DPF 2024, Dec. 19

Search for Boosted Dark Matter in COSINE-100

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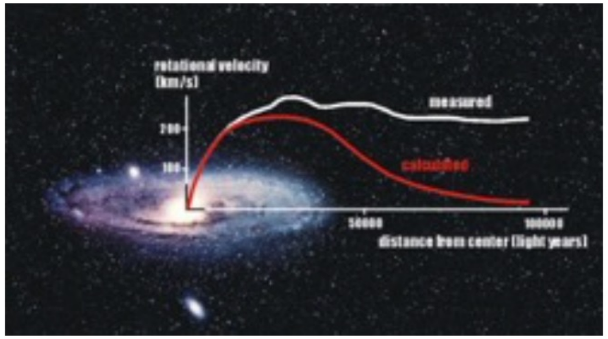
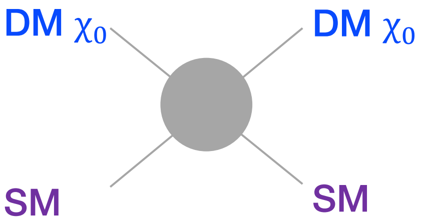
Center for Underground Physics, Institute for Basic Science

On behalf of the COSINE-100 collaboration

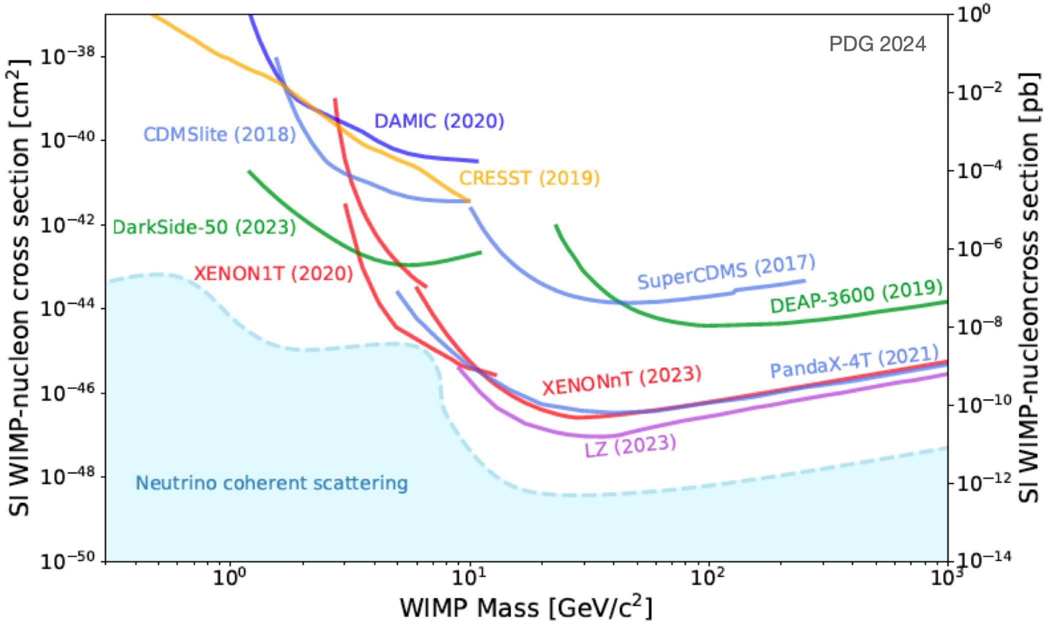
Dark Matter Searches

- Gravitational evidence of dark matter
- Dark matter candidate - WIMP
  - Massive particle, non-relativistic
  - WIMP miracle
- Detection principle





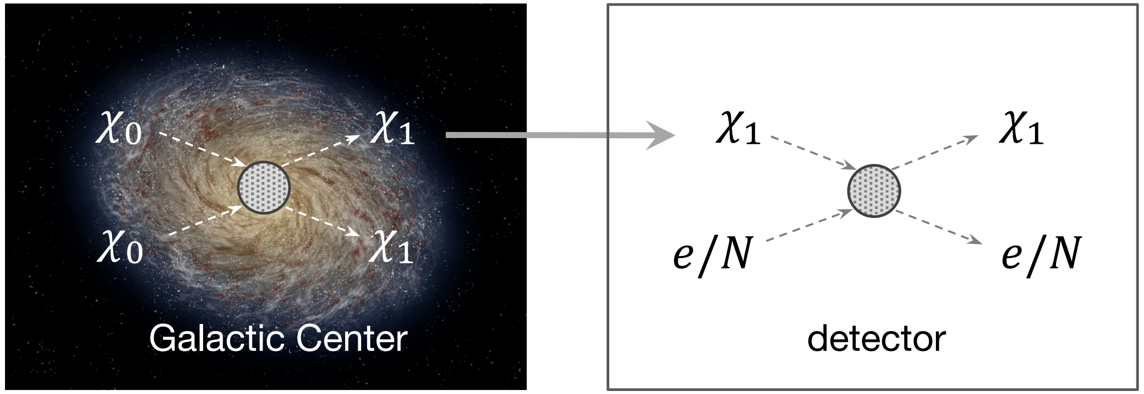
(lab)



- The search for WIMPs has progressed in the last years.
- No signals yet, but strong constraint for WIMP

Boosted Dark Matter

- New realization: Boosted dark matter (preserving WIMP miracle)
  - Considering two-component dark matter
  - Dark matter boosted by the dark sector structure at Galactic center



χ_0: heavy DM
χ_1: light DM

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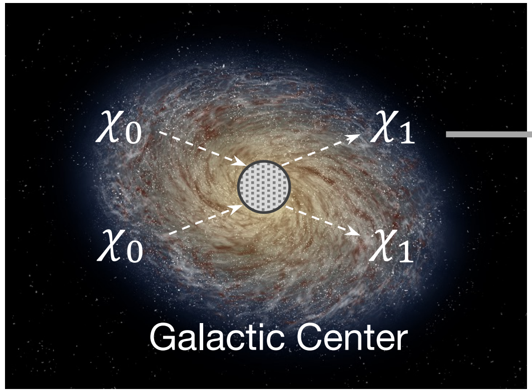

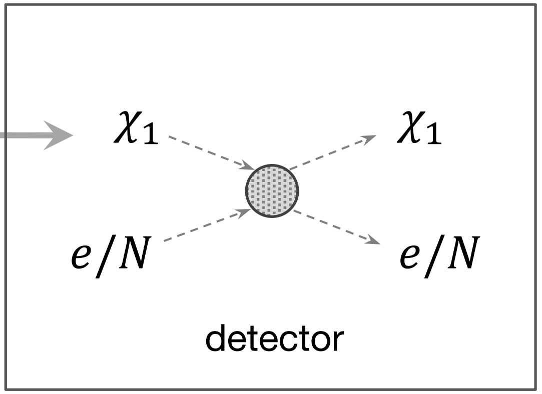

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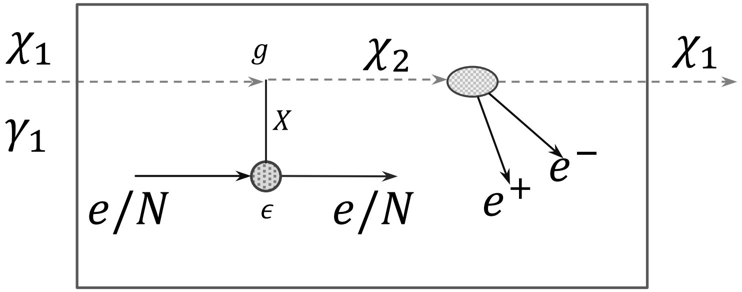
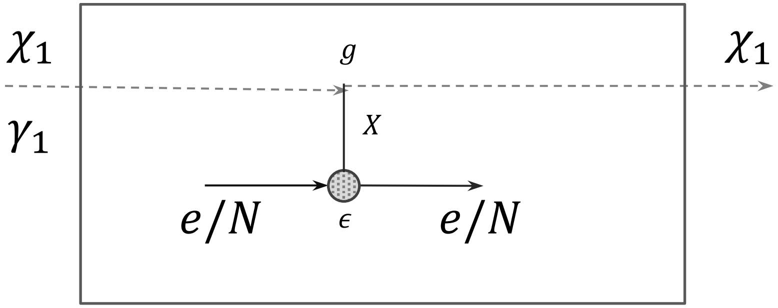


e-, e-/e+ or bremsstrahlung gamma



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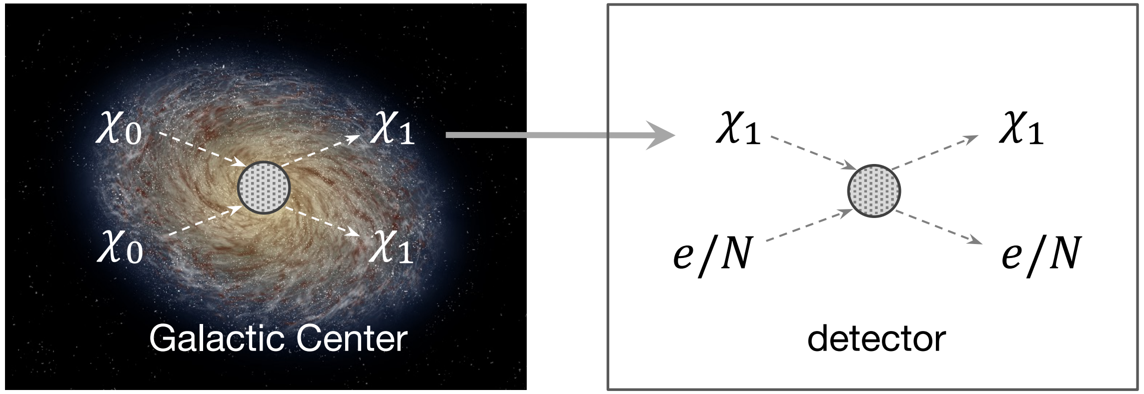

χ_0: heavy DM
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- Flux of $\chi_1 = 1.6\times10^{-4}cm^{-2}s^{-1}\left(\frac{\langle\sigma v\rangle_{0\to1}}{5\times10^{-26}cm^3s^{-1}}\right)\left(\frac{GeV}{m_0}\right)^2$

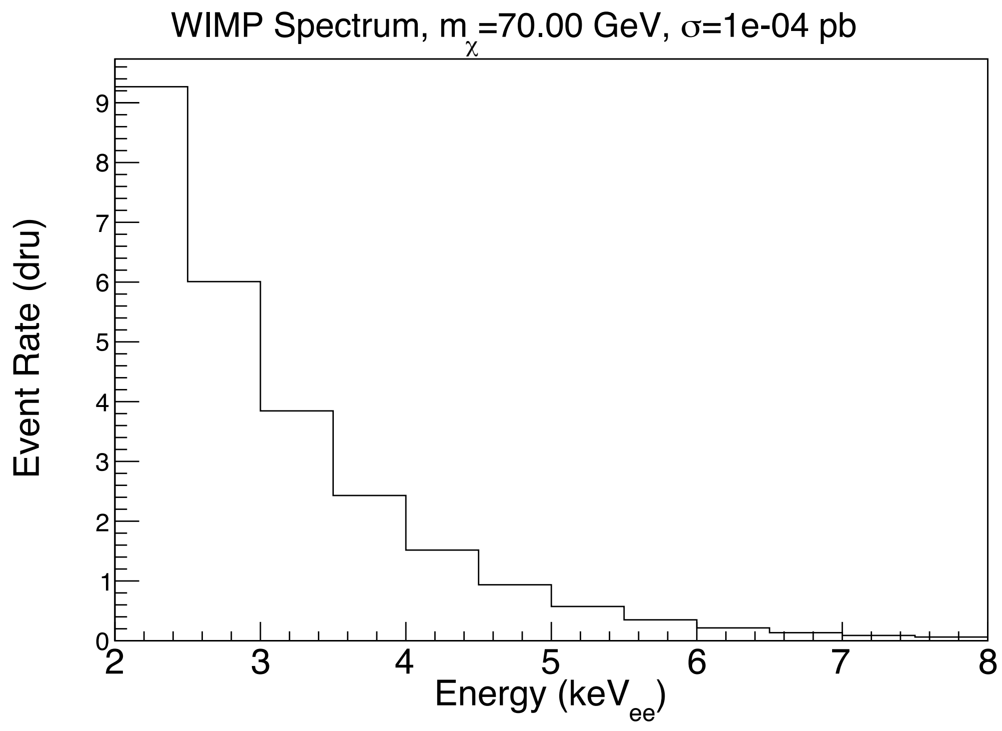
PLB 743 (2015) 256
PRL 119 (2017) 161801
JCAP10(2014)062

$m_{\chi_0} \gtrsim$ O(10 GeV): small flux, high energy → large volume neutrino detector

$m_{\chi_0} \lesssim$ O(1 GeV) : Ee, p ~ O(MeV) → small detector possible: ***Search in COSINE-100!***

Boosted Dark Matter (BDM) signal

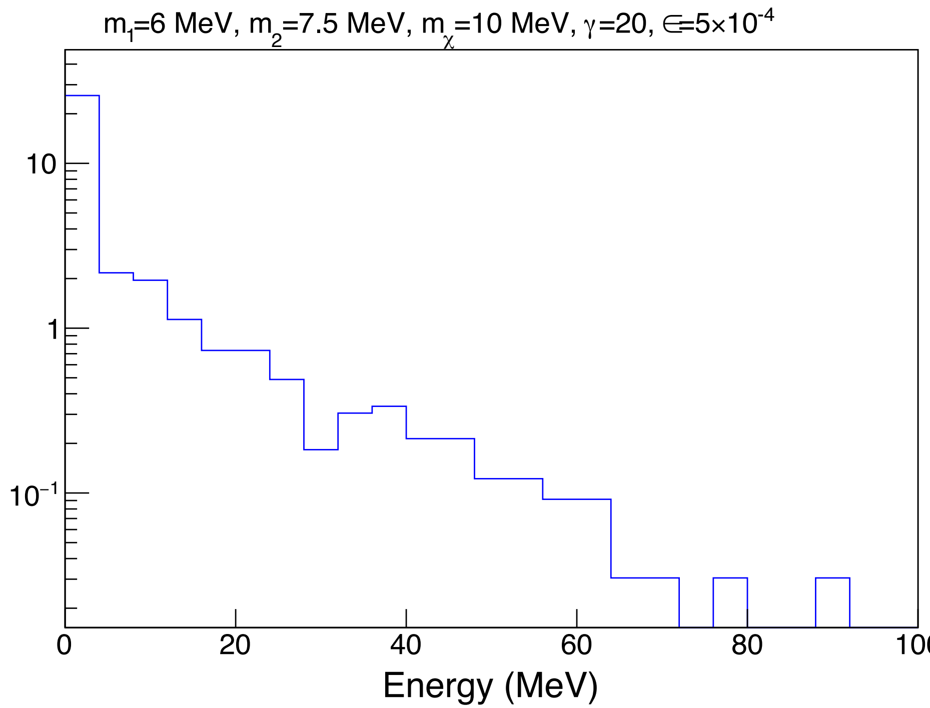
- WIMP signal in NaI(Tl) crystal
  - Nuclear recoil
  - Quenching factor (Eee/Enr) - 5~30%



WIMP search detector designed to focus on low energy

- BDM signal in NaI(Tl) crystal

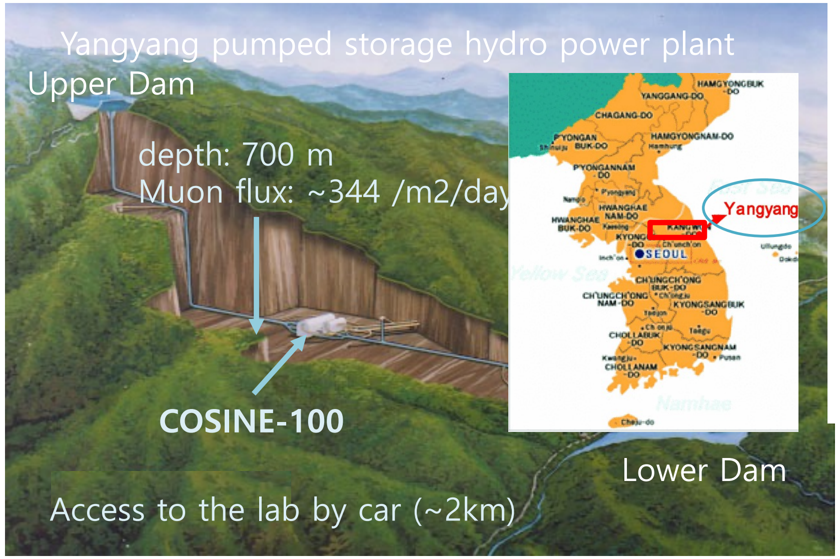
$$\mathcal{F} = 1.6\times10^{-4} cm^{-2} s^{-1} \left(\frac{\langle\sigma v\rangle_{0\to1}}{5\times10^{-26} cm^3 s^{-1}}\right)\left(\frac{GeV}{m_0}\right)^2$$

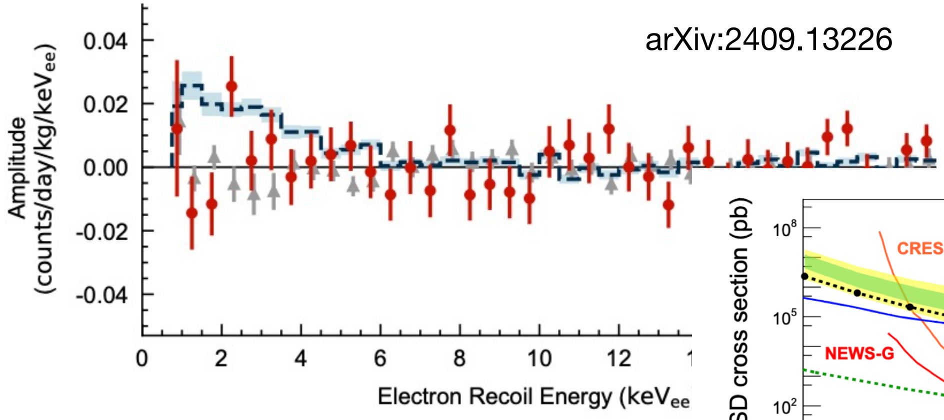


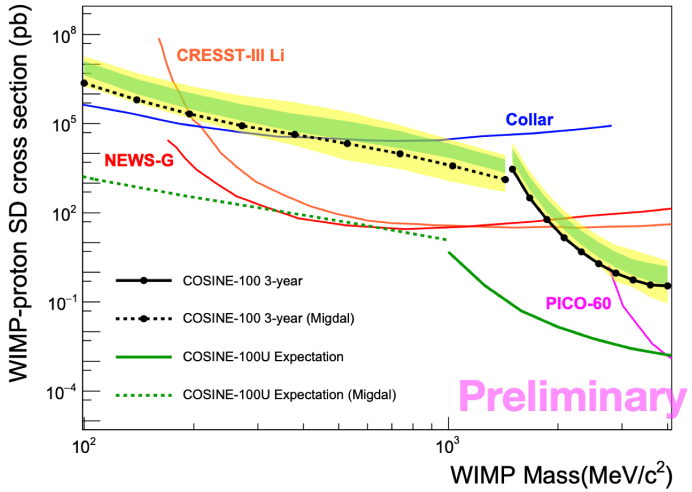
BDM signal -> high energy electron recoil

COSINE-100

- COSINE-100 dark matter search experiment
  - 2016.10. ~ 2023.3. (6.12 years operation)
  - Located at Yangyang underground laboratory (Y2L), South Korea
  - WIMP search - Annual modulation analysis & Signal extraction

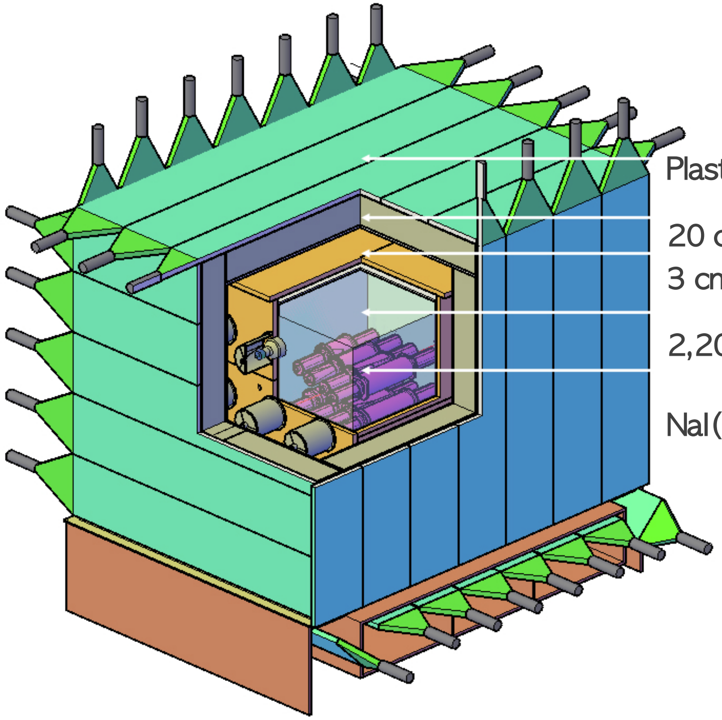






COSINE-100

- COSINE-100 dark matter search experiment
  - NaI(Tl) crystals, ~100 kg mass of 8 crystals arranged in 2 rows
  - 2200 L liquid scintillator (LS) as a veto
  - muon detector (plastic scintillator) at the outermost of detector shields



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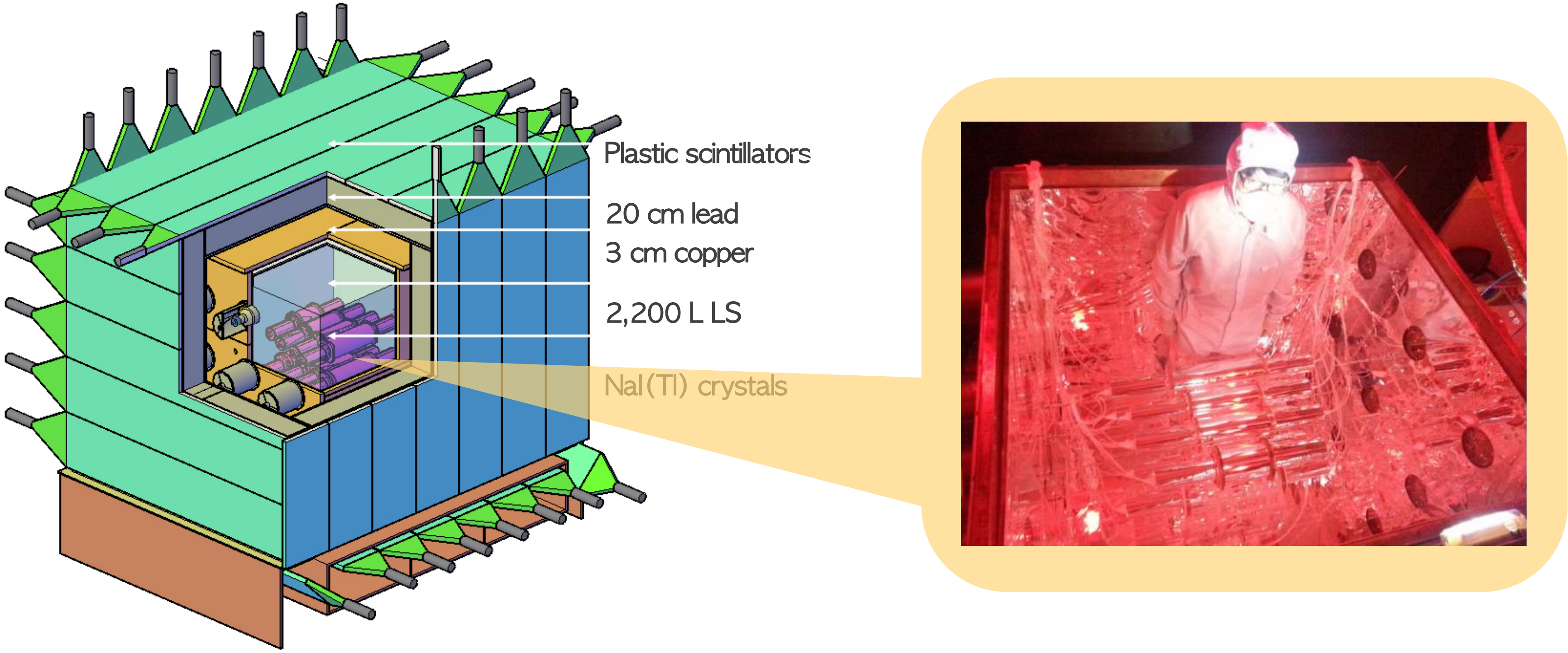

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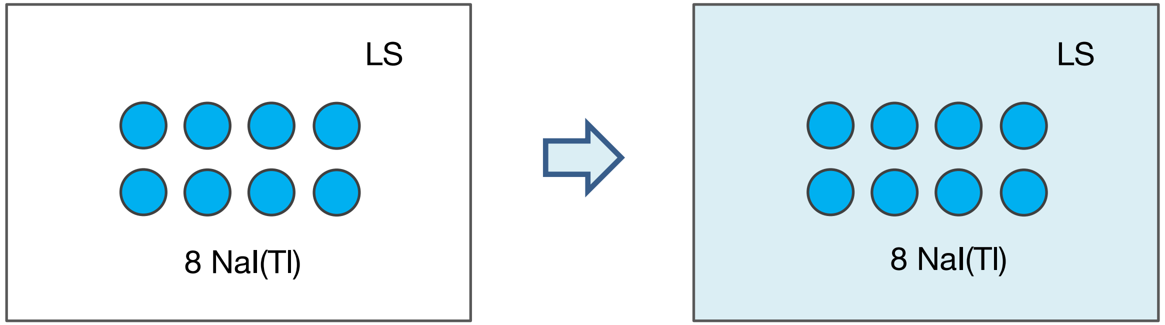

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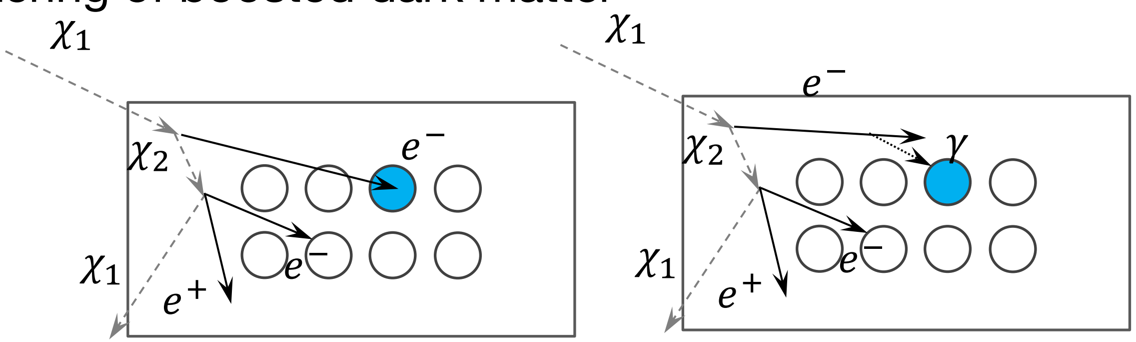
    - 8 crystals + LS: 9 separate detectors
  - Inelastic scattering of boosted dark matter



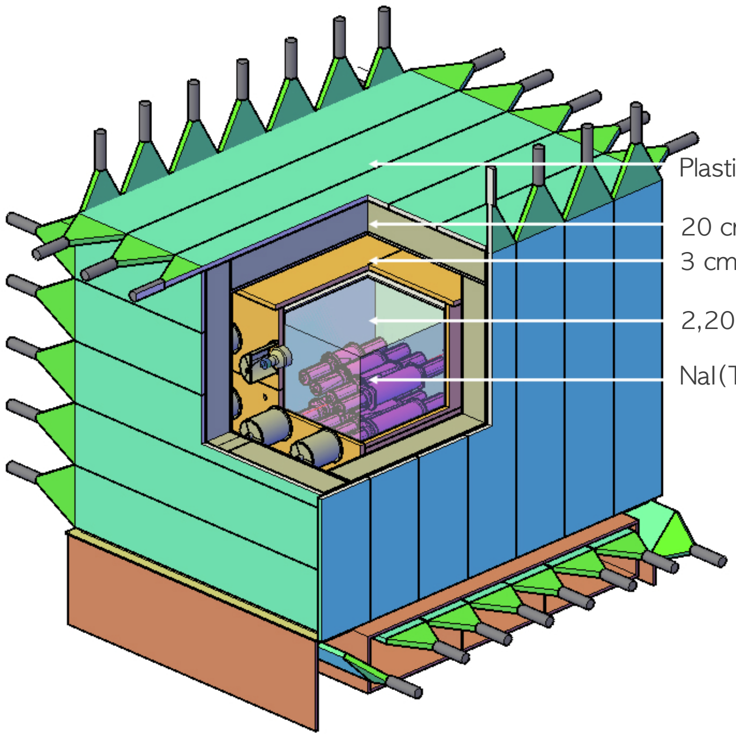
  - energetic electron (or positron) can produce bremsstrahlung gamma that may be tagged with other detectors

First BDM searches: **Inelastic Boosted Dark Matter search** (PRL 122, 131802, 2019)

Inelastic Boosted Dark Matter search

- Analysis strategy:
  - 59.5 days data
  - 106 kg Crystals + 2200 L Liquid Scintillator (LS)
  - Count number of events in a signal region
- Event selections:
  - No selected muon from muon detector
  - No alpha events in the NaI(Tl) crystals
  - Energy of LS > 4 MeV
  - Sum energy of NaI(Tl) crystals > 4 MeV

→ 21 candidate events in E > 4 MeV

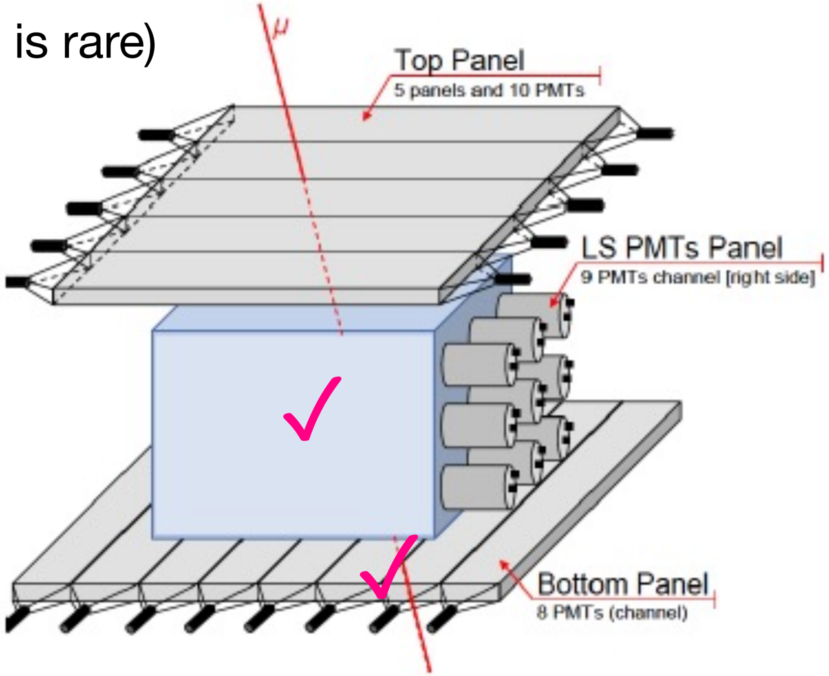


Inelastic Boosted Dark Matter search

- possible E > 4 MeV events: Muon mis-tag
  - COSINE-100 muon detector:
    - Plastic scintillator panel array → gap between each panels
    - muon passing through the gap, and stopped in LS or NaI(Tl)

    → estimate using hit in LS & bottom PS

    (upcoming muon is rare)



$$r_{untag} = \frac{N_{bottom\ PS-LS}}{N_{bottom\ PS-All}}$$
$$= 2.14 \pm 0.21\%$$

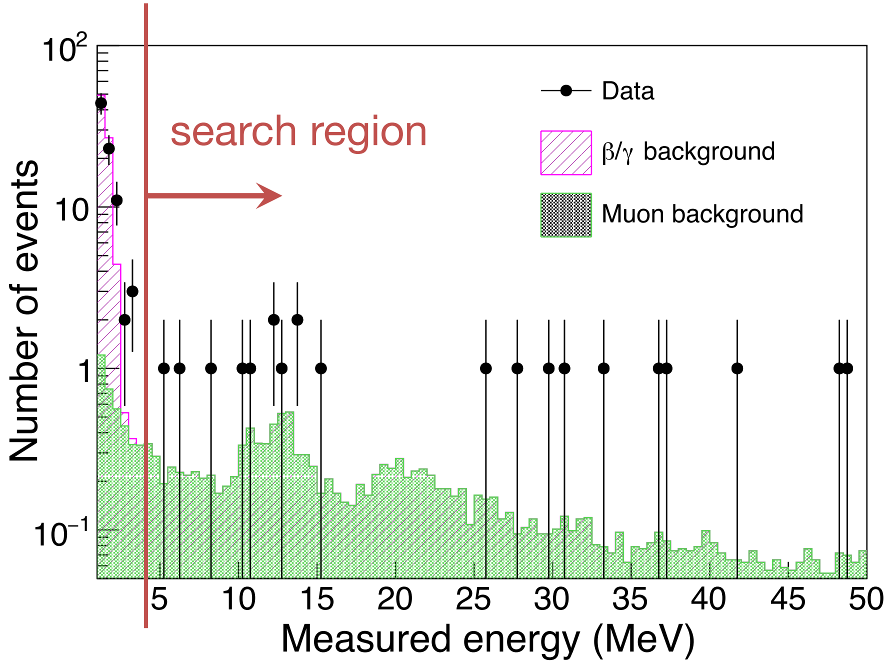
expected backgrounds from muon:

16.1$\pm$ 2.1 (data: 21 events)

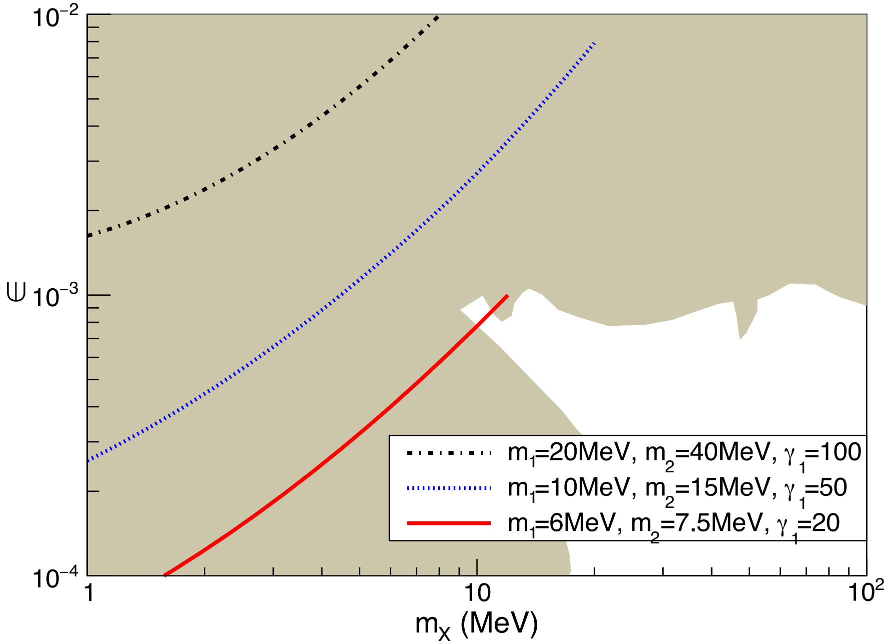
→ consistent number with muon

Inelastic Boosted Dark Matter search

- Energy spectrum of all crystals
  E > 4 MeV distribution shape matched with muon backgrounds



consistent with backgrounds only

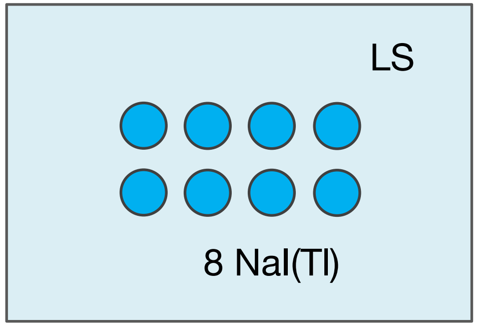


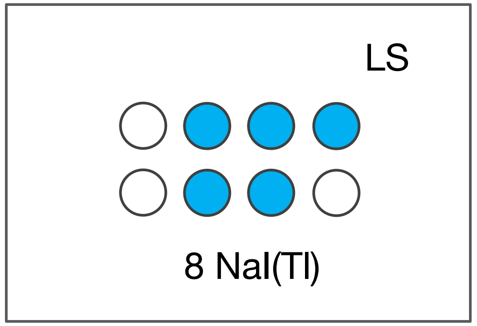
Dark photon Interpretation

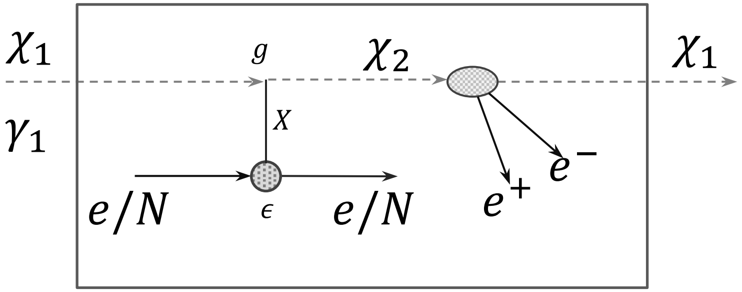
Elastic scattering channel

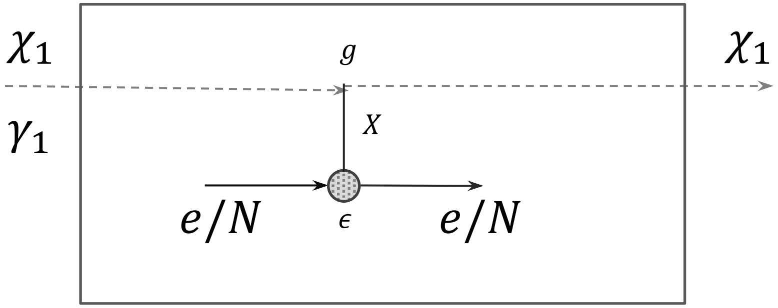
- Inelastic BDM
  - ~100 kg + 2 ton of LS
  - 59 days data
  - multi hit in detectors
  - counts number of events

- Elastic BDM
  - ~60 kg crystals
  - 1.7 years data
  - single hit & multi hit in detectors
  - reconstruct energy spectrum and fitting









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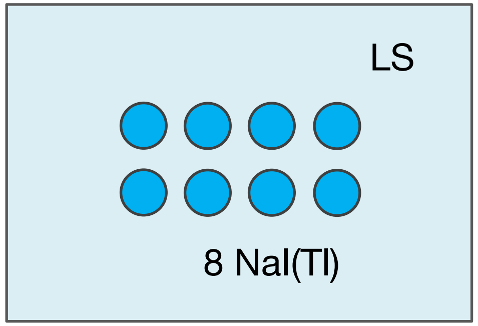

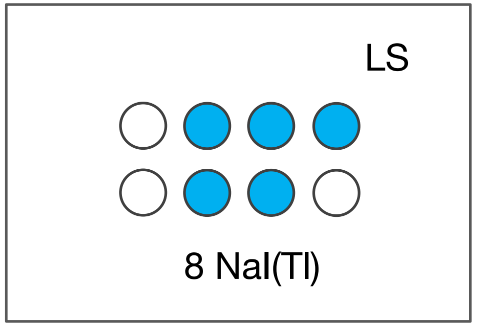

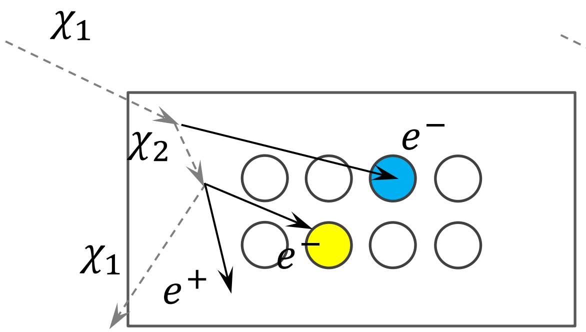

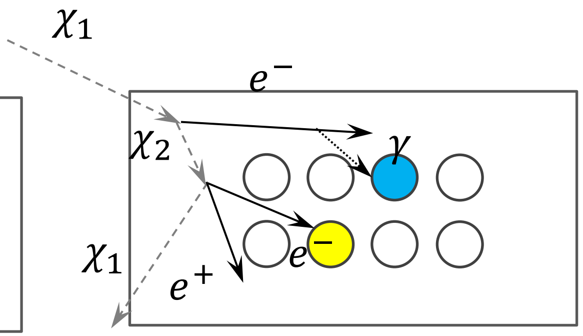

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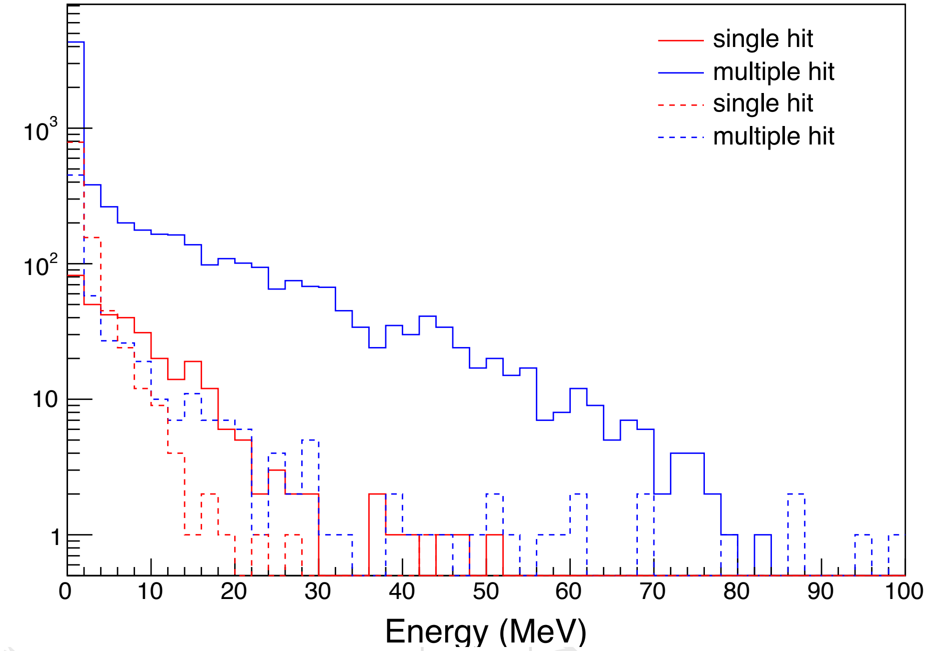

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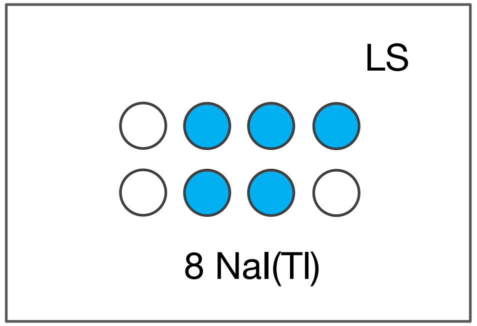
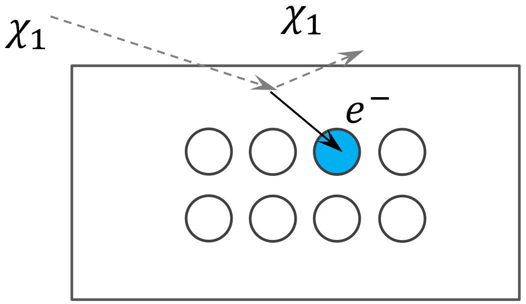
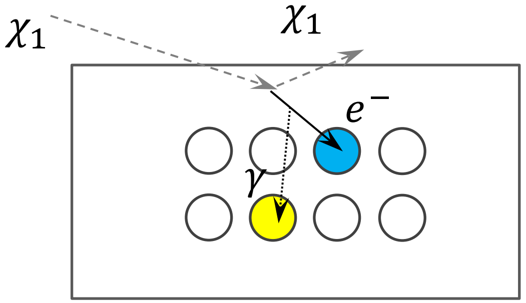
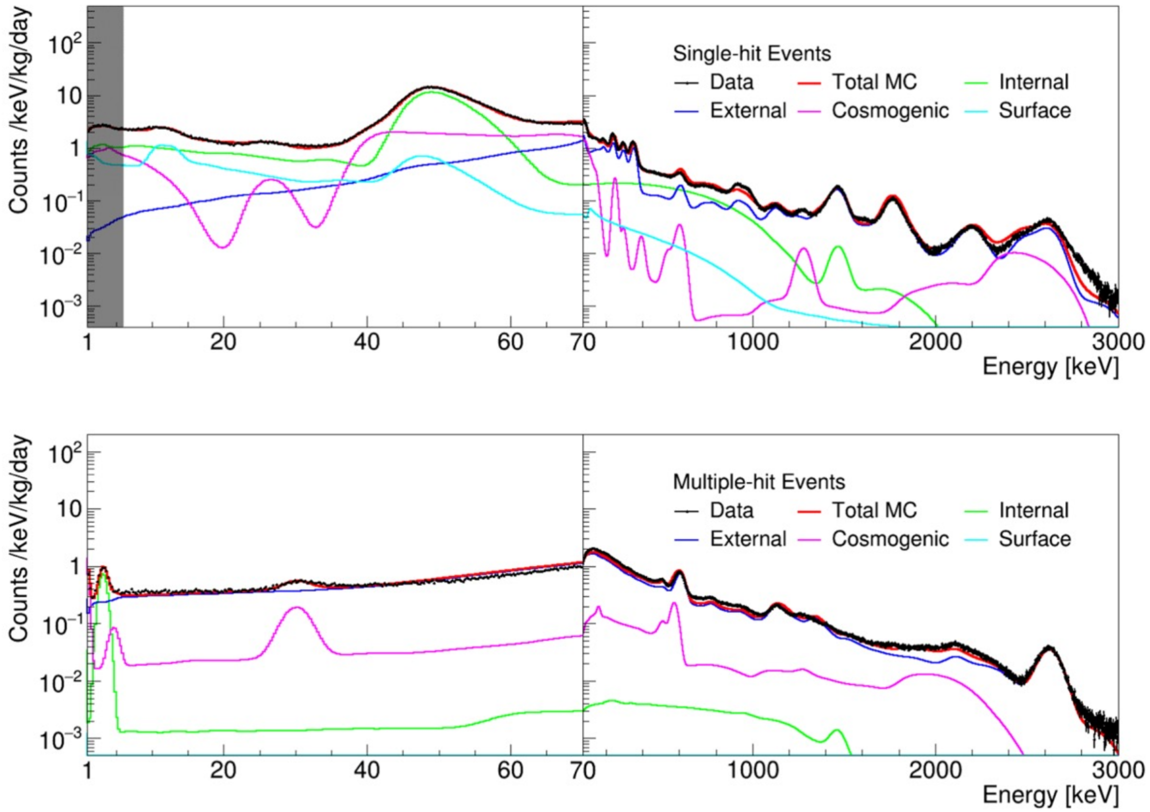






Elastic BDM channel – Energy reconstruction

- Backgrounds understanding in COSINE detectors



Eur. Phys. J. C. 81 837 (2021)

- DAQ designed for accurate low-energy recording
- Well-understood background below 4 MeV

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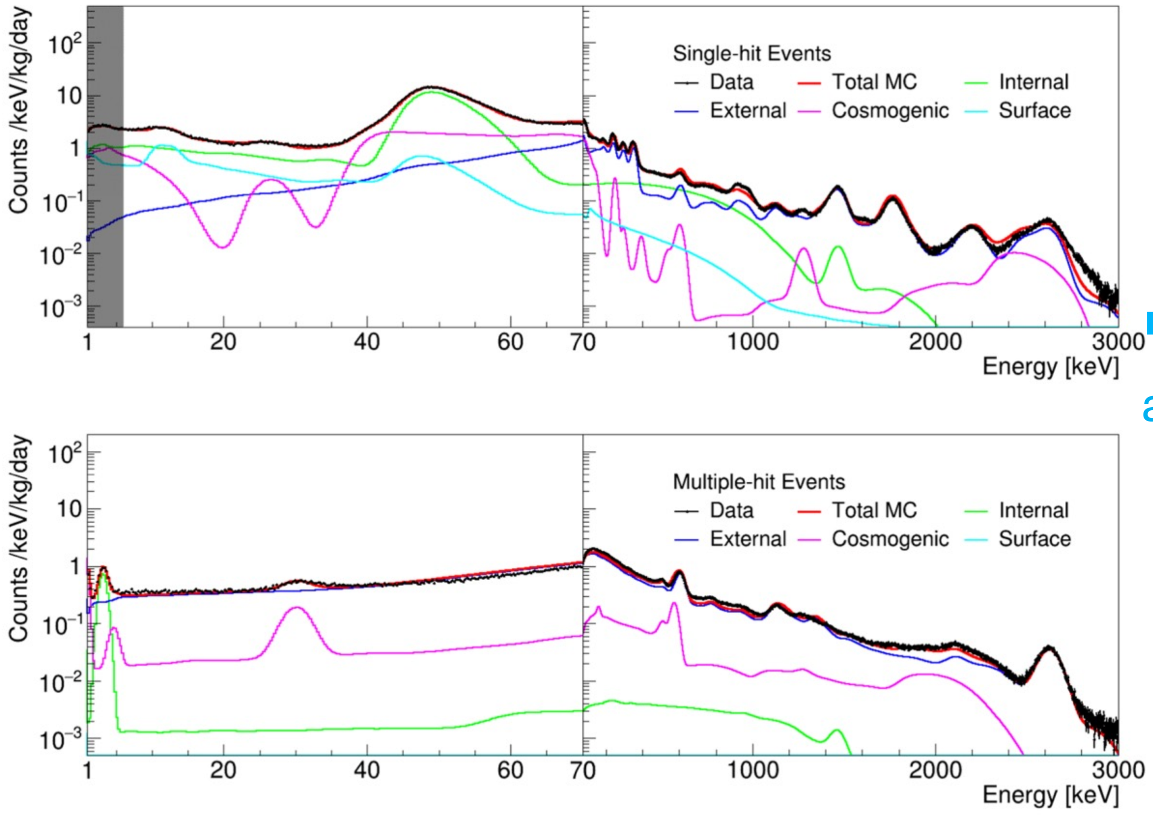

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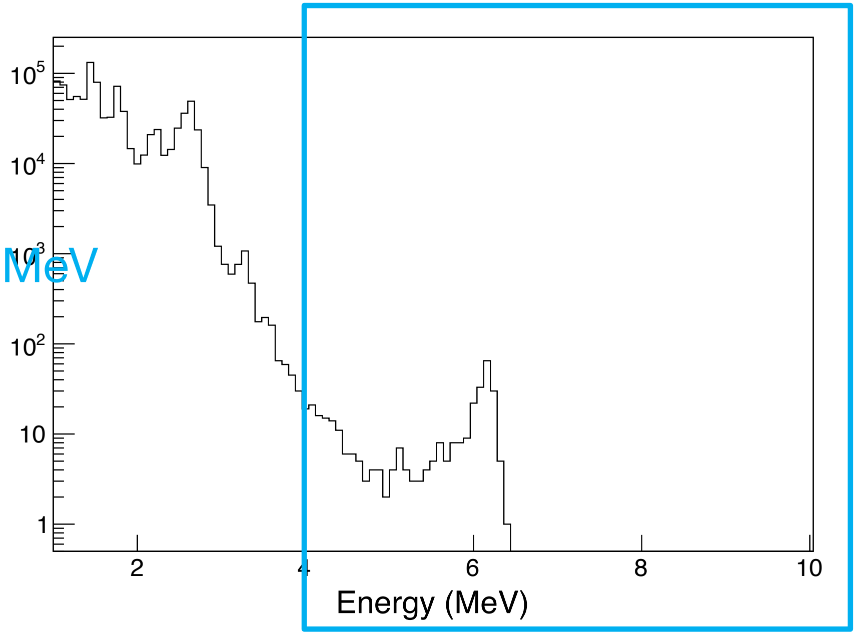
- Unexplored for BDM ROI in high energy range

above 4 MeV



Need to understand backgrounds above 4 MeV

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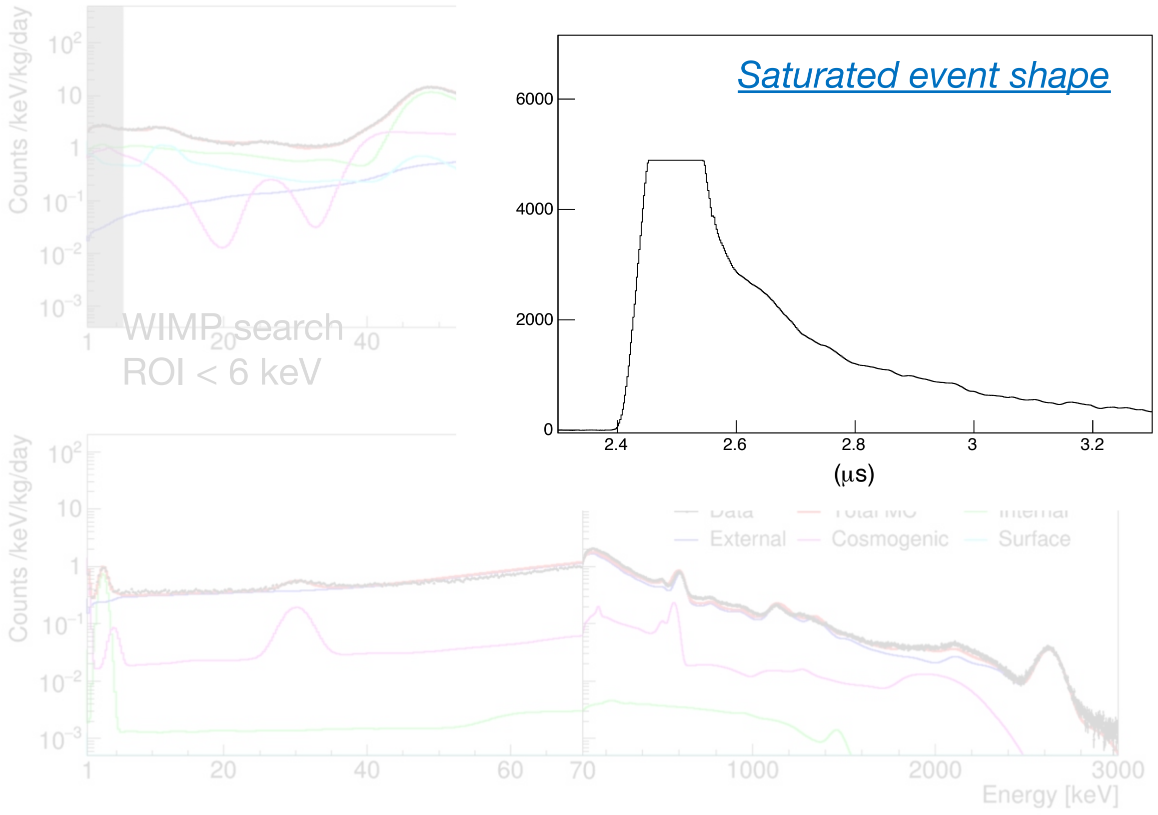

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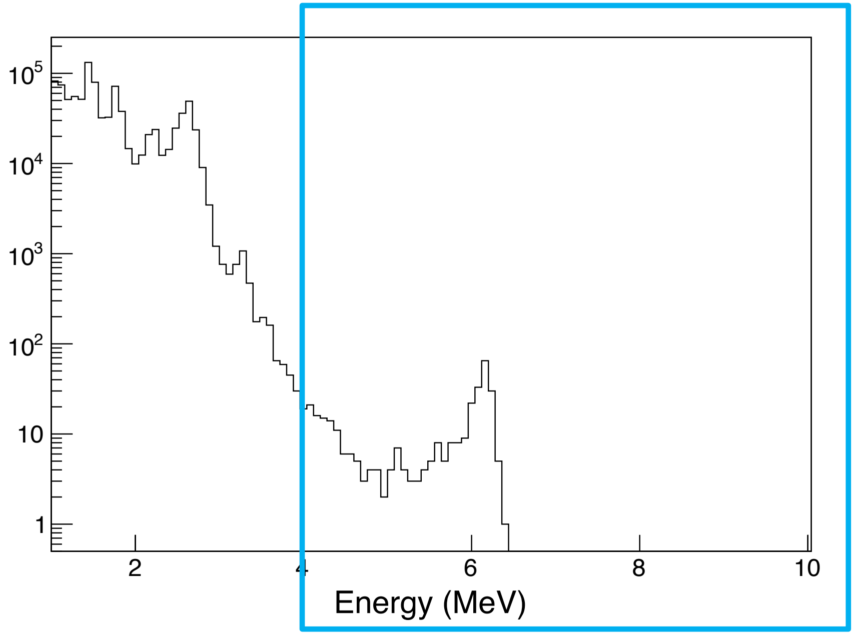

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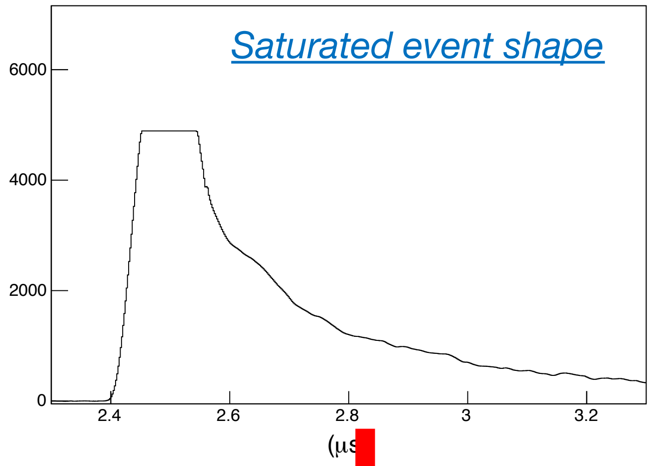

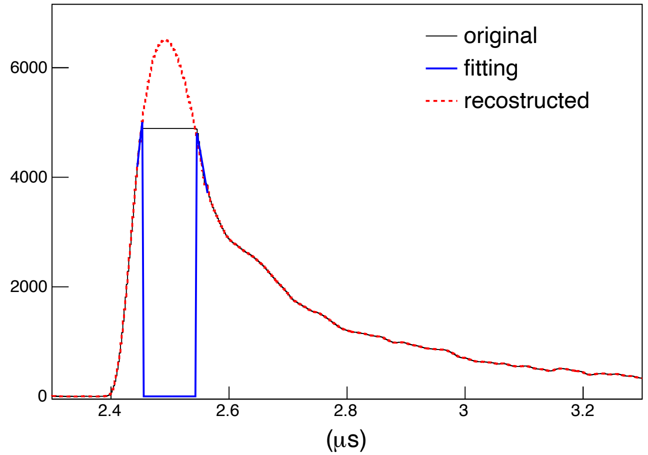

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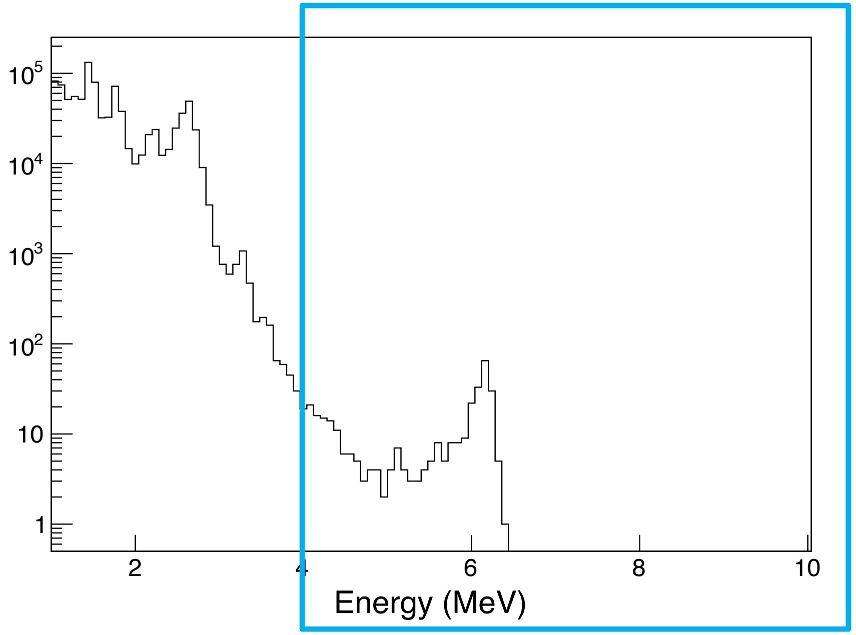

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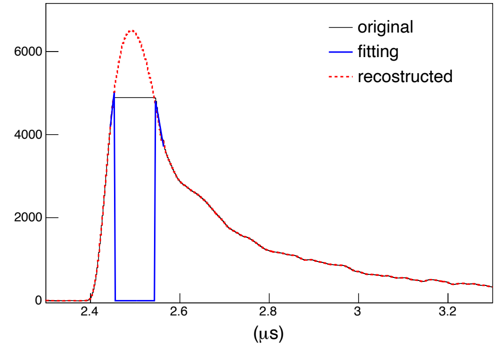

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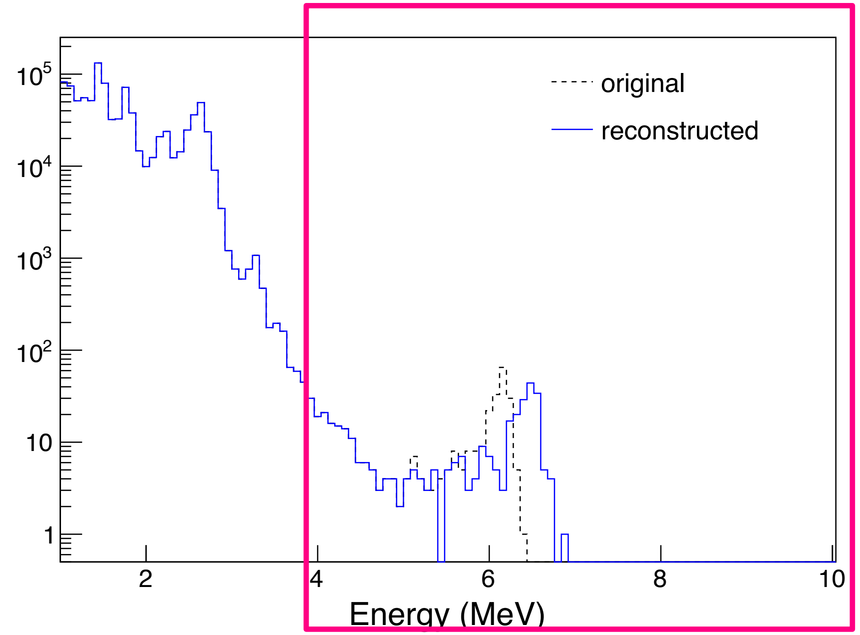

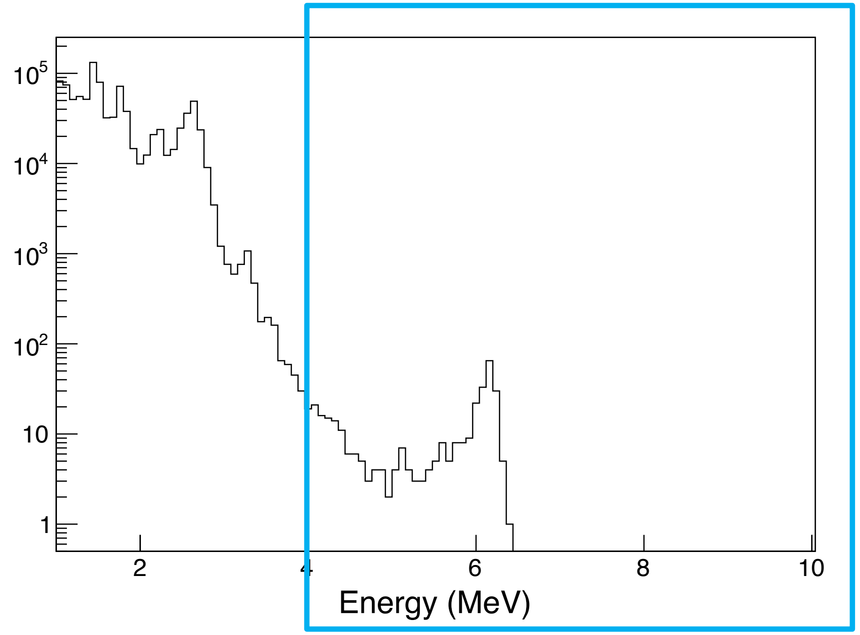

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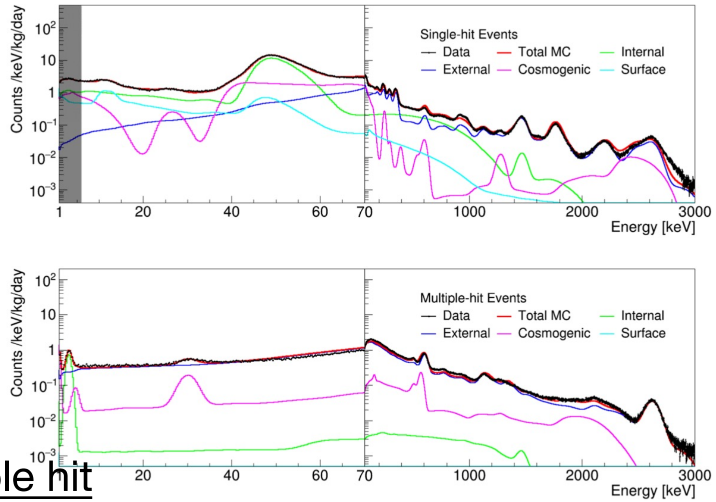
Energy distribution reconstructed

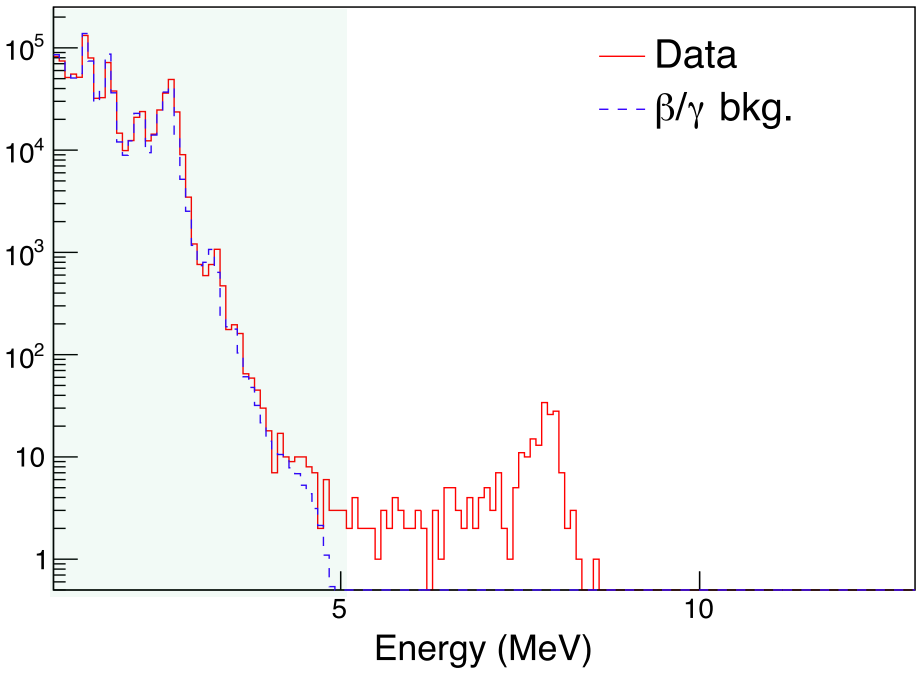
Need to understand backgrounds above 4 MeV

Elastic BDM channel – Bkgs.: Gamma



- BDM signal – high energy
- Well understood below 4 MeV from COSINE-100 background modeling

Single hit



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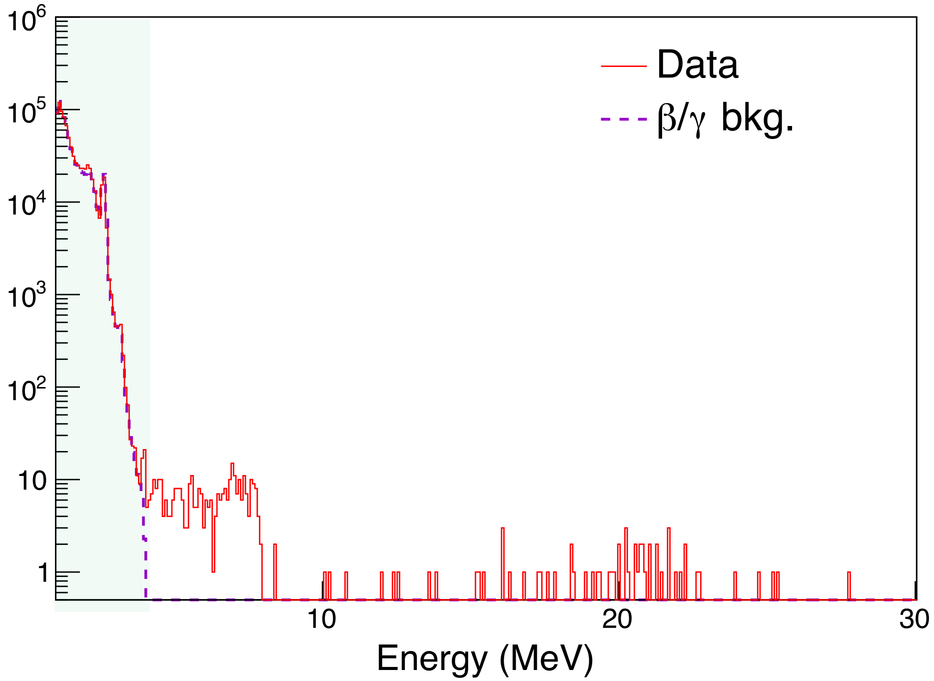

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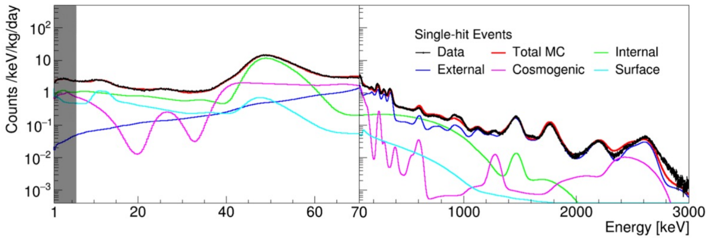

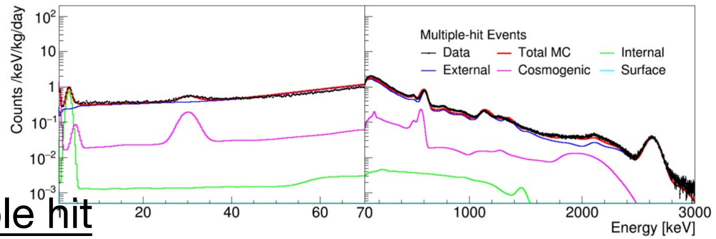

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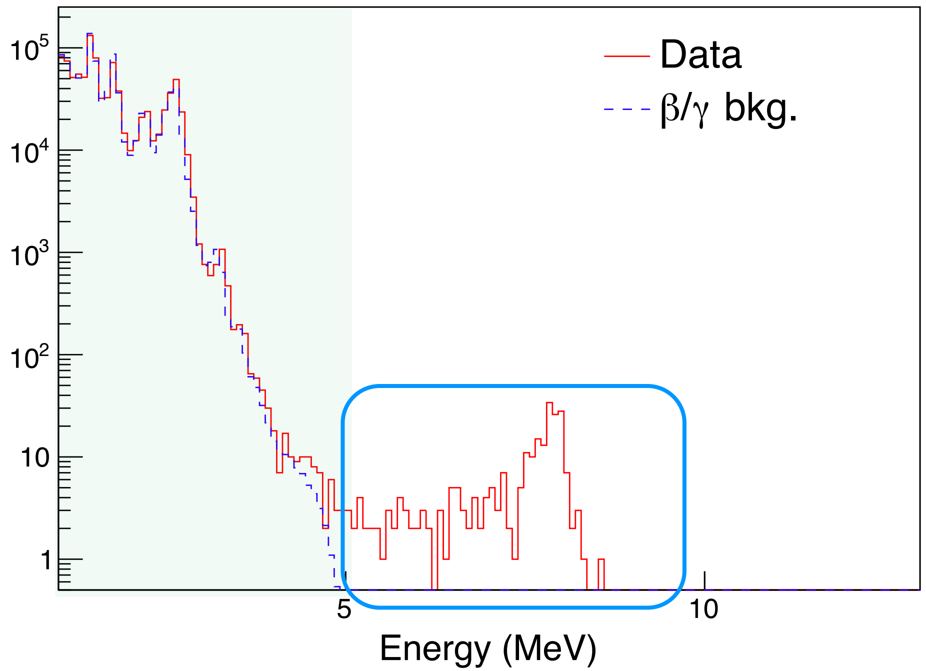

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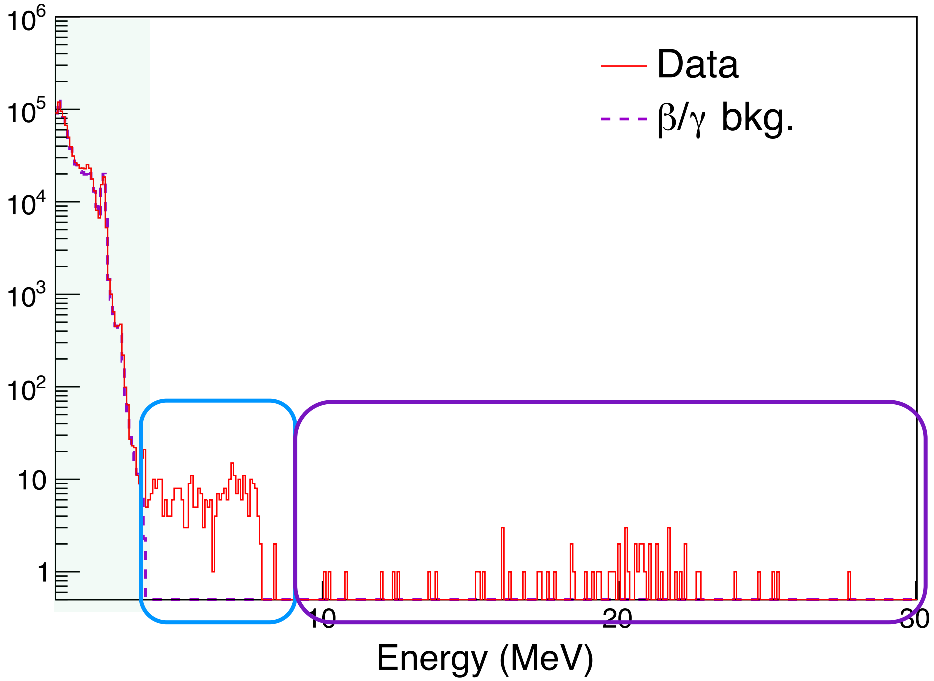

Sources contributing above 4 MeV?

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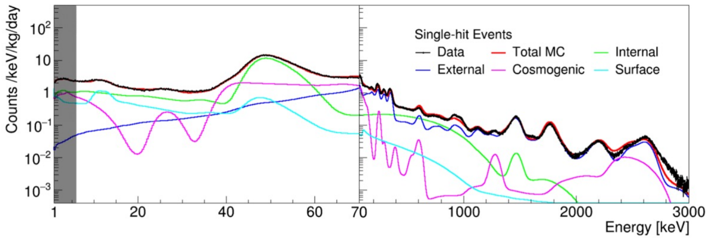

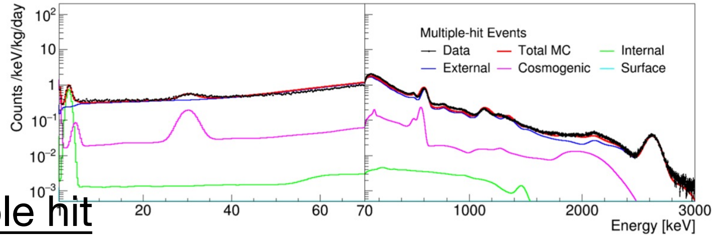

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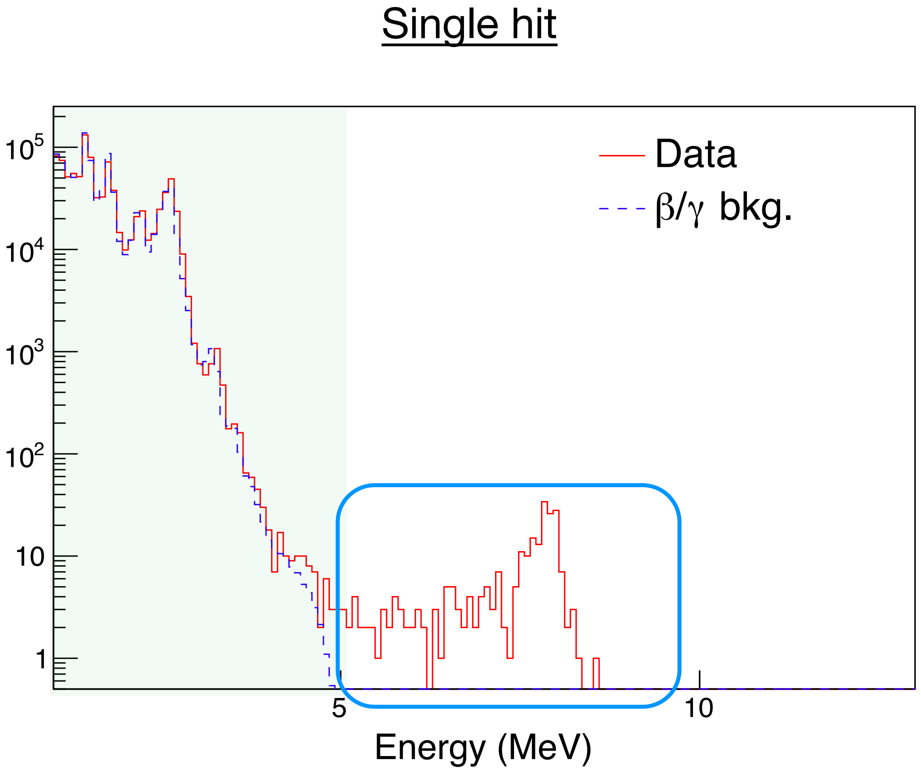
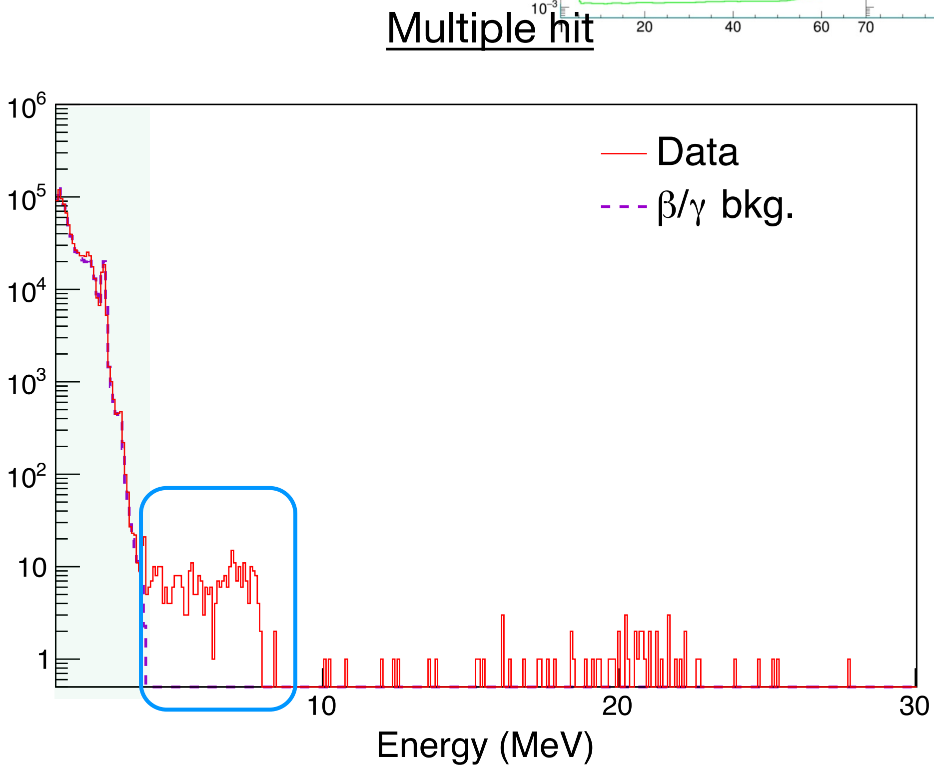
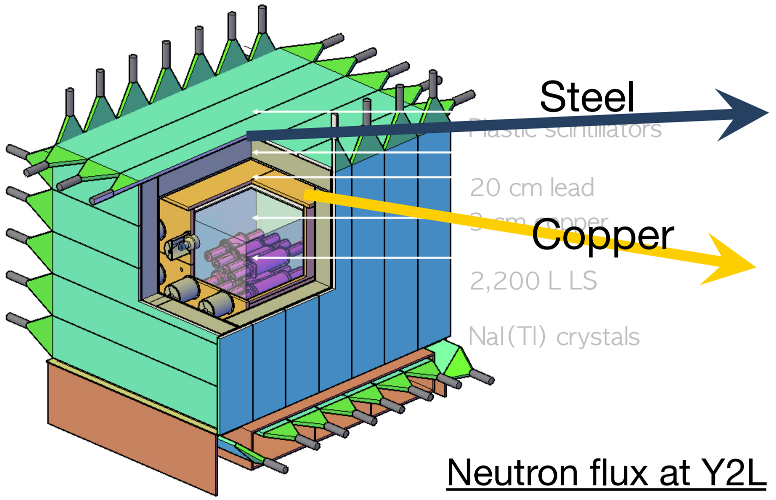




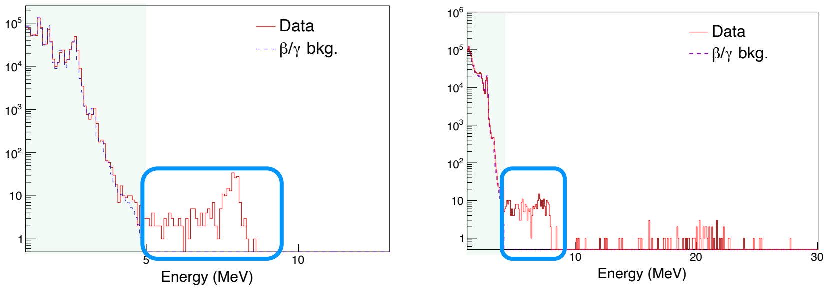
Sources contributing above 4 MeV?

Elastic BDM channel – Bkgs.: n-Capture Gamma

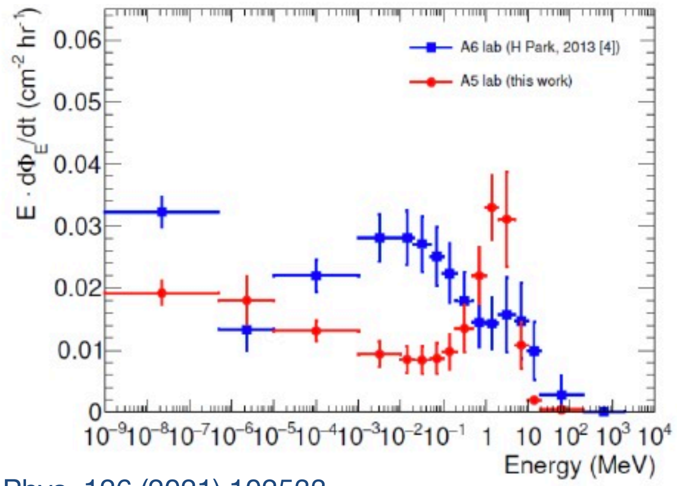
- 4 ~ 9 MeV: gamma by neutron capture



- neutron + Fe-56
  → n, γ + Fe57: Q = 7.6461 MeV
- neutron + Cu-63
  → n, γ + Cu64: Q = 7.916 MeV



Neutron flux at Y2L



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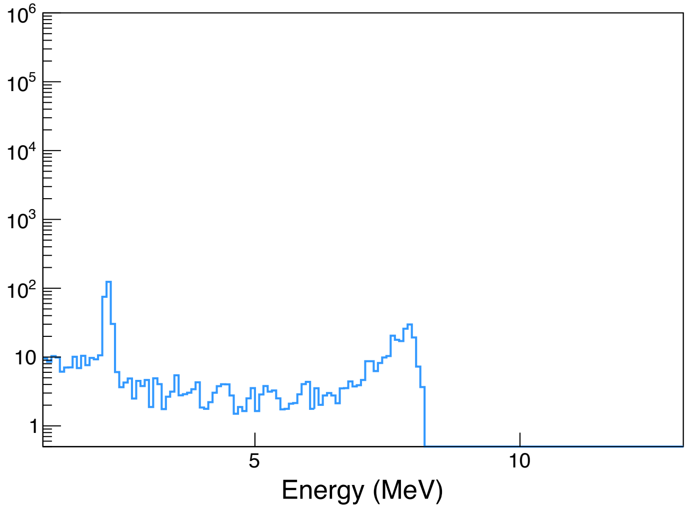
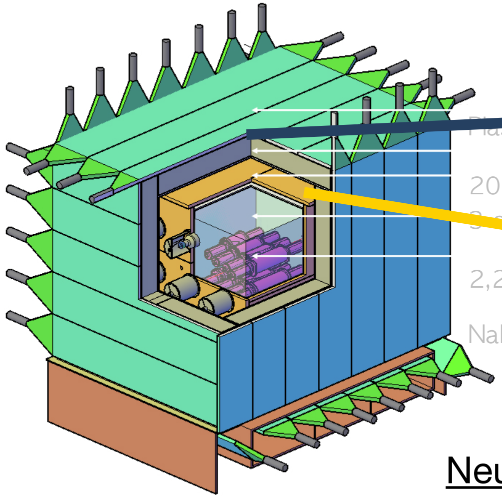
GEANT4 simulation ⇨

Deposited energy from gamma by neutron capture in NaI(Tl)



Elastic BDM channel – Bkgs.: n-Capture Gamma

- 4 ~ 9 MeV: gamma by neutron capture



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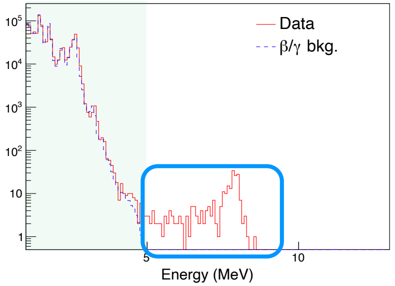
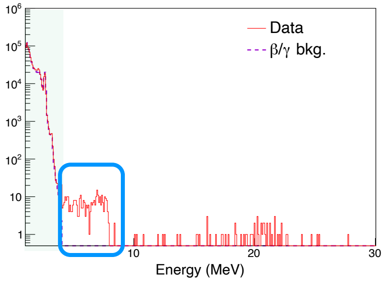
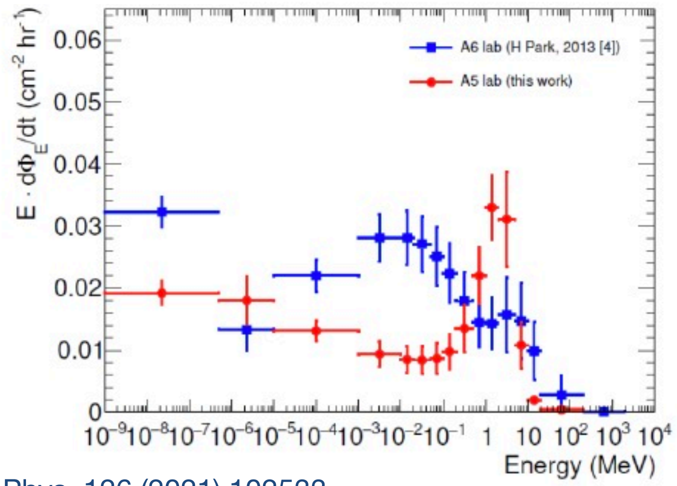




Neutron flux at Y2L



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GEANT4 simulation

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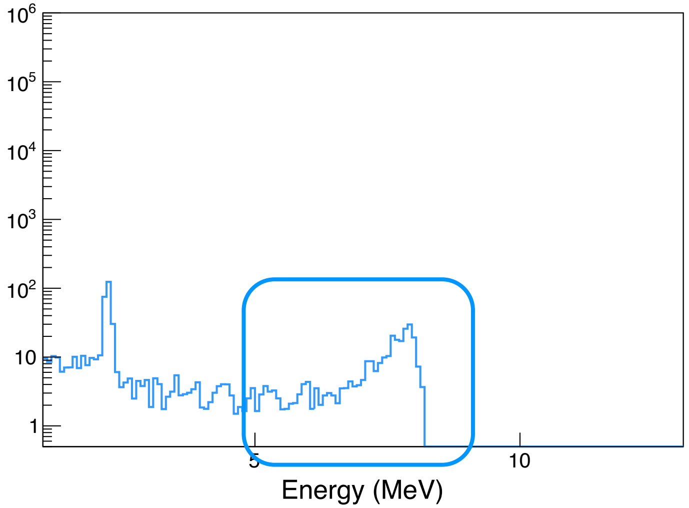
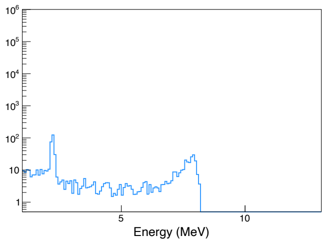
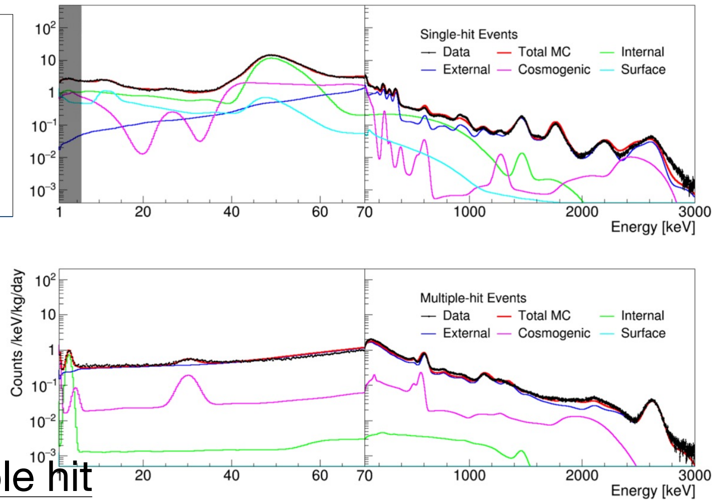


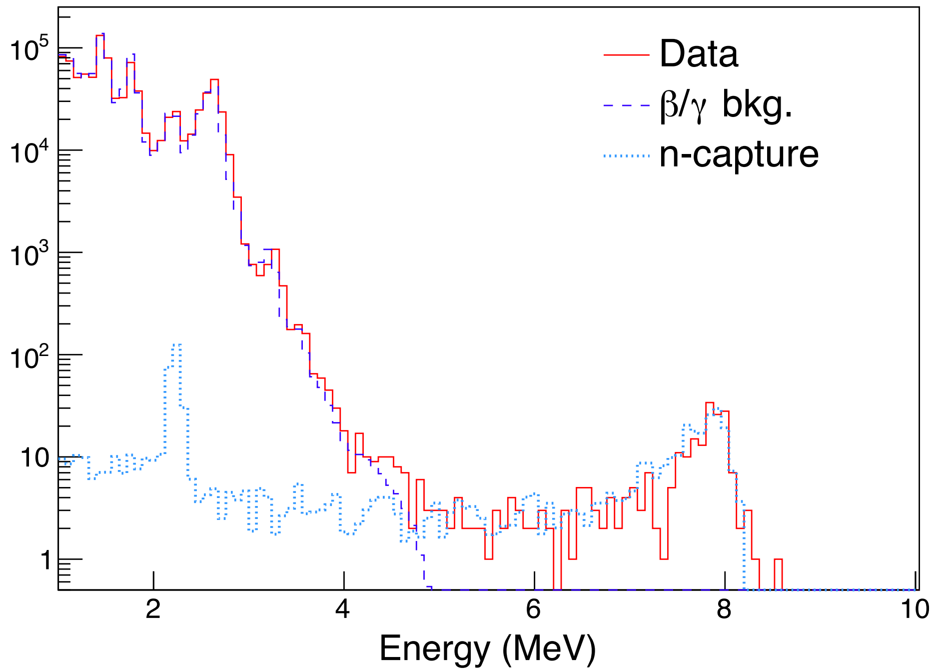
Elastic BDM channel – Bkgs. (E<10 MeV)



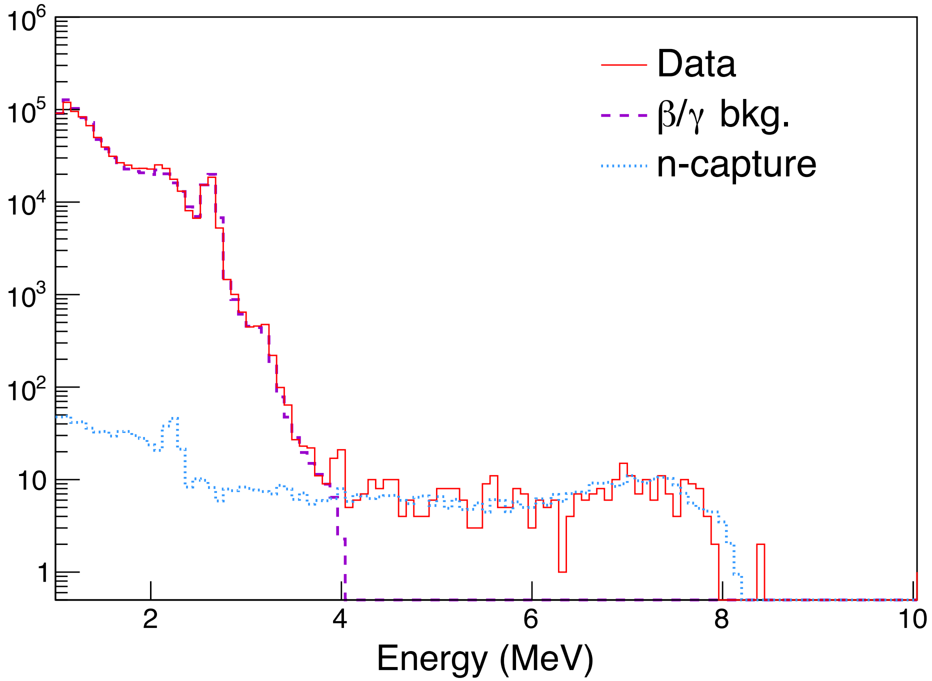


- BDM signal – high energy
- Well understood below 4 MeV from COSINE-100 background modeling

Single hit

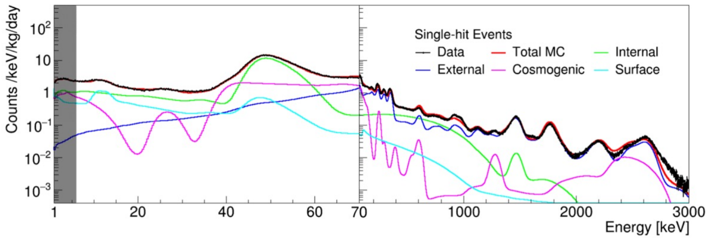


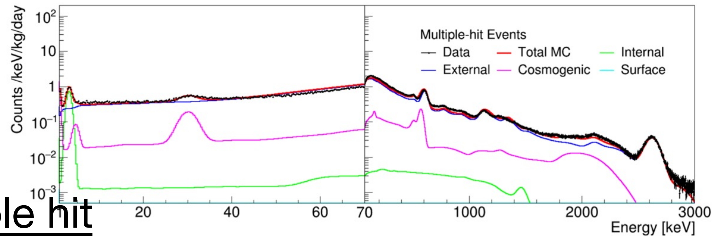
Multiple hit



Neutron captured gamma spectrum describes data well at 4~10 MeV.

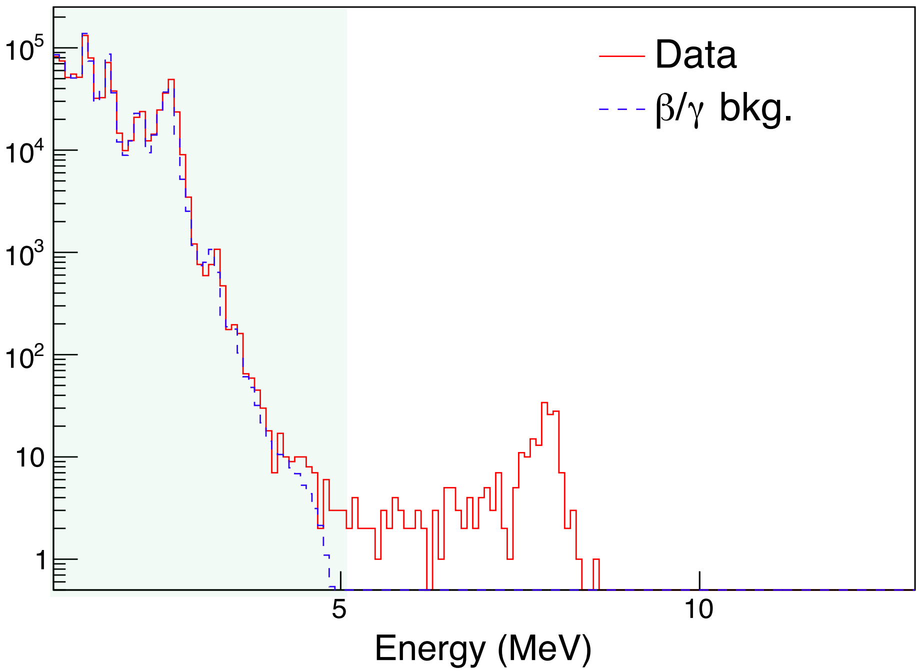
Elastic BDM channel – Bkgs. (E>10 MeV)



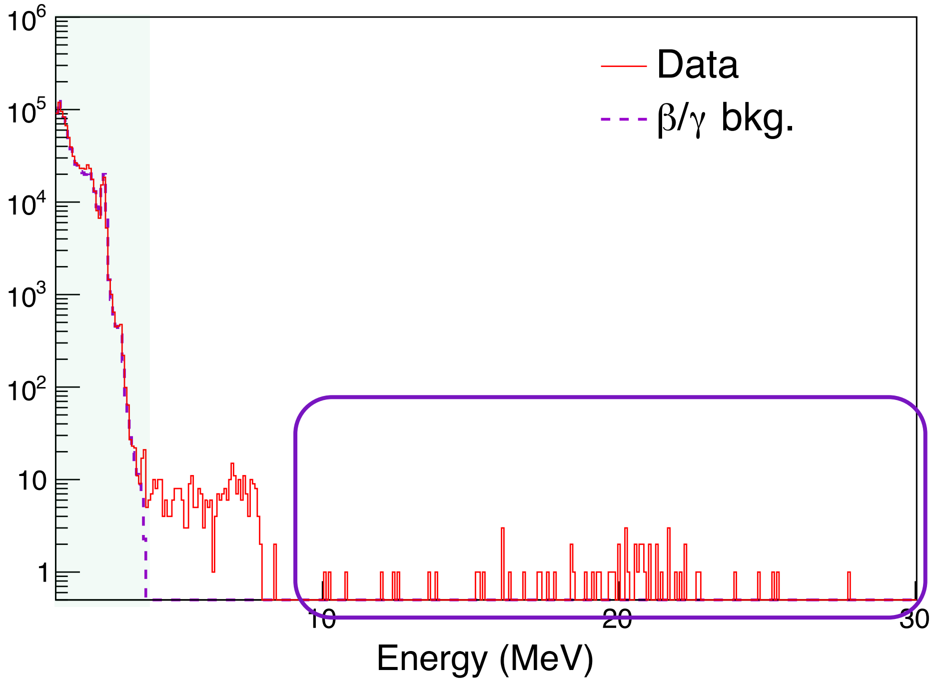


- BDM signal – high energy
- Well understood below 4 MeV from COSINE-100 background modeling

Single hit



Multiple hit

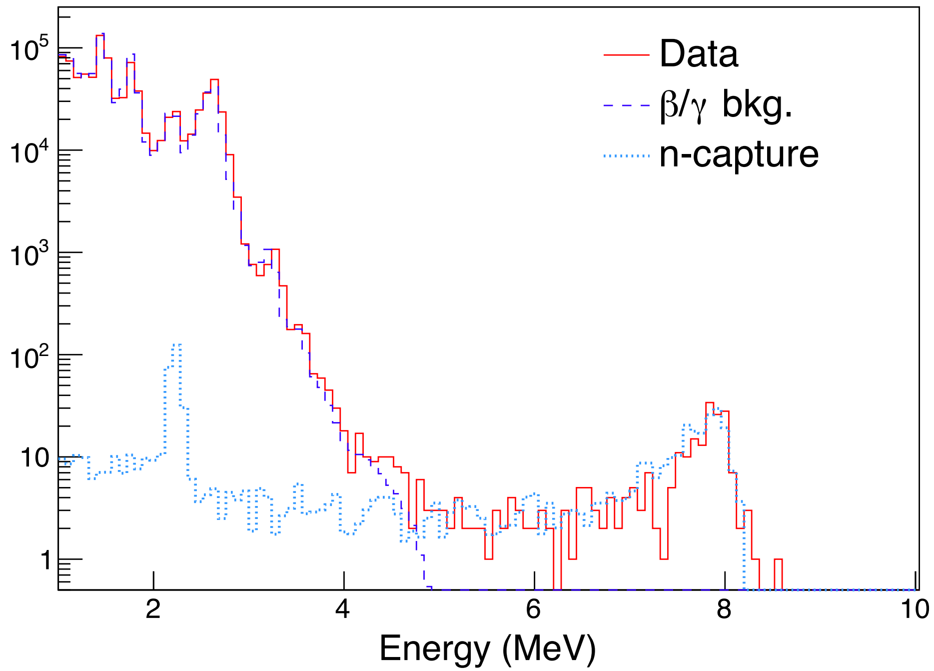


Sources contributing above 10 MeV?

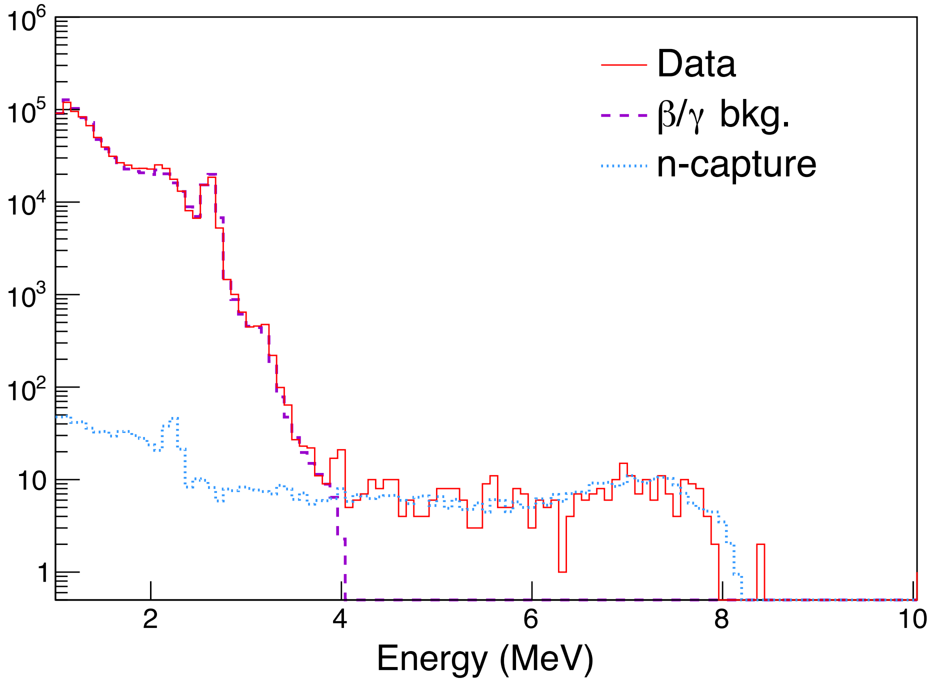
Elastic BDM channel – Bkgs. (E>10 MeV)

- BDM signal – high energy
- Well understood below 4 MeV from COSINE-100 background modeling

Single hit

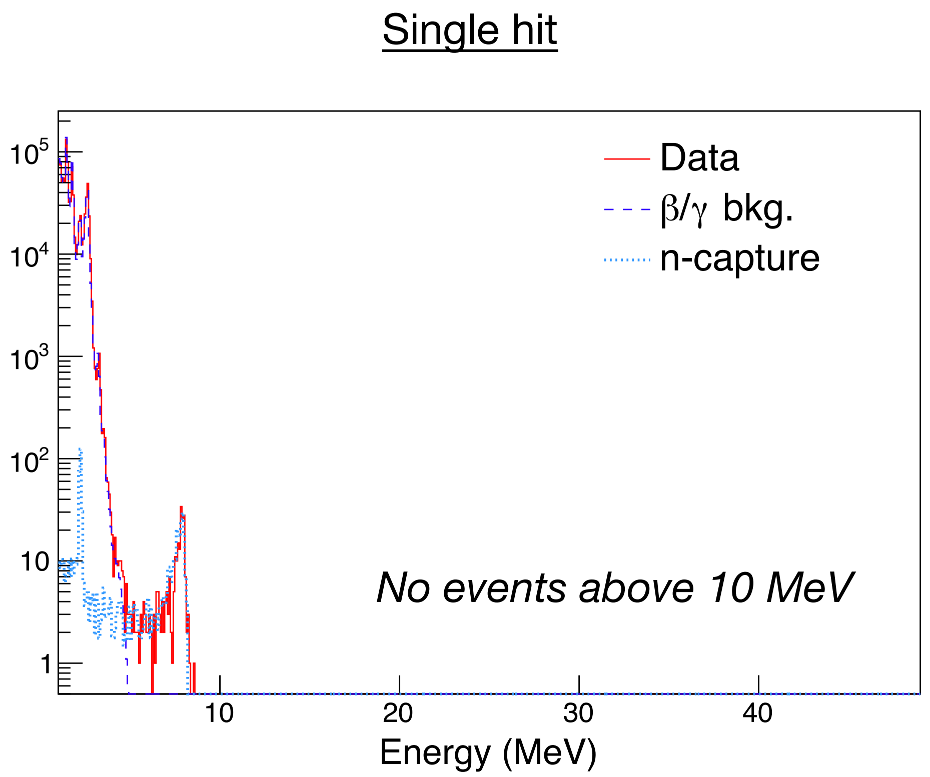


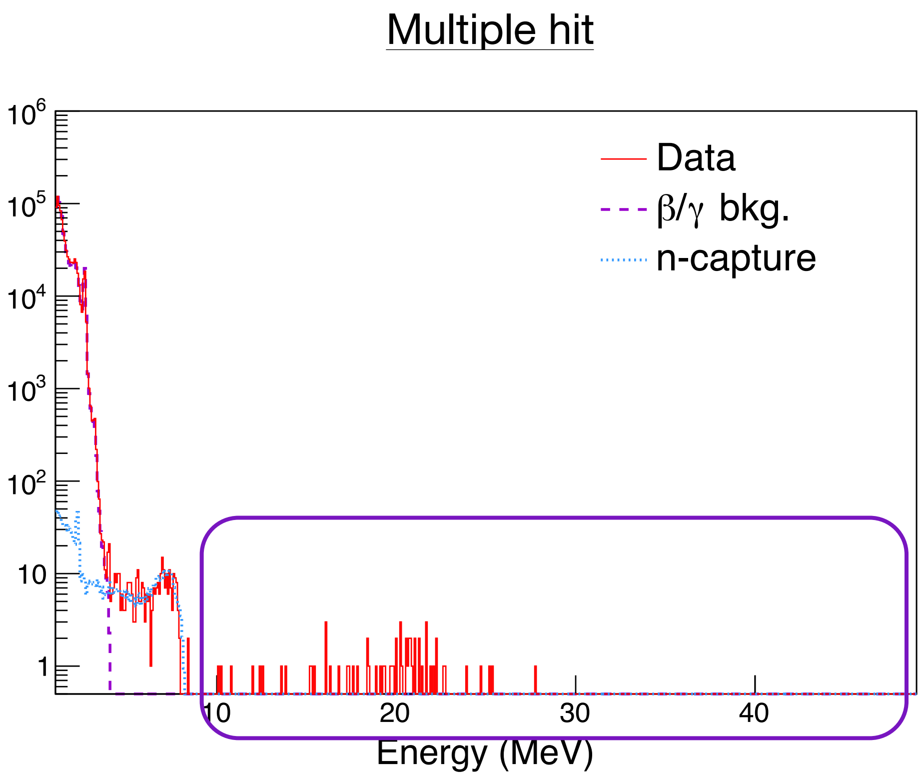
Multiple hit



Elastic BDM channel – Bkgs. (E>10 MeV)

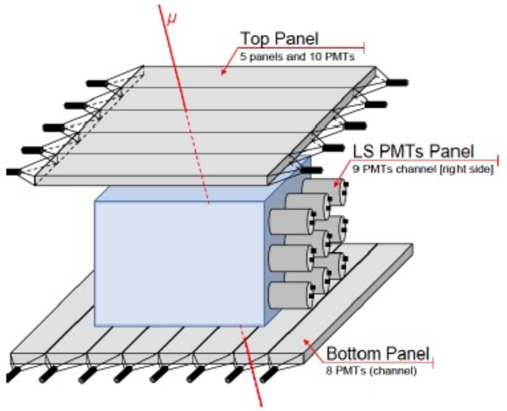
- BDM signal – high energy
- Well understood below 4 MeV from COSINE-100 background modeling





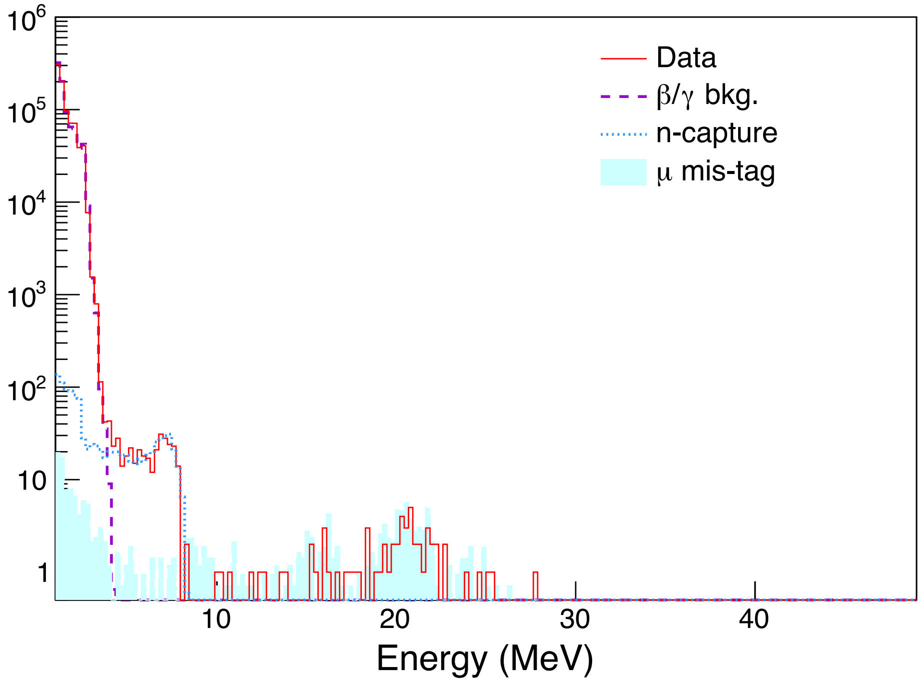
Elastic BDM channel – Bkgs. (E>10 MeV)

- Muon
  - muon passing through the gap between panels and stopped in NaI(Tl)
    → estimate using hit in LS & bottom PS
    (upcoming muon is rare)



→ model multiple hit using these events spectrum

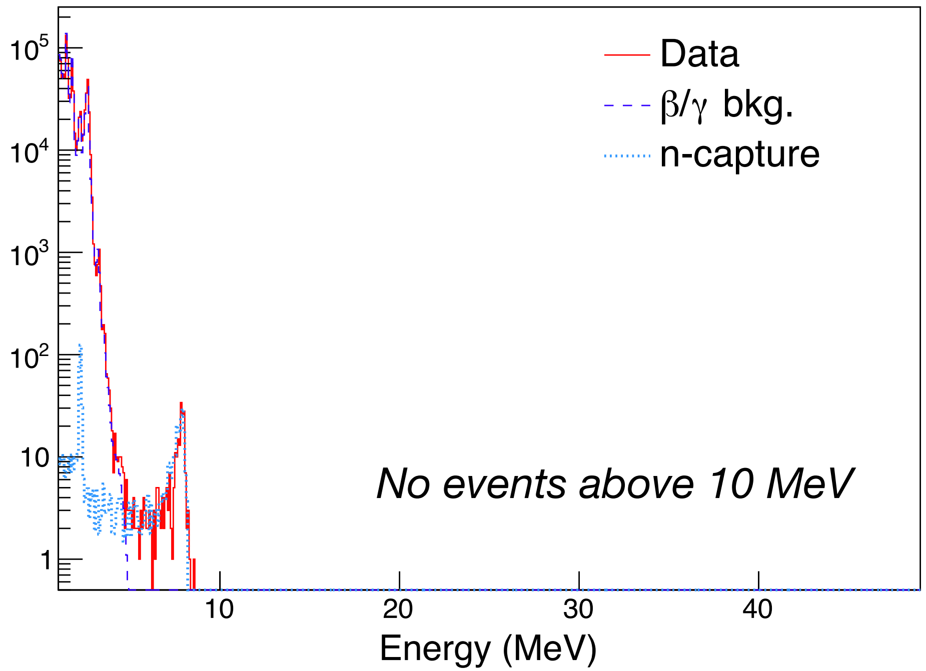
Multiple hit



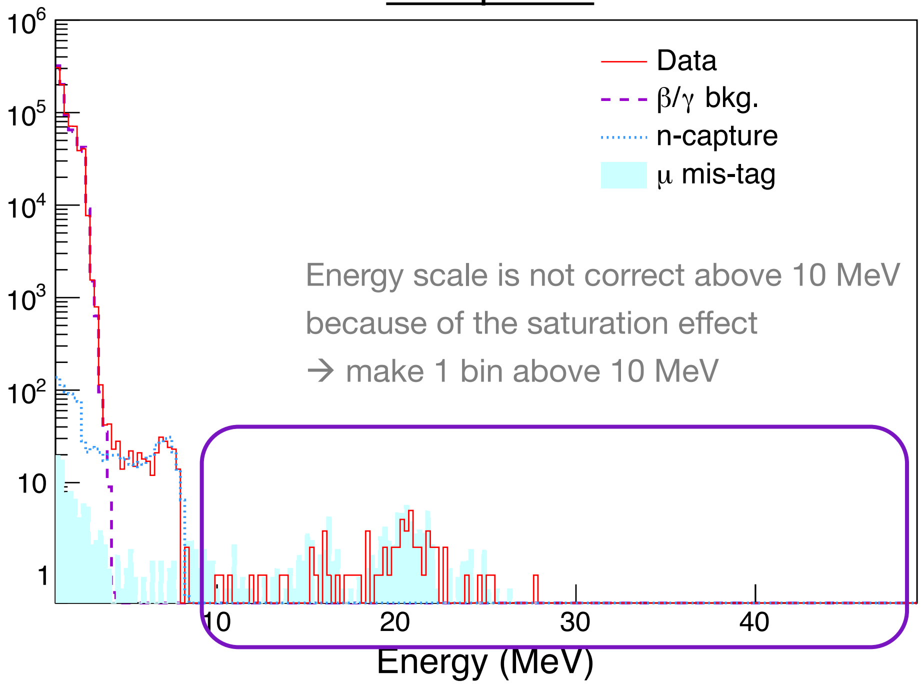
Elastic BDM channel – Fitting Bkgs. and Signal

- 1.7 years data, total 60 kg crystals
- Data fit:
  - Gaussian prior for Gamma bkg. & no constraint on others
  - Bayesian approach

Single hit



Multiple hit



Elastic BDM channel – Fitting results

- 1.7 years data, total 60 kg crystals
- Data fit:
    - Gaussian prior for Gamma bkg. & no constraint on others
    - Bayesian approach

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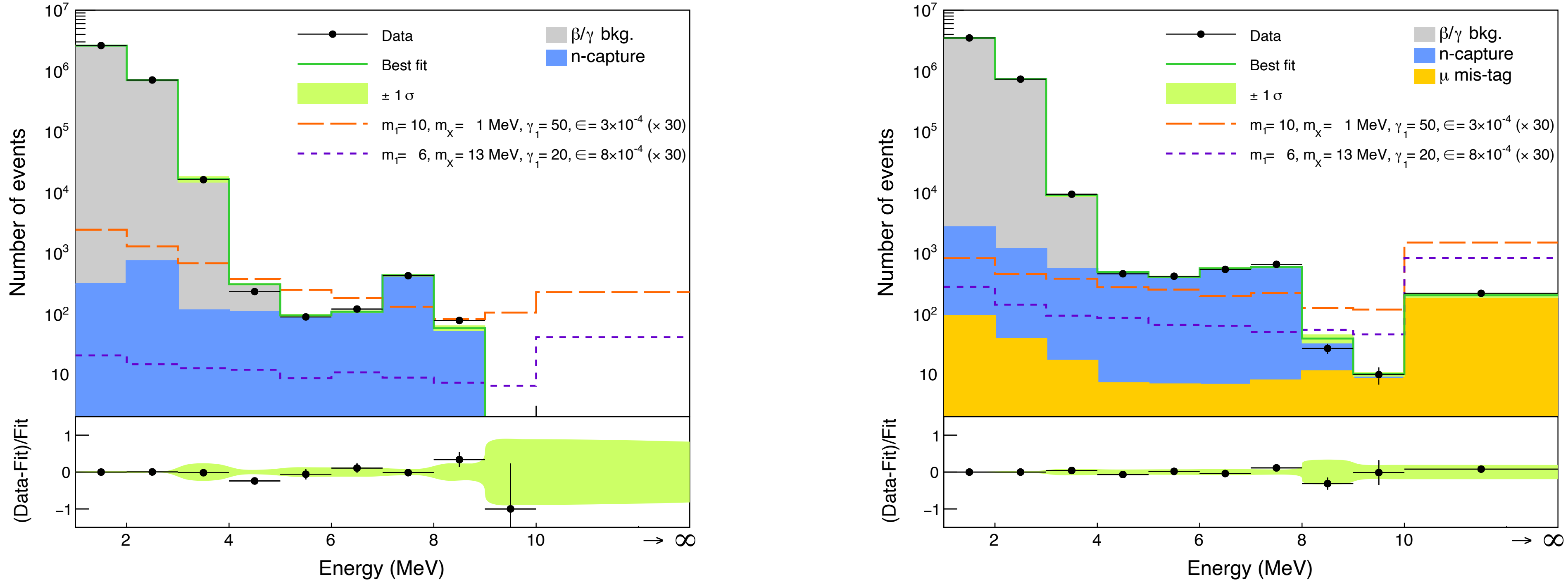
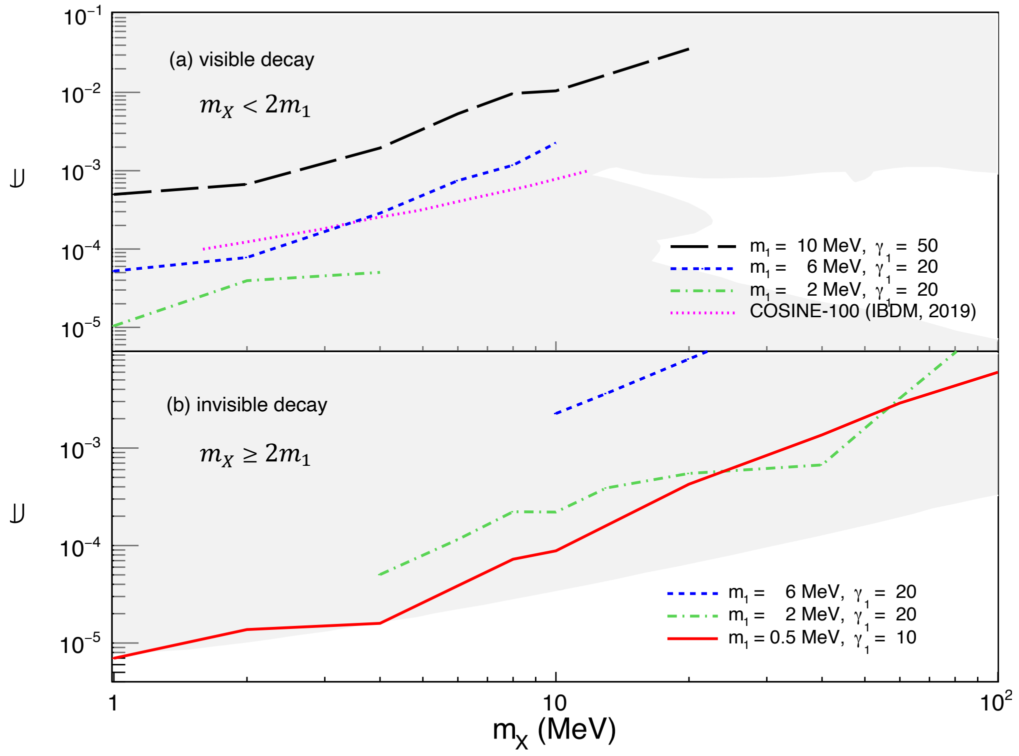


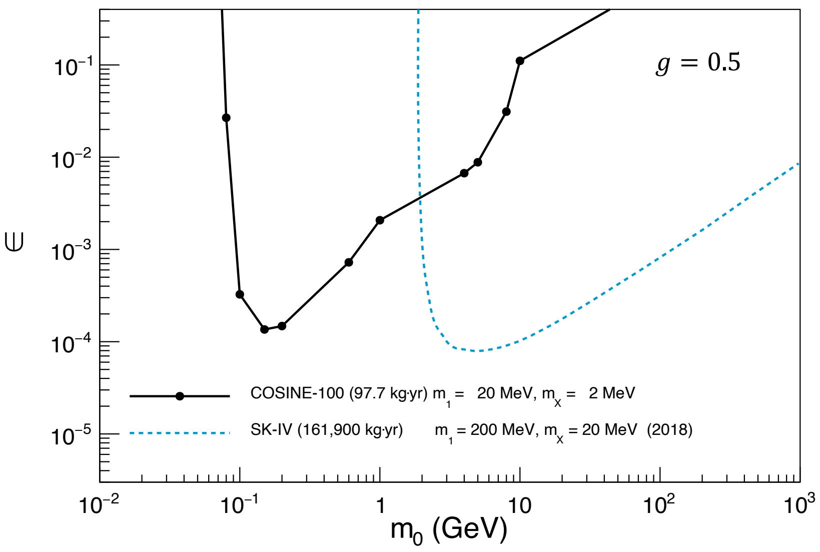
m_0: heavy DM mass
m_1: light DM mass
m_X: dark photon mass
$\gamma_1 = m_0/m_1$
ϵ: coupling

No signal excess

Elastic BDM channel – Fitting results

- 1.7 years data, total 60 kg crystals
- Data fit:
  - Gaussian prior for Gamma bkg. & no constraint on others
  - Bayesian approach





Summary

- There is growing interest in exploring beyond the WIMP paradigm.
- Boosted dark matter (BDM) as a generic variation of dark matter
- BDM via inelastic and elastic scattering channels is investigated with the COSINE-100 data.
- No signal excess found and set limits on parameter spaces.
- Because of well understanding of backgrounds above 4 MeV, the COSINE-100 data is complementary results from large detector.

Backup

Elastic BDM channel – Fitting results

- 1.7 years data, total 60 kg crystals
- Data fit:
  - Gaussian prior for Gamma bkg. & no constraint on others
  - Bayesian approach