Migdal効果による暗黒物質探索

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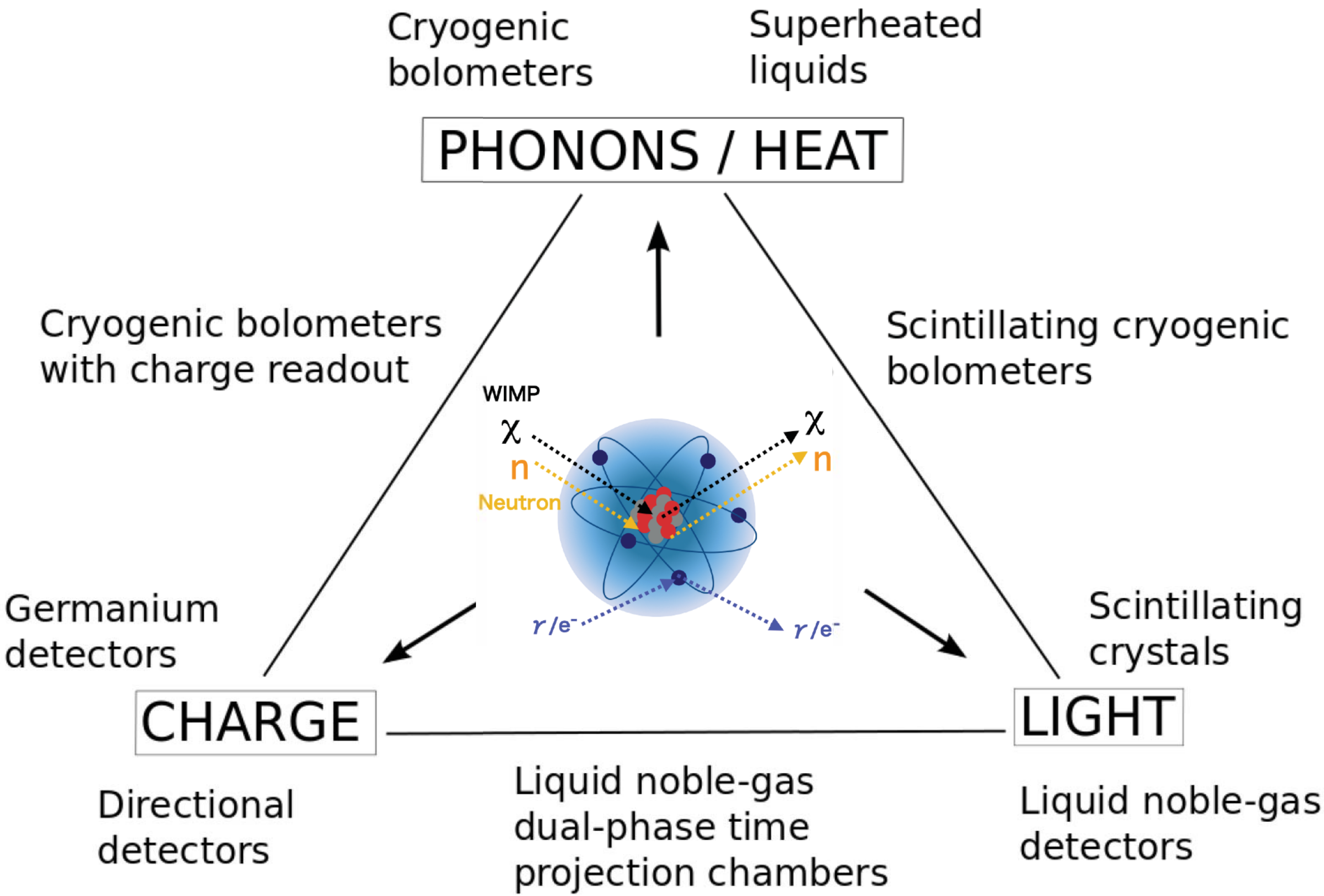
@ミグダル観測検討会2020

暗黒物質直接探索



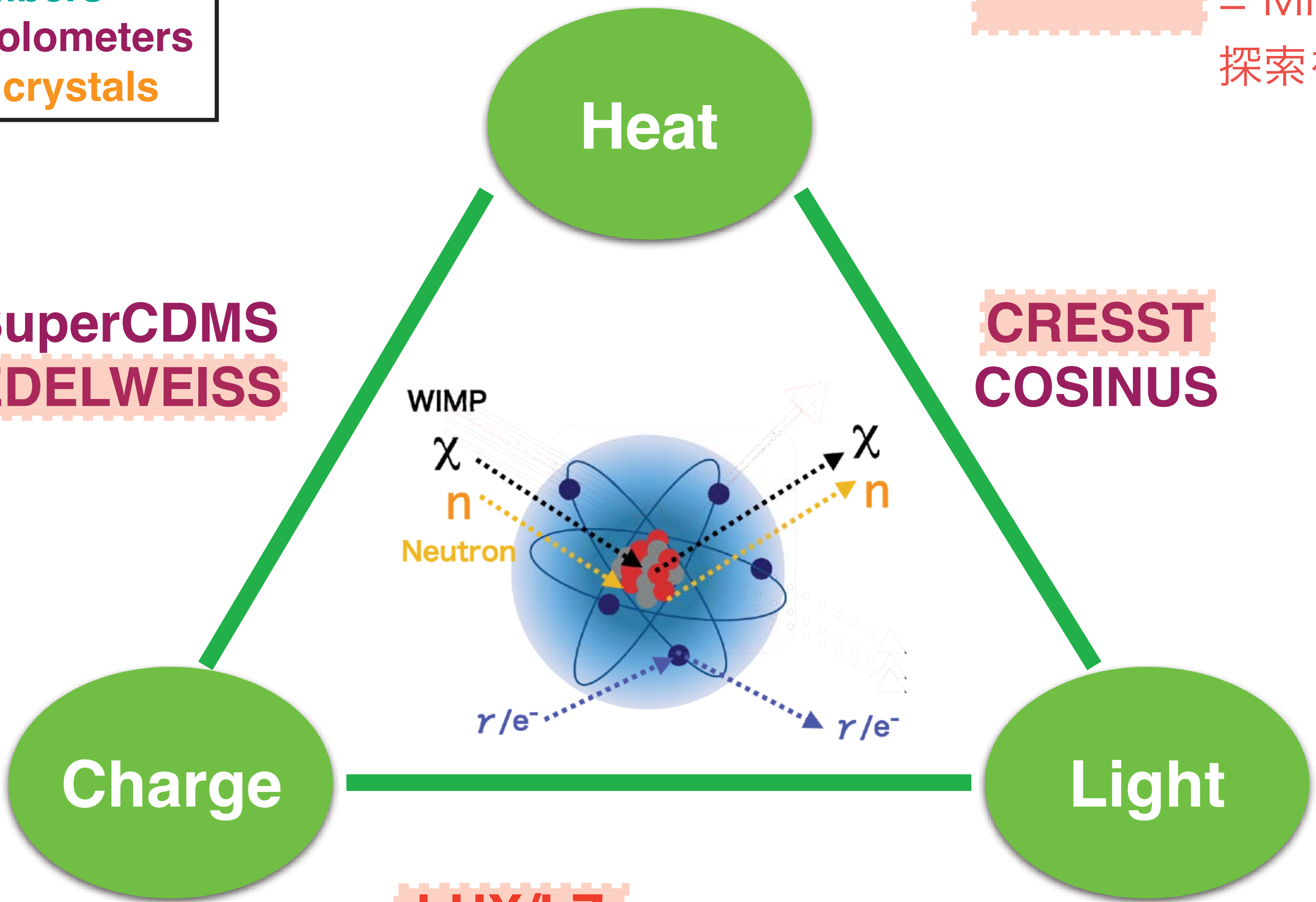
J. Phys. G43 (2016) 1, 013001& arXiv:1509.08767

暗黒物質直接探索

- Liquid argon
- Liquid xenon
- Directional detectors
- Low-threshold
- Bubble chambers
- Cryogenic bolometers
- Scintillating crystals

= Migdal効果を用いた探索を行った実験

SIMPLE
PICASSO
COUPP
PICO



SuperCDMS
EDELWEISS

CRESST
COSINUS

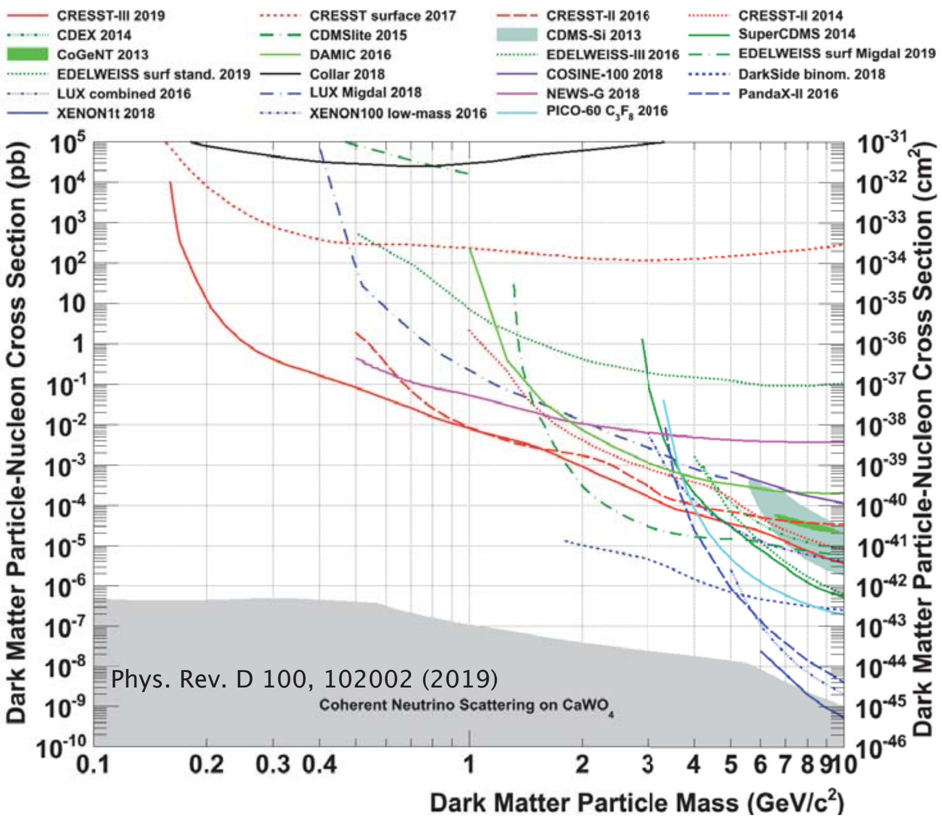
CoGeNT
CDEX
DAMIC
SENSEI
NEWS-G
DRIFT
MIMAC
DMTPC

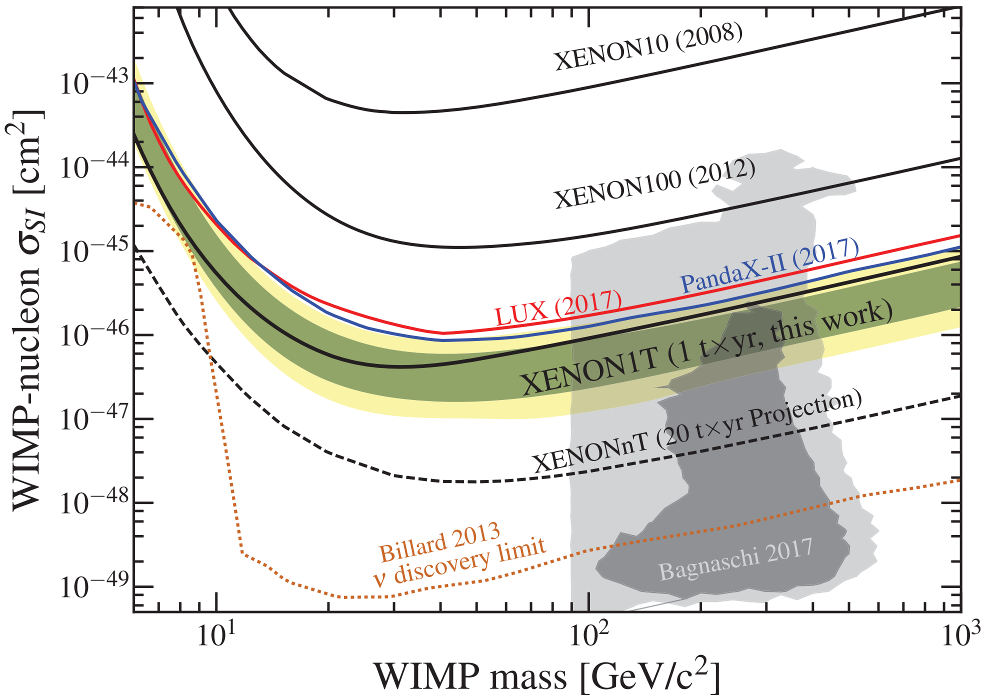
LUX/LZ
PandaX
XENON

ArDM
DarkSide

DAMA
DM-Ice
COSINE
SABRE
ANAIS
PICO-LON
DEAP
XMASS

暗黒物質探索の現状 (without Migdal Effect)





Low-mass (CRESST-III)

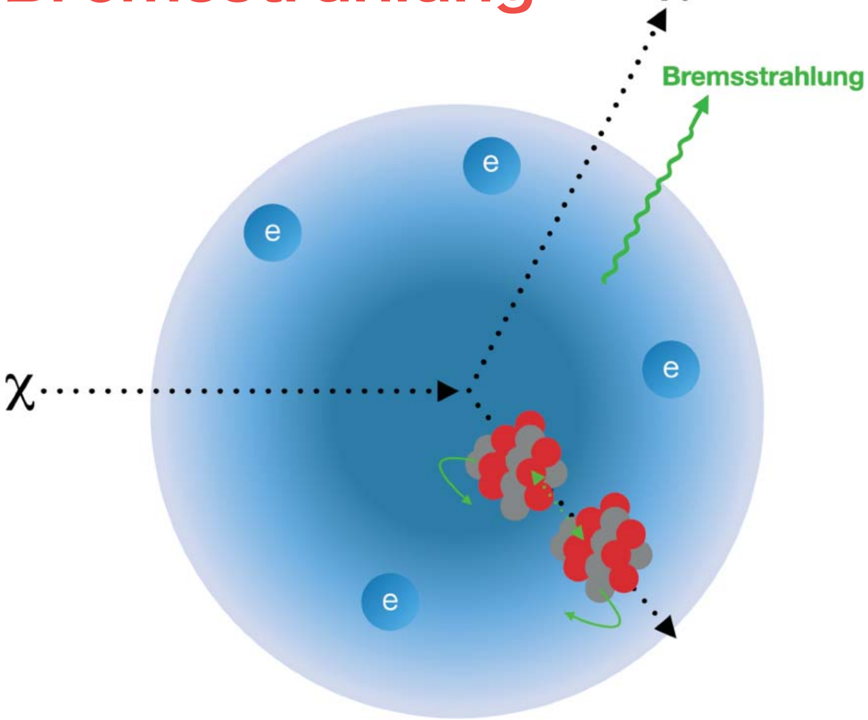
- 23.6 g CaWO4 (~15mK)
- NR threshold of 30.1 eVnr.
- Phonon and Scintillation signal

High-mass (XENON1T)

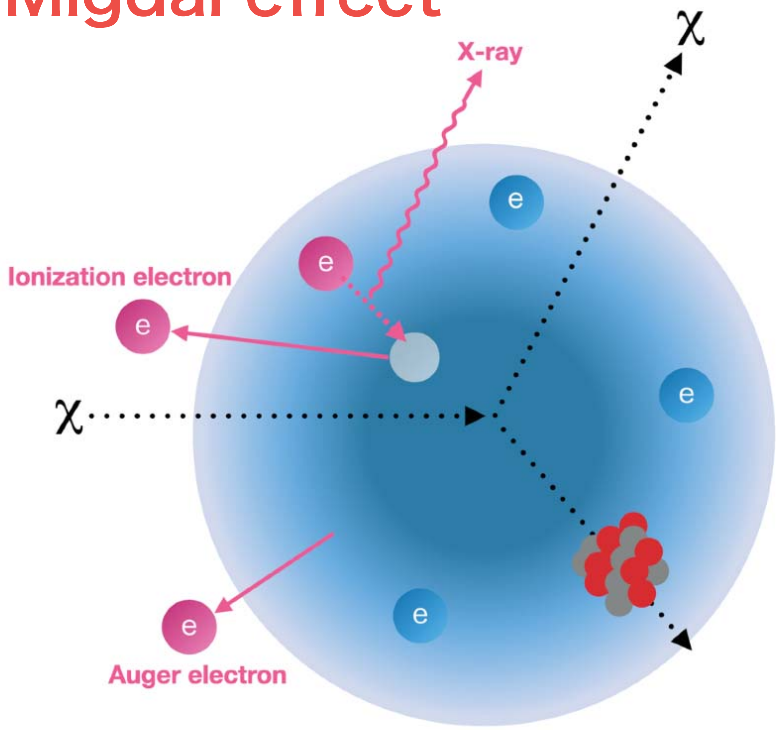
- ~1.3t LXe TPC
- NR threshold of ~4 keVnr
- Scintillation(S1) and Ionization(S2)signal
- ER threshold of
  - S1-S2: ~1 keVee
  - S2-only: 186 eVee

Bremsstrahlung and Migdal effect

Bremsstrahlung



Migdal effect



- When a particle elastically scatters off xenon nucleus, the nucleus undergoes sudden momentum change with respect to the orbital atomic electrons, resulting in the polarization of the recoiling atom and the shaking of atomic electrons
- These phenomena can lead to irreducible emission of Bremsstrahlung photon, as well as excitations and ionizations of atomic electrons (Migdal effect).
- **ER signals through the new detection channels significantly enhance the sensitivity to masses previously insensitive through the standard NR searches.**

Migdal効果を用いた暗黒物質探索

EDELWEISS (Germanium): "Searching for low-mass dark matter particles with a massive Ge bolometer operated above-ground", arXiv:1901.03588

CDEX-1B (Germanium): "Constraints on Spin-Independent Nucleus Scattering with sub-GeV Weakly Interacting Massive Particle Dark Matter from the CDEX-1B Experiment at the China Jin-Ping Laboratory" arXiv:1905.00354

LUX (Xenon): "Results of a Search for Sub-GeV Dark Matter Using 2013 LUX Data", arXiv:1811.1124

XENON1T (Xenon): "A Search for Light Dark Matter Interactions Enhanced by the Migdal effect or Bremsstrahlung in XENON1T", arXiv:1907.12771

SENSEI (Si): "SENSEI: Direct-Detection Results on sub-GeV Dark Matter from a New Skipper-CCD", arXiv:2004.11378

	CDEX-1B	EDELWEISS-SURF	LUX	XENON1T	SENSEI
Detector	Ge (charge-only) No ER/NR discri.	Ge (heat-only) (above ground)	LXe TPC (S1-S2)	LXe TPC (S1-S2, S2-only)	CCD (Si) (charge-only, 135 K)
Size	939 g	33.4 g	118 kg	~1.3 ton	~2g
Exposure	737.1 kg day	0.03 kg day (1-day blind, 5-days unblind)	13,775 kg day	S1-S2: 1 ton year S2-only: 22 ton day	~20 g day
Threshold	160 eVee	60 eVee	~1 keVee	S1-S2: ~1 keVee S2-only: 186 eVee	O(1) eVee (詳細不明) (1,2,3,4 e-)

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Analysis	n=2,3 only n=1: negligible (too tightly bound)	n=3 only n=1,2: negligible (too tightly bound)	n=3,4 only n=1,2: negligible (too tightly bound)	n=3,4 only n=1,2: negligible (too tightly bound)	詳細不明

n=4: neglected since they are easily affected by Ge band structure due to the small binding energy

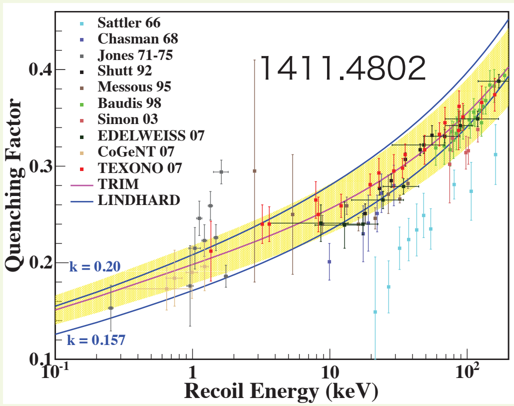
n=5: neglected since the surrounding atoms in the liquid may influence the ionization spectrum

伊部さんたちの計算はIsolated atom assumptionのもと計算されている点に注意

半導体中での計算は先週末に出た(2011.09496を参照)

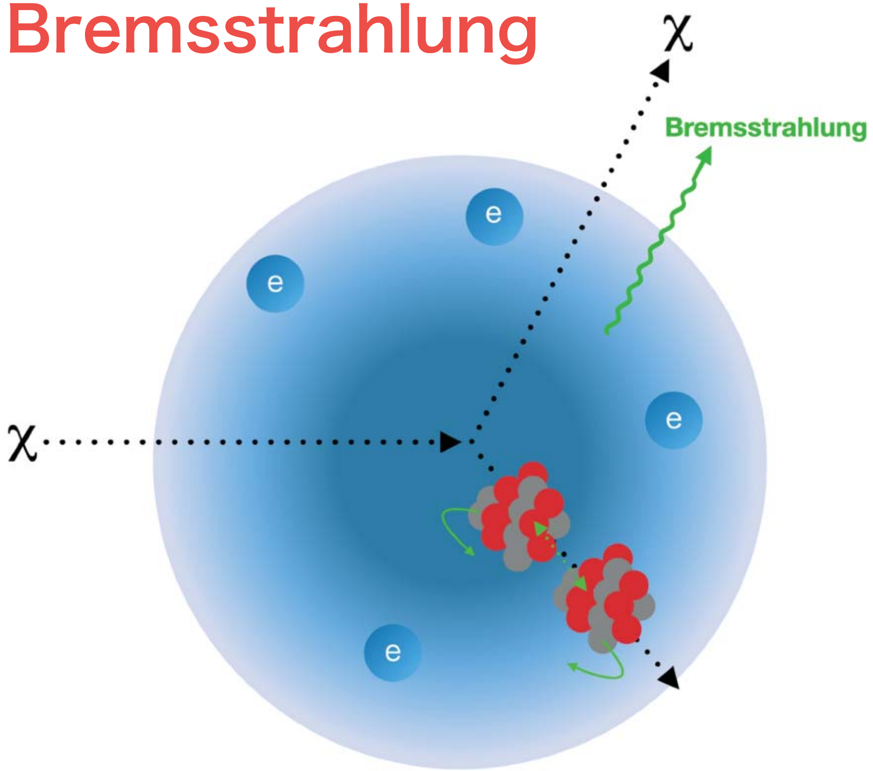
Because of the smaller gap for electron excitations, we find that the rate for the Migdal effect is much higher in semiconductors than in atomic targets.

Migdal効果を用いた暗黒物質探索

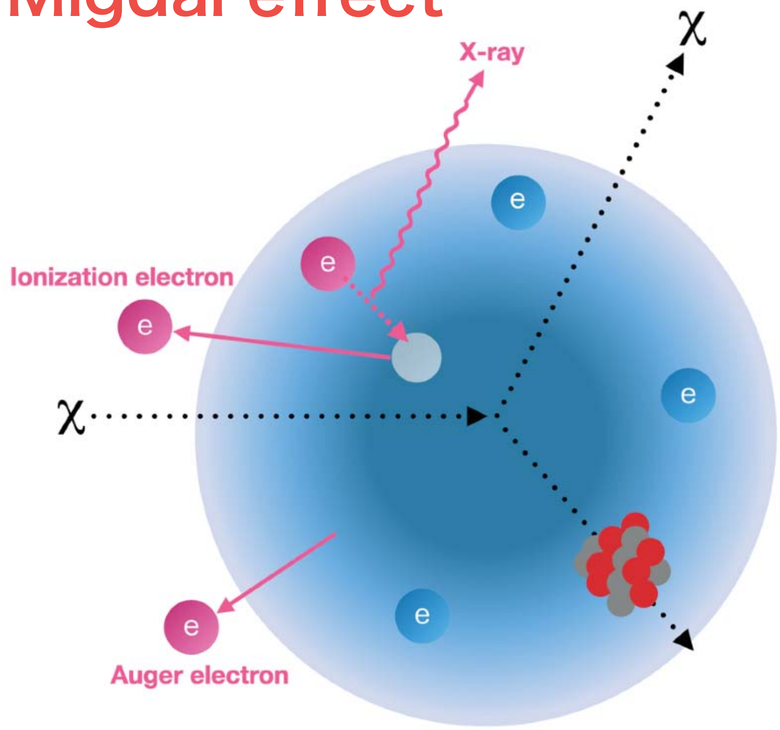
	CDEX-1B	EDELWEISS-SURF	LUX	XENON1T	SENSEI
Shell	n=2,3 only	n=3 only	n=3,4 only	n=3,4 only	詳細不明
シグナルの取り扱い	$E_{\rm det} = E_{\rm EM} + Q_{nr} E_R$ $E_{\rm EM} = E_e + E_{nl} = \Delta E$	$E_{\rm det} = E_{\rm EM} + E_R$	$E_{\rm det} = E_{\rm EM}$	$E_{\rm det} = E_{\rm EM}$	
	全てのエネルギー(Edet)がある1点で損失したと仮定				
	 	Quenching effects on the heat energy scale for nuclear recoils in Ge cryogenic detectors have been shown to be very small	5GeV以下のmassでは、NRのエネルギー損失は少ないと仮定して無視	2GeV以下のmassでは、NRのエネルギー損失は少ないと仮定して無視 (詳細は後述)	詳細不明

不明な(怪しい)点？

Bremsstrahlung



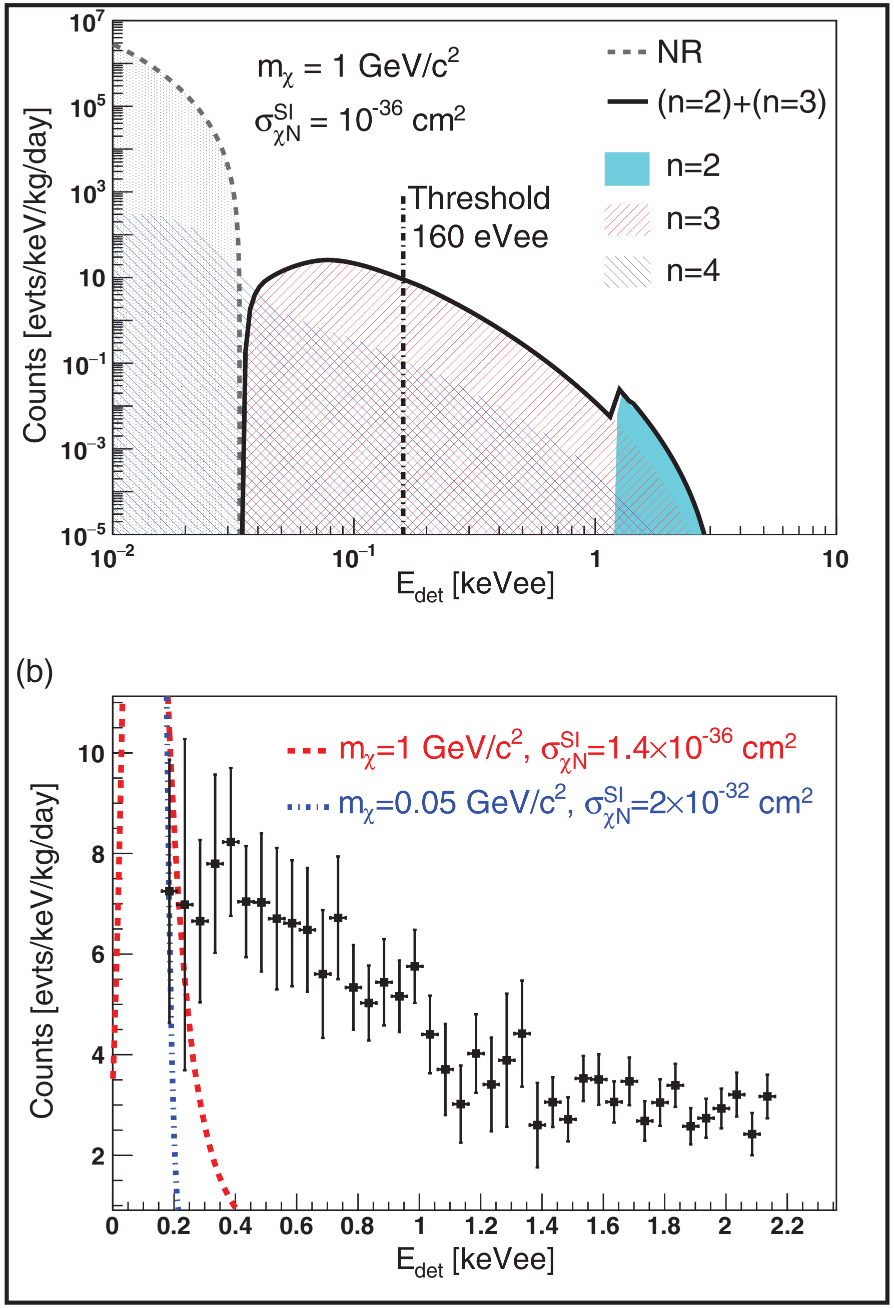
Migdal effect



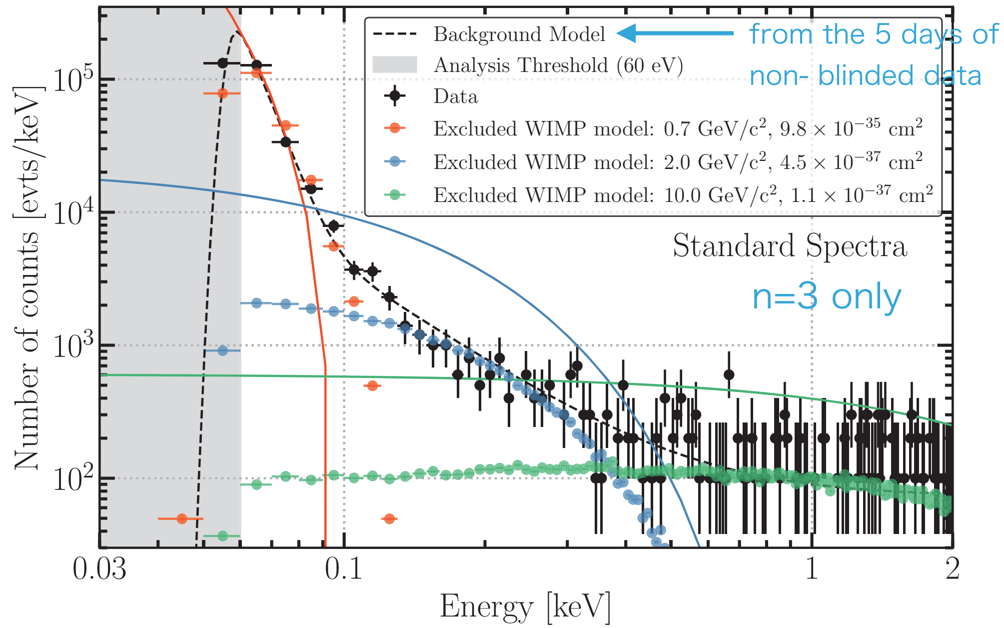
- Migdal効果に関わるIonization electron, x-ray/Auger electron + NRの全てのエネルギー損失がほぼ一点で起こる。LXe TPCの場合、同時にER+NRが起こる場合の再結合モデル等はよく分かってない(ER, NRを独立だと思った時のレスポンスと同じではない？)
    - LUX/XENON1Tでは、NRの寄与が無視できる範囲のみ探索を行っているのでOK
- Migdal効果が起きた場合、例えばXe+の様に原子核はプラスの電荷を帯びている。この場合、検出器レスポンスは中性の時と異なる？

Migdal効果を用いた暗黒物質探索

CDEX



EDELWEISS



- どちらもn=4の寄与は解析では取り入れてない

- どちらもwell establishedなBGモデルはないので、discovery potentialはない
  (実験データを全てシグナルだと思ってコンサバにlimitをつけるだけ)
  —> XENON1Tで言うところのS2-only解析

- EDELWEISSは、6日分のデータのうち5日分をunblindし、カットなどを最適化し、残り1日分のデータを用いてlimitを計算

- XENON1Tの結果は後ほど

Migdal効果を用いた暗黒物質探索
@XENON1T

XENON1T検出器@LNGS

EPJ-C 77 (2017) 12

Water tank

- 700 t of pure water

Cherenkov Muon Veto

- 84 8-inch PMTs (R5912)

External calibration

- ^{241}AmBe (NR)
- Neutron generator (NR)

Cryostat and support structure for TPC

TPC

- 248 3-inch PMTs (R11410-21, QE~34%@178nm)
- LXe mass: 3.2 t(total), 2.0t (active)

Cryogenics, and purification

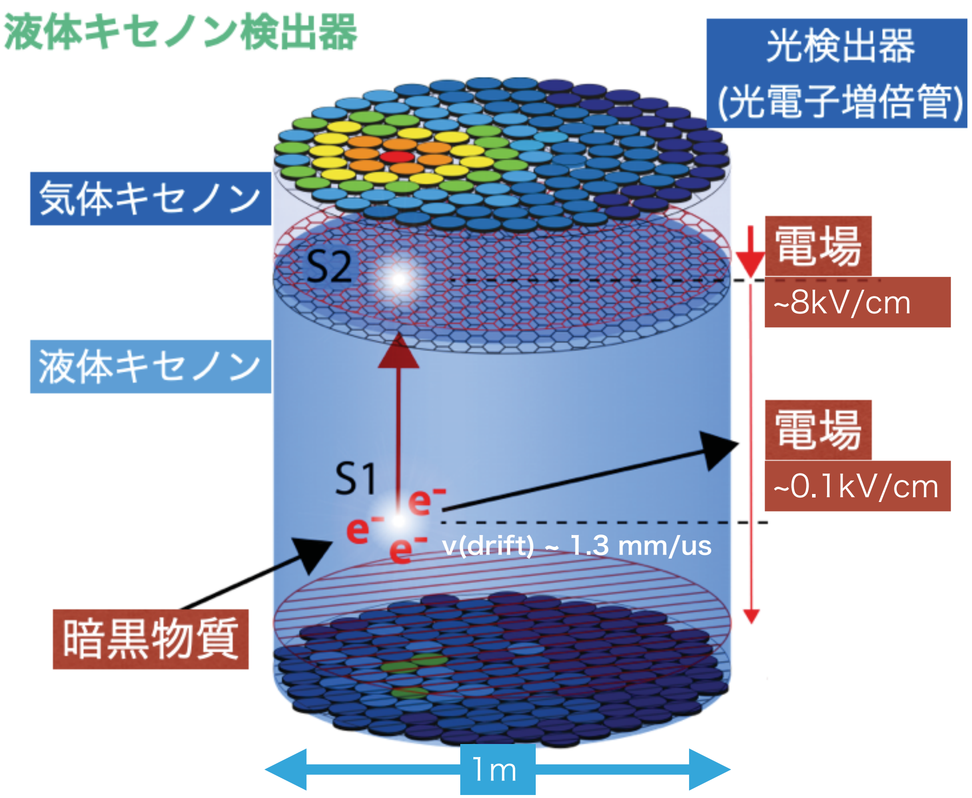
Internal calibration

- ^{83m}Kr (ER),
- ^{220}Rn (ER)

DAQ and slow control

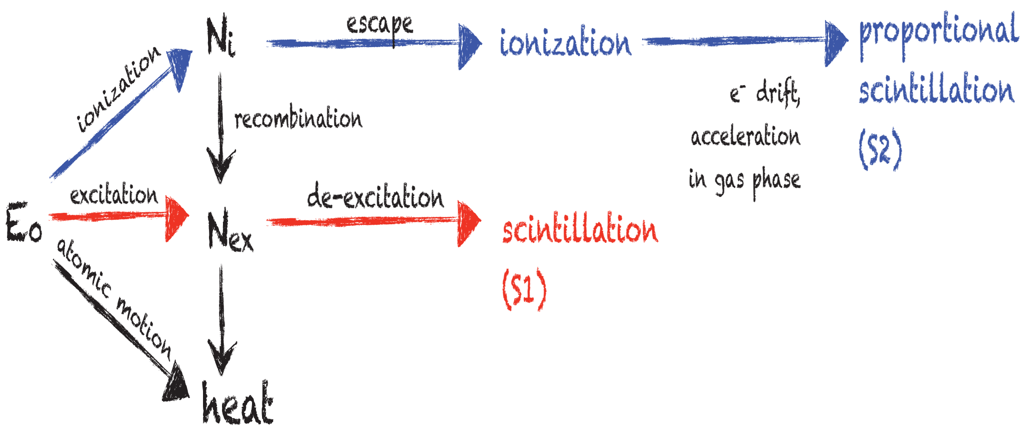
Xenon storage (ReStoX), handling and Kr distillation

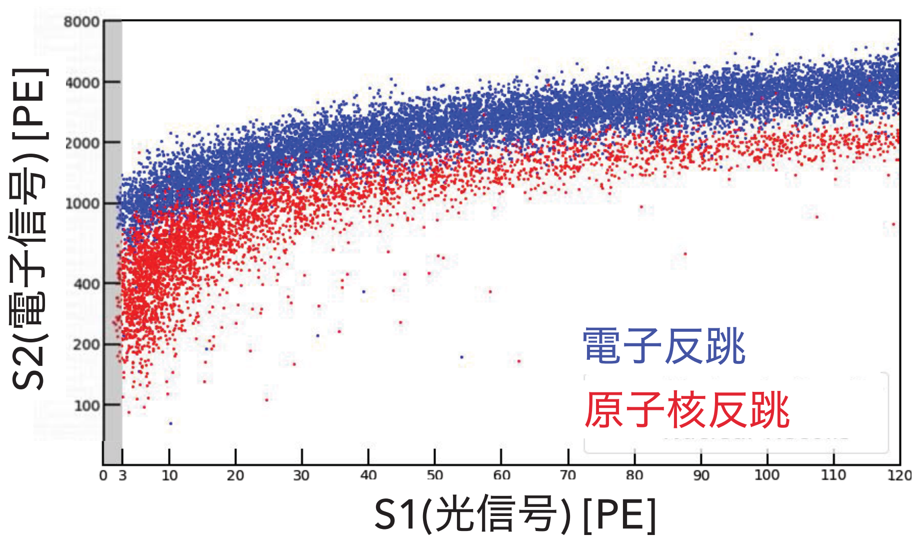
LXe TPCの動作原理



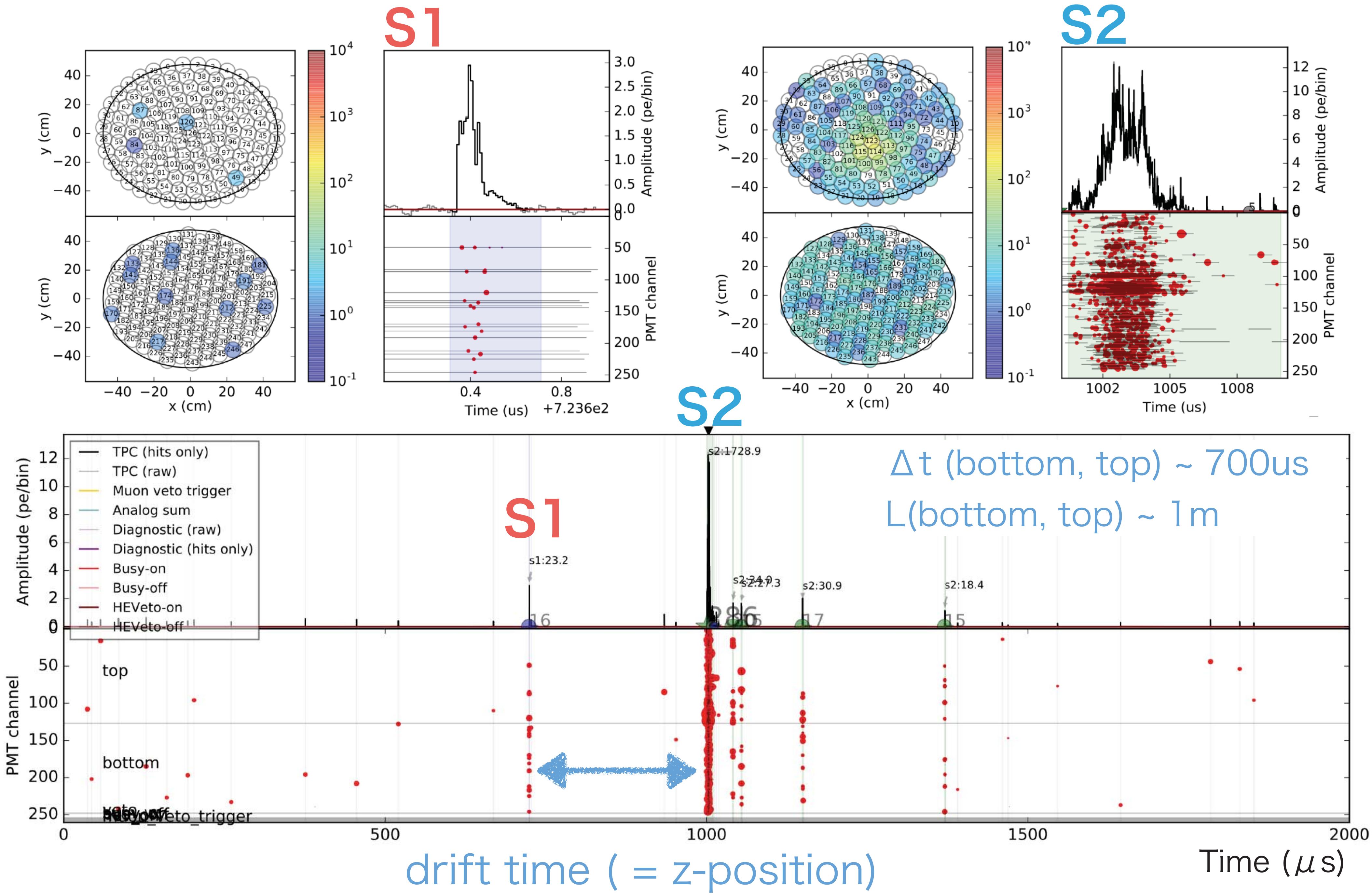
- 直接蛍光 (S1)が、反応点で生成され、上下のPMTで検出
- 電離電子は、電場によりGXeへ向かってドリフト
- 電子は一部がXe+イオンと再結合してS1を発生
- GXeまで辿り着いた電子は、より強い電場によりGXeへ引き抜かれて、比例蛍光(S2)を生成
- 反応点の3次元位置再構成が可能
  - X/Y位置: top PMT arrayでのS2のヒットパターン
  - Z位置: 電子のドリフト時間 = Δt (s1, s2)
- 粒子識別: (S2/S1)$_{\gamma,e}$ > (S2/S1)$_{\text{WIMP, neutron}}$

電子反跳(今回の解析)　原子核反跳

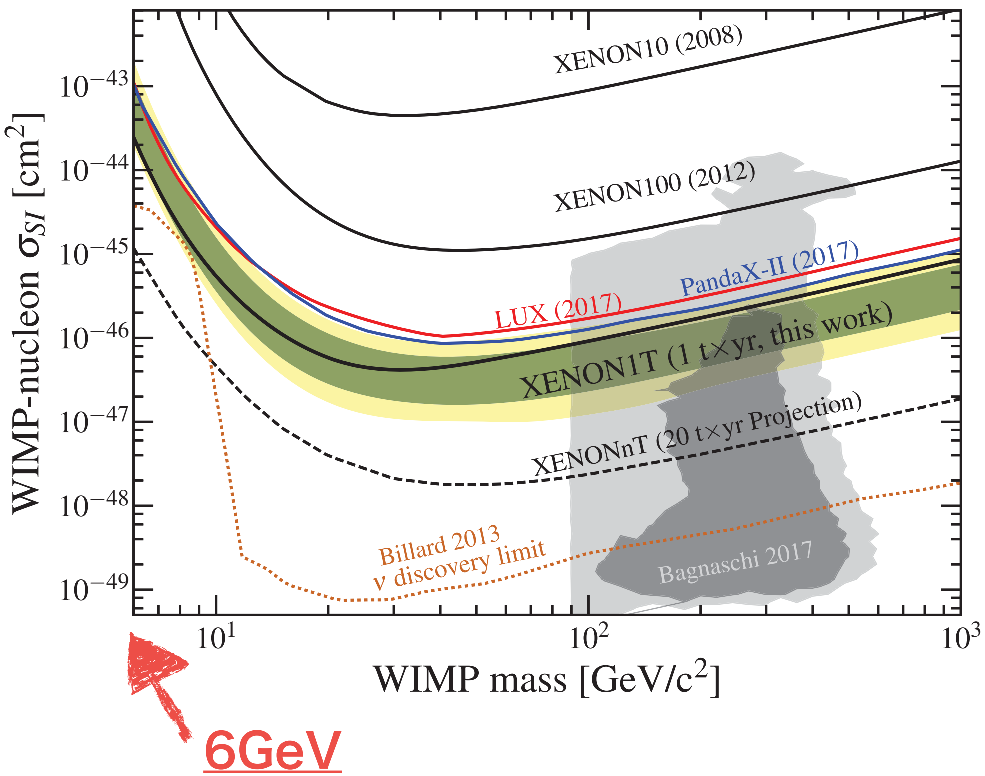


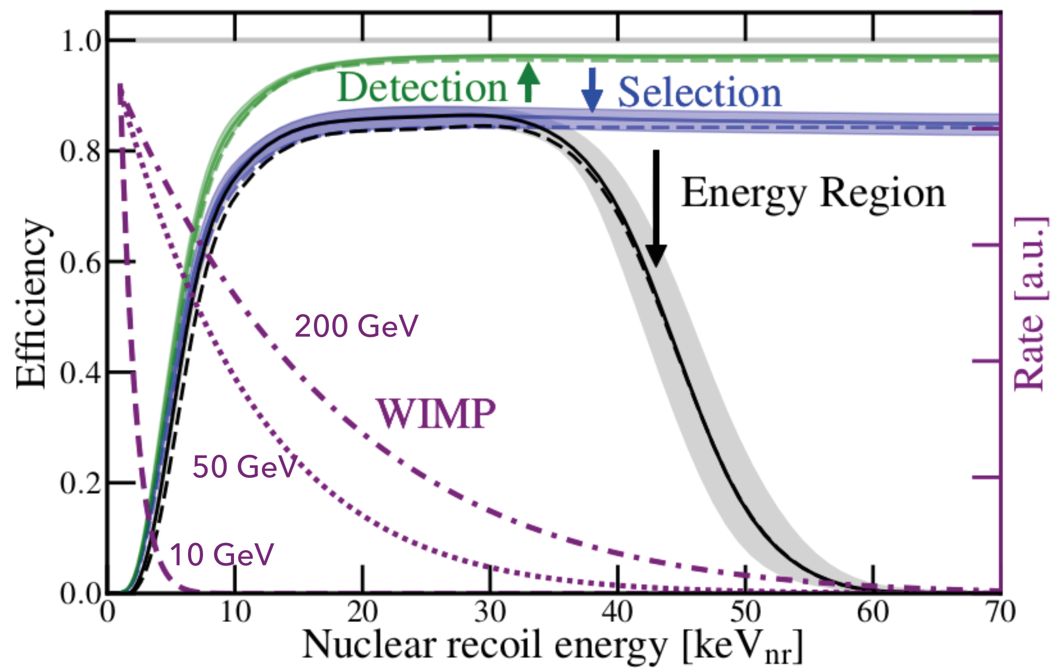


LXe TPC: Waveform & Hit-Pattern



XENON1T実験のWIMP探索結果 (without Migdal Effect)



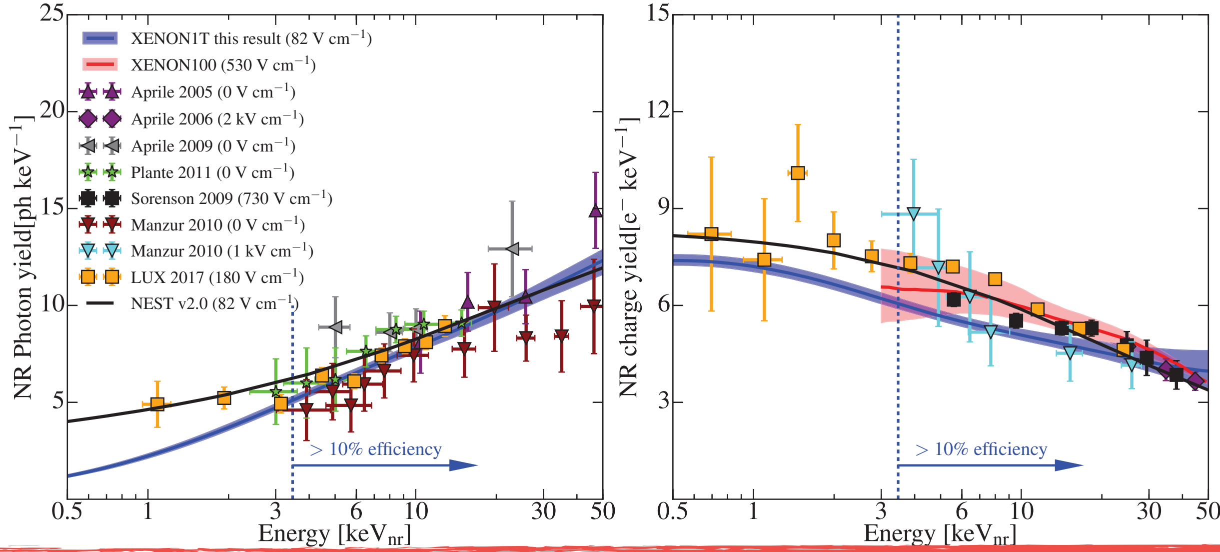


- XENON1T set the most stringent upper limit on SI WIMP-nucleon cross sections <u>> 6 GeV</u>
- However, the sensitivity to low-mass WIMP is quite limited because of 3-fold PMT requirement for S1 (threshold~ 4 keVnr)

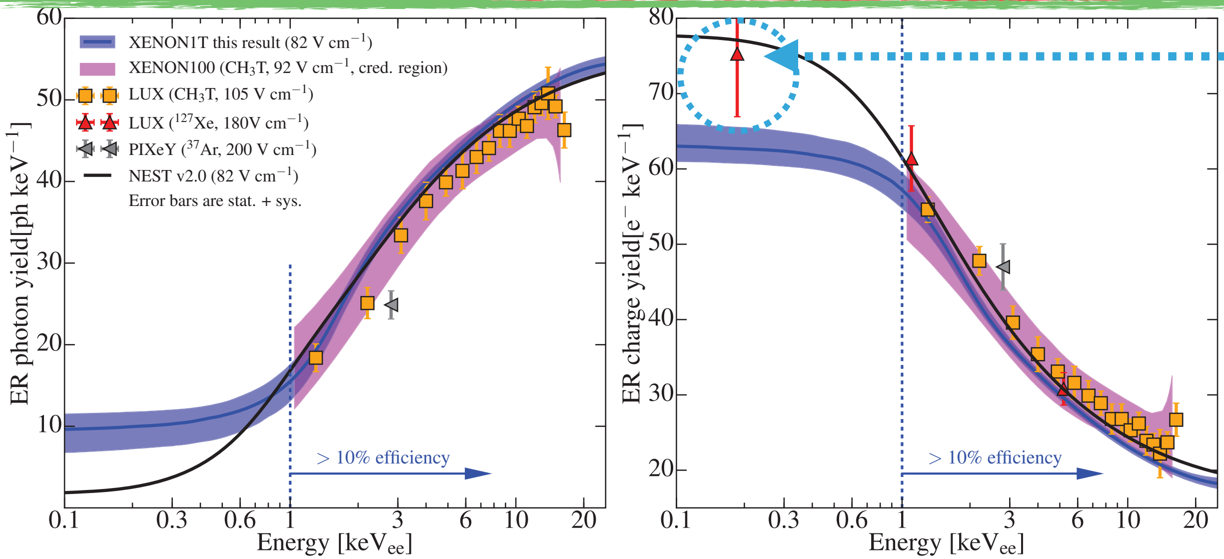
Electric recoil (ER) signals induced by Bremsstrahlung or Migdal effect enable us to lower the energy threshold

Light / Charge Yield for LXe TPC

NR



ER



For charge yield, there is a 0.186 keVee (^{127}Xe) measurement from LUX
Phys. Rev. D **96**, 112011

1e- produces ~30 PEs.
Photo-detection eff ~ 10%

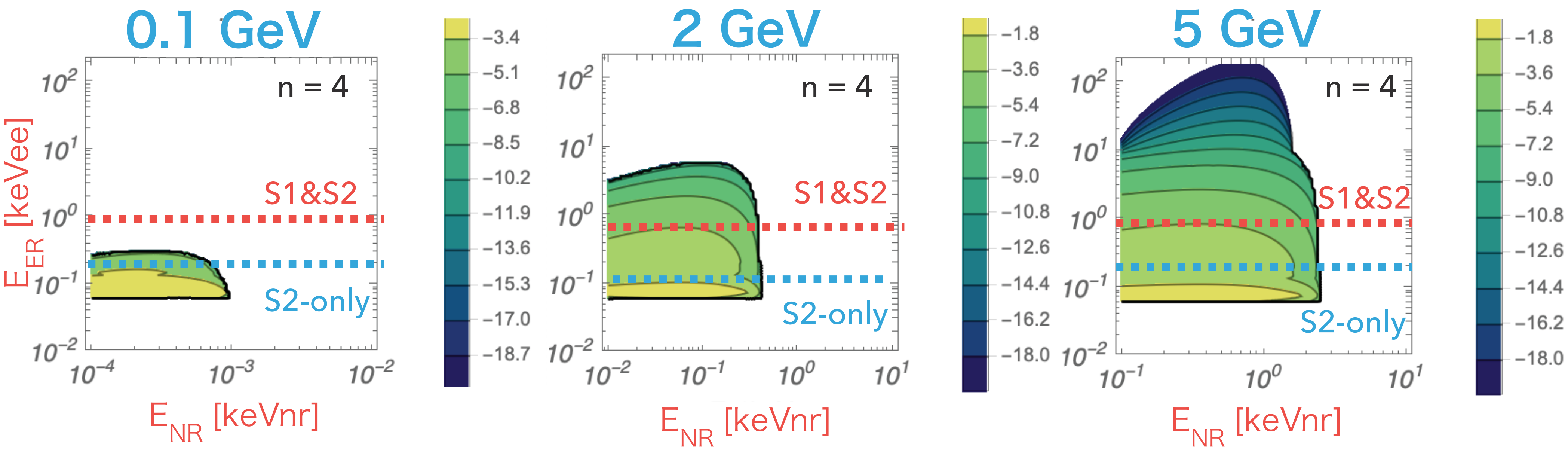
- Threshold (S1-S2): PMTに対する3-fold coincidence requirementで決まる: 4keV for NR信号
- ER信号が使えるようになれば、Thresholdは4 keVnr -> 1keVeeへ！
- Charge-only analysis (S2-only)が可能になれば、さらに1 keVee -> 0.186 keVeeへ！

Signal Spectrum: LXe TPC

Ibe et al, JHEP03(2018)194

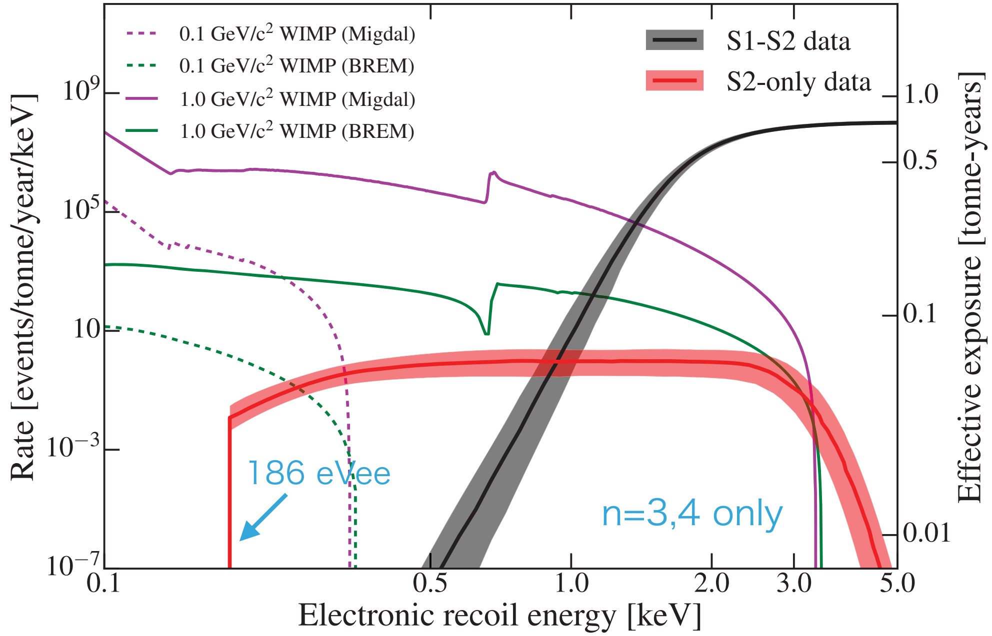
$$\frac{dR}{dE_R\, dE_{EM}\, dv_{DM}} \simeq \frac{dR_0}{dE_R\, dv_{DM}} \times \frac{1}{2\pi} \sum_{n,\ell} \frac{d}{dE_e} p^c_{q_e}(n\ell \to (E_{EM} - E_{n\ell}))$$

NR — Ionization (ER)



- The contribution of n=5 is neglected since the surrounding atoms in the liquid may influence the ionization spectrum. The inner electrons n ≤ 2 are too tightly bound to give an appreciable signal.
  - Therefore, the only contribution from n = 3 and 4 also considered.
- WIMP masses below 2 GeV, nuclear recoil energy is almost negligible, so only the ionization signal is considered.
- Above 2GeV, both NR and ER signals are produced simultaneously at the same position
  - We don't know detector response for such interactions at all.

Detection Efficiency and Signal Spectrum



S1& S2

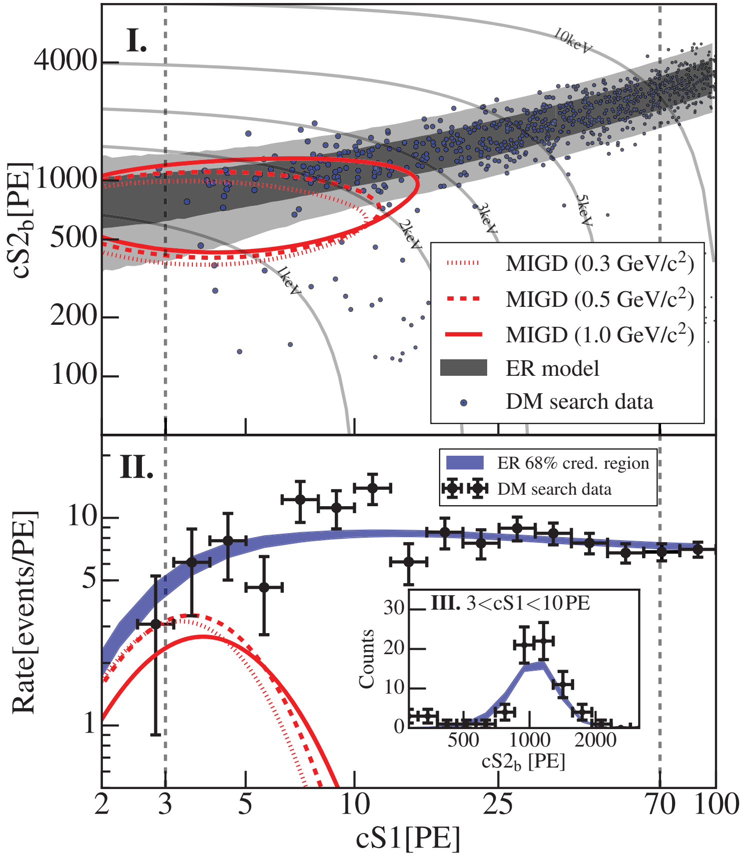
- Significant BG reduction is possible based on S2/S1 and fiducialization with position reconstruction in 3d.
- However, detection efficiency is limited by the S1 requirement (3-fold PMT coincidence)
- BG models are already established for the main analysis already published. Phys. Rev. Lett.**121**, 111302
- Re-interpretation of the main analysis, and treat the ER region as our signal region
- Energy threshold is **1 keVee**

S2-only

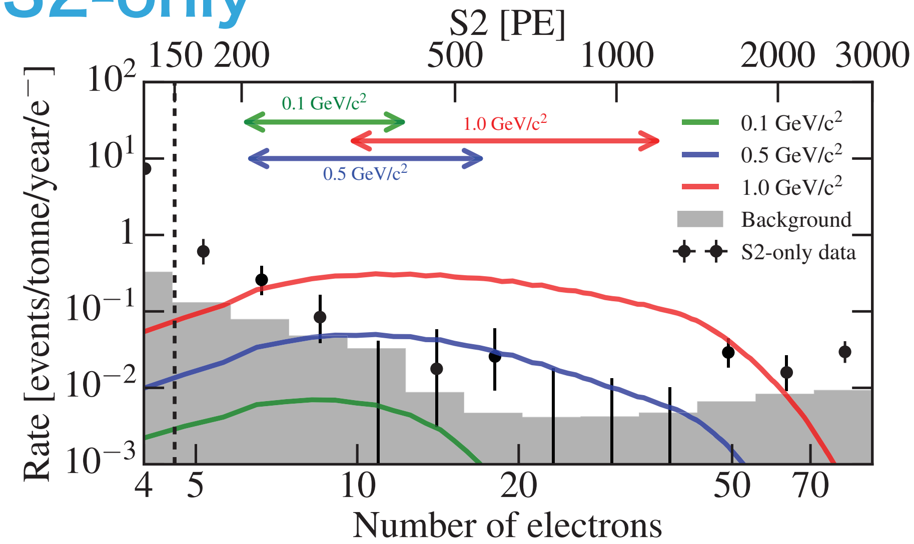
- 1e- produces ~30 PEs. If we do not require any S1s, it enables to recover detection efficiency significantly
- Energy threshold is **0.186 keVee**
- It is very difficult to construct well-established background models without S1 information
- 30% of the data was unblinded for choosing regions of interest (ROIs) in S2 and event selections.

Results

S1& S2



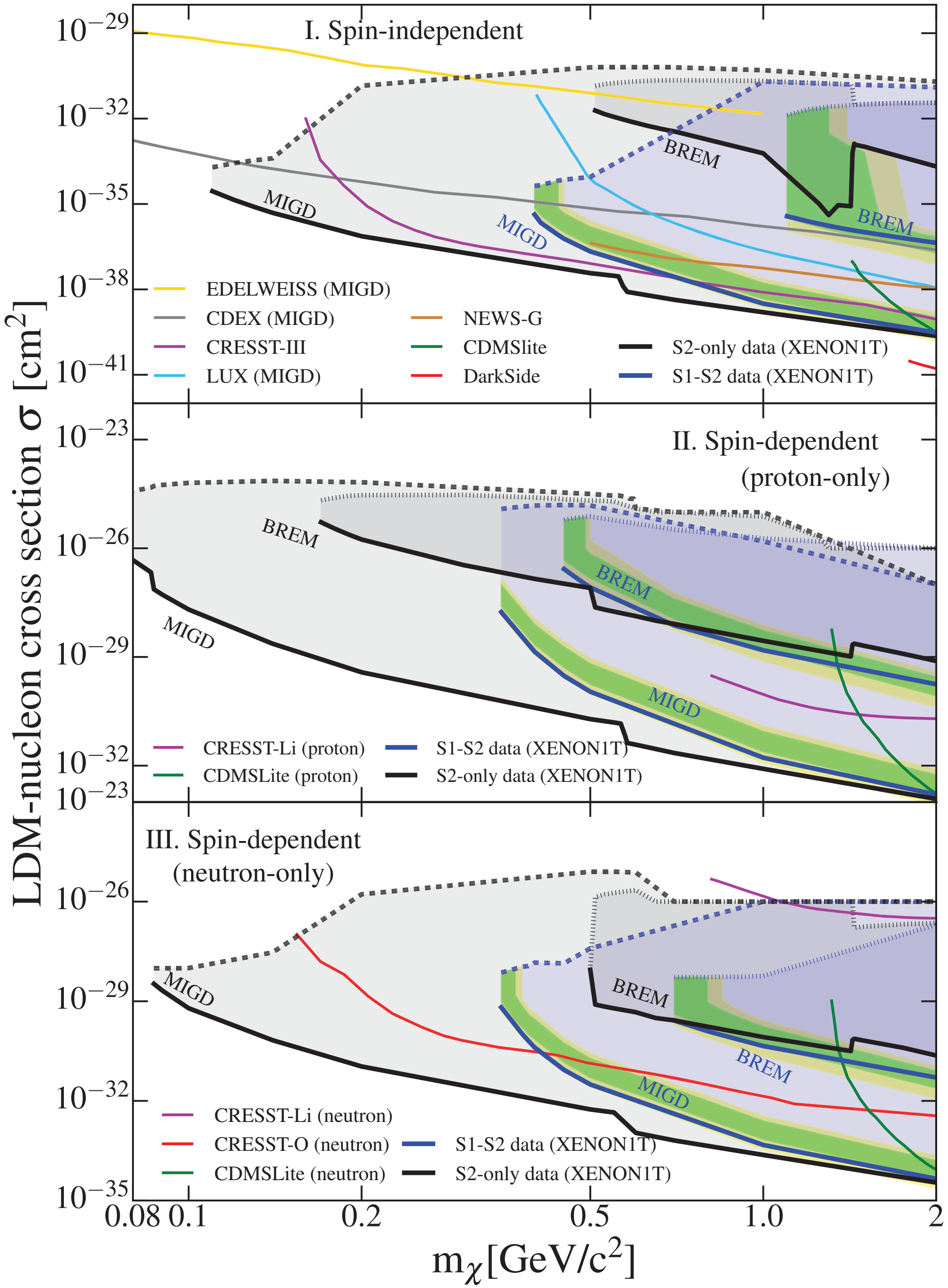
S2-only



- S2-only解析では一部理解しているBG(Pb214)は差っ引いているが、基本的にはデータを全てシグナルだと思って、コンサバに制限を引くのみ
- single-electronも見えているが、BGが膨大のため基本的には>5electronを見ている
- 閾値を下げることができれば、100kg程度のLXe TPCでも1T/nTを超える結果(low mass WIMPに対して)を得ることができる

	S1 & S2 Analysis	S2-only Analysis
Threshold	~1 keVee	~0.186 keVee
BG model	Yes	No
Sensitivity to Low Mass WIMP	Not Good	Good!
Discovery potential	Yes!	No (将来的にはYes?)

Results

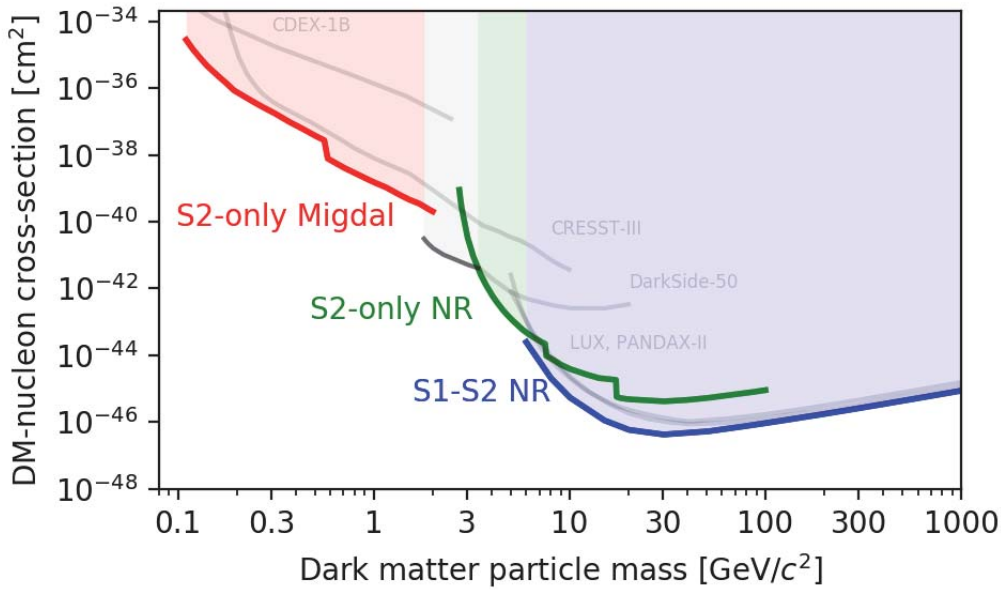


- 100 MeV - 2GeVのmass regionでも、XENON1T実験が世界最高感度を達成することに成功

- CRESSTあたりがMigdal効果を用いた探索をしたら負ける？

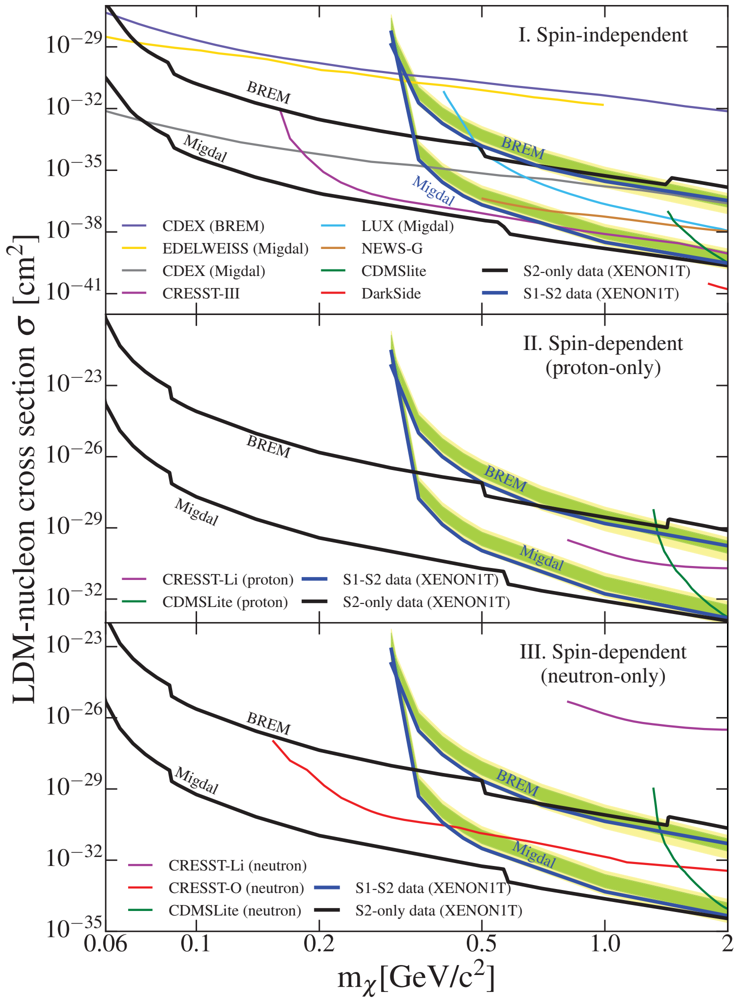
- NR searchの結果と合わせてまとめると以下の図になる。

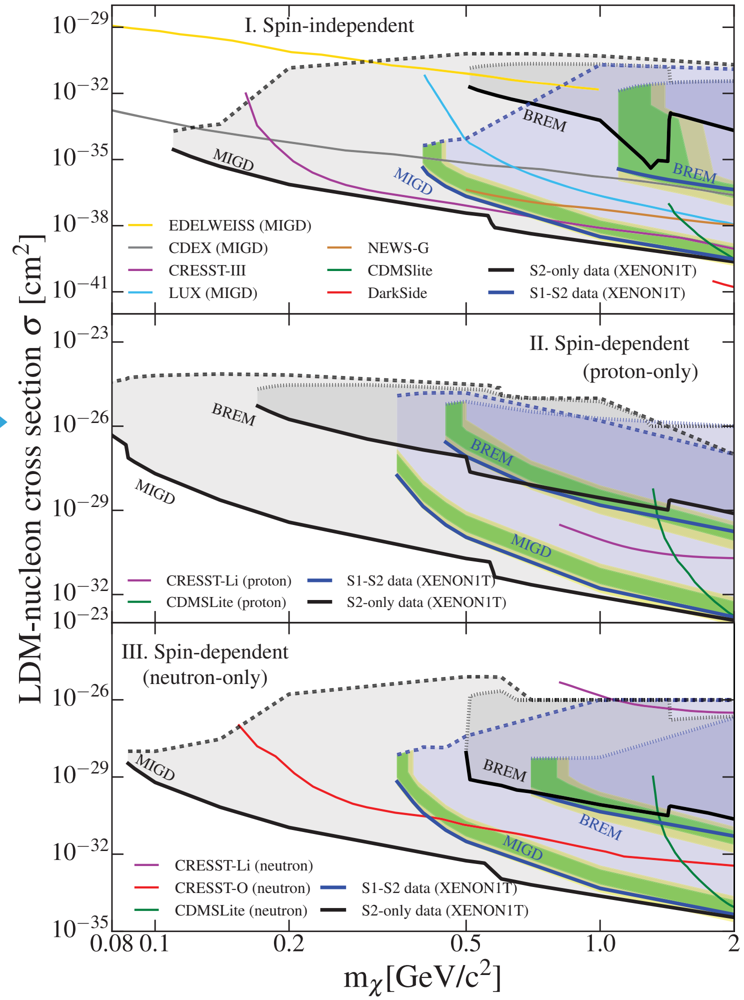
- Darkside (LAr TPC)のS2-only解析に一部負けているが基本的にlow/high-massの両極限でXENON1Tが世界最高感度



Earth-Shielding Effect

- DM particle may be stopped or scatter multiple times when passing through Earth's atmosphere, mantle, and core before reaching the detector (Earth-shielding effect)
- If the DM-matter interaction is sufficiently strong, the sensitivity for detecting such DM particles in terrestrial detectors, especially in underground laboratory, can be reduced or even lost totally.

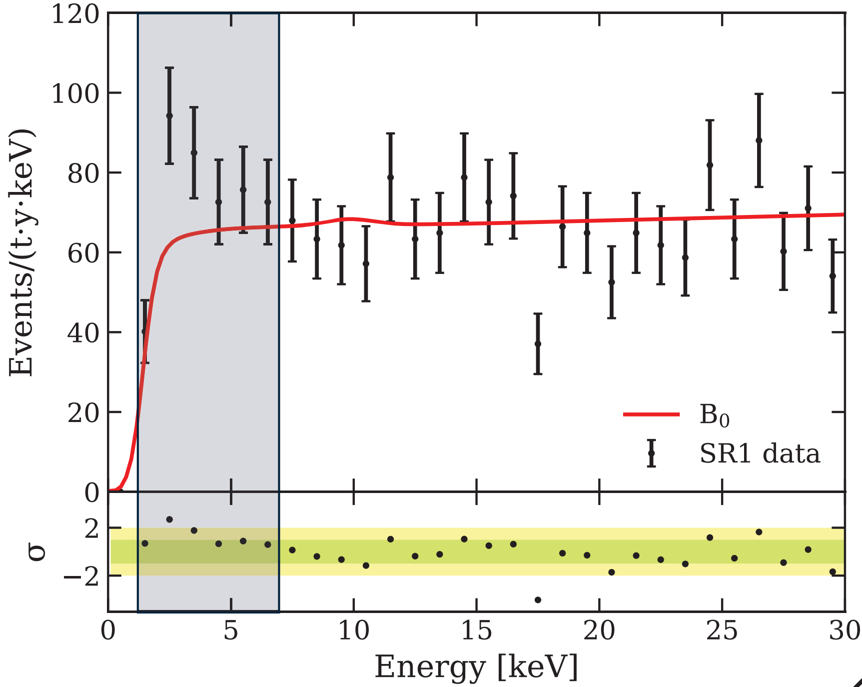


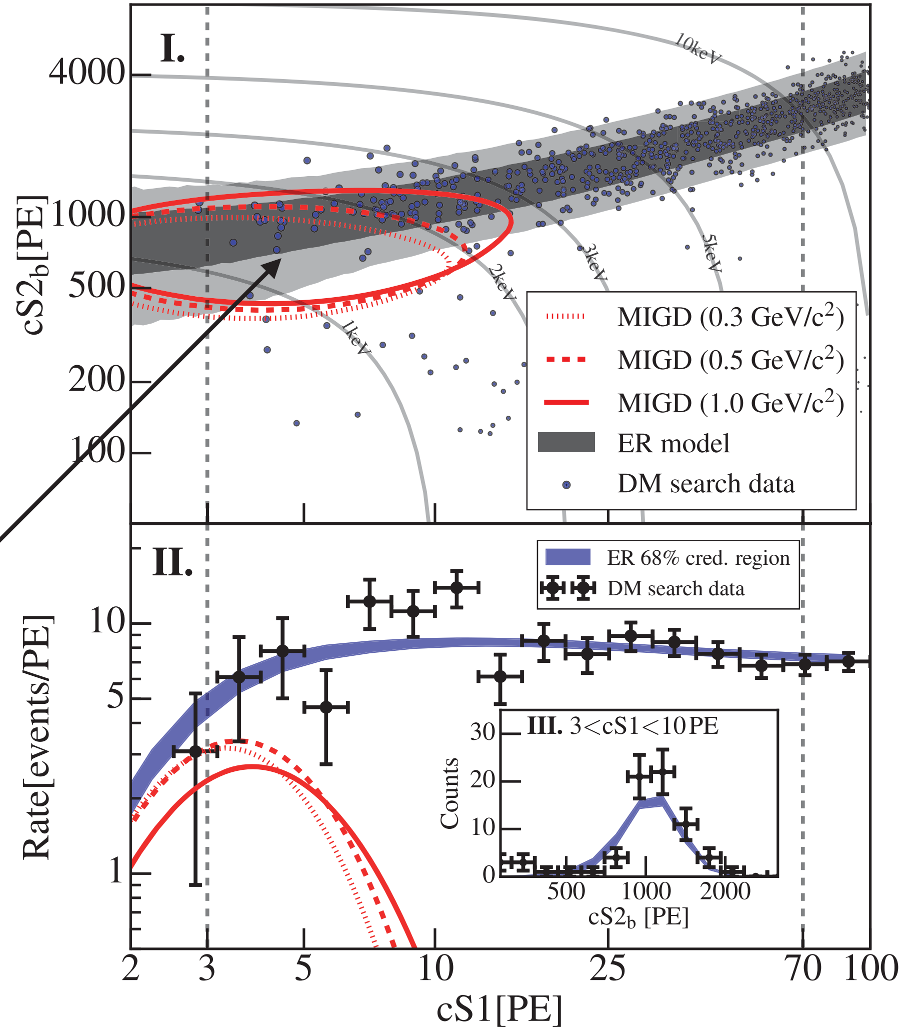


verneを使用: http://dx.doi.org/10.5281/zenodo.1116305

Low Energy ER excess?

Low Energy ER excessはMigdalを見ているのでは？





仮にlow ER excess (2keV付近)がMigdalから来ていると仮定すると、2keV以下でもっと信号が見ていないとおかしい

SUMMARY

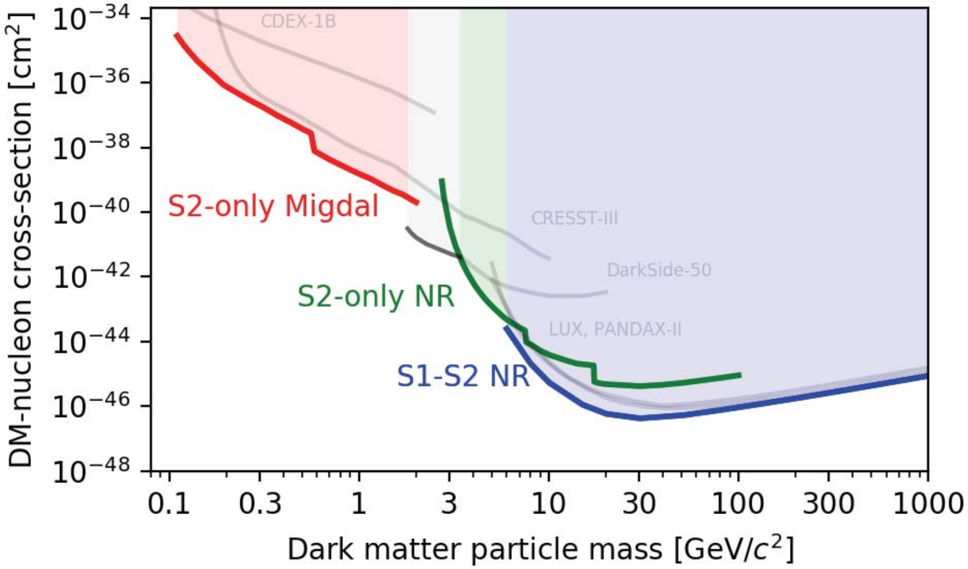
- Direct dark matter detection experiments based on LXe are leading the search for GeV-TeV scale DM, but have limited sensitivity to sub-GeV WIMPs because of the small momentum transfer of WIMP-nucleus elastic scattering.

- However, there is an irreducible contribution of inelastic signals that accompanies the elastic scattering, which leads to emission of photon and the excitations / ionizations of atomic electrons.

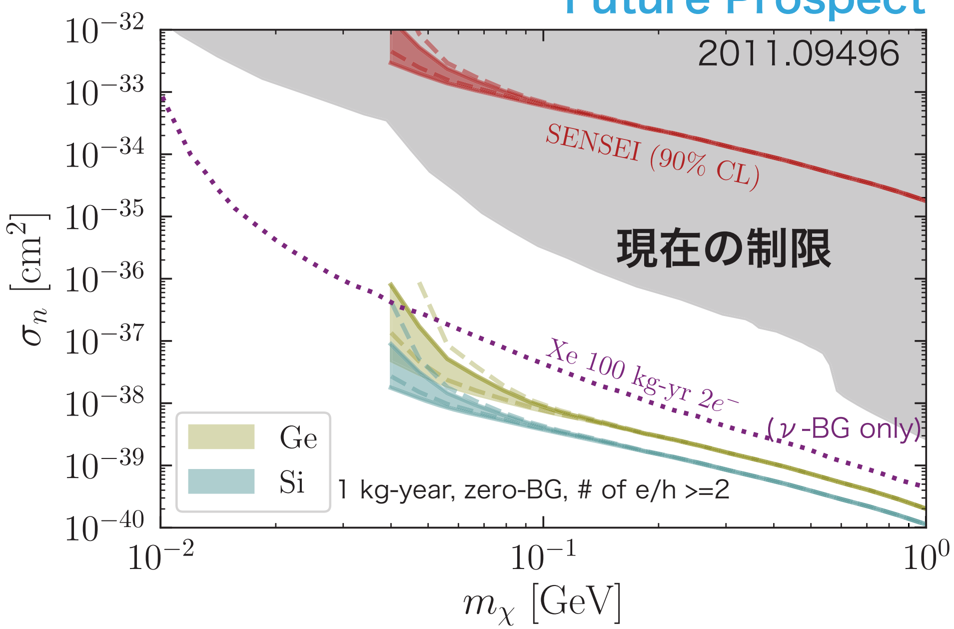
→ **Bremsstrahlung and Migdal Effect**

- XENON1T is currently leading the searches both in low & high mass regions!

Current Results



Future Prospect



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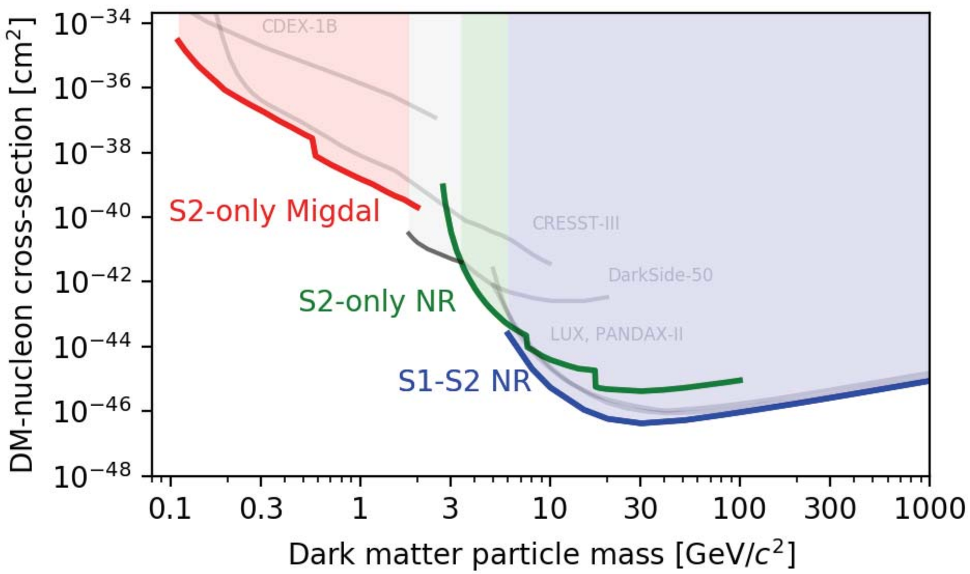

- Low massでの制限は、Migdal効果があって、そのレートは計算通りという過程に基づいている。

- α, β崩壊などでMigdal効果は見つかっているので(See backup)、NRでもおそらくあるはずだがNRではまだ未観測

- **Let's observe it with dedicated experiments!**