Search for 5.5 MeV Solar Axions in DEAP-3600

Carl Rethmeier for the DEAP-3600 Collaboration

2020 CAP PPD Virtual Sessions

Axions and CP Symmetry

- Axions are theoretical particles proposed to solve the strong CP problem
  - They are also a compelling dark matter candidate
- CP symmetry → interaction is invariant under:
  - **C**harge: Particle ↔ antiparticle
  - **P**arity: e.g., (X, Y, Z) → (-X, -Y, -Z)
- CP violation observed in weak interaction
- Strong CP problem
  - Why has CP violation not been observed in the strong interaction?

CP Conserved in Strong Interaction

- CP expected to be broken in strong interaction
  - $\mathcal{L}_{QCD} = \bar{\psi} i \gamma^{\mu} D_{\mu} \psi + \frac{1}{4} G^2 + \frac{g^2 \bar{\theta}}{32\pi^2} G \tilde{G}$

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  - From experiment: $\boldsymbol{\bar{\theta} < 1.98 \times 10^{-10}}$ radians [1]

1. J. Dragos, T. Luu, A. Shindler, J. de Vries, and A. Yousif, *arXiv:1902.03254* (2019).

CP Conserved in Strong Interaction

Axion field has "vev" at $a = -\frac{f_a}{\zeta}\bar{\theta}$

- CP expected to be broken in strong interaction
  - $\mathcal{L}_{QCD} = \bar{\psi} i \gamma^{\mu} D_{\mu} \psi + \frac{1}{4} G^2 + \frac{g^2 \bar{\theta}}{32\pi^2} G\tilde{G} - \frac{1}{2}\partial_{\mu} a \partial^{\mu} a + \mathcal{L}_{int}[\partial^{\mu} a / f_a ; \psi] + \zeta \frac{a}{f_a} \frac{g^2}{32\pi^2} G\tilde{G}$
  - From experiment: $\bar{\boldsymbol{\theta}} < \mathbf{1.98 \times 10^{-10}}$ radians [1]

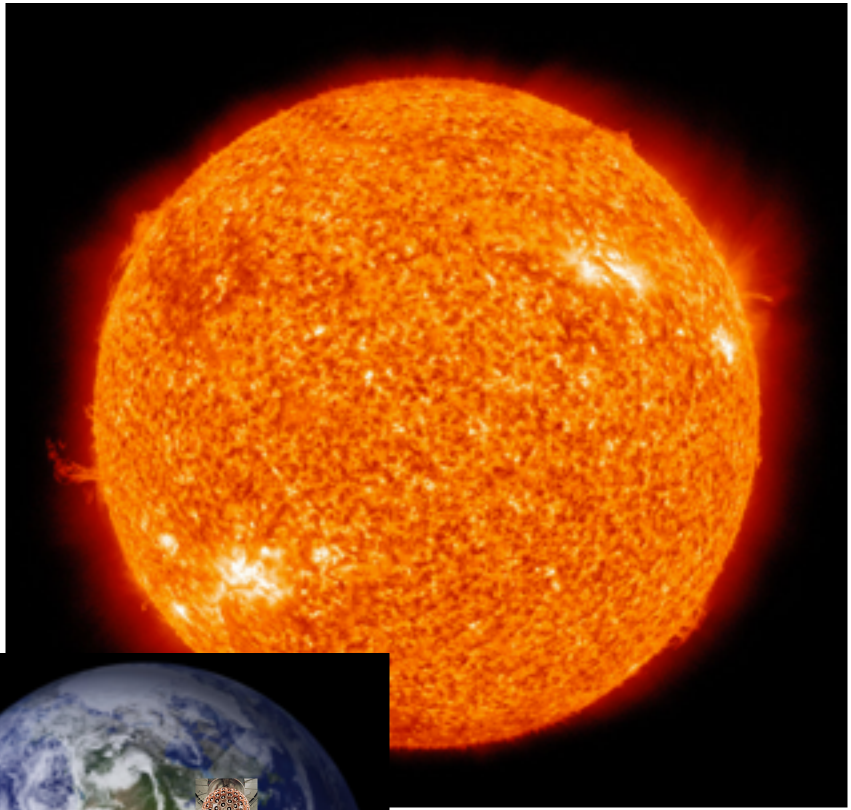
Peccei-Quinn (PQ) Theory [2]

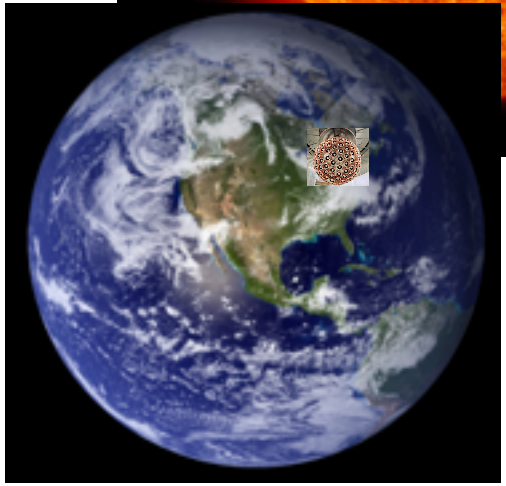
- Peccei-Quinn (PQ) theory solves Strong-CP Problem
  - Predicts a new particle, the axion [3,4]
  - Axions are very light and interact very rarely

1. J. Dragos, T. Luu, A. Shindler, J. de Vries, and A. Yousif, *arXiv:1902.03254* (2019).
2. R. D. Peccei and H. R. Quinn, Phys Rev. D **16**, 6 (1977).
3. S. Weinberg Phys. Rev. **40**, 4 (1978).
4. F. Wilczek, Phys. Rev. **40**, 5 (1978).

How are axions produced by the sun?

- One possibility in the proton-proton chain:
  - $p + p \rightarrow d + e^{+} + \nu_e$
  - $p + d \rightarrow {}^{3}He + \boldsymbol{\gamma}\ (\mathbf{5.5\ MeV})$ ← M-type transition
  - …





Images credit: NASA

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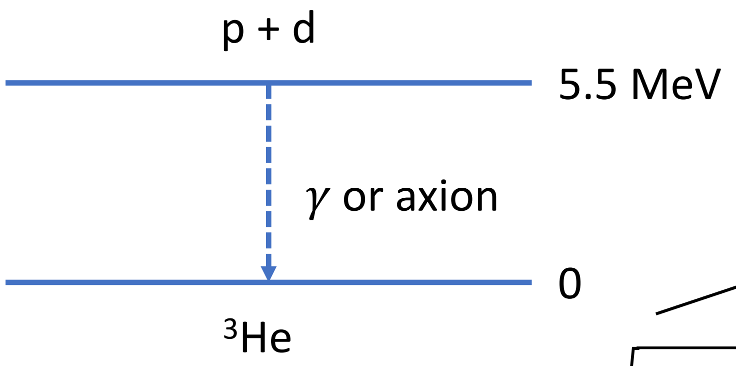
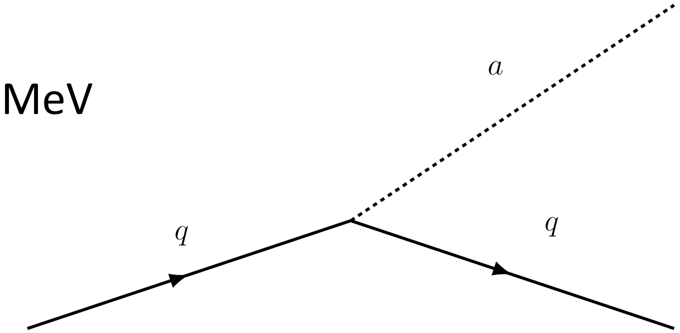
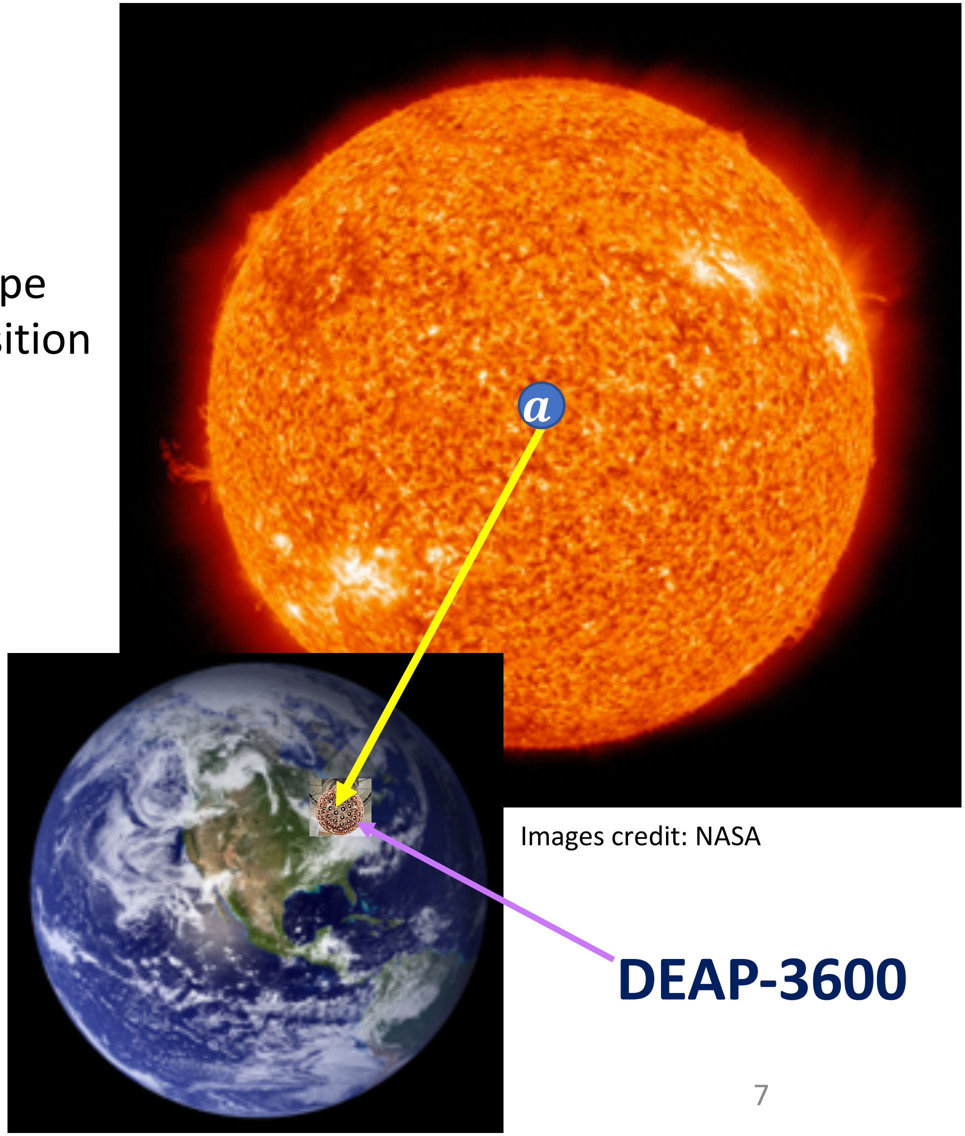
  - …
- Axion could be produced in place of photon:
  - $p + d \rightarrow {}^{3}He + \boldsymbol{a}\ (\mathbf{5.5\ MeV})$





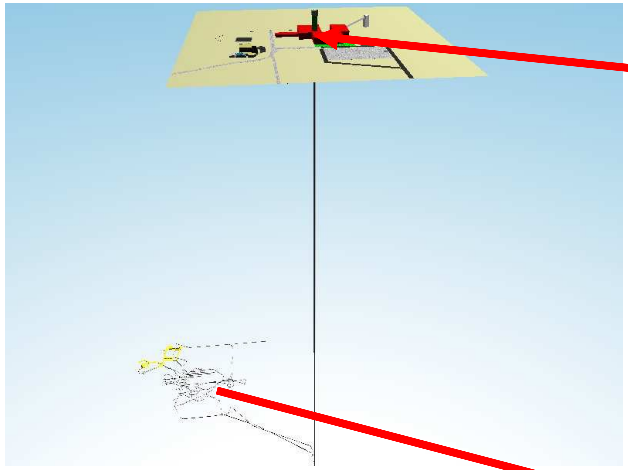
$$\sqrt{p_a^2 + m_a^2} = 5.5\ MeV$$

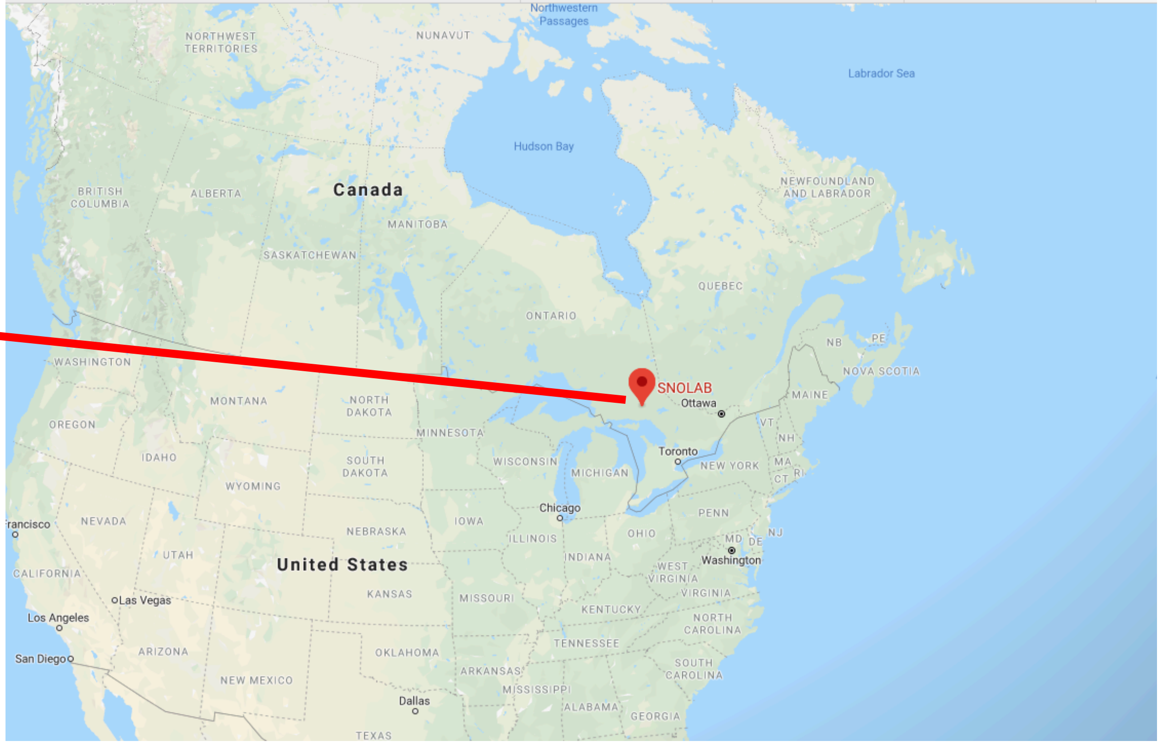


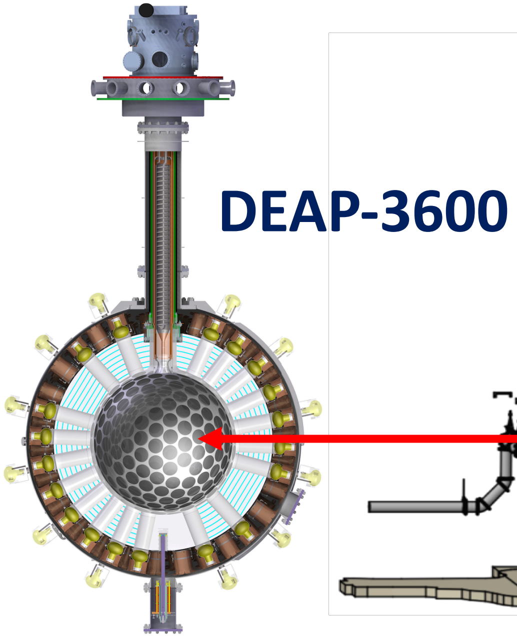
Images credit: NASA

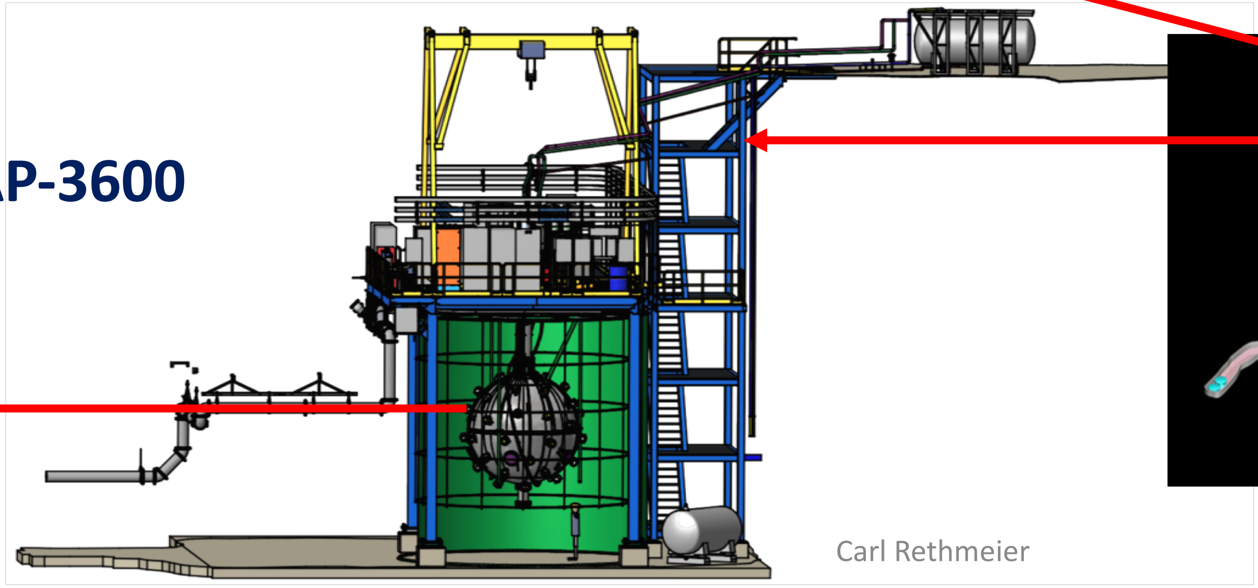
Where is our detector?

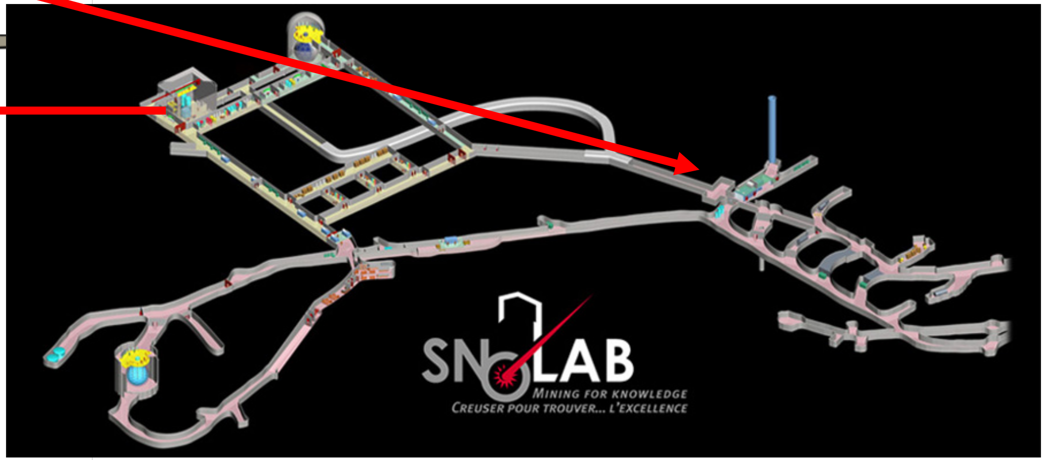
2 km underground in SNOLAB in Sudbury, ON





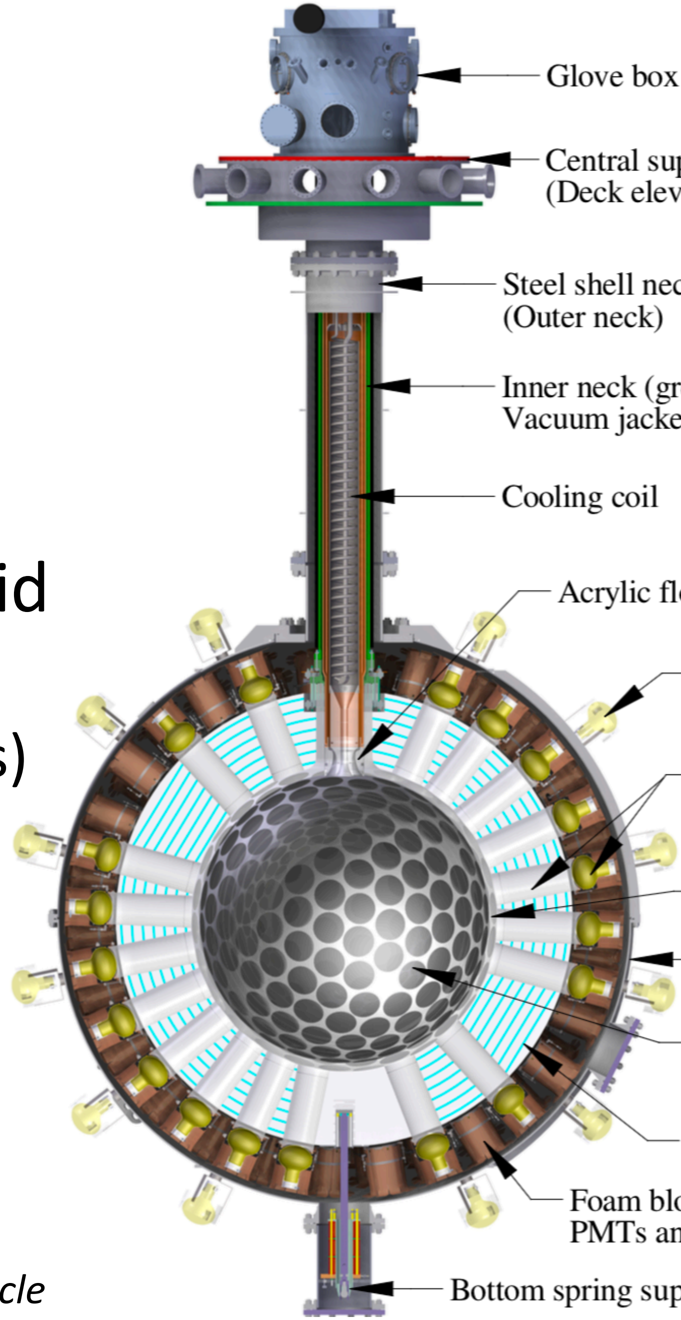






DEAP-3600

- Designed to look for WIMP dark matter
  - Made from very low radioactivity materials
- Acrylic vessel filled with over 3 tonnes of liquid argon
  - Surrounded by 255 Photo-Multiplier Tubes (PMTs)
- Scintillation light is detected by PMTs

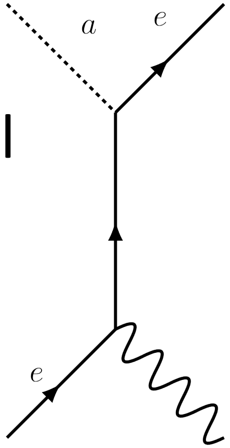


For more info: DEAP-3600 Collaboration (2019). Design and construction of the DEAP-3600 dark matter detector. *Astroparticle Physics*, *108*, 1-23.

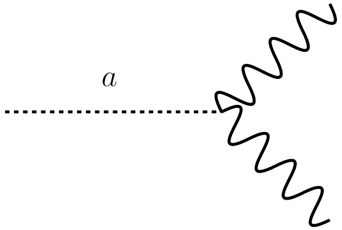
Axion interactions in DEAP-3600 produce EM events

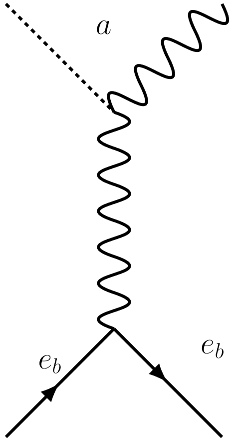
- Compton conversion
  - Get 1 gamma and 1 electron, with 5.5 MeV total kinetic energy
- Inverse Primakov
  - Get 1 gamma with 5.5 MeV energy
- Axio-electric effect
  - Get 1 electron with 5.5 MeV kinetic energy
- Axion decay into 2 gammas
  - Get 2 gammas with 5.5 MeV total energy

Compton Conversion

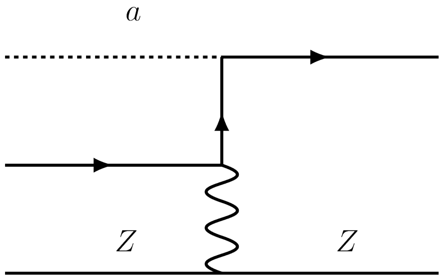


Decay to 2γ



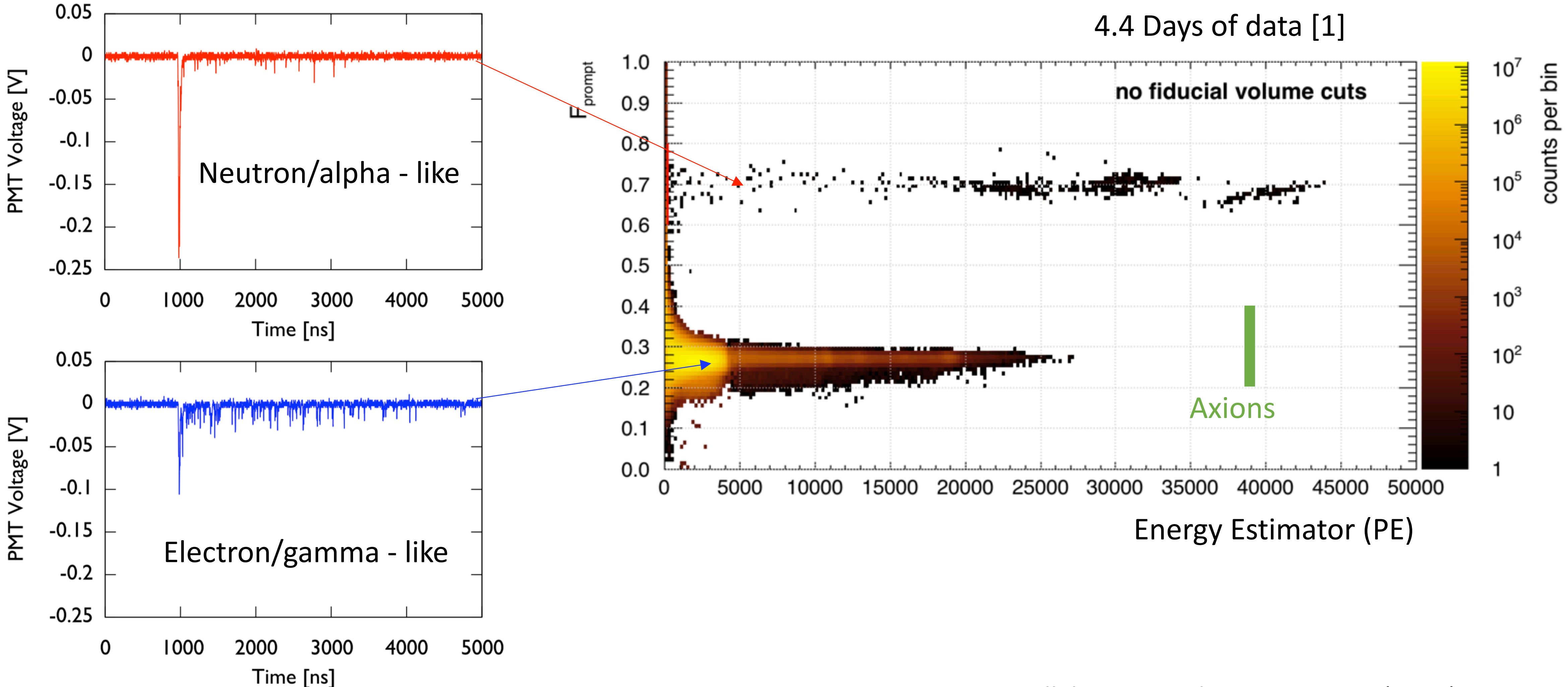


Inverse Primakov



Axio-Electric Effect

DEAP-3600 Signal Detection



1. DEAP-3600 Collaboration, Phys. Rev. 121, 7 (2018).

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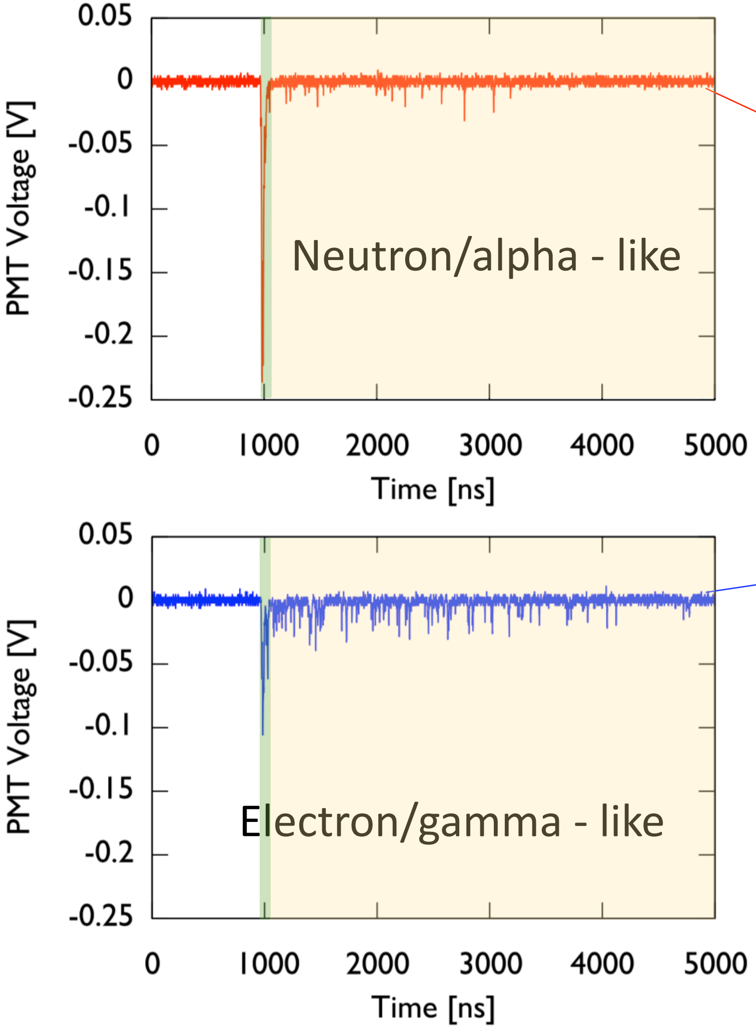

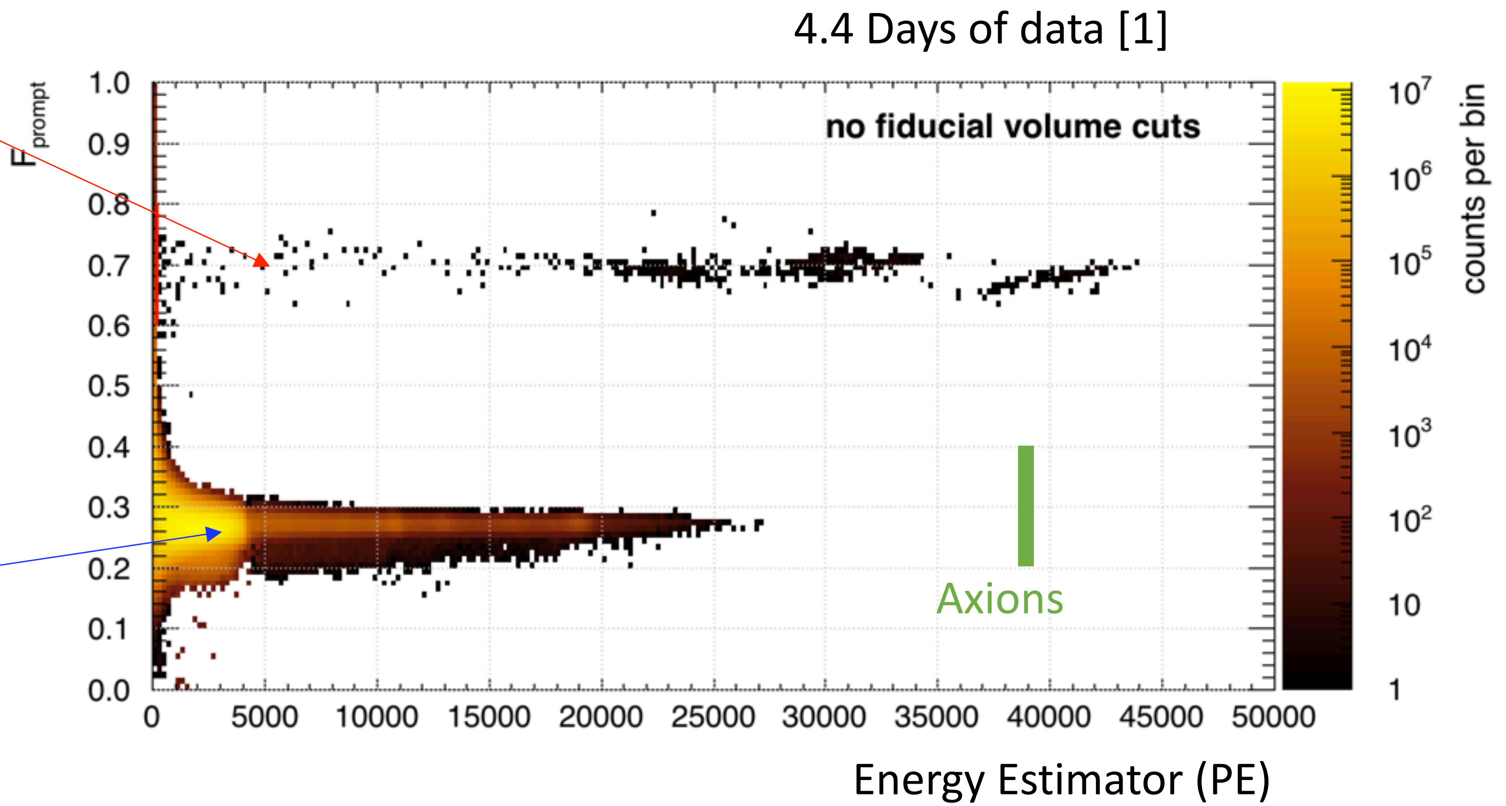

$$F_{prompt} = \frac{\int_{-28\,ns}^{60\,ns} \mathrm{PE(t)dt}}{\int_{-28\,ns}^{10{,}000\,ns} \mathrm{PE(t)dt}} \quad [2]$$

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2. DEAP Collaboration, Phys. Rev. D 100, 2 (2019).

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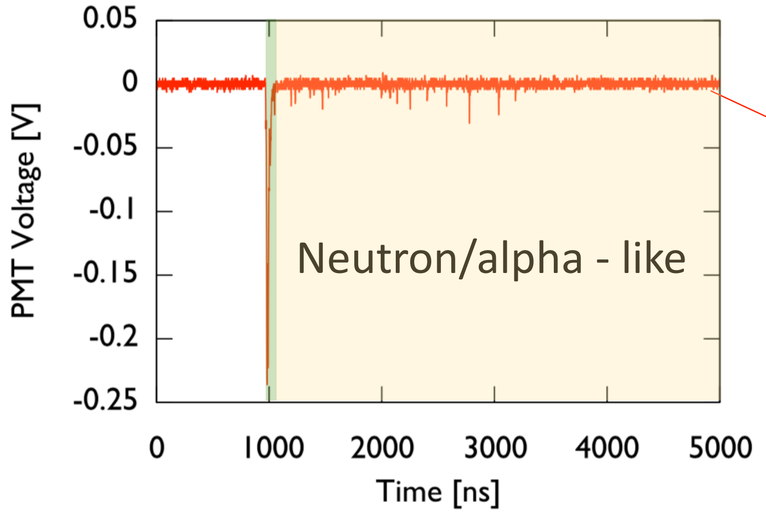
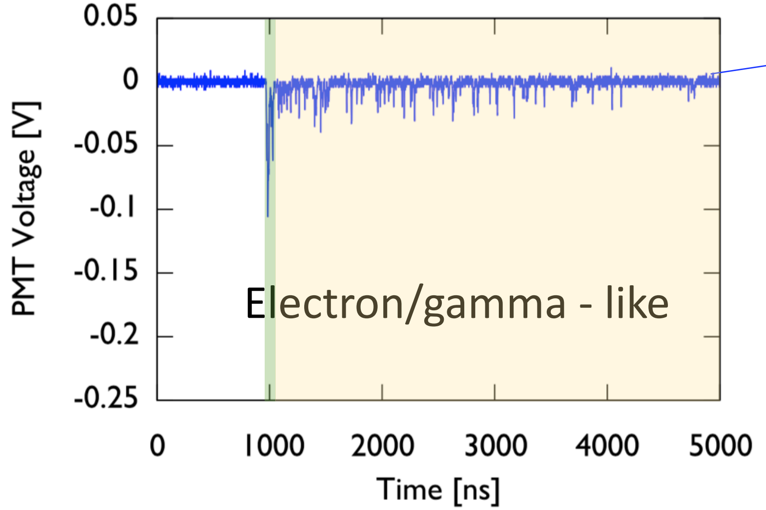
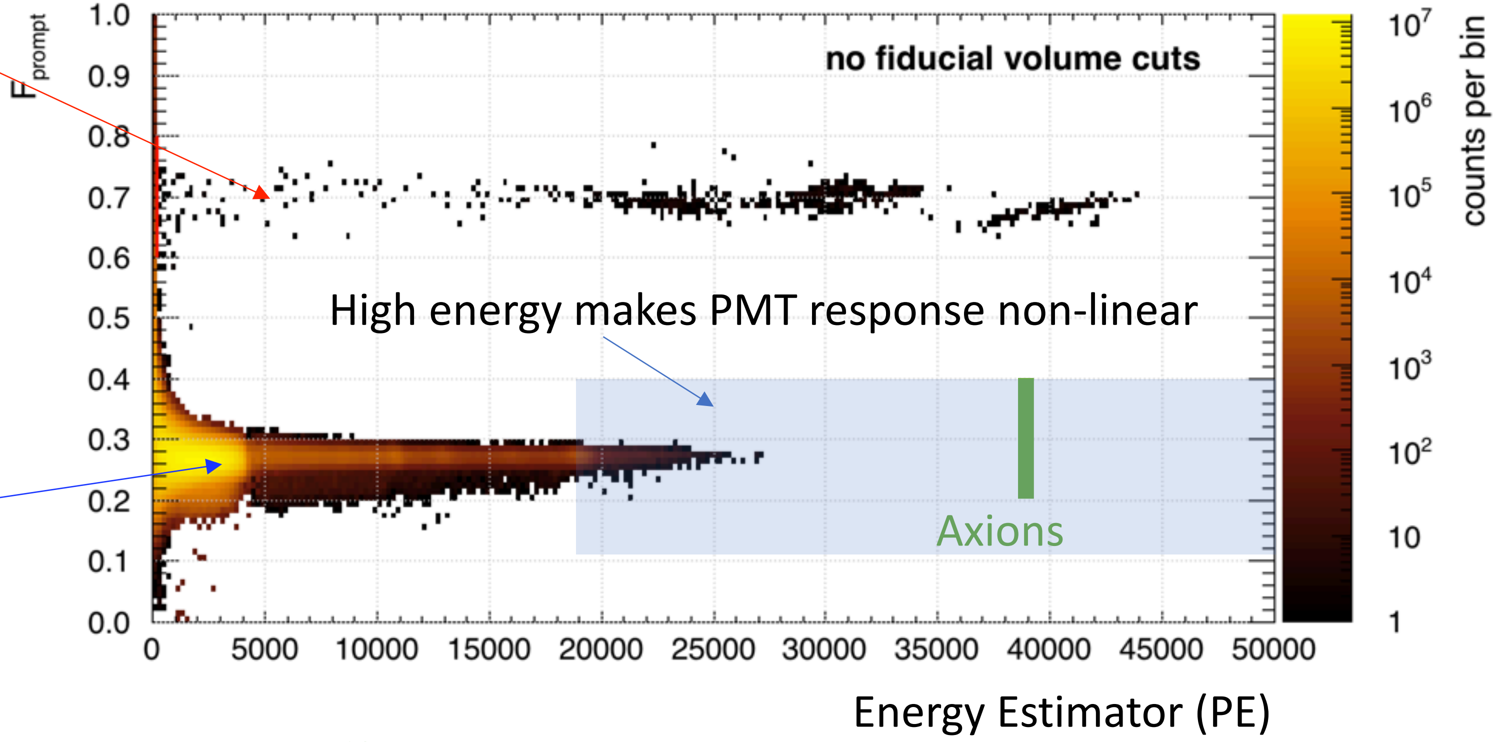




4.4 Days of data [1]



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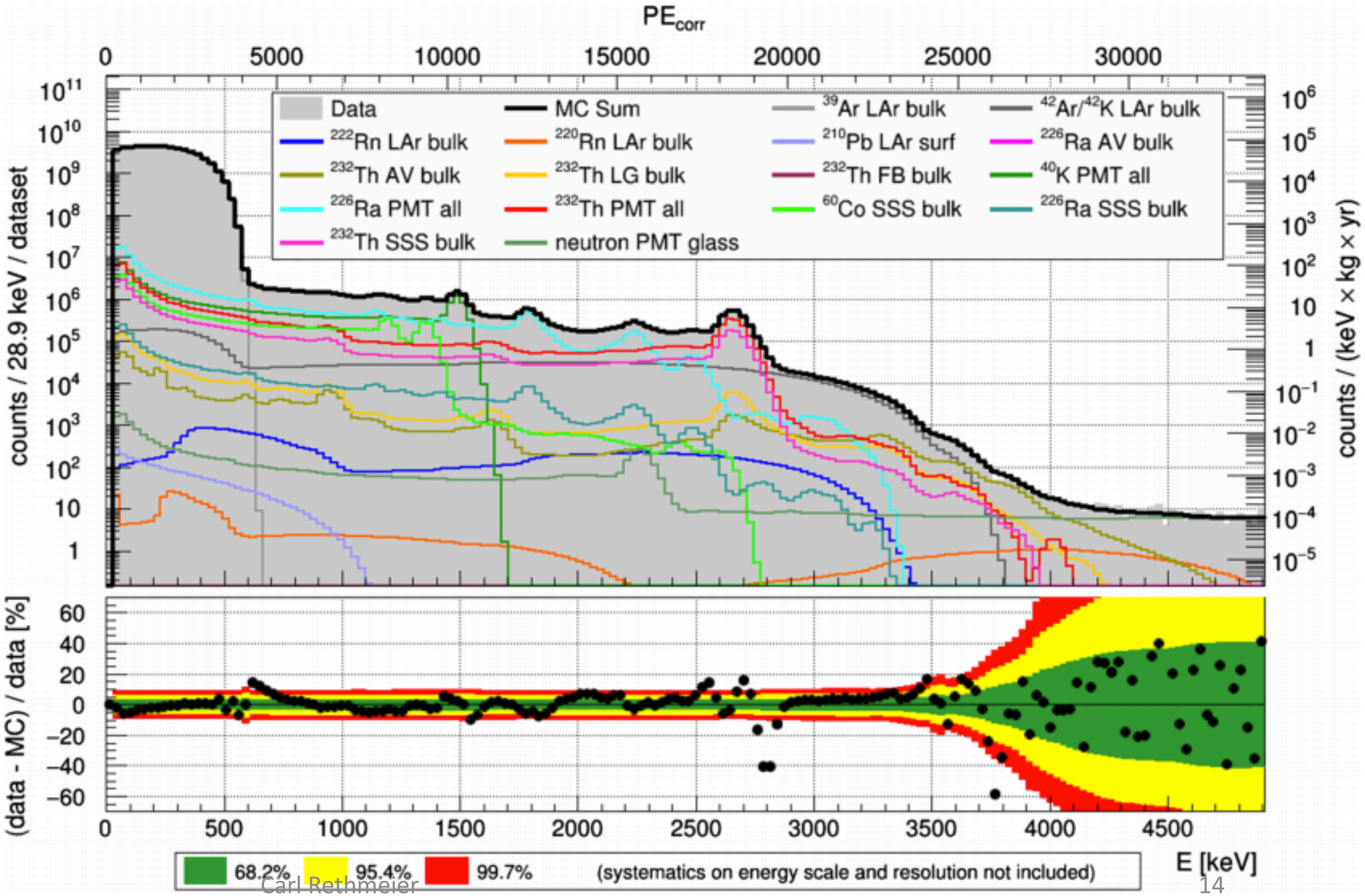
Electron/Gamma Backgrounds

DEAP Collaboration (2019). Electromagnetic backgrounds and potassium-42 activity in the DEAP-3600 dark matter detector. *Physical Review D*, *100*(7), 072009.

Fit of electromagnetic backgrounds published

Fit ends just below 5 MeV.

Axion region of interest is at 5.5 MeV



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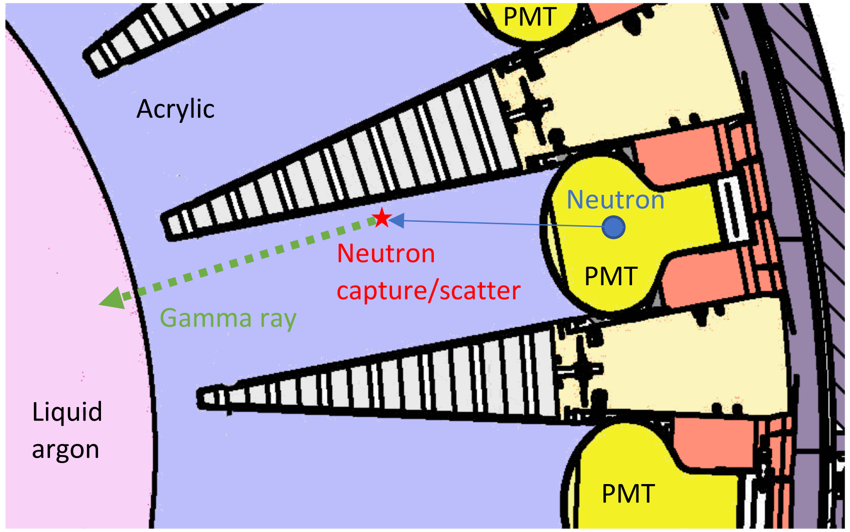
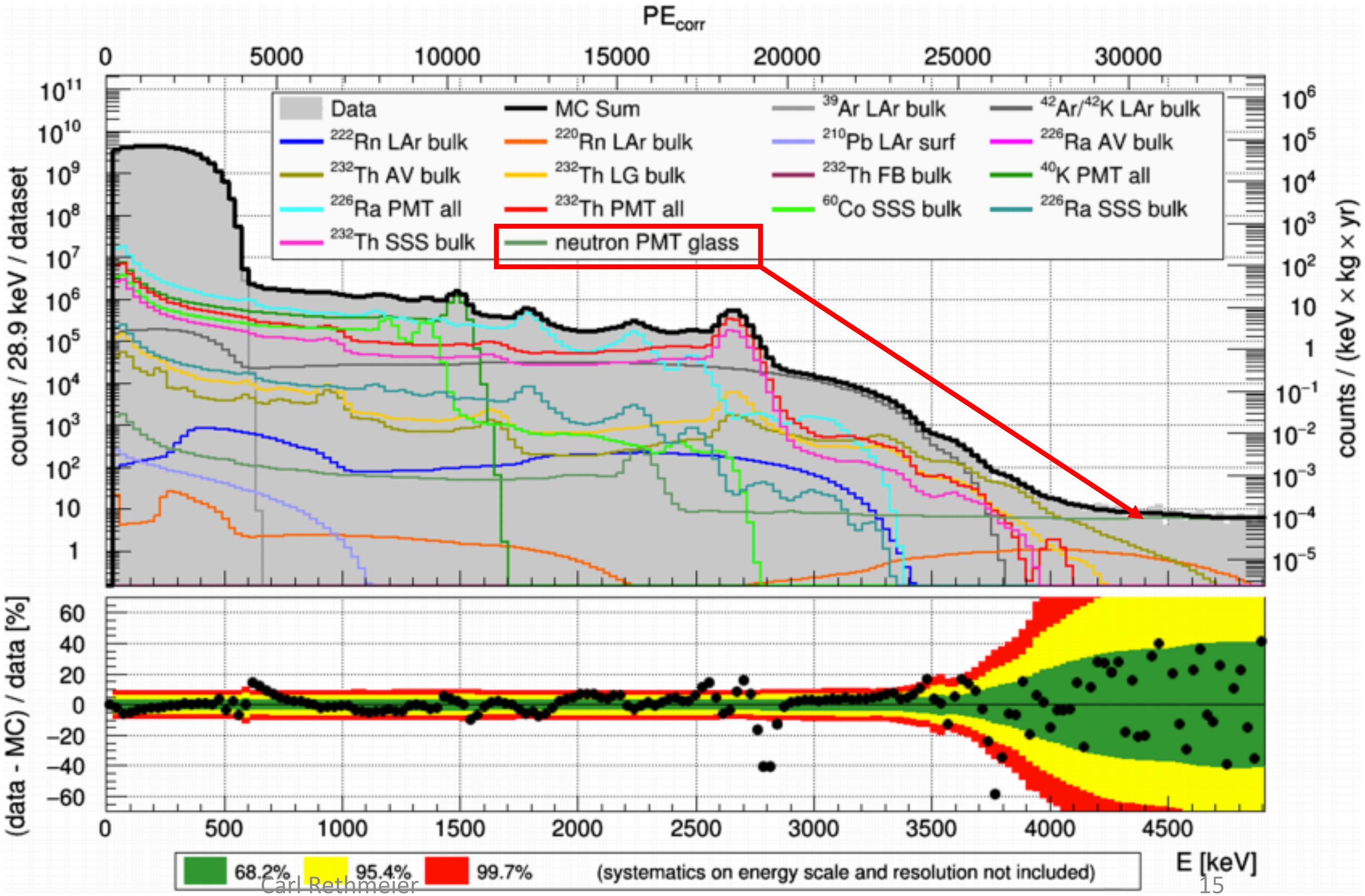
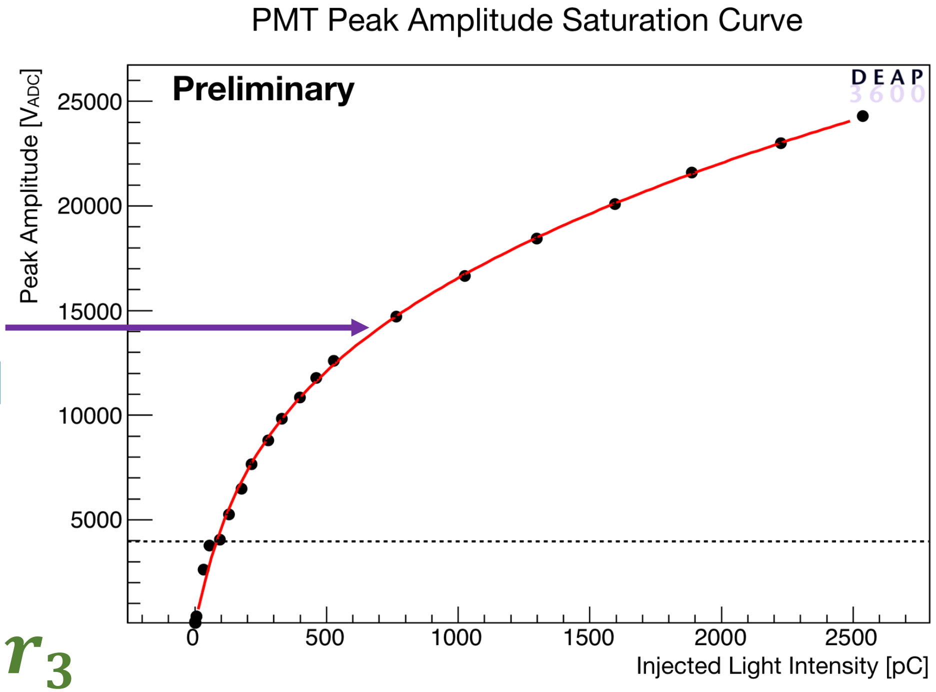




Simulations and Detector Response Function

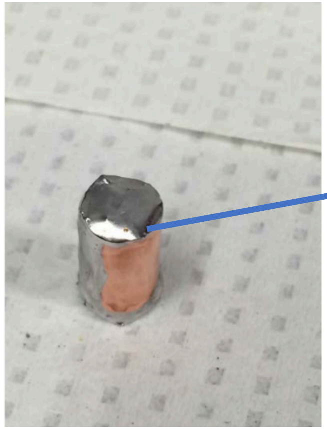
- Generated Monte Carlo simulations of signal and background energy depositions
- **Energy scale:** $PE_{mean} = A \cdot E^2 + B \cdot E + C$
  - A -> non-linear detector effects (PMT saturation)
  - B -> photons observed per unit energy deposited
  - C -> residual light, thermal noise, etc
- **Apply resolution:** $PE = \text{Gaus}(PE_{mean}, \sigma)$
- Where, $\sigma^2 = r_1 \cdot PE_{mean}^2 + r_2 \cdot PE_{mean} + r_3$
  - r_1 -> non-linear detector effects (PMT saturation, late and double pulsing, etc)
  - r_2 -> Poisson photon production, binomial photon counting, and afterpulsing
  - r_3 -> electronic noise

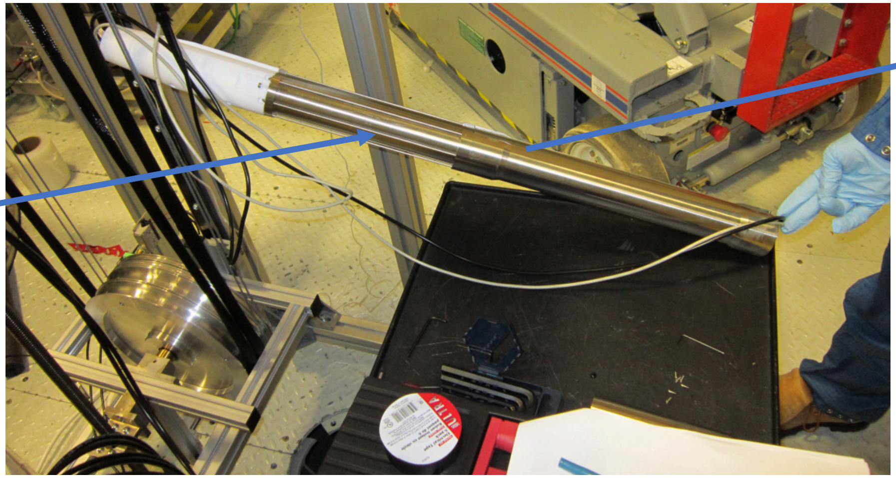


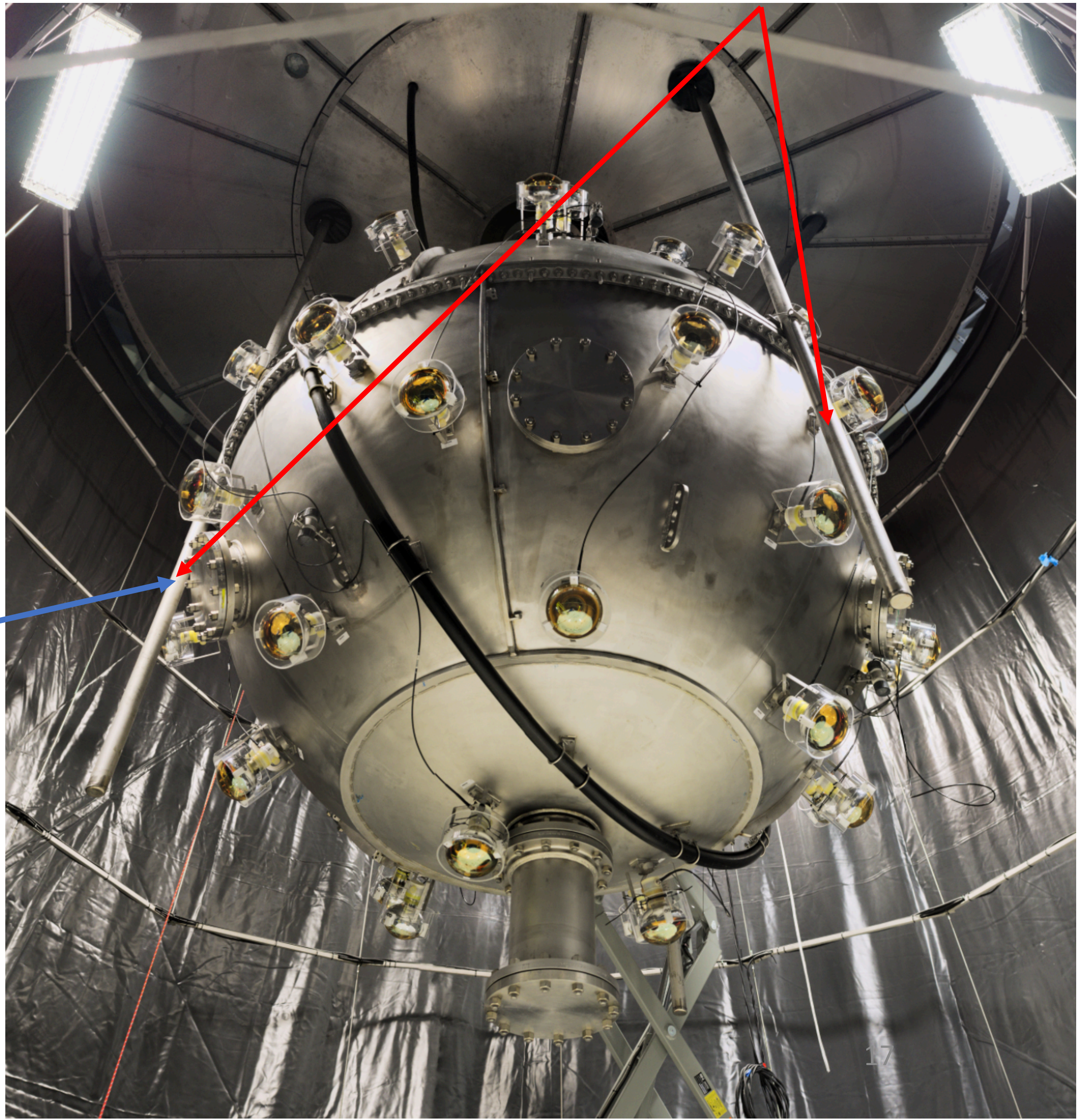
High energy response calibrated at 4.4 MeV and Above

Source containing Am241 and Be9 (AmBe) generates neutrons and gammas

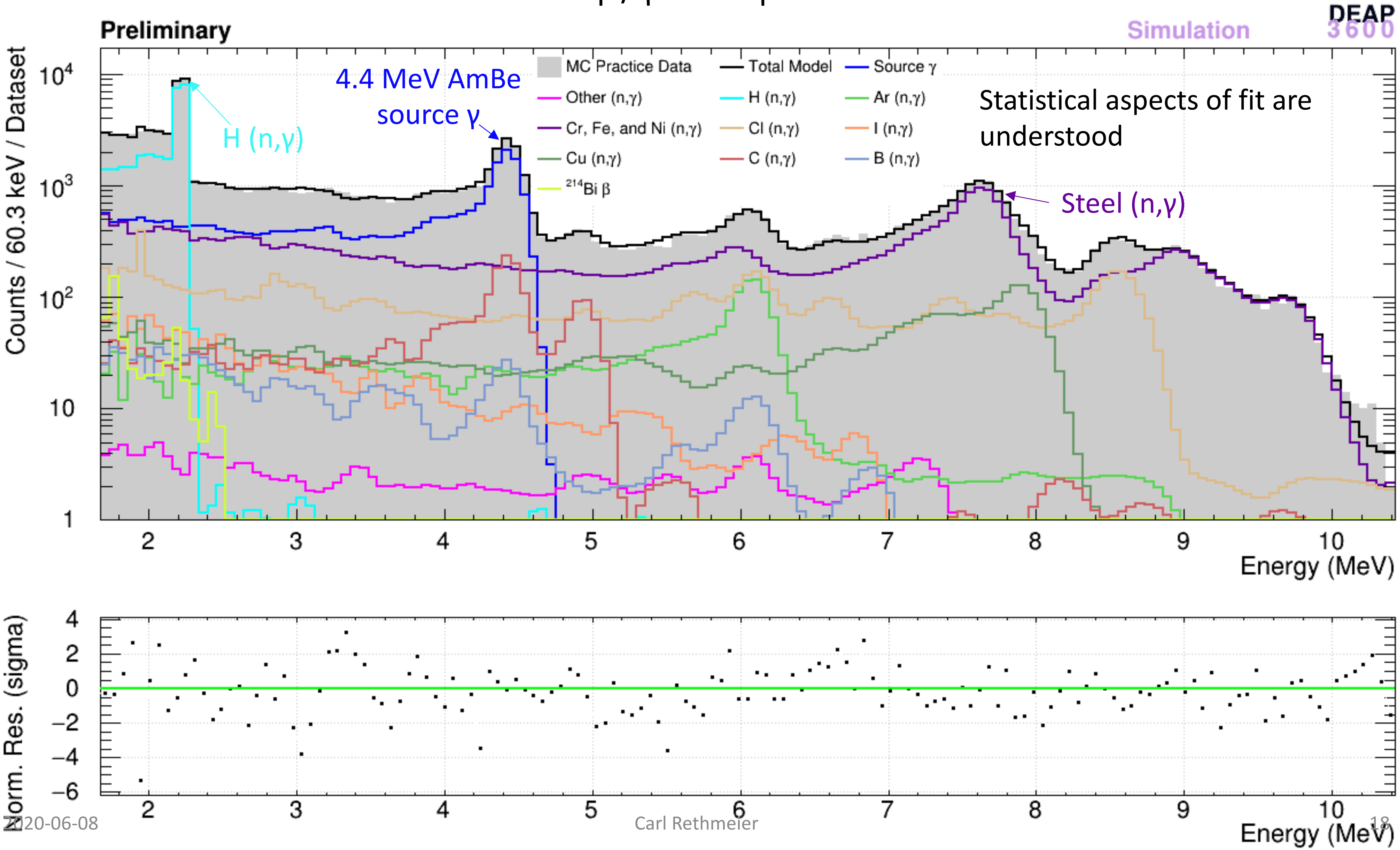
Complicated source geometry added to MC model







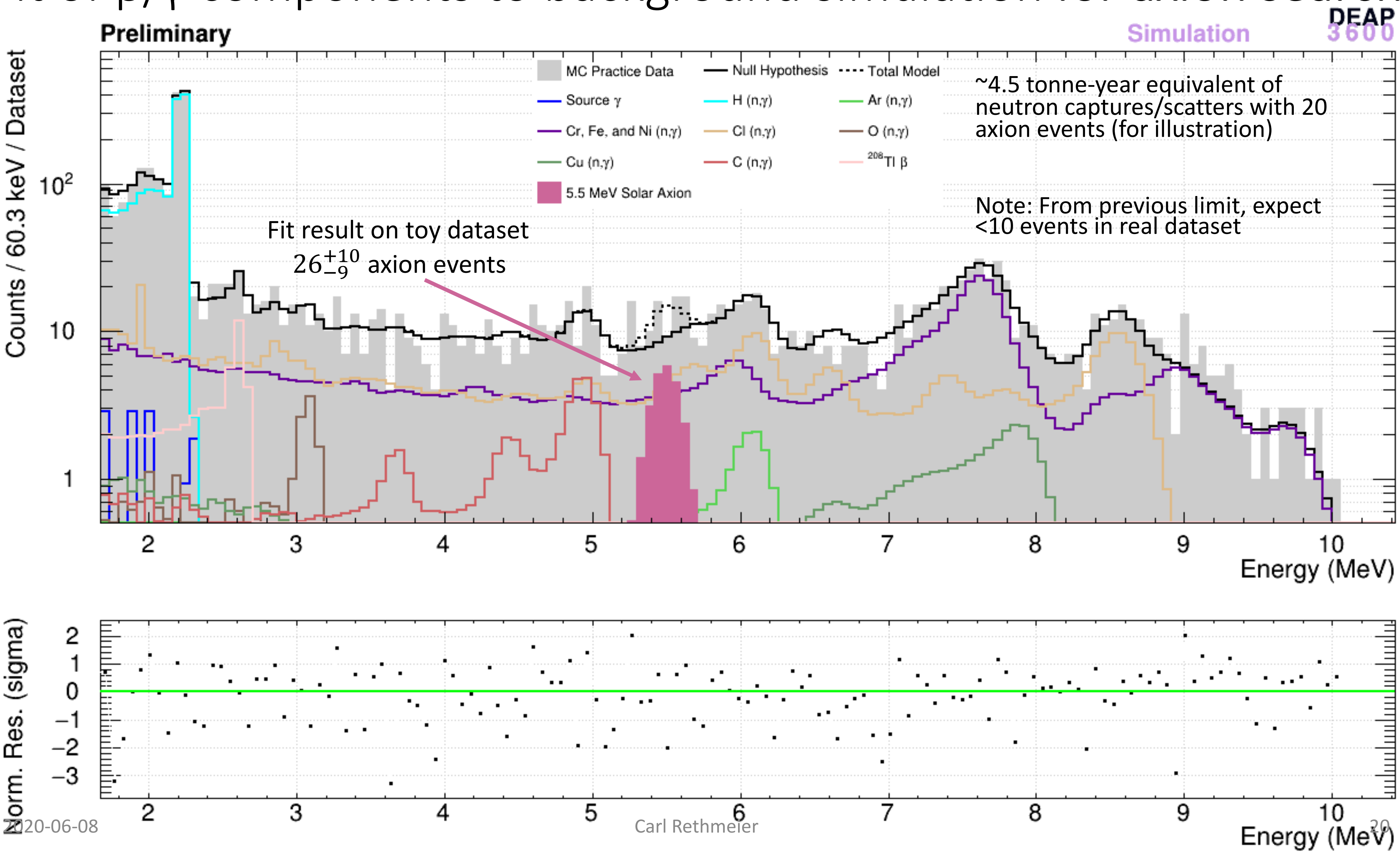
Binned-likelihood fit of simulated β/γ components to **AmBe source simulation**



From calibration to axion search fit…

- Fix response function parameters from calibration fits
- Try fitting on a toy dataset containing neutron-induced backgrounds and some axion events

Fit of β/γ components to background simulation **for axion search**



Summary

- A 5.5 MeV solar axion search in DEAP-3600 has exciting potential
  - Requires calibration of detector at high energy
  - Main background is neutron-induced gammas
- A MC-based model and response function is fit to the data to search for an axion signal
  - Detailed analysis of systematic uncertainties is underway
  - Results will be released as part of my PhD thesis and in an upcoming paper

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