DAMSA Experiment @ Fermilab PIP-II and Beyond

ACE Science Workshop
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Fermilab

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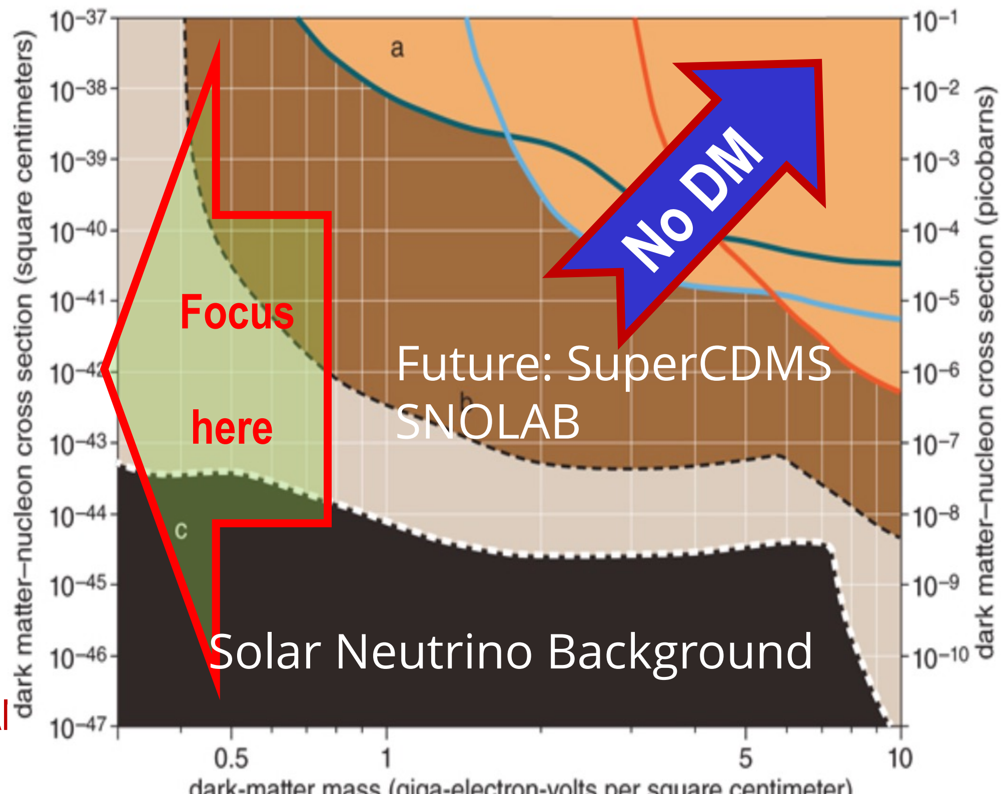
For the DAMSA Collaboration

What is DAMSA?

- Dark sector particle (DSP) search and discovery experiment 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 – Rumination or Reflection
    - Jang *et al*., PRD 107, L031901 (2023)
- Aims to discover DSP's in the low mass regime at an accelerator → ideally E_{beam} below the pion threshold
  - Originally developed for 600MeV proton beams at a nuclear rare isotope facility
- The 800MeV PIP-II and the ACE beams fit the bill
  - The goal is to build the experiment by 2029 in time for PIP-II

Physics Motivation For DSP

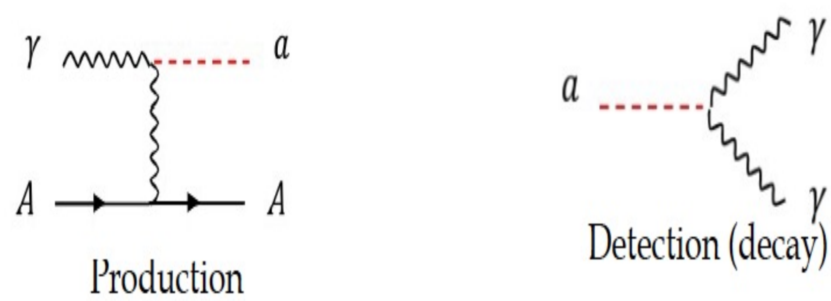
- The SM describes the visible ~5% of the matter in the universe ➔ becoming more solidly established, while the neutrinos sector requires modifications
- Dark matter (Dark Sector Particle, DSP) makes up about 25% of the universe ➔must be explored better
- Direct searches have limitations in kinematic reach, leaving low mass range un-explored
- Strategy:
  – Search for rare particles in unexplored kinematic regime
  – Make and discover DSPs in an accelerator
  – Establish human infra on DM production

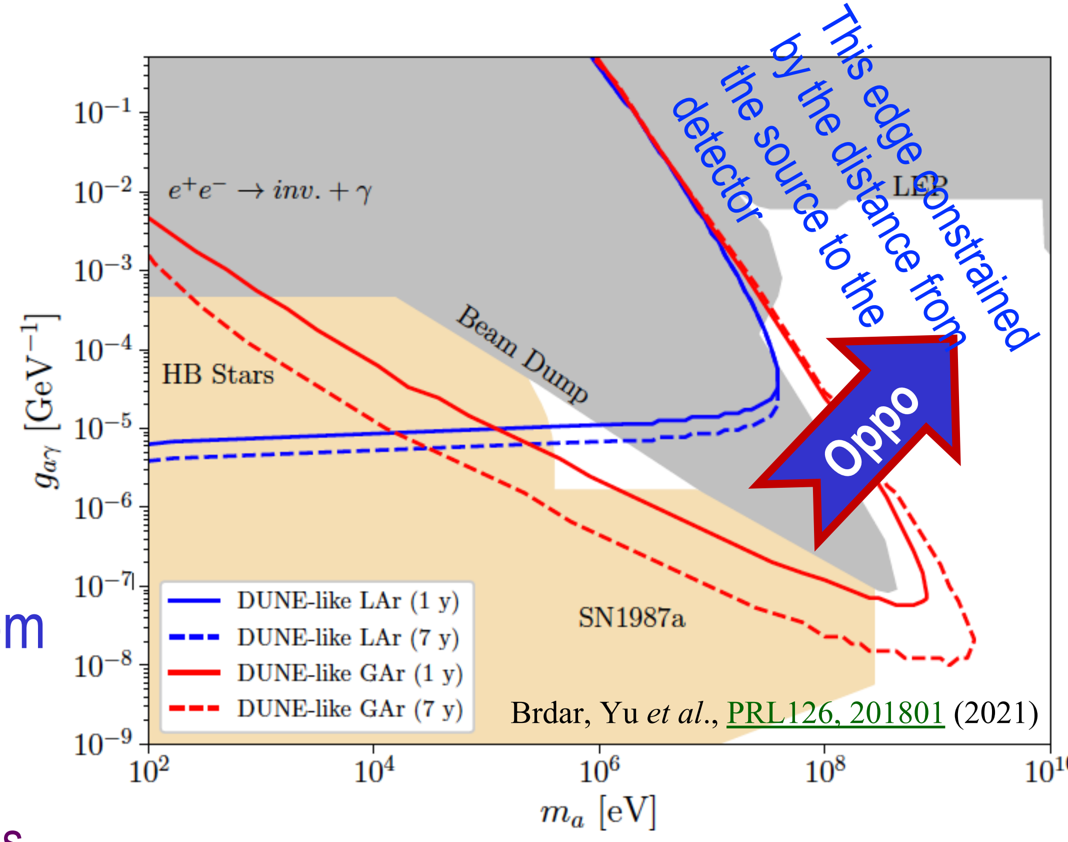


See Gordon K's talk

DAMSA Physics Strategy

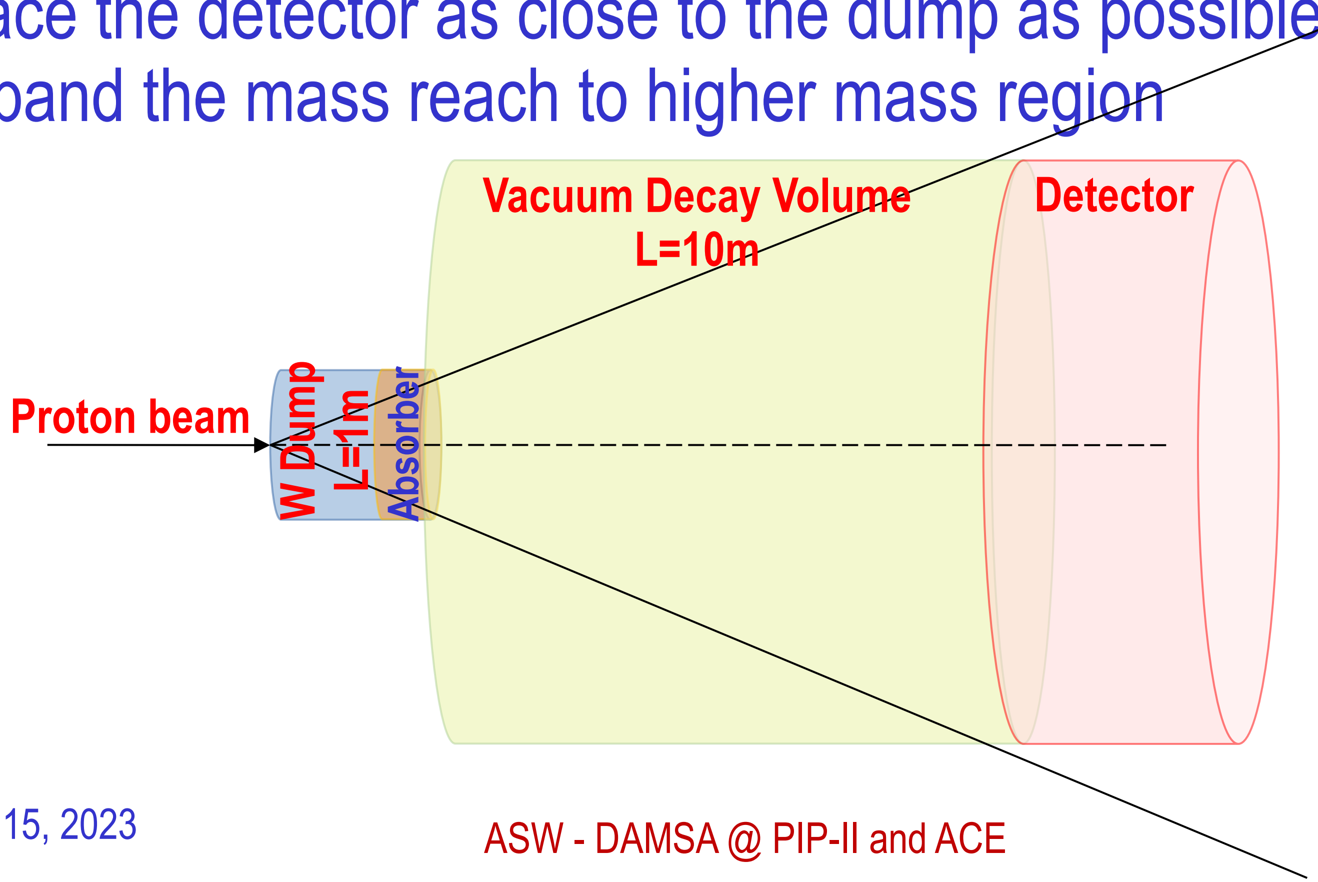
- Focus on Axion-like particles (ALP) in their **two-photon** final state via the Primakoff process as the use case
- Produce as many photons as possible in the beam source, namely the dump
- Capture as many ALPs as possible in as wide a mass range as possible
  - Shorten the distance from the source to the detector
  - Increase the detector angular coverage
- Minimize the backgrounds from neutral particles
  - Neutron spallation
  - ν QE, RES, and NC interactions



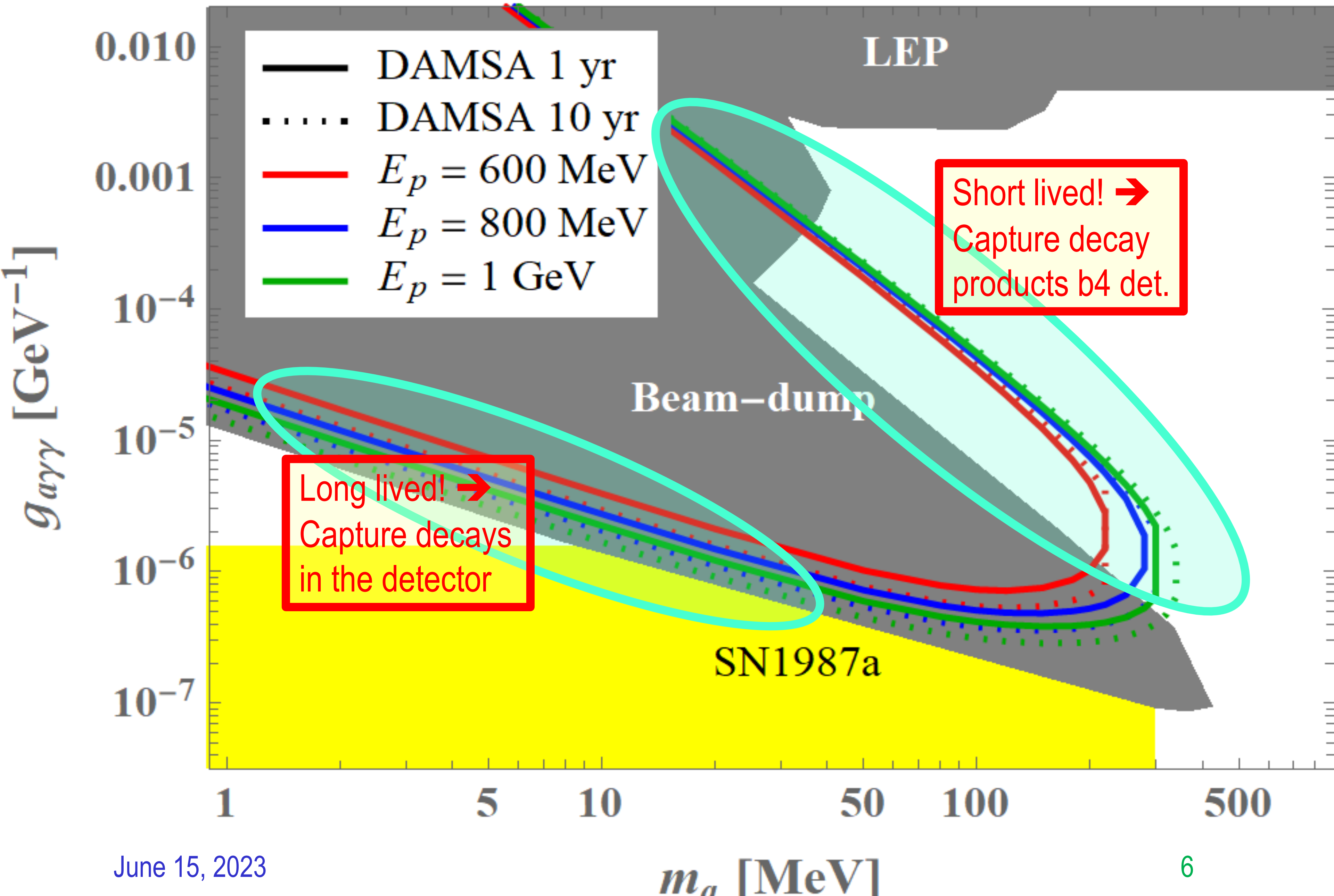


DAMSA Exp. Concept

- Inject and absorb as many low-E (1GeV or less) protons and produce as large number of γ in the dump as possible
- Allow higher mass ALP's to decay with as small a 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 Sensitivity Reach



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 the detector to meet the requirements with minimal R&D
  - Fast timing (~0.1ns or better)
  - High position resolution (~0.1mm or better)
  - Excellent energy and invariant mass resolution
  - Low threshold energy
- Discover Dark Sector Particles in the beam and produce the beam of them

Conclusions

- DAMSA is a DSP search and discovery experiment that leverages high intensity, low energy proton beams
  - ALP and other physics topics will be explored
- Detailed GEANT based studies performed for detector parameter requirements ➔ Optimization in progress
  - Neutron background consideration
- DAMSA collaboration building (6 US, 5 SK, 1 EU) w/ the goal to submit a proposal to Fermilab PAC Jan. 2024
- DAMSA presents an excellent opportunity for transforming Fermilab's PIP-II and ACE to a world-class DSP facility & to train the next generation physicists to lead dark matters in accelerators

Back Up Slides

Physics Motivation For DSP

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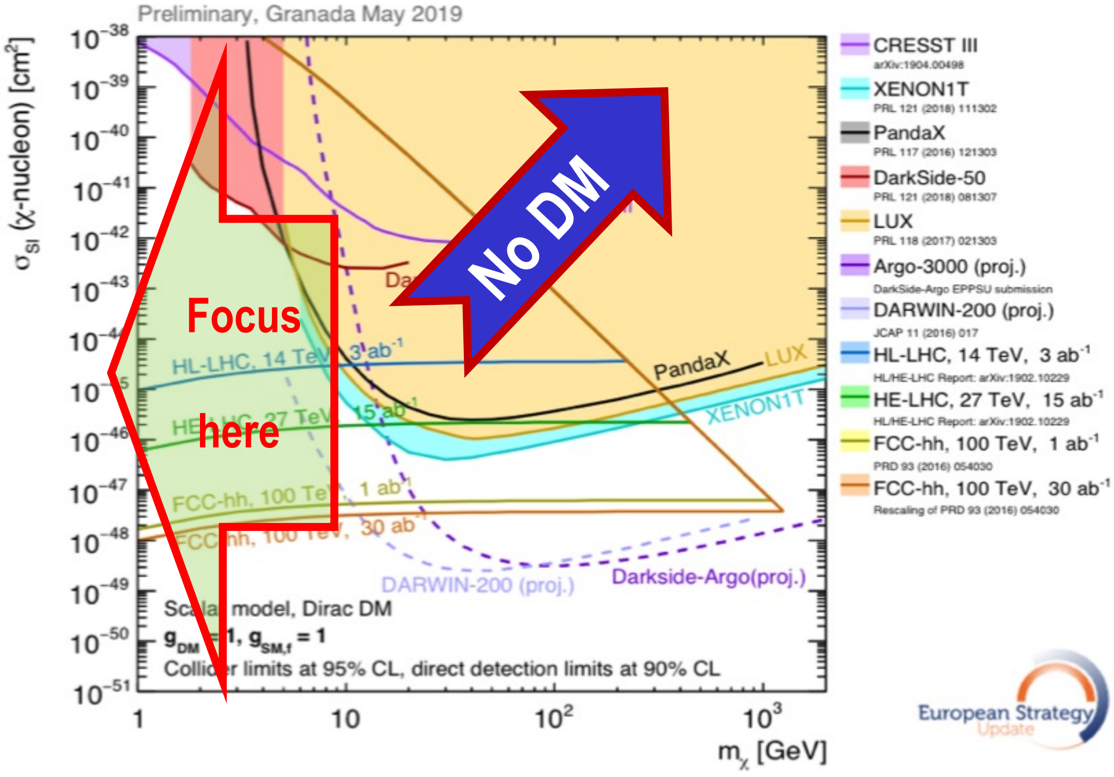
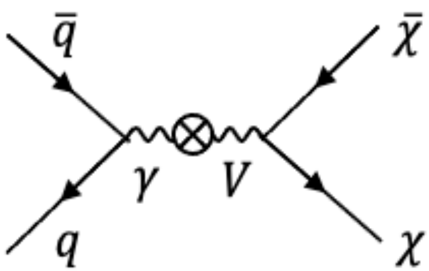
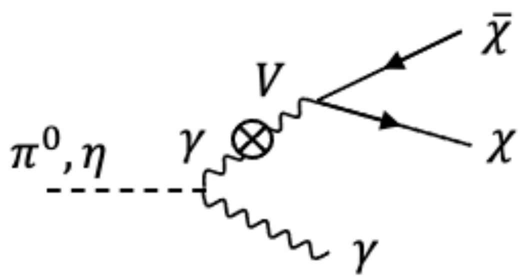


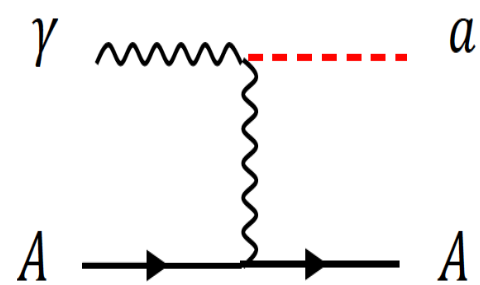
European Strategy Update

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

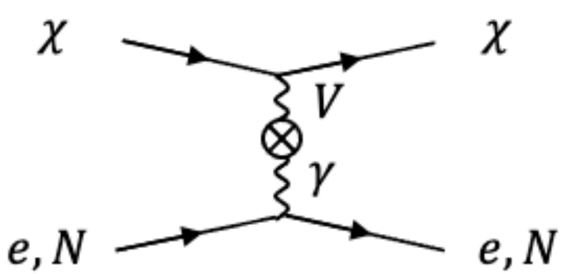
- Set of new particles which **do not experience the known forces**
- DSPs can be weakly coupled to visible sector thru a mediator or "portal"
- **High intensity proton beams** produce large number of photons from brem, DY and neutral mesons decays ➔ Make it possible to contemplate couplings of new U(1)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

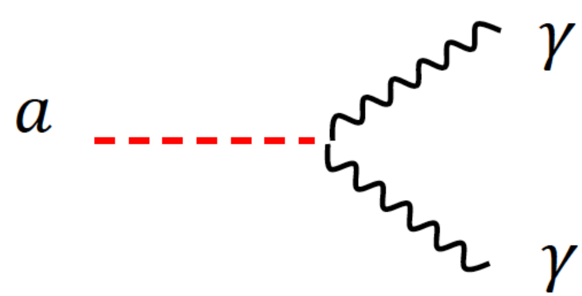






- Detection through an electron scattering, N(n) recoil or 1, 2 γ final states





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

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
  - ~1×10^{23} POT/yr was assumed in the PRD 600MeV physics study
  - ~1×10^{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/bunch : 8×10^7 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=2mA/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

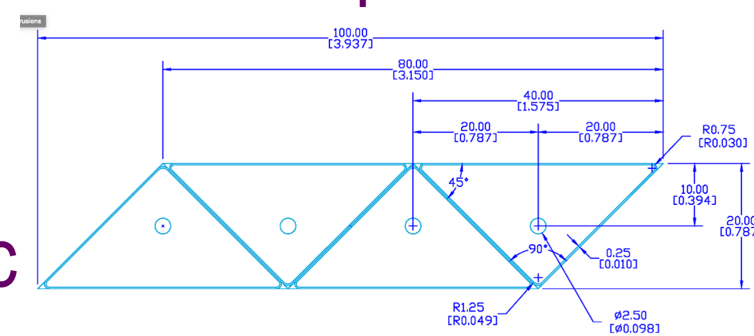
- What are other possible ways to further reduce the background from neutron spallation? ➔ Aim to reduce by order >=10^{10}
  - Leverage the speed of the neutrons ➔ Neutrons are 10 – 1000 times heavier than the ALPs, thus for the given momentum, the arrival time of the neutron induced photon accidentals 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 ~1MeV)

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 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

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?