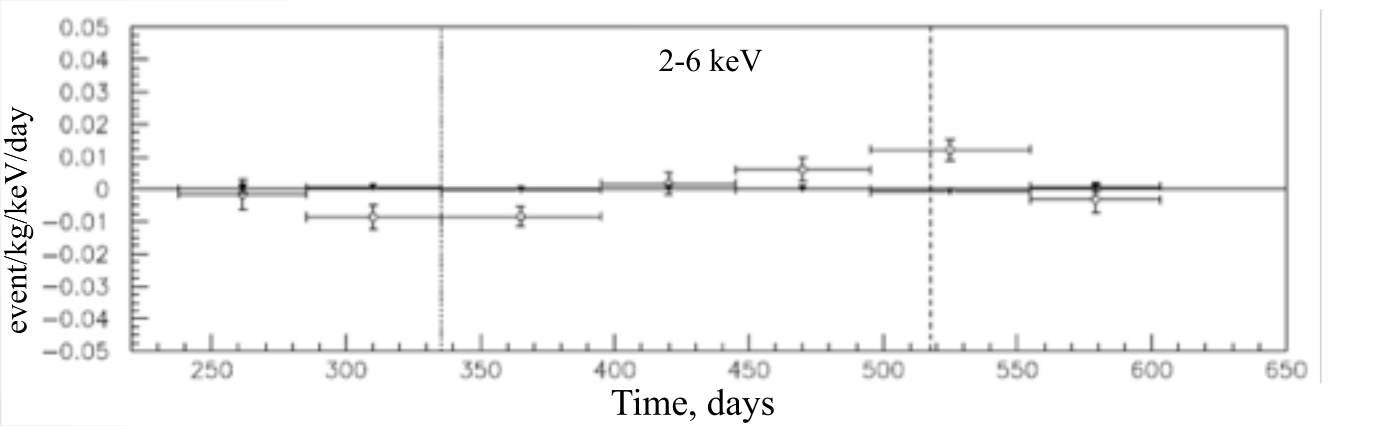
$A = (0.0114 \pm 0.0013)$ event/kg/keV/day, C.L. = $8.8\,\sigma$

Experiments: DAMA/LIBRA

Data reduced to one period:

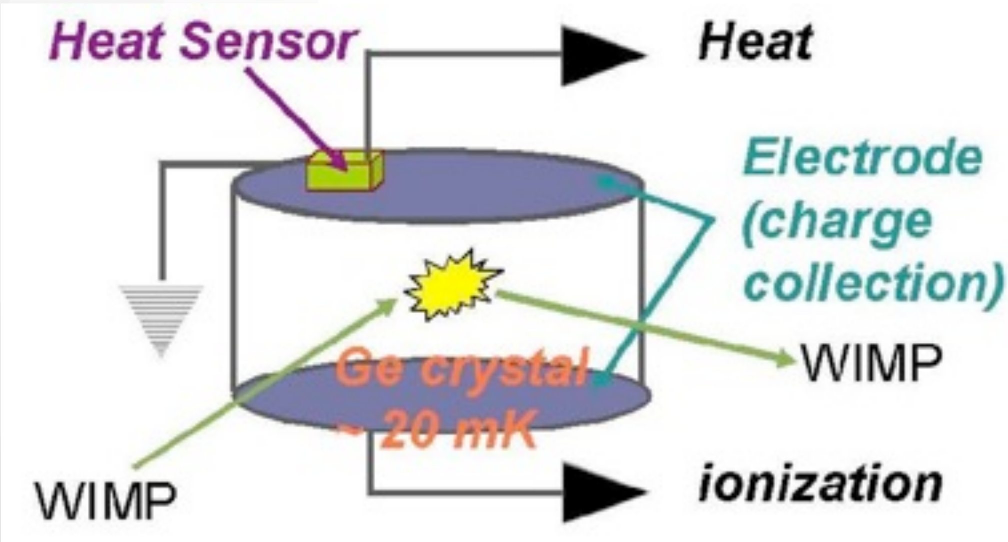


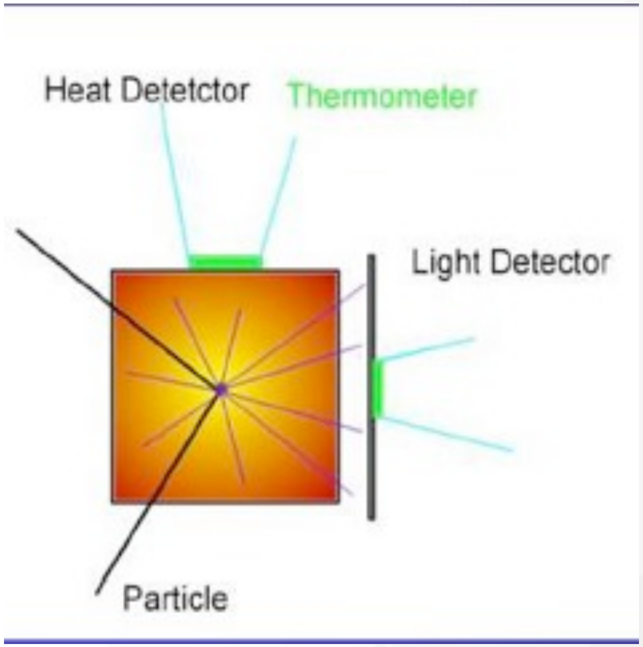
The effect takes place **only in 2-6-keV interval**



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

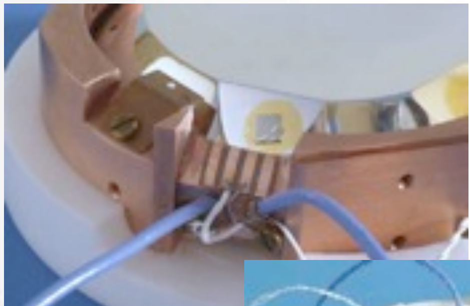
Cryogenic Experiments

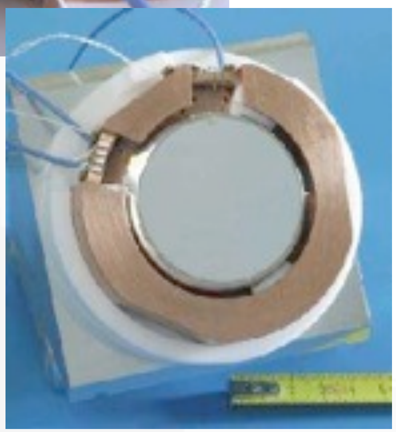


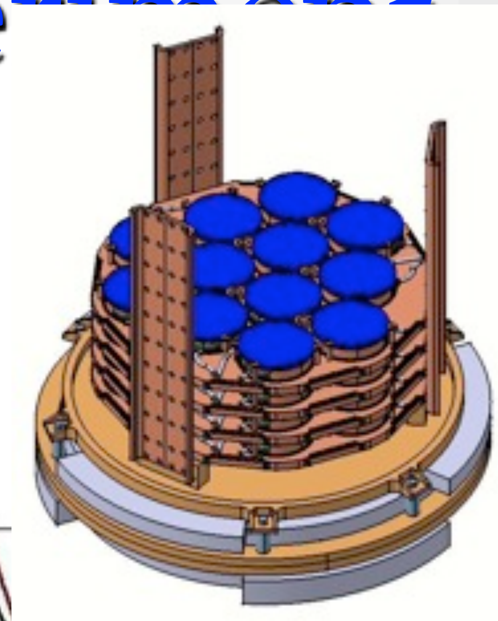


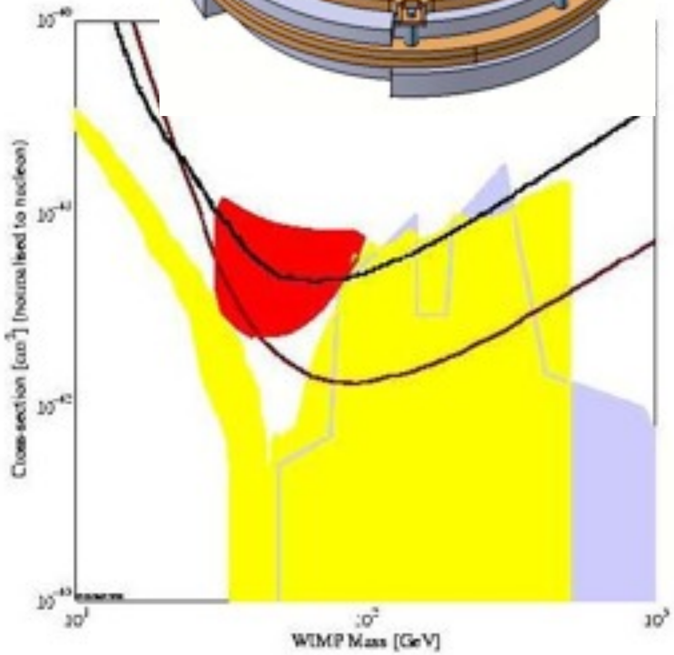
EDELWEISS Experiment

- High purity Ge
- 120 (30 kg)





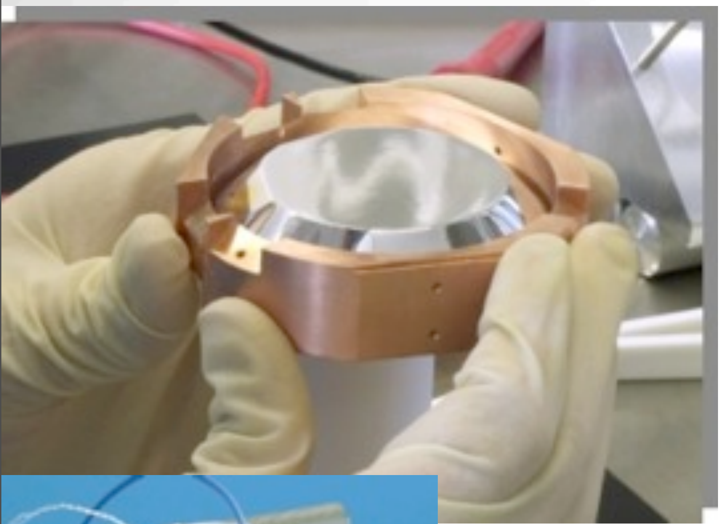


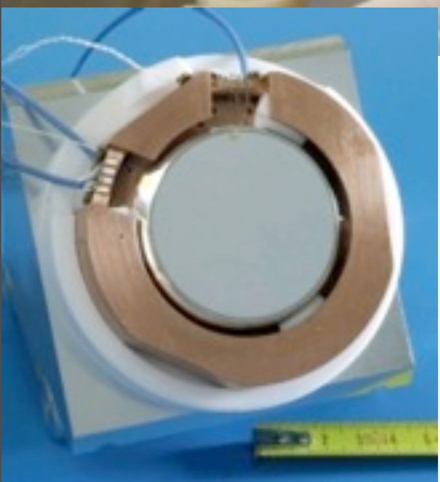


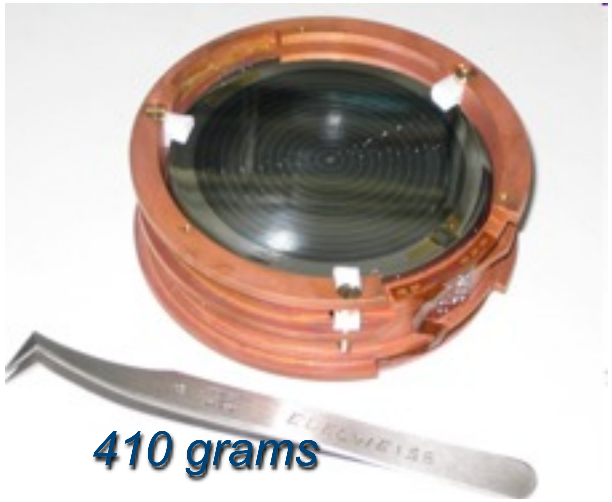
- Rashid Djilkibaev, NYU, Dark Matter Recoil Direction Meas.

Эксперимент EDELWEISS

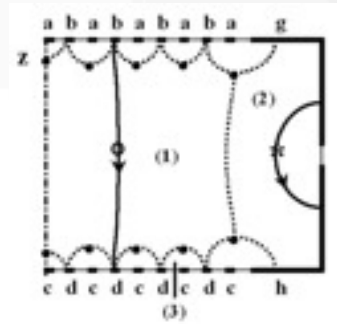
Laboratoire Souterrain de Modane (LSM)

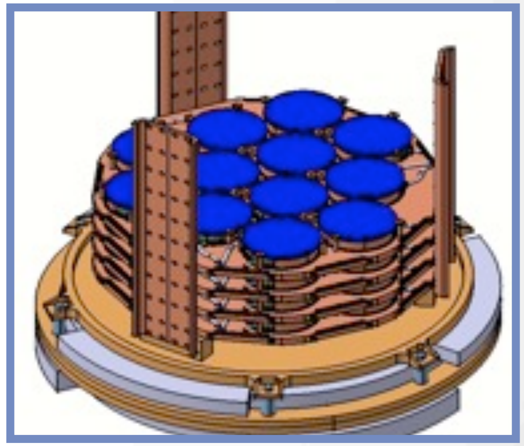






410 grams





320 grams

- *heat and ionisation Ge detector*
- *aluminium interlaying electrodes*
- *NTD sensor on guard ring electrode*

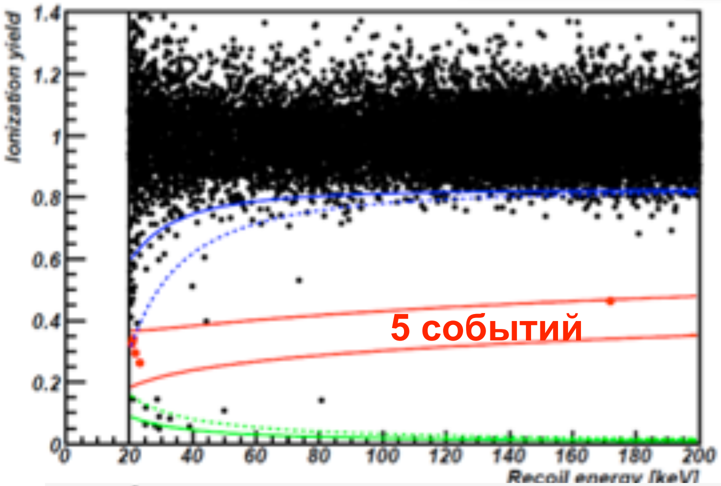
Resolutions @ 10 keV (@ 122 keV)

- *ionisation : 1.3 keV* 2.2 keV
  - *heat :1.0 keV* 3.0 k

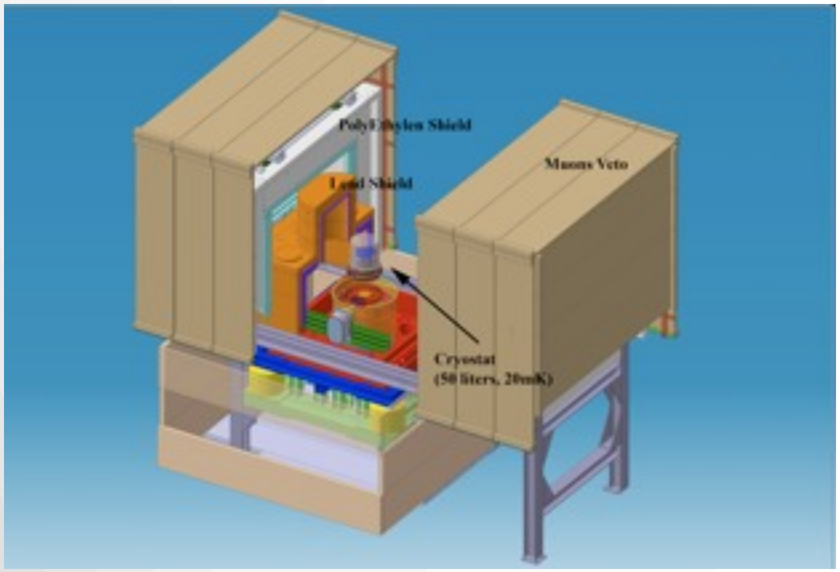
Эксперимент EDELWEISS

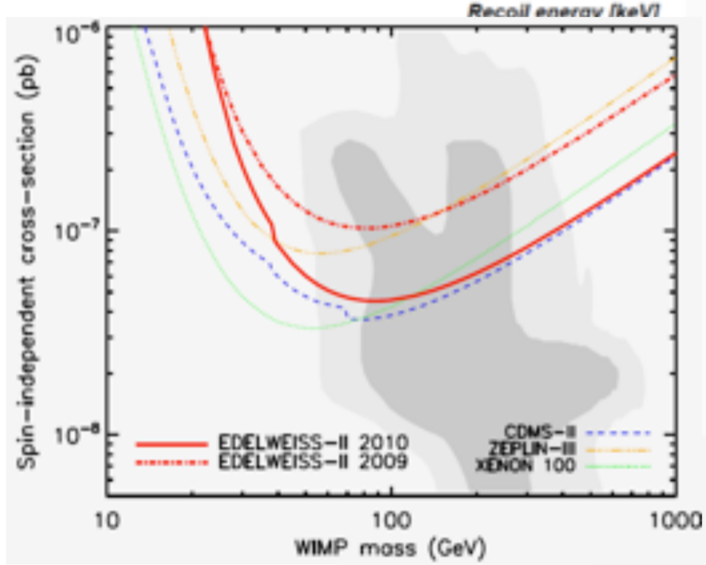
апрель 2009 по май 2010   384 кг сут

arXiv:1103.4070 [astro-ph.CO]



5 дет. 410 г
5 дет. 370 г





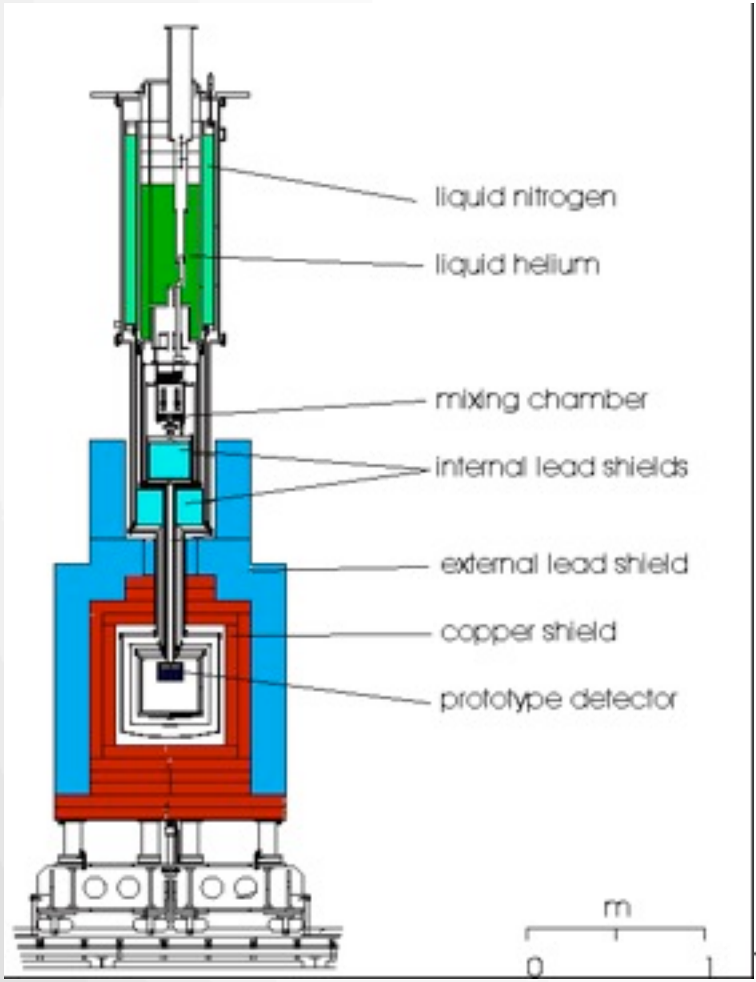
4.4×10^{-8} пб
для
M_w=85 ГэВ

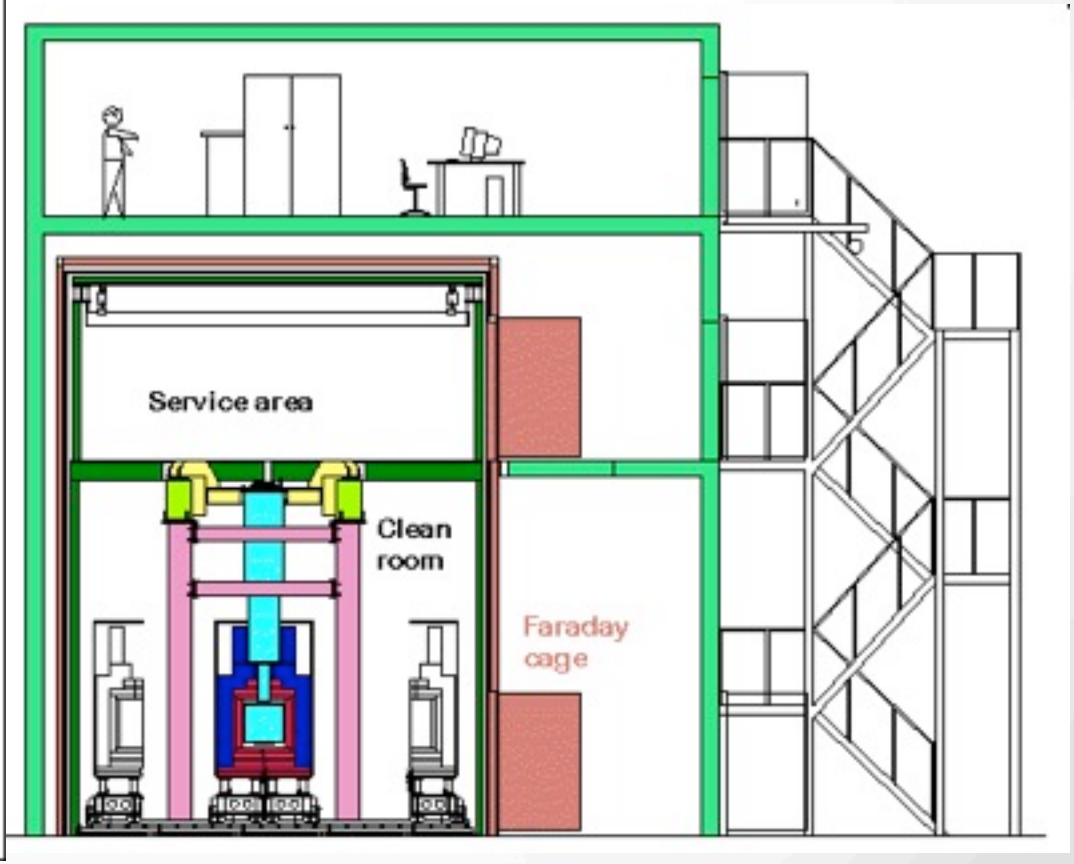
след. этап – 40 кг; 10^{-9} пб

Эксперимент CRESST

Cryogenic Rare Event Search with Superconducting Thermometers

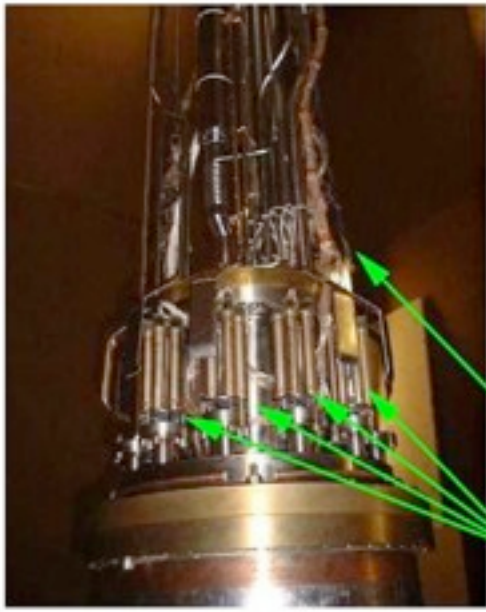
- Laboratori Nazionali Gran Sasso
- Max-Planck-Institut für Physic
- Technische Universität München
- University of Oxford

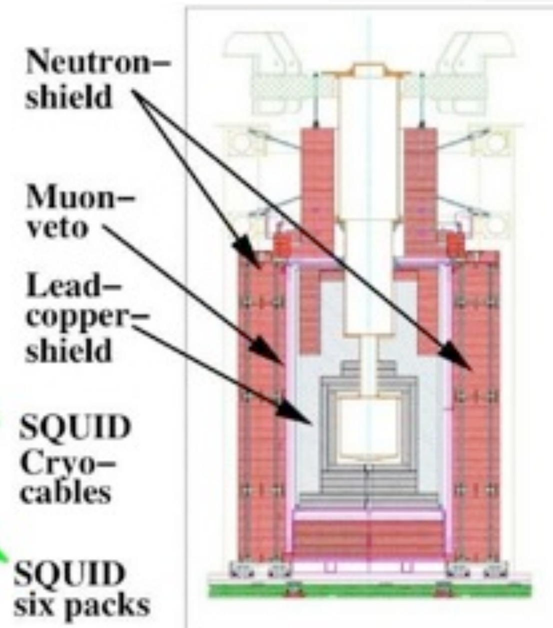




CRESST II Experiment

- 33 Crystal $CaWO_4$ (10 kg)

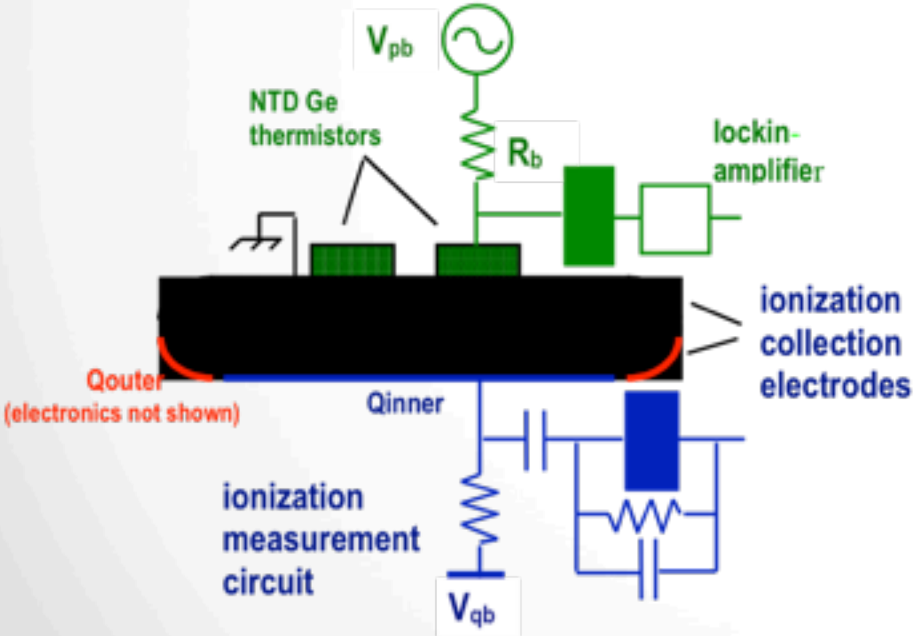


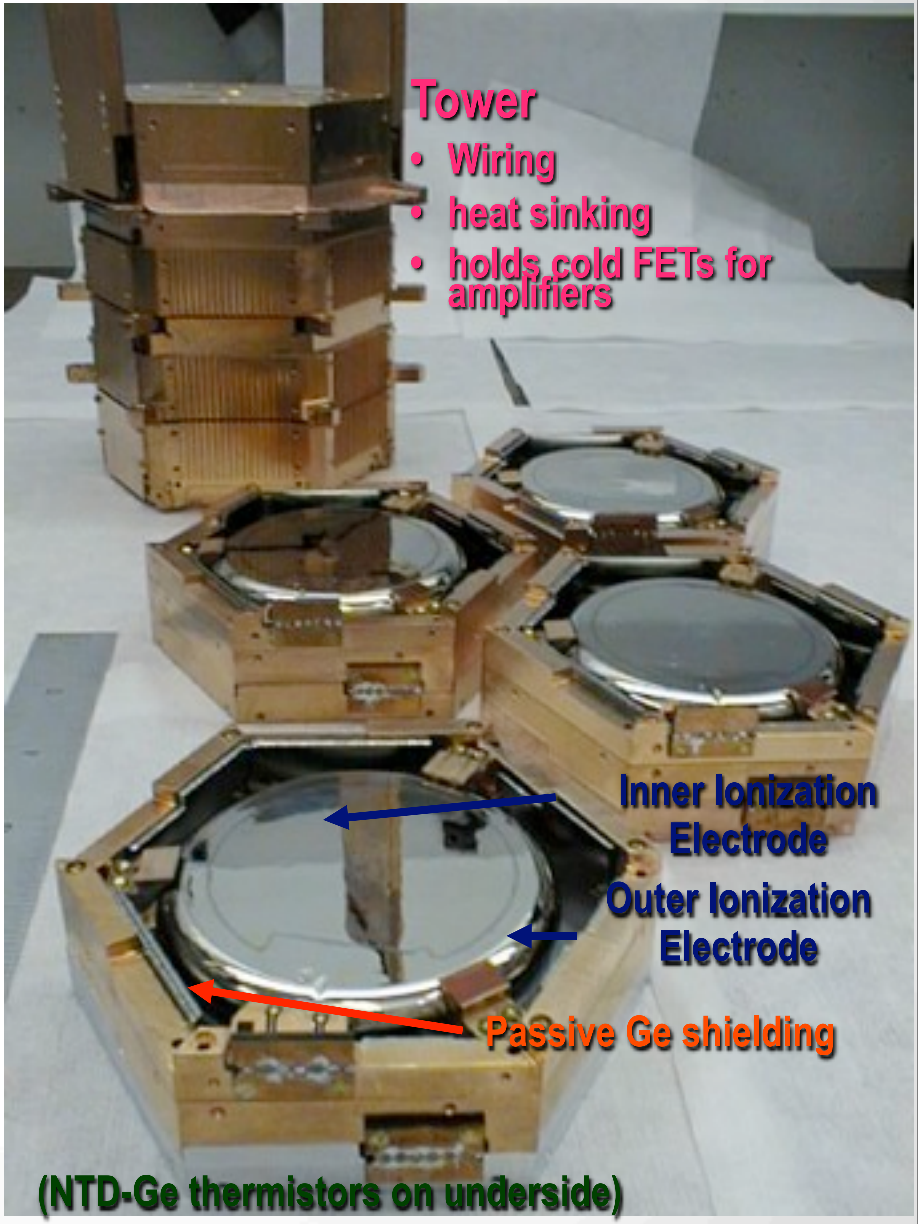


Коллаборация по поиску Тёмной Материи CDMS – Cryogenic Dark Matter Search

Ge BLIP Detectors

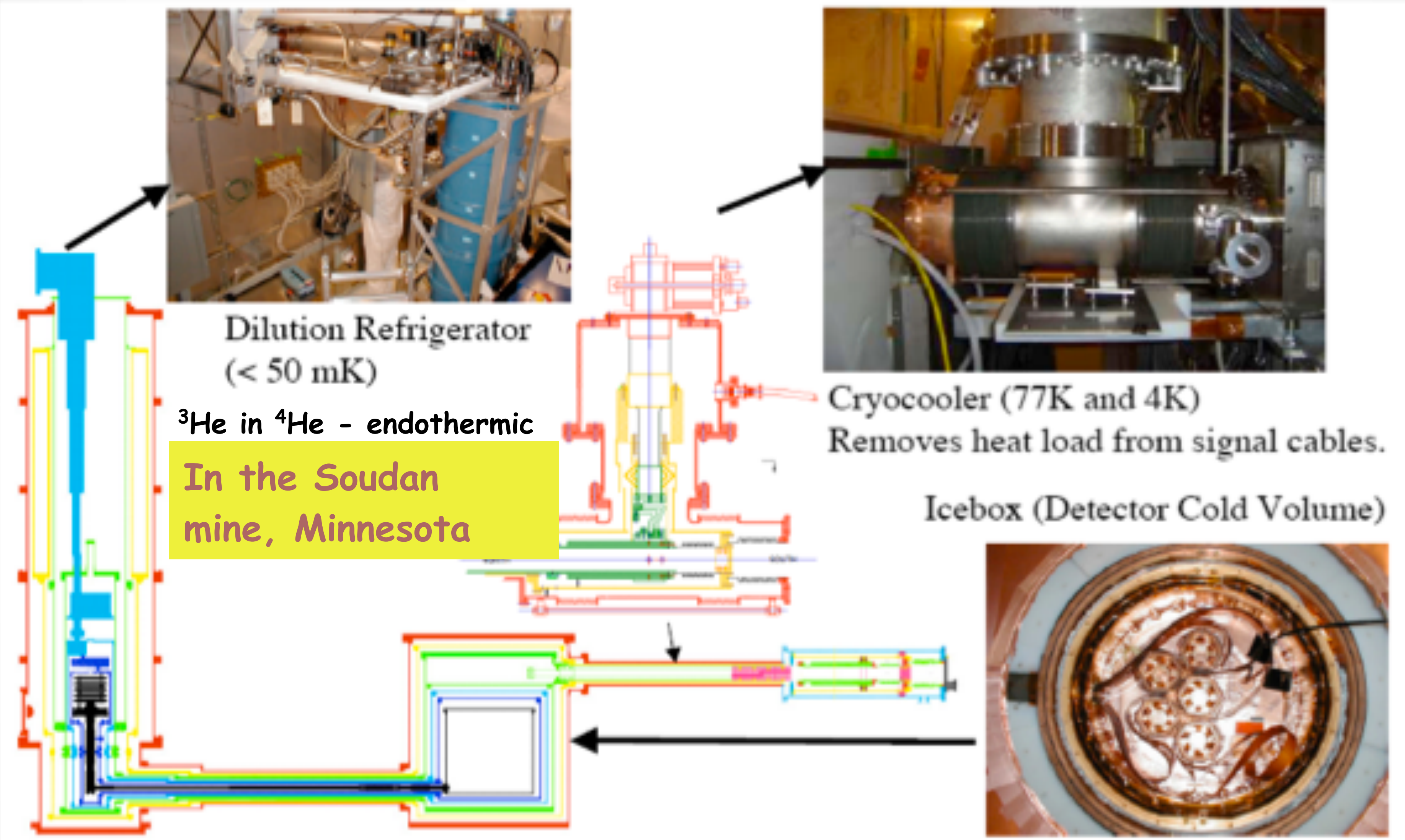
Berkeley **L**arge **I**onization- and **P**honon-mediated Detectors





● Д.Ю. Акимов, INR seminar

Experiments: CDMS

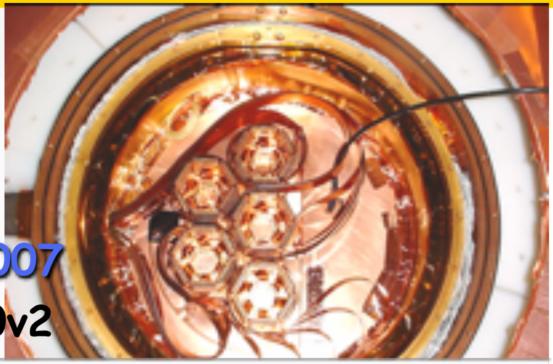


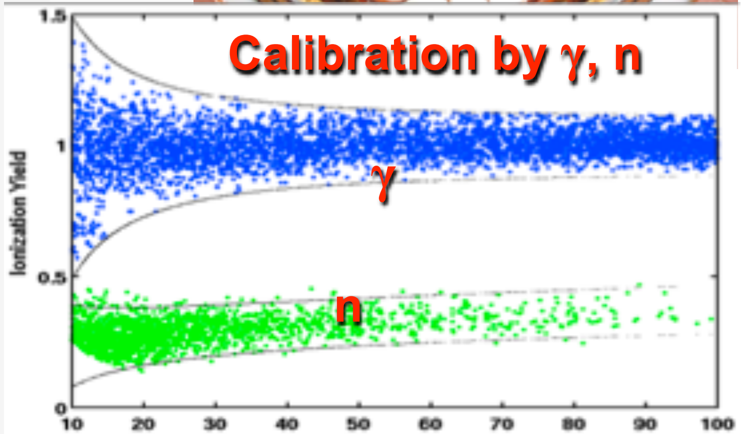
^{3}He in ^{4}He - endothermic

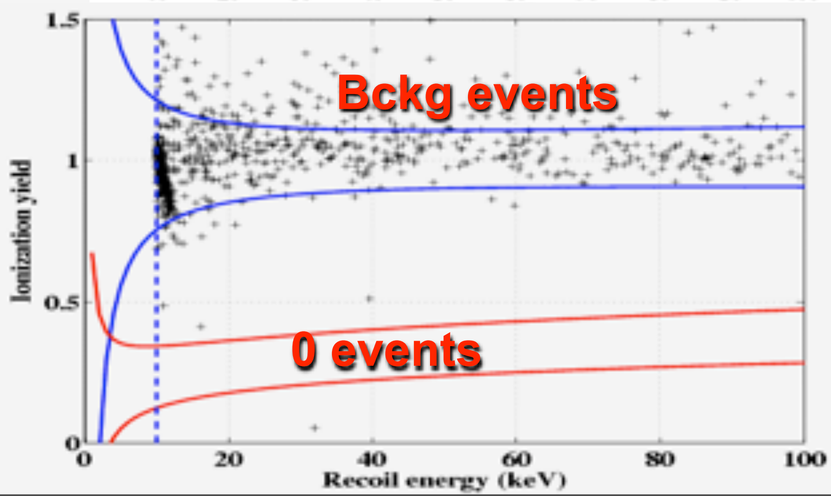
In the Soudan mine, Minnesota

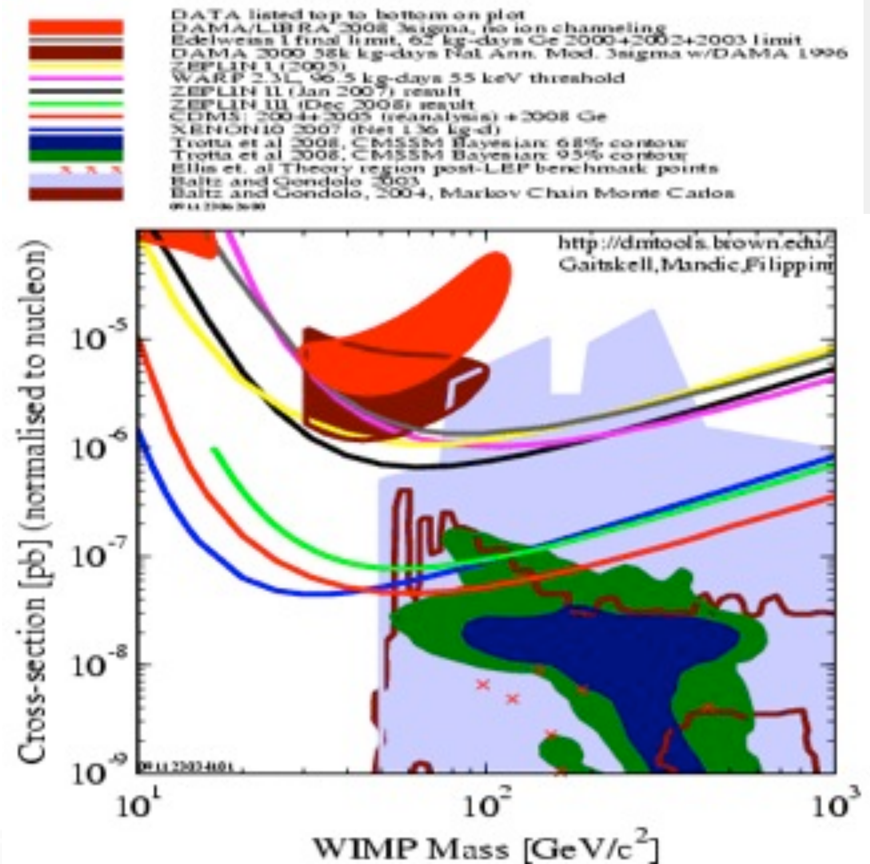
Experiments: CDMS

4.75 kg Ge,
1.1 kg Si
Data taking
Oct2006 - Jul2007
arXiv:0802.3530v2









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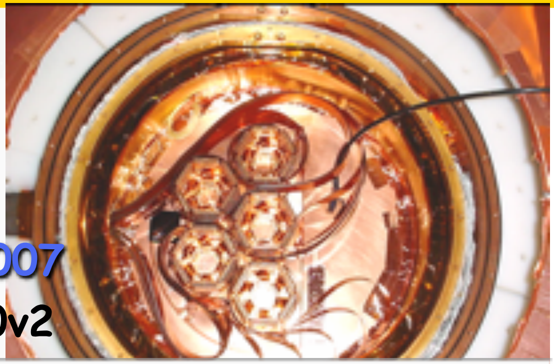

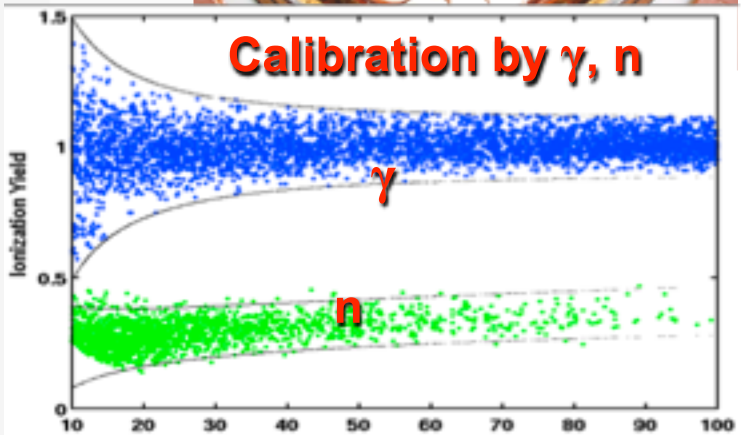

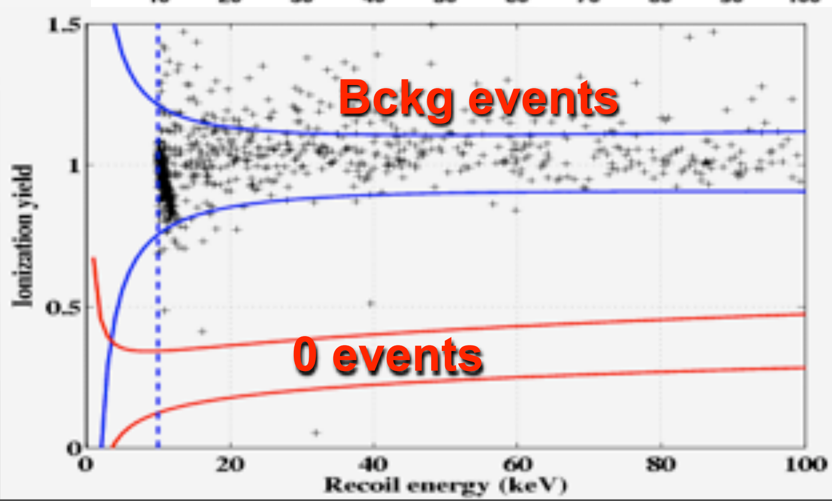

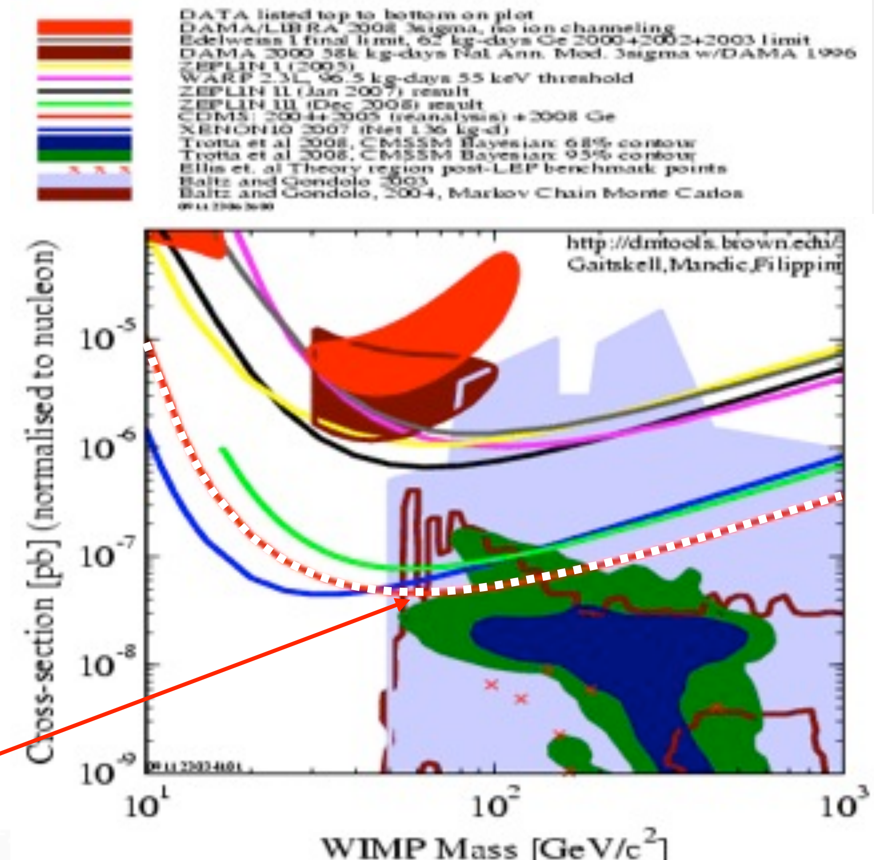

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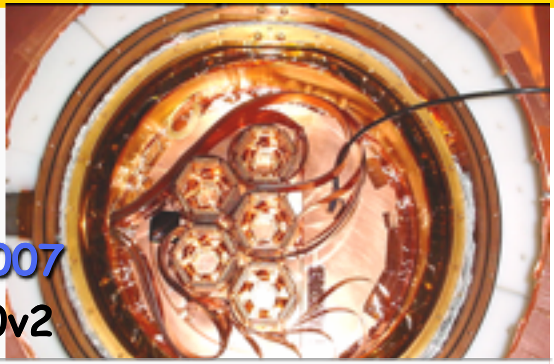
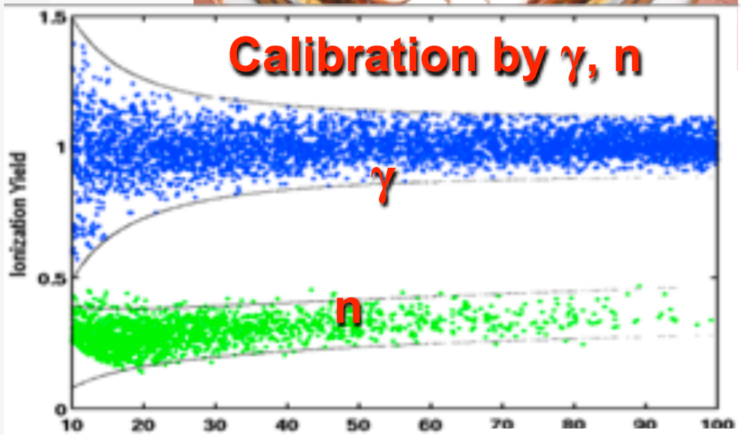
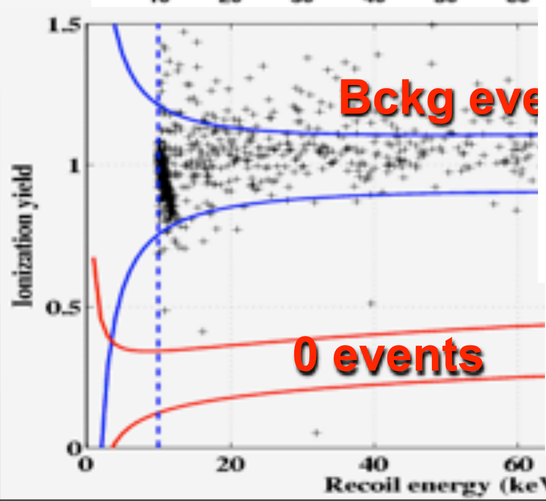
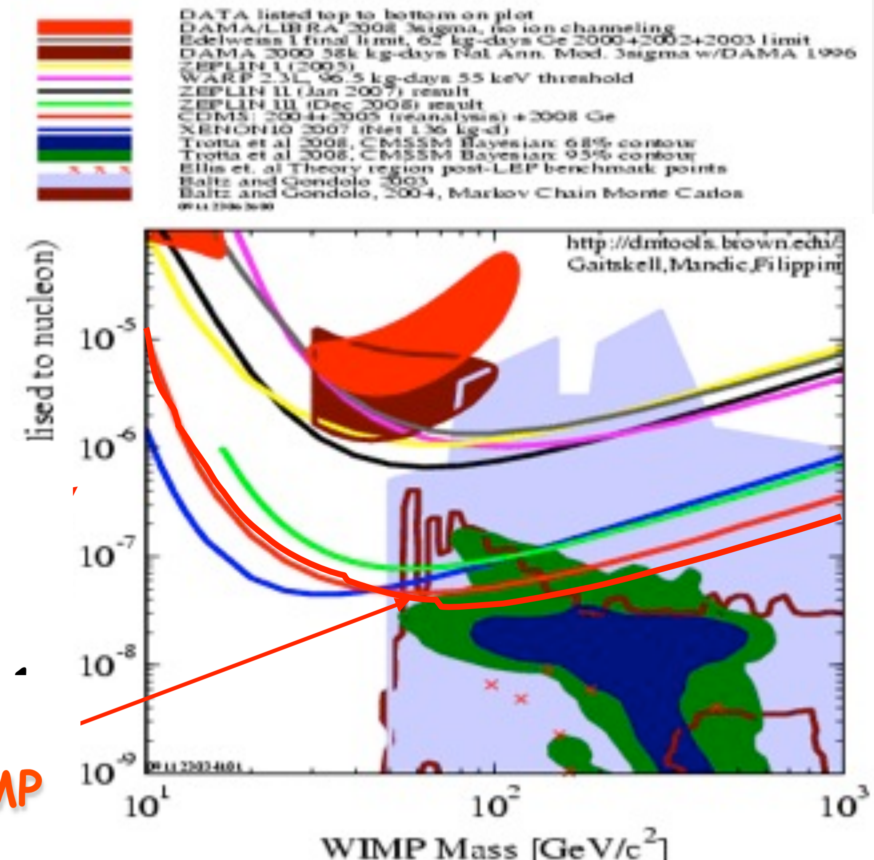




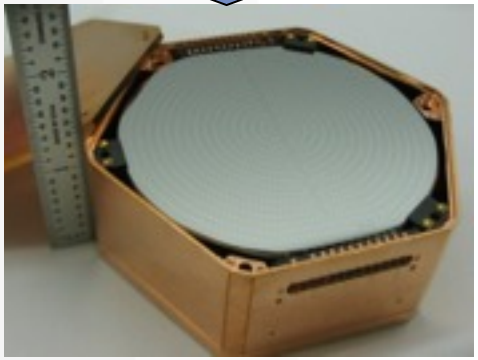


Data taking
Jul2007 -
Sep2008

2 events were
found in a WIMP
search region

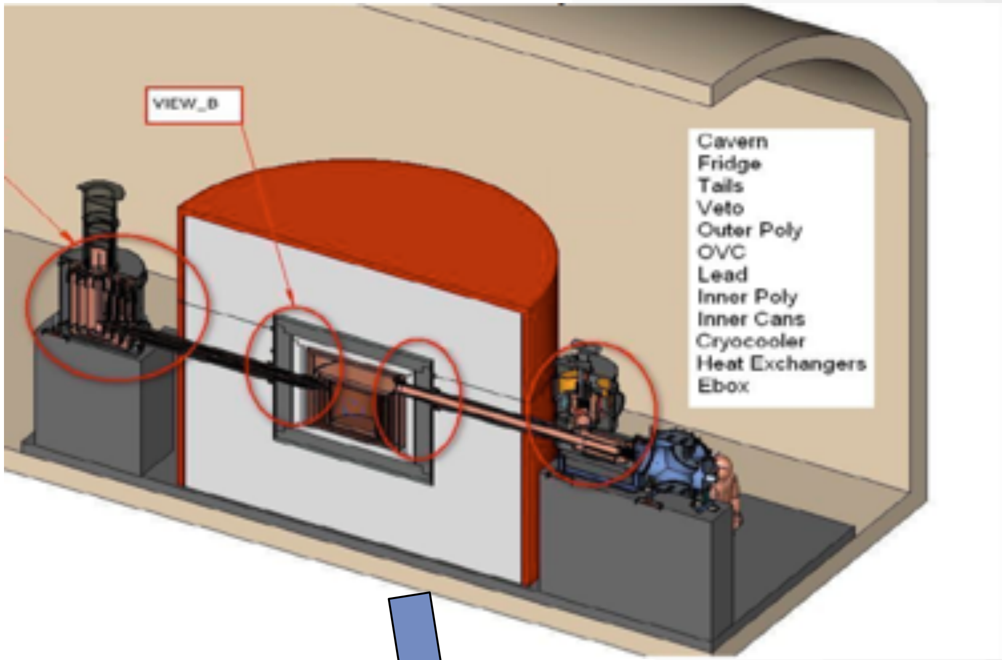


Experiments: SuperCDMS



Элемент детектора SuperCDMS
Ge : диам.76 мм, толщ. 25 мм, вес 607 г.

SuperCDMS в SNOLAB
150 кг – 3x10^{-10} пб

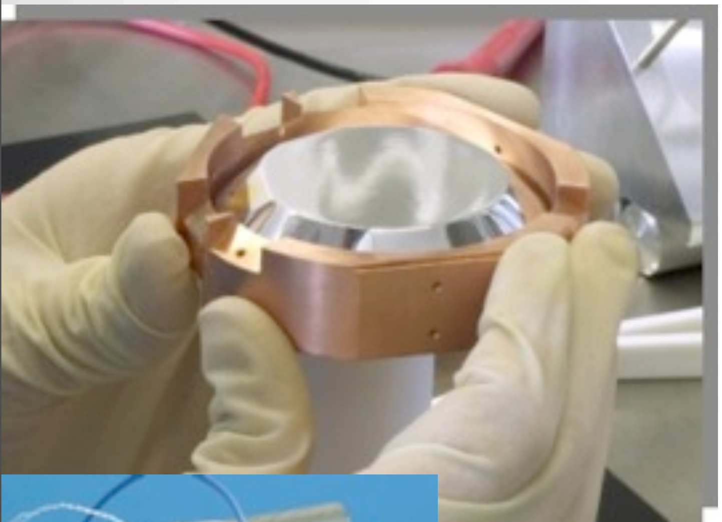


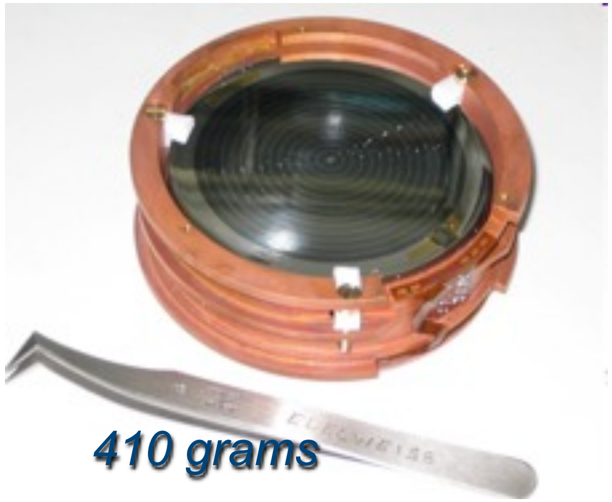
SuperCDMS в Soudan
15 кг – 5x10^{-9} пб

GEODM в DUSEL
1.5 т – 2x10^{-11} пб

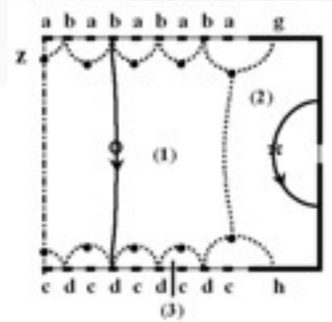
Эксперимент EDELWEISS

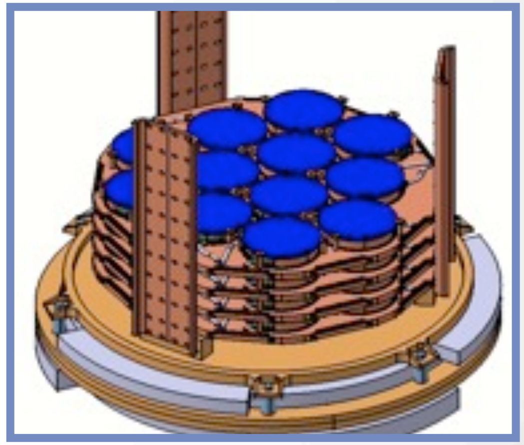
Laboratoire Souterrain de Modane (LSM)

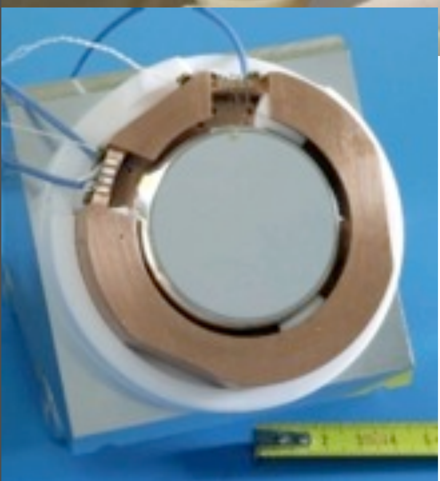




410 grams







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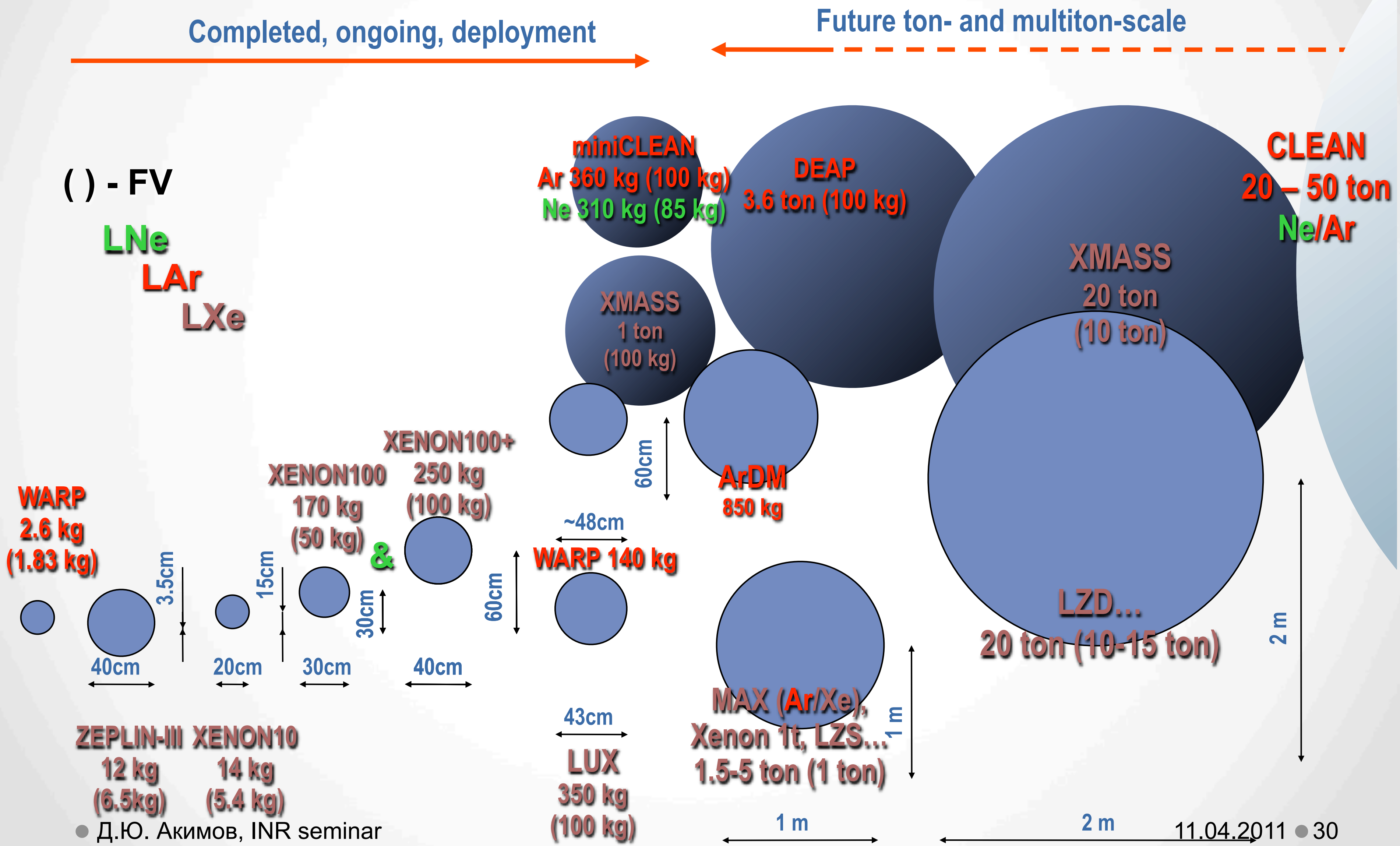
Resolutions @ 10 keV (@ 122 keV)

- *ionisation : 1.3 keV 2.2 keV*
  - *heat :1.0 keV 3.0 k*

- Д.Ю. Акимов, INR seminar

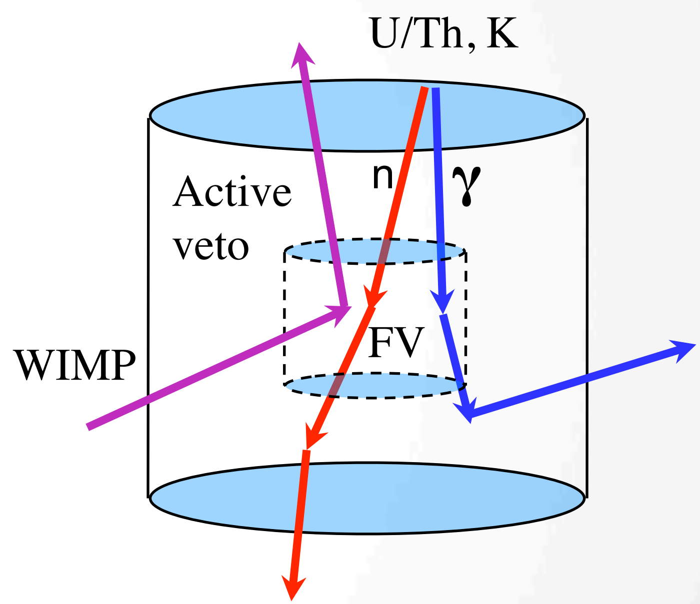
Family of noble-liquid DM detectors



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!!!



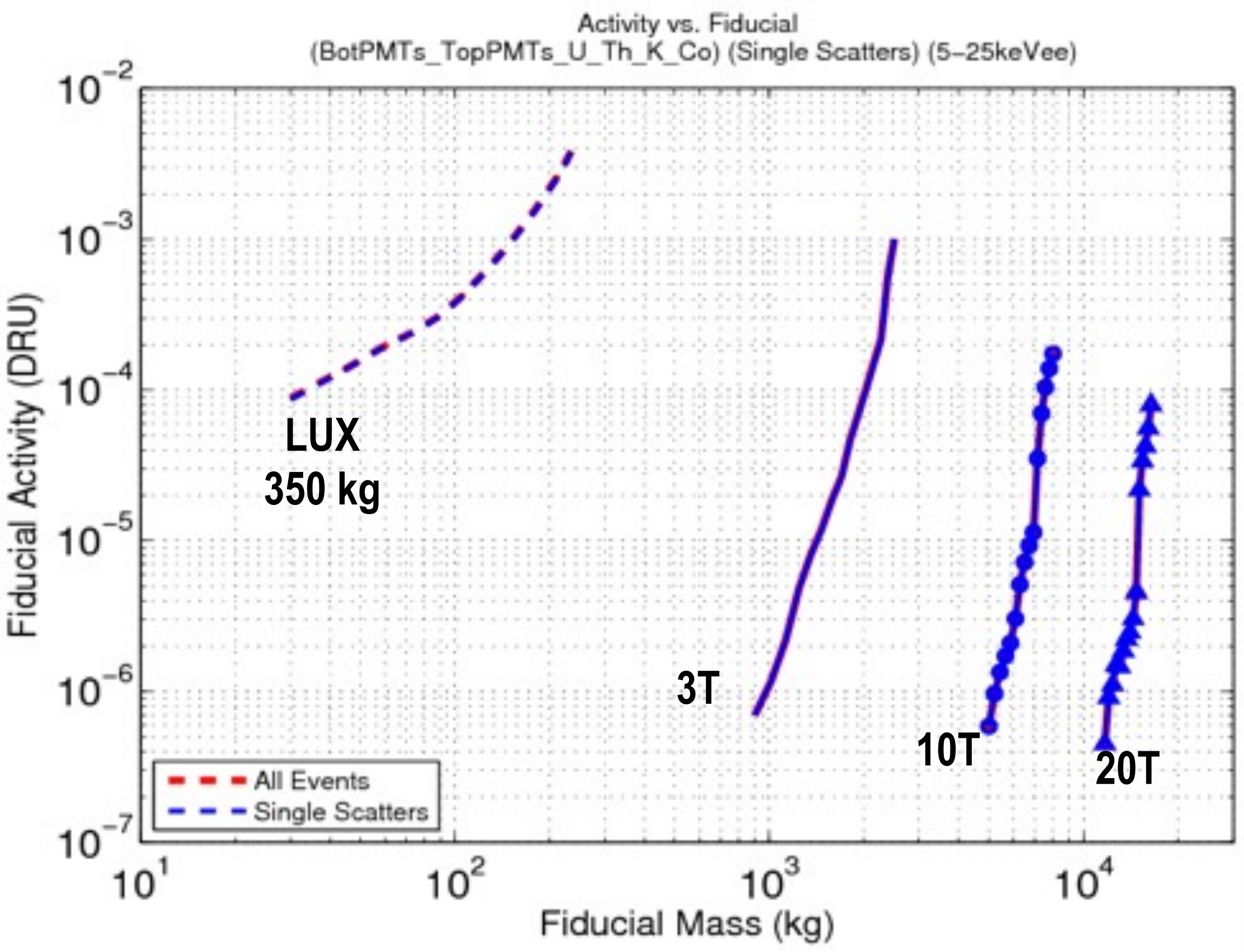
LAr, LXe: at the same mass LXe detectors have by an order of magnitude higher sensitivity:

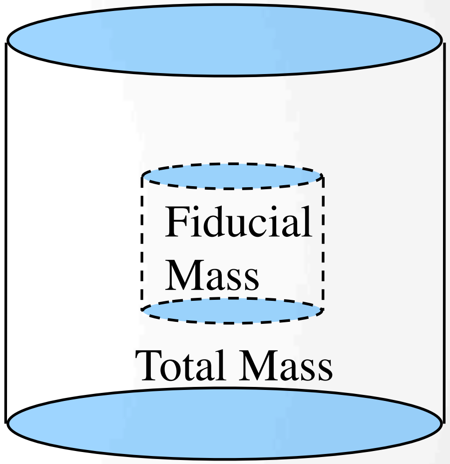
$\sigma_{SI} \sim A^2$, higher density and Z => better self-shielding

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



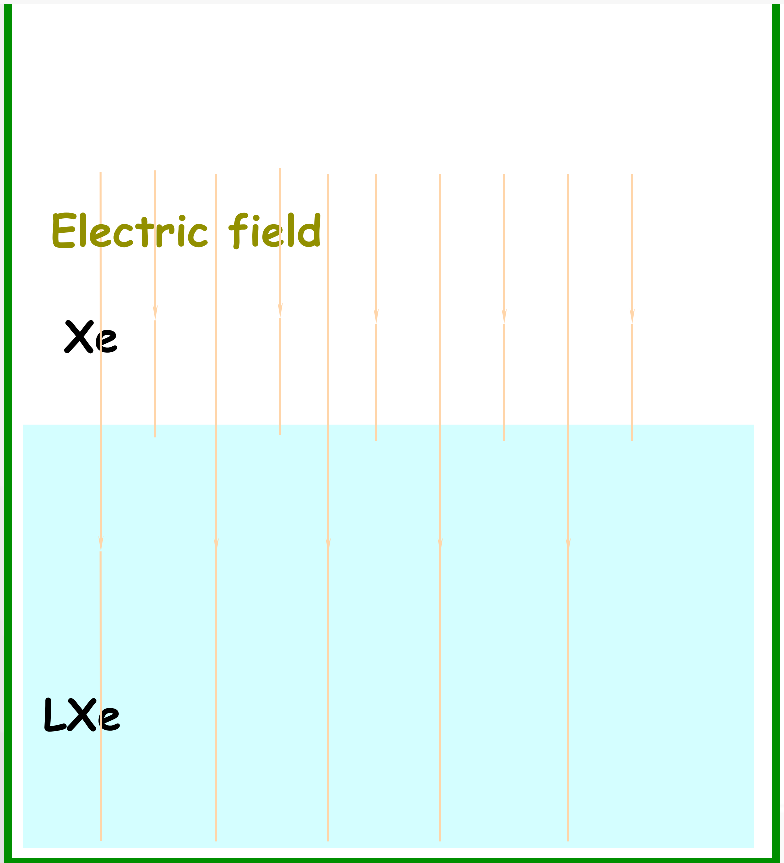


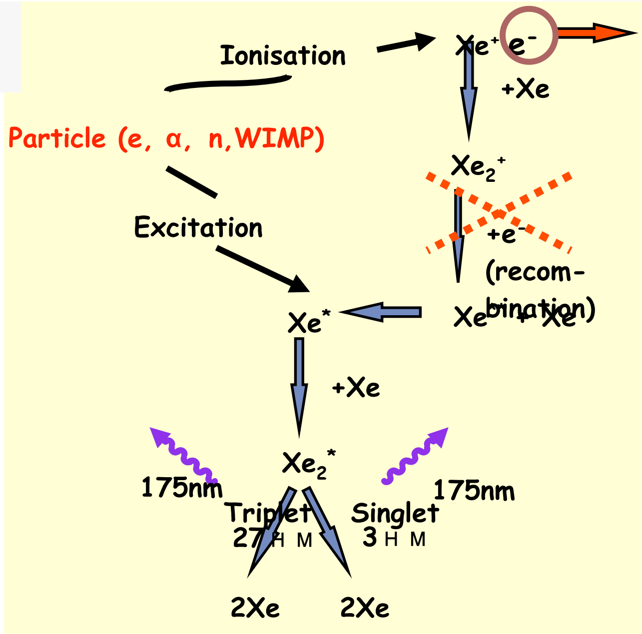
Experiments: LXe detectors

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

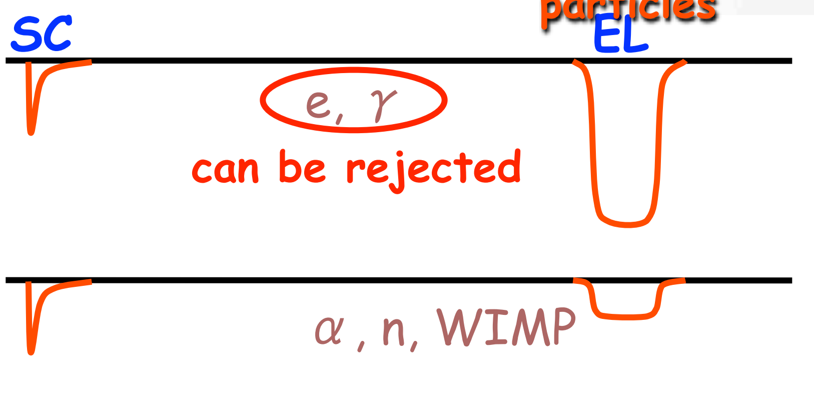




Electrons are partly extracted from the track: **recombination is suppressed**

Suppression depends on dE/dX

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



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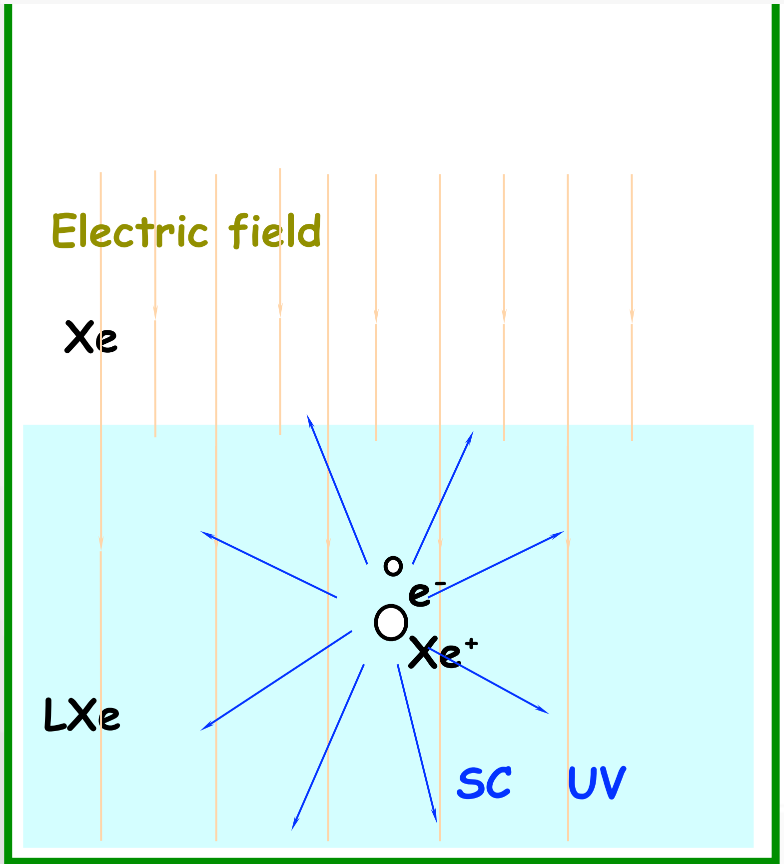

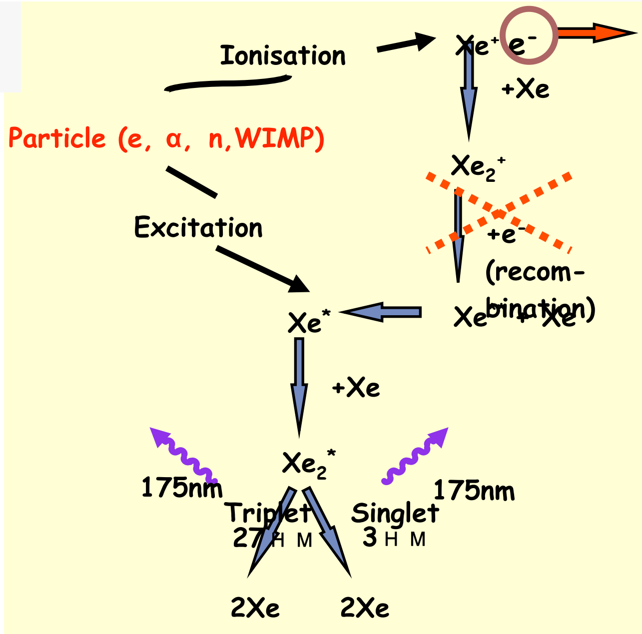

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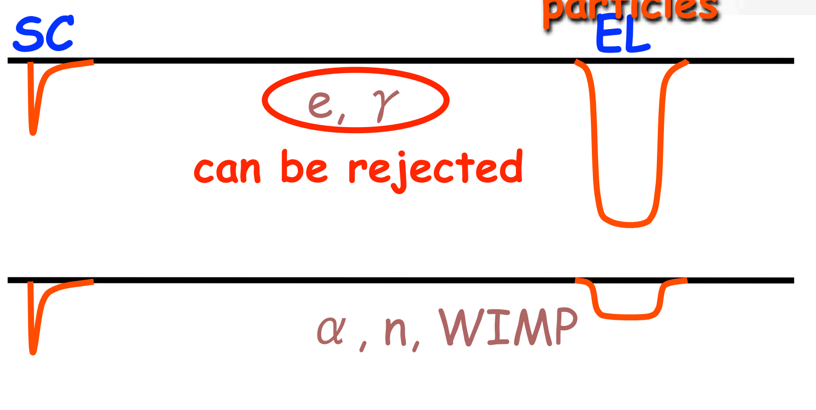

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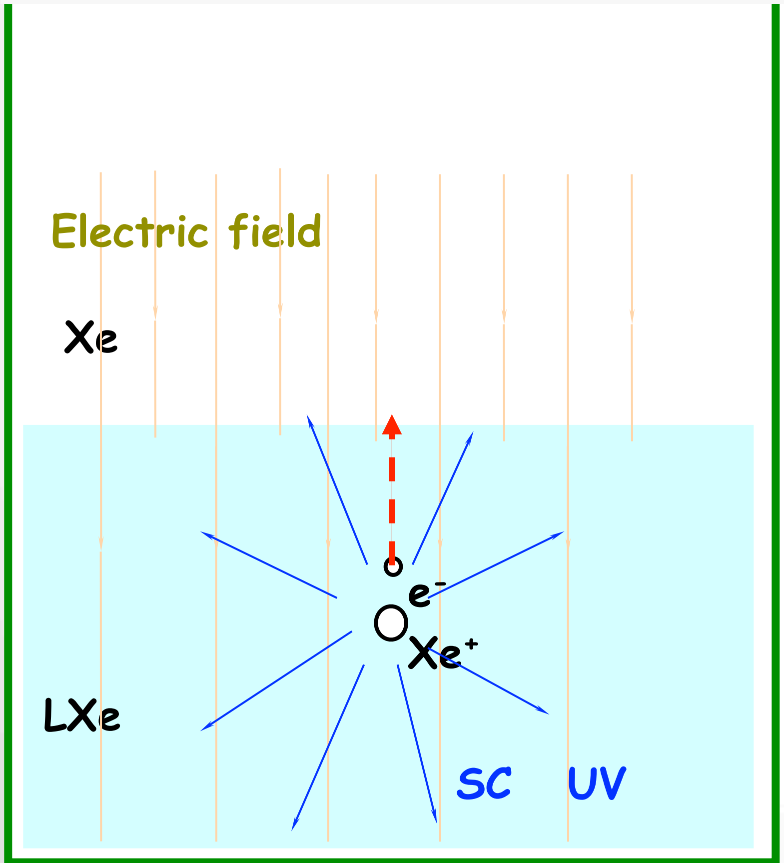

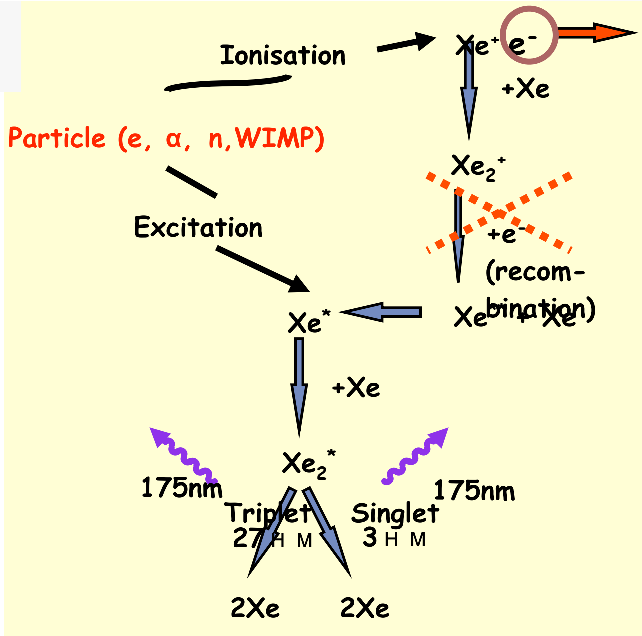

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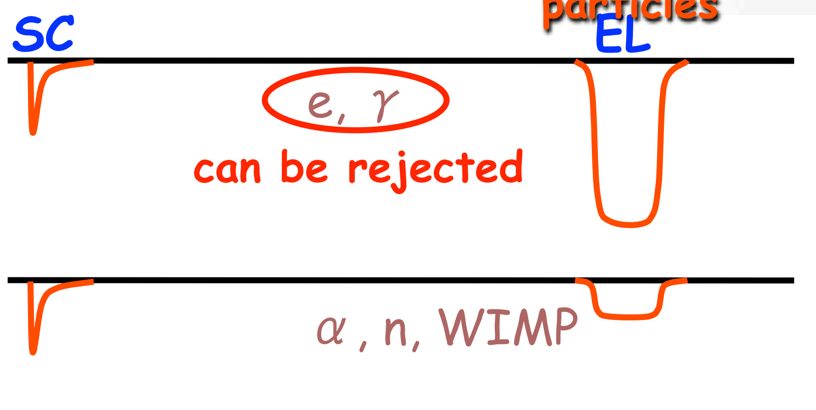

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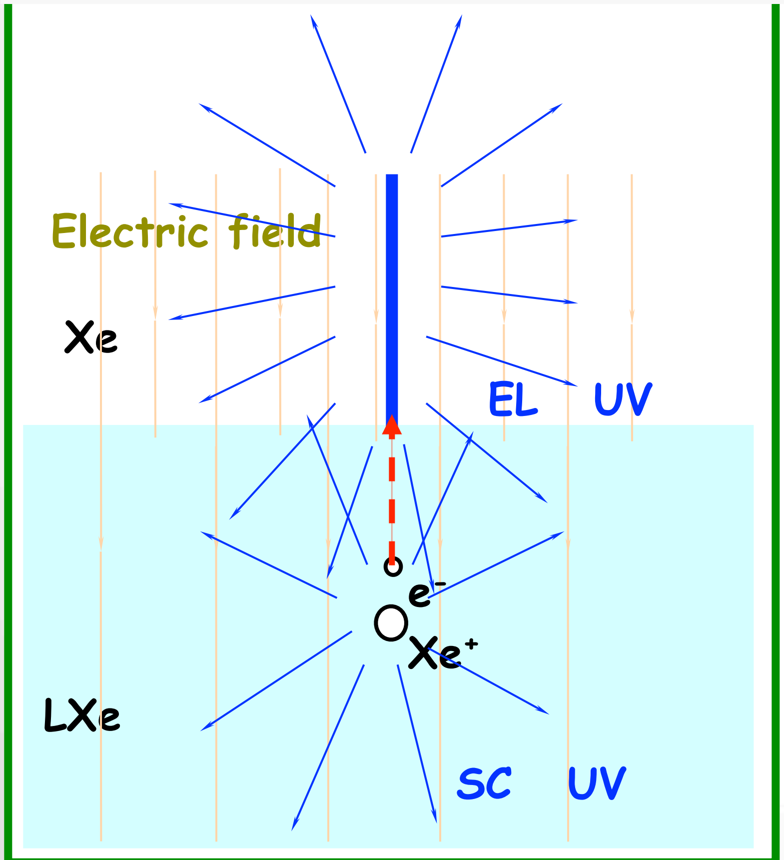

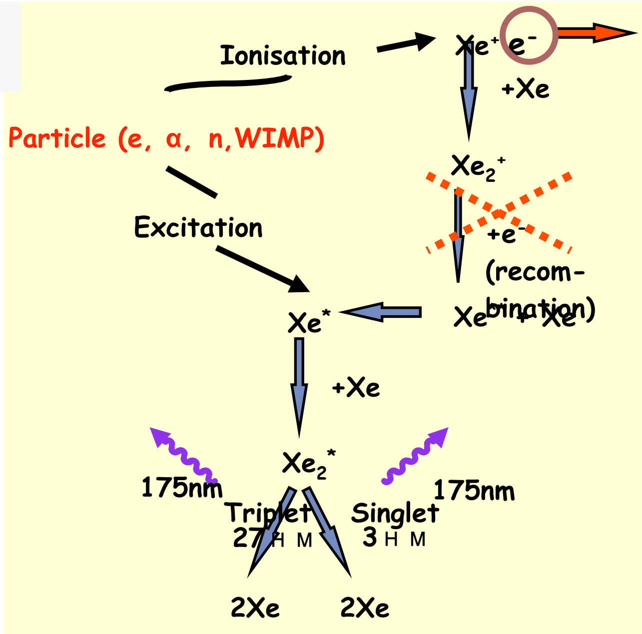

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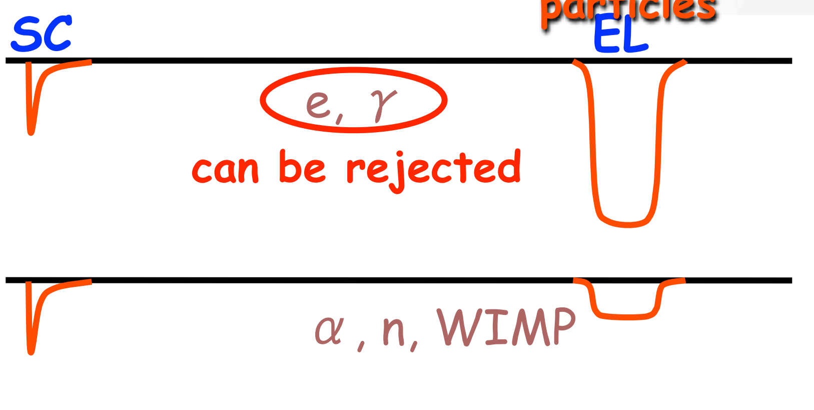
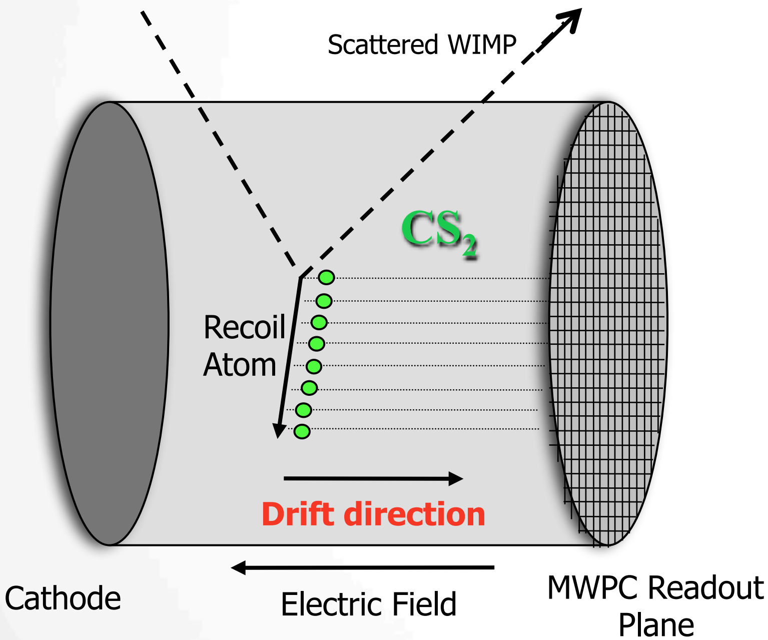


Tuesday, April 17, 2012

The DRIFT Concept

How to build a directional detector?

Problem: In solid or liquid targets <100keV recoil tracks ~ 1-100nm long



DRIFT: A Low Pressure Negative Ion Drift TPC (NITPC)

Low Pressure TPC:

- Low pressure target extends range of WIMP nuclear recoils to a few mm.
- 3D reconstruction possible by combining 2D readout with signal timing analysis.

Negative Ion DRIFT:

- Electron capture by electronegative gas reduces track diffusion.
- Diffusion of <0.5mm at 0.5m drift length (1000v/cm)

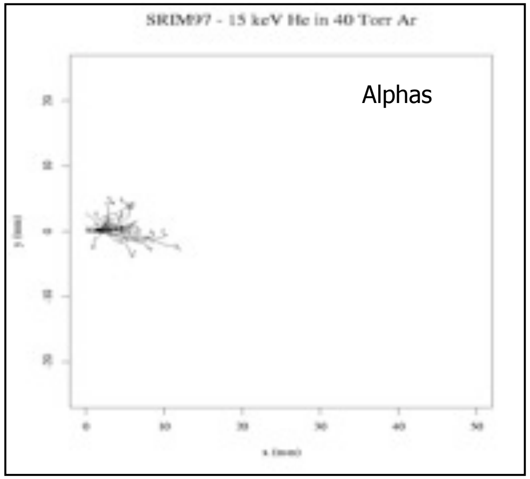
(Rediscovered by Martoff - Temple)

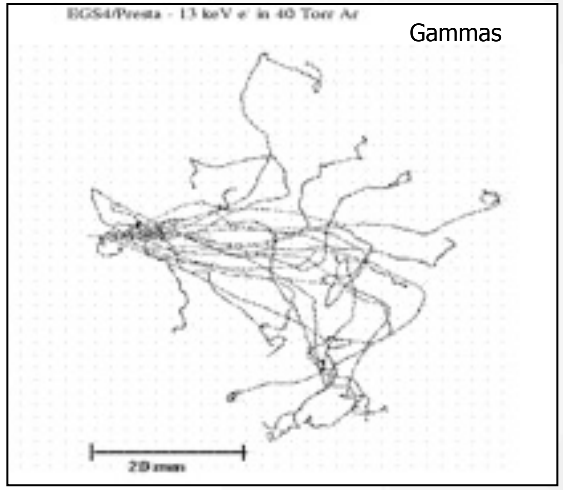
The DRIFT Concept

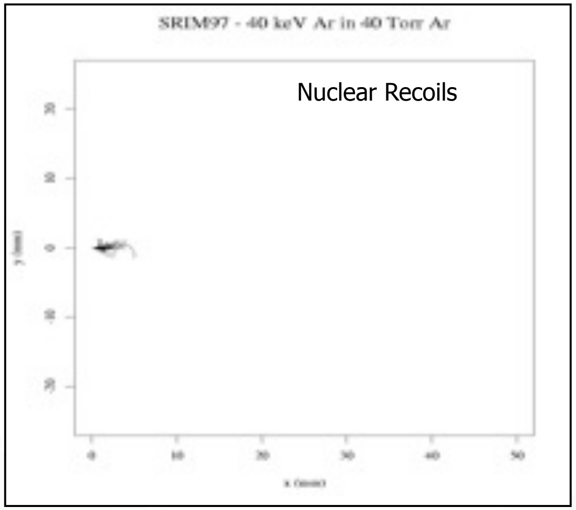
DRIFT Background discrimination

- Based on signal ENERGY and RANGE.
- Nuclear recoils have a higher dE/dx than background electrons or alphas.

Gamma discrimination of $>10^6$ so far demonstrated. *(Snowden-Ifft et al. NIM A 498 (2003), & - Kirkpatrick et al, in preparation)*







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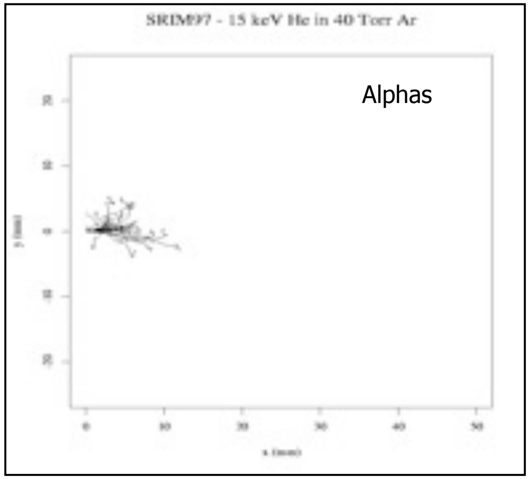

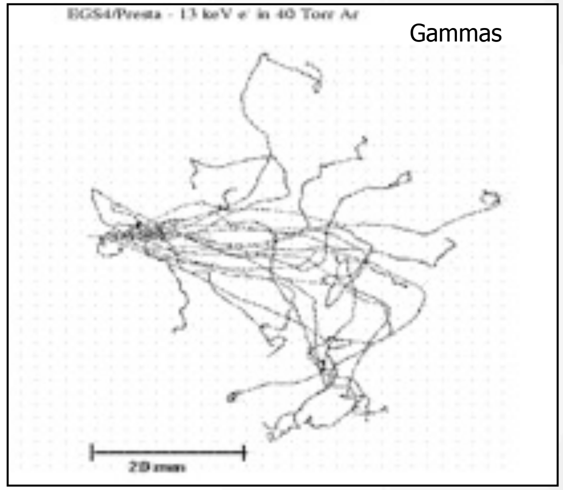

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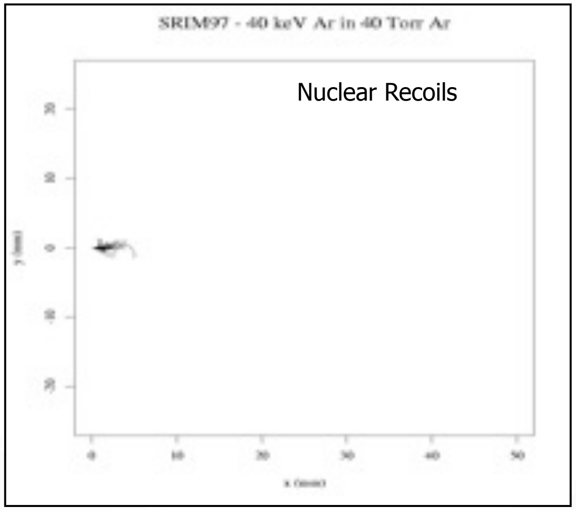


- Little / no gamma shielding!
- Competitive as hi-sensitivity, limit-setting detector.

DIIa - Construction & Commissioning

November 2004

1.5m^3 cubed stainless steel vacuum vessel (UK/USA)

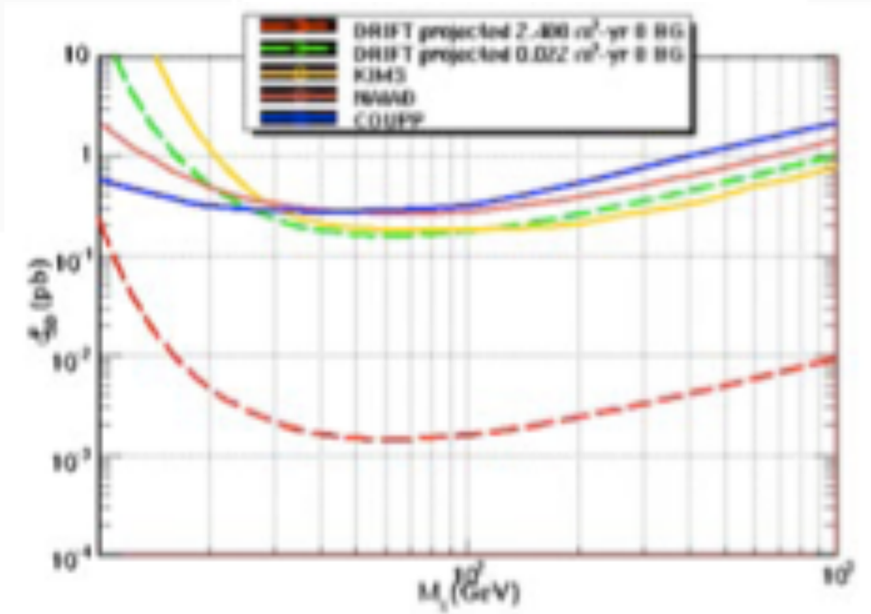
Inner detector stack

MWPCs, 512 20um anode wires: lucite frame with warp-adjust bars

Side-oriented back-to-back field cages with rigid Cu piping.

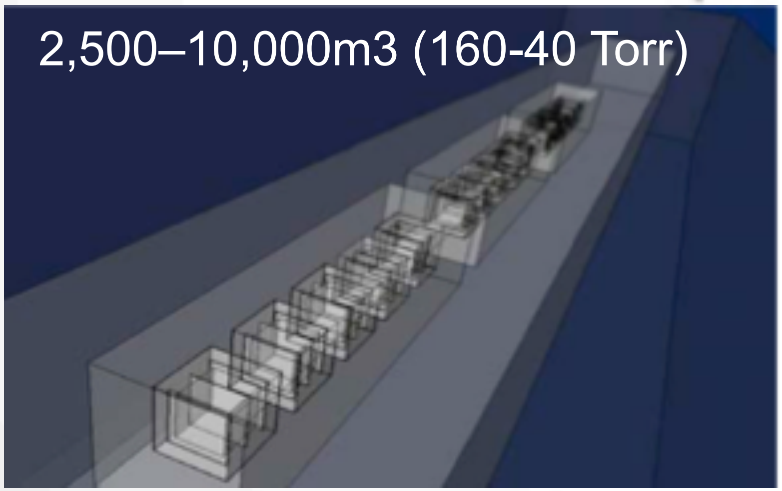
Grid amplification & grouping, prior testing.

DRIFT-IId SD limits

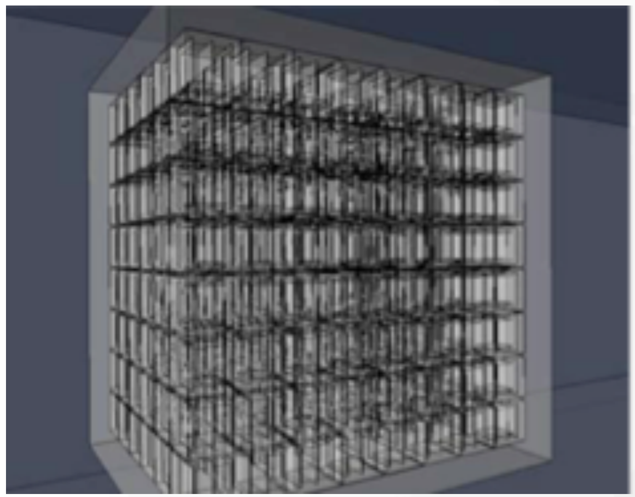


1 m^3 x 2.5 y

~ 1 t



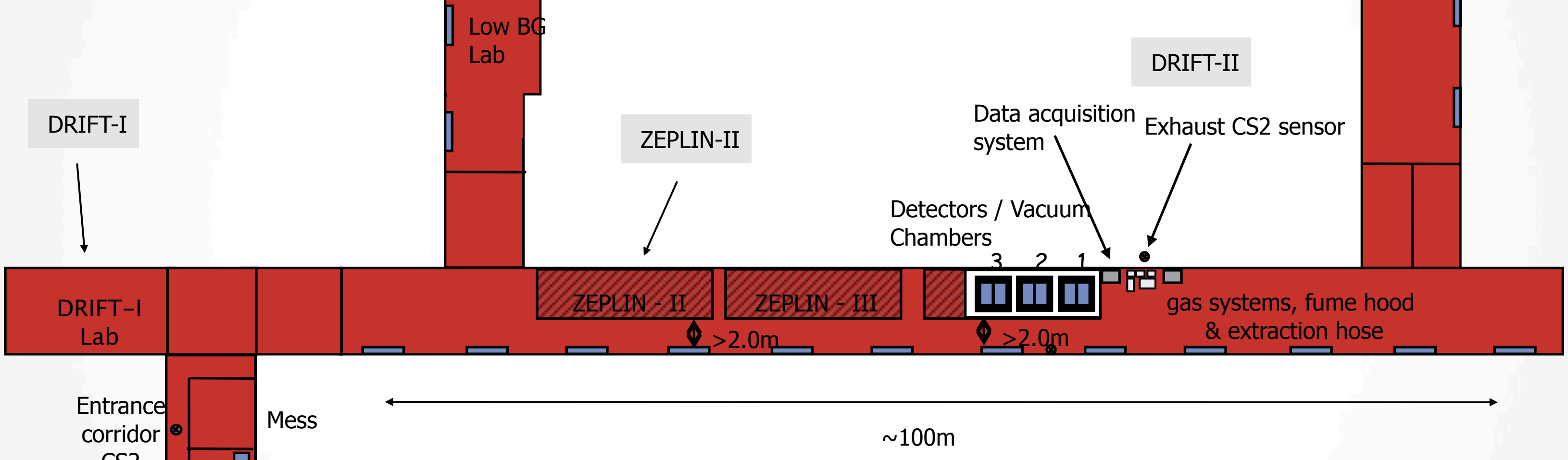
up 10 t!



Boulby Mine - The JIF Area

Boulby Mine (UK)
2805 mwe

Dark Matter 'JIF' Area

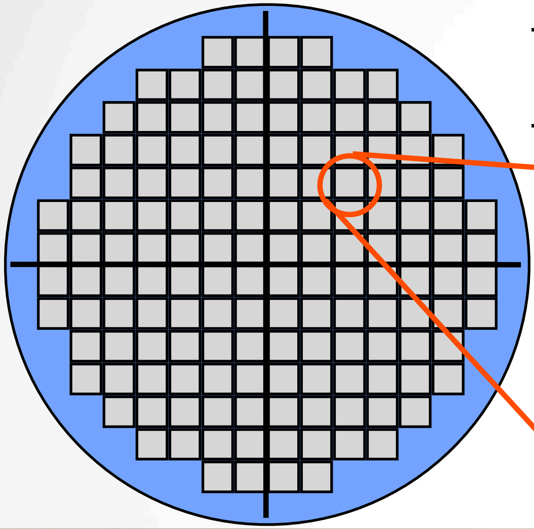


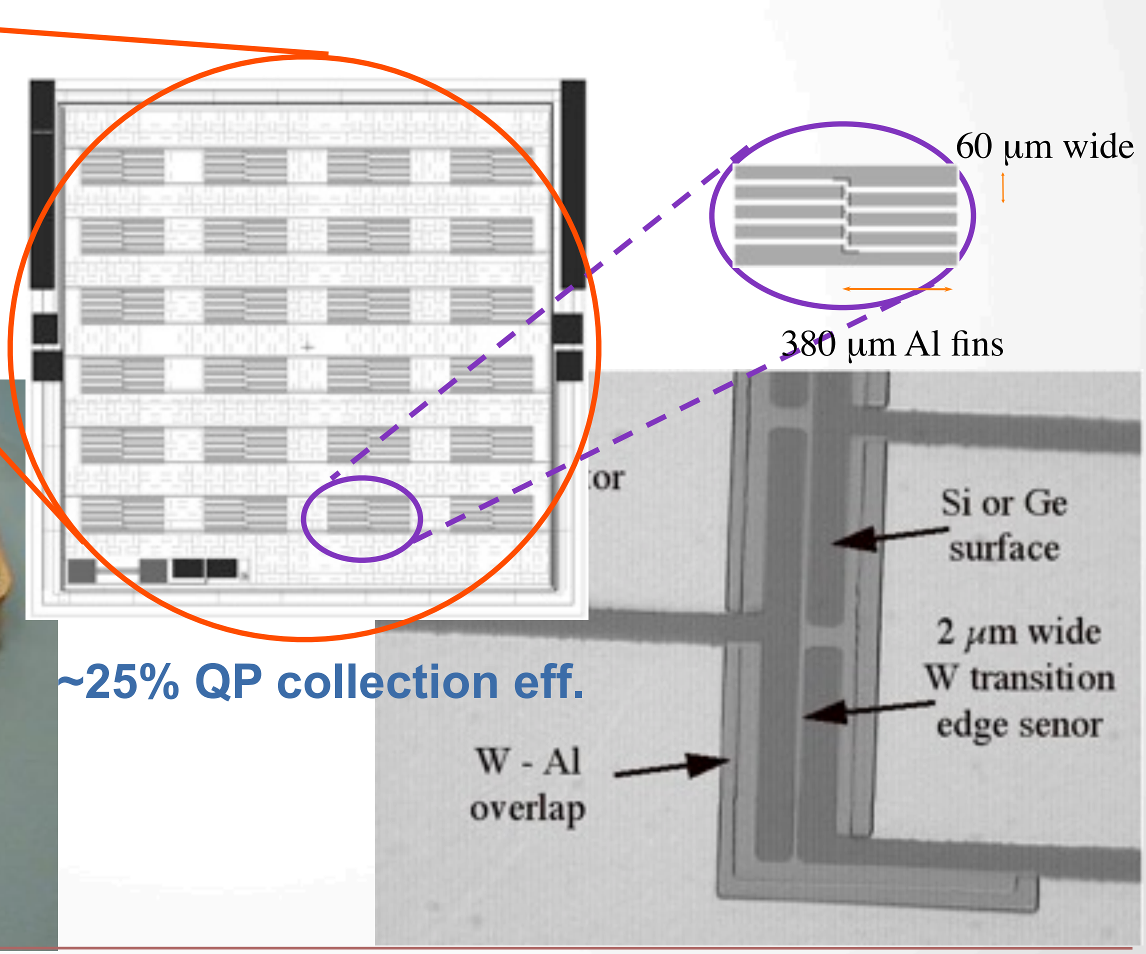
>1500m² floor space
(5m×3.5m cross section)
2T full XY crane
Communications, workshop
Storage, clean room

Late 2004

ZIP detector phonon sensor technology

- TES's patterned on the surface measure the full recoil energy of the interaction
- Phonon pulse shape allows for rejection of surface recoils (with suppressed charge)
- 4 phonon channels allow for event position reconstruction





WIMP Interaction

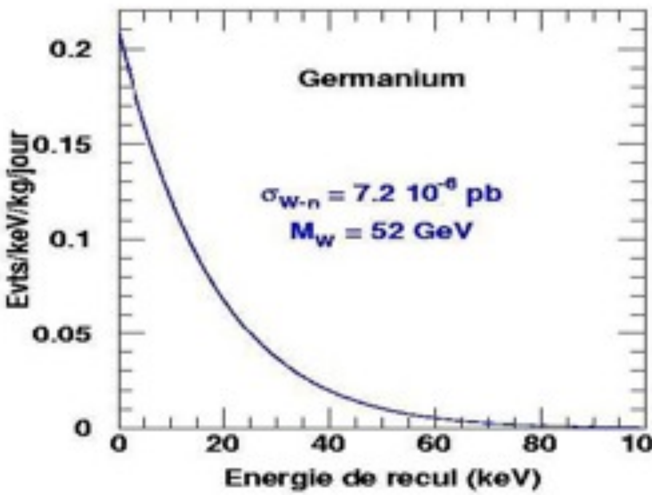
- Spin-Independent
- (coherent)
- Spin-Dependent
- Rate – 0.02 cpd/kg/keV

$$\frac{dR_{SI}}{dT} \approx A^2$$

$$\frac{dR_{SD}}{dT} \approx Const$$

$$\sigma_{SD} \approx \mu_A^2 \times \left(a_p \times \langle S_p \rangle + a_n \times \langle S_n \rangle\right)^2 \frac{J+1}{J}$$

$$\mu_A = \frac{m_X \times m_A}{m_X + m_A}$$



WIMP Rates

$$\frac{dR}{dE \times d\cos\gamma \left[kg \times keV \times day\right]} \cong \left(\frac{M\det}{kg}\right) \times \frac{1}{A} \times \frac{\rho_o}{GeV} \times \frac{1}{\upsilon_{halo}/c} \times \left(1+\frac{m_A}{m_X}\right)^2 \times \frac{1}{m_A \times m_X} \times \exp(\ldots) \times \sigma_{SI,SD}$$

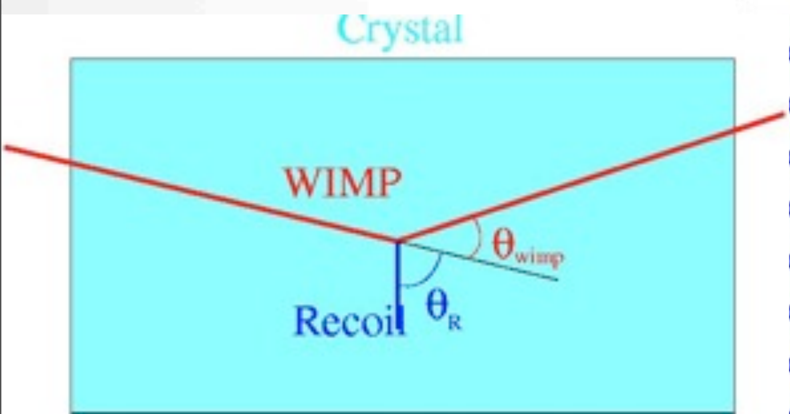
$$\sigma_{SI} \approx \left(\frac{m_X \times m_A}{m_X + m_A}\right)^2 \times A^2$$

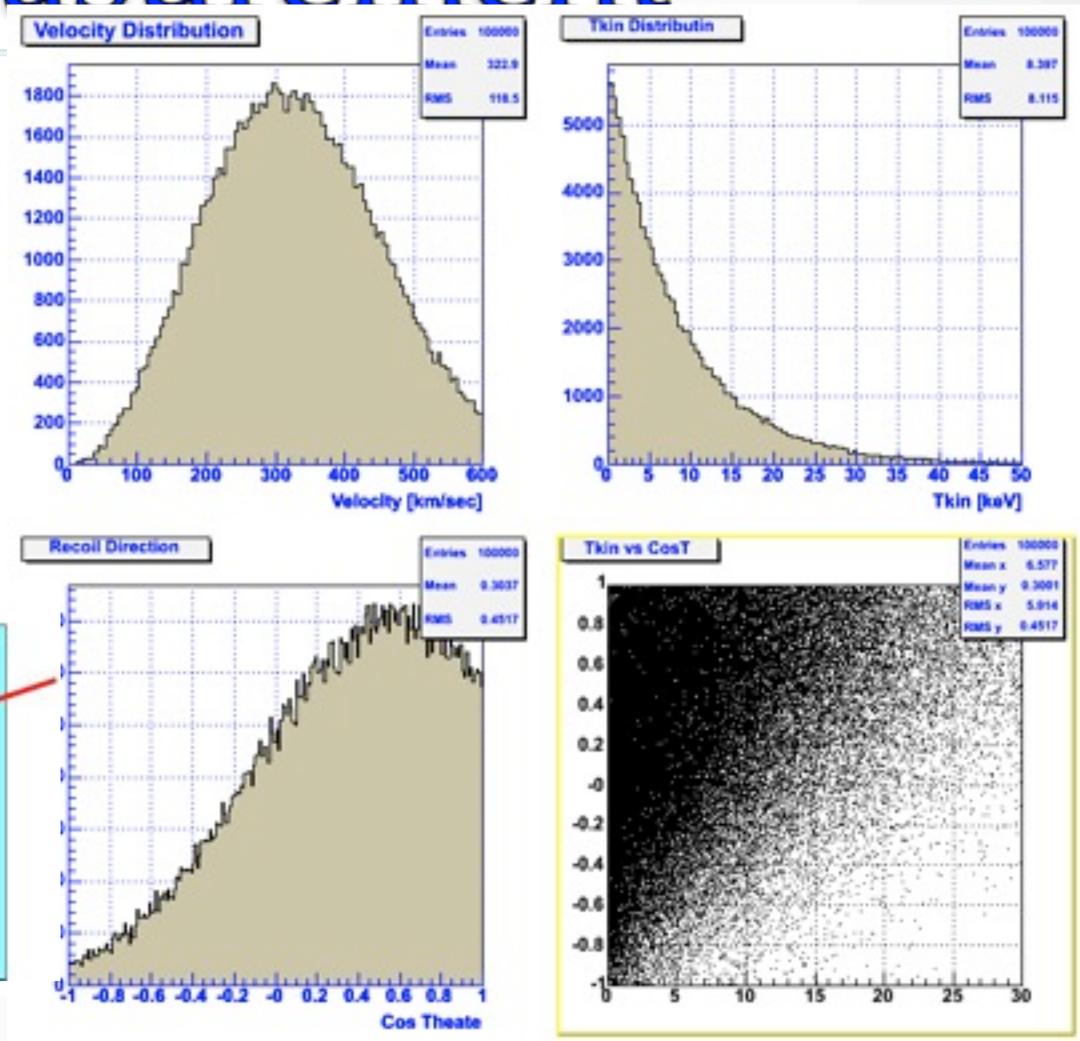
$$\exp\left(\frac{-\left(\upsilon_{Sun} \times \cos\gamma - \upsilon_{\min}\right)^2}{\upsilon_{halo}^2}\right)$$

$$\upsilon_{\min}^2 = \frac{\left(m_A + m_X\right)^2 \times E_R}{2 \times m_X^2 \times m_A}$$

Recoil Direction Measurement

- BGO Crystal
- Mx– 50 GeV





Spin-Dependent Targets

Bi – (BGO)	^{209}Bi -100% S = 9/2, m/m_N = 4.1
W – CRESST ($CaWO_4$)	^{183}W -14% S = 1/2, m/m_N = 0.1
Ge – CDMS,EDELWEISS	^{73}Ge -7.7% S = 9/2, m/m_N = -0.9
Xe – XENON,ZEPLIN DRIFT II (Xe/CS)	^{131}Xe -21.2% S = 3/2, m/m_N = 0.7 ^{129}Xe -26.4% S = 1/2, m/m_N = -0.9
I – DAMA (NaI)	^{127}I -100% S = 5/2, m/m_N = 2.8
Al – ROSEBUD(Al_2O_3)	^{27}Al -100% S = 5/2, m/m_N = 4.1
F – PICASSO (C_4F_8)	^{19}F -100% S = 1/2, m/m_N = 2.6
S – DRIFT (CS_2)	^{33}S -0.8% S = 3/2, m/m_N = 0.6

Spin-Independent Interaction

Bi – (BGO)	^{209}Bi -100%	100 %
W – CRESST ($CaWO_4$)	^{183}W -14%, ^{182}W – 26.5%, ^{184}W – 30.6%, ^{186}W – 28.4%	77 %
Ge – CDMS,EDELWEISS	^{73}Ge -7.7%, ^{70}Ge -20.8%, ^{72}Ge -27.5%, ^{74}Ge -36.3%, ^{76}Ge -7.6%	12.5 %
Xe – XENON,ZEPLIN DRIFT II (Xe/CS)	^{131}Xe -21.2%, ^{129}Xe -26.4%, ^{132}Xe -26.9%, ^{134}Xe -10.4%	40 %
I – DAMA (NaI)	^{127}I -100%	37 %
Al – ROSEBUD(Al_2O_3)	^{27}Al -100%	1.7 %
F – PICASSO (C_4F_8)	^{19}F -100%	0.8 %
S – DRIFT (CS_2)	^{33}S -0.8%, ^{32}S -95%, ^{34}S -4.2%	2.3 %

BGO Crystal

- BGO Decay Time – 300ns

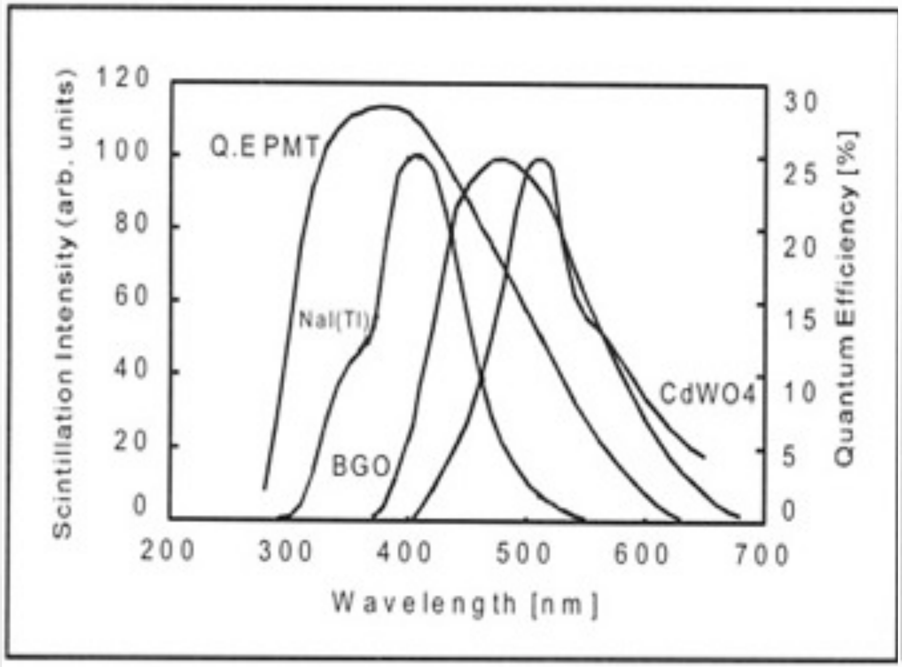


Fig. 3.1 *Emission spectra of NaI(Tl), BGO and $CdWO_4$, scaled on maximum emission intensity.*

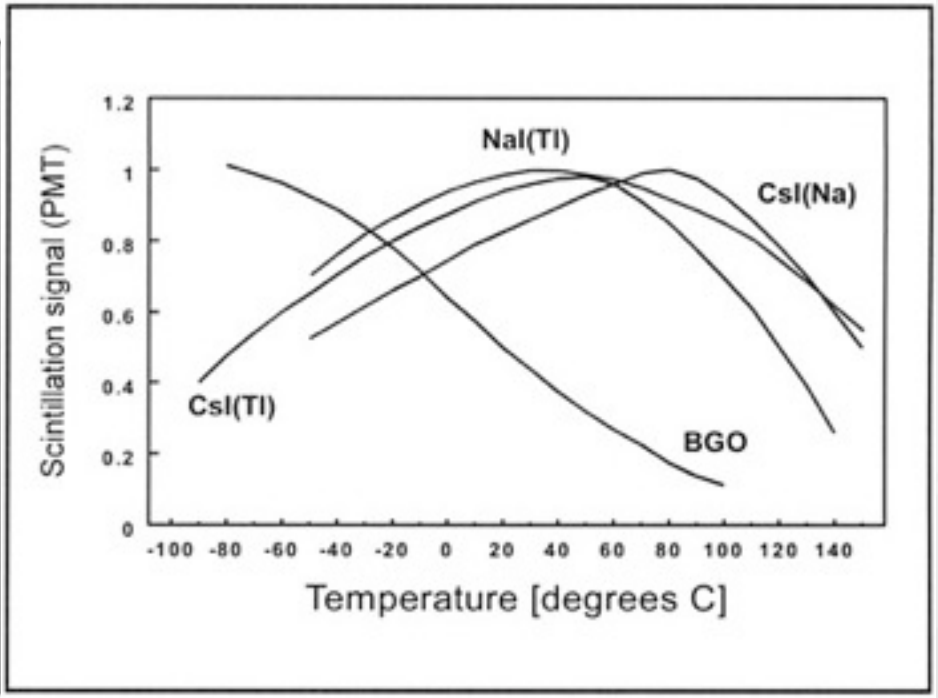


Fig. 3.3 *Temperature dependence of the scintillation yield of NaI(Tl), CsI(Na), CsI(Tl) and BGO.*

Experimental Measurements?

- BGO Light Yield
- BGO Decay Time
- BGO Properties Changes

- TDC
- FADC
- 2 PMT Hamamatsu R7281
- High Quantum Eff 27-30%