WIMP探索
(Review)

東京大学宇宙線研
山下雅樹
2017年1月27日@神戸大学梅田オフィス

Masaki Yamashita

話の内容

- **WIMP探索の歴史**
- **現在の状況**
  - 希ガスTPC先行
  - プロジェクトが絞られて来た。（お金）
- **近い将来**
  - low mass WIMPに流れる(逃げる)cryogenics detector
  - 数tonの検出器が数年で登場(液体キセノン）
- **その先?**
  - WIMP探索検出器でどこまで探索できるか？
  - ニュートリノフロアー(N + ν -> N+ν)　コヒーレント
  - 他のチャンネルなど

目に見えない暗黒物質だって存在するんだ!

Masaki Yamashita

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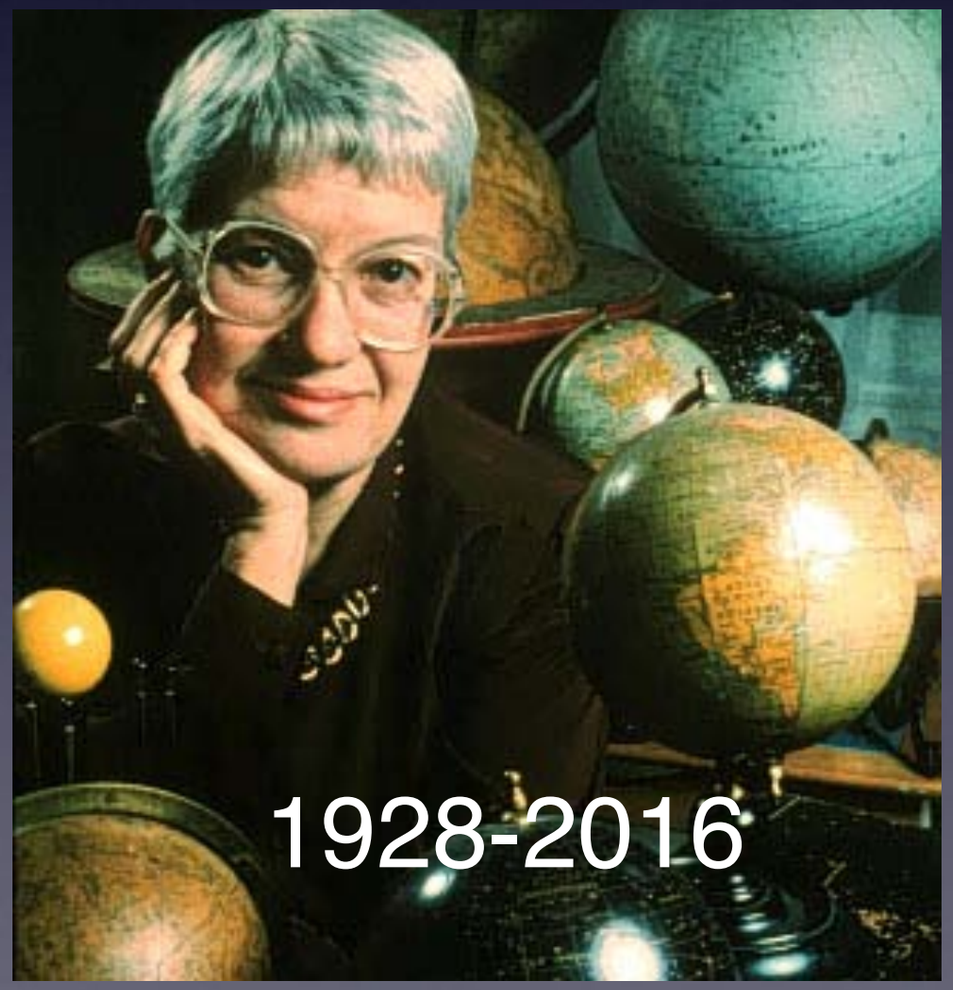
1933年　かみの毛座銀河団の質量欠損

目に見えない暗黒物質だって存在するんだ!


F. Zwicky

1933年　かみの毛座銀河団の質量欠損

1970年後半　Vera Cooper Rubinら渦巻き銀河の回転速度


1928-2016

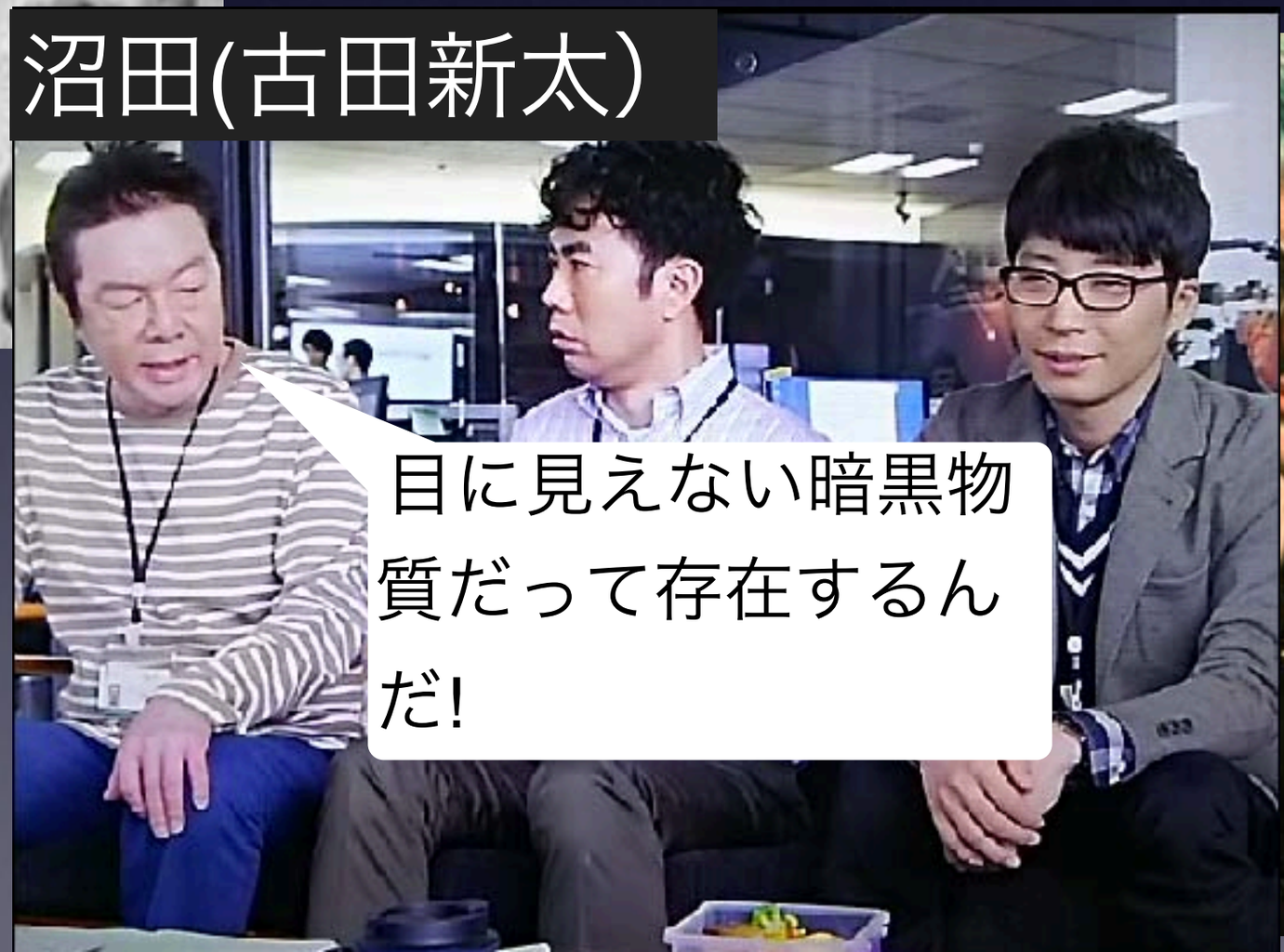
目に見えない暗黒物質だって存在するんだ!

F. Zwicky

1933年　かみの毛座銀河団の質量欠損

1970年後半　Vera Cooper Rubinら渦巻き銀河の回転速度

最近では人気ドラマでも（逃げ恥）



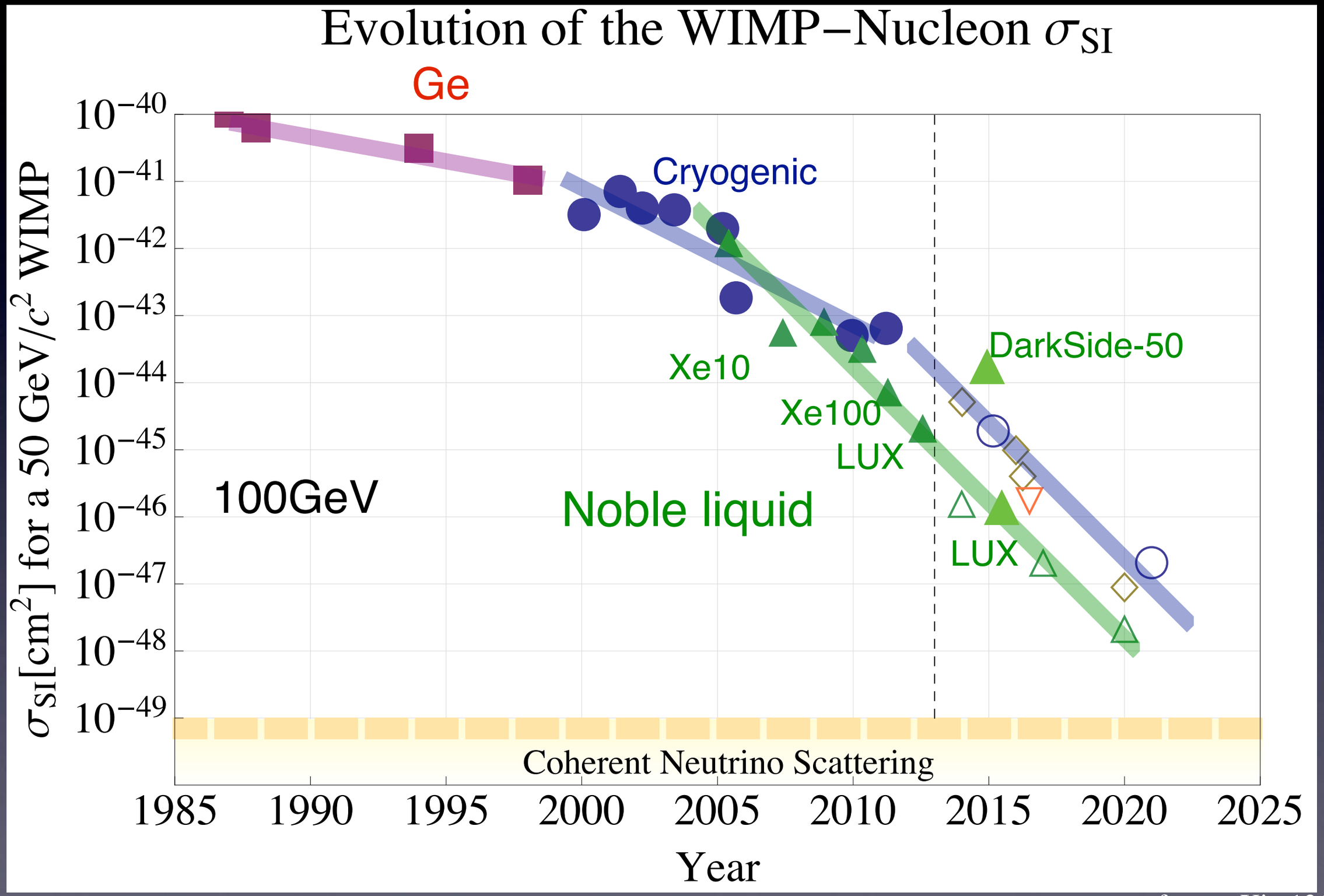
928-2016

激しい競争

最近数が絞られて来たか？

数億から数十億円実験になった。

30年の歴史、6桁掘った！



from arXiv:1310.8327v1

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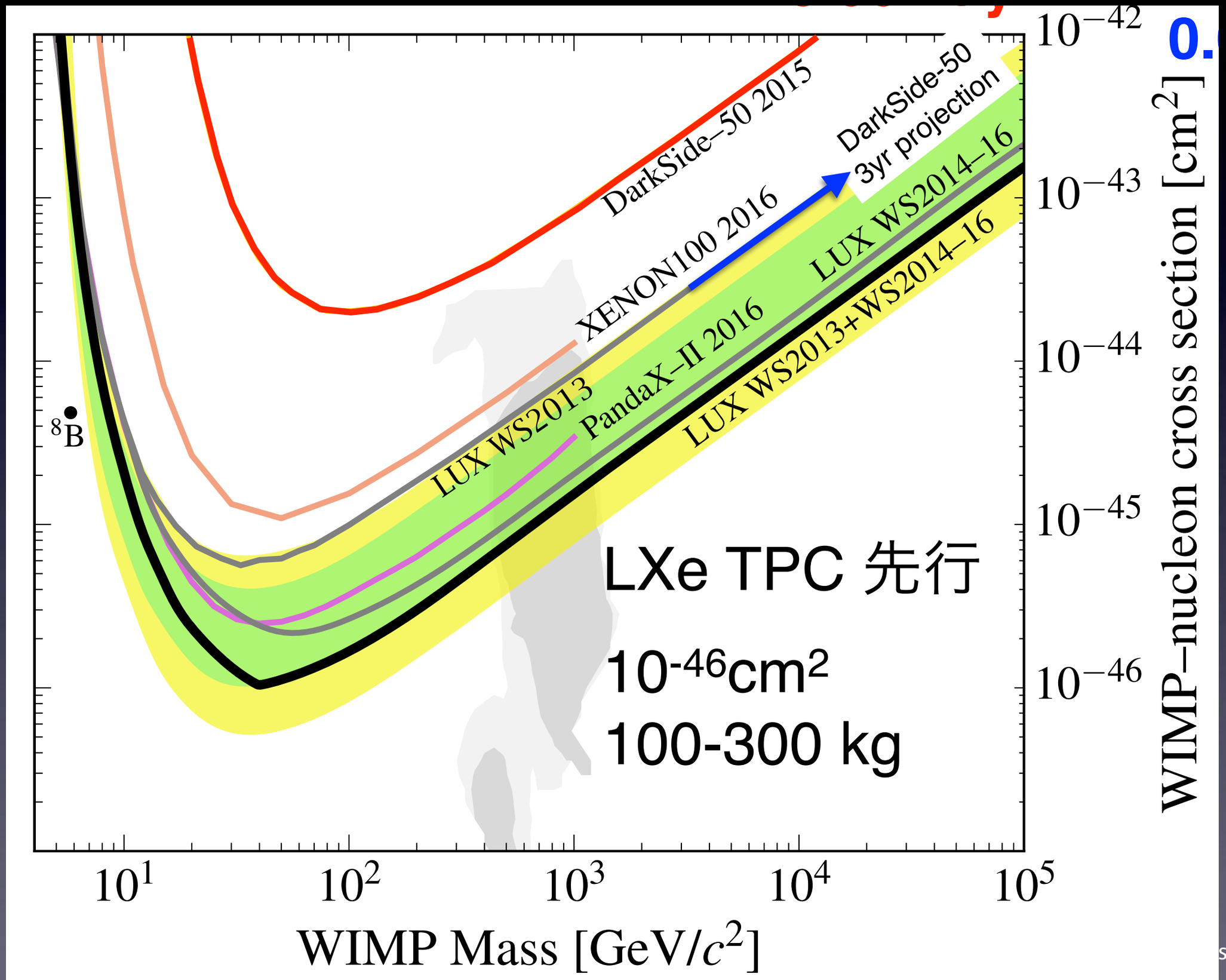
現状



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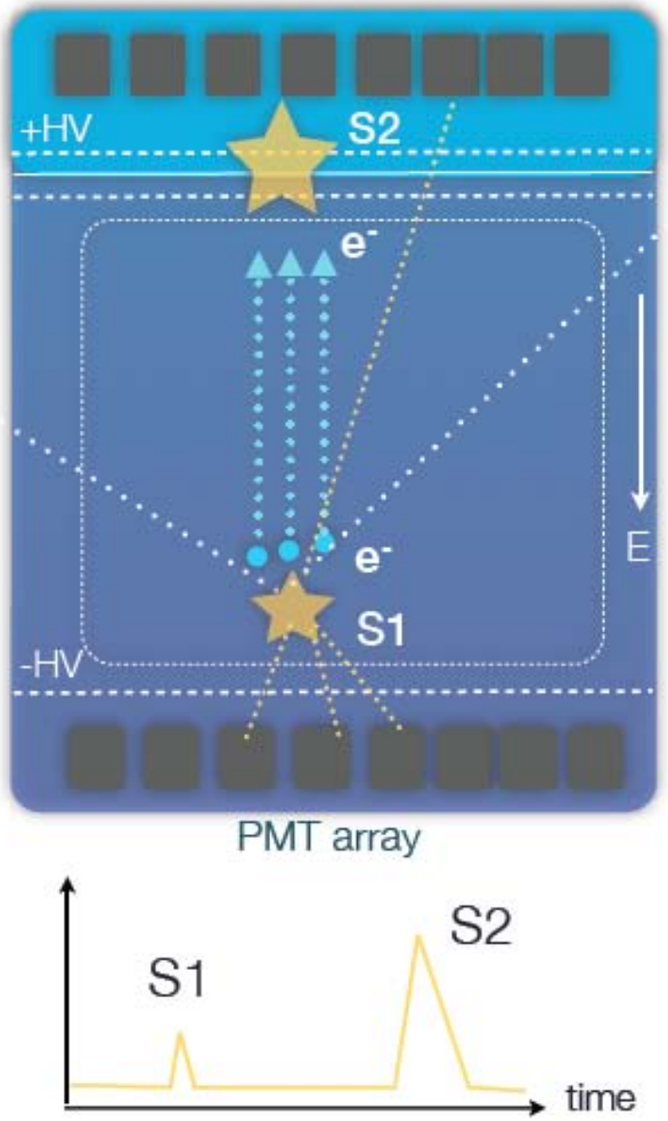
希ガス2相型サマリー

- LXeはXENON10以来10年トップを走っている。
  - 検出器サイズも 10 kgから1000 kgへ大型化された。
  - 電離電子ドリフト距離 15 cm -> 1000cm
    - 今後はHVがキーか？XE10からほとんど改善していない。
- キャリブレーションも飛躍的に発展した。
  - DD-neutron calibration for 1keVr !
  - Internal source. CH_3T (トリチウム化メタン）など
- LArはUnderground Arが必須。1/1400 reduction.
- 安いのがアルゴンの特徴だったが。。。。

Dual-phase noble liquid detectors



LXe: XENON100

LXe: LUX

LAr: DarkSide

XENON100 (LXe) and DarkSide (LAr) at LNGS

LUX (LXe) at SURF, PandaX (LXe) at CJPL

ArDM (LAr) at Canfranc

Target masses between ~ 50 kg - 1 ton

from E.Aprile

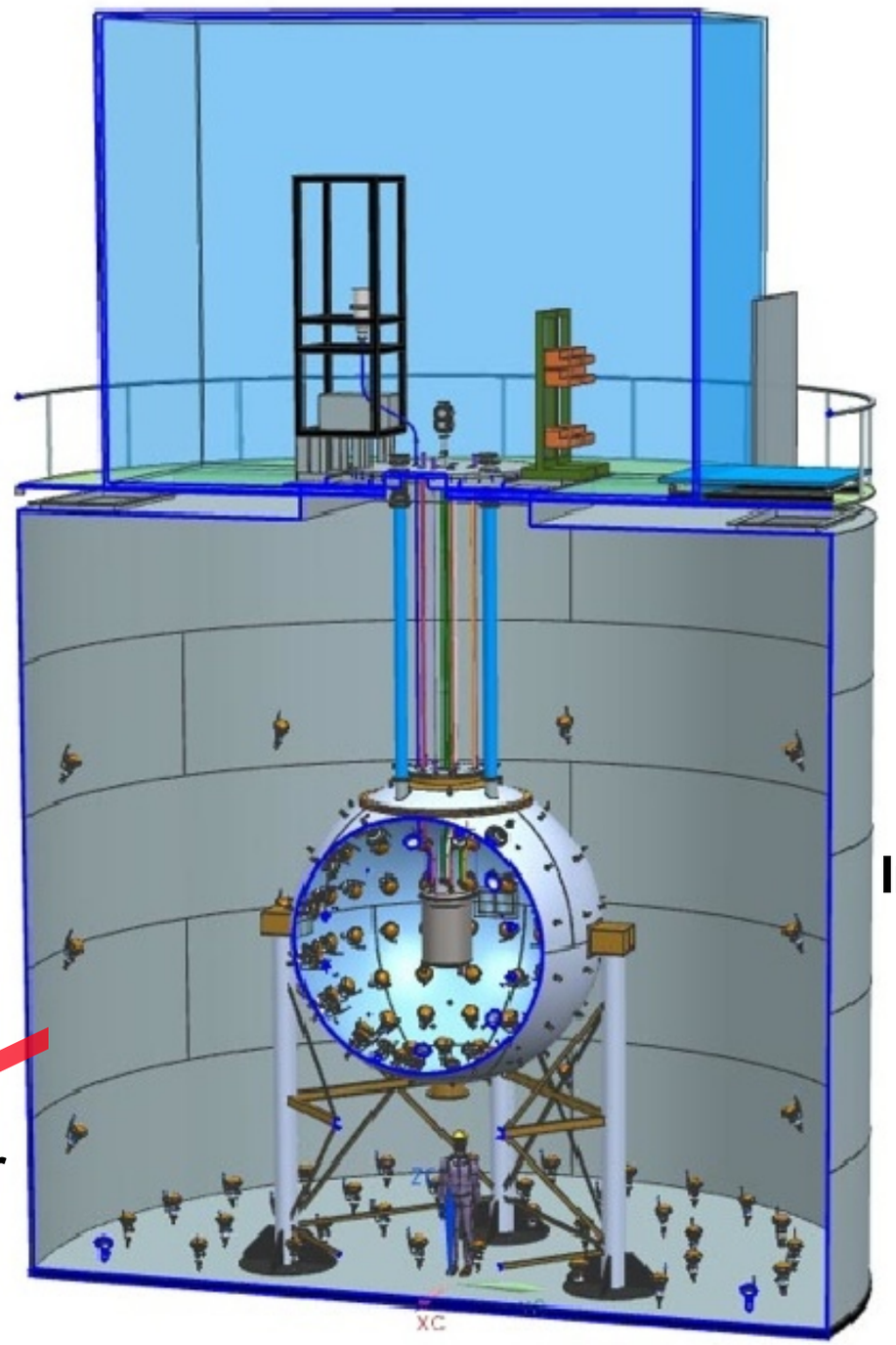
Liquid Xe TPCs are leading especially high mass WIMP.
Large mass detector (50 kg - 1 ton)
Particle ID: nuclear recoil against e/gamma ~1/1000

Liquid Ar TPC

-DarkSide 50 (LNGS)
-ArDM (Canfranc)

Radon-free clean room

Water Tank (Cherenkov muon veto)



TPC digitizers and DAQ computers

Inner detector TPC (Liquid Argon)

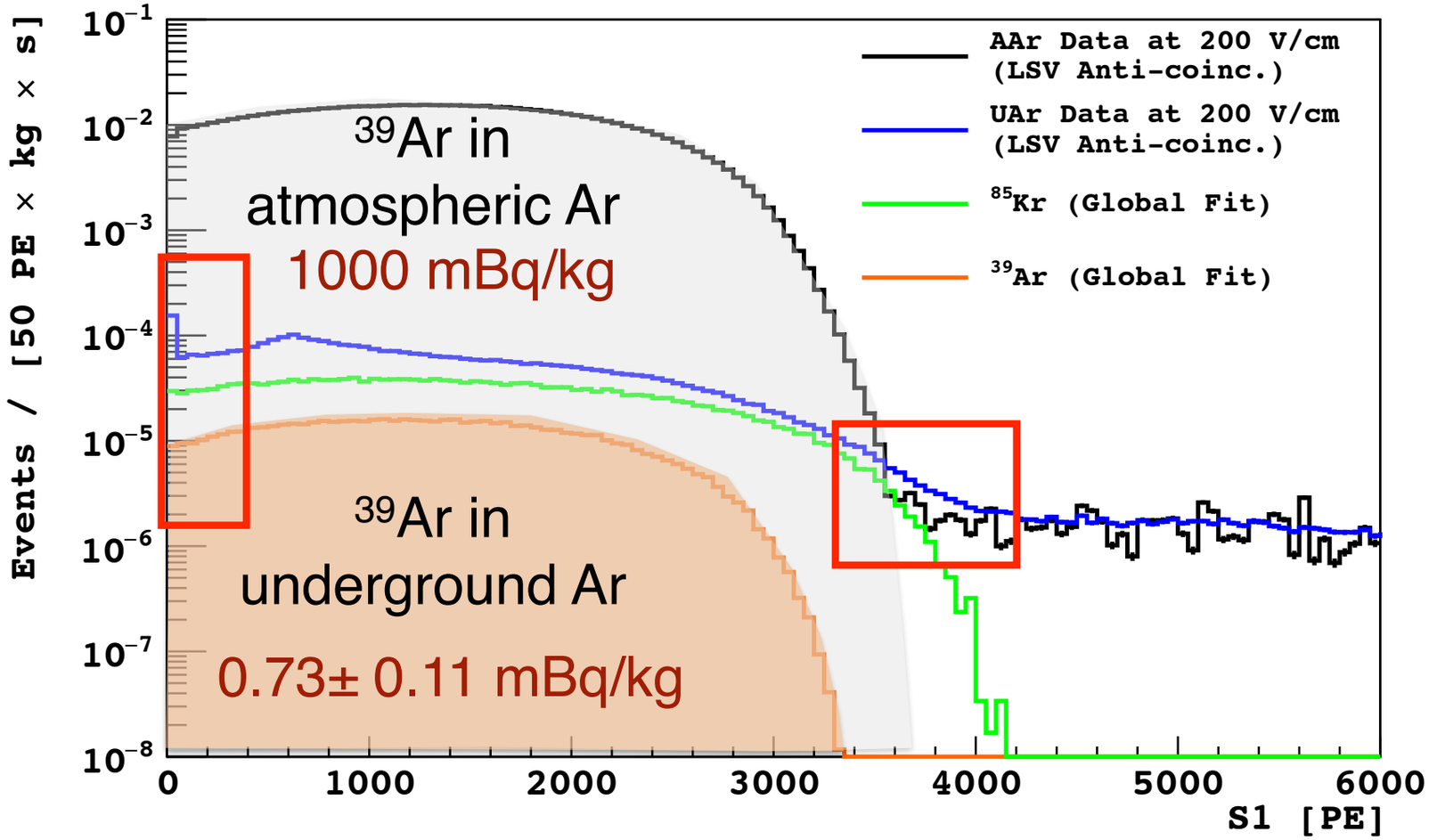
Organic Liquid Scintillator (neutron veto)

AAr/UAr reduction1400

Intrinsic background of Underground Argon

With respect to Atmospheric Ar:
> factor of **300** reduction of intrinsic radioactivity in UAr
~ factor of **1400** reduction of ^{39}Ar activity

Multidim. spectral fit of MC (g4ds) on AAr/UAr plus delayed coincidence tagging

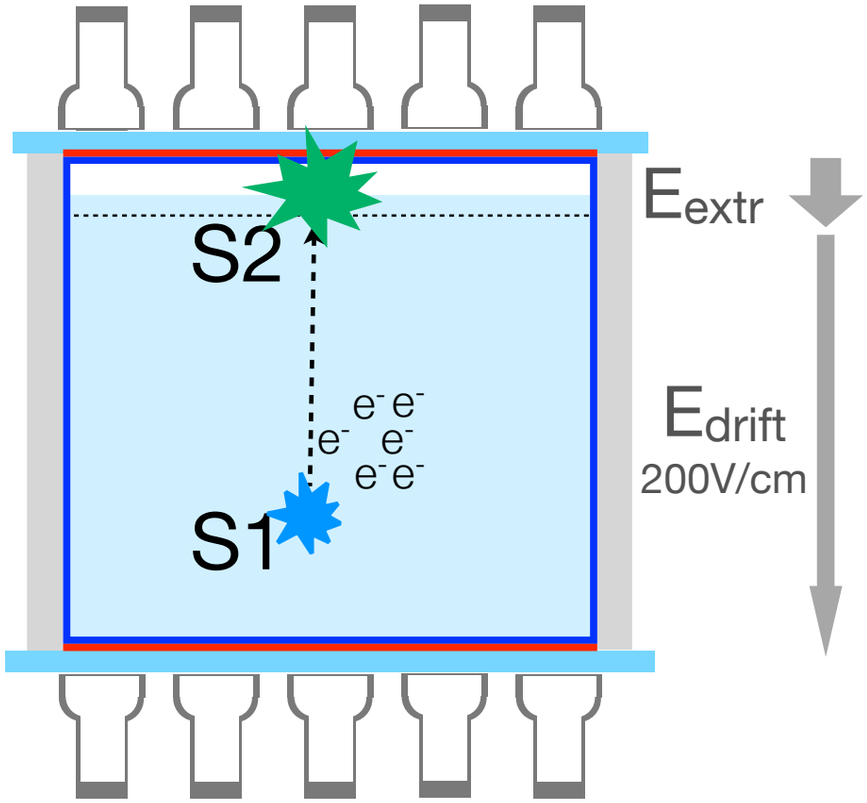


Background in ROI = ~50% β-events + ~50% of γ-events

Results from the first use of low radioactivity argon in a dark matter search, Phys.Rev. D93, no.8, 08110 (2016)

DarkSide-50 LAr dual phase TPC

Light + **Charge**

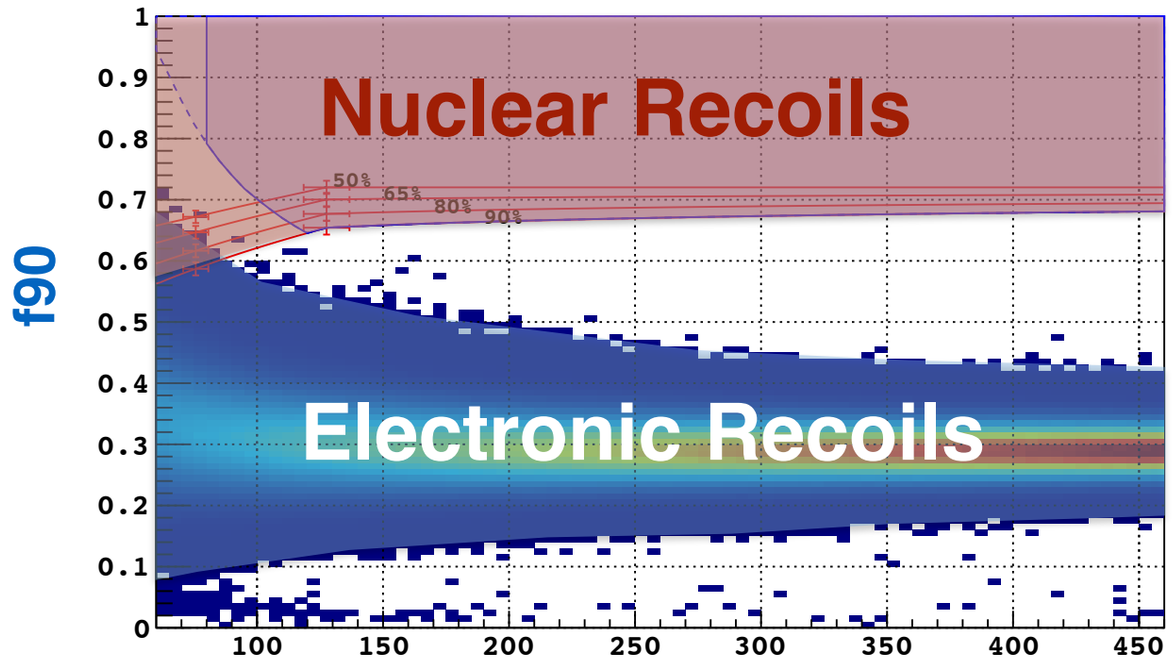


3D positioning ◎ (few mm)

S2/S1 discrimination of ERs

Pulse shape discrimination of ERs

f90 = fraction of S1 in the first 90ns



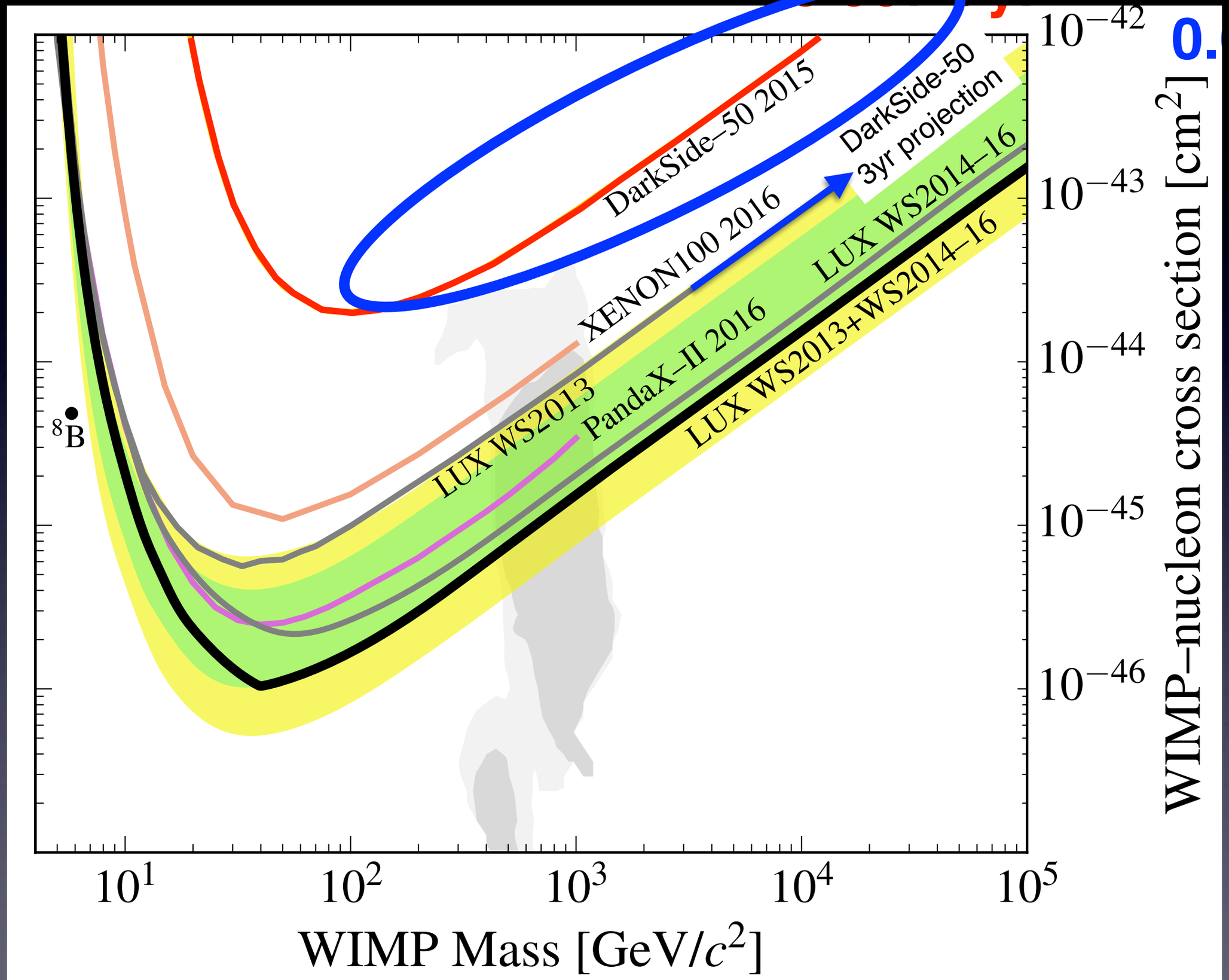
46kg of LAr
38 3” PMTs
TPB as wavelength shifter
cathode/anode = **ITO** on **fused silica**
Teflon as reflector
extraction grid

ER Rejection power >10^7

^{83m}Kr S1 Light Yield:

7.0 ± 0.3 PE/keV @ 200 V/cm

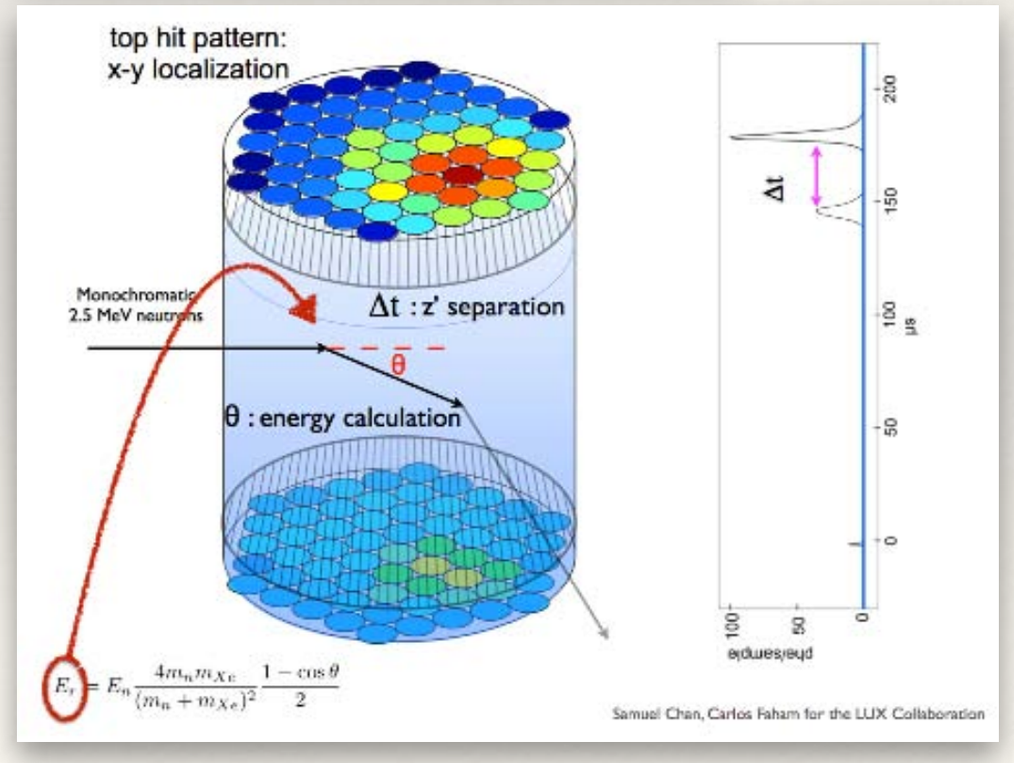
First Results from the DarkSide-50 Dark Matter Experiment at LNGS, Phys.Lett. B 743

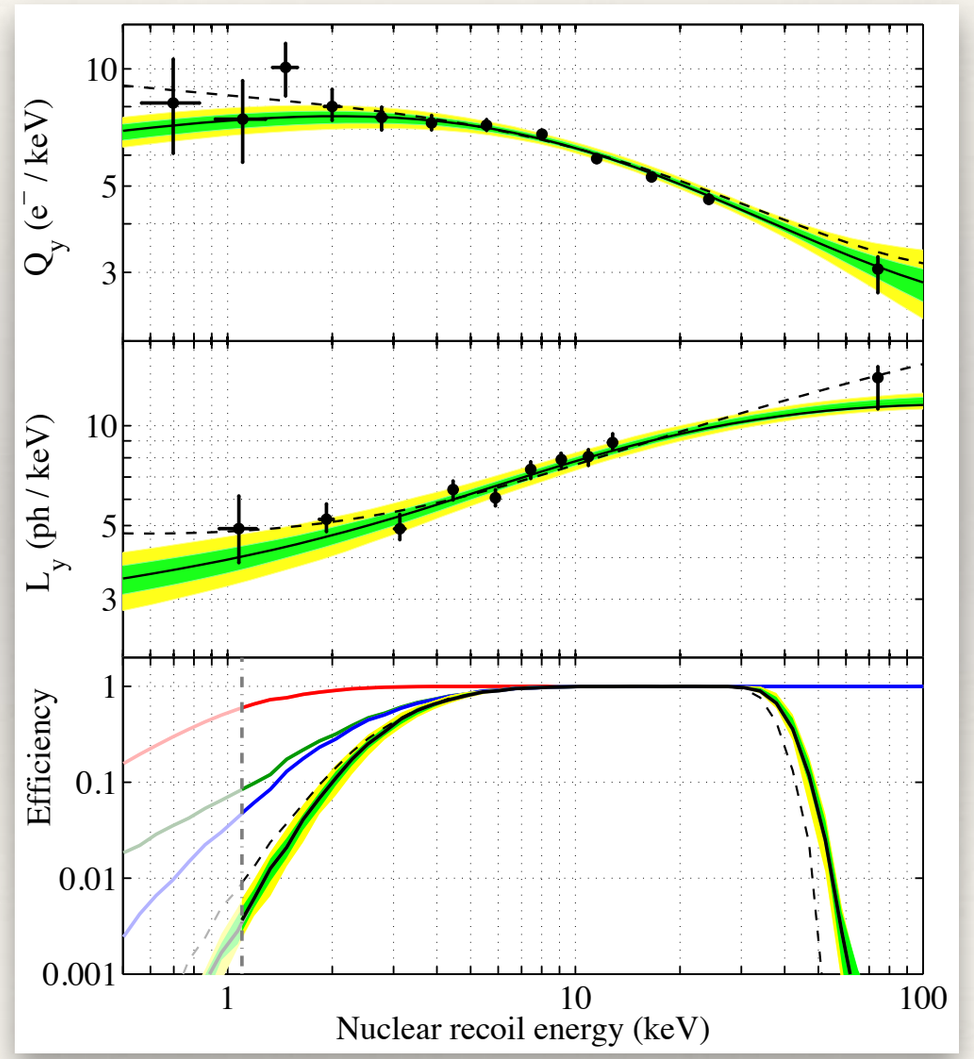

DarkSide–50 2015
XENON100 2016
DarkSide-50
3yr projection
LUX WS2014–16
LUX WS2013
PandaX–II 2016
LUX WS2013+WS2014–16
^{8}B
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
WIMP–nucleon cross section [cm^2]
10^1
10^2
10^3
10^4
10^5
WIMP Mass [GeV/c^2]

LUXキャリブレーション

Calibration #3: DD neutrons

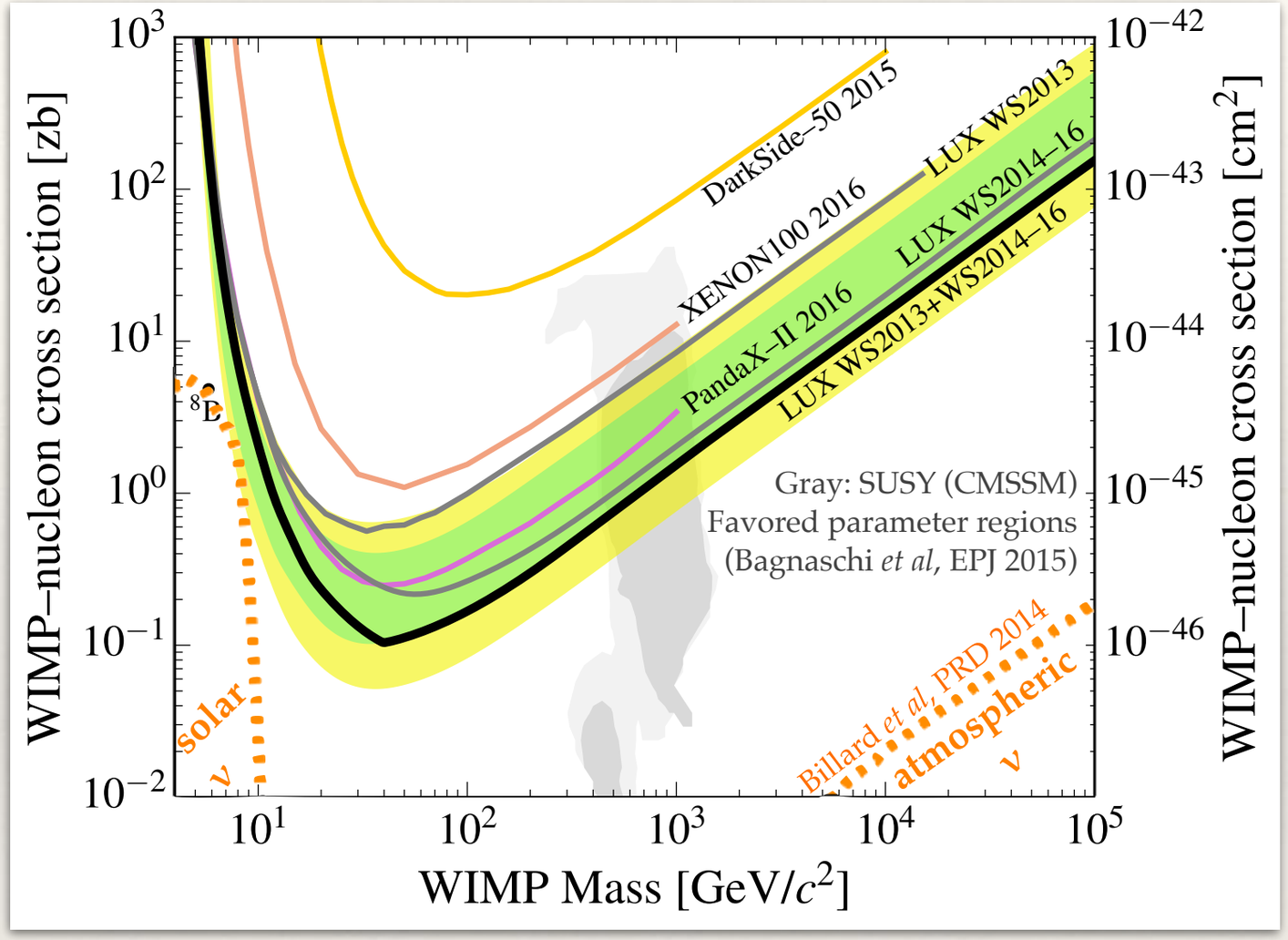
In situ Deuterium-Deuterium neutron calibration for nuclear recoils





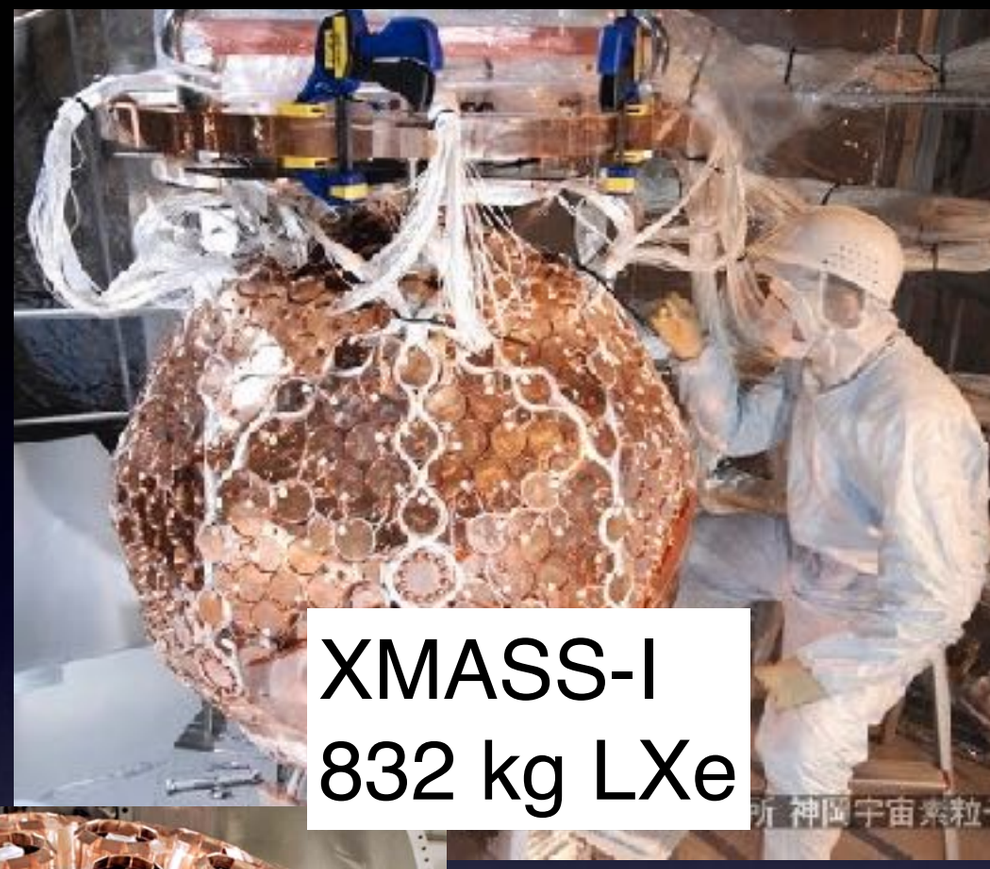
Full exposure spin-independent WIMP-nucleon exclusion

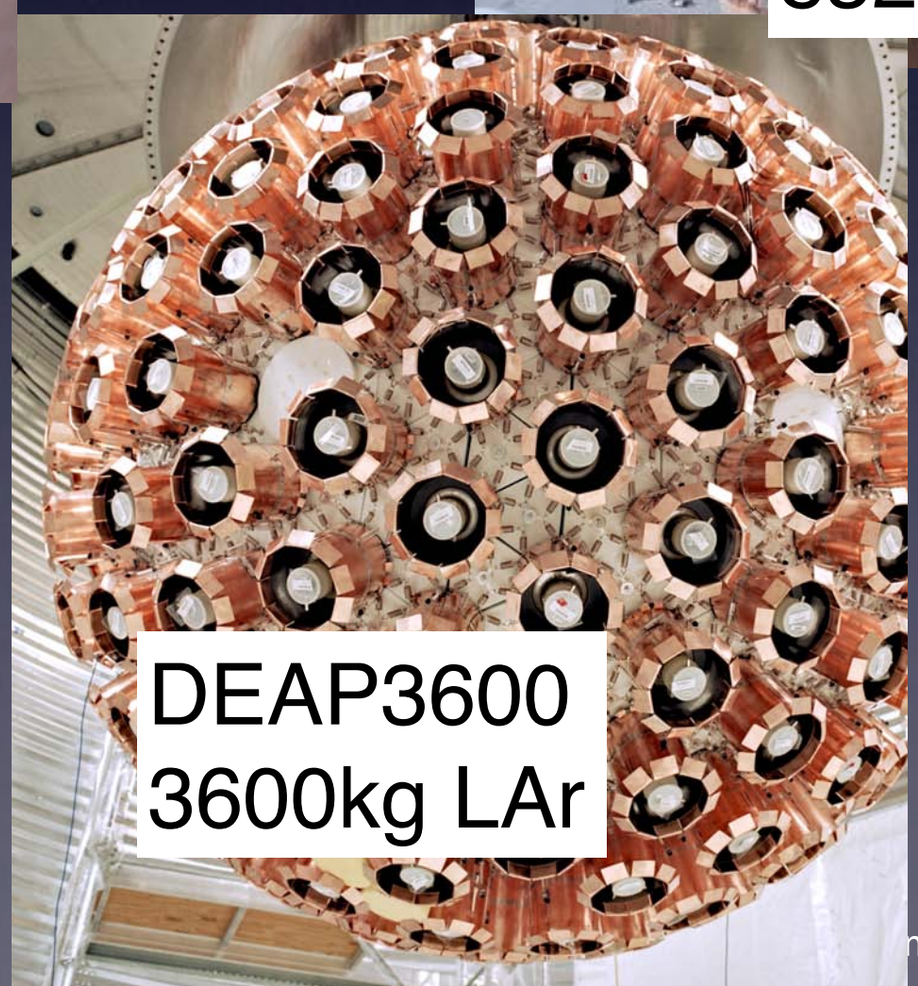
- The full LUX exposure is 4.75×10^4 kg·days
  - 130 kg·years
- Minimum of 1.1×10^{-46} cm^2 at a mass of 50 GeV/c^2
  - corresponds to 3.2 signal events
  - power constrained at -1σ
- Context:
  - more than 10x improvement upon XENON100
  - More exposure coming from PandaX (~2-5x)
  - XENON1T (~8-10x) and LZ (~100x) on the horizon



Read more!
[arXiv:1608.07648]
(recently accepted by PRL)

Single Phase ball

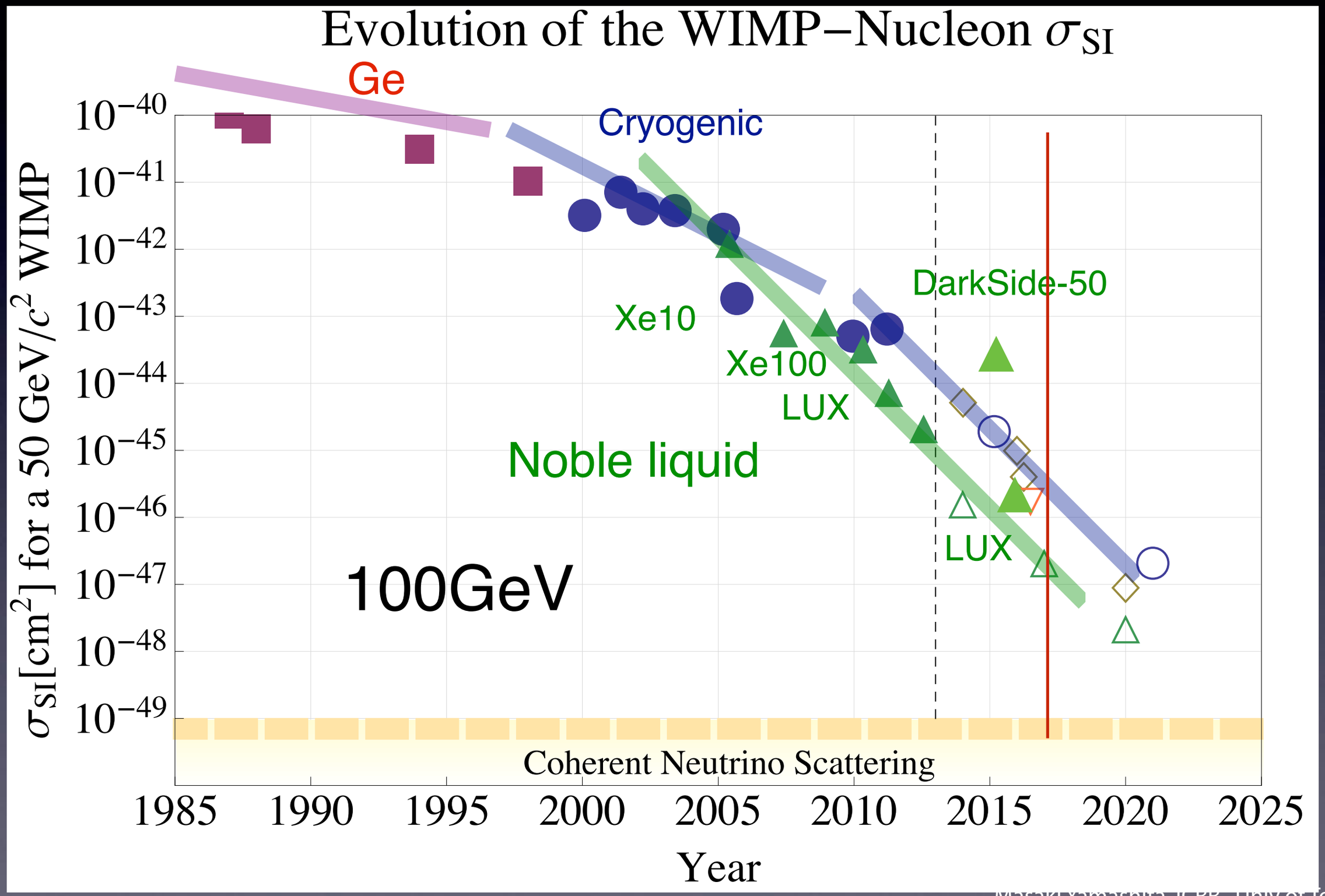




-simple design (no HV)
-Self-shielding against gamma-ray.
-Pulse Shape Discrimination (LAr)

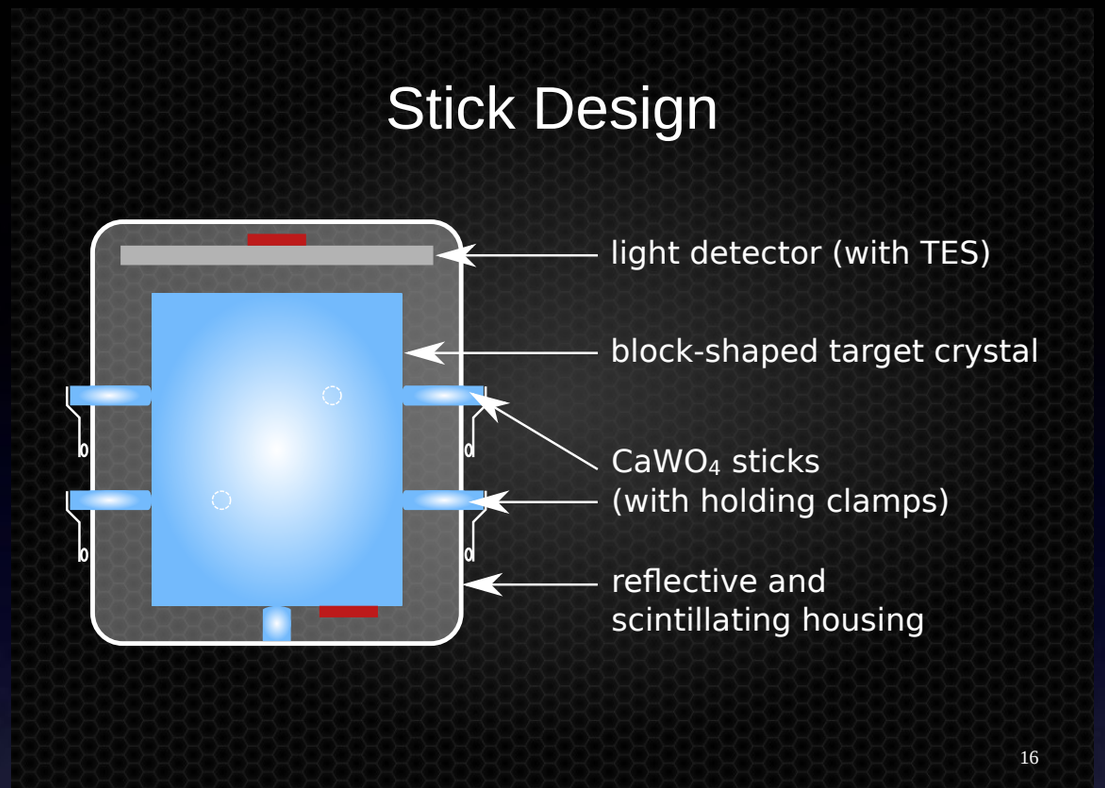
- 大型化が容易
- 高い光量
- DEAP3600は液化の手こずっている半年以上

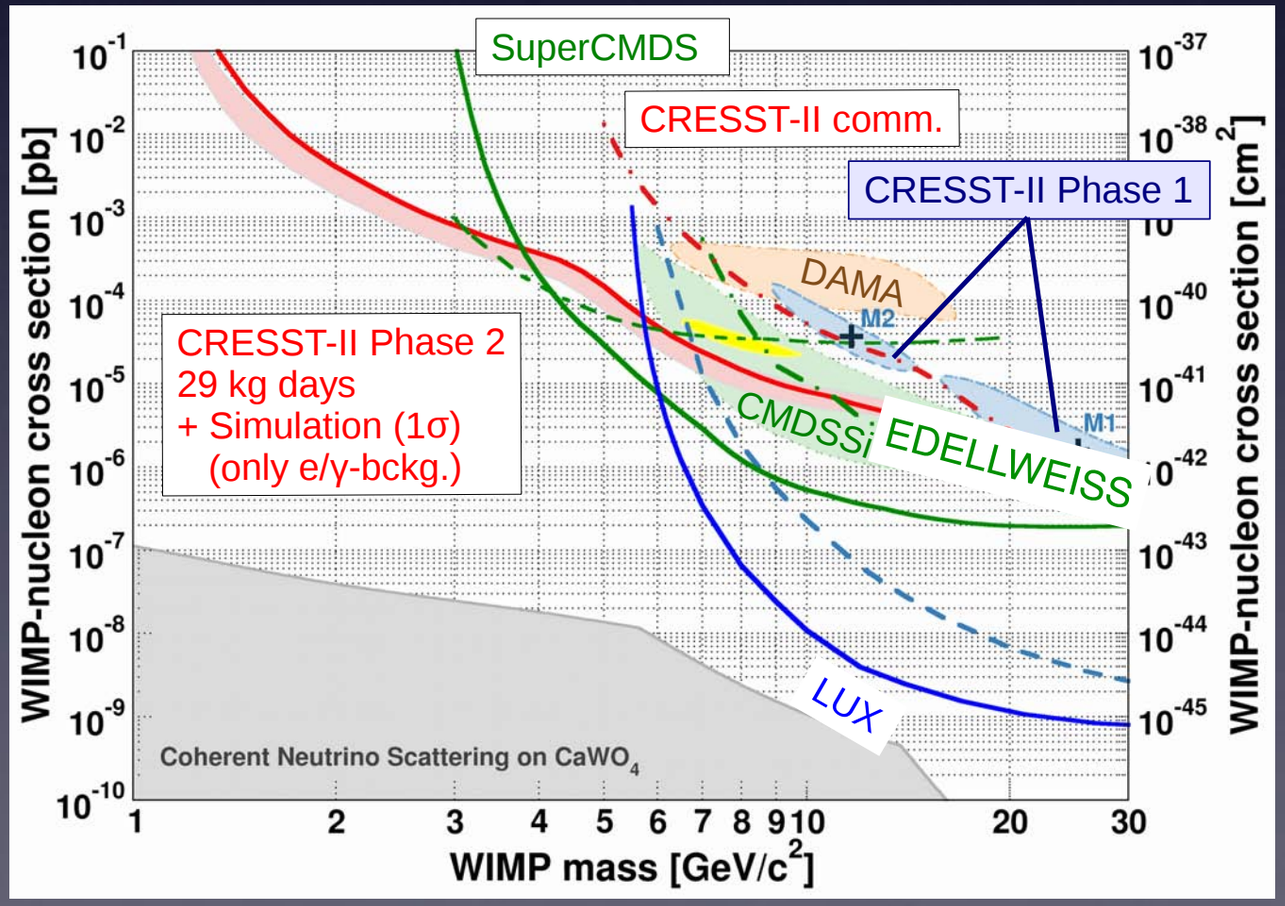
Cryogenic Detector

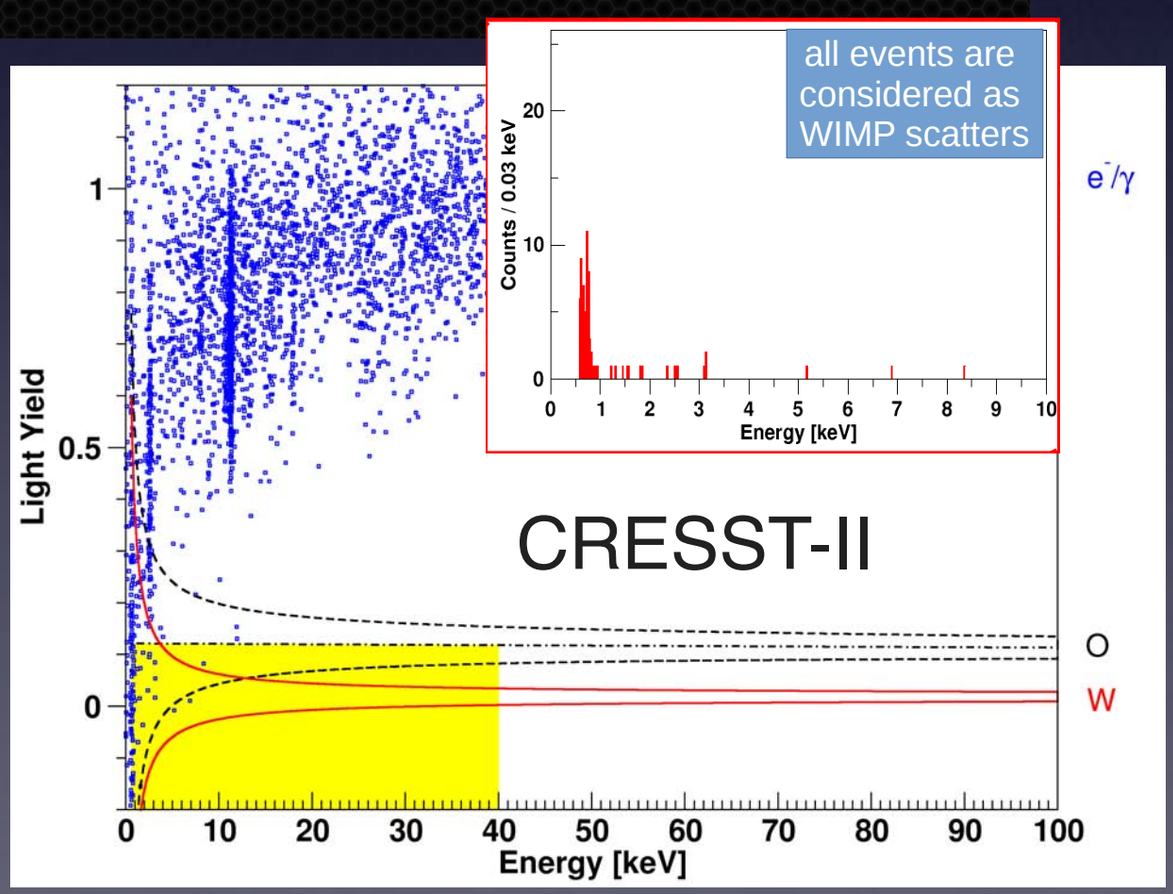


CRESST

CRESST
Scintillation + phonon
Target: $CaWO_4$
multiple target nuclei
identify background from clamp







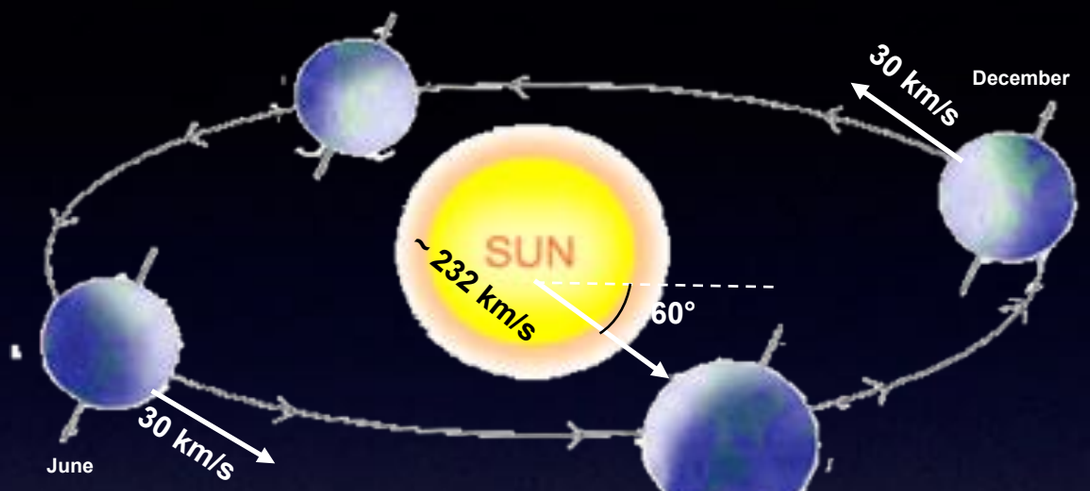
arXiv:1407.3146v2

DAMAはどうなる？

Masaki Yamashita, ICRR, Univ of Tokyo

DAMA/LIBRA in Gran Sasso

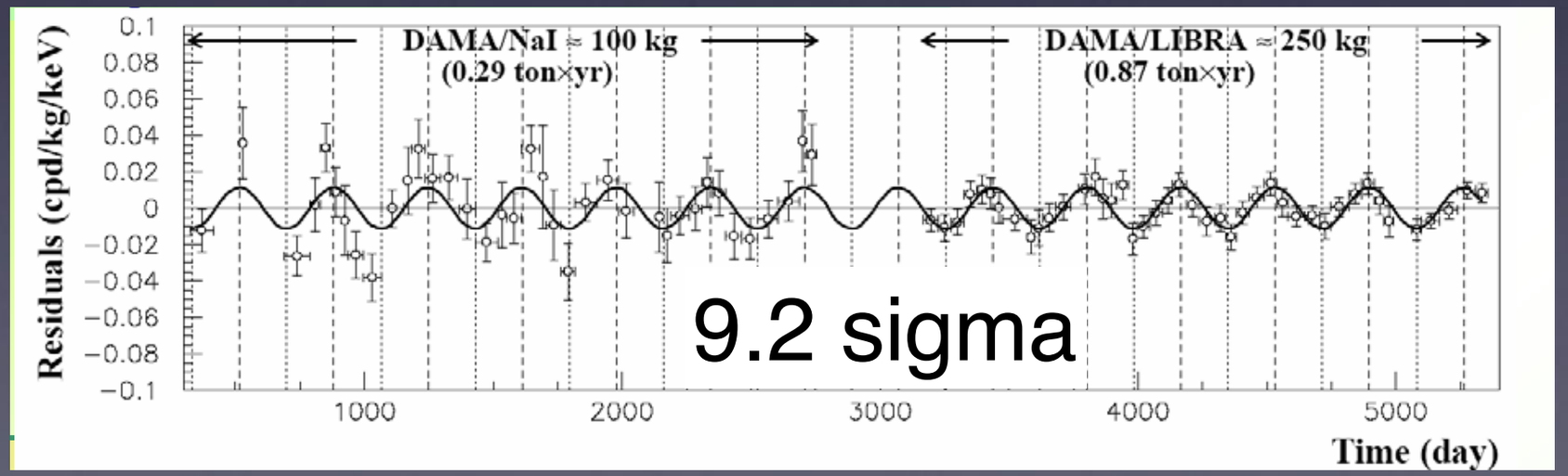
- DAMA(~100 kg) + LIBRA (~250 kg) of NaI
- Annual Modulation 9.2 σ
  - (14cycle -> 1.33ton x yr)
- Upgrade in 2010
  - high QE 35% at 420nm
  - Energy threshold
    - 2keV -> 1keV
  - a better energy resolution
  - a better noise/scintillation discrimination
  - less radioactivity



今年7年間のデータを発表する

と聞いている。

XMASSもアップデートの予定



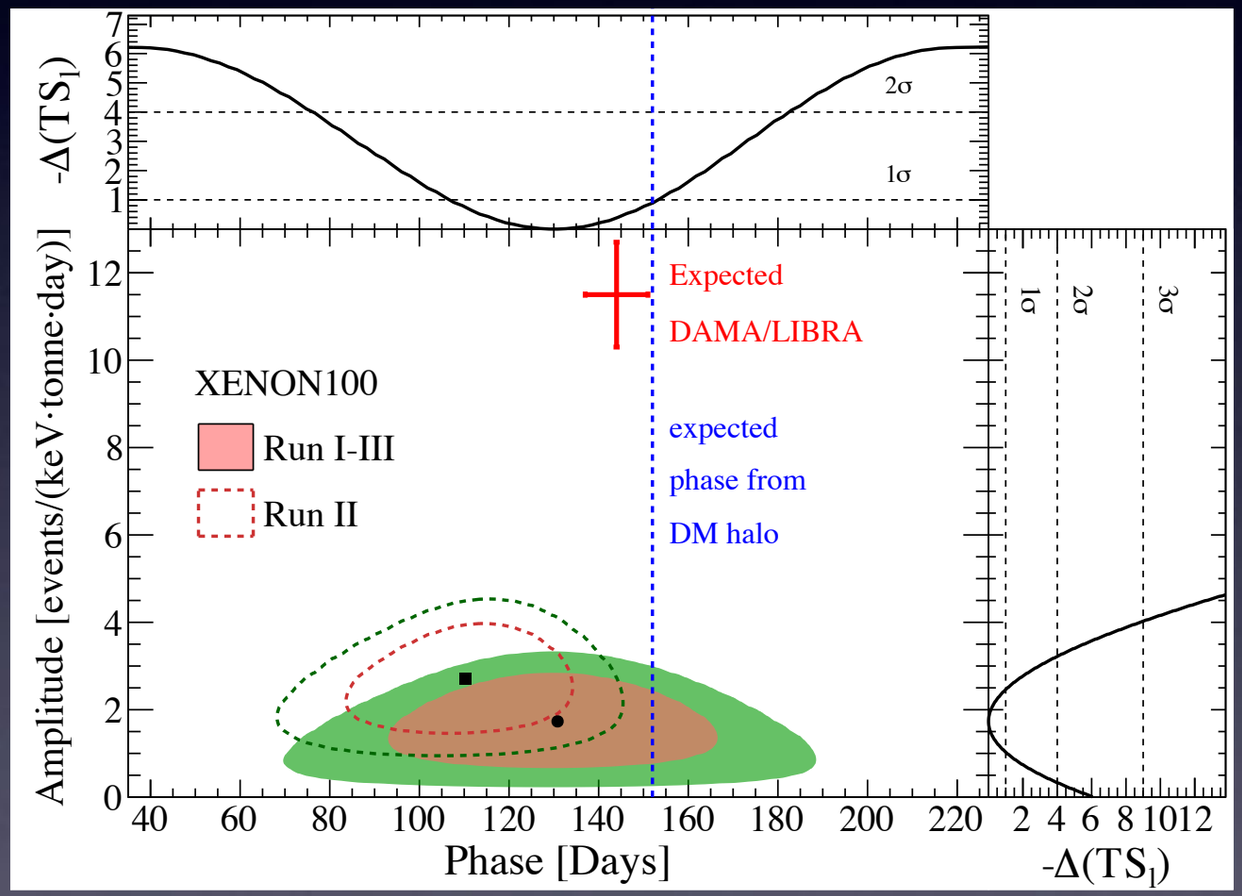
Eur. Phys.J. C(2013) 73, JINST 2012 7 P03009

by LXe

Nuclear recoilではすでに否定されているので

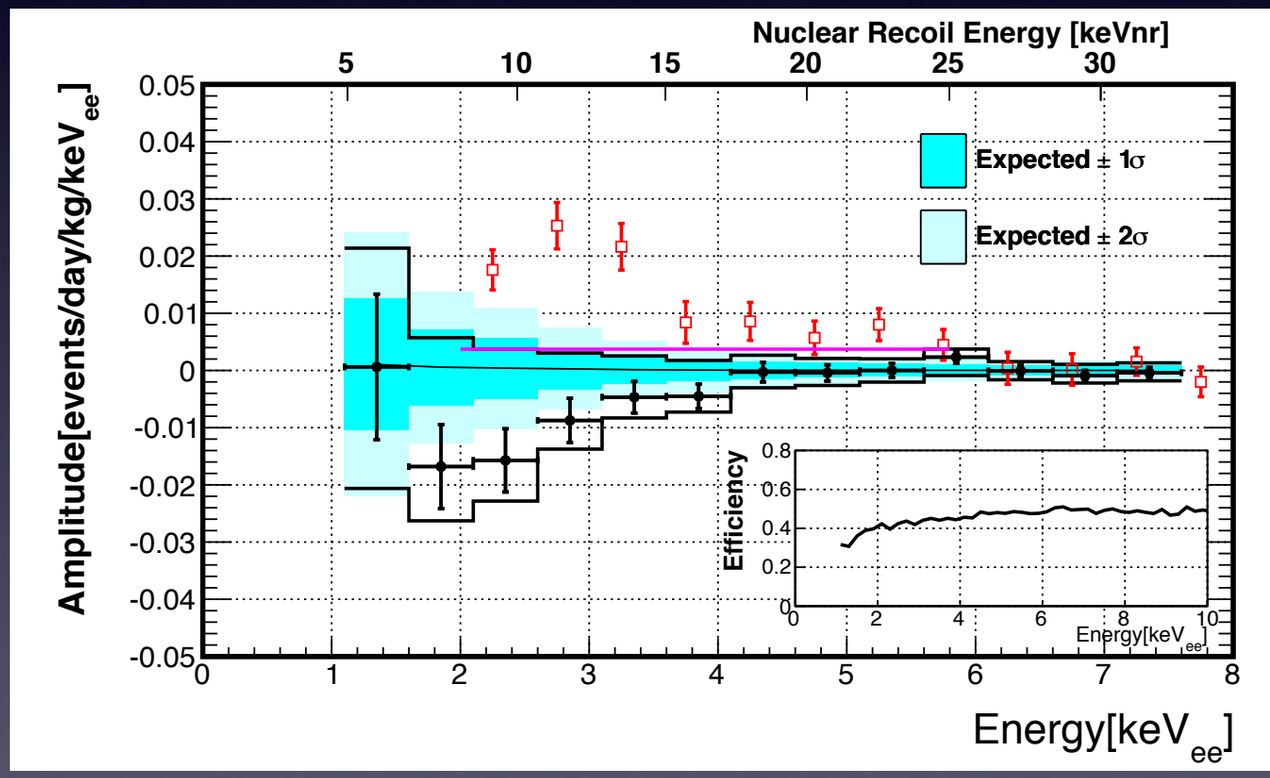
DM-electronなど

XENON100



arXiv:1701.00769v1

XMASS



Phys. Lett. B759 (2016) 272-276

NaI R&D Project

同じターゲットで。

追認？　それとも？

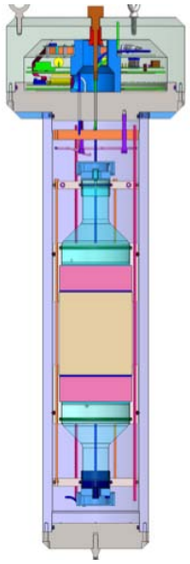
- -R&D for making radioactive pure NaI crystal by DM-ICE, ANAIS, KIMS, SABRE, PICOLON.
- DM-ICE => First Dark Matter Search in South Pole ICE.
- Entirely different environment=>annual modulation

(all rates in μBq/kg)

Decay	DM-Ice17[A]	ANAIS-0[B]	DAMA[C]	ANAIS-25[D]	KIMS-001[E]	KIMS-002[E]	DM-Ice37[F]
^{40}K	17000	12700	600	1250	1250	1490	<2000
^{232}Th	10	13		2	<12	2	
^{228}Ra – ^{208}Tl	160	35	2-30	2	<13	2	
^{238}U	17	75	4.4	10	<7	<12	
^{234}U, ^{234}Th	140	75, 23	15.8				
^{226}Ra – ^{214}Po	900	98	21.7	10	<0.3	<1.5	
^{210}Po	1500	188	24.2	3150	3280	1760	2100

A – Cherwinka *et al.*, Phys. Rev. D **90** (2014)
B – Cebrián *et al.*, Astropart. Phys. **37** (2012)
C – Bernabei *et al.* NIM A **592** (2008)
D – Amaré *et al.* NIM A **742** (2014)
E – Kim *et al.* Astropart. Phys. **62** (2014)
F – *PRELIMINARY*

DM-Ice17
(*January 2011 – present*)



First dark matter experiment in South Pole ice

- Demonstrated viability and advantage of environment

DAMA DM

NaI

LXe

軽い DM

重いDM

Cryogenics

LAr

Masaki Yamashita

Budget

Masaki Yamashita

US support ADMX, LZ, Super-CDMS

Cosmic Frontier Status

Dark Energy: Staged program of complementary suite of imaging and spectroscopic surveys

- ***BOSS*** **final results out soon;** ***eBOSS***, ***DES*** **continue operations**
- ***Large Synoptic Survey Telescope (LSST)*** **received CD-3 in August 2015**
- ***Dark Energy Spectroscopic Instrument (DESI)*** **received CD-3 in June 2016**
- **Have MOA's with NSF-AST for** ***LSST*** **partnership &** ***DESI*** **cooperation**

Dark Matter (direct detection): Staged program of current and next-generation experiments with multiple technologies

- **Completed DOE operations funding for current DM-G1 experiments in FY 2016.**
- **Progress continues on DM-G2 experiments:** ***ADMX-G2***, ***LZ***, ***SuperCDMS-SNOLAB***
  - **ADMX-G2 infrastructure complete at UW; Science data taking operations started in August 2016.**
  - ***LZ*** **&** ***SuperCDMS-SNOLAB*** **projects received Congressional "MIE starts" approval in FY 2015**
  - ***LZ*** **received CD-2/3B in August 2016;**
  - ***SuperCDMS-SNOLAB*** **received CD-1 December 2015**

Cosmic Microwave Background (CMB)

- ***South Pole Telescope polarization (SPTpol)*** **continues operations.**
- ***SPT-3G*** **begins operations in Feb 2017; partnership with NSF.**
- **Community planning proceeding for CMB-S4 experiment; AAAC subpanel, CMB-S4 Concept, Definition Task force (CDT), being formed.**

Cosmic-ray, Gamma-ray

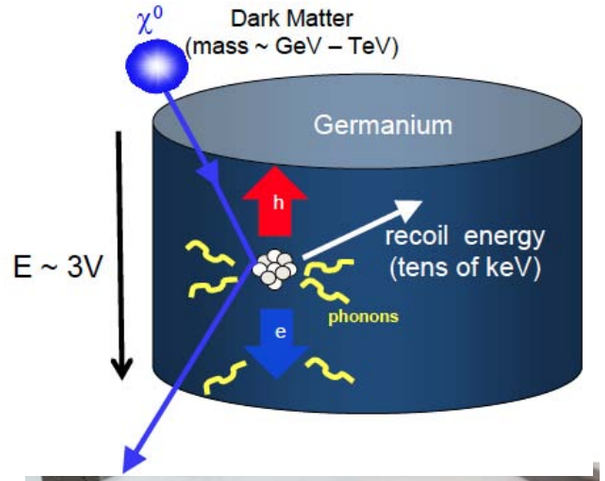
- ***Fermi/GLAST***, ***AMS***, **and** ***HAWC*** **continue operations**
  - ***HAWC*** **gamma-ray observatory began full science operations in early 2015**
- **DOE operations funding completed in FY 2016 for** ***VERITAS*** **and** ***Auger***

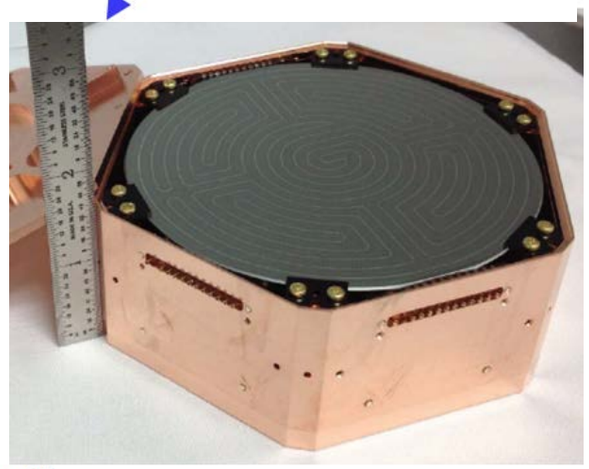
shita 27

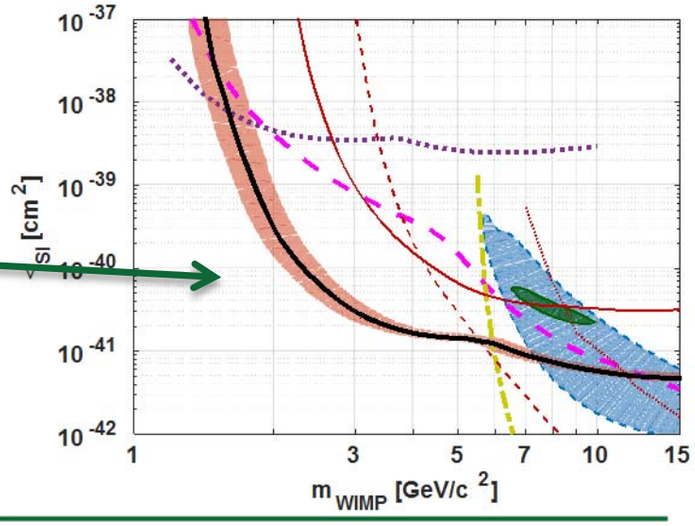
CDMS – Cryogenic Dark Matter Search
SuperCDMS-Soudan → SuperCDMS-SNOLAB

Physics: Direct detection of dark matter particles (WIMPs) using cryogenic solid-state germanium and silicon crystals with sensors that detect ionization and phonon signals. Sensitivity to very small energy depositions allows additional searches for axions and lightly ionizing particles.
Description: SuperCDMS Soudan G1 WIMP experiment 2010-2015; SuperCDMS SNOLAB G2 low-mass WIMP experiment 2016-2025.
Partnership: DOE and NSF, contributions from Canada (CFI, NSERC).
Collaboration: ~90 scientists from 13 US universities & 3 labs, plus institutions from Canada, India, UK and Spain. D. Bauer (FNAL, Spokesperson)
HEP funding: FNAL, SLAC, PNNL, Caltech, Minnesota, South Dakota, Stanford, Texas A&M
Project: FNAL leads SuperCDMS-Soudan operations (D. Bauer);
SLAC leads SuperCDMS-SNOLAB Project (B. Cabrera, Project Director)
Status:
SuperCDMS-Soudan operations completed in FY15; decommissioned in FY16; Analyses progressing.
SuperCDMS-SNOLAB selected as one of three G2 Dark Matter experiments (July 2014); CD-1 approved December 2015. CD-2/3 review planned Nov.2017.
Recent Highlights: (Oct 2016)
New limit on low-mass WIMPS from CDMSlite Run 2 (black line and orange band); > x10 improvement at 3 GeV/c^2 (http://arxiv.org/abs/1509.02448)

Expect new results from CDMSlite Run 3 and additional SuperCDMS Soudan analyses early 2017.







Non-G2 WIMP Search Experiments

PICO-60: Bubble chamber experiment at SNOlab (DOE, NSF, Canada)

Status: Operations funded by Canada in 2017. PICO-60 running with C3F8 target liquid. R&D on next generation bubble chambers with PICO-40L. Collaboration is proposing to Canadian agencies for ton-scale detector.

Highlights: Results in 2016 demonstrate world's best sensitivity to spin-dependent WIMP scattering and continued progress on background reduction.

DarkSide-50: LArTPC 50 kg active mass, Gran Sasso (LGNS), Italy (NSF-lead, major contribution from INFN, DOE)

Status: Running with 153 kg of low-radioactivity underground Ar (UAr).

Highlights: WIMP search results with 2616 kg-day UAr exposure (Oct 2015); Factor of >1000 reduction in 39 Ar measured in the UAr compared to atmospheric Ar.

DarkSide Collaboration planning to propose follow-on experiments:
DarkSide-20k :20-tonnes fiducial mass; 100 ton-year - background-free
Argo: 300-tons depleted argon; start of operations at LNGS 2025

DAMIC: Dark Matter in CCDs (DOE, NSF, +7 countries, operations at SNOLAB (Canada).

Status: Preparing for the deployment of the ~100g detector this year. The science detectors and electronics are currently being testing in a final integration test at FNAL.

Highlights: New results published with SNOLAB data in 2016 produced the best limits for low mass dark matter search using silicon target. The collaboration published a full calibration of the ionization yield of nuclear recoils in Silicon down to energies of 0.7 keV for the nuclear recoil in 2016.

DOE operations funding for these experiments ended in FY16.

nashita 29

近い将来

Masaki Yamashita

Ton sale future experiment goal

Spin independent

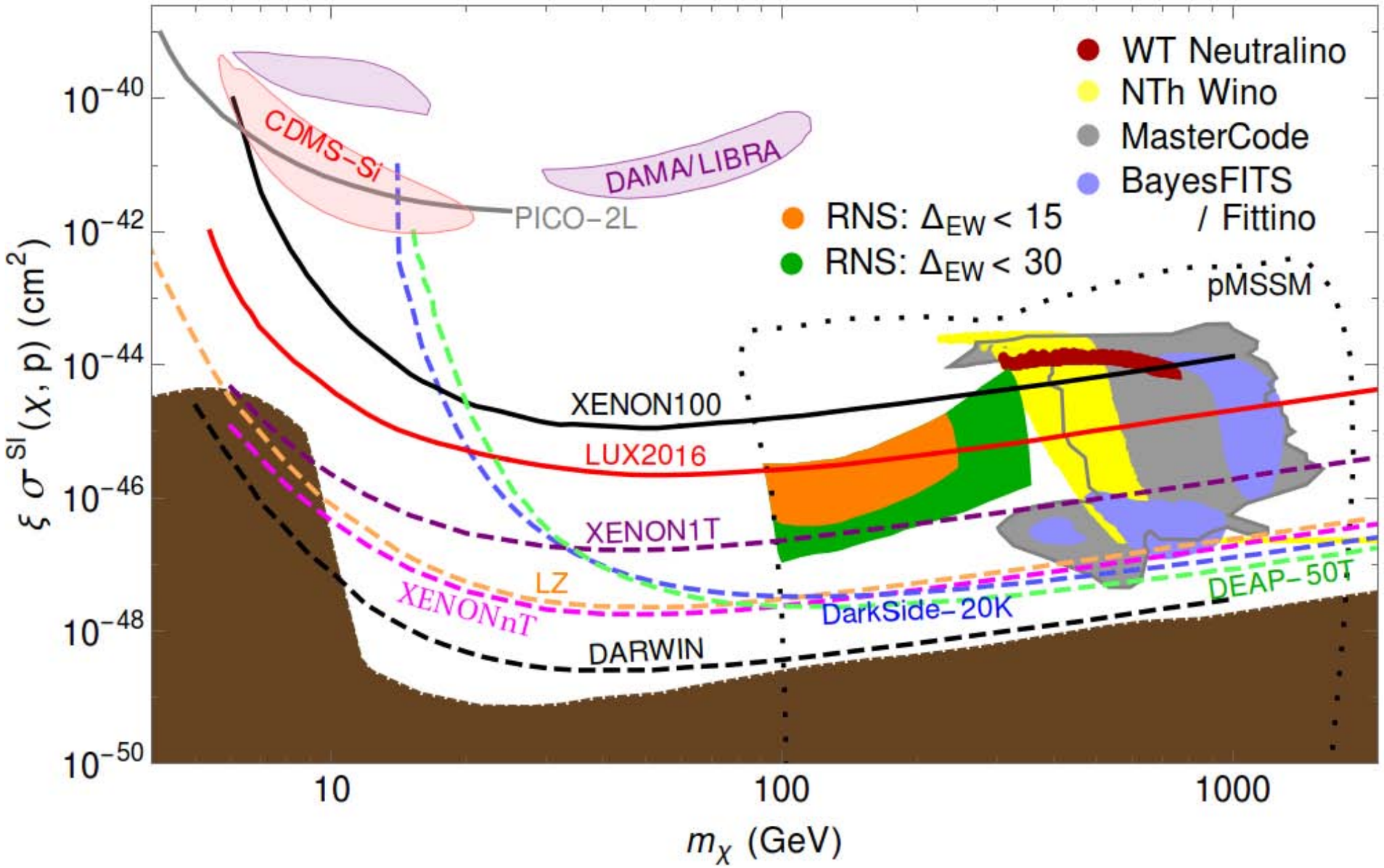


Figure 1: Plot of rescaled spin-independent WIMP detection rate $\xi\sigma^{SI}(\chi, p)$ versus m_χ from several published results versus current and future reach (dashed) of direct WIMP detection experiments. $\xi = 1$ (*i.e.* it is assumed WIMPs comprise the totality of DM) for the experimental projections and for all models *except* RNS and pMSSM.

Ton sale future experiment goal

Spin dependent

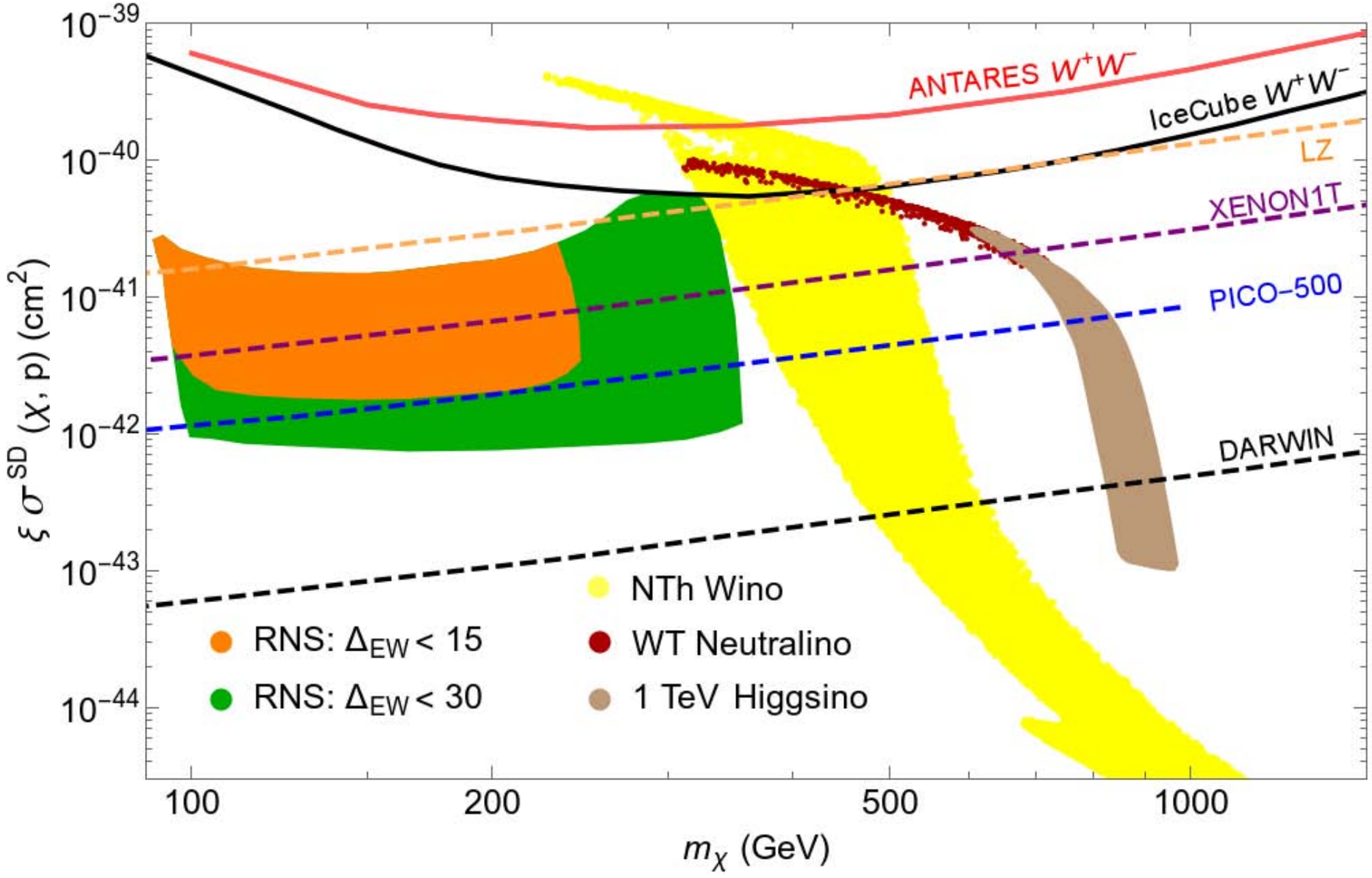
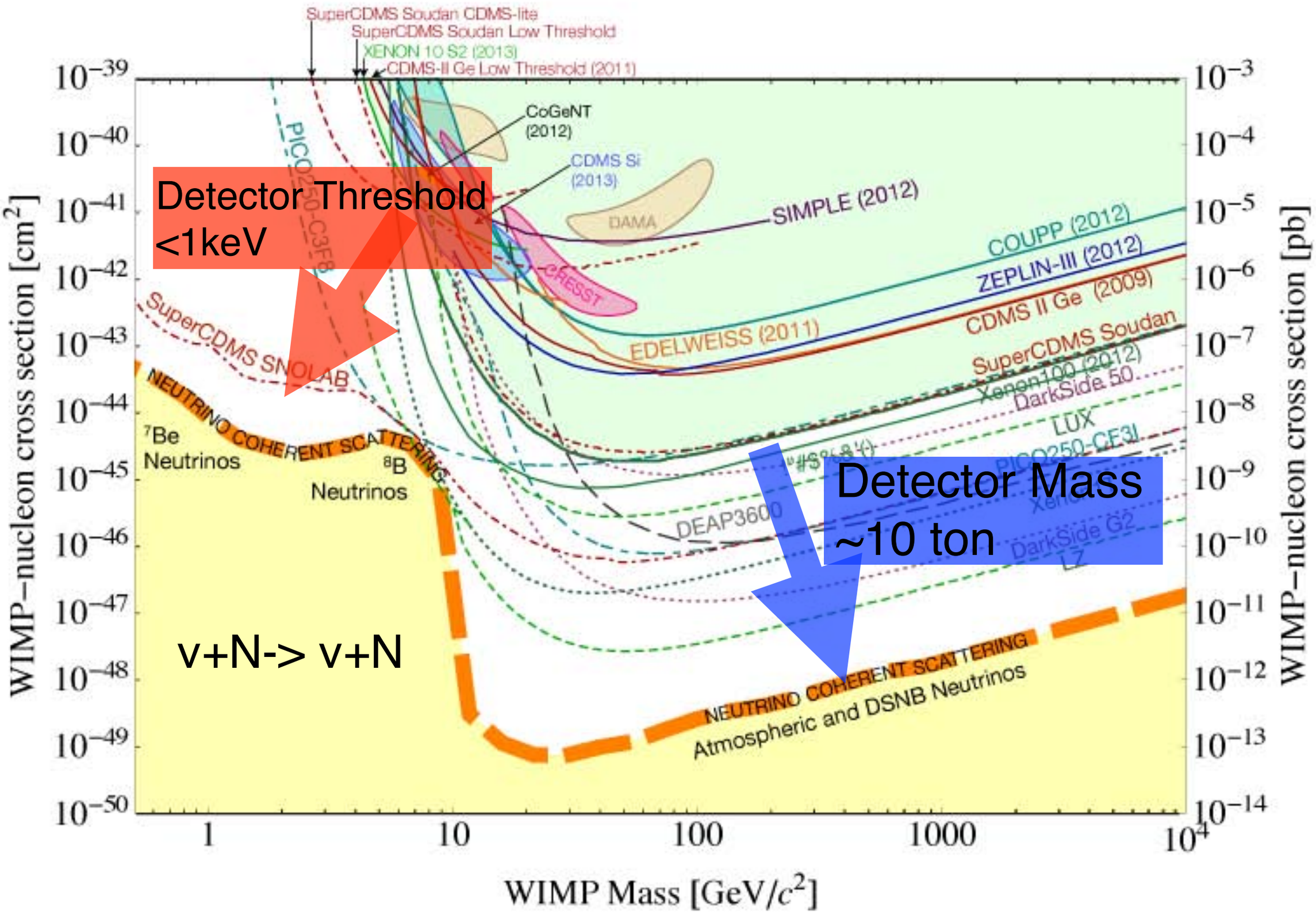


Figure 2: Plot of rescaled spin-dependent WIMP detection rate $\xi\sigma^{SD}(\chi, p)$ versus m_χ from several published results versus current ANTARES and IceCube reach and projected (dashed) LZ, XENON1T, PICO-500 and DARWIN reaches. $\xi = 1$ (*i.e.* it is assumed WIMPs comprise the totality of DM) for the experimental projections and for all models *except* RNS and pMSSM (not shown).

Future



from arXiv:1310.8327v1

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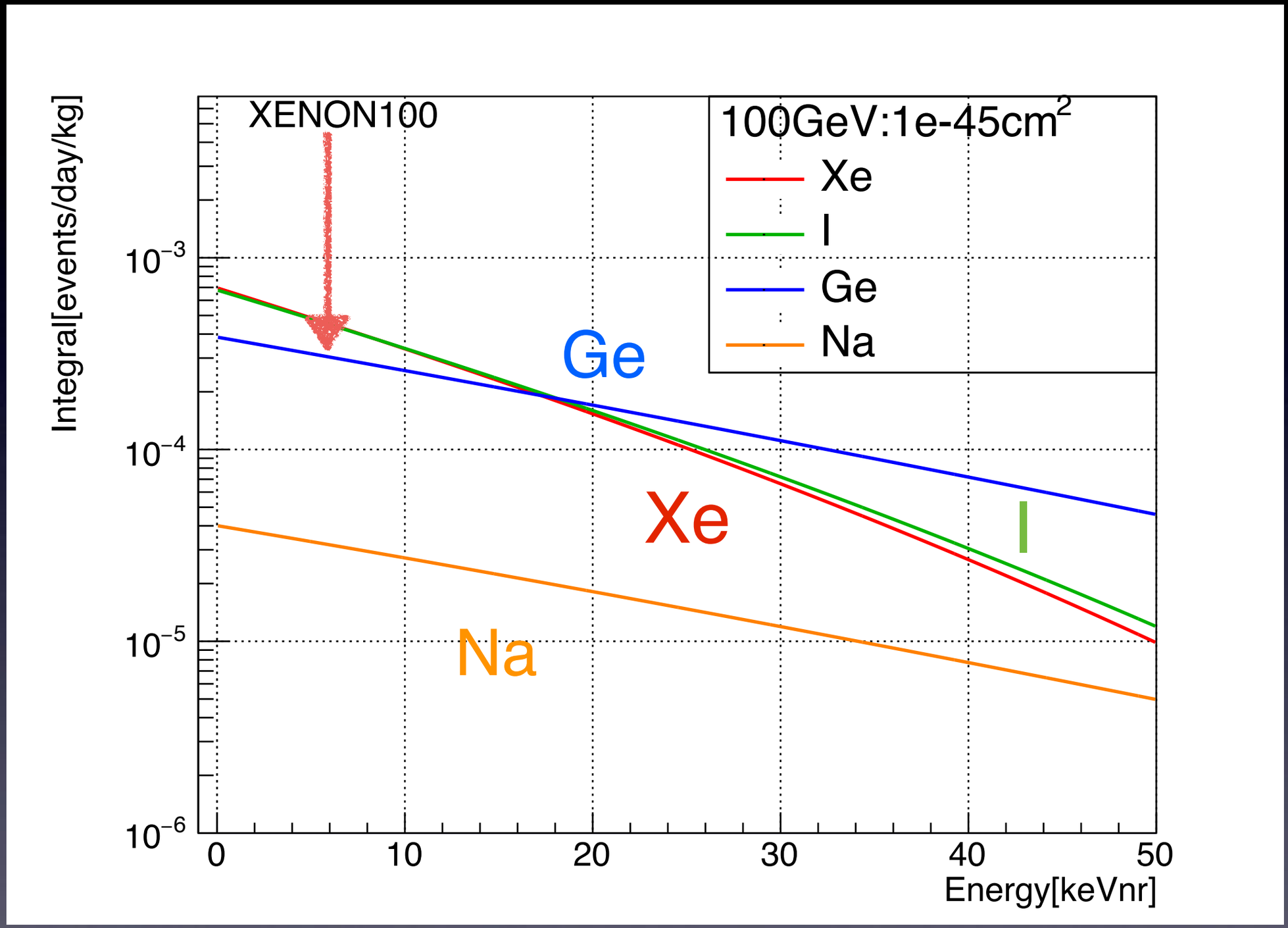
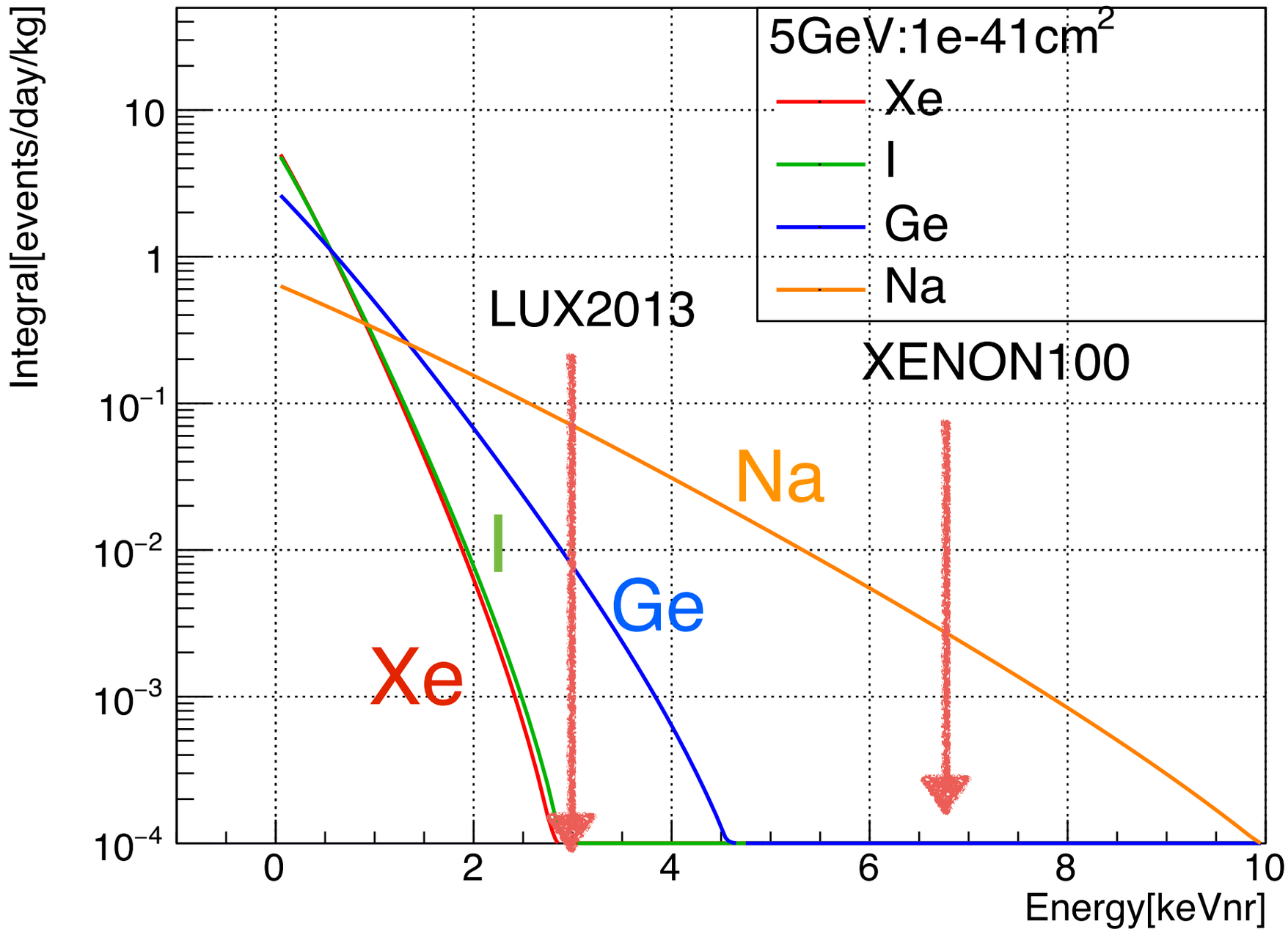
100GeV Spin independent case



Detector mass is important. (> 100 kg)

5GeV Spin independent case

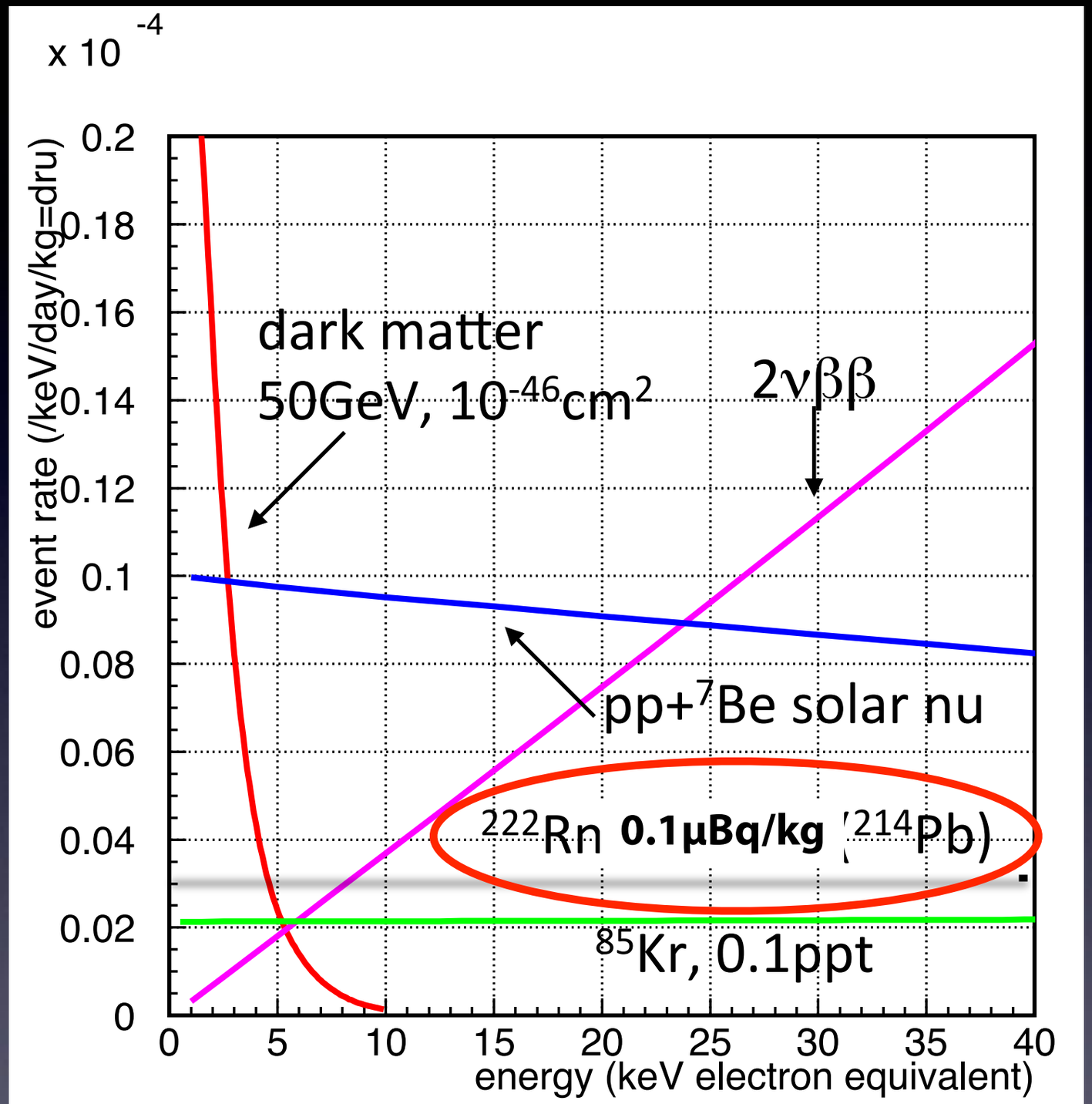


Energy resolution is not considered.

Energy threshold is very important.

For Xe target, detector resolution, systematic has to be well controll

近い将来の主なバックグラウンドはpp/Rn

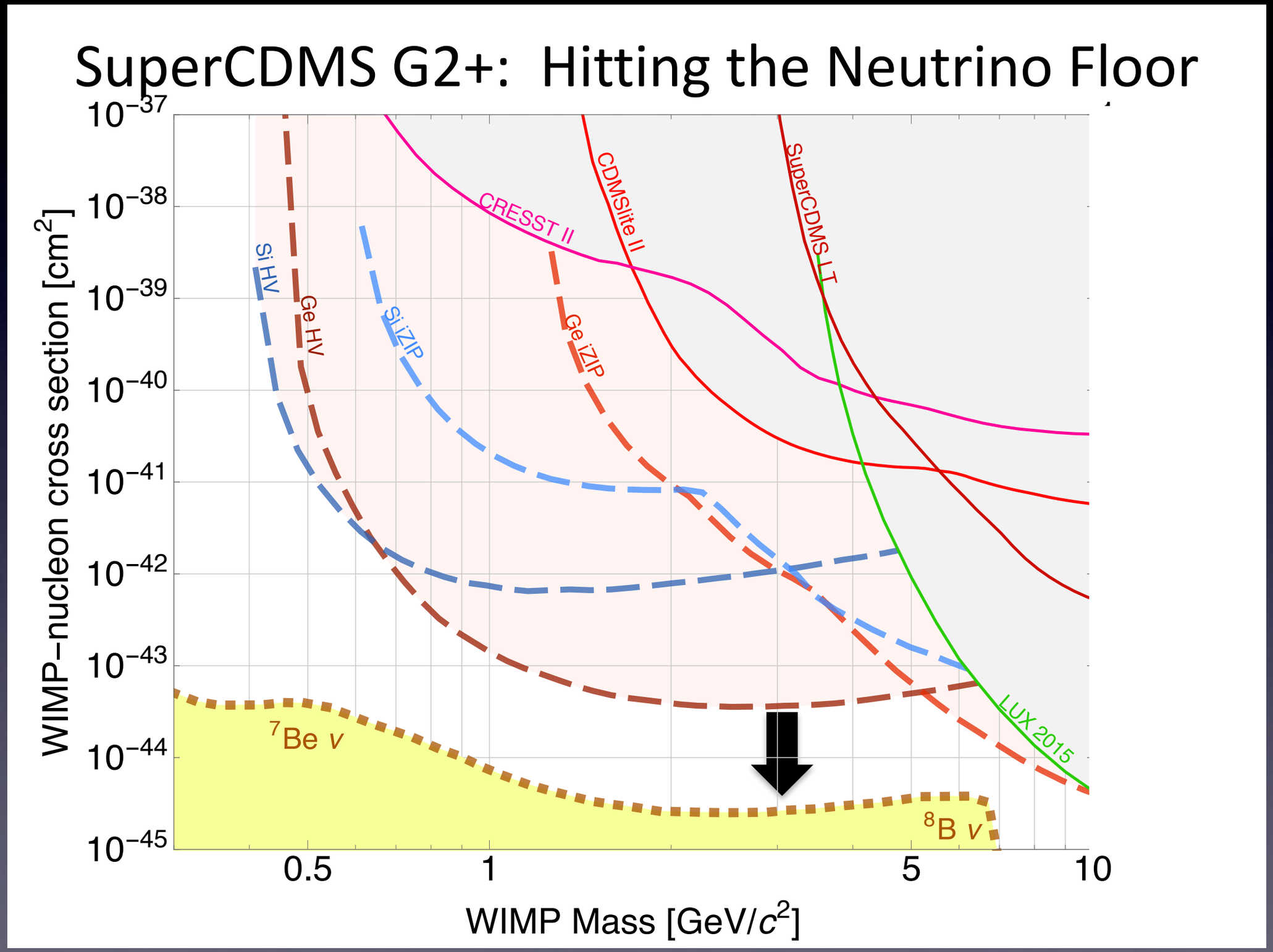


ラドンはXMASSで約10μ/kgが達成されている。

もう一桁以上減らしたい。

pp:昔は目的の一つであったが、今ではbackground.強力なparticle IDが必要q

CDMSの場合（low mass）



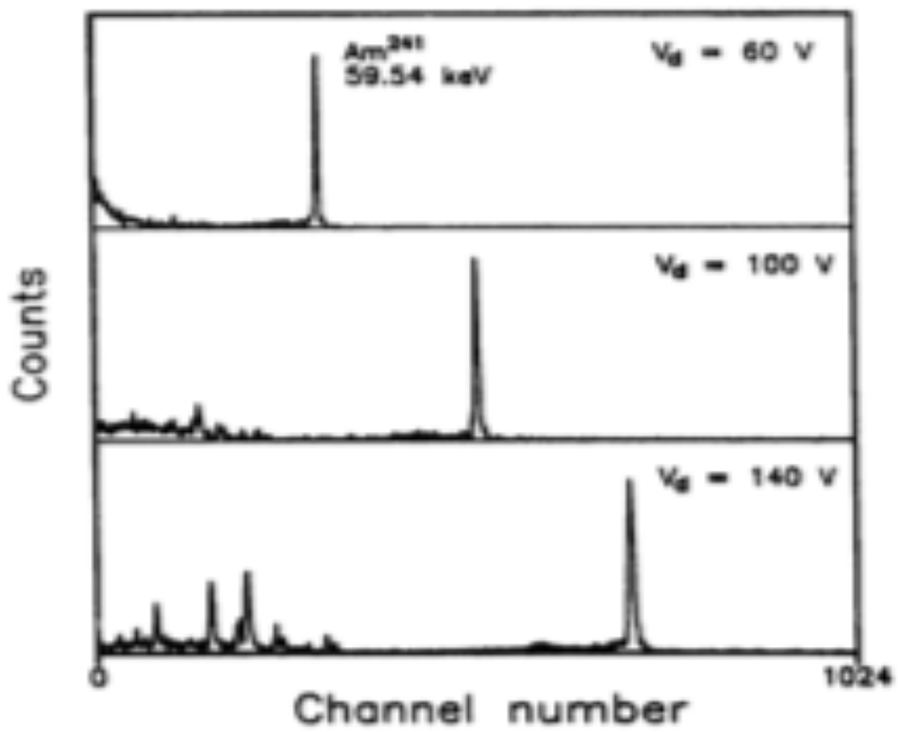
Masaki Yamashita

Luke-Neganov Ionization Amplification

$$E_{total} = E_{recoil} + E_{luke}$$
$$= E_{recoil} + Qe\Delta V$$

$$\lim_{\Delta V \to \infty} E_{total} \propto Q$$

At high voltage you've made an ionization amplifier



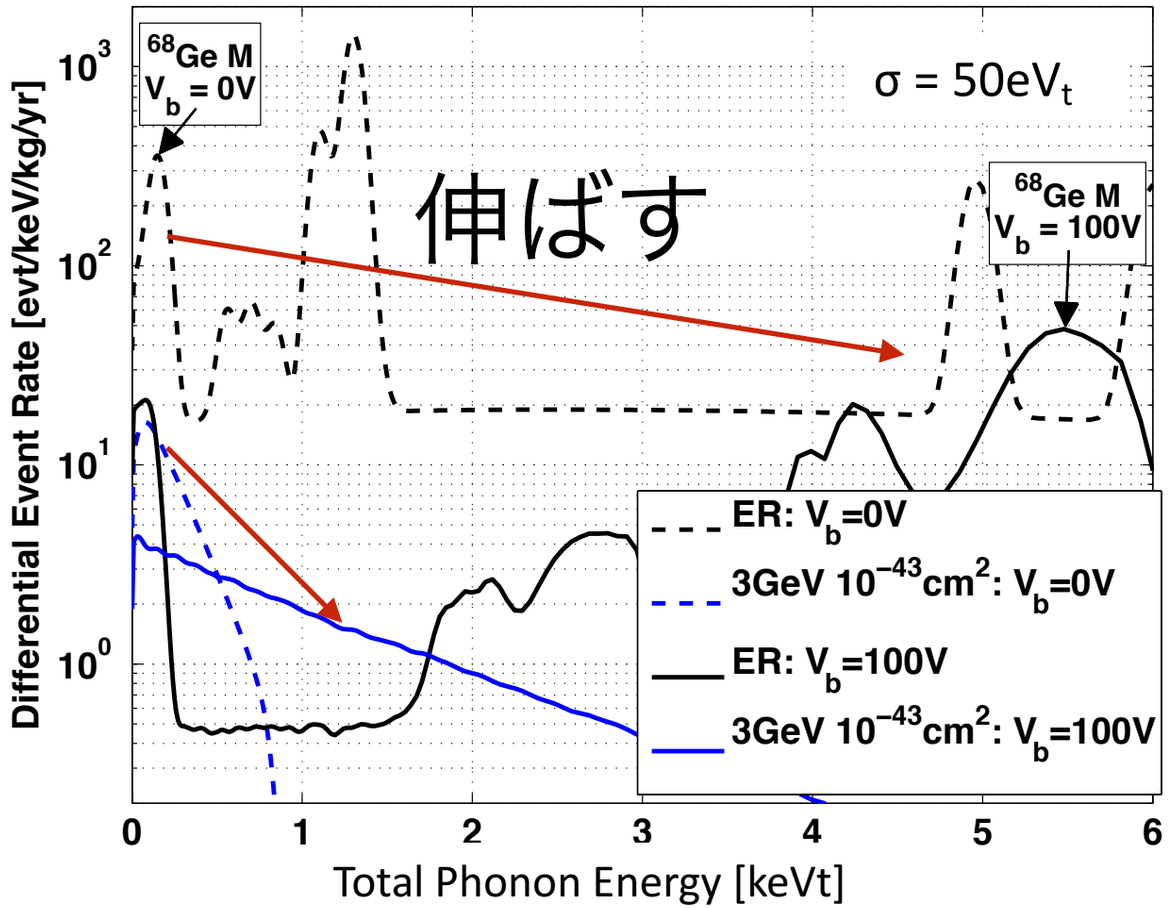
P.N. Luke et al. NIM A289, 405 (1990)

ER/NR discriminationもできる

Preferential Stretching of Electronic Recoils

$$E_{total} = E_{recoil} + E_{luke}$$
$$= E_{recoil} + QeV$$
$$= E_{recoil}\left(1 + \frac{YeV}{< E_{eh} >}\right)$$

Since Electronic Recoils (ER) have larger Ionization Yields than Nuclear Recoils (NR), they have larger Luke Neganov Gain



If you have phonon sensitivity to spare, this is tantamount to ER/NR Discrimination

Future liquid Xe TPC

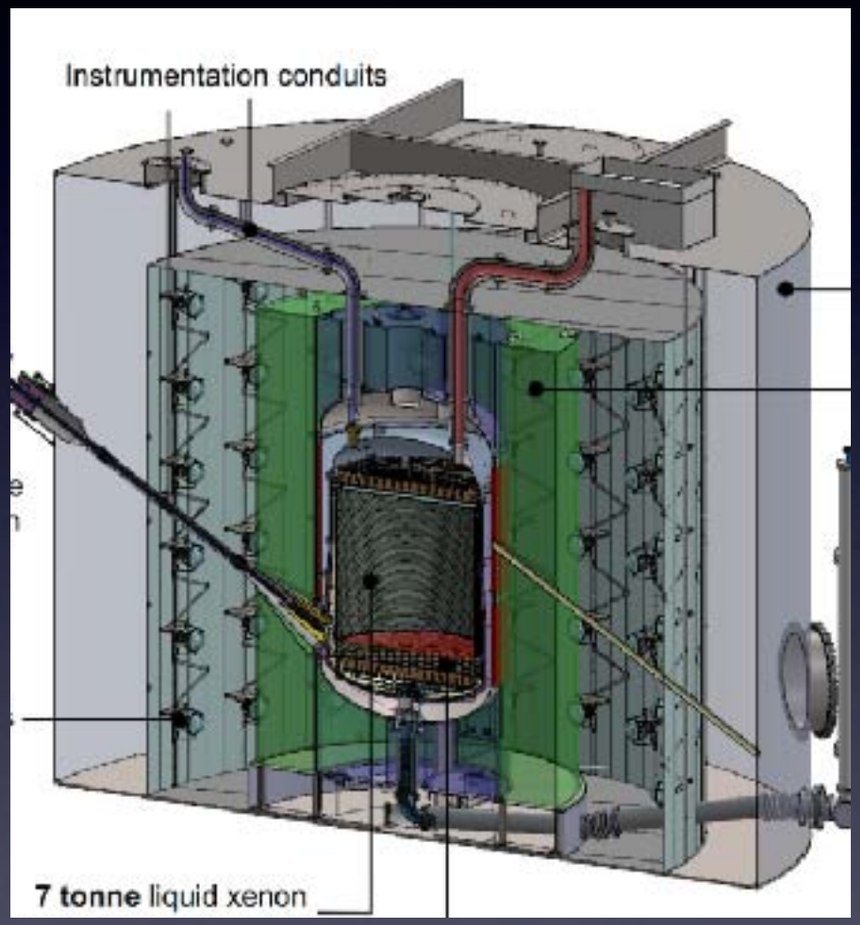
PandaX-IV

- **201X**
- **4 ton**

XENON1T/nT

- **2015- 3.3ton**
- **2018- 7 ton kg LXe**

LZ



- **2020- 7 ton kg LXe**

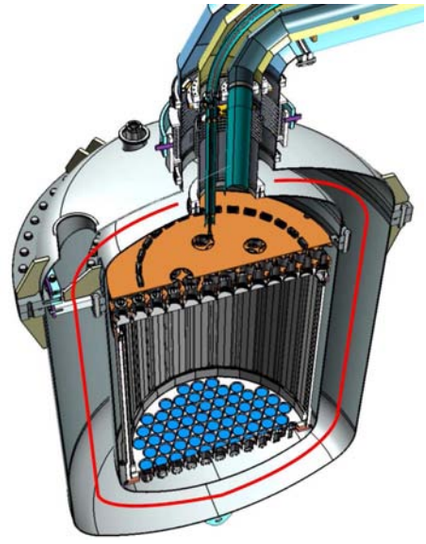
10^{-47} - 10^{-48} cm^2

Masaki Yamashita

XENON

XENON Program

XENON10 | XENON100 | XENON1T/XENONnT



2005-2007 | 2008-2015 | 2012-2018 / ~2018-2022

25 kg | 161 kg | 3500 kg / ~7000 kg

Achieved (2007)
$\sigma_{\mathrm{SI}} = 8.8 \times 10^{-44}\,\mathrm{cm}^2$

Achieved (2011)
$\sigma_{\mathrm{SI}} = 7.0 \times 10^{-45}\,\mathrm{cm}^2$
Achieved (2012)
$\sigma_{\mathrm{SI}} = 2.0 \times 10^{-45}\,\mathrm{cm}^2$

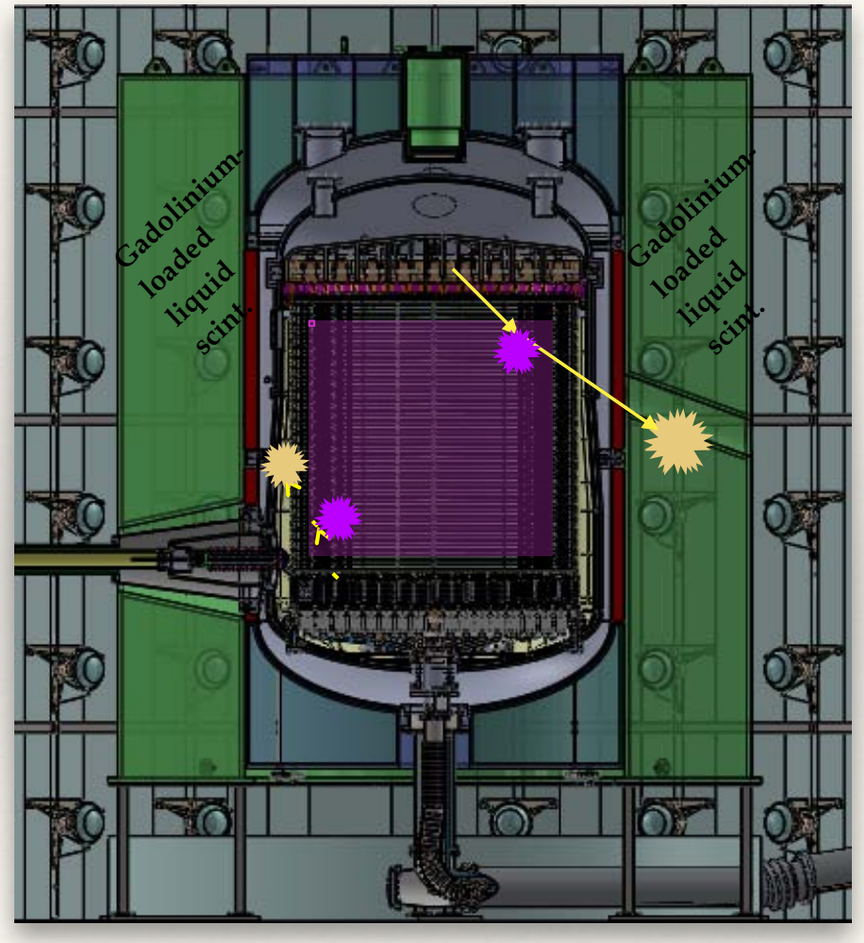
Projected (2018) / Projected (2022)
$\sigma_{\mathrm{SI}} = 1.6 \times 10^{-47}\,\mathrm{cm}^2$ / $\sigma_{\mathrm{SI}} = 1.6 \times 10^{-48}\,\mathrm{cm}^2$

XENON1Tが走り始めた。AmBeのキャリブレーションも終了。
2018年にXENON-nTにする。内側のvesselを変えるだけ。
お金は問題ないらしい。
2018年は、そのときにPMTが手に入るから。　その前に手に入るんだったらもっと早く始めたい。

Masaki Yamashita

LZ

Active veto volumes



- TPC field cage is not pressed up against the cryostat wall for two reasons
  - high fields
  - background rejection

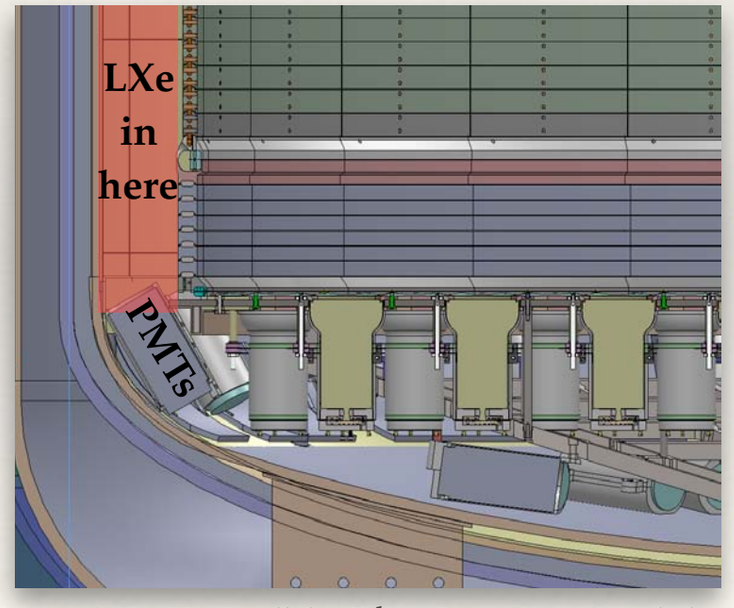


Image from *CPAD* talk by Ethan Bernard, UC Berkeley

200人を超える大きなグループになった。米国のフラッグシップ

DOEにサポートされ、厳密にスケジュールが管理されている。

LXe, 液シンのactive vetoが加わる

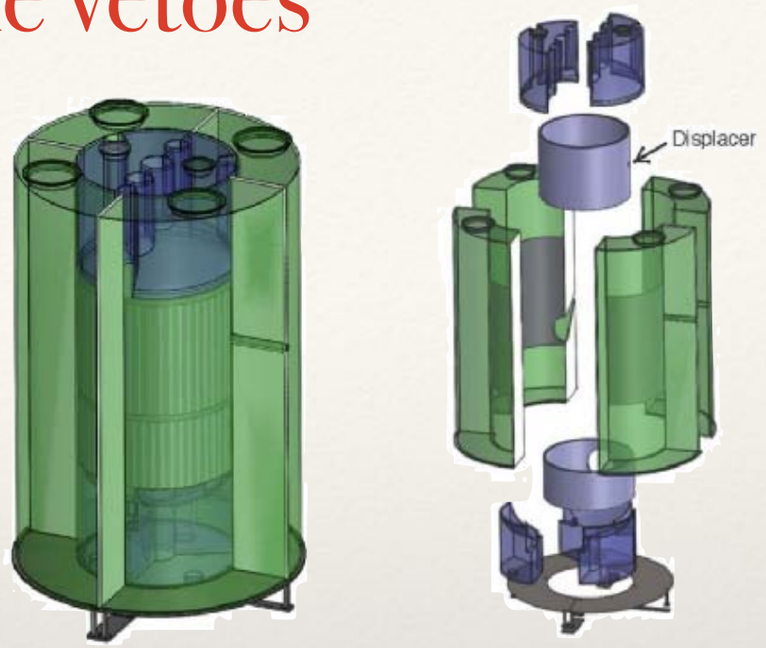
2020年スタート

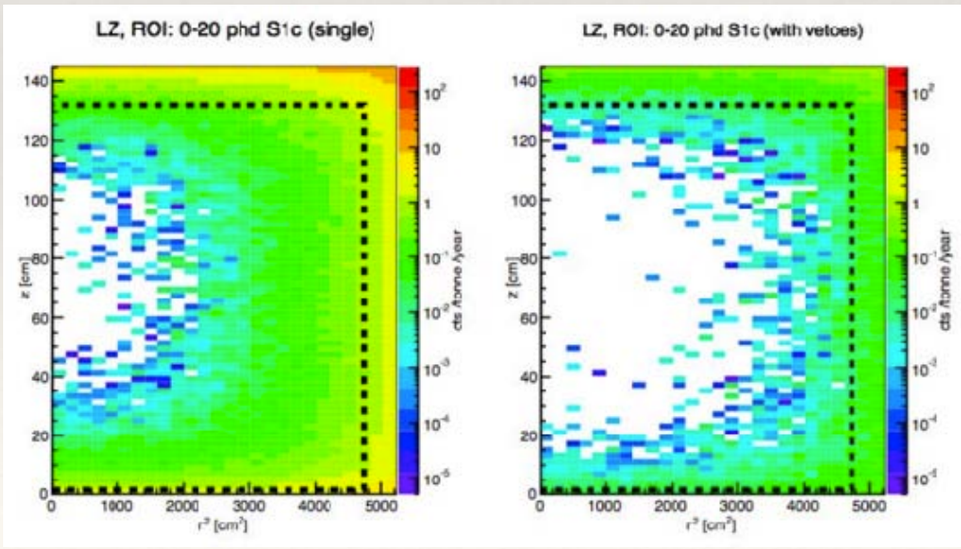
Masaki Yamashita

active vetoの効果

Effect of the vetoes

- Nine acrylic tanks, 60 cm thick, holding 17.5 tonnes of Gadolinium-loaded scintillator (LAB, linear alkylbenzene)
- 97% efficient for neutron detection
- Borrowing technology for scintillator and tanks (as well as people) from Daya Bay
- In combination with the instrumented LXe “skin,” the fiducial mass expands from 3.8 to 5.6 tonnes





Masaki Yamashita

Future LAr

DarkSide-20k Plans

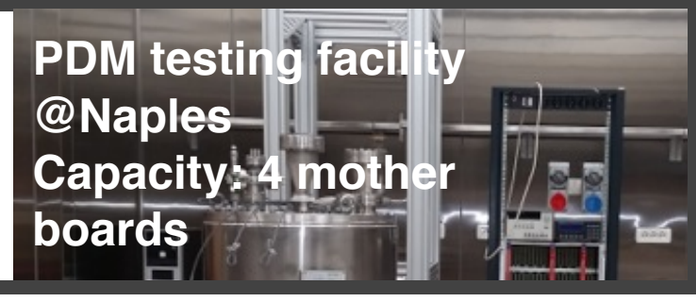
Proposal is submitted to NSF and INFN.

Continue with photodector modules F
optimize performance.
Start setting up facilities for mass pro
and testing.

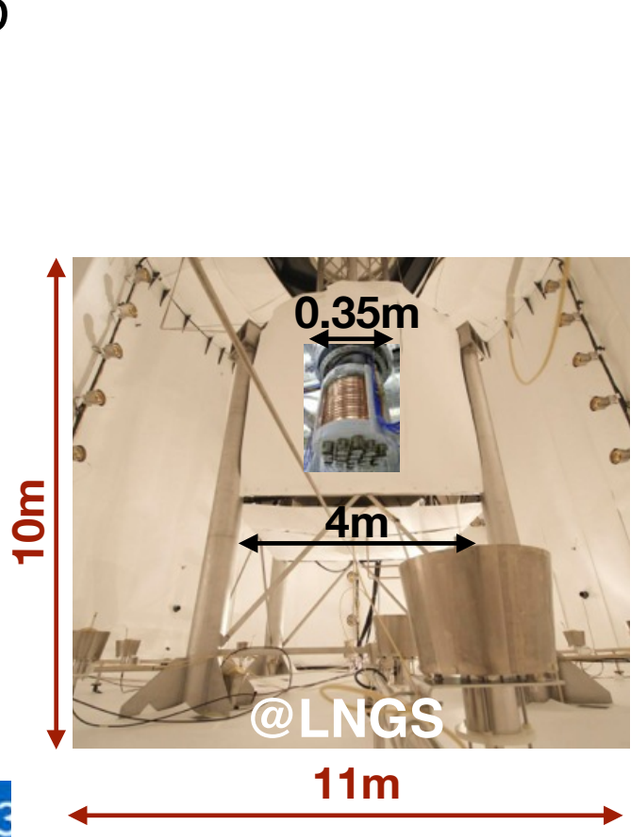
Continue with production of ARIA modules and testing.

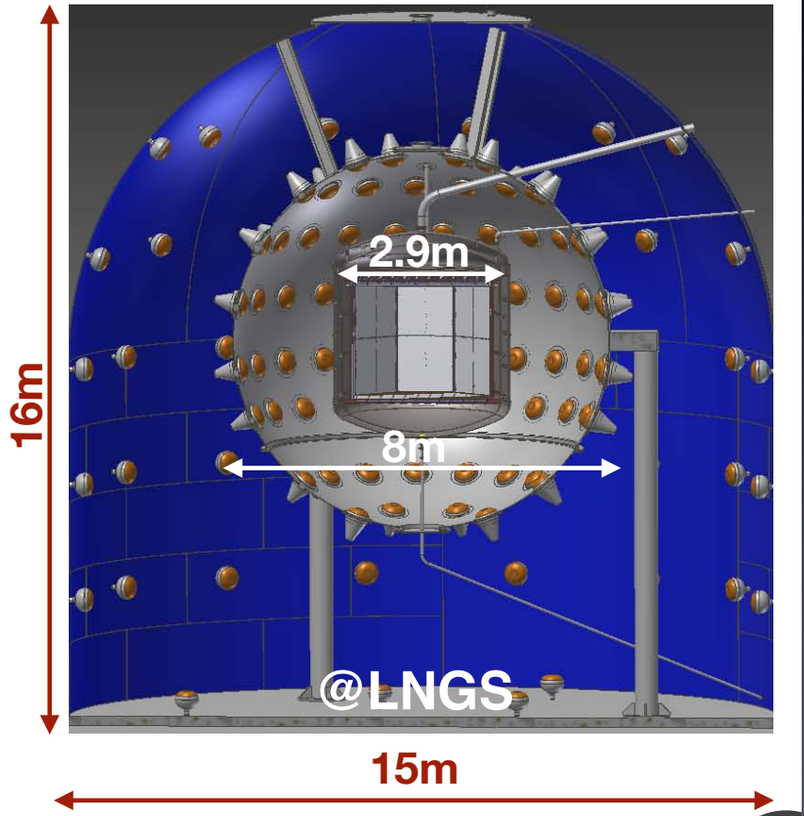
Full size components scaled down (1ton) TPC prototype including is planned for 2017.

Material Screening Strategy is being finalized.



DarkSide-20k challenges and status





20-	15	16	17	18	19	20	21	22	23
DS-20k									

Number of collaborating institutions is growing.

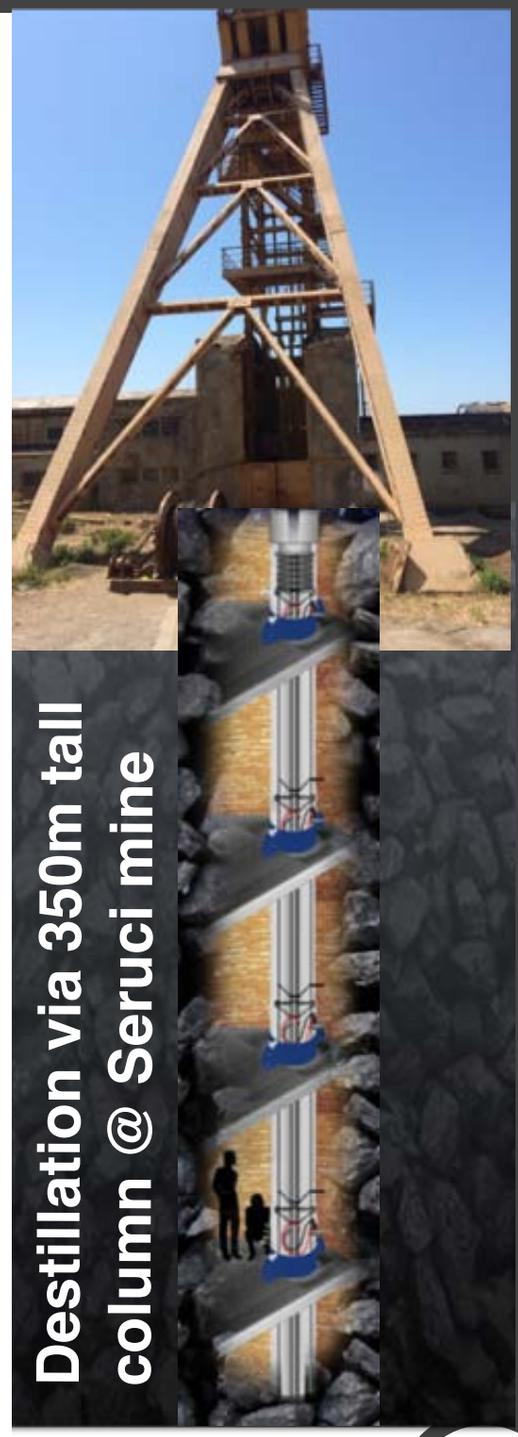
LAr

UAr (地下から採取したアルゴン。<cosmogenic)

URANIA and ARIA

Urania
UAr extraction/ purification@100kg/d
Ar extraction expected to start in 2017.

Aria
Seruci1 - purification of UAr
Seruci2- isotopic separation of Ar-39
Rate @150kg/d
Depletion factor goals:
~10 for Ar-39 and >1000 for N2,02,Kr per pass



Pantic (UC Davis) on DarkSide @ Berkeley Workshop 2016

Urania in cooperation with Kinder Morgan
ARIA in cooperation with Regione Sardegna (production of other isotopes of interest for medical application)

WIMP検出器でなにができるか？

Masaki Yamashita

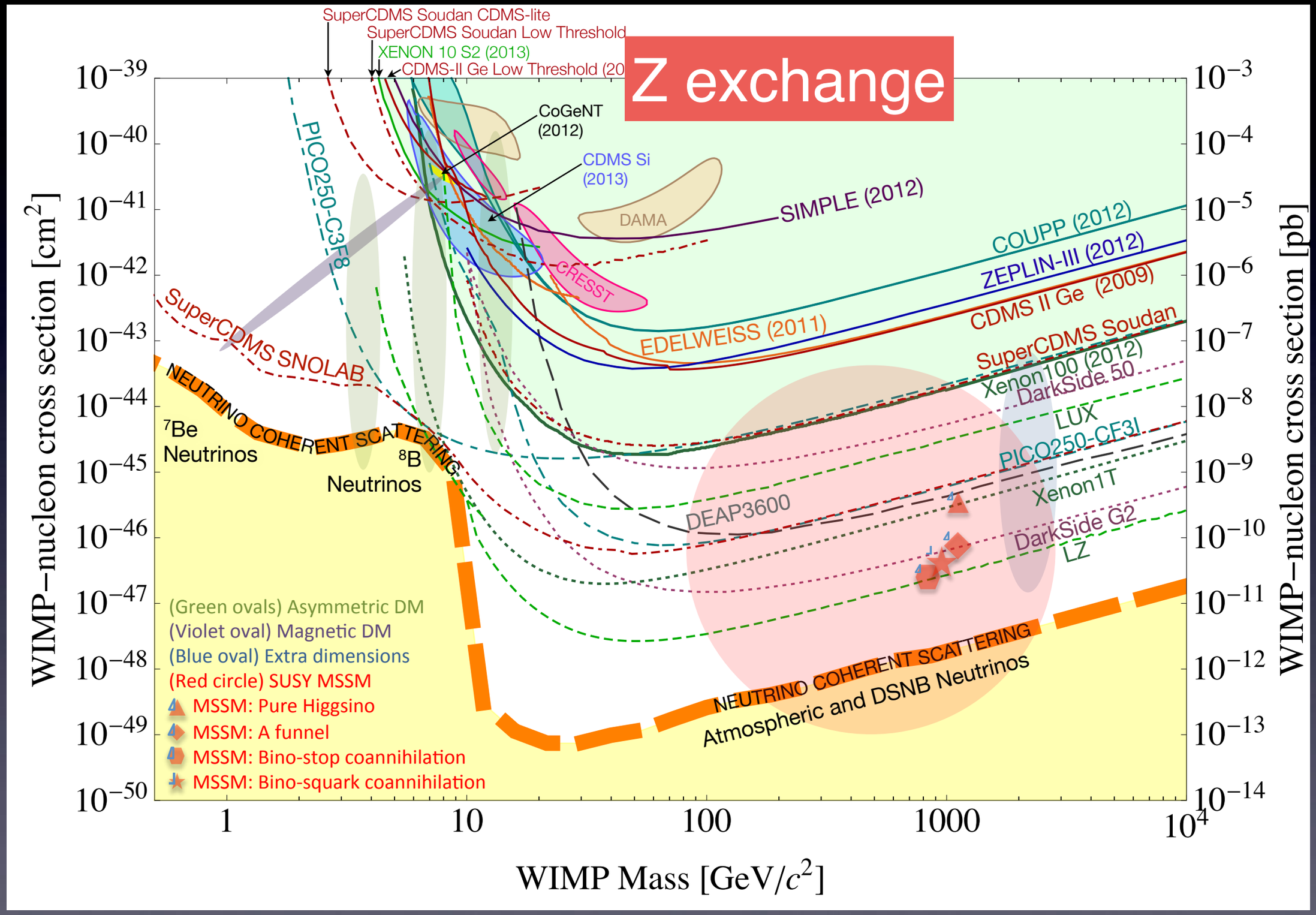
理想的には（ここ掘れワンワン）

素晴らしい実験屋

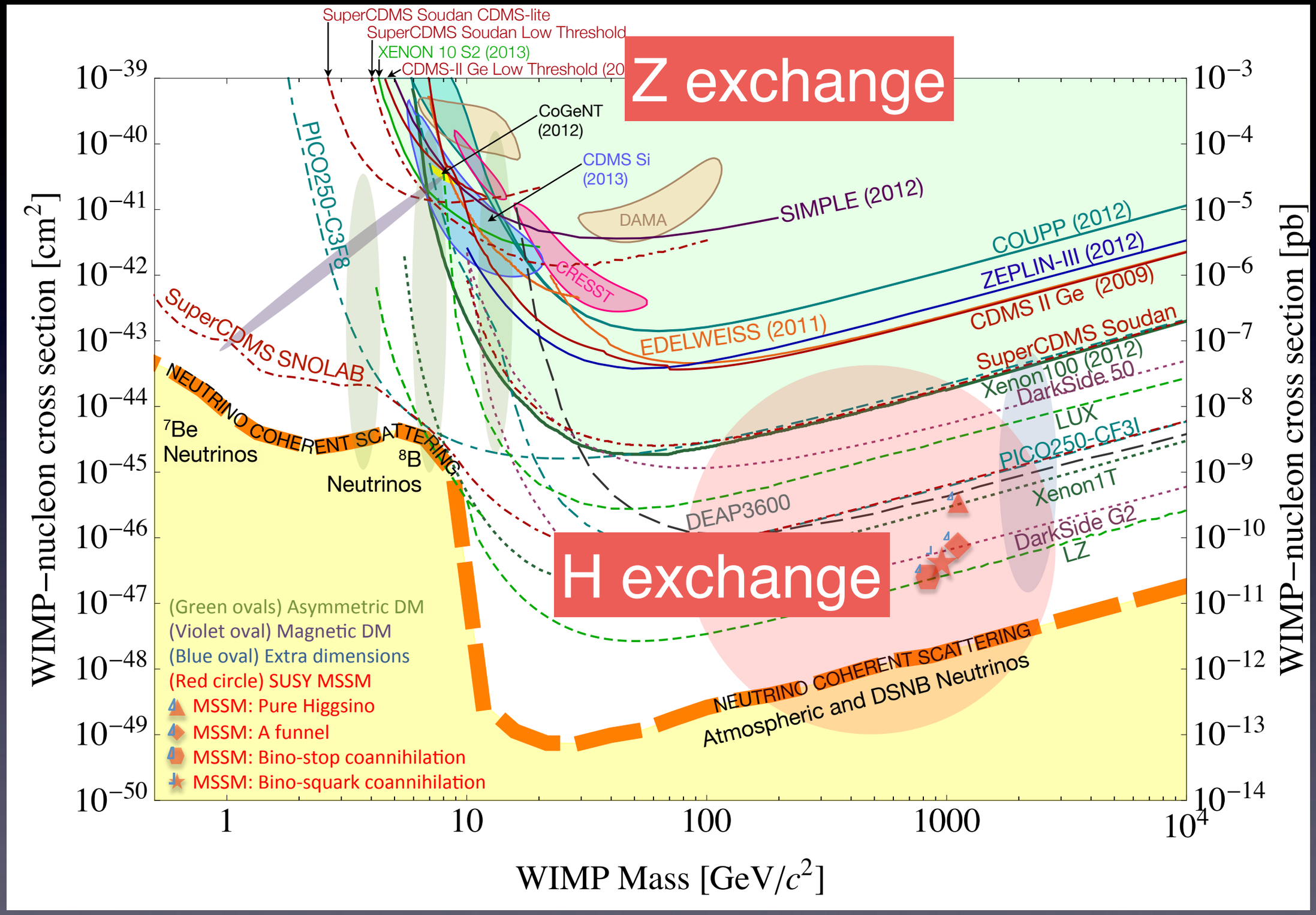
素晴らしい理論屋

Masaki Yamashita

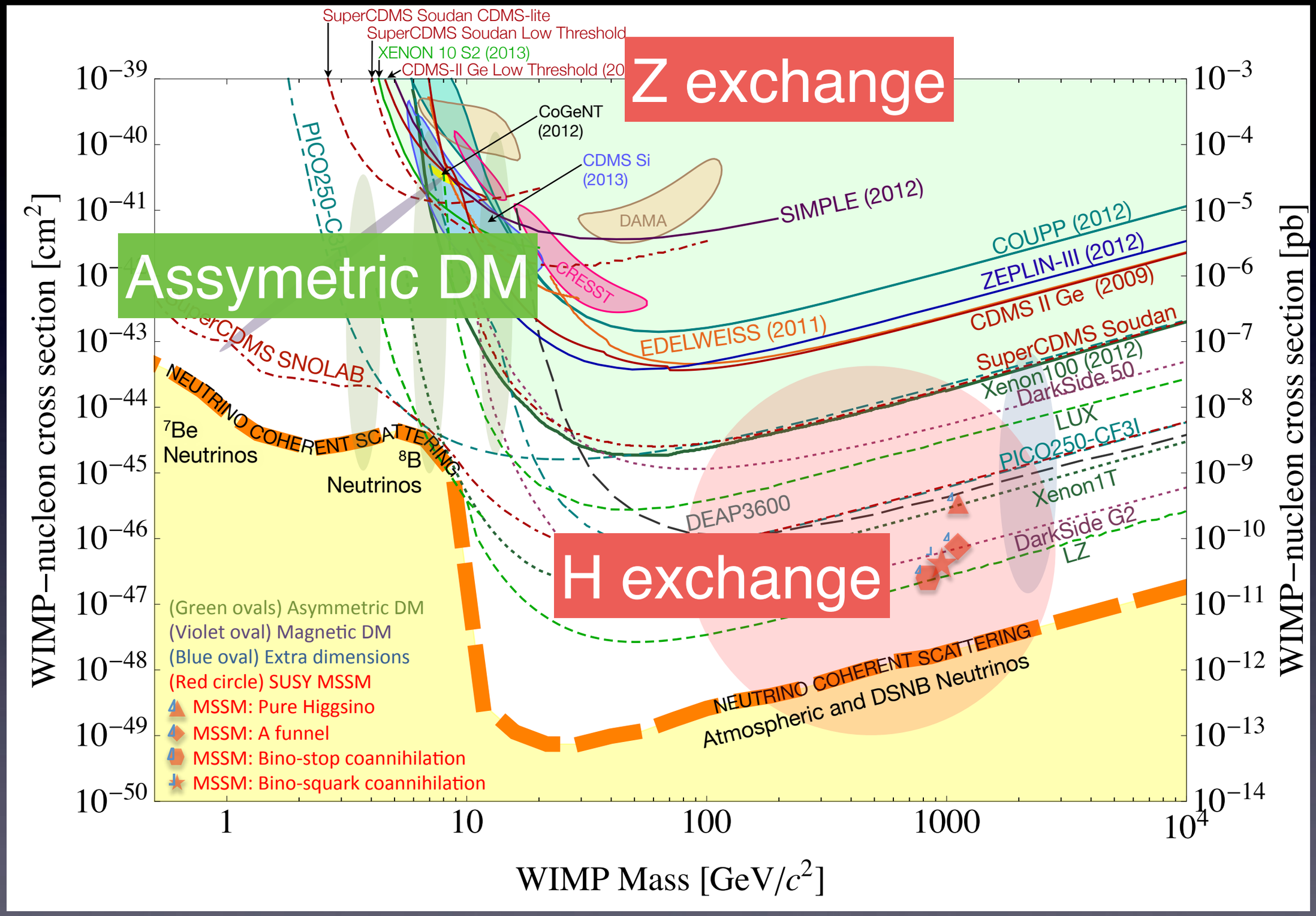
Z exchange



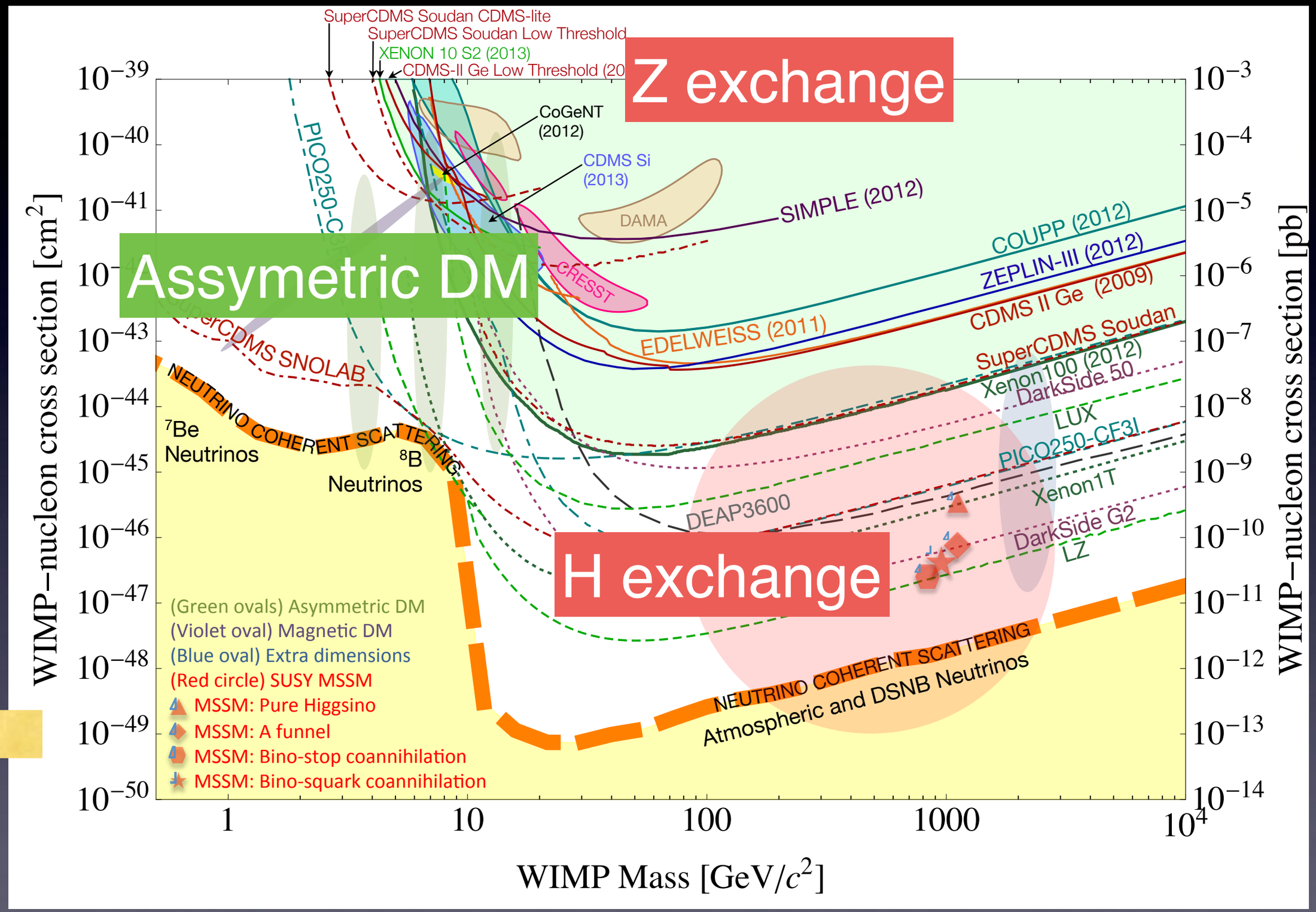
from arXiv:1310.8327v1



from arXiv:1310.8327v1



from arXiv:1310.8327v1

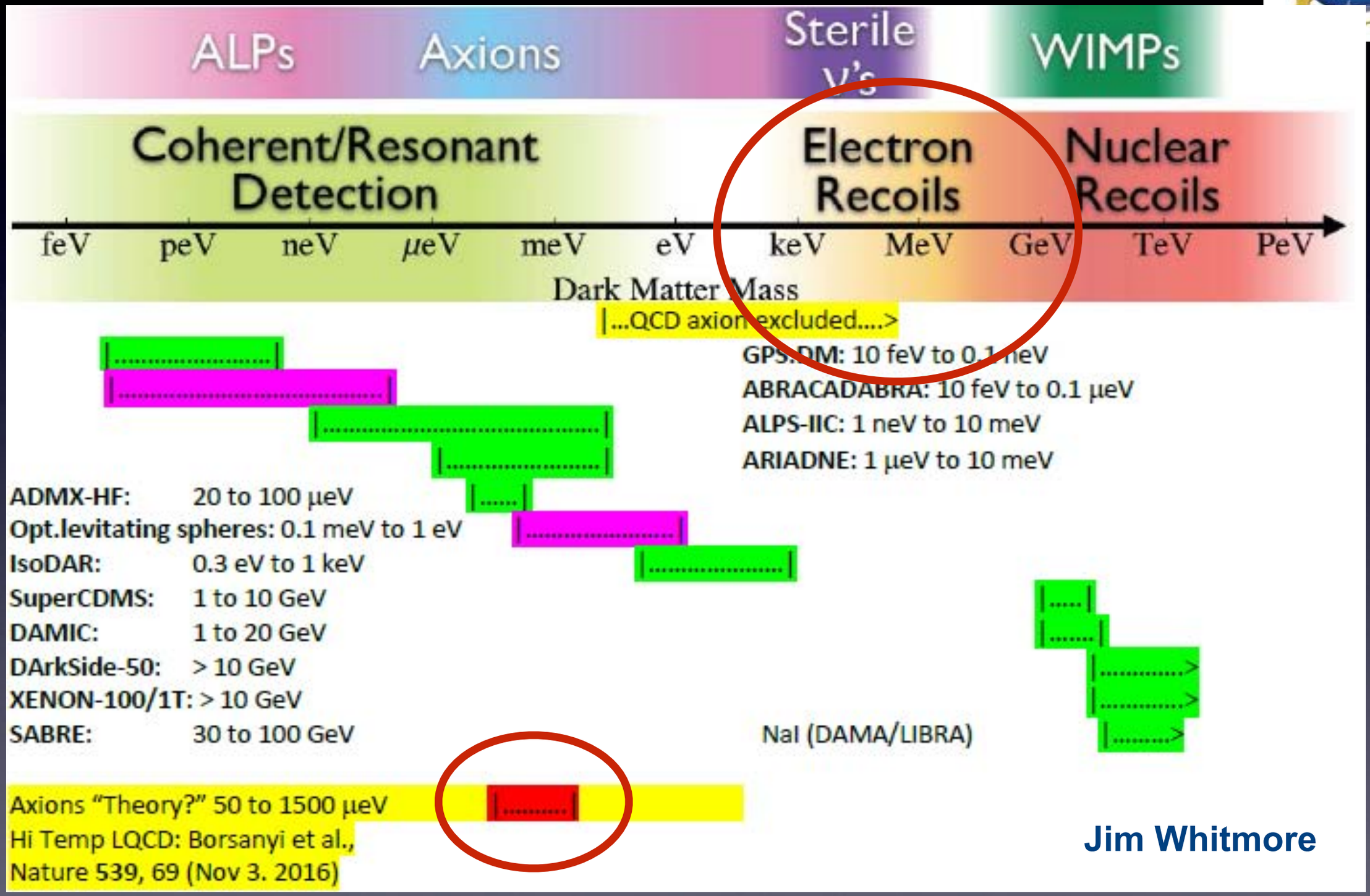


MeV DM (dark sector, hidden photon)

from arXiv:1310.8327v1

質量の小さい方まで探索する努力

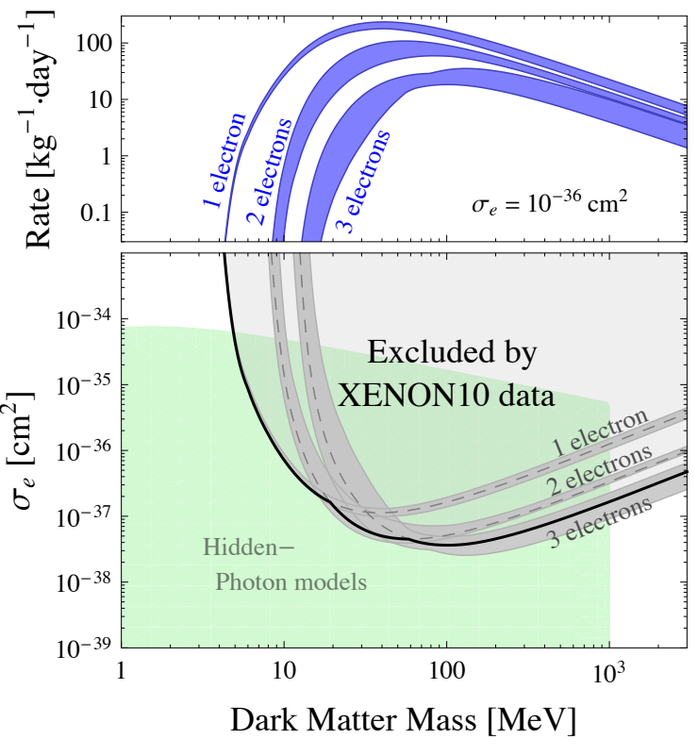
Dark Matter Candidates



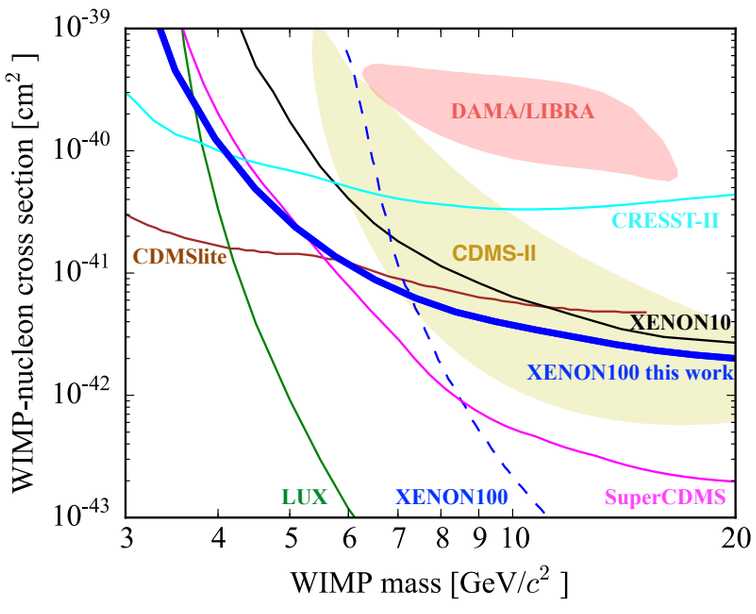
Jim Whitmore

二相型液体キセノンの場合

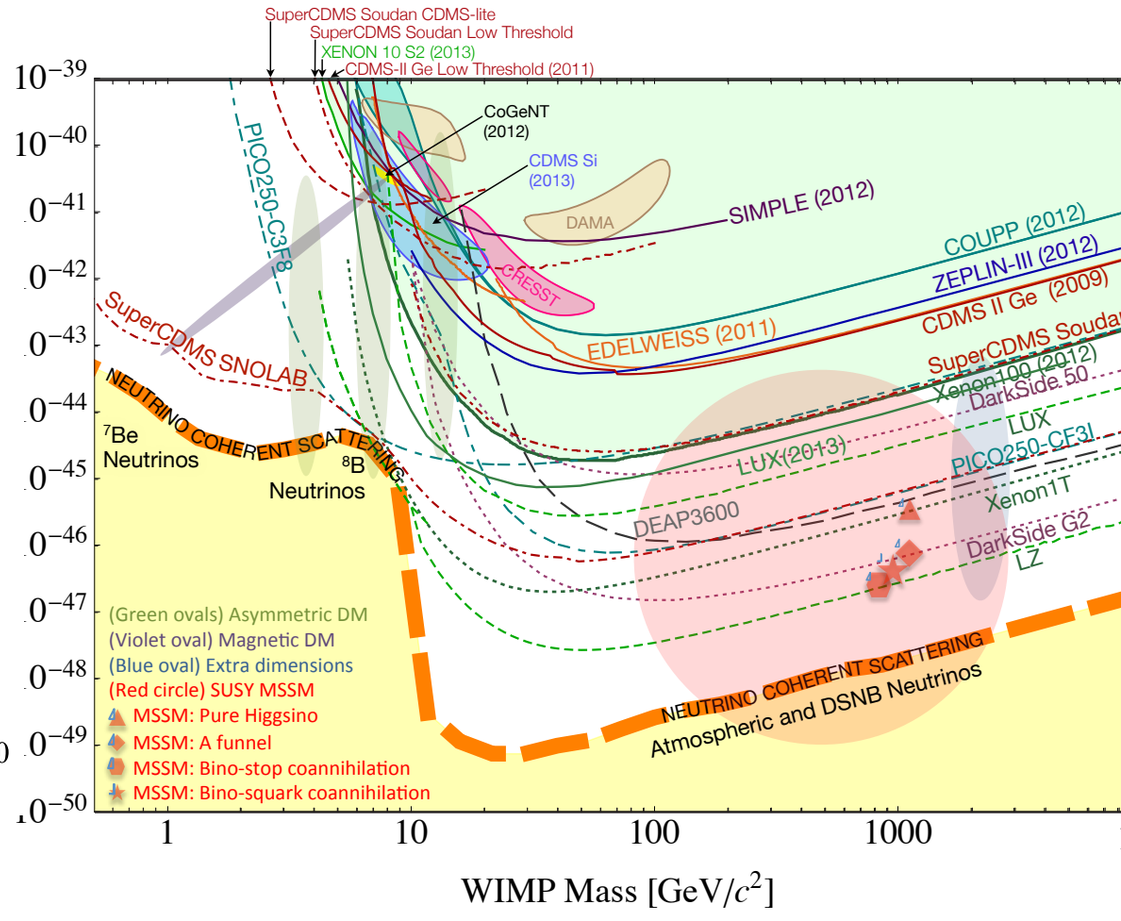
MeV scale DM



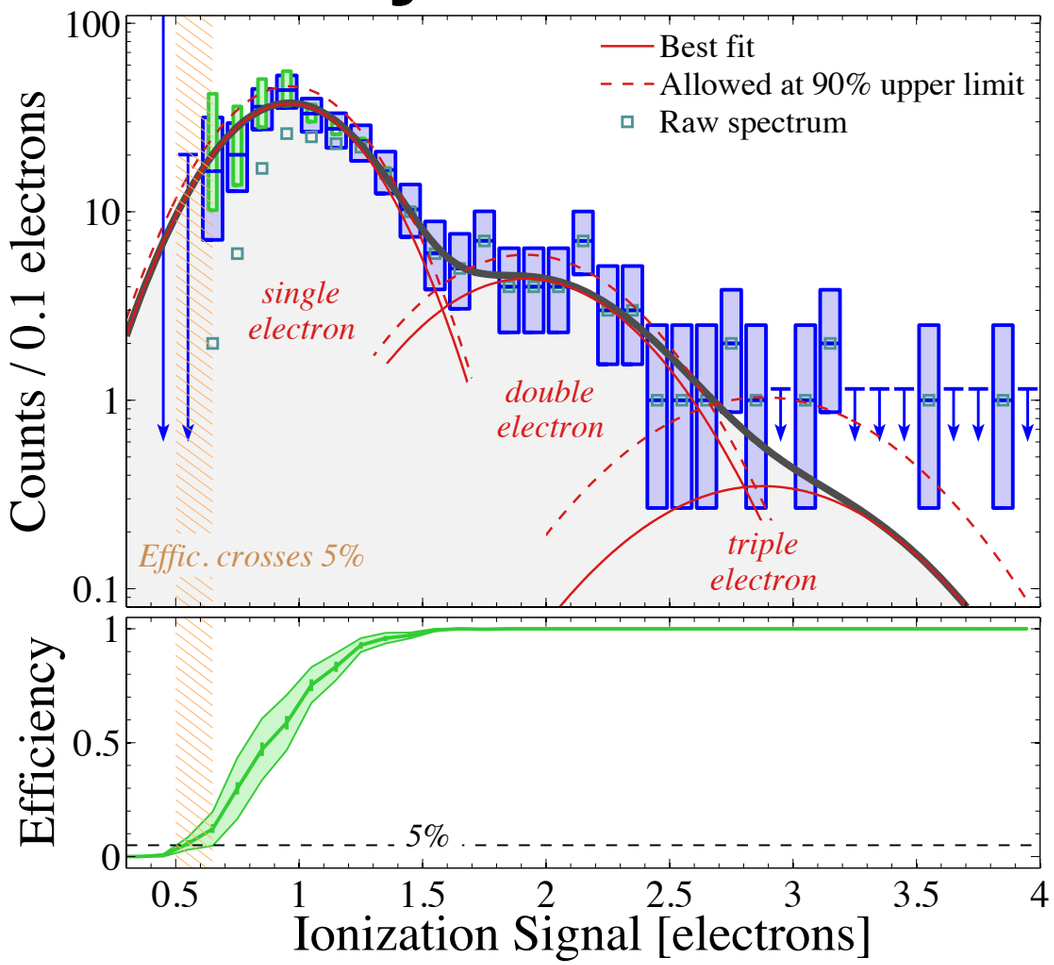
GeV scale DM

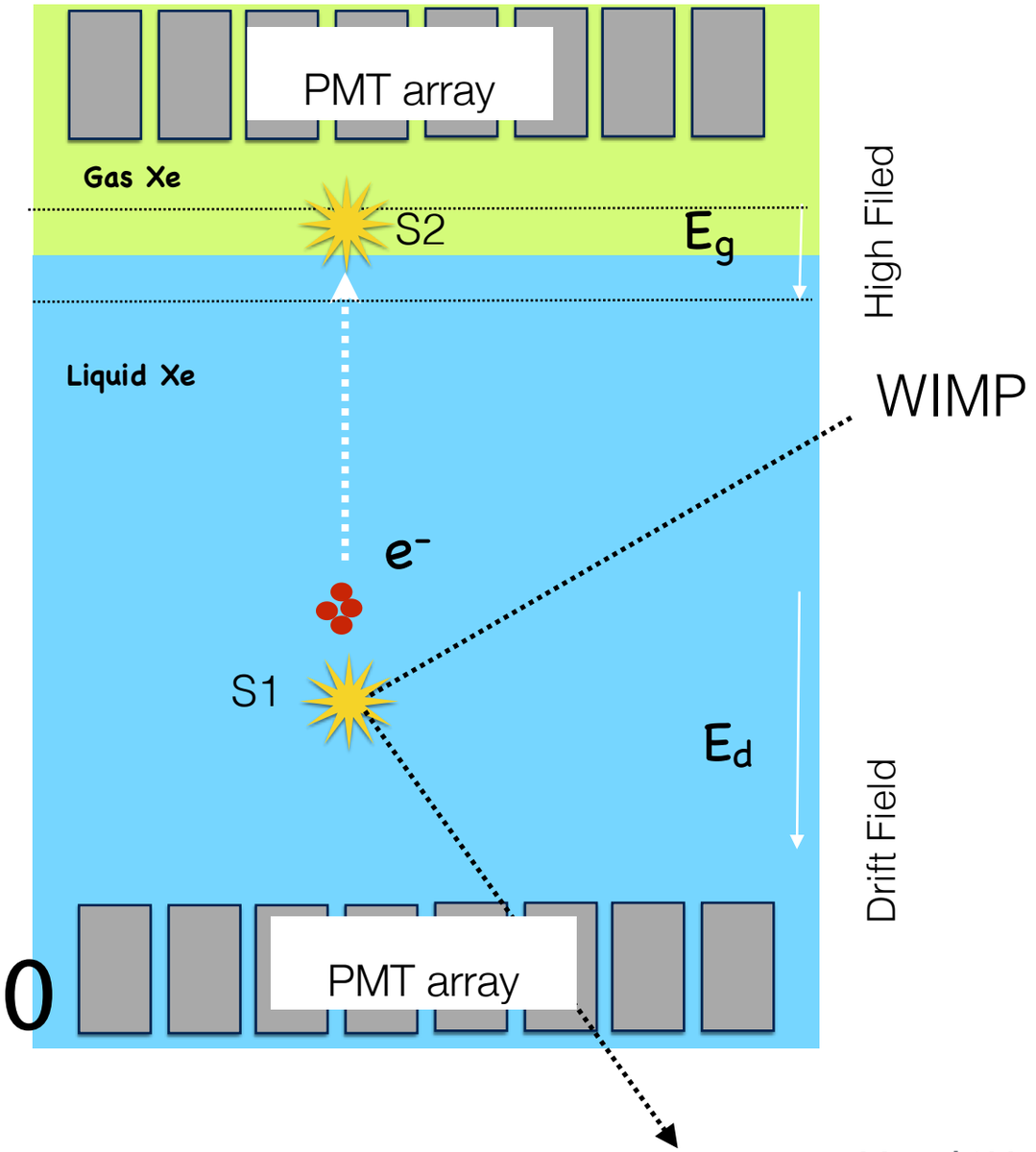


TeV scale DM



S2 only search





single electron in Xenon10

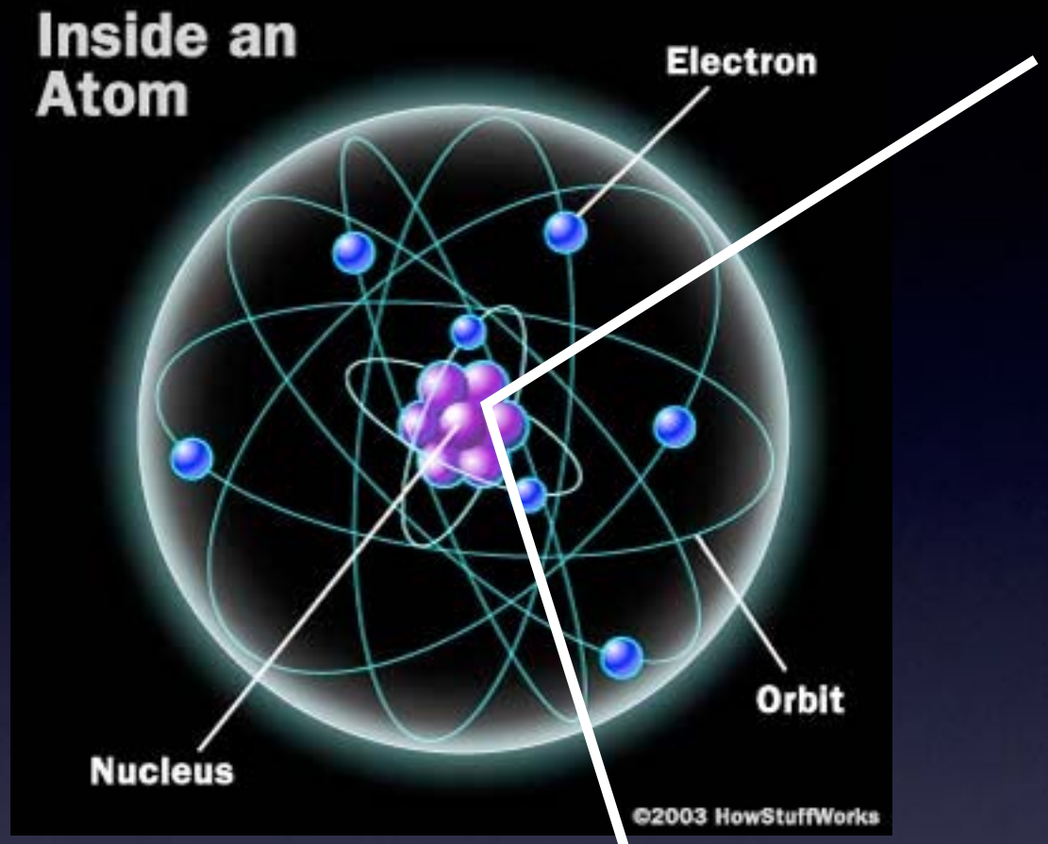
~25 PE!

一個の電離電子も見える。ただし、ER/NR判別は

ー＞annual modulation

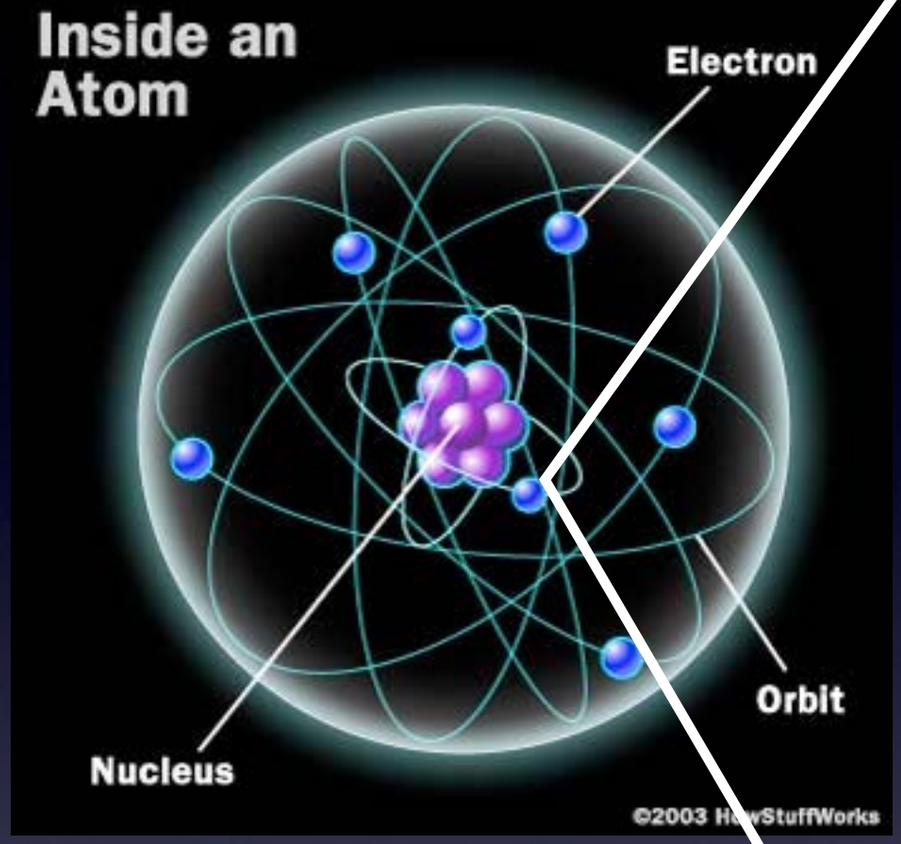
DM-electron channelも

nuclear recoil



fast neutron
WIMP
(SUSY, KK …)

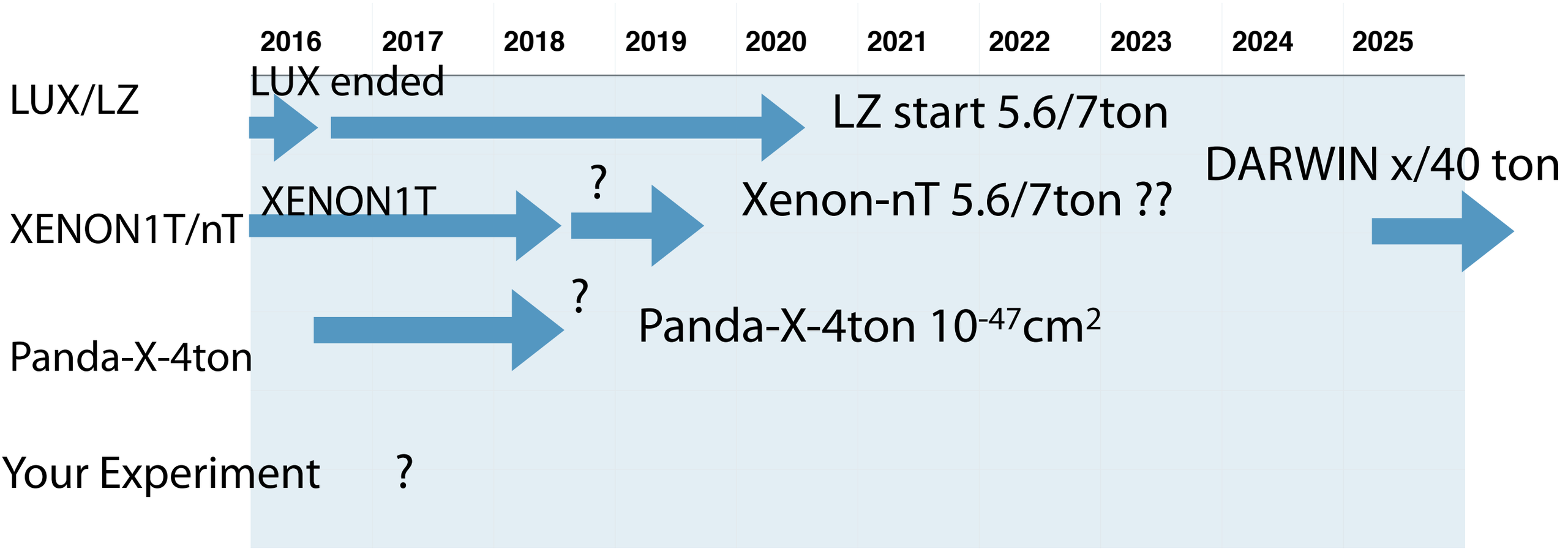
electronic recoil



-U/Th/^{40}K etc background
-WIMP-electron
-inelastic scattering (χ+N-> χ+N*)
-Super WIMP (bosonic)
-Axion/Axion like particle
-Mirror DM
-Luminous DM …

The signal is in electronic recoil ?

まとめ



ここを埋めてもらうのがこの懇談会の目標