MicroBooNE's Beyond Standard Model Physics Program

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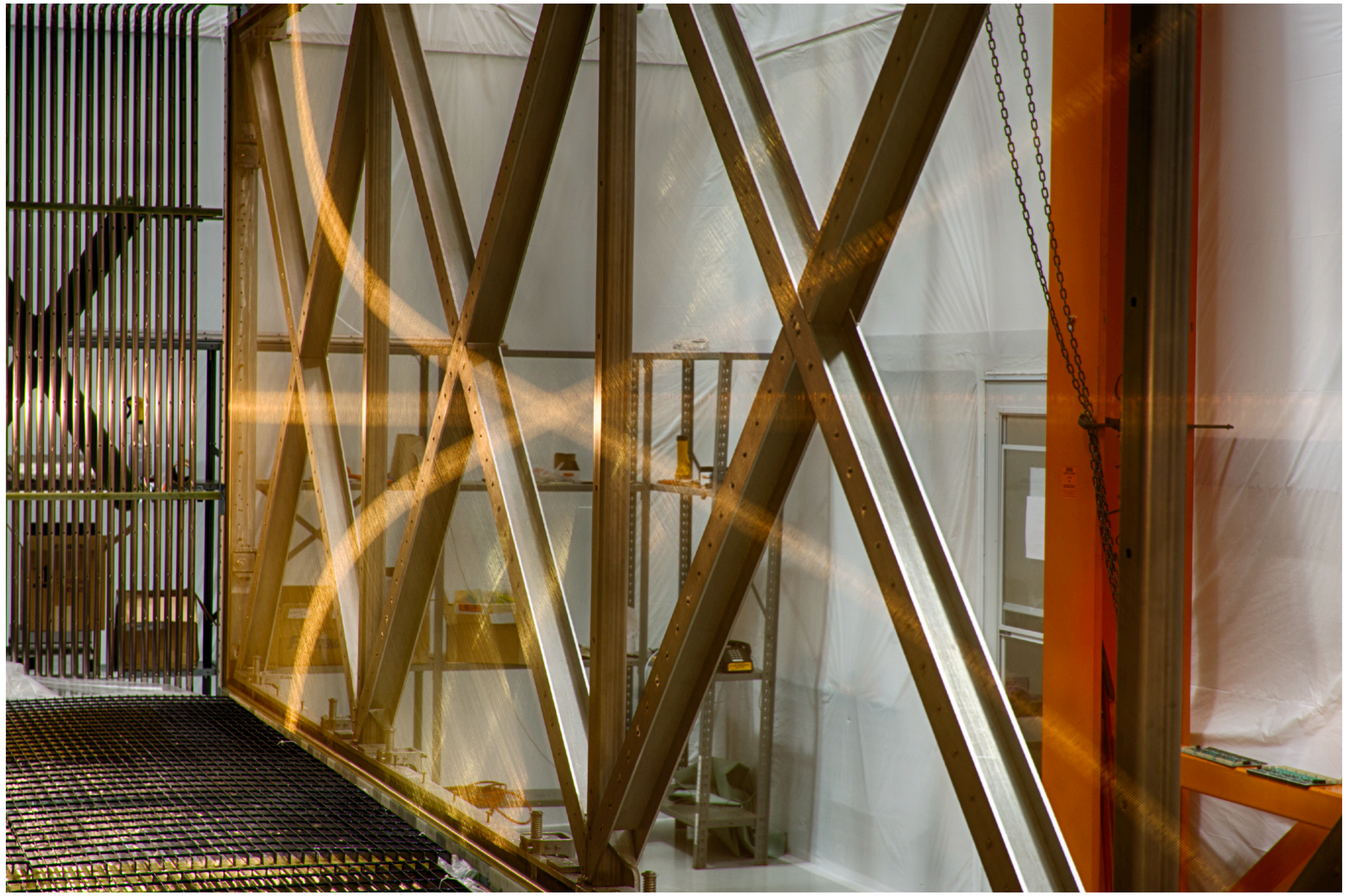
On behalf of the MicroBooNE Collaboration

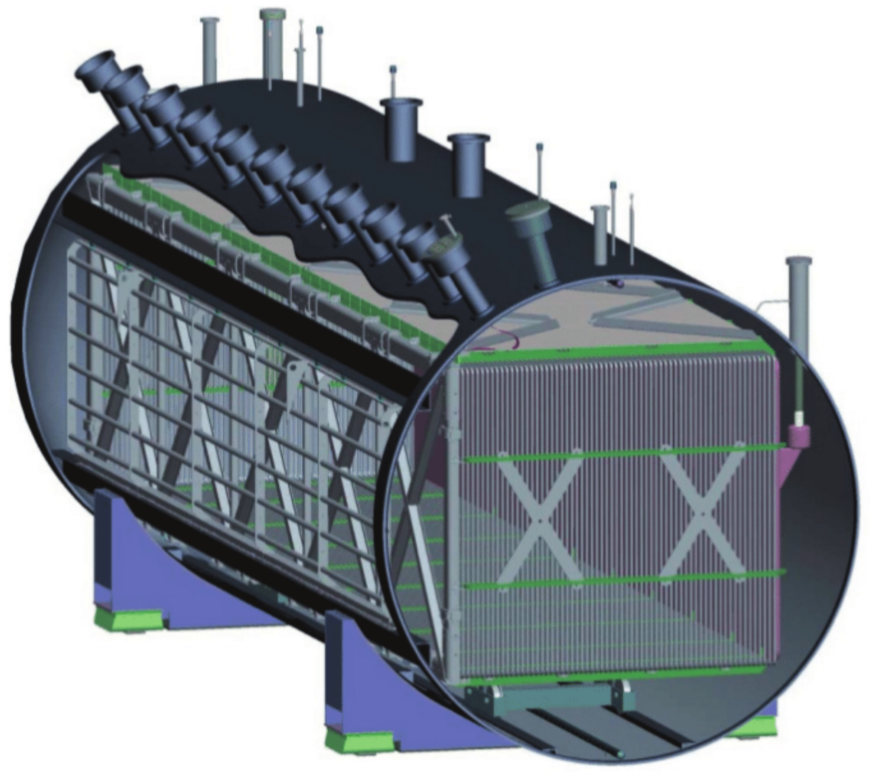
August 26, 2024
TeV Particle Astrophysics 2024

MicroBooNE Dark Neutrino
e^+e^- Simulation

MicroBooNE

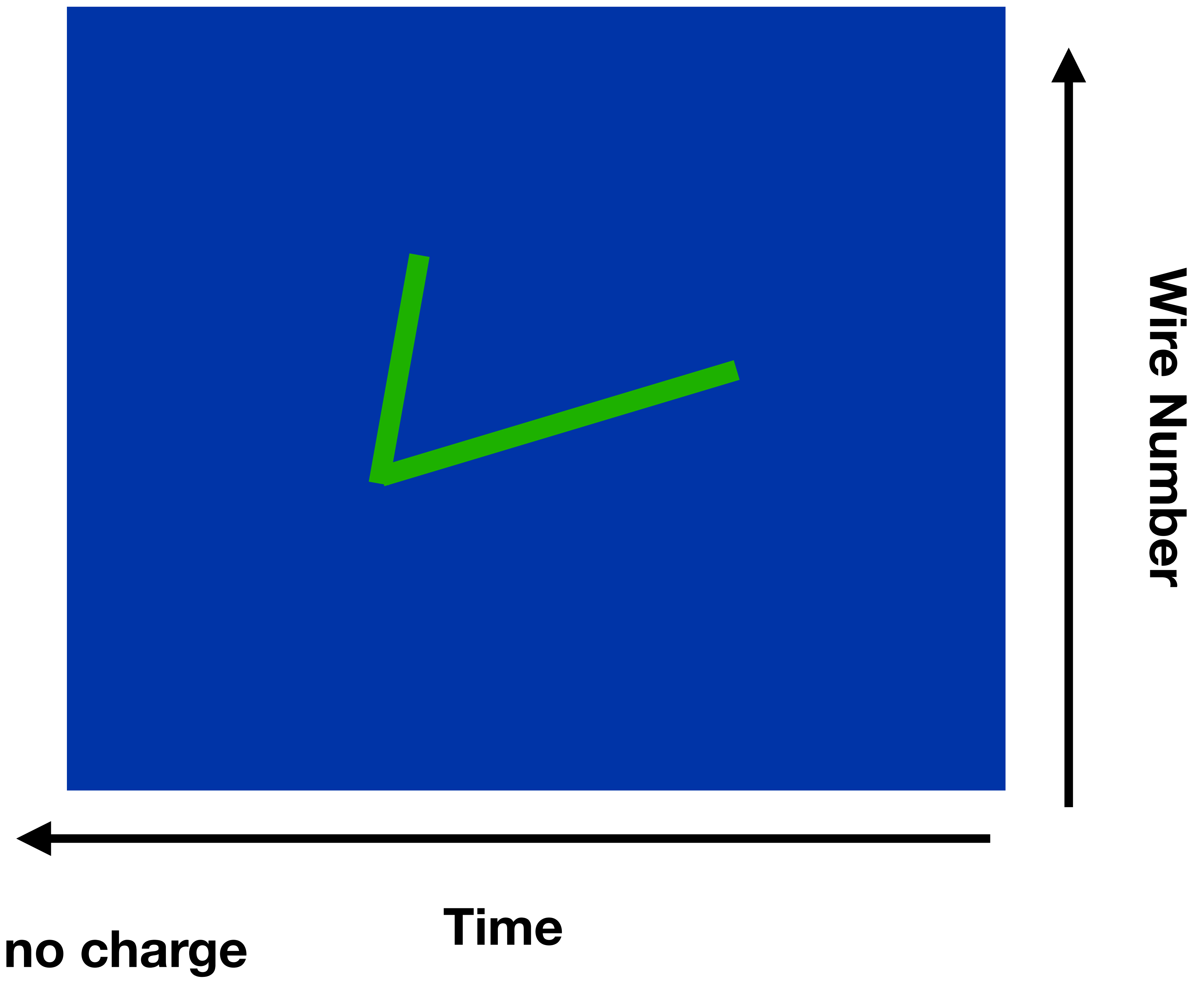
- Goals:
  - Investigate neutrino anomalies (MiniBooNE LEE)
  - Measure O(GeV) neutrino-argon cross sections
  - Perform beyond-standard-model searches



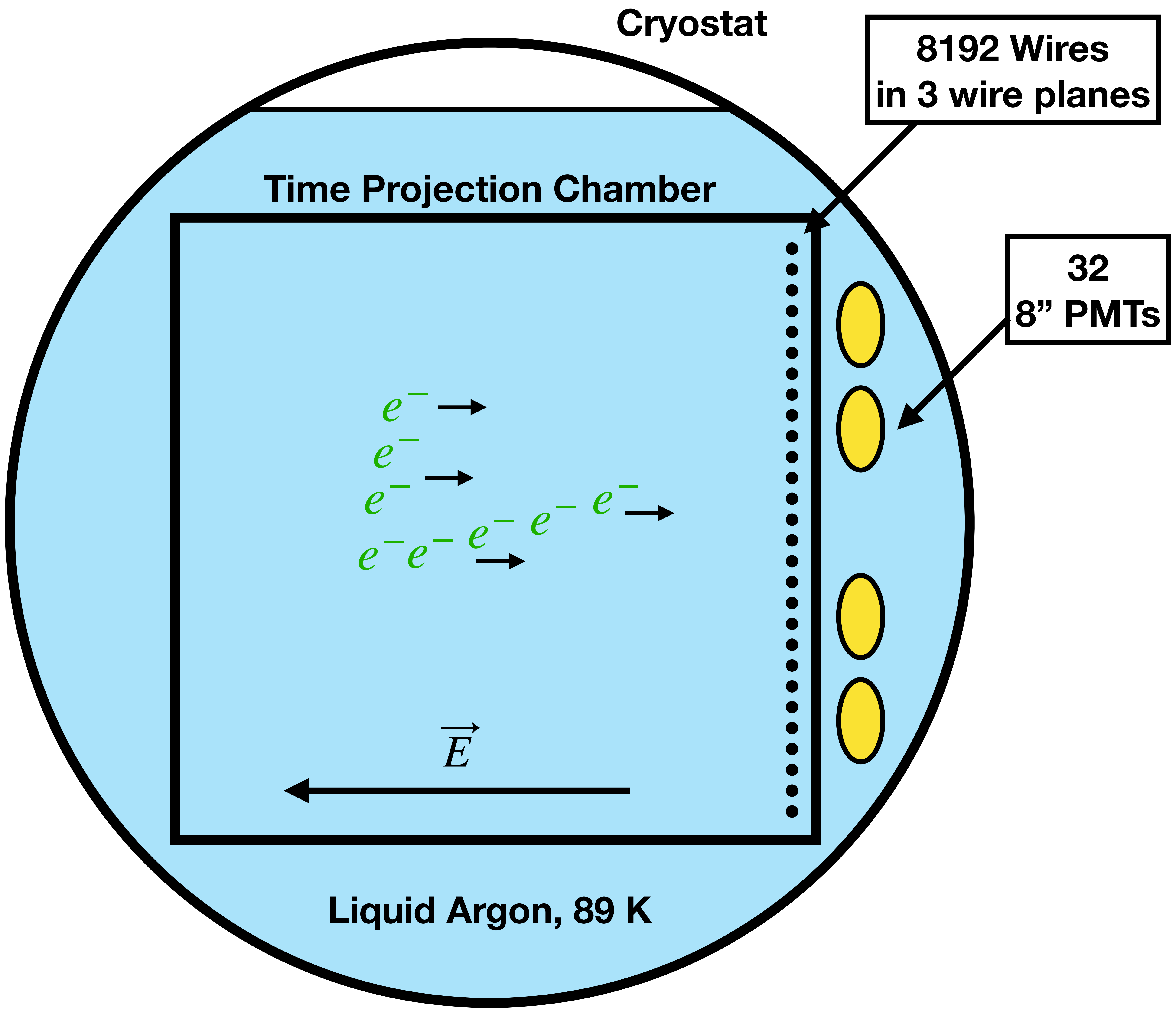


LArTPC Principle

- Charged particles ionize argon atoms in their trails
- As ionization electrons arrive at our wires, they can be detected with sensitive electronics
- This gives us a school-bus-sized, 85 tonne, millimeter/MeV-scale-resolution, fully active calorimeter



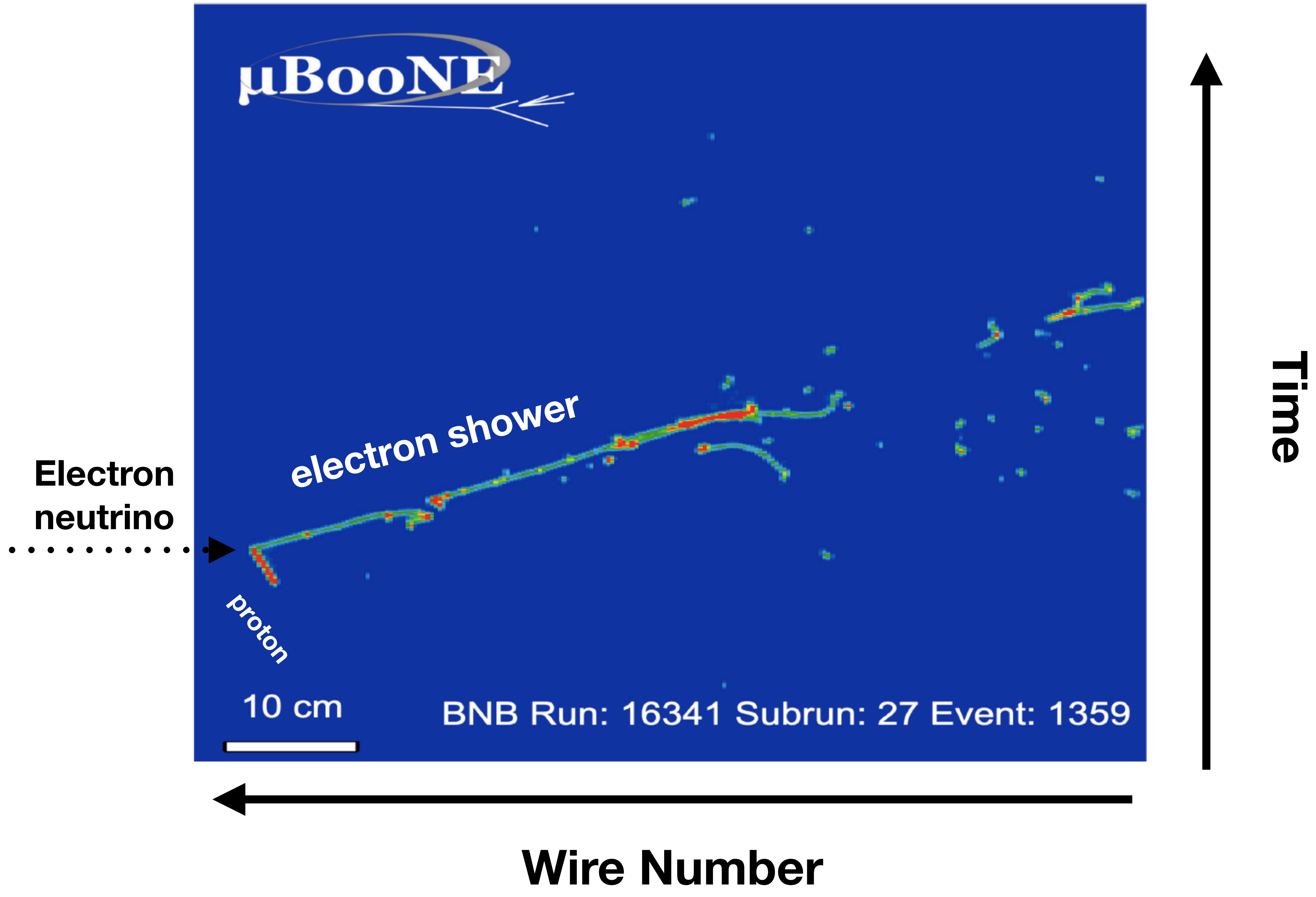
blue = no charge
green = charge

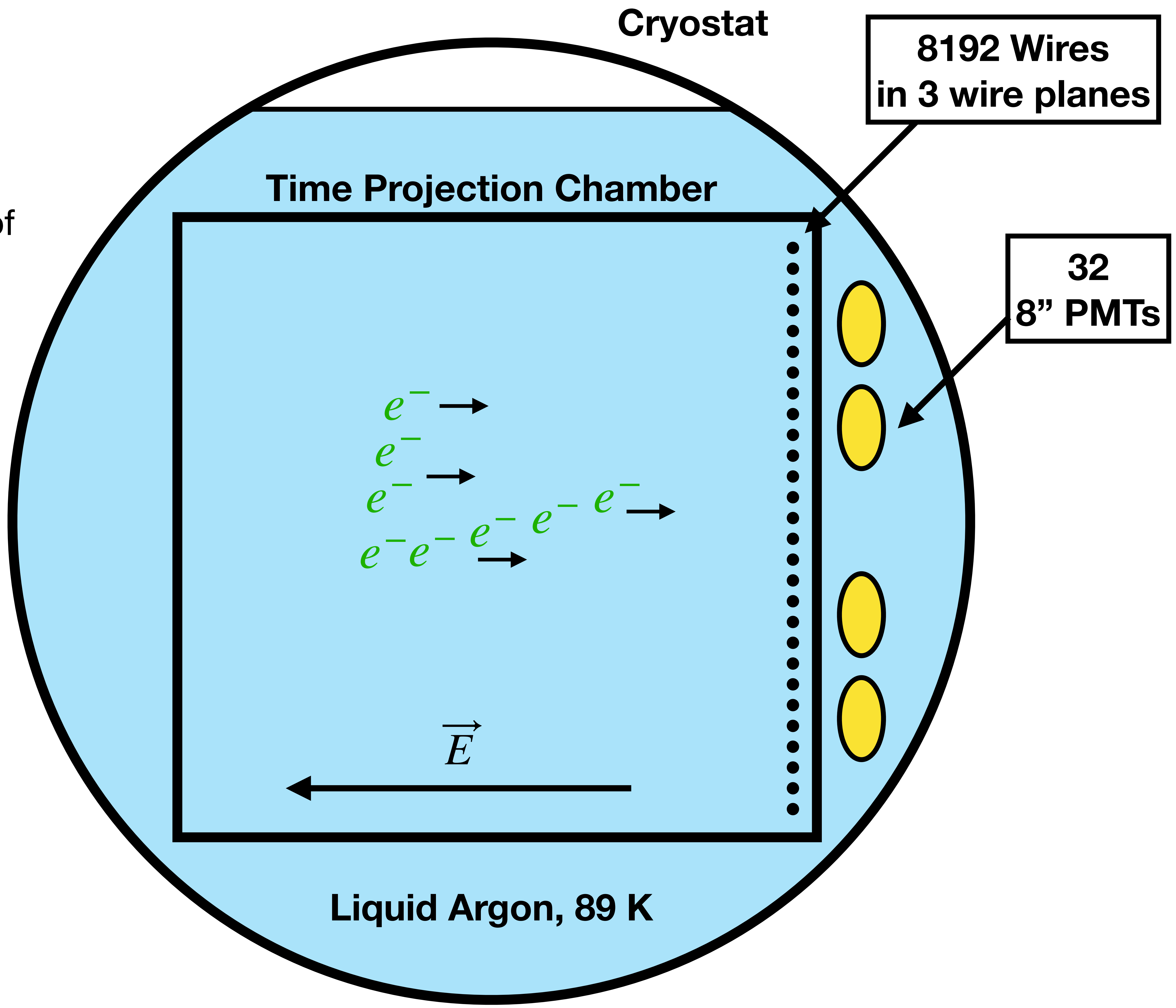


Active TPC dimensions:
2.6 x 2.3 x 10.4 m

LArTPC Principle

- Tracks: Simple line segments in the image
  - Indicating a single higher-mass particle (proton, pion, muon, etc.)
- Showers: Branching clusters of many line segments
  - Indicates an electron, positron, or photon, leading to a cascade of electromagnetic activity (electrons, positrons, photons)





Fermilab Neutrino Beams

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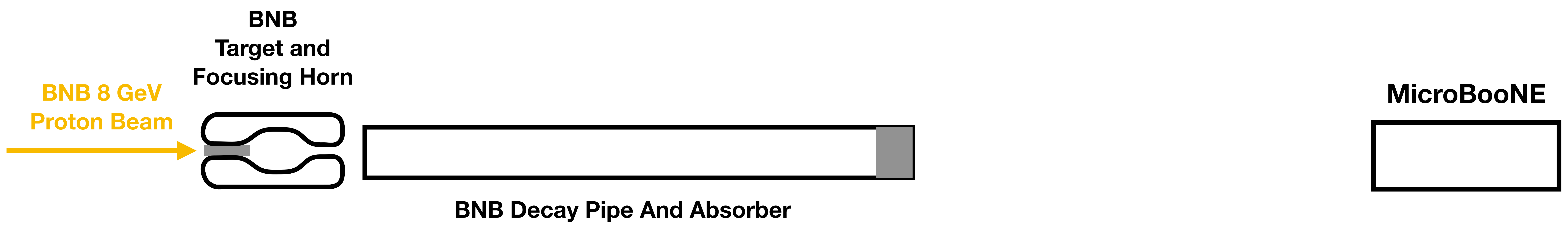
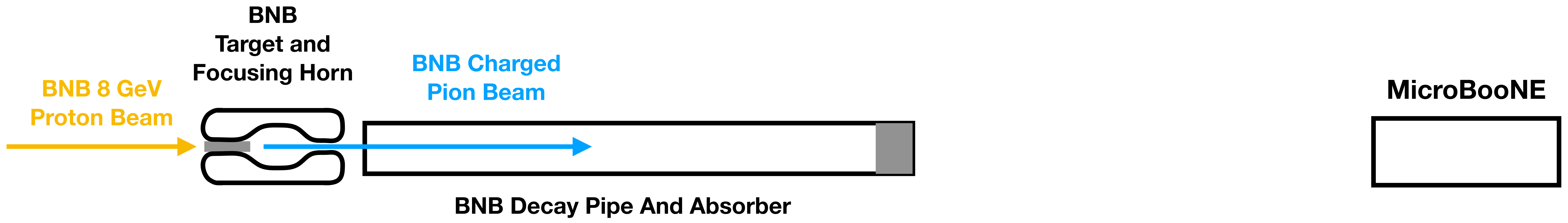
MicroBooNE Neutrino Sources



Not to scale!

MicroBooNE Neutrino Sources



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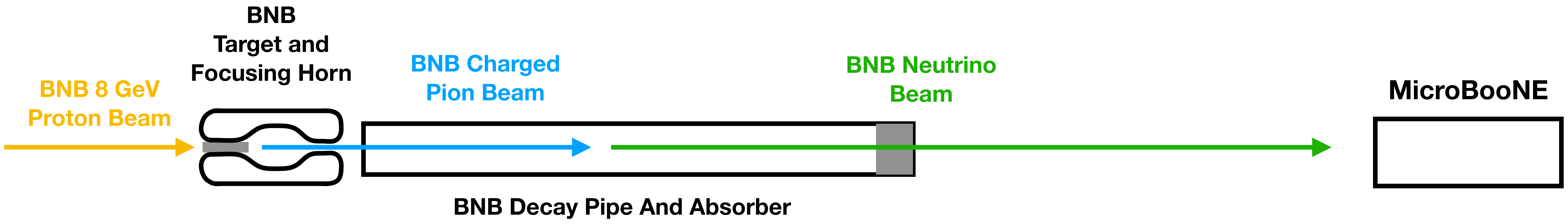
MicroBooNE Neutrino Sources



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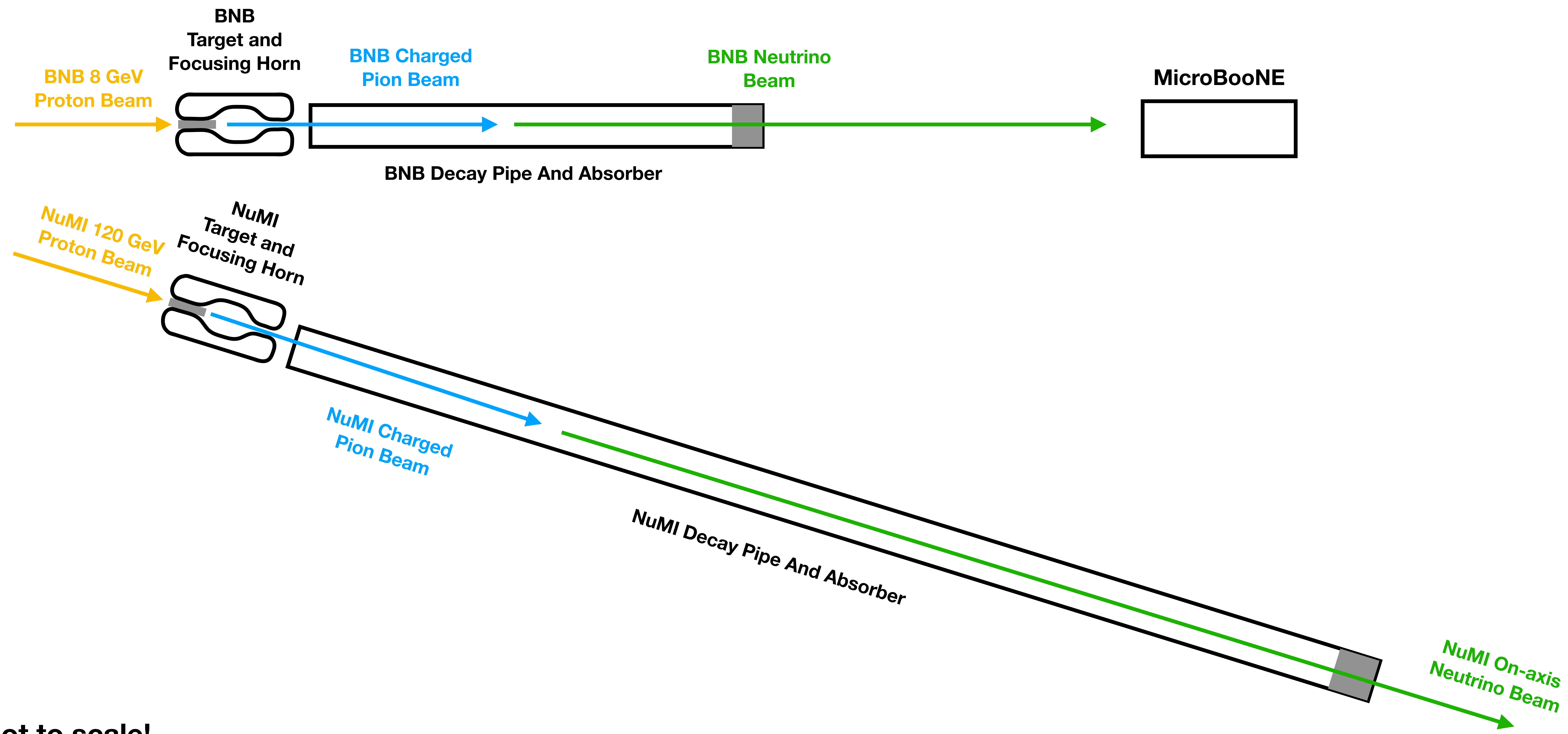
MicroBooNE Neutrino Sources



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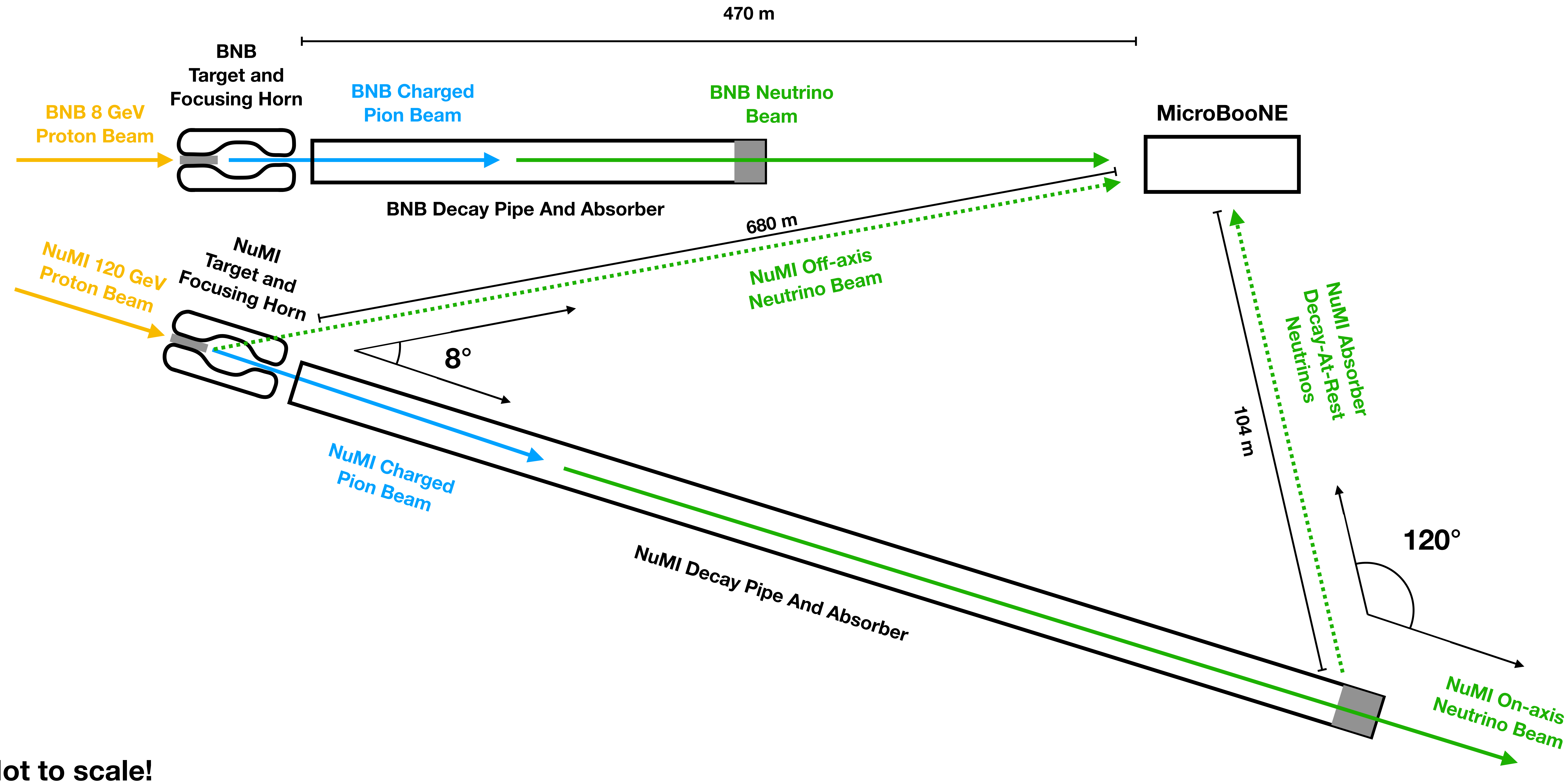
MicroBooNE Neutrino Sources



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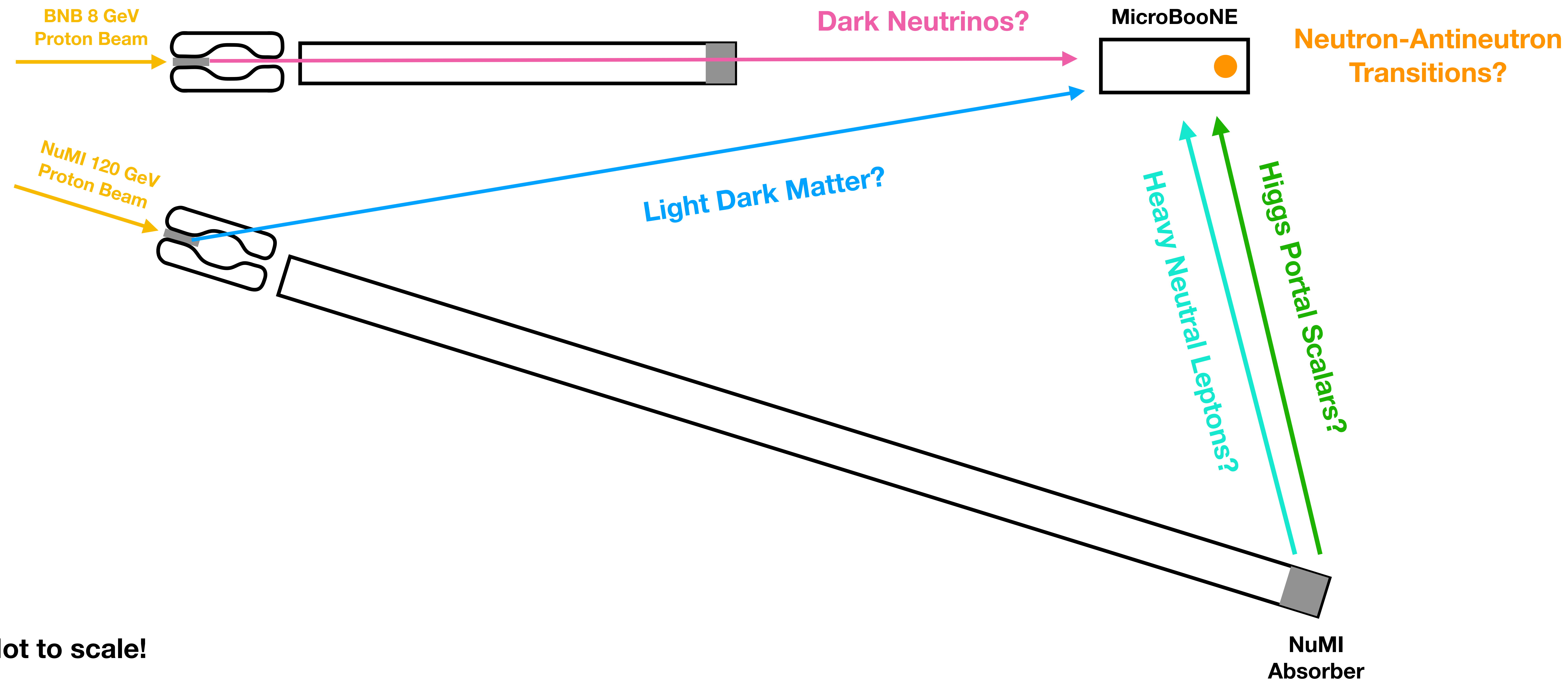
MicroBooNE BSM Sources



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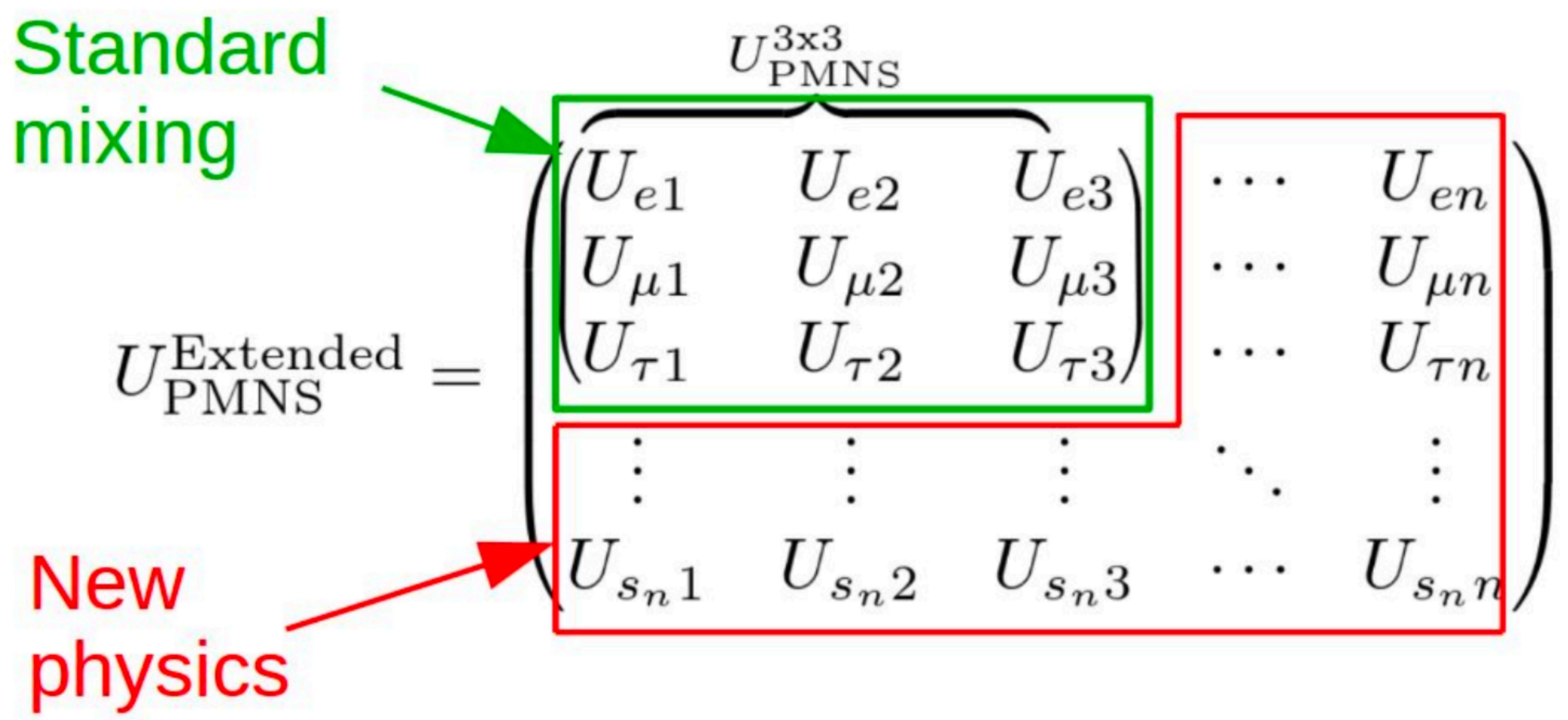
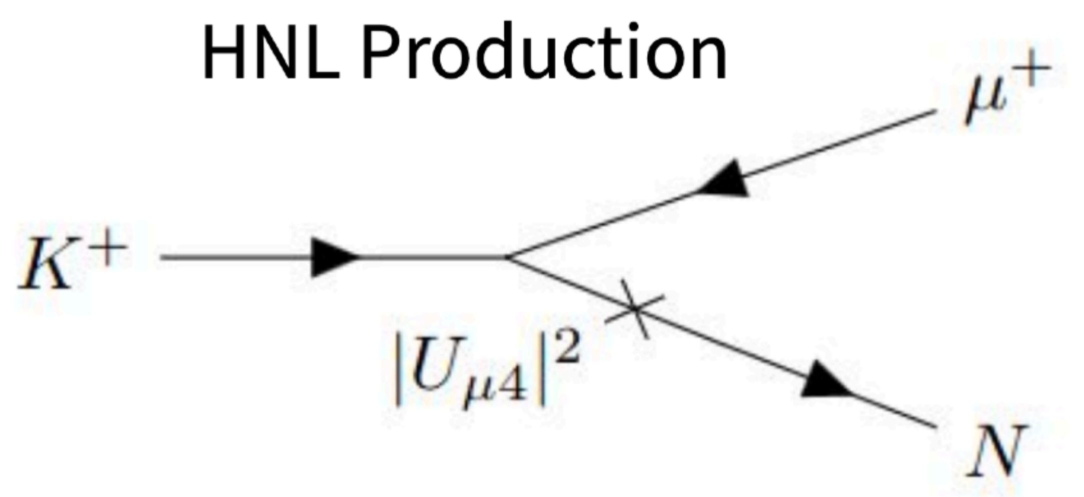
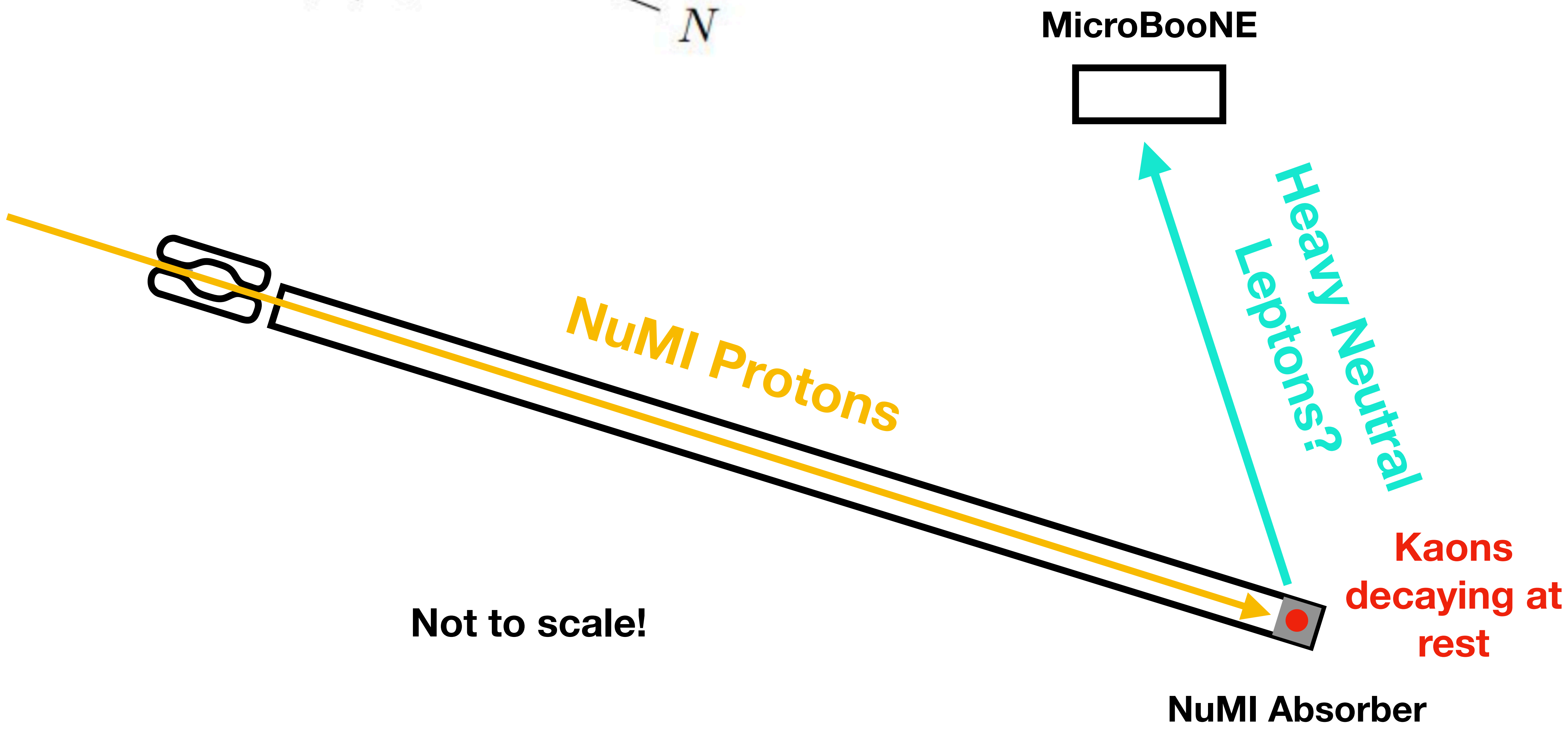
Heavy Neutral Leptons

- Heavy neutral leptons are right-handed fermion singlets that could explain neutrino masses, baryon asymmetry, and dark matter
- They mix with SM neutrinos through the extended PMNS matrix
- We reduce neutrino backgrounds by looking for events pointing backwards in the detector, coming from kaon decay at rest in the NuMI absorber

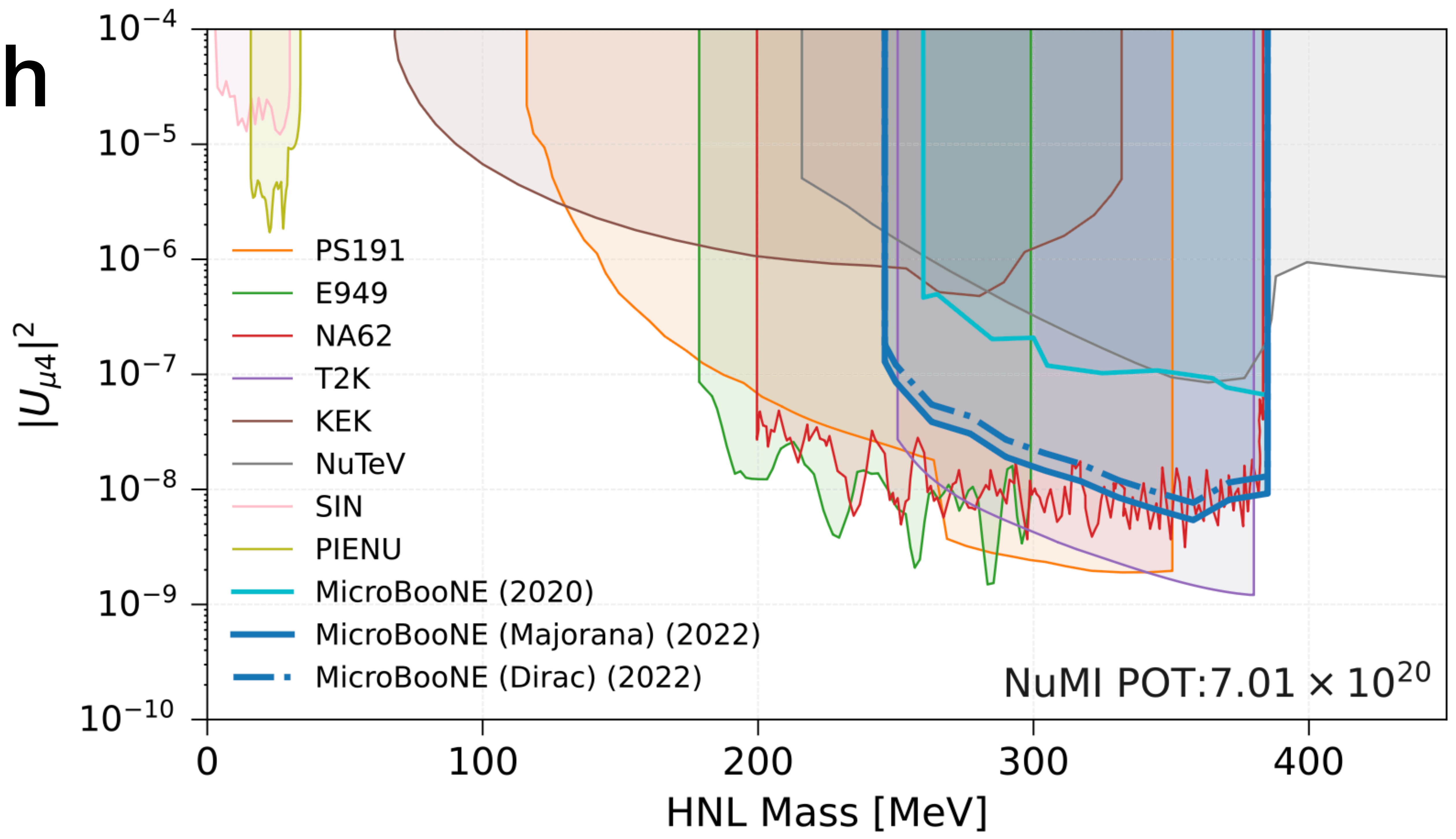


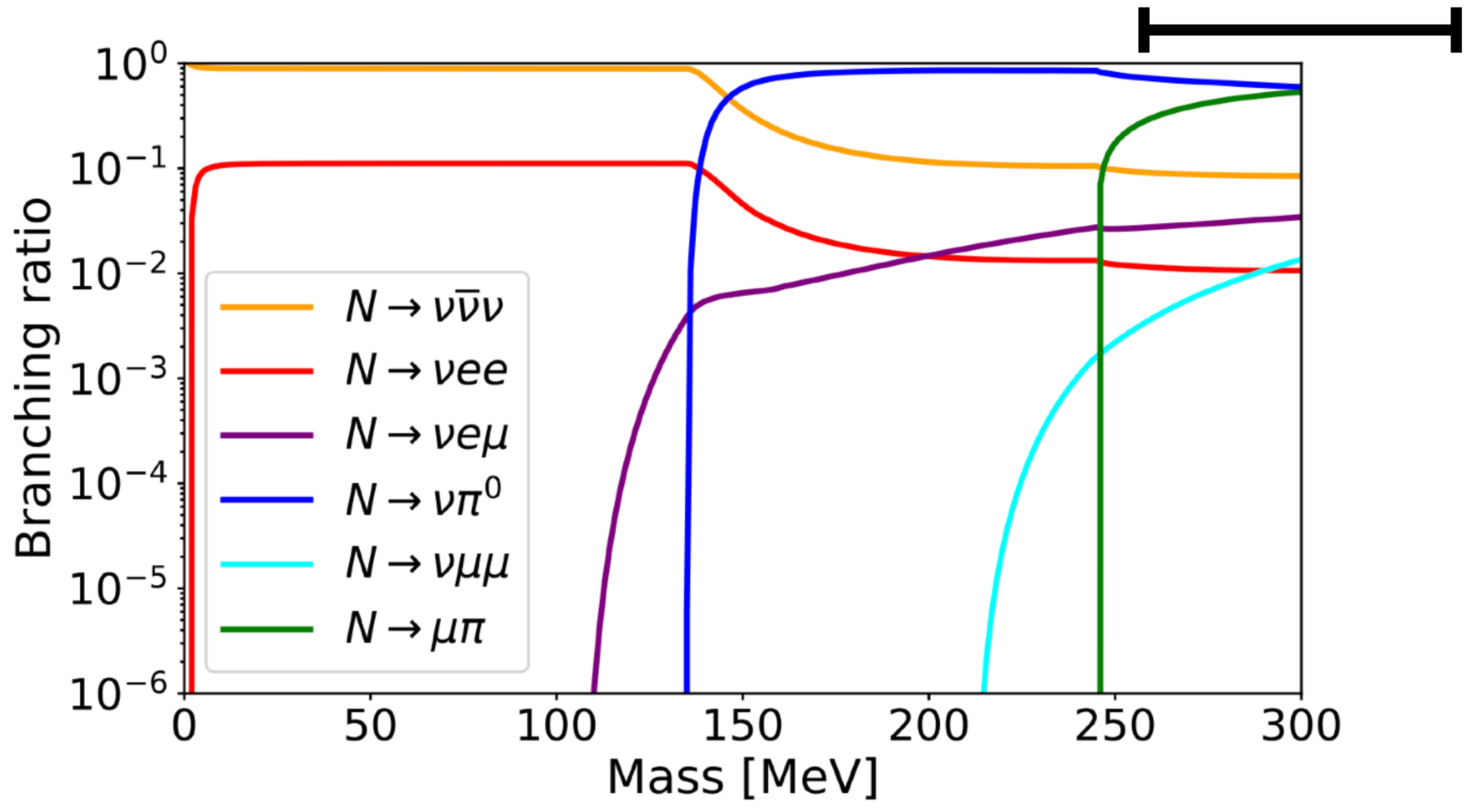


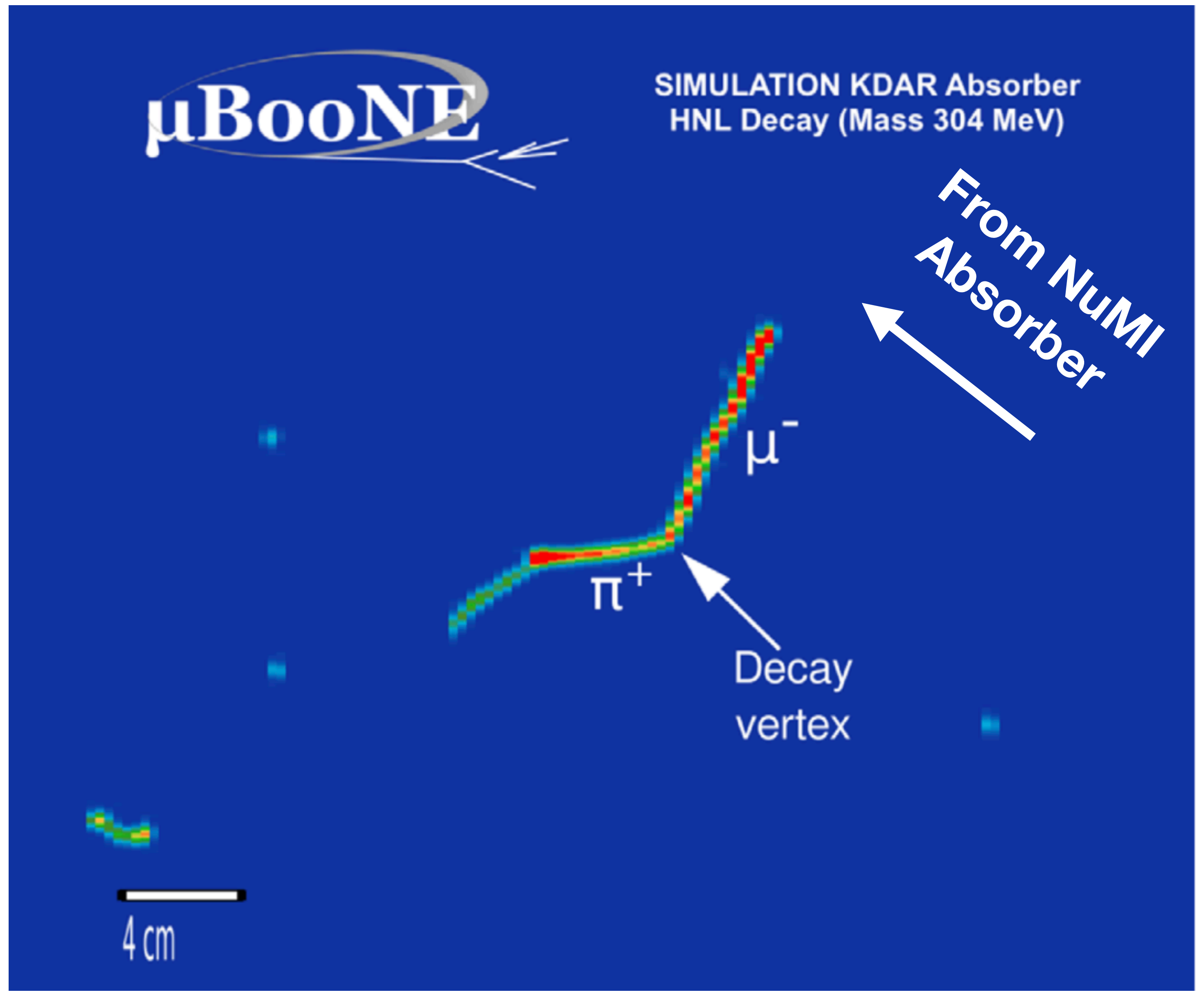


Heavy Neutral Leptons, Track Search

- Probing 260-385 MeV of HNL mass
- Looking for pairs of tracks
  - HNL $\rightarrow \pi^+ + \mu^-$ (or $\pi^- + \mu^+$)

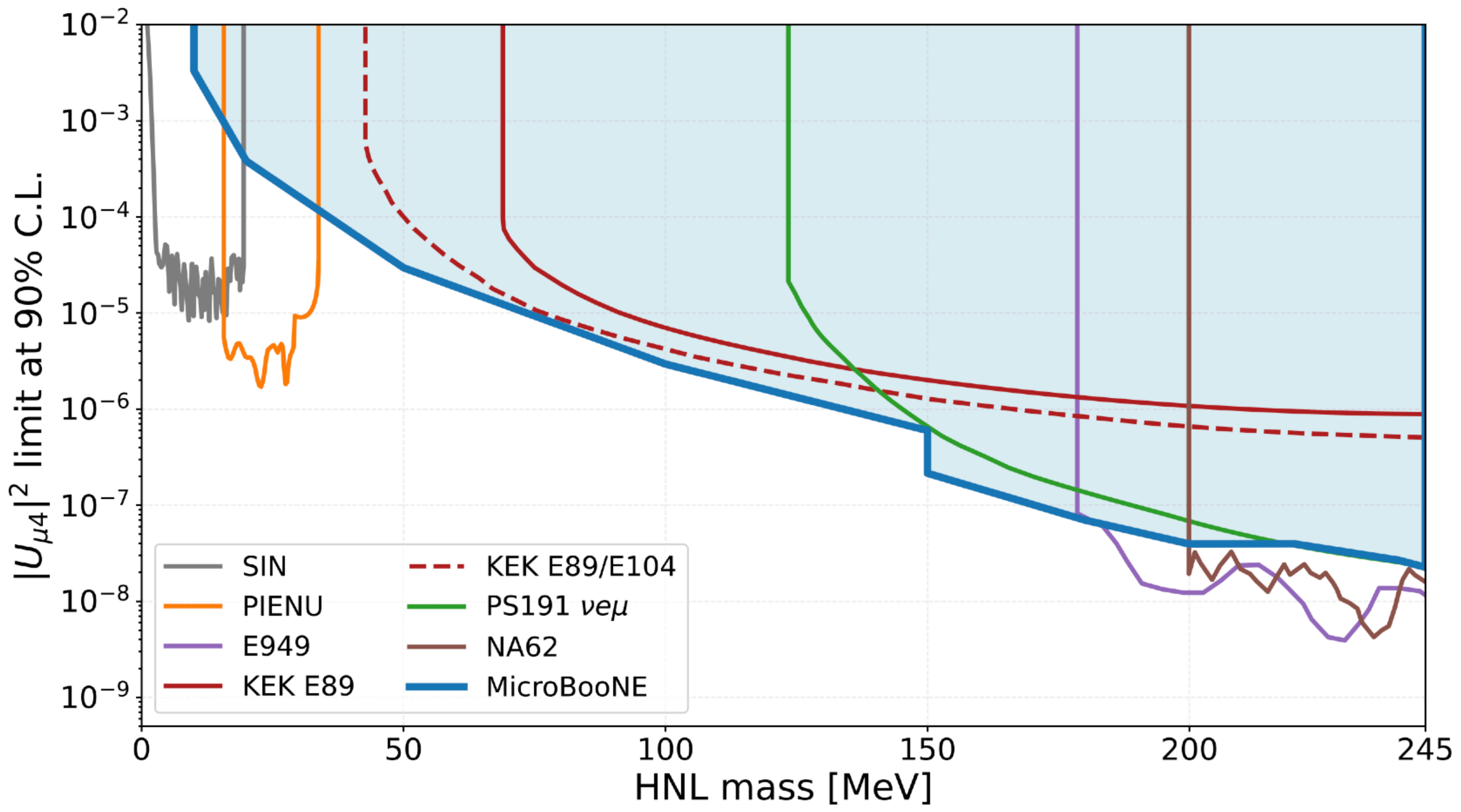




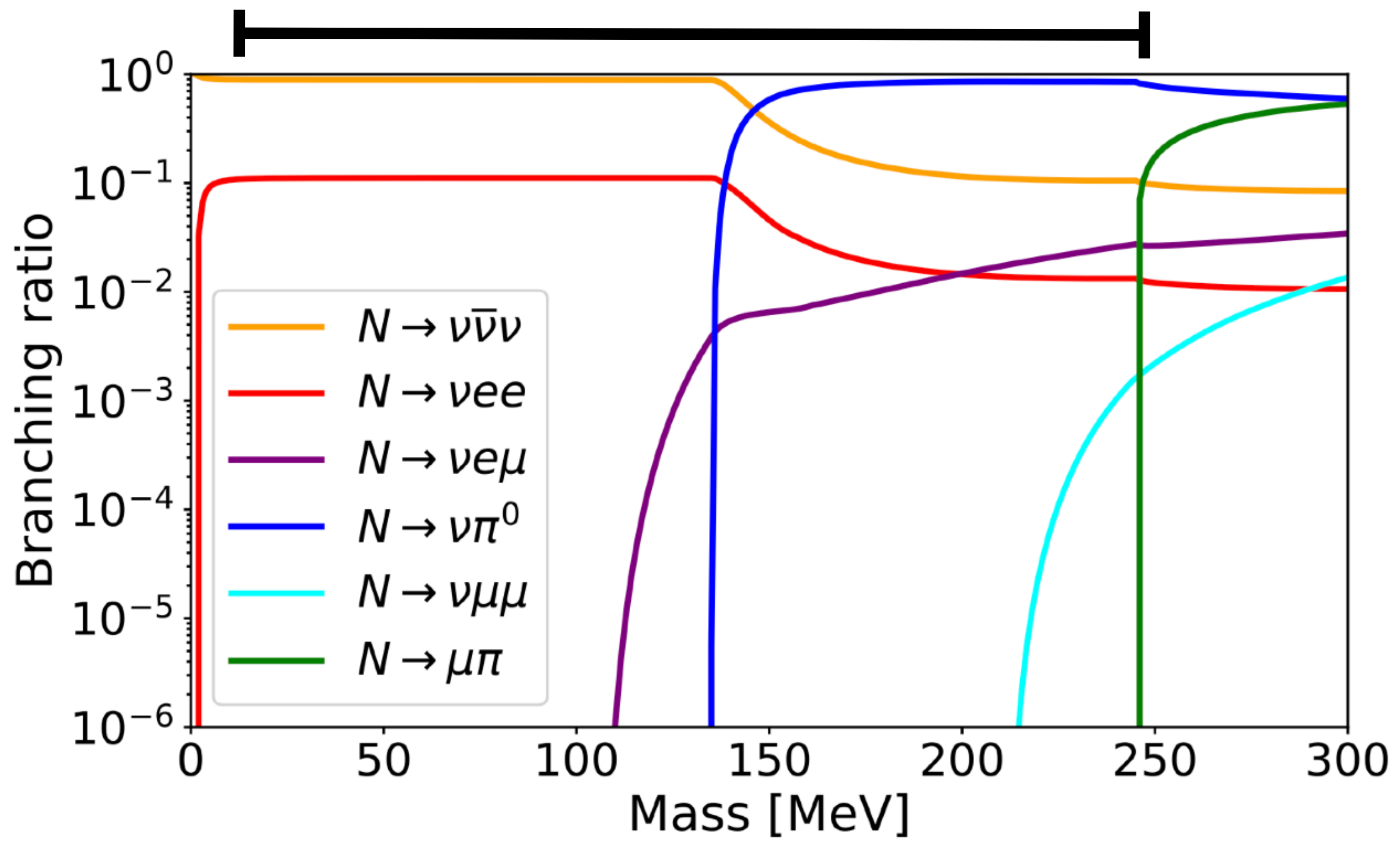


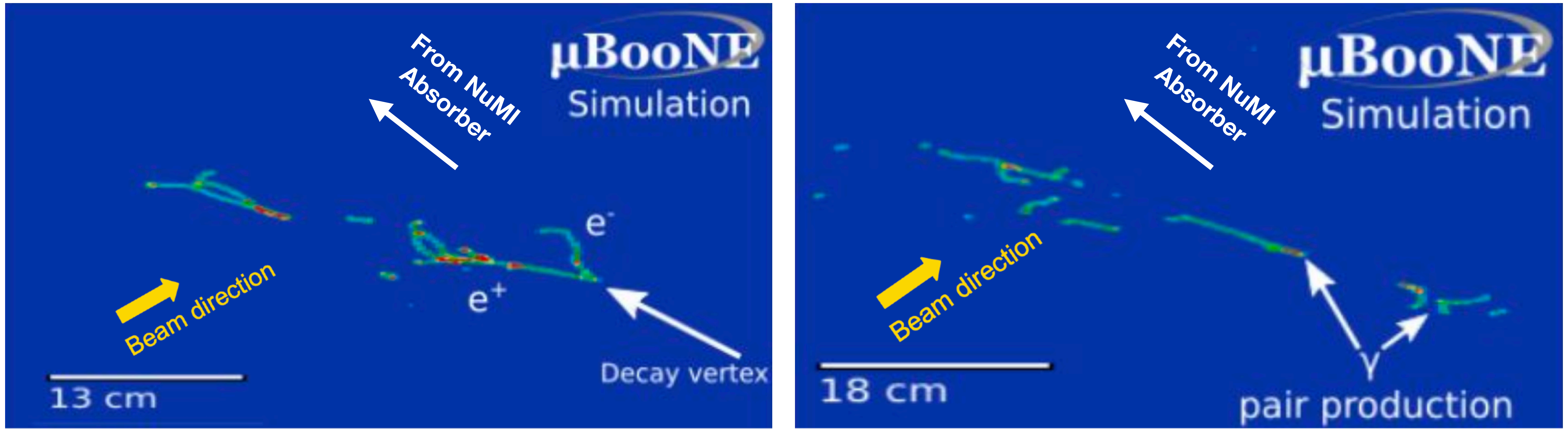
Phys. Rev. D 106, 092006 (2022)

Heavy Neutral Leptons, Shower Search



- Probing lower HNL masses, 10-245 MeV
- Looking for pairs of showers
  - HNL $\rightarrow \nu + e^{+} + e^{-}$, we see e^{+} and e^{-}
  - HNL $\rightarrow \nu + \pi^{0} \rightarrow \nu + 2\gamma$, we see 2γ
    - (first ever search using this decay mode)





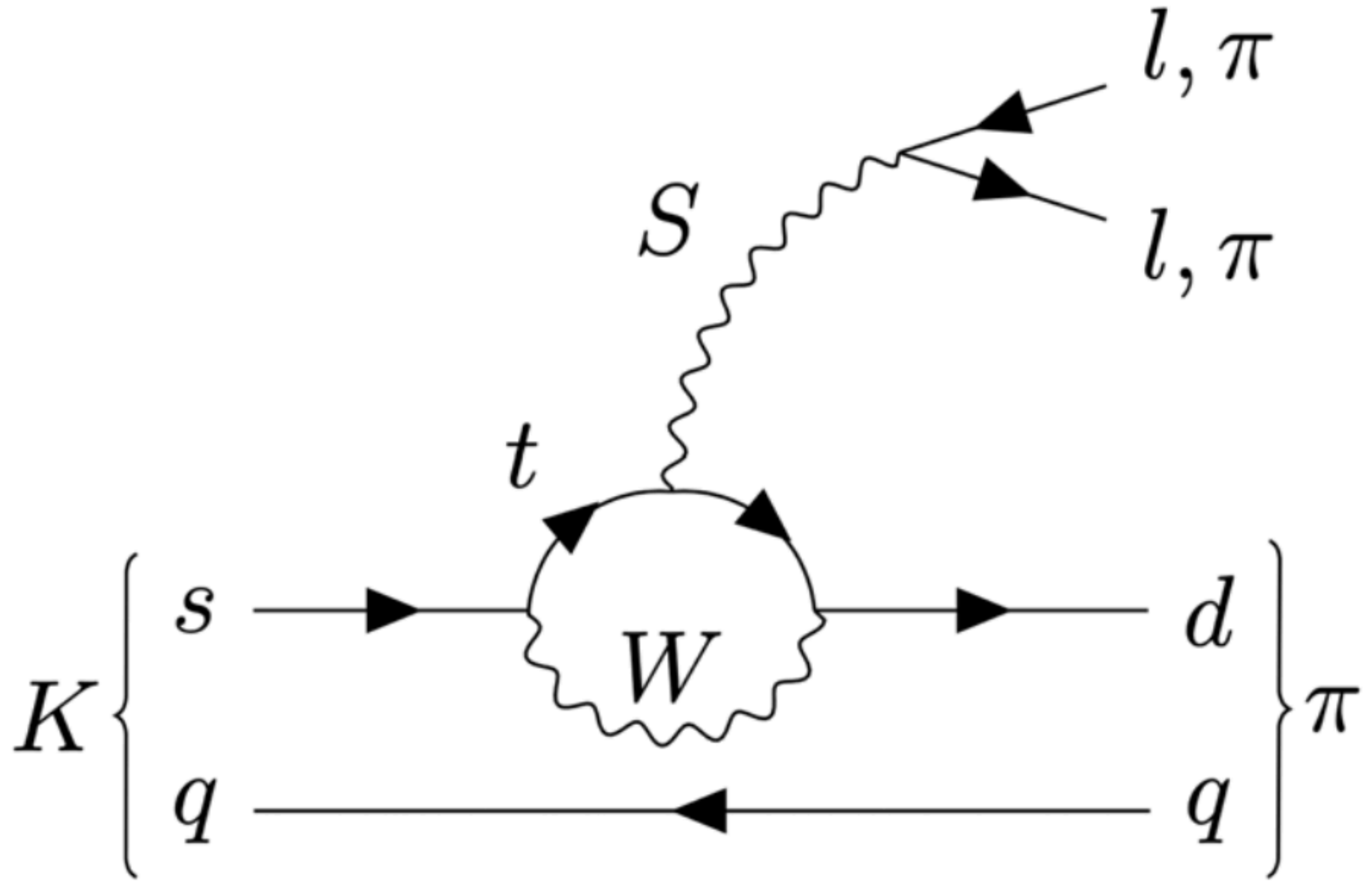
[Phys. Rev. Lett. 132, 041801 (2024)]

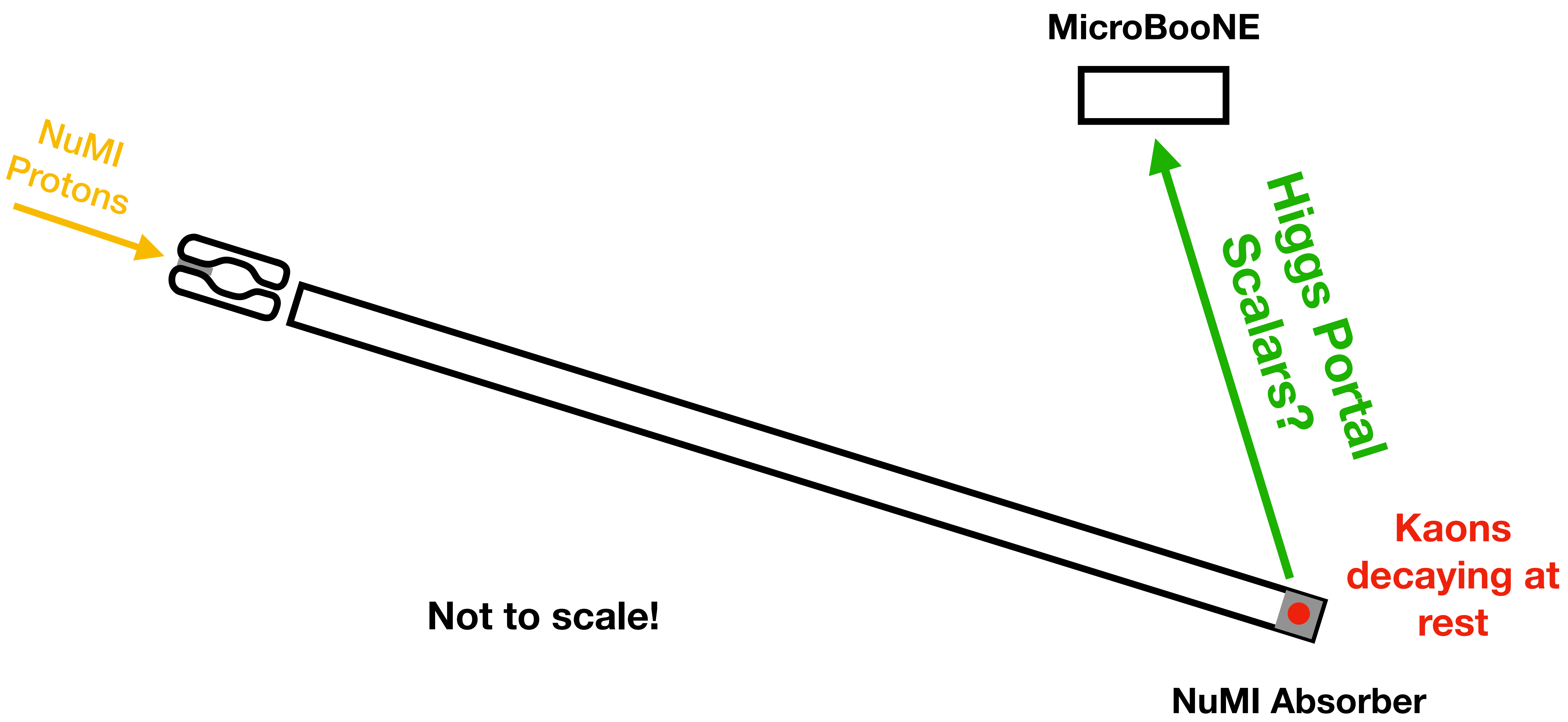
Higgs Portal Scalars

- Extension to the SM, where an electrically neutral singlet scalar boson mixes with the Higgs boson with a mixing angle θ

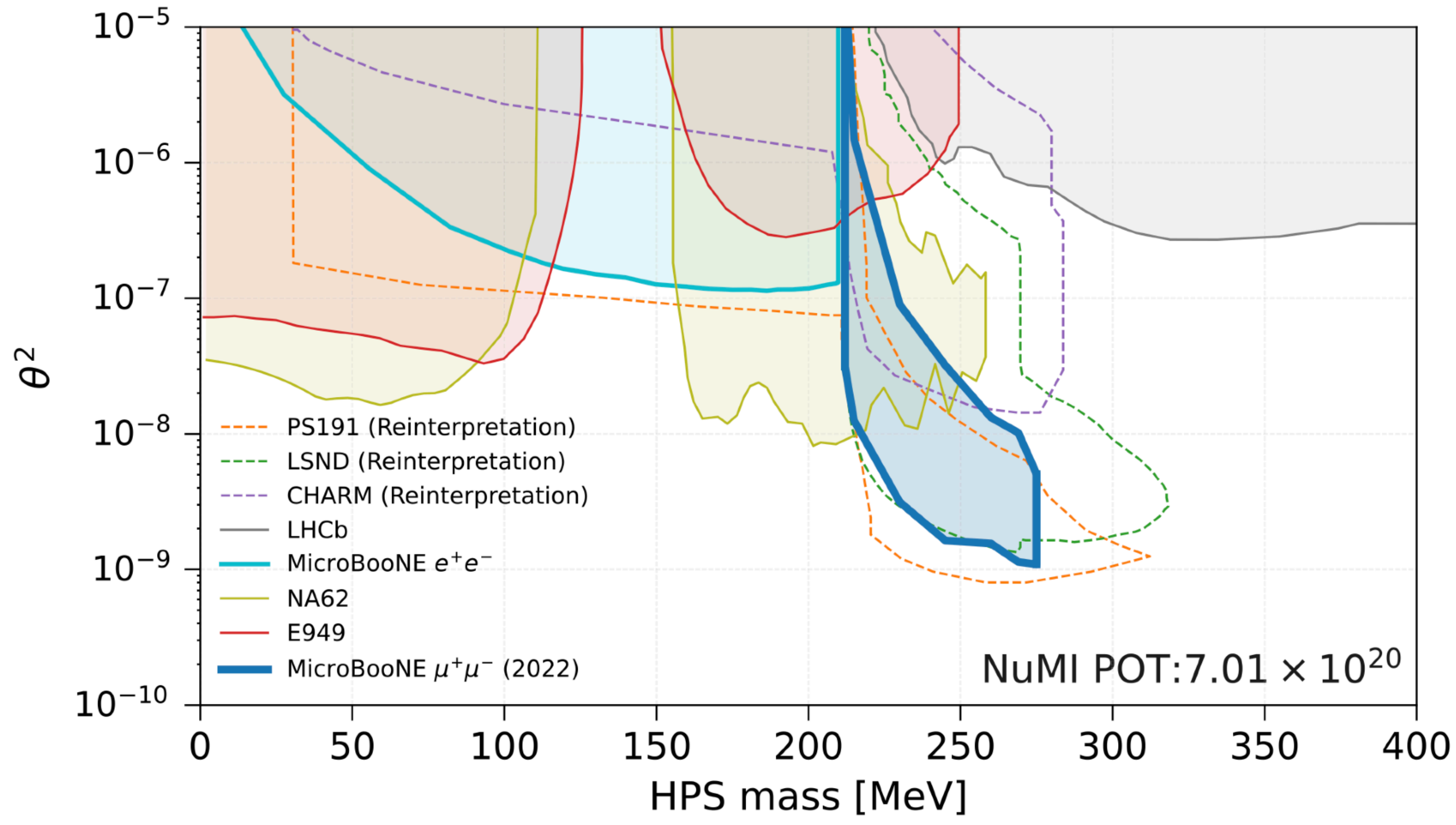
- Similarly to HNLs, we reduce neutrino backgrounds by looking for events coming from NuMI absorber kaon decays

Higgs Portal Scalar Production

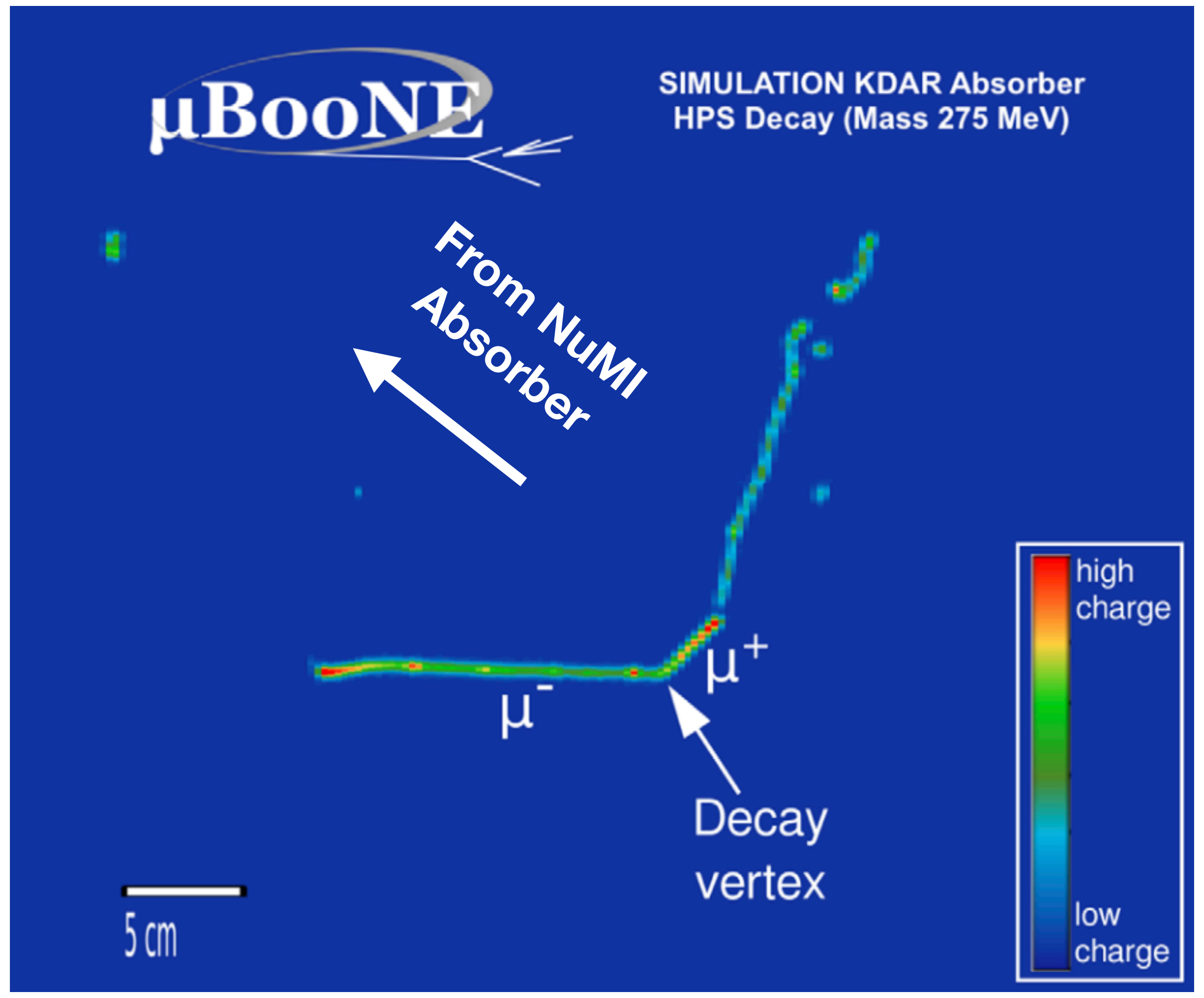


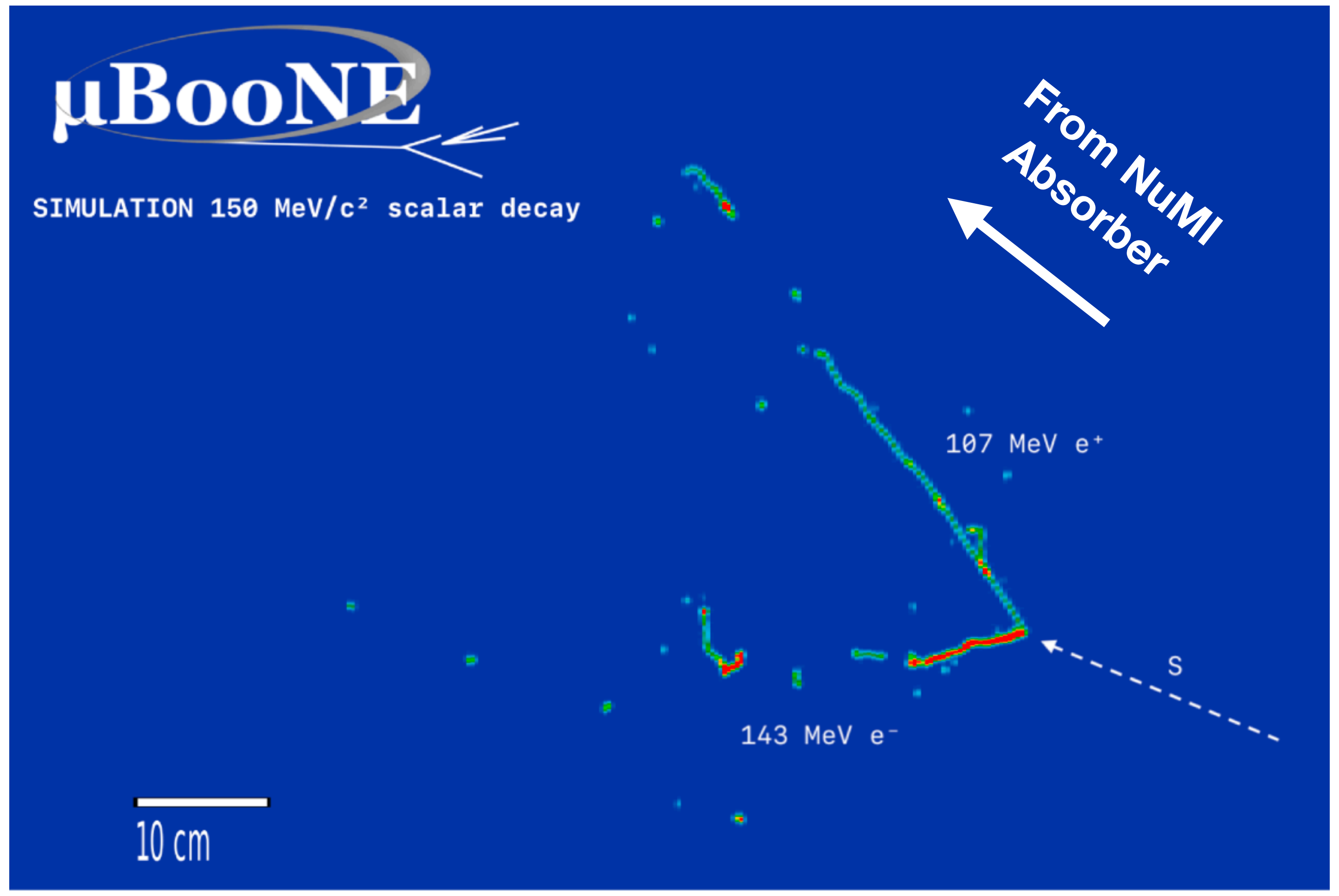


Higgs Portal Scalars



- Searched using two methods:
  - Pairs of tracks, S $\rightarrow \mu^+ + \mu^-$
  - Pairs of showers, S $\rightarrow e^+ + e^-$



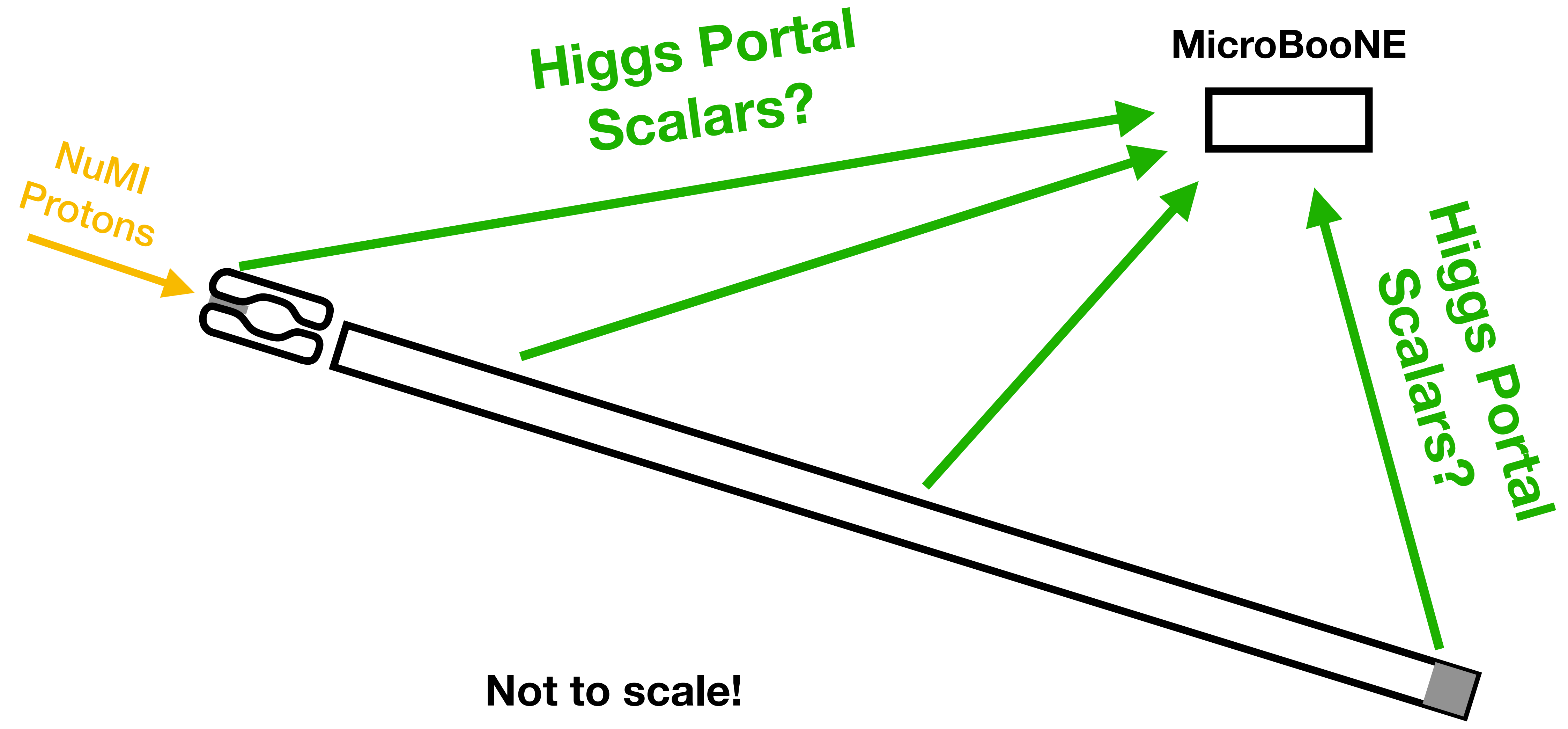


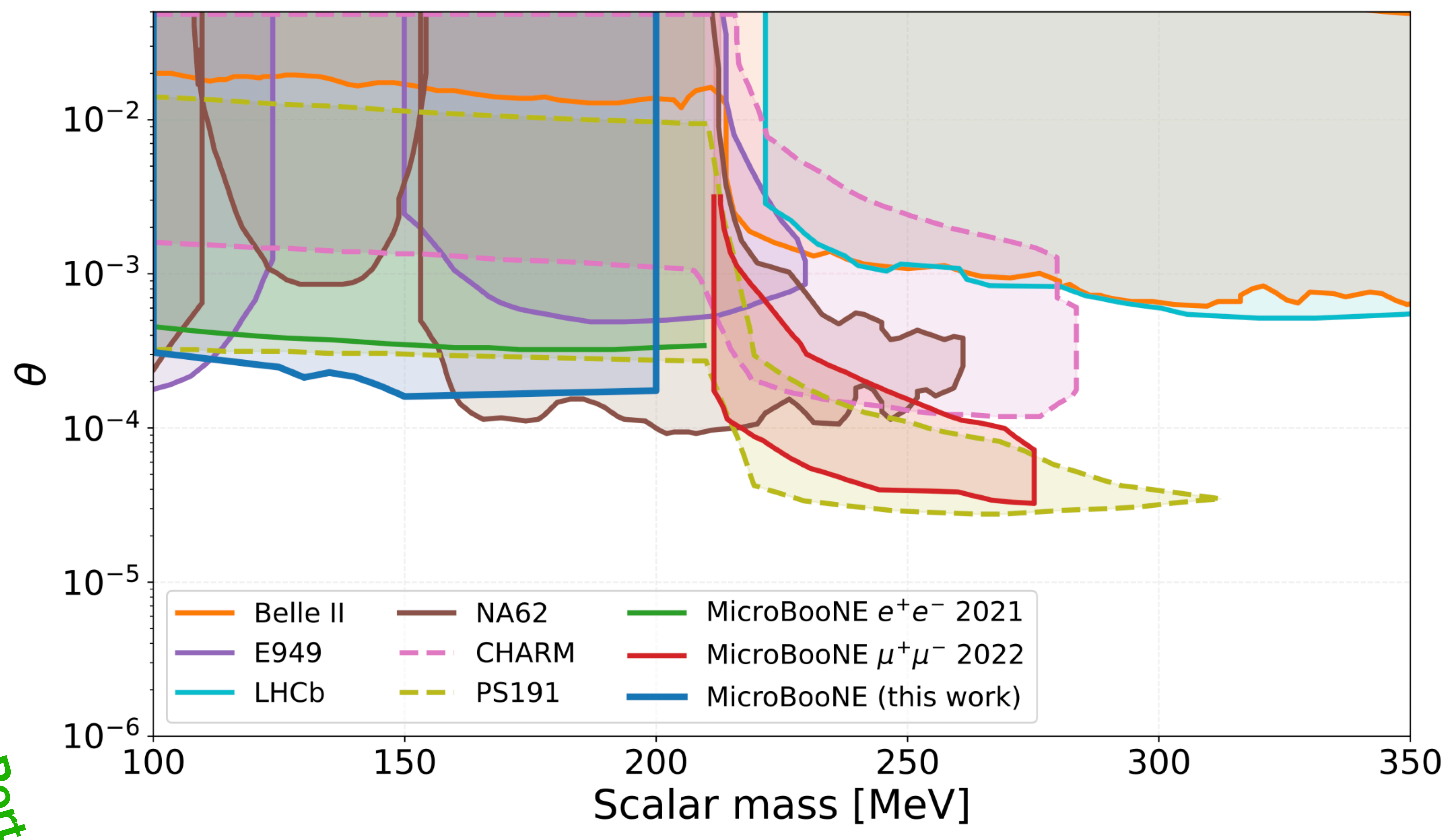
Phys. Rev. Lett. 127, 151803 (2021)

Phys. Rev. D 106, 092006 (2022)

Higgs Portal Scalars

- We recently expanded our e^+e^- search, including decays in flight and decays at rest in the beam target





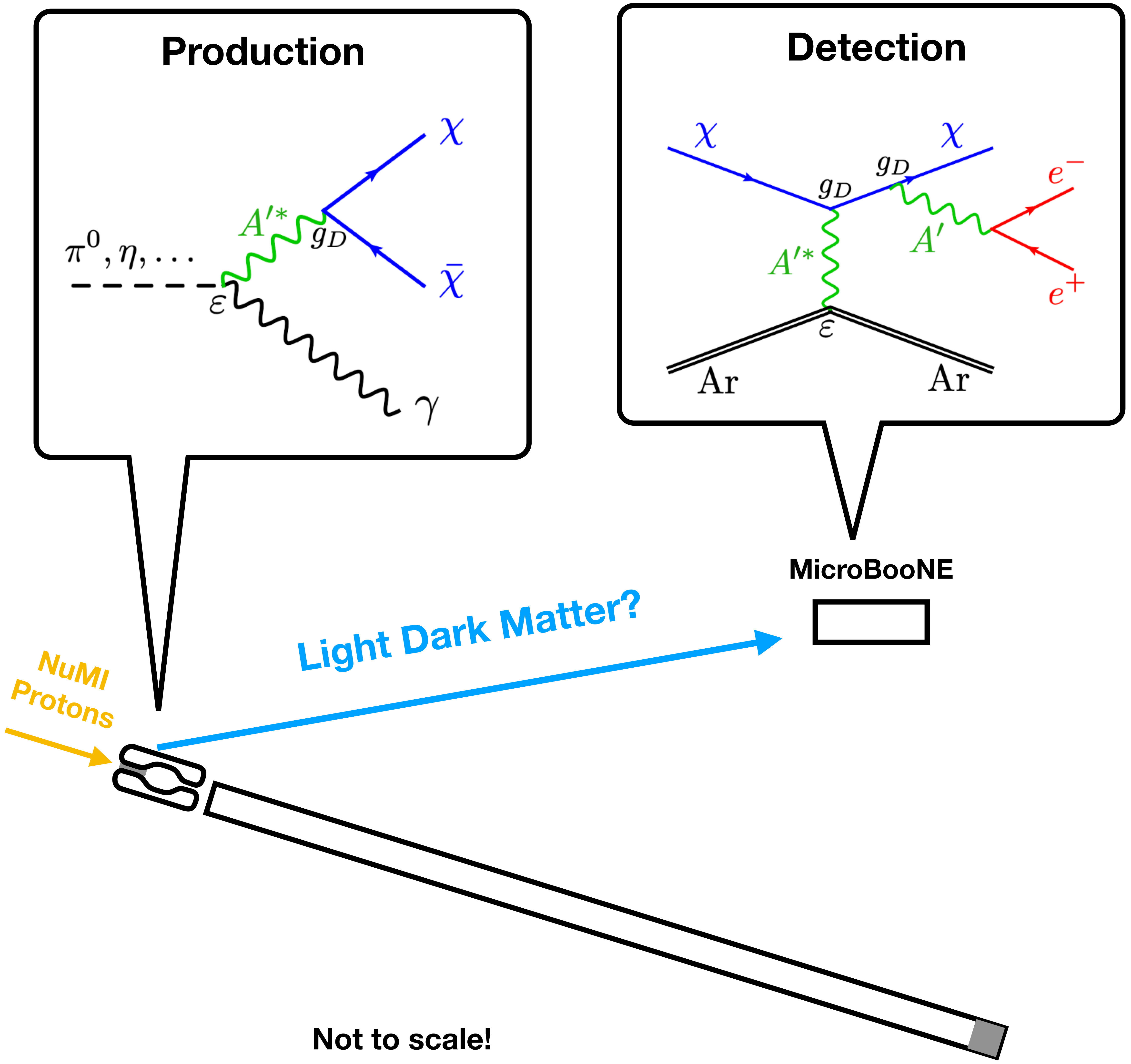
https://agenda.infn.it/event/37867/contributions/229769/

Light Dark Matter

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_\chi - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}M^2_{A'}A'_\mu A'^\mu - \frac{\varepsilon}{2}F'_{\mu\nu}F^{\mu\nu}$$

$$\mathcal{L}_\chi = \begin{cases} i\bar{\chi}\not{D}\chi - M_\chi\bar{\chi}\chi, & \text{(Dirac fermion DM)} \\ |D_\mu\chi|^2 - M_\chi^2|\chi|^2, & \text{(Complex scalar DM)} \end{cases}$$

- Dark matter model, sub-WIMP-mass, couples via a dark photon
- DM pairs are produced by neutral meson (π^0 and η) decays from the NuMI target
  - These neutral mesons are not focused by beam magnets, so using the off-axis beam flux is helpful to reduce neutrino backgrounds
- Dark-trident process:
  - DM scattering with argon produces a dark photon which decays to an e^+e^- pairs



Mass regime:
$M_{A'} < 2M_\chi$

- Dark photon coupling: α_D
- Dark matter mass: M_χ
- Dark photon mass: $M_{A'}$
- Coupling to SM: ε

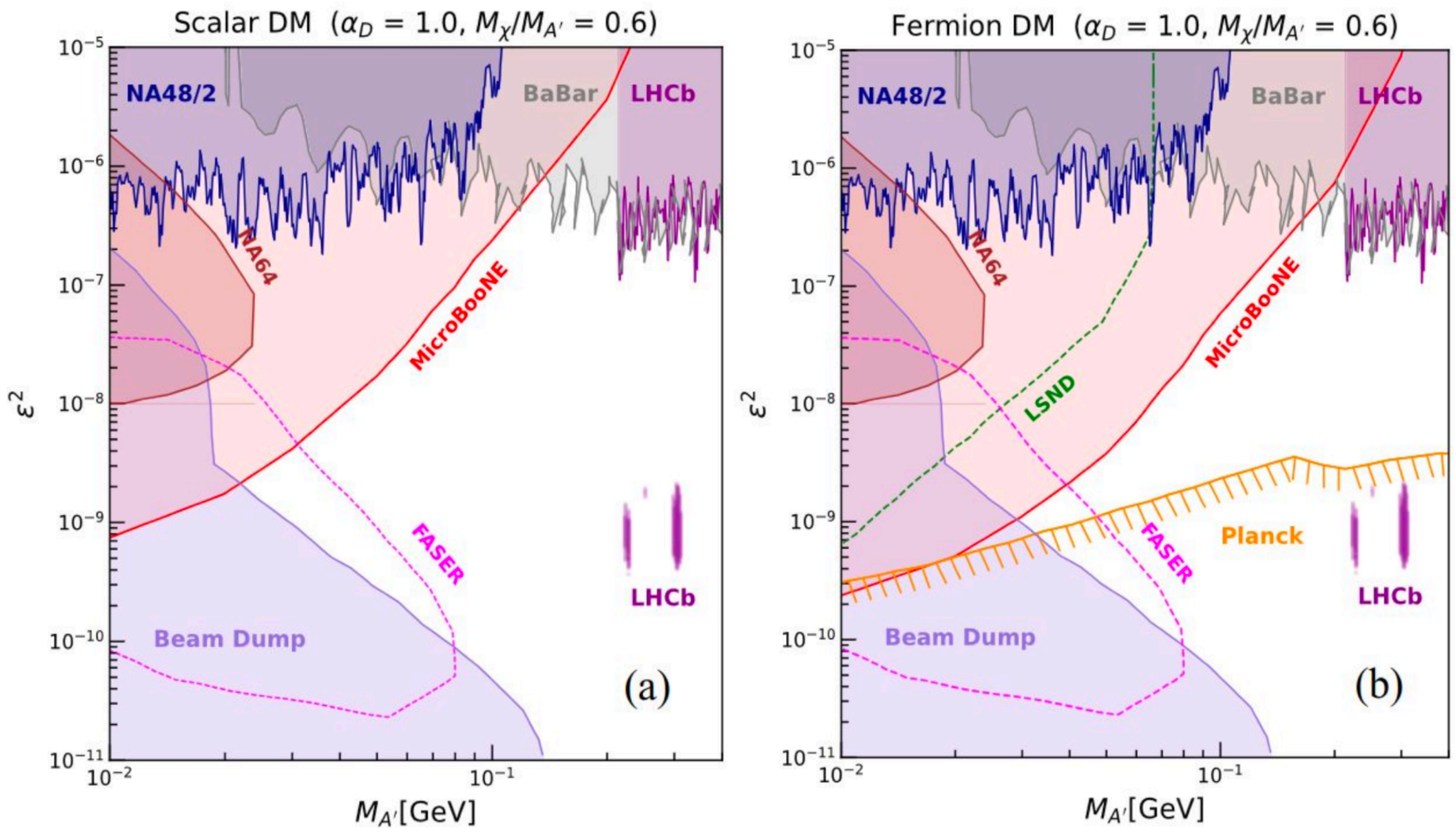
André de Gouvêa, Patrick J. Fox, Roni Harnik, Kevin J. Kelly, Yue Zhang

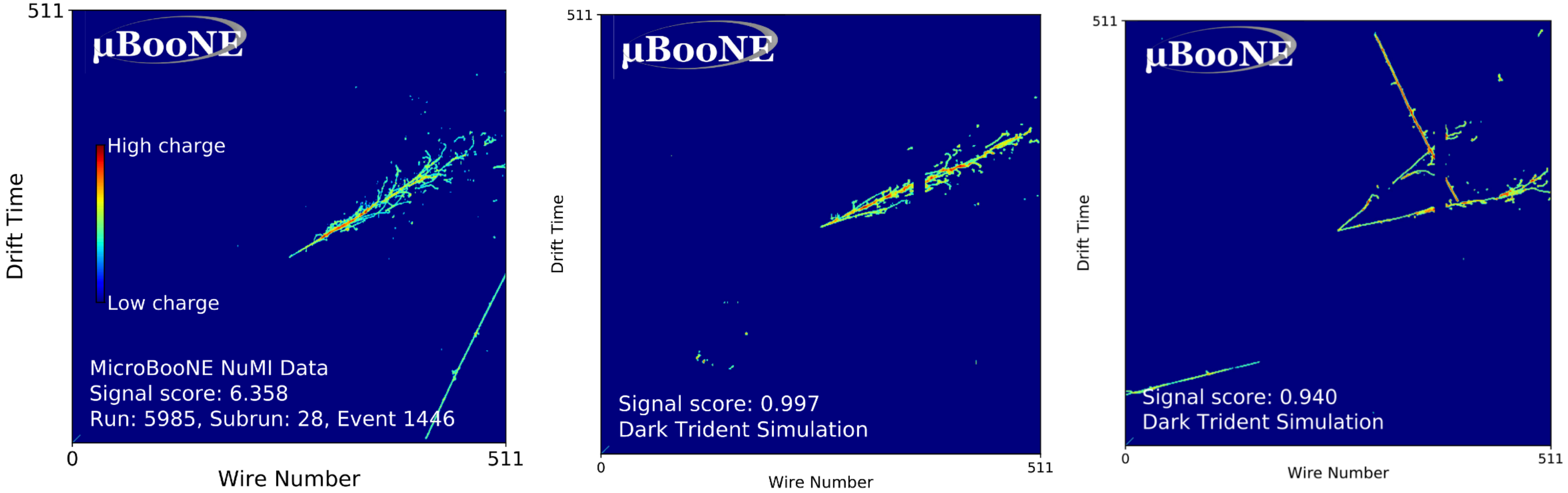
[J. High Energ. Phys. 2019, 1 (2019)]

Light Dark Matter

- Uses a convolutional neural network to identify dark-trident-like e^+e^- events among many cosmic ray and neutrino backgrounds

- We set word-leading limits for both scalar and fermion dark matter

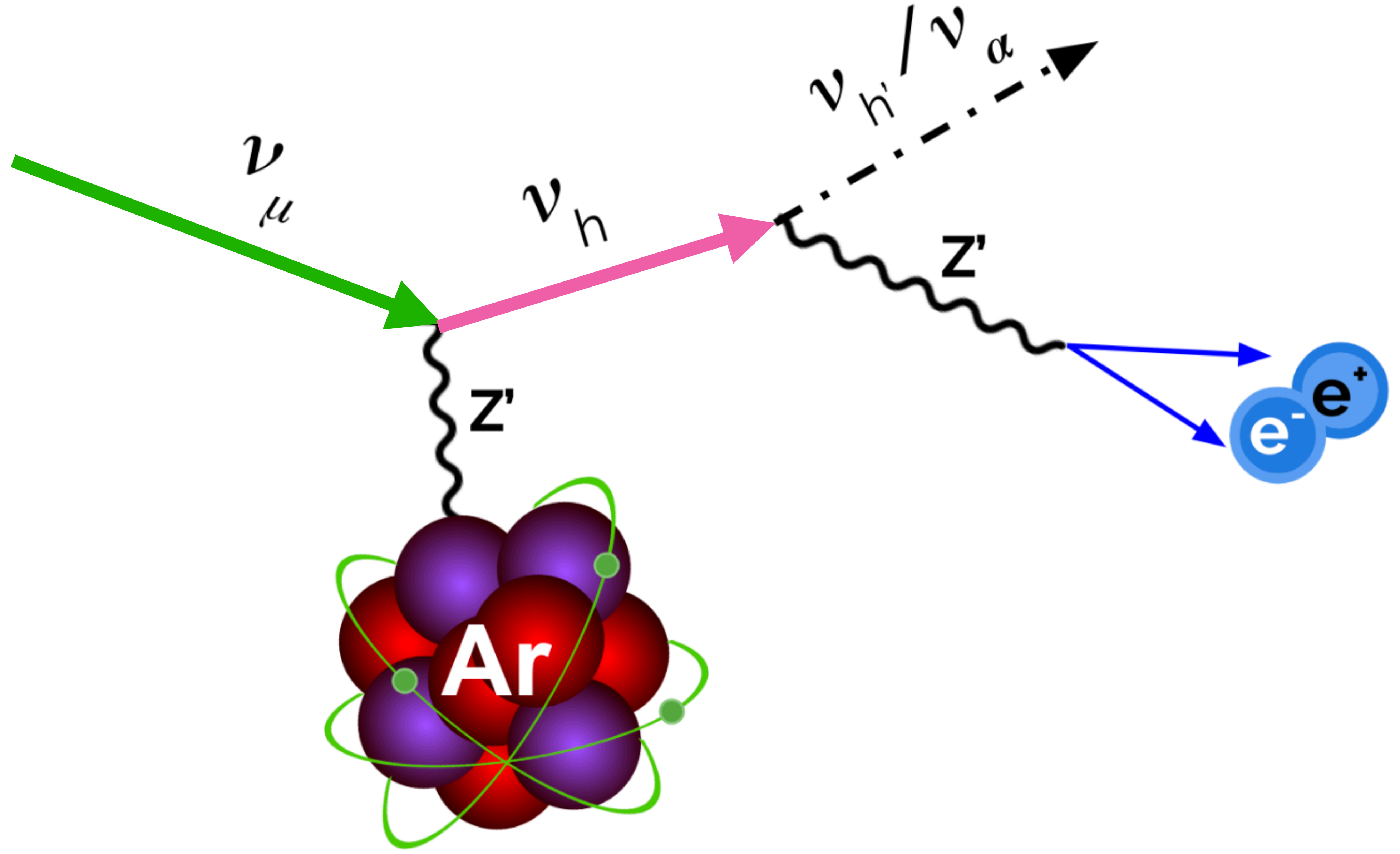




Phys. Rev. Lett. 132, 241801 (2024)

Dark Neutrinos

- Neutrinos up-scatter to heavy sterile neutrinos (dark neutrinos)
- These dark neutrinos can be long or short lived, produced in the dirt upstream of MicroBooNE, or inside MicroBooNE
- The dark neutrinos then decay to e^+e^- pairs
- This model could explain the MiniBooNE Low Energy Excess (LEE) of electromagnetic events
    - A 4.8σ unexplained neutrino anomaly just 90 m downstream in the same neutrino beam!



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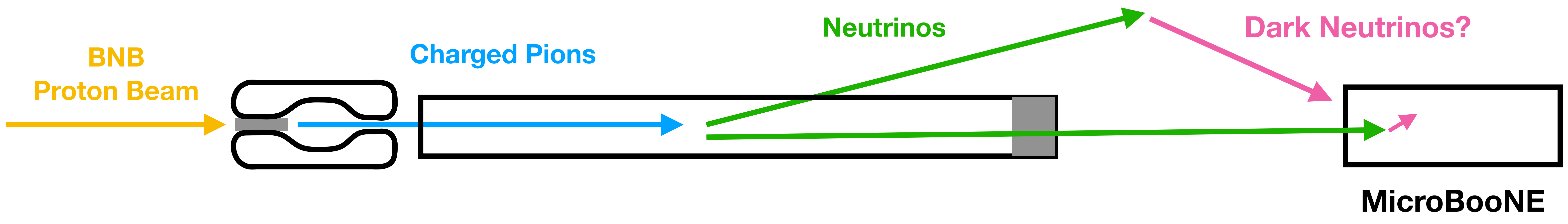


Asli M. Abdullahi, Jaime Hoefken Zink, Matheus Hostert, Daniele Massaro, Silvia Pascoli

https://arxiv.org/abs/2308.02543

https://arxiv.org/abs/2207.04137

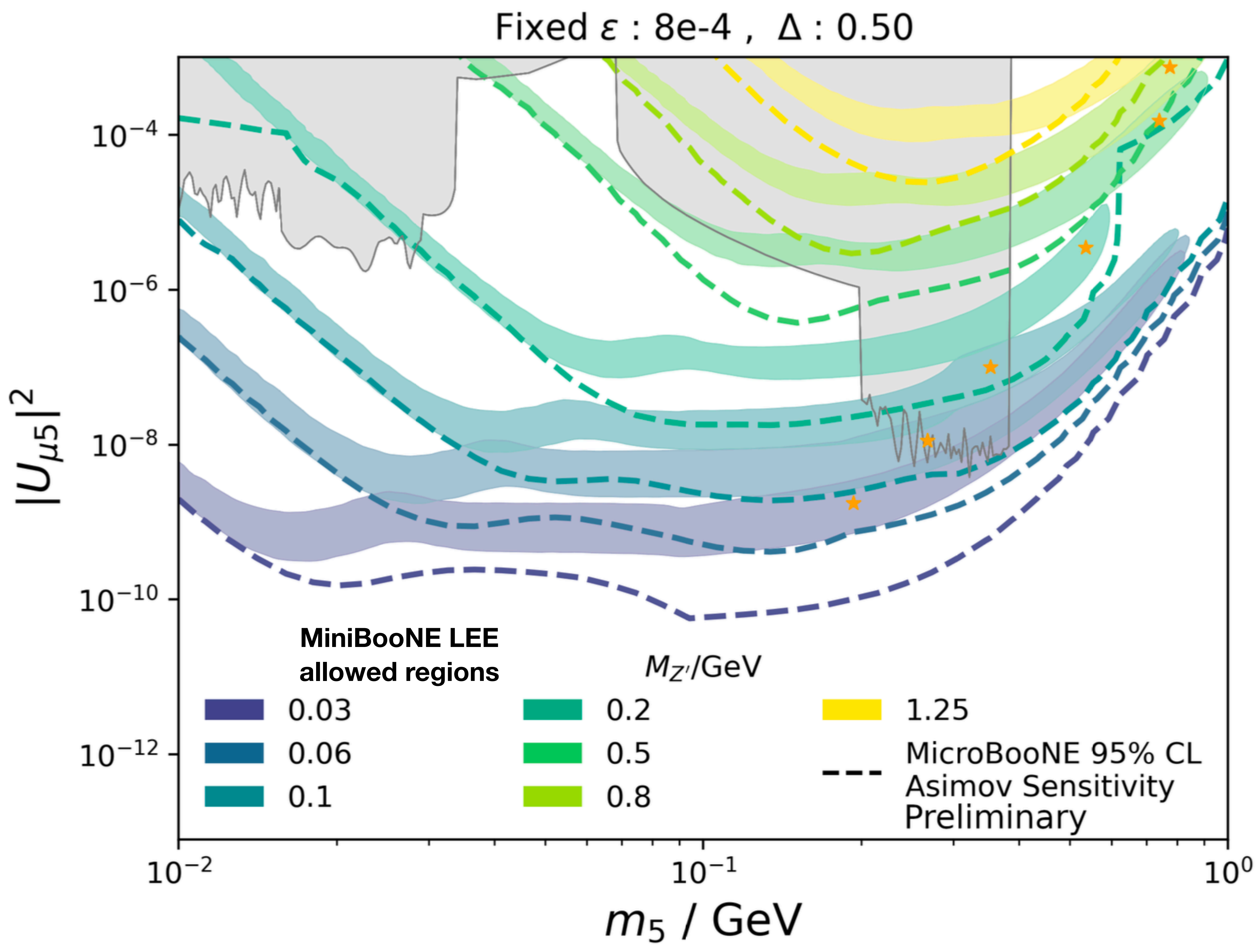
Enrico Bertuzzo, Sudip Jana, Pedro A.N. Machado, Renata Zukanovich Funchal

Phys. Rev. Lett. 121, 241801 (2018)

https://microboone.fnal.gov/wp-content/uploads/2024/06/MICROBOONE-NOTE-1124-PUB.pdf

Dark Neutrinos

- Most sensitivity in MicroBooNE comes from coherent scattering
  - Here, the large argon nucleus gives us a boost in expected event rate relative to MiniBooNE
- We expect to be able to exclude almost all of the MiniBooNE-allowed phase space of this model
- Look forward to unblinded results soon!



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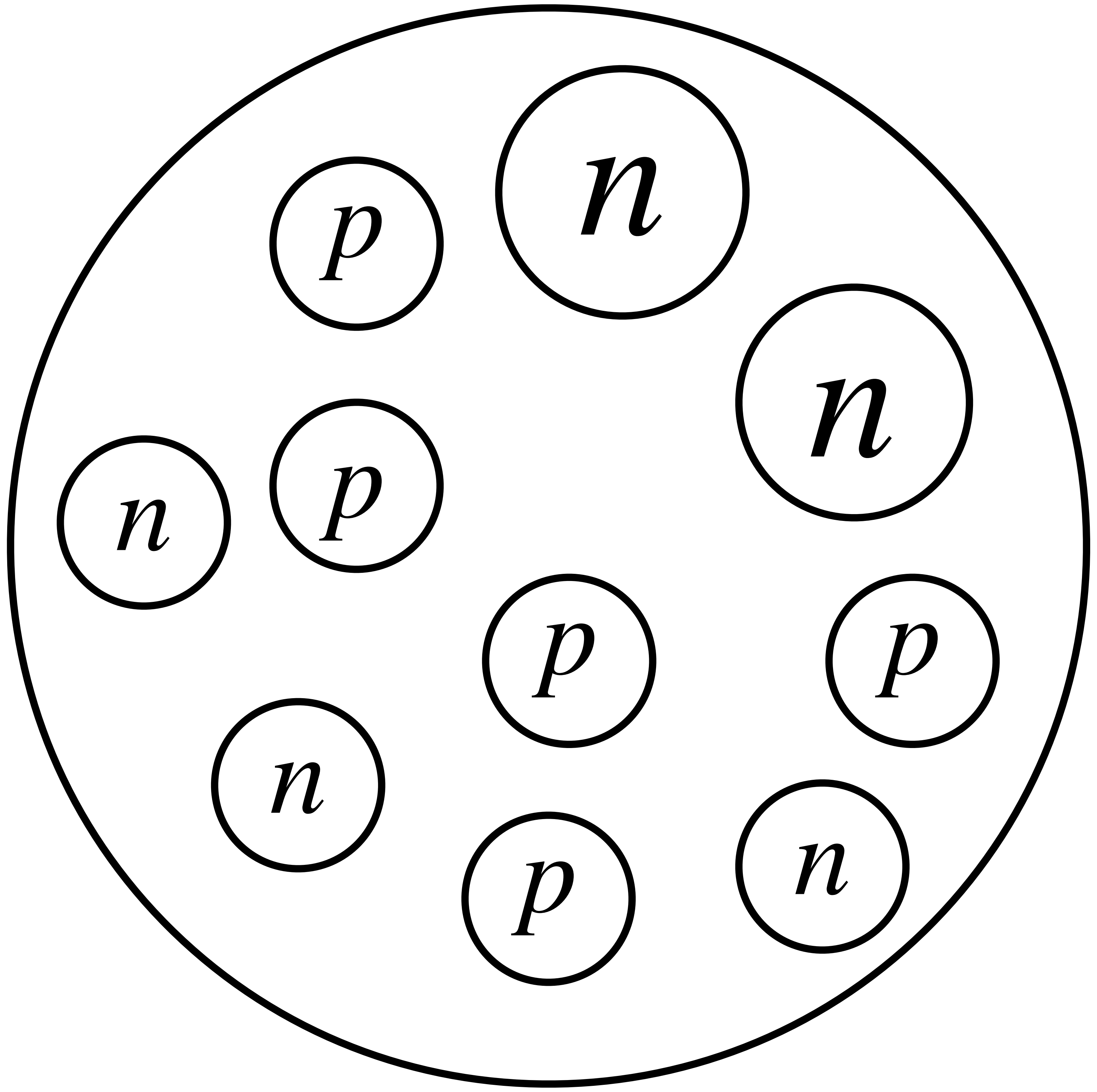
Neutron-Antineutron Transitions

- Neutron to antineutron transition ($n \rightarrow \bar{n}$) is a theoretically motivated BSM process which would violate baryon number by two units

- Important to understand the baryon asymmetry of the universe

- In a nucleus, a neutron can spontaneously convert to an antineutron, which then annihilates with a neutron or proton, producing pions in the final state

Argon-40 Nucleus



JINST 19 P07032 (2024)

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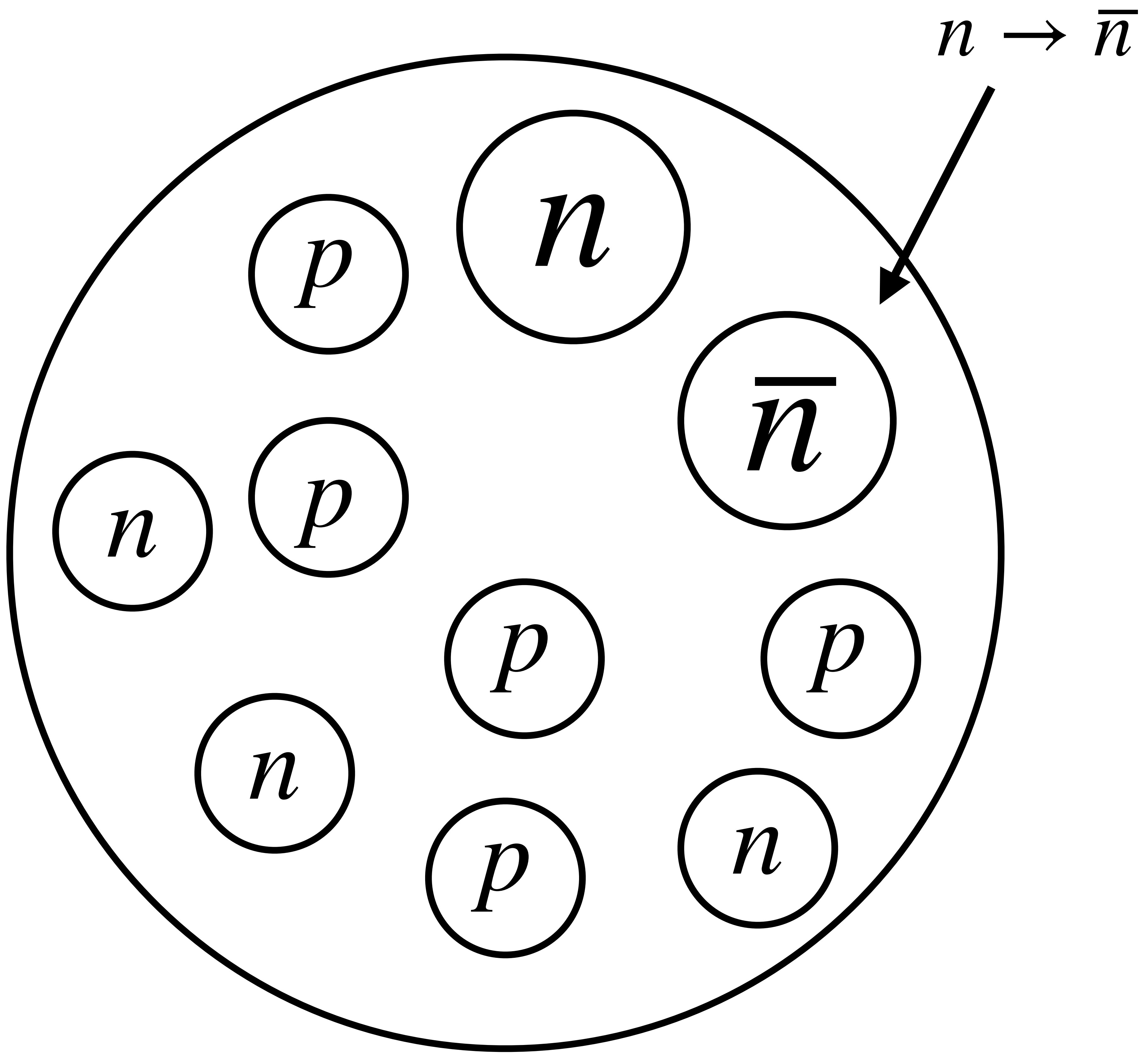

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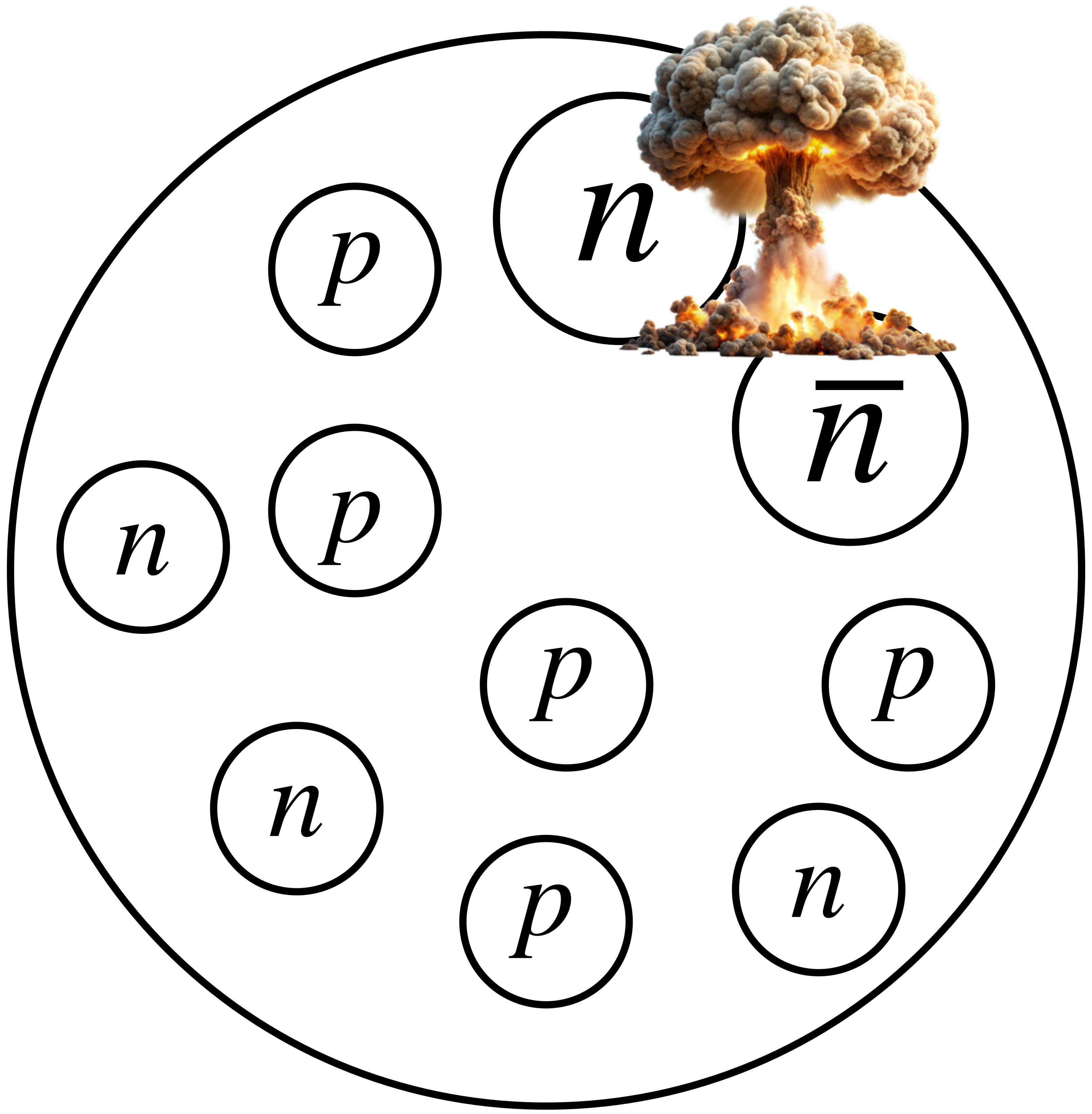

~9x more energy released than a U-235 fission

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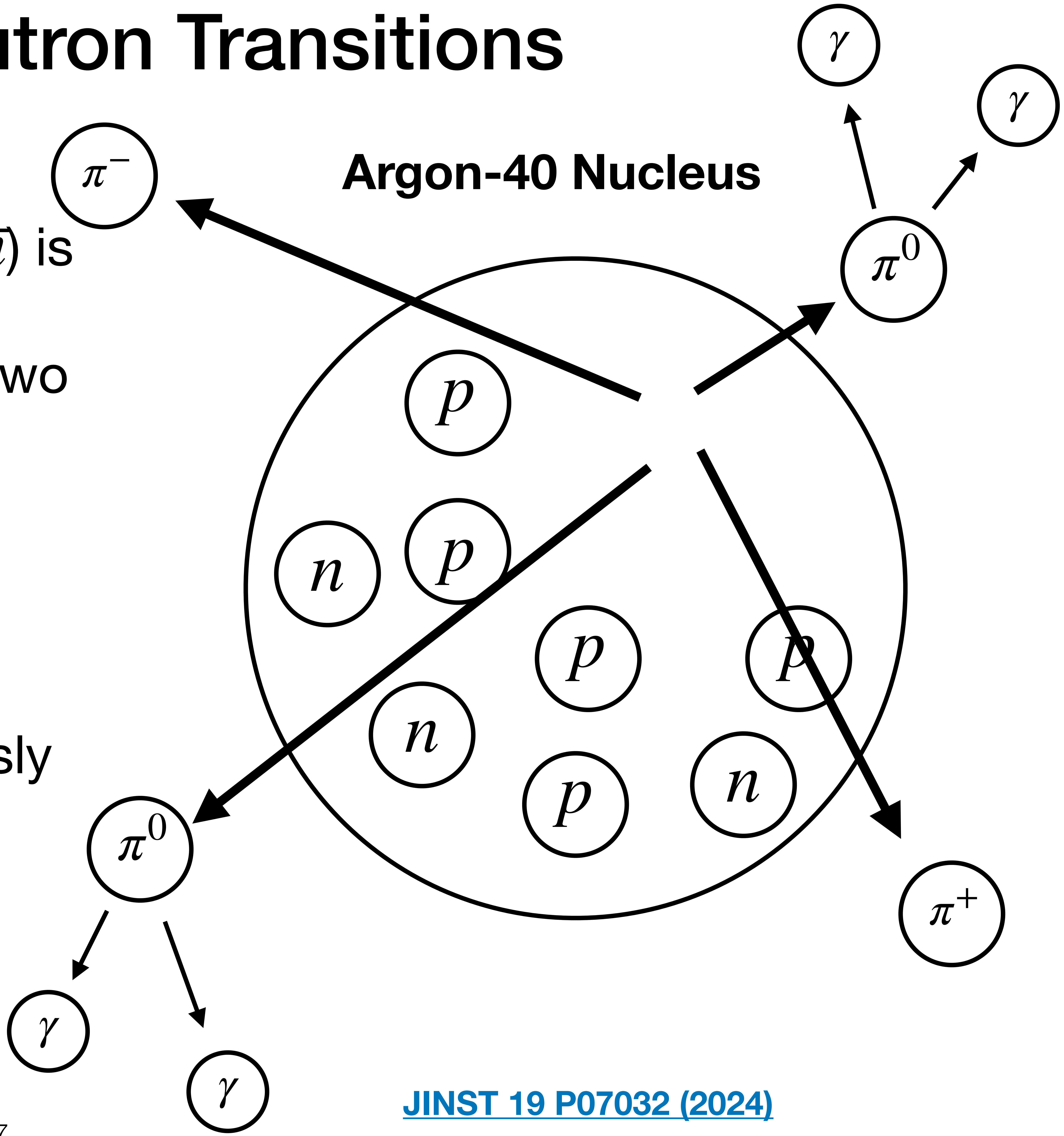

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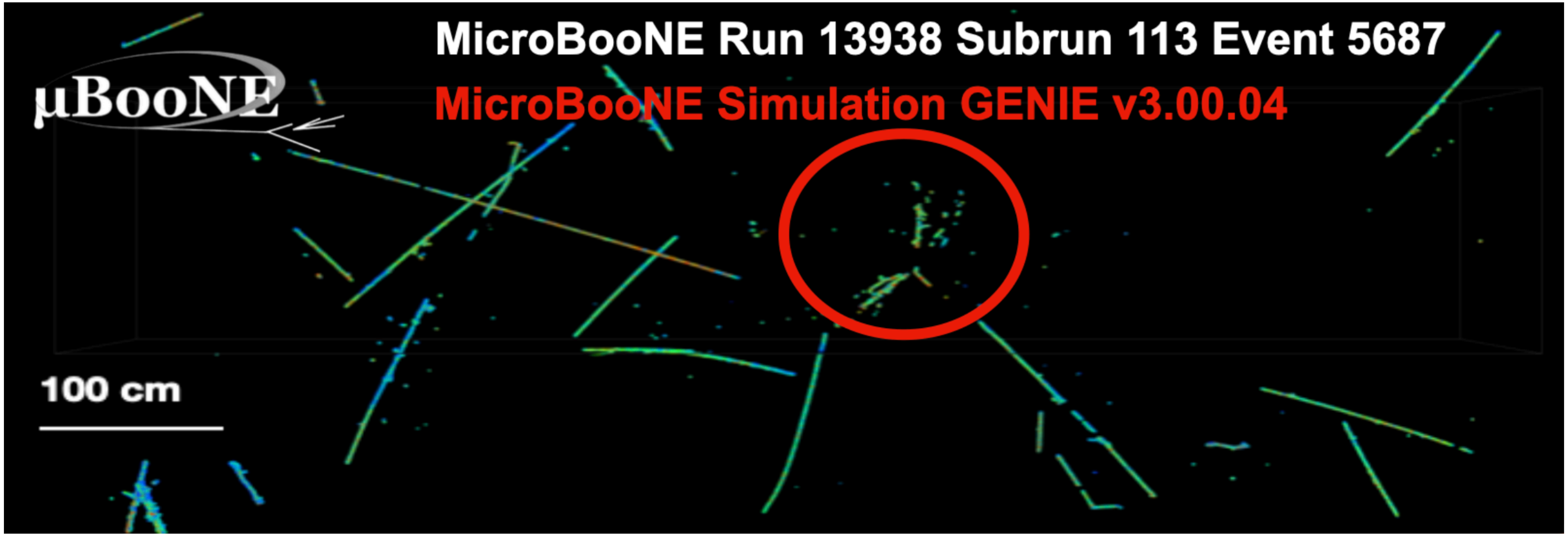
Neutron-Antineutron Transitions

- In MicroBooNE, we use a convolutional neural network to identify these events and reject cosmic ray backgrounds
- Unique isotropic star-like topology



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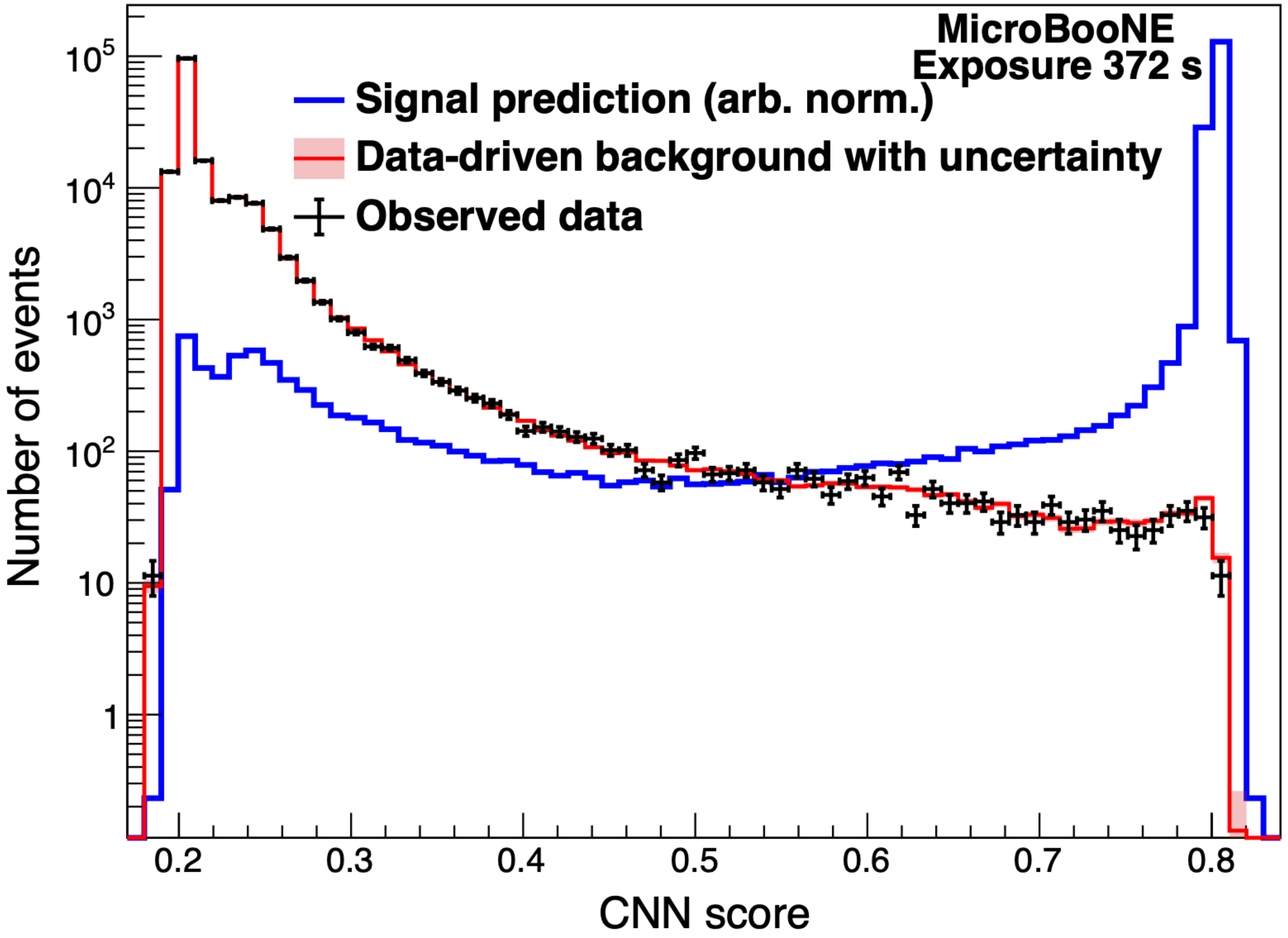
Neutron-Antineutron Transitions

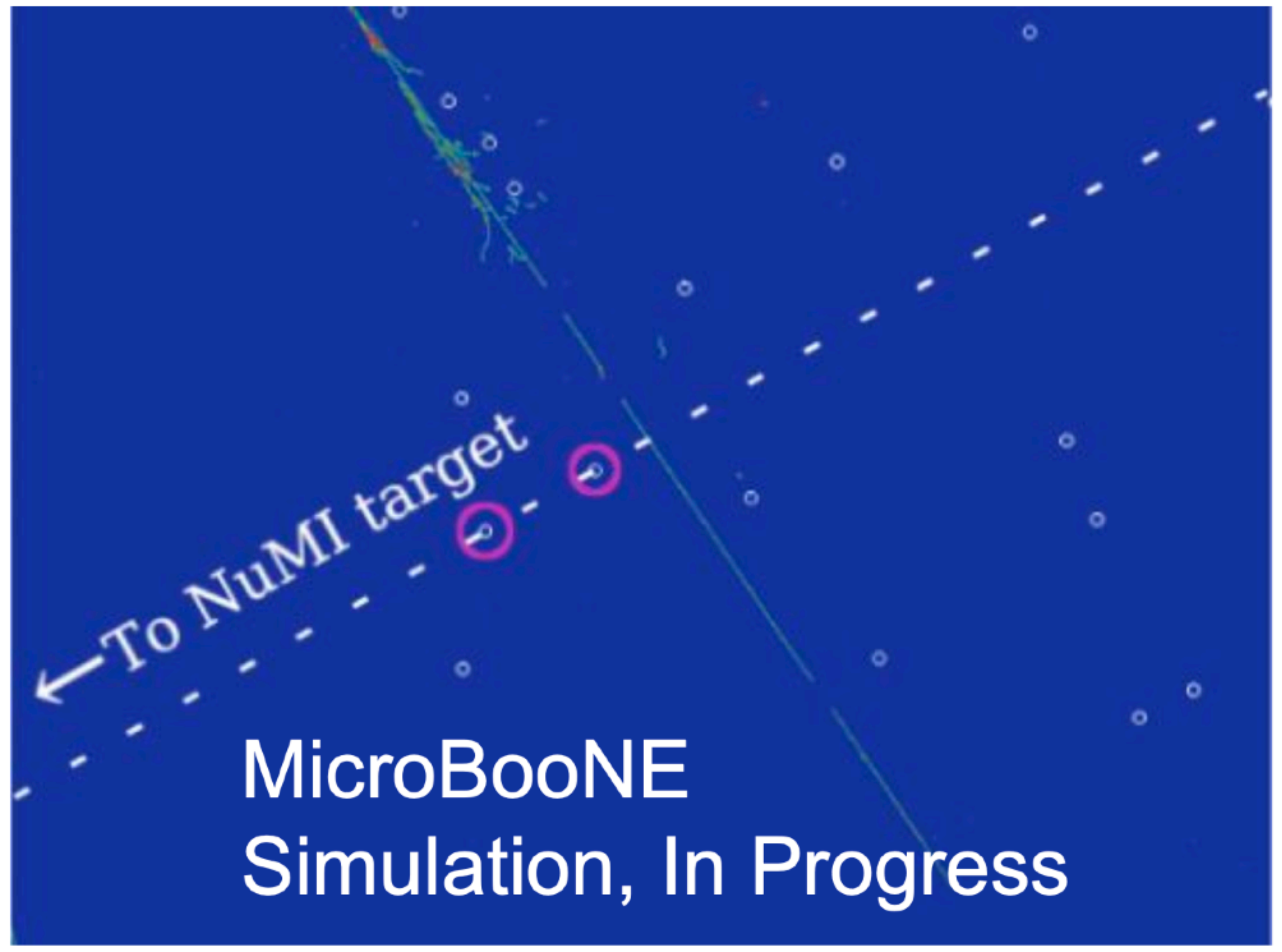
- We find that a CORSIKA cosmic ray simulation is insufficient to describe relevant backgrounds, so we set a “demonstrative” limit, assuming no signal and forming a data-driven background estimate
  - $\tau_m \gtrsim 1.2 \times 10^{26}$ yr in ^{40}Ar (90% CL)
  - $\tau_{n\to\bar{n}} \gtrsim 2.6 \times 10^{5}$ s for a free neutron (90% CL)
- This demonstrates a high efficiency selection of this topology, important for DUNE
  - DUNE will set a much more competitive limit, by scaling up this LArTPC technology by a factor of ~500x, deep underground with vastly reduced cosmic rays

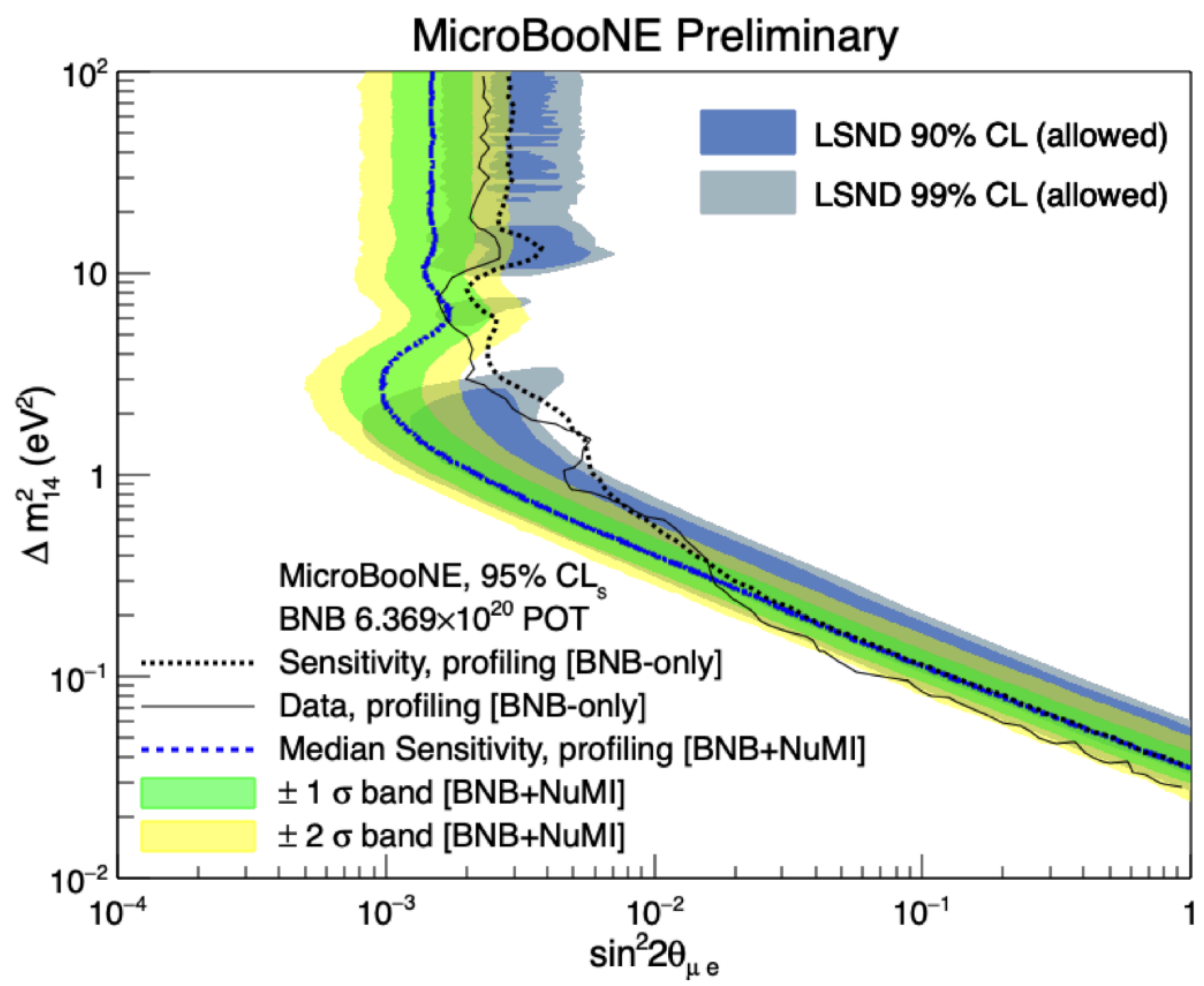


JINST 19 P07032 (2024)

More Ongoing BSM Analyses At MicroBooNE

- Millicharged particles
- Heavy QCD axions
- Short baseline neutrino oscillations using BNB+NuMI
- More general photon/e^+e^- anomaly searches





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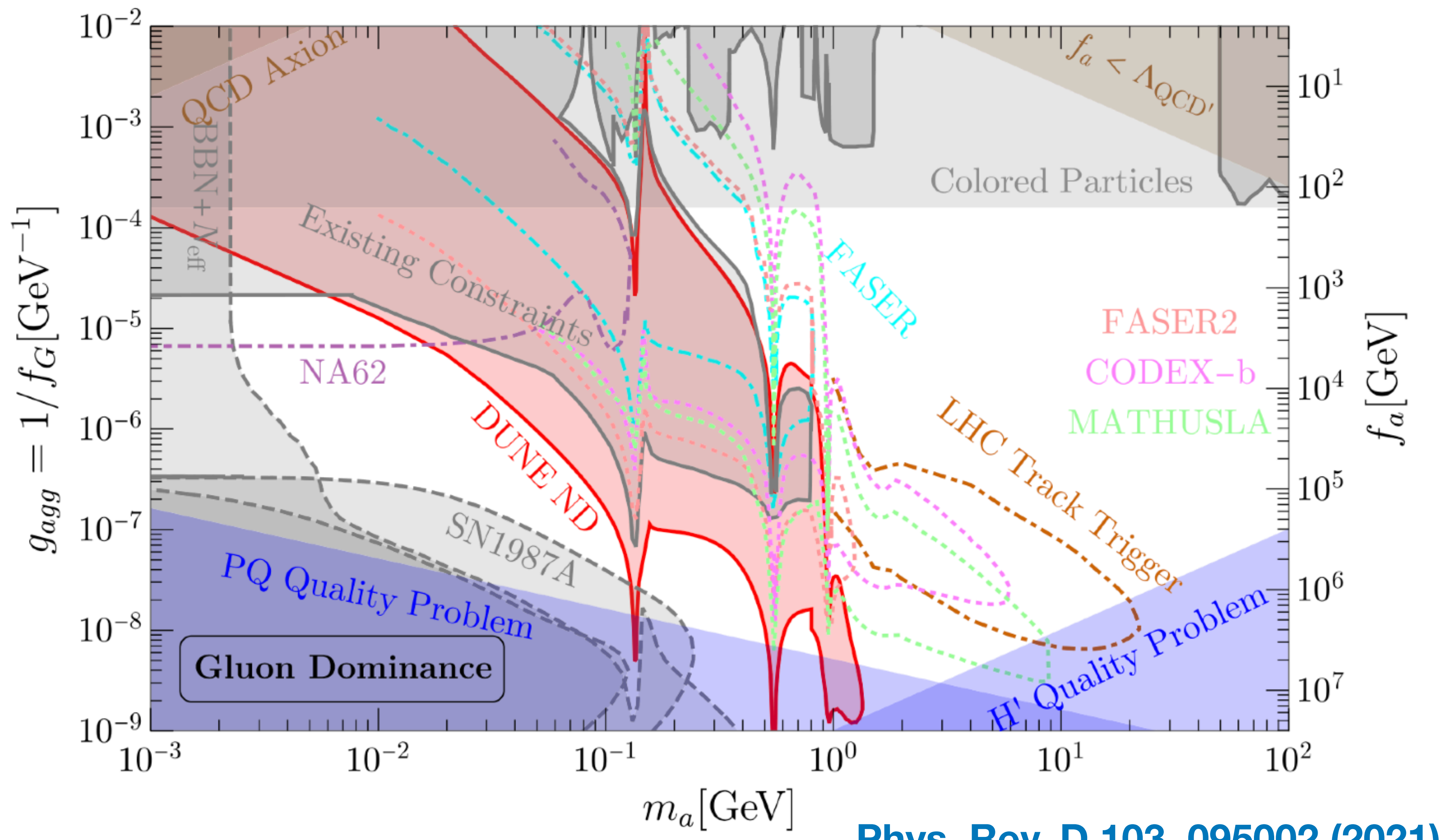

[Phys. Rev. D 103, 095002 (2021)](https://doi.org/10.1103/PhysRevD.103.095002)

Thanks for your attention!