Status and Perspectives of Dark Matter annual modulation
(annual modulation review + XMASS)

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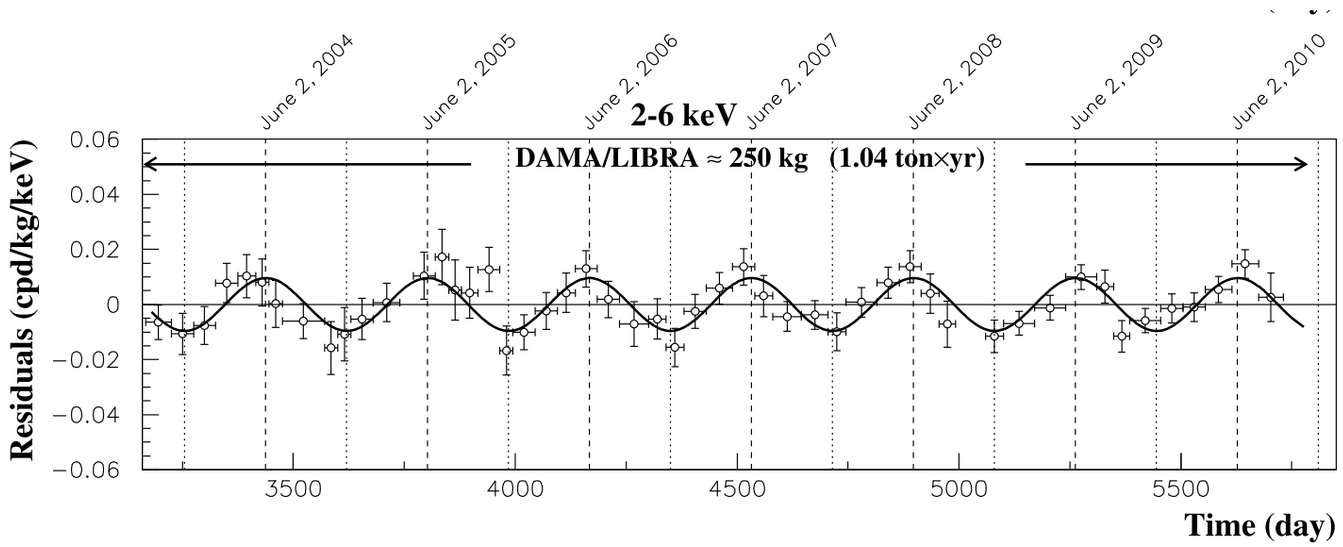
The University of Tokyo

XVII International Workshop on Neutrino Telescopes March 13-17, 2017

DAMA/LIBRA

Eur. Phys.J. C(2013) 73, JINST 2012 7 P03009

- DAMA(~100 kg) + LIBRA (~250 kg)
- 14cycle -> 1.33ton x yr
- Annual Modulation 9.2 σ
- Fit with all the parameters free:



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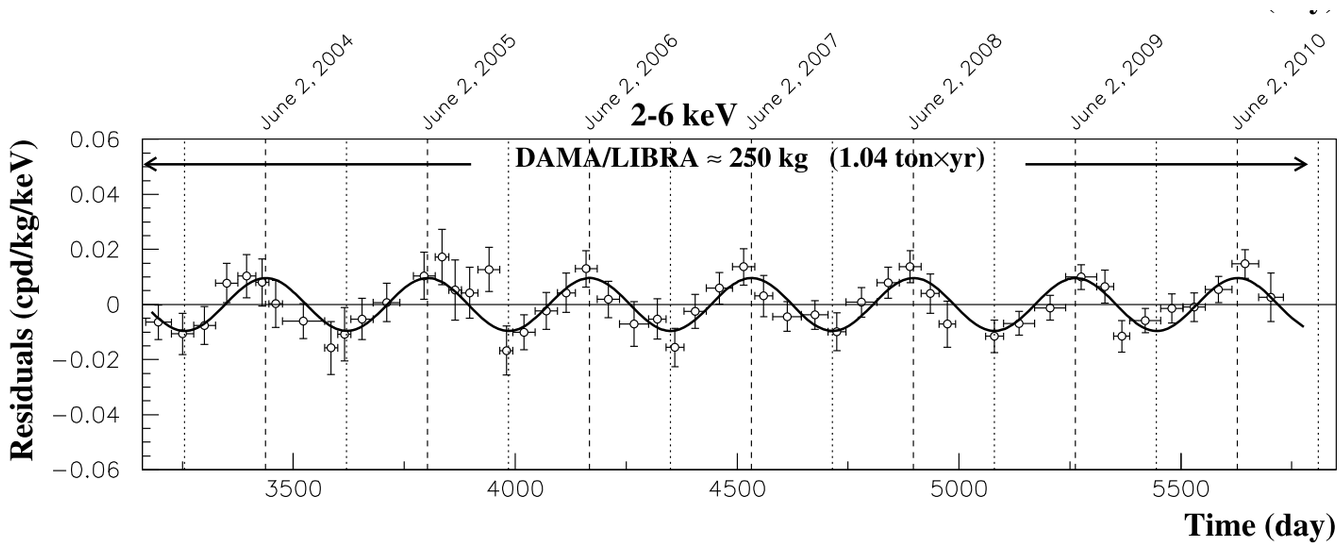

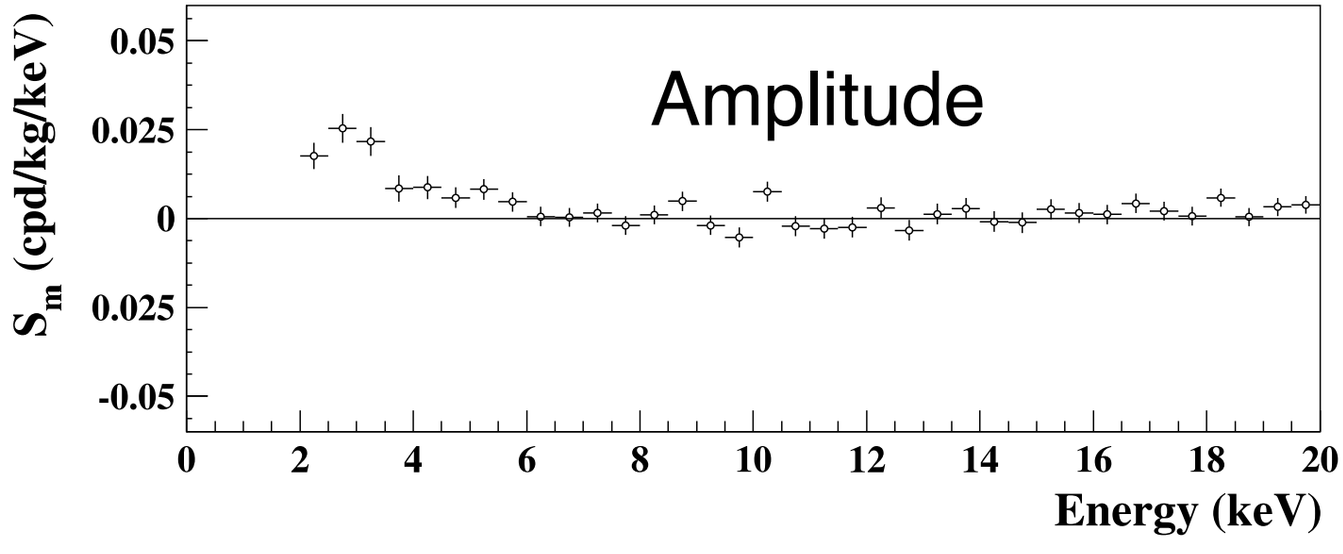

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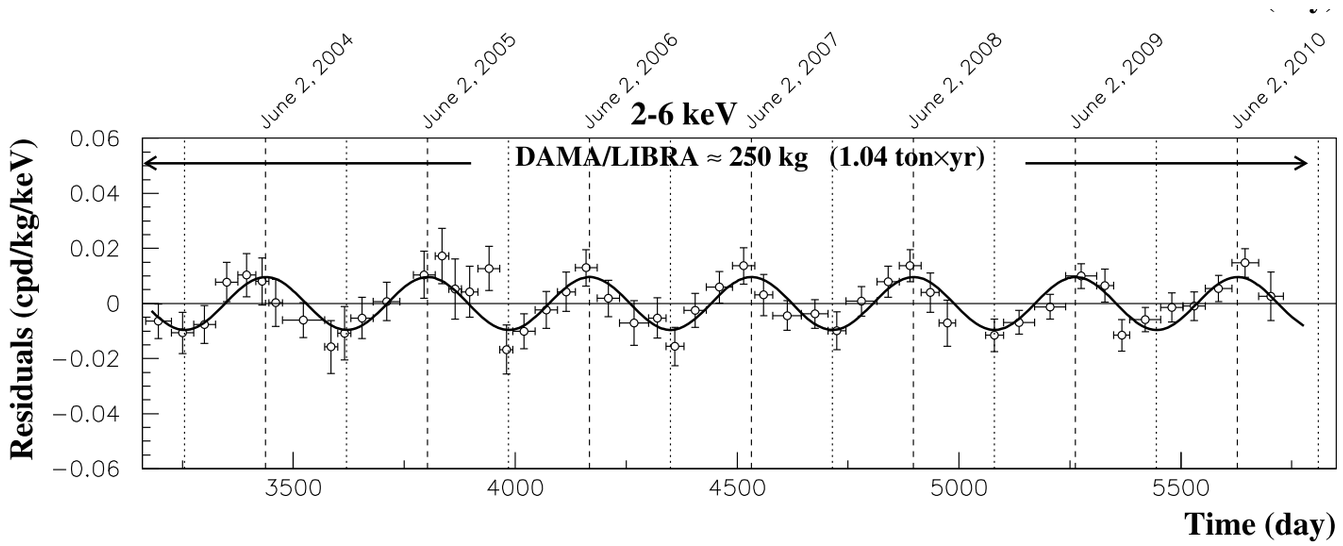
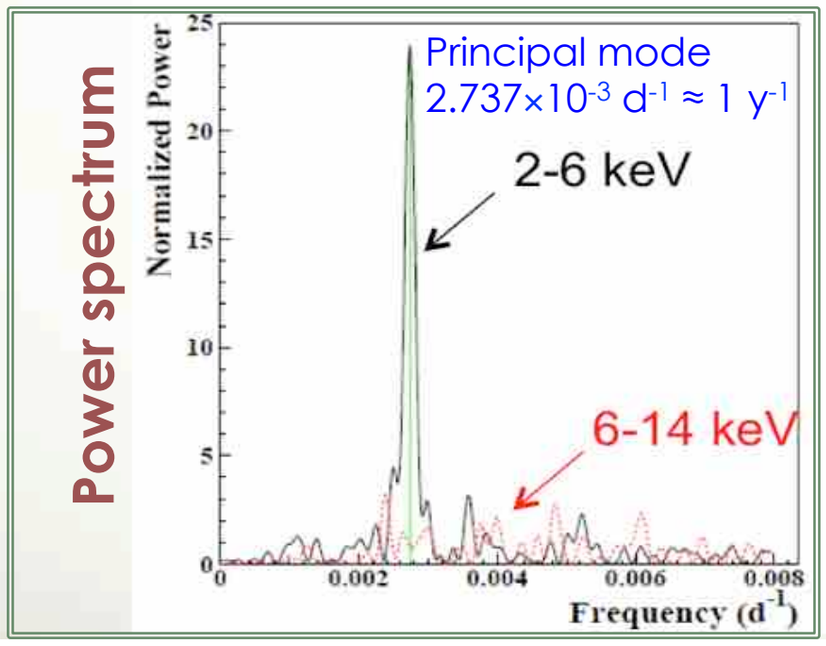
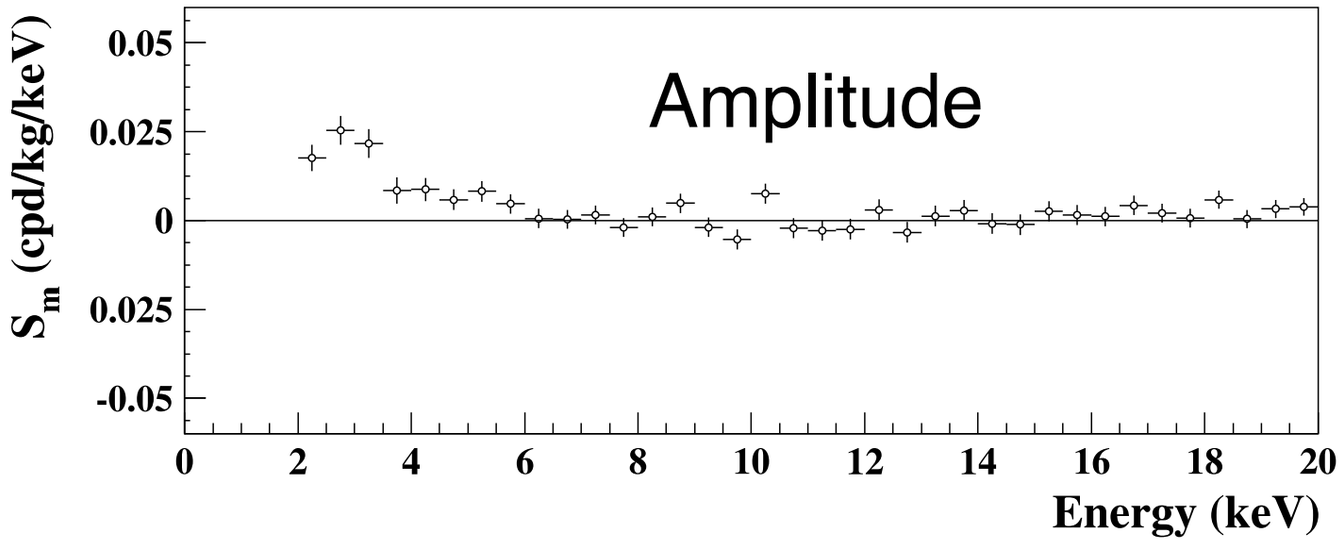
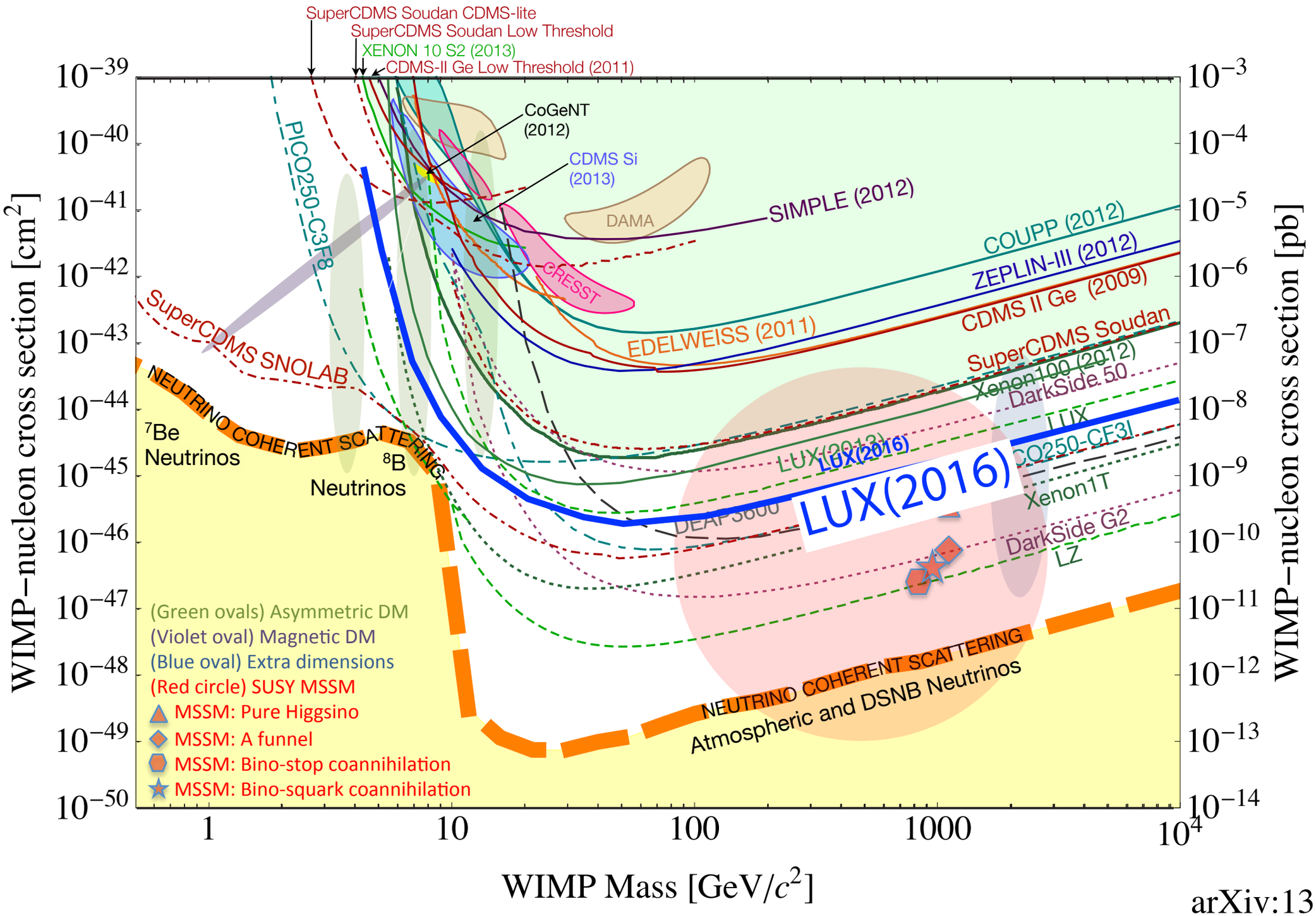






Direct Dark Matter Search (standard halo model)

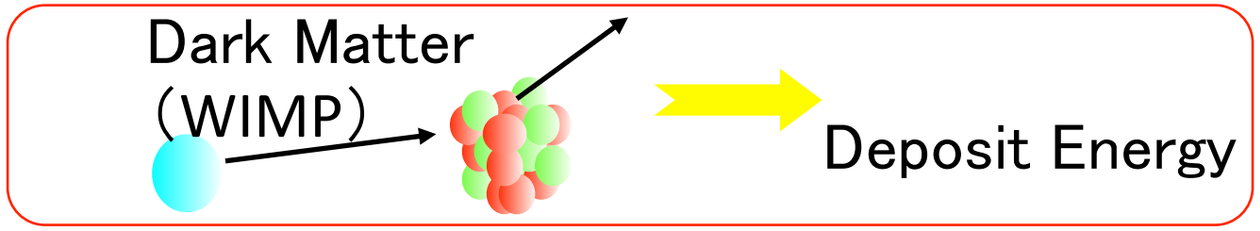


arXiv:1310.8327v1

Differential Rate

Measuring the deposited energy due to elastic scattered nuclei by WIMP.

Expected spectrum:



$$\frac{dR}{dE_R} = \frac{R_0 F^2(E_R)}{E_0 r} \frac{k_0}{k} \frac{1}{2\pi v_0} \int_{v_{min}}^{v_{max}} \frac{1}{v} f(\mathbf{v}, \mathbf{v_E}) d^3\mathbf{v}$$

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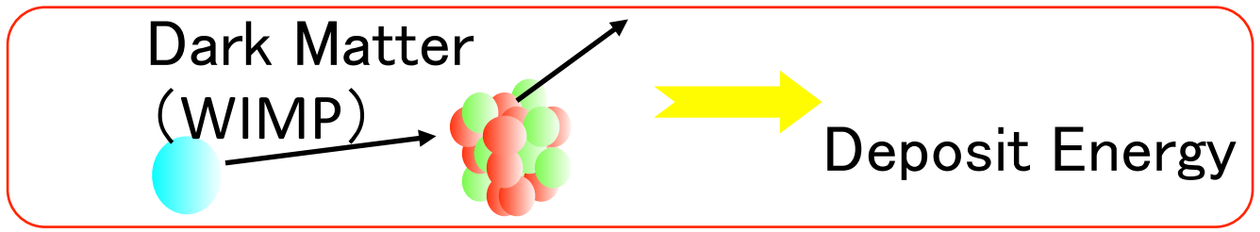

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R0: Event rate @ zero momentum transfer

Spin independent

$$\sigma_0 = A^2 \frac{\mu_T^2}{\mu_p^2} \sigma_{\chi-p}$$

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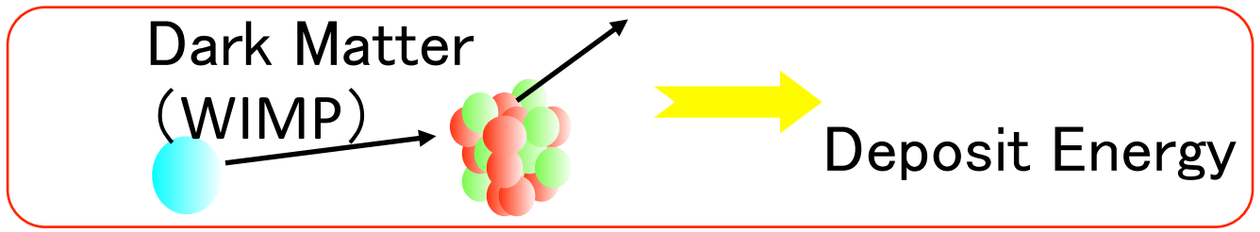

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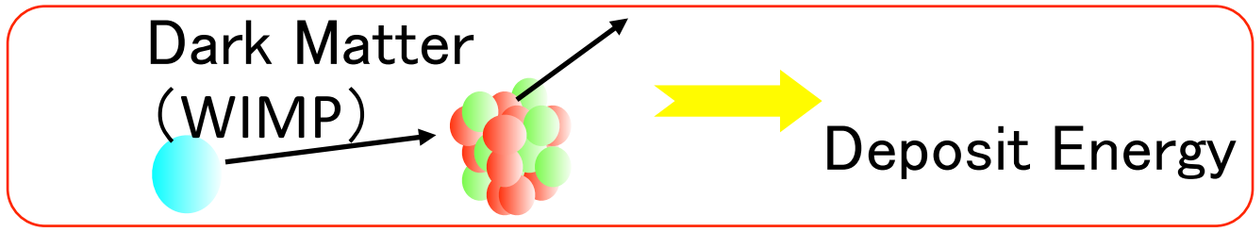

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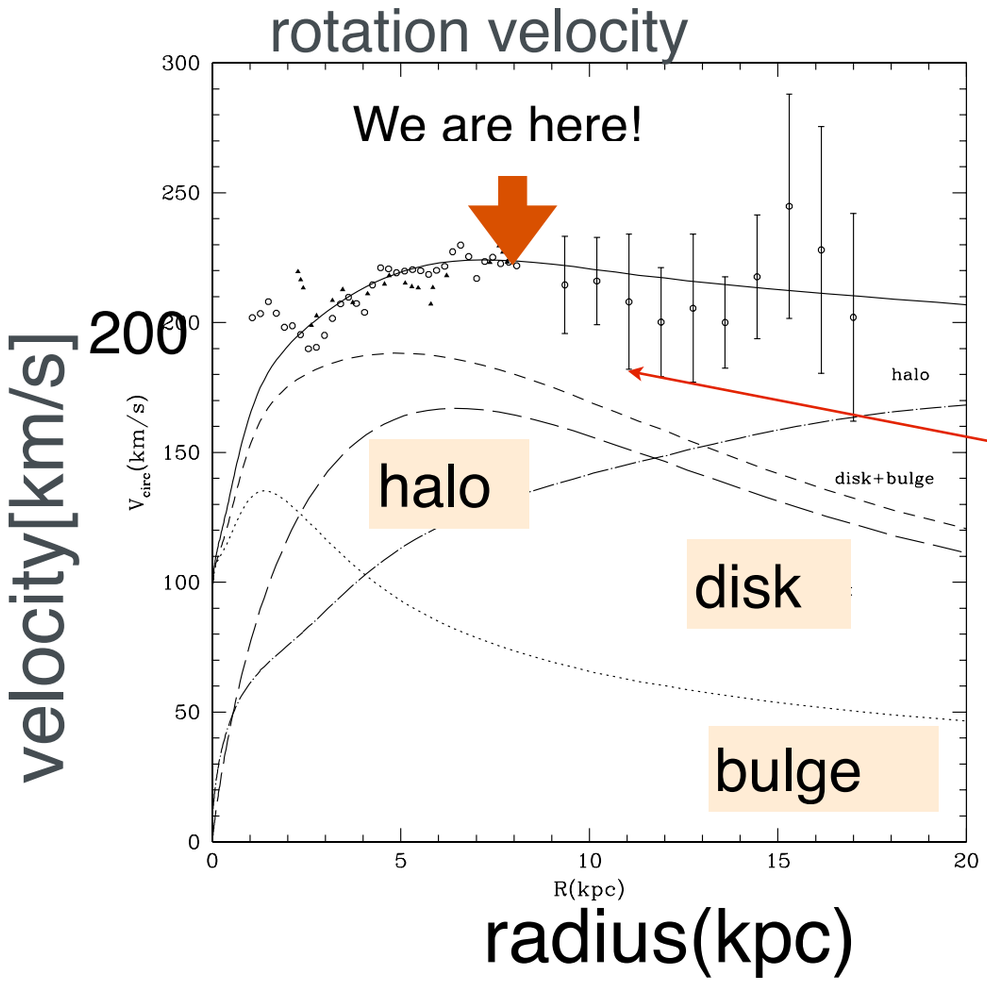
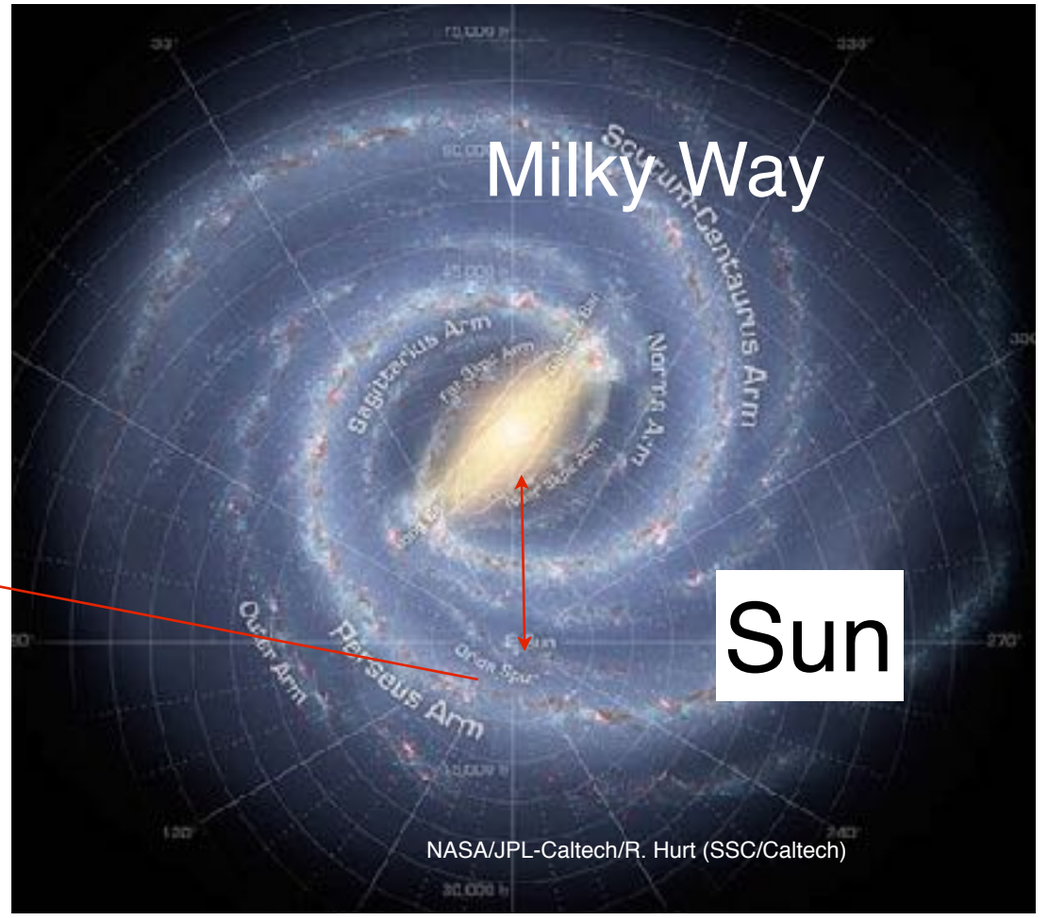
motion dynamics

V :velocity onto target,
VE: Earth's motion around the Sun
Maxwellian distribution for DM velocity is assumed.

Annual modulation signal

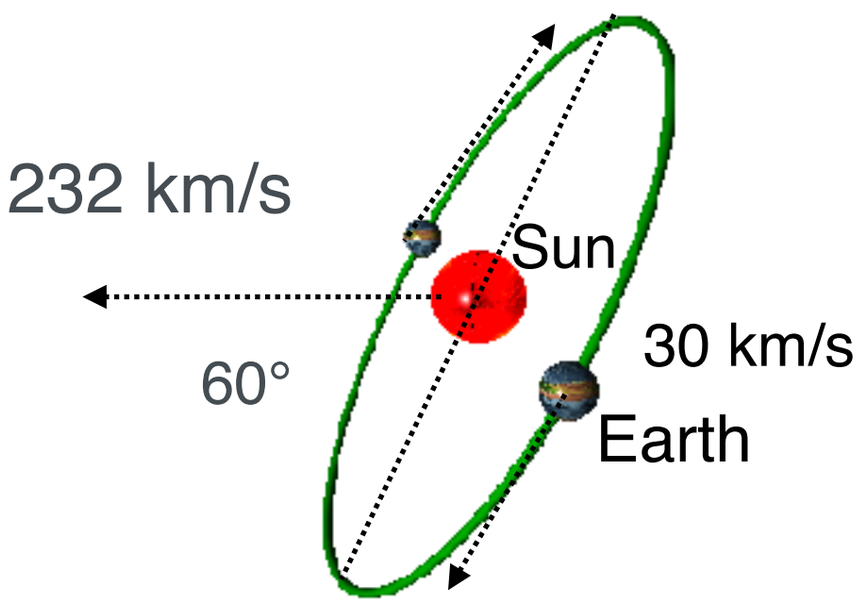


KLYPIN et al. APJ 2002

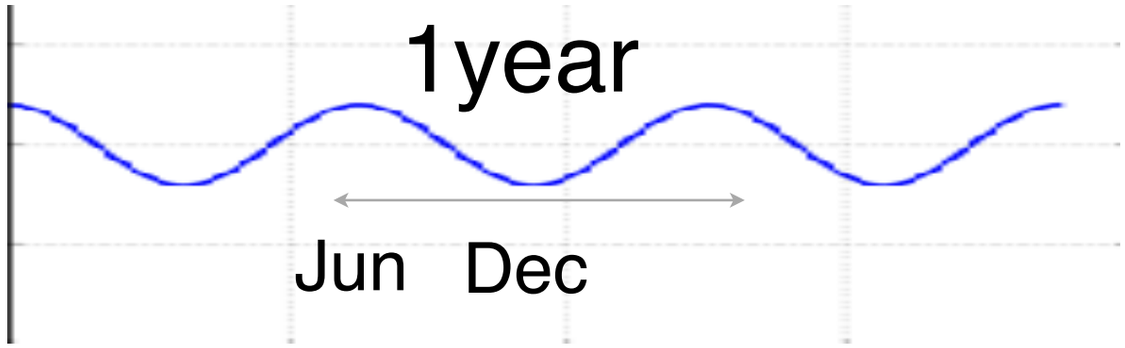


$$\frac{\mathrm{d}R}{\mathrm{d}E}(E,t) \approx S_0(E) + S_m(E)\cos\omega(t-t_c)$$

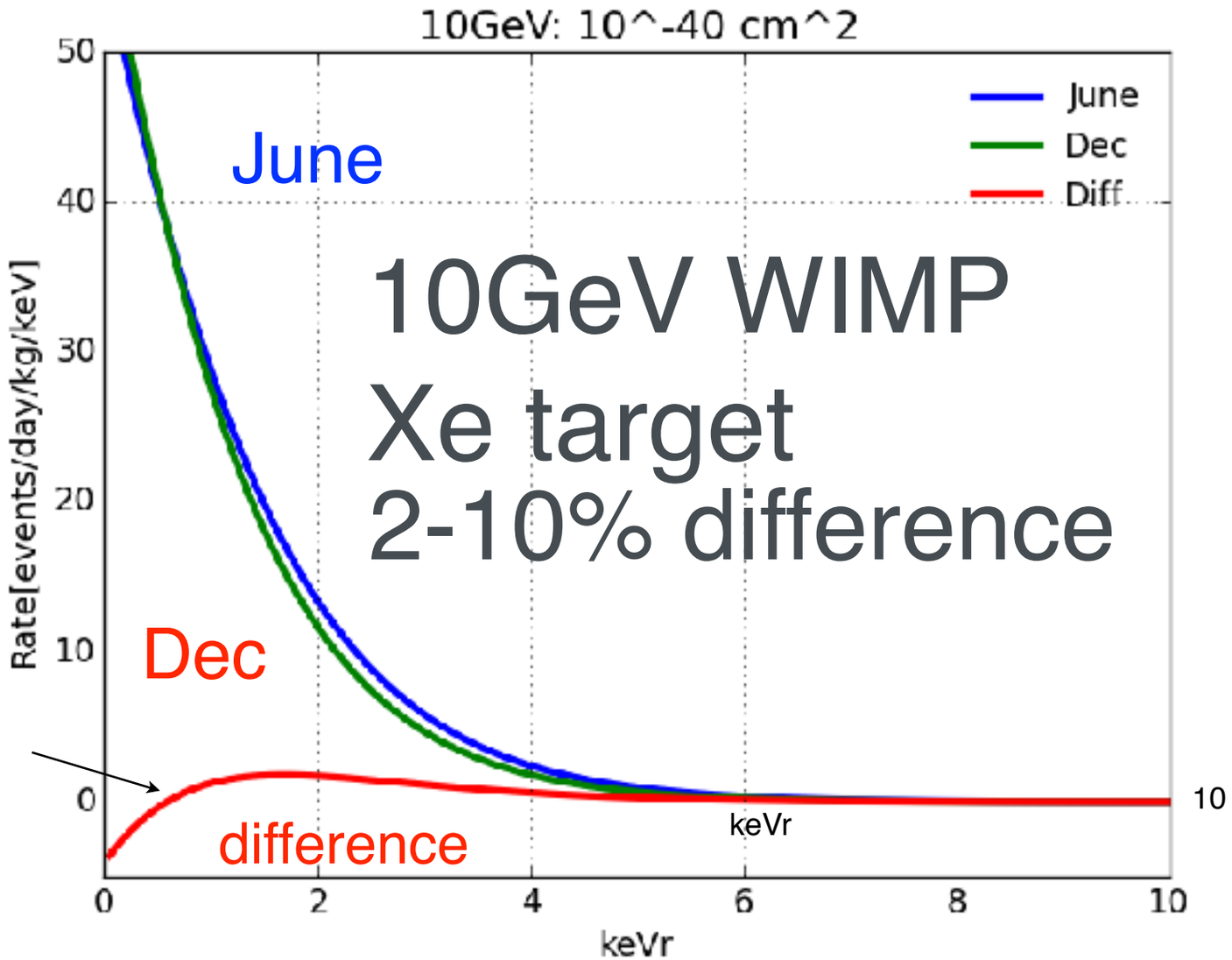
$$S_m(E) = \frac{1}{2}\left[\frac{\mathrm{d}R}{\mathrm{d}E}(E,\ \text{June 1}) - \frac{\mathrm{d}R}{\mathrm{d}E}(E,\ \text{Dec 1})\right]$$



Energy spectrum



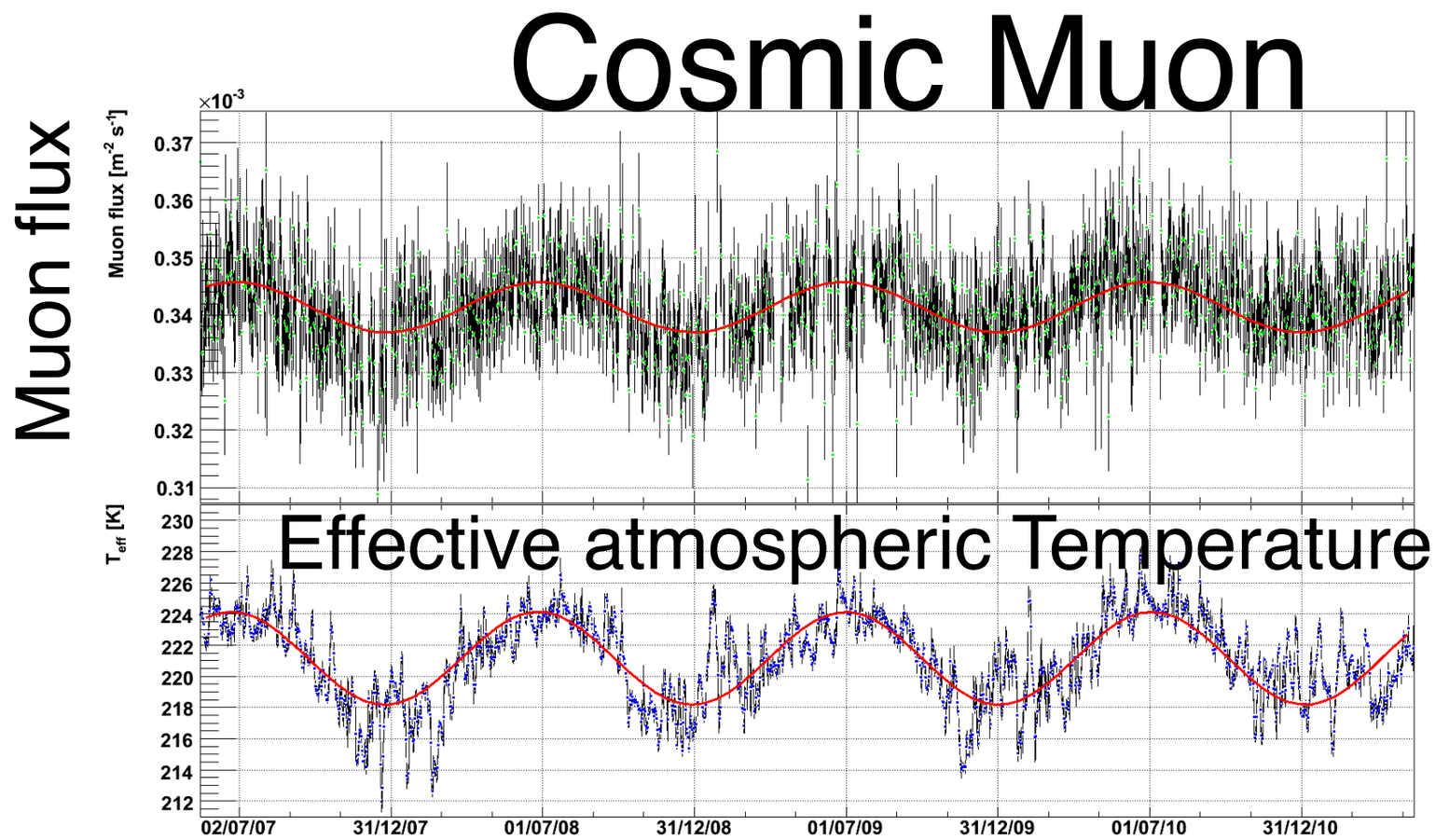
cross over point



Contents

Muon induced background@Gran Sasso

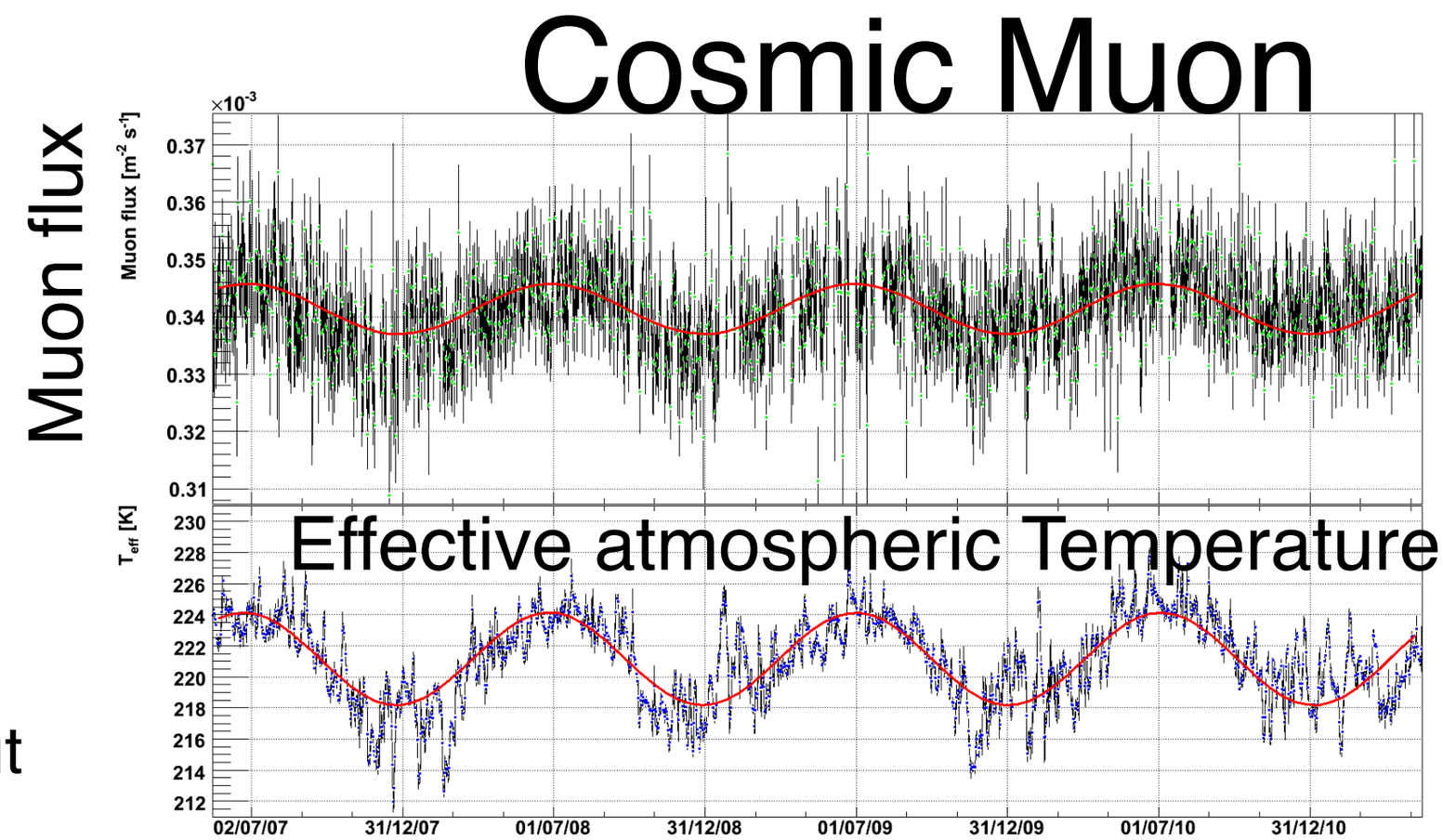
- Annual modulation of the muon reported by Borexino LVD and MACRO.



Borexino collaboration, arXiv:1202.6403

Muon induced background

- Annual modulation of the muon reported by Borexino LVD and MACRO.
- Muon rate is depend on atmosphere temperature.
- Modulation amplitude is about 1.4%
- Several papers report about muon induced background.

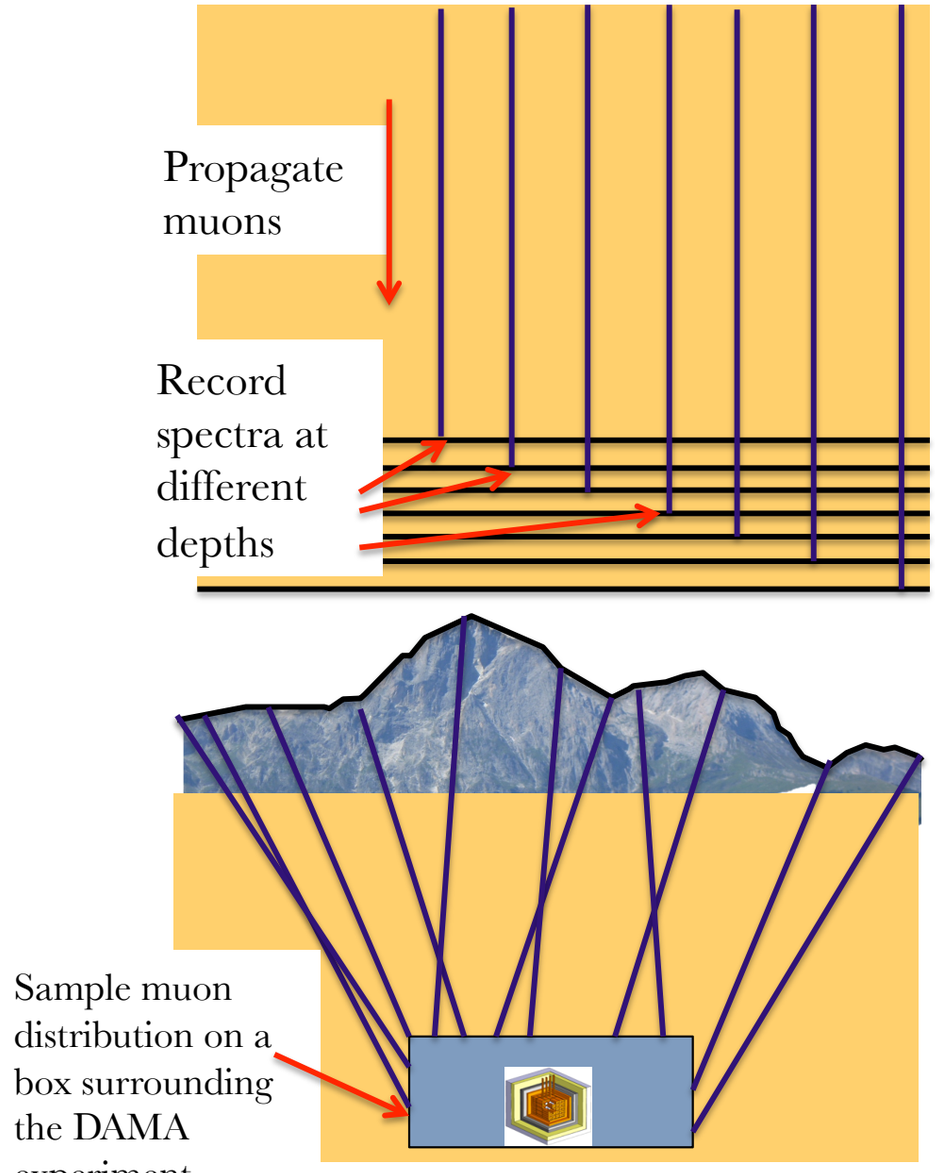


Borexino collaboration, arXiv:1202.6403

Full Monte Carlo

PRL 114, 151301 (2015) J. Klinger and V. A. Kudryavtsev

- Propagate muons though LNGS rock.
- Neutron production and transport by GEANT4
- Detector simulation for NaI(Tl) array
- Event analysis to sample single hit events.
- Conclusion
  - 3.5x10-5 counts/kg/day/keV => 0.3% of the measured
  - Muon-induced neutrons can not explain the DAMA data.



from Vitaly Kudryavtsev

Contents

DAMA/LIBRA vs others

Background ?

Isospin violation ?

Why not NaI(Tl) ?

DM-electron recoil signal ?

Future prospects

Isospin violation

A. Kurylov et al. Phys. Rev. D 69 (2004) 063503

J.L. Feng et al. PLB 703 (2011) 124

$$\sigma_A = \frac{\mu_A^2}{M_*^4}\left[f_p Z + f_n (A - Z)\right]^2$$

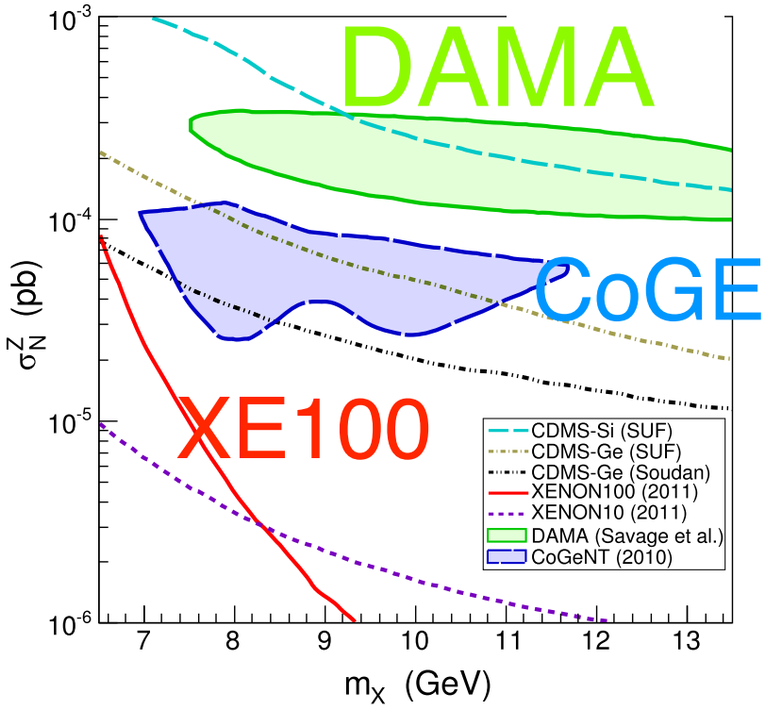
A: atomic mass
Z: atomic number

fp: coupling to proton, fn for neutron

Usually, we assume fp = fn Then,

=> $\propto A^2$

$f_n / f_p = 1.0$



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If $f_n/f_p = -Z/(A-Z)$

e.g. z=54, A=131, fn/fp = -0.7

means DM doesn't like to scatter with Xe!

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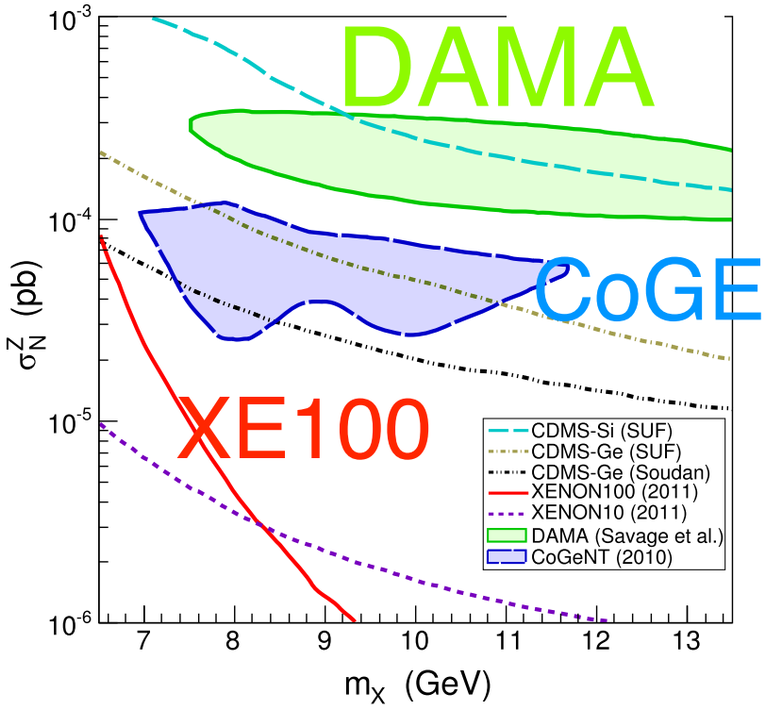

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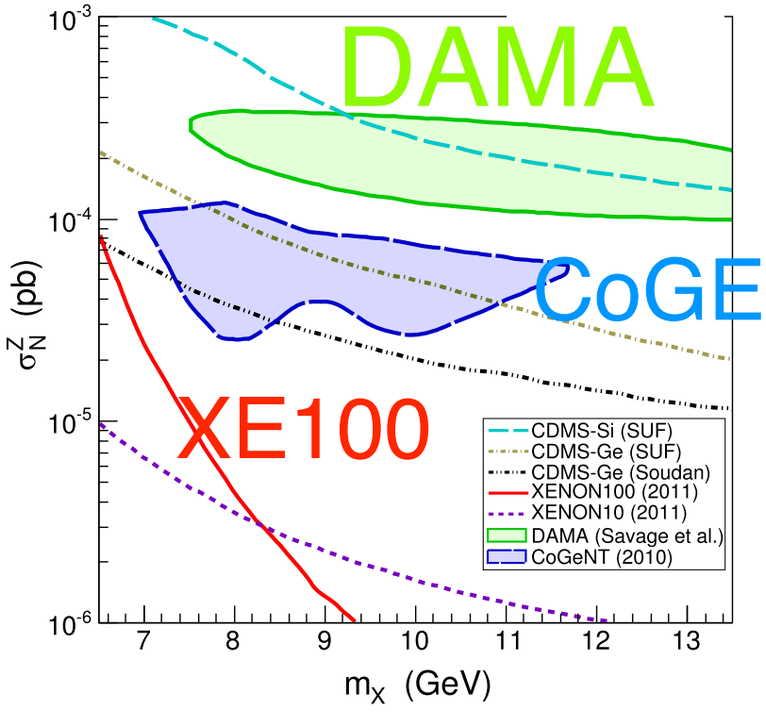

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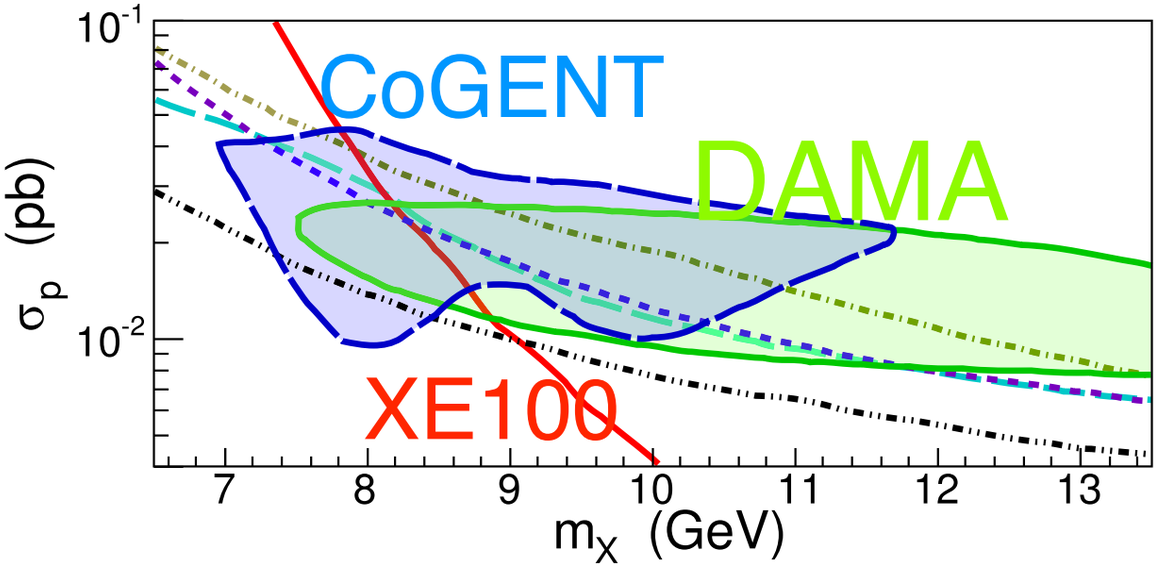
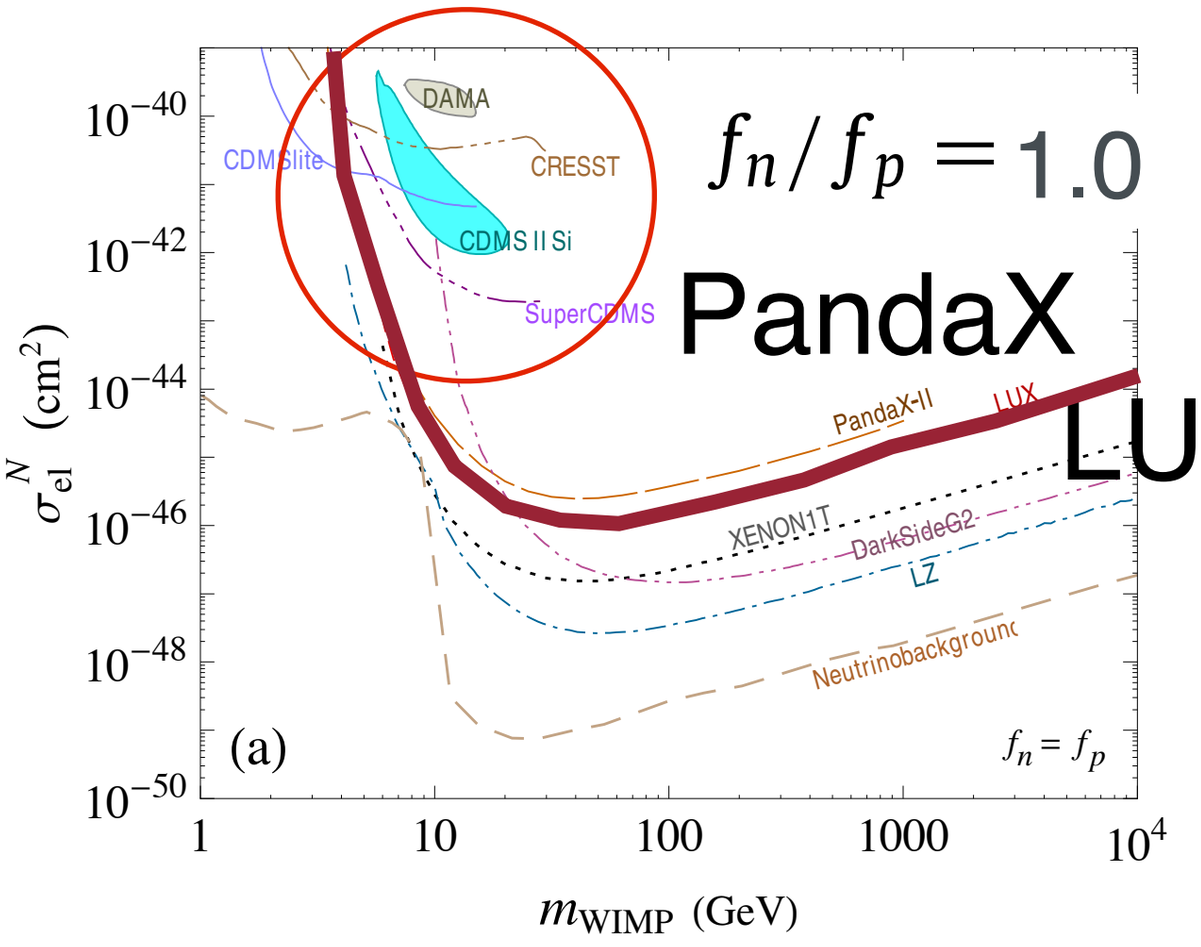
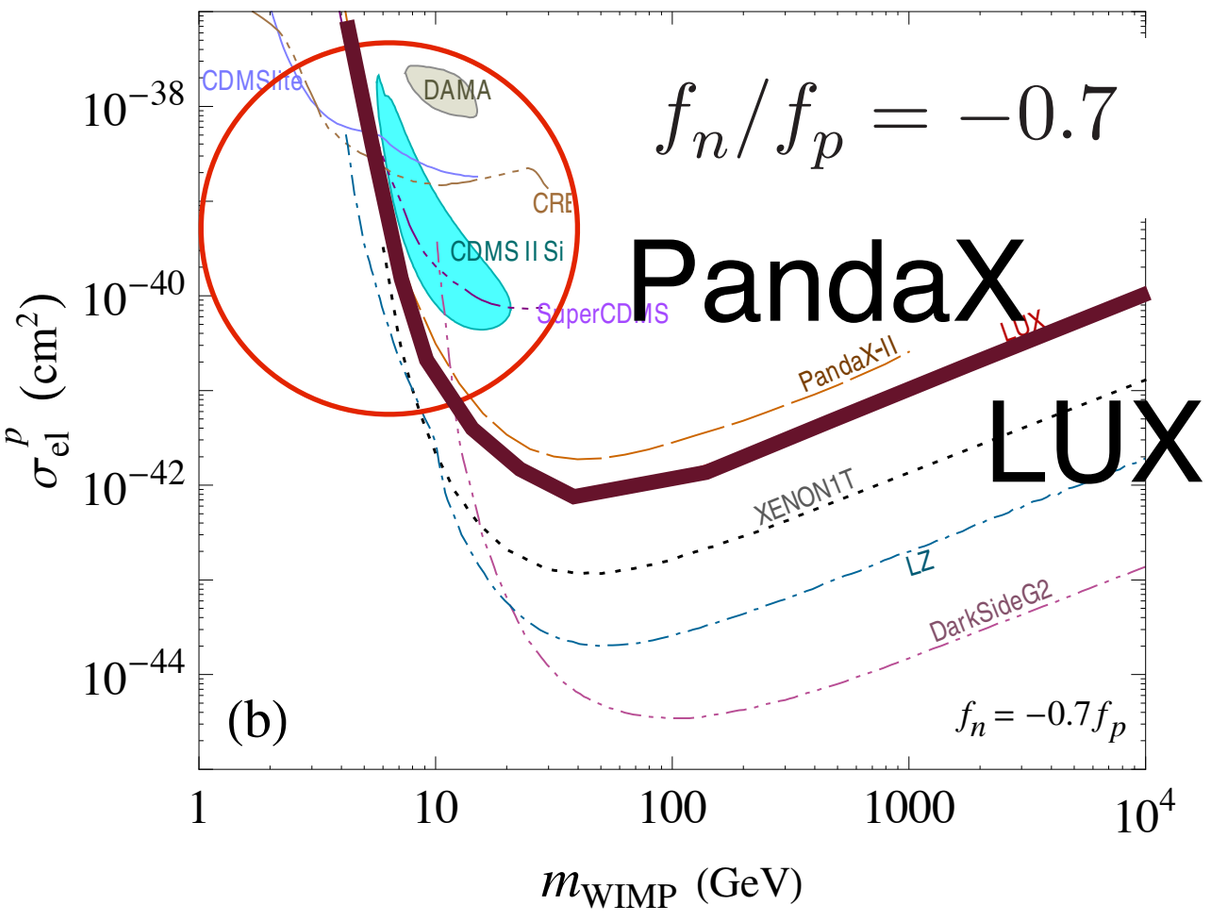


isospin violation (2016)

arXiv:1609.03551v2, X. He et al

+ LUX and PandaX-II in 2016





Positive signal regions are no longer viable after LUX and PandaX-II

Contents

Why not NaI(Tl)?

-No experiments could confirm/deny DAMA/LIBRA result for a long time by NaI (Tl)

  -The reason is no one could get pure NaI(Tl) as good as DAMA/LIBRA crystal, especially for 40K and 210Pb.

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-The reason is no one could get pure NaI(Tl) as good as DAMA/LIBRA crystal, especially for 40K and 210Pb.

-But recently, the R&D for making pure NaI(Tl) crystal have been carrying out by several group.

- COSINE-100,

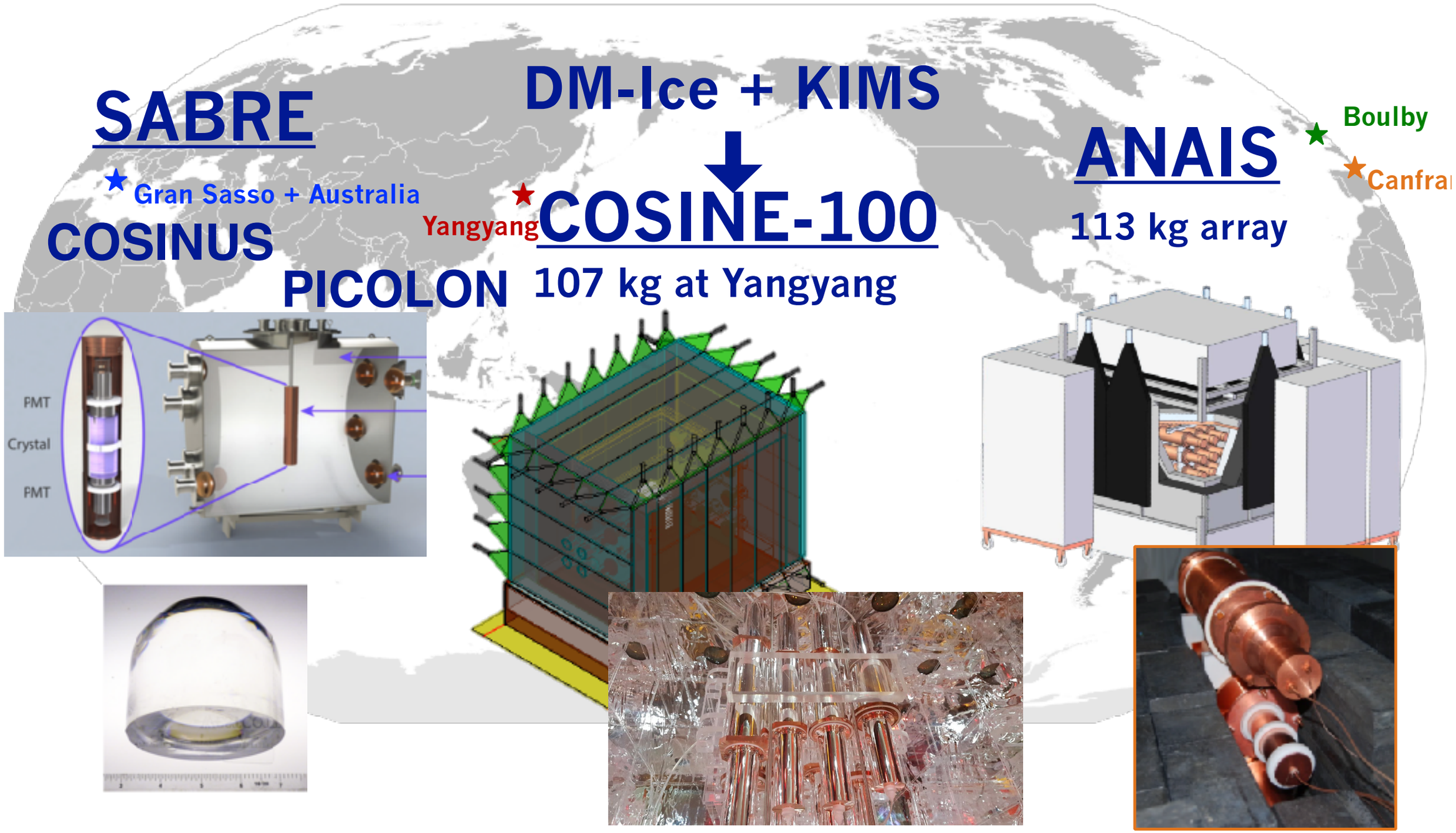
40K below DAMA, 210Po ~ DAMA,

total 2-4 x DAMA's avg

	Mass (kg)	Powder Type	^{40}K (ppb)	^{238}U (ppt)	^{232}Th (ppt)	^{210}Po (mBq/kg)
Crystal 1	8.26	Powder B	43.4±13.7	<0.02	1.31±0.35	3.20±0.04
Crystal 2	9.15	Powder C	82.7±12.1	<0.12	<0.63	2.06±0.03
Crystal 3	9.16	WIMPScint-II	41.1±6.8	<0.04	0.44±0.19	0.76±0.02
Crystal 4	18.01	WIMPScint-II	39.5±8.3		<0.3	0.74±0.01
Crystal 5	18.28	Powder C	86.8±10.8		2.35±0.31	2.06±0.02
Crystal 6	12.5	WIMPScint-III	12.2±4.5	<0.018	0.56±0.19	1.52±0.02
Crystal 7	12.5	WIMPScint-III	18.8±5.3		<0.6	1.54±0.02
Crystal 8	18.28	Powder C	56.15±8.1		<1.4	2.05±0.02
DAMA			<20	0.7 - 10	0.5 - 7.5	<0.5

COSINE-100 NaI(Tl) crystal from R. Maruyama

Current & Planned NaI(Tl) Experiments

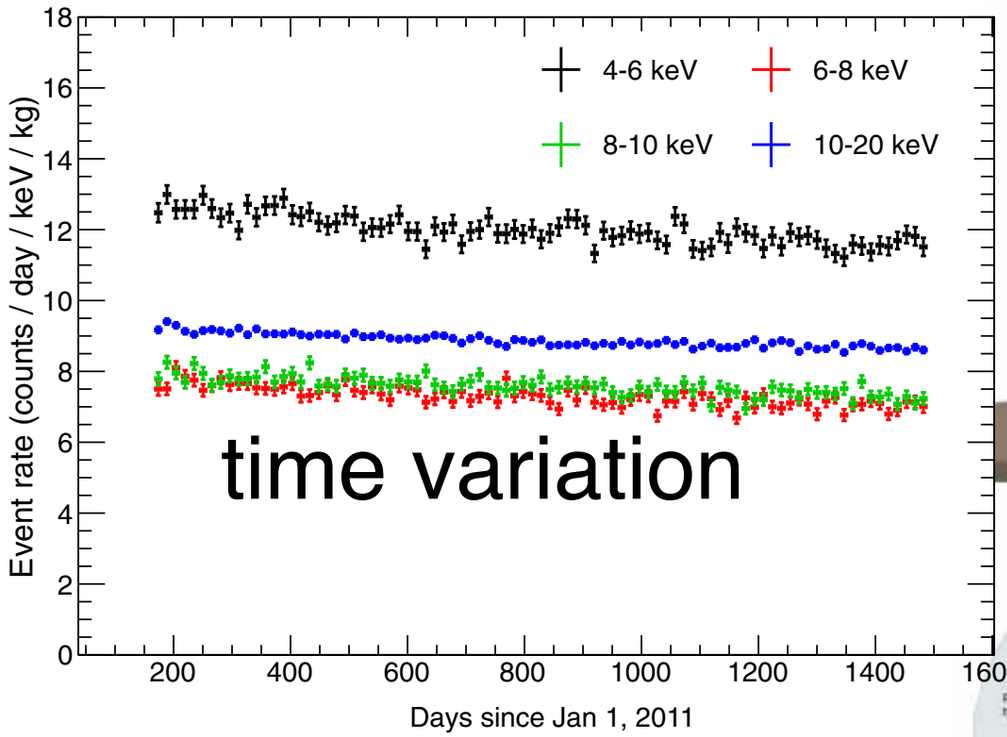


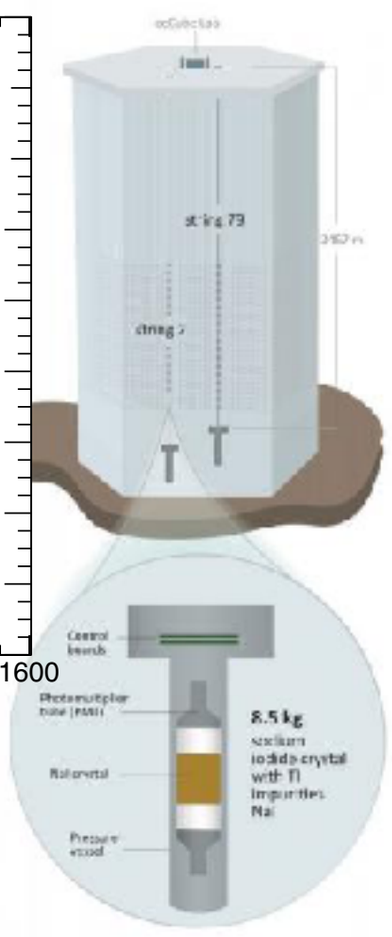
from Reina Maruyama

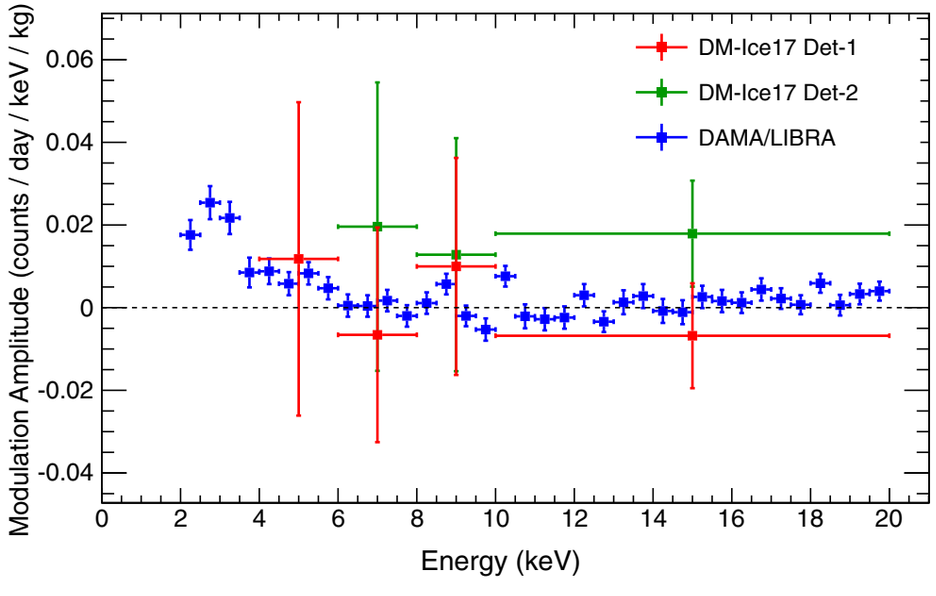
DM-ICE

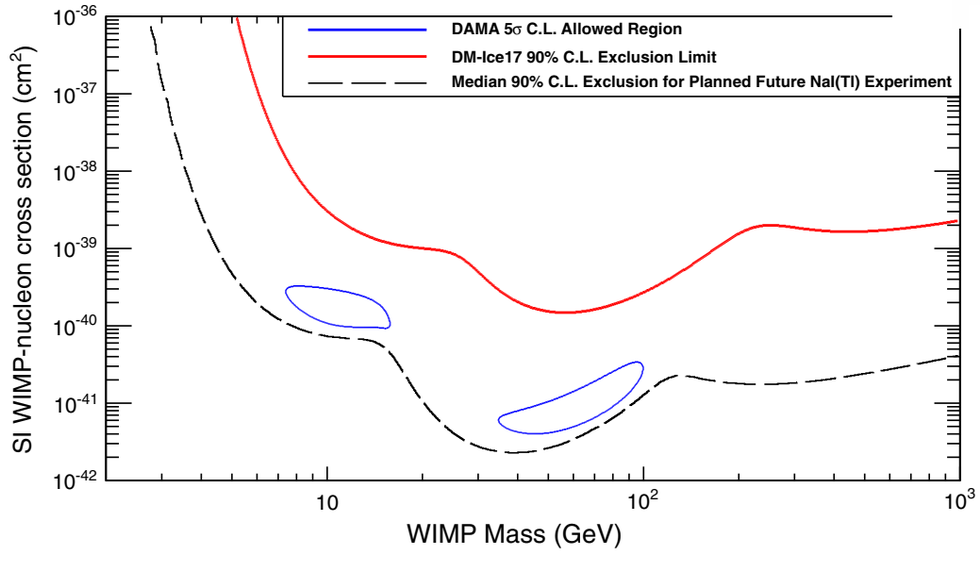
PRD 95 032006 (2017)
E. Barbosa de Souza et al.

- the detector was deployed at the geographic South Pole in December, 2010.
- Two 8.47 kg crystals (originally used in the NAIAD)
- 2457 m (2200 m.w.e.) overburden from the Antarctic ice.
- the first search for annual modulation dark matter signal with NaI(Tl) detectors in the Southern Hemisphere.





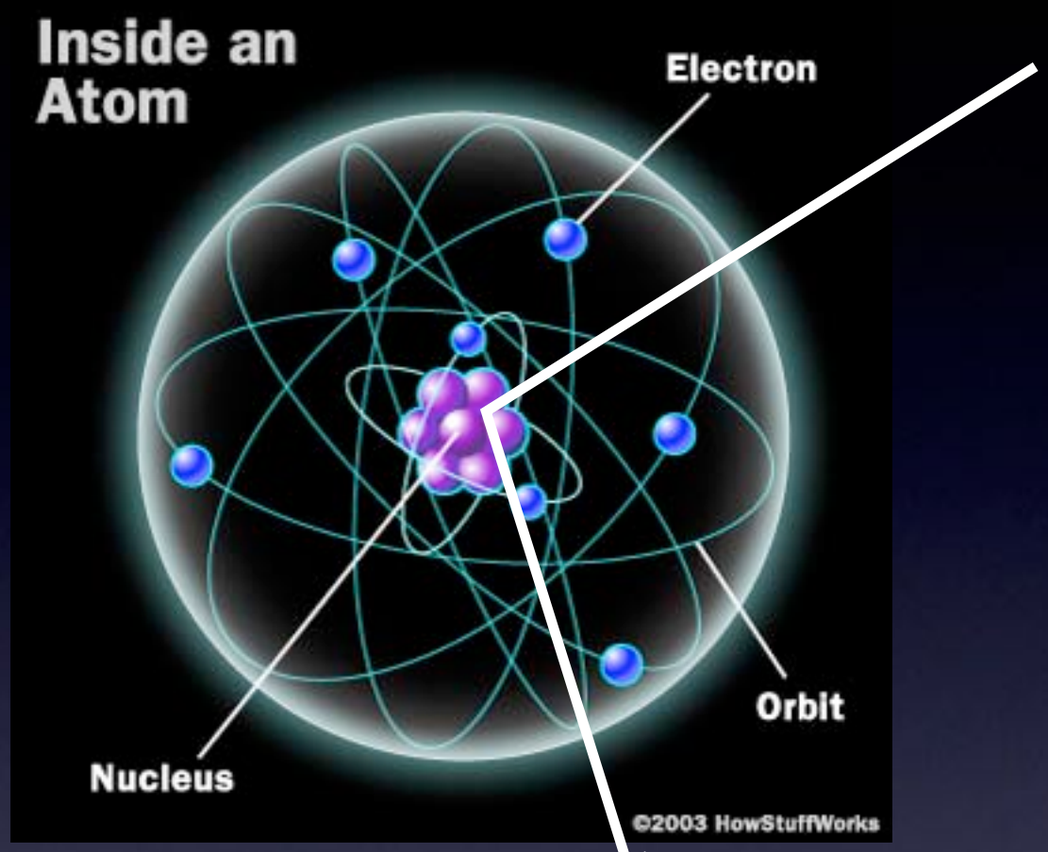




Contents

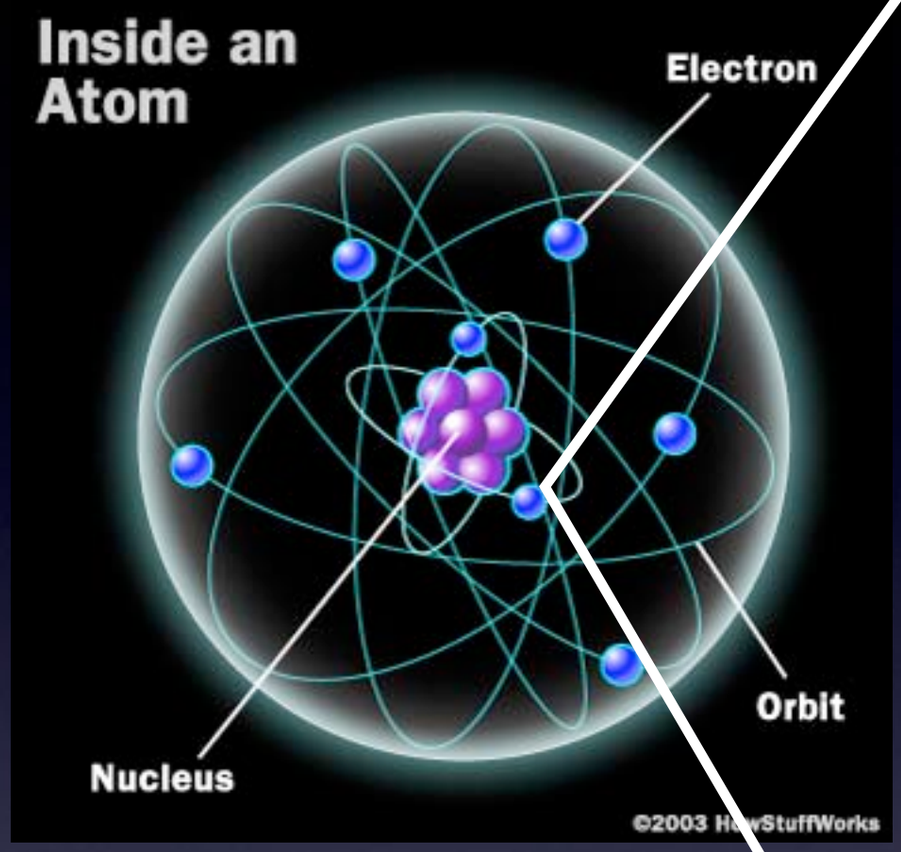
Interaction with dark matter

nuclear recoil



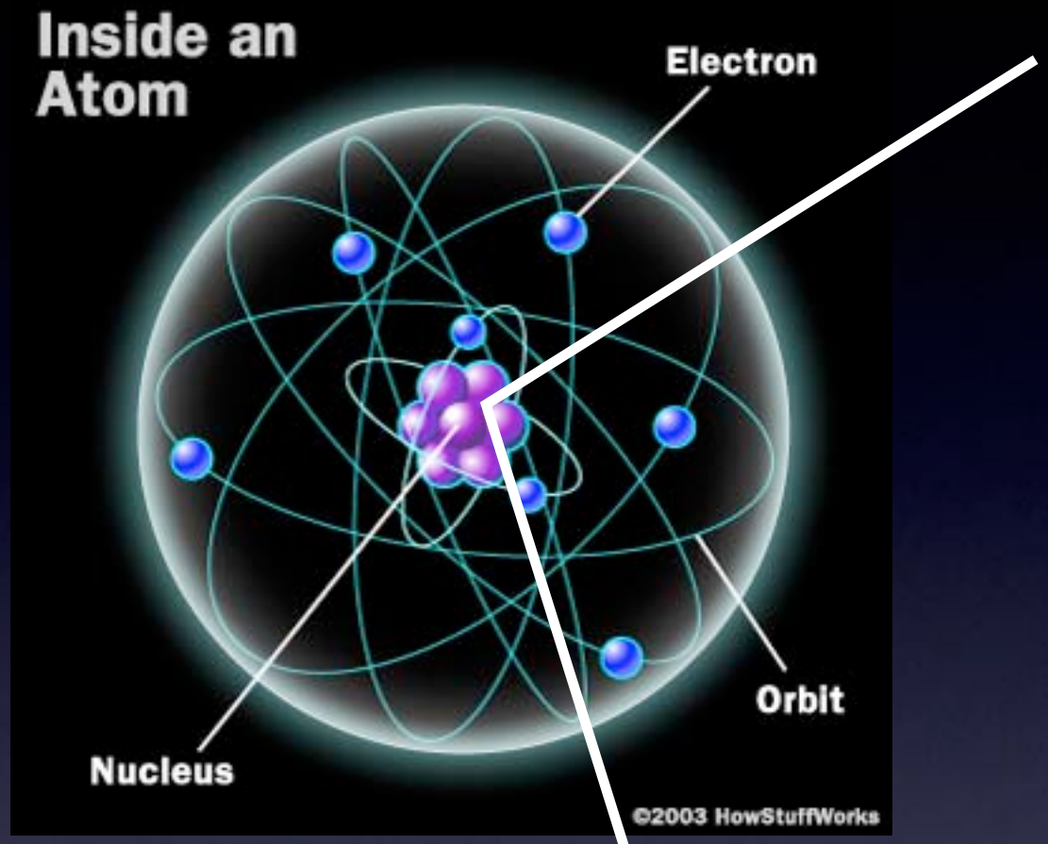
fast neutron
WIMP
(SUSY, KK …)

electronic recoil



-U/Th/^{40}K etc background

nuclear recoil



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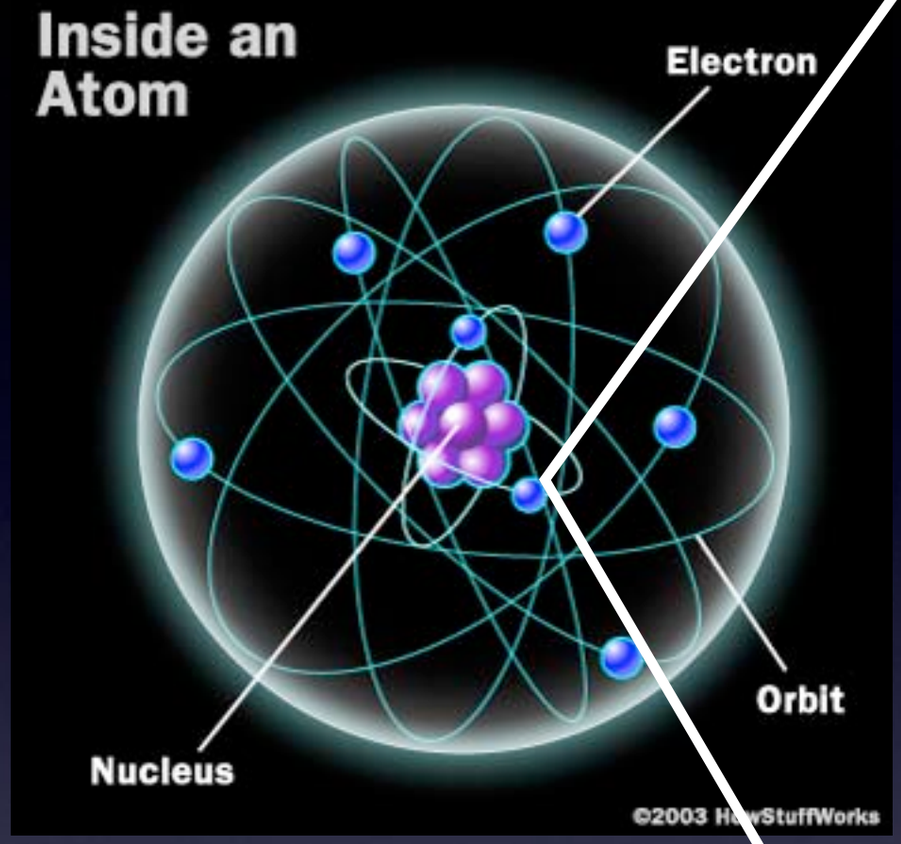
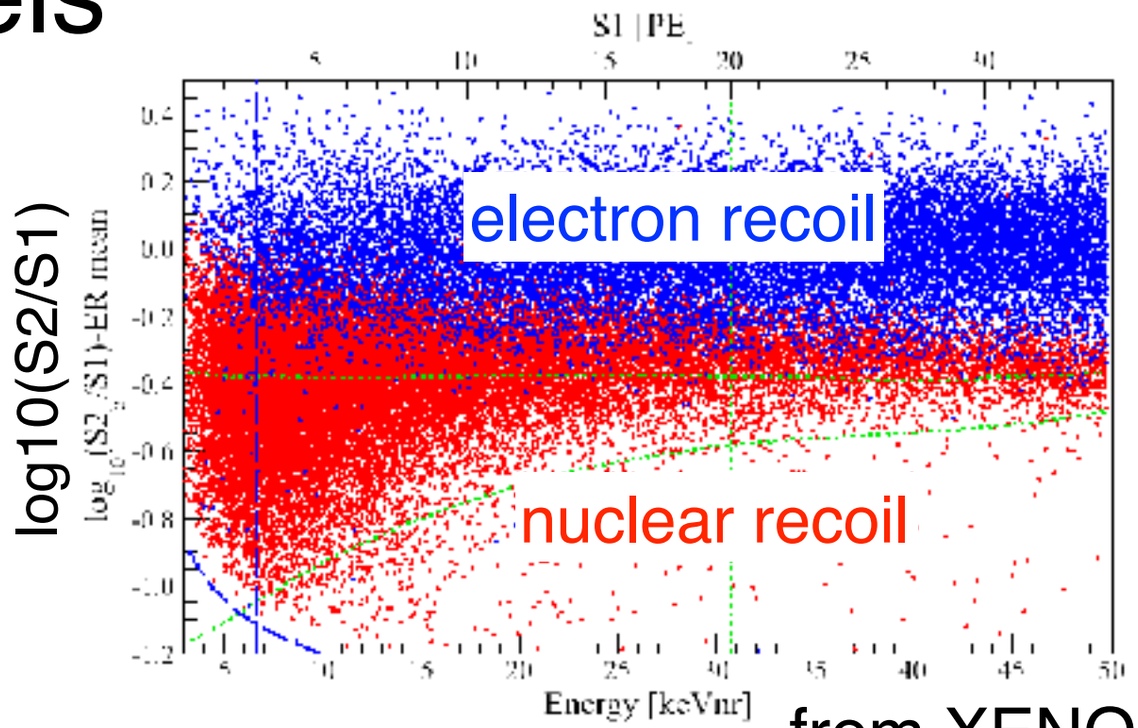


-U/Th/^{40}K etc background
-WIMP-electron
-Super WIMP (bosonic)
-Axion/Axion like particle
-Mirror DM
-Luminous DM …

The signal is in electron recoil ?

DM - electron recoil models

- Signal is not a nuclear recoil.
  - e.g.
    - no loop-induced nuclear recoil - axial vector interaction
    - photon emission from excited DM (Luminous dark matter)
- modulation signal
  - axion like particle can not be candidate because σ ~1/v , dm flux ~ v.
- DAMA/LIBRA vs LXe
  - Energy deposit ~ 3 keV energy deposit. (from DAMA/LIBRA)
- Event rate is similar for Xe(z=54) and Iodine (z=53)
- modulation analysis is not depend on the halo model.



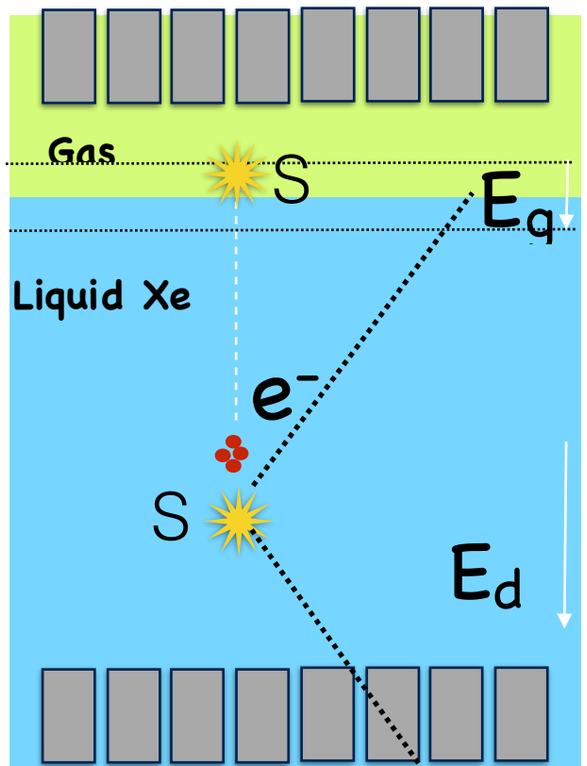
from XENON

- WIMP-electron scattering
  - R. Bernabei et al. PRD, 77 02308 (2008),
  - J. Kopp et al. PRD 80, 083502 (2009)
  - B.M. Roberts et al., PRL 116, 023201 (2016)
- Luminous dark matter
  - B. Feldstein et al., PRD 82, 075019 (2010)
- Mirror Dark Matter
  - R. Foot, Int. J. Mod. Pays. A 29, 126, (2014)
- Plasma Dark Matter
  - J. D. Clarke at el. axXiv1512.06471v
- …

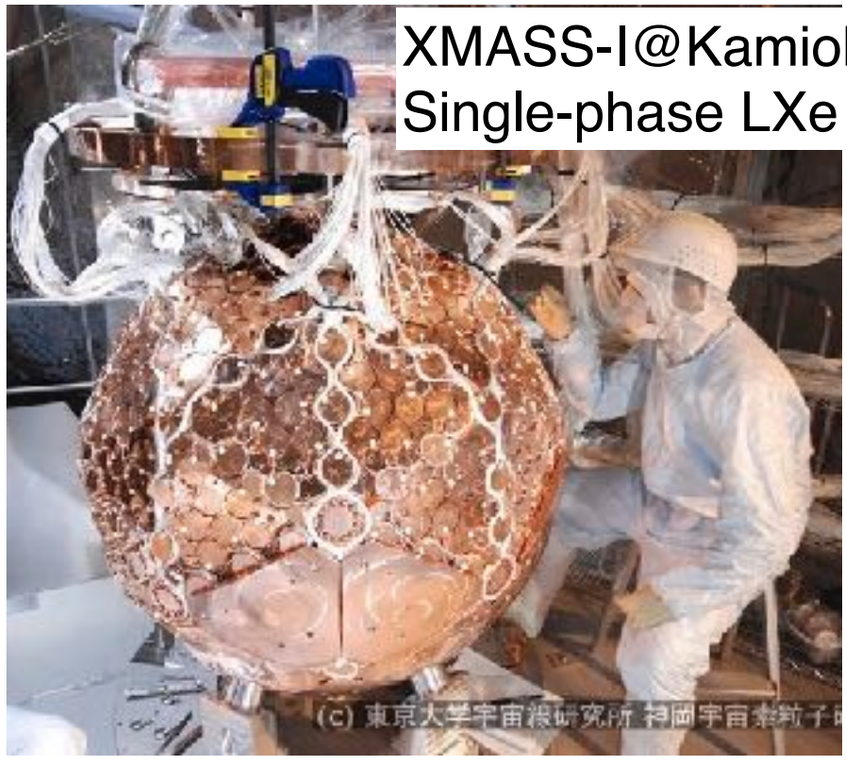
Modulation search by LXe (electron recoil signal)

XENON100@LNGS
Two-phase Xe TPC

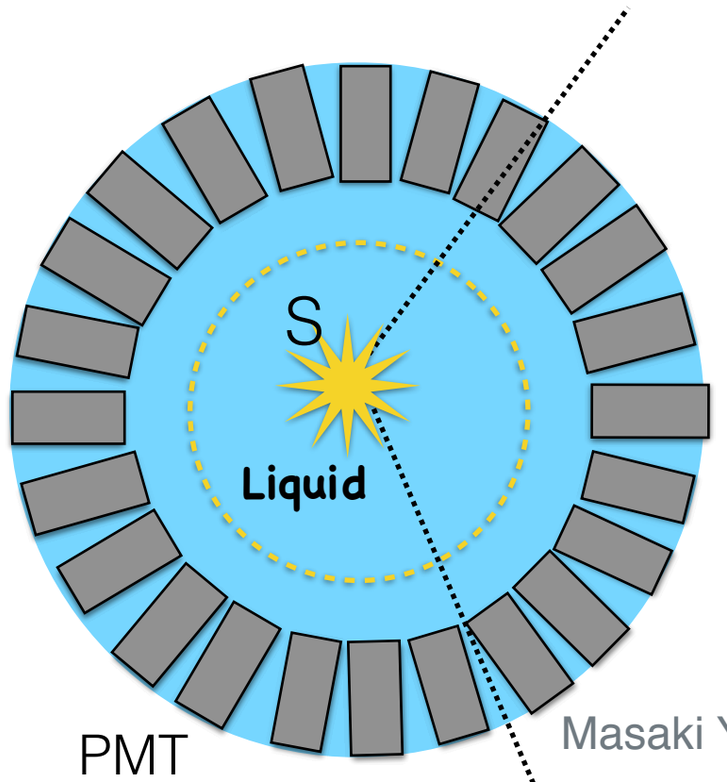
Two phase



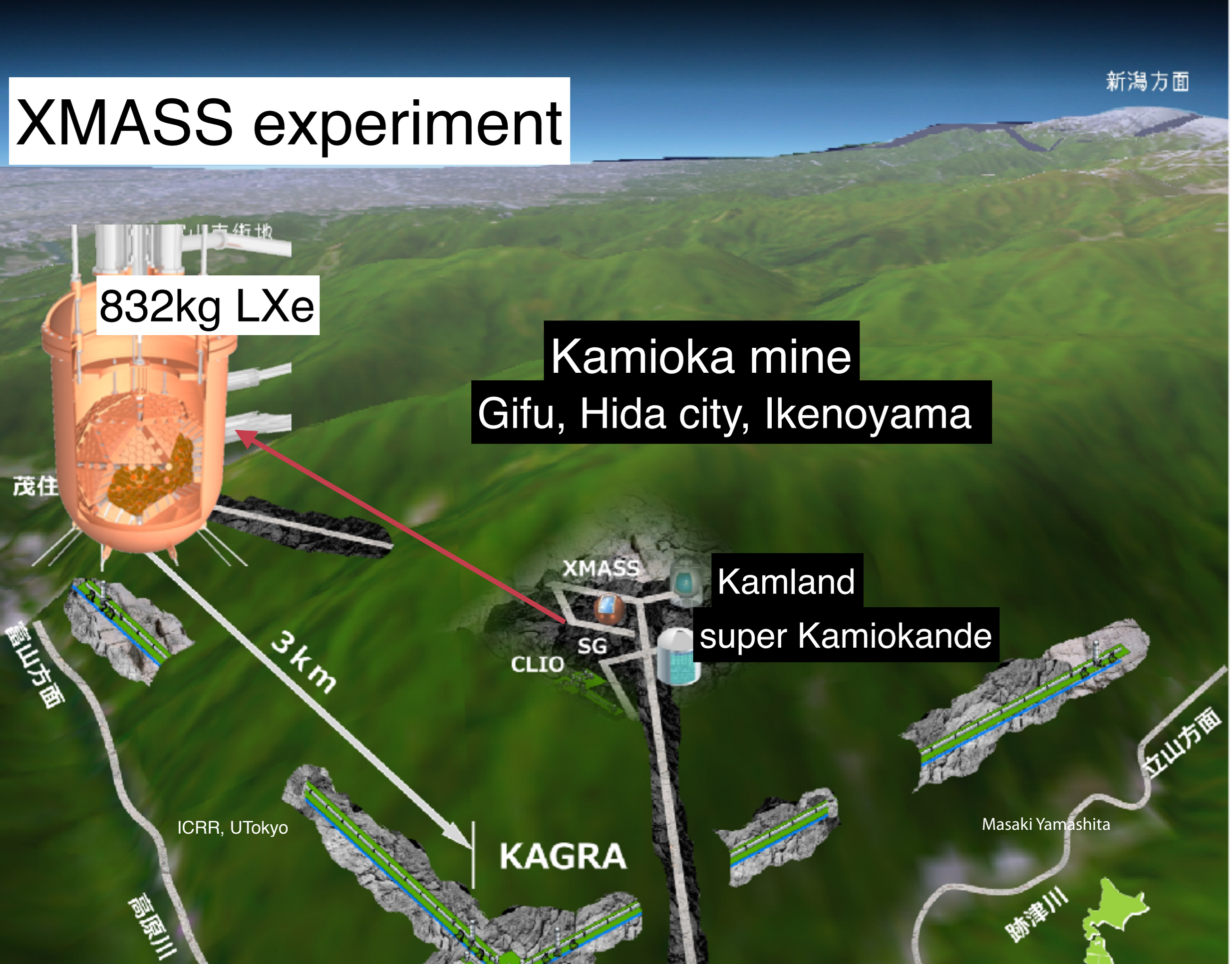
XMASS-I@Kamioka
Single-phase LXe scintillator

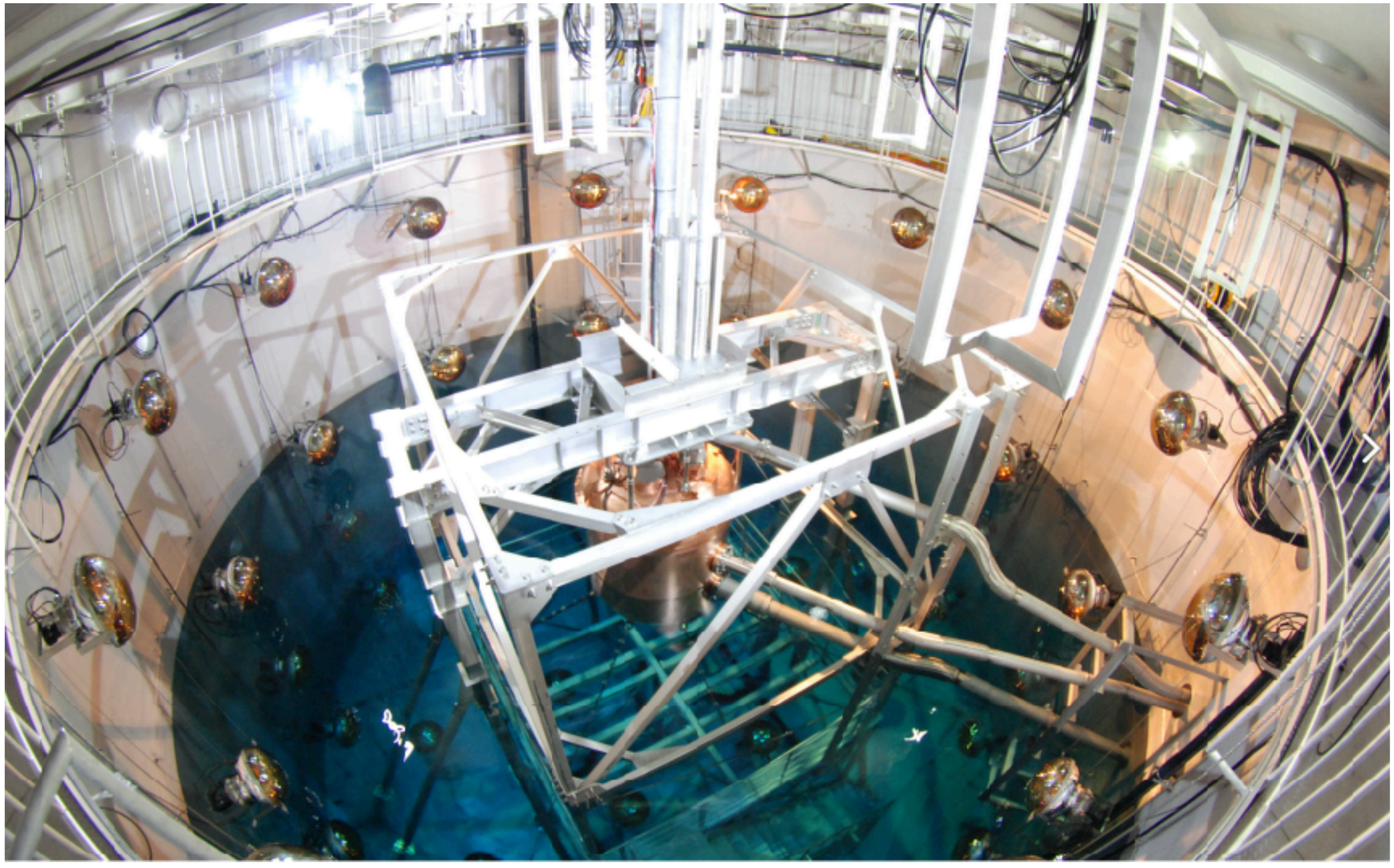


Single phase



XMASS experiment





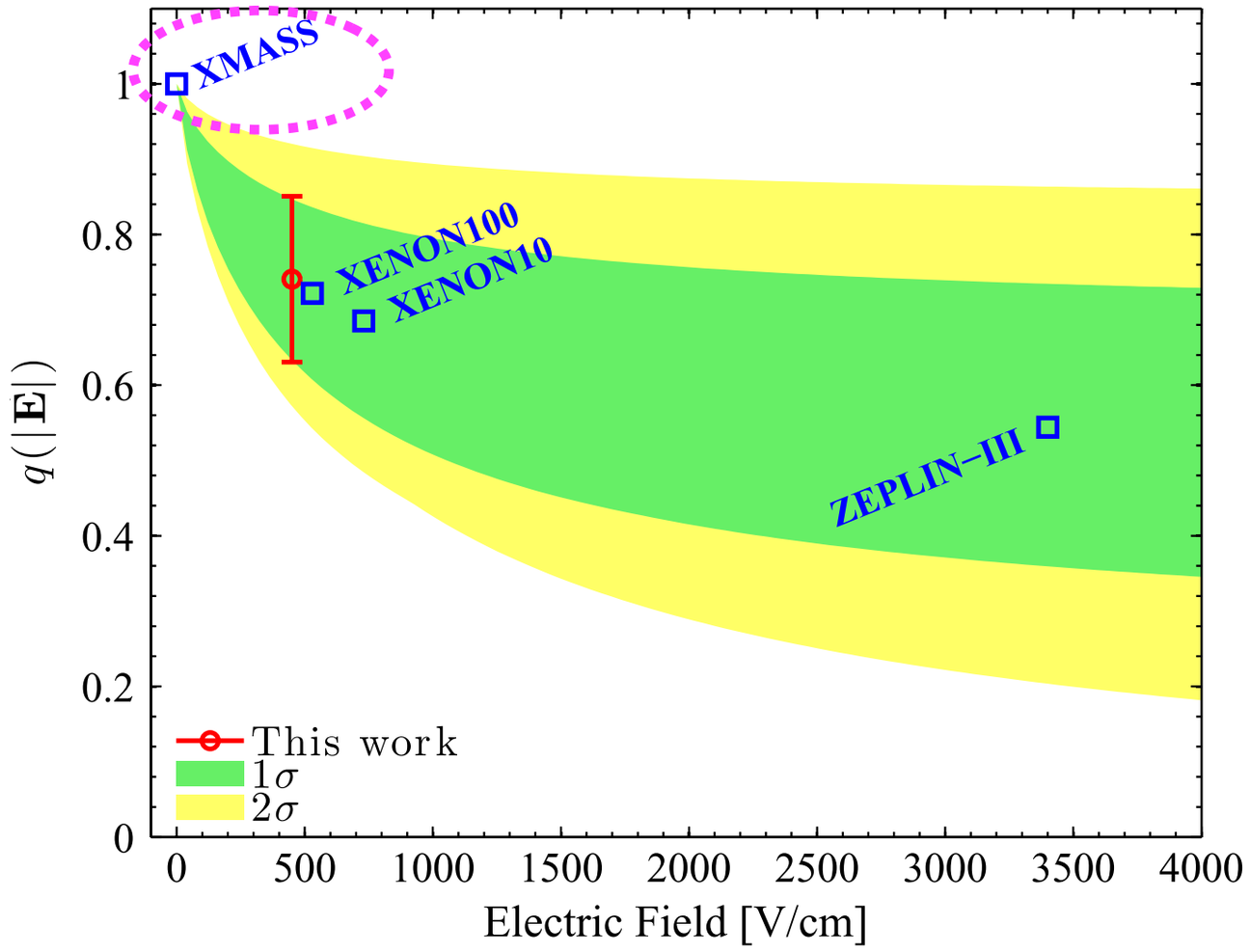
-φ10m x 10m ultra pure water shield with 20 inch x 70 PMTs for muon veto

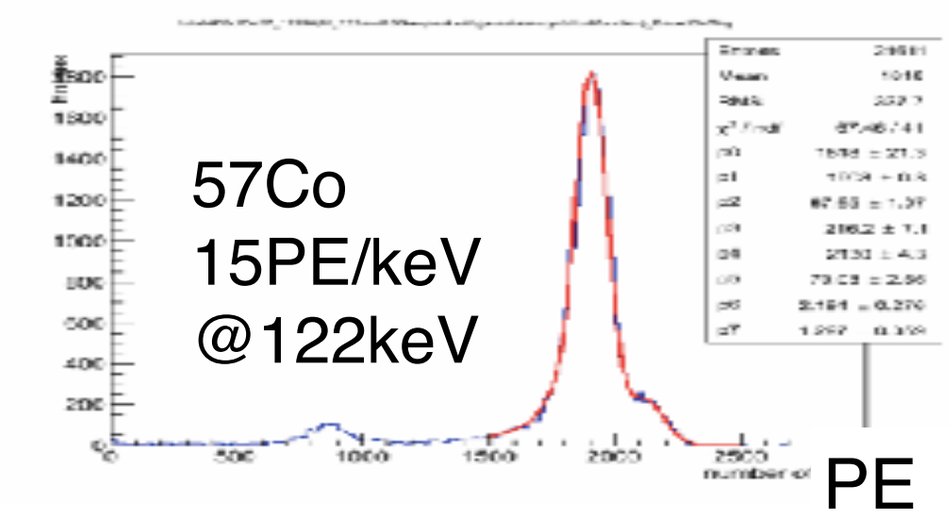
XMASS-I detector

- XMASS-I has very large mass (832 kg) LXe detector and unique detector which is operated in single phase.
- Largest light yield (15 PE/keV) among the dark matter detector (4 π photo-coverage)
- very large exposure.

  DAMA/LIBRA 1.33 ton year vs XMASS 0.82 ton year

  2013/11/20 - 2015/03/29 data was used for the analysis.





Experiment	$\lvert\vec{\mathbf{E}}\rvert$ (V/cm)	$S1_{\mathrm{thr}}$ (PE)	$\mathrm{LY}_{\mathrm{Co}}(\frac{\mathrm{PE}}{\mathrm{keV}})$	E_{thr} (keV)
ZEPLIN-III	3400	2.6	1.3	$2.8^{+0.5}_{-0.5}$
XENON10	730	4.4	3.0	$2.5^{+0.4}_{-0.3}$
XENON100	530	3.0	2.3	$2.3^{+0.4}_{-0.3}$
XMASS	0	4.0	14.7	$1.1^{+0.4}_{-0.2}$

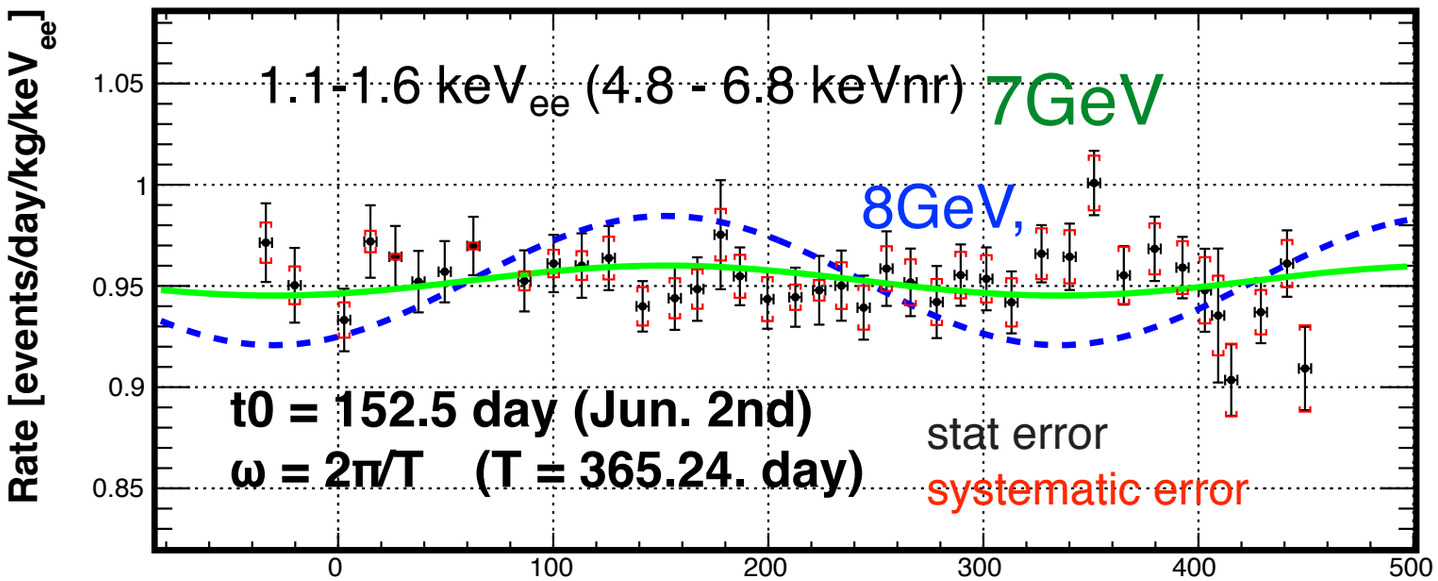
L. Baudis et al. PhysRevD.87.115015

WIMP case

Abe et al. (XMASS collaboration) Phys Lett. B (2016)272

time variation data was fitted by

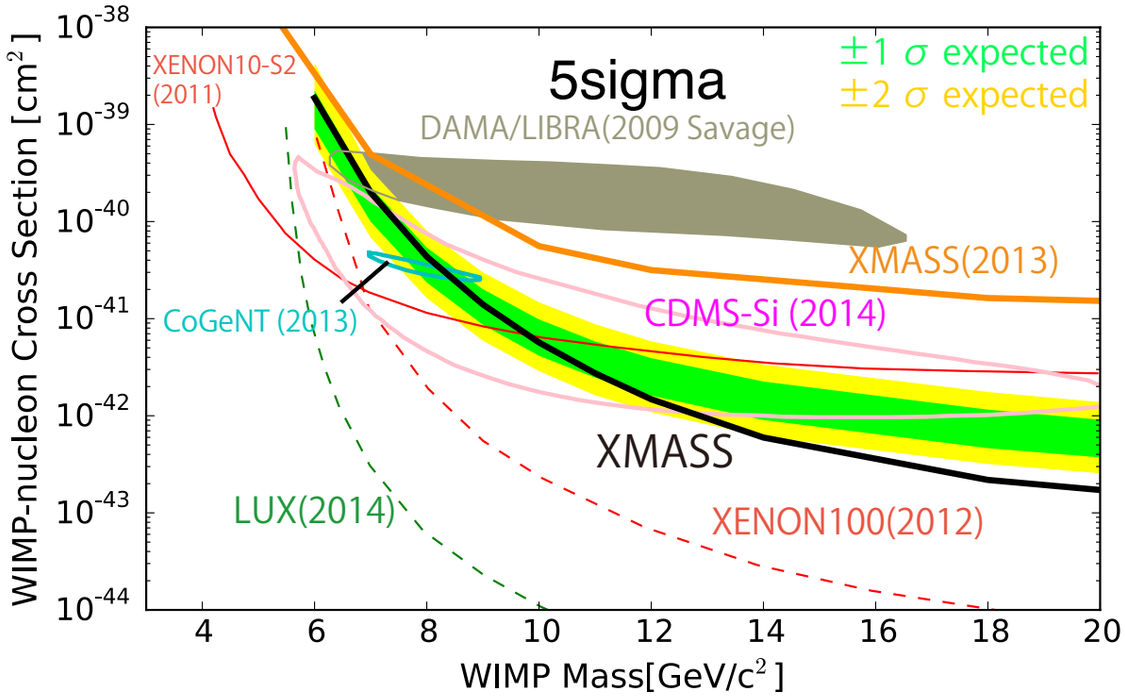
- 2013 Nov - 2015 March (359.2 live days)
- 0.82 ton x year (DAMA/LIBRA 1.33 ton x year
- assuming WIMP spectrum
- 2D fitting (time and energy bin)
- DAMA/LIBRA region is mostly excluded by annual modulation search.



$<4.3 \times 10^{-41}\ \mathrm{cm}^2$ (90% CL) @ 8GeV

$$R_{i,j}^{\mathrm{ex}} = \int_{t_j-\frac{1}{2}\Delta t_j}^{t_j+\frac{1}{2}\Delta t_j} \left(C_i + \sigma_{\chi n}\cdot A_i(m_\chi)\cos 2\pi\frac{(t-t_0)}{T}\right)dt,$$

Ai: amplitude
Ci: constant
σ_χ: WIMP-nucleus cross section
m_χ:WIMP mass
t0:152.5 day
T : 1 year



Model Independent Case

Abe et al. (XMASS collaboration) Phys Lett. B (2016)272

$$R_{i,j}^{\mathrm{ex}} = \int_{t_j-\frac{1}{2}\Delta t_j}^{t_j+\frac{1}{2}\Delta t_j} \left(C_i + A_i \cos 2\pi \frac{(t-t_0)}{T} \right) dt$$

free in energy bin

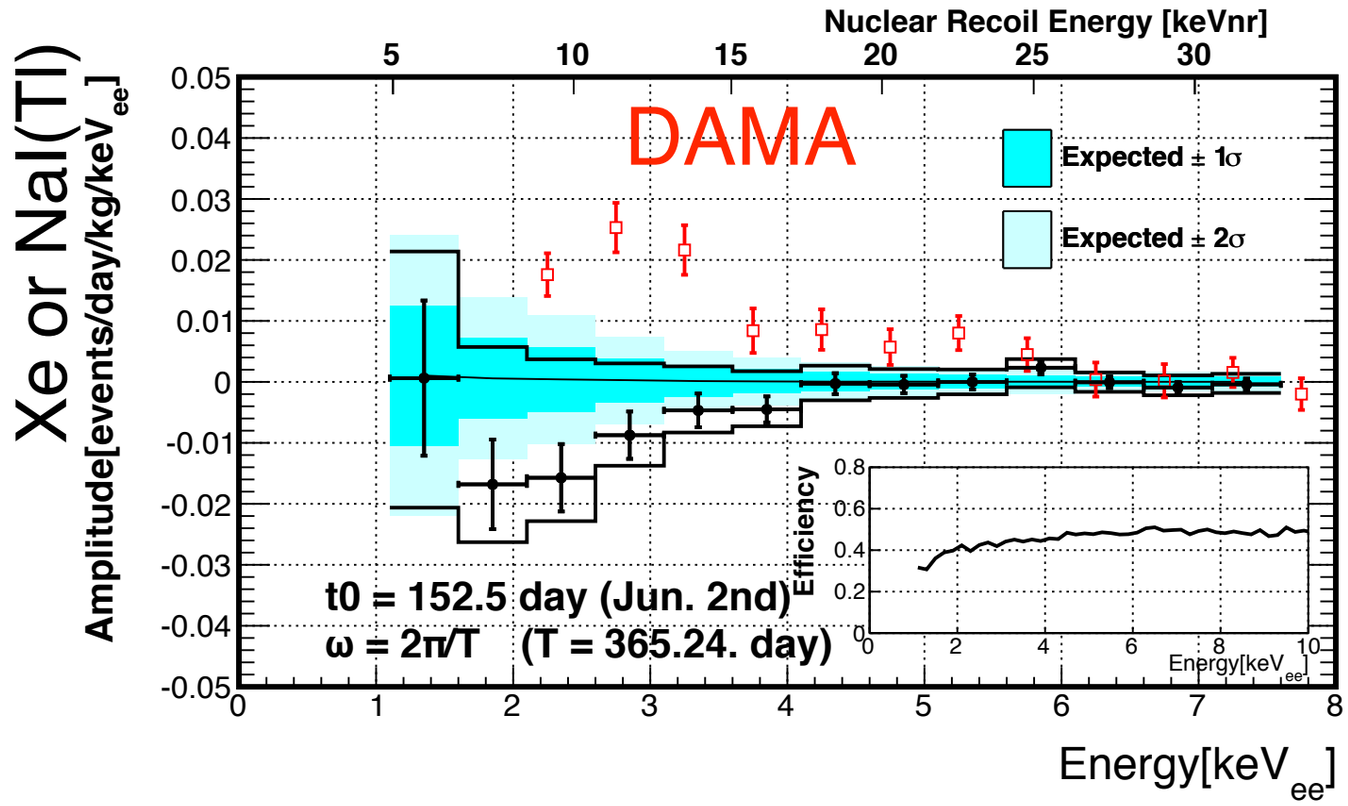
$$\chi^2 = \sum_i^{E_{bins}} \sum_j^{t_{bins}} \left(\frac{(R_{i,j}^{\mathrm{data}} - R_{i,j}^{\mathrm{ex}} - \alpha K_{i,j})^2}{\sigma(\mathrm{stat})_{i,j}^2 + \sigma(\mathrm{sys})_{i,j}^2} \right) + \alpha^2,$$

Model independent analysis :

- No sign for SUSY particle at LHC so far.
- No sign in direct detection for more than decade.
- important to look for variety candidate.
- Annual modulation signal is searched for without any model assumption.
- Amplitude (Ai) and Constant (Ci) are free parameter.
- Slightly negative amplitude was observed.

  Significance was evaluated with test statistic (10,000 sample) and no significant modulated signal has been observed. (1.8σ)

< (1.7-3.7)x10^{-3}x10^{-3} counts/day/kg/keVee in 2-6keVee (0.5keVee bin width). (90 CL, Bayesian)



Current Status (modulation)

XMASS:

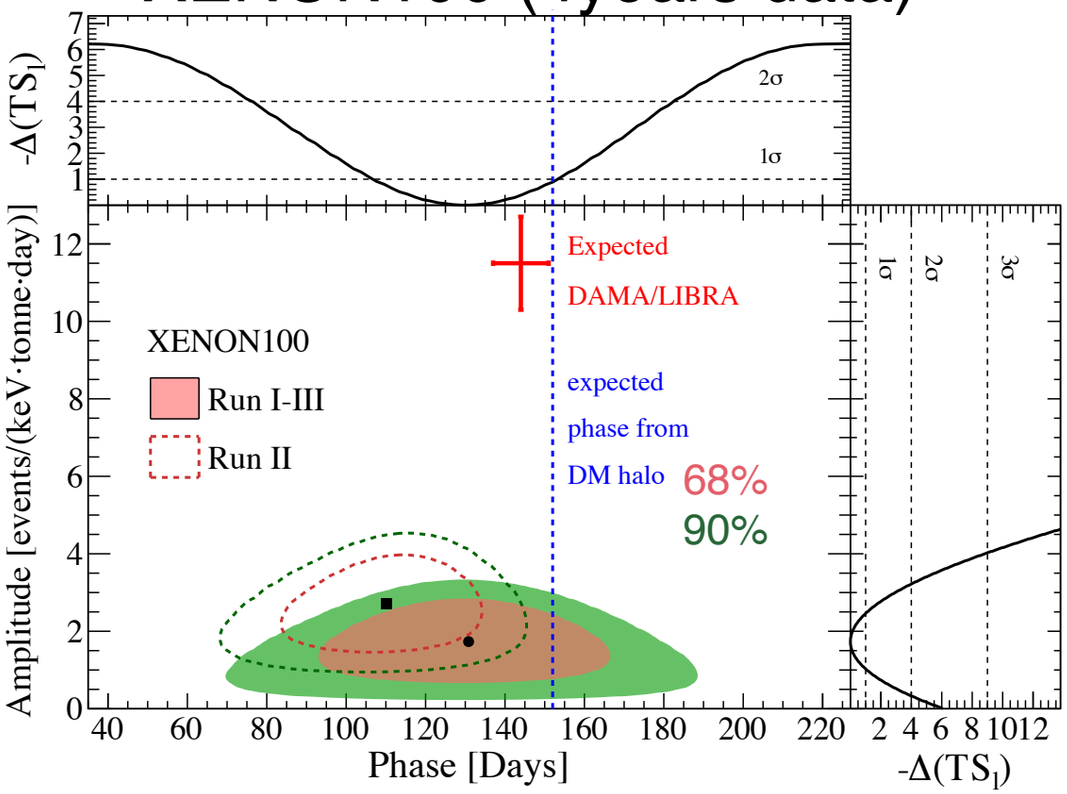
<(1.7-3.7)x10^{-3} counts/day/kg/keVee CL90 in 2-6keVee.

XENON100 (electronic signal):

(1.67+-0.73) x 10^{-3} counts/day/keVee (2.0-5.8 keV)

disagree at 5.7σ

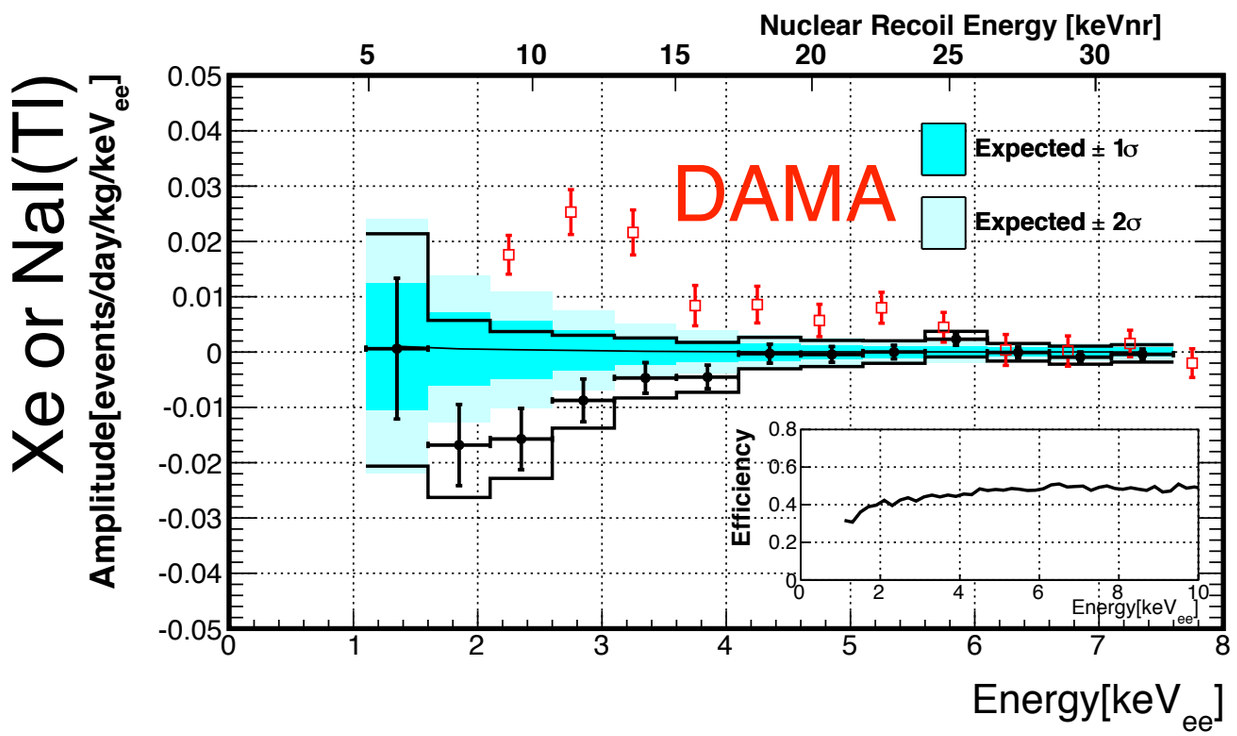
XENON100 (4years data)



axial-vector

arXiv:1701.00769v1

XMASS-I

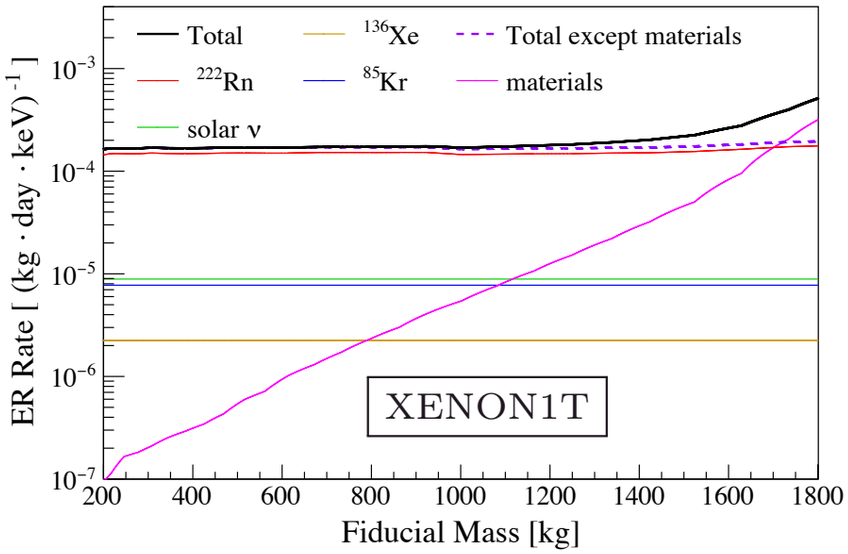


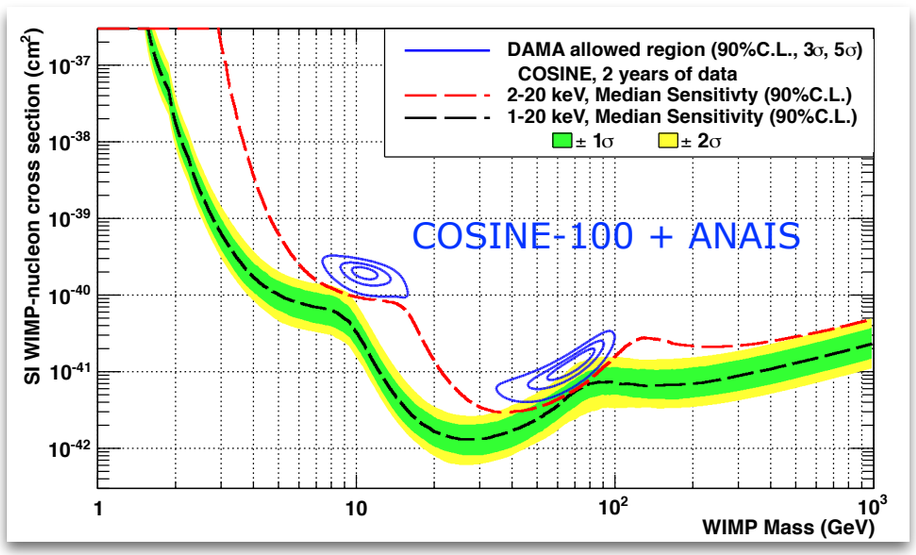
Contents

Near Future prospects

- **DAMA/LIBRA upgrade** (another 7 cycles)
  - high QE 35.1% at 420nm
  - Energy threshold
  - 2keV -> 1keV(5.5-7.5 ph.e./keV-> 6- >10 ph.e./keV)
  - a better energy resolution
  - a better noise/scintillation discrimination
  - less radioactivity
- **COSINE-100** sensitivity will reach DAMA/LIBRA for 2 years of data. (started 2016. Sep)
- **XMASS**
  - continuously taking data and almost another two years of data in hand with 1 keVee threshold and will be reported soon.
- **XENON1T** is on going and it is expected to be lowest background with largest target mass (1ton).

Eur. Phys.J. C(2013) 73, JINST 2012 7 P03009





Summary

- Isospin violation can not solve the DAMA vs others in standard halo WIMP model.
- Very active R&D on radio-pure NaI(Tl) by several groups and the site locations are in north/south semi-sphere.
- XENON100 and XMASS results contradicts with DAMA/LIBRA even for DM via recoil electron models.
- We expect to see update result from DAMA/LIBRA with 1keVee threshold as well as XMASS this year.

Thank you