Search Axions & ALPs in PandaX-II

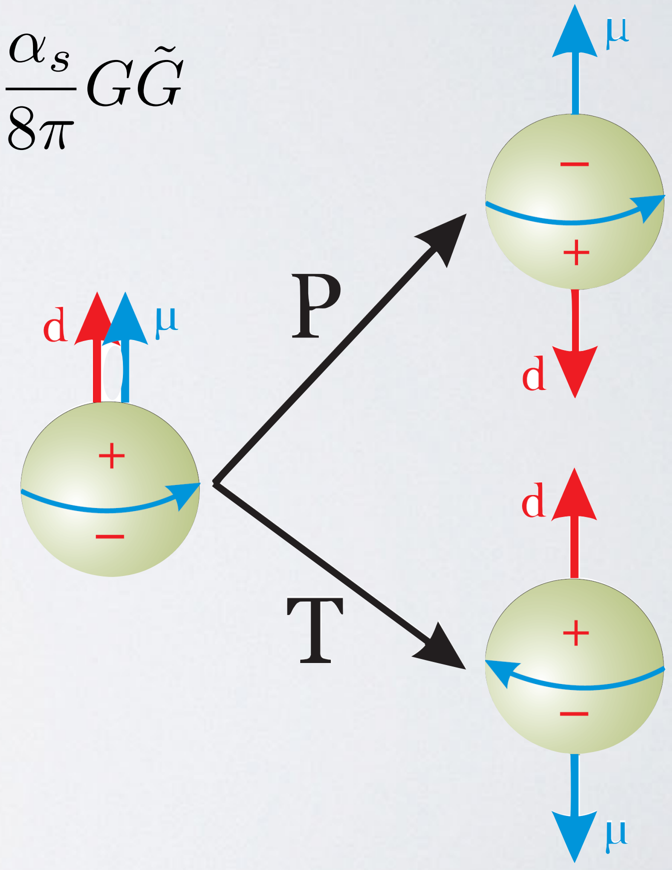
Xiaopeng ZHOU

Strong CP Problem

- Weak interaction violates CP. Why not STRONG ?
  - there are natural terms in the QCD Lagrangian that are able to break the CP-symmetry.

$$\mathcal{L}_{QCD} = \sum_q \bar{\Psi}_q (iD - m_q)\Psi_q - \frac{1}{4}GG - \underbrace{(\Theta - arg\ det\ M_q)}_{-\pi \leqslant \bar{\Theta} \leqslant +\pi} \frac{\alpha_s}{8\pi} G\tilde{G}$$

- The measured upper limit of CP violation in strong interaction is ~10 orders of magnitude smaller than predictions
  - nEDM constrains this angle to be less than 10^{-10} rad



$$|d| < 2.9 \times 10^{-26} e\ cm$$

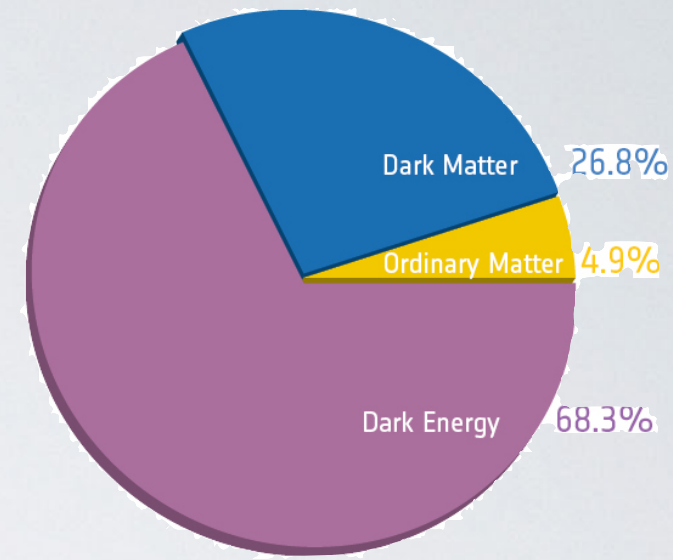
Peccei-Quinn theory and Axion

- PQ theory (1977,Peccei & Quinn) is plausible to solve
  - explain $\bar{\Theta}$ by a symmetry → $\mathbf{U(1)_{PQ}}$.
- $\mathbf{U(1)_{PQ}}$ spontaneously broken → **Nambu–Goldstone bosons**
  - **Axion** (1978, Wilczek & Weinberg)

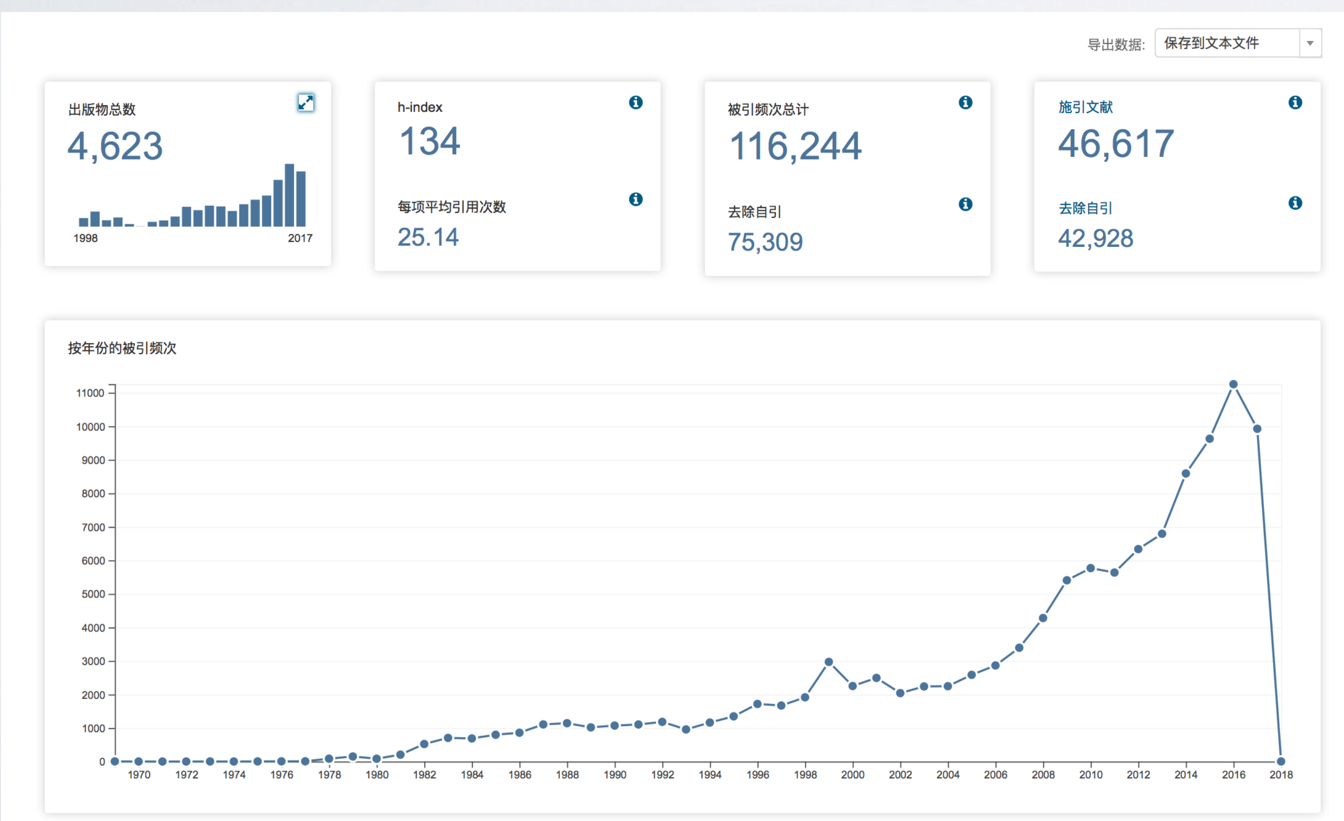
I named them after a laundry detergent, since they clean up a problem with an axial current. (2004 Nobel Lecture)

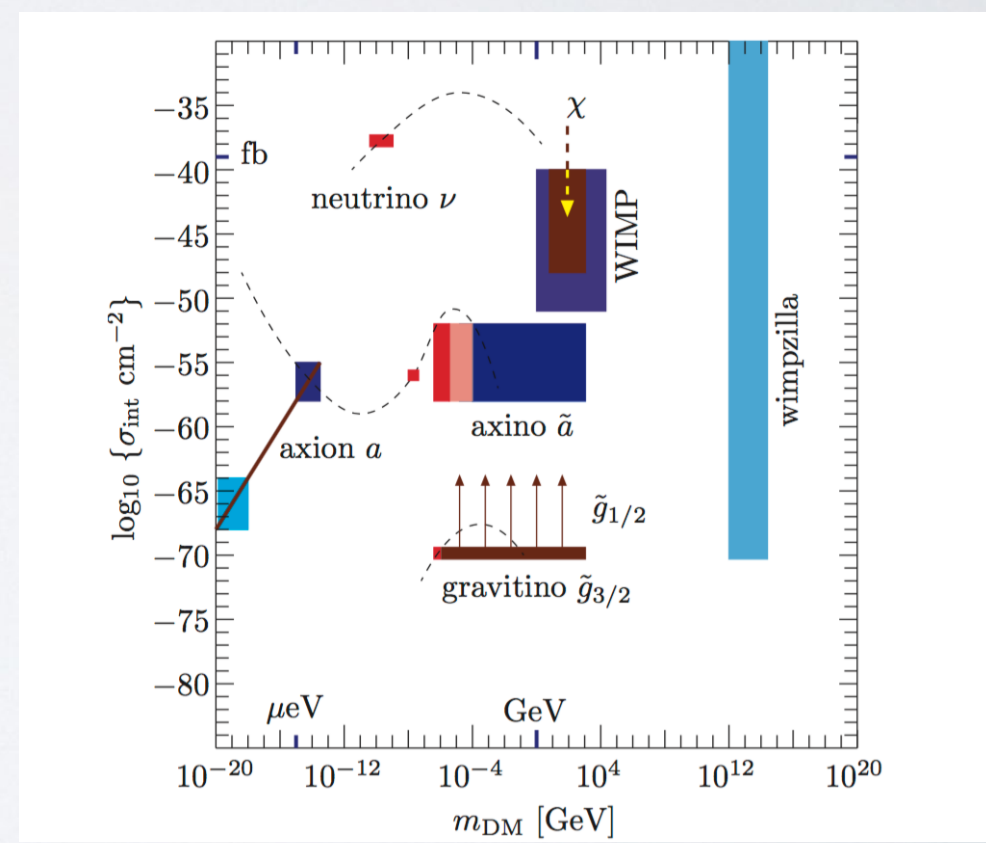
Axion and DM

" I'm much more optimistic about the dark matter problem.
Here we have the unusual situation that **two** good ideas exist…" from Wilczek *(Physics Today, Oct. '03)*



http://www.esa.int/spaceinimages/Images/2013/03/Planck_cosmic_recip

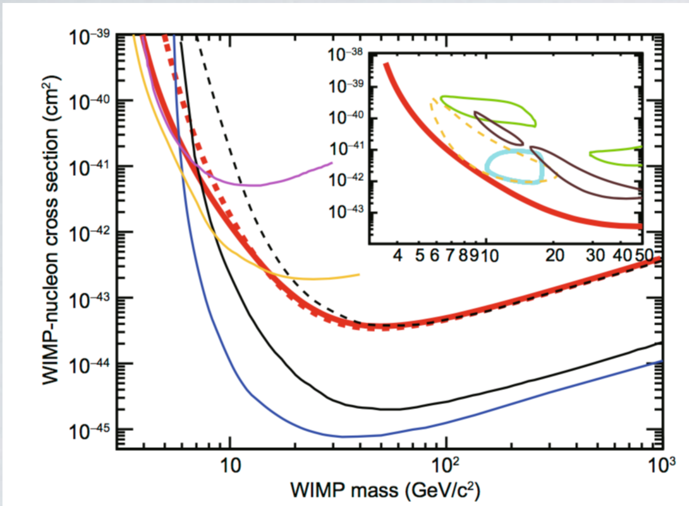




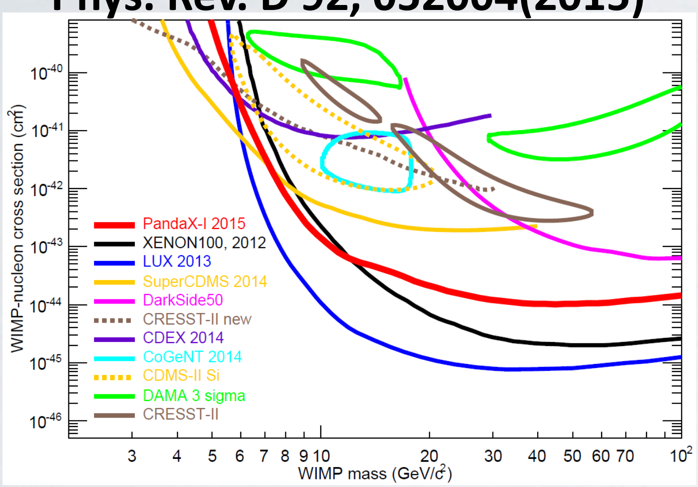
Kim, Jihn E., and Gianpaolo Carosi. "Axions and the strong CP problem." *Reviews of Modern Physics* 82.1 (2010): 557.

PandaX

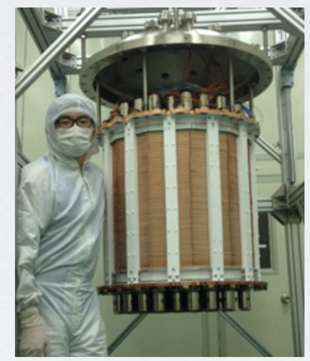
Sci. China Phys. Mech. Astron. (2014) 57: 2024.



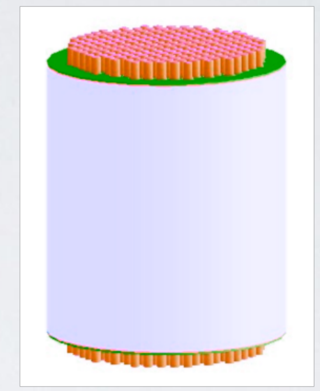
Phys. Rev. D 92, 052004(2015)



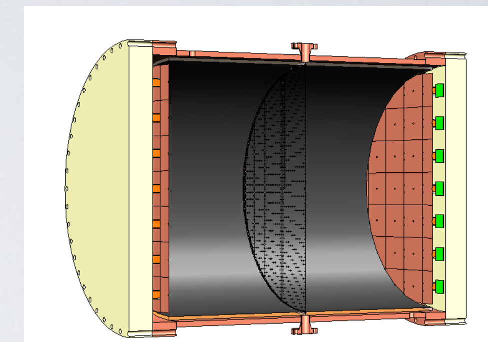
Phase I:
120 kg DM
2009-2014



Phase II:
500 kg DM
2014-2018

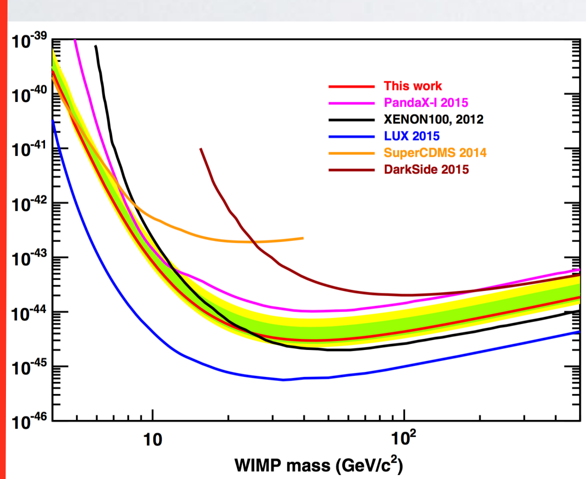


PandaX-xT: multi-ton DM
future

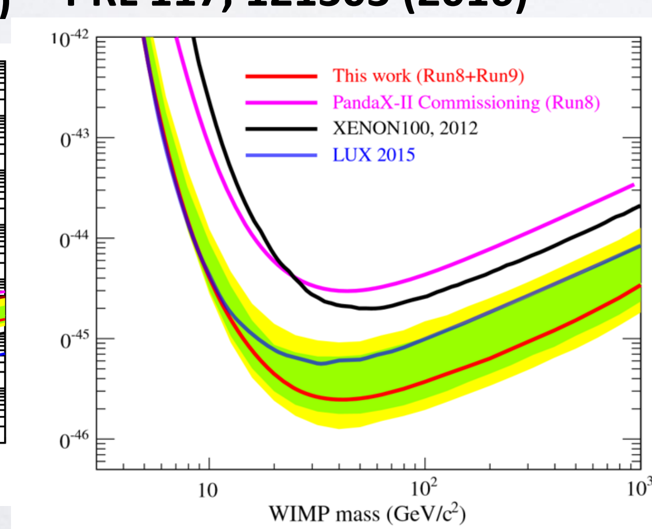


PandaX-III:
0.2- 1 ton ^{136}Xe 0vDBD
future

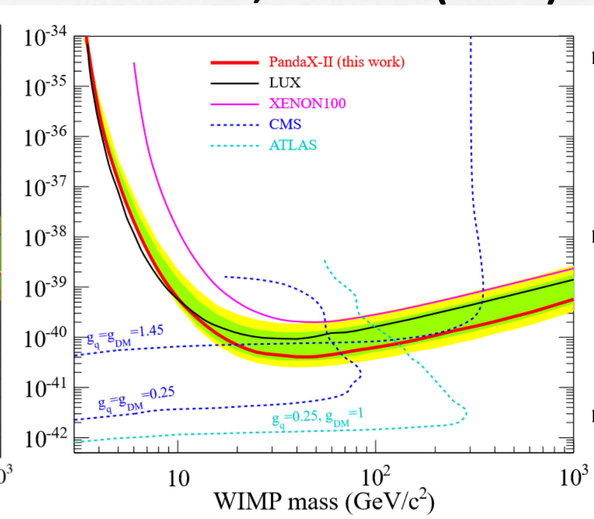
Phys. Rev. D 92, 052004(2015)



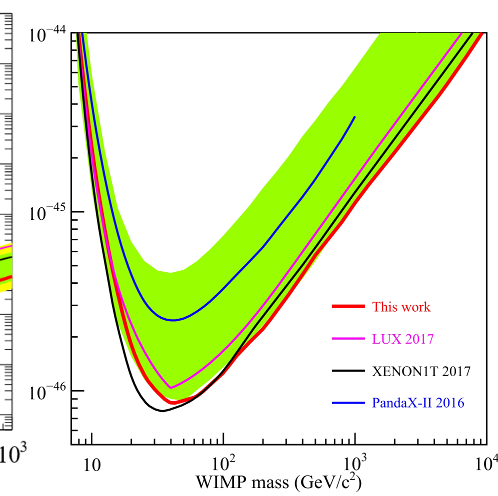
PRL 117, 121303 (2016)



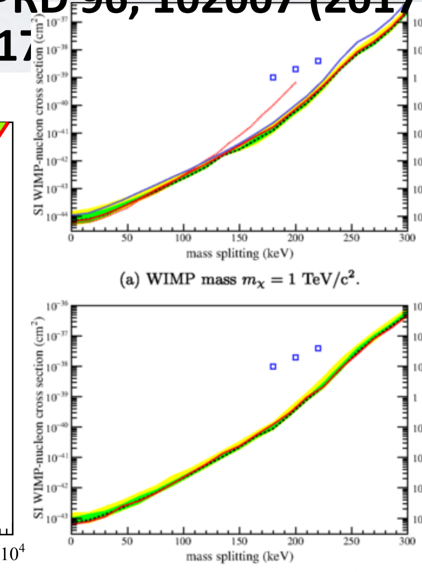
PRL 118, 071301 (2017)



PRL 119, 181302 (2017)

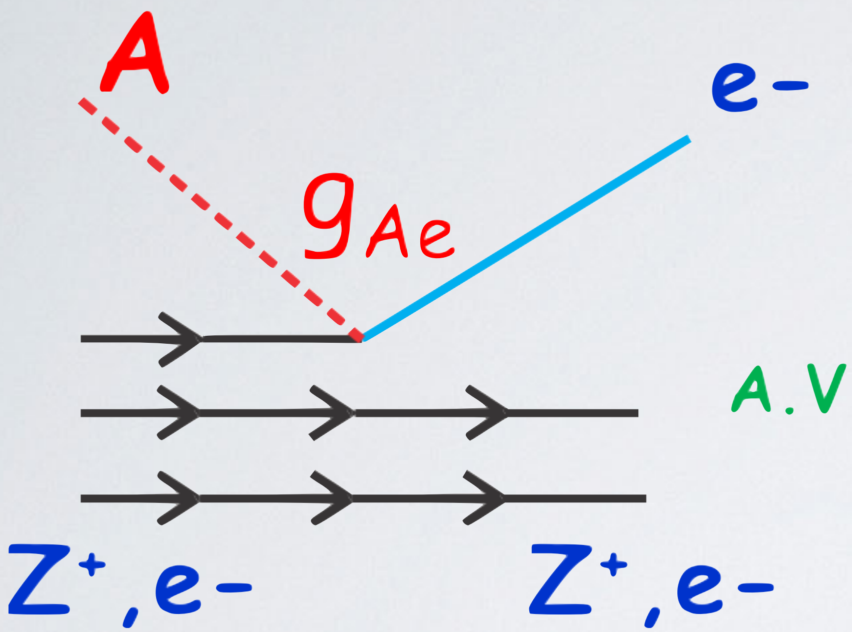


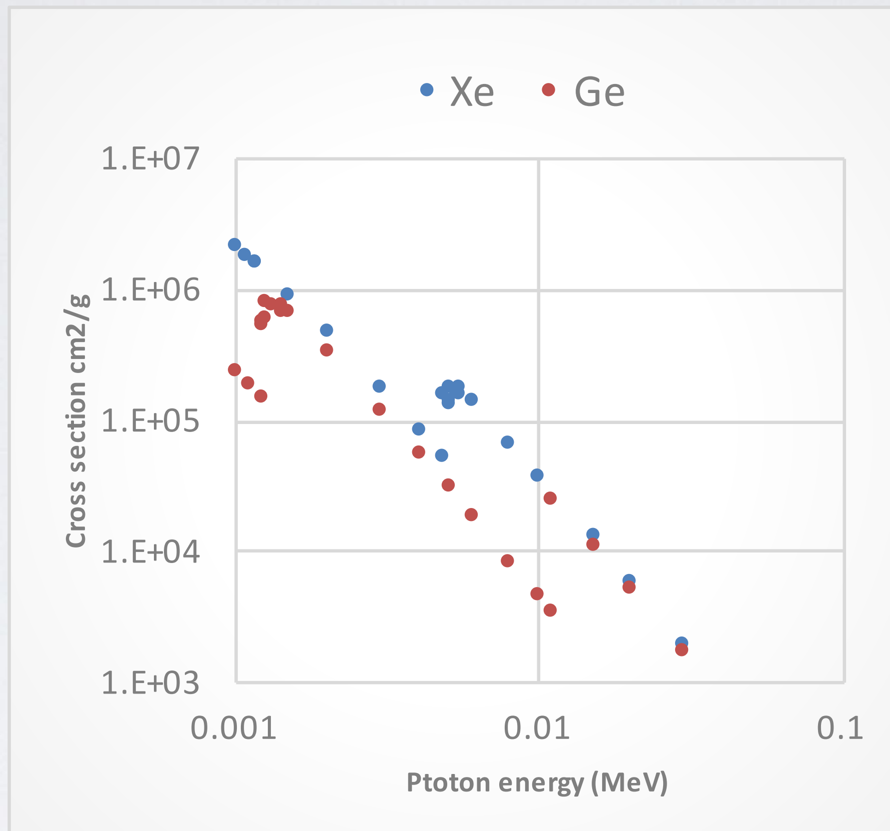
PRD 96, 102007 (2017)

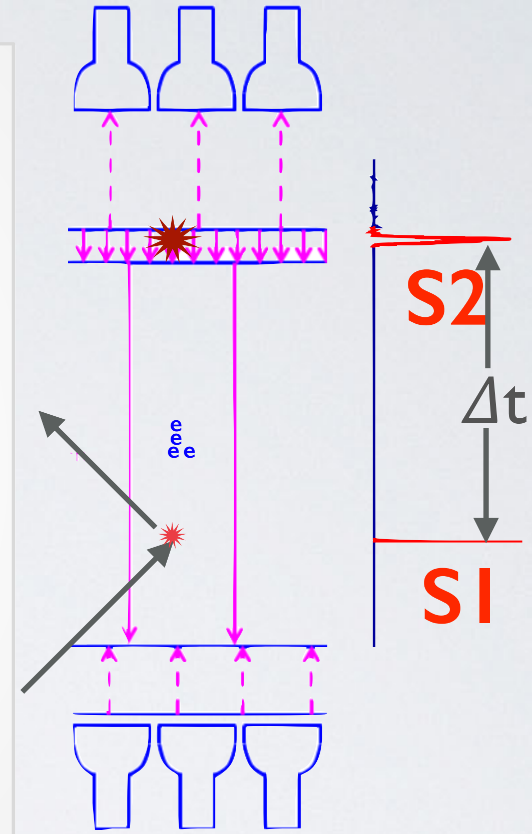


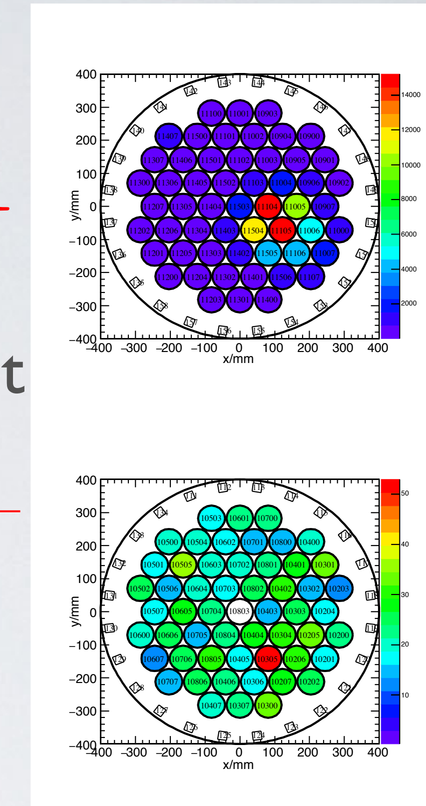
Axion searches in Underground Experiments

Axio-electric effect









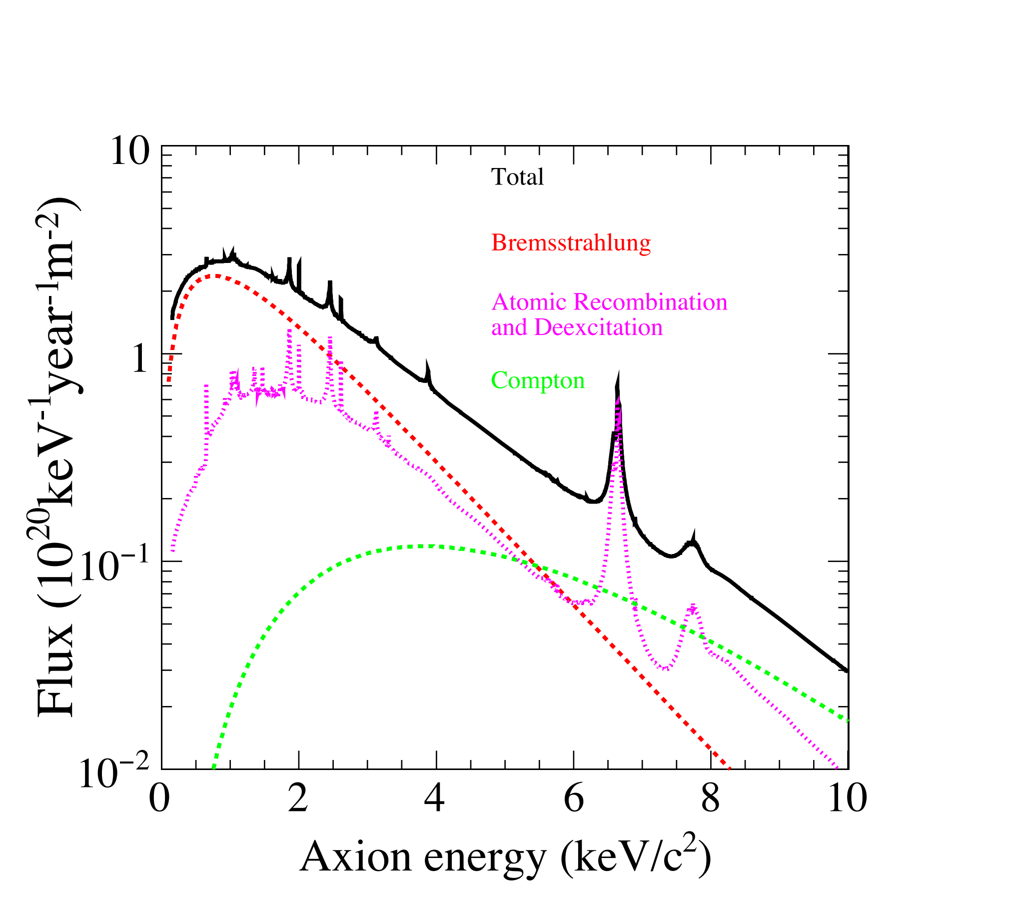
$$\sigma_{Ae}(E_A) = \sigma_{pe}(E_A)\frac{g_{Ae}^2}{\beta}\frac{3E_A^2}{16\pi\alpha m_e^2}\left(1-\frac{\beta^{2/3}}{3}\right)$$

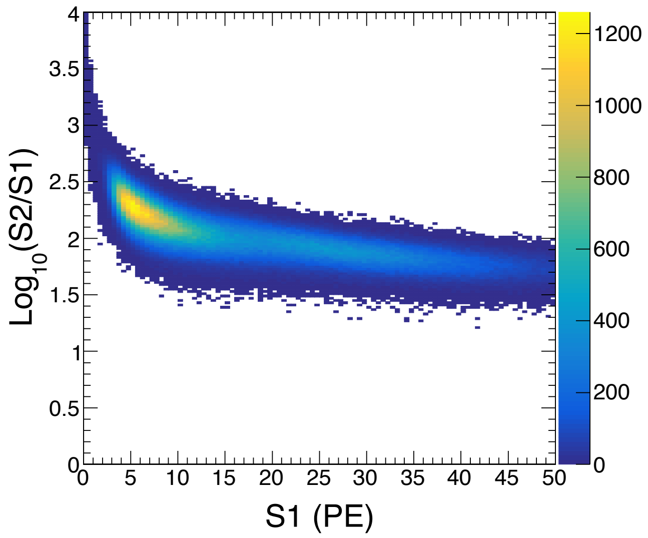
Search excess in Electron Recoil Spectrum!

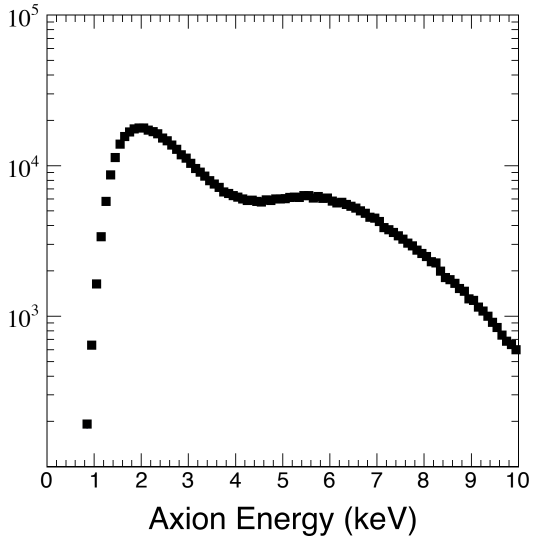
Solar Axion and Galactic ALPs

- Solar Axion
- Fe57 Axion
- G-ALPs

$$Compton - like\ scattering(C),\ \gamma + e^- \rightarrow e^- + a$$
$$axion - Bremsstrahlung(B),\ e^- + X \rightarrow e^- + X + a$$
$$atomic - Recombination(R),\ e^- + Y^+ \rightarrow Y + a$$
$$atomic - Deexcitation(D),\ Z^\star \rightarrow Z + a$$

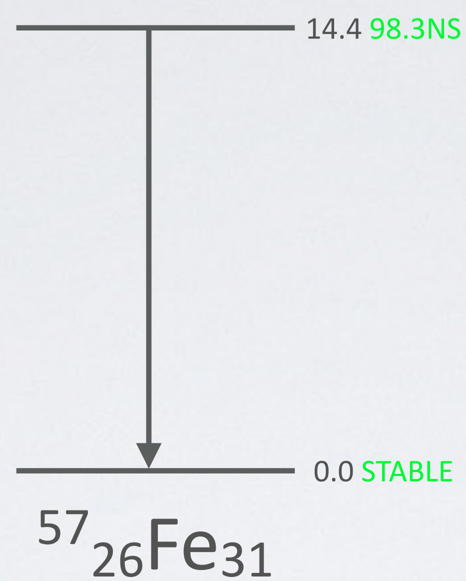






Solar Axion and Galactic ALPs

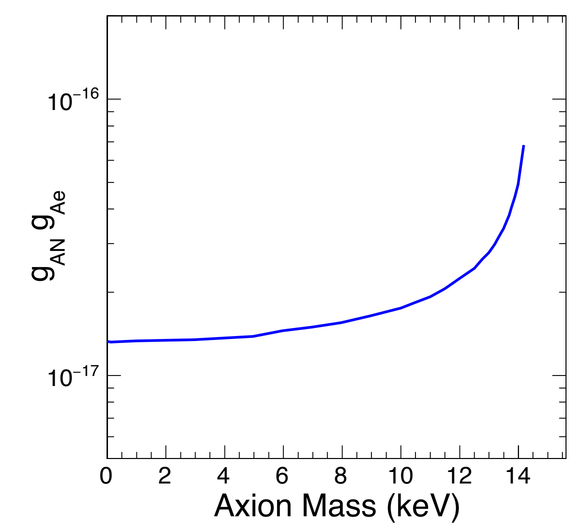
- Solar Axion
- **Fe57 Axion**
- G-ALPs

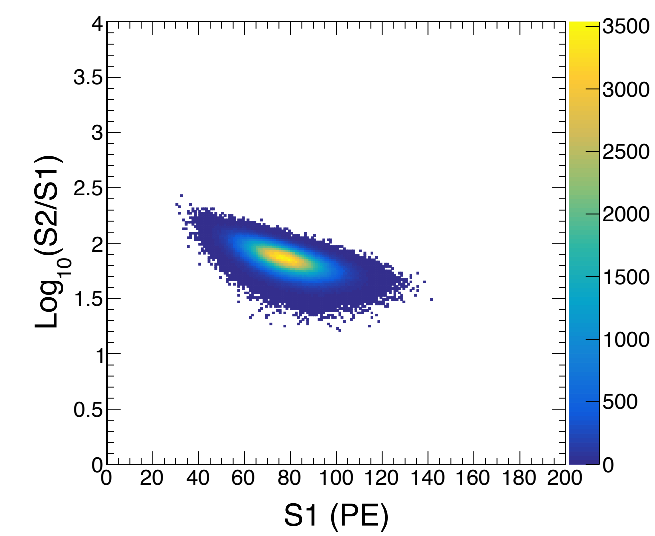


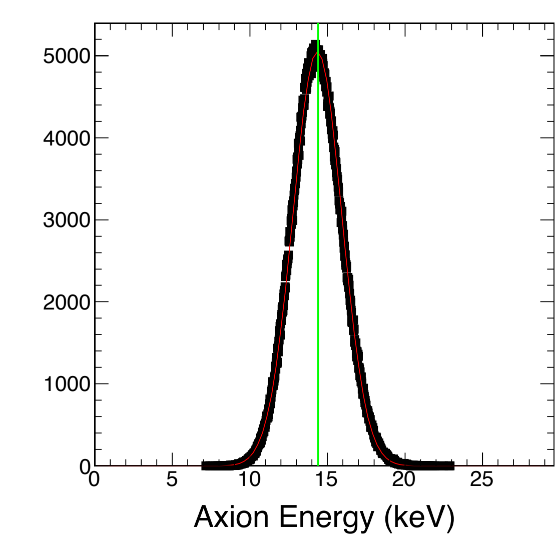
- 9e19/cm3 @ core
- low energy
- nuclei coupling (model dependent)

$$\Phi_{14.4} = 4.56 \times 10^{23} \cdot (g_{AN}^{\mathrm{eff}})^2 \left(\frac{k_A}{k_\gamma}\right)^3 \ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

- other possible source: $p + d \rightarrow \ ^3He + a(5.5\ MeV)$

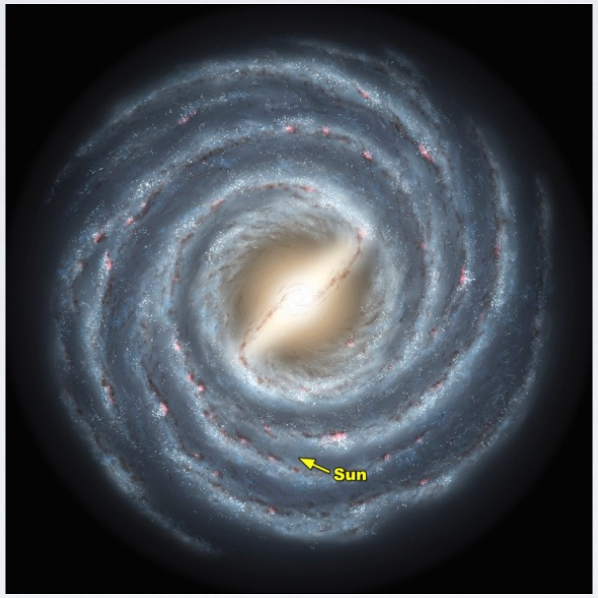




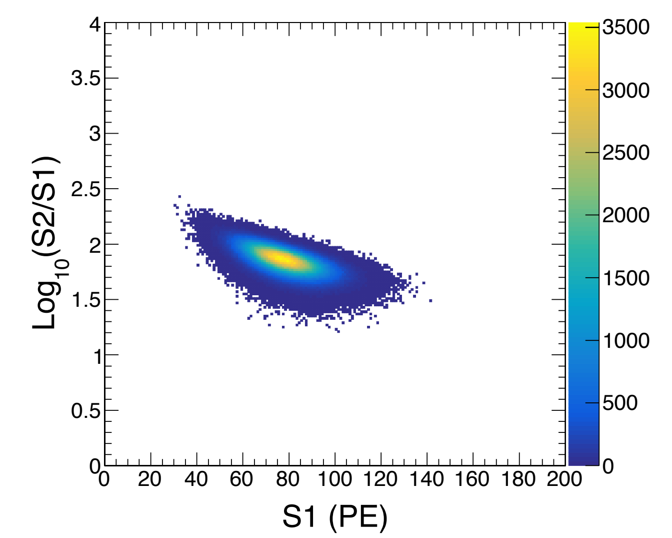


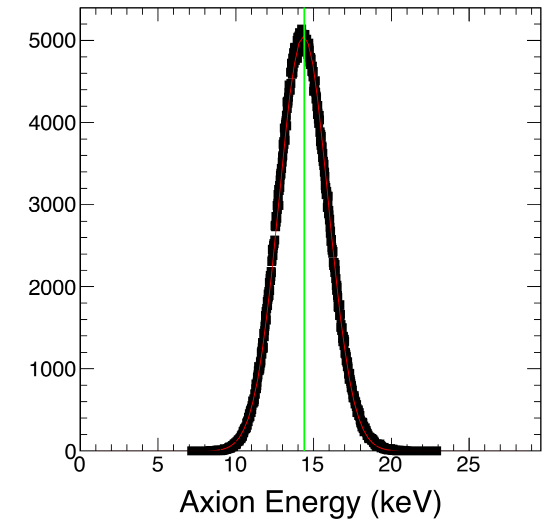
Solar Axion and Galactic ALPs

- Solar Axion
- Fe57 Axion
- G-ALPs

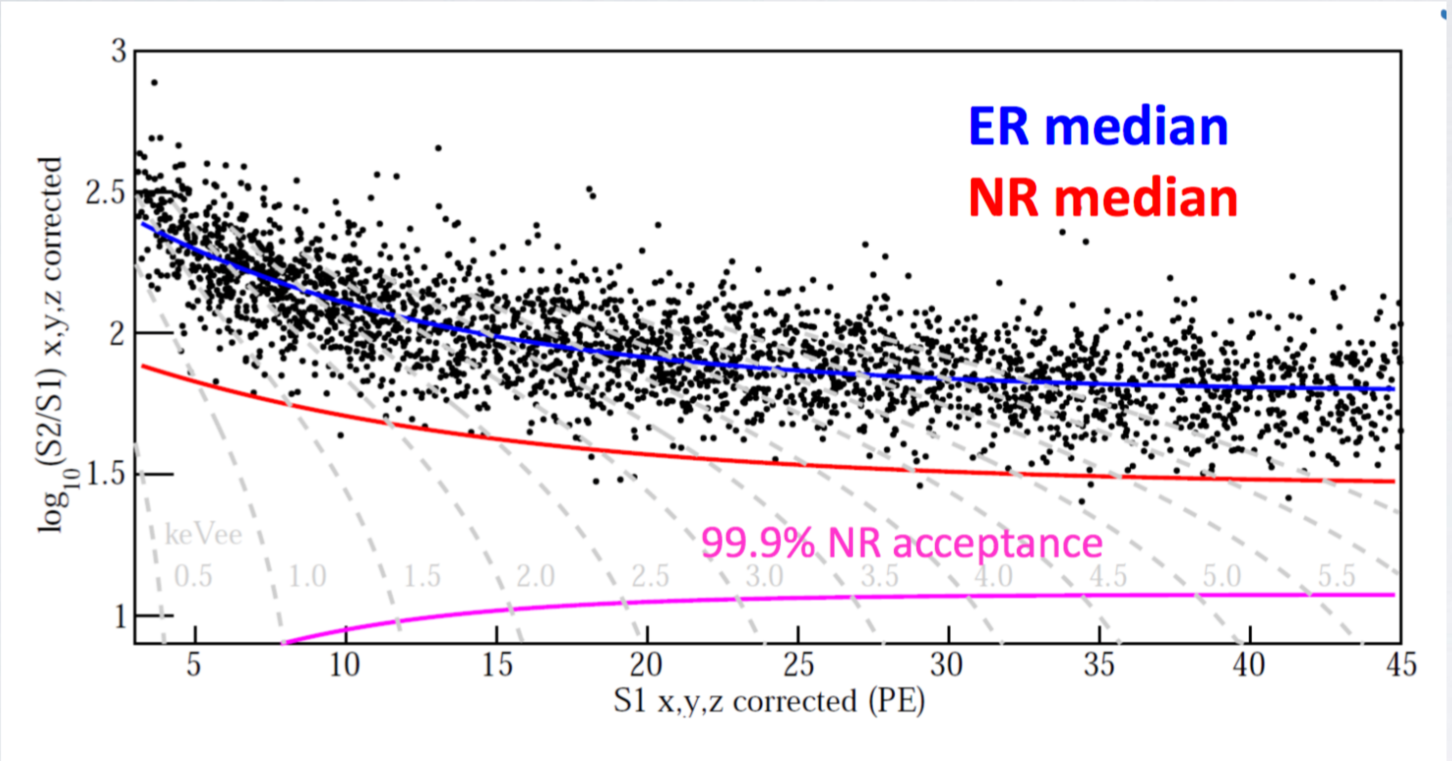


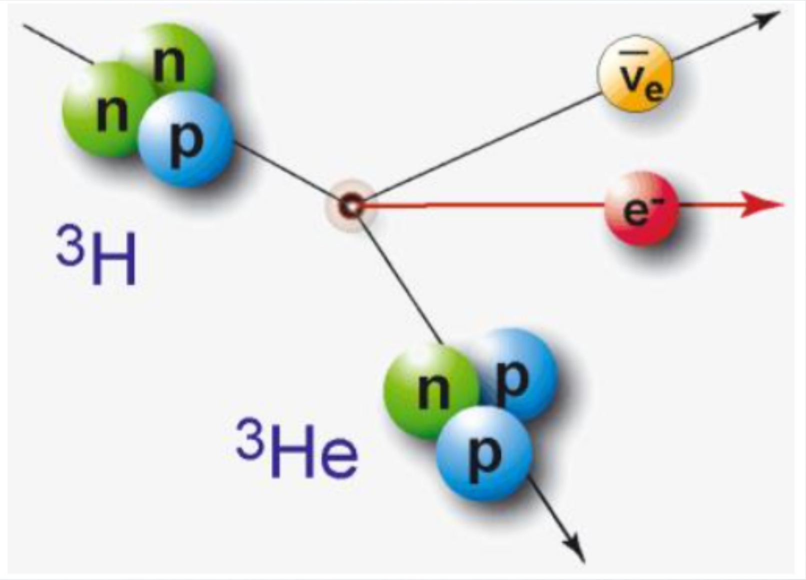
- 0.3GeV/cm3
- β~0.001
- same σ with axion
- extended energy scale

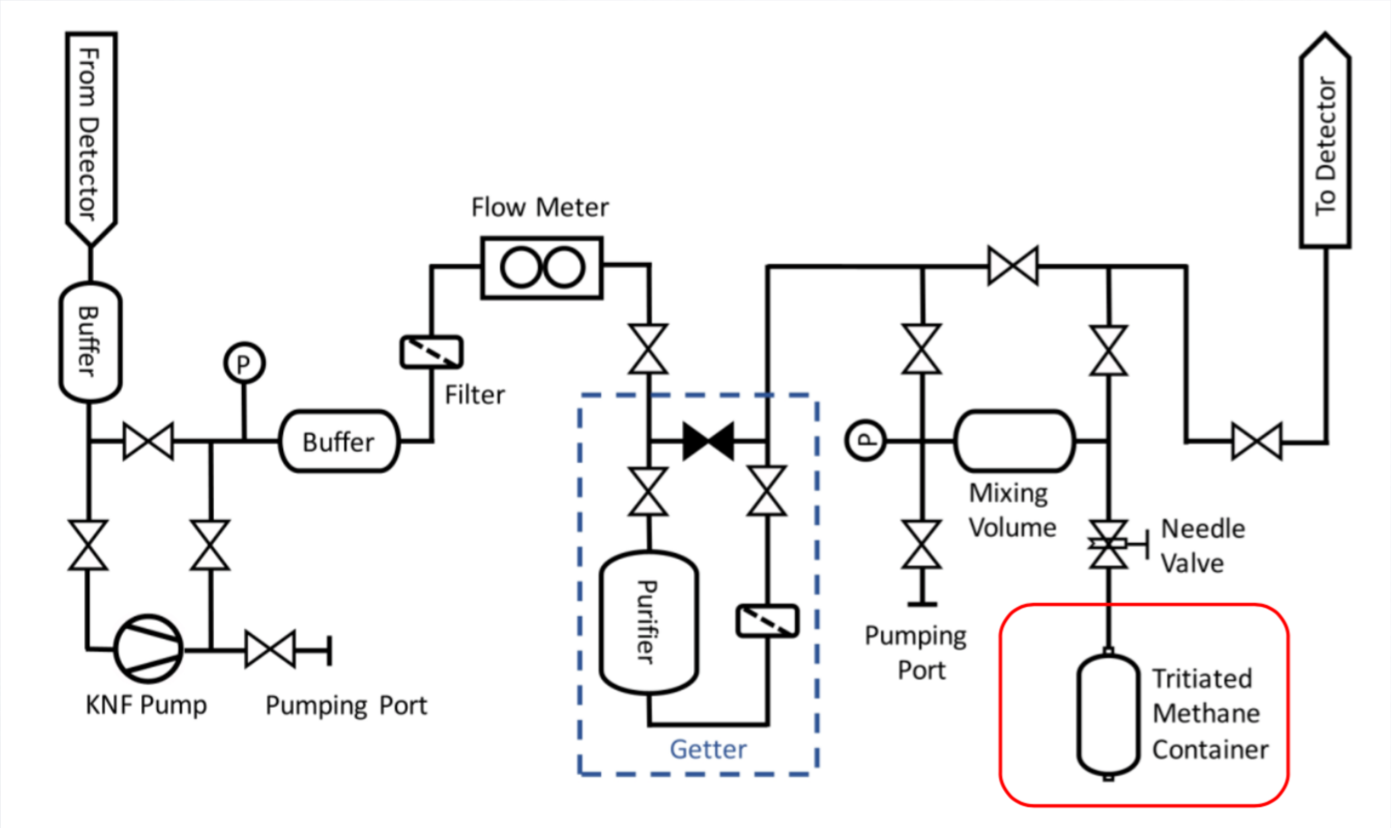




CH_3T Calibration in PandaX-II



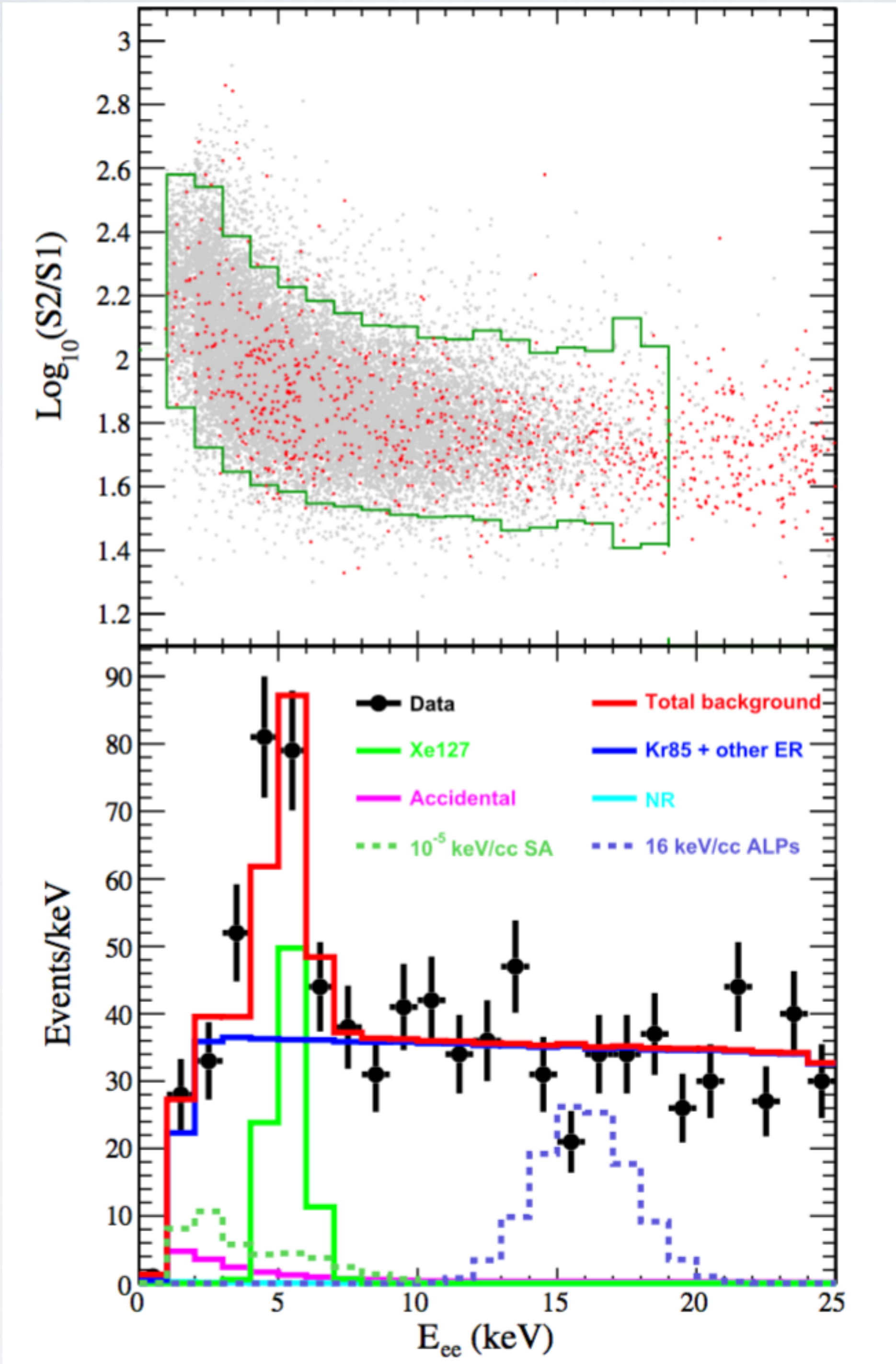


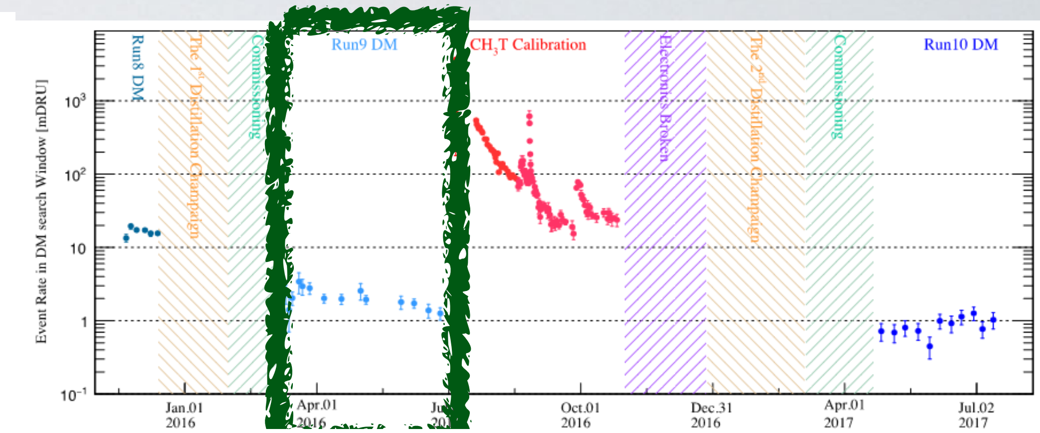


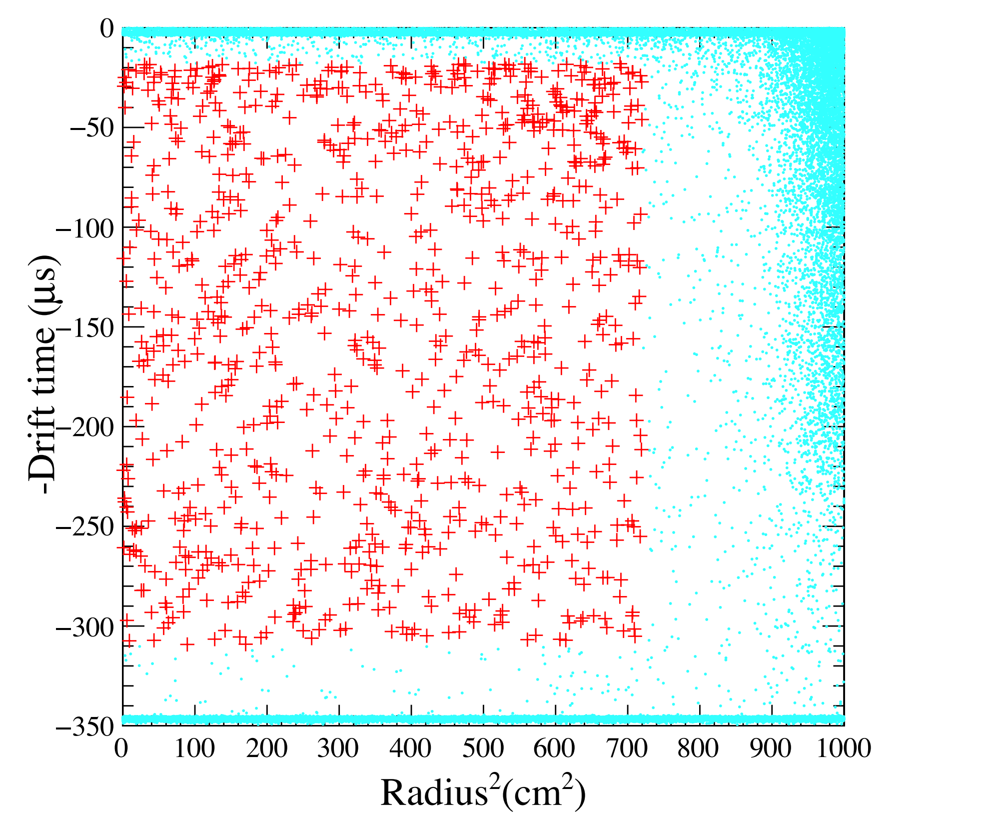
- Low energy ER evts response
- Efficiency (1.29keV threshold and 94% @ High energy region)

Data

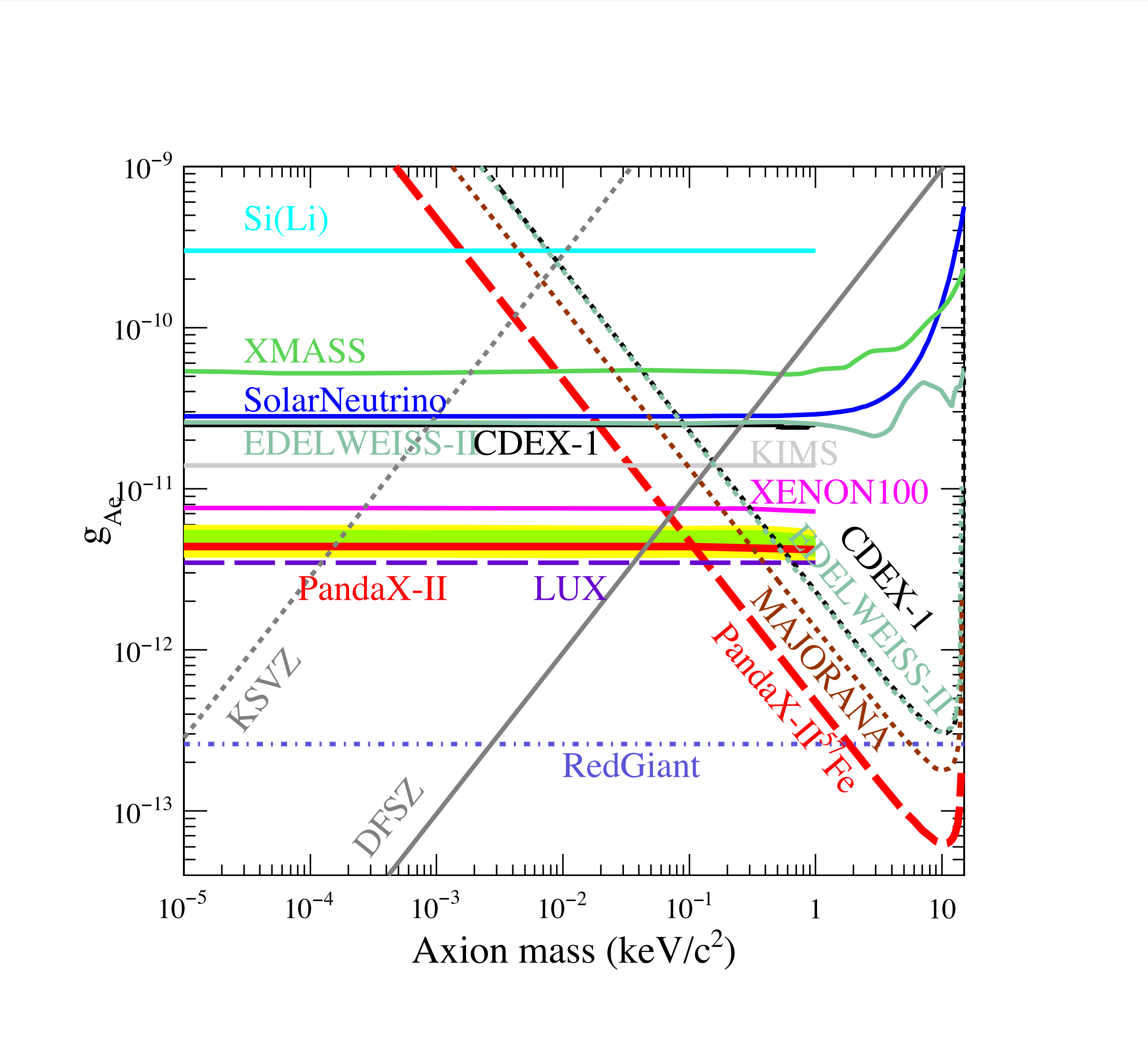
- 79.6 days
- main BKG
  - Xe127
  - Kr
  - Acc





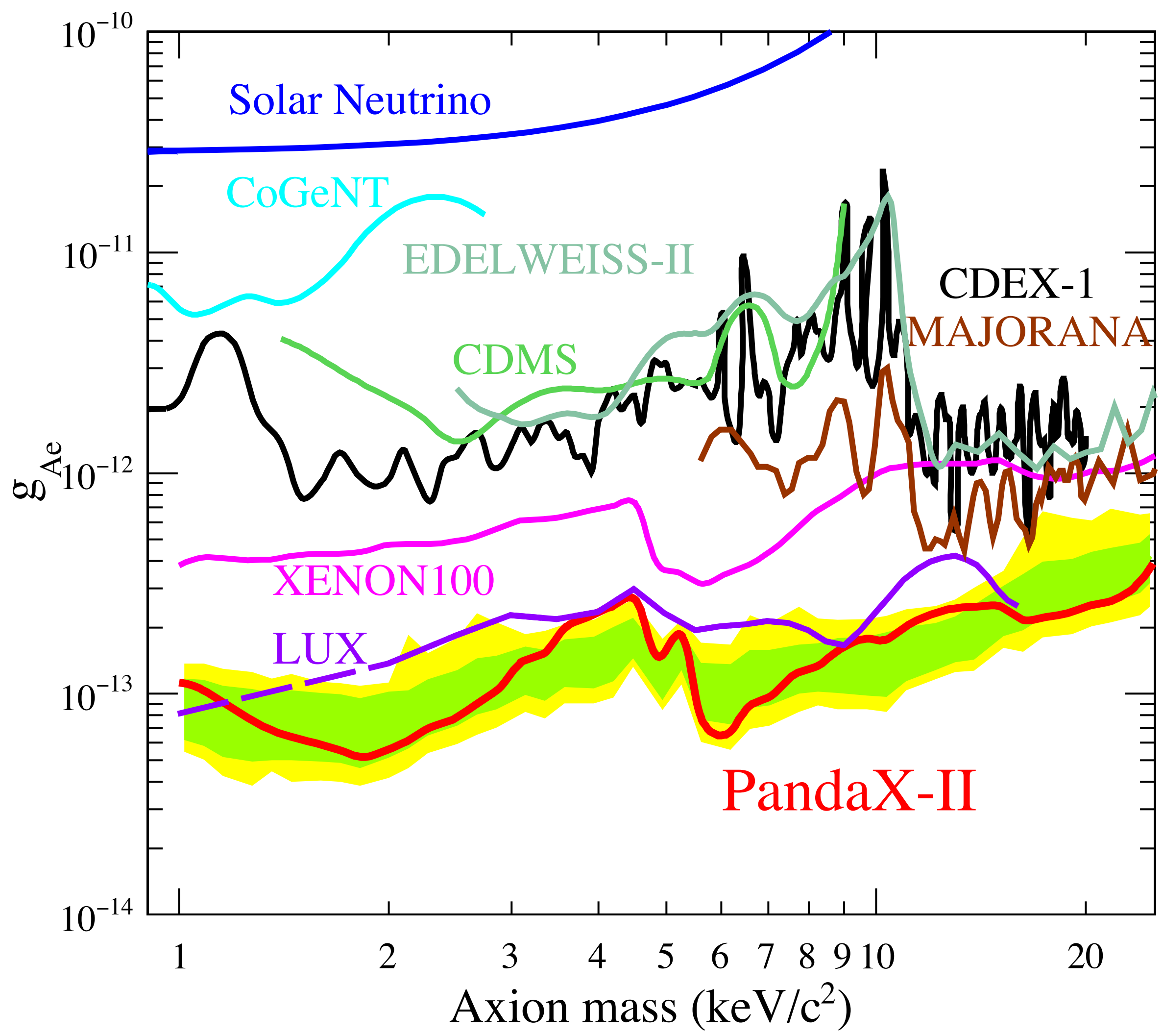


Solar axion results



PRL 119, 181806 (2017)

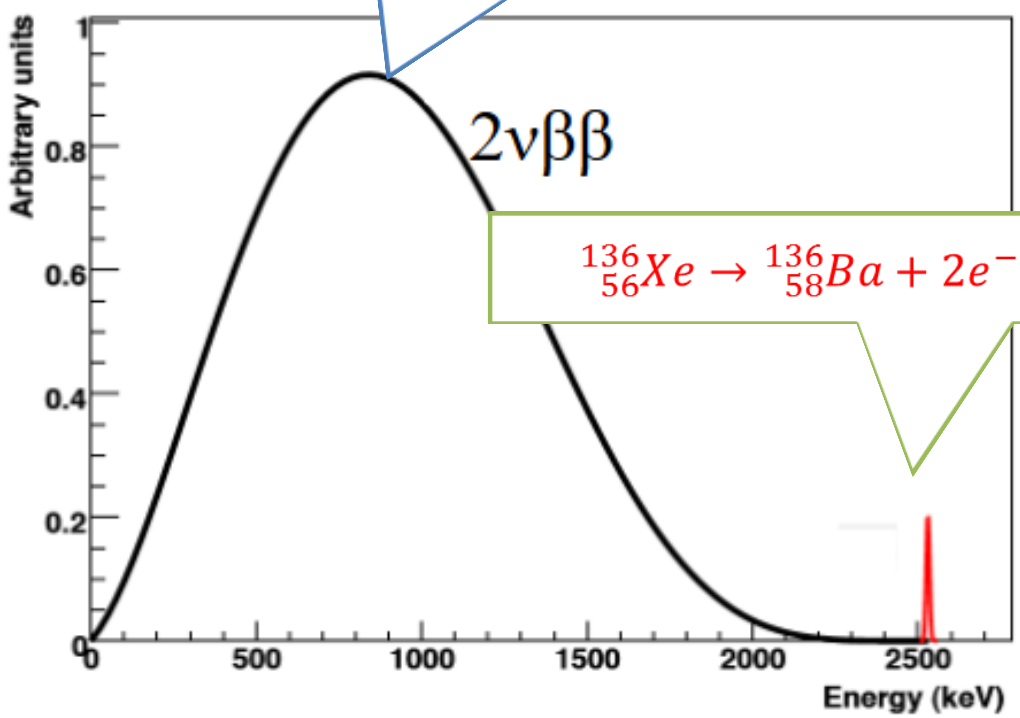
ALPs results



PRL 119, 181806 (2017)

Q values and Total 2e Kinematic Energy Spectrum

$^{136}_{56}Xe \rightarrow ^{136}_{58}Ba + 2e^- + 2\bar{\nu}_e$

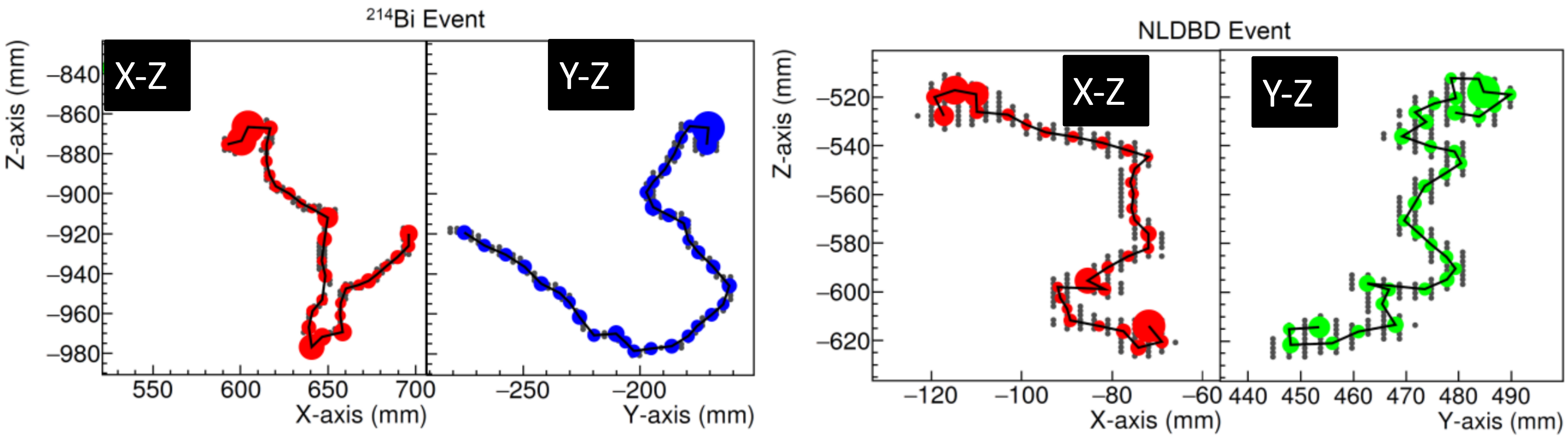


$^{136}_{56}Xe \rightarrow ^{136}_{58}Ba + 2e^-$

Sum of two electrons energy

Isotope	nat. abund. (%)	Q-value (keV)	Experiment
^{48}Ca	0.187	4272 ± 4	CANDLES
^{76}Ge	7.8	2039.006 ± 0.050	GERDA, MAJORANA
^{82}Se	9.2	2995.5 ± 1.9	SuperNEMO, LUCIFER
^{96}Zr	2.8	3347.7 ± 2.2	-
^{100}Mo	9.6	3034.40 ± 0.17	AMoRE
^{110}Pd	11.8	2017.85 ± 0.64	-
^{116}Cd	7.5	2813.50 ± 0.13	COBRA, $CdWO_4$
^{124}Sn	5.64	2287.8 ± 1.5	-
^{130}Te	34.5	2527.518 ± 0.013	CUORE
^{136}Xe	8.9	2457.83 ± 0.37	EXO, NEXT **PandaX-III** KamLAND-Zen
^{150}Nd	5.6	3371.38 ± 0.20	SNO+, DCBA

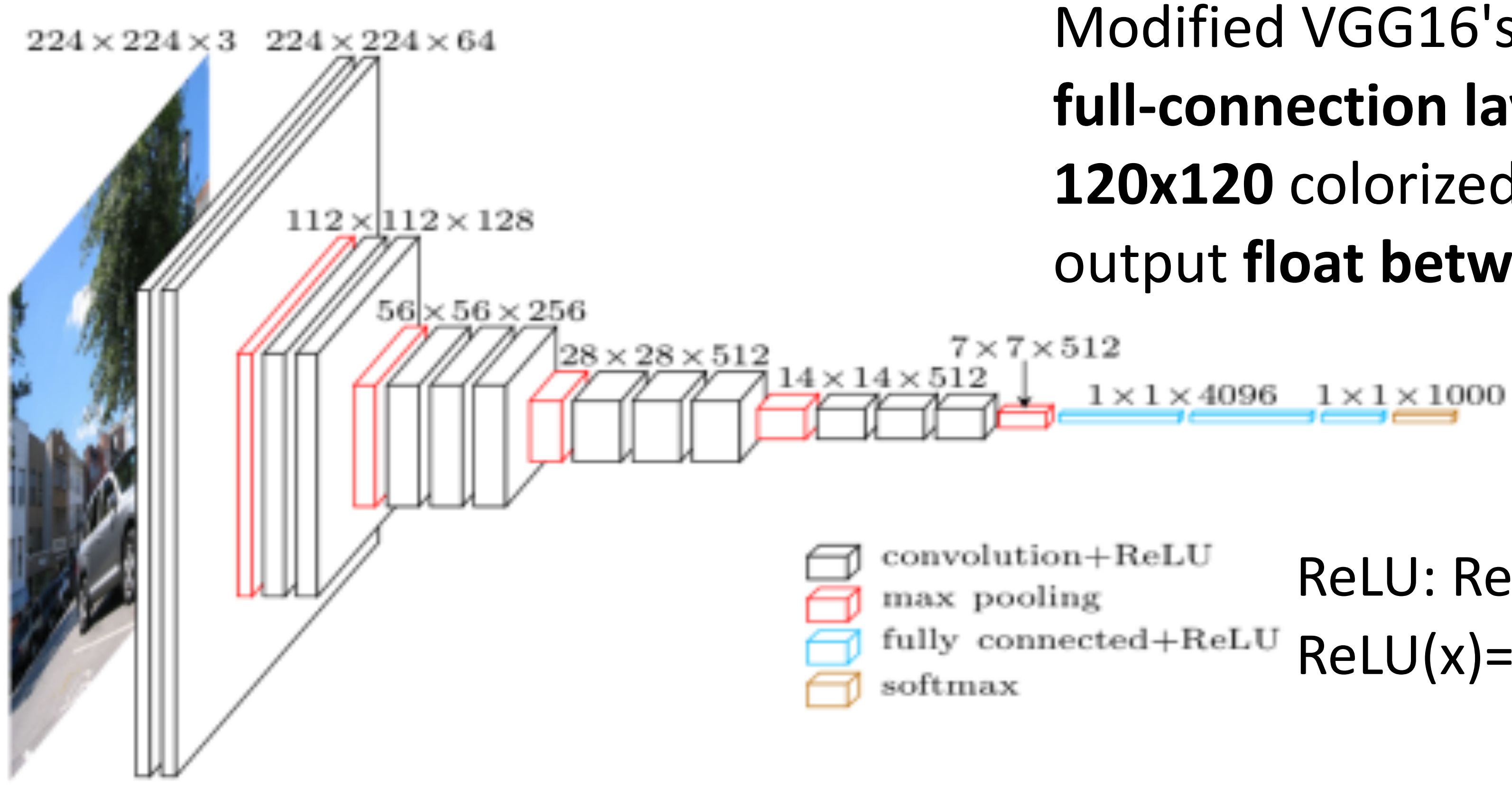
Q value of $^{136}_{56}Xe \rightarrow ^{136}_{58}Ba$:
2457.83(37) keV PRL 98, 053003(2007)



Track Length around 30cm for e- in 10-bar Xe gas

Reconstruction of the projected electron tracks (XZ and YZ) produced by two Monte Carlo simulated events, a typical background event coming from a ^{214}Bi decay (Left), and a 2β event (Right). The size of the circles is related to the charge density allowing to identify visually the blobs at the end of the tracks.

- The VGG16 is a model been used by the VGG team in the ILSVRC-2014(ImageNet Large Scale Visual Recognition Challenge 2014) competition.
- It accept 244x244 colorized picture as input and classify that into 1000 classes.

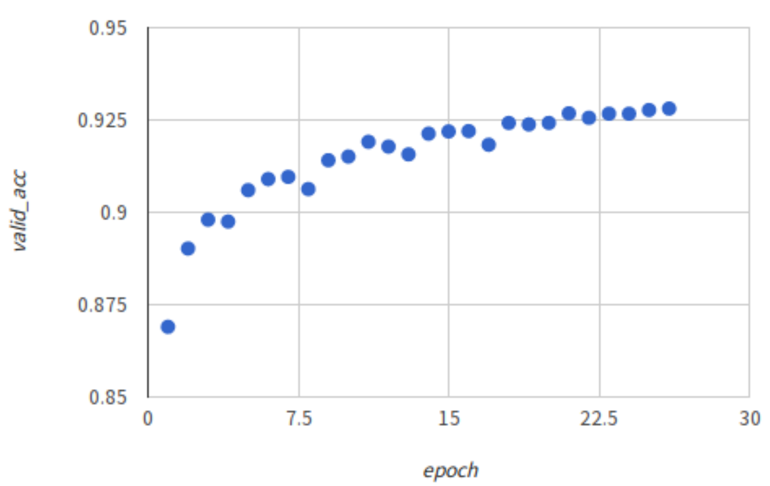


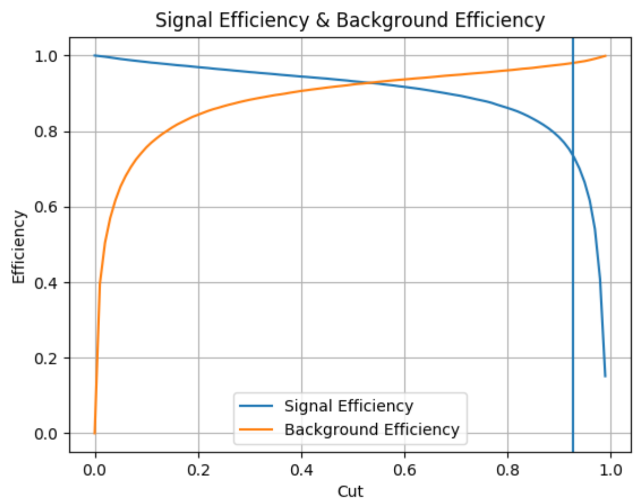
Modified VGG16's **input layer** and **full-connection layer** to accept **120x120** colorized picture and output **float between 0 and 1**.

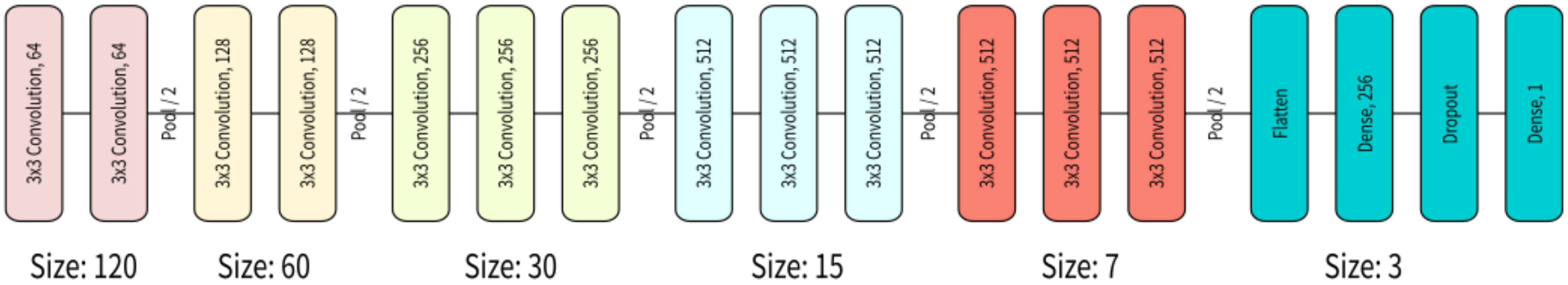
ReLU: Rectified Linear Unit, e.g. ReLU(x)=max(x， 0)

Results of VGG16

After train VGG16 in 30 epoch, the valid accuracy (valid_acc) finally stable at about 92.8%(cut @0.5). Signal efficiency reach 73.9% when suppress background 50 times.

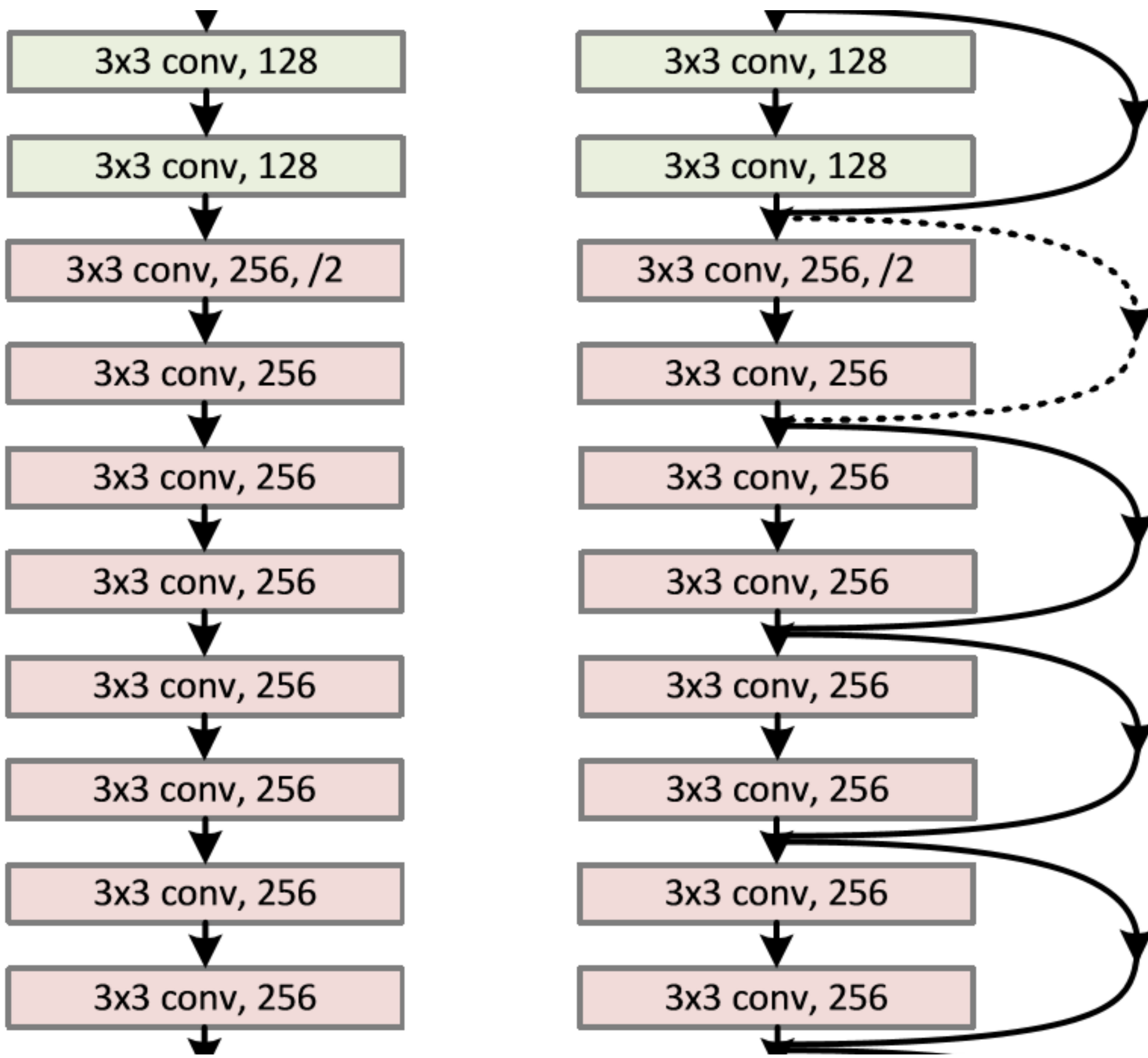






by Hao QIAO 乔颢(PKU), Chunyu LU陆纯钰 (SJTU), Xun CHEN谌勋(SJTU)

ResNet 50

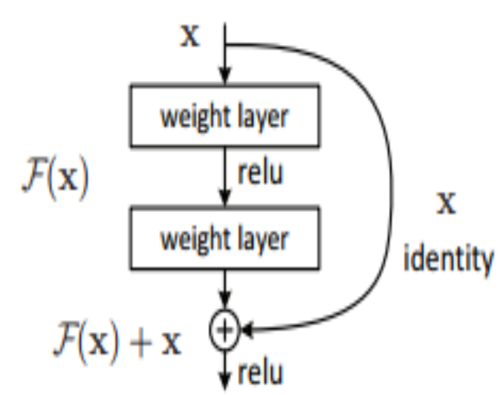


CNN

ResNet

ResNet (Deep Residual Networks) is the Convolutional Neural Networks of Microsoft team that won ILSVRC 2015 competition and surpass the human performance on ImageNet dataset. ResNet 50 is one of the version provided in experiments.

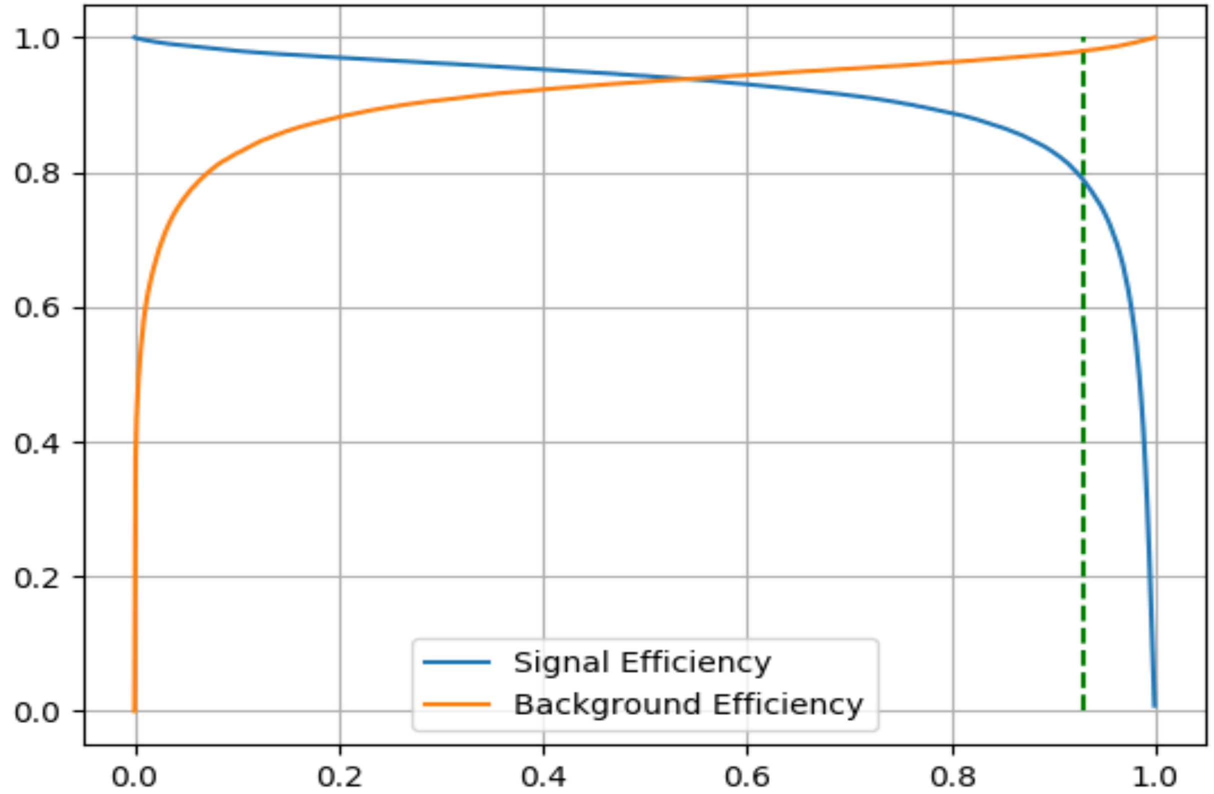
ResNet add an **identical mapping** to directly across some layer of CNN. That the output of layer should be something like **F(x)+x**. ResNet believe that it is much more easier to optimize the residual mapping than to optimize the original, unreferenced mapping.



https://arxiv.org/pdf/1512.03385.pdf

Results of RESNET50

Using RESNET50 can reach a better result. The valid accuracy can reach at 94%. The signal efficiency is 79% when lower background 50 times.



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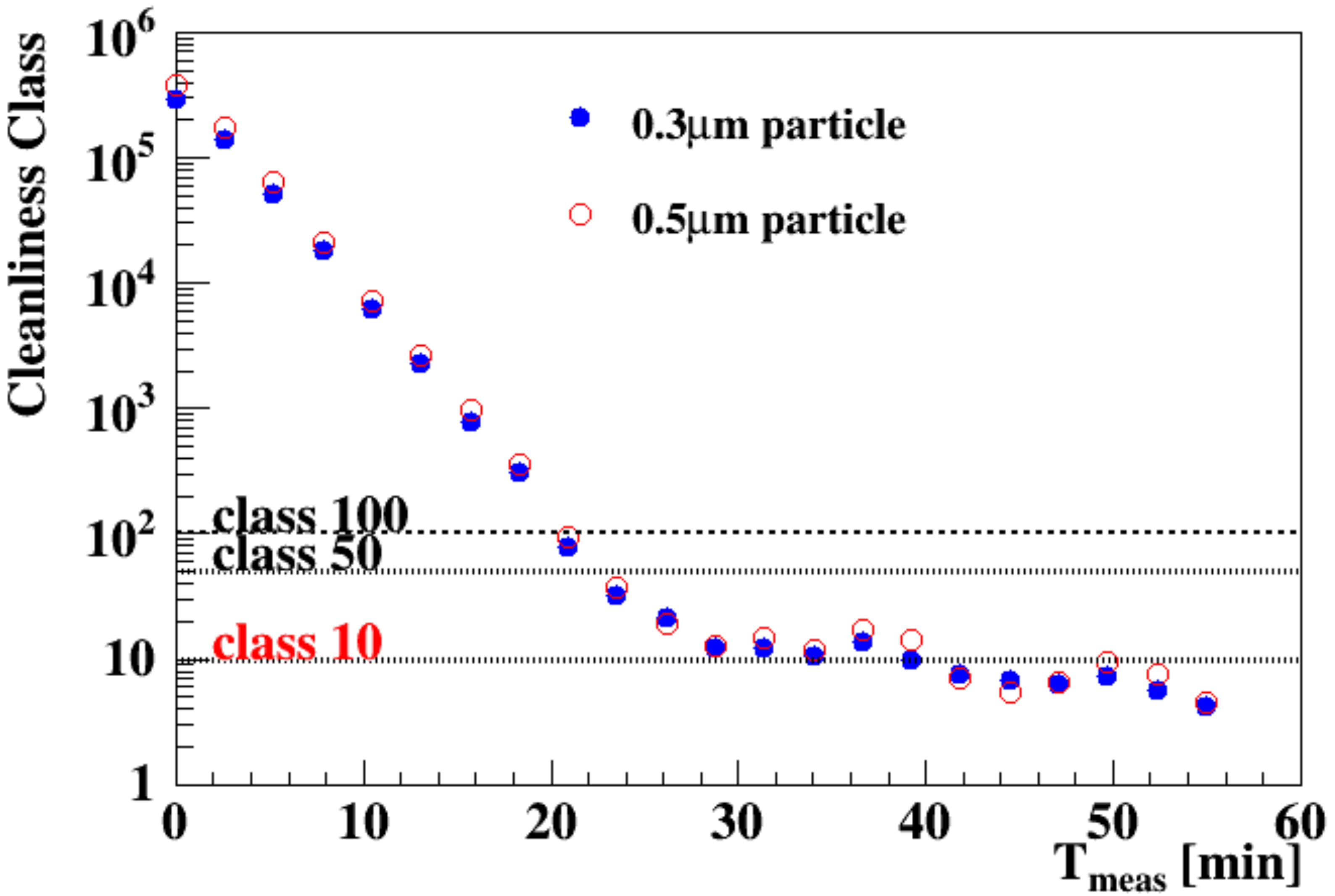
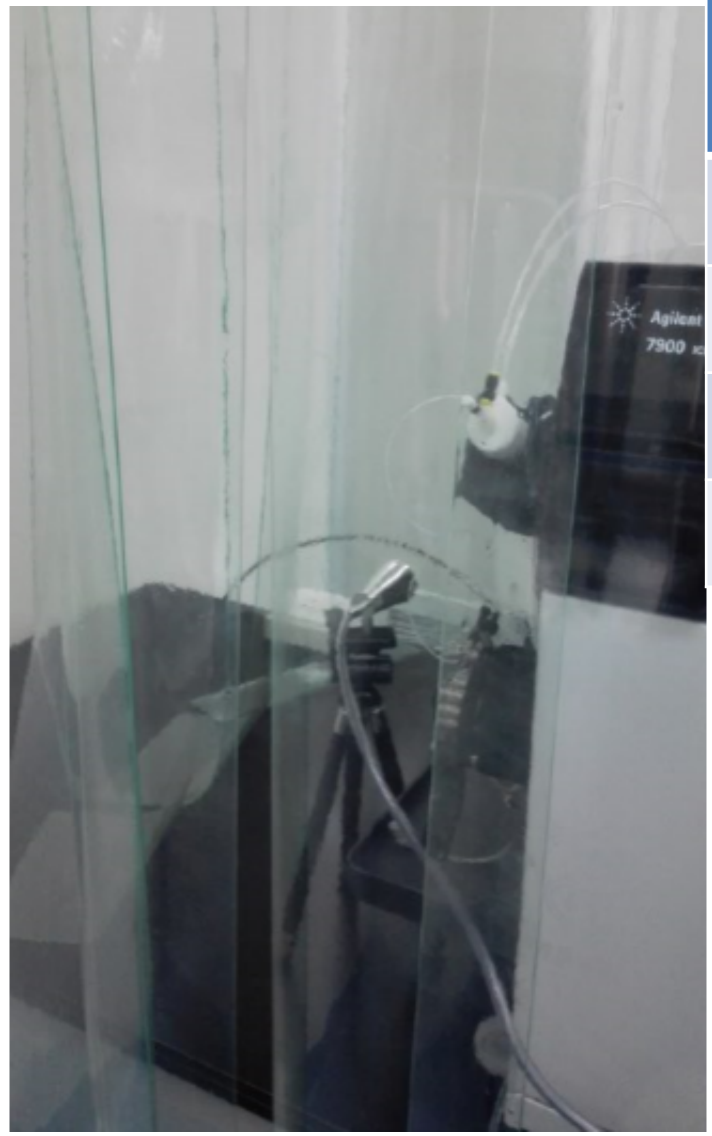
by Chunyu LU陆纯钰 (SJTU), Hao QIAO 乔颢(PKU), Xun CHEN谌勋(SJTU)

Cleanliness of Air outside of Air-Shower Door



Using the air from outlet to protect the entrance of clean room—outside of air-shower door

Cleanliness in sample region of ICP-MS



Time (min)	Class (0.3μm)	Class (0.5μm)	Class (1.0μm)
0	0. 0	0. 0	0. 0
1. 45	0. 0	0. 0	0. 0
2. 9	0. 0	0. 0	0. 0
4. 35	0. 3	0. 0	0. 0

Far better than class 10

Class	maximum particles/m^3		FED STD 209E equivalent
	≥0.3 μm	≥0.5 μm	
ISO 3	102	35	Class 1
ISO 4	**1,020**	**352**	**Class 10**

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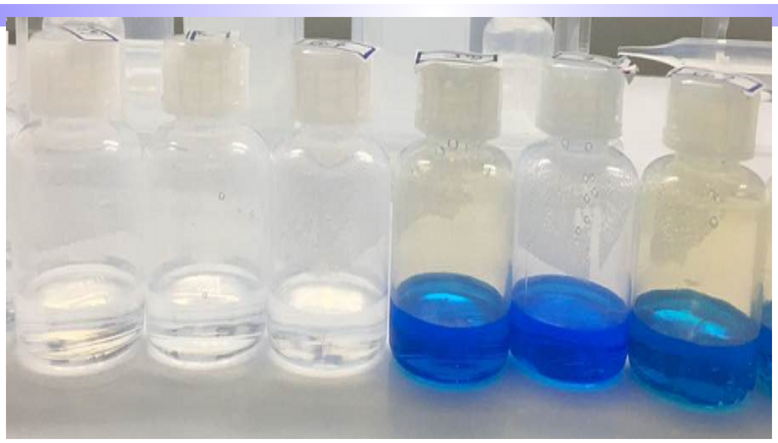
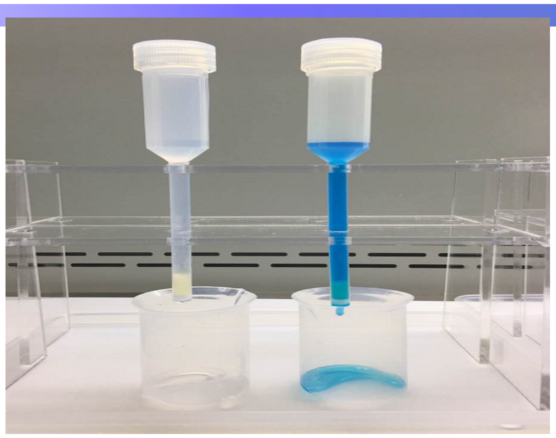
U and Th in Single Crystal Copper





Ca. 0.85 g

- Surface treatment
- Dissolved in 8 M HNO_3 (spiked with ^{230}Th and ^{235}U)
- Loaded on the Extraction Chromatography Column
- Analyze

Detection Limits：

0.035 pg ^{232}Th/g (0.14 μBq ^{232}Th/kg)

0.073 pg ^{238}U/g (0.90 μBq ^{238}U/kg)

flow rate ： 0.8 mL/min

Sample	^{232}Th pg/g	^{238}U pg/g
Cu 1	0.22±0.07	0.37±0.08
Cu 2	0.28 ±0.14	0.37±0.07
Cu 3	0.27±0.07	0.59±0.19
Cu 4	0.16±0.07	0.58±0.04
Cu 5	0.14±0.07	0.54±0.15
Average*	0.21±0.06	0.49±0.10

* The errors are standard deviations

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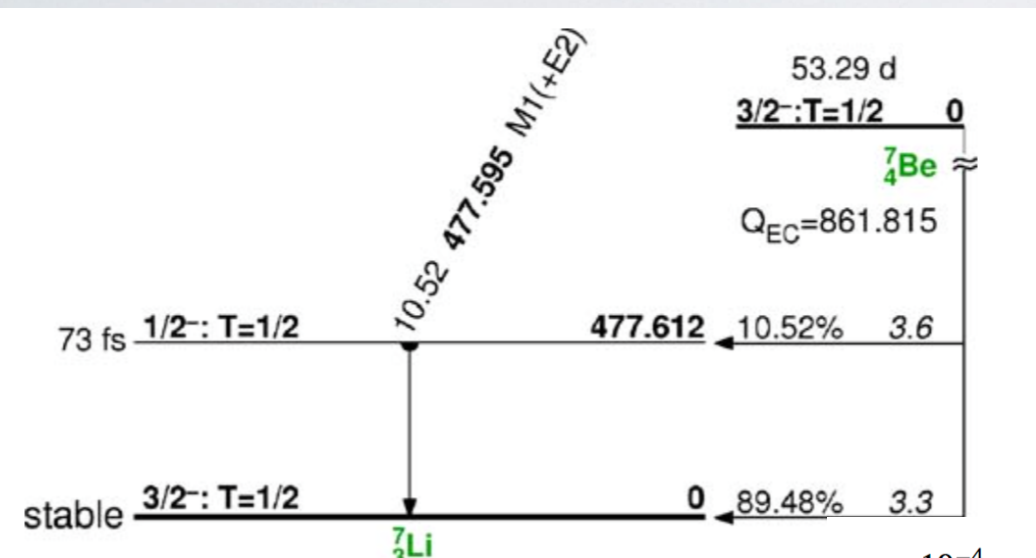
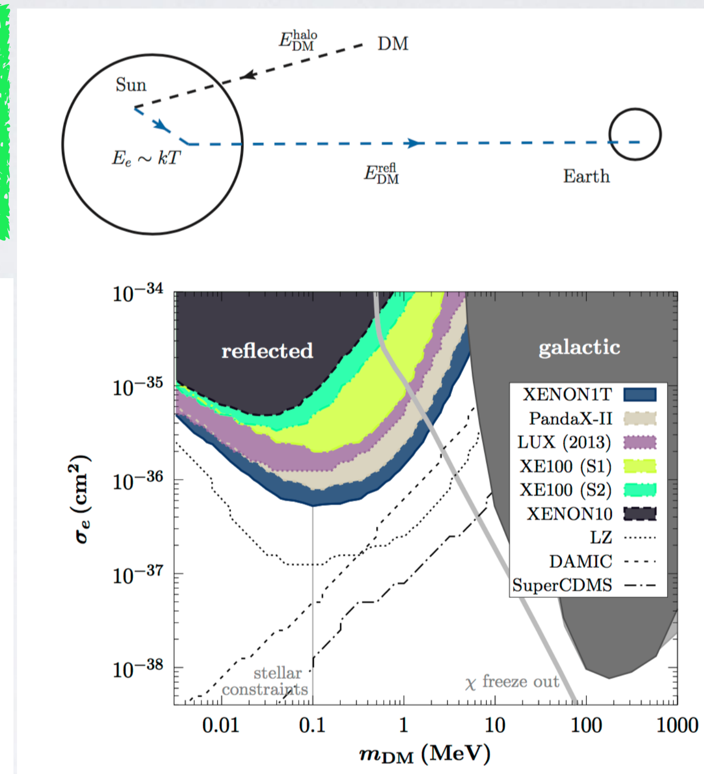
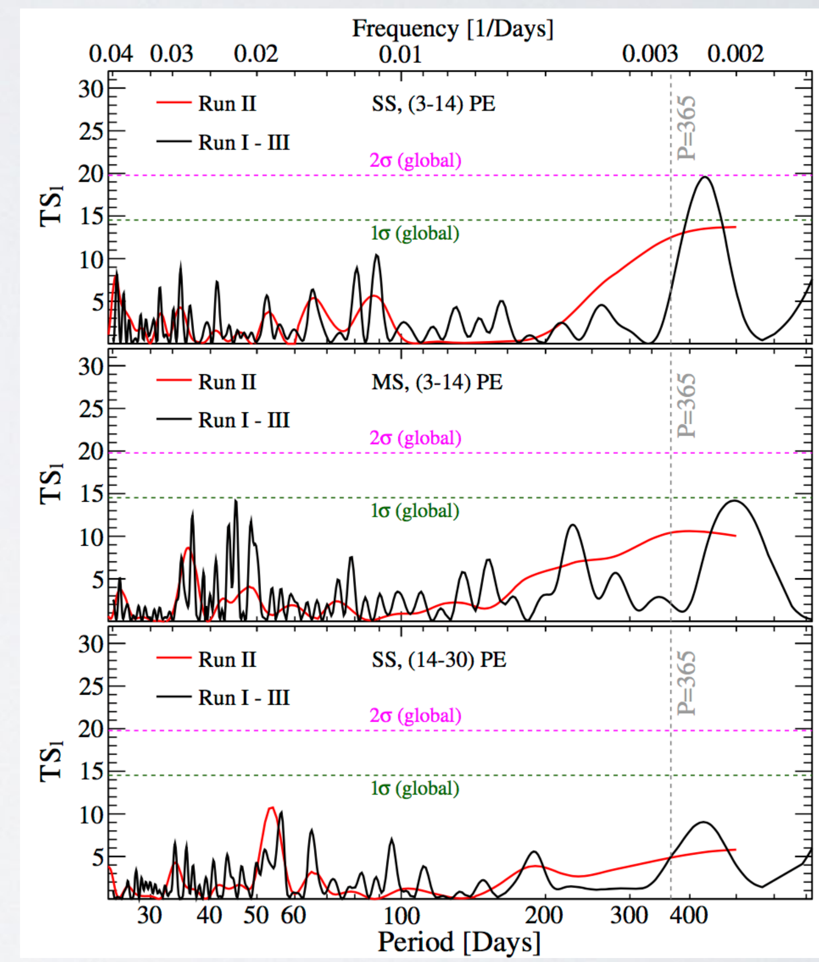
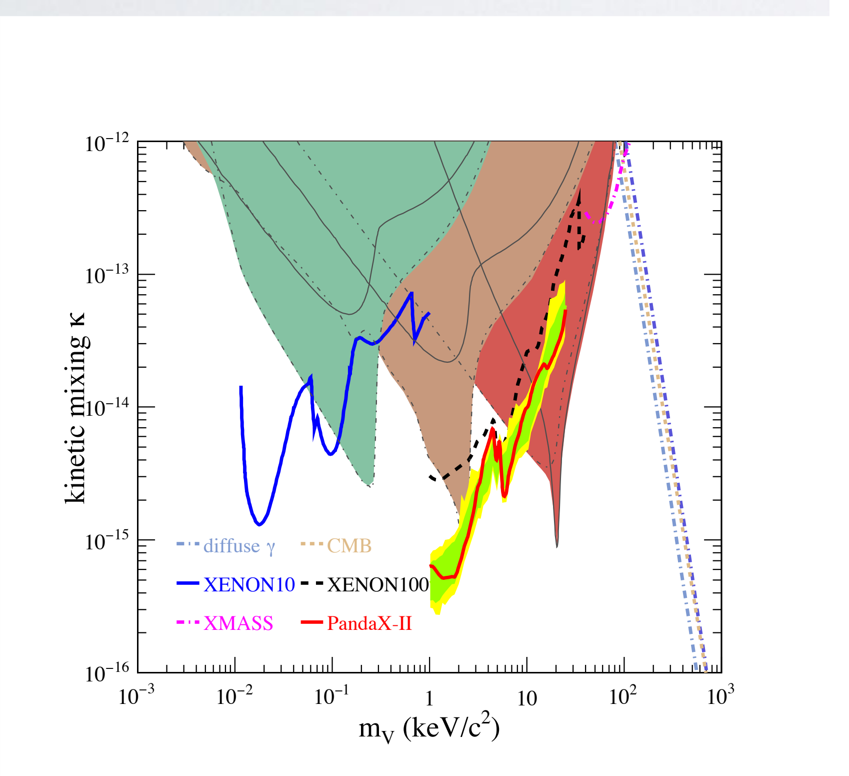
Other topics on Axion or Dark Photon

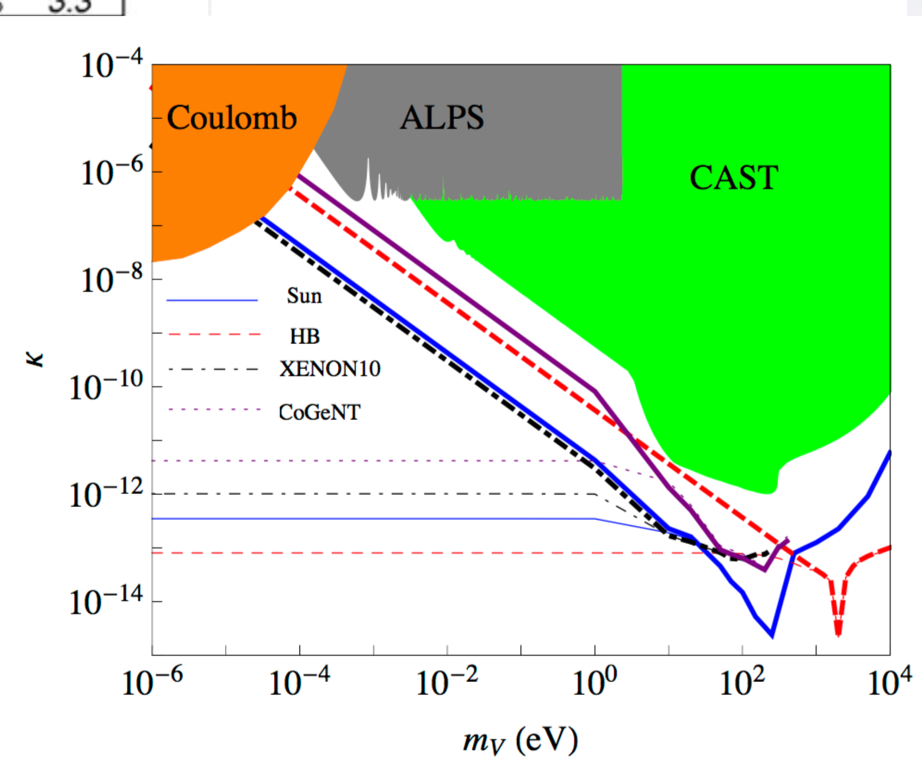
- other possible source: $p + d \to {}^3He + a(5.5\ MeV)$









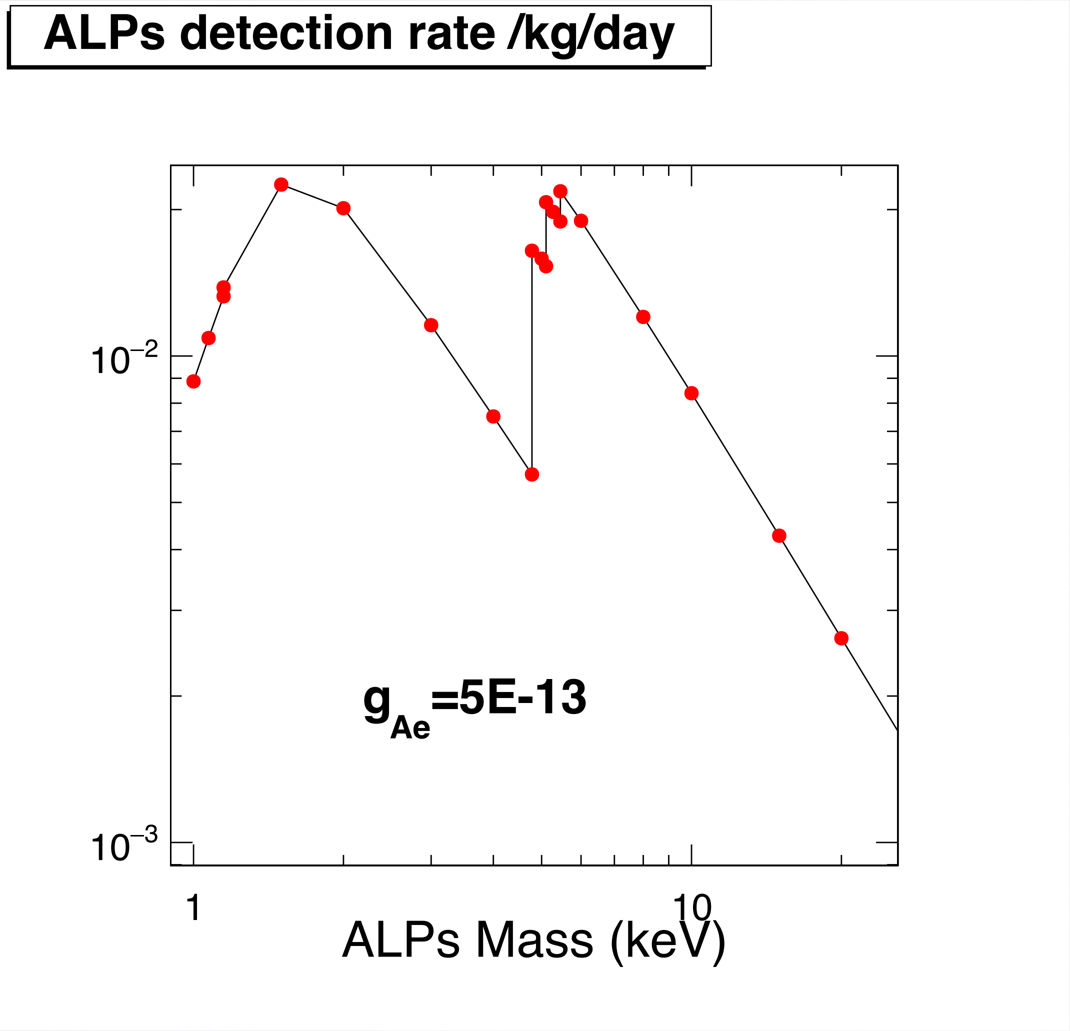


THANKS

$$g_{AN}^{eff} \equiv -1.19 g_{AN}^{0} + g_{AN}^{3},$$

$$g_{AN}^{0} = 5.2 \times 10^{-8}\left(\frac{6.2 \times 10^{6} GeV}{f_A}\right)\left[\frac{(3F - D)(X_u - X_d - 3)}{6} + \frac{S(X_u + 2X_d - 3)}{3}\right],$$

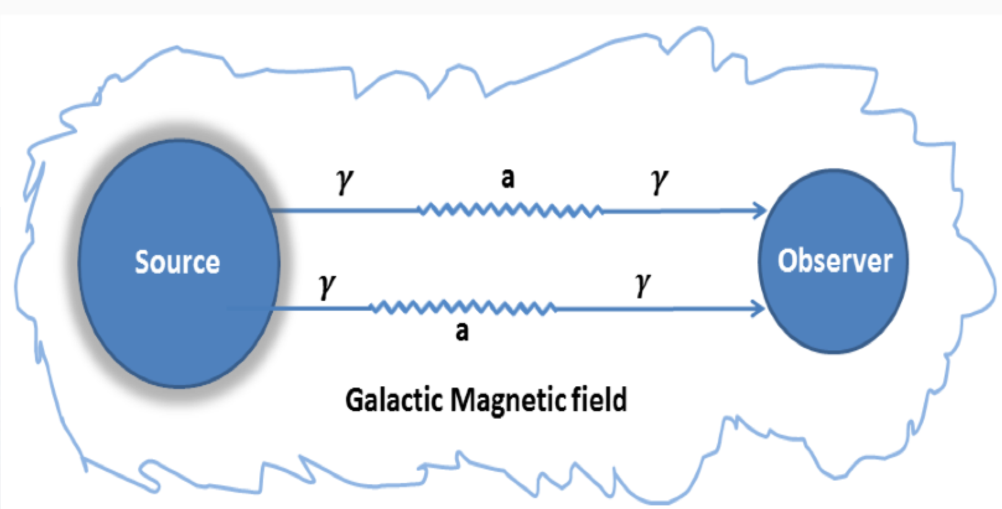
$$g_{AN}^{3} = 5.2 \times 10^{-8}\left(\frac{6.2 \times 10^{6} GeV}{f_A}\right)\frac{D + F}{2}\left(X_u - X_d - 3\frac{1 - z}{1 + z}\right),$$



News from Fermi LAT

Summary:

- Indications for ALPs in case of Fermi LAT data of **galactic pulsar candidate**.
- Photon-ALPs mixing is non-linear in the spiral arms and in the large scale field of the inner Galaxy.
- ALPs mass bounds: 5 neV$\leq m_a \leq$ 8 neV
- Photon-ALPs coupling bound: 20 - 80 $\times 10^{-11} GeV^{-1}$
- Significance level : 7.5σ.
- The main challenge of this work is to choose the magnetic field model as the resulting mixing parameters are quite model dependent.



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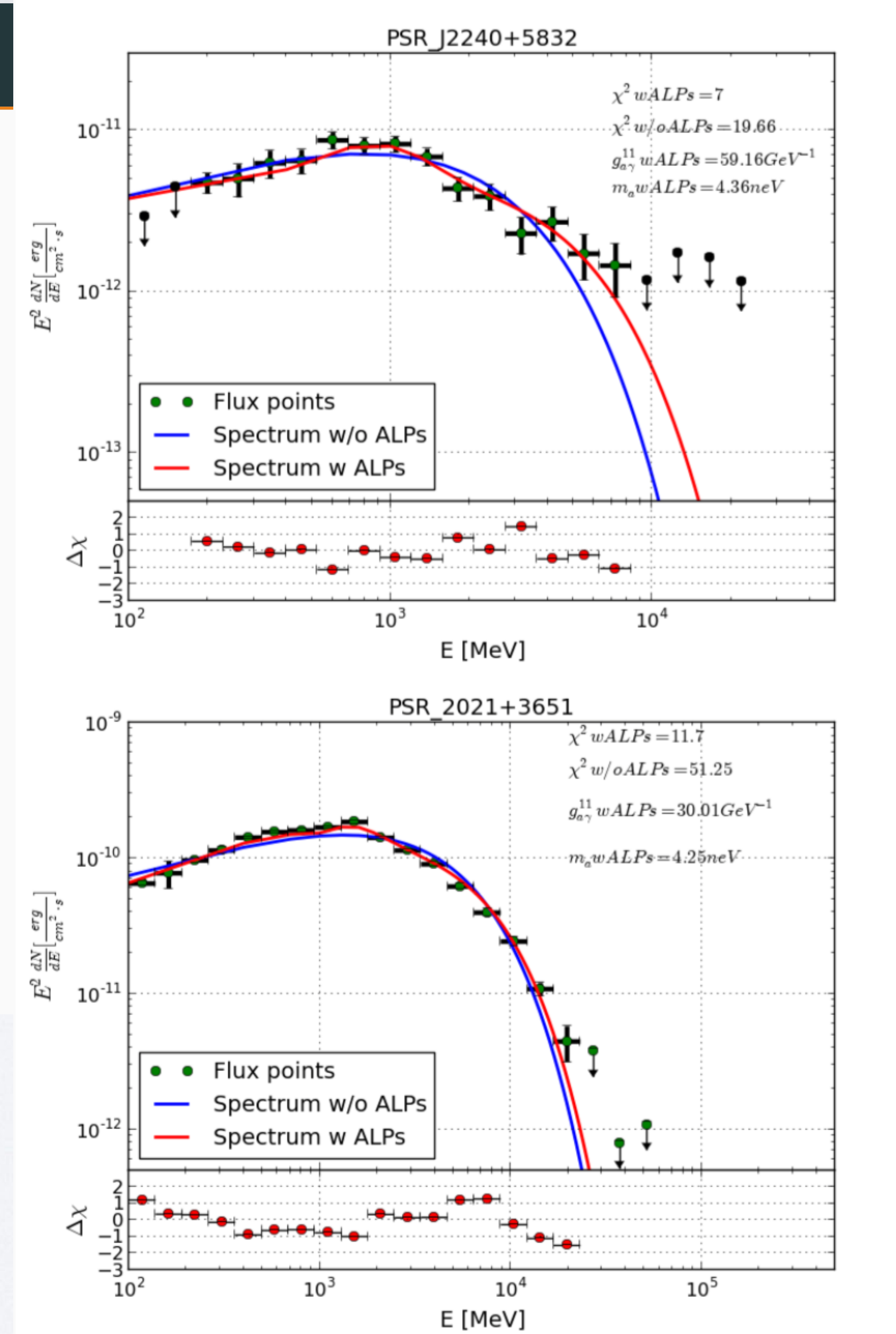

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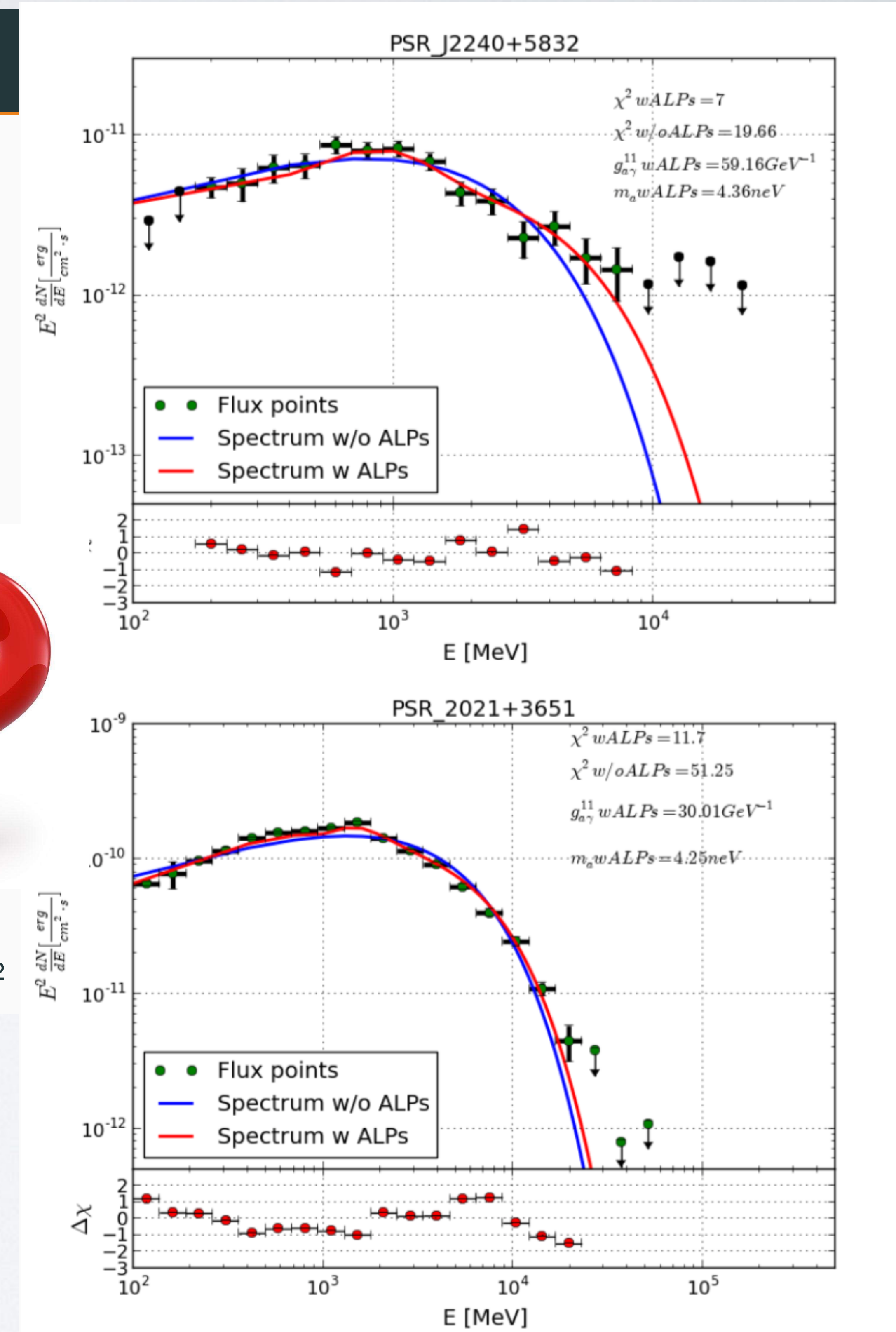
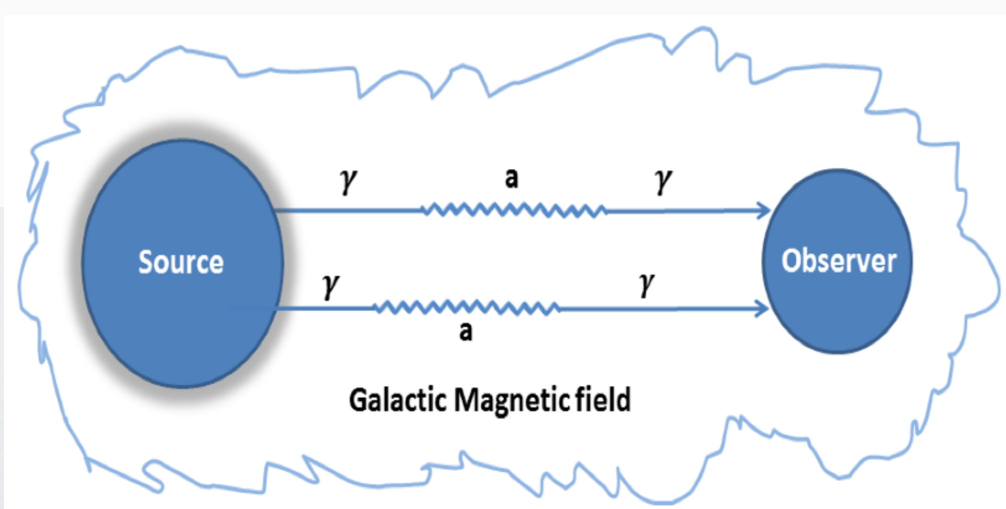
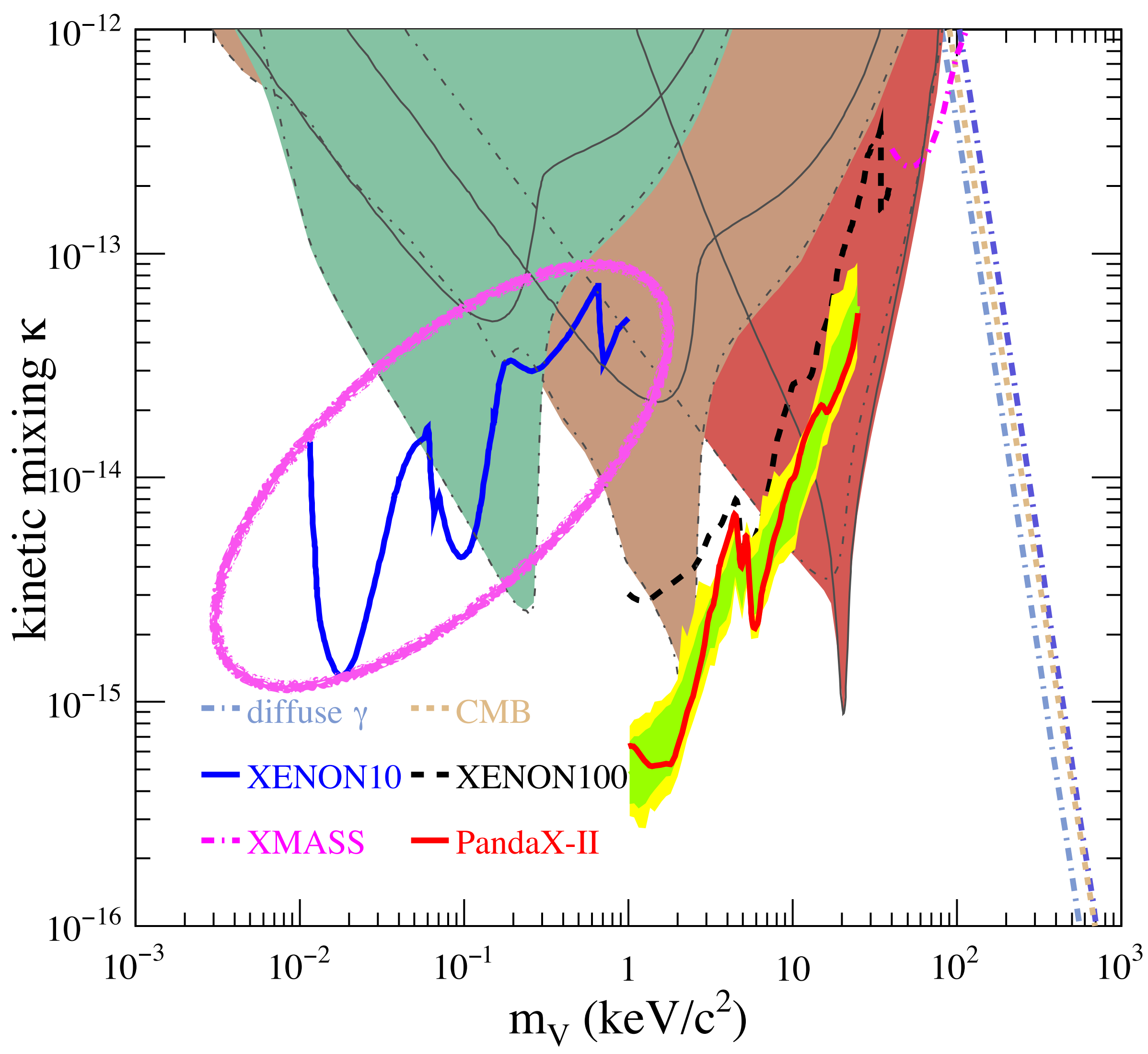


12

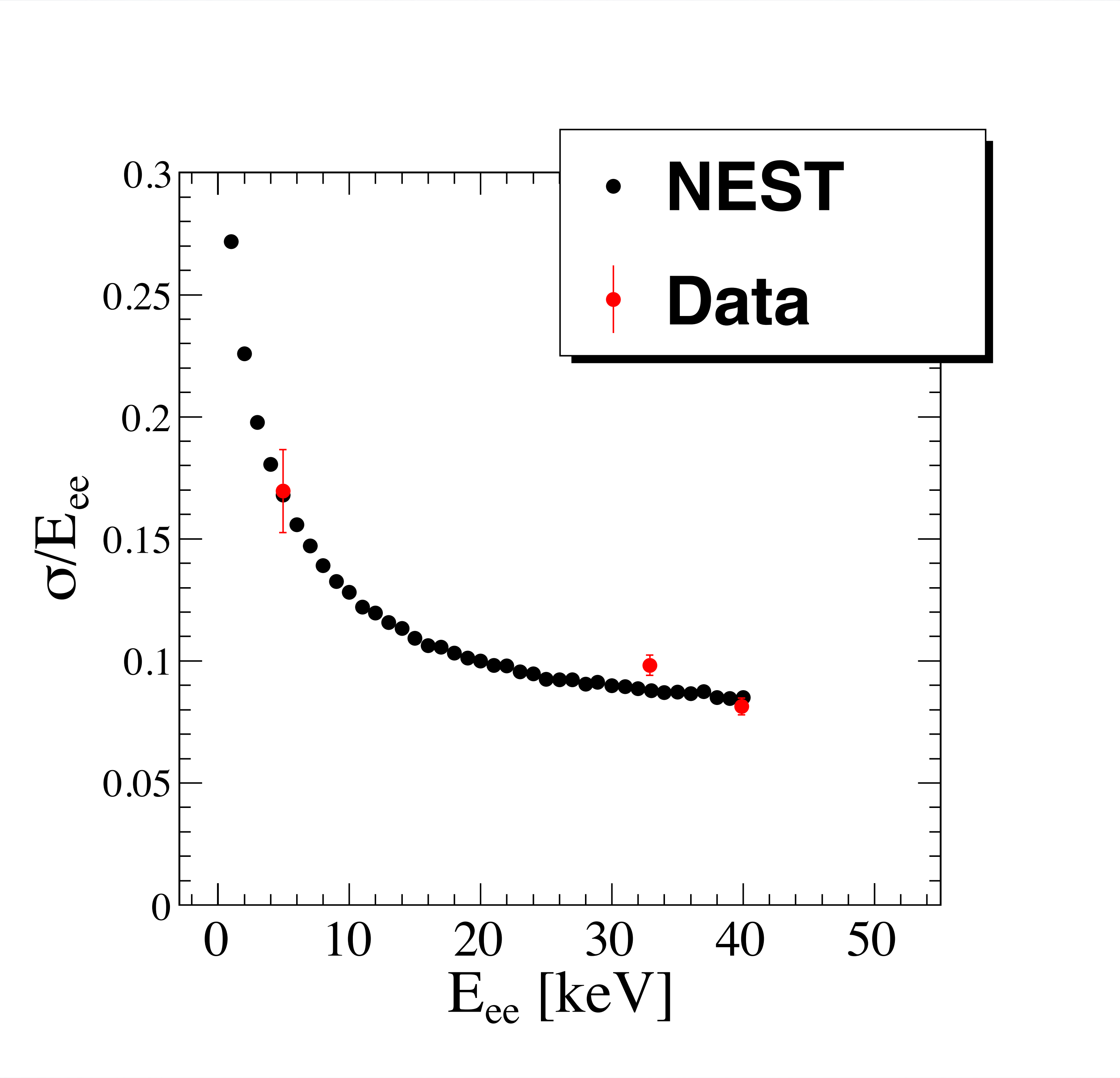


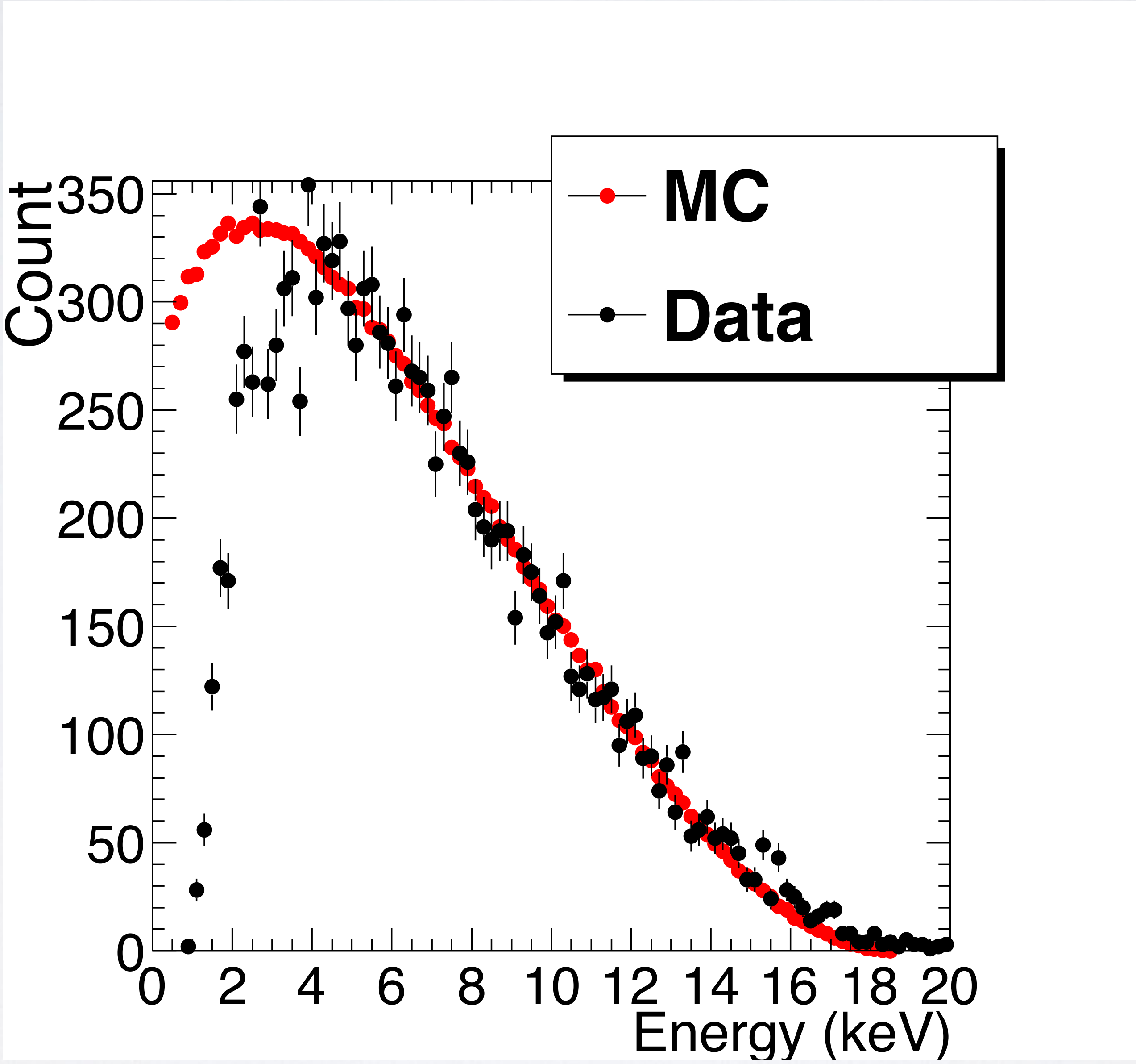
Dark Photon



kinetic mixing κ
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}
m_V (keV/c^2)
diffuse γ
CMB
XENON10
XENON100
XMASS
PandaX-II

Resolution





MC
Data
Count
350
300
250
200
150
100
50
0
0 2 4 6 8 10 12 14 16 18 20
Energy (keV)