DAMSA at Fermilab PIP-II

Heavy Ion Meeting
May 26 – 27, 2023
Yeonsei University

Jaehoon Yu
University of Texas at Arlington

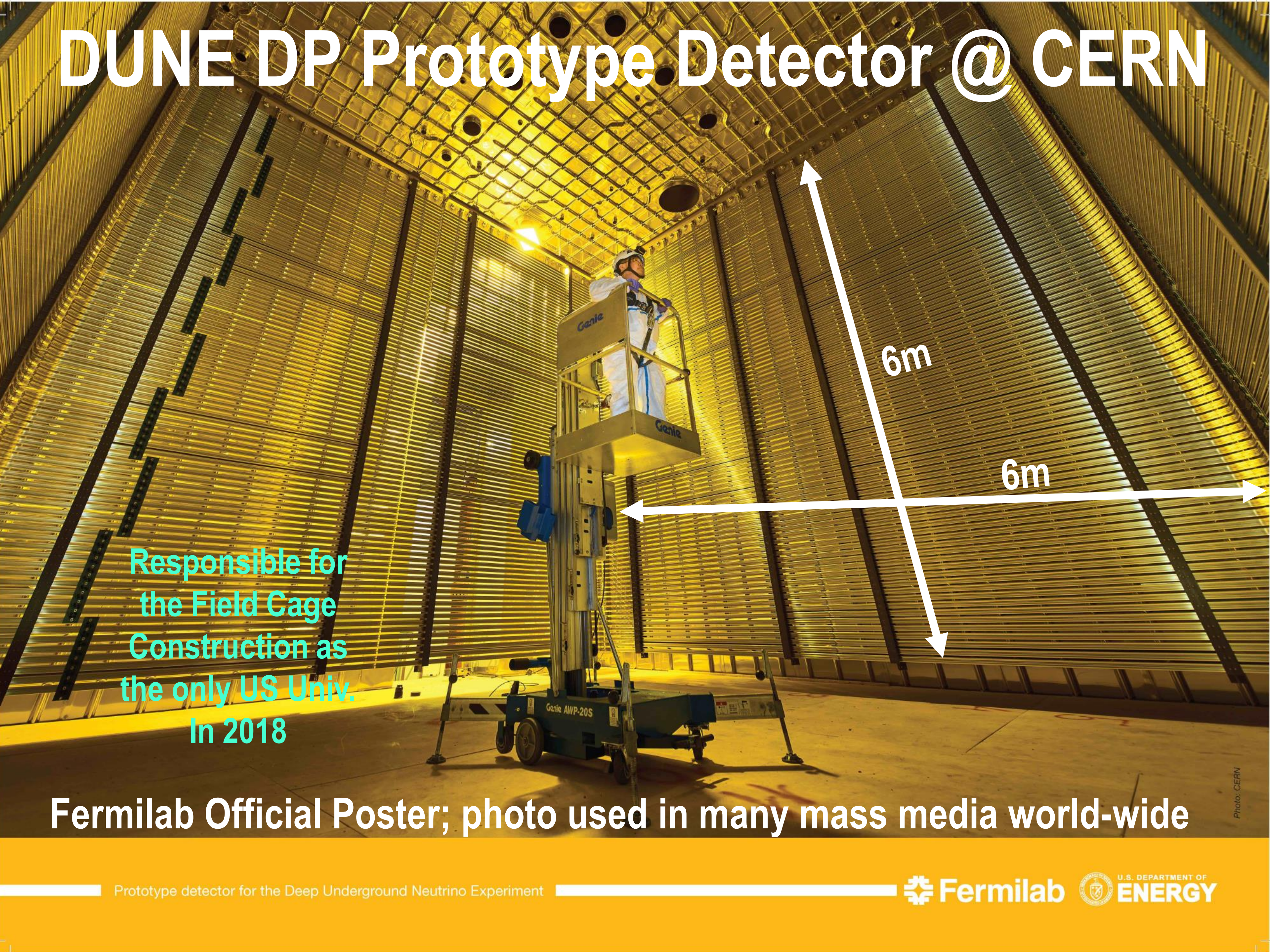
Outline

- 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

Who am I? – 1

- Professor at U. Texas Arlington (2001 – present)
  - High Energy Particle Physicist who worked on collider and fixed target experiment at Fermilab and CERN
  - Responsible for field cage construction for the 1st two 17kt DUNE FD
  - Led the Beyond the Standard Model (BSM) physics group in neutrino experiments in the completed U.S. HEP decadal study, Snowmass2021
  - Founding convener of the BSM@ν group in 2013 (1st in the community!)
  - Constructed three DUNE field cages for ProtoDUNE @CERN

DUNE DP Prototype Detector @ CERN



Responsible for
the Field Cage
Construction as
the only US Univ.
In 2018

Fermilab Official Poster; photo used in many mass media world-wide

Photo: CERN

Prototype detector for the Deep Underground Neutrino Experiment

Fermilab U.S. DEPARTMENT OF ENERGY

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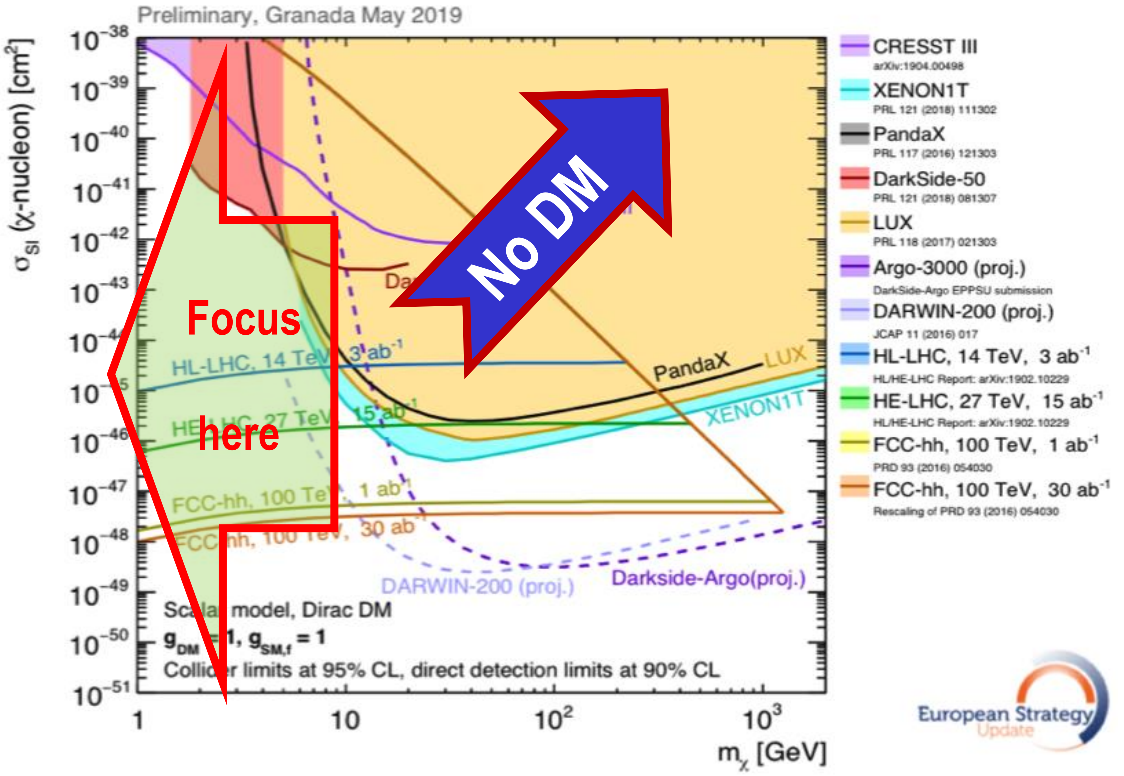
  - Contributed to the 2012 Higgs discovery and the subsequent precision property measurements in ATLAS
  - Convener of the International Linear Collider detector R&D beam testing
  - Responsible for the design and implementation of D-Zero computing grid
    - Led a physics group on discovery of Higgs in WW final states

Who am I? – 2

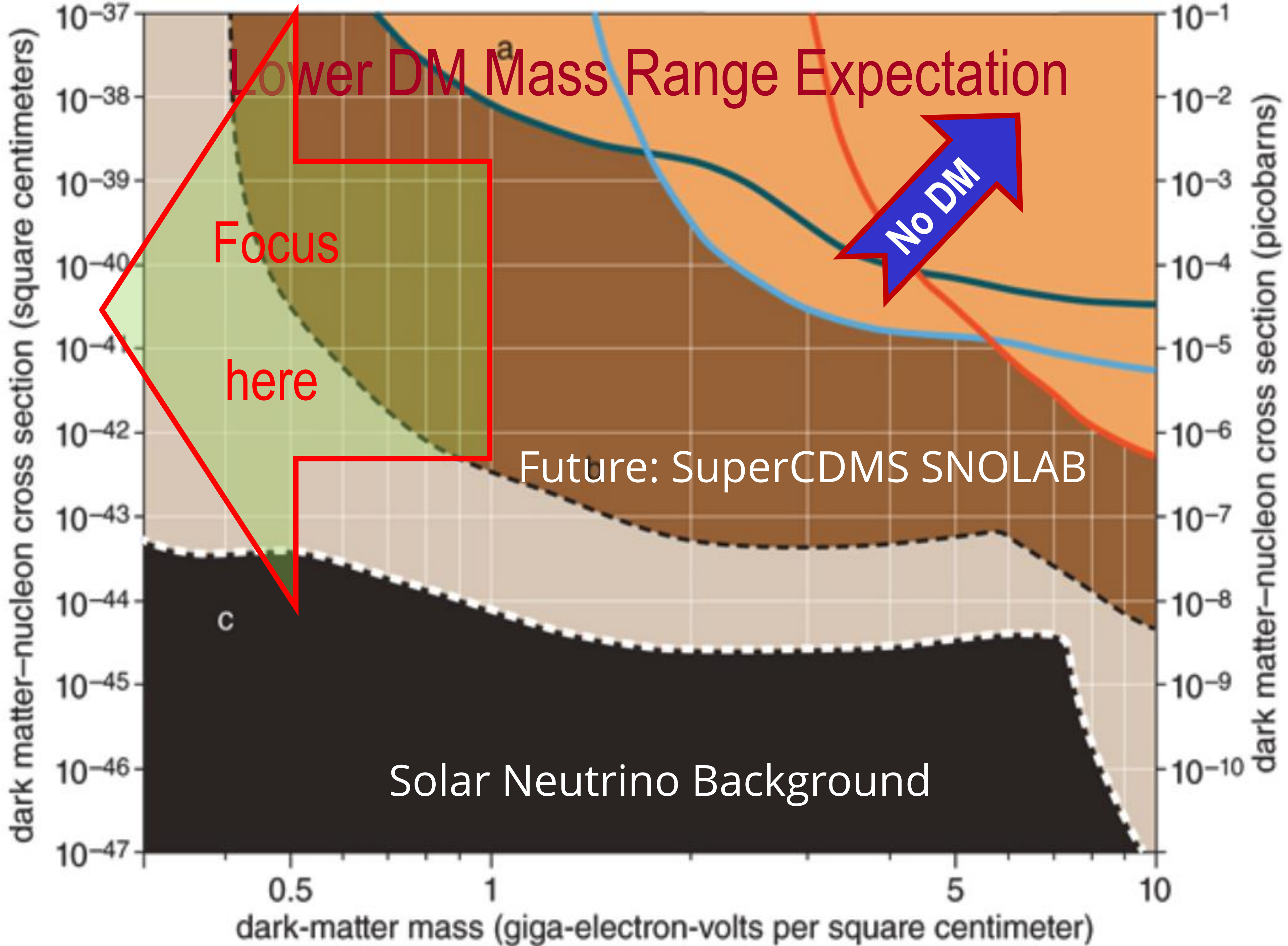
- Commission leader of the upgraded D-Zero detector as a Fermilab staff scientist (98 – 2001)
- 1st postdoc at D-Zero with U. of Rochester (93 – 96) followed by the 2nd postdoc at Fermilab (96 – 98) on a neutrino experiment (NuTeV), built the calibration beamline, managed the calib program and published the results
- Ph.D. in HEP at Stony Brook U. in 1993 on D-Zero @ FNAL
  - Participated in prototyping, beam testing, construction, assembly, commissioning, data taking, collision data analysis, thesis writing and publication of the thesis
- Physics B.S. and M.S. from Korea U., 1983 and 1985

Physics Motivation For DSP

- 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 accelerators
  - Establish human infra on DM production



Lower DM Mass Range Expectation



Focus here

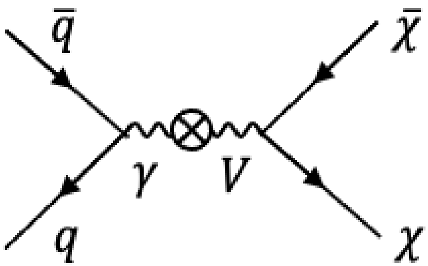
No DM

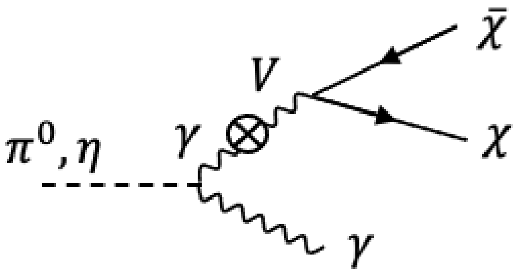
Future: SuperCDMS SNOLAB

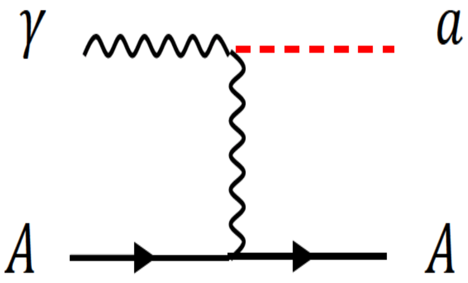
Solar Neutrino Background

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

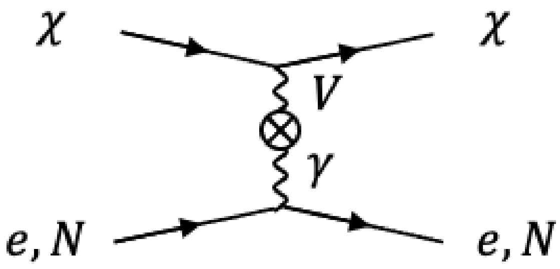
- Set of new particles which **do not experience the known forces**
- DSPs can be weakly coupled to visible sector thru a mediator or "portal"
- **High intensity proton beams** produce large number of photons from brem, DY and neutral mesons decays ➔ Make it possible to contemplate couplings of new U(1)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

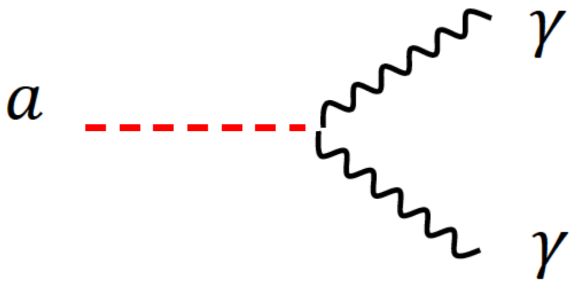






- Detection through an electron scattering, N(n) recoil or 1, 2 γ final states





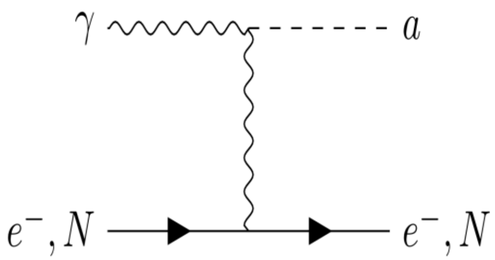
What's needed to discover a DSP?

- 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

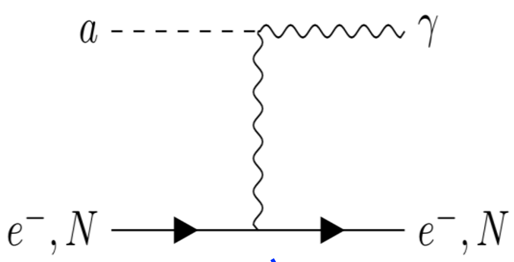
Opportunities on ALP Searches

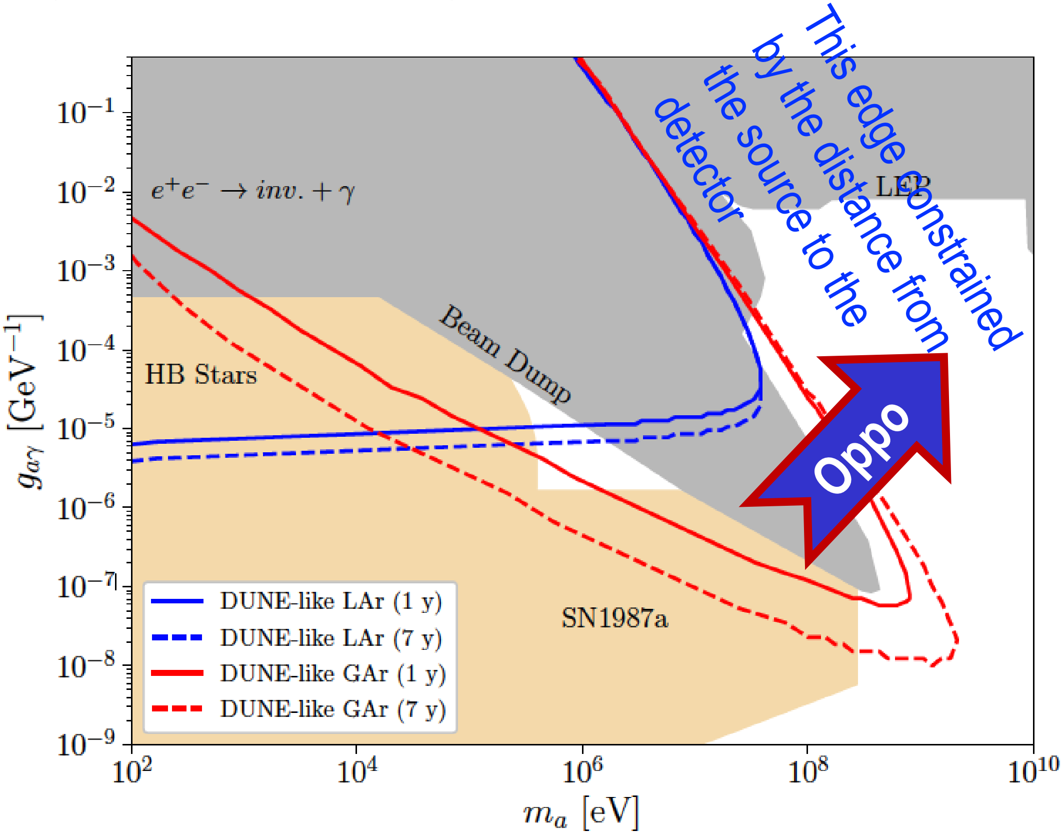
- Axion-like particles (ALP) can be produced via the Primakoff process in high intensity proton beams
- Detection via the inverse Primakoff process either in a scattering with e/N + γ or decays of the ALP to two γ
- A case study on DUNE ND shows a potential to fully close the cosmic triangle
  - Brdar,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

Production in ν target



Detection - scattering





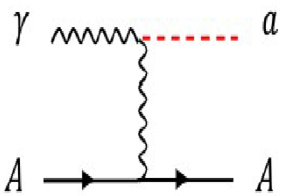
This edge constrained by the distance from the source to the detector

What is DAMSA?

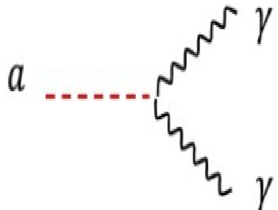
- Dark sector particle (DSP) search concept at low E, high intensity proton beam facility
- Stands for Dump produced Aboriginal Matter Search at an Accelerator (DAMSA)
  - 담사 (潭思) = 깊은생각 – Rumination or Reflection
    - Jang *et al*., PRD 107, L031901 (2023)
- Search for DSP in the low mass regime, using low energy, high intensity beam capability → ideally below the pion threshold
  - Originally developed for 600MeV proton beam at RAON
- The 800MeV PIP-II LINAC beams fit the bill

DAMSA Physics Strategy

- Focus on Axion-like particles (ALP) search through their **two-photon** final state via the Primakoff process



Production

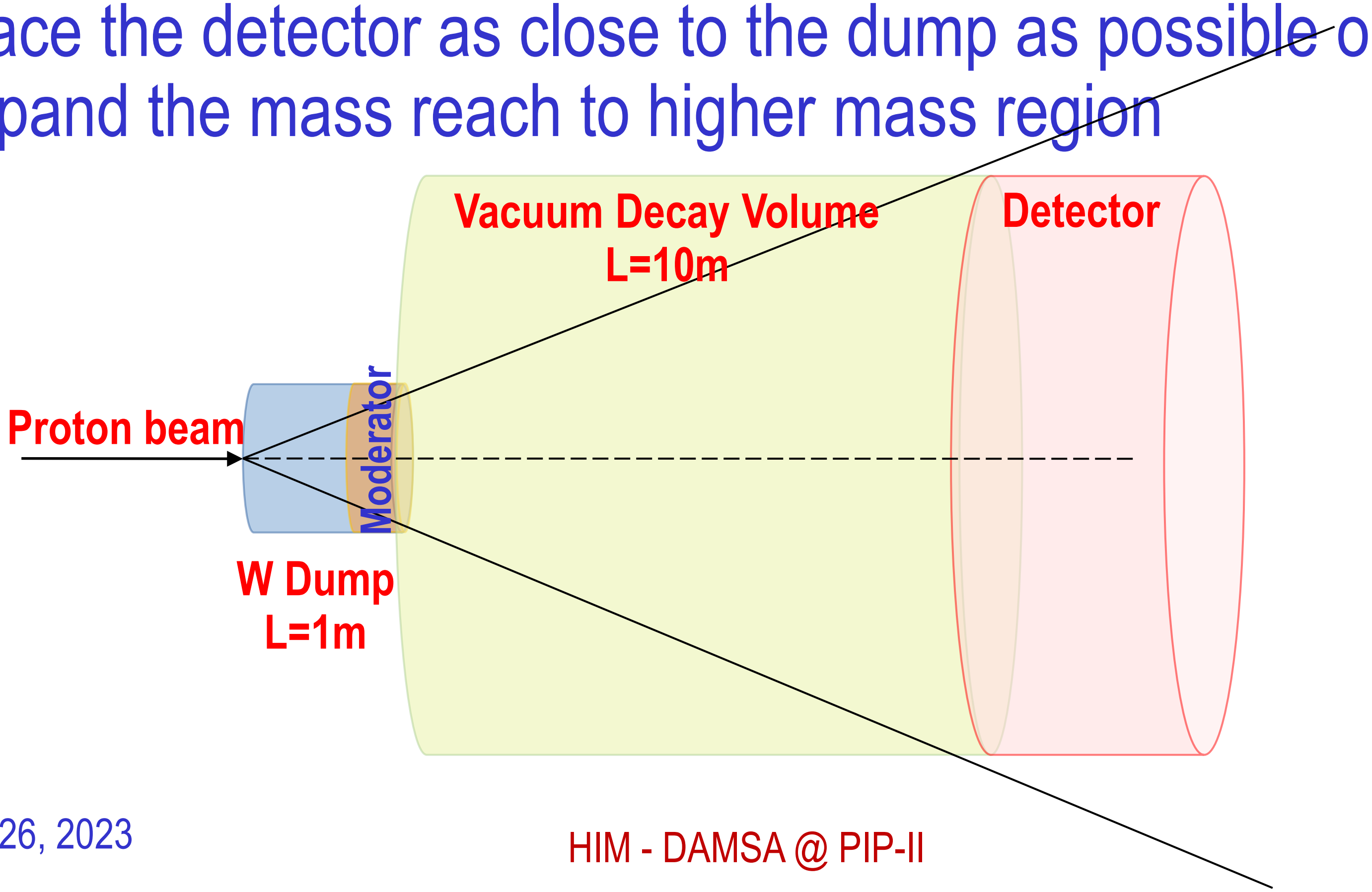


Detection (decay)

- 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 → accidental photon overlaps
  - Neutrino NC and QE interactions → produce $\pi^0 \rightarrow 2\gamma$

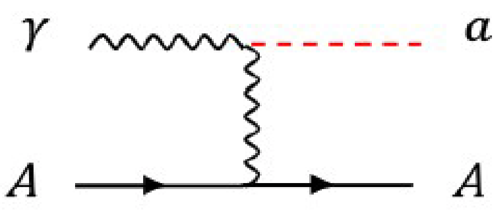
DAMSA Exp. Concept

- 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

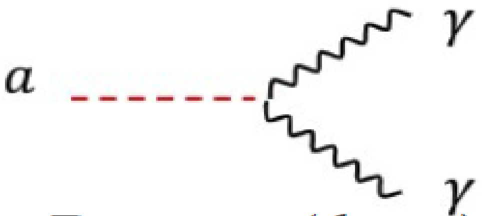


May 26, 2023

DAMSA Experiment Signature



Production



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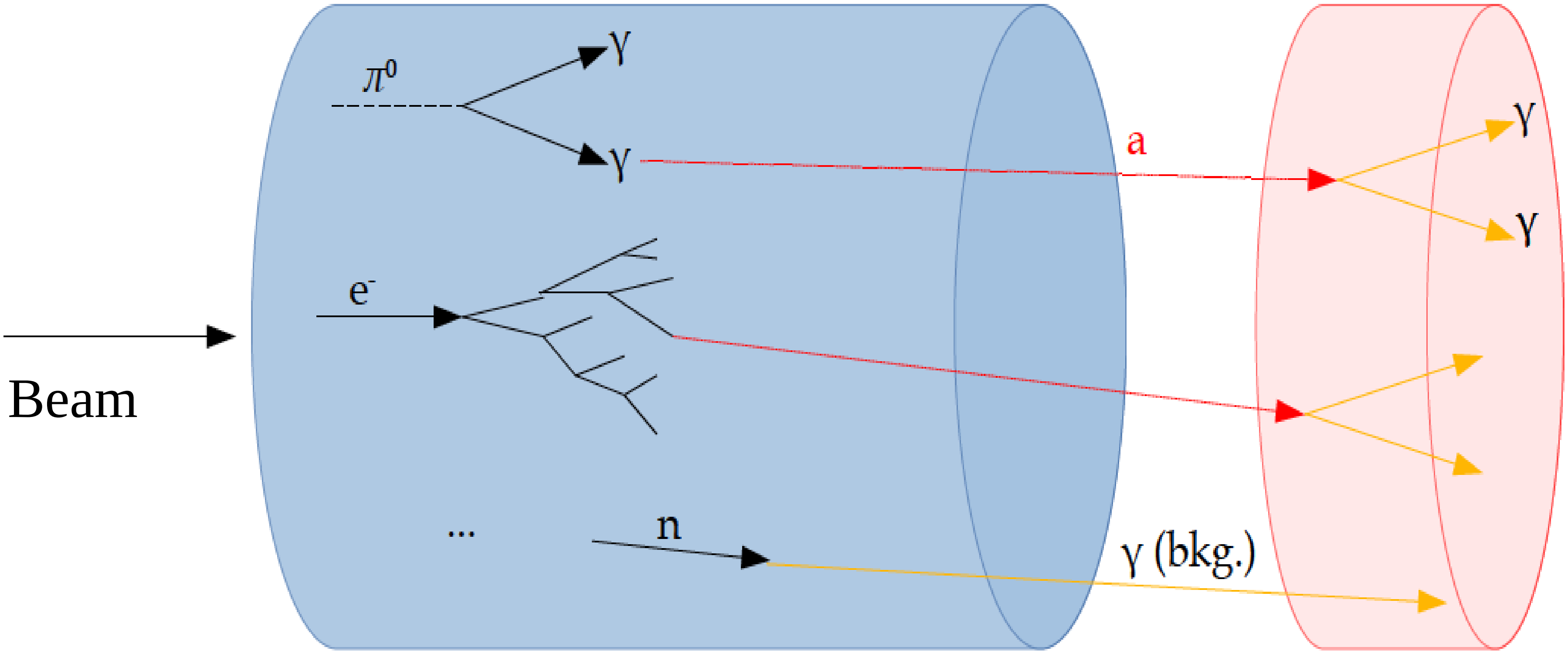
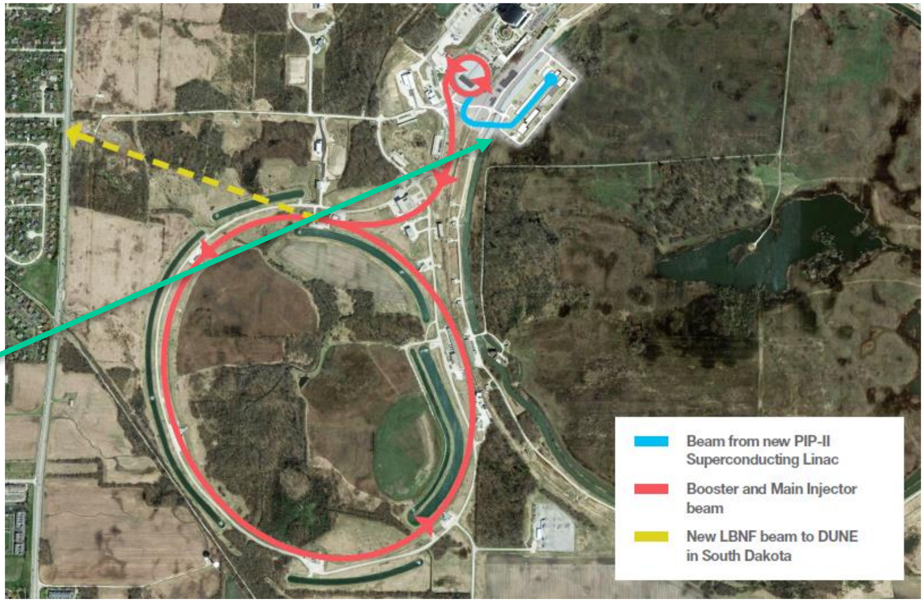


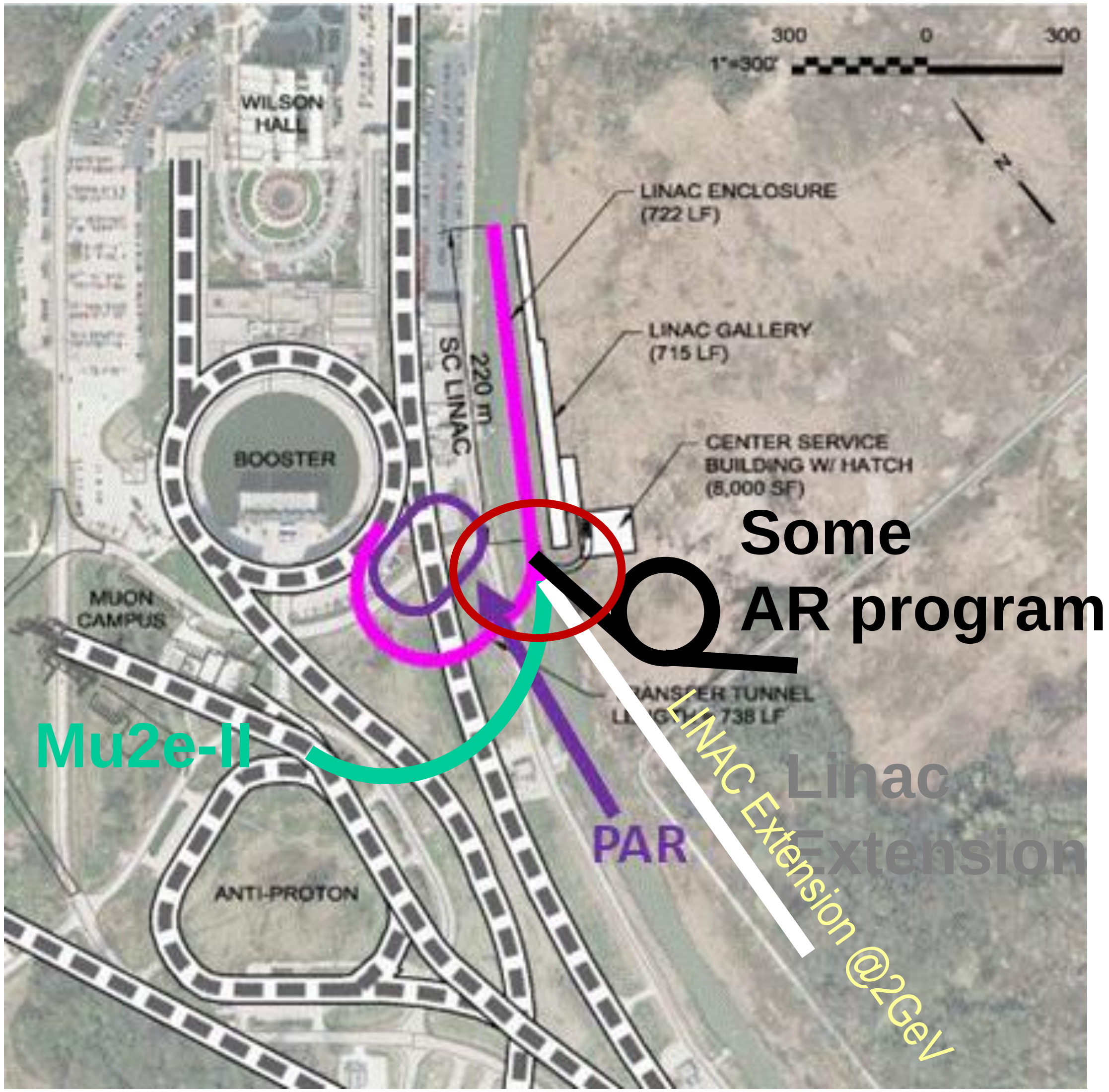
Accelerator Complex in PIP-II Era

- 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

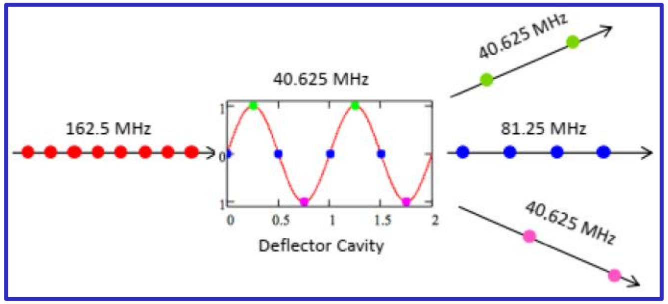


B. Flauger

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
  - ~1x10^{23} POT/yr was assumed in the PRD 600MeV physics study
  - ~1x10^{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 : 8x10^7 p/bunch
  - Bunch spacing: 6.2ns
- PIP-II CW Chopping possibility?
  - micro-pulses w/ two 14x10^7 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

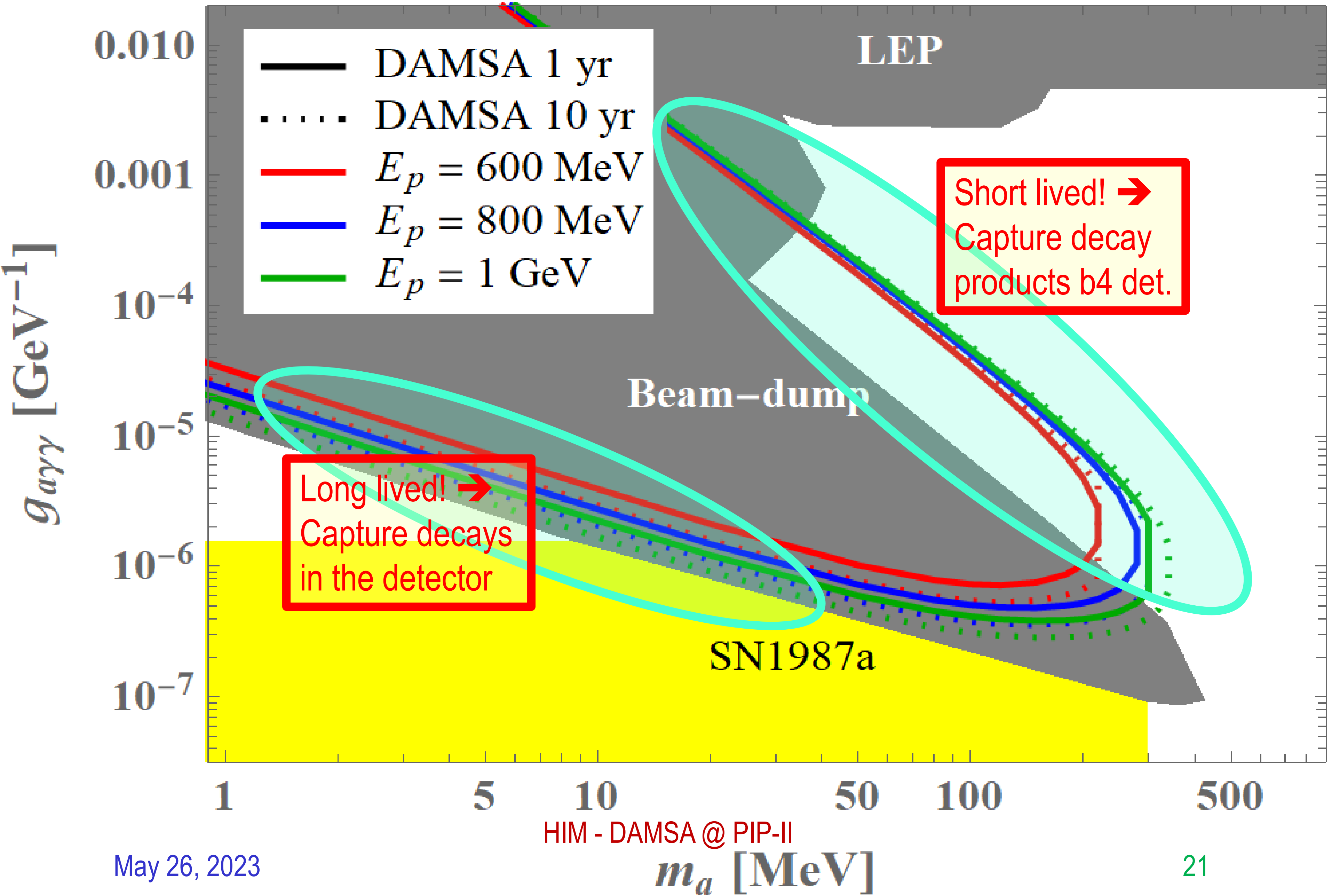
DAMSA Requirements – The Detector 1

- 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
  - 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 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)

Expected DAMSA Sensitivity



Short lived! ➔
Capture decay
products b4 det.

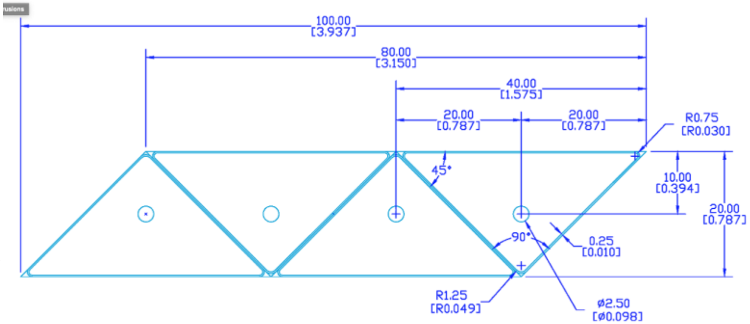
Long lived! ➔
Capture decays
in the detector

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 ~3x10^{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 (~0.1ns 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

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 (8): FNAL, OU, TAMU, UCR, UCI, U. of Kansas (TBC), LANL (TBC), **UTA**
    - SK (8): **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

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 Korea to be an essential partner in transforming Fermilab's PIP-II LINAC to a world-class DSP facility & to train the next generation physicists to lead dark matters in accelerators