DAMSA, A Novel Dark Matter Discovery Experiment @ PIP-II

CERN Detector Seminar

November 10, 2023

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Outline

- Introduction
- What does DUNE got to do with dark matter?
- What is DAMSA and are its requirements?
- What is in Fermilab PIP-II Era?
- DAMSA experiment specifics and sensitivity reach
- The strategy, the team and the timeline
- Conclusions

How do we design a HEP experiment?

1. Decide on physics goals to accomplish
2. Determine the capabilities and parameters for an experiment to meet the goals, taking into account the background mitigation
3. Decide on the beam and the best detector technology to meet the parameters
4. Perform R&D for the beam and the detector
5. Design and build prototype detectors to test the performance
6. Finalize the design and build the full-scale experiment

Neutrino fundamentals – 1

- Postulated in 1930s to explain the nuclear β-decay and detected experimentally in 1956 (**1995 Nobel**)
- Fundamental particles of matter in the current Standard Model of Particle Physics
  - Make up a quarter of the whole particle table in TSM as **massless particles**
  - Have three flavors – electron (ν_e – **2002 Nobel**), muon (ν_μ – **1988 Nobel**) , and tau (ν_τ)
  - Charge neutral and only interact via the weak force → do not interact often in matter
    - Need high intensity neutrino beams to obtain large number of interactions!!

Neutrino fundamentals – 2

- Large numbers of low E neutrinos (ν_e) produced in the Sun (**2002 Nobel**) and in reactors
  - → $65\text{x}10^9$ ν_e /s/cm^2 (FFT: how many passes throughout your body/sec?)
- Neutrino flavor oscillation was discovered & confirmed throughout late 1990 and early 2000 (**2015 Nobel**)
  - Happens because flavor and mass eigenstates differ (oscillation probability dependent on L/E_ν)

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$

  - Neutrinos have mass! → SM in BIG trouble!

The Next Big Thing - DUNE Experiment

- Stands for Deep Under Ground Neutrino Experiment
- US flagship long baseline (1300km) { experiment
  - 1500m underground in an old South Dakota gold mine

Yes, you are right, again!
That Sturgis is right next door!

solar ν
is
s
New DUNE area being
excavated (>85%)

The Next Big Thing - DUNE Experiment

- Stands for Deep Underground Neutrino Experiment
- The US flagship long baseline (1300km) ν experiment
  - 1500m underground in an old South Dakota gold mine
- Needs a very high intensity proton beams (1.2MW → 2.4MW!)
  - Result in a large number of ν for property measurements
  - Opportunity for dark matter search and other BSM physics
  - FFT: How many 120GeV p/sec correspond to these powers?
- Large mass (~70kt! total) **LArTPC** Far Detector at SURF
- Powerful near detector complex to control systematics
- Was born in March 2015!
  - Combination of LBNE (US) and LBNO (EU)
- >1500 collaborators from 209 institutes in 36 countries + CERN

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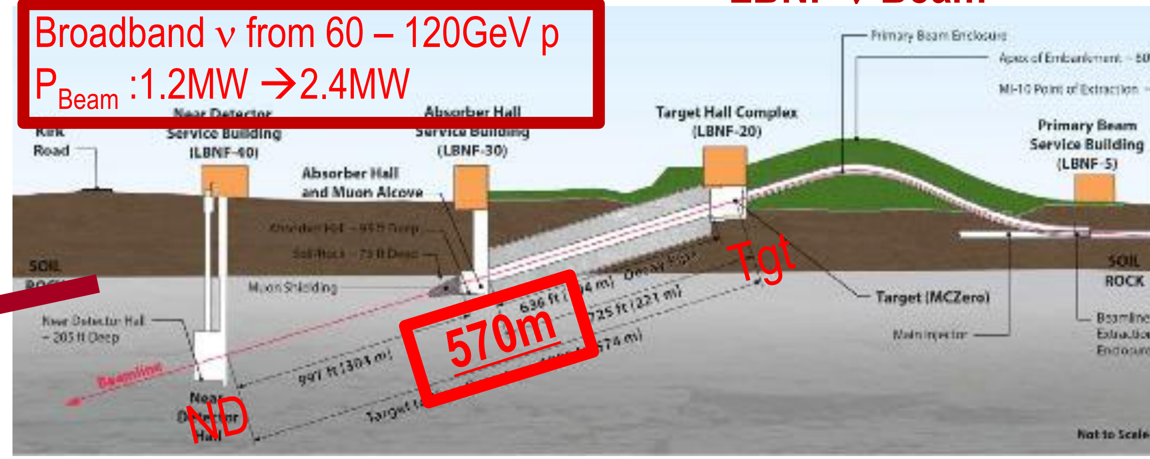
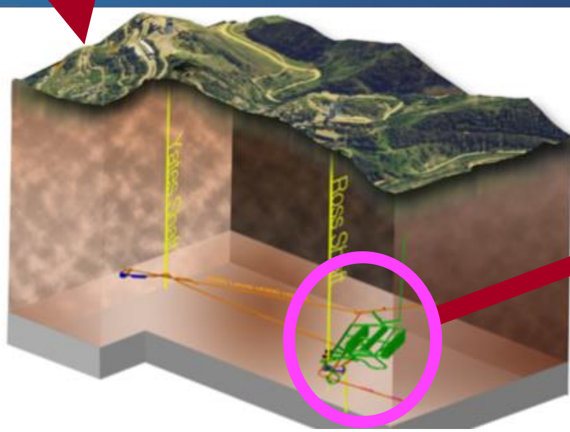
ut-the-collaboration/

Anatomy of DUNE

LBNF ν Beam

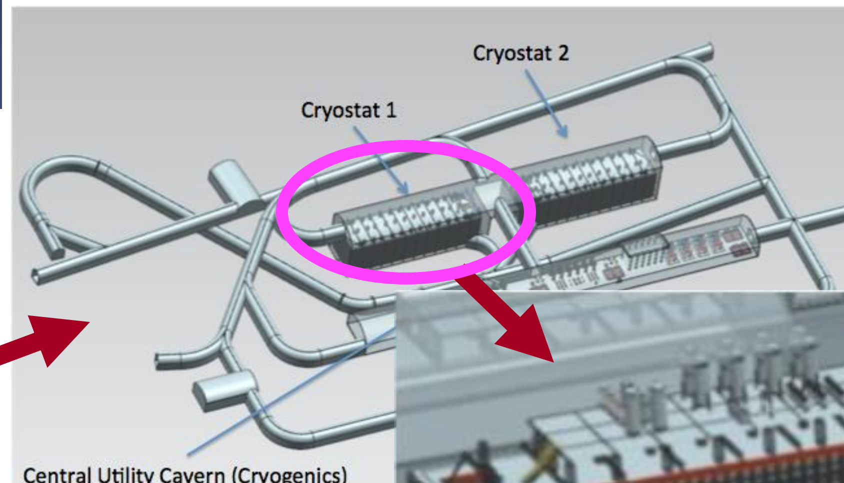
Broadband ν from 60 – 120GeV p
P_{Beam} :1.2MW →2.4MW



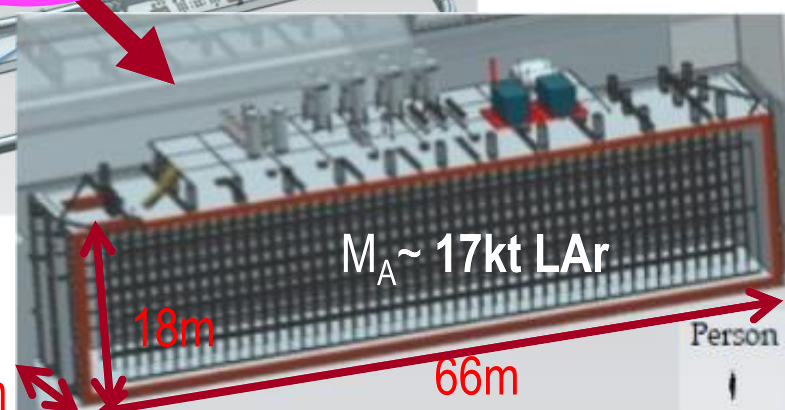


LBNF Far Detector Site, SURF

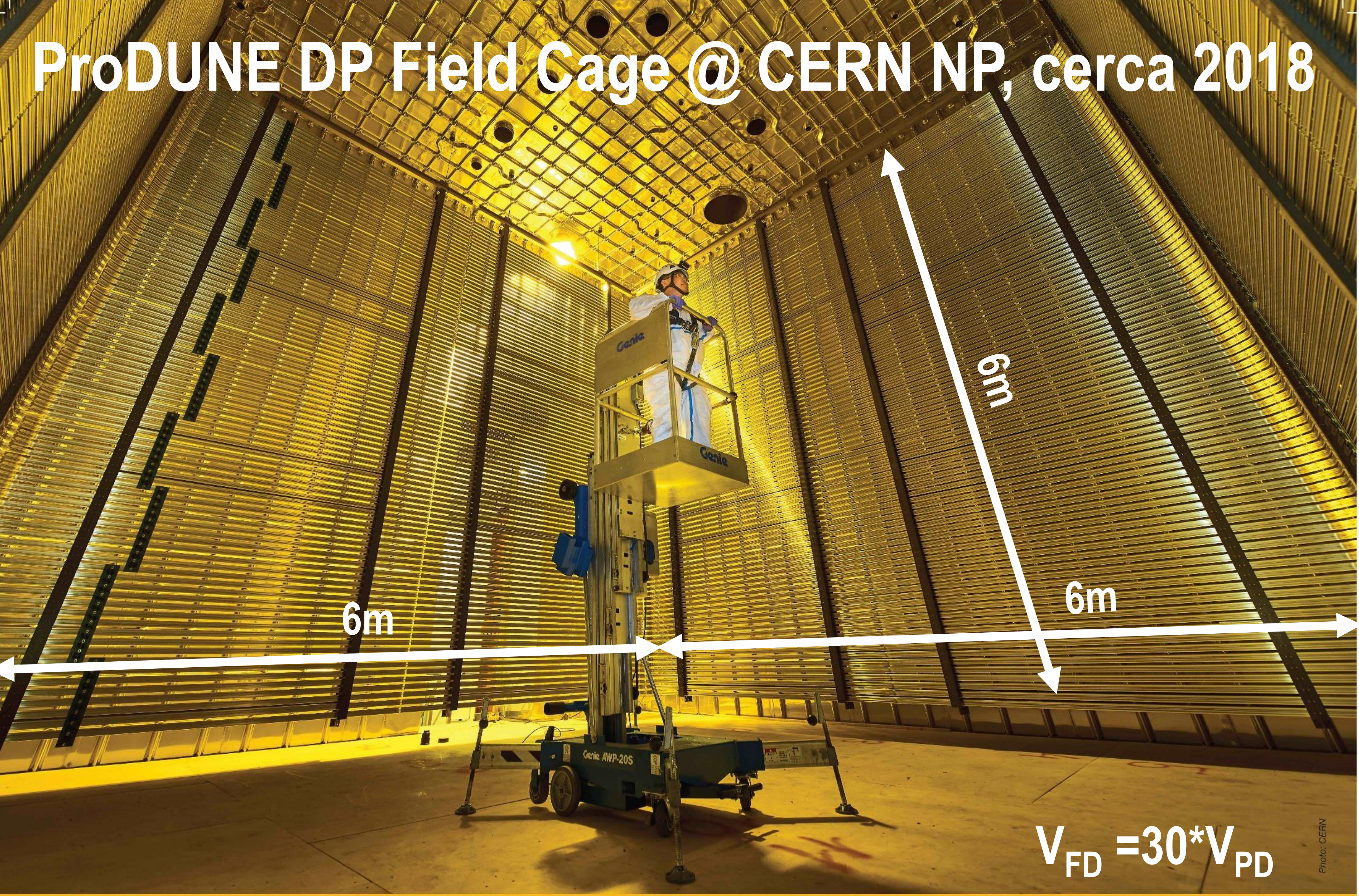
1500m underground



4 caverns for
M_t~ **70kt LAr**
(>85% complete)



ProDUNE DP Field Cage @ CERN NP, cerca 2018



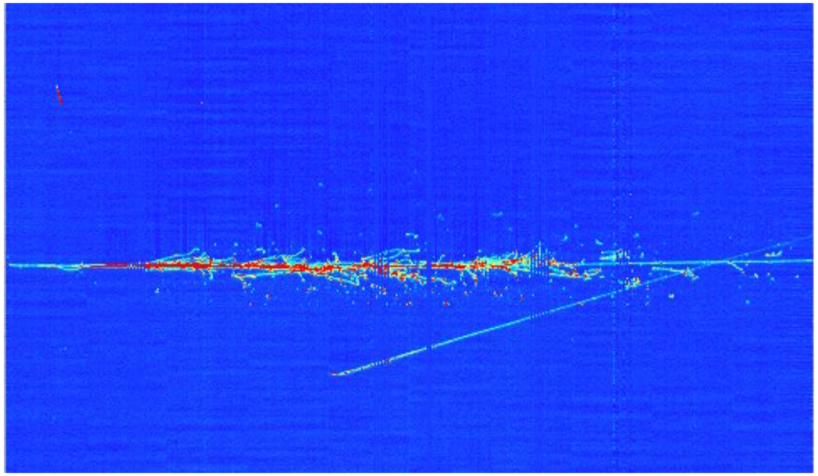
$V_{FD} = 30*V_{PD}$


ProtoDUNE VD@NP, cerca 2023

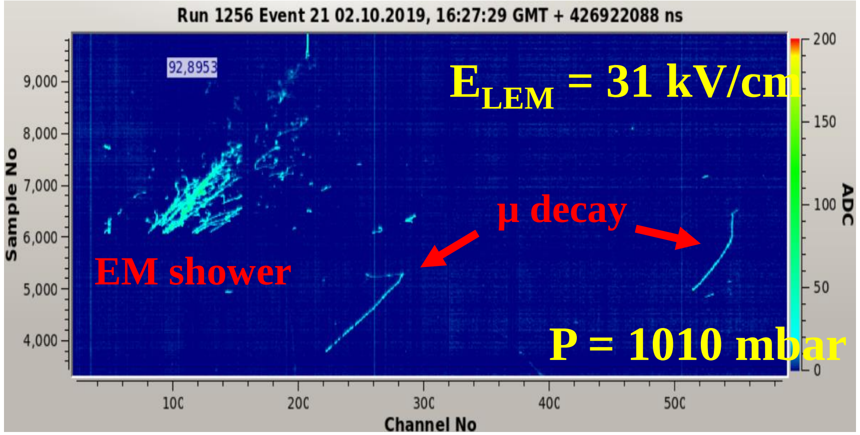

@NP, cerca 2022

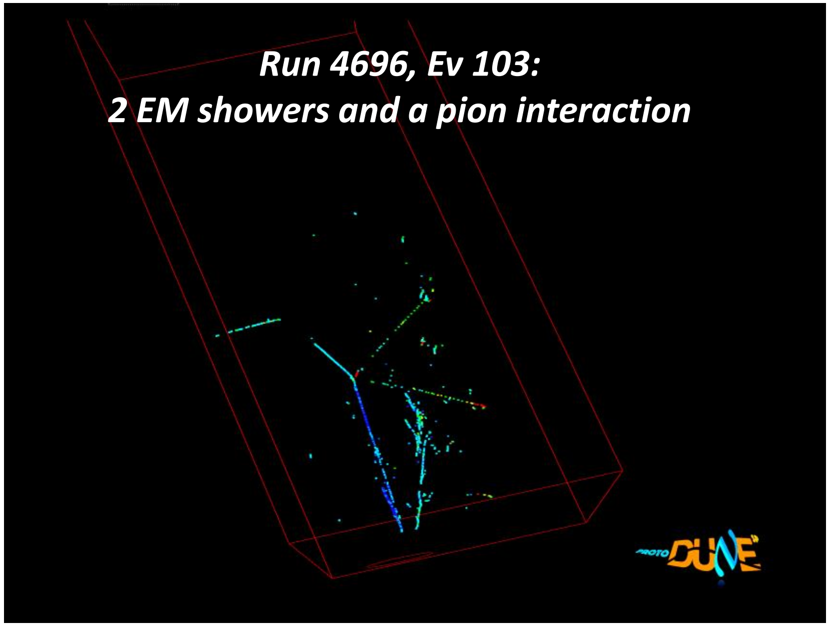
Images in DUNE LAr-TPC Prototypes

Throughgoing μ

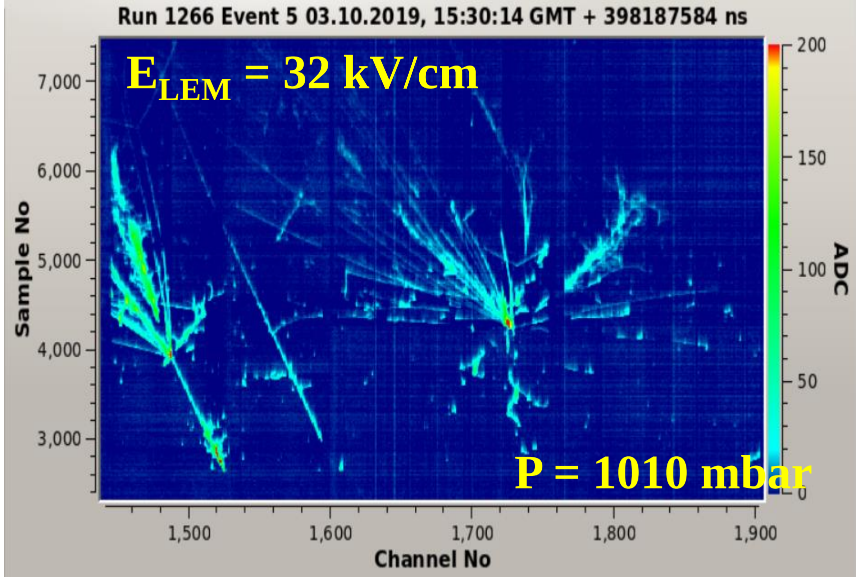


Electromagnetic shower + two muon decays





Multiple hadronic interactions in a shower

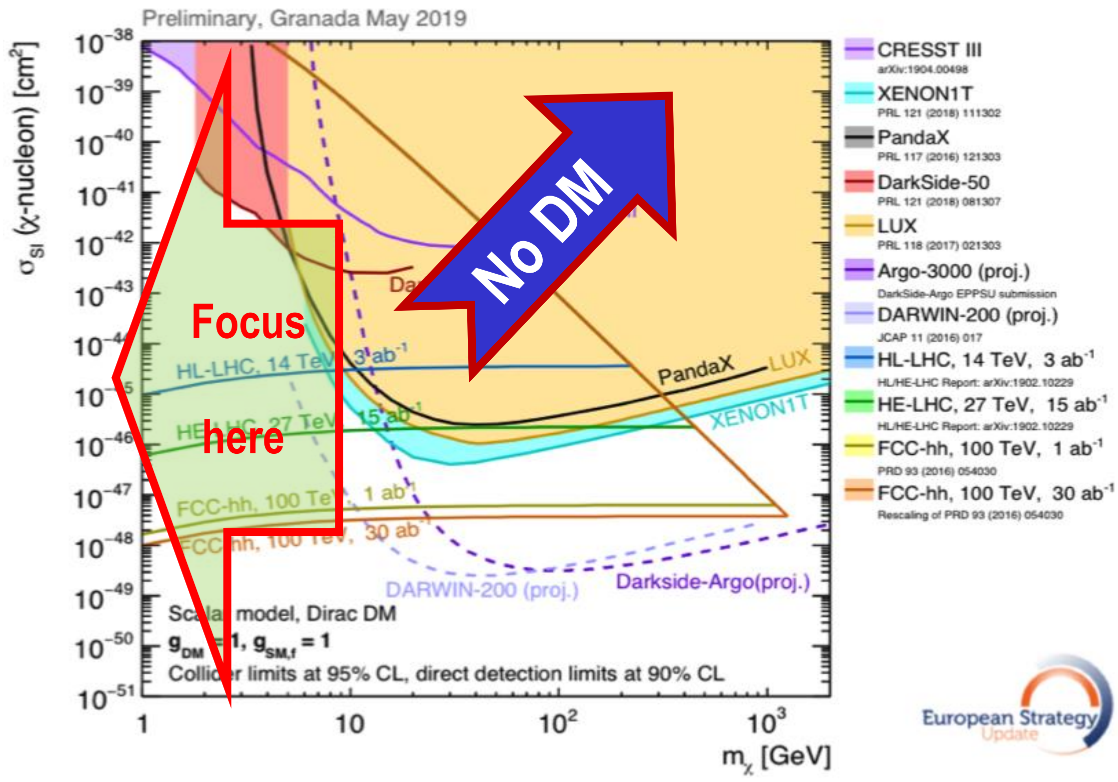


BSM Topics @ DUNE

- DUNE's facility enables **DUNE a BSM physics machine**
  - Recall the Signal to Bck. ratio grows by the sqrt of the beam power
  - Near Detector Searches ➔ Take advantage of high beam power
    - Axion-like Particles (ALP)
    - Low mass Dark Matter (LDM)
    - Heavy Neutral Leptons (HNL)
    - Dark Photon
    - Neutrino Trident
    - Milli-charge Particles (mCP)
    - **And many many more..**
  - Far Detector Searches ➔ Takes advantage of large mass LArTPC
    - Sterile neutrino searches
    - Non-standard Interactions, Non-Unitarity, CPT violation
    - Large Extra Dimensions (LED)
    - Inelastic Boosted Dark Matter (iBDM)
    - **And many many more…**
- Strong collaborations of theorists and experimentalists generate many new ideas
- Some of these topics are covered in DUNE's EPJ C.81, 322 (2021)

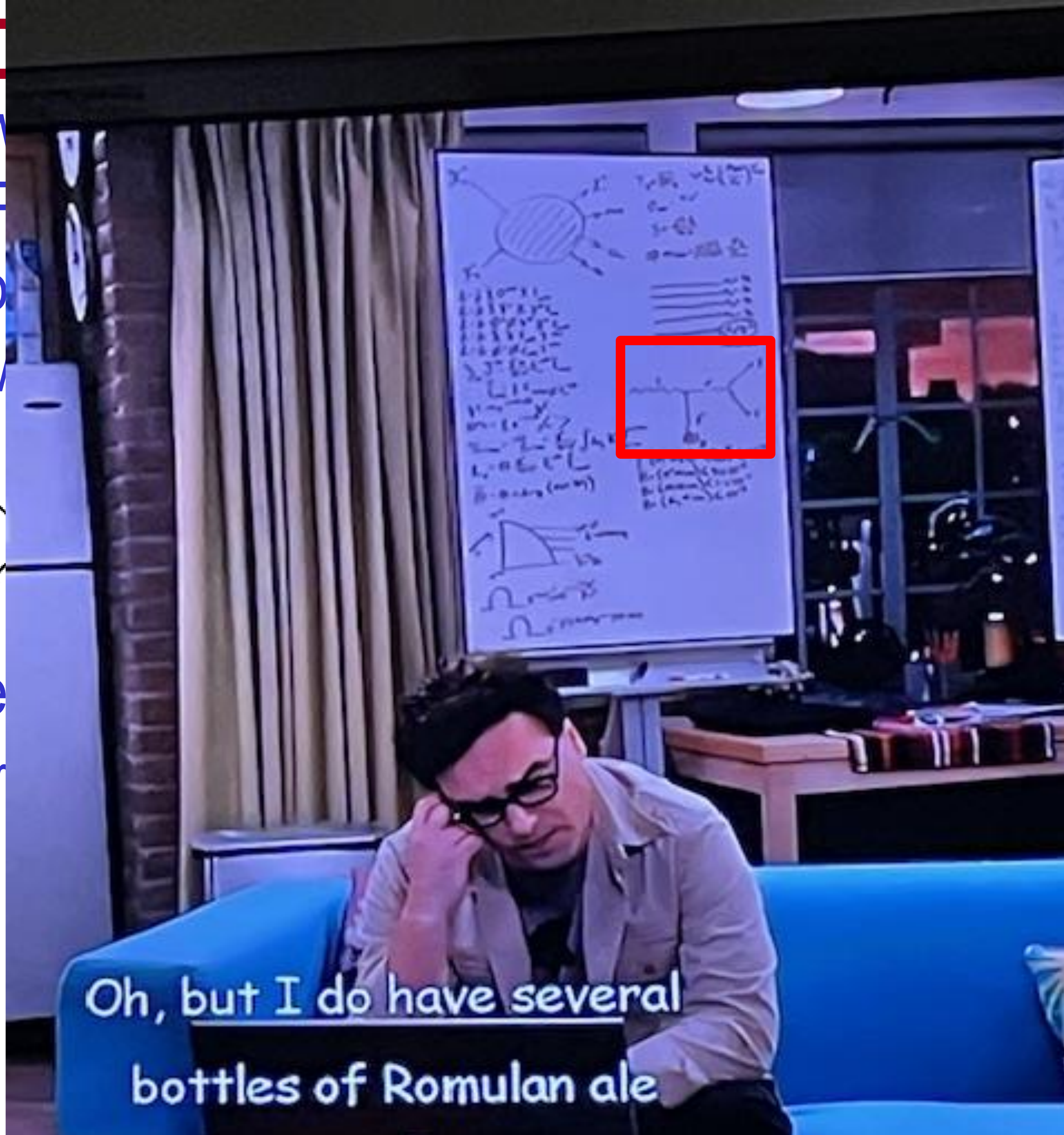
Physics Motivation For DSP

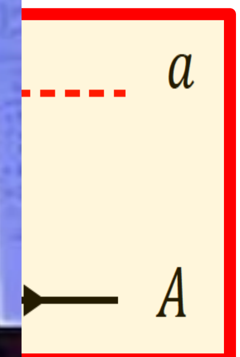
- SM describes the visible ~5% of the matter in the universe ➔ becoming more solidly established, while the neutrinos sector requires modifications
- Dark matter (Dark Sector Particle, DSP) makes up about 25% of the universe ➔must be explored better
- Direct searches have limitations in kinematic reach, 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



D… n?

- New … **orces**
- DSP … ediator
- Pho … cays →
  new

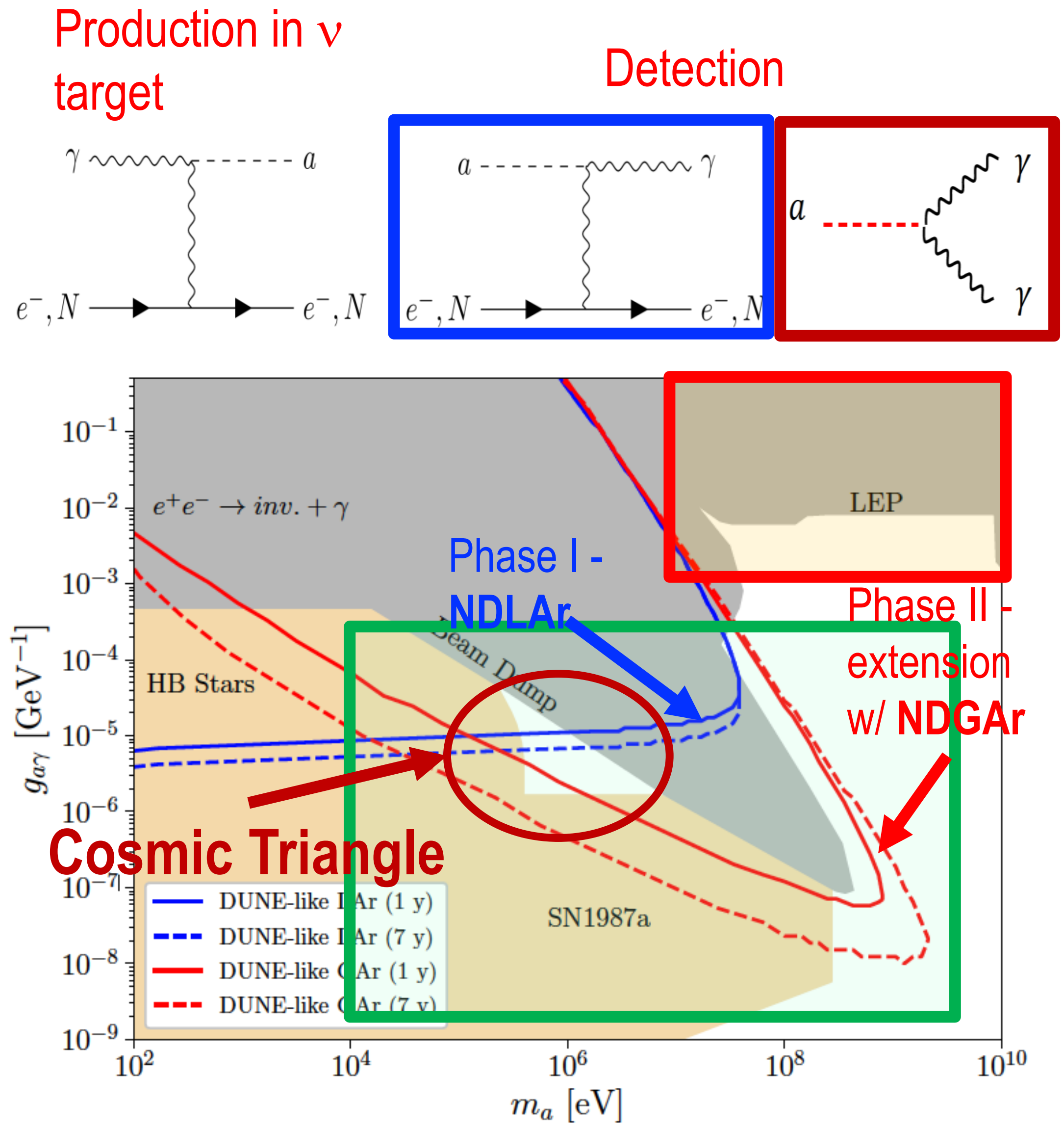




- Dete … coil or
  1, 2 …

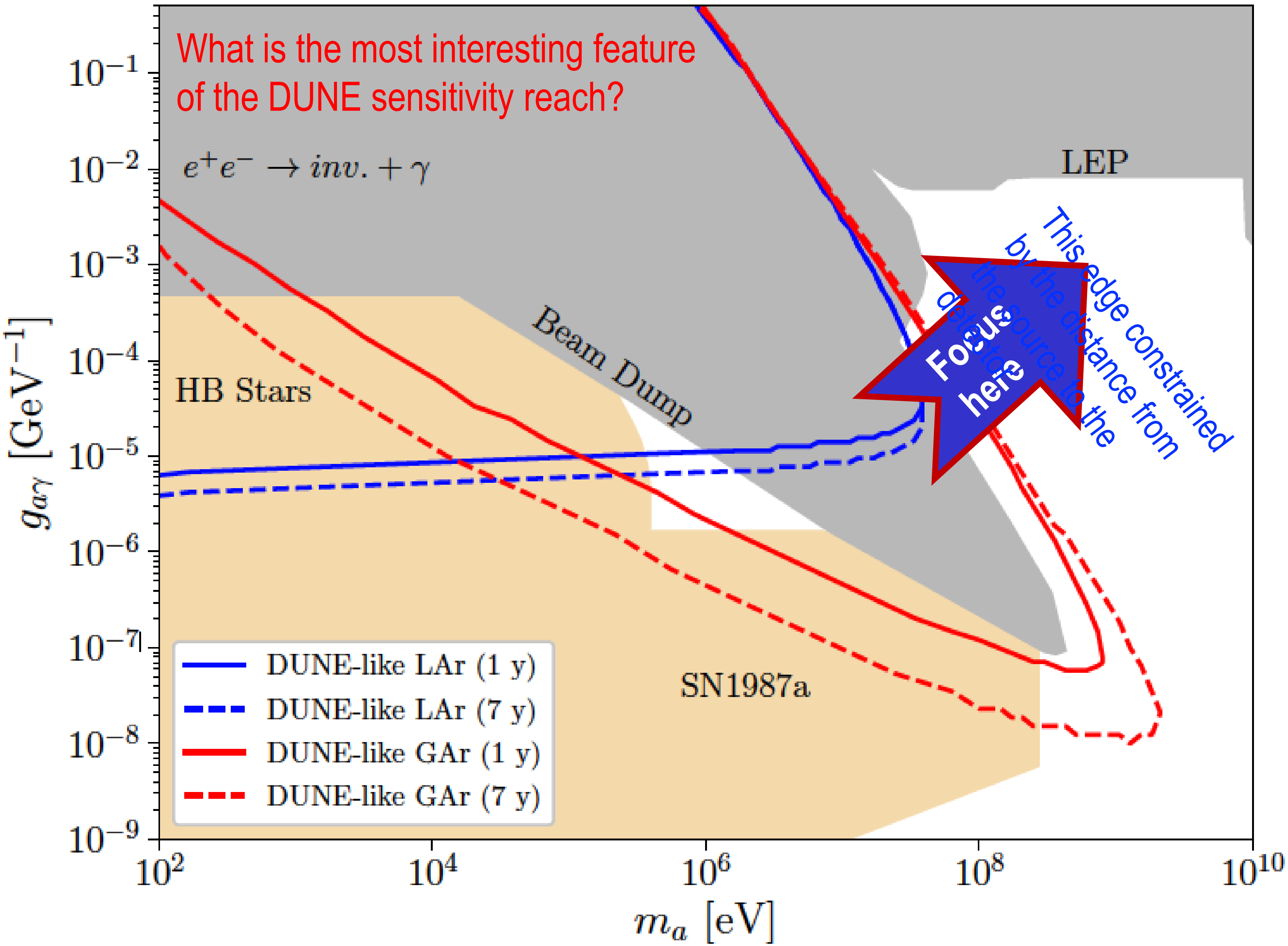
ALP Searches @ DUNE ND

- Axion-like particles (ALP) produced in Primakoff process in the ν target
- Detection through a scattering with e/N + γ or decays to two γ
- DUNE ND Phase II enables complete closure of the Cosmic Triangle!!



Brdar, Yu et al., PRL126, 201801 (2021)

Opportunities on ALP Searches

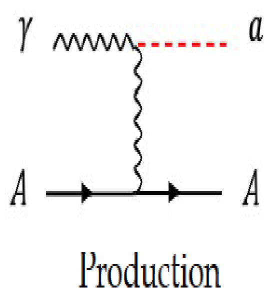


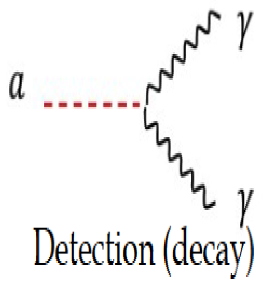
What is DAMSA?

- A dark sector particle 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 – Deep thoughts, Rumination
    - Jang, Yu *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 to be built in SK
- The 800MeV PIP-II LINAC beams fit the bill
  - The goal is to build the experiment in time for PIP-II LINAC

DAMSA Physics Strategy

- Focus on Axion-like particles (ALP) search through their **two-photon** final state via the Primakoff process as the use case but 2e or 2μ final states also work

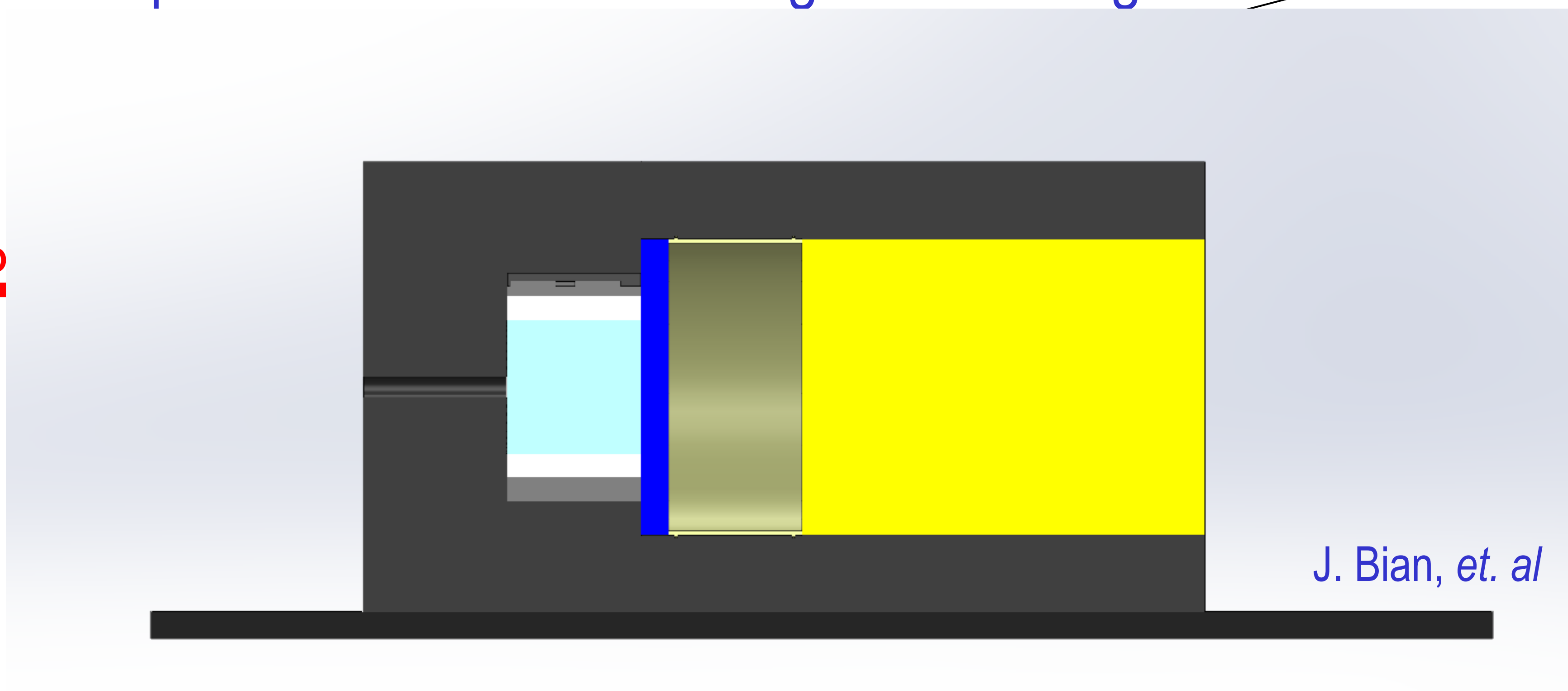




- Produce as many photons as possible in the dump
- Capture as many ALPs as possible in as wide a mass range as possible in its 2γ final state
  - Minimize the distance from the source to the detector
  - Utilize a vacuum chamber to further extend effective detector coverage
- Minimize/mitigate the backgrounds from neutral particles
  - Neutron spallation
  - ν QE, RES, and NC interactions

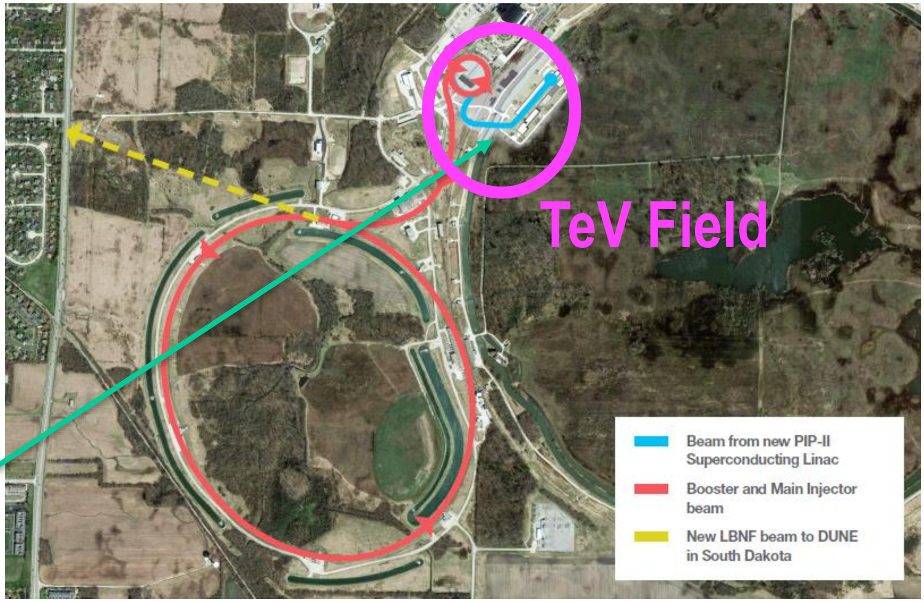
DAMSA Exp. Concept

- Inject and absorb as many low-E protons and produce as large number of γ in the dump as possible
- Allow higher mass ALP's to **decay in the vacuum** w/ 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



Accelerator Complex in the PIP-II Era

- PIP-II LINAC is the essential first element for DUNE
- PIP-II (Proton Improvement Plan – II) provides
  - New SRF LINAC for injection into Booster at 800MeV
    - Total proton current of 2mA which translates up to ~4×10^{23} PoT/yr
  - 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

The three key elements

- The bad / The man
- The ugly / The dump
- The good / The detector

DAMSA Requirements – The Beam

- PIP-II LINAC's 800MeV beam energy enables access to the tangible ALP mass range
  - With much reduced neutrino backgrounds
- PIP-II LINAC CW beam characteristics (total proton current: **2mA**)
  - Bunch length: 1ns
  - N_p/bunch : $8x10^7$ p/bunch (~$4x10^{23}$ p/yr)
  - Bunch spacing: 6.2ns
- Can chop the bunches to mimic pulsed beam structure & raster the beam for dump thermal considerations
  - Studies show that the intended physics reach can be accomplished even w/ 10% of the LINAC proton intensity

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
  - Maintain short distance (~1m) to the detector
- 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
  - Charged pions get observed in the dump

DAMSA Requirements – The Detector 1

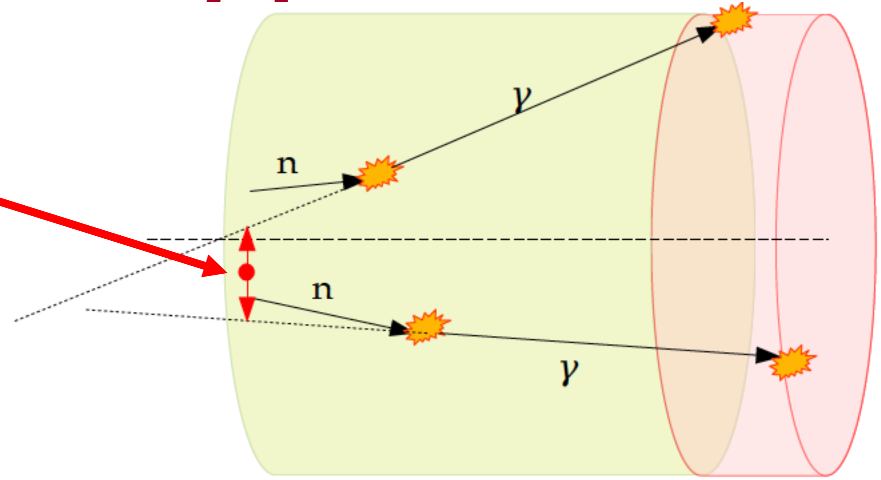
- What detector capabilities are needed to
  - Capture as many ALP's as possible in as wide a mass range as possible
    - **Higher mass, high coupling** ALP's have **shorter lifetime** ➔ Need to be able to capture two photons from the ALP decays upstream of the detector
    - **Lower mass, low coupling** 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
    - Minimize the materials upstream of the detector for neutron interactions
- Place a large decay volume in vacuum to fill the gap between the dump and the detector ➔ Extends effective detector range
  - Allows higher mass ALPs to decay ➔ giving clear vertices where the two final state photons originate from
  - Neutron interactions confined to the decay chamber walls

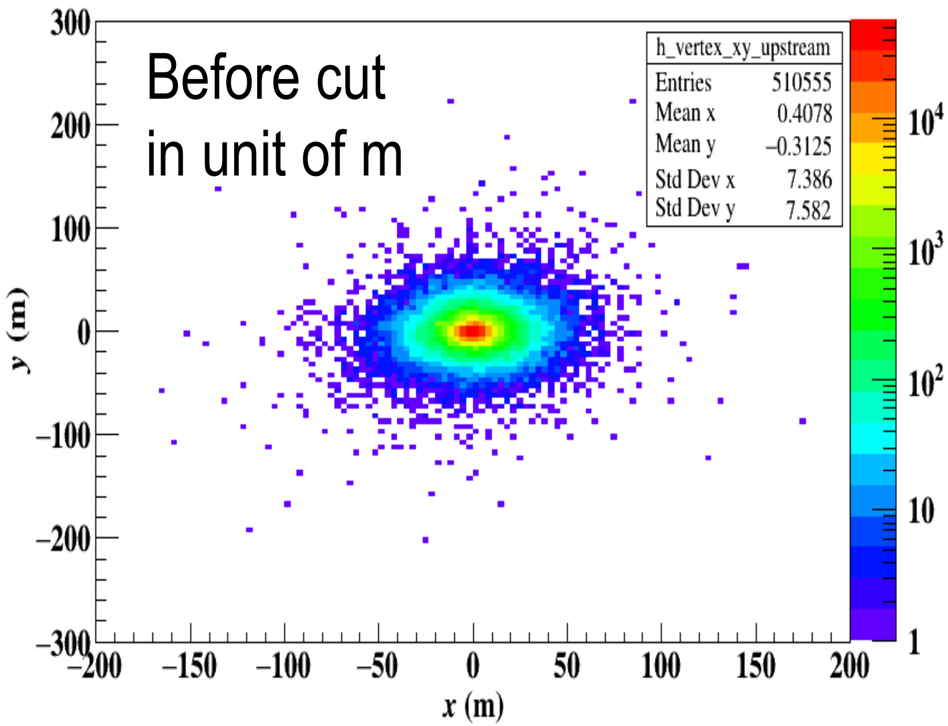
DAMSA Requirements – The Detector 2

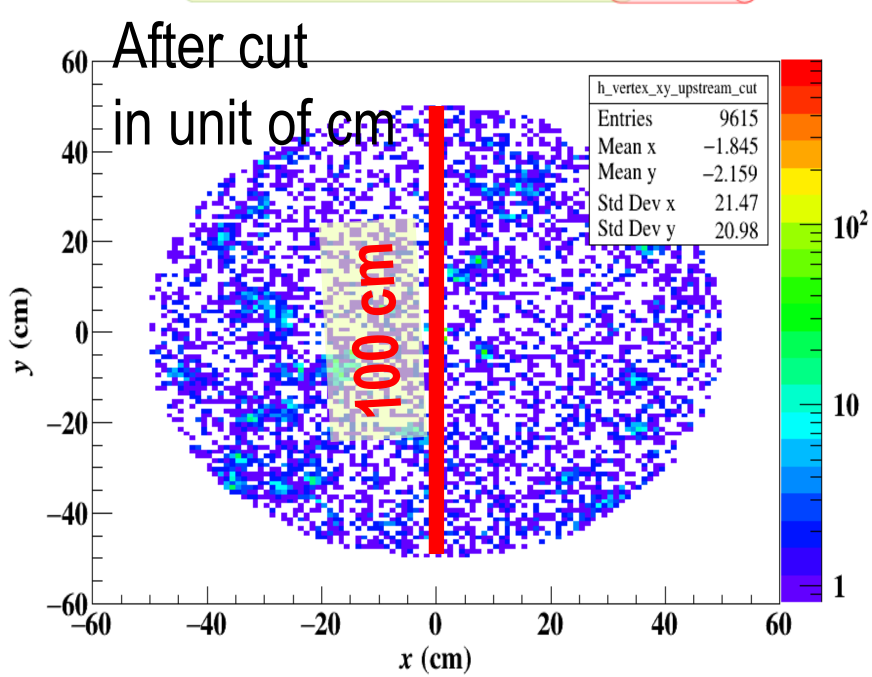
- What are other possible ways to further reduce the background from neutron spallation? ➔ Aim to reduce by order >=10^{10}
  - Leverage the speed of the neutrons ➔ Neutrons are 10 – 1000 times heavier than the ALPs, thus for the given momentum, the arrival time of the neutron induced photon accidentals would be slower than that of the ALP's
  - Arrival time difference between the two photons
  - Leverage the distance of closest approach of the two photon traces
  - Require the traceback of the overlapping two photon momentum sum point the dump

DAMSA Detector – The γ pair traceback

- Require two photon track trace back position be inside the dump perimeter
- 2×10^{-2} of γ pairs remain







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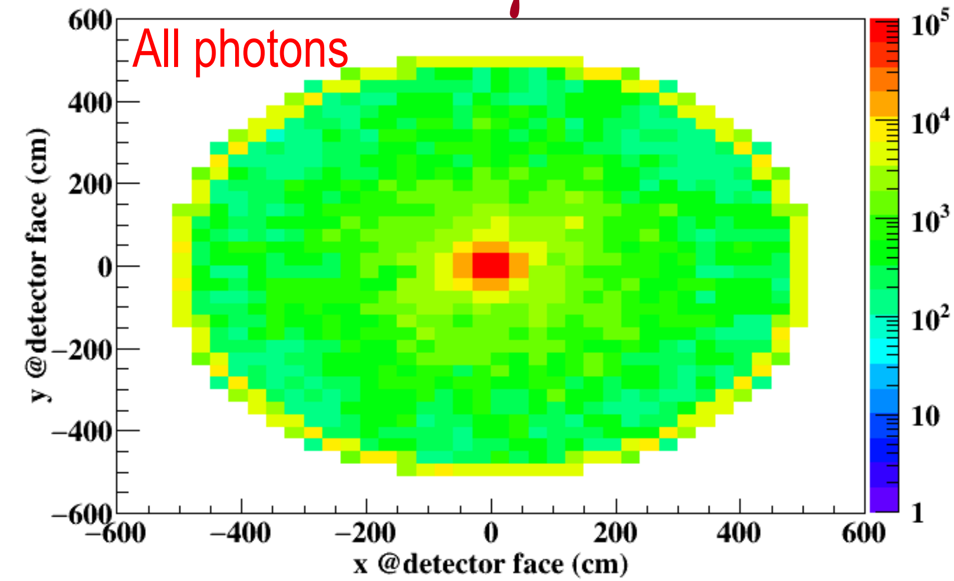
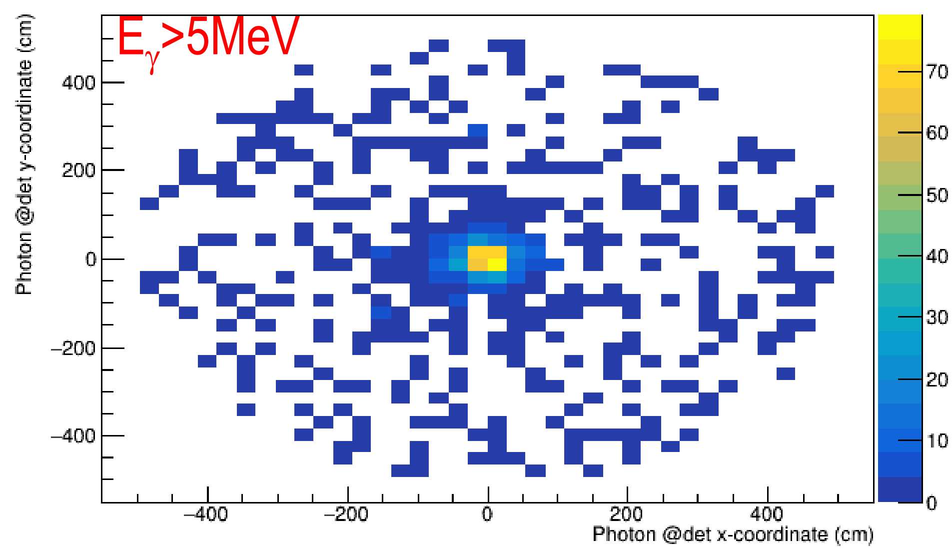
  - Arrival time difference between the two photons
  - Leverage the distance of closest approach of the two photon traces
  - Require the traceback of the overlapping two photon momentum sum point the dump
  - Invariant mass of the two photon momenta be within the interested mass range
- Large number of photons from neutrons at low kinetic energy ➔ Require the photon energy to be greater than 15 MeV (we can drive all the way up to 100MeV!!)

DAMSA Detector Study E_γ Cut

- Geometry implemented in GEANT4
- 10^8 600MeV protons injected to dump
- 260k neutrons enter the decay chamber
  - 2.6×10^{-3} n/p
- 1.6×10^6 γ produced from n
- 3.2×10^3 γ with E>5MeV → ~1k enter the detector fiducial volume
- 5.1×10^5 γ–pair combination possible





Neutron Background Reduction Summary

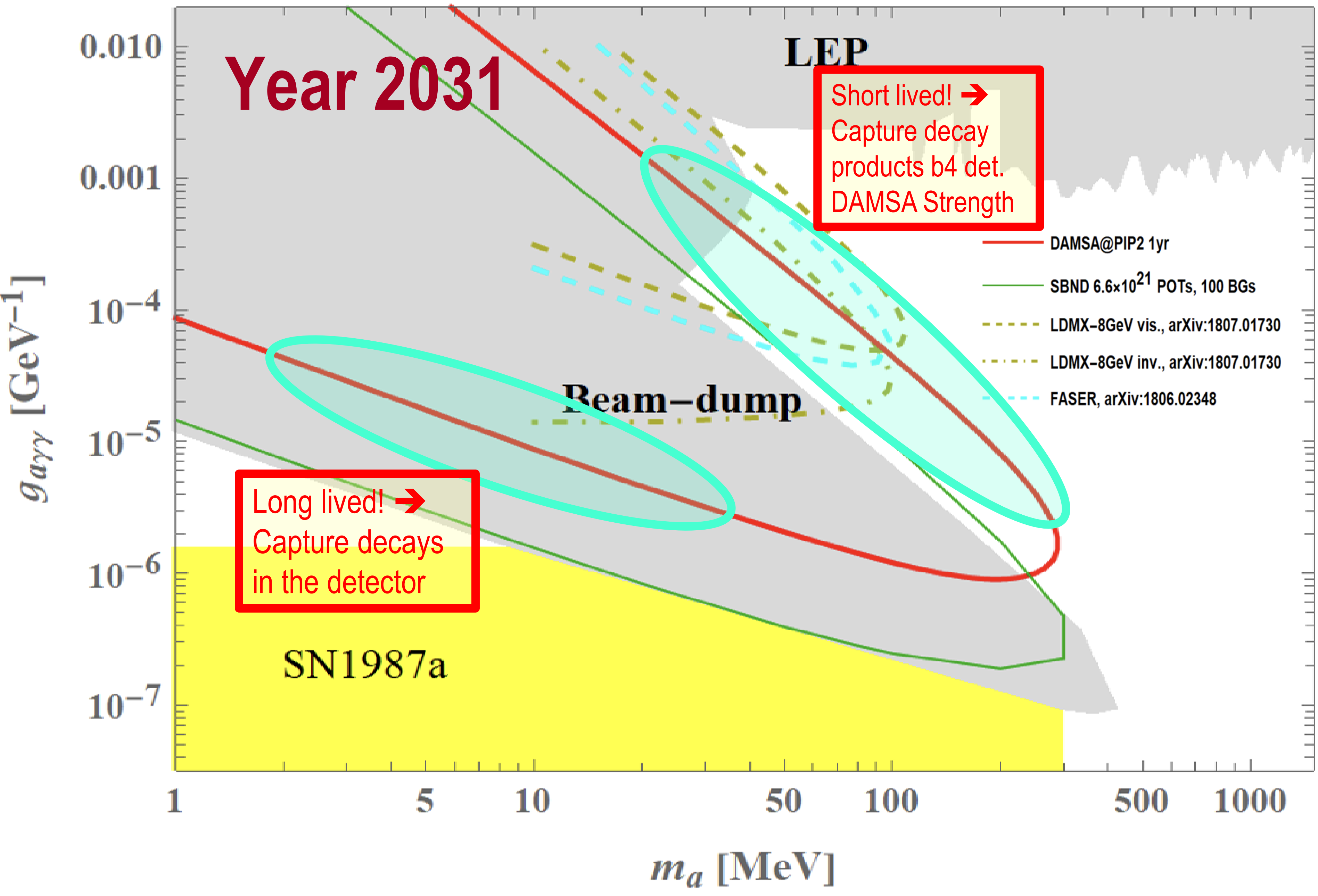
- Benchmark Beam Parameters -
Beam energy (E_{beam}) : 600 MeV
Beam current (I_{beam}) : 660 μA
Beam power (P_{beam}) : 400 kW
Protons-on-target per year : 1.3×10^{23}

Description	Symbol	Numbers
Protons per pulse	n_p	4.8×10^7
Beam induced neutrons	n_n	1.29×10^5
Neutron-induced photons	n_γ	2.74×10^5
n_γ after 15 MeV threshold cut	$n_{\gamma,th}$	25.1
Neutron-induced photons hitting the detector	$n_{\gamma,th,det}$	2.94
< 40 ns arrival time cut	$n_{\gamma,th,det,TOA}$	1.47
Number of photon pair combinations	$n_{\gamma\gamma}$	< 1
Cut	**Symbol**	**Efficiency**
Fiducial volume cut	$\epsilon_{fid.vol.}$	6.13×10^{-1}
DCA < 1 cm	ϵ_{DCA}	4.23×10^{-3}
$\Delta TOA < 0.1$ ns	$\epsilon_{\Delta TOA}$	2.01×10^{-1}
Back-tracing	$\epsilon_{backtrace}$	4.16×10^{-2}
Invariant mass ($29MeV < m_{inv} < 31MeV$)	$\epsilon_{m_{inv}}$	1.46×10^{-2}
Invariant mass ($99MeV < m_{inv} < 101MeV$)	$\epsilon_{m_{inv}}$	1.25×10^{-3}
Invariant mass ($199MeV < m_{inv} < 201MeV$)	$\epsilon_{m_{inv}}$	2.02×10^{-5}

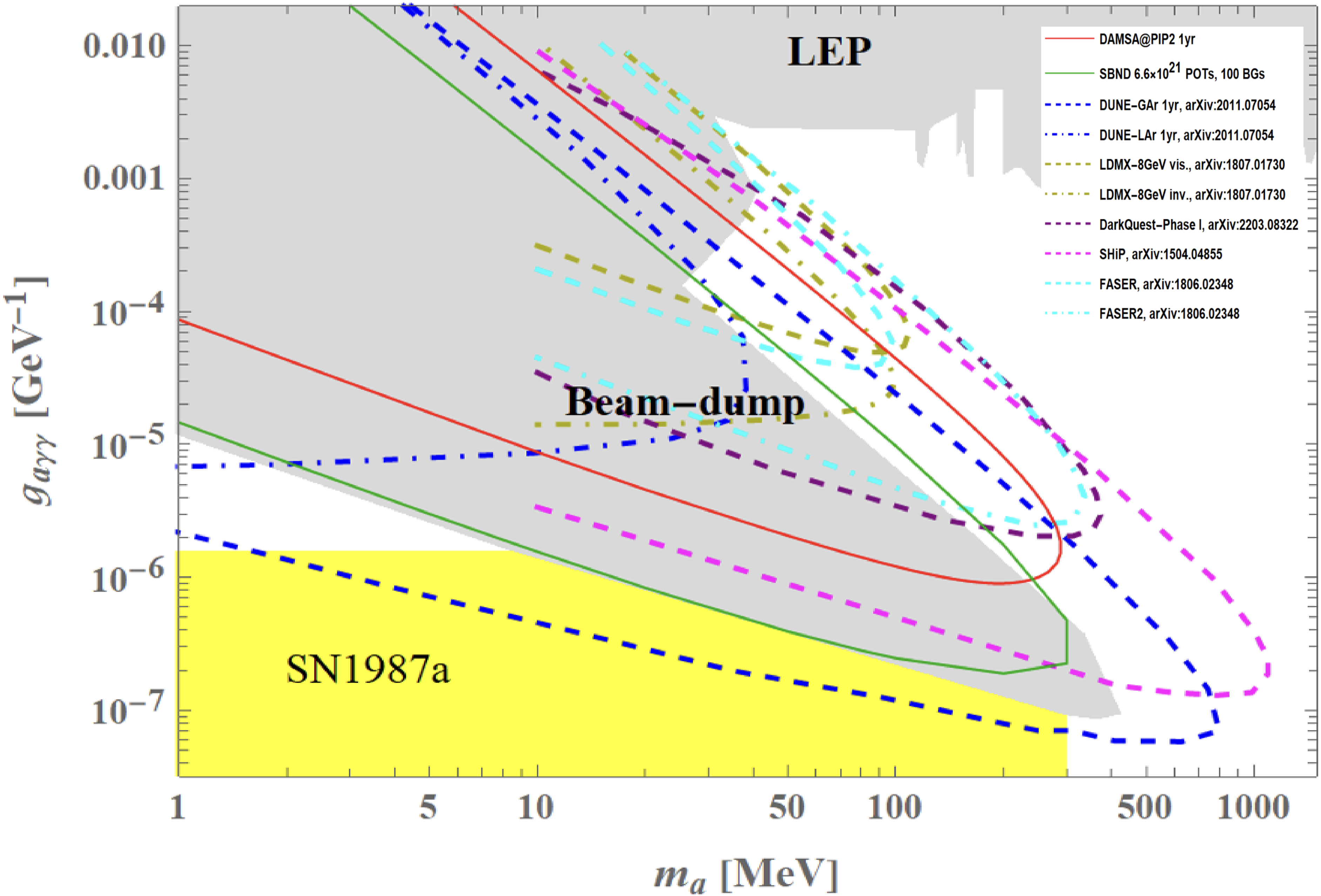
neutron-induced photons are reduced by (1 / 2.74e-5) = **3.6e-6**

Overall rejection factors
1.92e-7
9.51e-9
1.54e-10

DAMSA Sensitivity – Running Experiments



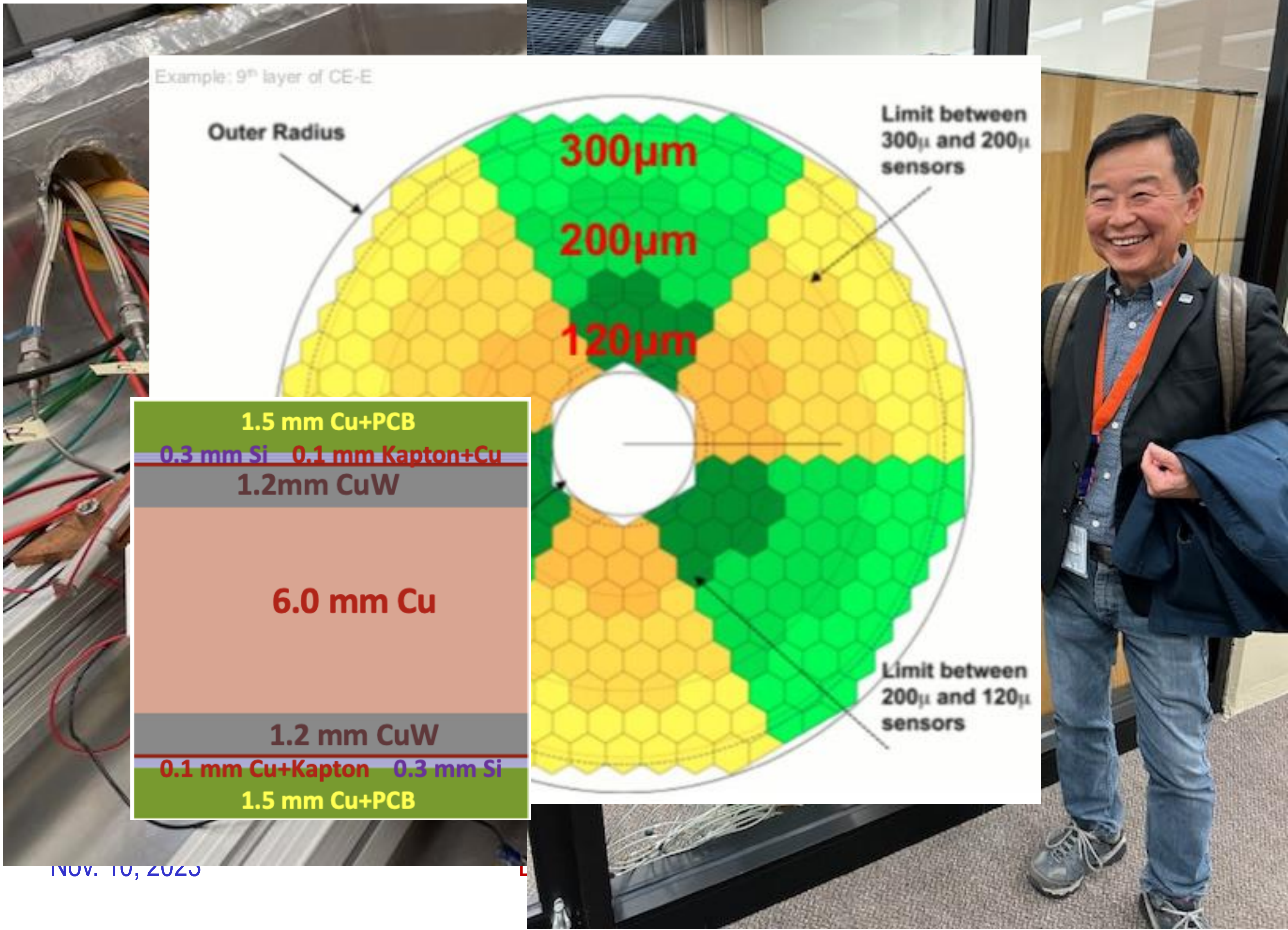
DAMSA Sensitivity – All Experiments



Physics Driven DAMSA Detector

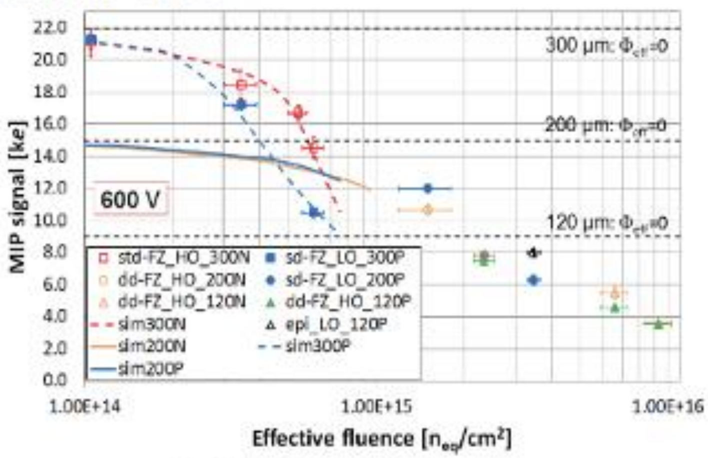
- Based on the physics studies using GEANT4 and neutron background mitigation ➔ The detector must have
  - Fine granularity for a superb shower position and angular resolutions for two photon vertex pointing & DCA precision better than 1cm in the vacuum decay volume
  - Fast timing capability at sub-ns level (100ps or better) for two photon arrival time differences
  - Capability of measuring up to 500 MeV photons with as fine a mass resolution as accomplishable

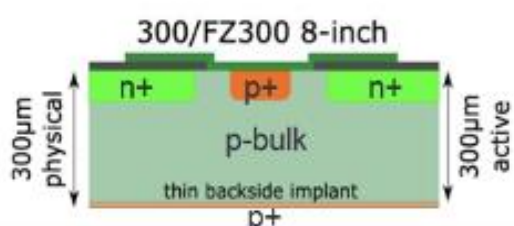
Potential DAMS

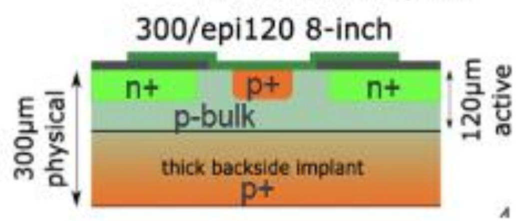


Silicon Sensor Design

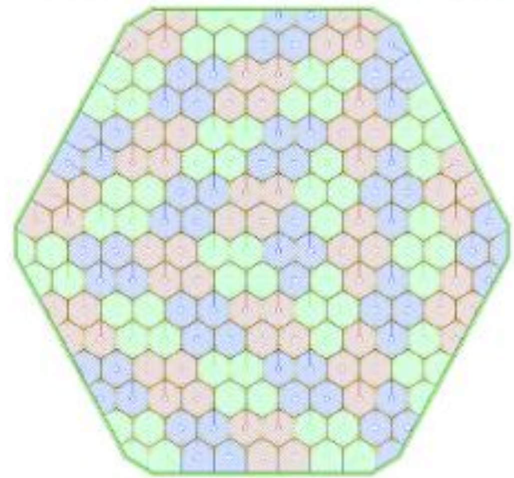
- **Design has been finalized in 2021**
- **Hexagonal shape to maximize usage of circular wafers**
- **8" wafers to lower cost wrt 6"**
  - Established new production line with Hamamatsu
- **Planar, DC-coupled, p-type sensors**
  - more radiation hard than n-type
- **Thin sensors collect more charge at high fluence**
  - Publication



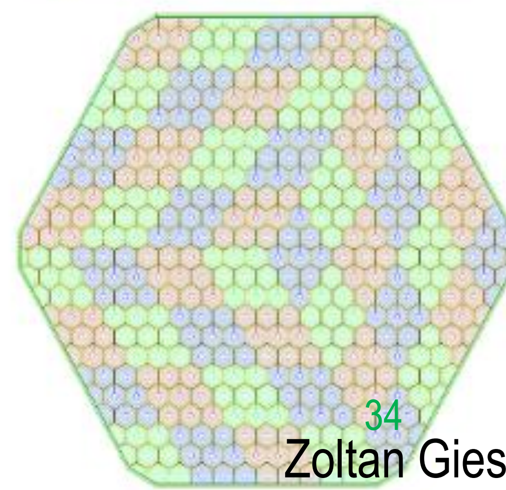




LD: ~200 cells of 1.2cm^2
300um & 200um thickness



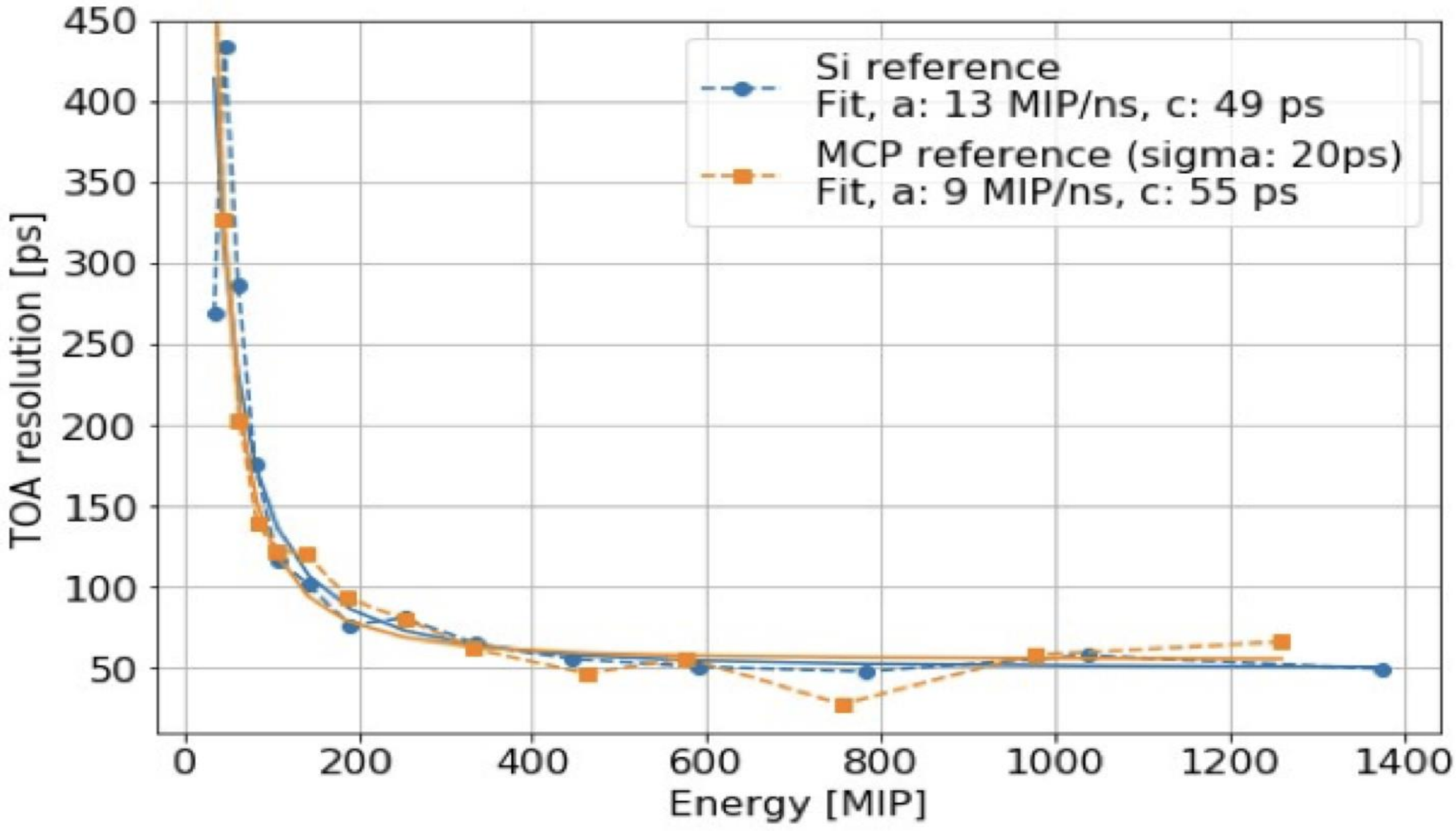
HD: ~450 cells of 0.5cm^2
120um active thickness



Zoltan Giesce

HGCAL Performances

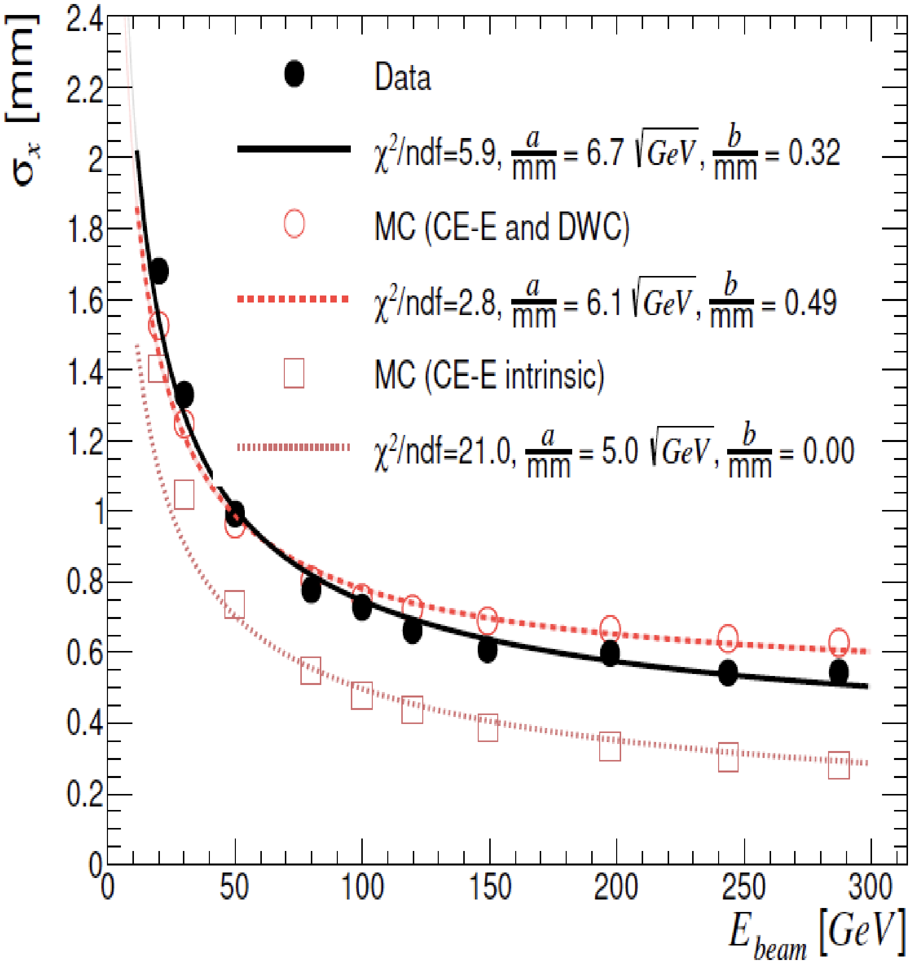
- Timing resolution : 30ps @ P_T>5GeV

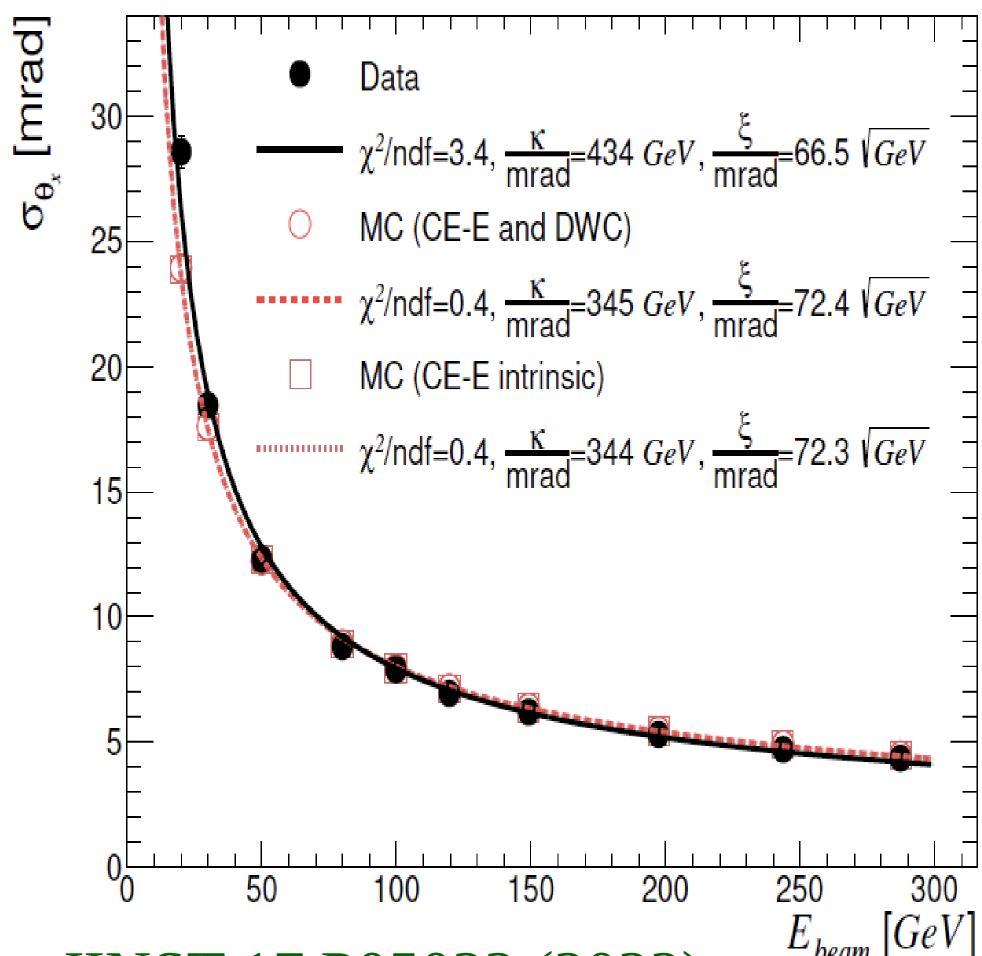


JINST 15 C07003 (2020)

Shower axis position & angular resolution

- 3.3mm @ E_e=5GeV & 117mrad @ E_e=5GeV

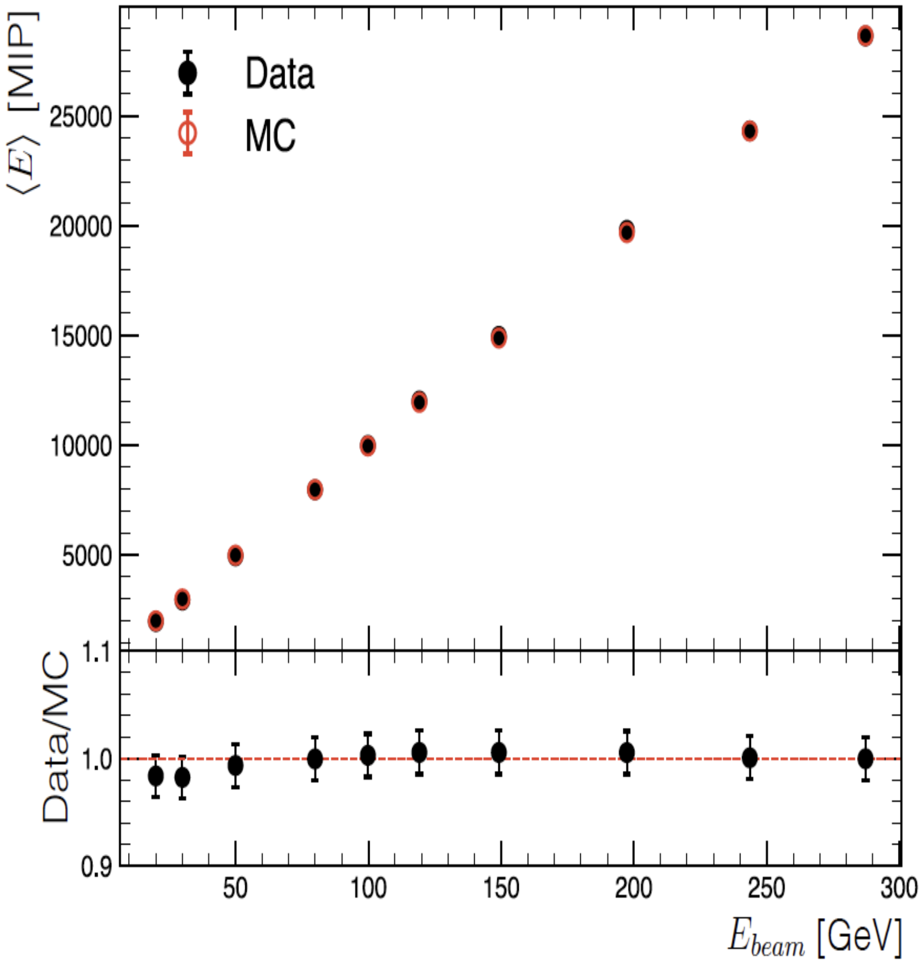


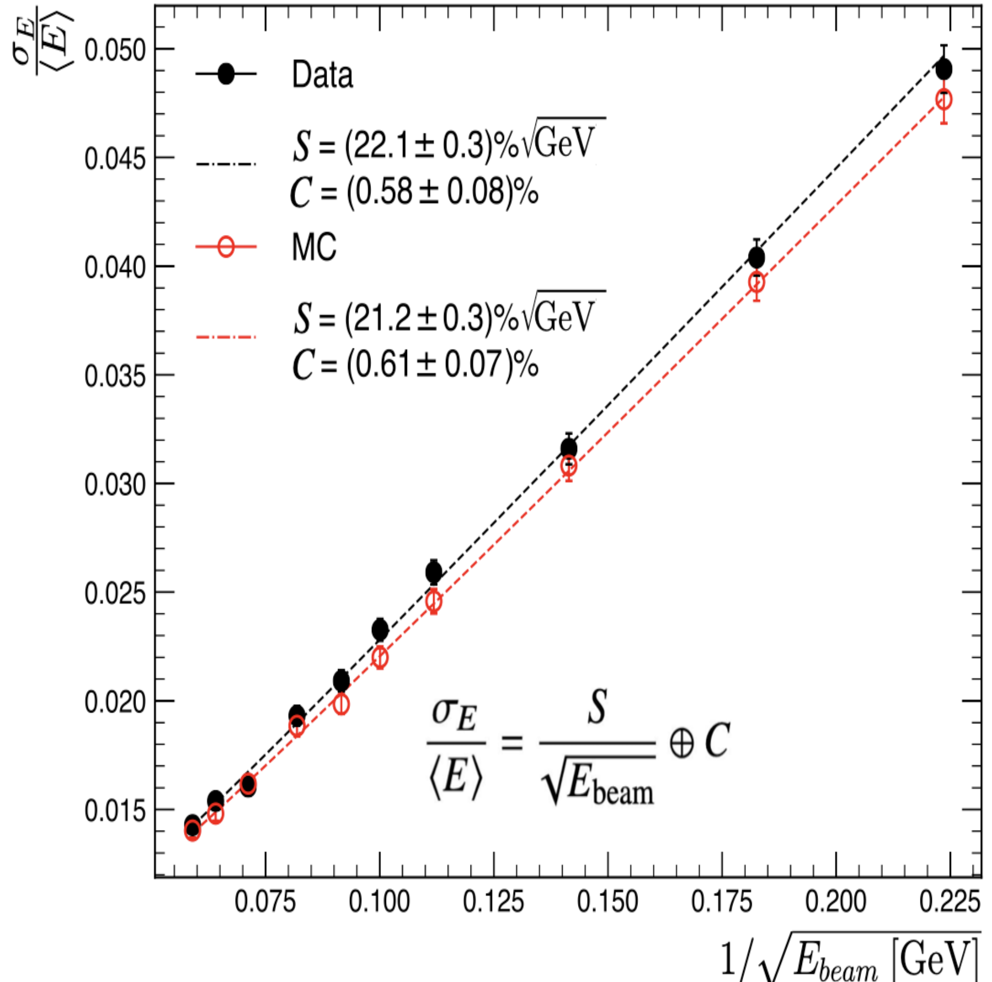


JINST 17 P05022 (2022)

HGCAL Performances – E measurements

- Energy resolution: 50%@E_e=5GeV





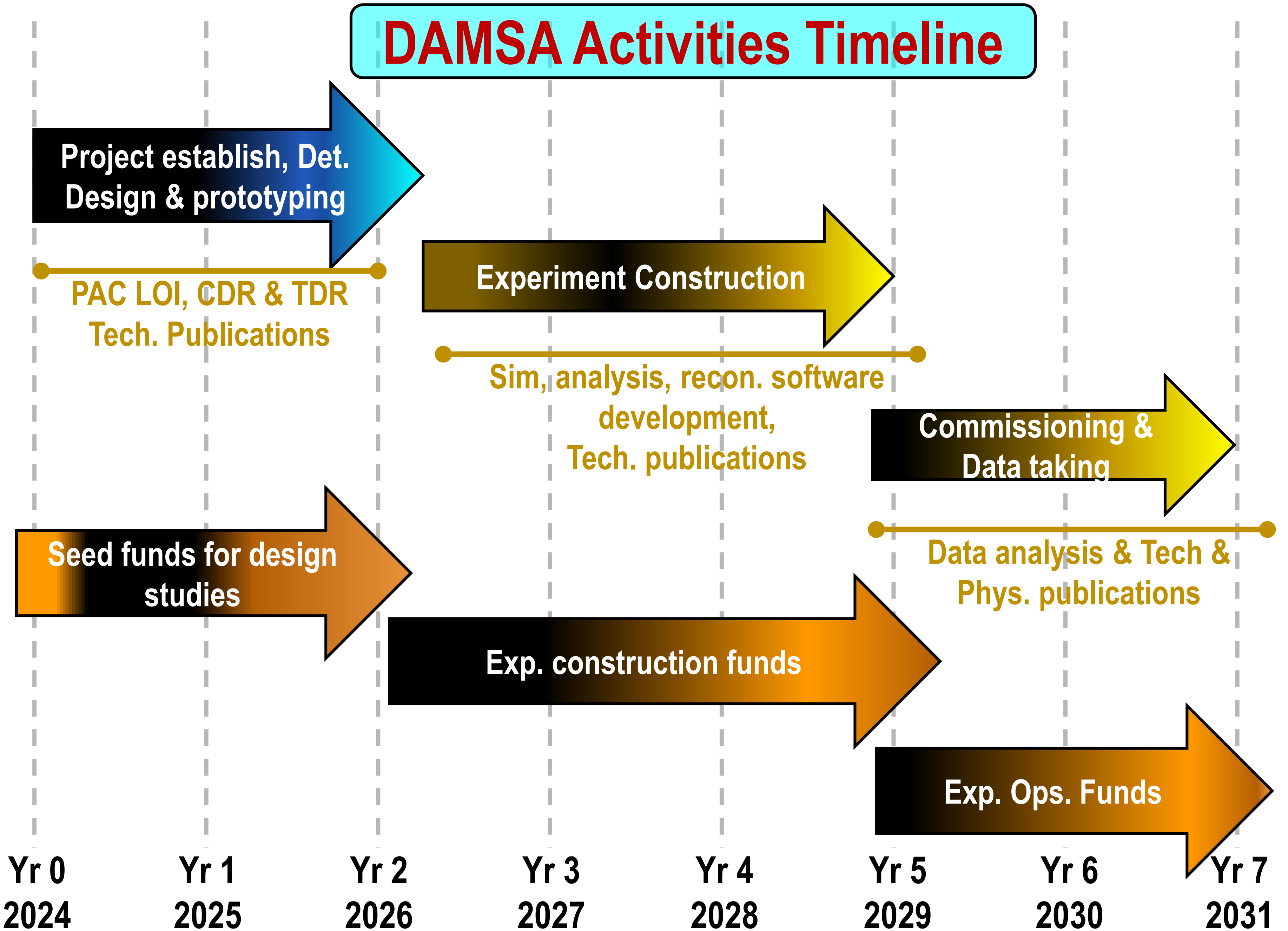
JINST 17 P05022 (2022)

Ongoing Studies

- Detector geometry optimization
- Dump design optimization to meet the safety requirements, while keeping the distance from the source to the detector @ 1m and high Z
- Understanding neutron background impacts
  - Optimal beam timing structure thru the chopping feature and the impact of it to the neutron flux
  - Neutrons from the surrounding shielding materials, such as concrete walls
- Other physics topics to be probed with DAMSA
  - Promising results on dark photon to e^+e^- final states

DAMSA Experiment Timeline

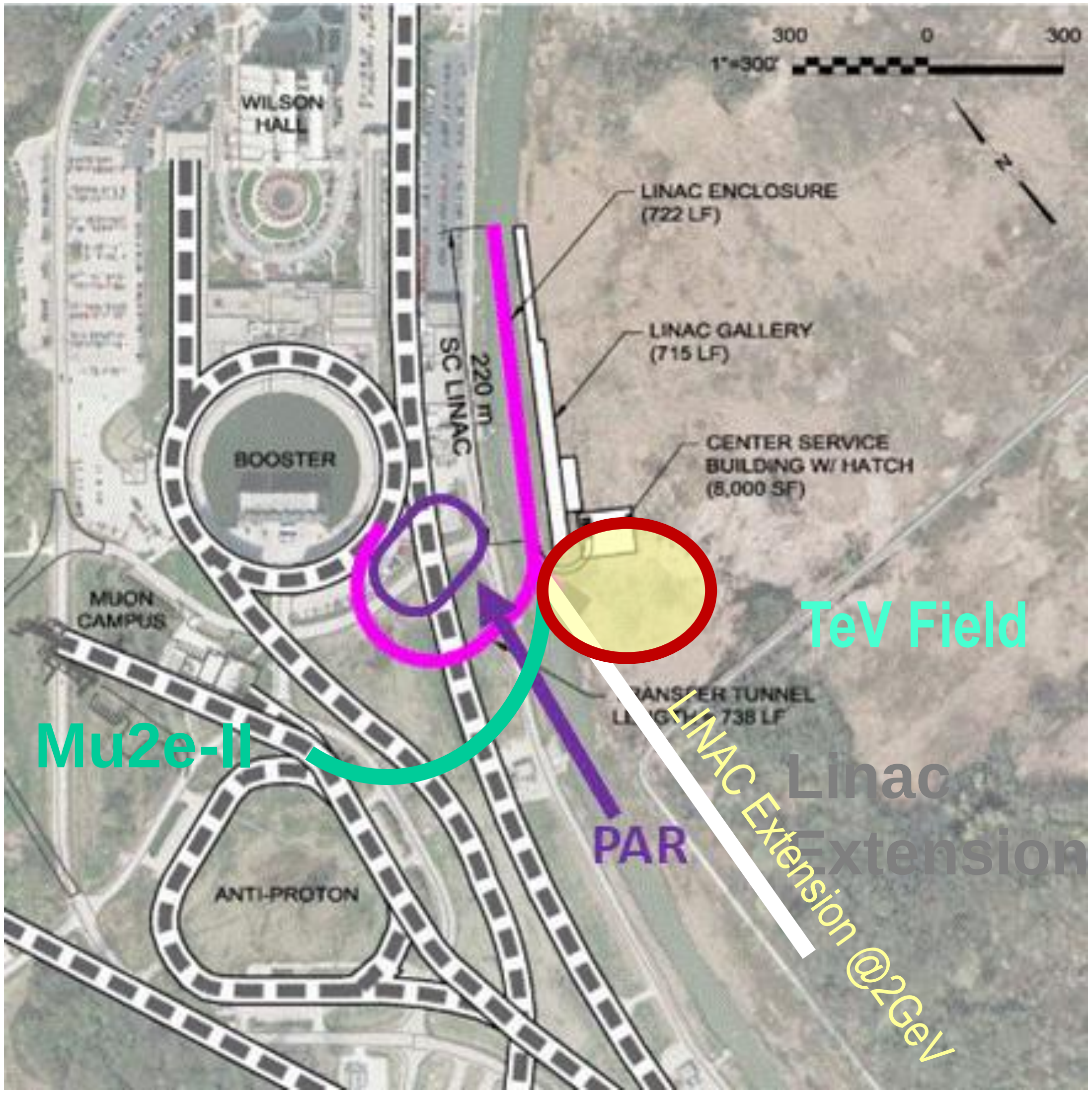
- **Overarching strategic goal: Get the detector ready to take data in time for PIP-II LINAC completion in 2029**
- Mid Dec. 2023 : Prepare & submit an LOI to Fermilab PAC
  - Both the beam dump facility and the day 1 detector, DAMSA
- Jan. 2024: Present the LOI to Fermilab PAC
- 2024 – 2025/2026: detector design, prototyping, experiment establishment and securing funds
- 2025/2026 – 2028: experiment construction
  - Essential for Fermilab beam dump facility to be completed
    - White paper on PIP-II BD opportunity to be released soon
- 2029: Complete the detector construction and start commissioning for data taking


DAMSA Activities Timeline
Project establish, Det. Design & prototyping
PAC LOI, CDR & TDR Tech. Publications
Experiment Construction
Sim, analysis, recon. software development, Tech. publications
Commissioning & Data taking
Data analysis & Tech & Phys. publications
Seed funds for design studies
Exp. construction funds
Exp. Ops. Funds
Yr 0 2024
Yr 1 2025
Yr 2 2026
Yr 3 2027
Yr 4 2028
Yr 5 2029
Yr 6 2030
Yr 7 2031

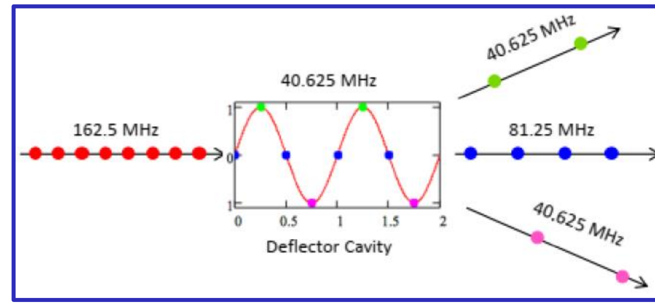
Fermilab Experimental Facility

- Proposed Name: F2D2
  - **F**ermilab **F**acility for **D**ark matter **D**iscovery
- Requirements
  - Basic assumption : >=4 experiments operate simultaneously (2 on-axis and 2 off-axis)
  - Sufficient footprint per experiment
  - Sufficient height of the hall w/ a large capacity crane coverage
  - Sufficient overburden (>=40.m.w.e.)

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.

J. Eldred

DAMSA Collaboration Building

- DAMSA has been introduced to the community throughout the past 2.5 years, more intensely in 2023
  - Concept included in a few Snowmass2021 white papers
  - Physics case study published on PRD (Jan. 2023)
  - Multiple presentations made at conferences, workshops and seminars in the U.S., SK and CERN LLP conf. in 2023
    - Presented at a couple of P5 townhall meetings
  - Introduced to Fermilab leadership April, May, Aug & Sept. 23
- Lead Investigators: J. Yu (UTA) & J. Estrada (FNAL)
- Institutions expressed interests thus far:
    - US (8): UTA, FNAL, OU, TAMU, UCR, UCI, CSU and SDSMT
    - SK (8): SNU, UoS, KNU-CHEP, Korea U., KyungHee U., Korea U. – Chochiwon campus, CNU, CBU
    - Strongly encourage European colleagues to join in

Conclusions

- DAMSA is a DSP search and discovery experiment that aims to be ready for beam on day 1 of FNAL PIP-II era
- DAMSA has been making serious progress to meet the goal of being ready for PIP-II LINAC beam in 2029
- DAMSA collaboration building ongoing
- Detailed GEANT studies have been performed for detector requirements → Optimization in progress
- DAMSA presents an excellent opportunity for the community to turn Fermilab's new accelerator facility to a DSP search and discovery facility

Parting Questions

- Is the CMS style HGCAL detector sufficient to meet the physics goals? Are there others?
  - Impact of the beam radiations to the detectors?
  - Various performance requirements for low E γ?
- What other physic topics can we do with the DAMSA experiment configuration?
  - Is there a SM measurement DAMSA can contribute?
- What modifications to the DAMSA experimental configuration could dramatically expand the physics reach? – B field? μ-detector?

Interested in joining DAMSA?

Contact

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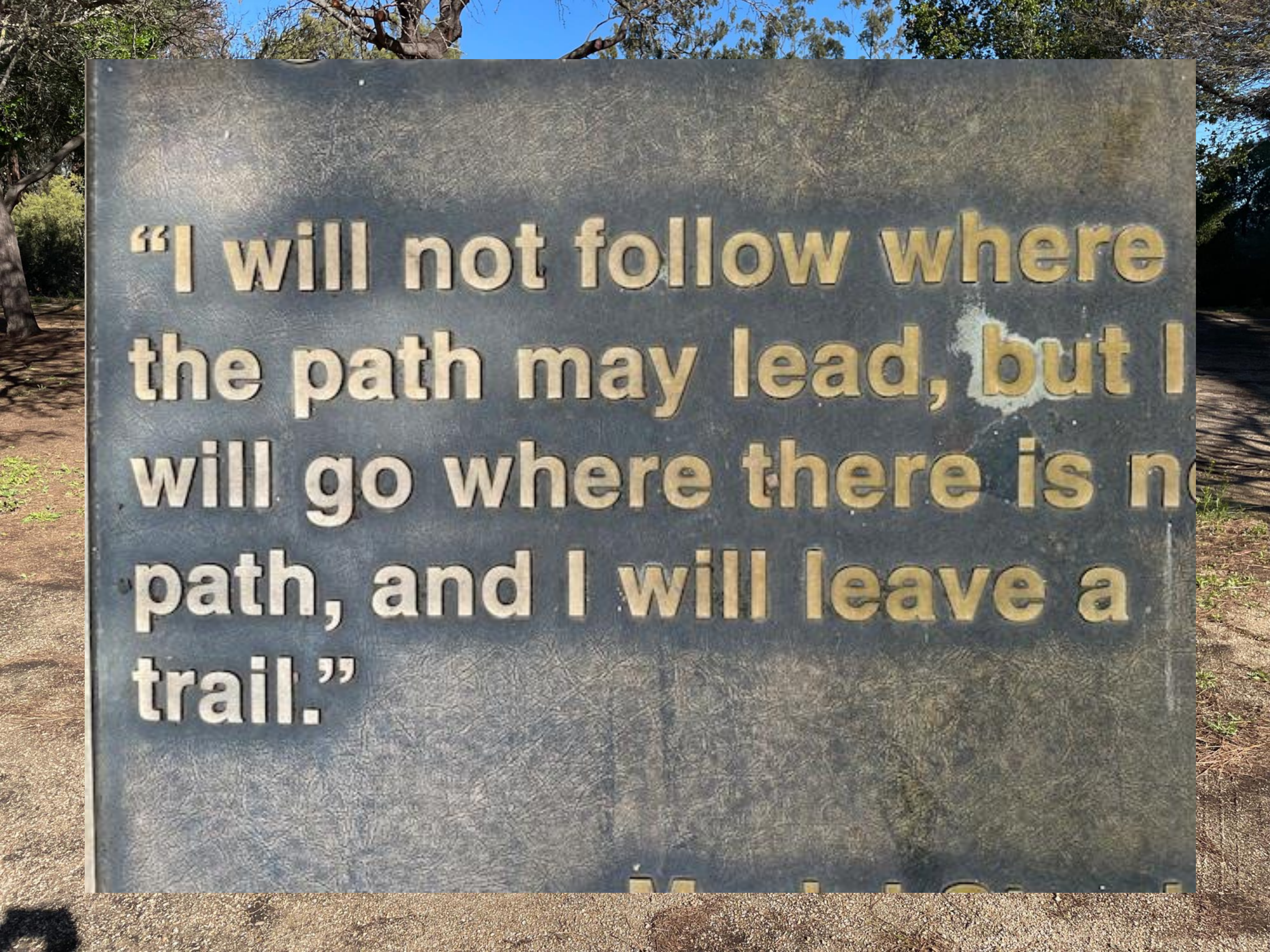
or

Juan Estrada (estrada@fnal.gov)


"I will not follow where
the path may lead, but I
will go where there is n
path, and I will leave a
trail."

Take Home Messages

Time for the community to look for dark matter in the beams

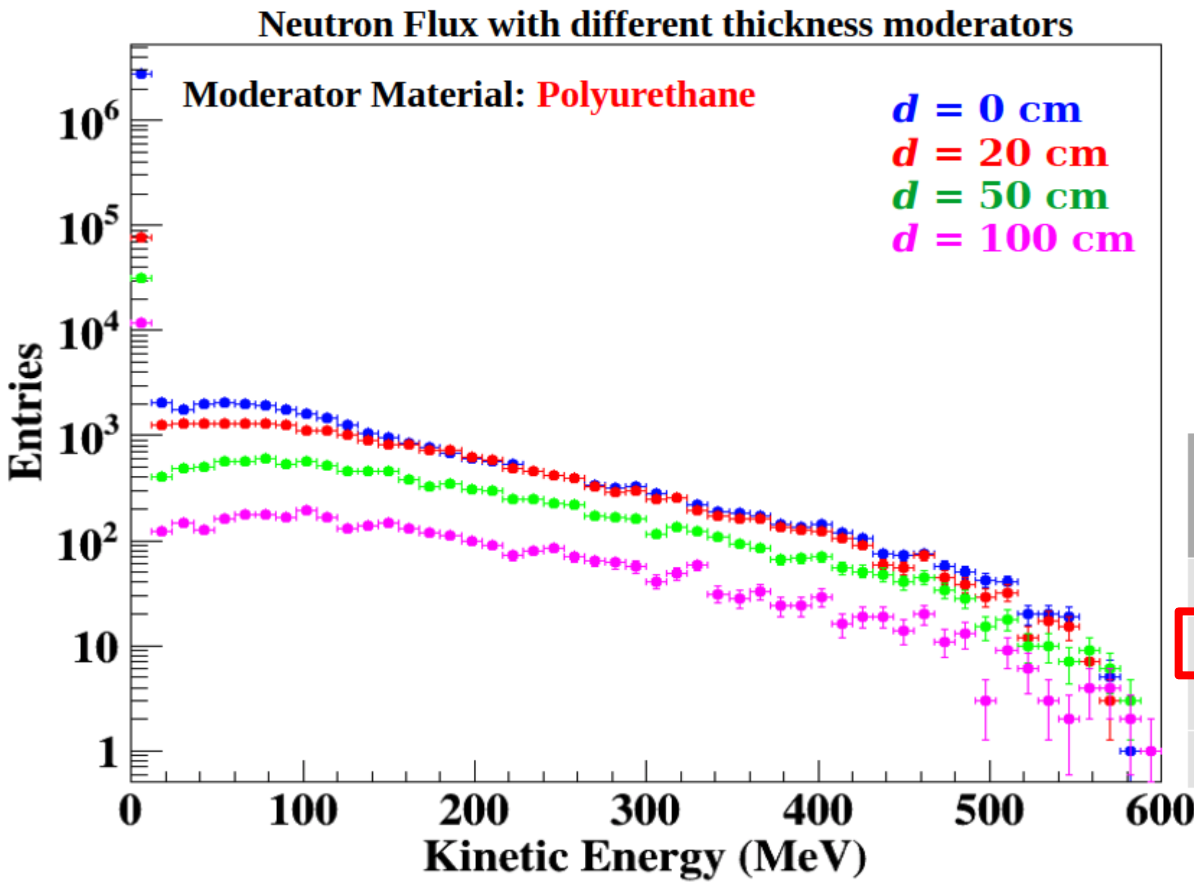
Accelerator facilities must leverage their capabilities fullest

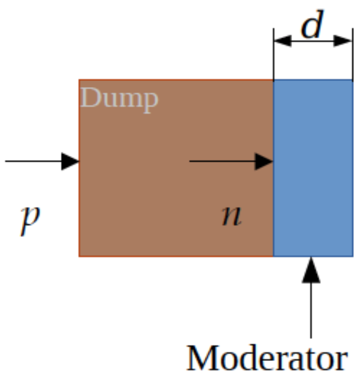
We must search wide, aim high, and delve deep!!

Back Up

DAMSA Requirements – The absorber

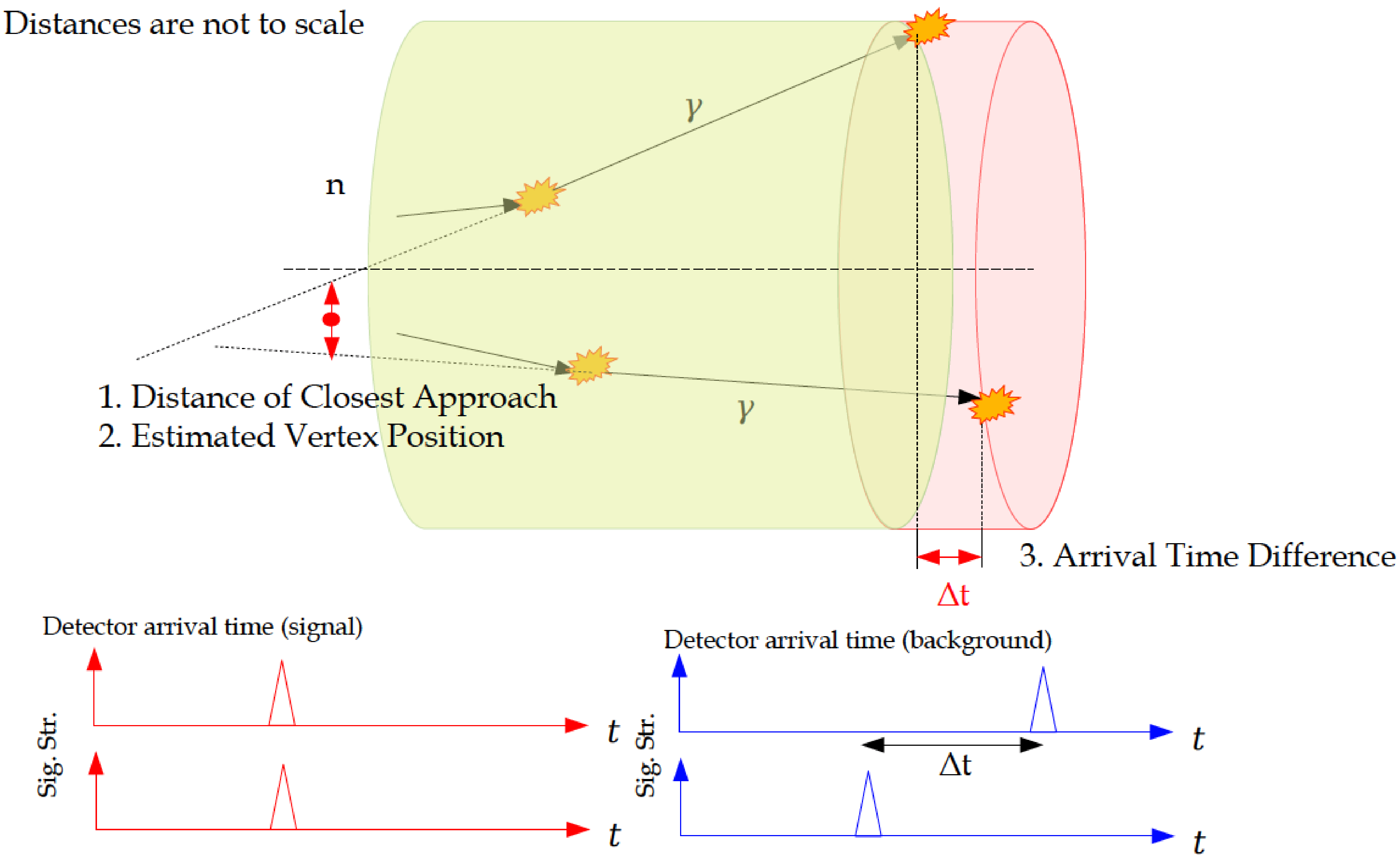
- Must reduce the number of n out the dump
- What material at what depth optimal for neutron absorption?
- GEANT4 based study shows the polyeuthrane provide most cost-effective solution for neutron moderation



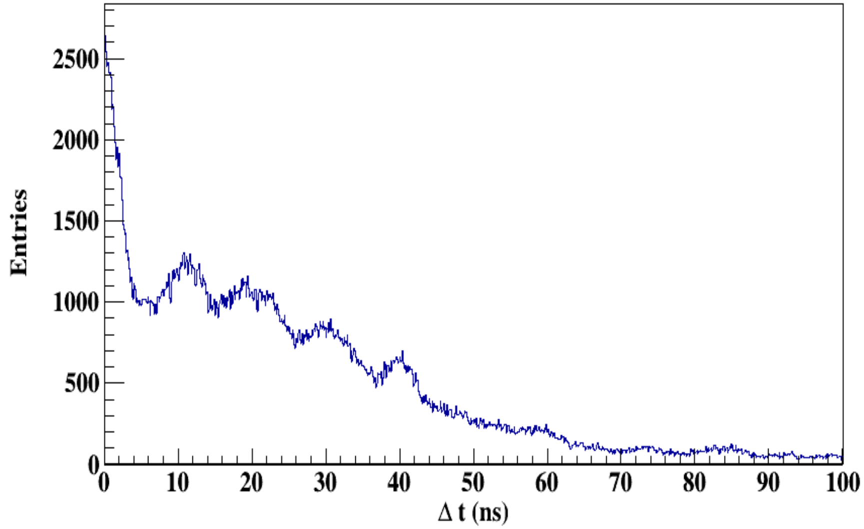


Thickness (d, cm)	Neutron Survival Rate
10	13.1 %
20	3.5 %
50	1.5 %
100	0.5 %

DAMSA Requirements – The Detector 2

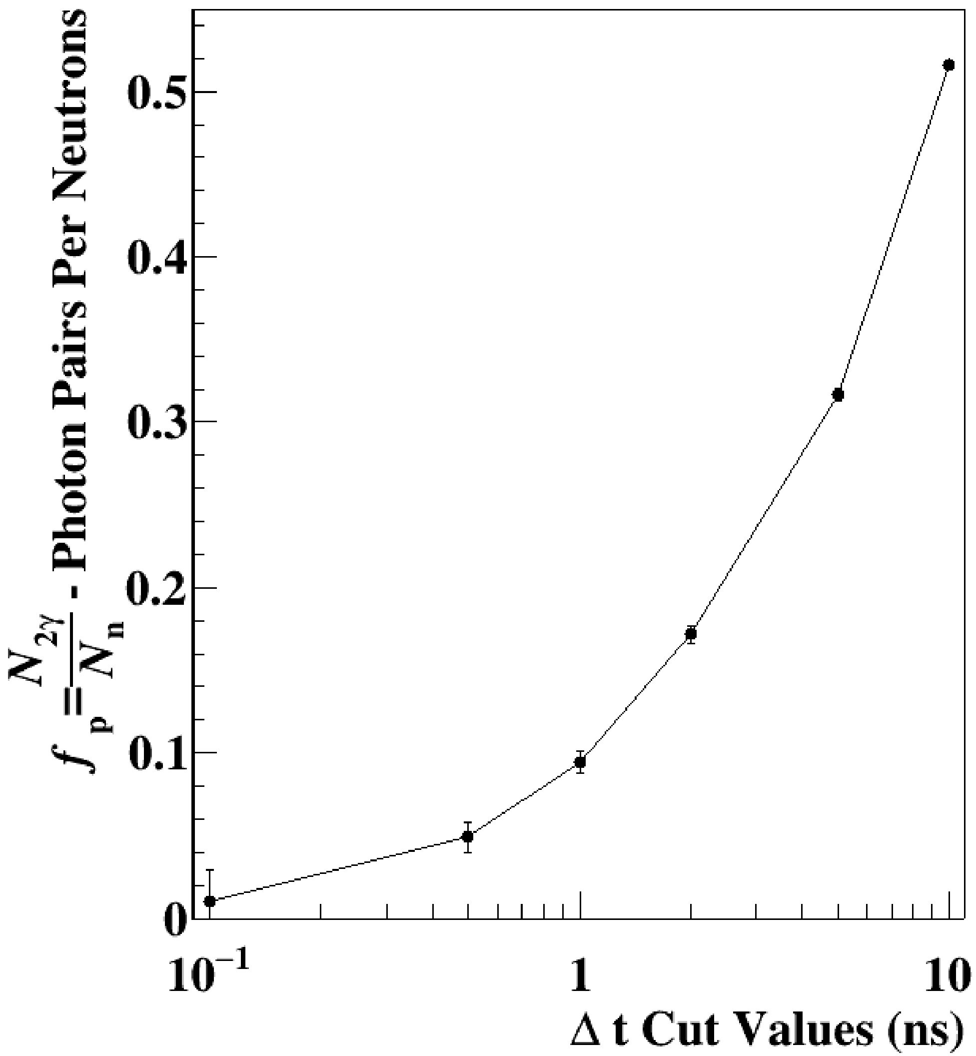


DAMSA Detector – The γ Arrival Time



$N_{2\gamma}/N_n$ after cut

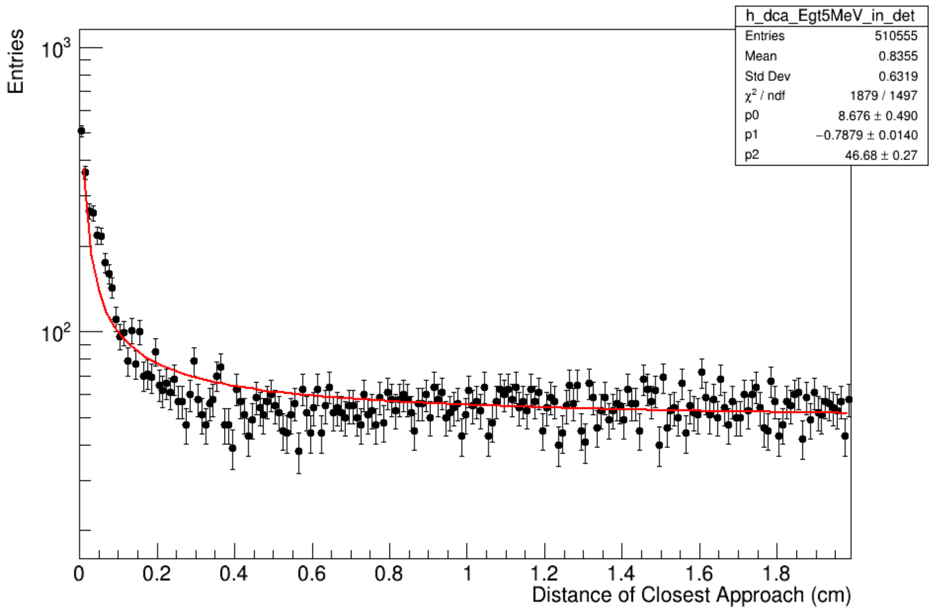
Δt cut (ns)	$N_{2\gamma}/N_n$
<10	0.516
<5	0.317
<2	0.172
<1	0.095
<0.5	0.049
<0.1	0.010

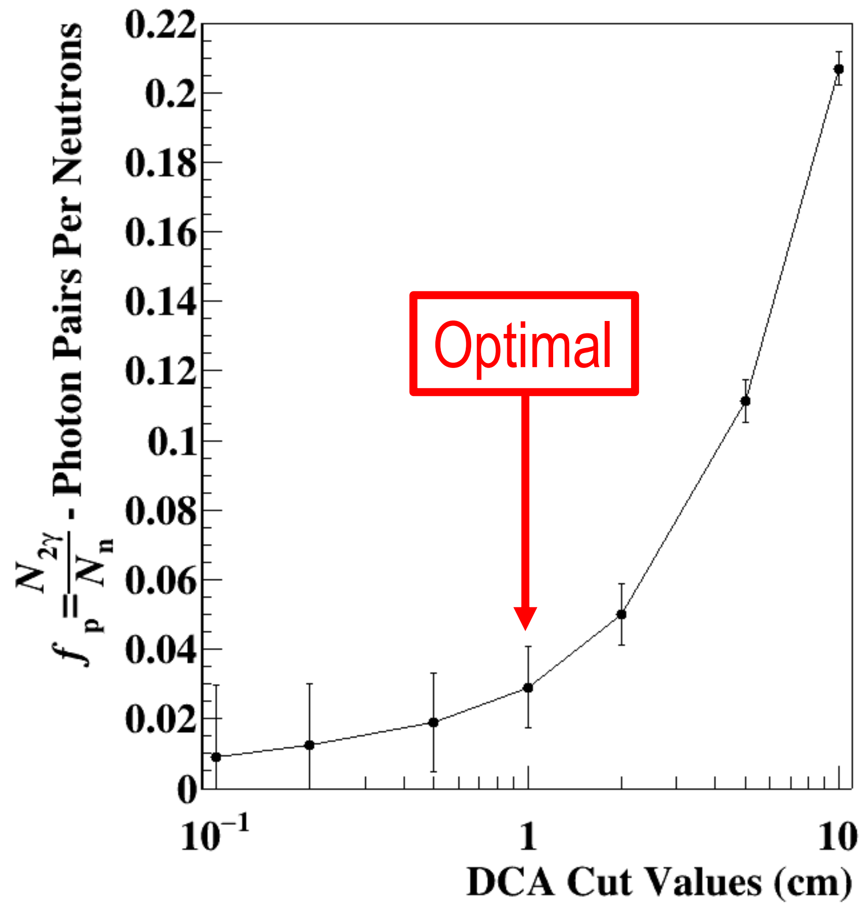


$\Delta t_{\gamma\gamma}$<0.1ns ➔ ~10^{-2} remain

DAMSA Detector – DCA

Distance of closest approach (DCA) computed the distance at the closest approaching point of the traces of all photon combinations





$N_{2\gamma}/N_n$ after cut

DCA cut (cm)	$N_{2\gamma}/N_n$
<10	0.206
<5	0.111
<2	0.050
<1	0.029
<0.5	0.019
<0.2	0.012
<0.1	0.009

DCA<1cm ➔ 2.9×10^{-2} remain

DAMSA Detector – Invariant Mass

- Optimize the selection based on the interested mass range
- Could obtain an additional reduction factor of 10^{-3} depending on mass range