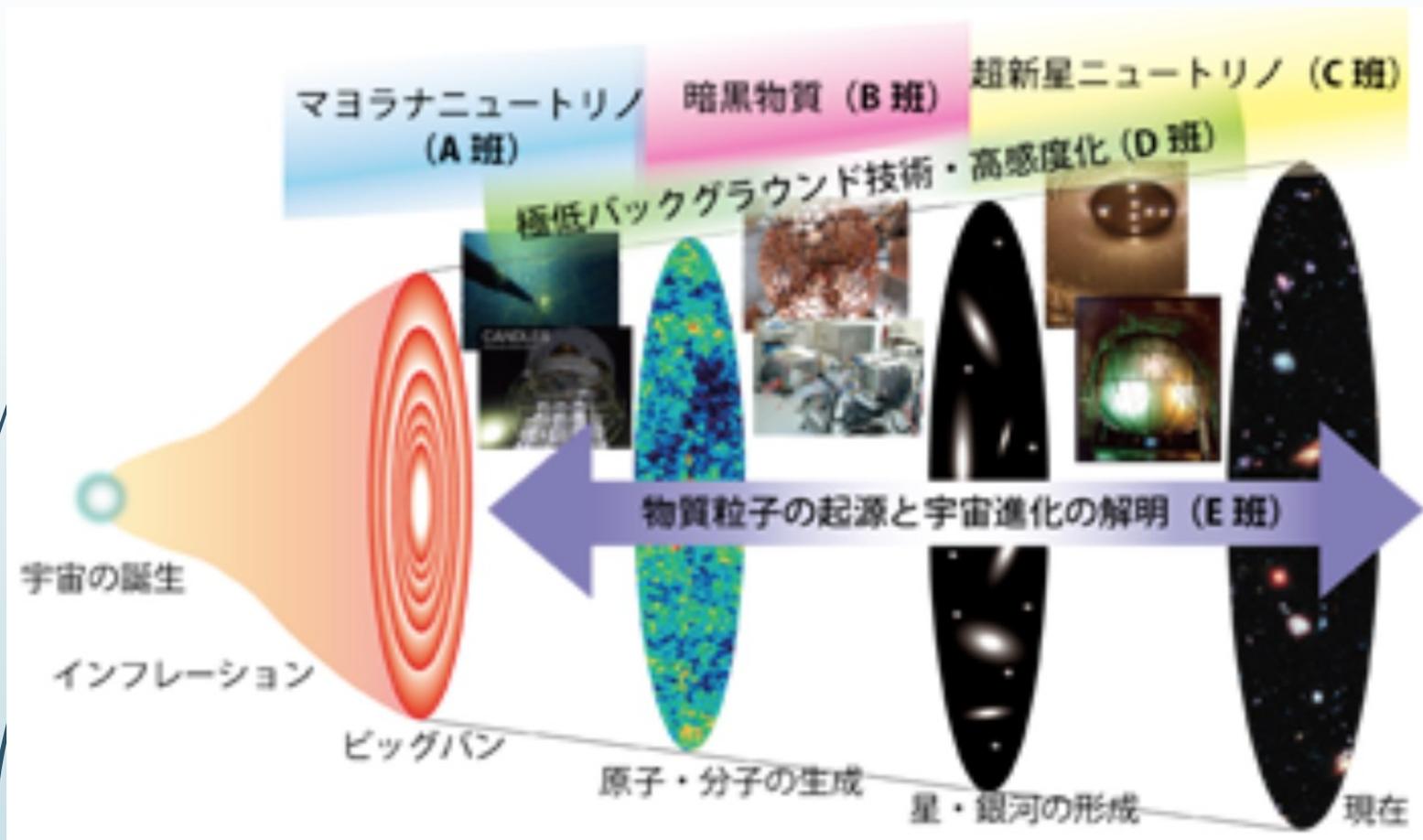


# 地下素核研究 B01 「大型検出装置による 暗黒物質直接探索」

岸本 康宏 for XMASS collaboration

於：2017年5月 岡山大学

# 領域全体の中の位置づけ

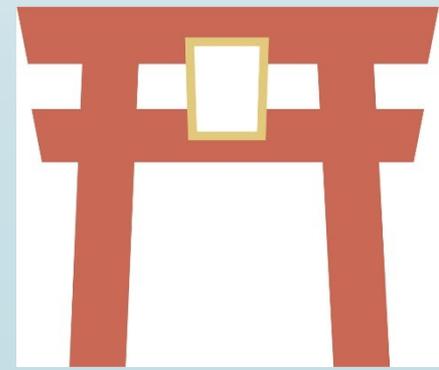


暗黒物質の発見により，宇宙の歴史を解明する



## B01の2本の柱

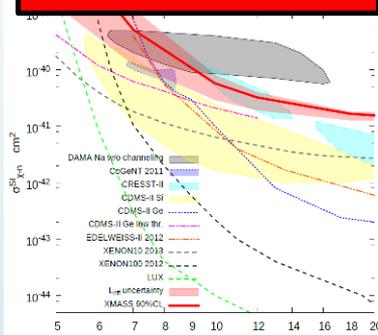
- 現在のXMASS実験装置を用いた暗黒物質探索
- 将来の大型暗黒物質探索装置のための開発・研究
  - 特に低バックグラウンド化



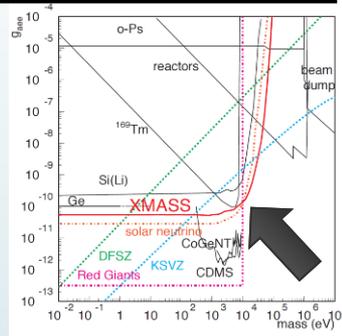
# XMASS physics results

Owing to low background for e/ $\gamma$  events (not only nuclear recoil), various kinds of dark matter candidate and physics topics have been searched for.

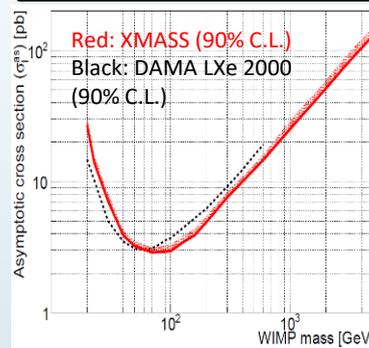
Low mass WIMPs search, PLB 719 (2013) 78



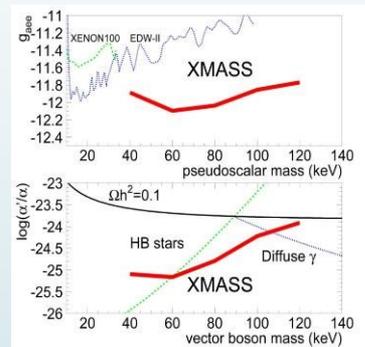
Solar axion search, PLB 724 46 (2013)



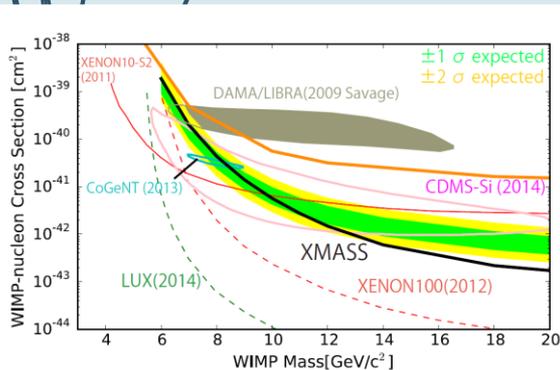
Inelastic WIMP nucleus scattering search, PTEP 063C01 (2014)



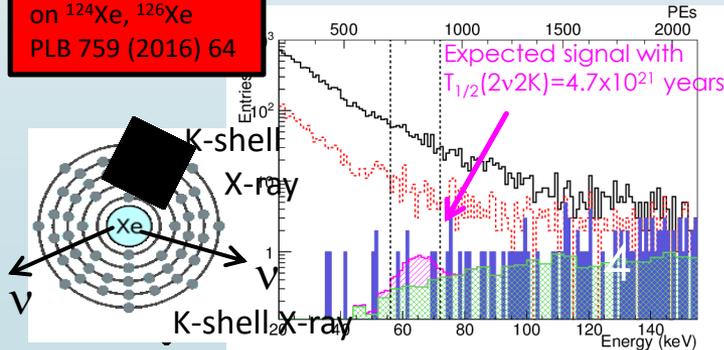
Bosonic super-WIMPs search, PRL 113, 121301 (2014)



Annual modulation, PLB 759 (2016) 272

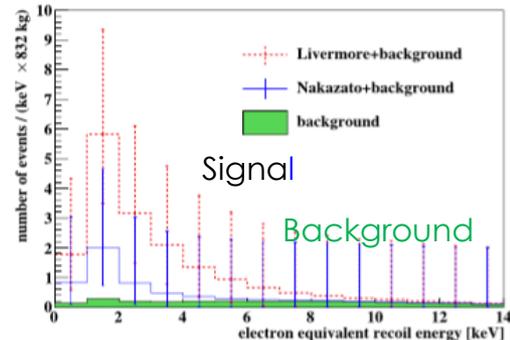


Search for  $2\nu$  2EC on  $^{124}\text{Xe}$ ,  $^{126}\text{Xe}$  PLB 759 (2016) 64



Possibility of supernova neutrino detection, Astropart. Phys. 89 (2017) 51

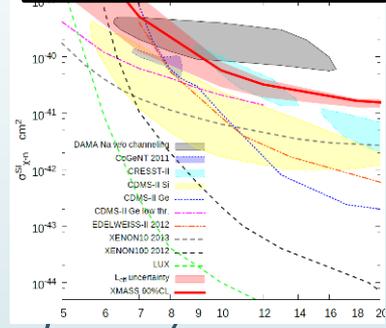
Supernova at 10kpc



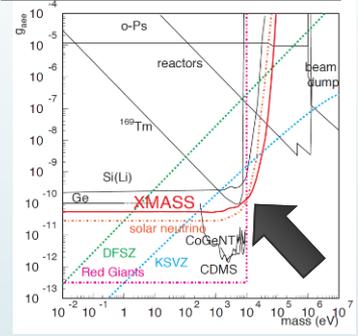
# XMASS physics results

Owing to low background for e/ $\gamma$  events (not only nuclear recoil), various kinds of dark matter candidate and physics topics have been searched for.

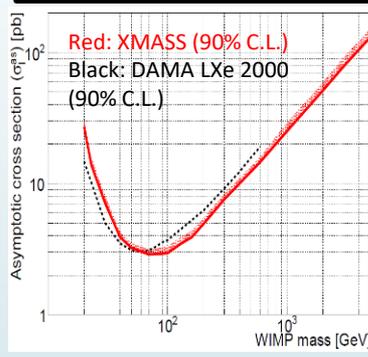
Low mass WIMPs search, PLB 719 (2013) 78



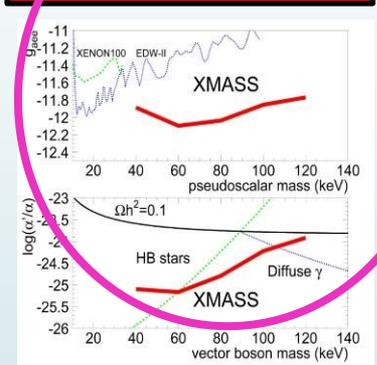
Solar axion search, PLB 724 46 (2013)



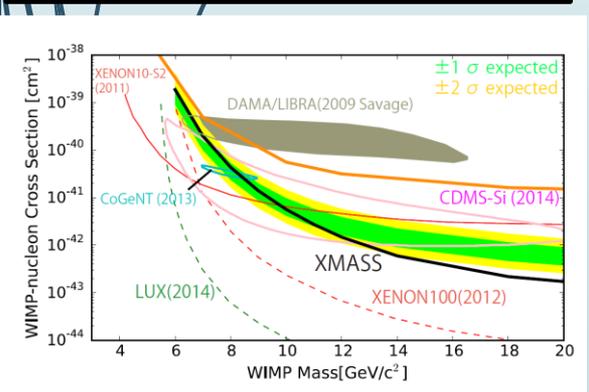
Inelastic WIMP nucleus scattering search, PTEP 063C01 (2014)



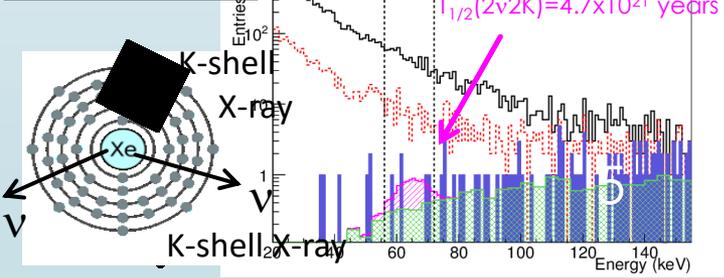
Bosonic super-WIMPs search, PRL 113, 121301 (2014)



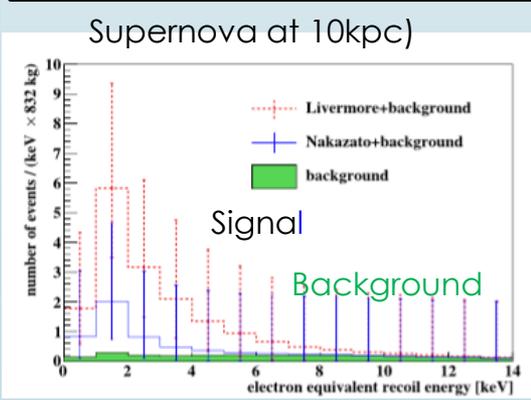
Annual modulation, PLB 759 (2016) 272



Search for  $2\nu$  2EC on  $^{124}\text{Xe}$ ,  $^{126}\text{Xe}$  PLB 759 (2016) 64

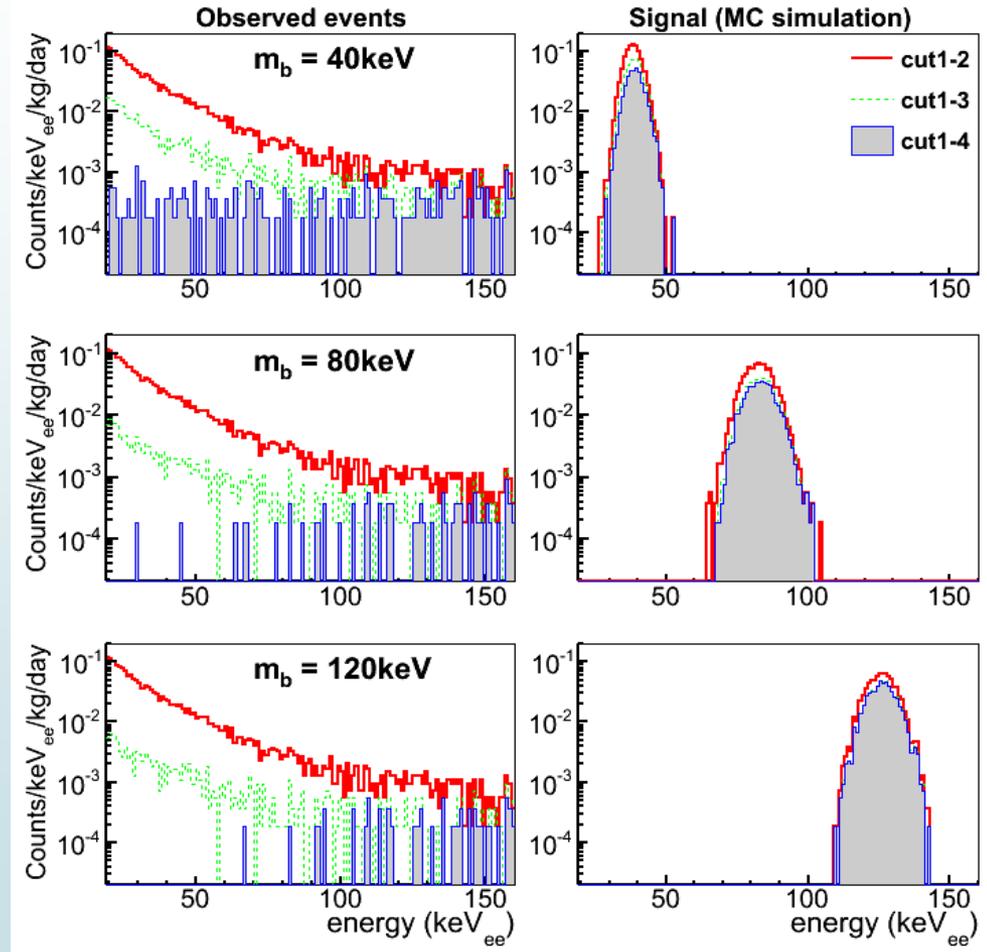
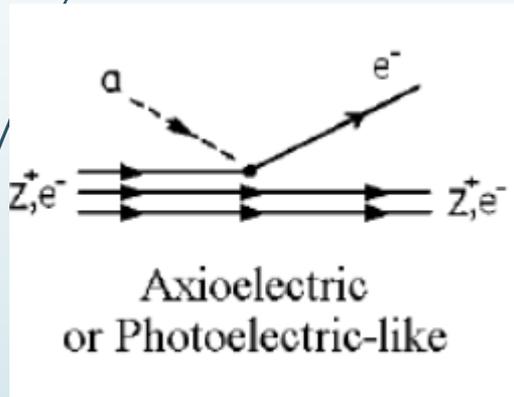


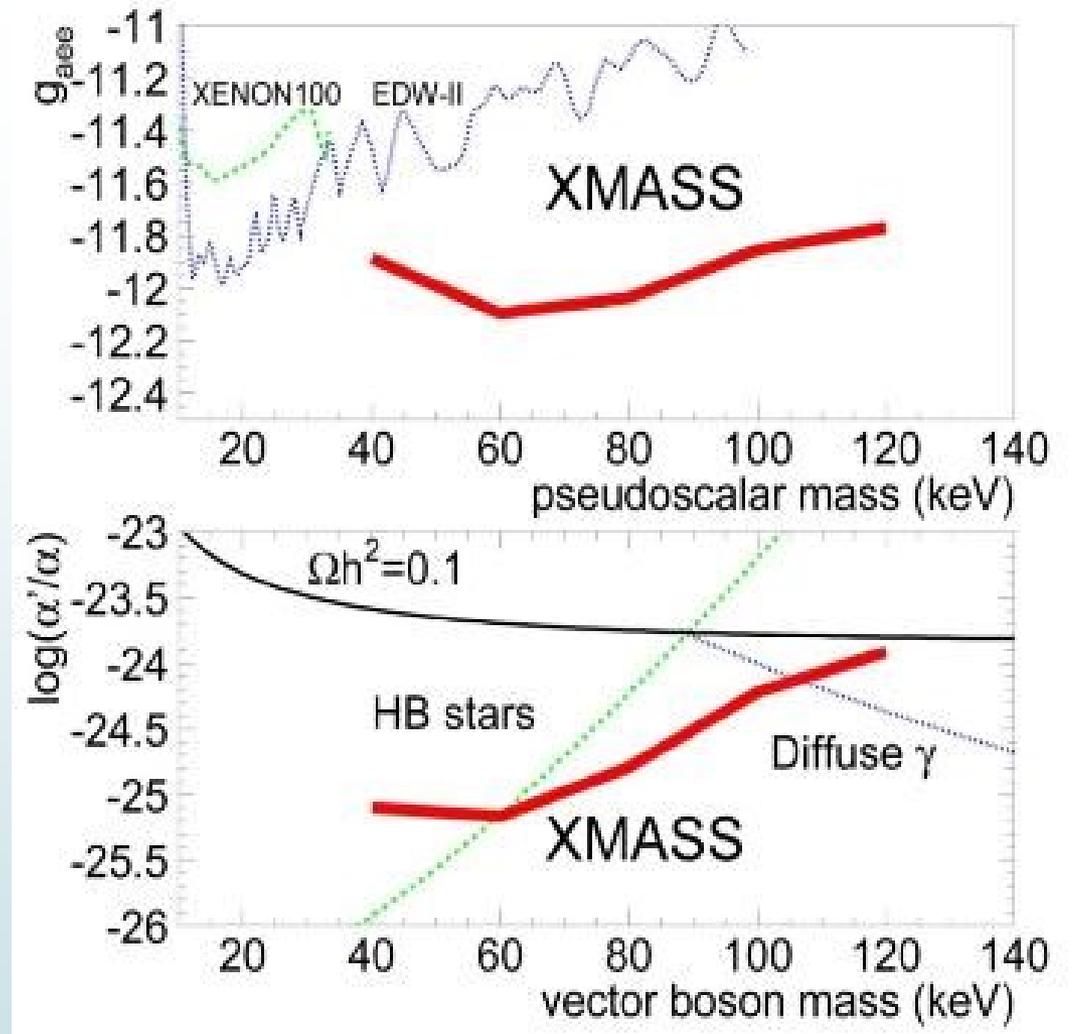
Possibility of supernova neutrino detection, Astropart. Phys. 89 (2017) 51



# Bosonic Super-WIMPs

A warm DM candidate



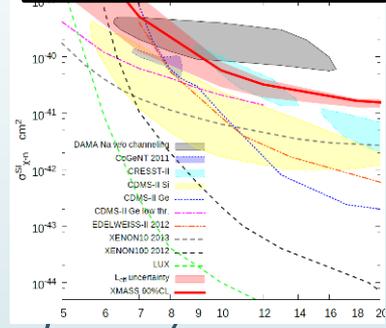


- ▶ ベクトル型の場合，熱的生成シナリオを否定

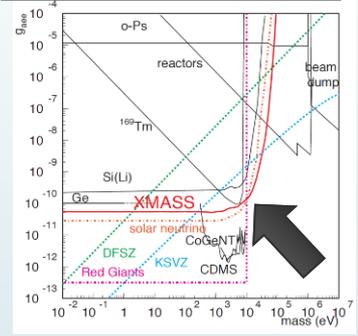
# XMASS physics results

Owing to low background for e/ $\gamma$  events (not only nuclear recoil), various kinds of dark matter candidate and physics topics have been searched for.

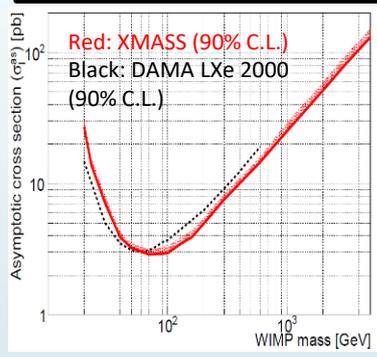
Low mass WIMPs search, PLB 719 (2013) 78



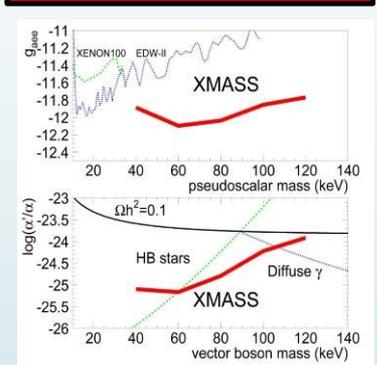
Solar axion search, PLB 724 46 (2013)



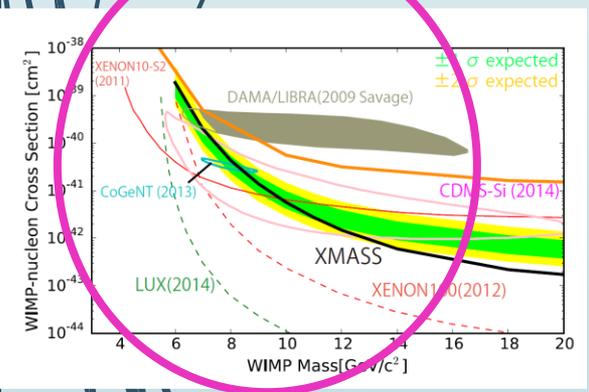
Inelastic WIMP nucleus scattering search, PTEP 063C01 (2014)



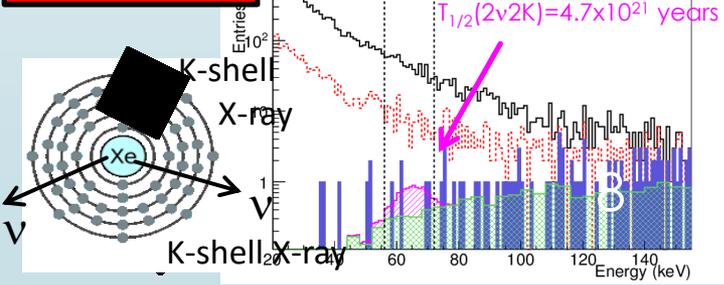
Bosonic super-WIMPs search, PRL 113, 121301 (2014)



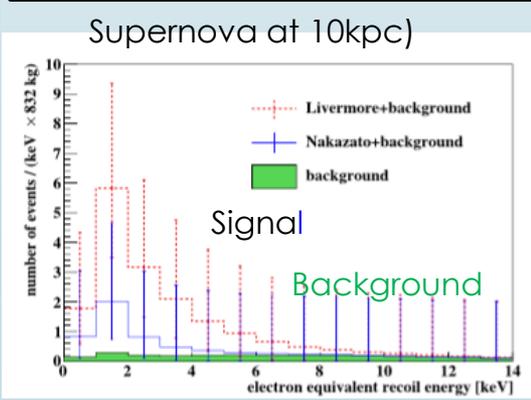
Annual modulation, PLB 759 (2016) 272



Search for  $2\nu$  2EC on  $^{124}\text{Xe}$ ,  $^{126}\text{Xe}$  PLB 759 (2016) 64

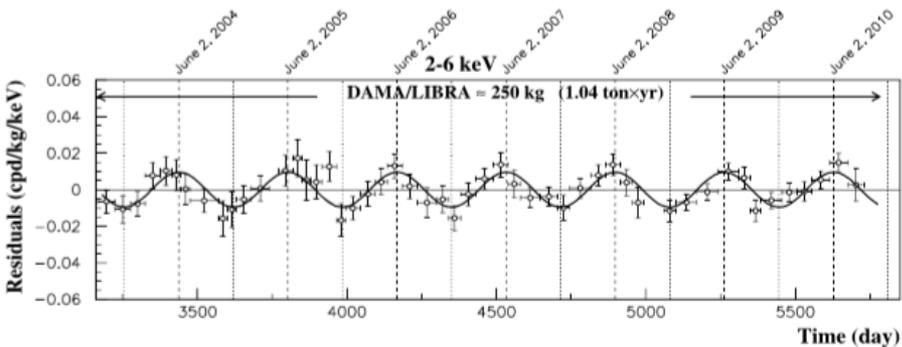
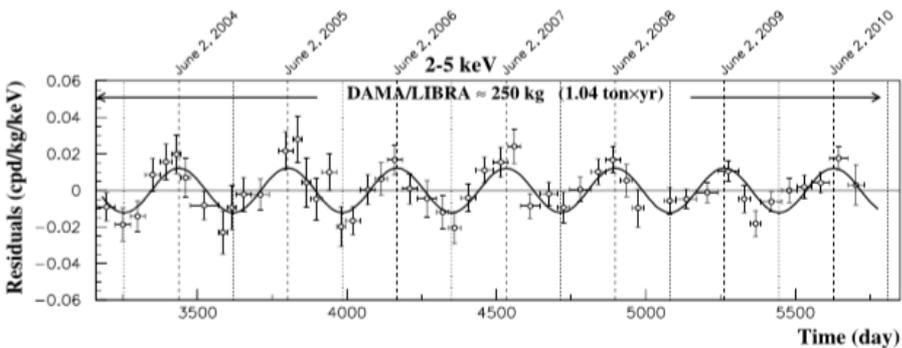
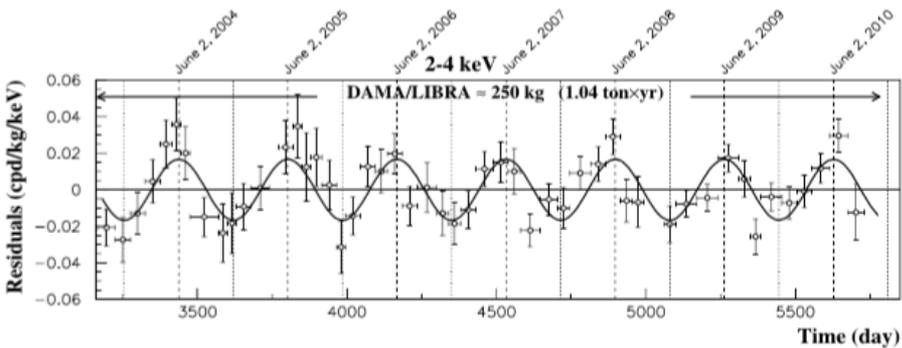


Possibility of supernova neutrino detection, Astropart. Phys. 89 (2017) 51



竹田さんの XeSAT2017のスライドから

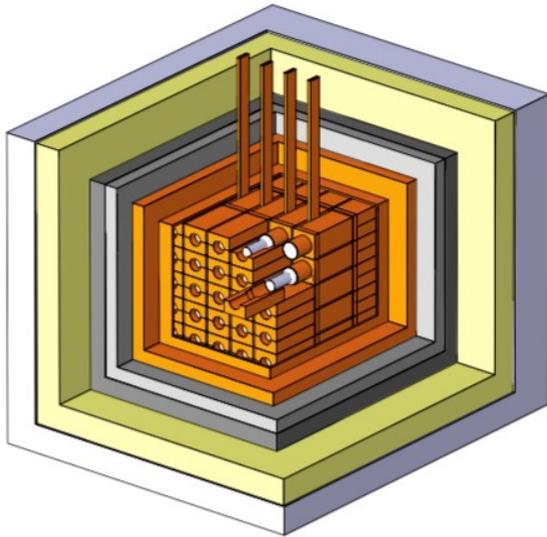
# Annual modulation by DAMA/LIBRA



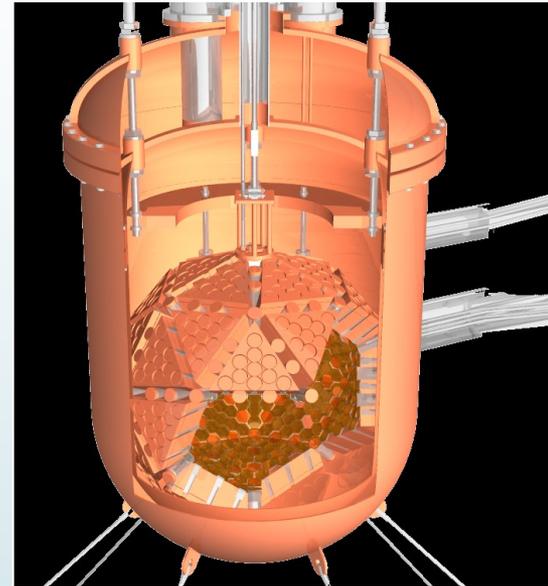
## 3 Conclusions

The data of the new DAMA/LIBRA-7 annual cycle have further confirmed a peculiar annual modulation of the *single-hit* events in the (2–6) keV energy region satisfying all the many requirements of the DM annual modulation signature; the cumulative exposure by the former DAMA/NaI and DAMA/LIBRA–phase I is 1.33 ton × yr.

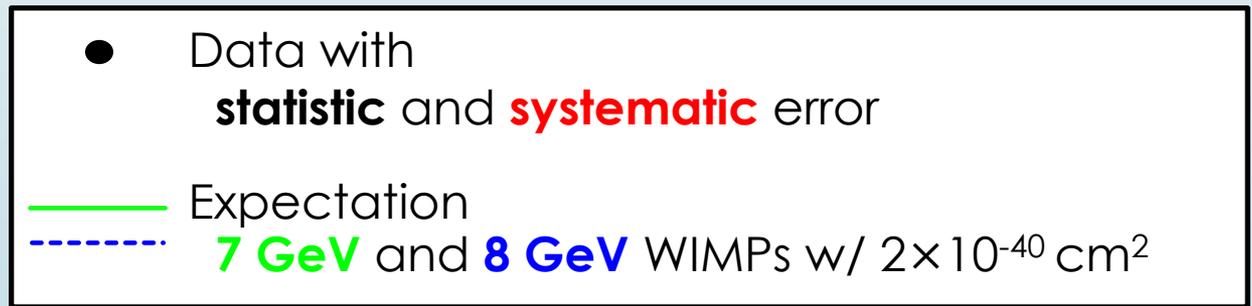
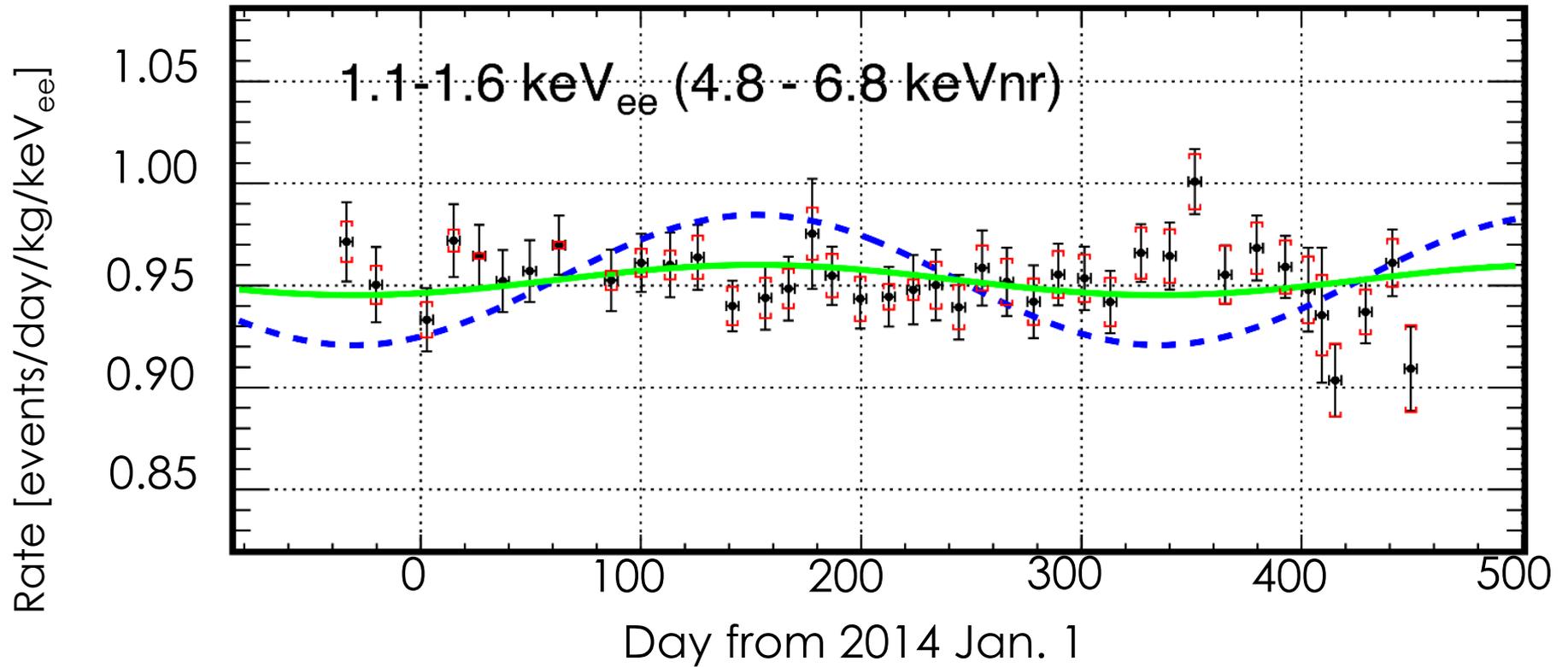
# XMASSとDAMA/LIBRA



2 5 0 kg NaI(Tl) シンチレータ  
No particle ID  
1.33 ton\*year

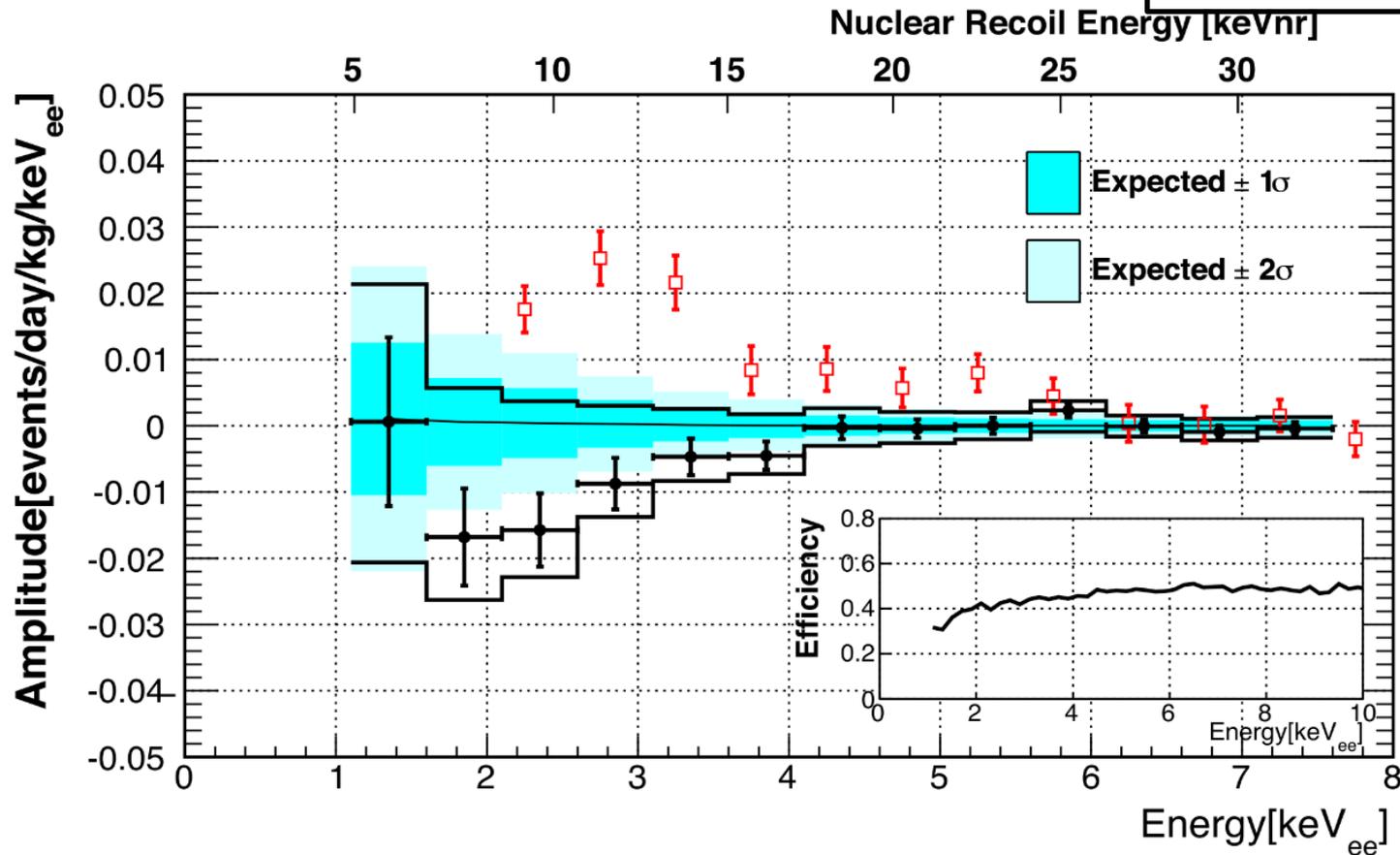


8 3 2 kg Xe シンチレータ  
No particle ID  
0.82 ton\*year (Nov. 2013 → Mar. 2015)



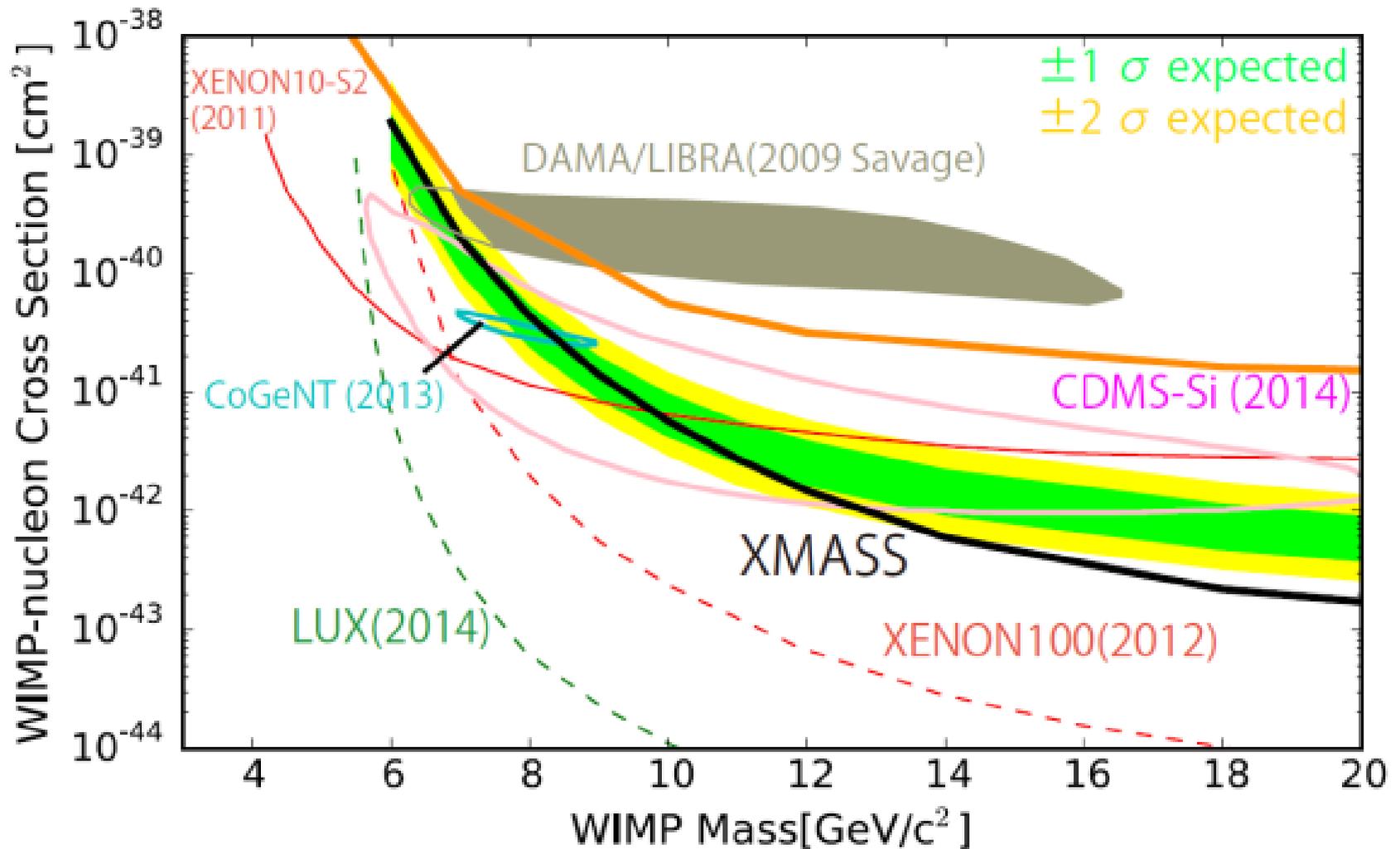
$$R_{i,j}^{\text{ex}} = \int_{t_j - \frac{1}{2}\Delta t_j}^{t_j + \frac{1}{2}\Delta t_j} \left( C_i + A_i \cos 2\pi \frac{(t - t_0)}{T} \right) dt,$$

-  XMASS
-  90% C.L. positive and negative upper limits
-  DAMA/LIBRA



同じ相互作用チャンネル, ほぼ同等の統計量で,  
 同じ事象 (季節変動) を検証

季節変動は見られなかった.

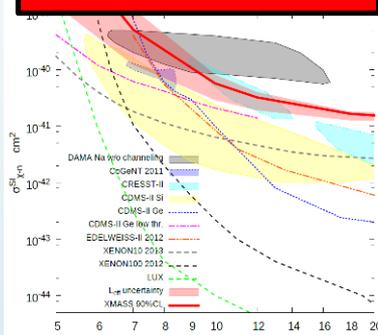


標準的な暗黒物質モデルを仮定した場合、  
**DAMA/LIBRAの領域のほとんどを排除**

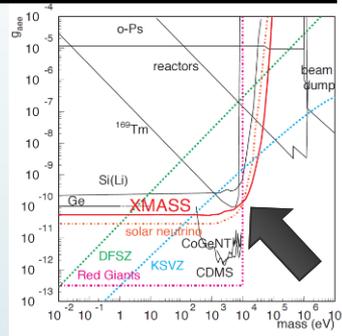
# XMASS physics results

Owing to low background for e/ $\gamma$  events (not only nuclear recoil), various kinds of dark matter candidate and physics topics have been searched for.

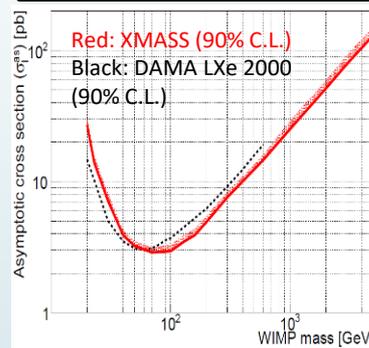
Low mass WIMPs search, PLB 719 (2013) 78



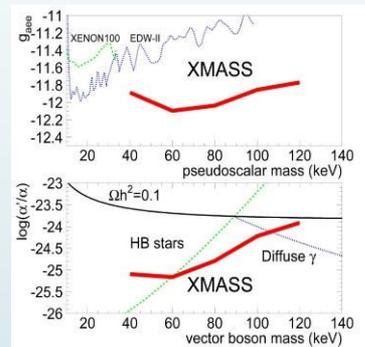
Solar axion search, PLB 724 46 (2013)



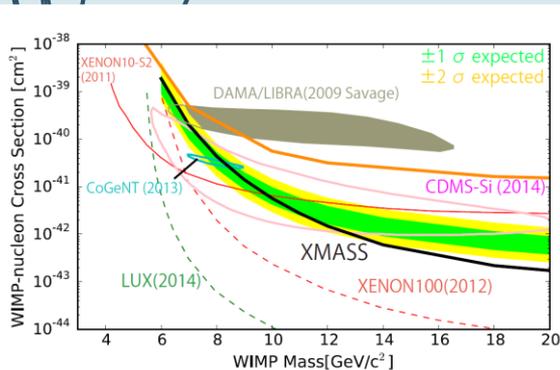
Inelastic WIMP nucleus scattering search, PTEP 063C01 (2014)



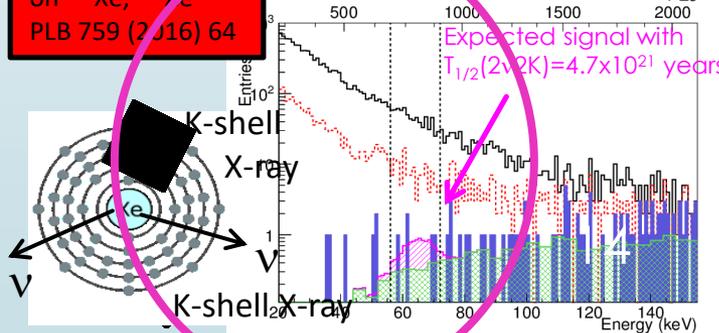
Bosonic super-WIMPs search, PRL 113, 121301 (2014)



Annual modulation, PLB 759 (2016) 272

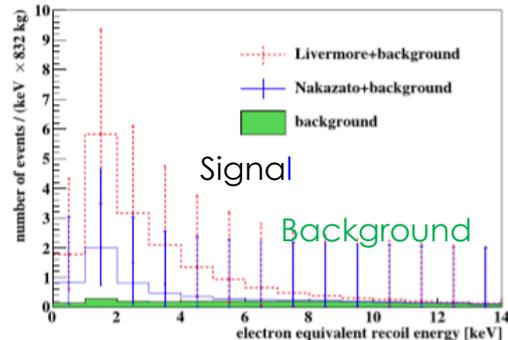


Search for  $2\nu 2\beta\beta$  on  $^{124}Xe$ ,  $^{126}Xe$ , PLB 759 (2016) 64



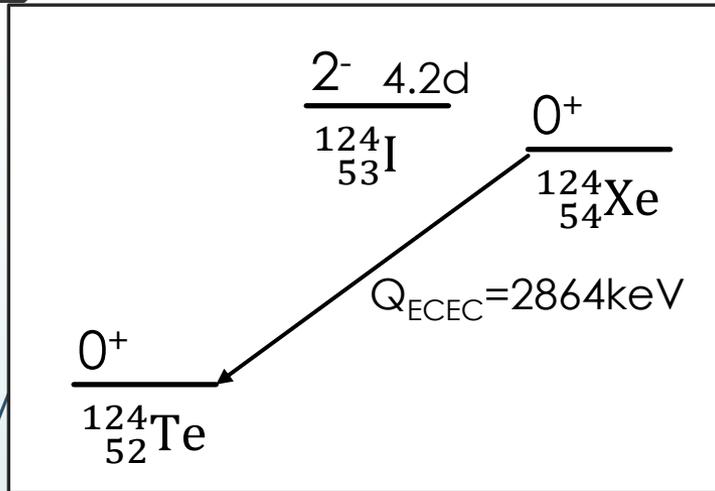
Possibility of supernova neutrino detection, Astropart. Phys. 89 (2017) 51

Supernova at 10kpc



竹田さんの XeSAT2017のスライドから

# 2ν double EC search

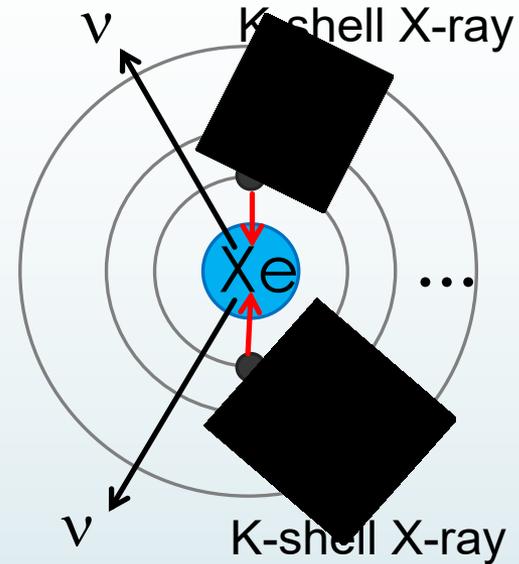


NA of  $^{124}\text{Xe} = 0.095\%$



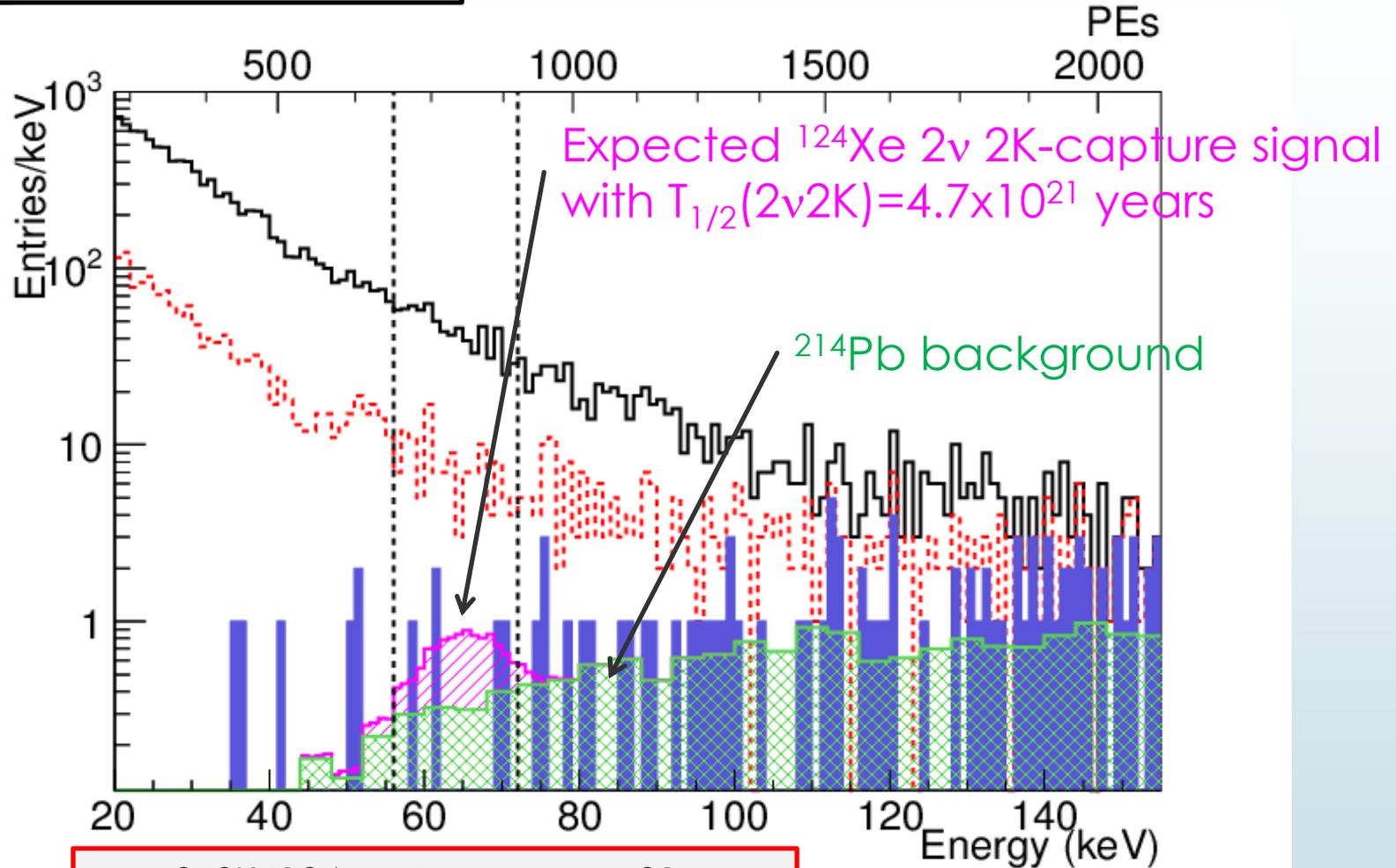
$^{126}\text{Xe}$  (NA=0.089%) も同様 (但しQ=896 keV)

- ▶ 寿命の測定は、原子核行列要素計算に重要なデータとなる
  - ▶ Expected half-life is  $10^{20}$ - $10^{24}$  years
- ▶  $0\nu$  のモードならレプトン非保存



XMASSでも二重ベータ崩壊を通じて、宇宙の歴史に迫ることが可能

- Fiducial volume cut
- Timing cut
- Band-like pattern cut



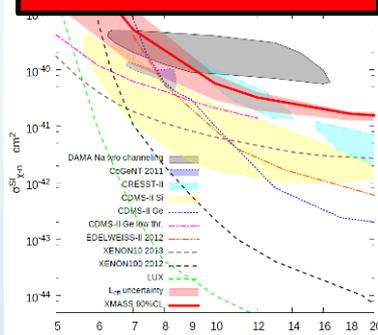
$T_{1/2}^{2\nu 2K}(^{124}\text{Xe}) > 4.7 \times 10^{21} \text{ y}$   
 $T_{1/2}^{2\nu 2K}(^{126}\text{Xe}) > 4.3 \times 10^{21} \text{ y}$   
 (90%CL)

The world best limits to date !!

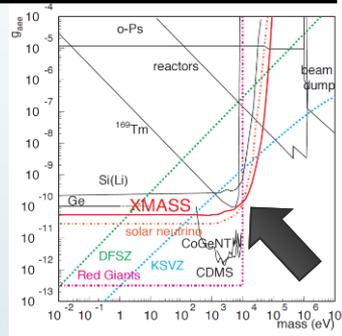
# XMASS physics results

Owing to low background for e/ $\gamma$  events (not only nuclear recoil), various kinds of dark matter candidate and physics topics have been searched for.

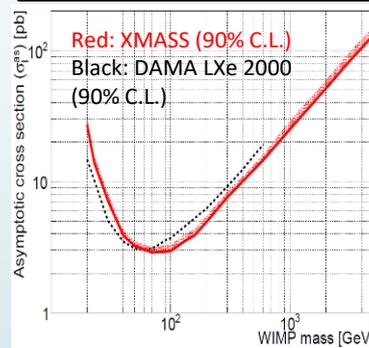
Low mass WIMPs search, PLB 719 (2013) 78



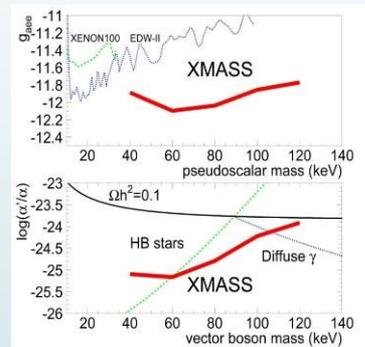
Solar axion search, PLB 724 46 (2013)



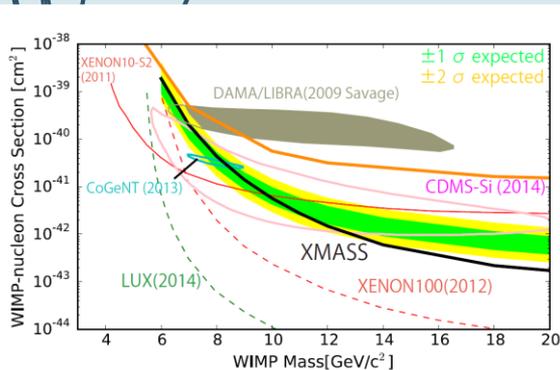
Inelastic WIMP nucleus scattering search, PTEP 063C01 (2014)



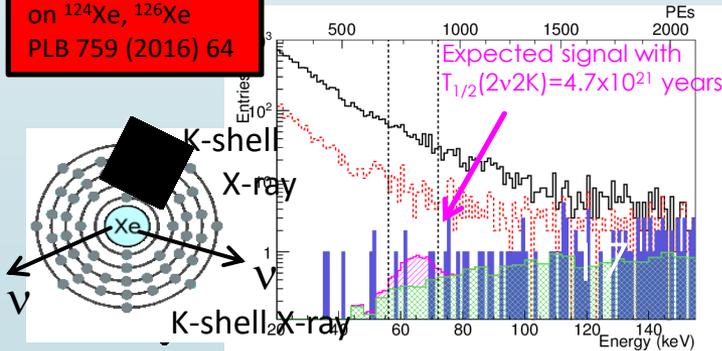
Bosonic super-WIMPs search, PRL 113, 121301 (2014)



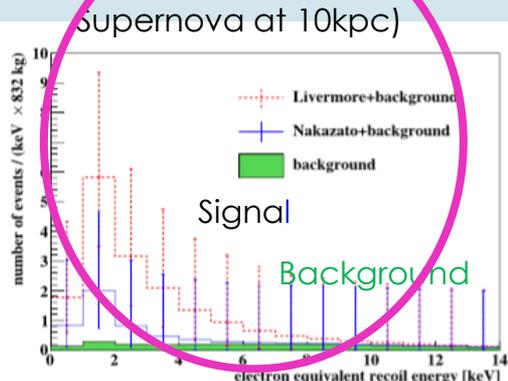
Annual modulation, PLB 759 (2016) 272



Search for 2 $\nu$  2EC on <sup>124</sup>Xe, <sup>126</sup>Xe PLB 759 (2016) 64

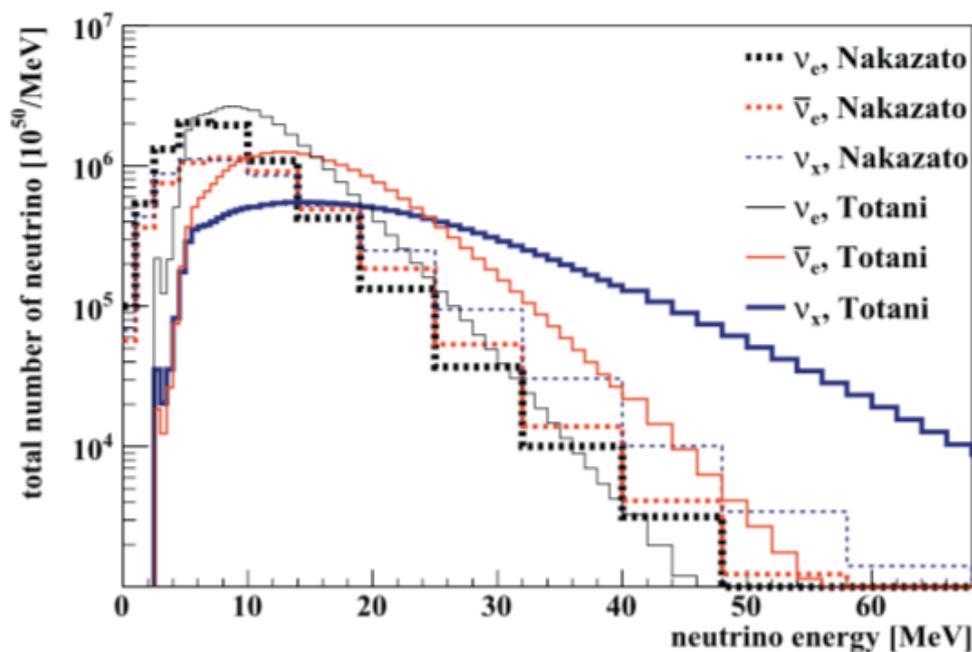


Possibility of supernova neutrino detection, Astropart. Phys. 89 (2017) 51



# XMASSによるSN $\nu$ 観測の可能性

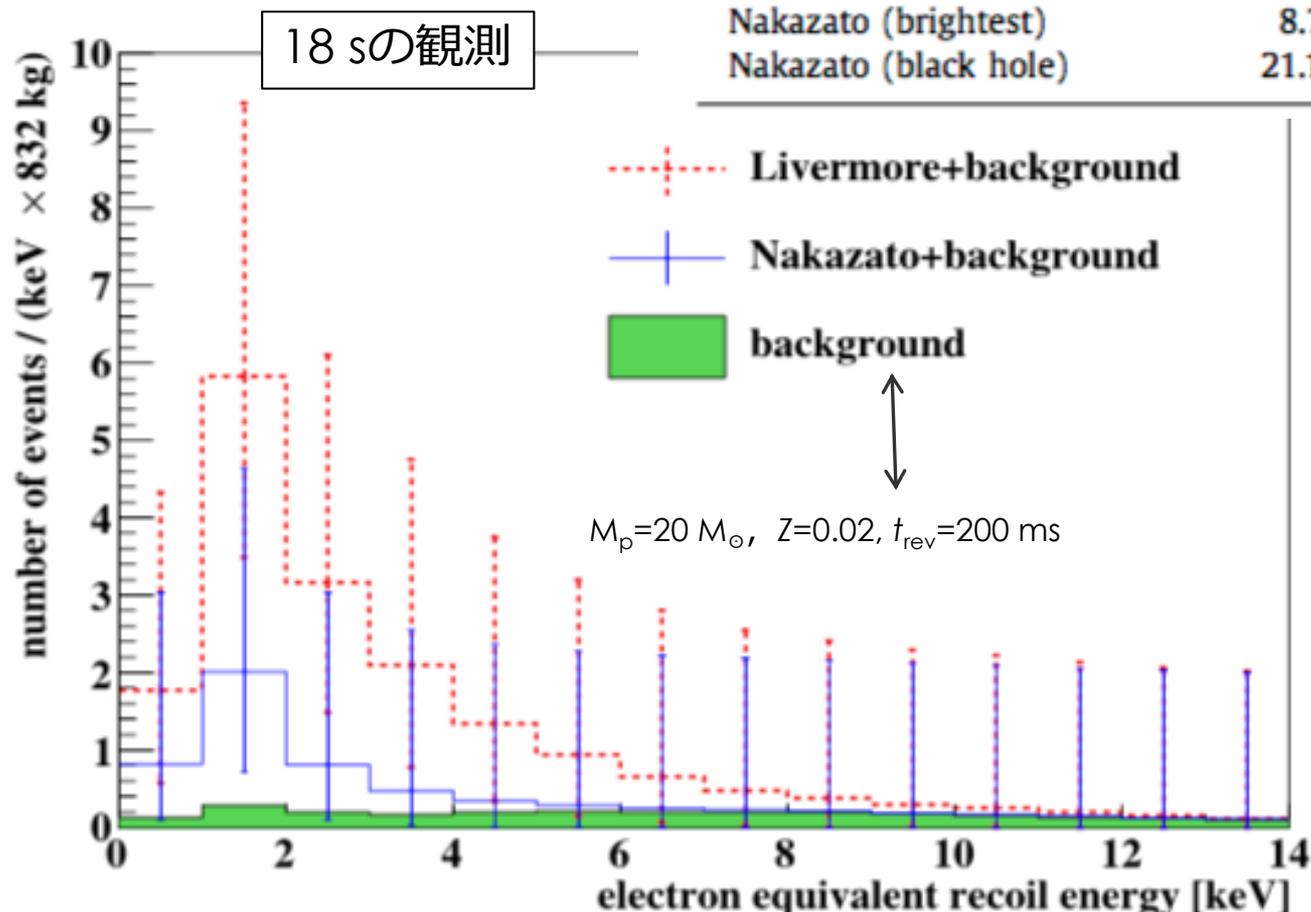
- ▶ 銀河内での超新星爆発のニュートリノ検出を検討
  - ▶ 超新星爆発のモデルは、中里さんの数値データを使用
    - ▶ 10.1088/0067-0049/205/1/2
- ▶ 検出はコヒーレント散乱過程
  - ▶ コヒーレント散乱は確実と思われるが、未確認
  - ▶ 全てのニュートリノに感度有



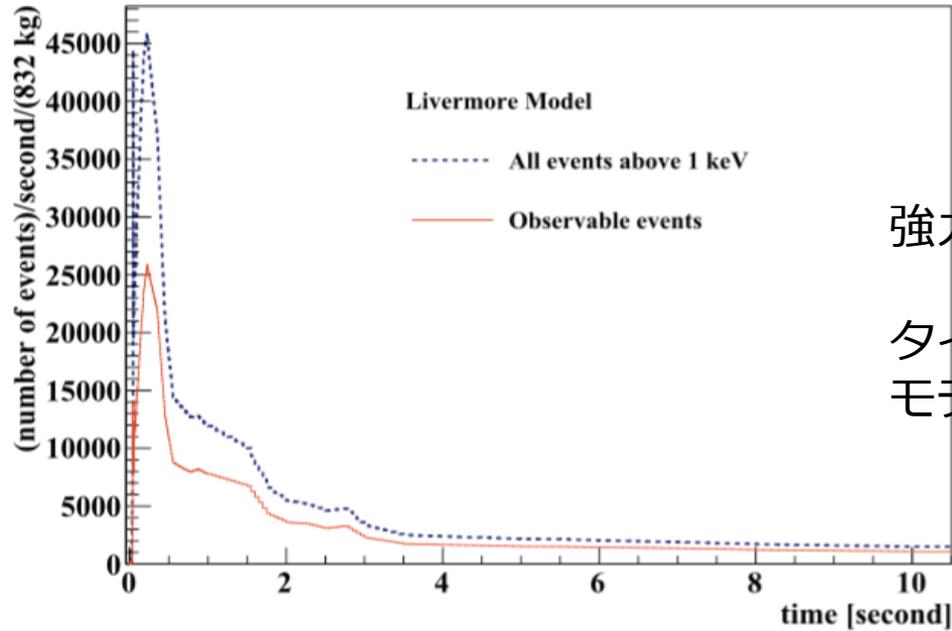
**Table 2**

Number of observable supernova events in XMASS. The weakest Nakazato model is the one with  $M_p = 20 M_\odot$ ,  $Z = 0.02$  and  $t_{\text{rev}} = 100$  ms. The brightest Nakazato model is the one with  $M_p = 30 M_\odot$ ,  $Z = 0.02$  and  $t_{\text{rev}} = 300$  ms. The black-hole-forming model is the one with  $M_p = 30 M_\odot$ ,  $Z = 0.004$ . Neutrino energy spectra used in the calculation are all integrated from core collapse till about 18 s later.

Supernova model	$d = 10$ kpc	$d = 196$ pc
Livermore	15.2	$3.9 \times 10^4$
Nakazato (weakest)	3.5	$0.9 \times 10^4$
Nakazato (brightest)	8.7	$2.3 \times 10^4$
Nakazato (black hole)	21.1	$5.5 \times 10^4$

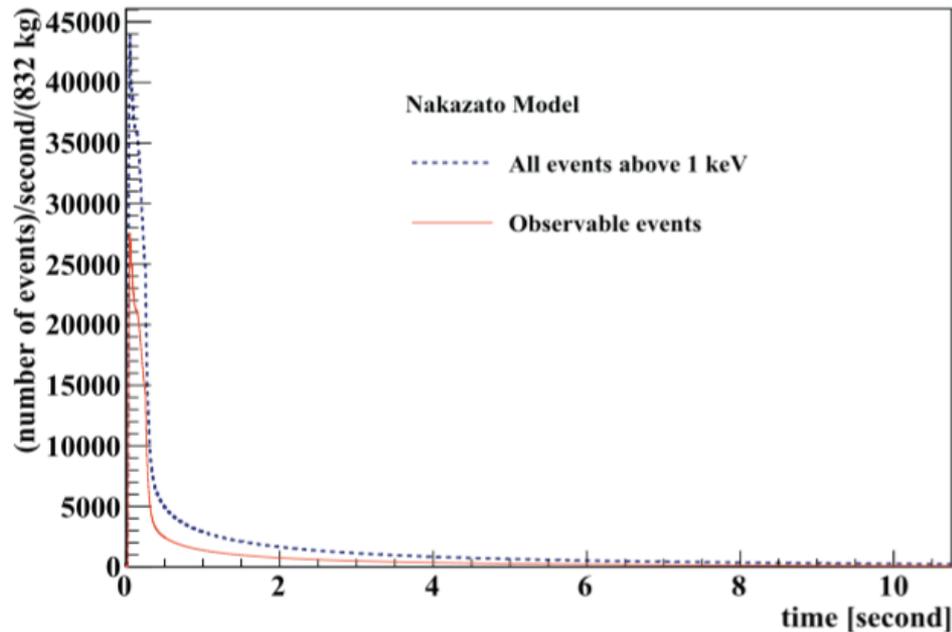


# ベテルギウスなら



強力なDAQ系が必要

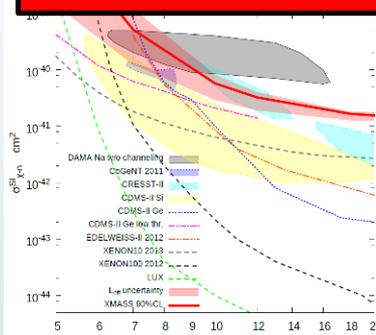
タイムスペクトルから、  
モデルの選別も



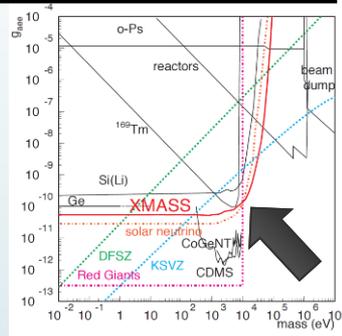
# XMASS physics results

Owing to low background for e/ $\gamma$  events (not only nuclear recoil), various kinds of dark matter candidate and physics topics have been searched for.

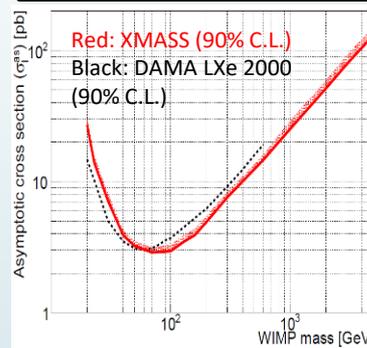
Low mass WIMPs search, PLB 719 (2013) 78



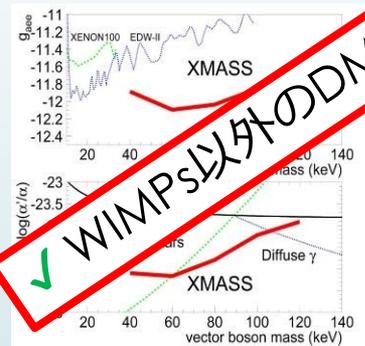
Solar axion search, PLB 724 46 (2013)



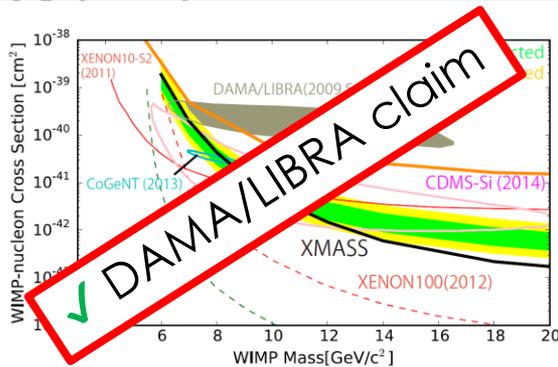
Inelastic WIMP nucleus scattering search, PTEP 063C01 (2014)



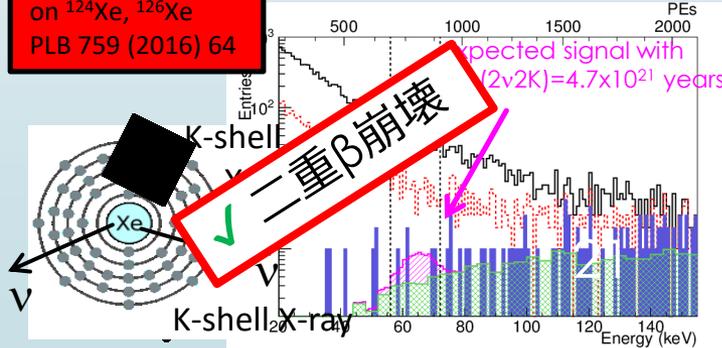
Bosonic super-WIMPs search, PRL 113, 121301 (2014)



Annual modulation, PLB 759 (2016) 272

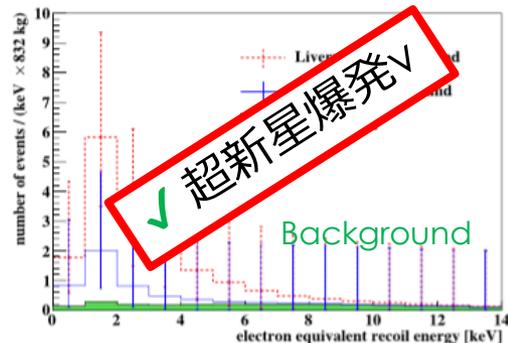


Search for  $2\nu$  2EC on  $^{124}\text{Xe}$ ,  $^{126}\text{Xe}$  PLB 759 (2016) 64



Possibility of supernova neutrino detection, Astropart. Phys. 89 (2017) 51

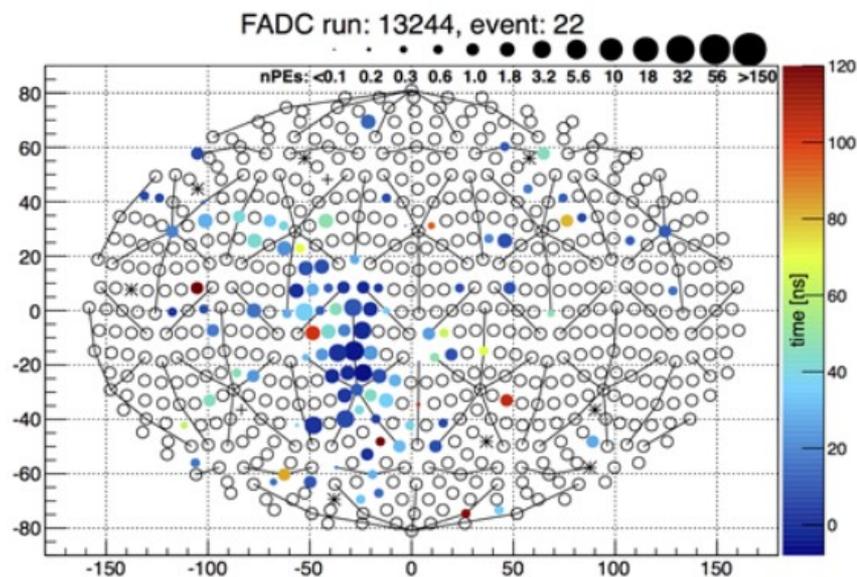
Supernova at 10kpc



# XMASSの有効体積解析の現状

- ▶ XMASSの事象再構成
  - ▶ 「場所によって、検出する光量パターンに違いがある」ことを利用
    - ▶  $R(\text{PE}) < 20 \text{ cm}$  ( $M = 96.5 \text{ kg}$ )
  - ▶ 検出器表面のBG事象を除くために、時間パターンの差も利用
    - ▶  $R(\text{T}) < 38 \text{ cm}$

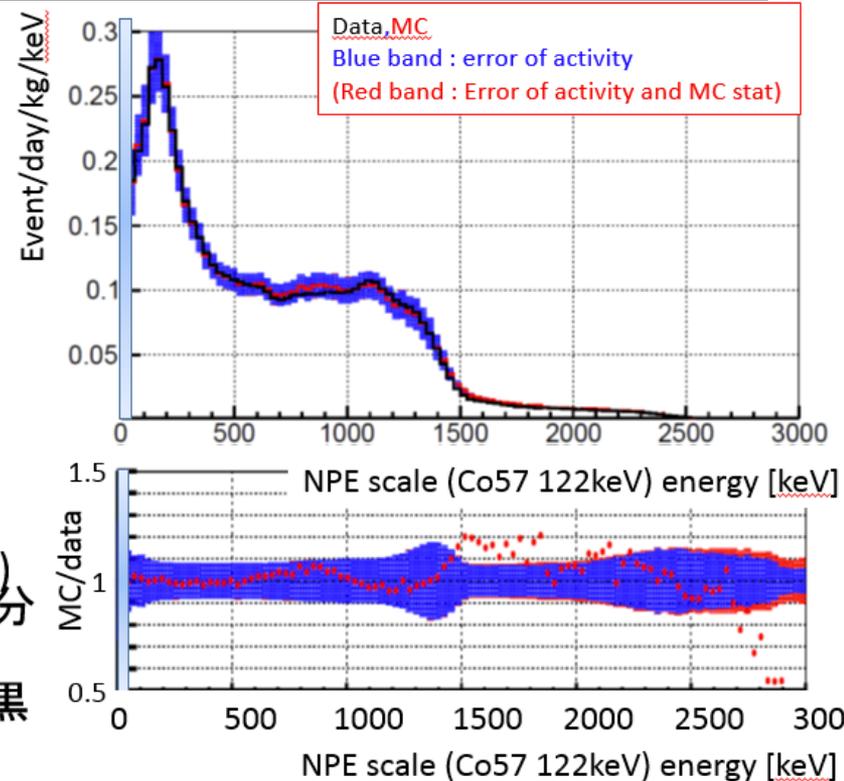
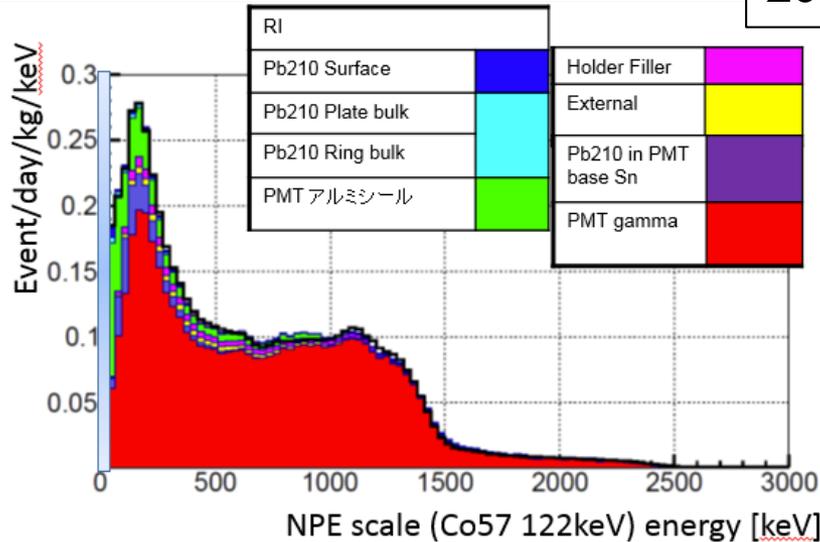
10 keV energy deposit by DM particle (MC)



## 有効体積解析 :

- 全体積でバックグラウンドを評価
- このバックグラウンドに有効体積カットをかける

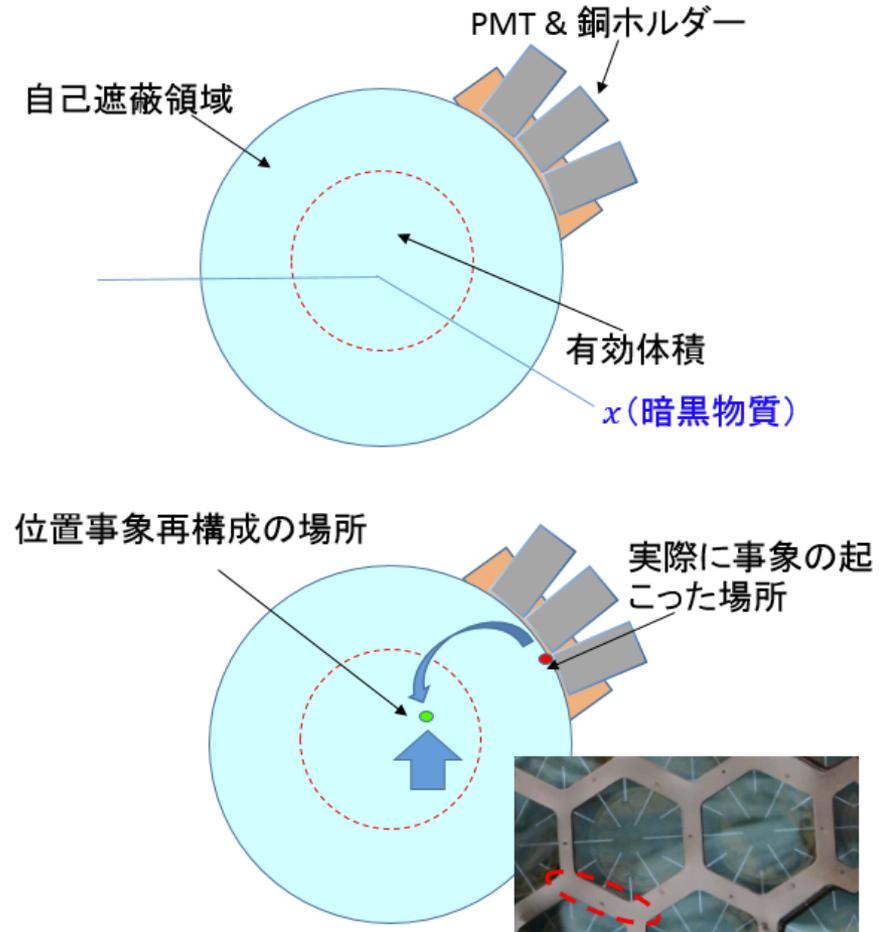
2016年秋の学会での小川さんのスライド



- 左図: fitで求めたRI activityのmean (右図の赤点) によるBGMCとdataのNPEスケールのエネルギー分布。有効体積カットはしていない。
- 右上図: fitで求めたRI activityの誤差 (右上図の黒線)を含むBGMCとdataのNPEスケールのエネルギー分布。有効体積カットはしていない。
- Fit後は、DataとMCの予想はよく一致している。
- 右下図: MC/dataの分布。1500~1800keV付近除いて誤差(青+赤)の範囲内である。

# どのような事象が有効体積内に残るのか

- 壁ぎわ・隙間事象: ~90%
  - PMT死角部分で起こった事象が、PMTにより検出される光量分布が有効体積内事象と似てしまう。
  - 検出器銅表面・内部のPb210, 検出器部材からの $\gamma$ が壁ぎわ・隙間で発光したもの。
  - ※銅内部のPb210含有:  $\alpha$ カウンタの測定についてはJPS2016Mar報告済み(小林)
- 液体キセノン中のRI事象: ~10%
  - Rn222娘核種Pb214, Bi214や Kr85, Ar等
- 中性子起源: 少ない
  - 検出器部材の( $\alpha, n$ ), fissionからの中性子
  - 詳細: 竹田



**このBGに対する系統誤差の見積もりを慎重に行っている。**

- 検出器Geometry (最大と見積もられる)
- Xenon の発光特性
- 事象再構成

# 近い将来に期待される成果

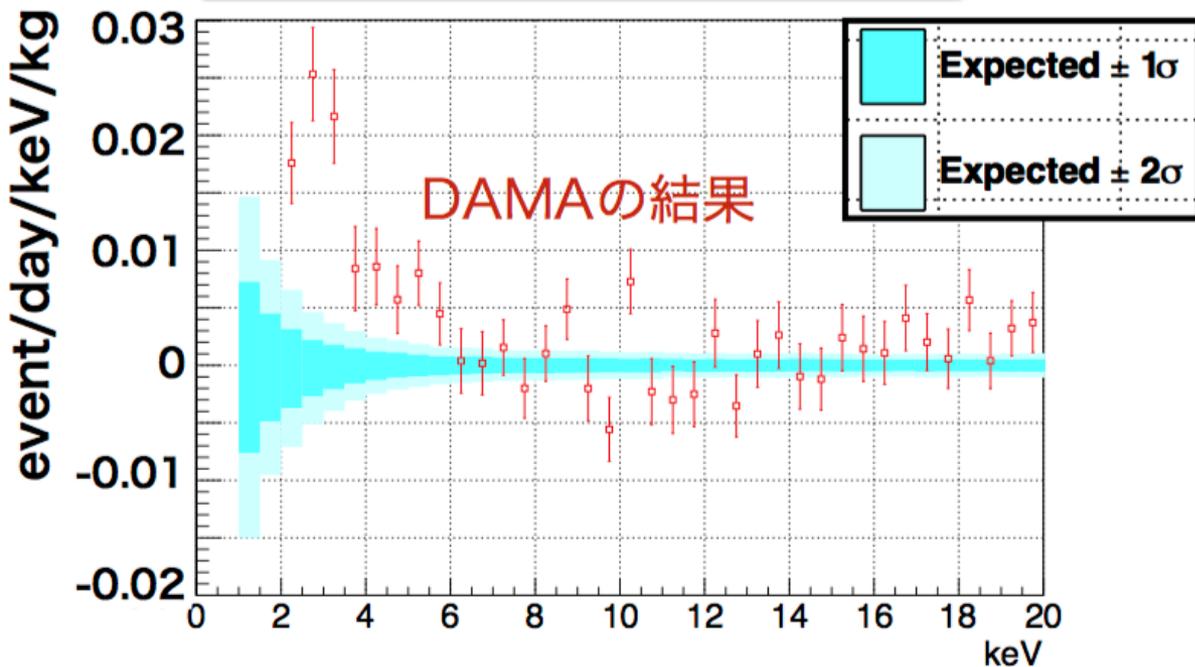
## Annual modulation

- 345.5 d  $\rightarrow$  787.7 d
- データがより安定
- (低閾値でのDAQ (2015年12月から))

pe/keV



Modulationがない場合に対する振幅の感度



DAMA/LIBRA claim の  
全領域を追試

(申請時の公約の達成)

# 近い将来に期待される成果(Cont.)

- ▶ 有効体積解析による結果
- ▶ 二重電子捕獲反応探索のUpdate
- ▶ Super WIMPs 探索のUpdate
- ▶ KK-Axion 探索
- ▶ (銀河内の超新星爆発があれば) 超新星爆発 $\nu$ の観測
- ▶ など

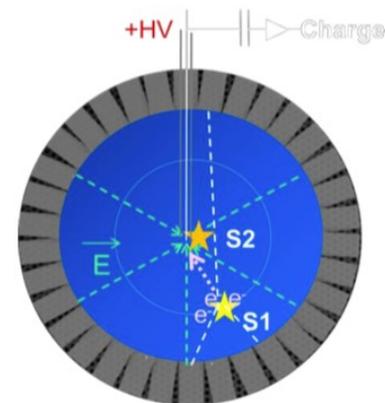
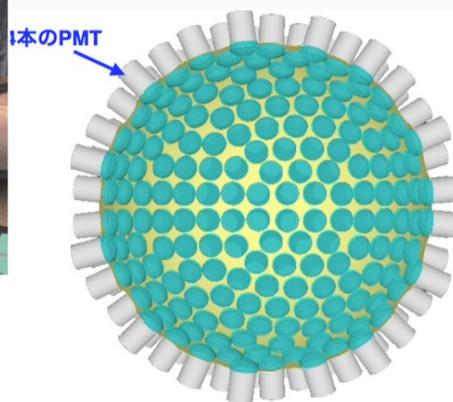
# 将来の低バックグラウンド検出器

新型3"凸型PMT開発



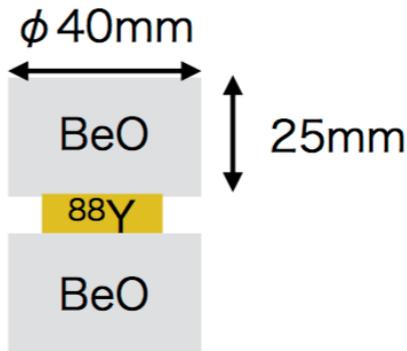
Geスクリーニング

検出器のデザイン

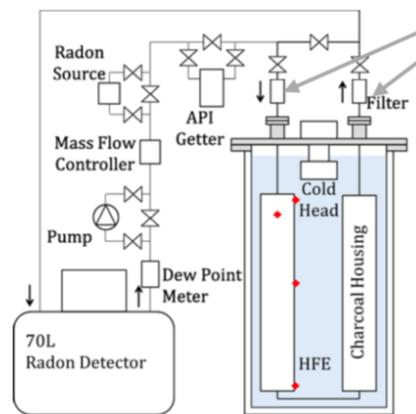


液体TPCの基礎研究

低エネルギー単色中性子線源



Rn対策フィルムの開発



液体キセノンからのRn除去



アルファ線検出器による表面測定と内部の鉛測定

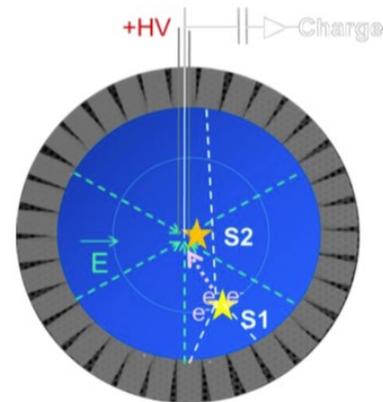
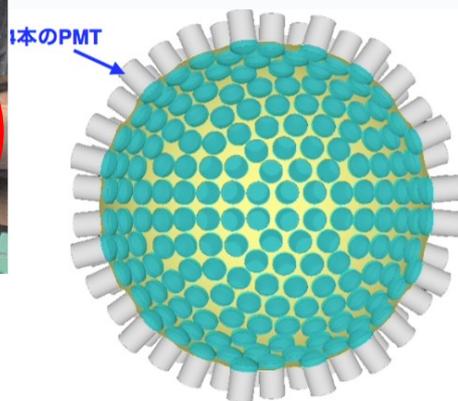
# 将来の低バックグラウンド検出器

新型3"凸型PMT開発



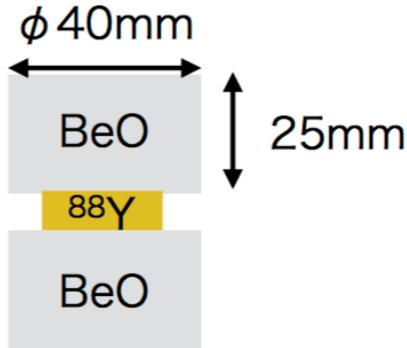
Geスクリーニング

検出器のデザイン

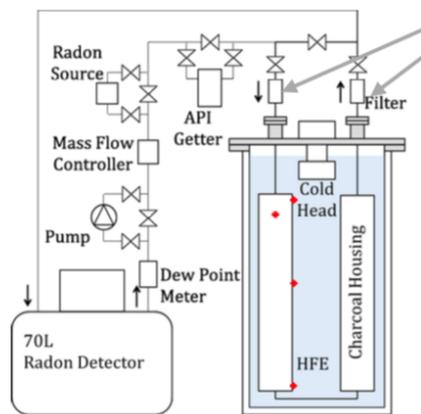


液体TPCの基礎研究

低エネルギー単色中性子線源



Rn対策フィルムの開発



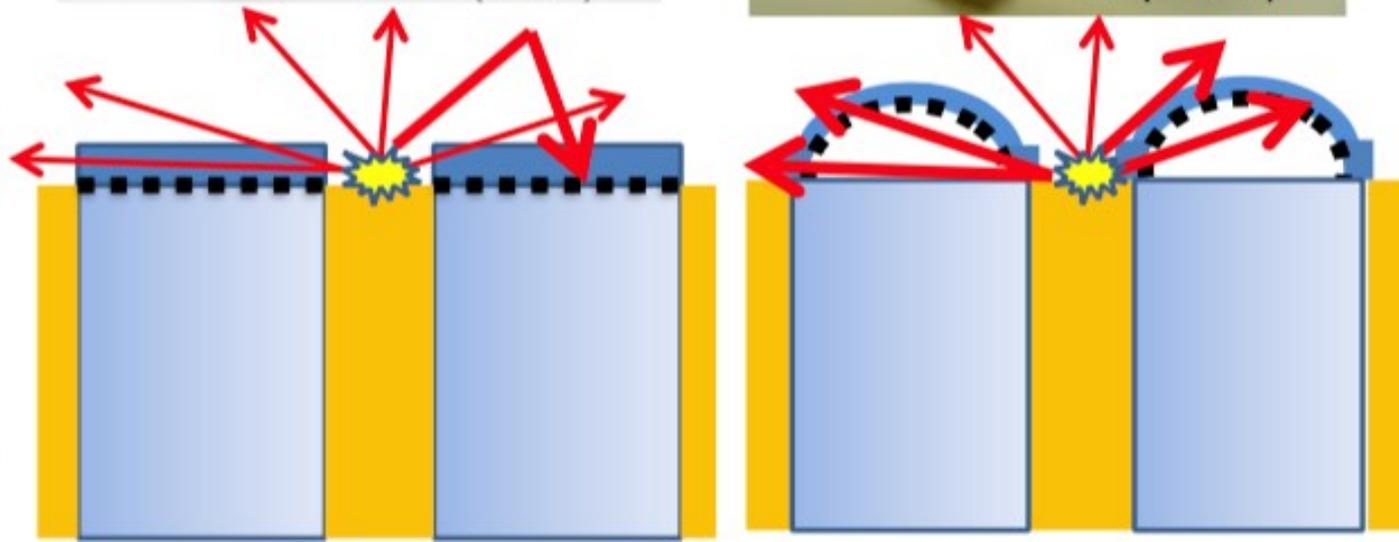
液体キセノンからのRn除去



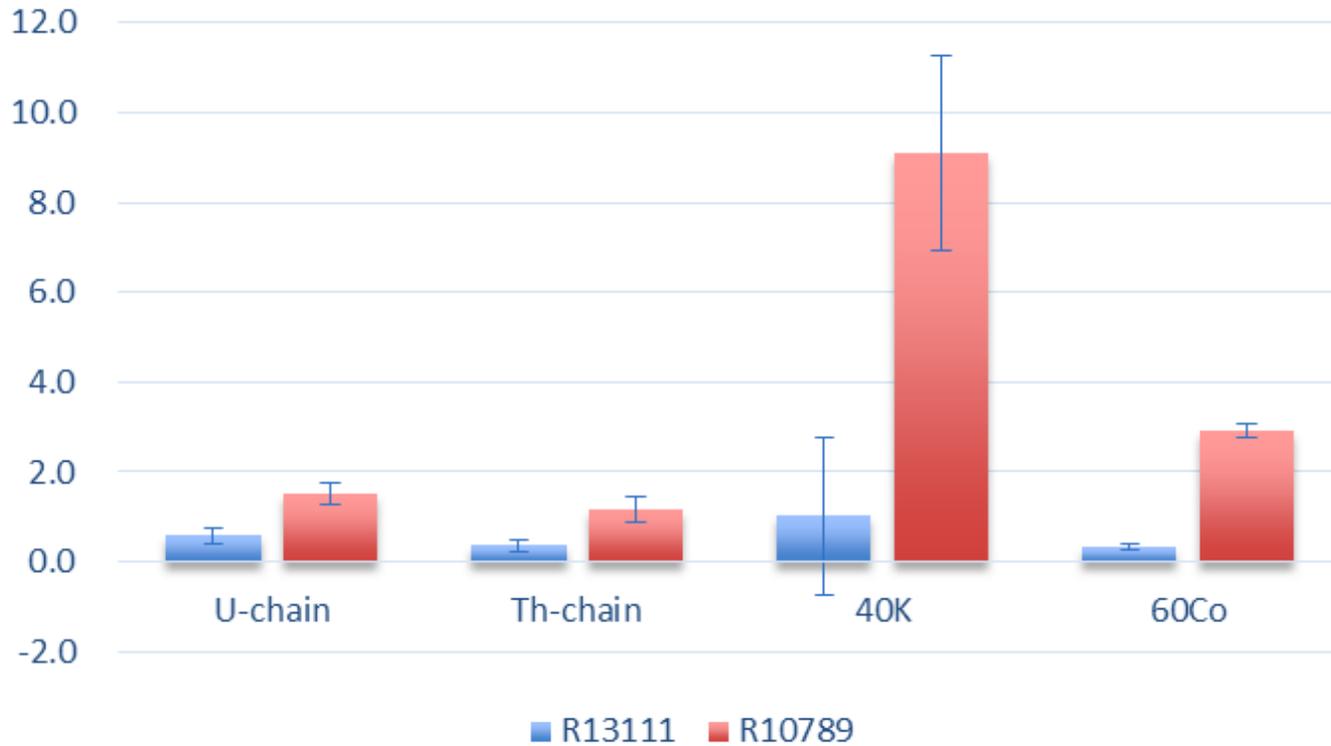
アルファ線検出器による表面測定と内部の鉛測定

# 新型 3"凸型PMT

- ▶ 超低バックグラウンド
- ▶ 新型 3"凸型PMT (R13111) で表面の事象を逃さない



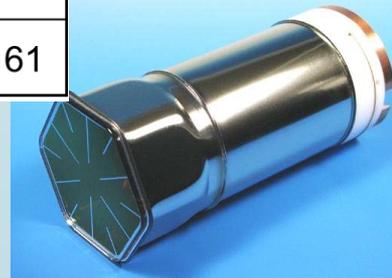
# R13111とR10789比較



[mBq/PMT]	U chain	Th chain	40K	60Co
Target	0.15		1.00	0.30
R13111	0.624±0.168	0.478±0.152	<1.24	0.478±0.0567
R10789	1.51±0.243	1.16±0.27	9.10±2.15	2.92±0.161

**R 1 3 1 1 1**

**R 1 0 7 8 9**



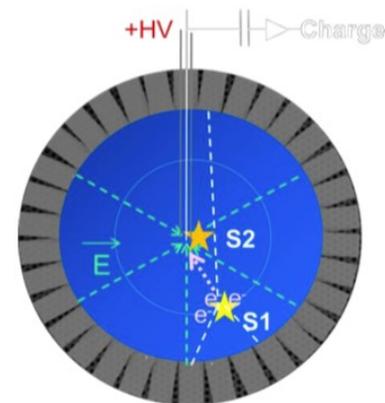
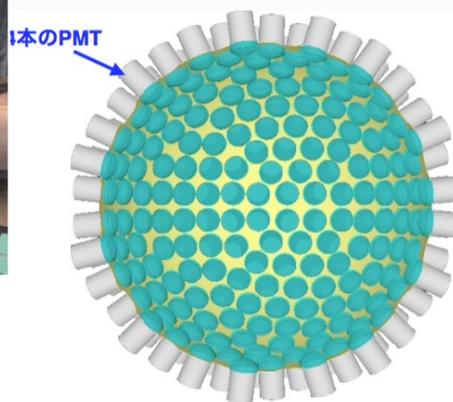
# 将来の低バックグラウンド検出器

新型3"凸型PMT開発



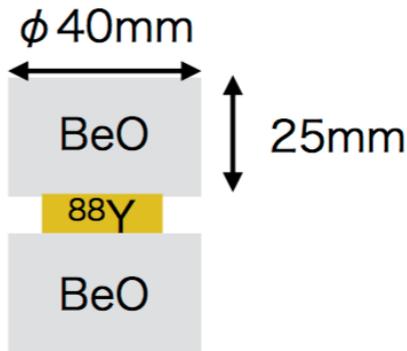
Geスクリーニング

検出器のデザイン

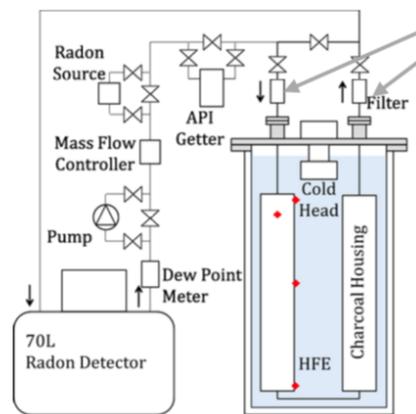


液体TPCの基礎研究

低エネルギー単色中性子線源



Rn対策フィルムの開発



液体キセノンからのRn除去

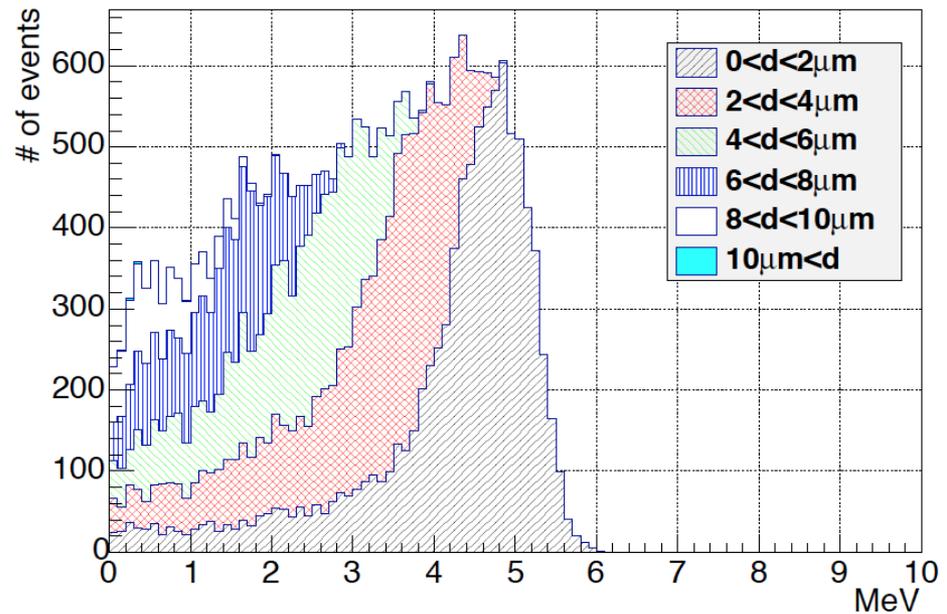


アルファ線検出器による表面測定と内部の鉛測定

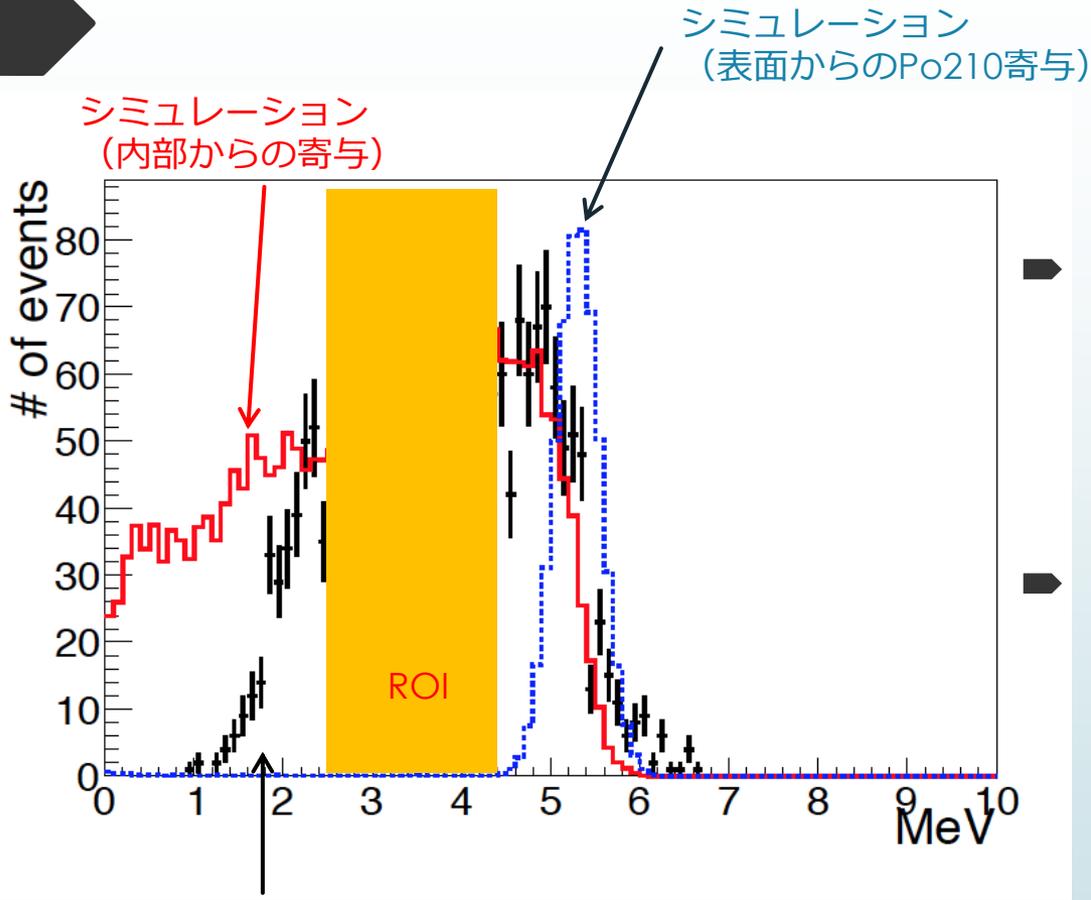
# 表面アルファ線検出器を用いた Cu内部の放射性鉛の微量測定



- ▶ アルファ線も短距離なら金属中も突き抜ける
- ▶ 電解研磨表面など滑らかな面の凹凸は、この距離より短い



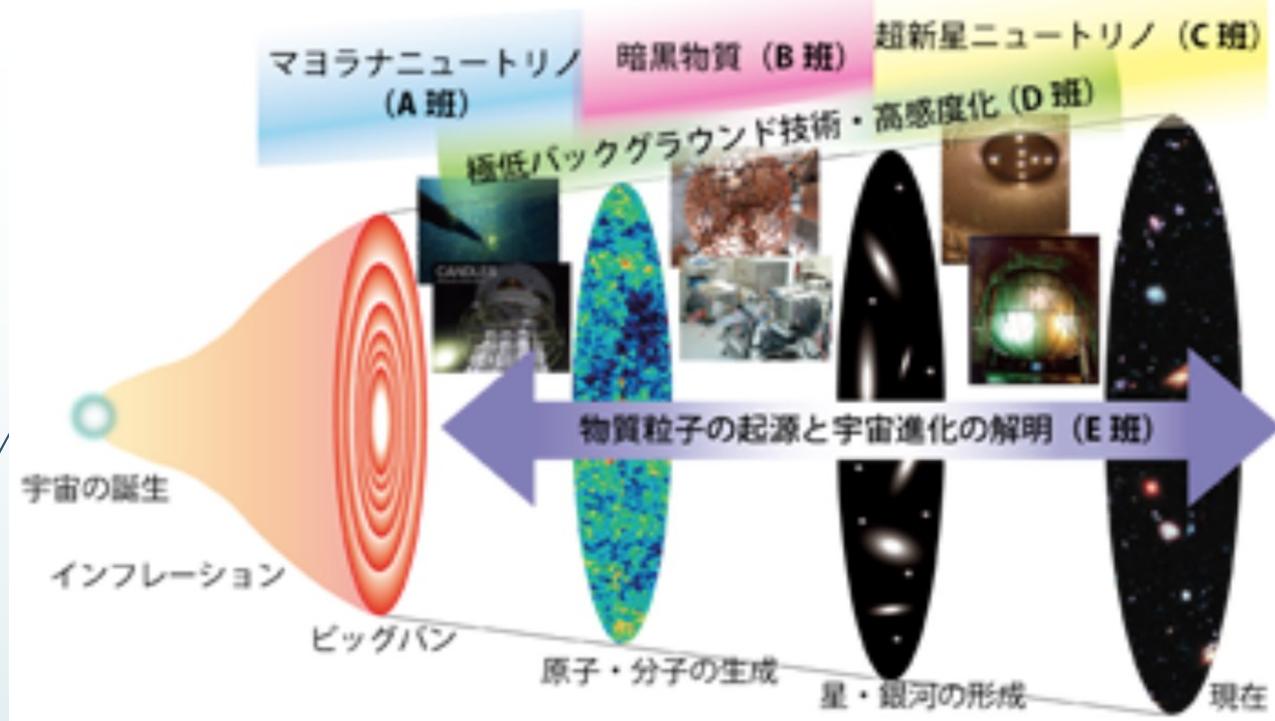
内部からの (Po210の) アルファ線は、  
表面α線ピーク位置から離れた場所に連続スペ  
クトルをなす



実データ  
(2 MeV以下はEfficiencyの影響で下がっている)

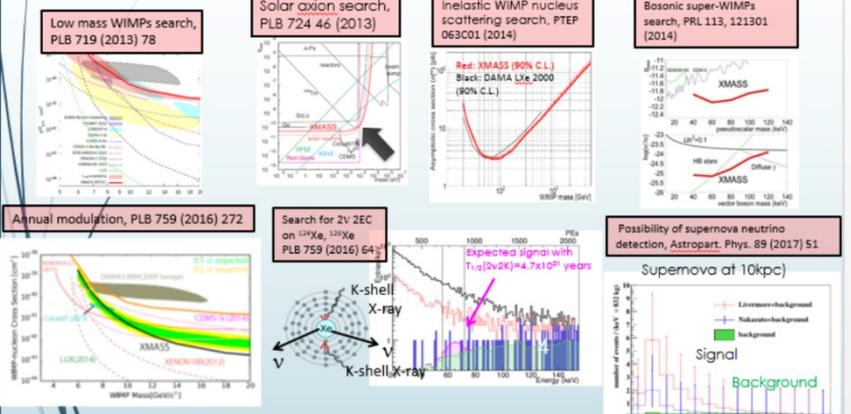
- ▶ これまでにはない感度での含有鉛測定が可能
  - ▶ 数 mBq/kg
  
- ▶ 6 N 銅, 電鍍銅は非常にきれい
  - ▶ 上限値のみ
  - ▶ 6 N :  $^{210}\text{Pb} < 4.0 \text{ mBq/kg}$
  - ▶ 電鍍 :  $^{210}\text{Pb} < 2.8 \text{ mBq/kg}$

みなさん使ってください



### XMASS physics results

Owing to low background for  $e/\gamma$  events (not only nuclear recoil), various kinds of dark matter candidates and physics topics have been searched for.



竹田さんの XeSAT2017のスライドから

### 将来の低バックグラウンド検出器

新型3"凸型PMT開発

検出器のデザイン

Geスクリーニング

Rn対策フィルムの開発

低エネルギー単色中性子線源

液体キセノンからのRn除去

アルファ線検出器による表面測定と内部の鉛測定

液体TPCの基礎研究