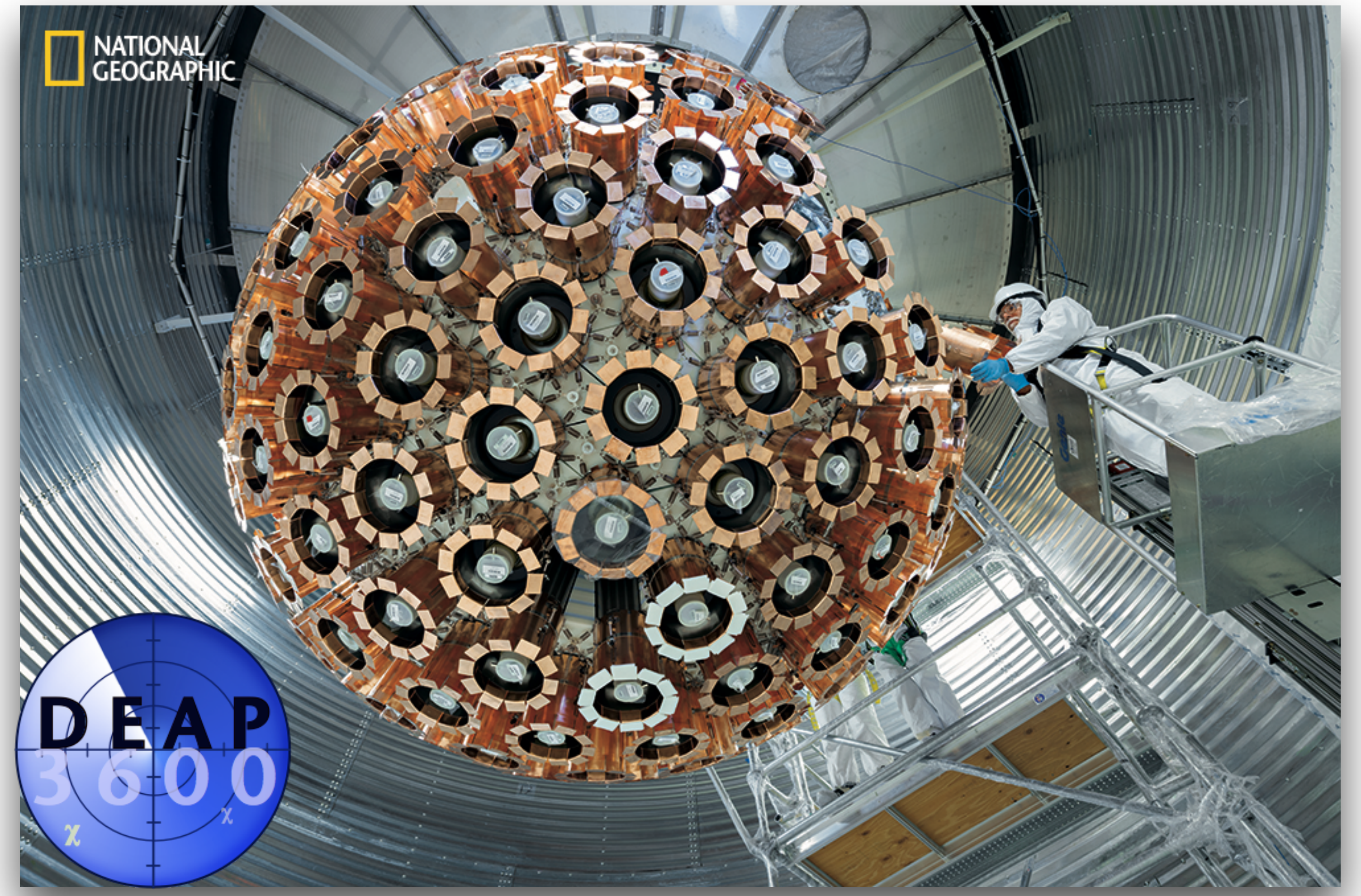
Neutrino absorption in DEAP-3600

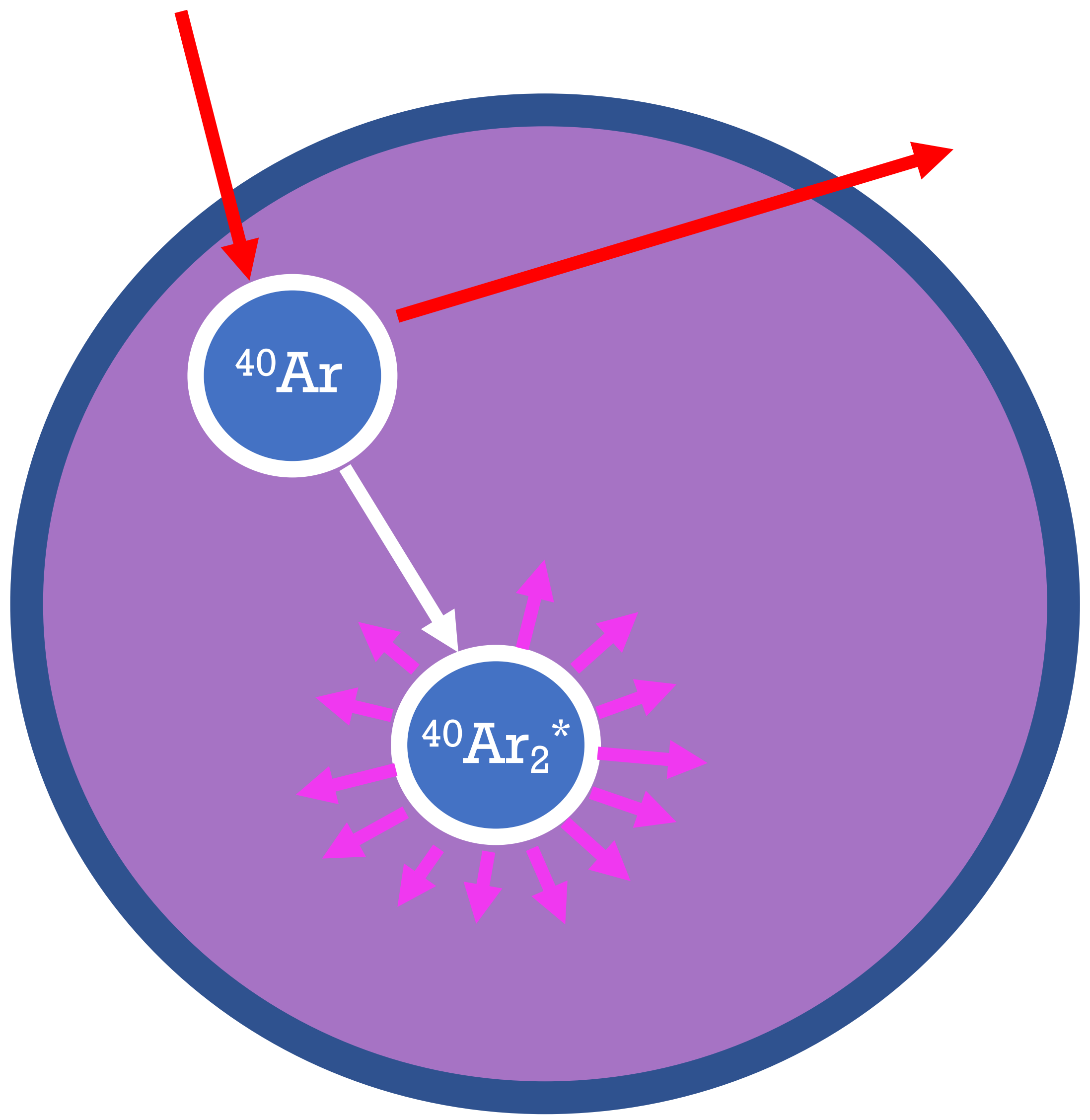
August 12th, 2021

Emma Ellingwood and Andrew Erlandson

Outline

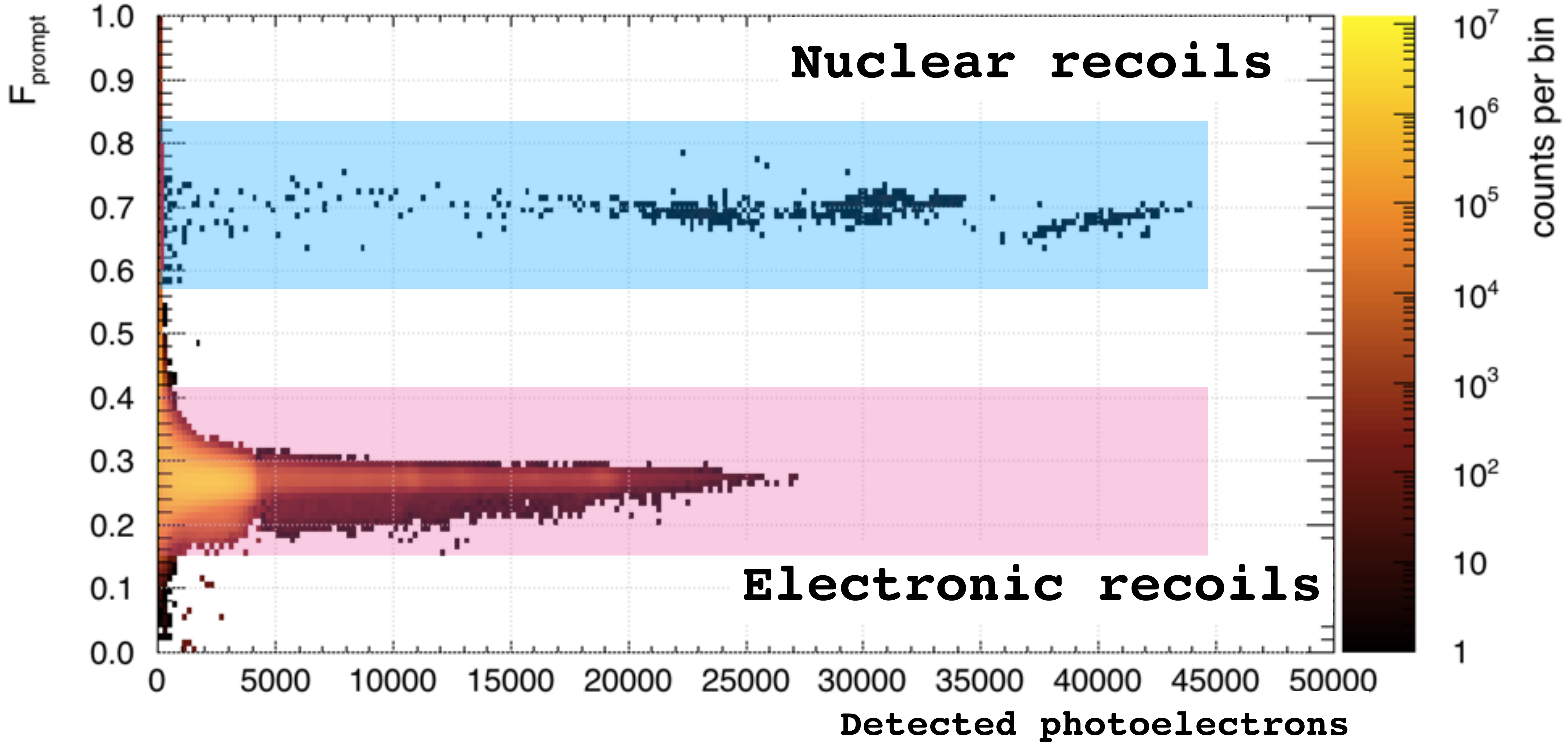
- Dark matter experiment using argon pulseshape discrimination(DEAP-3600)
- Solar neutrinos
- Signal phenomenology
- Charged current interactions on argon ($\nu_e CC$/IBD/Absorption)
- Reaction rates
- Coincidence tagging validation using ^{212}BiPo
- Preliminary coincidence tagging efficiency
- Future work





DEAP-3600

- DEAP-3600 is a "light-only" dark matter (and maybe neutrino!) detector
- ^{39}Ar background (0.953 ± 0.028) Bq kg^{-1} suppressed by pulseshape discrimination (PSD)
- 128 nm scintillation light emission timing depends on how much singlet/triplet light was produced
  - This depends on the incident radiation
  - Neutrons/α's product less triplet light than β/γ
  - The shape of the scintillation pulse (detection time of photons) tells one whether the event was due to a "nuclear" recoil or an "electronic" recoil
- Using photon timing, PSD parameter (f_{prompt}) is calculated:



$$f_{prompt} = \frac{\sum_{t=-28\ ns}^{150\ ns} PE(t)}{\sum_{t=-28\ ns}^{10\ \mu s} PE(t)}$$

Solar neutrinos

- **Components of the solar neutrino spectrum are well established (except hep spectrum which has yet to be formally detected)**
- **^{8}B is the dominant source of neutrinos in this analysis (neglecting a convenient supernova)**
- **Can safely ignore the vast majority of the solar neutrino flux (kinematically forbidden)**

Fusion reactions in the sun:

$$p + p \rightarrow d + e^+ + \nu_e$$

$$d + p \rightarrow {}^3He + \gamma$$

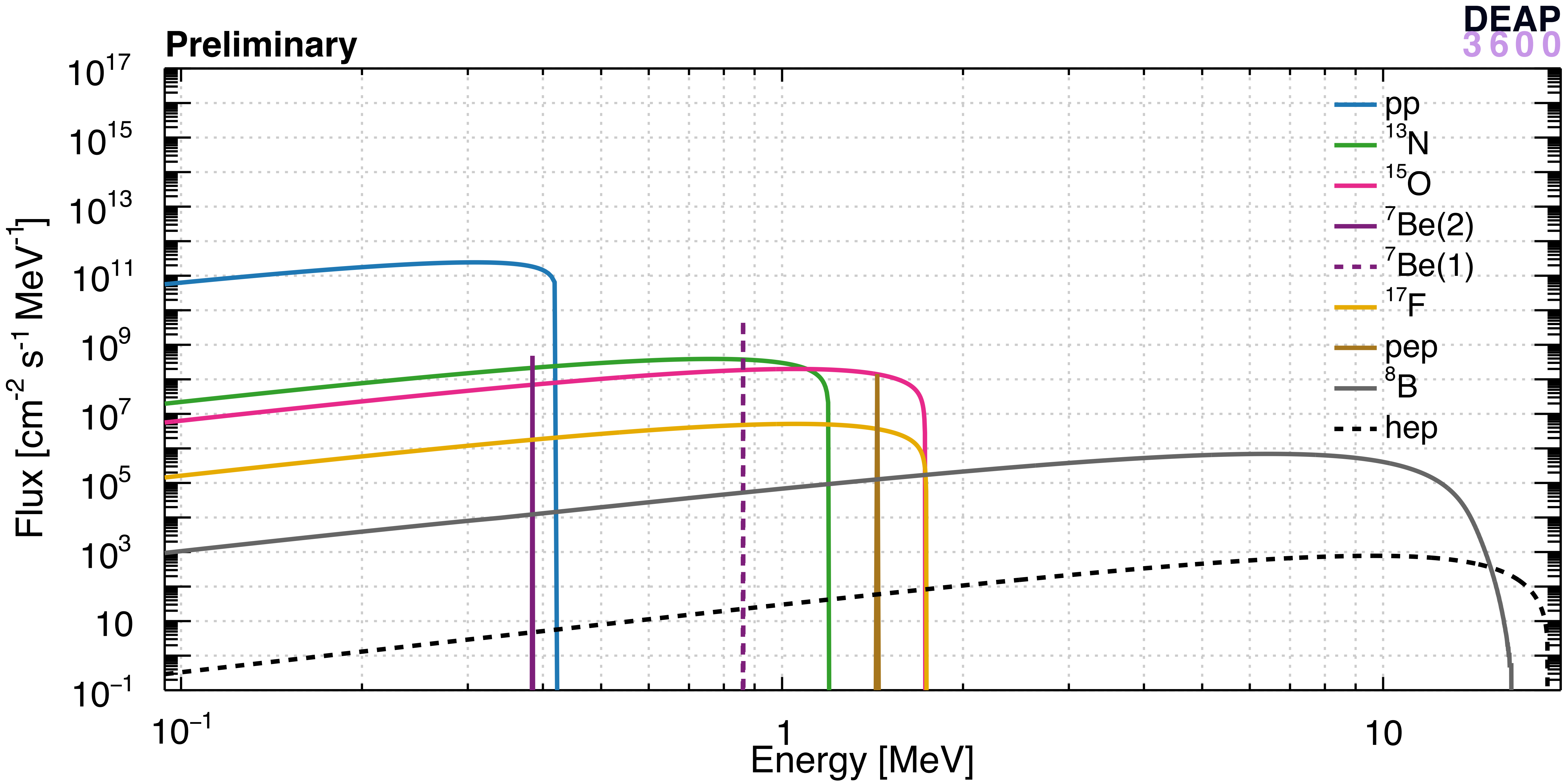
$$^3He + {}^3He \rightarrow {}^4He + 2p$$

$$^3He + {}^4He \rightarrow {}^7Be + \gamma$$

$$^7Be + e^- \rightarrow {}^7Li + \nu_e$$

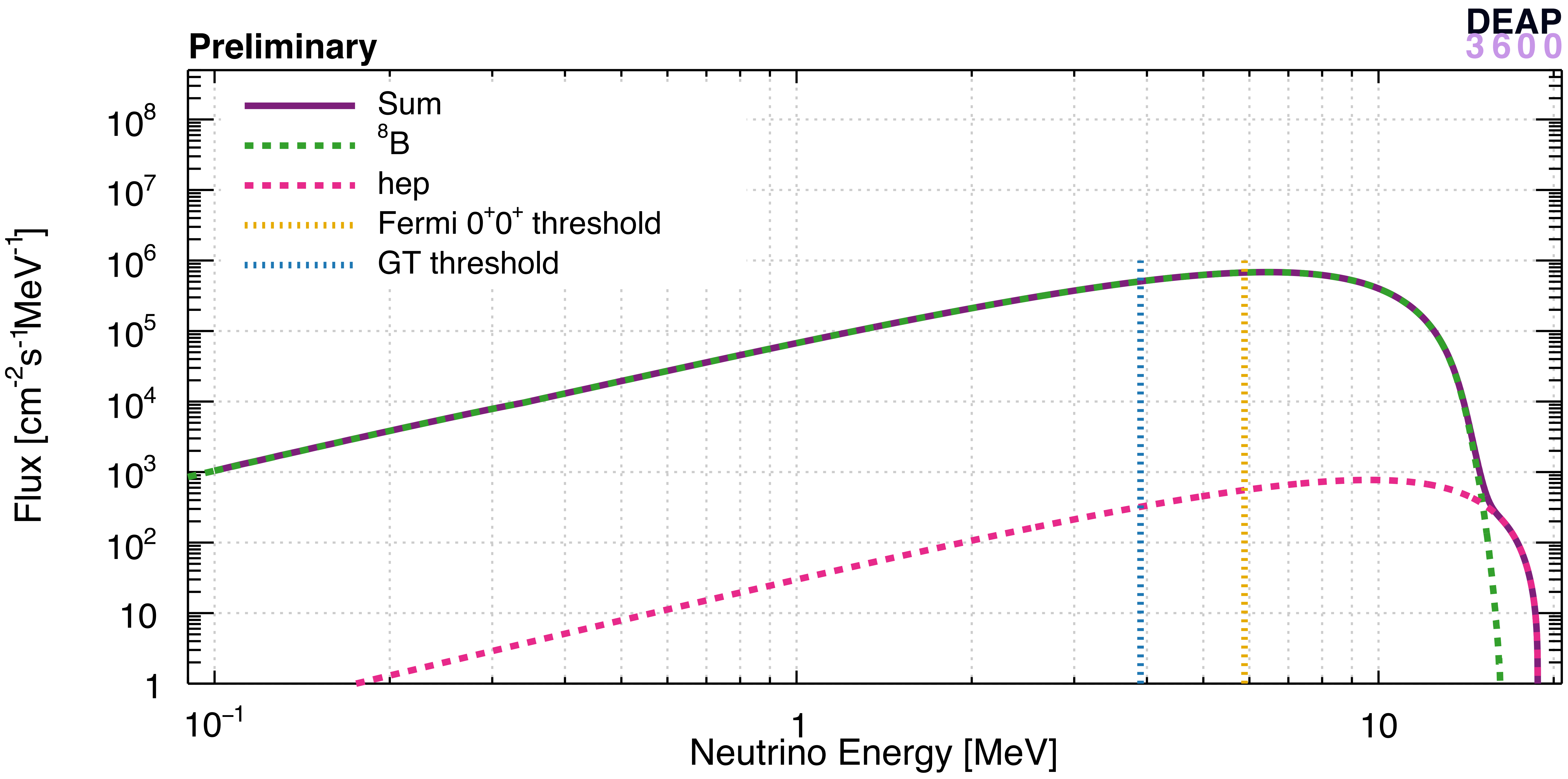
$$^7Be + p \rightarrow {}^8B + \gamma$$

$$^8B \rightarrow {}^8Be^* + e^+ + \nu_e$$



Solar neutrinos

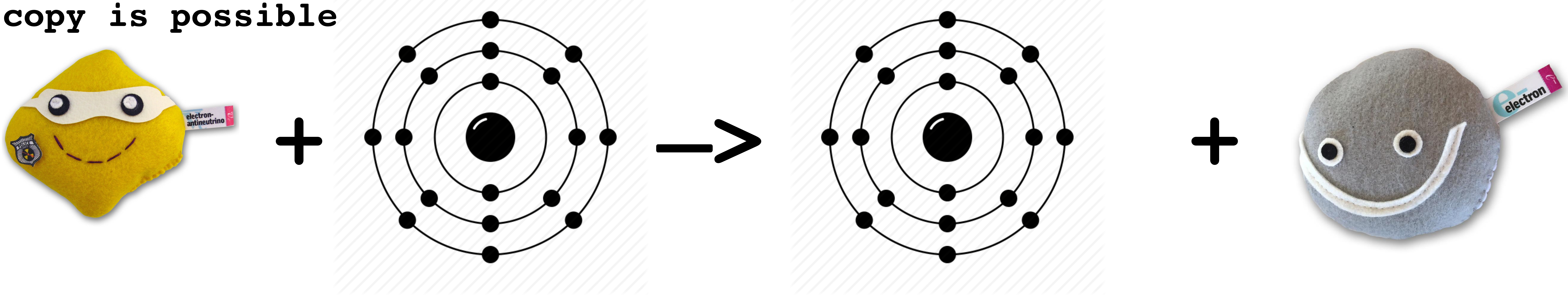
- **Considering only ^{8}B and hep neutrinos (negligible contributions from atmospheric or cosmic neutrinos)**
- **SNO measured flux:** $\left(5.25 \pm 0.16(stat.) \pm {}^{0.11}_{-0.13}(sys.)\right) \times 10^6$ **cm^{-2} s^{-1} (Phys. Rev. C 88 (2013) 025501)**
- **SNO measured survival probability** $= \left(0.317 \pm 0.016(stat.) \pm 0.009(sys.)\right)$ **at 10 MeV (day time)**



- **Increase flux acceptance by ~25% from 5.8 MeV and 3.9 MeV**
- **DEAP is located "down the hall" from SNO, so, the neutrino flux should be pretty much identical**
- **hep flux is only ~0.15% of total flux - DEAP is probably too small to see these neutrinos**

Signal phenomenology

- **Fundamentally, this process is an neutrino-induced transmutation of the nucleus**
- **Final state particles include an excited K nucleus and an electron**
  - **^{40}K* very quickly decays to the ground state via available nuclear transitions**
  - **To first order, electron energy spectrum is a very typical "beta decay" spectrum**
  - **Hadrons (neutrons) in the final state are possible but unlikely (more likely at higher energies)**
- **Basic process is to see the prompt electron and gammas, if you're lucky, a delayed gamma with an energy of ~1.64 MeV (delayed coincidence!)**
- **Mean lifetime of metastable state $\tau = 480$ ns**
- **Some kinematics:**
  $E_\nu = E_e + E_\gamma + E_{gs}$
- **With reasonable energy resolution (and full containment of gammas), neutrino spectroscopy is possible**



^{40}Ar **^{40}K***

not to scale!

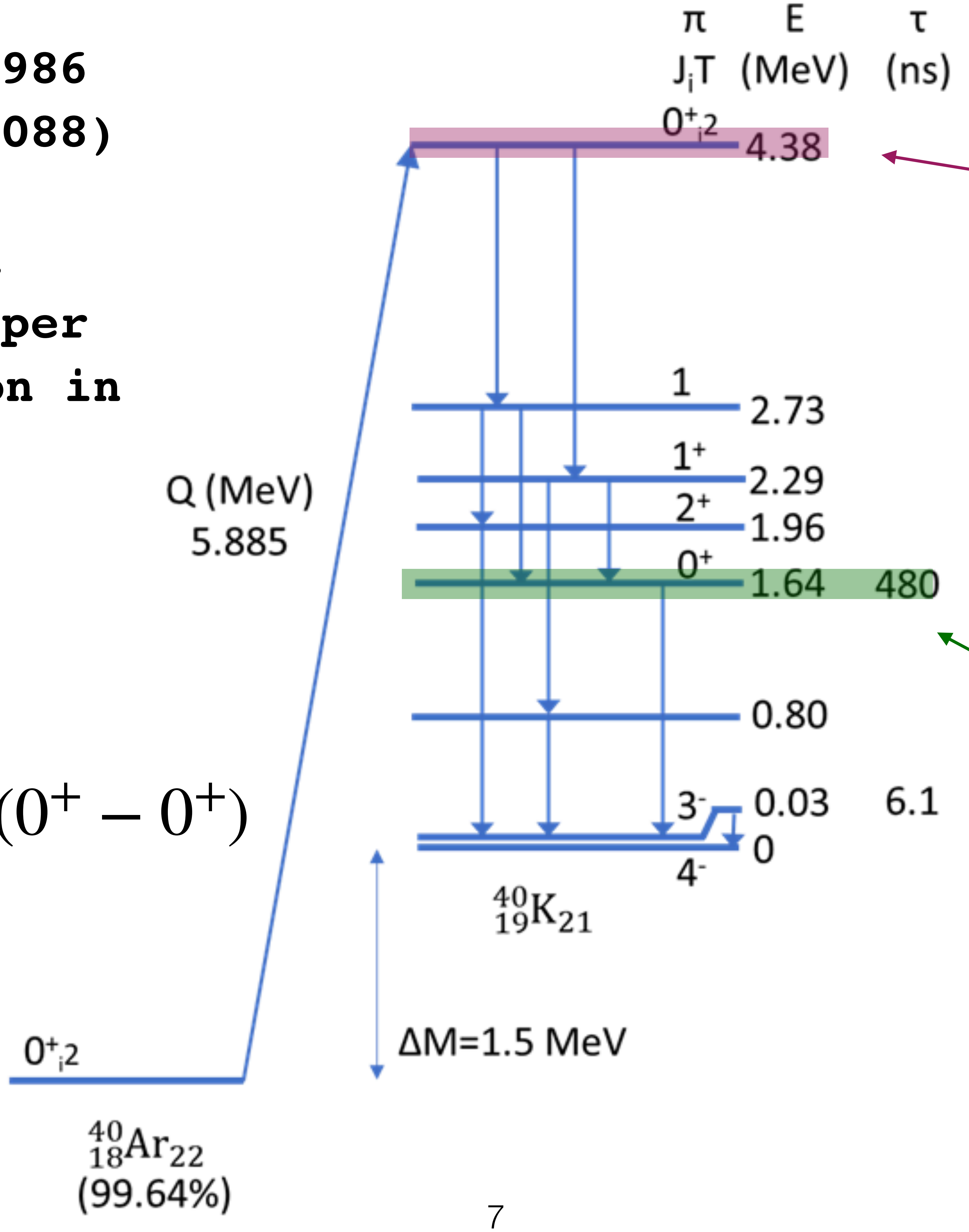
Source: particlezoo.net

Charged current interaction on ^{40}Ar

- **Proposed by R.S. Raghavan in 1986 (doi.org/10.1103/PhysRevD.34.2088)**
- ^{8}B **(and hep) solar** ν_e **have high enough energy to induce the super allowed** $0^+ \rightarrow 0^+$ **Fermi transition in Argon**
- **Basic reaction:**

$$\nu_e + ^{40}Ar \rightarrow ^{40}K^* + e^-$$

$$\sigma(E_\nu) = \sigma_0 W_e (W_e - 1)^{\frac{1}{2}} F(W_e) / ft(0^+ - 0^+)$$



Charged current interaction on ^{40}Ar

- **Bhattacharya extended the work of Raghavan (https://journals.aps.org/prc/pdf/10.1103/PhysRevC.58.3677) to include Gamow-Teller transitions**
- **More transitions means a larger matrix element which boosts the total cross section**

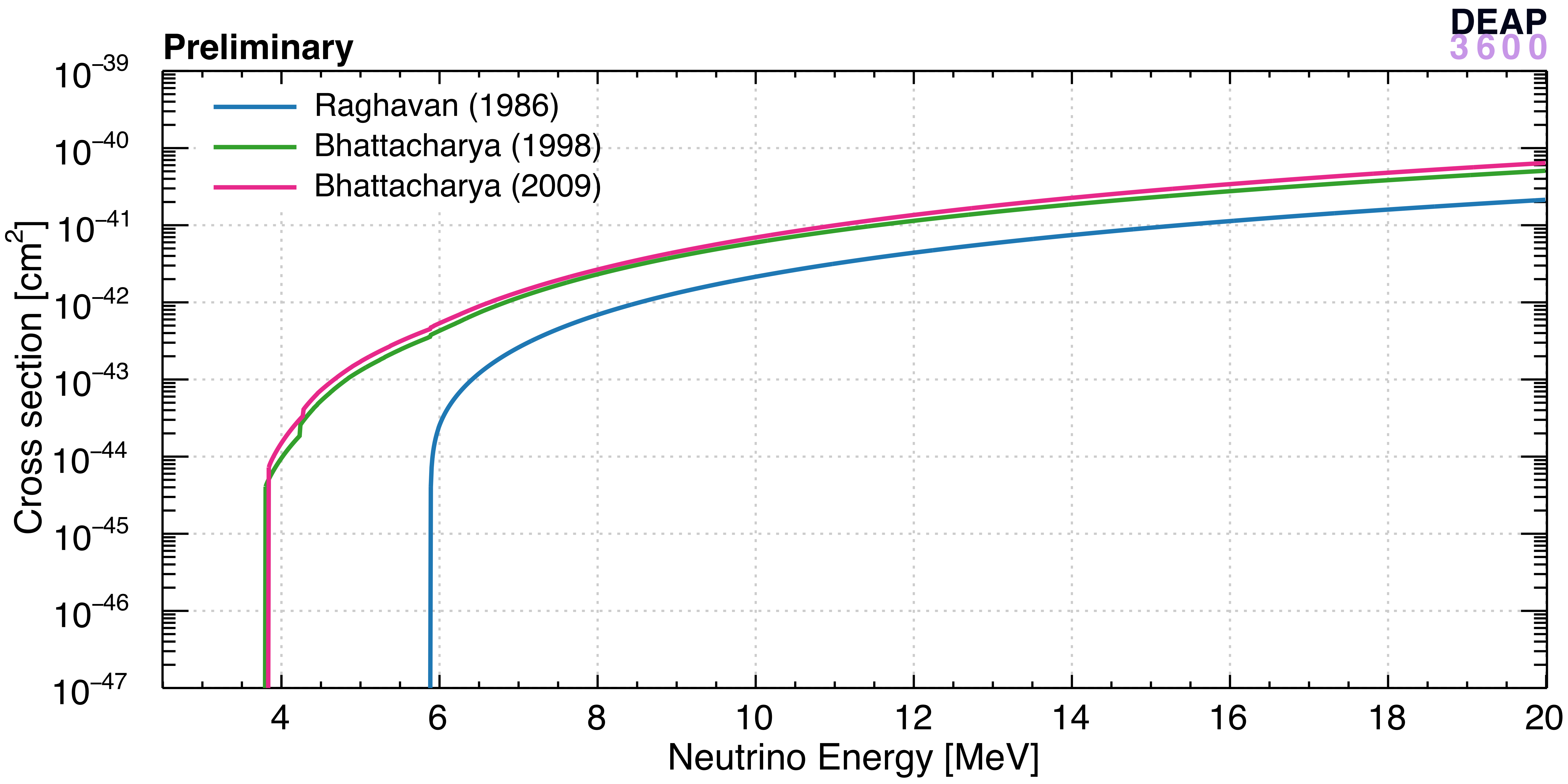
$$\sigma(E_\nu) = \sum_i \frac{G_{F,\beta}^2 |V_{u,d}|^2}{\pi} |M_{0\rightarrow i}|^2 E_e^i p_e^i F(E_e)$$

where $|M_{0\rightarrow i}|^2 = B_i(F) + B_i(GT)$

- **Depending on which nuclear model is used, the total cross section increases by a factor of 2.5-3x**
- **Larger cross section means, for a given flux, a higher interaction rate (yield of events in some exposure)**

Δ E (keV)	B(F)	B(GT)
2333		1.64(16)
2774		1.49(14)
3204		0.06(2)
3503		0.16(2)
3870		0.44(5)
4384	4.0	
4421		0.86(14)
4763		0.48(5)
5162		0.59(6)
5681		0.21(3)
6118		0.48(5)
6790		0.71(8)
7468		0.06(2)
7795		0.14(2)
7952		0.97(10)
Total	**4**	**8.29(31)**

Charged current interaction on ^{40}Ar



- XS calculated under "allowed" approximation
- Integral cross section up to 18.7 MeV:
  $\sigma_{Fermi} \sim 7.98 \times 10^{-41}$ cm^2
  $\sigma_{F+GT(98)} \sim 1.99 \times 10^{-40}$ cm^2
  $\sigma_{F+GT(09)} \sim 2.44 \times 10^{-40}$ cm^2
- GT transitions are numerous!
- Beyond the solar neutrino spectrum, this process makes detecting neutrino bursts from supernova very accessible

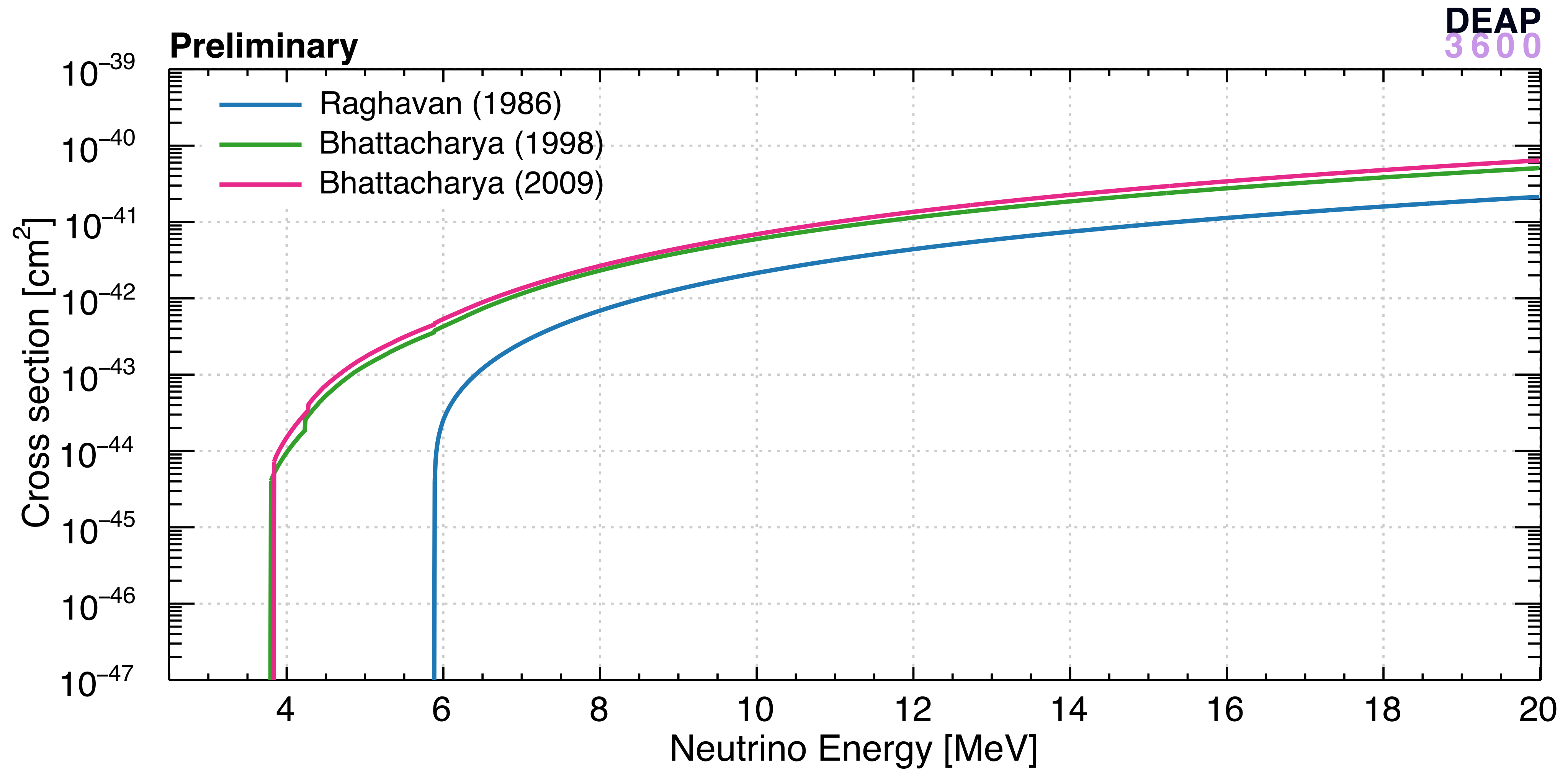
Expected Rates

- Taking the solar ^{8}B+hep spectrum as an input along with the cross sections for several models, the rates can be calculated:

$$\Gamma = N_{nucleons} \int_{E_{min}}^{E_{max}} \frac{d\phi(E)}{dE} \sigma_{tot} \, dE$$

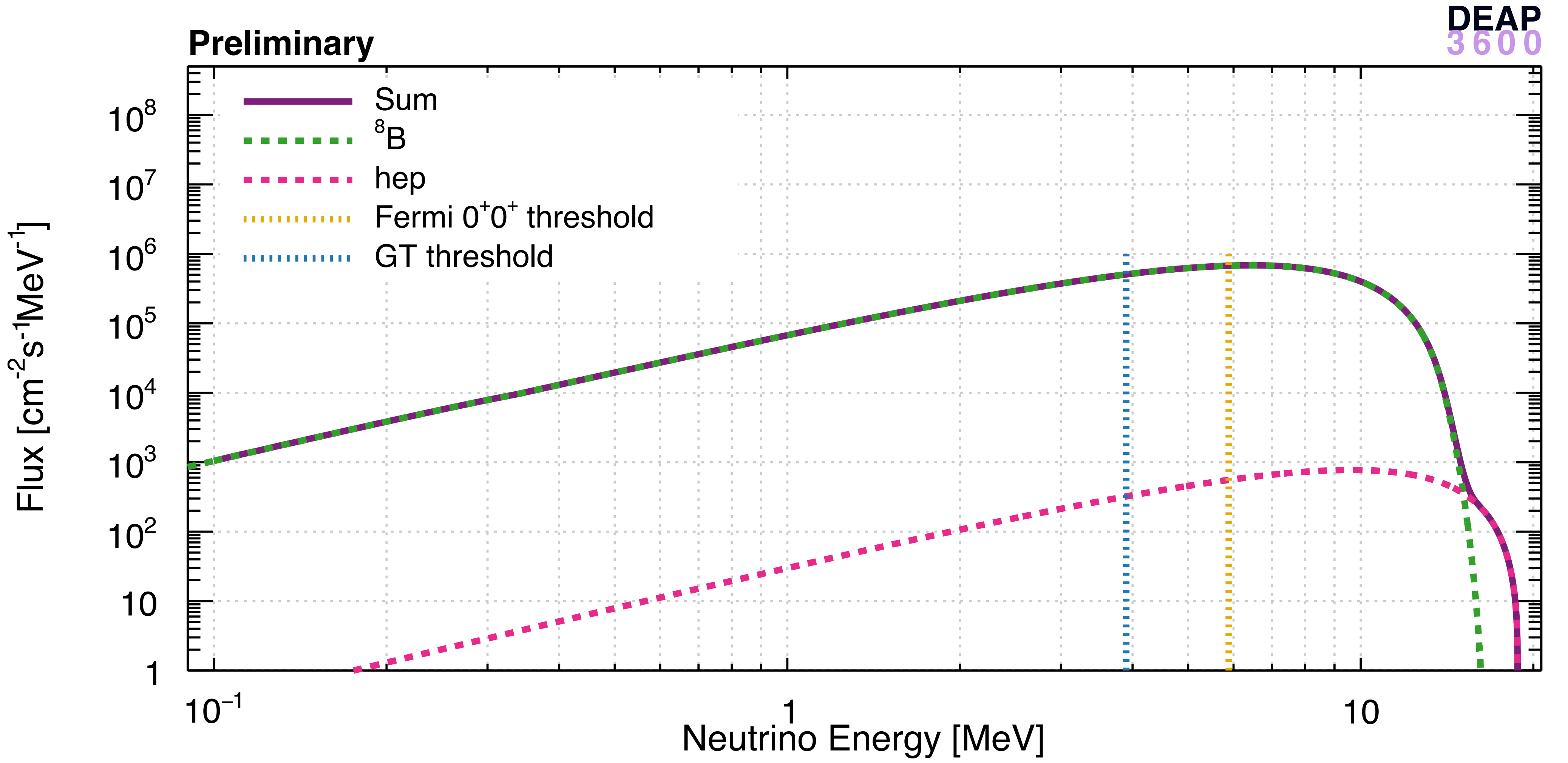
Rates [ton^{-1} $year^{-1}$]: (oscillated flux)

- Fermi = 0.63
- Fermi + GT (2008) = 1.86
- Fermi + GT (2019) = 2.19



- Scaling to a reasonable exposure (7.25 ton-year) in DEAP-3600 yields ~ 15.8 ± $1.5_{sys.}$ events using the most optimistic model

- This is very much a detectable signal!
- Can measure the neutrino flux given a cross section or, can measure the cross section given the flux



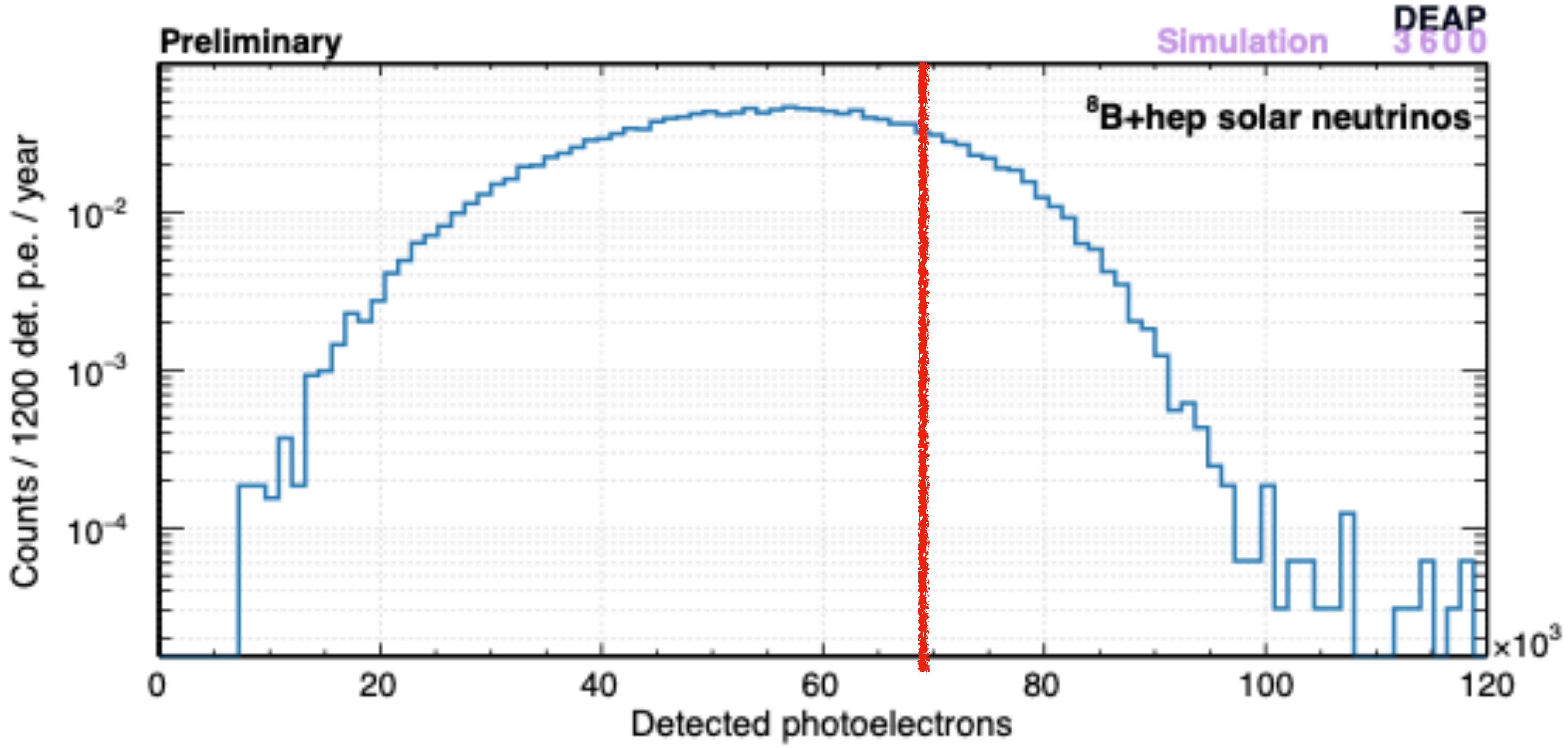
Expected Rates

- **Using the MARLEY event generator, the probability for the Fermi+GT model to produce delayed final state can be estimated**
- **Marley predicts this probability to be (29.47±0.01)% averaged over all energies**

Rates [ton^{-1} $year^{-1}$]: (oscillated flux)

- **Fermi = 0.19**
- **Fermi + GT (2008) = 0.55**
- **Fermi + GT (2019) = 0.65**

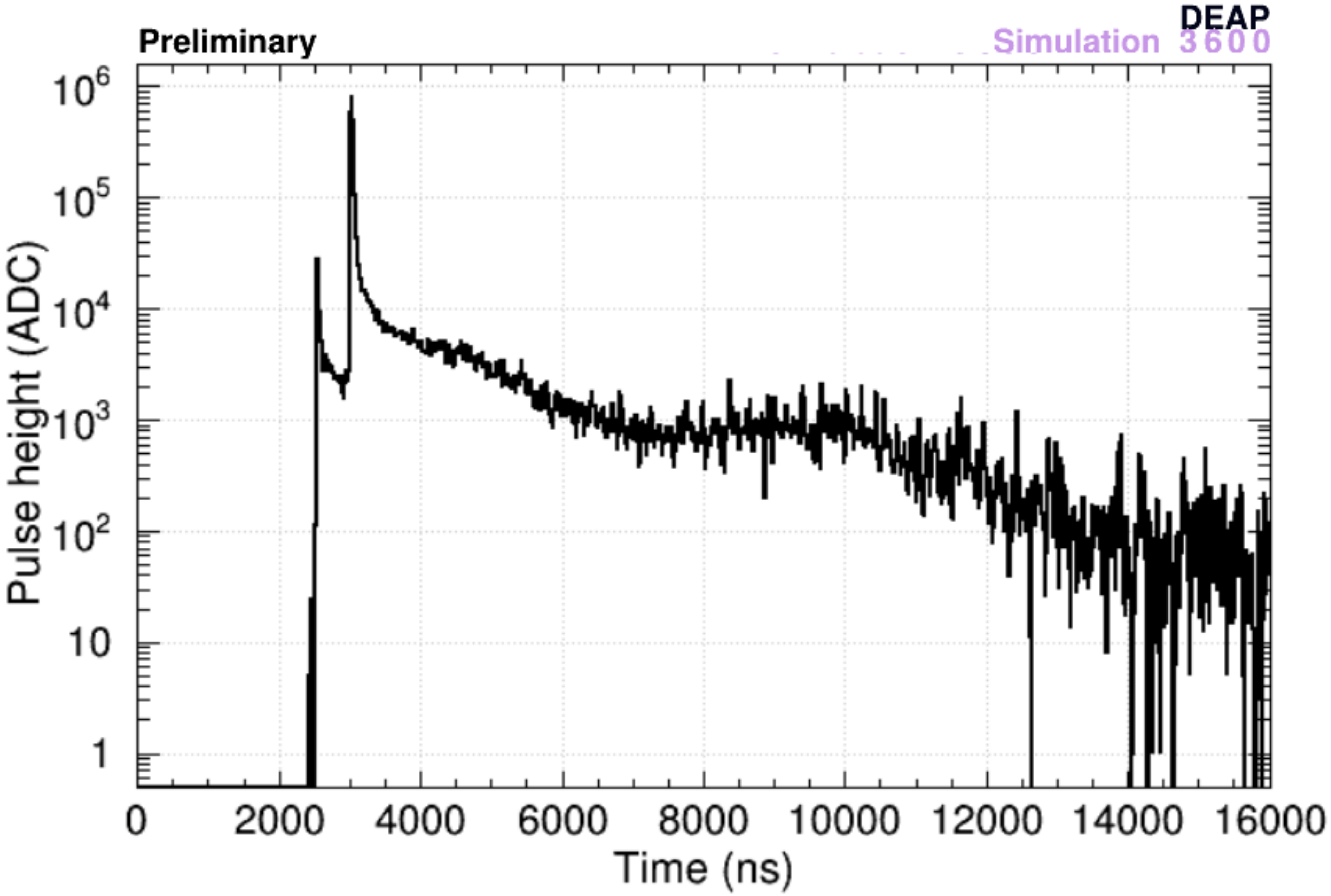
- **Scaling to a reasonable exposure (7.25 ton-year) in DEAP-3600 yields ~ 4.7 ± $0.4_{sys.}$ events using the most optimistic model assuming 100% acceptance**



Signal PDF normalized by total average acceptance of ~20%

High Energy Coincidence Algorithm

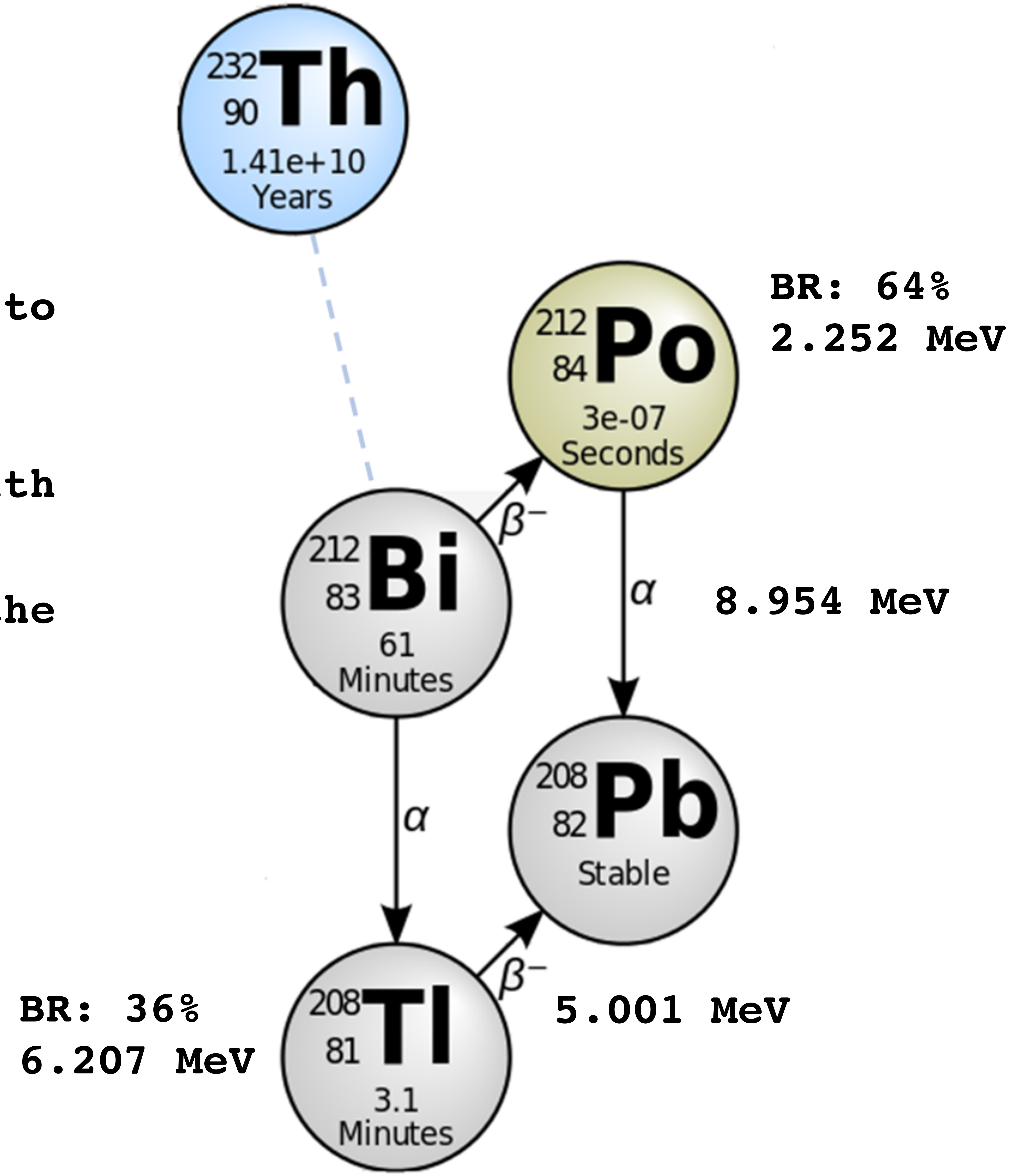
- This an algorithm to identify delayed coincidence signatures in waveforms
- It is a derivative-based approach that identifies the height and time of waveform peaks that occur after the derivative passes a specified threshold
- The efficiency and accuracy can be tested by tagging ^{212}BiPo delayed coincidence events



DEAP-3600 summed waveforms for a ^{212}BiPo candidate event with coincidence

Radioactive ^{212}Bi

- ^{212}Bi can decay through ^{212}Po to produce a delayed coincidence event with a mean lifetime of <u>432 ns</u>.
- The overall timing structure and energies are similar to the delayed coincidence expected in ^{40}Ar neutrino absorption.
- In addition, ^{212}Po has already been measured in DEAP with an activity of 3.4 nBq/kg.
- We can use data and MC to validate the processor and the ability to reconstruct prompt/delayed energies.



^{212}Bi Monte Carlo

- **The simulation of these events produces several distinct features:**
  - **A region with the α emission from the BiTl decay**
  - **A prompt BiPo region where both decays are within the prompt integration window**
  - **A delayed region where the α falls outside the prompt window**

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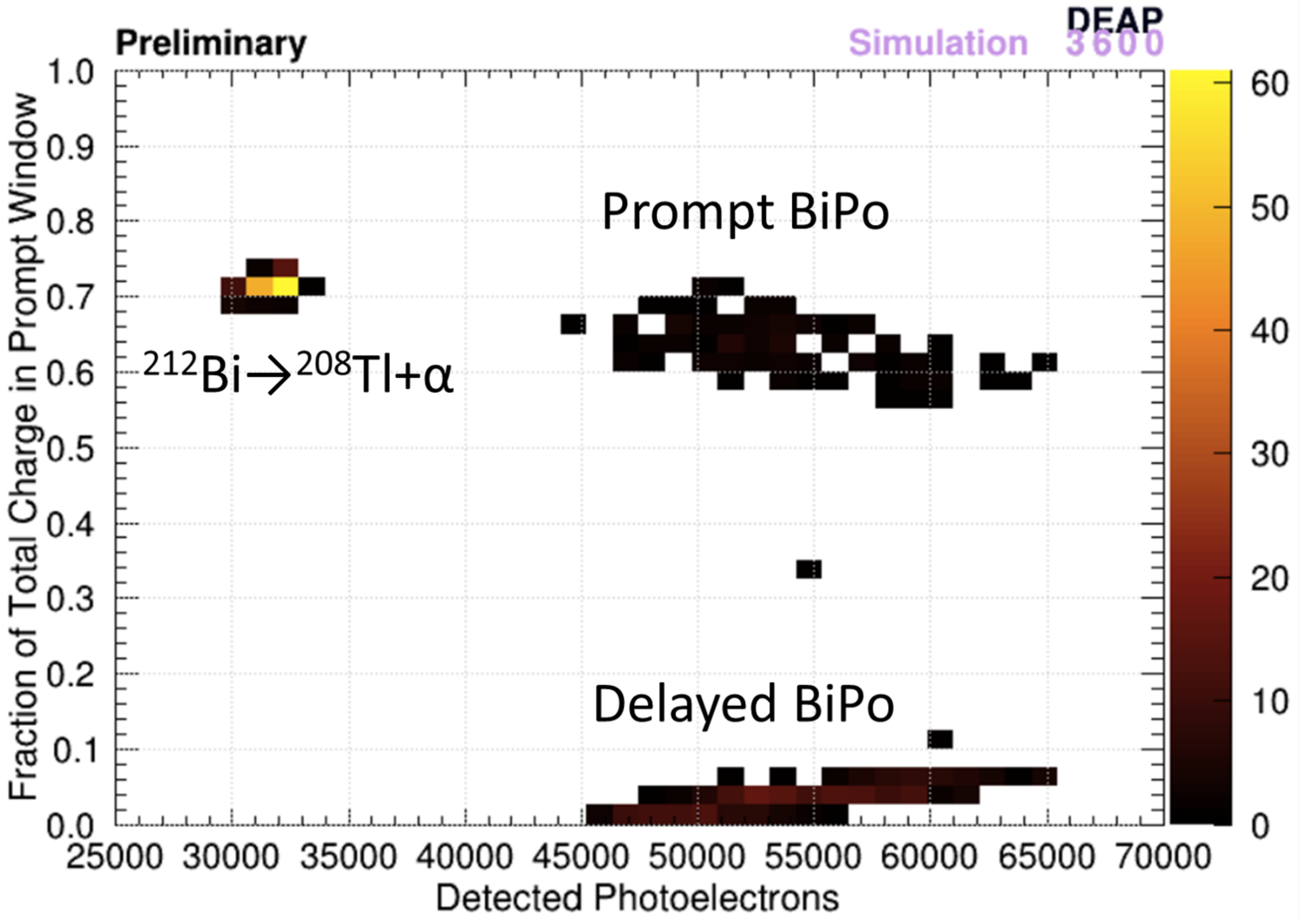
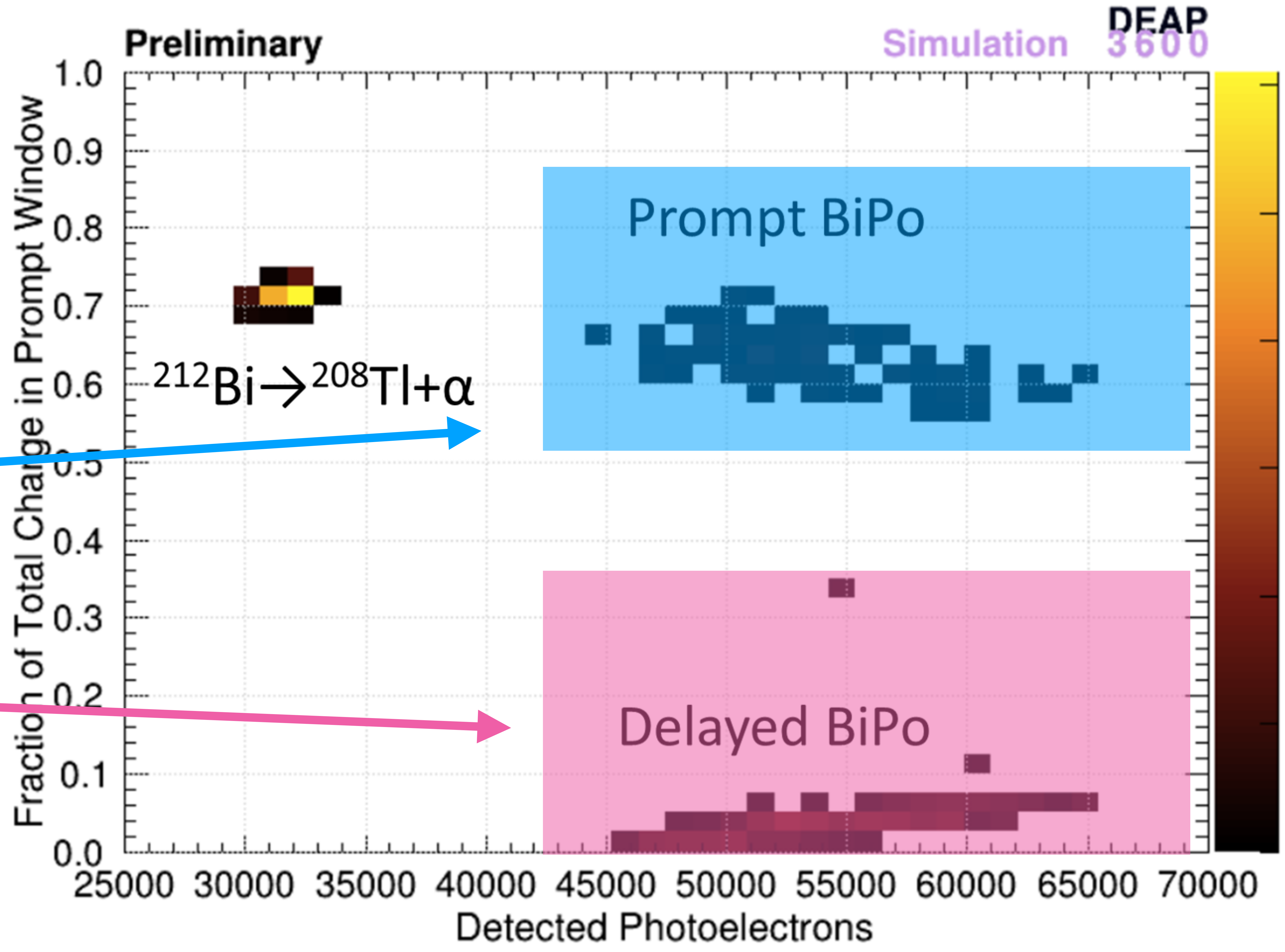


Simulated ^{212}BiPo events: $\tau(^{212}\mathrm{Po}) = 432\ ns$

Coincidence tagging efficiency from ^{212}BiPo Monte Carlo

- Current default settings in coincidence algorithm yield 84.5% efficiency in identifying ^{212}BiPo coincidences
- The tagging efficiency differs between the prompt and delayed regions:
  - 64% in the "prompt" region due to the small time separation between prompt electron and delayed α
  - 93% in the "delayed" region due to larger differences in time



Simulated ^{212}BiPo events: $\tau(^{212}\text{Po}) = 432\ ns$

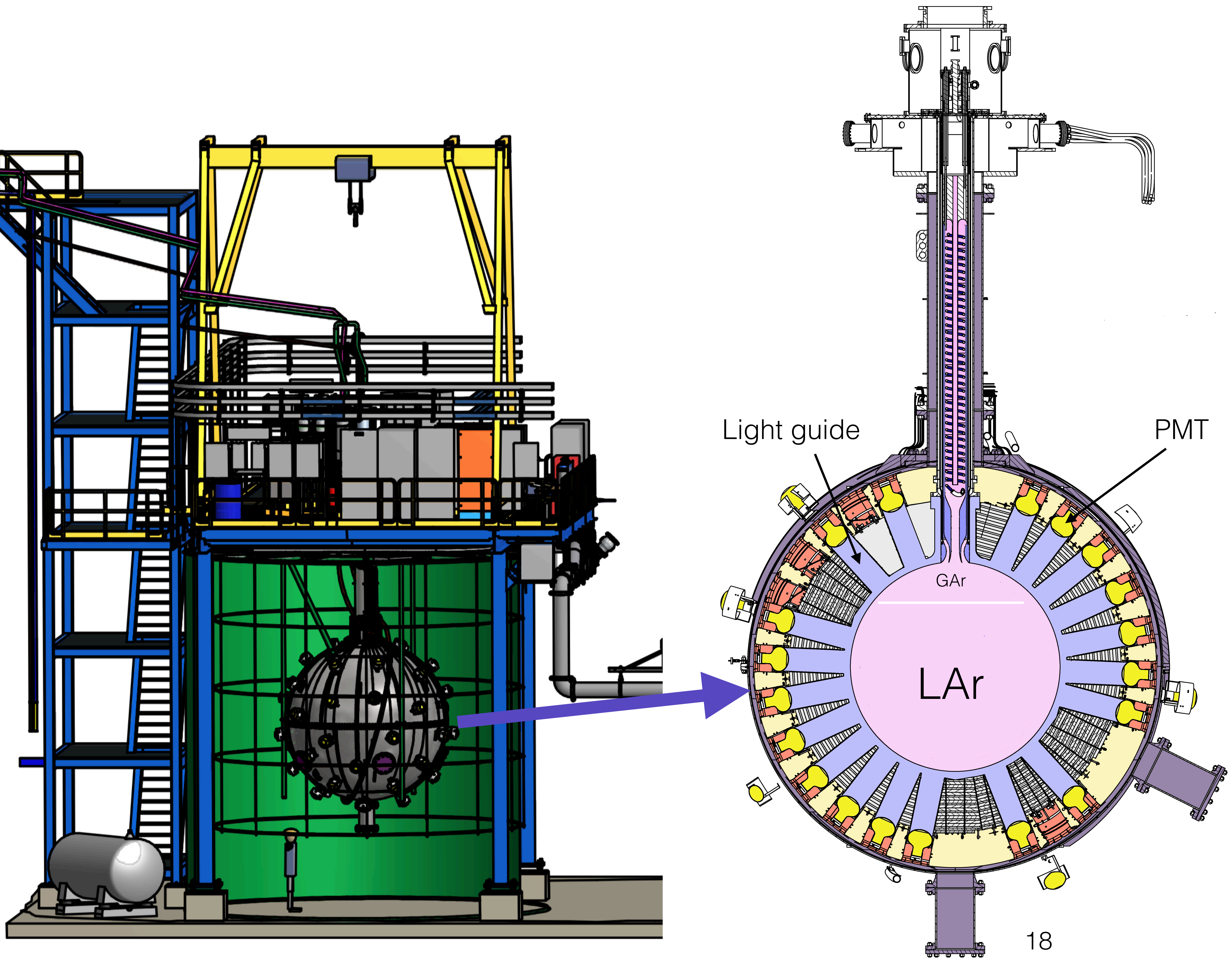
Future work

- **Current efforts dedicated toward building a comprehensive background model:**
  - **Coincidence backgrounds from internal radioactivity**
  - **Muon induced background**
- **Currently building an energy response model to reconstruct delayed energy with minimal bias**
- **Acceptance studies driven by neutrino absorption Monte Carlo and internal backgrounds underway**
- **Expect first results very soon!**

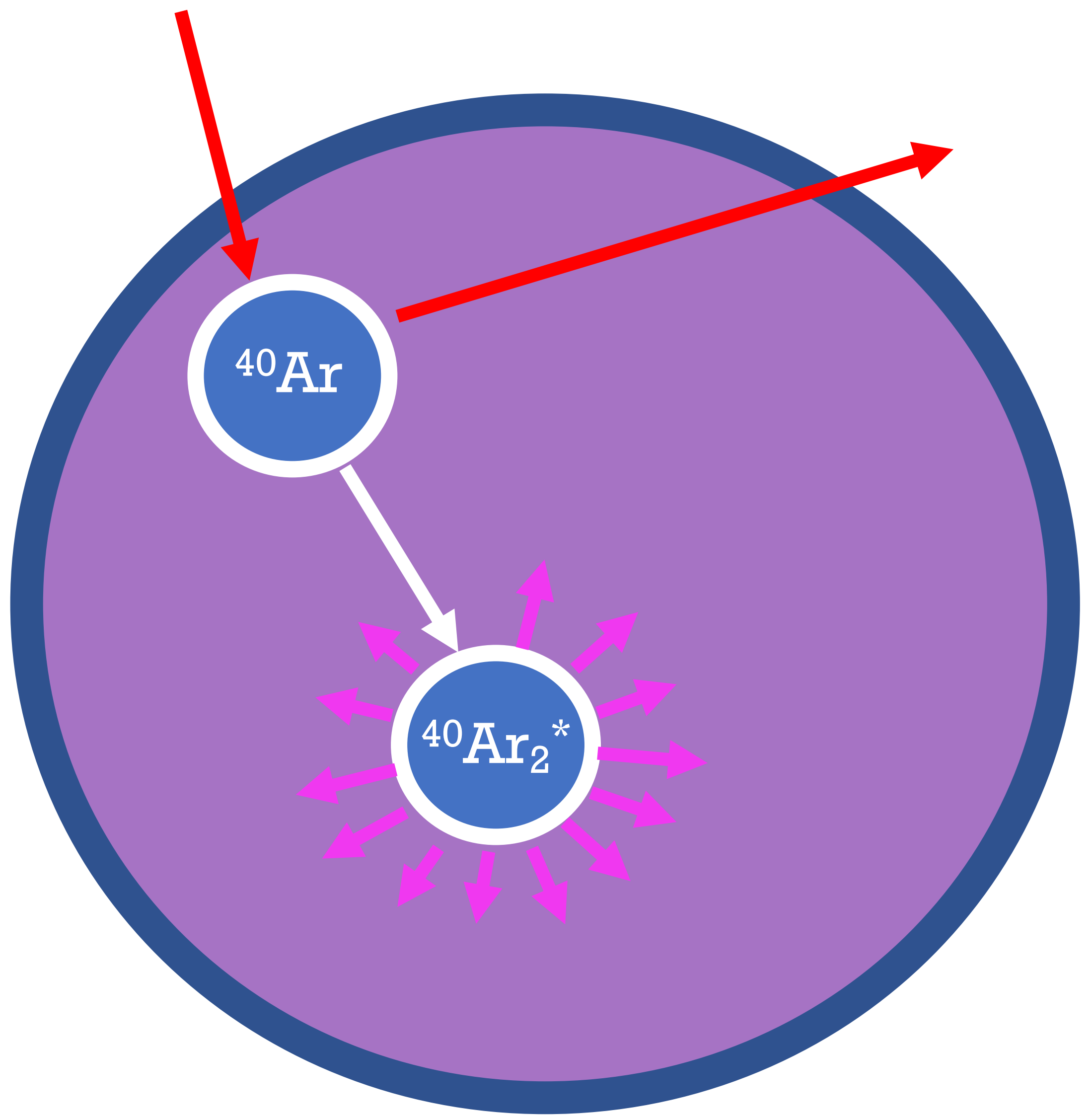
Back up

DEAP-3600

Reference: 10.1016/j.astropartphys.2018.09.006



- **Conceptually simple/elegant detector:**
  - **Large spherical mass of liquid argon (LAr) contained within acrylic vessel and instrumented with 255 8″ photomultipliers (PMTs)**
  - **PMTs insulated from cryogenic liquid by ~50 cm light guides**
  - **Light guides also shield LAr from radioactivity in PMTs**
  - **Detector constructed with painstaking attention to radioactive inventory (clean materials)… it's <u>deep</u> AND <u>clean</u>!**
- **Design sensitivity to SI WIMP-nucleon scattering $10^{-46}\,cm^2$ for $m_\chi = 100$ GeV**
- **Most significant internal background from ^{39}Ar β decay**
- **Operating in "dual phase" configuration with target mass ~ 3300 kg**



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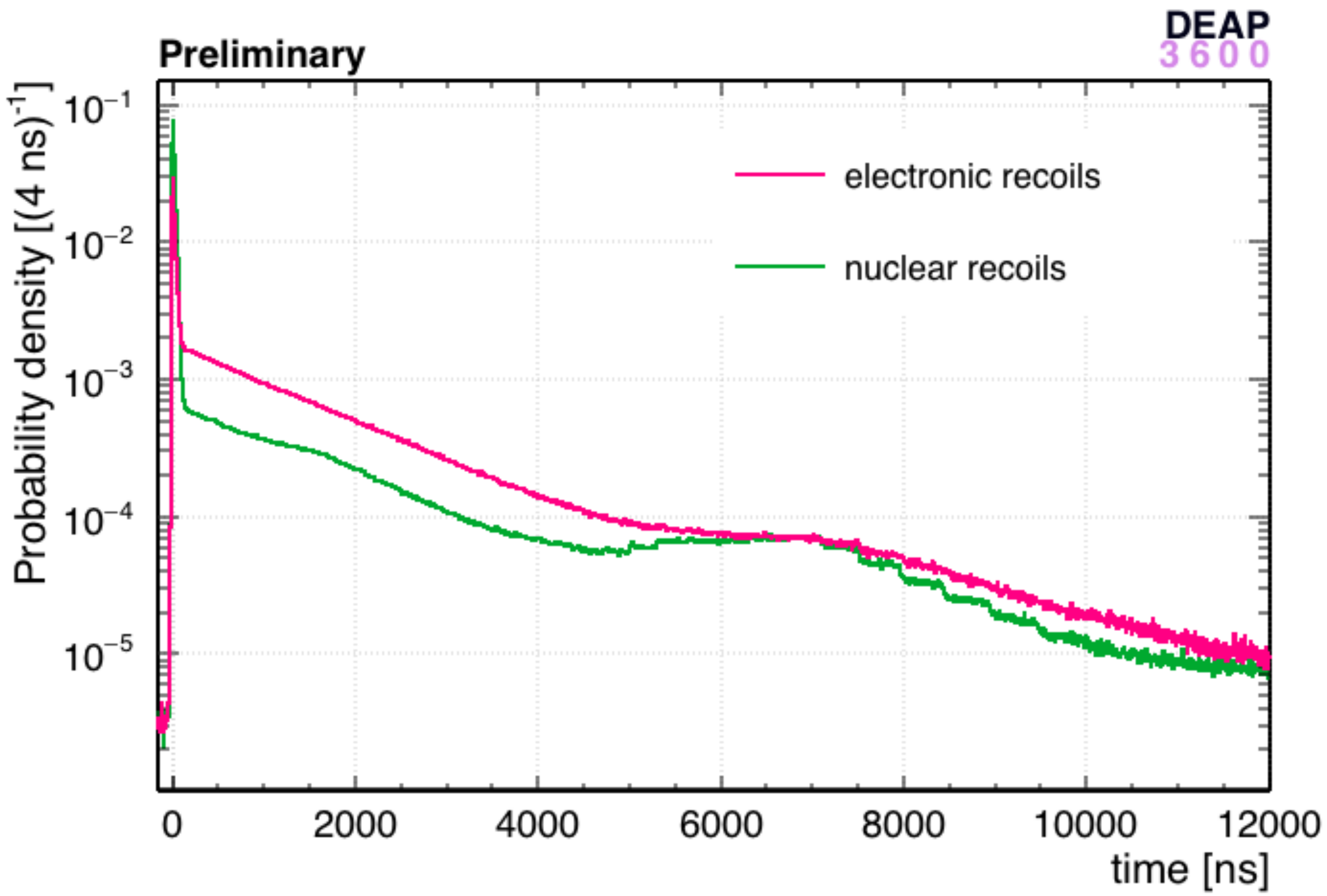


https://doi.org/10.1103/PhysRevD.100.022004

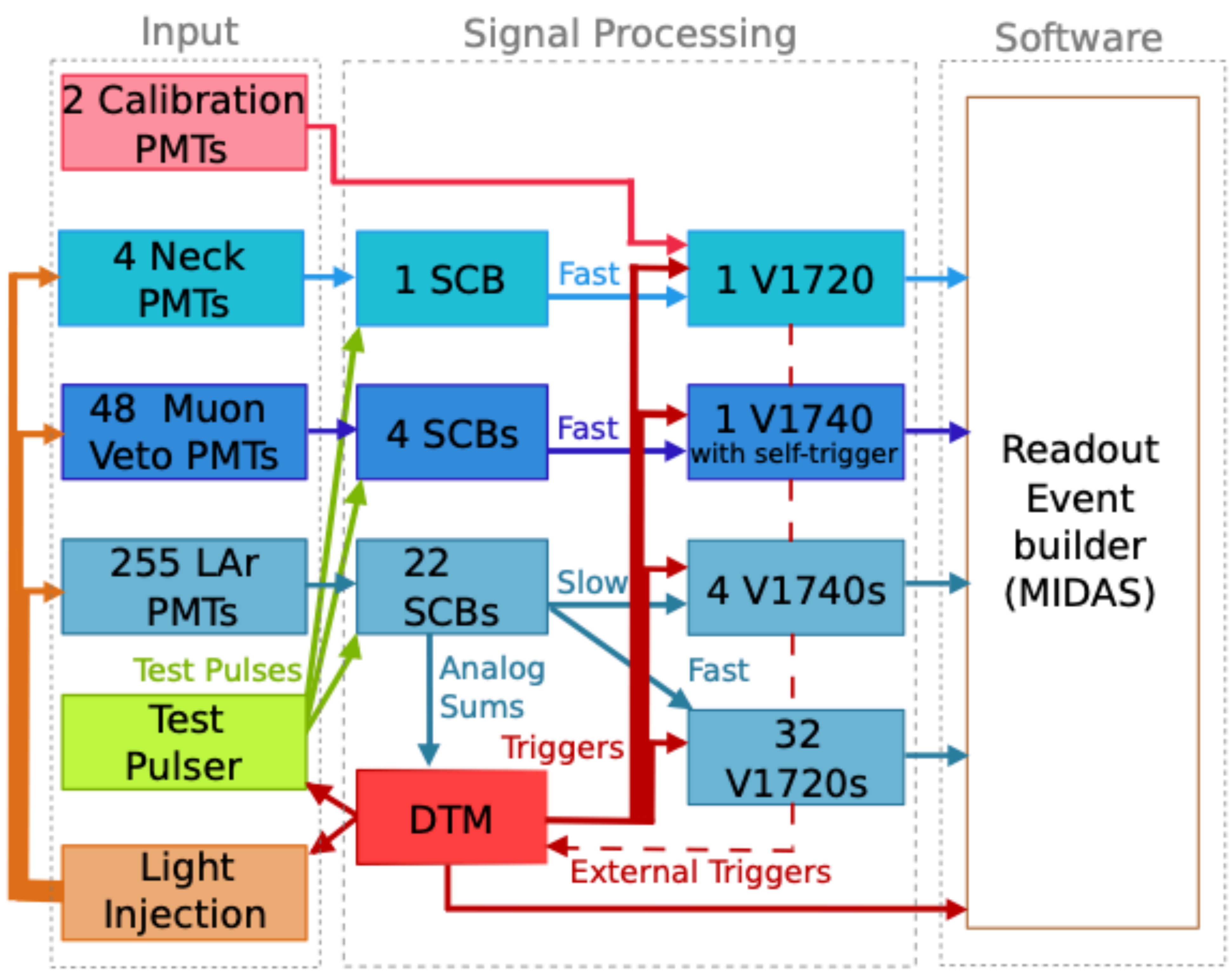


FIG. 2. A block diagram of the DEAP-3600 data acquisition system, adapted from [10]. Shown are the PMTs, the digitizer and trigger module (DTM), the signal conditioning boards (SCBs), the event builder, the light injection system, the test pulser systems, the fast high-gain channel digitizers (V1720s), and the slow low-gain channel digitizers (V1740s).

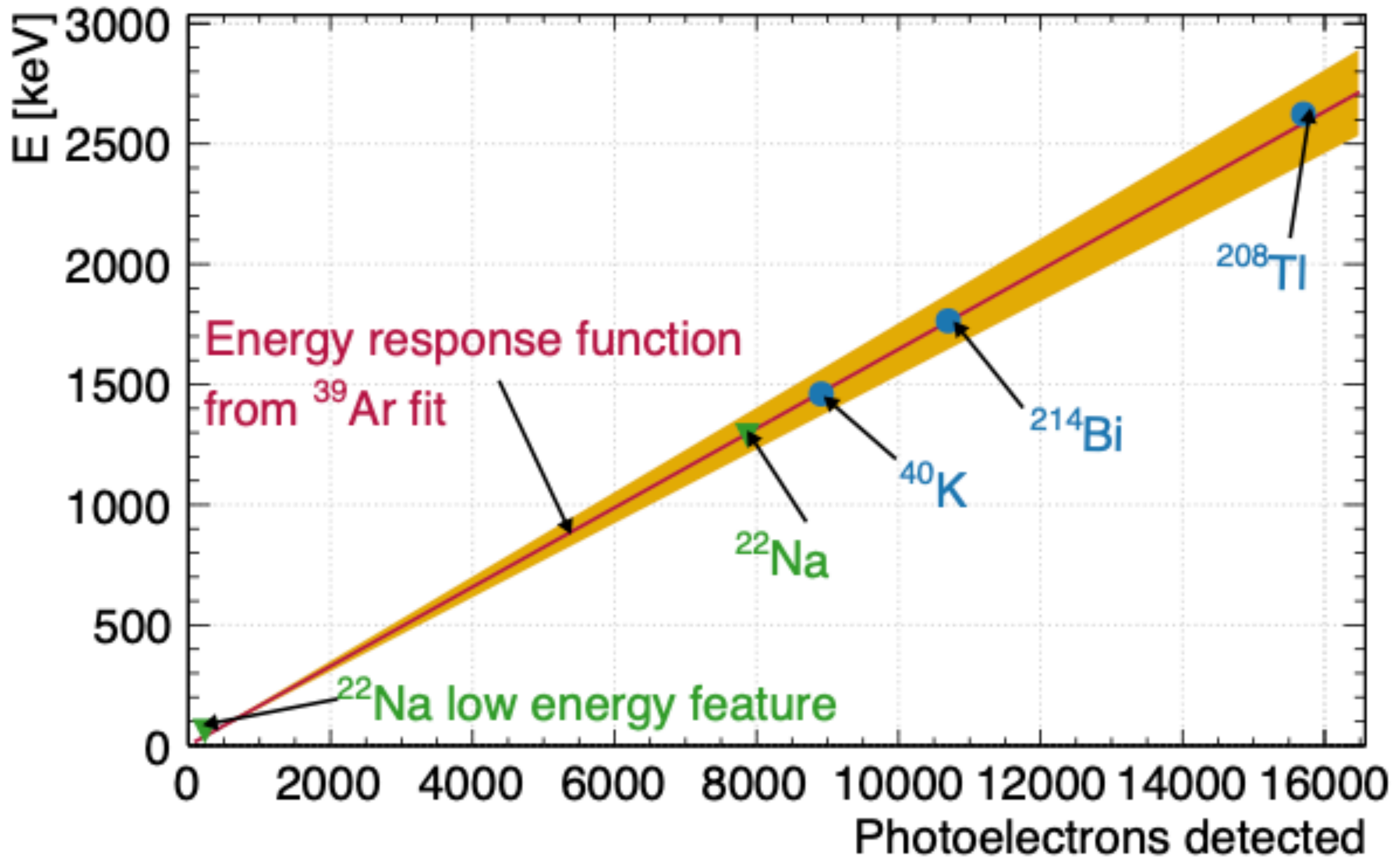


FIG. 5. The energy response function (red), showing the number of detected PE for an event depositing energy E in the LAr. The uncertainties of the response function are also shown (yellow band). The response function agrees with the number of PE detected from known mono-energetic sources of γ-rays from the detector materials.

https://doi.org/10.1103/PhysRevD.100.022004

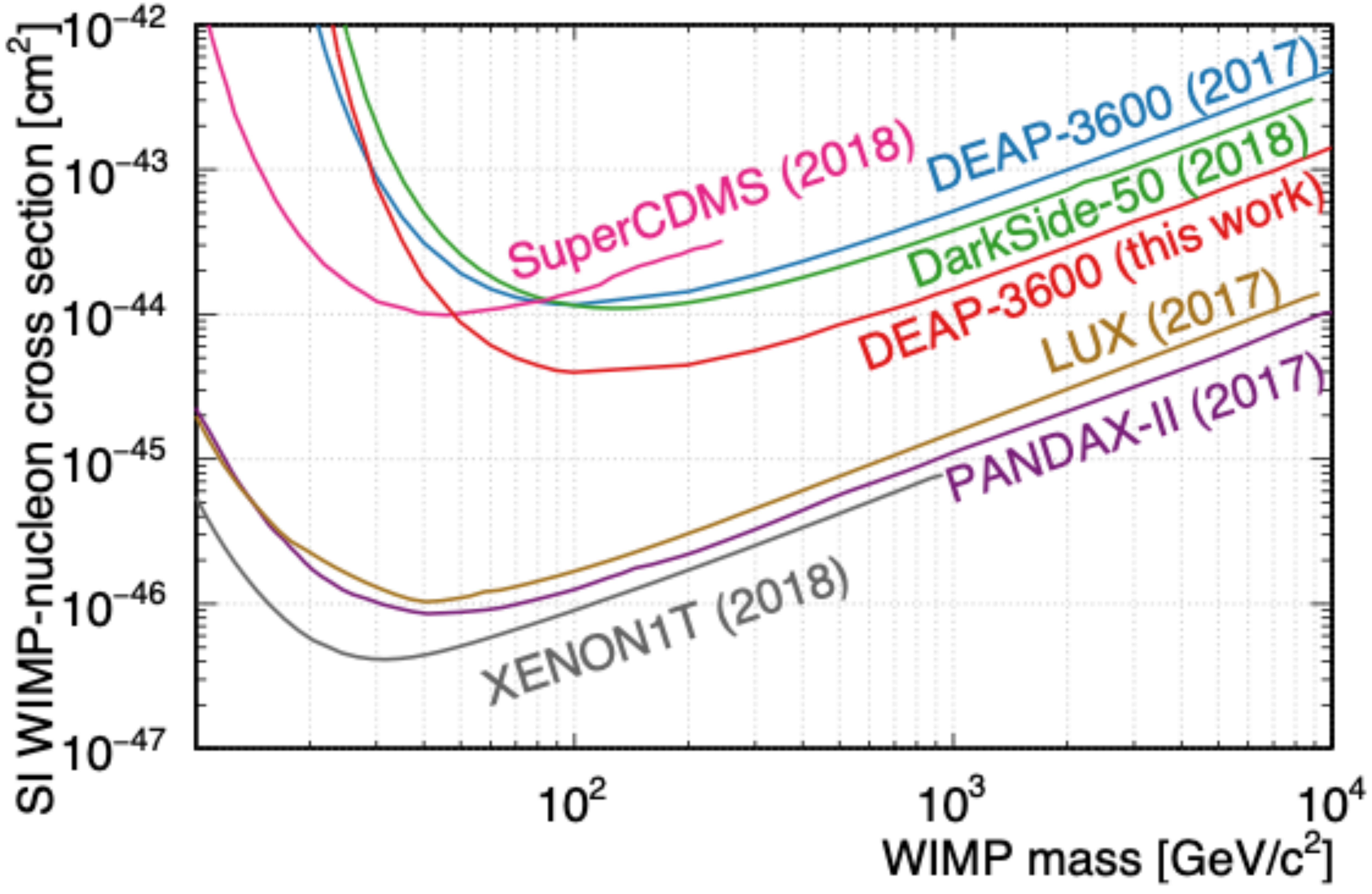
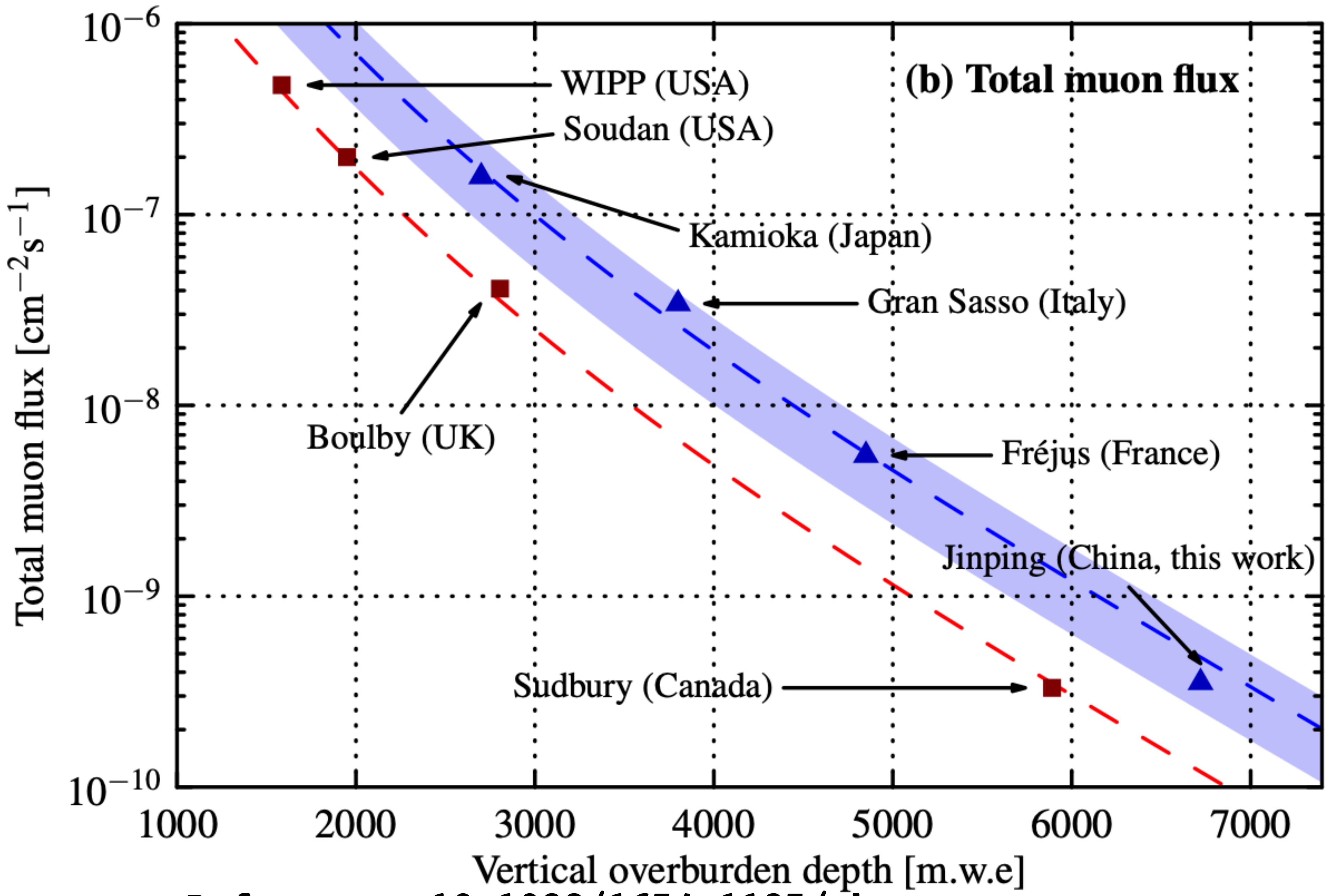


FIG. 24. 90% confidence upper limit on the spin-independent WIMP-nucleon cross sections based on the analysis presented in this paper (blue), compared to other published limits, including our previous limit [6], SuperCDMS [45], DarkSide-50 [7], LUX [46], PANDAX-II [47], and XENON1T [5].

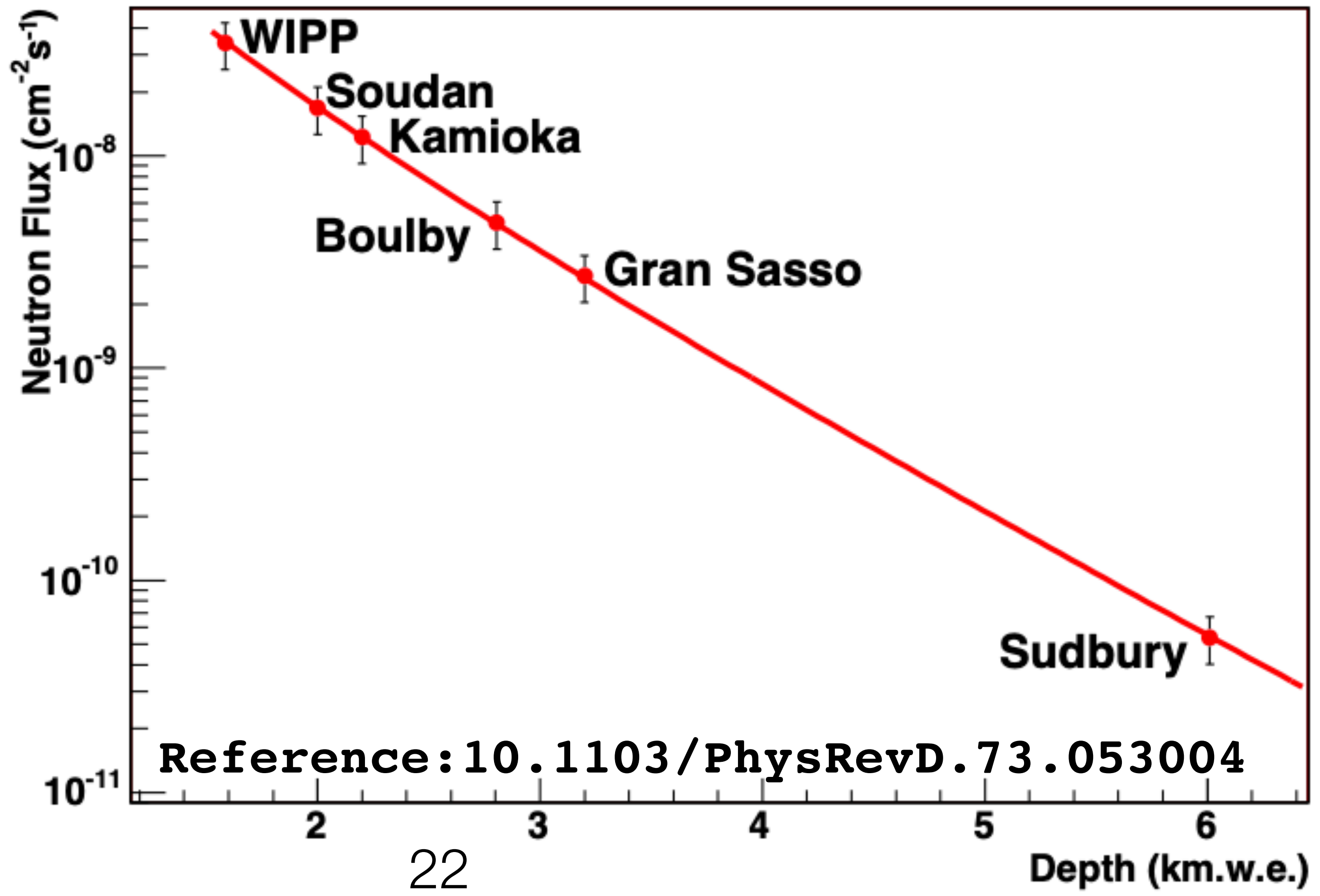
DEAP-3600

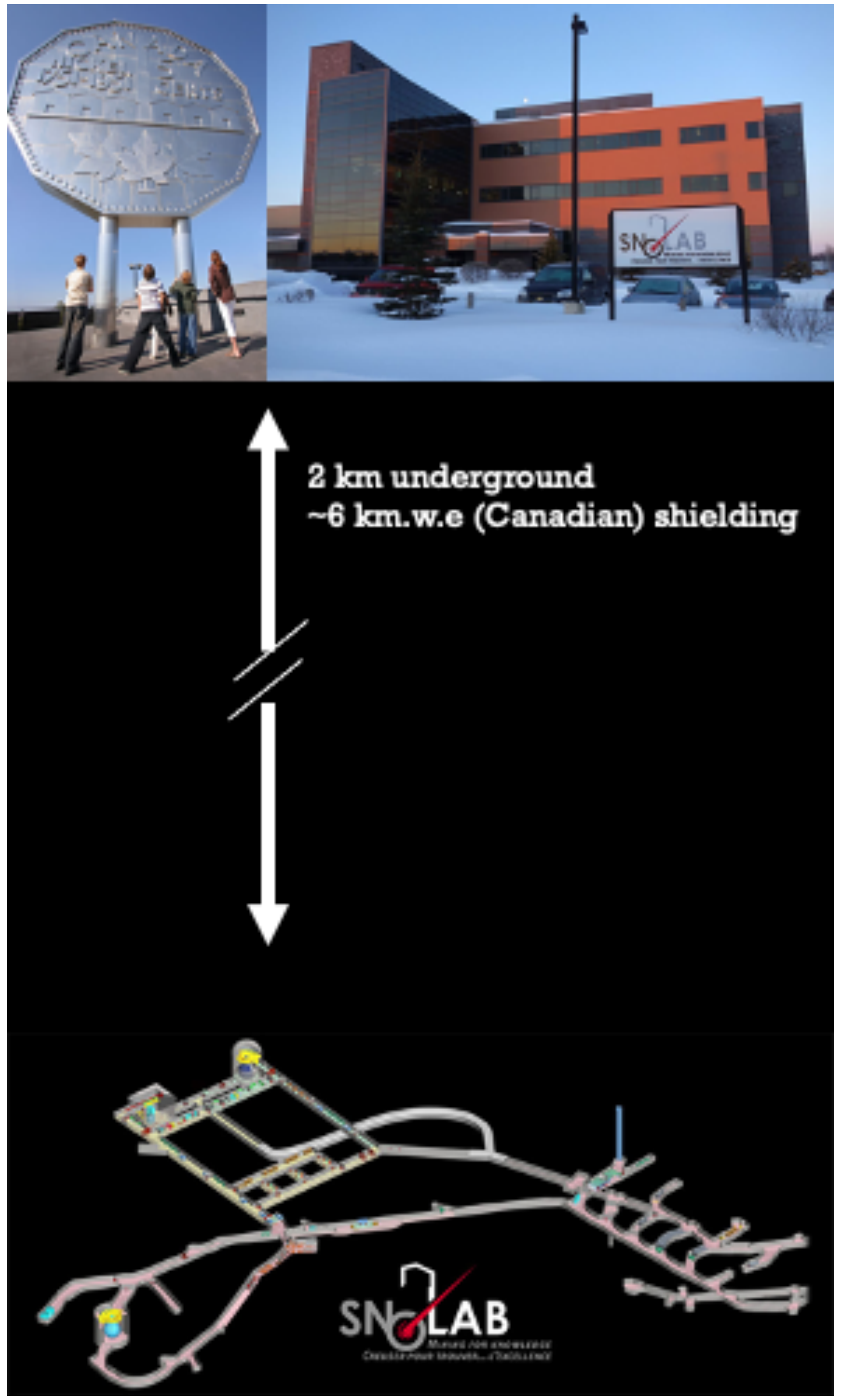
- **Reaching design sensitivity requires extreme shielding**
- **Most difficult background to suppress is from muons and muon-induced showers**
  - **Muons are impossible to completely get away from…**
- **DEAP-3600 located ~2 km underground at SNOLAB**
  - **Common to compare against other underground site by converting depth in rock to an equivalent depth of water**
  - **SNOLAB is ~ 6 km.w.e - flat overburden**



Reference: 10.1088/1674-1137/abccae

- **Muon rate in DEAP-3600 LAr** $(0.65 \pm 0.03_{stat})\ \mu$ **day**$^{-1}$ **based on calculations using Mei & Hime's model**





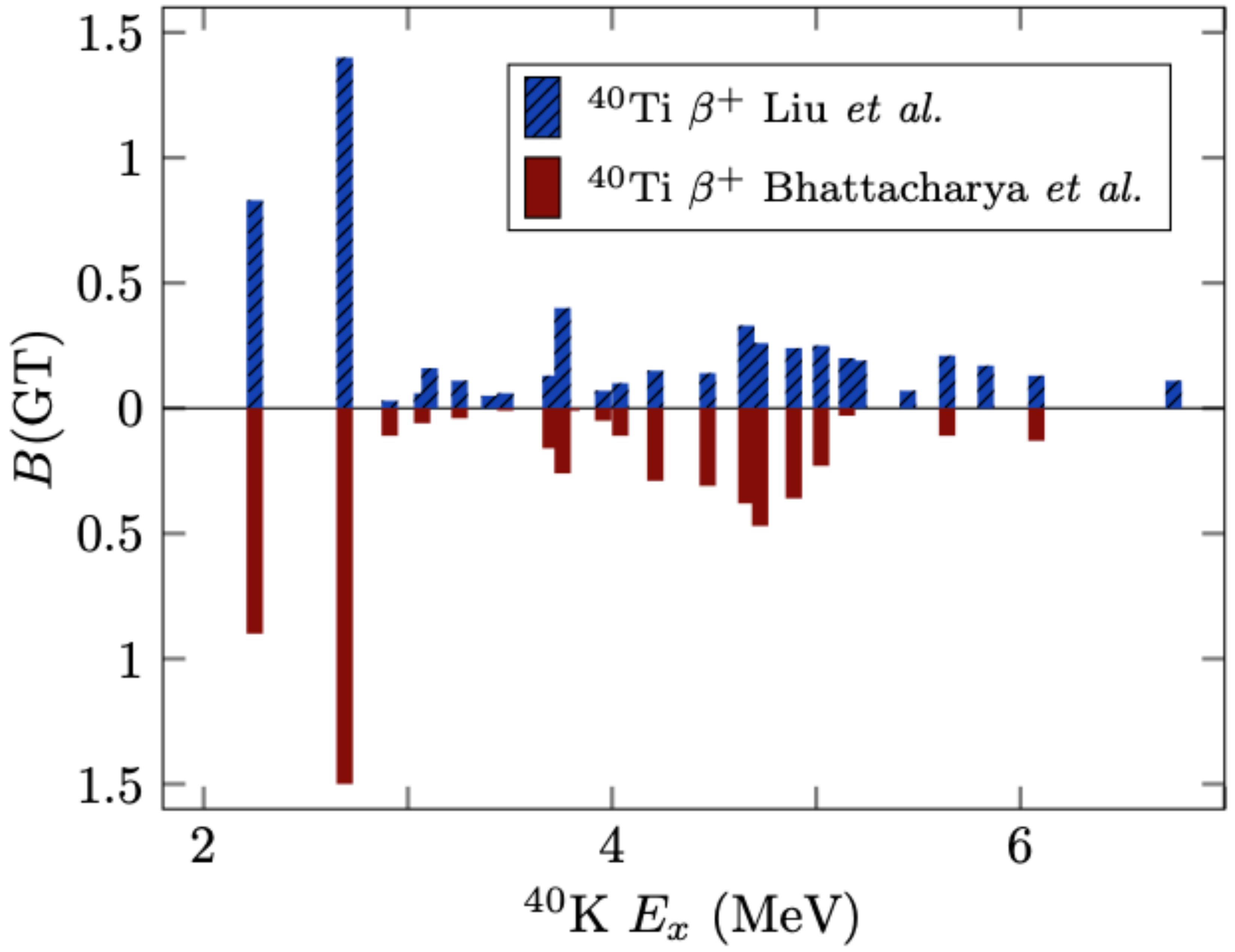


FIG. 1: Gamow-Teller strengths $B(\mathrm{GT})$ from two independent measurements of ^{40}Ti β^+ decay by Liu *et al.* [56] and Bhattacharya *et al.* [57].

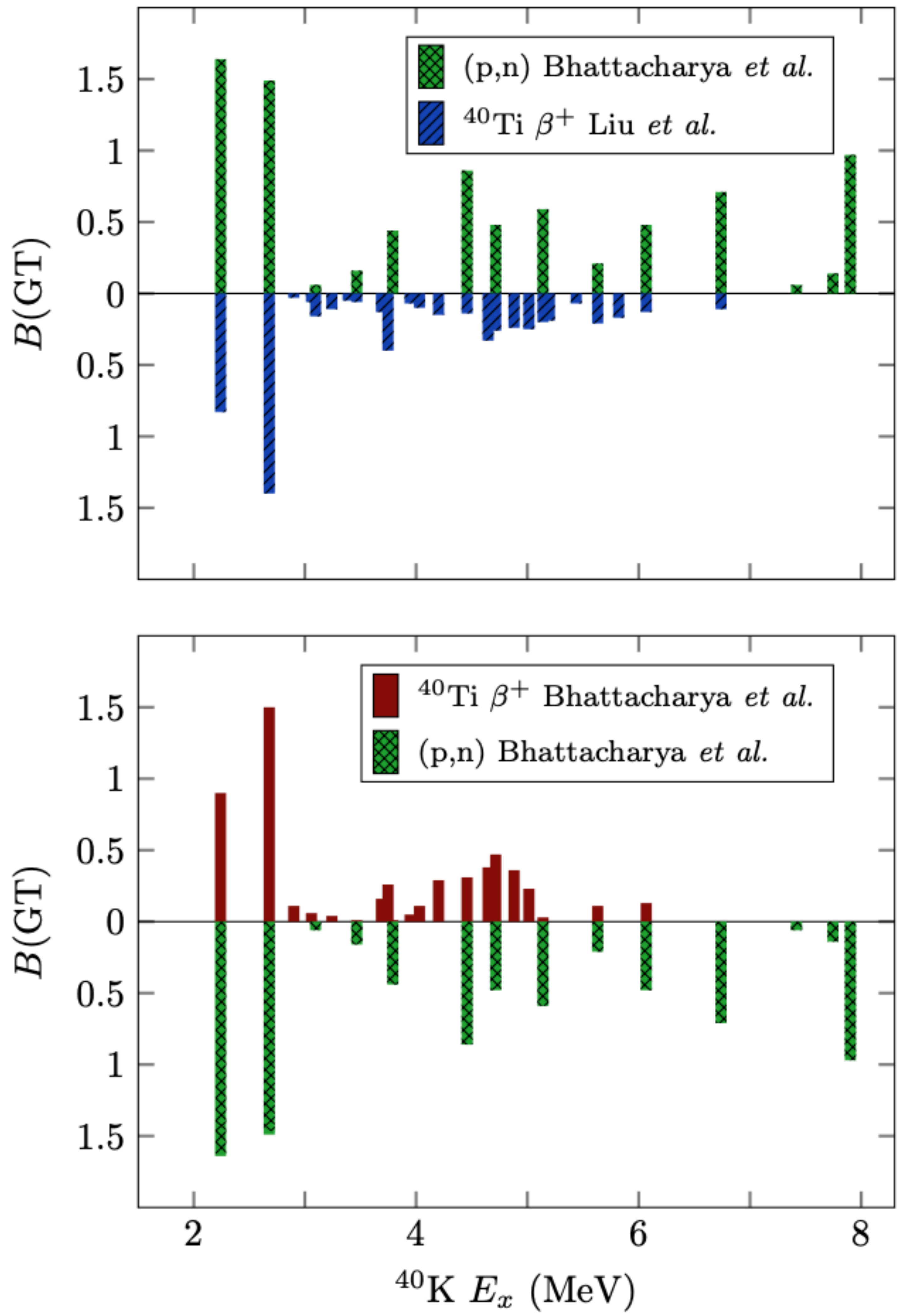
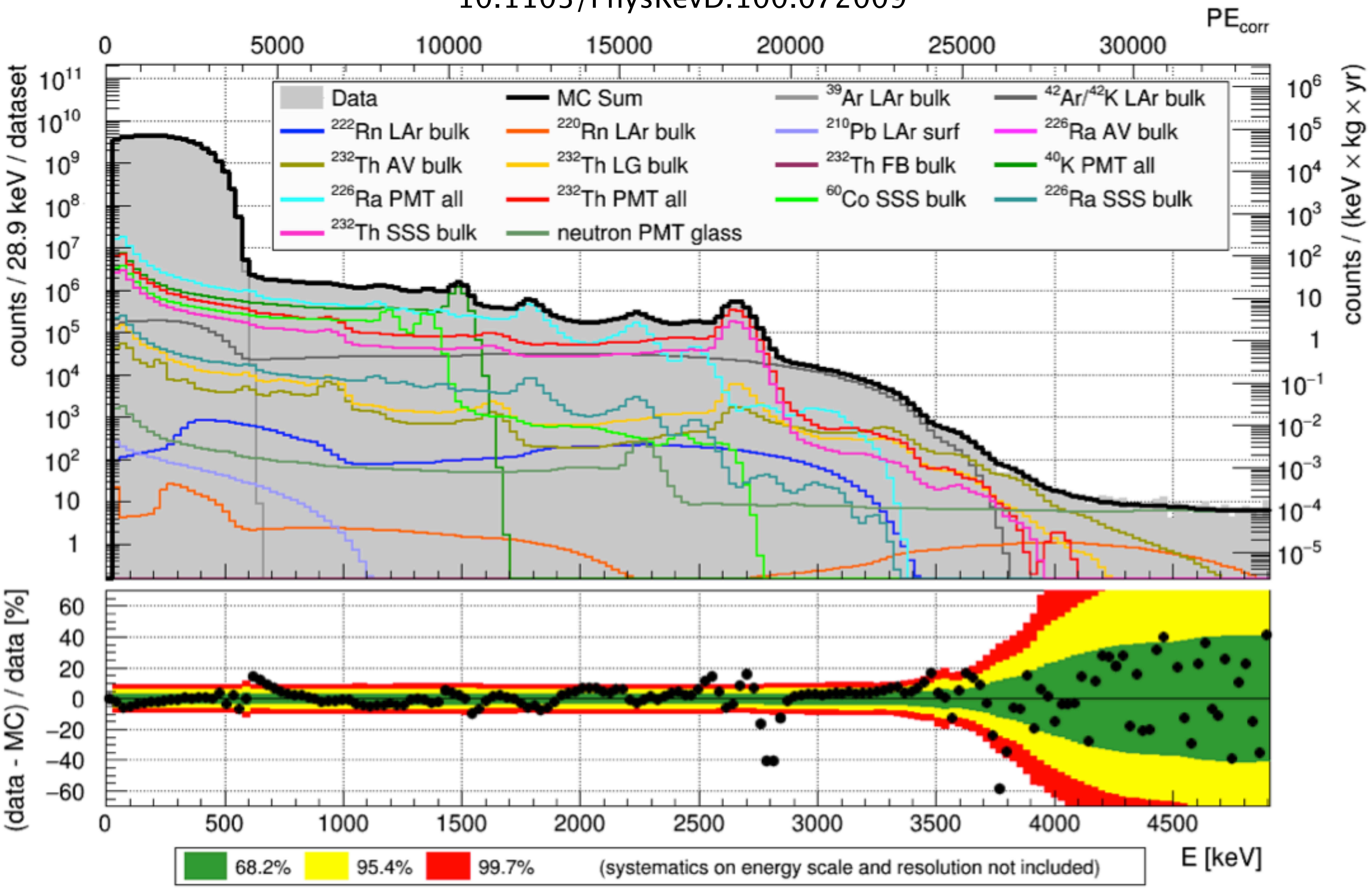


FIG. 2: Comparison of the Gamow-Teller strengths $B(\mathrm{GT})$ measured using ^{40}Ti beta decay (see fig. 1) with those obtained using a measurement of 0° (p,n) scattering by Bhattacharya *et al.* [58].

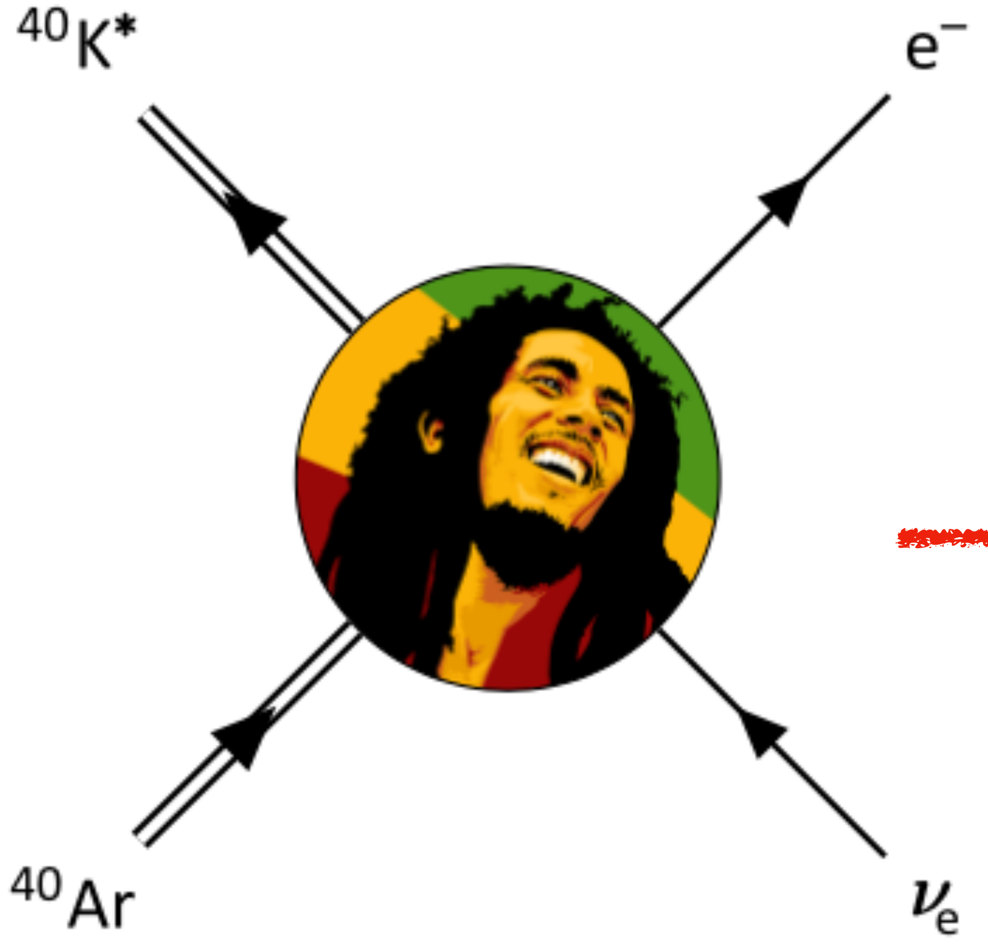
Figures from https://arxiv.org/pdf/2010.02393.pdf

10.1103/PhysRevD.100.072009

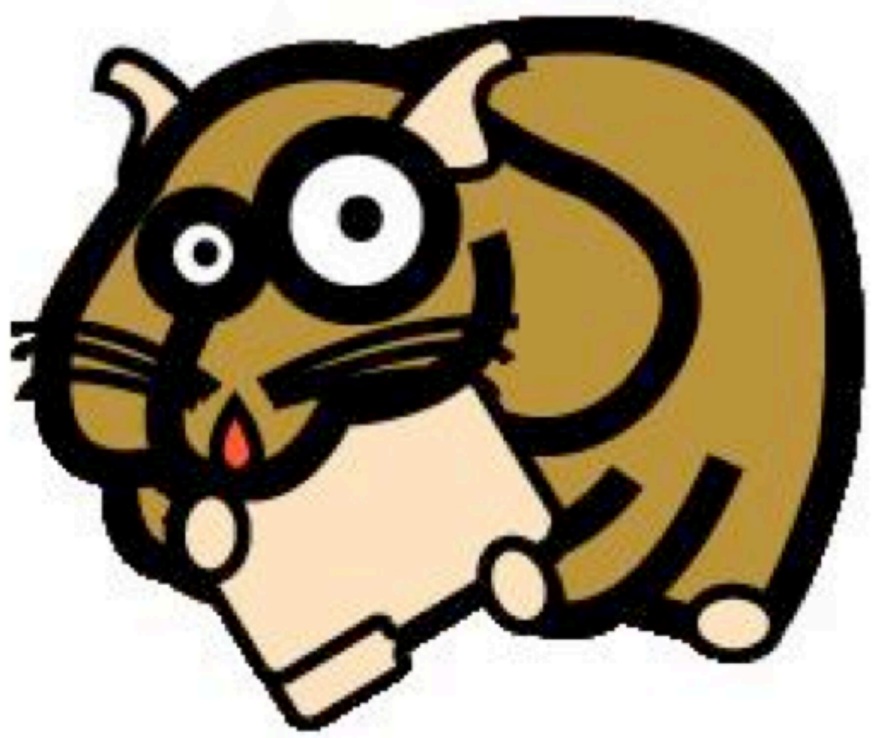


Signal phenomenology

- **As demonstrated by many near surface reactor anti-neutrino experiments, delayed coincidence tagging is a very effective way to suppress backgrounds**
- **Requires robust model of <u>detector response</u>, <u>signal</u> (energy/timing), and prediction of <u>pile up backgrounds</u>**
- **Dedicated analysis searching for "golden channel" (delayed coincidence) events**



"BuffaloSoldier"
Marley/RAT
interfacing code



- **Use S. Gardiner's Marley event generator to generate MC events (finals states)**
- **Interfacing code adds additional pseudo-randomness to Marley output**
- **RAT (Reactor Analysis Tool) uses interface as external event generator to simulate the Marley final states in DEAP-3600**
- **RAT models everything from the primary interactions, scintillation, full optics, PMT/ electronics response, DAQ, event reconstruction (identical processing for DEAP data)**