Dark Interactions:
New Perspectives
from Theory and
Experiment

Opportunities for Axion Searches at Beam Dumps and Stopped Pion Facilities

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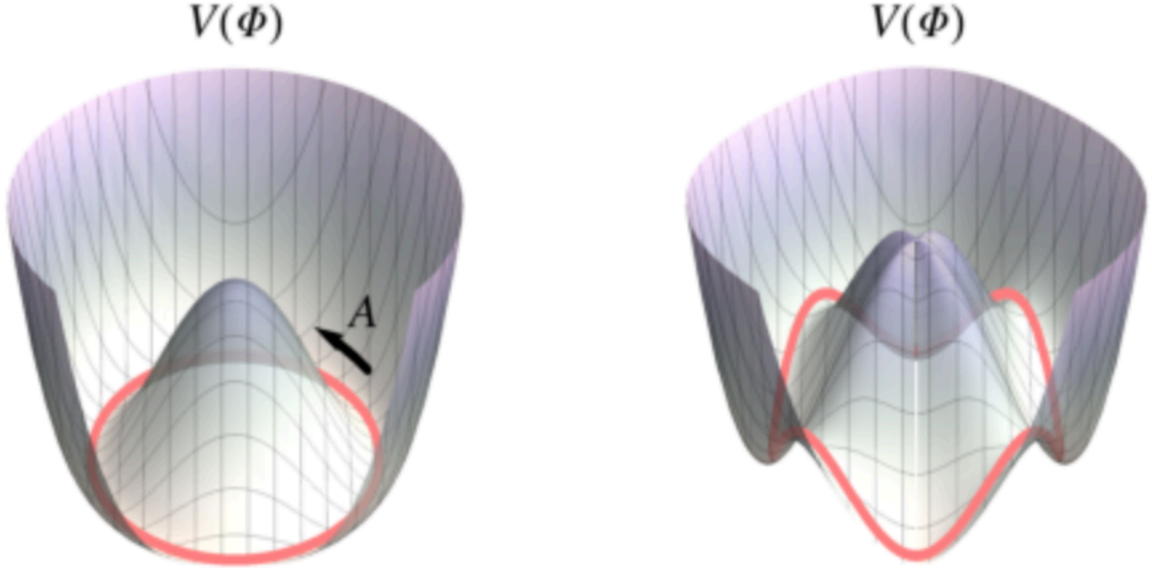
November 16, 2022

Outline

1. Why ALPs?
2. MeV sources: Reactors and low-energy beam targets
3. ALPs at stopped-pion facilities: CCM case study
4. ALPs at beam dumps: MiniBooNE case study
5. What about the future?

Why study axions?

- Broken symmetries + QM corrections → massive goldstone modes
- Example: **the QCD Axion** - introduced to explain why the strong force seems to conserve Charge-Parity
- Other massive pseudoscalar examples:
  - **string theory** pseudoscalars from compactification → "***axiverse***"
  - Majorons, Familons, etc. → **neutrino masses** and **flavor structure, spontaneous breaking of symmetries**
  - pseudoscalar **dark matter**



Couplings to SM fermions and photons can be easily generated:

$$\mathcal{L}_{\rm ALP} \supset -\frac{g_{a\gamma}}{4}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} - g_{ae}\, a\, \bar{e}\, i\gamma_5\, e$$

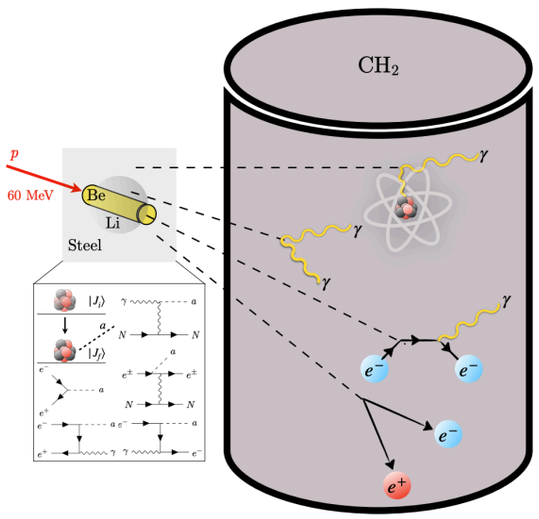
<u>Heavy ALPs in the MeV mass range are well motivated!</u>

- "High quality" QCD axions: heavy to make their potential robust to corrections
- Axiverse: towers of o(10) - o(100) ALP masses

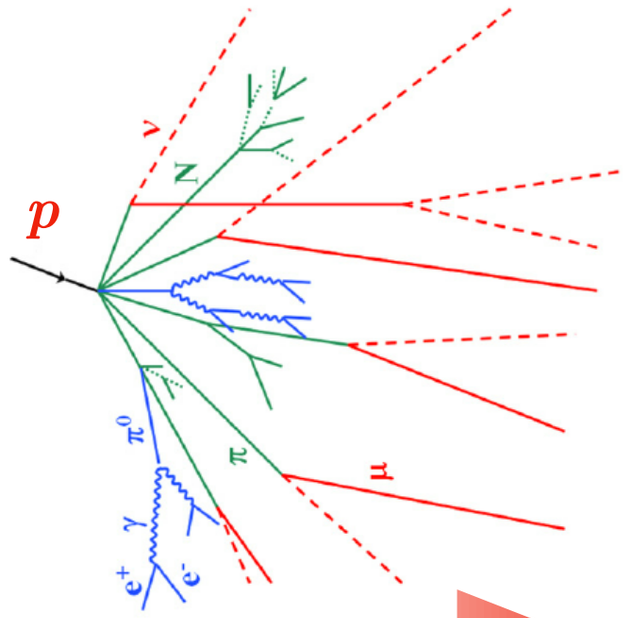
Laboratory Probes of Axion-like Particles

Couplings to electrons and photons enable a rich set of source channels in EM cascades

$$\mathcal{L}_{\rm ALP} \supset -\frac{g_{a\gamma}}{4}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} - g_{ae}\, a\, \bar{e}\, i\gamma_5\, e$$



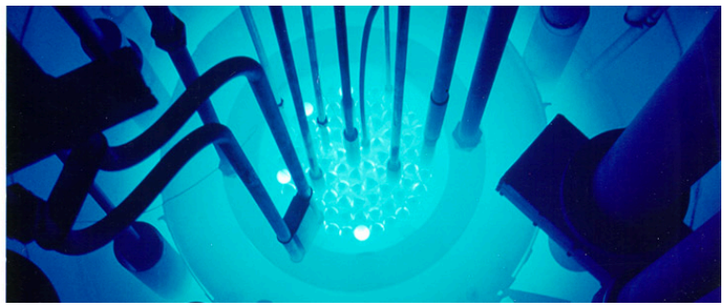
Stopped-Pion Facilities,
MeV-GeV p Beam Targets

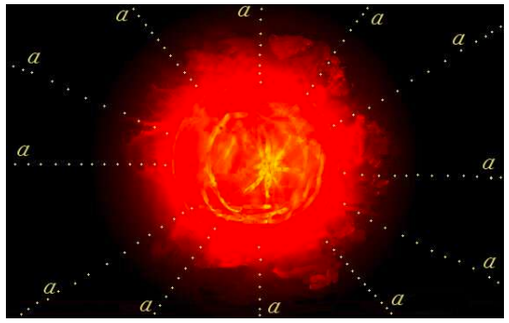


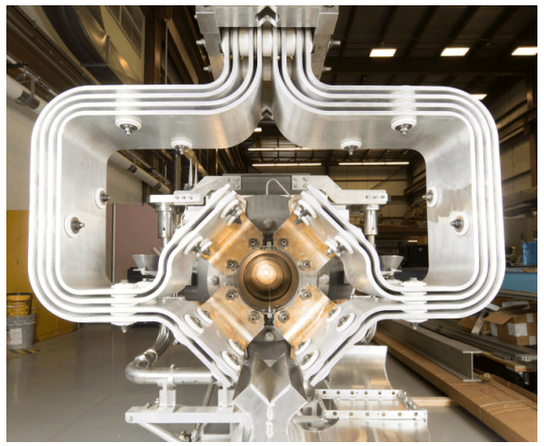
Energy Scale: **keV** **1 MeV** **100 MeV** **> GeV**

Stellar Cores,
Reactors

$\mathcal{O}(10) - \mathcal{O}(100)$ GeV $e^{\pm}, p$
beam dumps

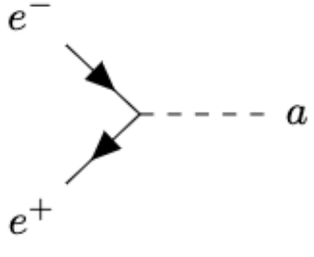




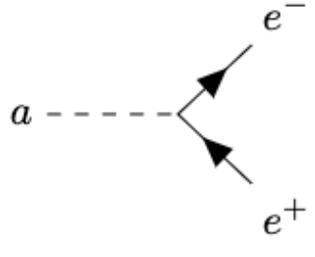


Meet the ALP Channels:

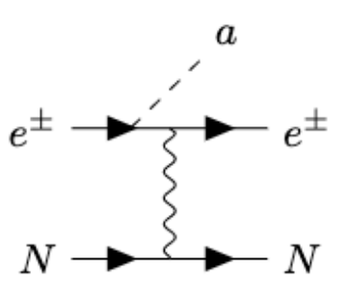
$$\mathcal{L}_{\text{ALP}} \supset -\frac{g_{a\gamma}}{4}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} - g_{ae}\, a\, \bar{e}\, i\gamma_5\, e$$



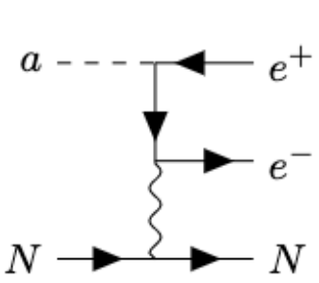
(g) Resonant production



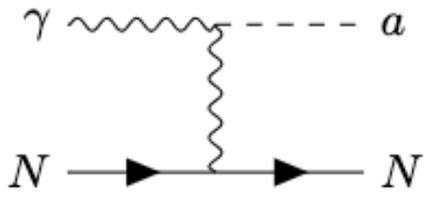
(h) e^+e^- decay



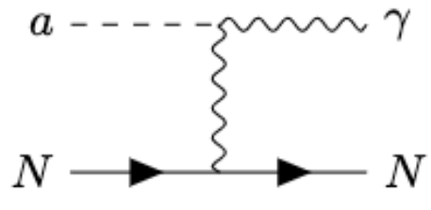
(i) ALP-bremsstrahlung



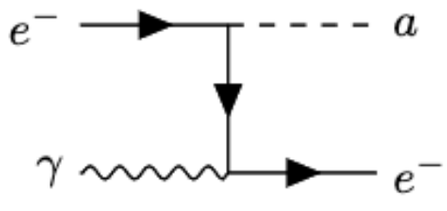
(j) External pair conversion



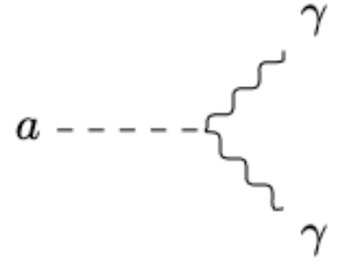
(a) Primakoff



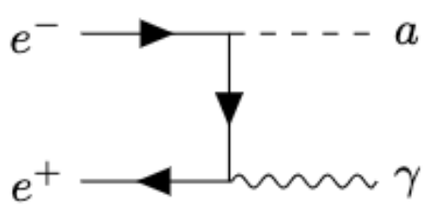
(b) Inverse Primakoff



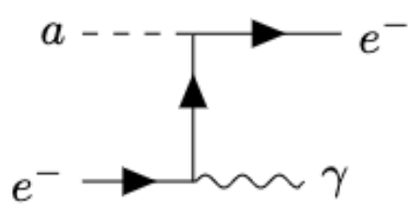
(c) Compton



(d) Diphoton decay



(e) Associated production



(f) Inverse Compton

- Accelerator Beam Targets: Protons on target induce hadronic processes (stopped pions, charged pions) as well as **E&M cascade**s (e+/e- production, gammas)
- Many channels; builds off our previous work:
  - Reactors: **MINER (*Phys.Rev.Lett.* 124 (2020) 21, 211804)**
  - Beam dumps: **DUNE (*Phys.Rev.Lett.* 126 (2021) 20, 201801)**

MeV-scale Axion Searches at Reactors

PHYSICAL REVIEW D **75,** 052004 (2007)

Search for axions from the Kuo-Sheng nuclear power reactor with a high-purity germanium detector

H. M. Chang,[1,2] H. T. Wong,[1,*] M. H. Chou,[1] M. Deniz,[1,3] H. X. Huang,[1,4] F. S. Lee,[1] H. B. Li,[1] J. Li,[5,6] H. Y. Liao,[1,2] S. T. Lin,[1,2] V. Singh,[1] S. C. Wu,[1] and B. Xin[4]

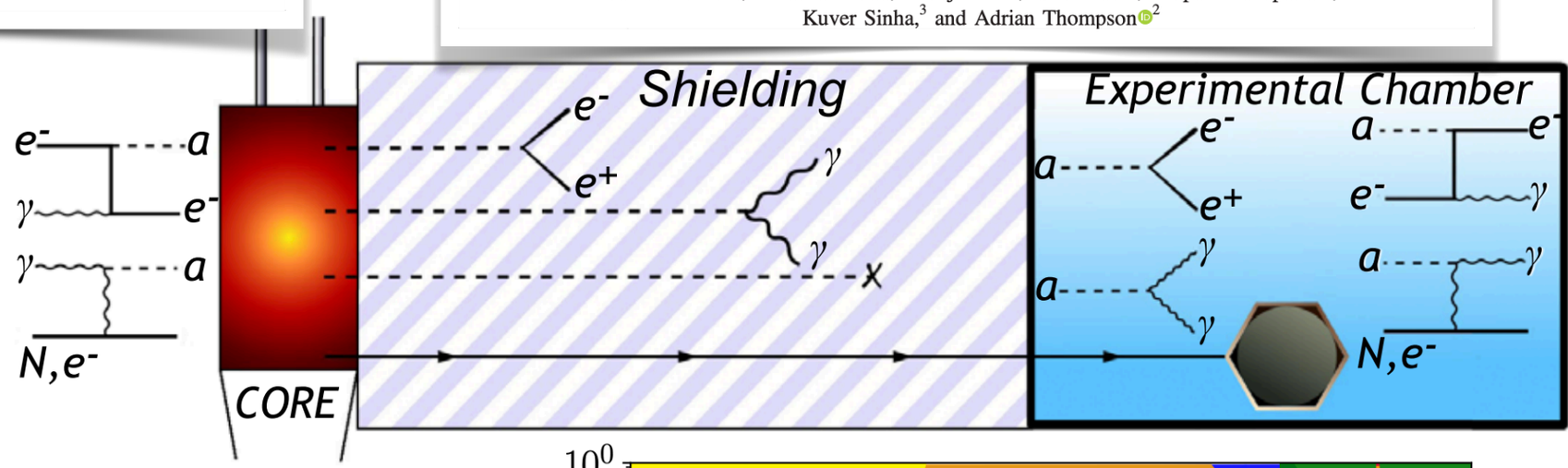
TEXONO: ALP produced from nuclear excited state transitions Detection from Primakoff & Compton scattering, decays

PHYSICAL REVIEW LETTERS **124,** 211804 (2020)

Our work: **1912.05733**

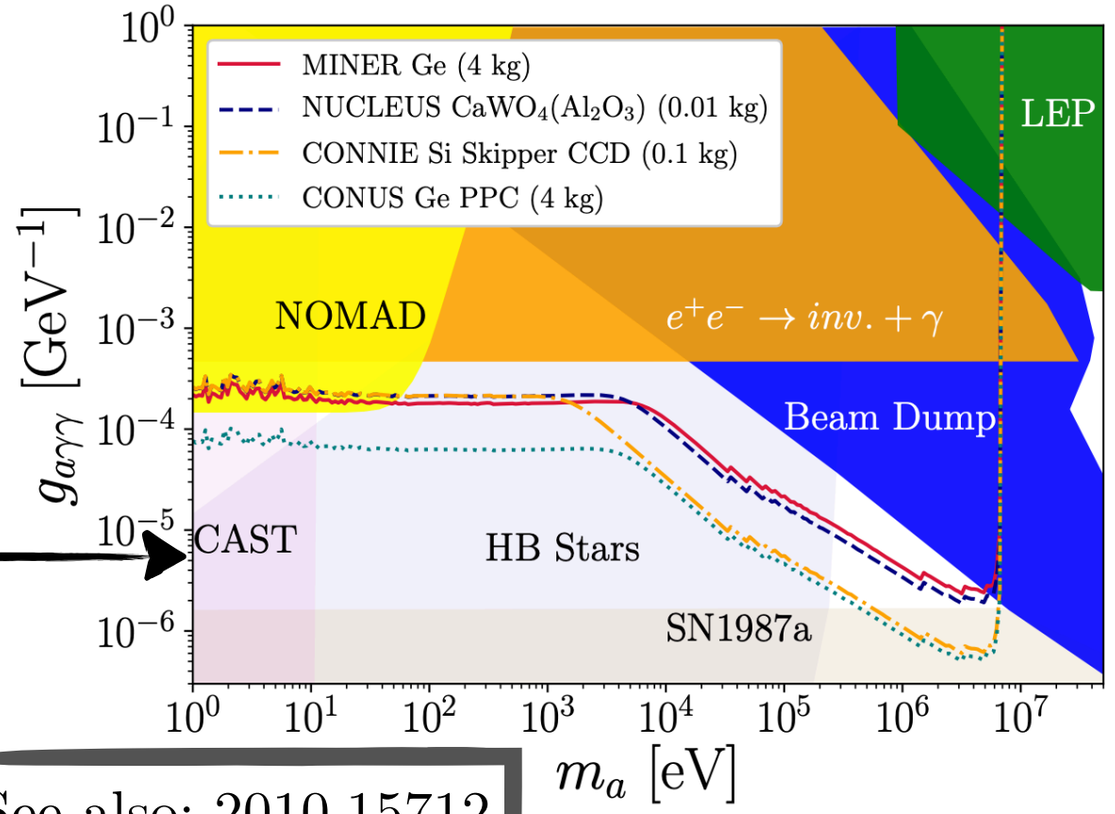
New Directions for Axion Searches via Scattering at Reactor Neutrino Experiments

James B. Dent,[1] Bhaskar Dutta,[2] Doojin Kim,[2] Shu Liao,[2] Rupak Mahapatra,[2] Kuver Sinha,[3] and Adrian Thompson[2]



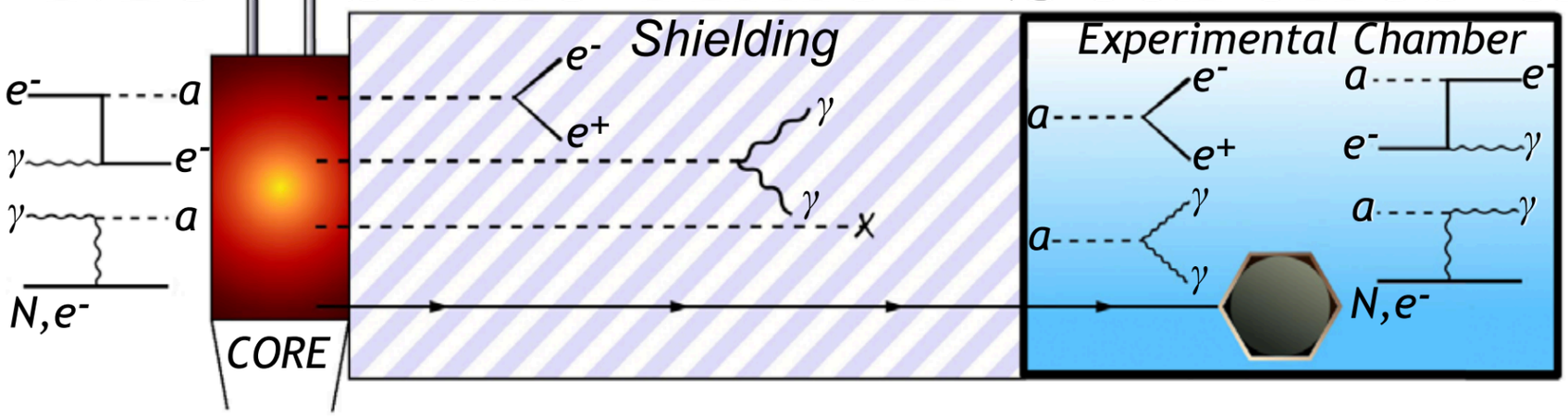
New approach:

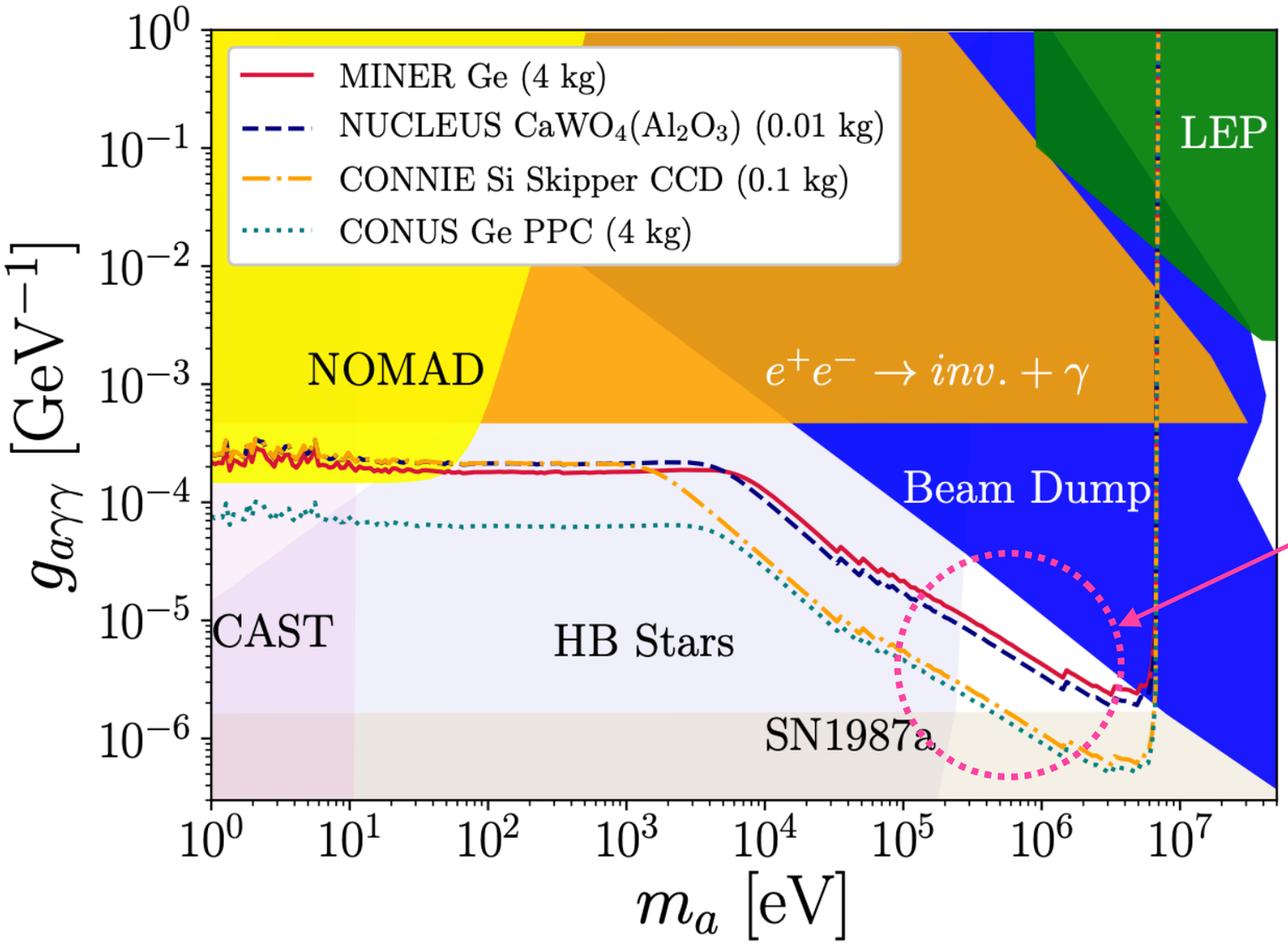
- High-Z core material (Uranium decay chain elements) → good for coherent production (Primakoff) $\sigma \propto Z^2$
- Also include Compton-like scattering in the core material
- Allows for exclusive limits over single coupling ($g_{ae}, g_{a\gamma}$)



See also: 2010.15712

MeV-scale Axion Searches at Reactors

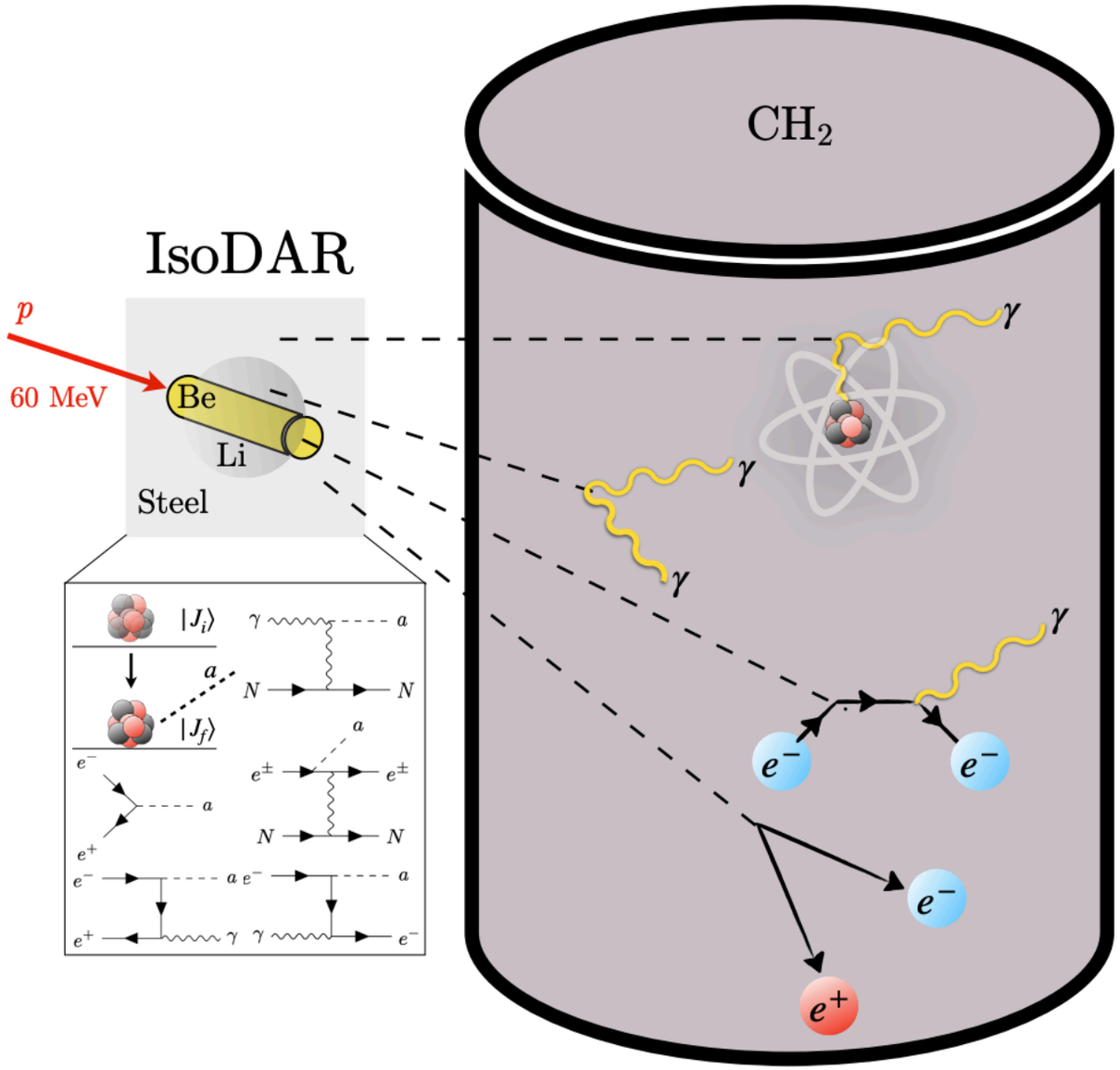


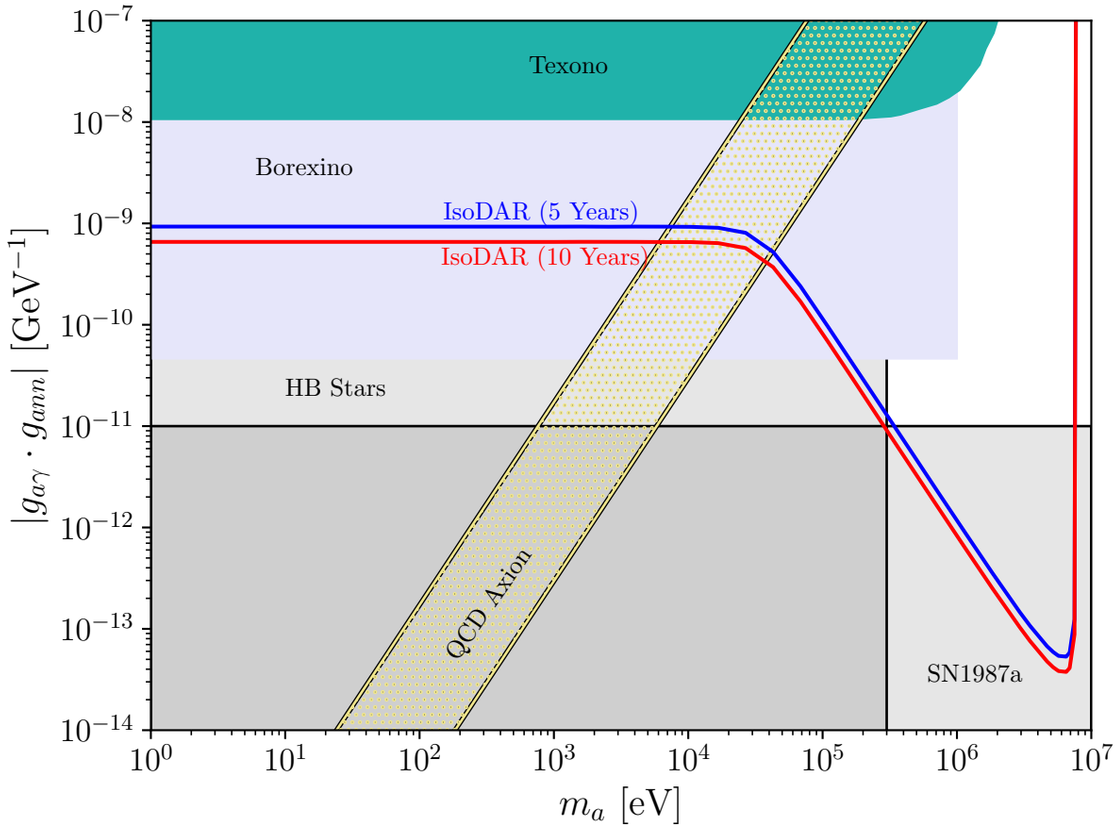


"Cosmological triangle"
Region unconstrained by laboratory physics

See also: 2010.15712

Low Energy Beam Targets: 60 MeV



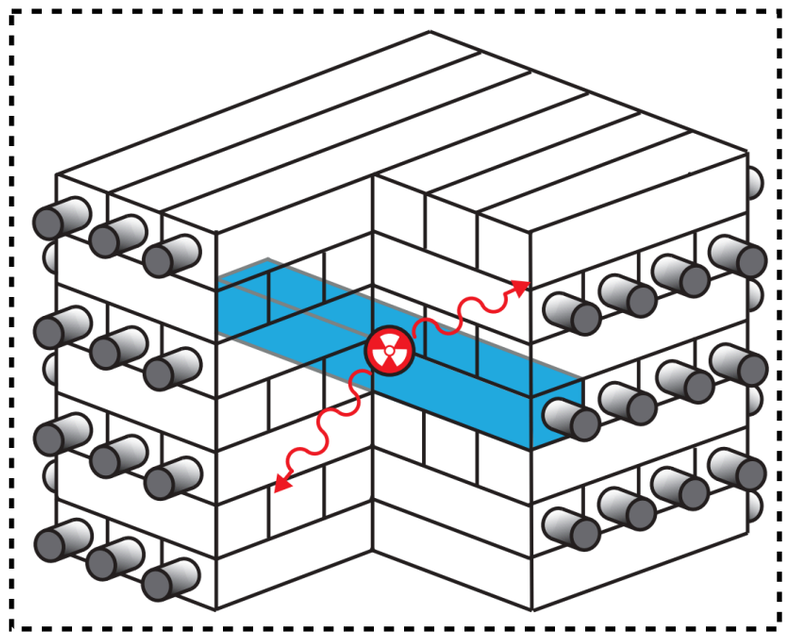


- GEANT4 Simulation with `QGSP_BIC_AllHP`

2207.13659

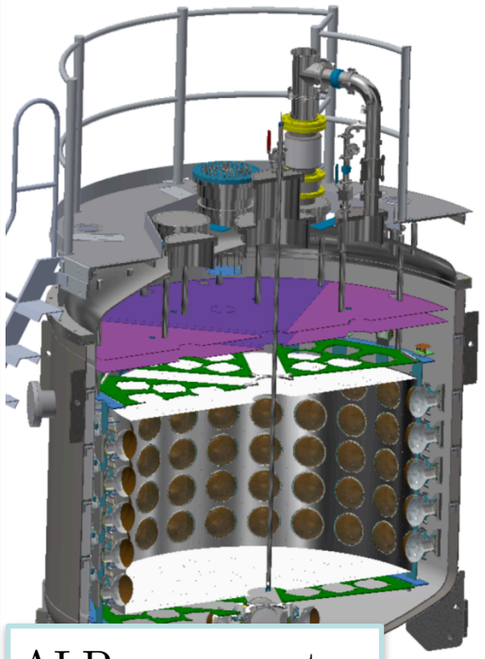
Loyd Waites, Adrian Thompson, Adriana Bungau, Janet M. Conrad, Bhaskar Dutta, Wei-Chih Huang, Doojin Kim, Michael Shaevitz, Joshua Spitz

Builds off previous work looking for missing energy in nuclear de-excitations:
Phys.Rev.D 105 (2022) 1, 015030
Phys.Rev.D 99 (2019) 3, 035025



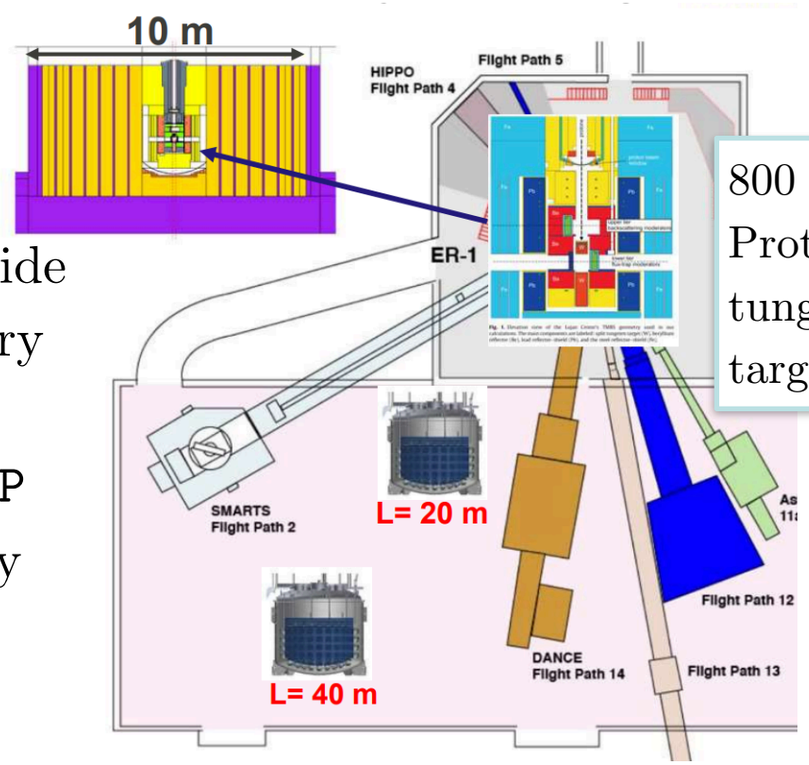
800 MeV Stopped-Pion Facilities

Axion-like Particles at CCM: 2112.09979

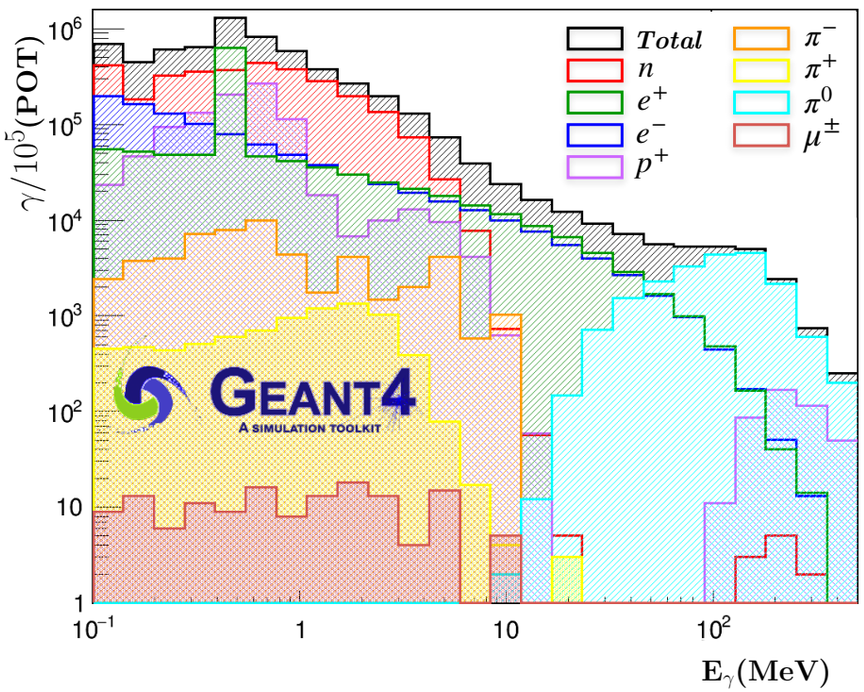


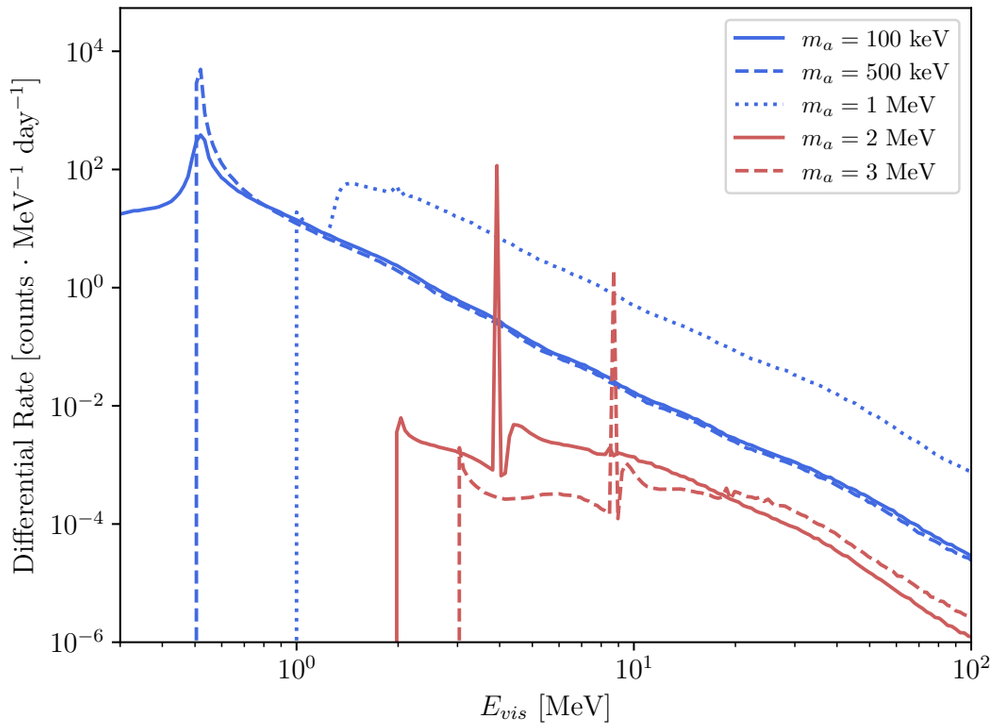
ALPs propagate isotropically to CCM (LAr)

- Photon, electron, and positron fluxes inside the Lujan target must be known as theory input to predict ALP signals
- Simulations performed with `QGSP_BIC_HP` physics list with detailed target geometry

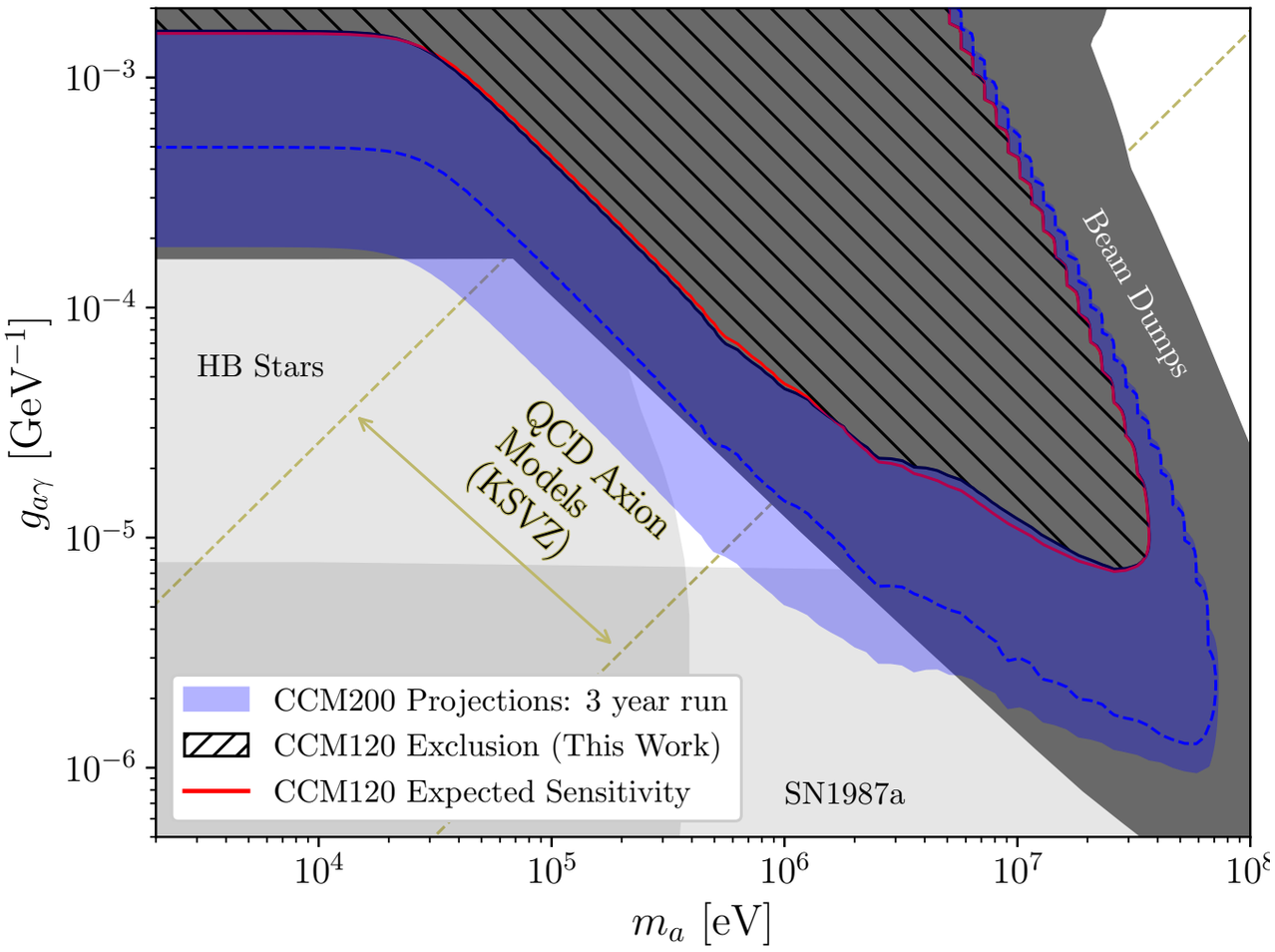


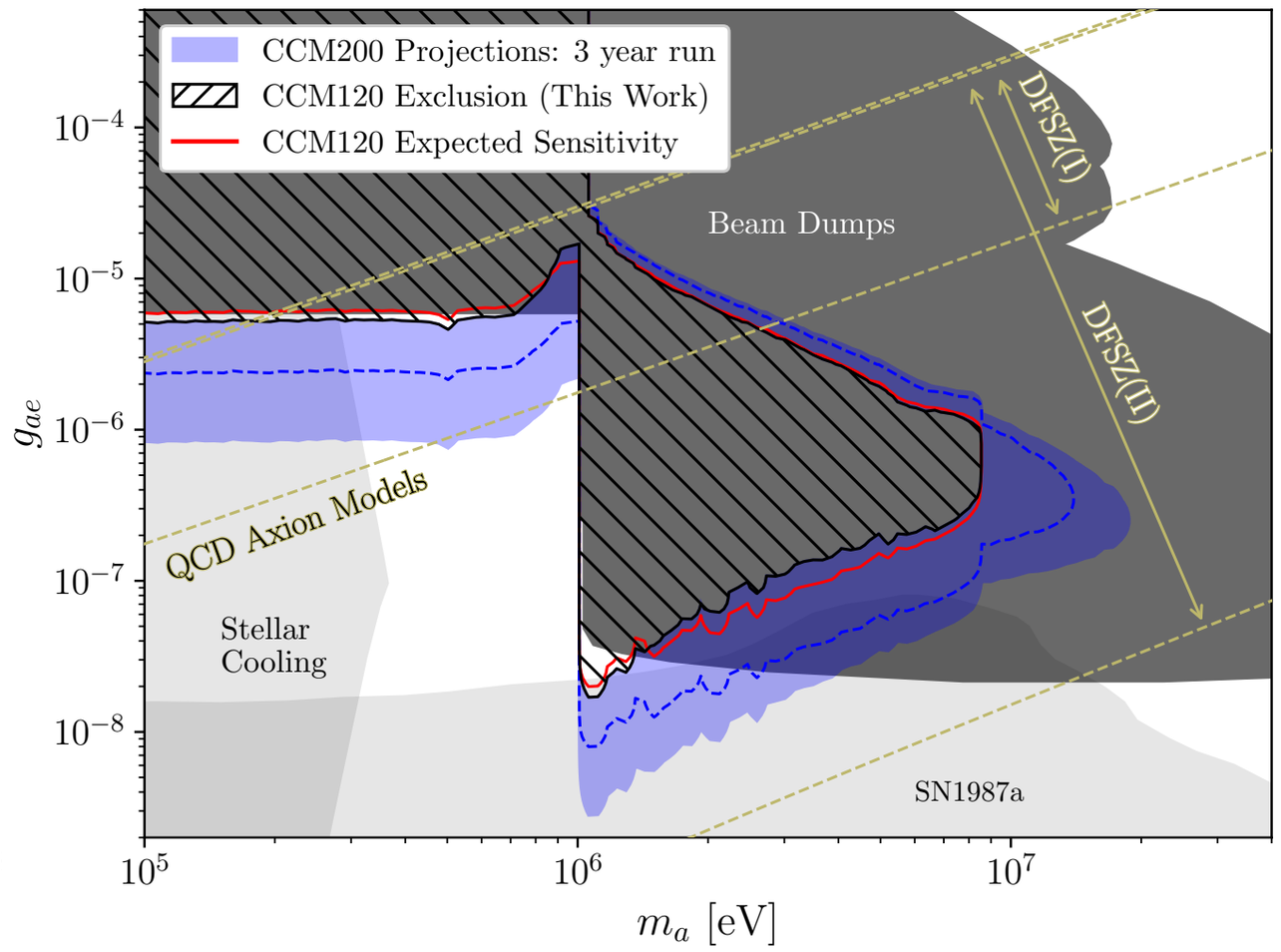
800 MeV Protons on tungsten target





Constraining Electron and Photon Couplings

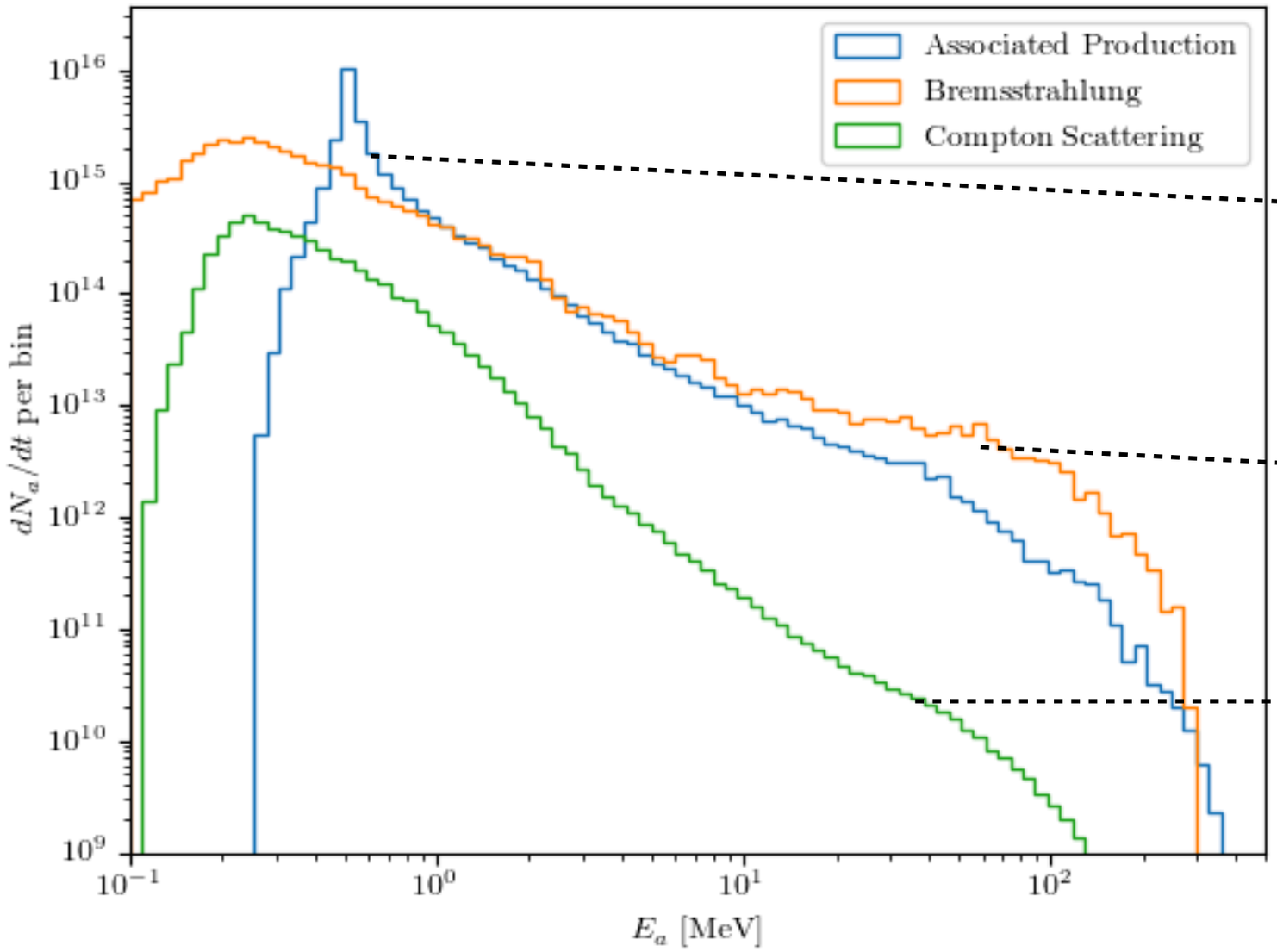


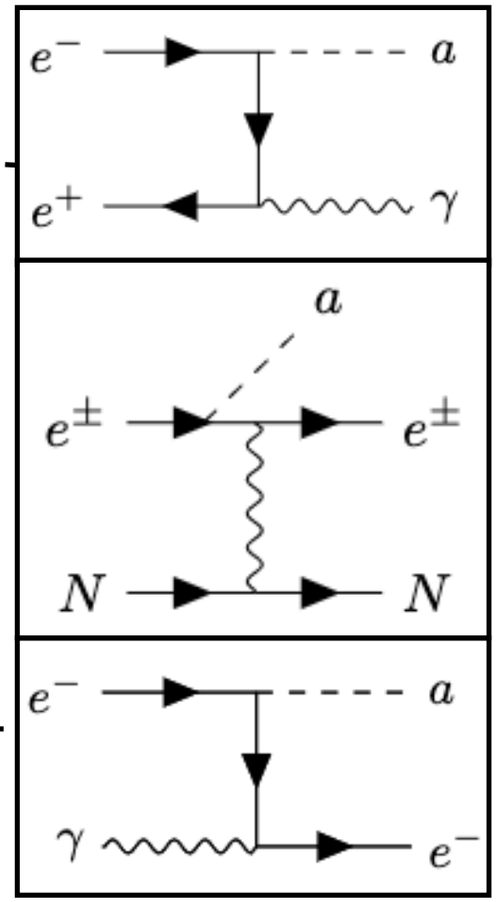


- CCM120 data already begins to test new ALP parameter space (90% CL)
- CCM200 data forecasted to be sensitive to significant regions of QCD axion model parameter space

GeV-scale Beam Targets

GEANT4 Electromagnetic cascades as input → Event Generator MCMC ALP Fluxes → Event Generator MCMC Scattering, Decays in Detector



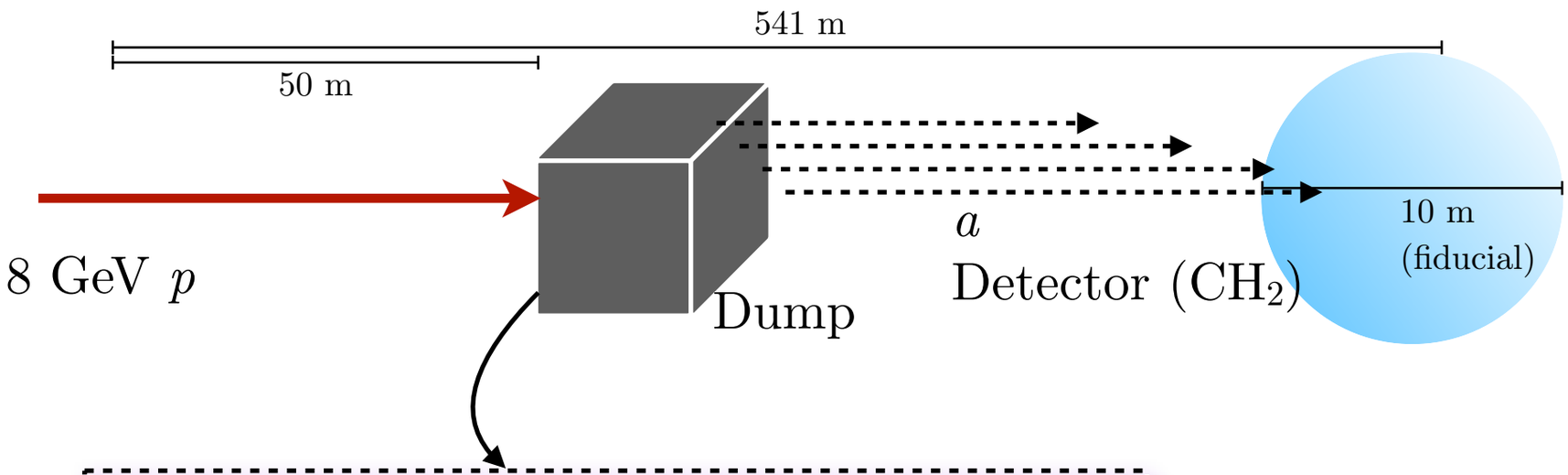


GitHub: alplib

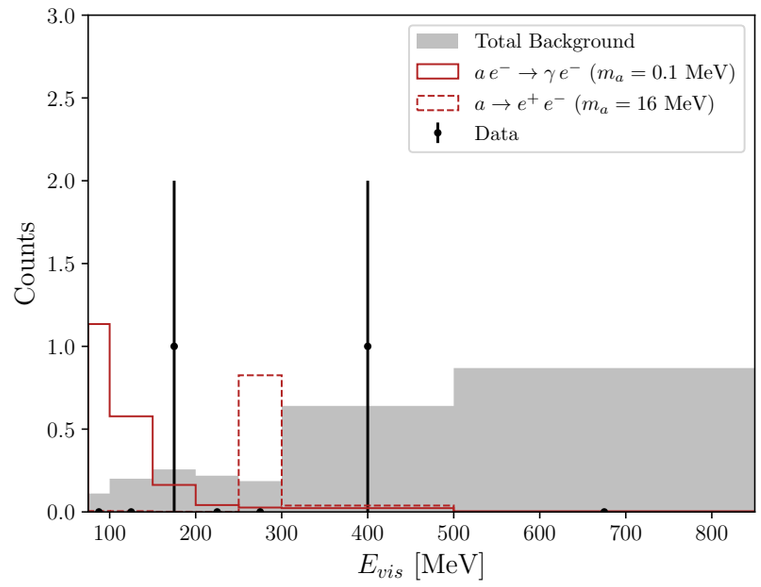
8 GeV

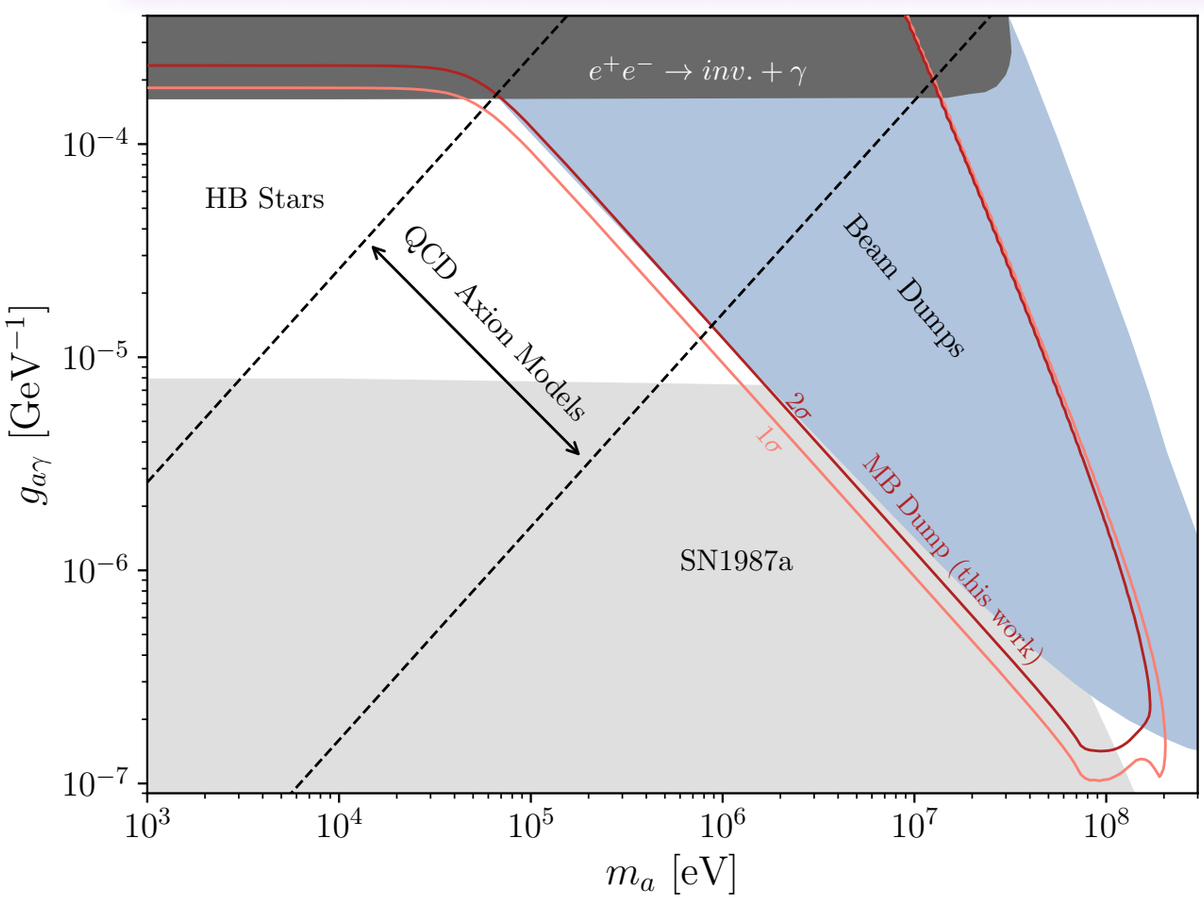
Paper forthcoming! Capozzi, Dutta, Gurung, Jang, Shoemaker, Thompson, Yu

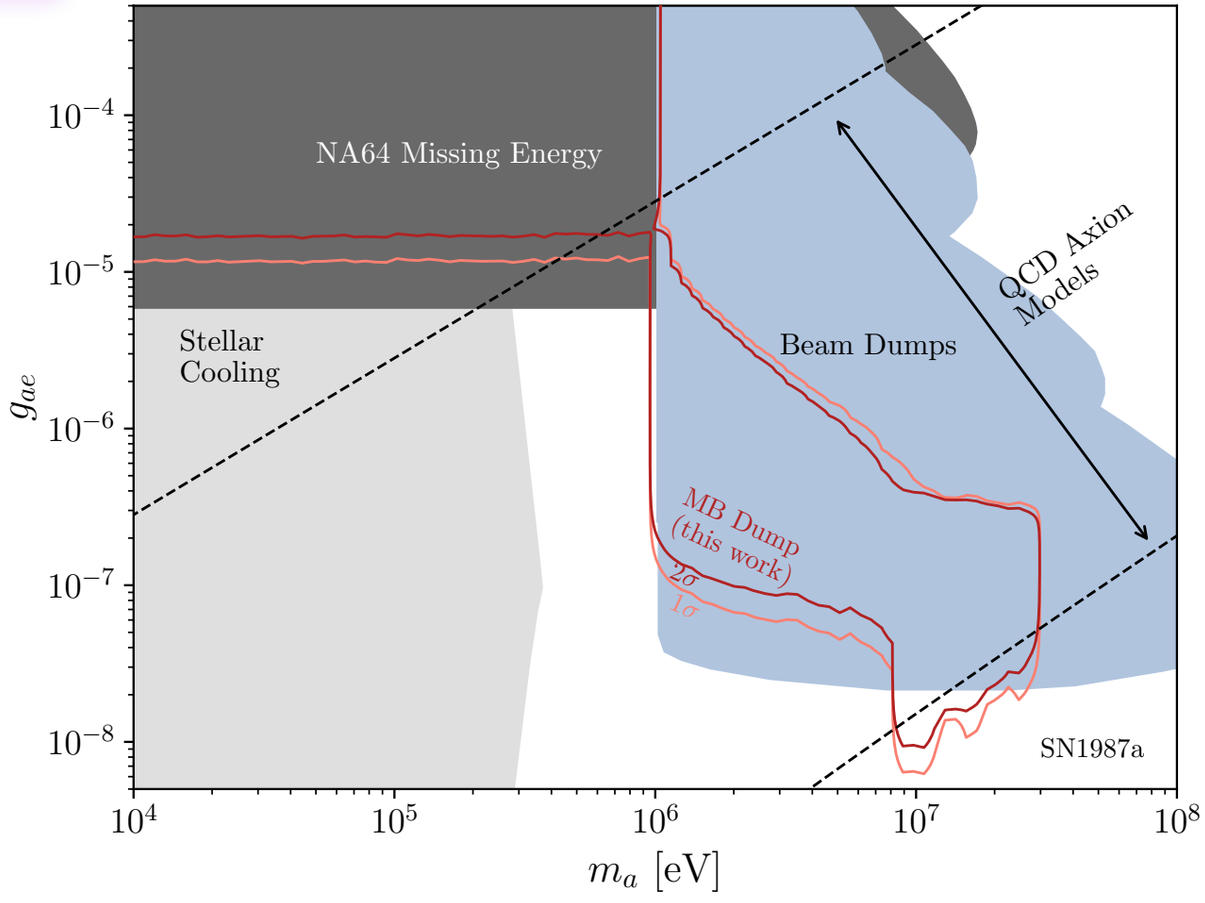
New Results from the MiniBooNE Dump Mode



Thick target: Neutrino flux suppressed





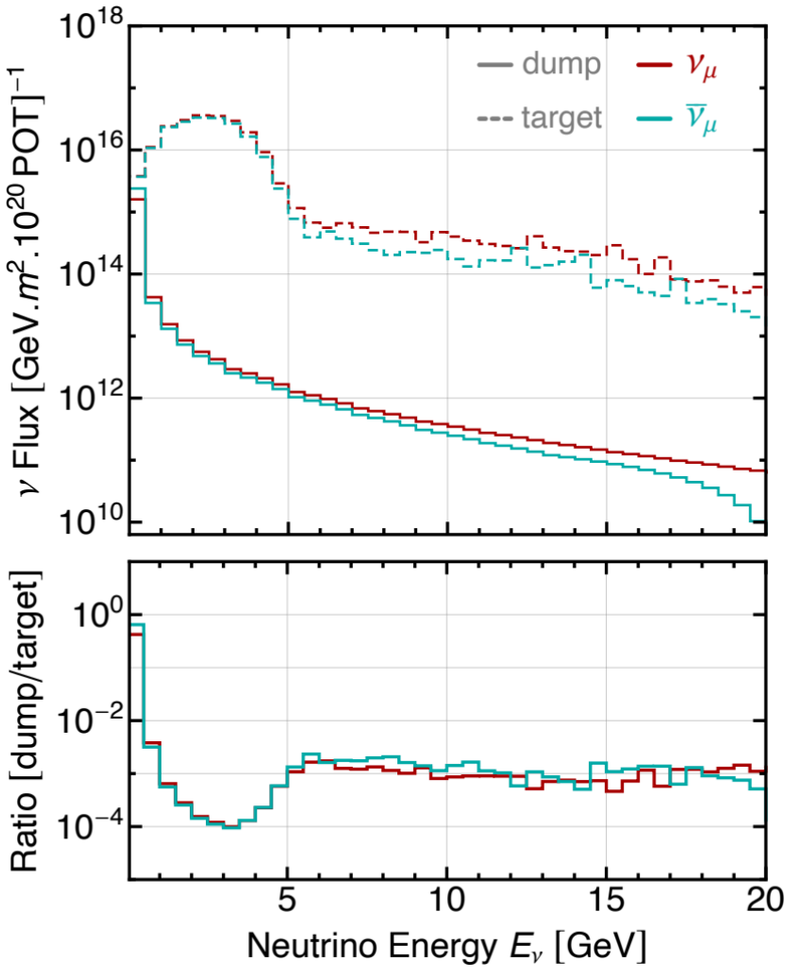


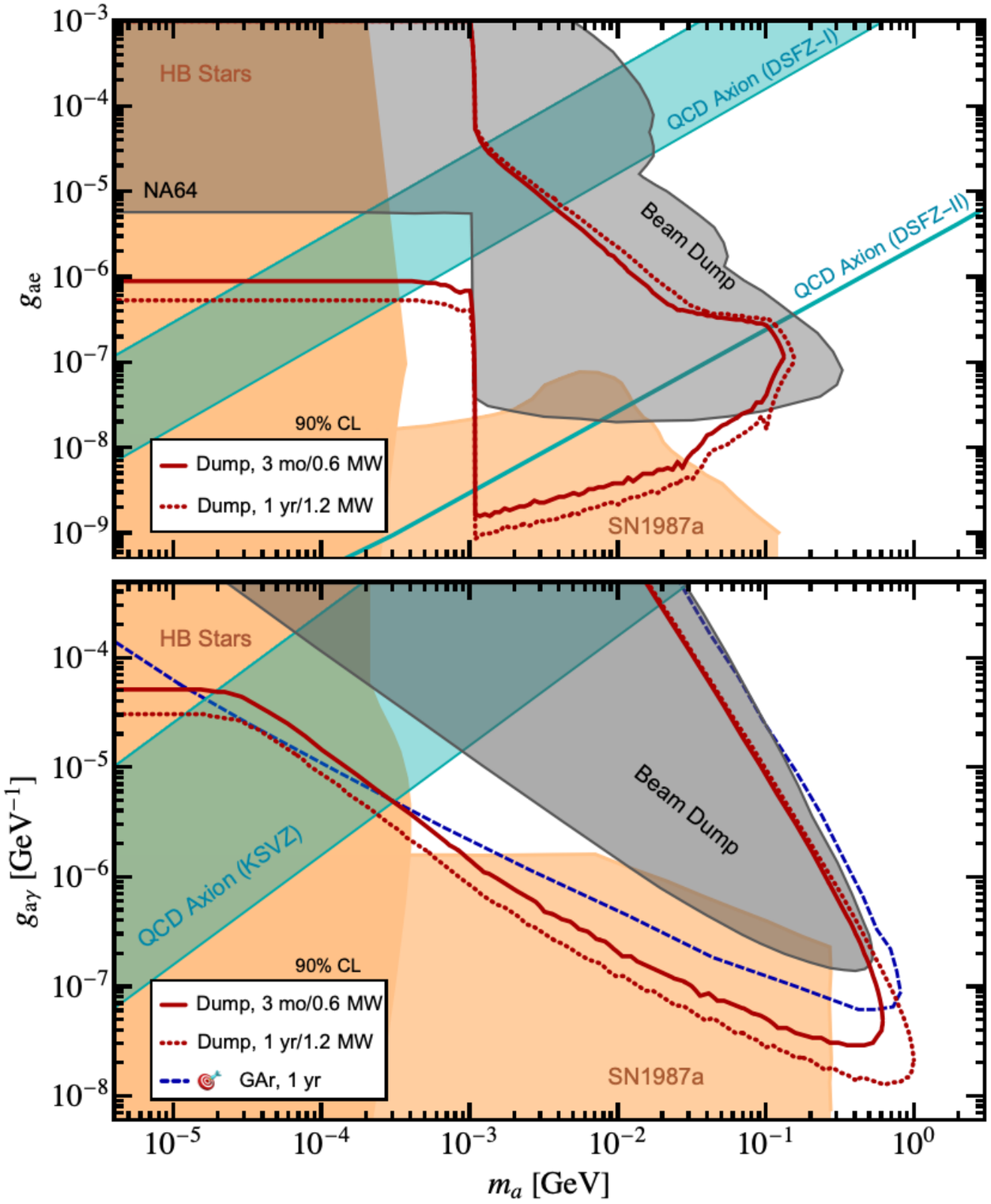
120 GeV

Brdar, Dutta, Jang, Kim, Shoemaker, Tabrizi, Thompson, Yu [2206.06380](2206.06380)

Future Possibilities with a "Targetless" DUNE

- Proposed off-target running mode for short exposure relative to total DUNE live time (3 months - 1 year)
- Challenge: Reduced power to accommodate thermal load on the dump
- Optimized for BSM searches - suppression of the neutrino "background" due to thick target and absence of focusing horns





Outlook for Laboratory Physics

- Electromagnetic and hadronic couplings have good pheno handles in busy EM environments:
  - ✦ Reactors / Beam Dumps / Beam targets
  - ✦ Lots of photons, electrons, excited nuclei mean that we are operating at the **intensity frontier**
  - ✦ This motivates us to **truly** understand these environments (GEANT4 + validation)
- CCM (stopped pion) has already begun to set constraints on ALPs in the MeV mass range
- Reactors (e.g. MINER) currently taking data
- Lots to look forward to over the next decade: CCM200, IsoDAR, MicroBooNE, DUNE...

Acknowledgements

TEXAS A&M UNIVERSITY
Physics & Astronomy

Close Collaborators:

Bhaskar Dutta (Advisor)
Doojin Kim
Edward Dunton
Rupak Mahapatra
Michael Shaevitz
Remington Tyler Thornton
Richard Van De Water
Bill Lewis
Nityasa Mishra
Shubham Verma
Zahra Tabrizi
Ian Shoemaker
Wooyoung Jang
Jaehoon Yu
Vedran Brdar
Francesco Capozzi
Gajendra Gurung
Aayush Bhattarai
Harikrishnan Ramani
Surjeet Rajendran
James B. Dent
Janet Conrad
Loyd Waites
Wei-Chih Huang

. . . and many others!