DAMSA: A Novel Dark Sector Particle Search Experiment at Fermilab PIP-II and Beyond

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Introduction – What is DAMSA?

- **DAMSA** stands for **D**ump produced **A**boriginal **M**atter **S**earch at an **A**ccelerator.
  - 담사 (潭思) = Rumination or Reflection, a deep thought.
- DAMSA is an experiment concept to search and discovery of Dark Sector Particles.
- DAMSA aims **low mass regime** at an accelerator → ideally E_{beam} below the pion production threshold.
  - It was originally developed for **600 MeV** proton beams at a nuclear rare isotope facility. (Jang *et al.*, Phys. Rev. D 107, L031901 (2023))
- The 800 MeV, or 1 GeV PIP-II beam will provide an ideal condition for DAMSA.
- The DAMSA experiment team is led by lead investigators Jae Yu (UTA) and Juan Estrada (FNAL) and it has been introduced to the community throughout the past two years.
- I've been working on Geant4 simulation of this project.

A South Korean national treasure.
A statue of Buddha thinking deeply about mysteries of life (or of universe?)

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What is new about DAMSA?

- It requires **short distance** from the target to the detector. (< 10 m)
  - This allows us to have more acceptance for **short-lived DSPs**.
  - However, at the same time, we have to deal with enormous **beam-related neutron (BRN)** backgrounds.
- Focusing on signatures with **two-body decay** event topology.
  - DAMSA has adopted a strategy that utilizes **combinatorics** of selecting two particles extensively to **actively reject random backgrounds**.
- In a perspective of someone who studies BSM physics at neutrino facility, many neutrino facilities have never been tried to put detector close to target because all neutrino experiments wanted to avoid hadron backgrounds. Especially to avoid the BRNs.

Experiment	Distance (m)
DUNE	574
SBN	110
T2K	280
COHERENT	27.5
CCM	20
DAMSA	**< 10**

Distances from the target to the detectors of some selected experiments.

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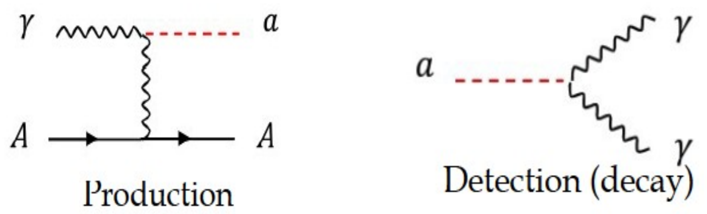
DAMSA Physics Strategy – Axion-like Particles

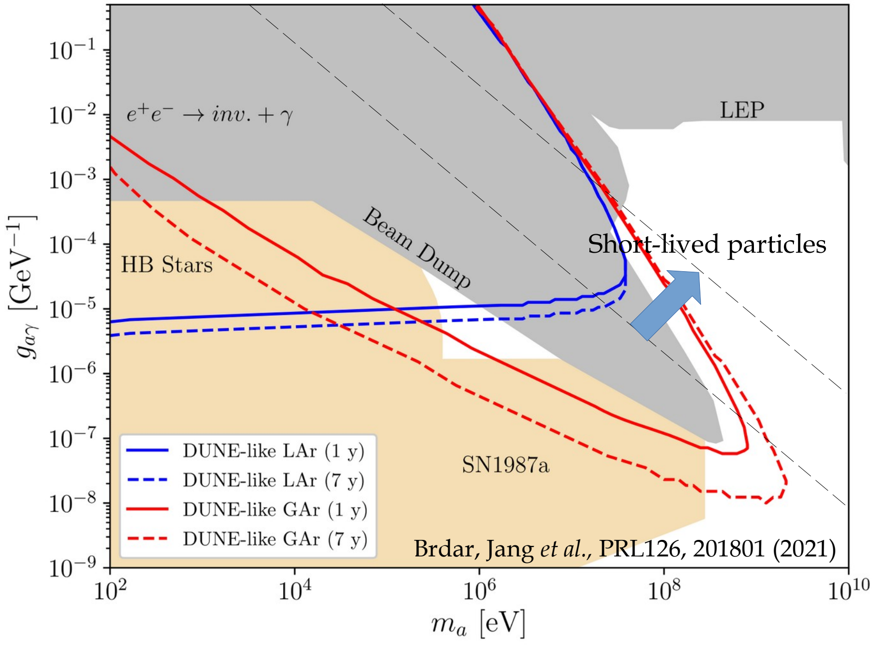
- Focus on **Axion-like particles (ALP)** in their **two-photon final state.**
- Produce **as many photons as possible** in the beam dump. (high-Z, high-density target and high-intensity beam)
- Capture **as many ALPs as possible**.
  - **Shorten** the **distance** from the source to the detector

$$g_{a\gamma} = \sqrt{\frac{1}{\tau_a}\frac{64\pi}{m_a^3}}$$

→ Increase acceptance for short-lived particles

  - Increase the detector angular coverage
- Minimize the backgrounds from **neutral particles**.
  - **BRN**
  - Neutrino interactions





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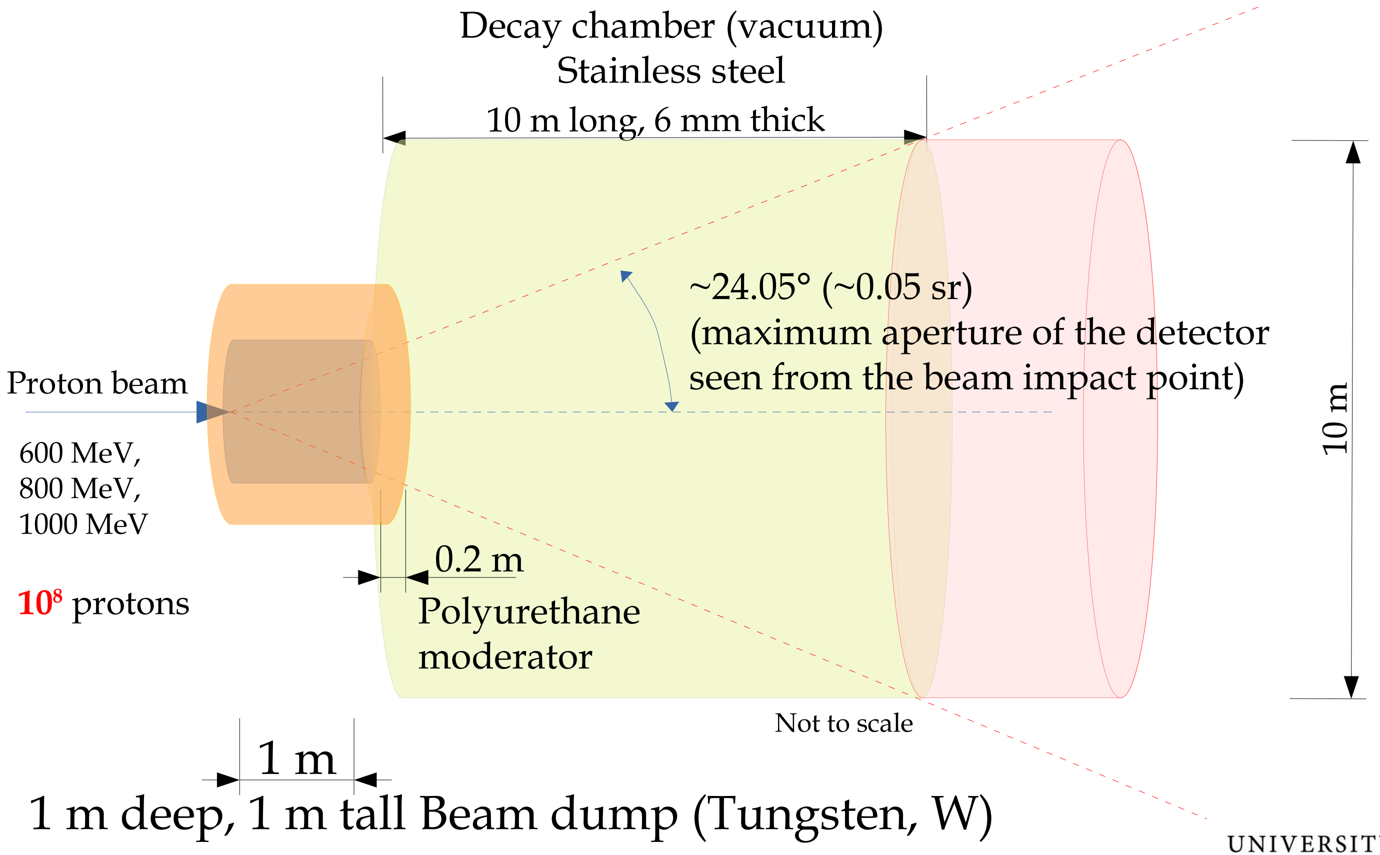
DAMSA Experiment Layout

- DAMSA = Beam Dump(and moderator) + Decay Chamber + Detector

Detector optimization study in many aspects is in progress. Not a final design



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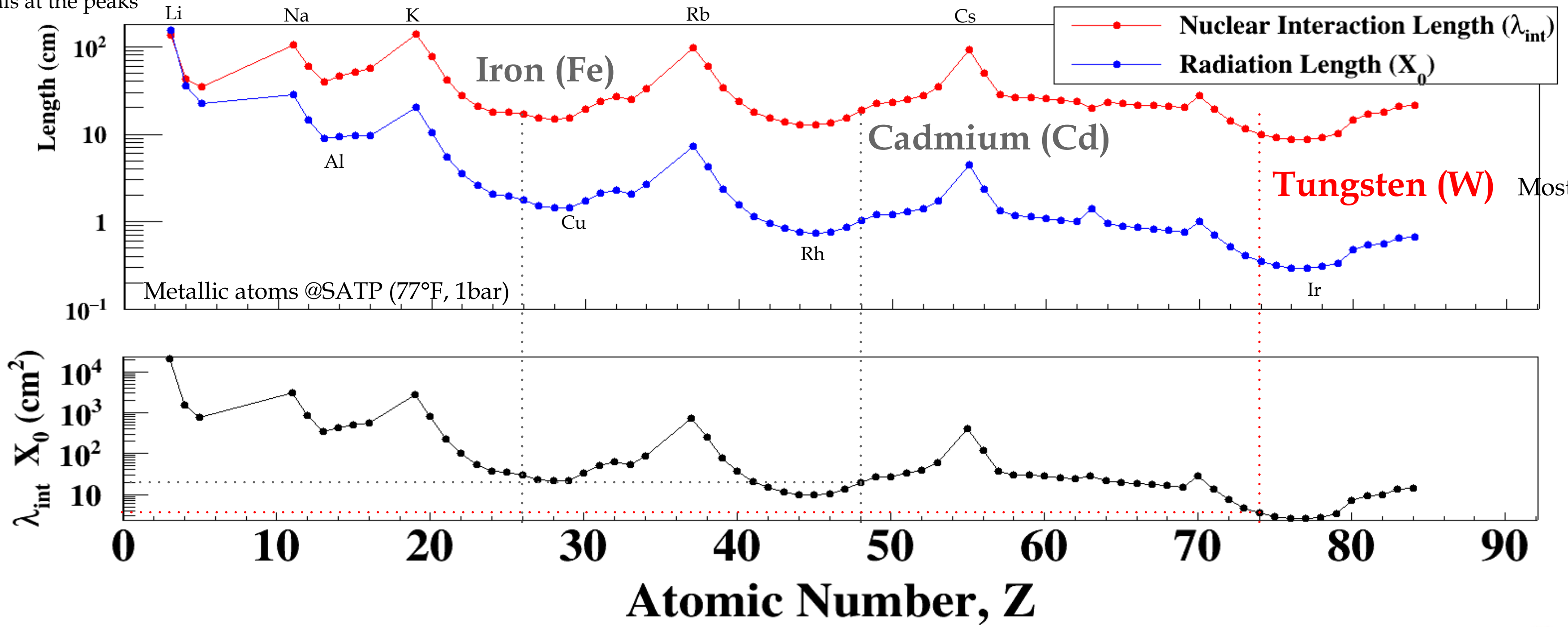
DAMSA Strategy – Dump Material

- **Short radiation length (X_0)** and thick enough material → **more signals!**
- **Short nuclear interaction length (λ_{int})** with deep enough dump → **less neutrons! less neutrinos!**

Dump itself act as a shield

Alkali metals at the peaks



Most ideal!

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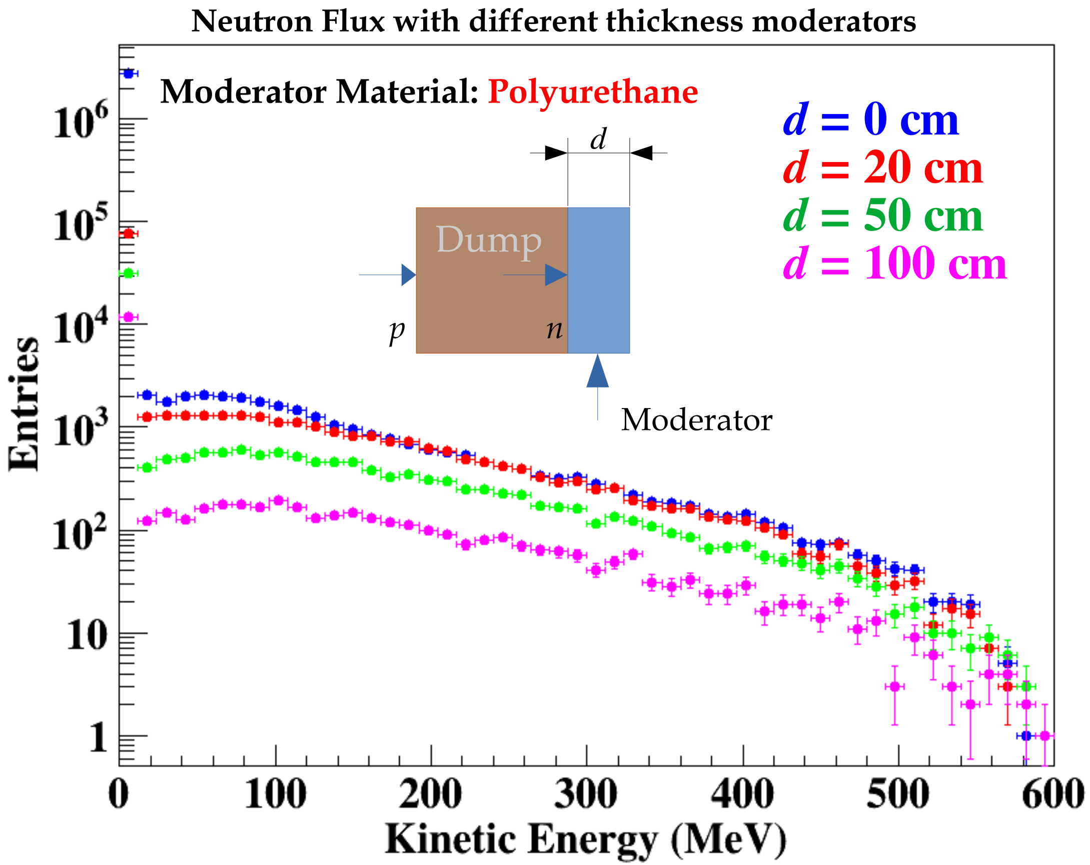
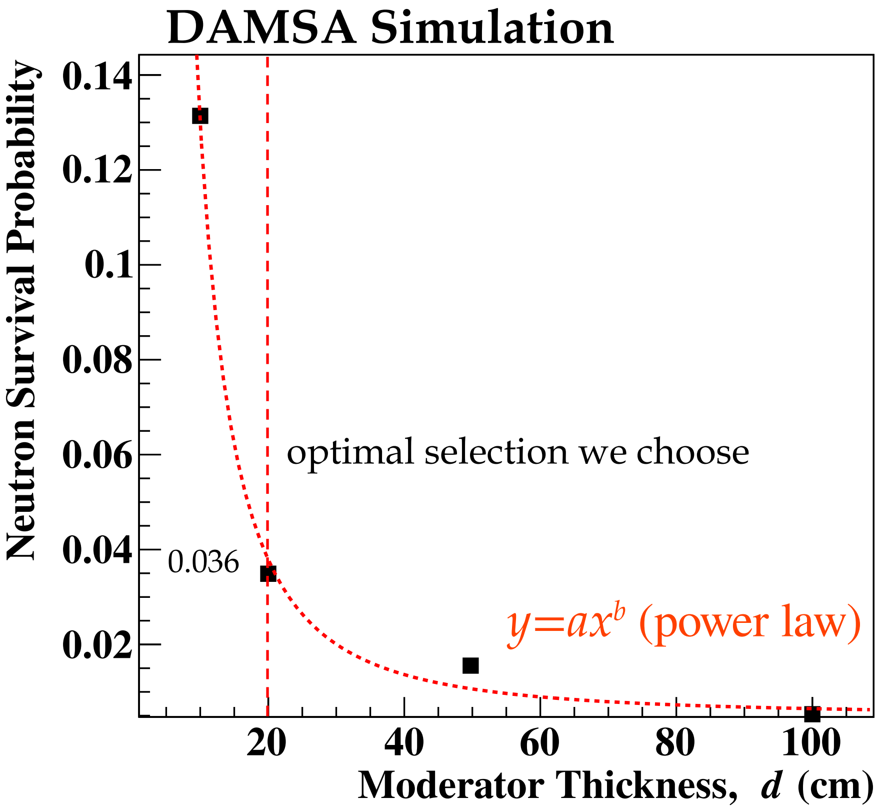
DAMSA Strategy – Neutron Absorber





GEANT4 simulation

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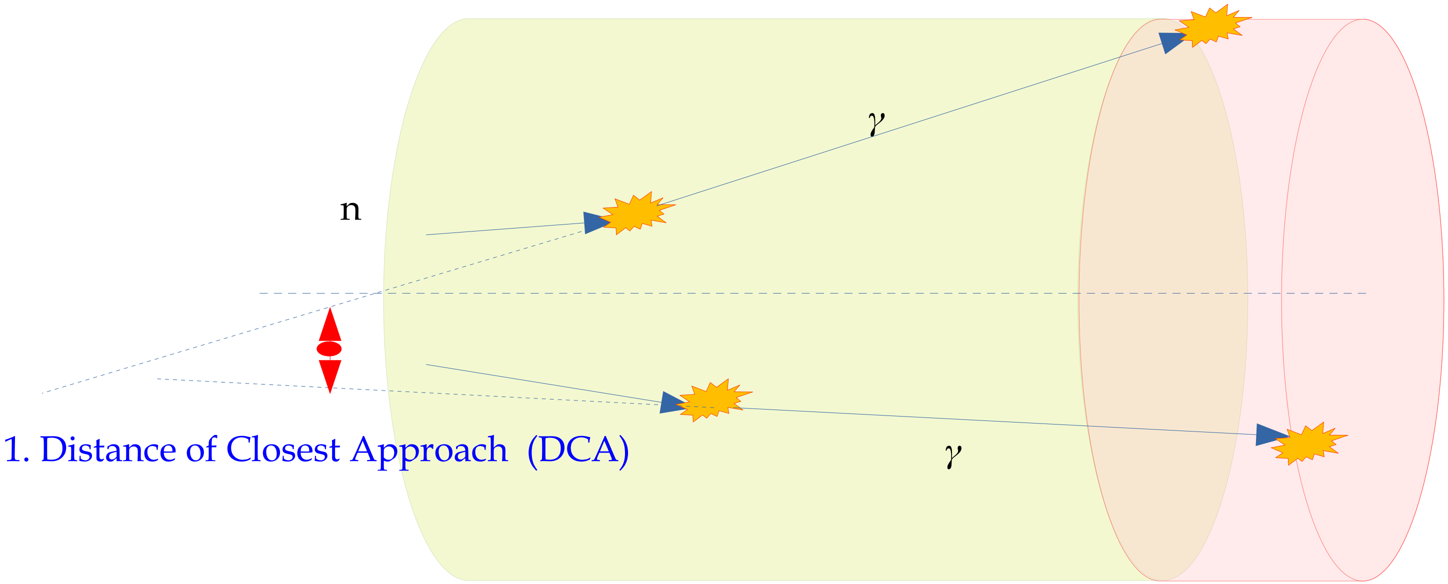
DAMSA Strategy – Background Mitigation (1)



1. Consider a combination of two photons.
2. Extrapolate their trajectories back to beam upstream.
3. What is the distance of closest approach (DCA)?
4. If the combination is not from random events but from two-body decay, DCA must be very short within the angular resolution of the detector.

DCA < **1 cm** cut gives **~10^{-3}** background reduction

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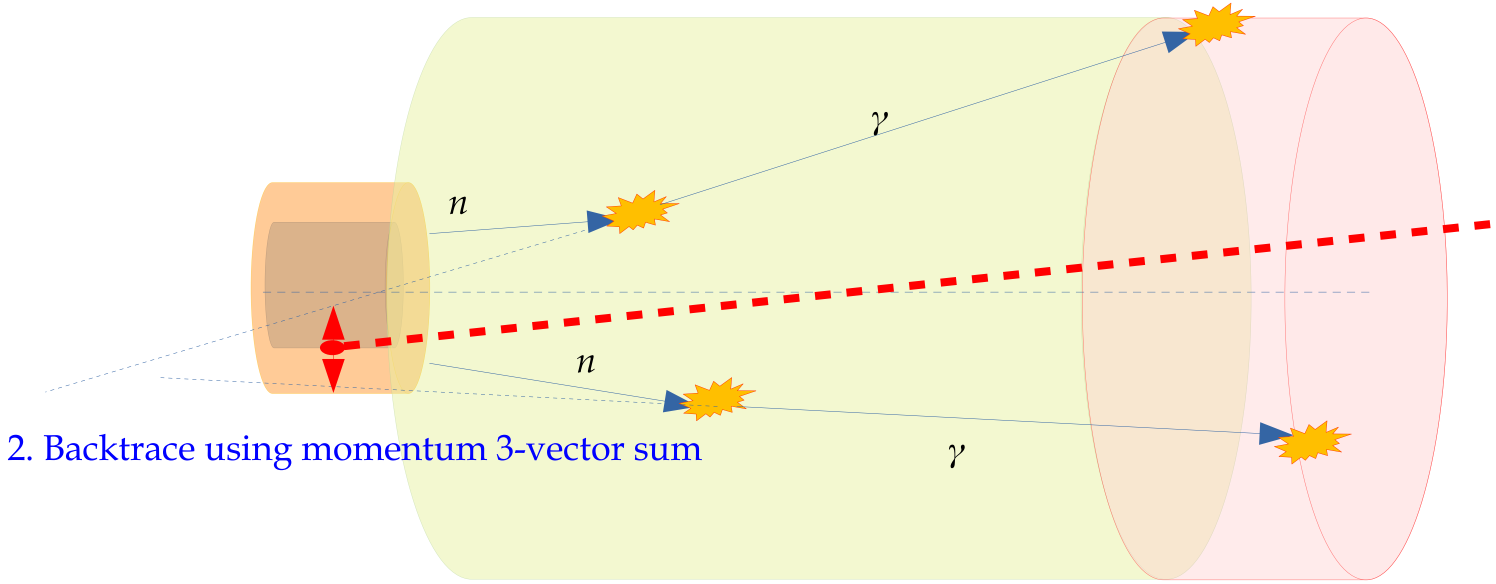
DAMSA Strategy – Background Mitigation (2)



Also, we can think about 3-momentum sum of two photons:

1. find a straight line that pass through the point of closest approach and has a direction vector of the sum of two photon 3-momentum.
2. if this straight line does not point back the beam dump, we reject it.

This gives **~10^{-2}** background reduction.

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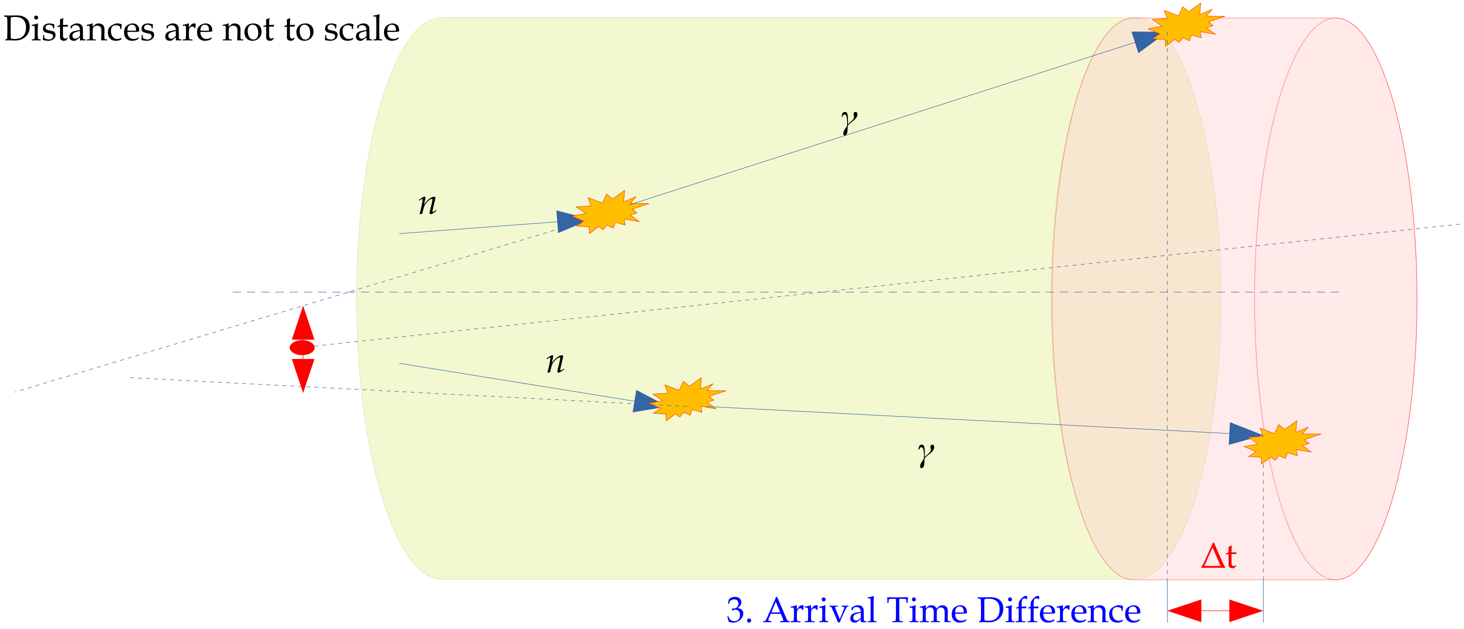
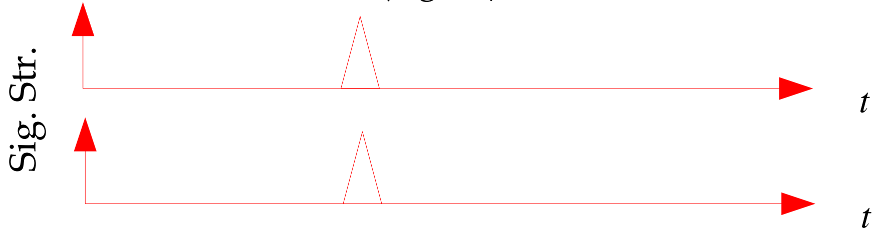
DAMSA Strategy – Background Mitigation (3)

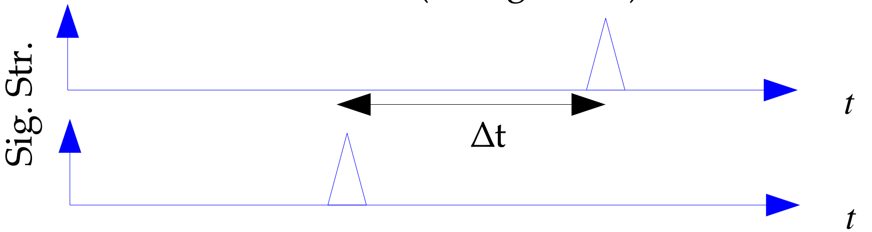


This gives additional **~10^{-3}** background reduction.

Detector arrival time (signal)



Detector arrival time (background)



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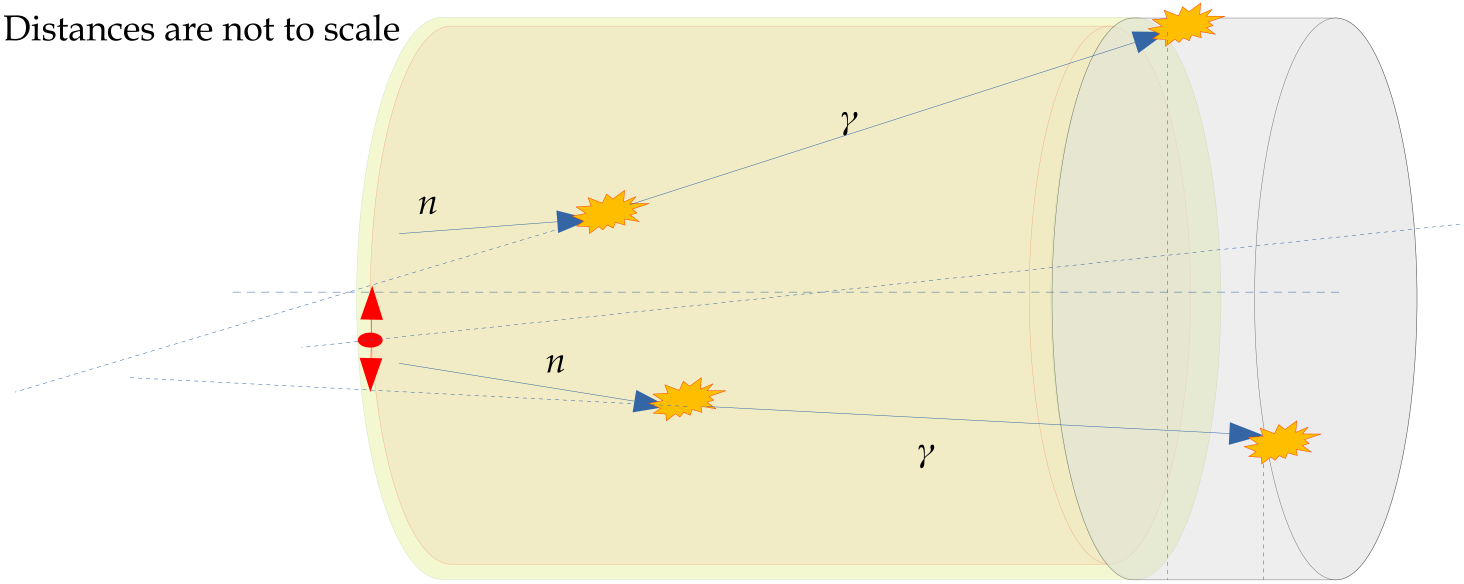
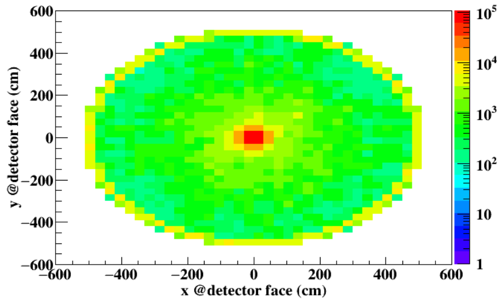
DAMSA Strategy – Background Mitigation (4)

Distances are not to scale





4. Position of Closest Approach ∈ FV

$$\prod \epsilon_i \approx 10^{-11} \sim 10^{-14}$$

From the DCA calculation, we can get the position of closest approach.
We require the position of closest approach must be inside fiducial volume that we defined.
The fiducial volume can be obtained by removing a 5 cm thick region from the edges of the chamber volume. (pink shaded region)

After all these cuts applied, we have approximately **~10^{-11}-10^{-14}** background reduction factor for 800 GeV case. (depending on invariant mass selection)

You can find more details such as rejection powers of these cuts from [Jang *et al.*, Phys. Rev. D 107, L031901 (2023)]

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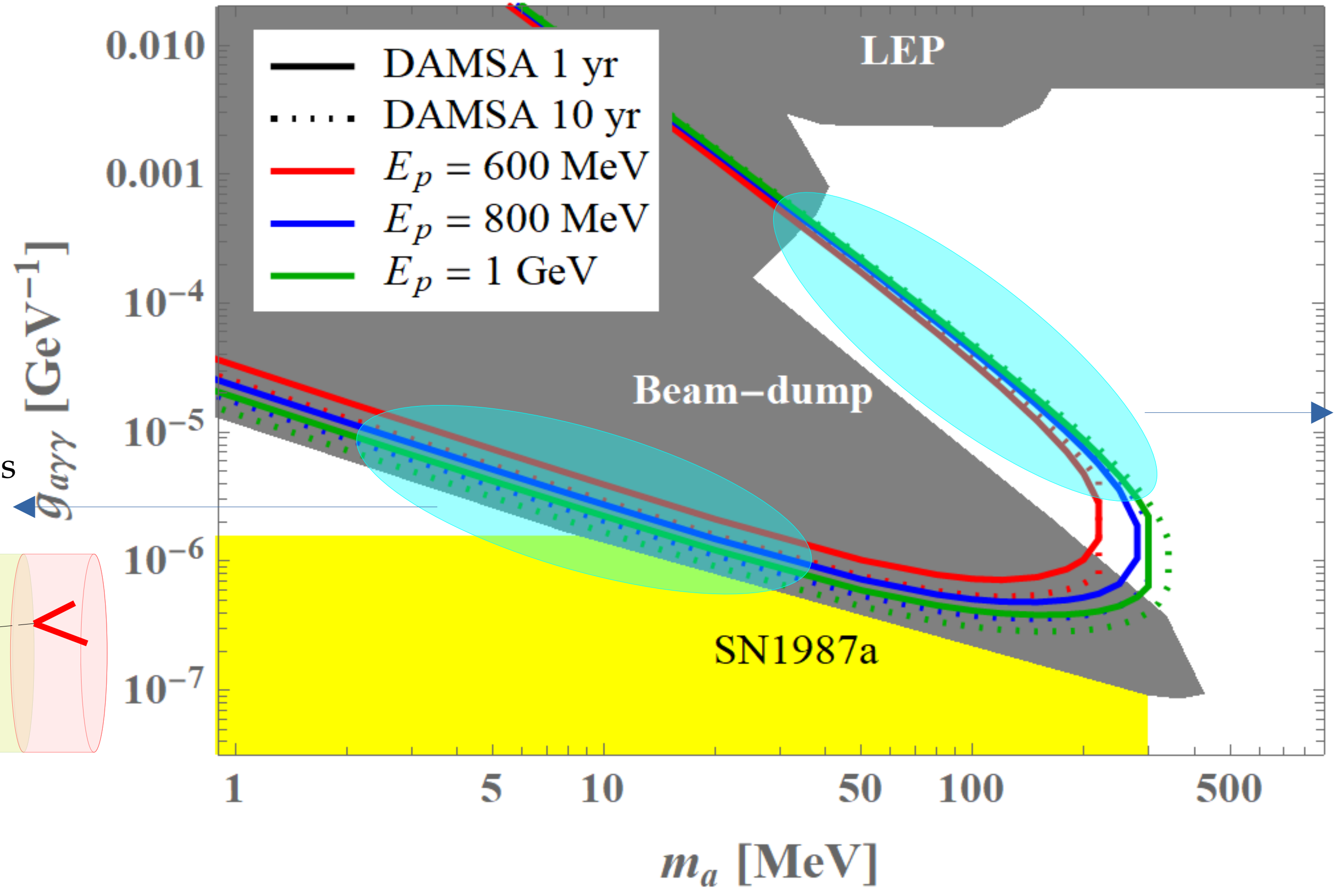
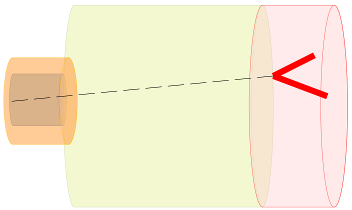
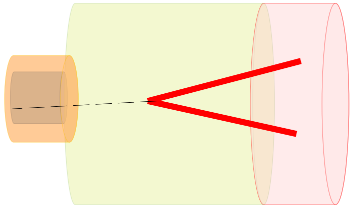
DAMSA Sensitivity Reach



Long-lived:
Capture decays
in the detector



Short-lived:
Capture decay products
in the detector



Proximity of the detector
to the target enabled it.

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DAMSA Strategic Goal

- **Overarching strategic goal:** Get the detector ready to take data in time for PIP-II LINAC completion in 2029
- **Design and build the detector to meet the requirements**
  - Capable of measuring up to **500 MeV** photons with a **MeV or better** energy resolution
  - Fine granularity for superb shower position (**1 cm or better**) and angular resolution
  - Fast timing capability, ideally at the sub-ns (**100 ps or better**) timing resolution
- **Potential DAMSA technologies considered for the detector are:**
  - A total absorption EM calorimeter
  - Crystal or plastic scintillator with fine lateral and longitudinal granularity
  - A study to develop the most optimal detector for the physics has begun
- Also, we're expanding our physics study to other physics topics as well.

Conclusions

- DAMSA is a dark sector search and discovery experiment that leverages high-intensity proton beams
  - ALP and other physics topics will be explored
- GEANT4 based simulation studies performed and it provided detector requirements
- More detailed simulation studies are in progress
  - Neutron background consideration
    - Neutron ray-tracing simulation for bouncing neutrons or back-scattered neutrons at the beam dump
    - Thermal analysis for the beam dump
    - Alternative decay chamber configurations
  - EM calorimeter concept study is in progress as well
- DAMSA presents an excellent opportunity for transforming Fermilab's PIP-II and ACE to a world-class DSP facility

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