

# DAMSA at Fermilab PIP-II

*The Mitchell Conference on ....*

*May 16 – 19, 2023*

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## **Outline**

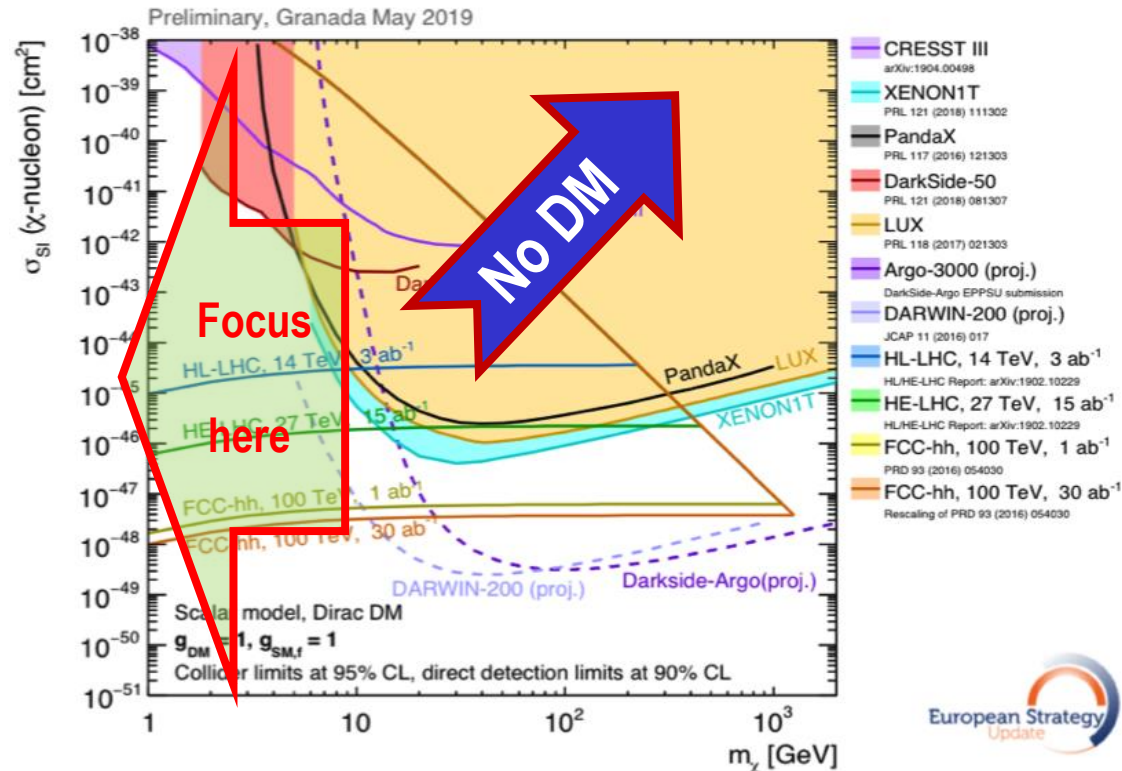
- Introduction
- What is DAMSA and are its Requirements?
- What is in Fermilab PIP-II Era?
- DAMSA Experiment Specifics
- Strategy, the Team and the Timeline
- Conclusions

# Physics Motivation For DSP

- SM describes the visible  $\sim 5\%$  of the matter in the universe  $\rightarrow$  becoming more solidly established, while the neutrinos sector requires modifications
- Dark matter (Dark Sector Particle, DSP) makes up about 25% of the universe  $\rightarrow$  must be explored better
- Direct searches have limitations in kinematic reach, leaving low mass range un-explored

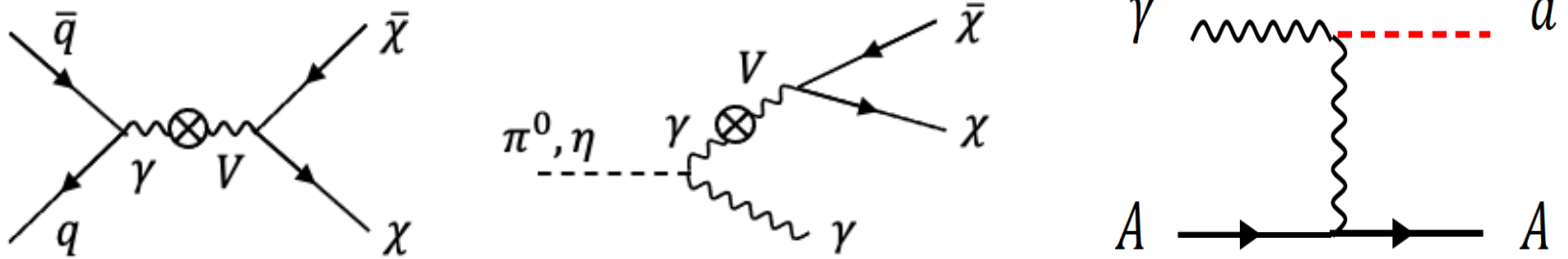
## Strategy:

- Search for rare particles in unexplored kinematic regime
- **Make** and discover DSPs in accelerators

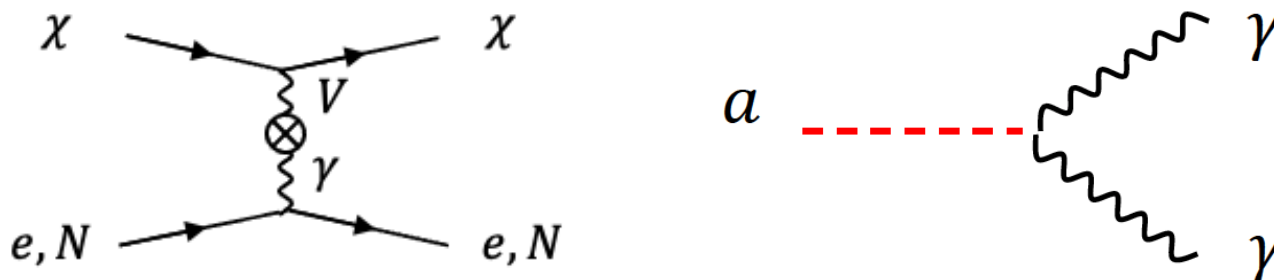


# DSP's? How do we make & see them?

- Set of new particles which **do not experience the known forces**
- DSPs can be weakly coupled to visible sector thru a mediator or “portal”
- **High intensity proton beams** produce large number of photons from brem, DY and neutral mesons decays → Make it possible to contemplate couplings of new U(1) gauge to SM  $\gamma$



- Detection through an electron scattering, N(n) recoil or 1, 2  $\gamma$  final states

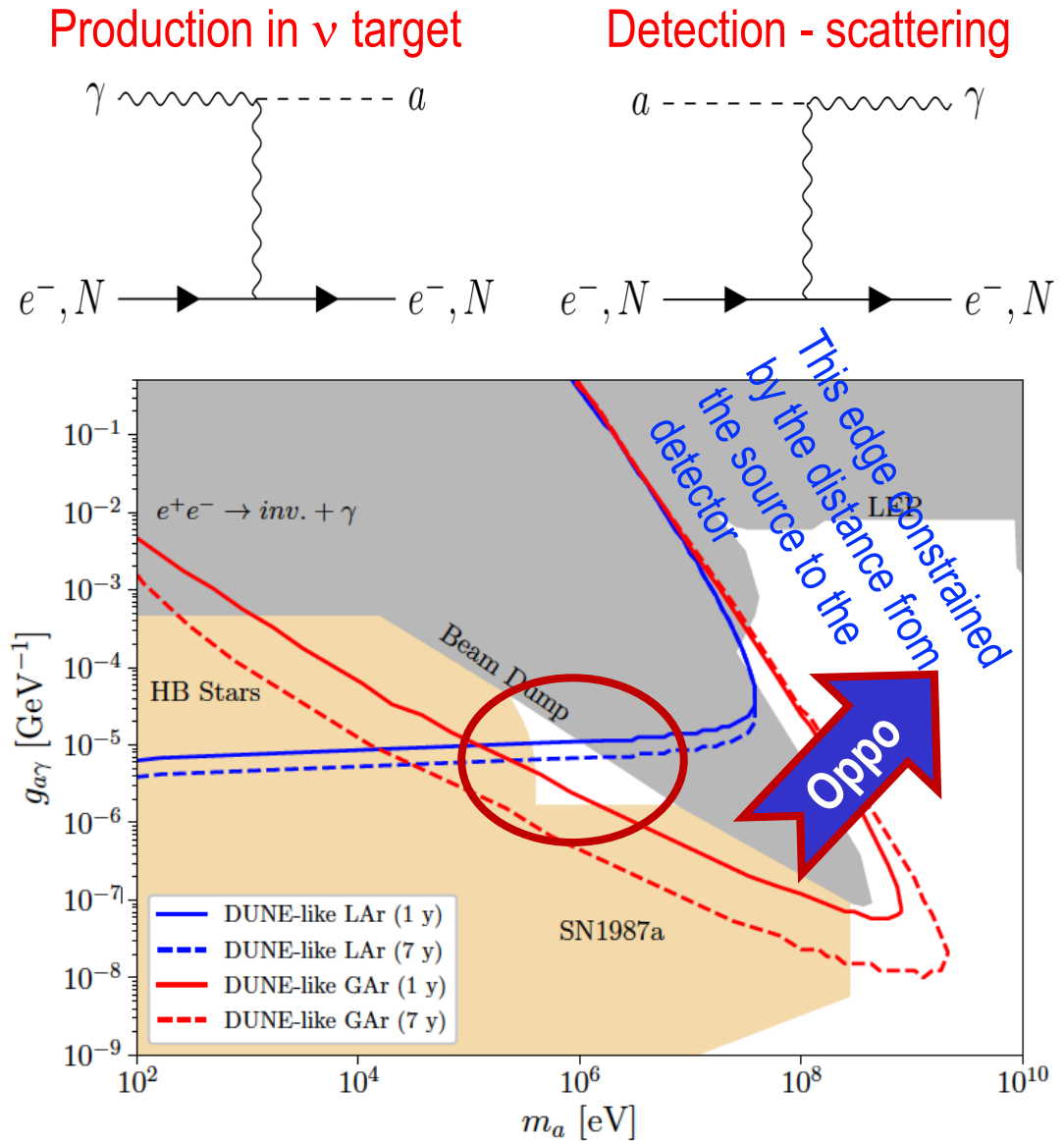


# What's needed to discover a DSP?

- Direct Observation Signatures
  - Requires high beam flux
  - Large detector mass for scattering signatures
  - Large detector volume for decay signatures
- Inferred Observation Signatures from both beam and cosmogenic sources
  - Leverage oscillatory behaviors
  - Large mass detectors for interactions
- What do we need to know?
  - Signal flux and realistic behaviors in the detector
  - Neutrino flux and their interactions in the detector as bck

# Opportunities on ALP Searches

- Axion-like particles (ALP) can be produced via the Primakoff process in high intensity proton beams
- Detection via the inverse Primakoff process either in a scattering with  $e/N + \gamma$  or decays of the ALP to two  $\gamma$
- A case study on DUNE ND shows a potential to fully close the cosmic triangle
  - Brdar *et al.*, [PRL126, 201801](#) (2021)

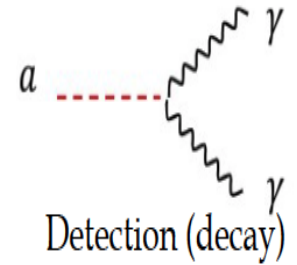
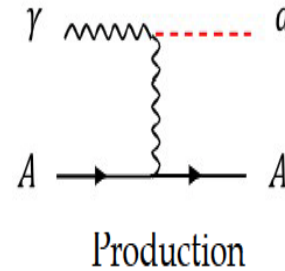


# What is DAMSA?

- Dark sector particle (DSP) search concept at low E, high intensity proton beam facility
- Stands for **D**ump produced **A**boriginal **M**atter **S**earch at an **A**ccelerator (DAMSA)
  - 담사 (冥想) = 깊은생각 – Ruminatioin or Reflection
    - [Jang et al., PRD 107, L031901 \(2023\)](#)
- Search for DSP in the low mass regime, using low energy, high intensity beam capability → ideally below the pion threshold
  - Originally developed for 600MeV rare nuclear isotope facility
- Expand the search beyond the ALP
- The 800MeV PIP-II LINAC beams fit the bill

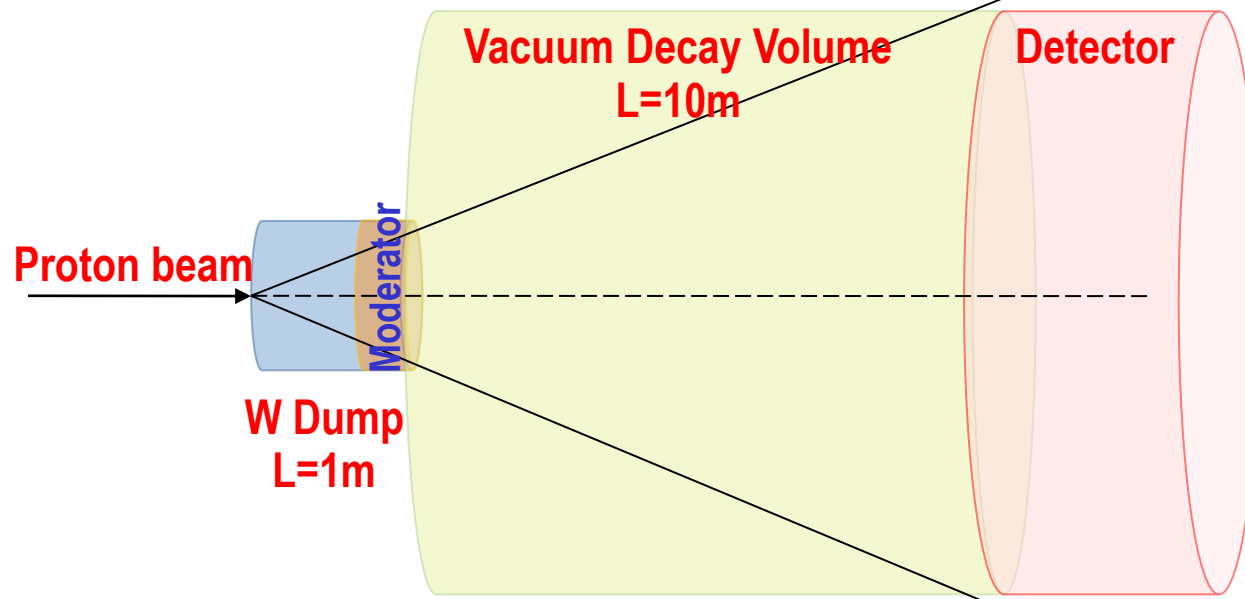
# DAMSA Experiment Requirements

- Focus on Axion-like particles (ALP) search through their **two-photon** final state via the Primakoff process
- Produce as many photons as possible in the beam source, namely the dump
- Capture as many ALPs as possible in as wide a mass range as possible
  - Shorten the distance from the source to the detector
  - Increase the detector angular coverage
- Minimize the backgrounds from neutral particles
  - Neutron spallation  $\rightarrow$  accidental photon overlaps
  - Neutrino NC and QE interactions  $\rightarrow$  produce  $\pi^0 \rightarrow 2\gamma$



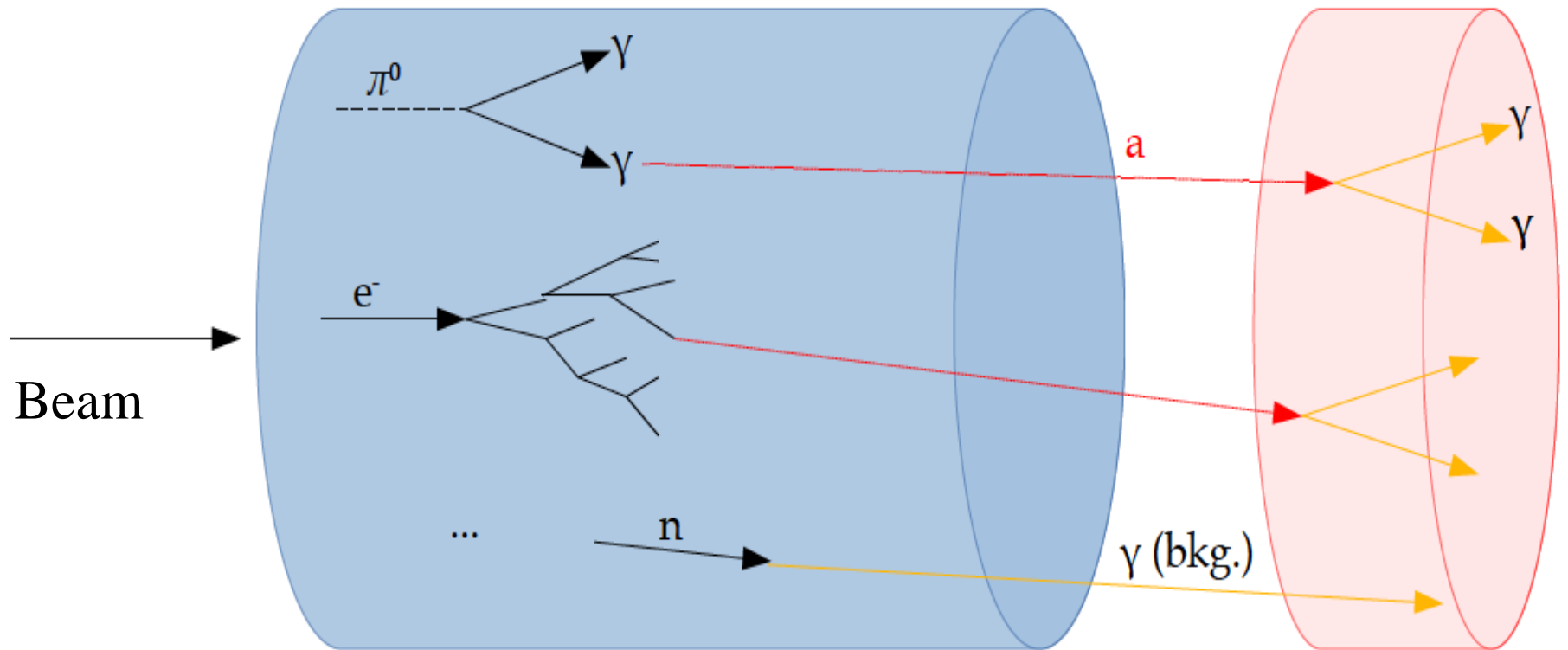
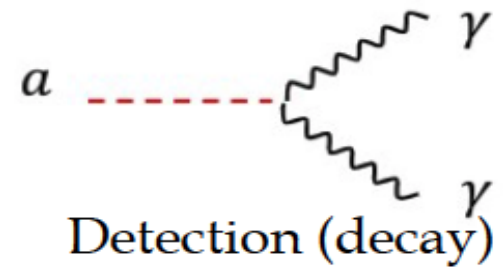
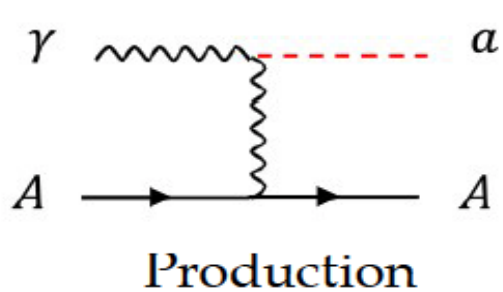
# DAMSA Exp. Concept

- Inject and absorb as many low-E (1GeV or less) proton beam particles in the dump as possible
- Allow higher mass ALP's to decay with as small number of neutrons escaping the dump as possible
- Place the detector as close to the dump as possible on axis to expand the mass reach to higher mass region



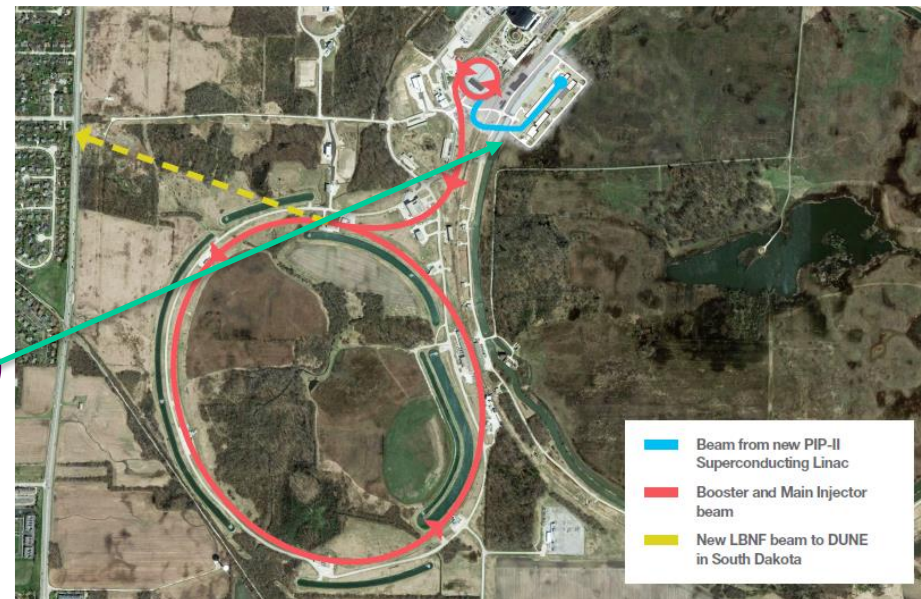


# DAMSA Experiment Signature

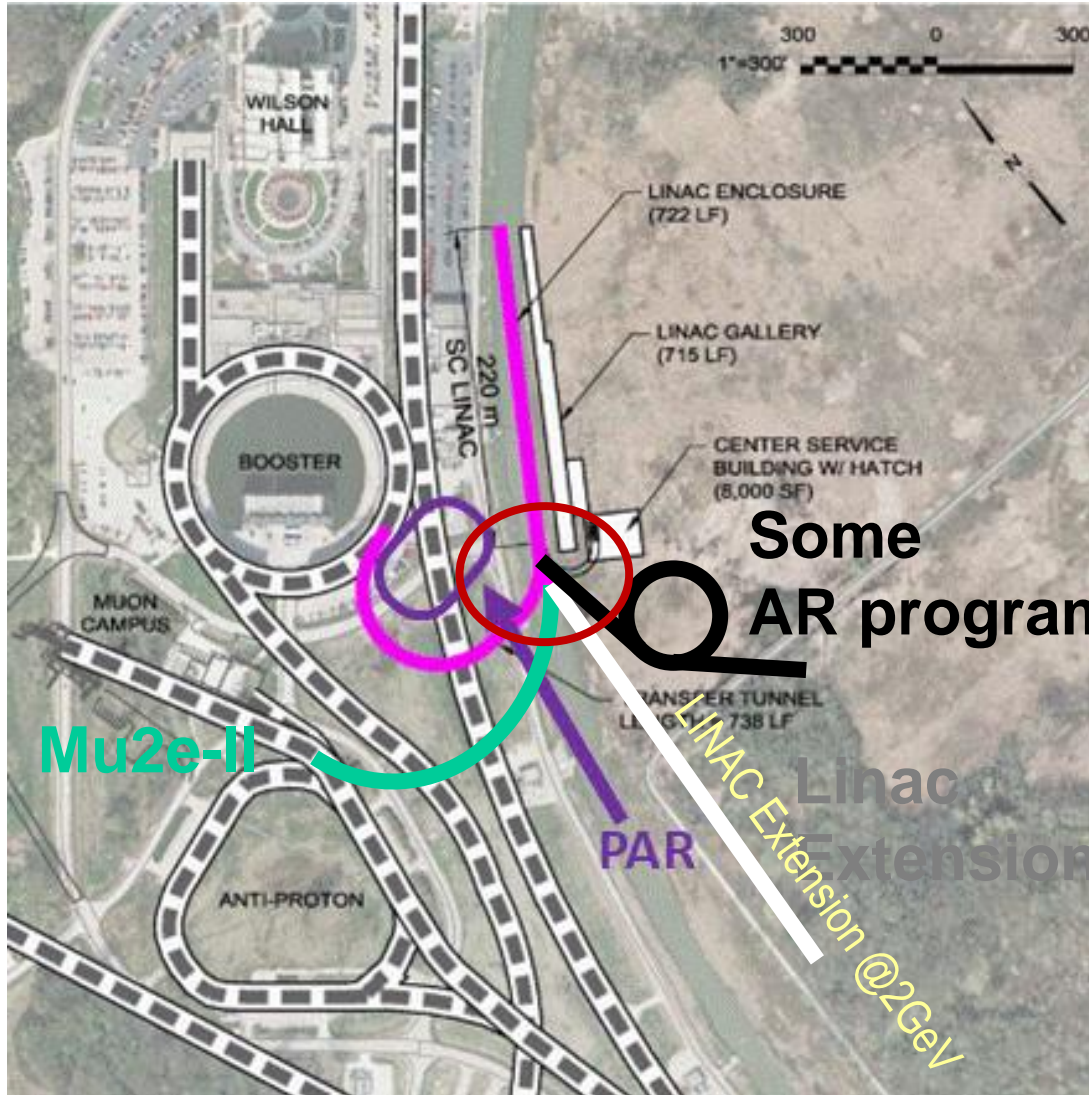


# Accelerator Complex in PIP-II Era

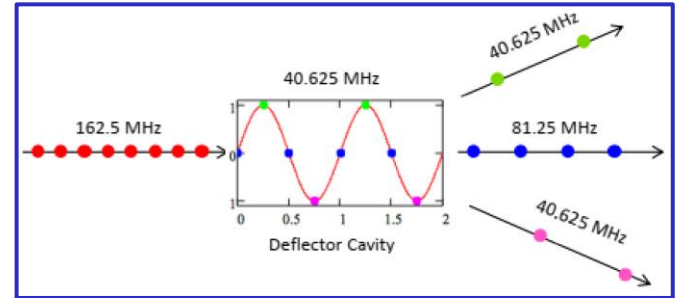
- PIP-II provides
  - New SRF LINAC for injection into Booster at 800MeV (present 400MeV)
  - Booster cycle rates upgraded to 20Hz from current 15Hz
  - Increased proton beam intensity at 8GeV for 1.2MW beam power from main injector
- PIP-II era begins in **2029**, DUNE 2031
  - Mu2e (8GeV)
  - Fixed target, test beams (120 GeV)
  - 0.8 GeV beam available for other exp, eg. With PAR and may be other options for beam dump



# PIP-II Siting Enables Further Expansion



- Magnetic switching elements and RF splitters can divide beam.



- Real estate in TeV field allows for a variety of rings and lines, shapes and sizes.

# DAMSA Requirements – The Beam

- PIP-II LINAC's 800MeV beam energy enables access to the tangible ALP mass range
- Need to have as much beam as possible
  - $\sim 1 \times 10^{23}$  POT/yr was assumed in the PRD 600MeV physics study
  - $\sim 1 \times 10^{23}$  POT/yr for PIP-II 800MeV and 1GeV physics study
- PIP-II CW beam characteristics
  - Bunch length: 1ns
  - $N_p/\text{bunch} : 8 \times 10^7$  p/bunch
  - Bunch spacing: 6.2ns
- PIP-II CW Chopping possibility?
  - micro-pulses w/ two  $14 \times 10^7$  p-bunches separated by 6.2ns and the next pair separated by 16.2ns, repeating every 22.4ns
  - Each micro-pulse lasts for 0.6ms spaced every 50ms →  
 $I = 2\text{mA}/\text{micro-pulse}$

# DAMSA Requirements – The Dump

- What material on what depth would be most optimal?
  - Produce most photons per unit length
  - Produce least number of neutrons out the dump
  - Absorb most particles per unit length
- GEANT4 based study shows 1m diameter, 1m long cylindrical shape tungsten dump (~10 nuclear interaction lengths) produces most photons and absorb ~99.995% 600MeV protons
  - Neutrons produce additional photons in the dump, providing additional source for ALP

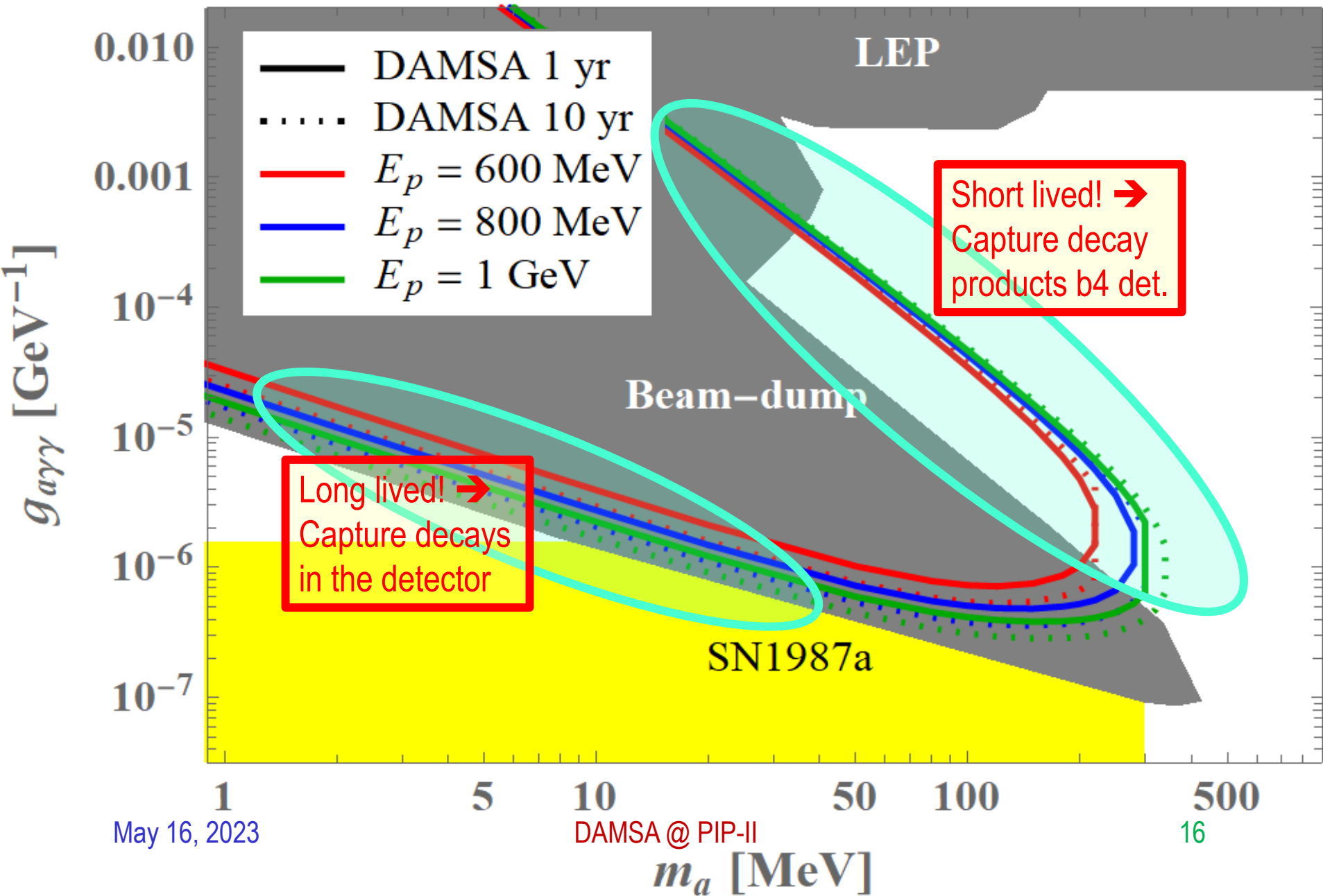
# DAMSA Requirements – The Detector 1

- What detector capabilities are needed to
  - Capture as many ALP's as possible in as wide a mass range as possible
    - **High mass** ALP's have **shorter lifetime** → Need to be able to capture two photons from the ALP decays upstream of the detector
    - **Low mass** ALP's **live longer** → Allow them to decay and interact in the detector and capture decay products upstream of the detector as much as possible
  - Reject accidental backgrounds from neutron spallation in the detector
    - Reduce the materials upstream of the detector for neutron to interact
- Place a large decay volume in vacuum to fill the gap between the dump and the detector
  - Vacuum decay chamber w/ 0.6cm SS wall thickness assumed → this may have to be thicker
  - Allows high mass ALPs to decay → giving clear vertices where the two final state photons originate from
  - Neutron interactions confined to the decay chamber walls

# DAMSA Requirements – The Detector 2

- What are other possible ways to further reduce the background from neutron spallation? → Aim to reduce by order  $\geq 10^{10}$ 
  - Leverage the speed of the neutrons → Neutrons are 10 – 1000 times heavier than the ALPs, thus for the given momentum, the arrival time of the neutron induced photon accidentals would be slower than that of the ALP's
  - Leverage the distance of the closest approach of the two photon traces
  - Require the traceback of the overlapping two photon momentum sum point the dump
  - Invariant mass of the two photon momenta be within the interested mass range
  - Arrival time difference between two photons
- A large number of neutrons have low kinetic energy → Require the photon energy to be greater than 5 MeV (detector threshold  $\sim 1$  MeV)

# Expected DAMSA Sensitivity





# DAMSA Detector Requirements

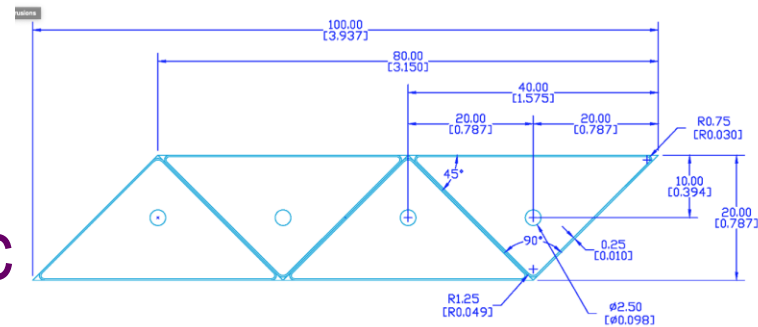
- Based on the concept studies using GEANT4 and neutron background rejection studies →

The detector must be

- Capable of measuring up to 500 MeV photons with a MeV or better mass resolution
- Fine granularity for superb shower position (1cm or better) and angular resolutions
- Fast timing capability, ideally at the sub-ns (100ps or better) level resolution

# Potential DAMSA Detector Technology

- A total absorption EM calorimeter
  - Sufficient depth to absorb photons up to 500MeV
  - Need further optimization for low mass ALP decays
- Crystal or plastic scintillation counter with fine lateral and longitudinal granularity (M~160t)
  - A thin (<5cm) triangular pixels with a fast photon detector attached to the pixel
    - Lateral and longitudinal granularity
  - SPAD, MCP, Hybrid SiPM, etc
- A study to develop the most optimal detector for the physics has begun



# Potential DAMSA Experiment Timeline

- May – Dec. 23 : Form a team and prepare a proposal to Fermilab PAC
  - Physics goals and sensitivity reach
  - Detector design and rough cost estimates
- Jan. 2024: Submit the DAMSA proposal to PAC
- 2024 – 2025/2026: experiment approval and project establishment
- 2025/2026 – 2028: experiment construction
- 2029: Complete the detector construction and start commissioning for data taking
  - Request 1 –  $3 \times 10^{23}$  POT total
- Internationality would be important – Korean and European colleagues

# DAMSA@Fermilab PIP-II SRF LINAC

- Capable of 2mA @ 800MeV (1.6MW)
  - Translates to  $\sim 3 \times 10^{23}$  POT/year
- DUNE and other higher energy programs use  $\sim 2\%$  of the proton flux
- Continuous wave
- Scheduled to complete by 2029
- Prepare DAMSA to be ready for beam in time for the LINAC



# DAMSA Experiment Strategy

- Overarching strategic goal: Get the detector ready to take data in time for PIP-II LINAC completion in 2029
- Design and build detectors to meet the requirements with minimal R&D
  - Fast timing ( $\sim 0.1$  ns or better)
  - High position resolution ( $\sim 0.1$  mm or better)
  - Excellent energy and invariant mass resolution
  - Low threshold energy
- Discover Dark Sector Particles in the beam and produce the beam of them

# DAMSA Experiment Team

- DAMSA has been introduced to the community throughout the past 2 years
  - Multiple presentations made at conferences and workshops
  - The concept was included in a few Snowmass2021 white papers
  - At the physics opportunities at PIP-II BD and beyond at Fermilab 5/10
    - 5/13/23, the discussion on DAMSA experiment occurred 5/12 – 5/12/23
  - Introduced to Fermilab leadership Apr and May 2023
- The team consists of
  - Lead Investigators: Jae Yu and Juan Estrada (FNAL)
  - Institutions expressed interests thus far:
    - US (7): FNAL, OU, TAMU, UCR, U. of Kansas, LANL, UTA
    - SK (5): SNU, Yeonsei U., U. of Seoul, Chungnam U., Jeonbuk U.
    - Portugal: LIP

# Conclusions

- DAMSA is a DSP search and discovery experiment that leverages high intensity, low energy proton beams
- ALP is the signal of interest but the experiment can explore variety of other BSM physics
- GEANT based study has been performed for the 600MeV rare nuclear isotope facility and for 800MeV and 1GeV PIP-II LINAC cases
- DAMSA team is forming to submit a proposal to PAC
  - Collaborators are welcome!!
- DAMSA presents an excellent opportunity to transform Fermilab's PIP-II LINAC to a world-class DSP facility