

DAMSA at Fermilab PIP-II

Path to Dark Sector Discoveries Workshop

June 5 – 7, 2023

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Outline

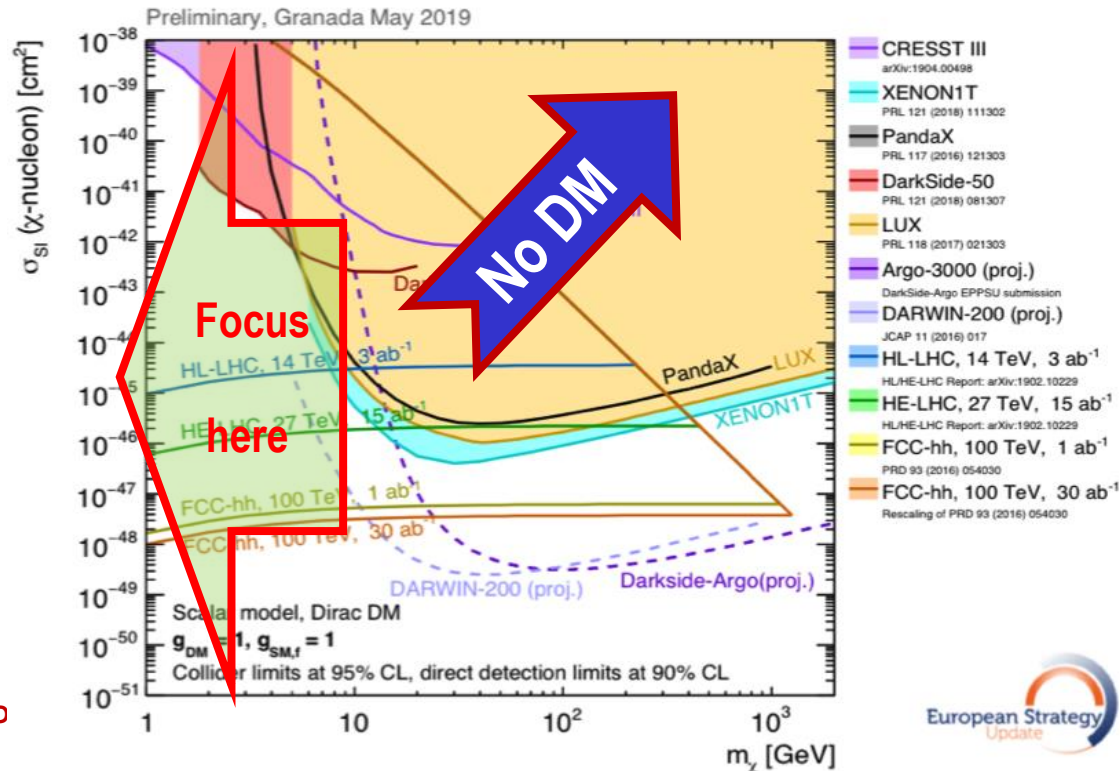
- Introduction
- What is DAMSA and are its Requirements?
- What is in Fermilab PIP-II Era?
- DAMSA Experiment Specifics
- The Strategy, the Team and the Timeline
- Conclusions

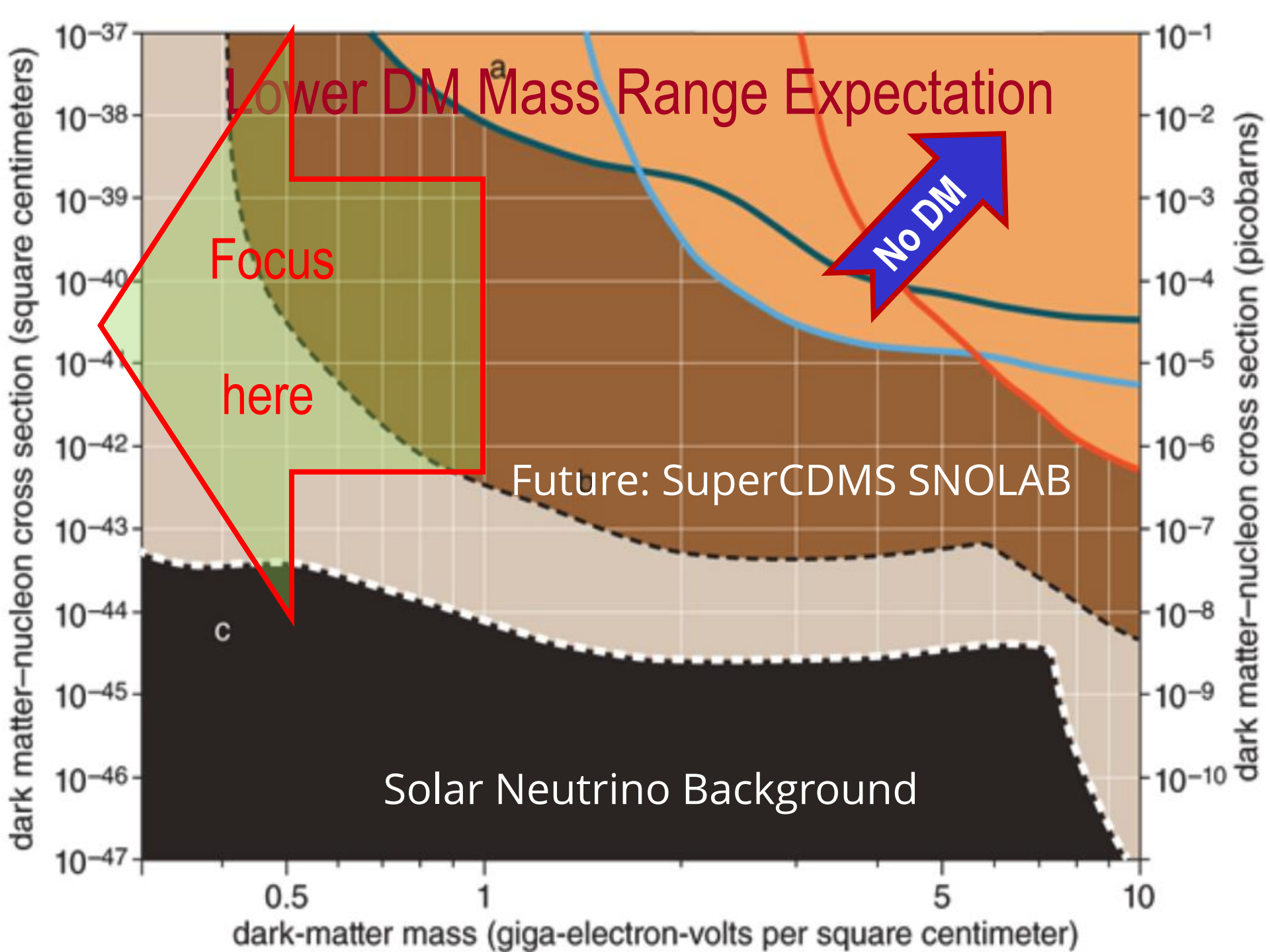
Physics Motivation For DSP

- 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:

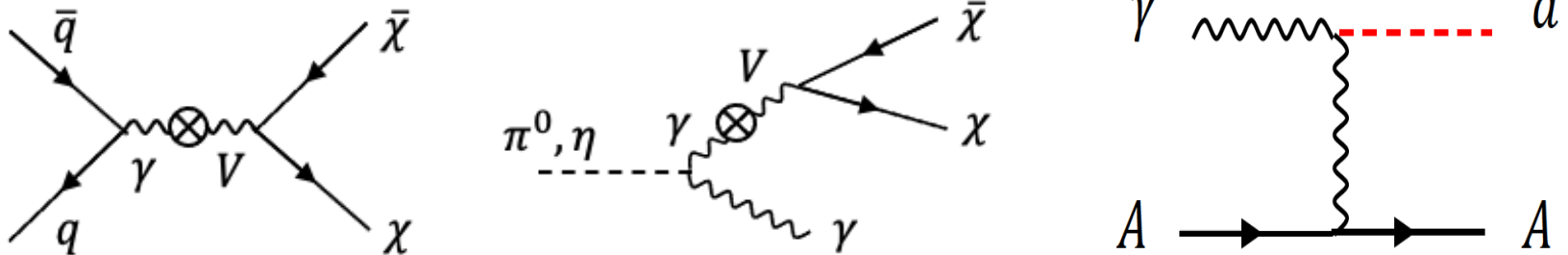
- Search for rare particles in unexplored kinematic regime
- Make and discover DSPs in accelerators
- Establish human infra on DM production



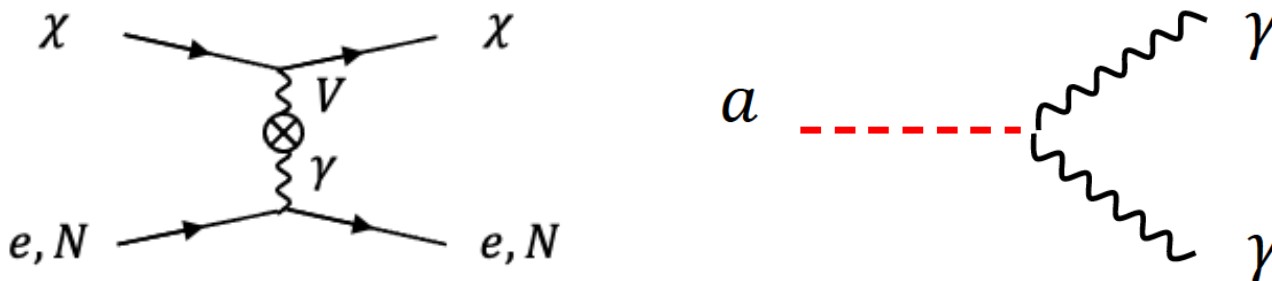


DSP's? How do we make & see them?

- 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 γ



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

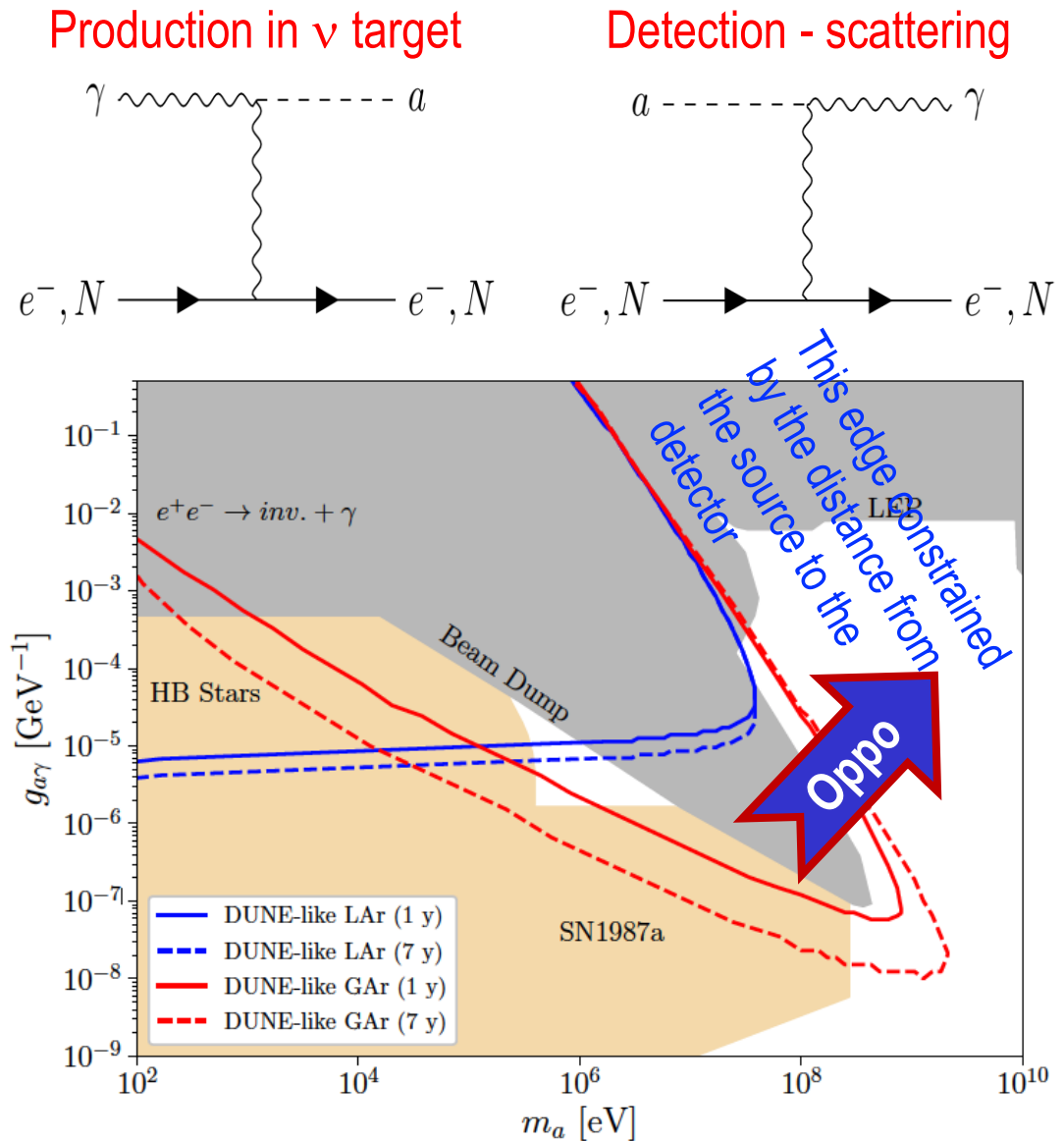


What's needed to discover a DSP?

- Direct Observation Signatures
 - Requires high beam flux
 - Large mass, high density detector for scattering
 - Large volume, low density detector for decay
- 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 γ
- A case study on DUNE ND shows a potential to fully close the cosmic triangle
 - Brdar, Yu *et al.*, [PRL126, 201801](#) (2021)

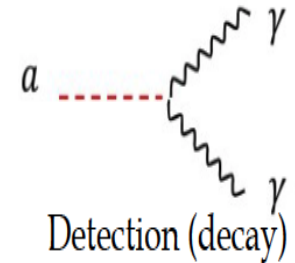
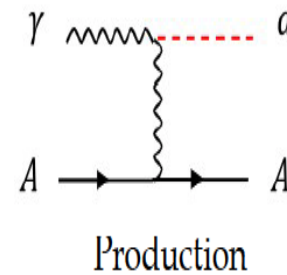


What is DAMSA?

- 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 (潭思) = 깊은생각 – Ruminaton 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 proton beams at rare nuclear isotope facility
- The 800MeV PIP-II LINAC beam fits the bill

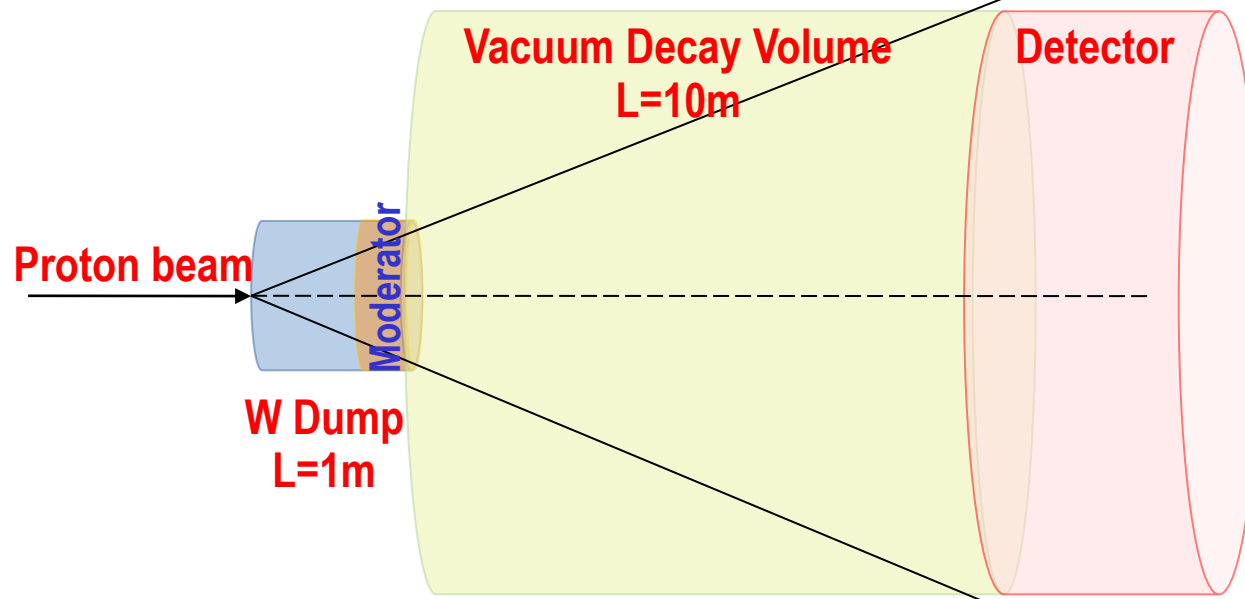
DAMSA Physics Strategy

- 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 $\pi^0 \rightarrow 2\gamma$

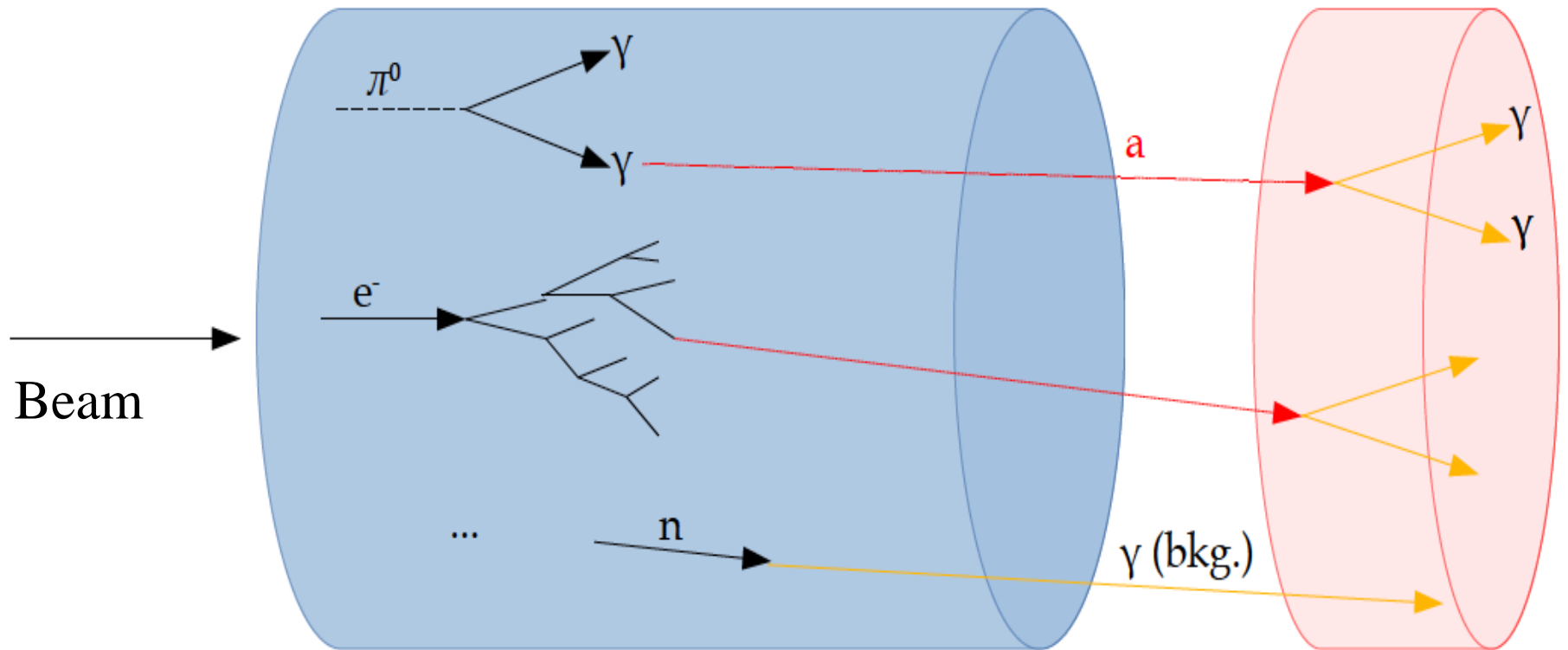
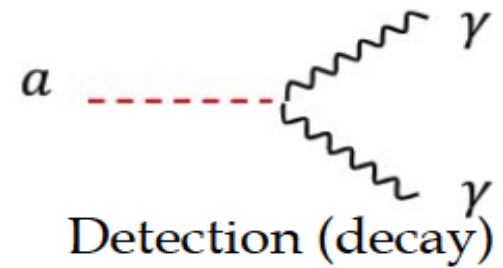
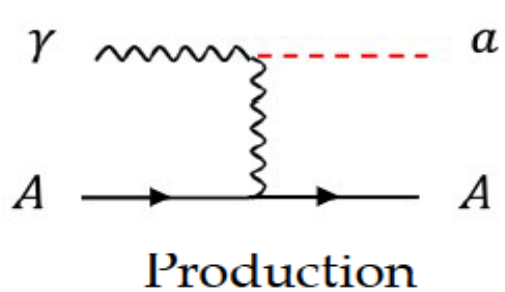


DAMSA Exp. Concept

- 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

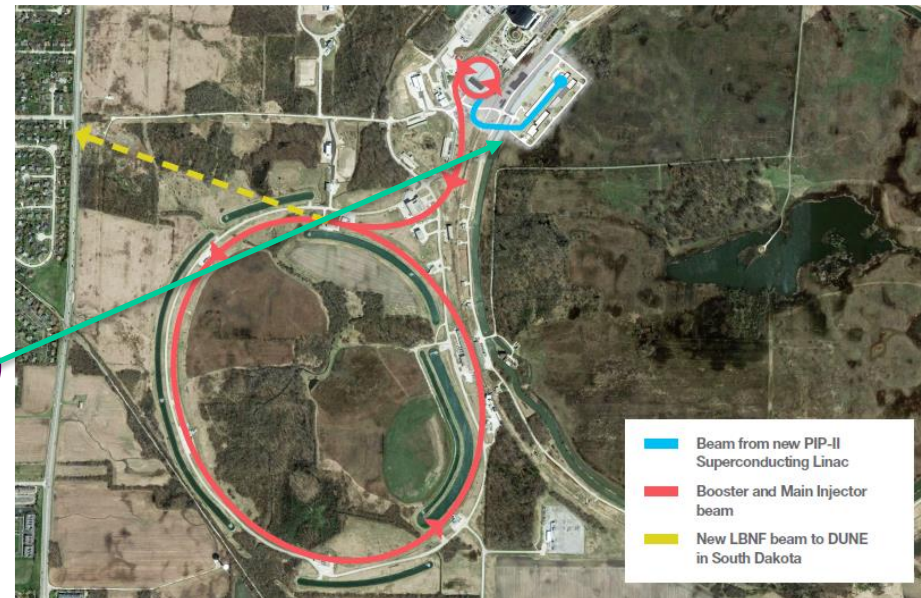


DAMSA Experiment Signature

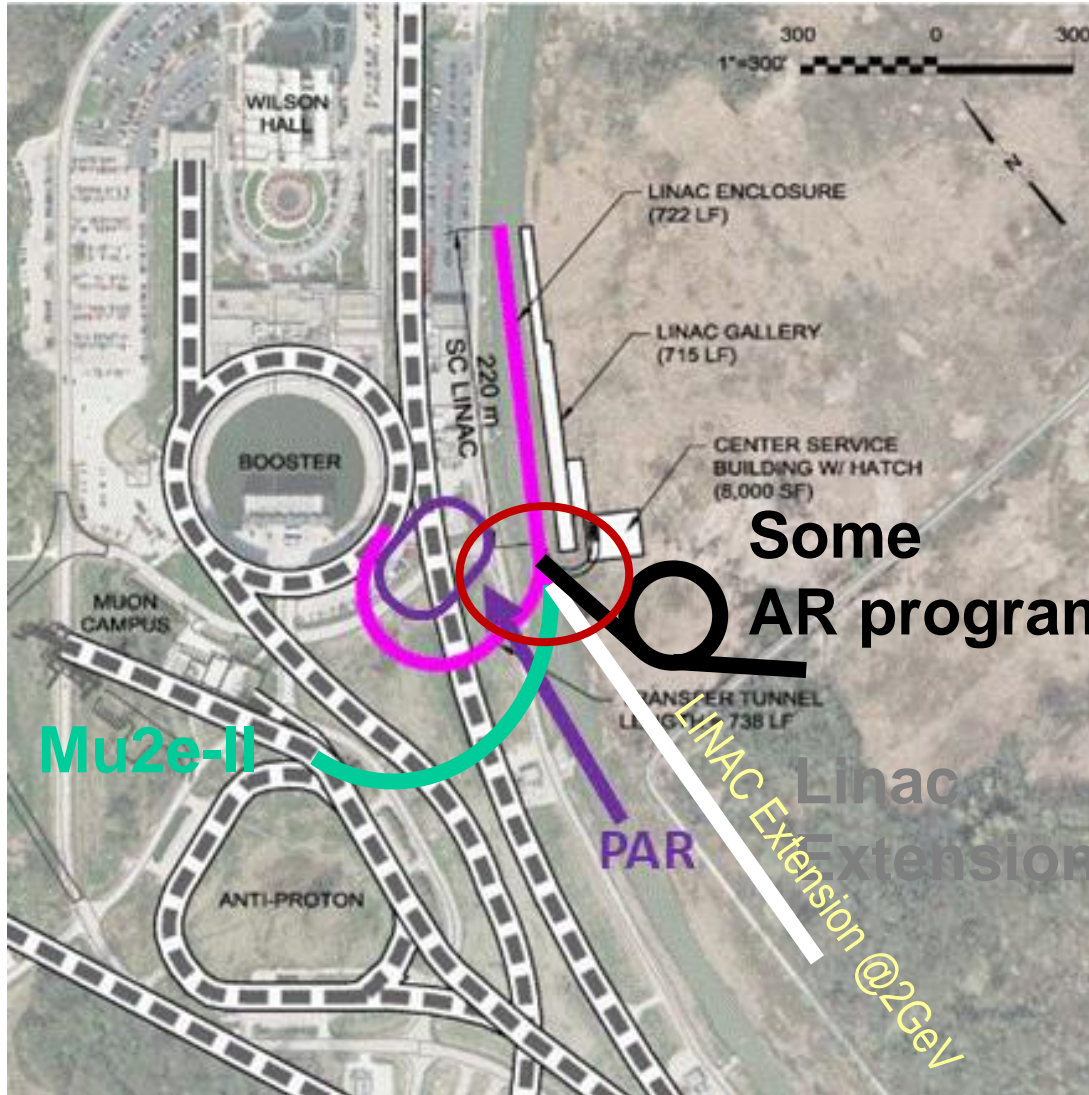


Accelerator Complex in PIP-II Era

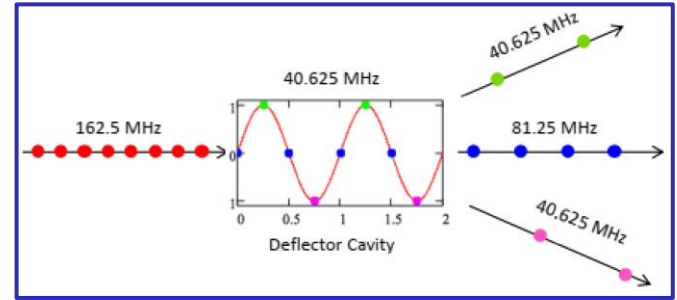
- PIP-II provides
 - New SRF LINAC for injection into Booster at 800MeV (present 400MeV)
 - Booster cycle rates upgraded to 20Hz from current 15Hz
 - Increased proton beam intensity at 8GeV for 1.2MW beam power from main injector
- PIP-II era begins in **2029**, DUNE 2031
 - Mu2e (8GeV)
 - Fixed target, 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

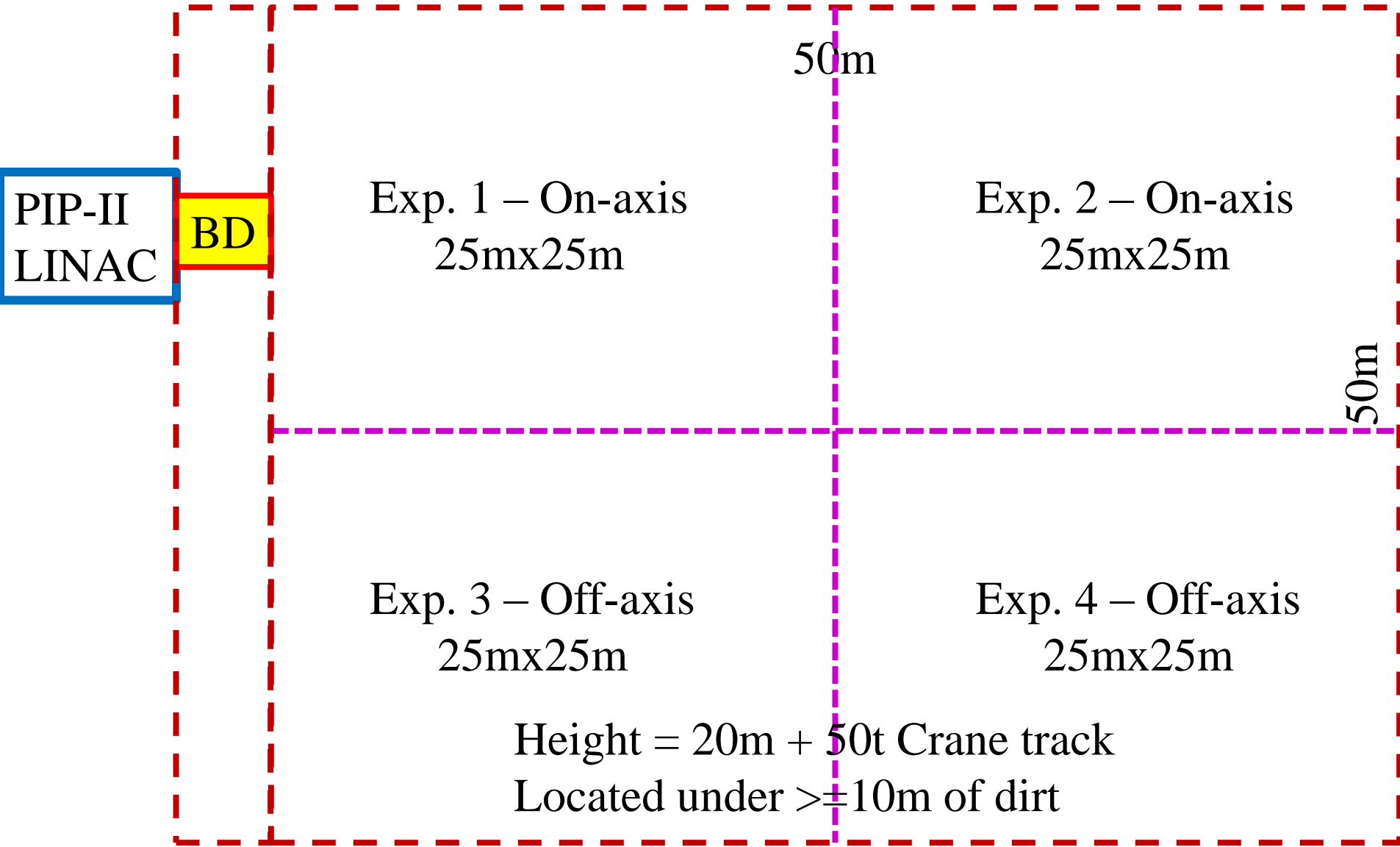


- Magnetic switching elements and RF splitters can divide beam.



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

Potential PIP-II Experimental Hall Conf.



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 (total proton current: **2mA**)
 - 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 14×10^7 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

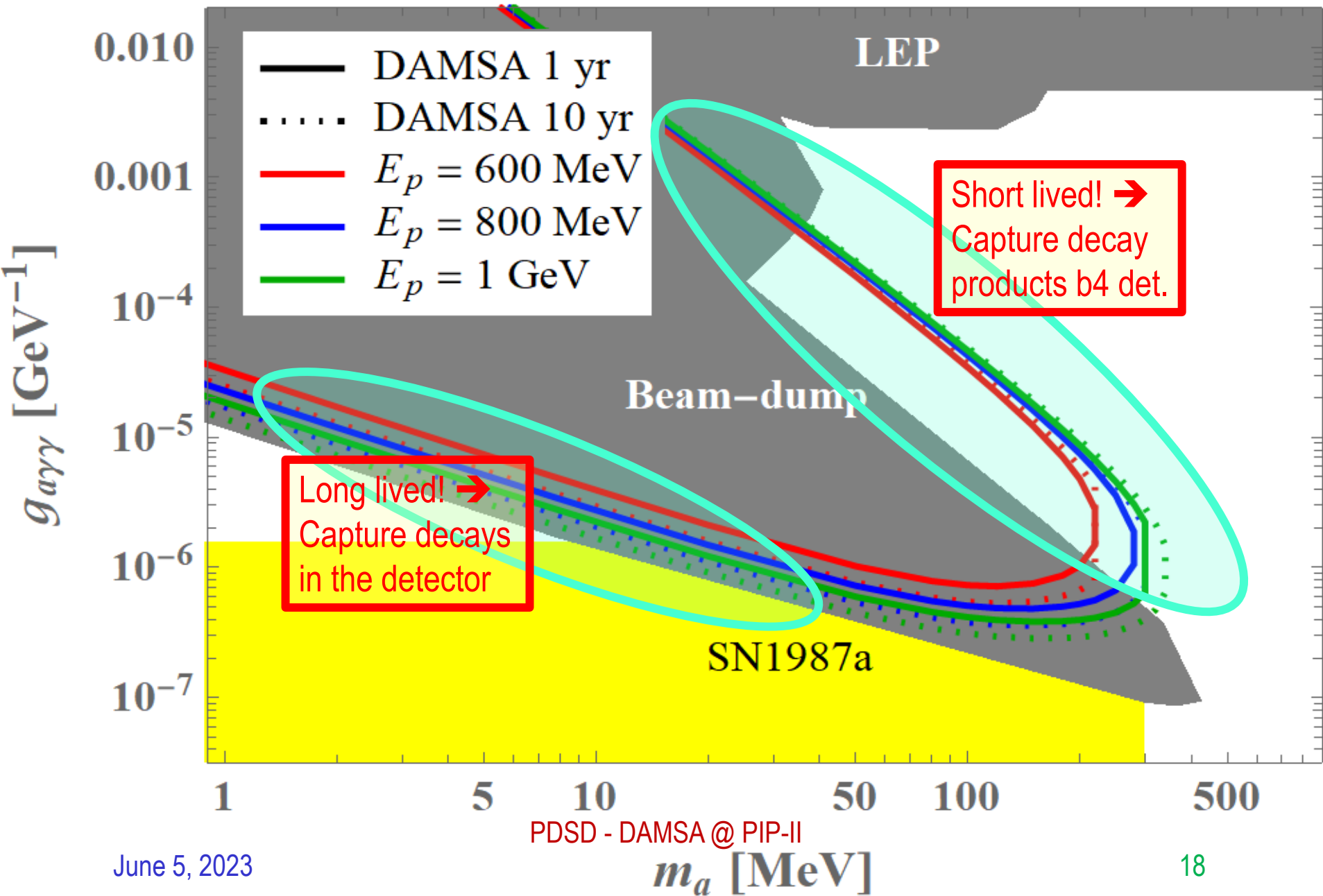
DAMSA Requirements – The Detector 1

- 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 → Extends detecting volume
 - 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 to 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 ~ 1 MeV)

Expected DAMSA Sensitivity

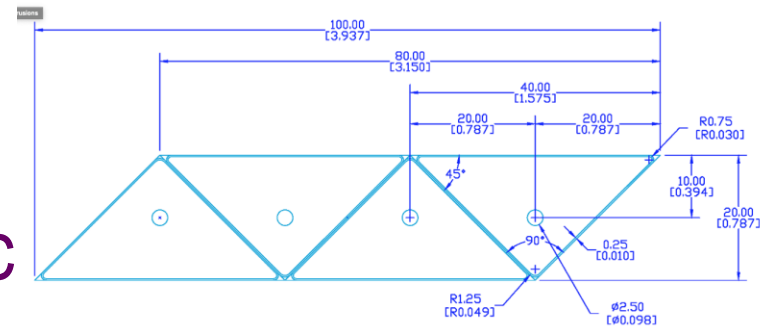


DAMSA Detector Characteristics

- 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
- 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 1~2% 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 (~ 0.1 ns or better)
 - High position resolution (~ 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, more intensely in 2023
 - 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 April and May 2023
- The team consists of
 - Lead Investigators: Jae Yu and Juan Estrada (FNAL)
 - Institutions expressed interests thus far:
 - US (6+2): FNAL, OU, TAMU, UCR, UCI, U. of Kansas (TBC), LANL (TBC), UTA
 - SK (5+3): SNU, Yeonsei U. (TBC), U. of Seoul, Chungnam U. (TBC), Jeonbuk U. (TBC), KNU-CHEP, Korea U., Korea U. - Chochiwon Campus
 - Portugal: LIP (TBC)

1st Workshop on Physics Opportunities at PIP-II

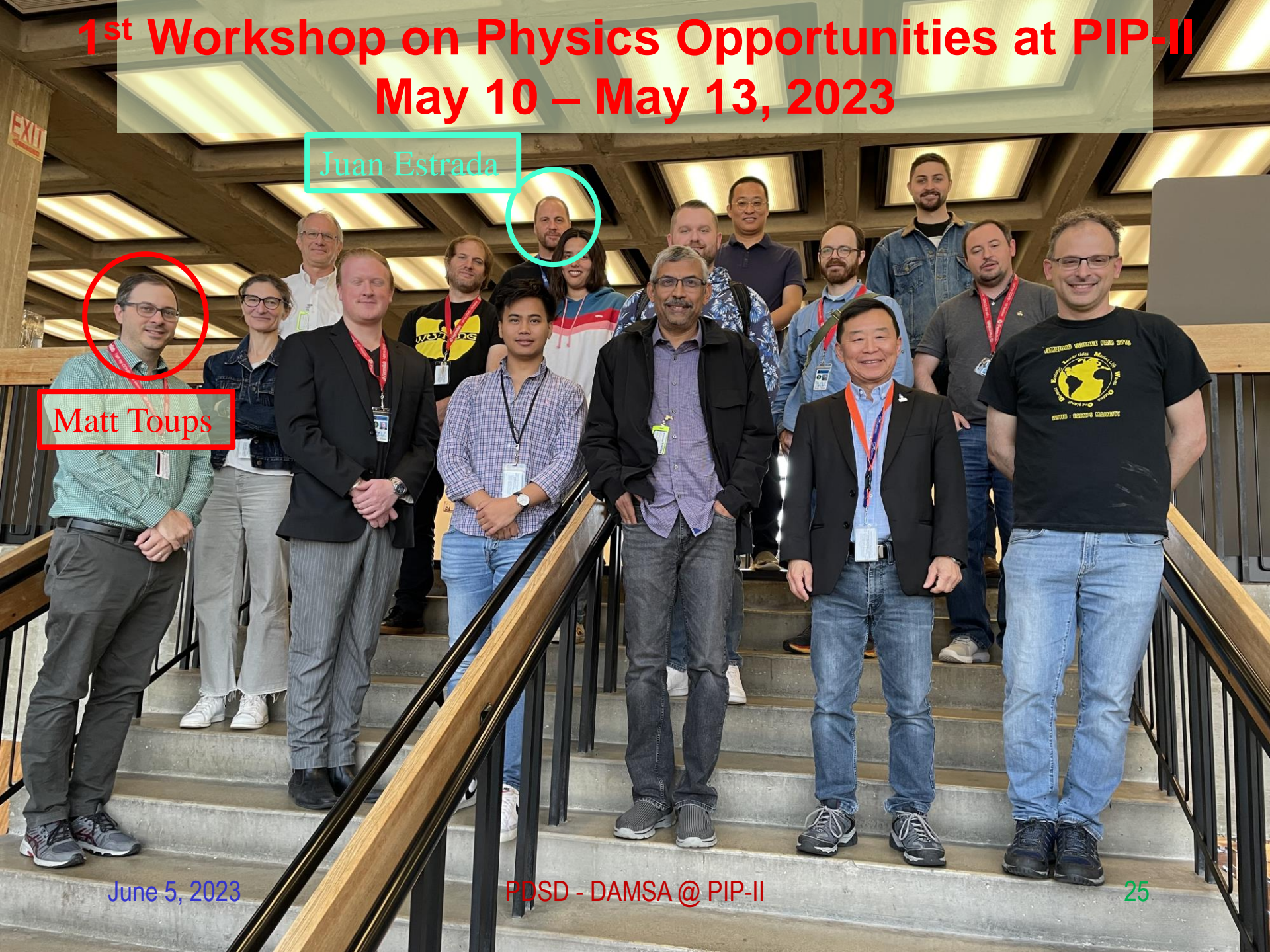
May 10 – May 13, 2023

Juan Estrada

Matt Toups

June 5, 2023

PDSD - DAMSA @ PIP-II



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 PIP-II LINAC cases
- DAMSA team is forming to submit a proposal to PAC
 - Collaborators are welcome!!
- DAMSA presents an excellent opportunity for transforming Fermilab's PIP-II LINAC to a world-class DSP facility & to train the next generation physicists to lead dark matters in accelerators

Parting Questions to this crowd

- What other physics can we do with the DAMSA experiment configuration?
- What modifications to DAMSA experimental configuration to dramatically expand the physics reach?
- What are the tools necessary for DAMSA physics reach in a timely manner?