Utilizing the Iron Dump at Short Baseline Neutrino Facilities to Probe Heavy Neutral Lepton and Dark Matter

By Debopam Goswami

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Collaborators: Bhaskar Dutta, Aparajitha Karthikeyan, Kevin James Kelly

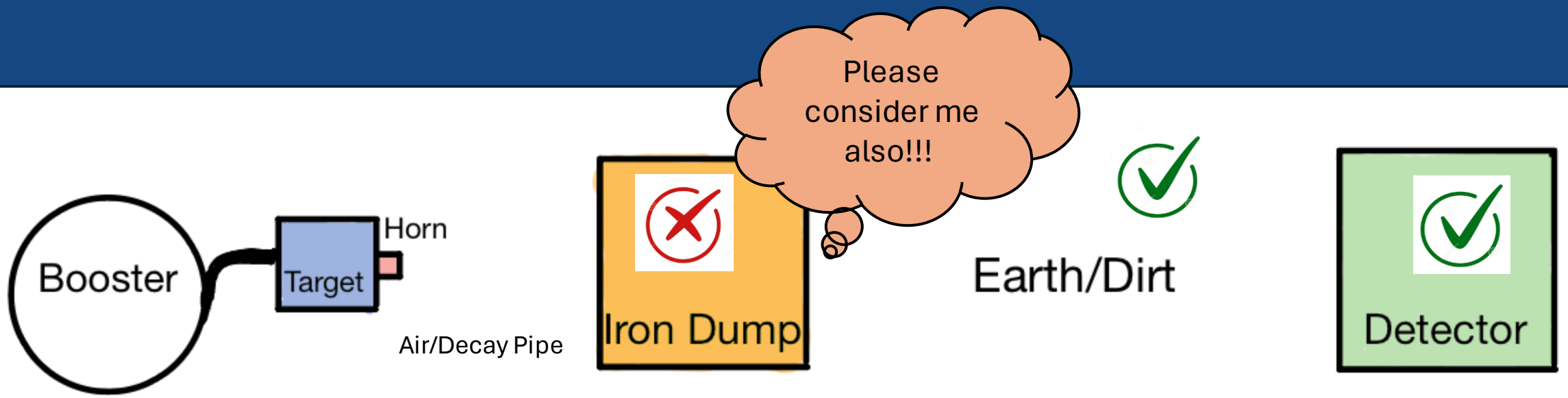
DPF-PHENO 2024

Date: 14th May 2024

Motivations

Schematic of SBN Experimental Setup

Motivations

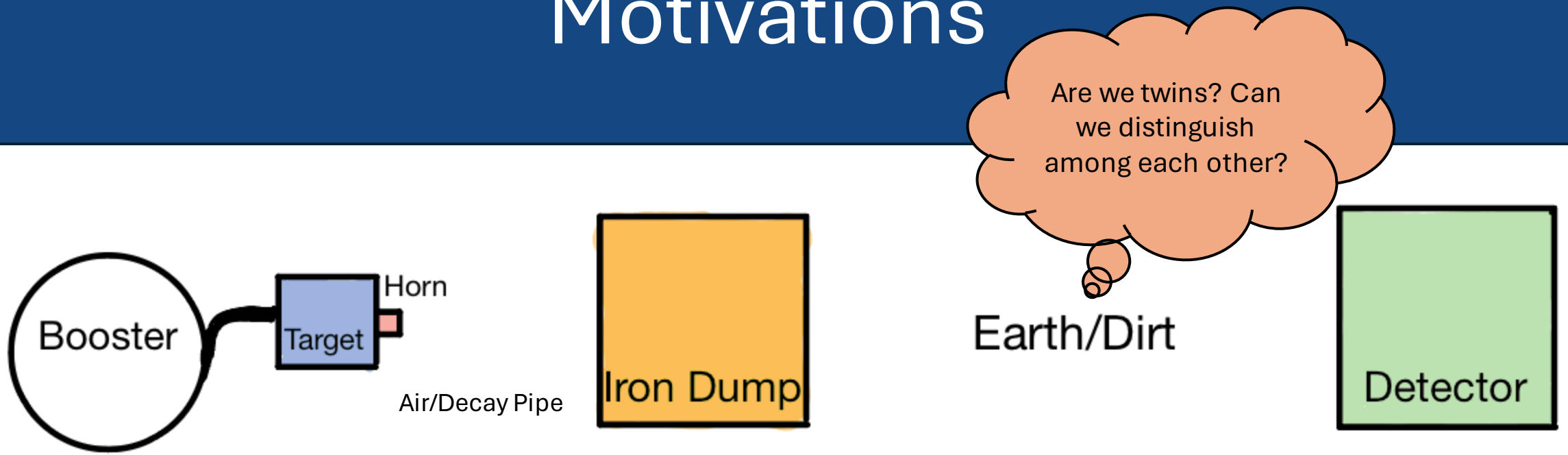


Schematic of SBN Experimental Setup

GOAL 1!

- G Magill, R Plestid, M Pospelov, Yu-Dai Tsai, Phys. Rev. D 98, 115015
- N W. Kamp, M Hostert, A Schneider, S Vergani, C A. Argüelles, J M. Conrad, M H. Shaevitz, M A. Uchida, Phys. Rev. D 107, 055009

Motivations



Schematic of SBN Experimental Setup

GOAL 2!

Motivations

Schematic of SBN Experimental Setup

GOAL 3!

- A M. Abdullahi, J H Zink, M Hostert, D Massaro, S Pascoli, arXiv.2308.02543
- V Brdar, O Fischer, A Y. Smirnov, Phys. Rev. D 103, 075008

Motivations

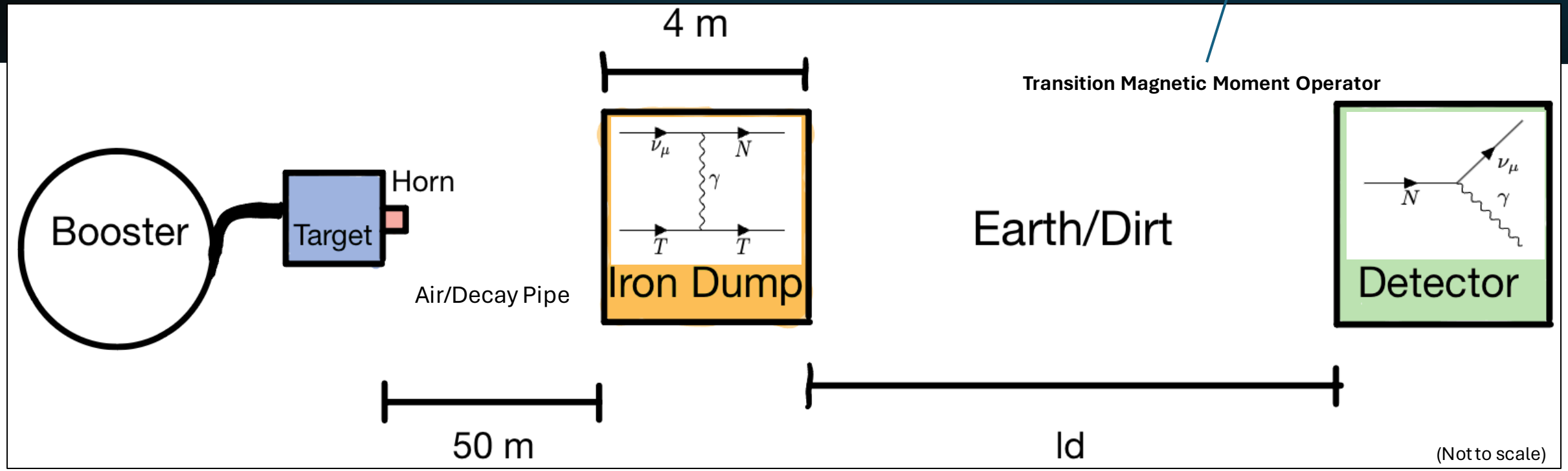
Schematic of SBN Experimental Setup

GOAL 4!

Model: Heavy Neutral Lepton

$$\mathcal{L} \supset d(\bar{\nu}_L \sigma_{\mu\nu} F^{\mu\nu} N) + h.c.$$

Transition Magnetic Moment Operator



I M. Shoemaker, Y-D Tsai, J Wyenberg, Phys. Rev. D 104, 115026

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Model: Heavy Neutral Lepton

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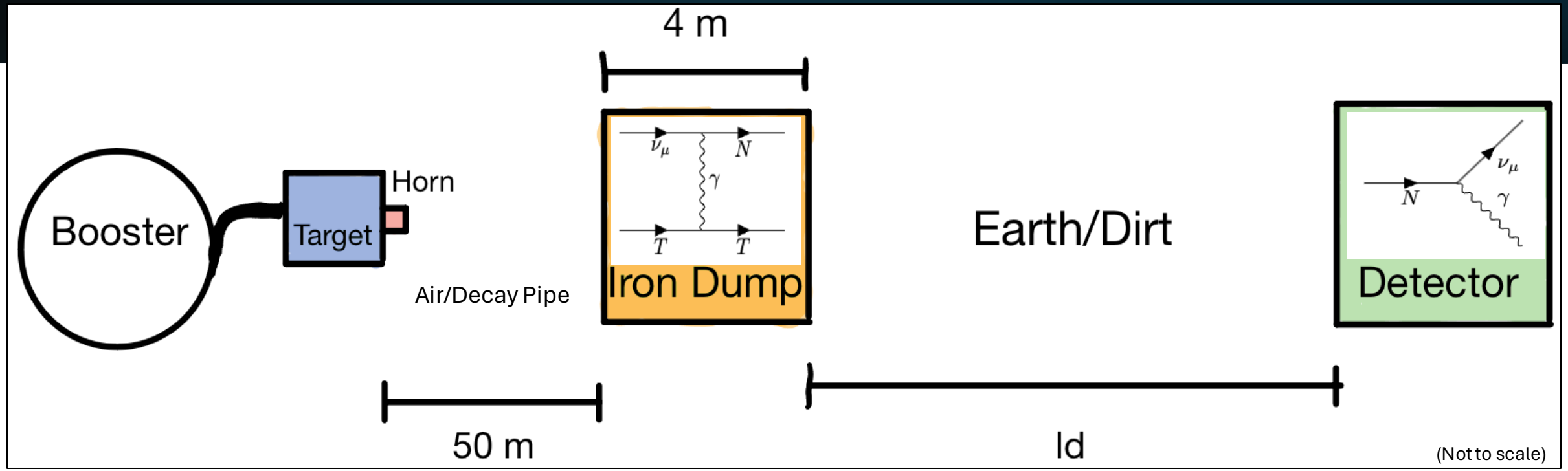


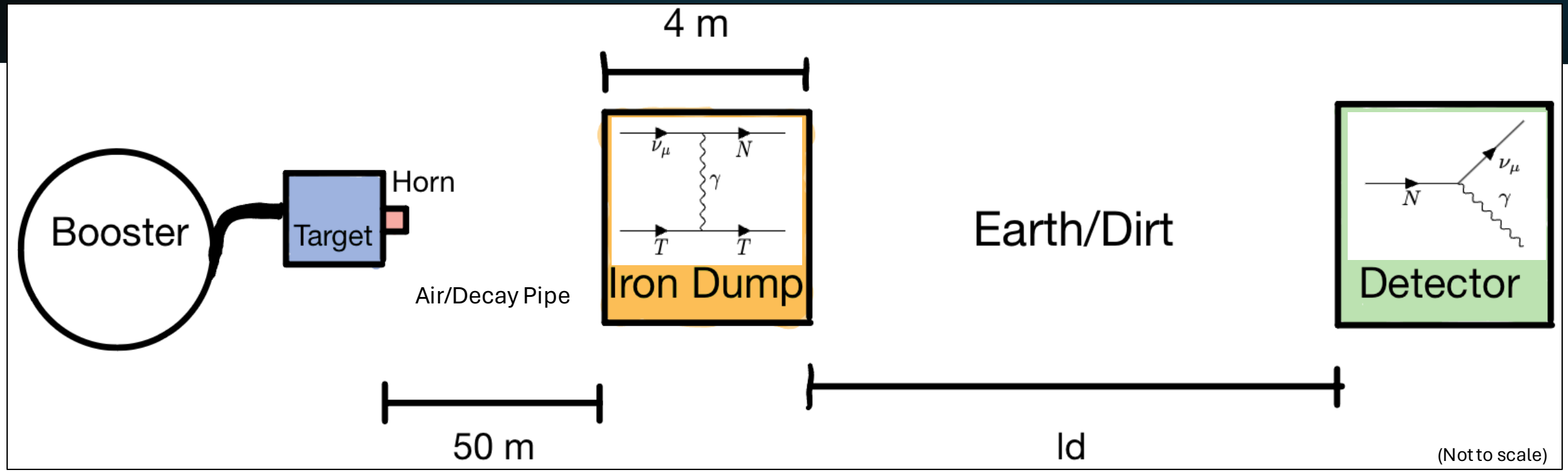
I M. Shoemaker, Y-D Tsai, J Wyenberg, Phys. Rev. D 104, 115026

N W. Kamp, M Hostert, A Schneider, S Vergani, C A. Argüelles, J M. Conrad, M H. Shaevitz, M A. Uchida, Phys. Rev. D 107, 055009

$$\frac{d\sigma_{(\nu N \to N n)}}{dE_R} = d^2 \alpha Z^2 F^2(E_R) \left(\frac{1}{E_R} - \frac{m_4^2}{2E_\nu E_R m_N} \left(1 - \frac{E_R}{2E_\nu} + \frac{m_N}{2E_\nu} \right) - \frac{1}{E_\nu} + \frac{m_4^4 (E_R - m_N)}{8 E_\nu^2 E_R^2 m_N^2} \right)$$

Model: Heavy Neutral Lepton

$$\mathcal{L} \supset d(\bar{\nu}_L \sigma_{\mu\nu} F^{\mu\nu} N) + h.c.$$



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N W. Kamp, M Hostert, A Schneider, S Vergani, C A. Argüelles, J M. Conrad, M H. Shaevitz, M A. Uchida, Phys. Rev. D 107, 055009

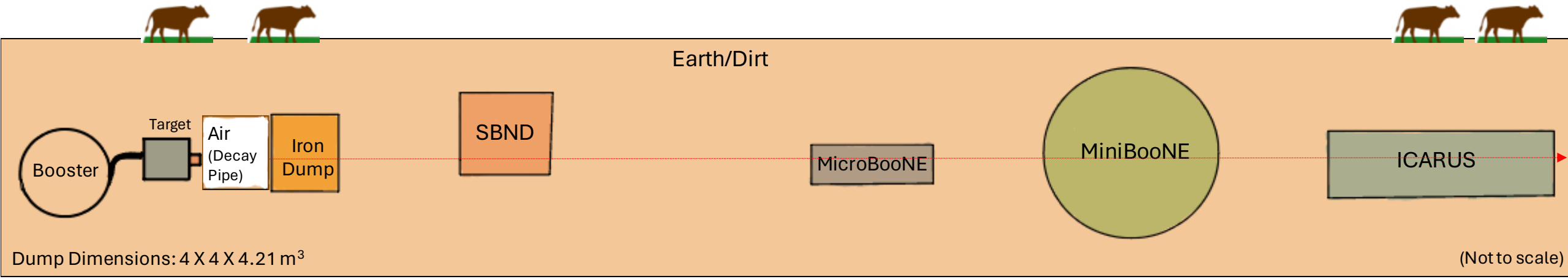
Z^2 Enhancement

$$\frac{d\sigma_{(\nu N \to N n)}}{dE_R} = d^2 \alpha Z^2 F^2(E_R) \left(\frac{1}{E_R} - \frac{m_4^2}{2E_\nu E_R m_N} \left(1 - \frac{E_R}{2E_\nu} + \frac{m_N}{2E_\nu} \right) - \frac{1}{E_\nu} + \frac{m_4^4 (E_R - m_N)}{8 E_\nu^2 E_R^2 m_N^2} \right)$$

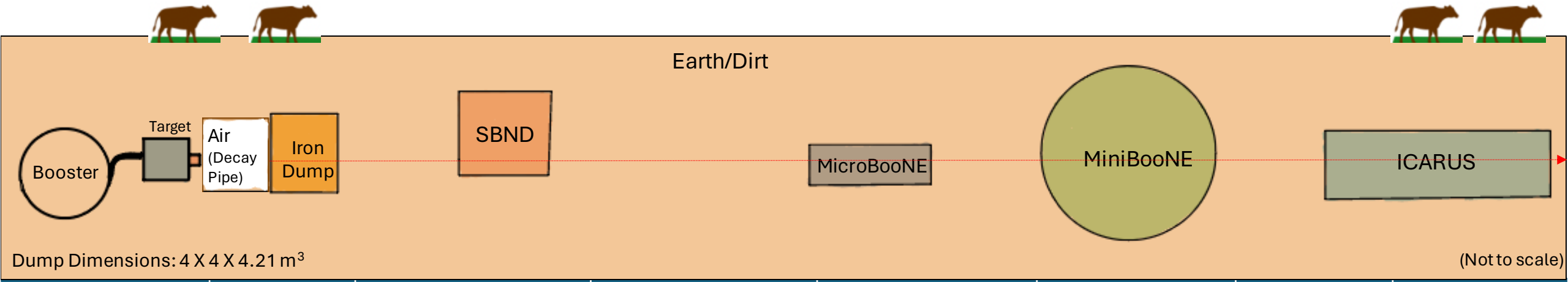
Upscattering Cross-Section

Helm's Form Factor: $F(E_R) = \frac{3}{(\kappa r)^3} e^{-\kappa^2 s^2/2} (sin(\kappa r) - \kappa r cos(\kappa r))$

SBN Experimental Specifications



SBN Experimental Specifications

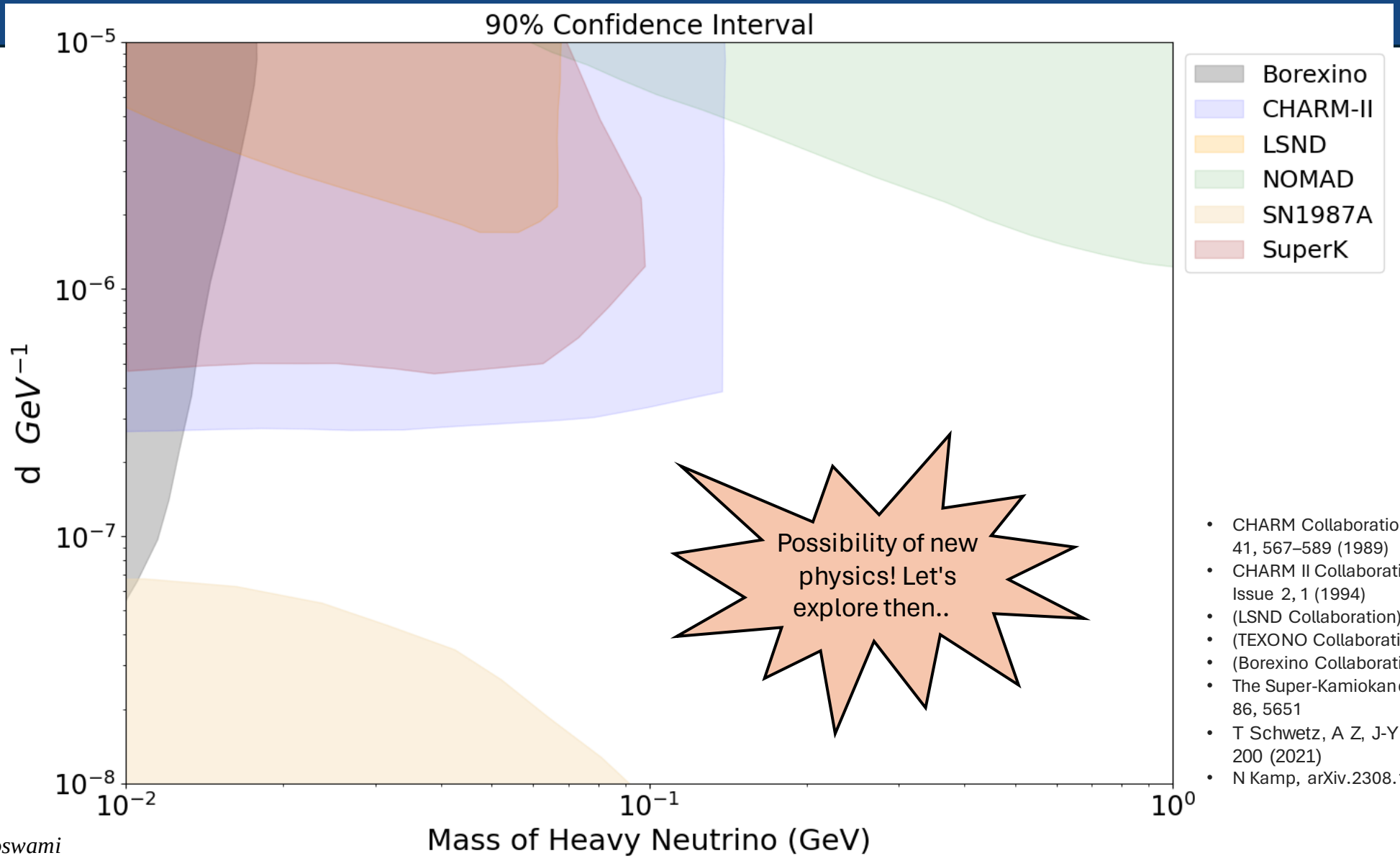


Experiment	Mass (in tons)	Dimensions (in m^3)	Distance from target (in m)	POTs (Total)	Total Background Counts	Angle	Threshold Energy (MeV)
SBND (LAr), (Ongoing)	112.0	4 X 4 X 5	110	$6.6*10^{21}$	200	Off-axis	30
MicroBooNE (LAr), (Ongoing)	86.8	2.6 X 2.3 X 10.4	470	$6.6*10^{20}$	167	On-axis	100
MiniBooNE (Mineral Oil CH_2), (Completed)	818.0	Radius = 6.1	537	$1.88*10^{21}$	2215	On-axis	100
ICARUS T600 (LAr), (Ongoing)	476.0	3.6 X 3.9 X 19.6	600	$6.6*10^{21}$	200	On-axis	30

BNB Target: Be
Beam Energy: 8 GeV

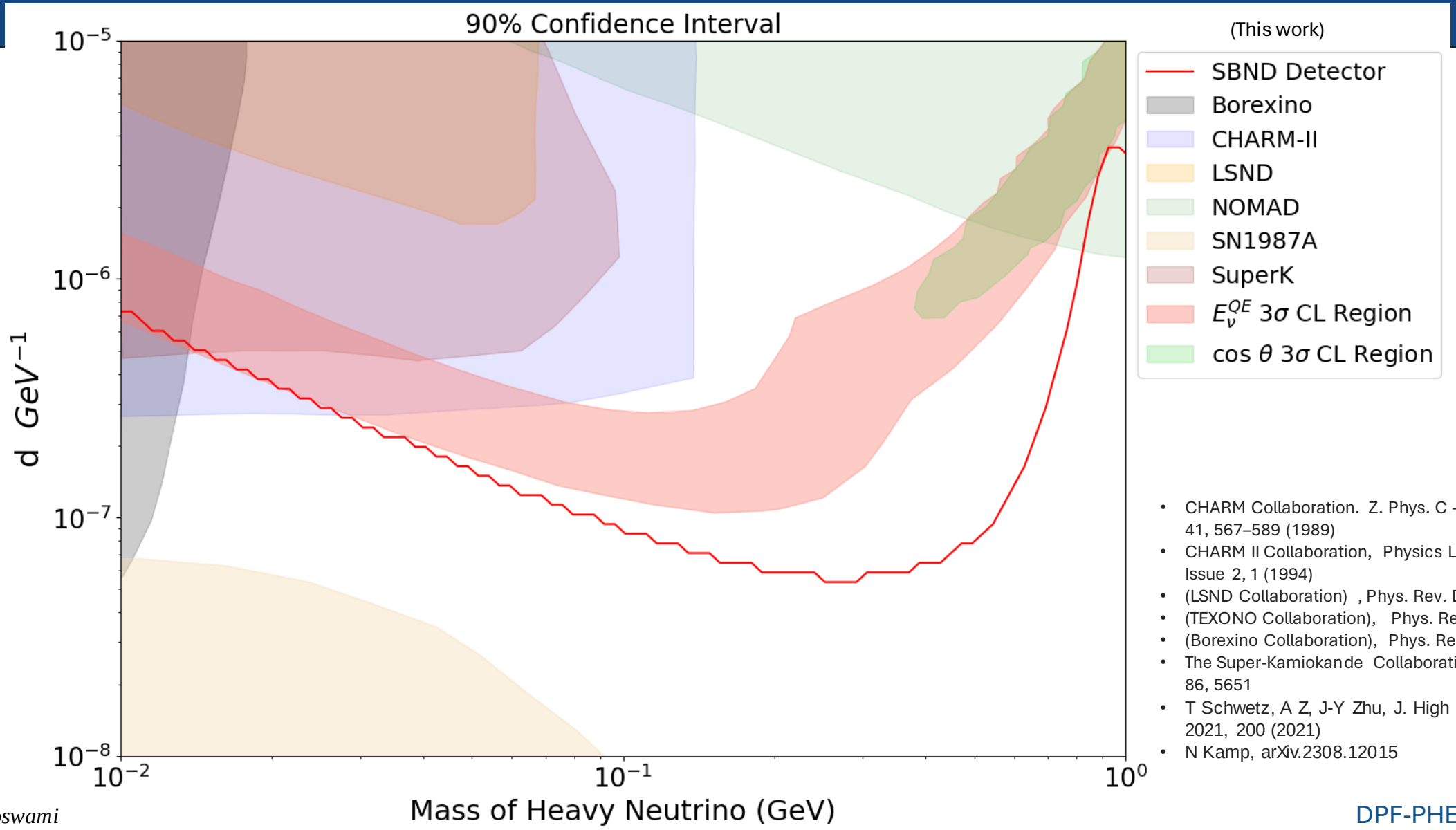
- ICARUS Collaboration, arXiv.2301.08634
- M D Tutto, V Pandey, P Machado, K Kelly, and R Harnik, SBND PRISM NuSTEC CEWG (2021)

Constraints in the Parameter Space



- CHARM Collaboration. Z. Phys. C - Particles and Fields 41, 567–589 (1989)
- CHARM II Collaboration, Physics Letters B Volume 335, Issue 2, 1 (1994)
- (LSND Collaboration) , Phys. Rev. D 63, 112001
- (TEXONO Collaboration), Phys. Rev. D 81, 072001
- (Borexino Collaboration), Phys. Rev. Lett. 107, 141302
- The Super-Kamiokande Collaboration, Phys. Rev. Lett. 86, 5651
- T Schwetz, A Z, J-Y Zhu, J. High Energ. Phys. 2021, 200 (2021)
- N Kamp, arXiv.2308.12015

SBND Sensitivity Plot



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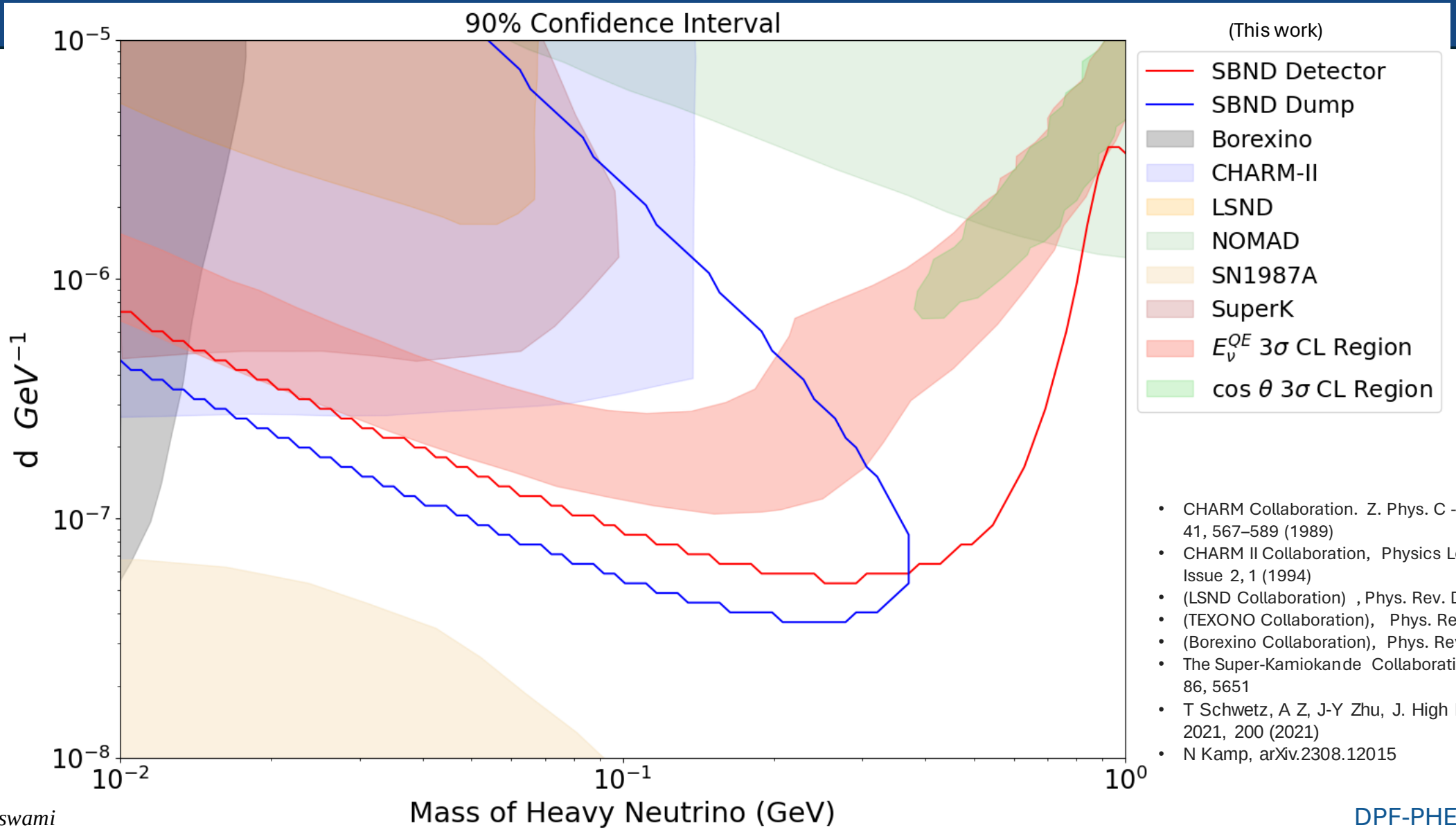

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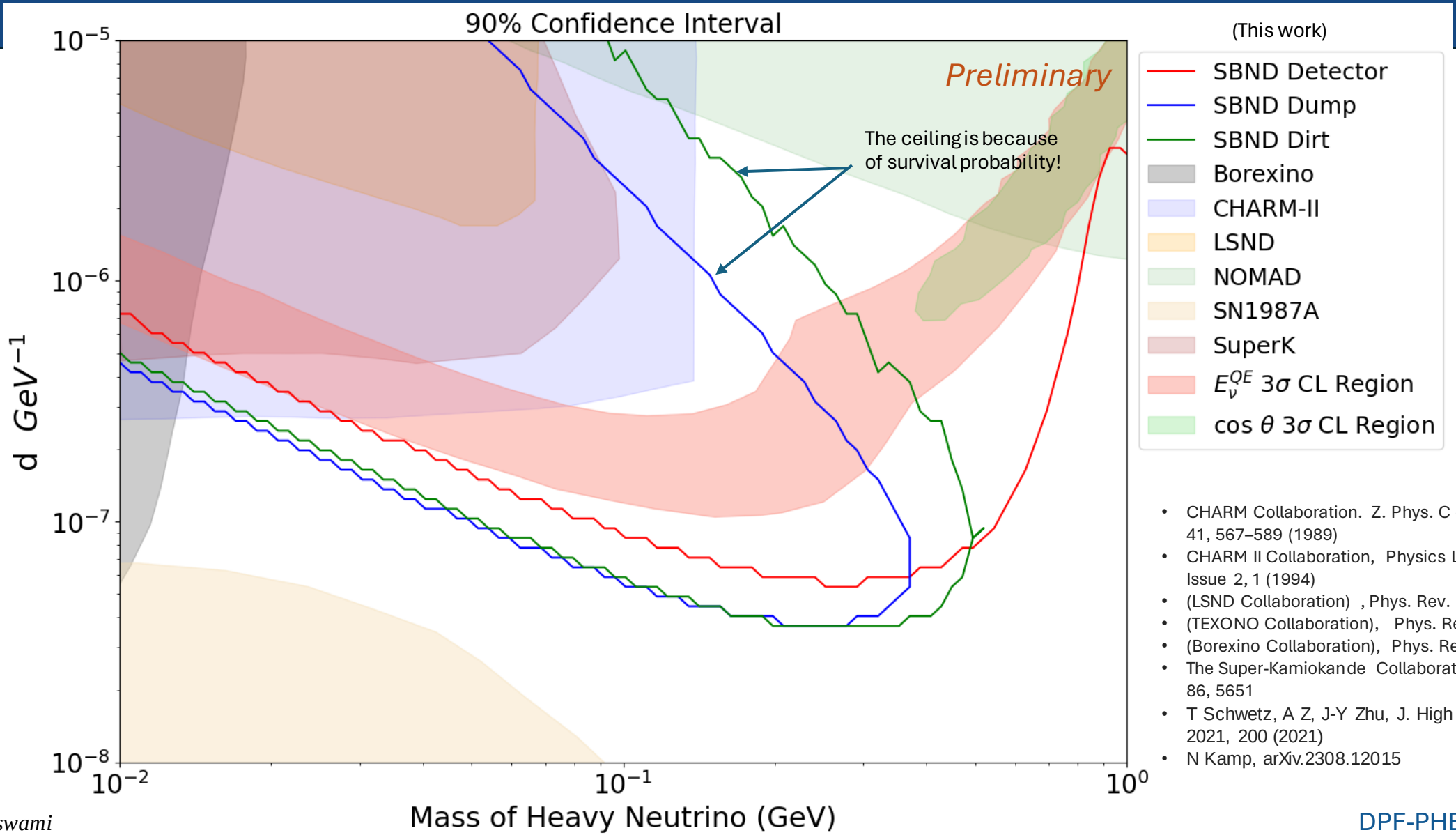

- CHARM Collaboration. Z. Phys. C - Particles and Fields 41, 567–589 (1989)
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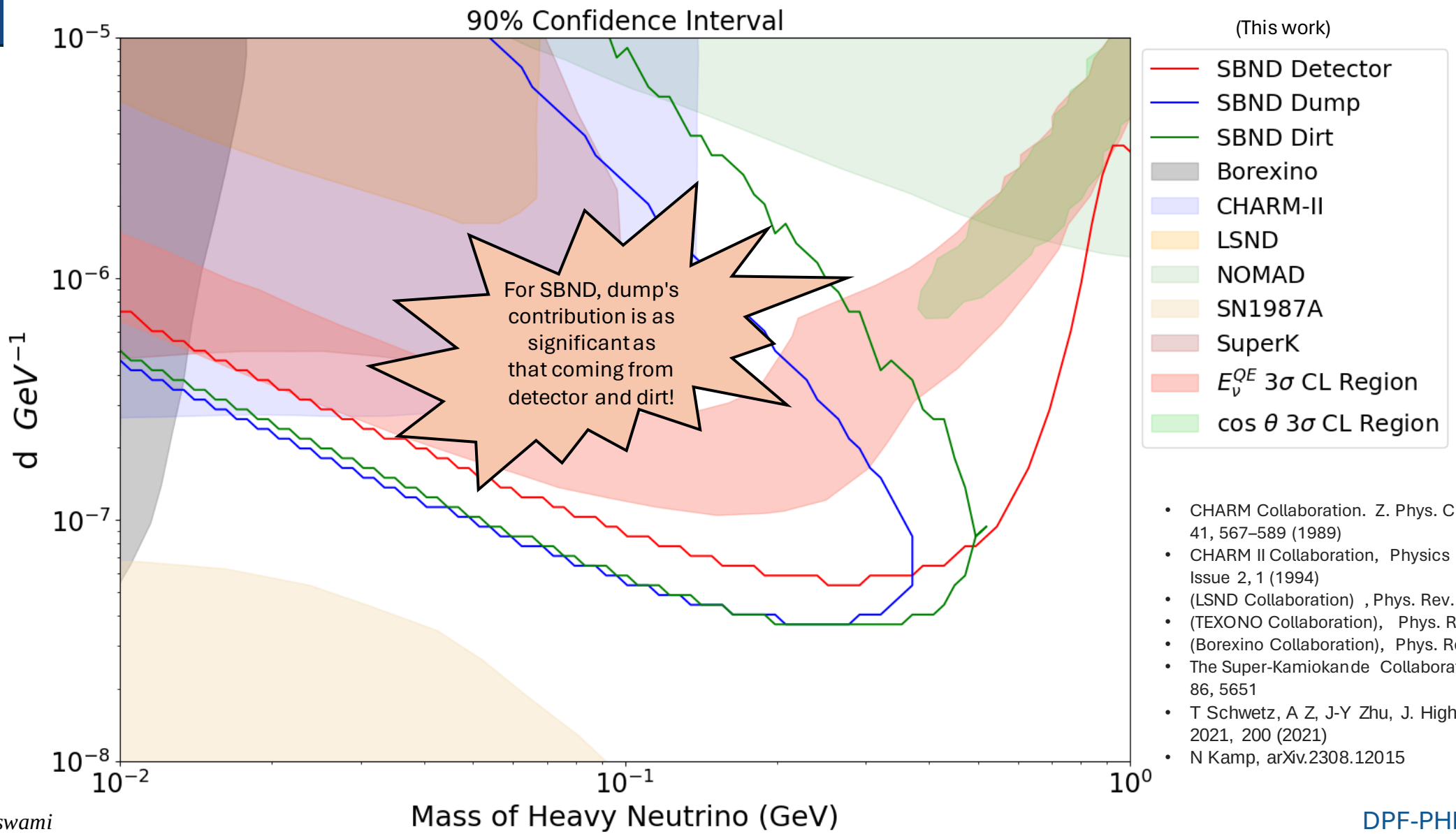

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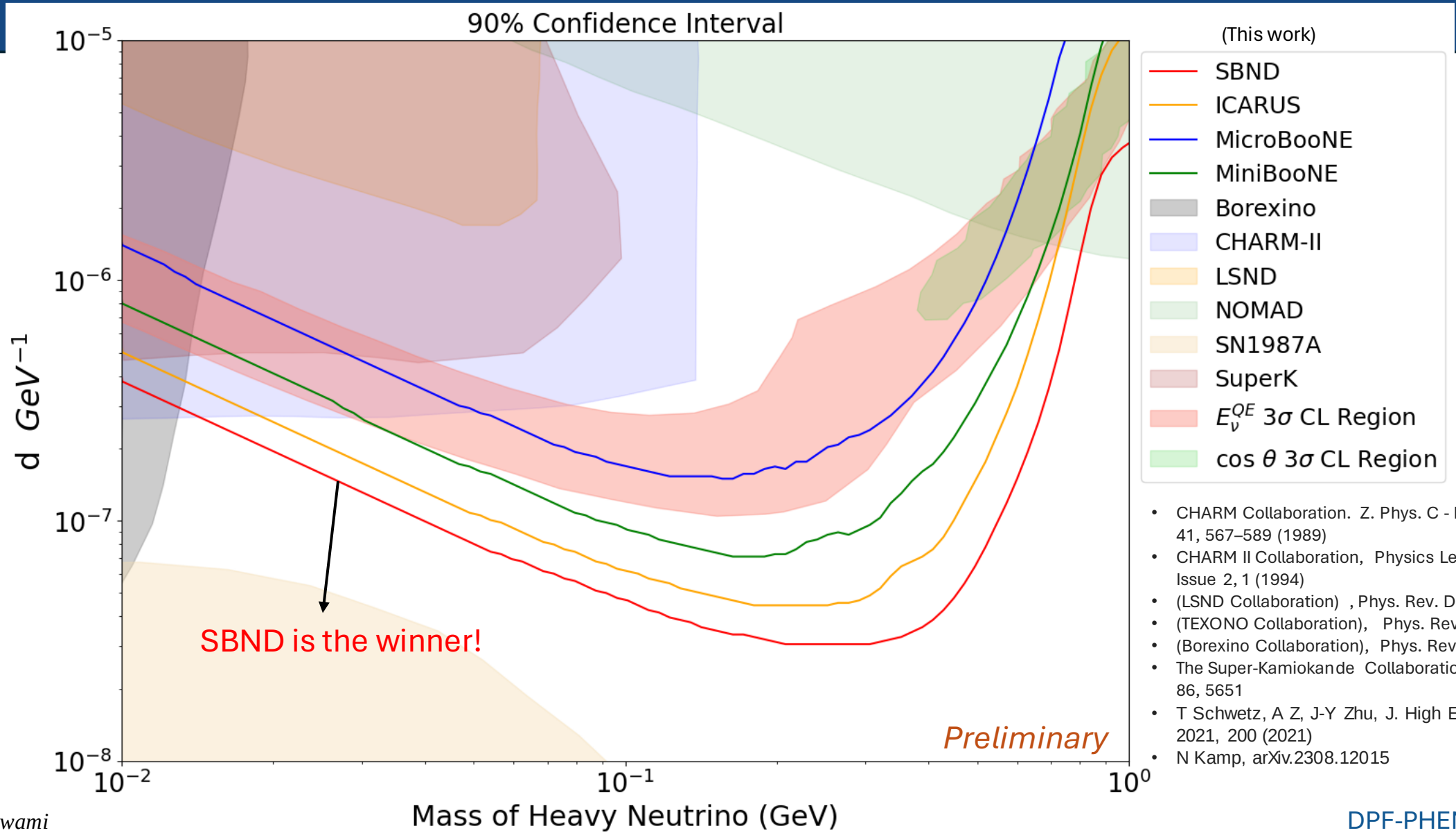
- N Kamp, arXiv.2308.12015

Comparison Sensitivity Plot



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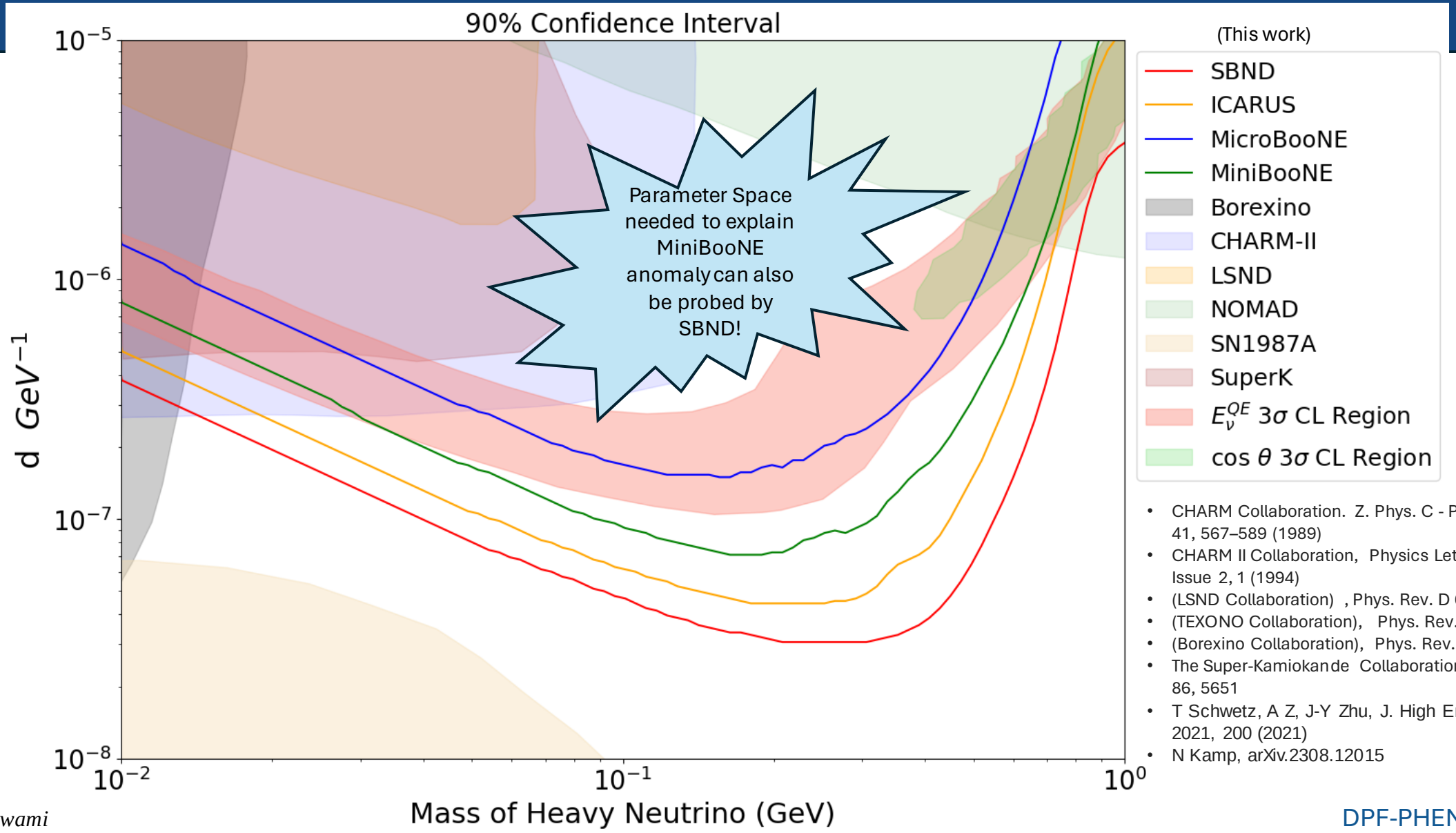

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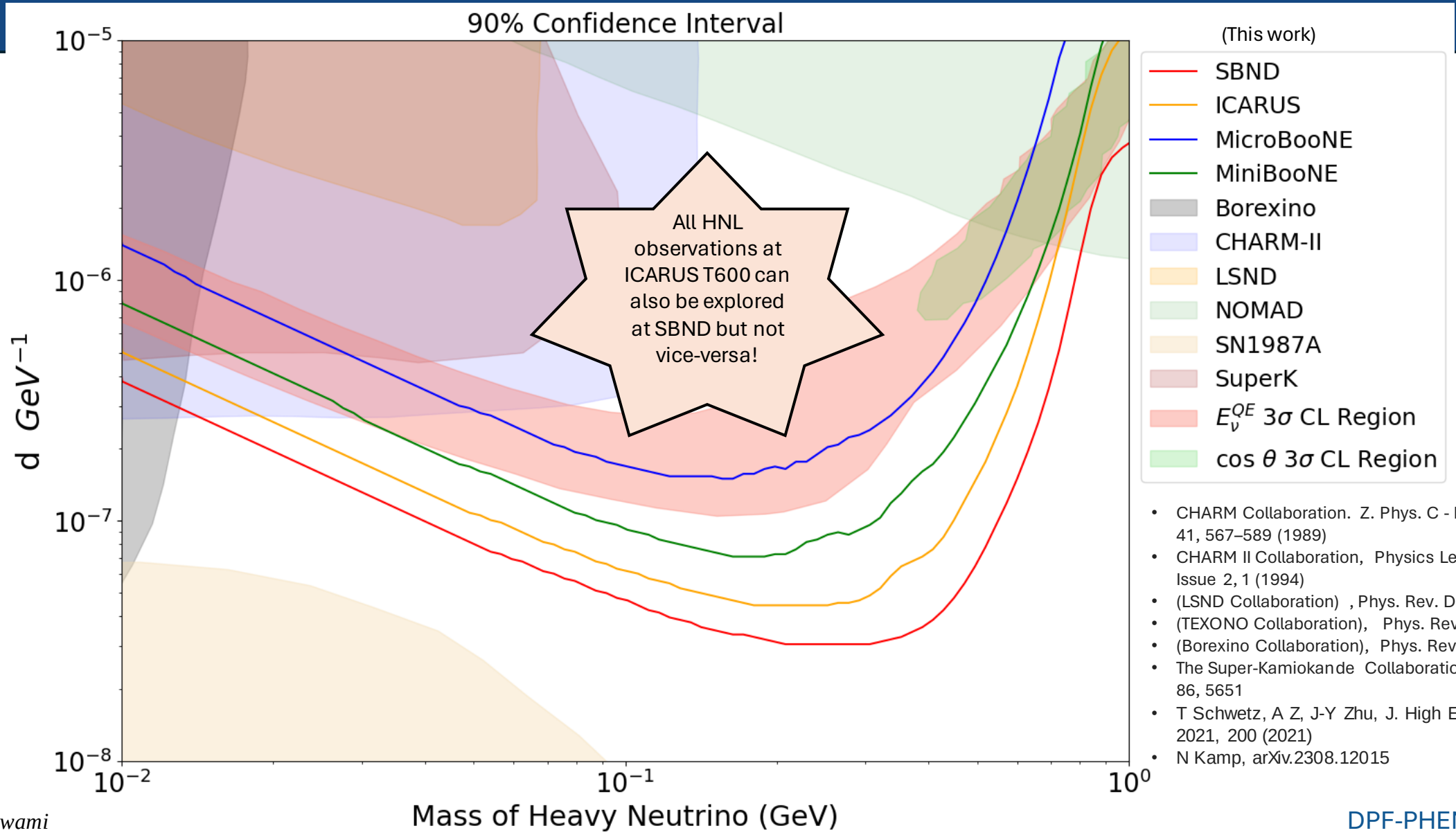

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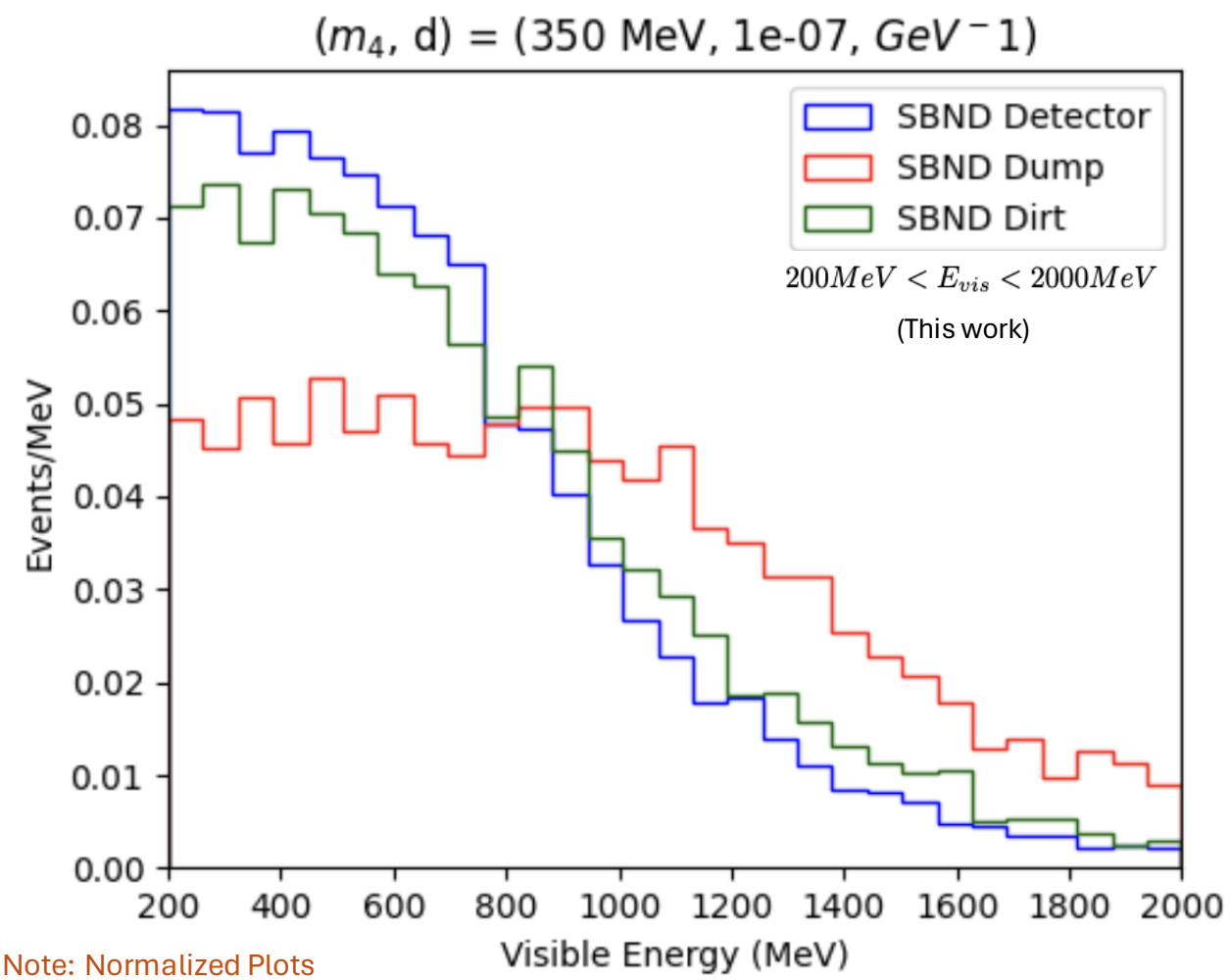
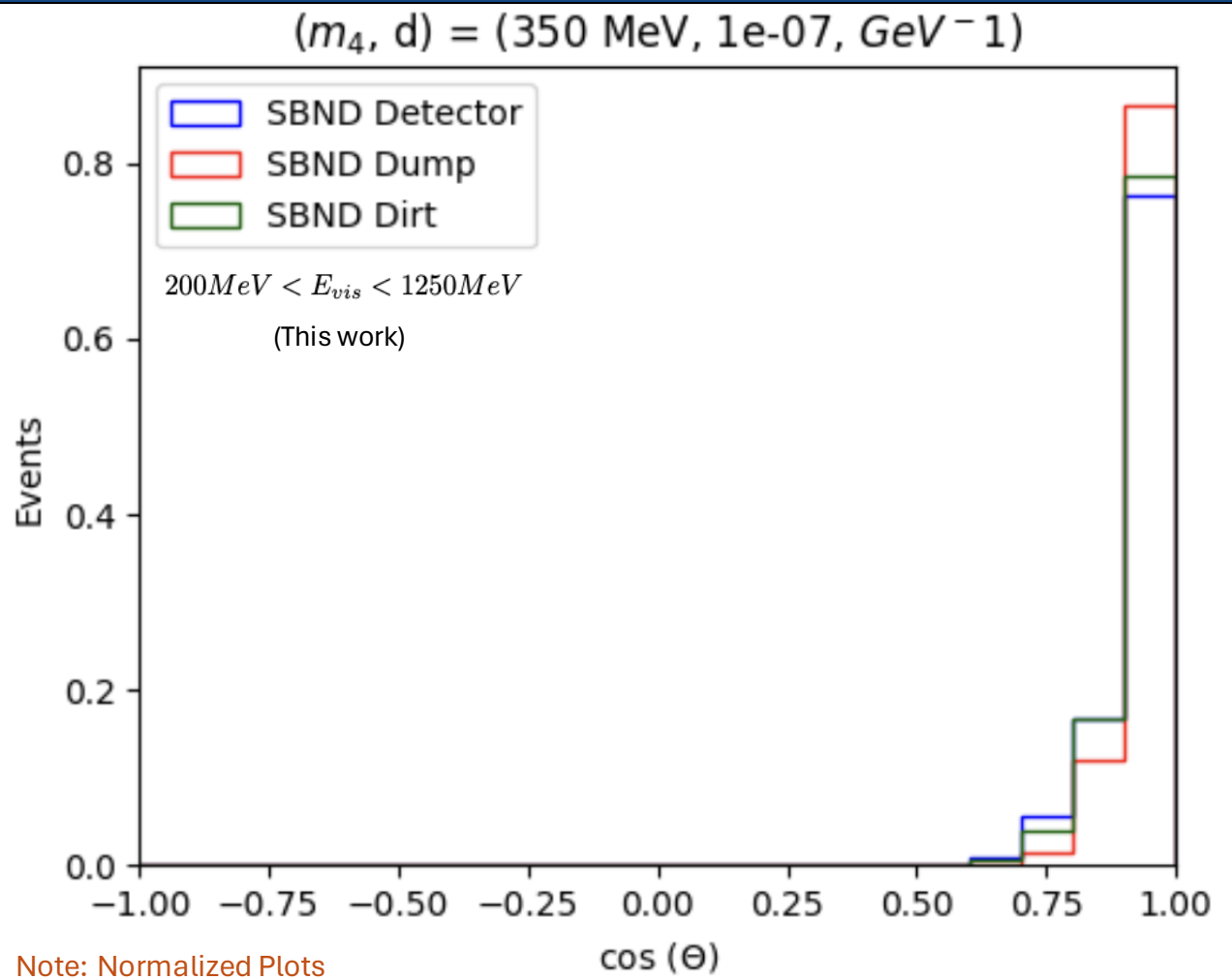
- N Kamp, arXiv.2308.12015

SBND Detector vs Dump vs Dirt I

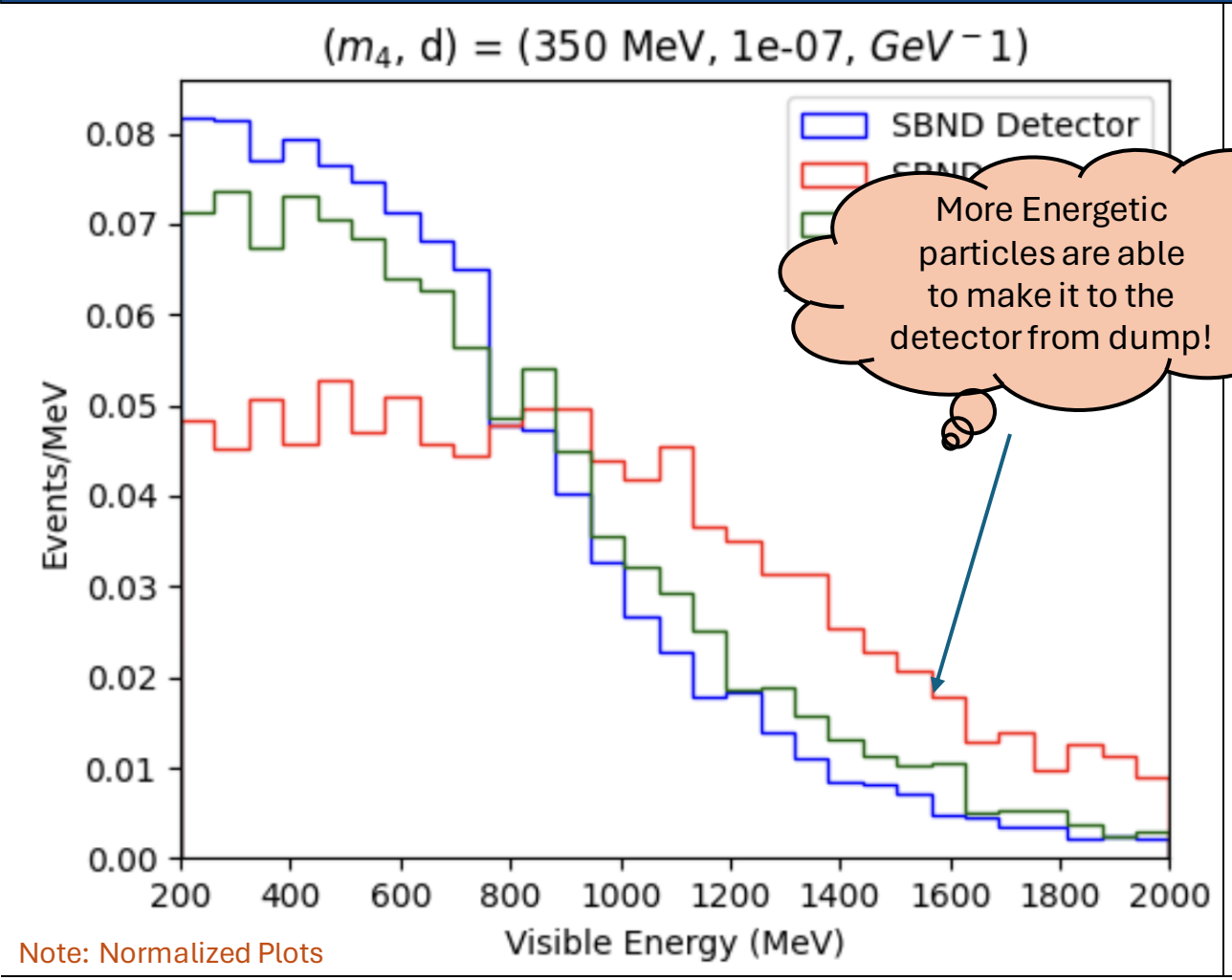


Note: Normalized Plots

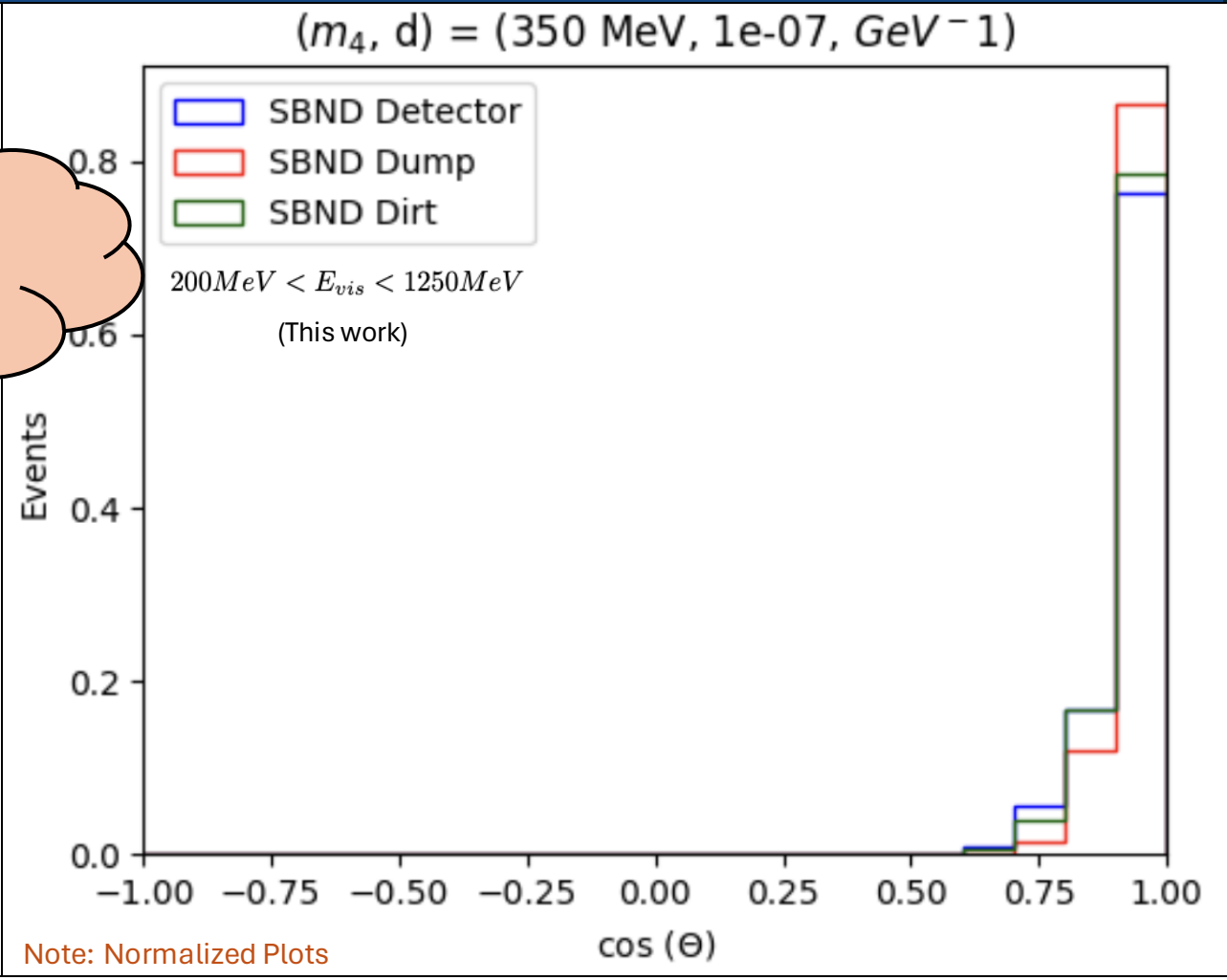


Note: Normalized Plots

SBND Detector vs Dump vs Dirt I

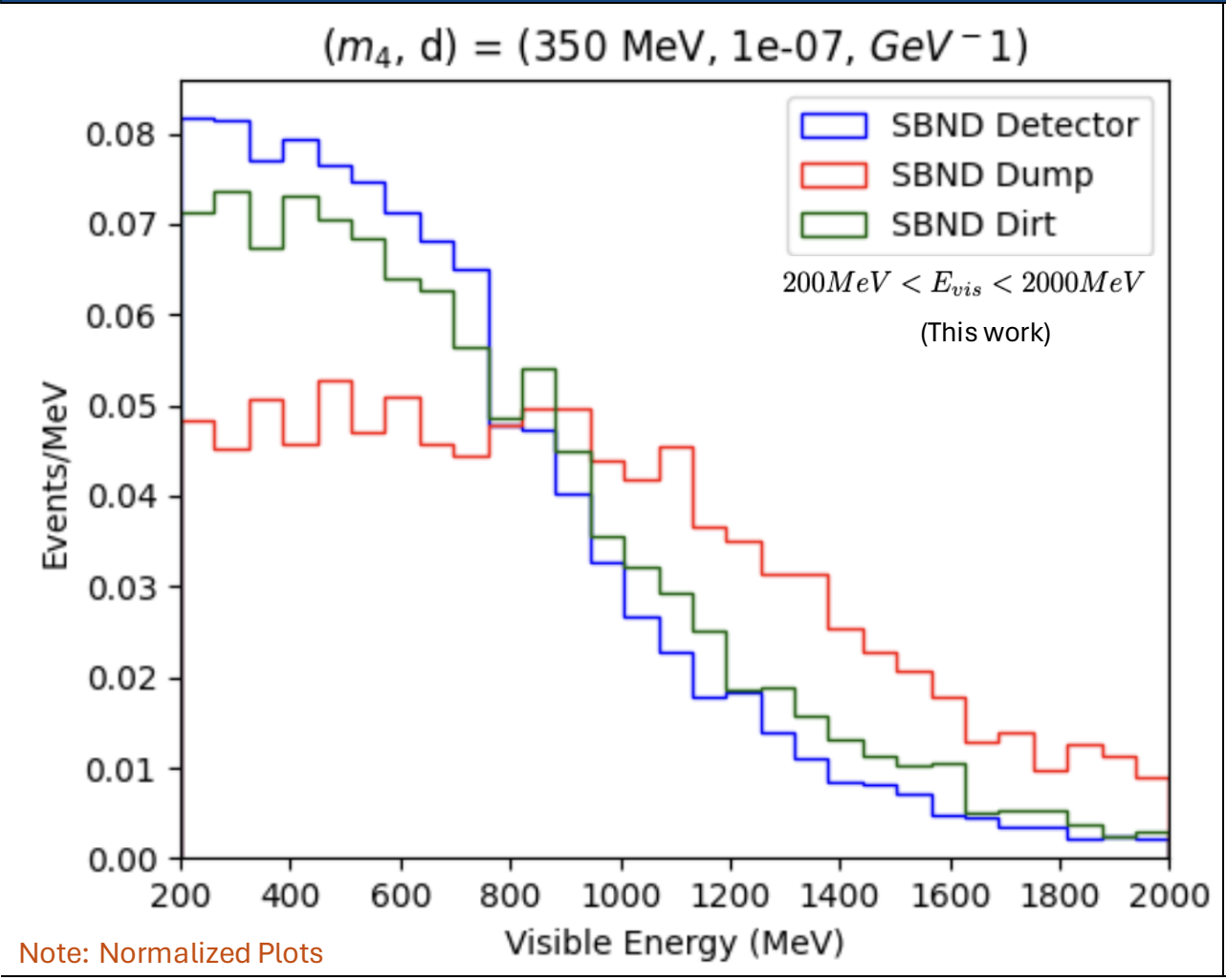


Note: Normalized Plots

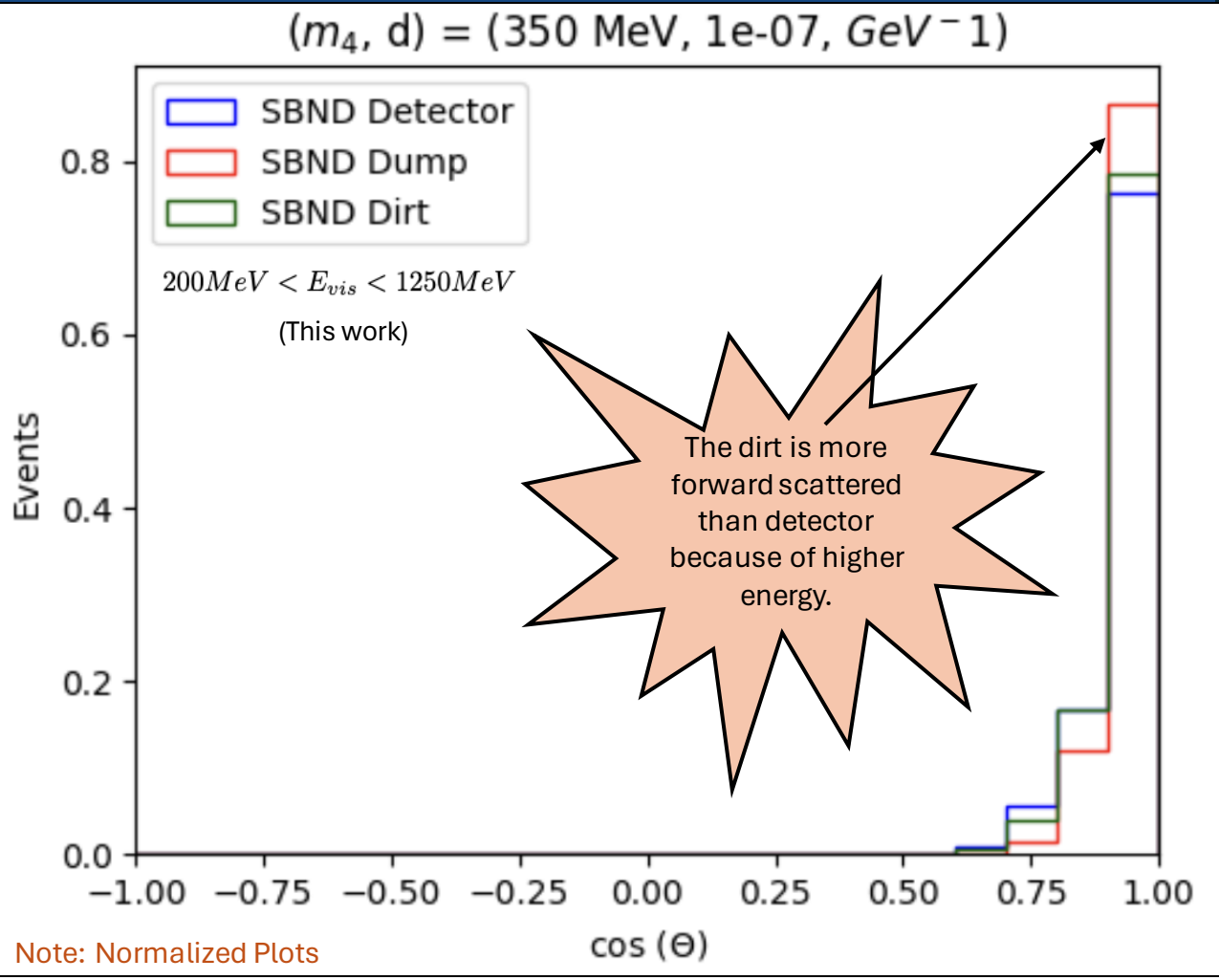


Note: Normalized Plots

SBND Detector vs Dump vs Dirt I

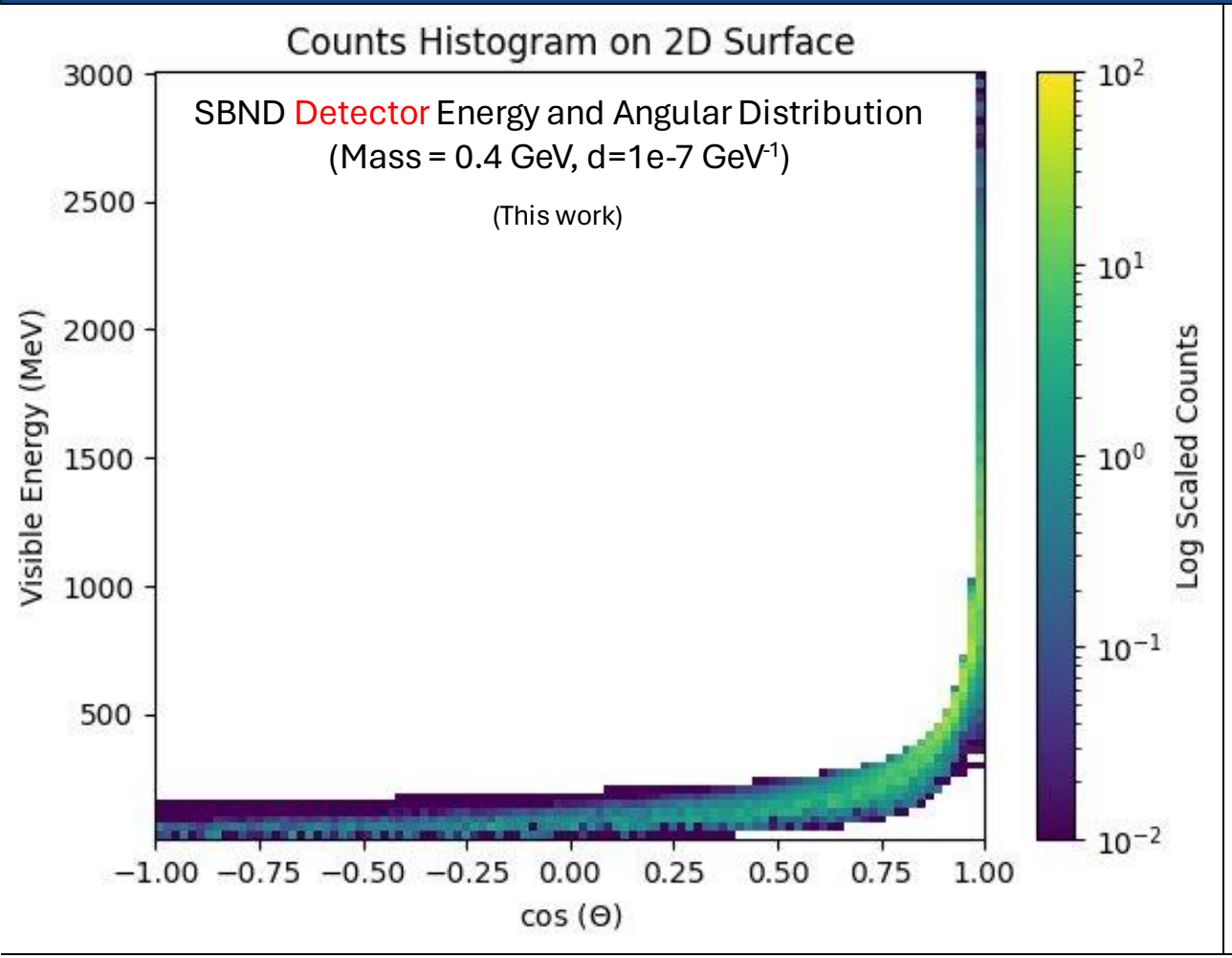


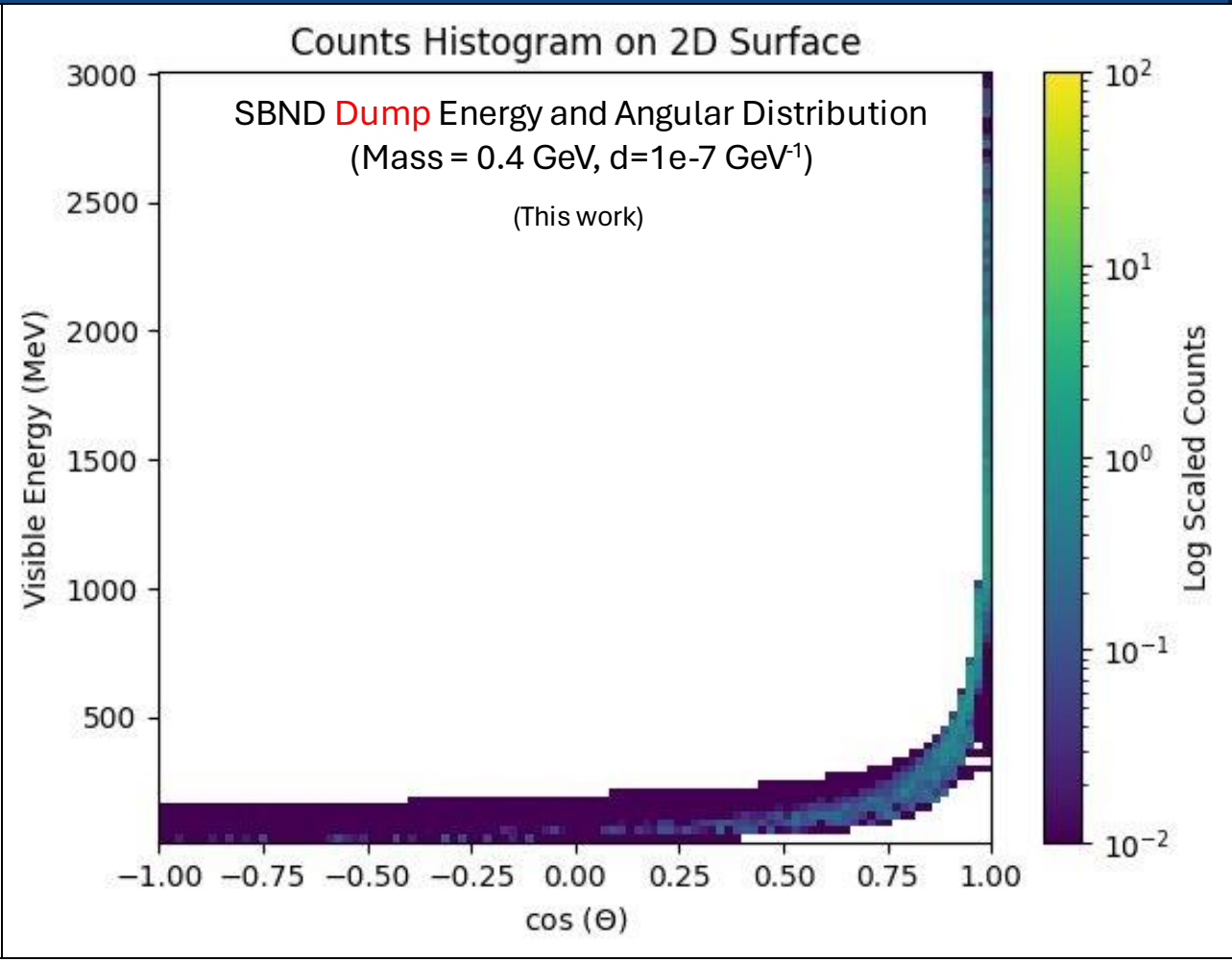
Note: Normalized Plots



Note: Normalized Plots

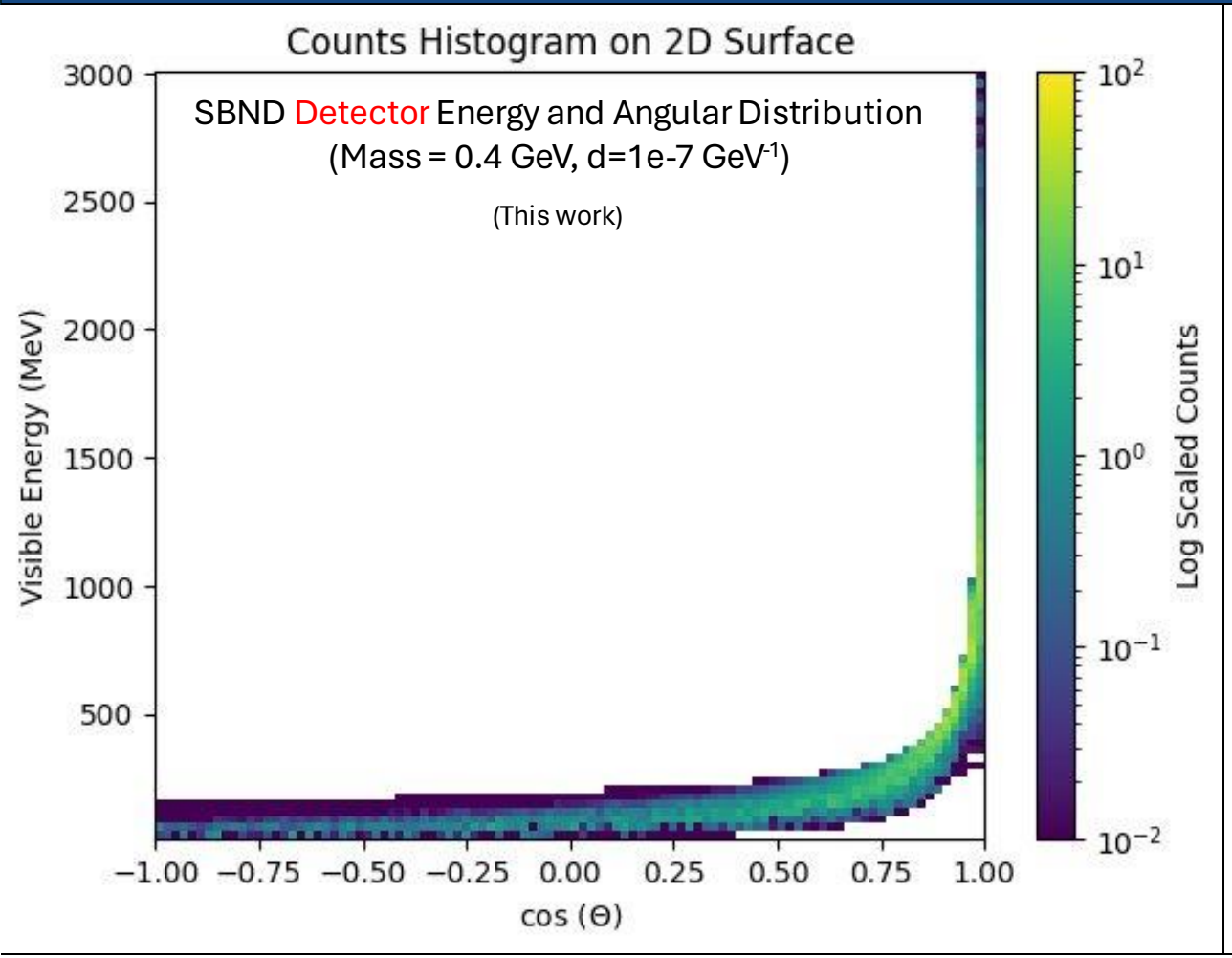
SBND Detector vs Dump vs Dirt II

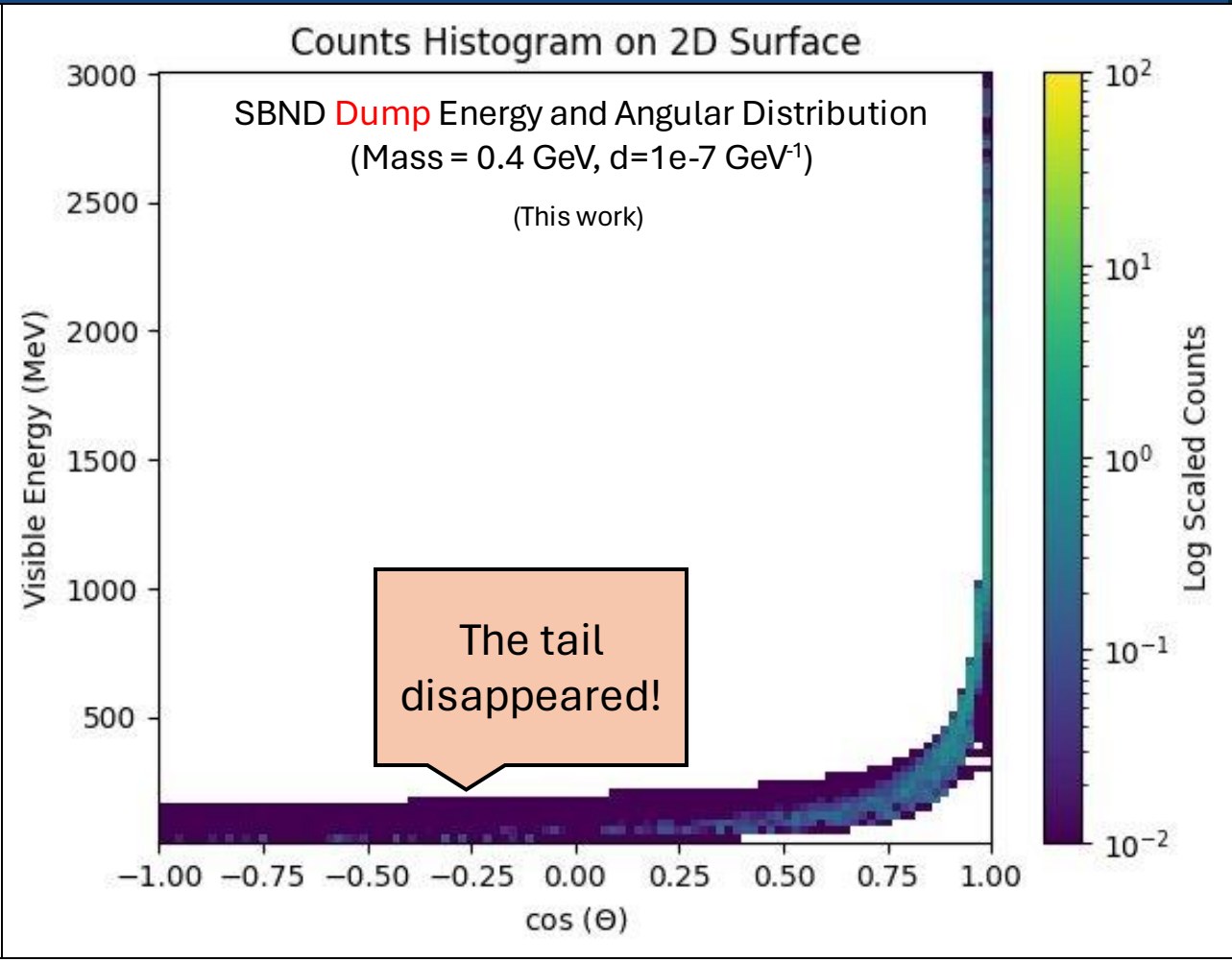




M D Tutto, V Pandey, P Machado, K Kelly, and R Harnik, SBND PRISM NuSTEC CEWG (2021)

SBND Detector vs Dump vs Dirt II





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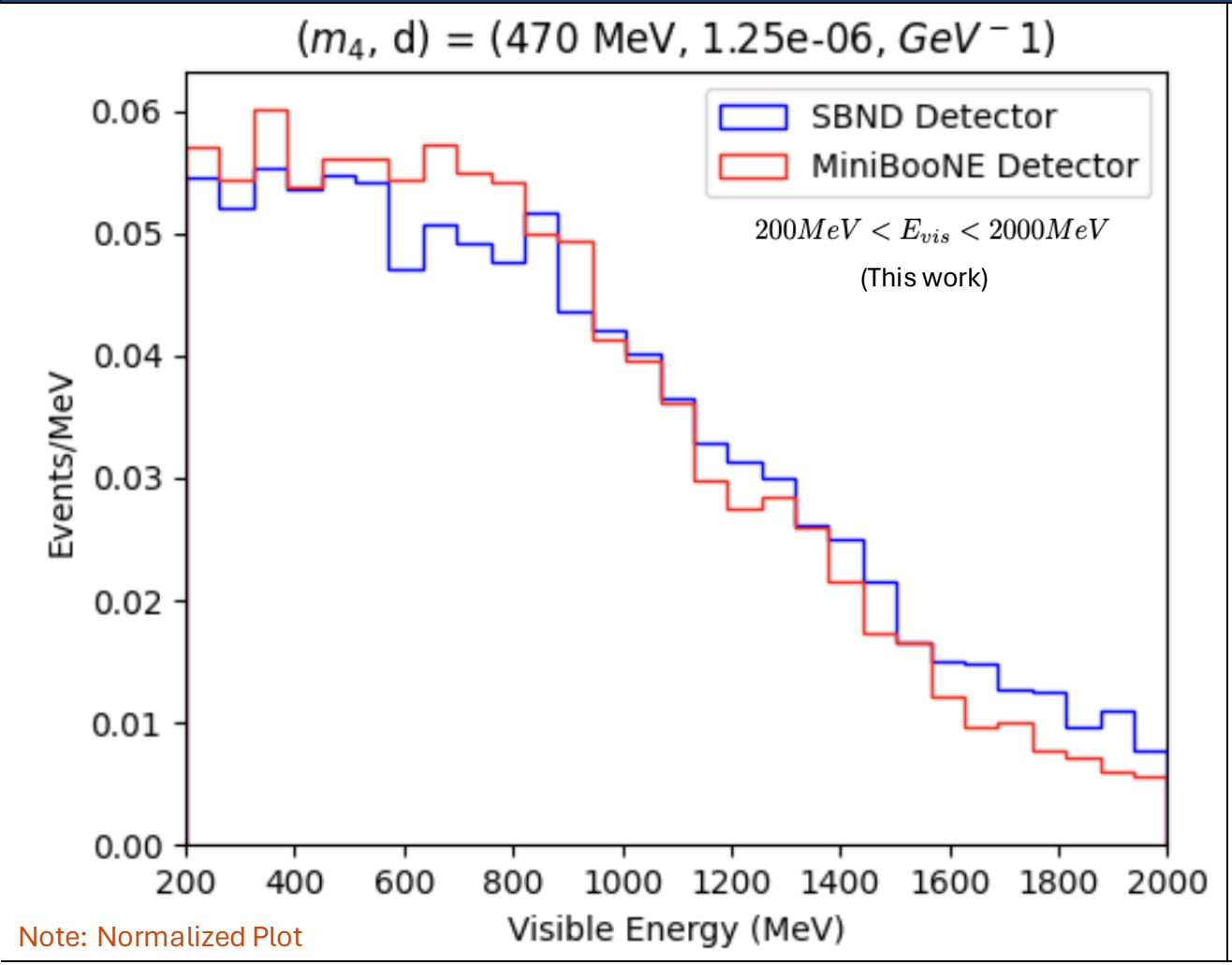
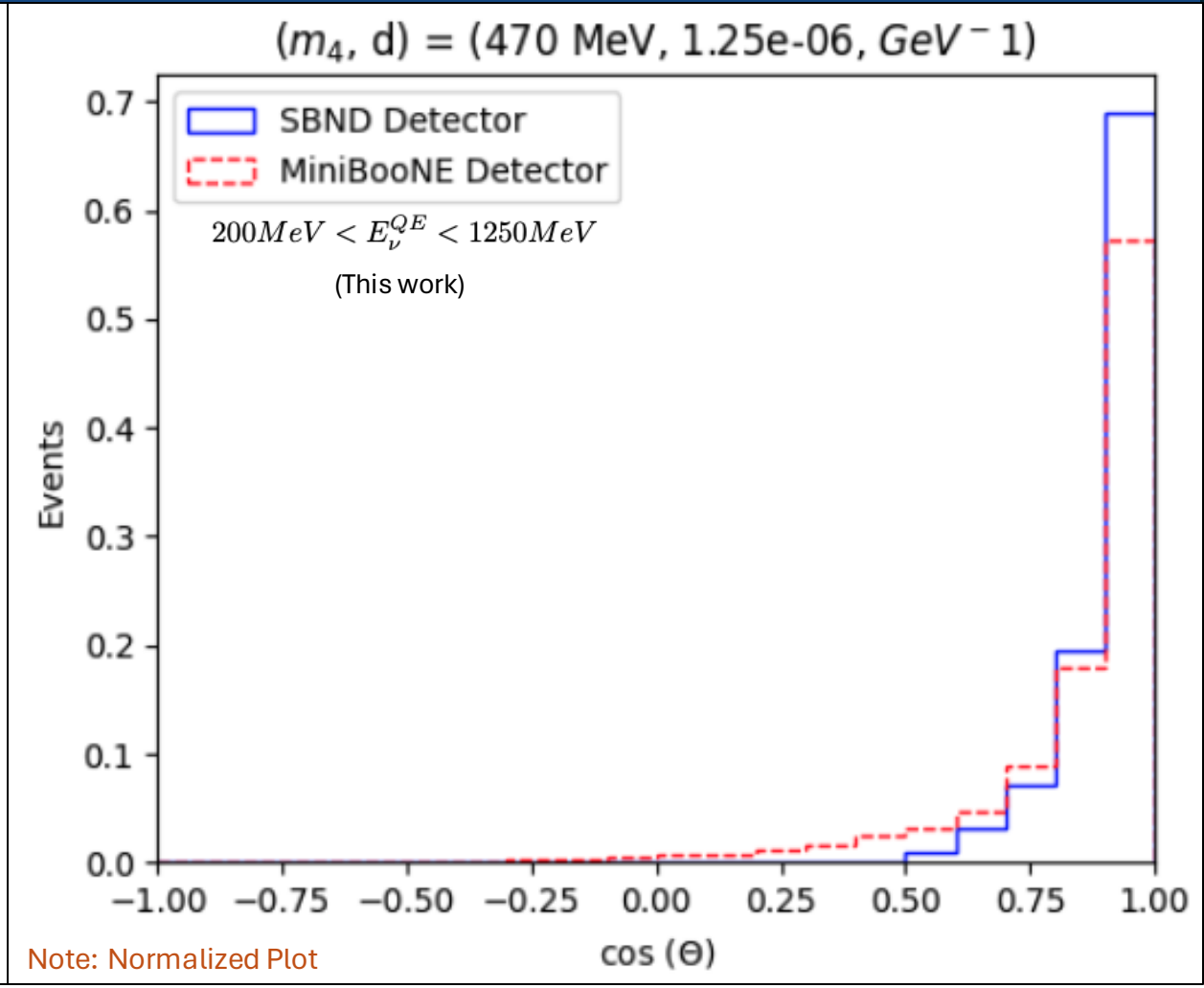
MiniBooNE Anomaly in SBND I



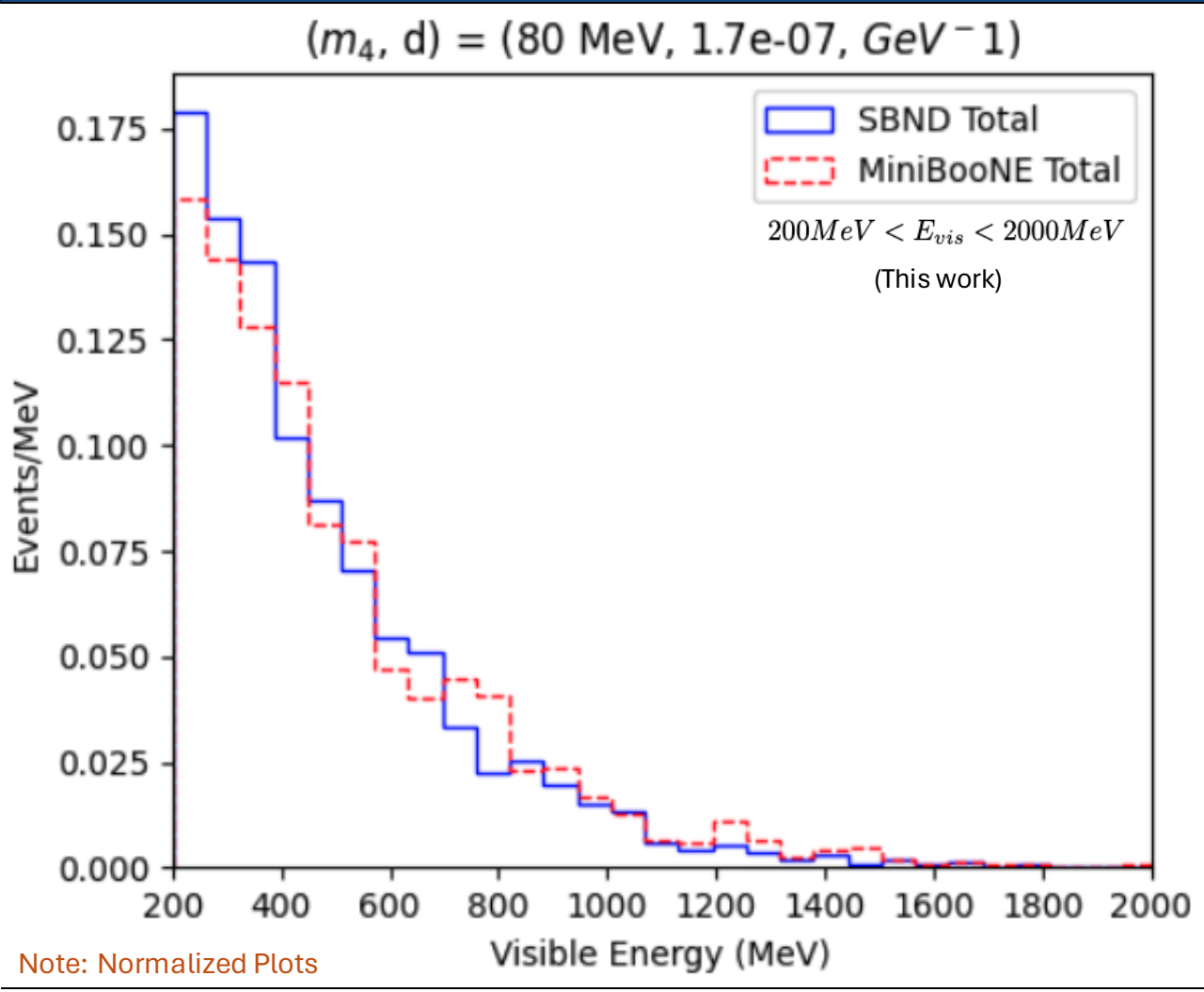
Note: Normalized Plot



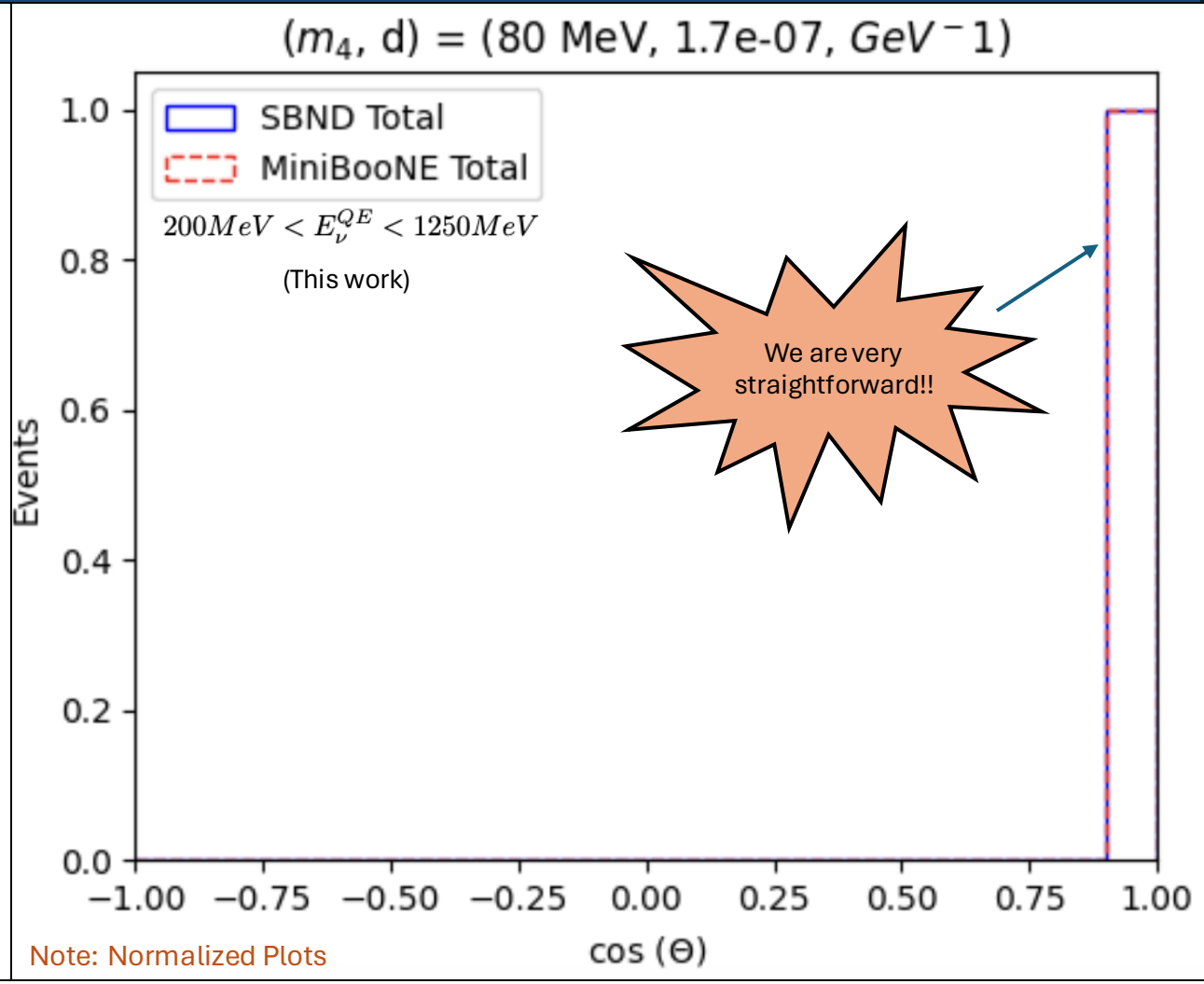
Note: Normalized Plot

- N W. Kamp, M Hostert, A Schneider, S Vergani, C A. Argüelles, J M. Conrad, M H. Shaevitz, M A. Uchida, Phys. Rev. D 107, 055009

MiniBooNE Anomaly in SBND II



Note: Normalized Plots

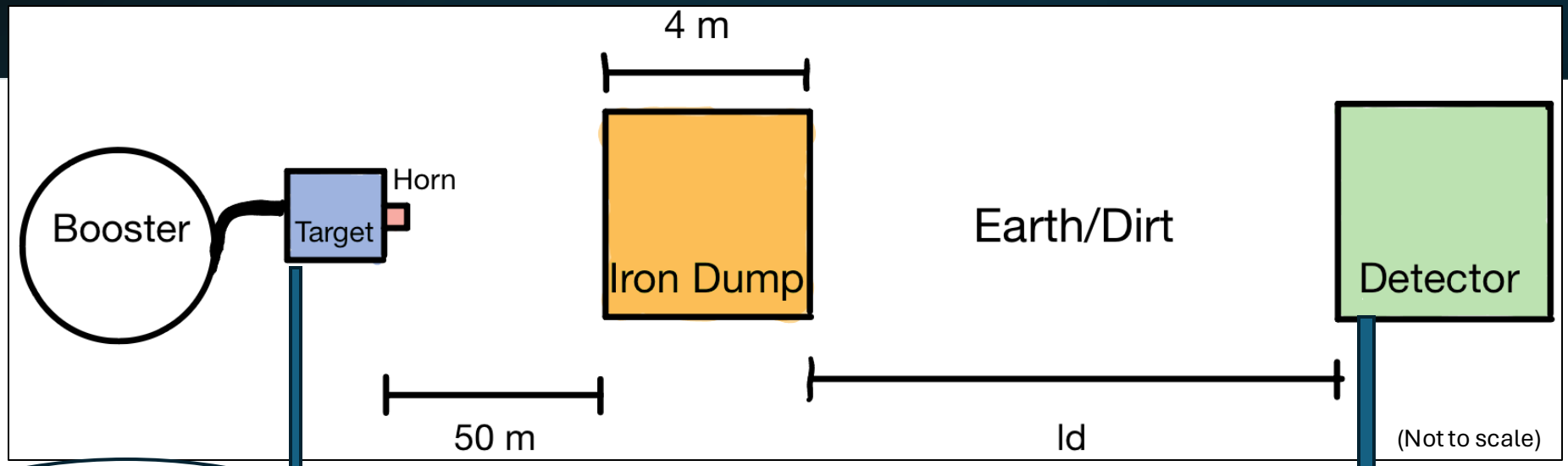


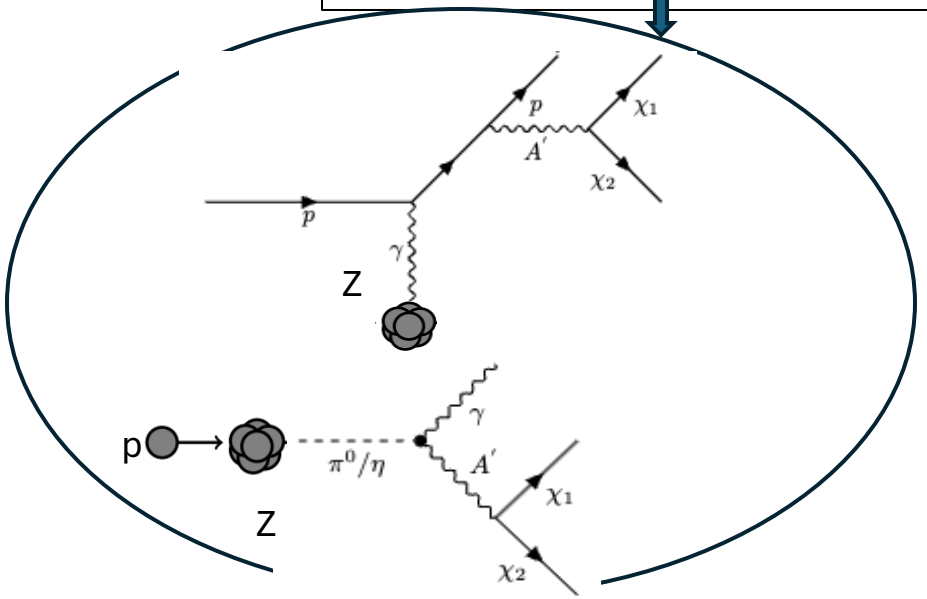
Note: Normalized Plots

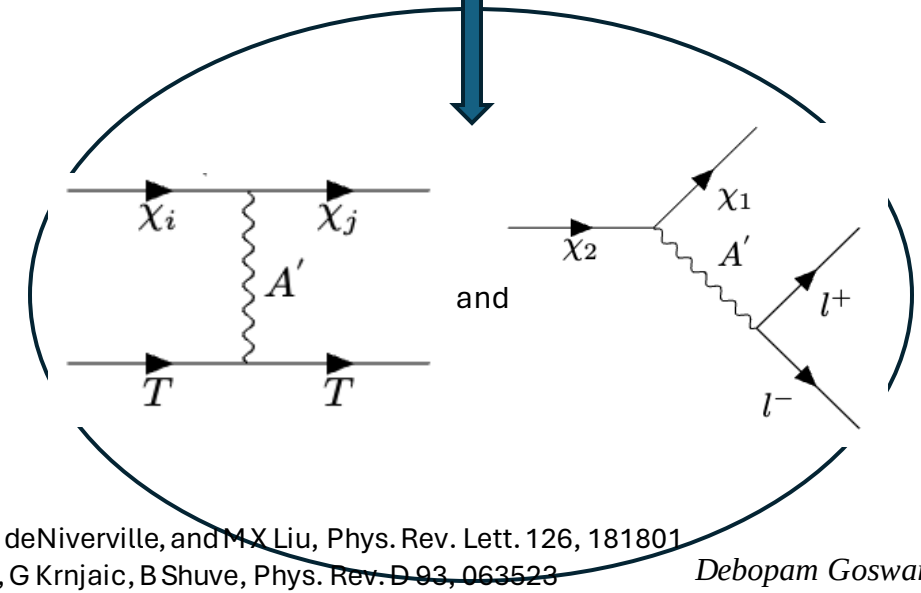
- N W. Kamp, M Hostert, A Schneider, S Vergani, C A. Argüelles, J M. Conrad, M H. Shaevitz, M A. Uchida, Phys. Rev. D 107, 055009

Model: Inelastic Dark Matter

$$\mathcal{L} \supset g_{\chi A'} A'_{\mu} \bar{\chi}_2 \gamma^{\mu} \chi_1 + e\epsilon A'_{\mu} \bar{N} \gamma^{\mu} N + h.c.$$





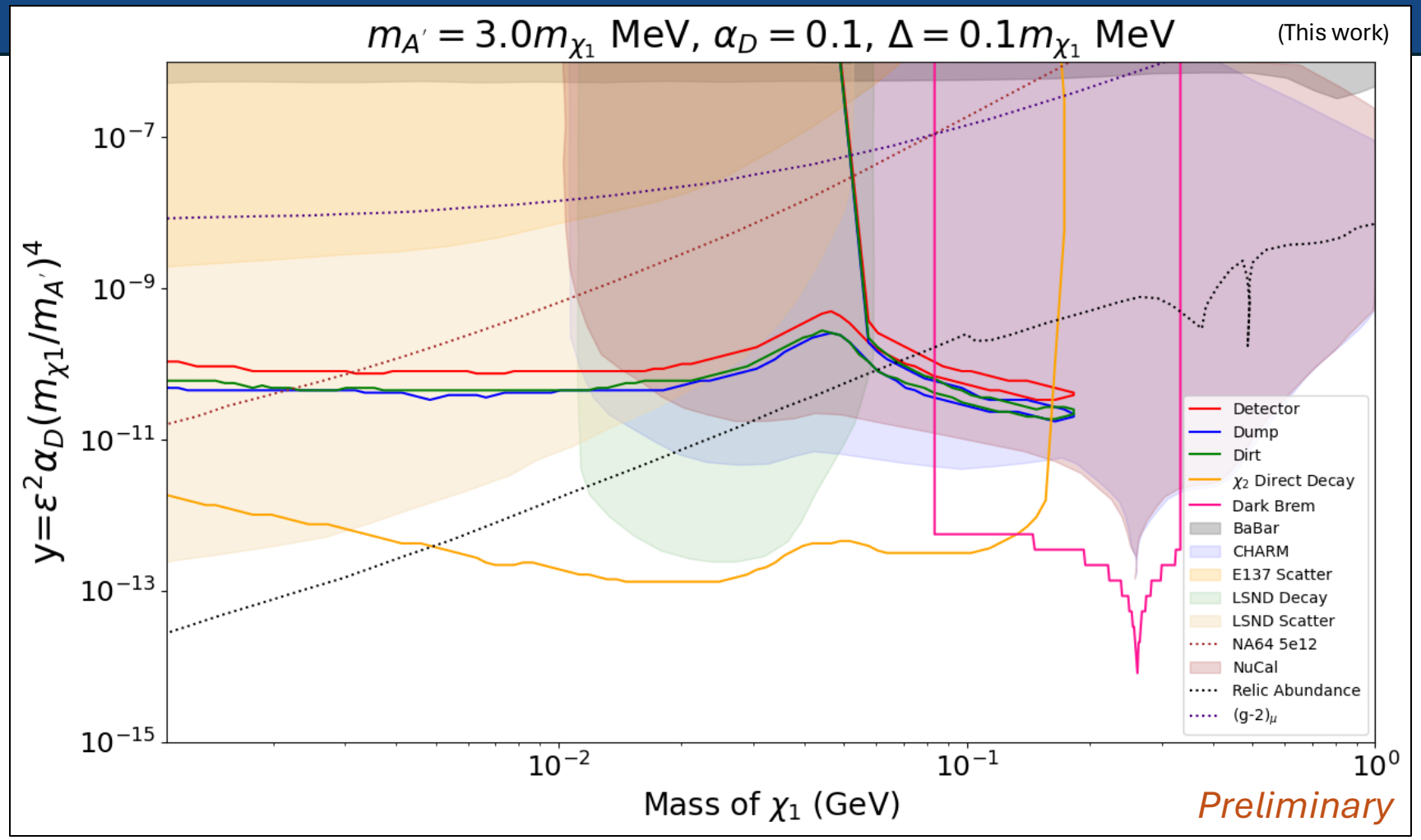


E Izaguirre, Y Kahn, G Krnjaic, M Moschella, Phys. Rev. D 96, 055007

N F. Bell, J B. Dent, B Dutta, S Ghosh, J K, J L. Newstead, I M. Shoemaker, Phys. Rev. D 104, 076020

Y-D Tsai, P deNiverville, and MX Liu, Phys. Rev. Lett. 126, 181801
E Izaguirre, G Krnjaic, B Shuve, Phys. Rev. D 93, 063523
Gopolang Mohlabeng, Phys. Rev. D 99, 115001

SBND Inelastic Dark Matter Sensitivity Plots



M Mongillo, A Abdullahi, B B Oberhauser, P Crivelli, M Hostert, D Massaro, L M Bueno, S Pascoli, Eur. Phys. J. C 83, 391 (2023)

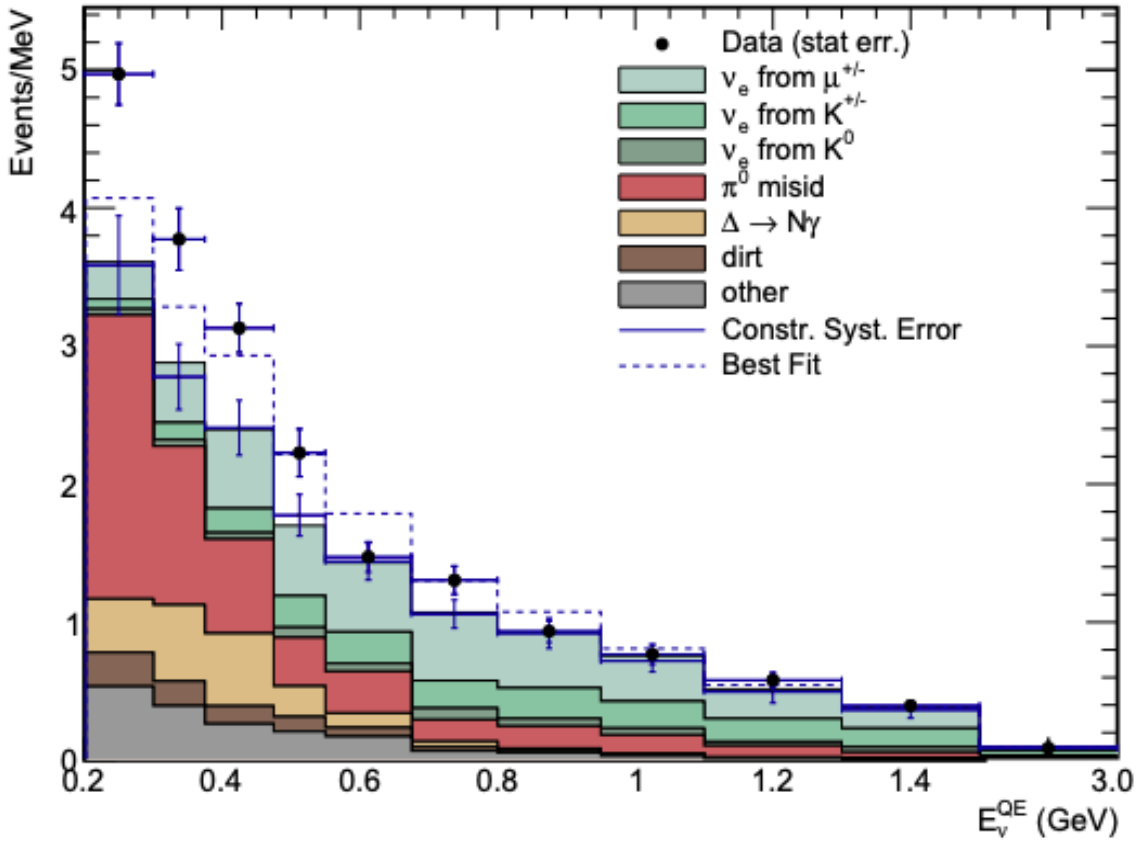
Results and Conclusions

- In this work contributions from dump, dirt and detector have been taken into consideration for transition moment operator for all the SBN experiments.
- The dump allows us to probe more unexplored parameter space.
- SBND covers the most unexplored parameter space!
- The Z^2 enhancement makes the contribution from the dump significant.
- Dump, dirt & detector leave distinguishing signals in both energy & angular spectra for mass range (200 MeV and above within sensitivity region).
- SBND can also explore the parameter space required to explain the MiniBooNE anomaly.
- This work also predicts what SBND will observe for the explanation of MiniBooNE excess (more forward).

Thank You!

BACKUP SLIDES

MiniBooNE Anomaly



Neutrino mode POTs: $12.84 * 10^{20}$

Process	Neutrino Mode	Antineutrino Mode
ν_μ & $\bar{\nu}_\mu$ CCQE	73.7 ± 19.3	12.9 ± 4.3
NC π^0	501.5 ± 65.4	112.3 ± 11.5
NC $\Delta \rightarrow N\gamma$	172.5 ± 24.1	34.7 ± 5.4
External Events	75.2 ± 10.9	15.3 ± 2.8
Other ν_μ & $\bar{\nu}_\mu$	89.6 ± 22.9	22.3 ± 3.5
ν_e & $\bar{\nu}_e$ from $\mu^\pm$ Decay	425.3 ± 100.2	91.4 ± 27.6
ν_e & $\bar{\nu}_e$ from $K^\pm$ Decay	192.2 ± 41.9	51.2 ± 11.0
ν_e & $\bar{\nu}_e$ from K_L^0 Decay	54.5 ± 20.5	51.4 ± 18.0
Other ν_e & $\bar{\nu}_e$	6.0 ± 3.2	6.7 ± 6.0
Unconstrained Bkgd.	1590.6 ± 176.9	398.2 ± 49.7
Constrained Bkgd.	1577.8 ± 85.2	398.7 ± 28.6
Total Data	1959	478
Excess	381.2 ± 85.2	79.3 ± 28.6
0.26% (LSND) $\nu_\mu \rightarrow \nu_e$	463.1	100.0

Figure: Number of Events observed

$$200 < E_\nu^{QE} < 1250 MeV$$

- 381.2 ± 85.2 excess events are observed at a 4.5σ confidence level in the neutrino mode.

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LSND Collaboration, Phys. Rev. Lett. 77, 3082

Flux Energy Spectrum SBN

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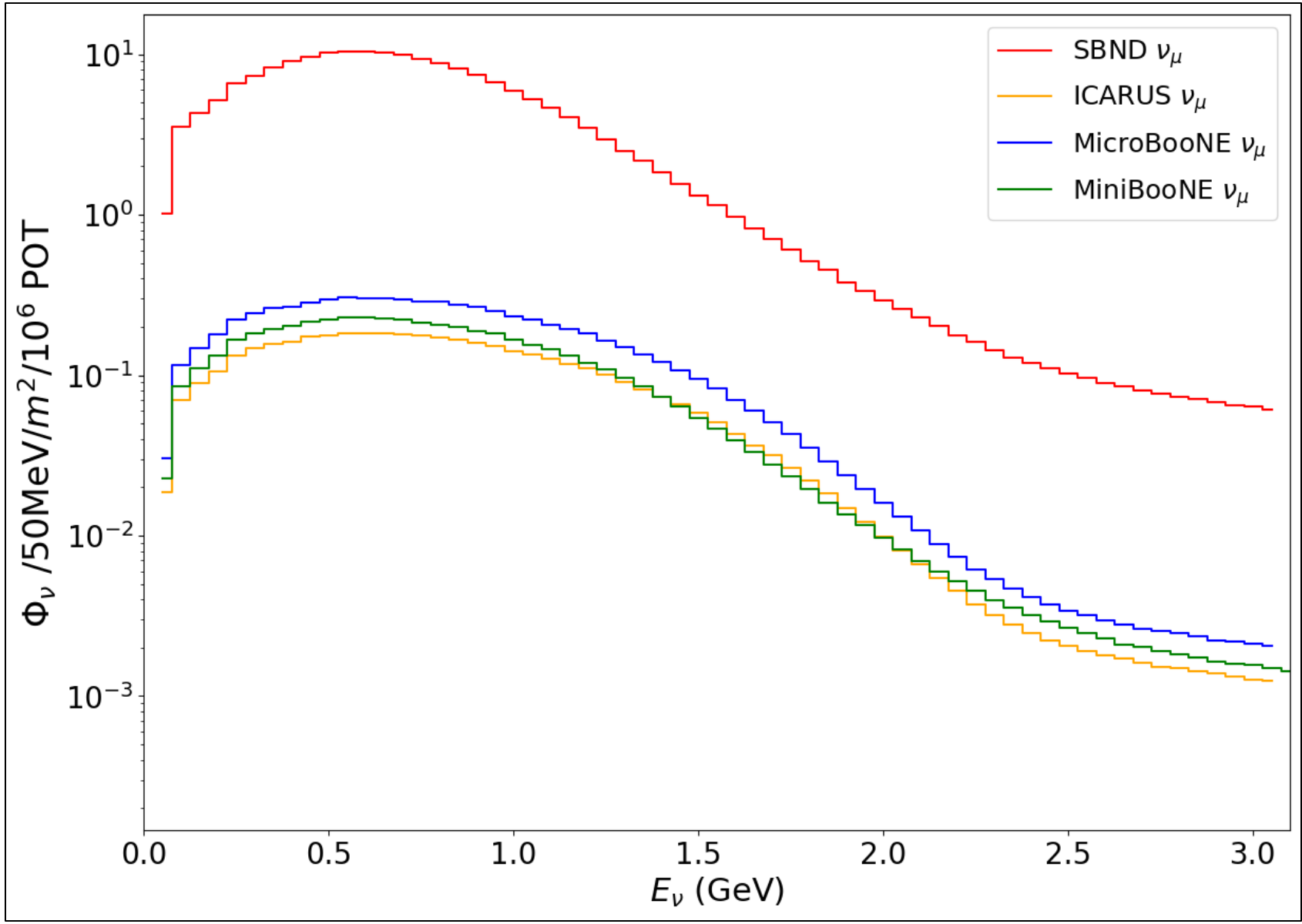
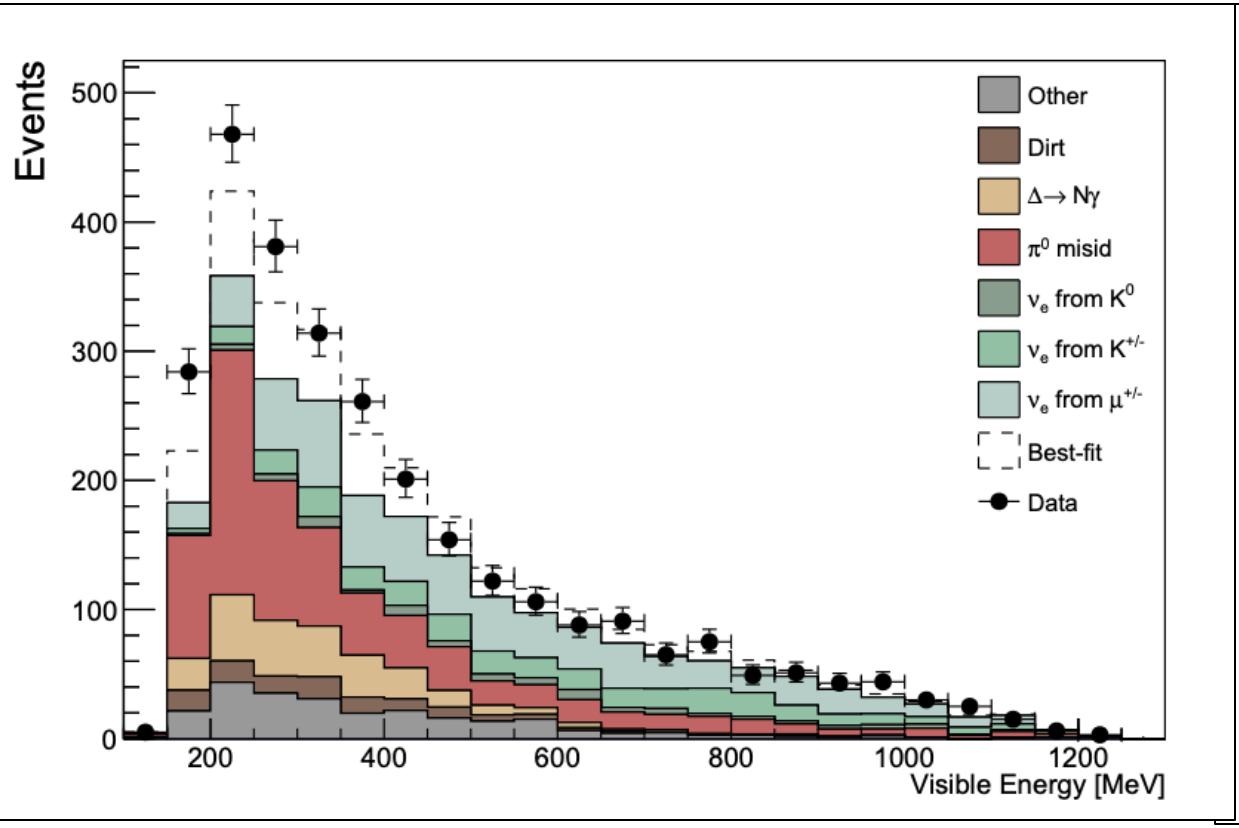
- SBN Proposal: arXiv:1503.01520



Note: All these fluxes are in neutrino mode.

Backgrounds



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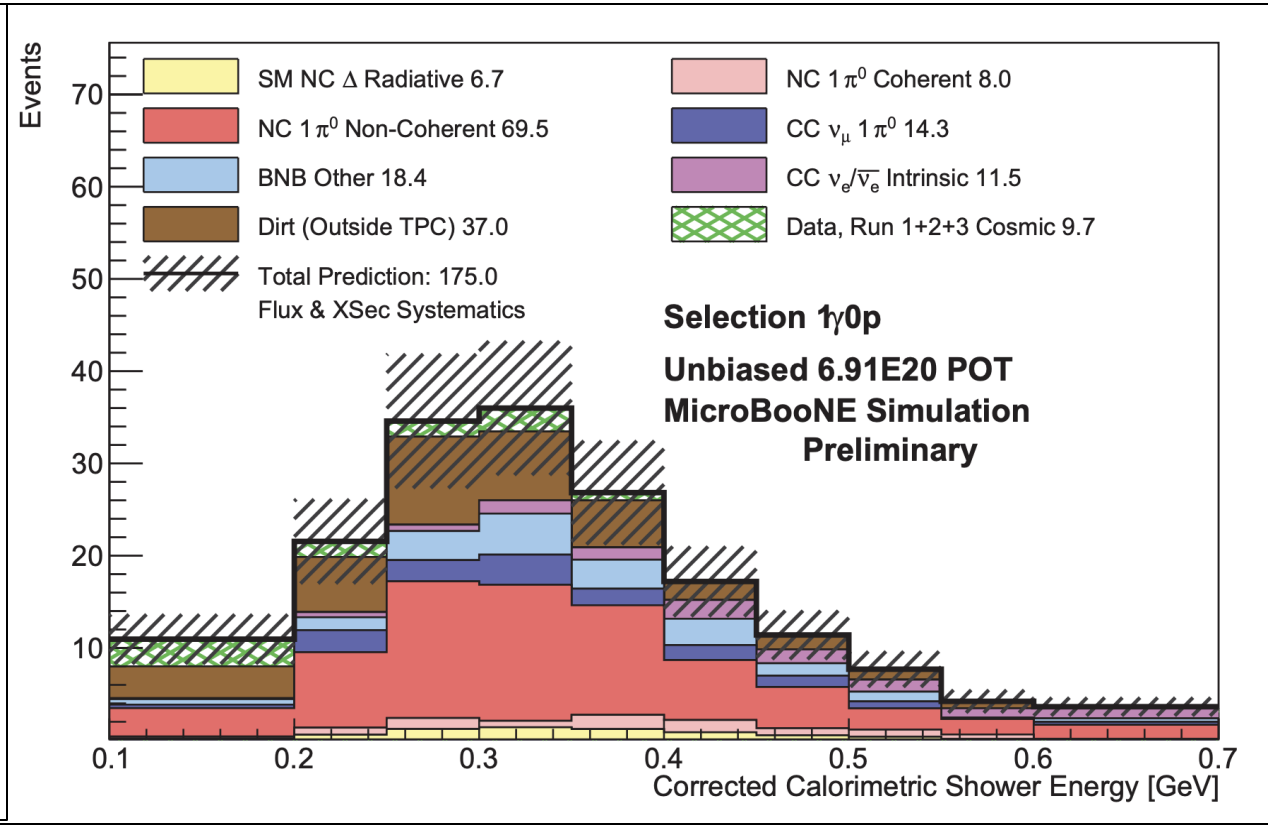
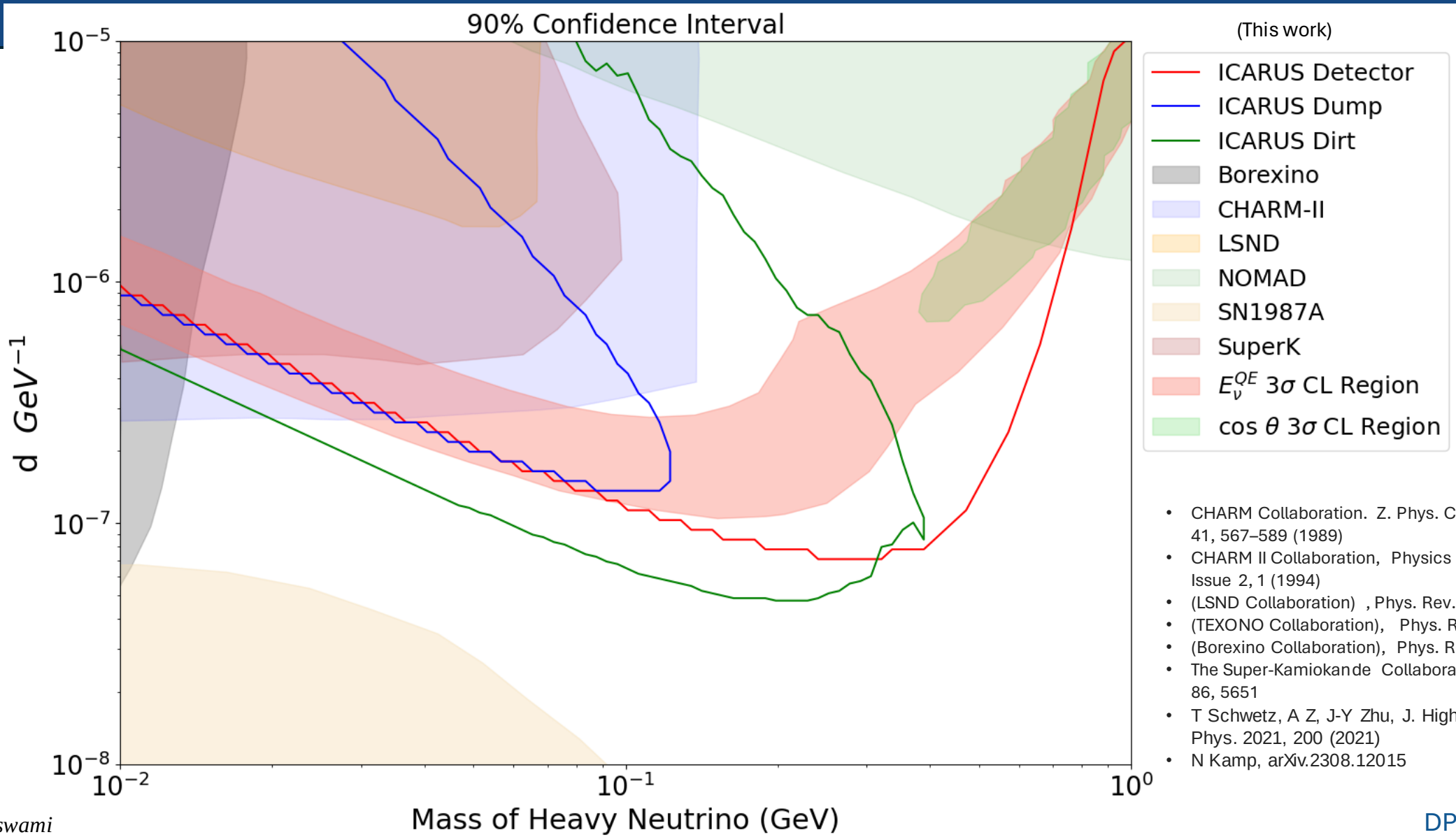


A J Mogan, FERMILAB-THESIS-2021-04

ICARUS Sensitivity Plot



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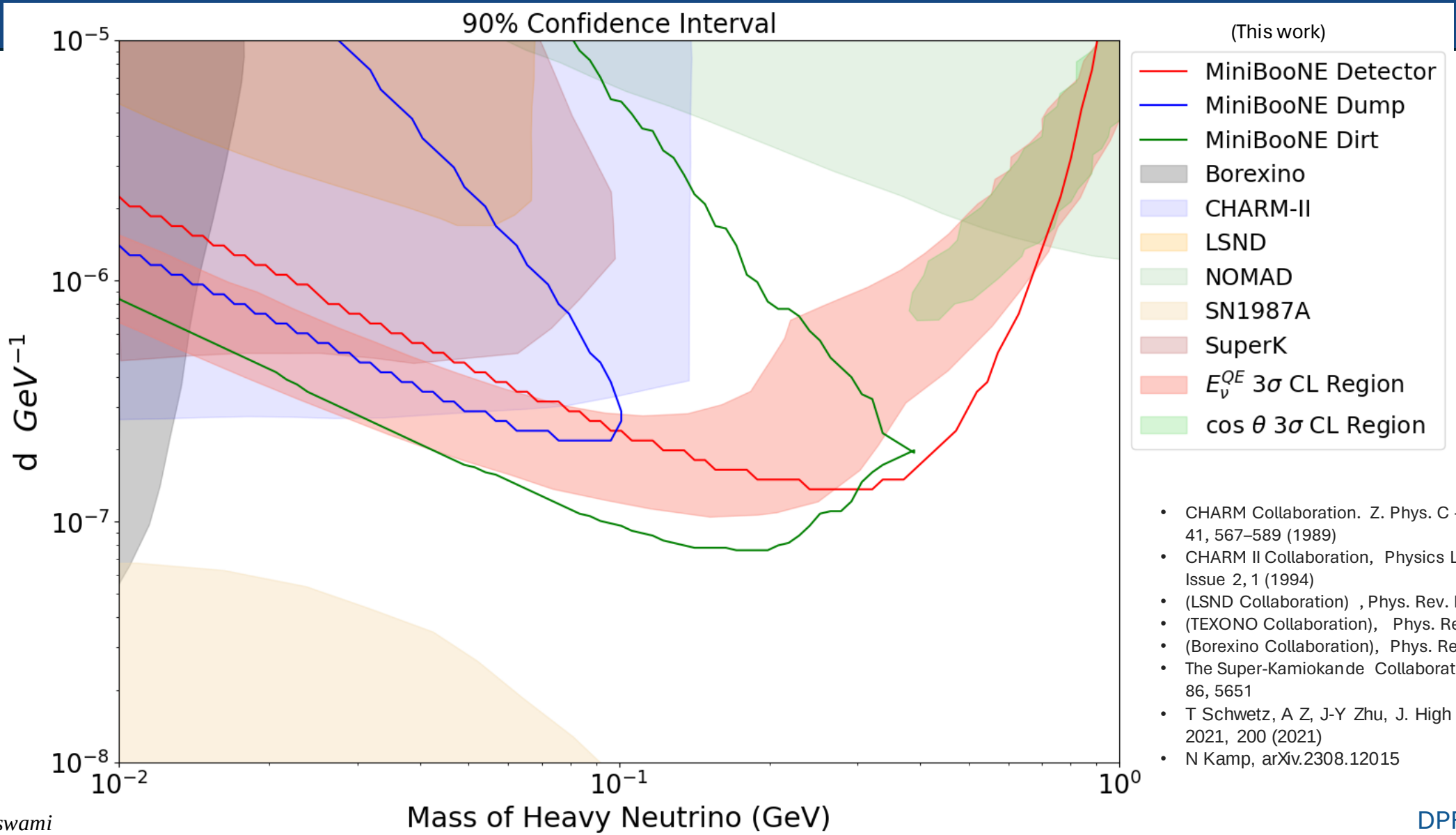
- (LSND Collaboration) , Phys. Rev. D 63, 112001
- (TEXONO Collaboration), Phys. Rev. D 81, 072001
- (Borexino Collaboration), Phys. Rev. Lett. 107, 141302
- The Super-Kamiokande Collaboration, Phys. Rev. Lett. 86, 5651
- T Schwetz, A Z, J-Y Zhu, J. High Energ. Phys. 2021, 200 (2021)
- N Kamp, arXiv.2308.12015

MiniBooNE Sensitivity Plot



- CHARM Collaboration. Z. Phys. C - Particles and Fields 41, 567–589 (1989)
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- (TEXONO Collaboration), Phys. Rev. D 81, 072001
- (Borexino Collaboration), Phys. Rev. Lett. 107, 141302
- The Super-Kamiokande Collaboration, Phys. Rev. Lett. 86, 5651
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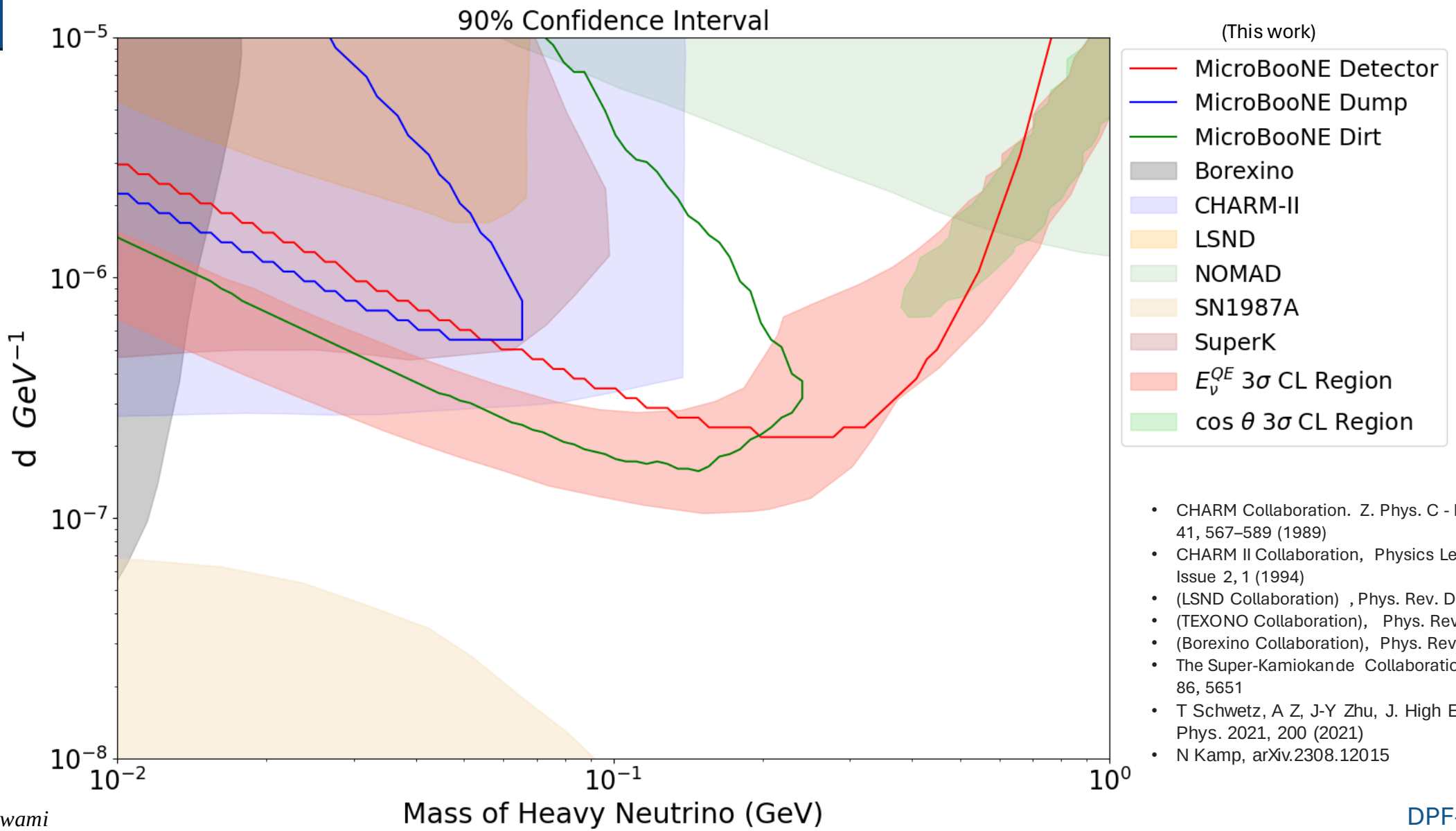
MicroBooNE Sensitivity Plot



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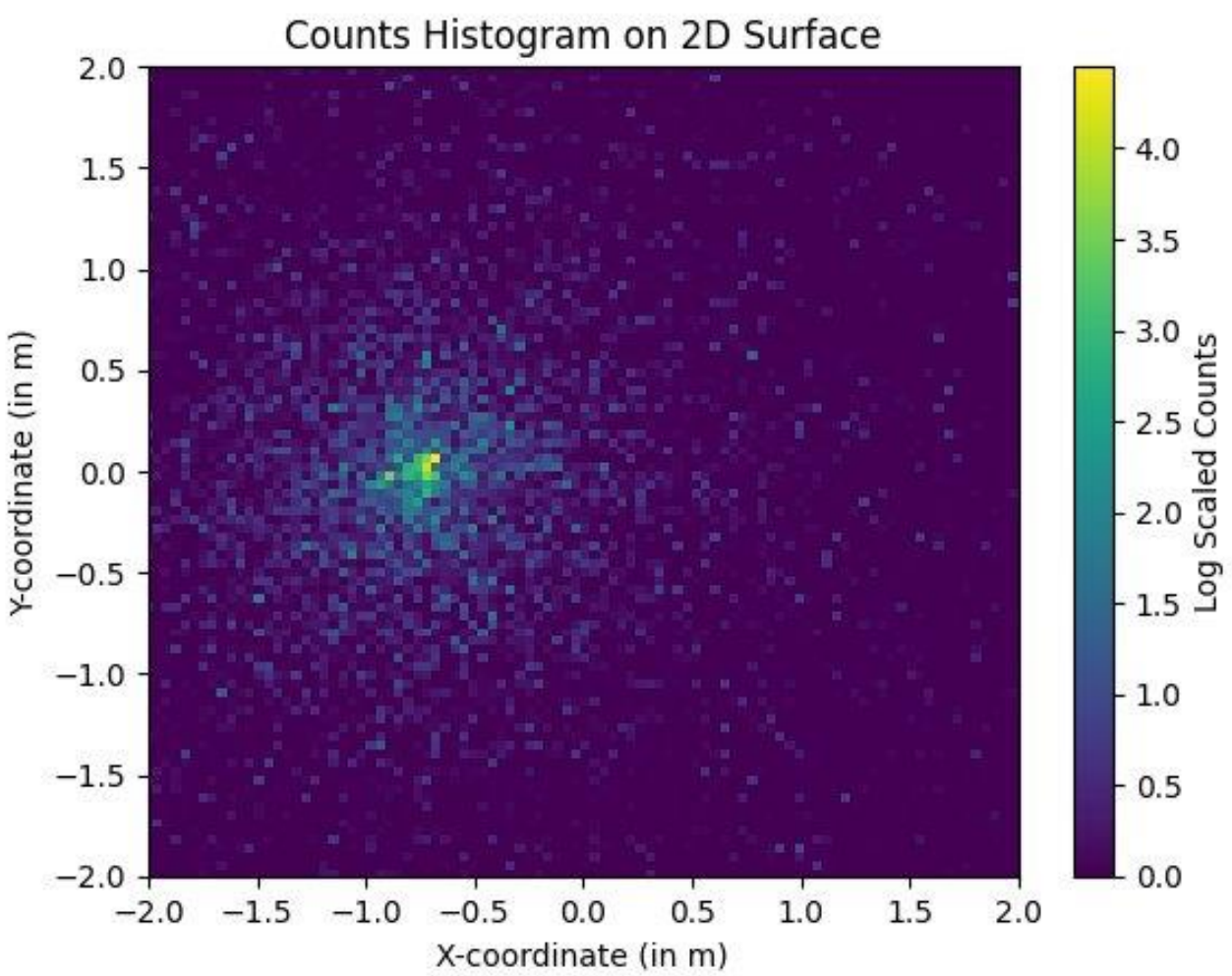
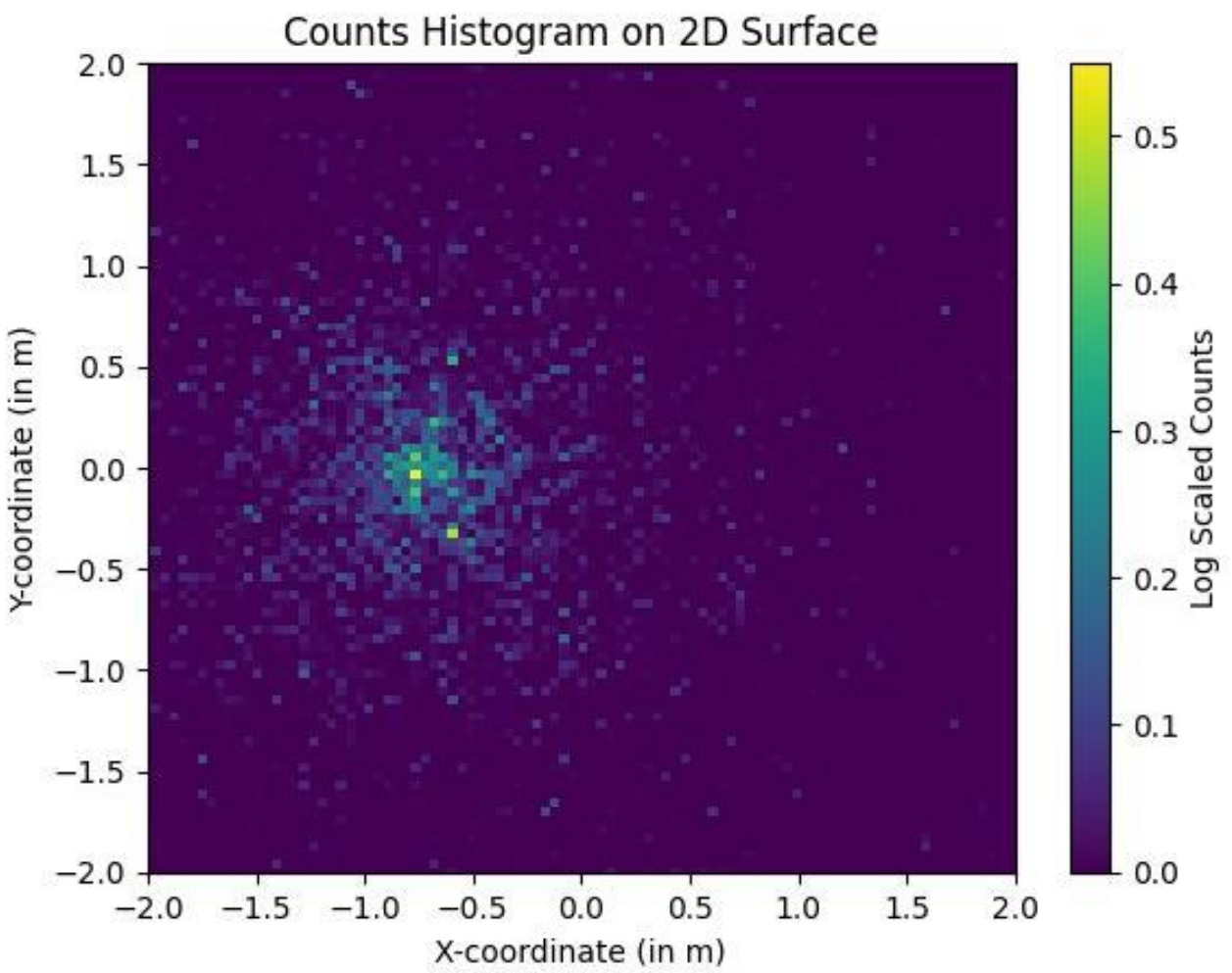
SBND Detector vs Dump vs Dirt III

SBND Detector X-Y Distribution
(Mass = 0.4 GeV, d=1e-7 GeV^{-1})



SBND Dump X-Y Distribution
(Mass = 0.4 GeV, d=1e-7 GeV^{-1})

(This work)



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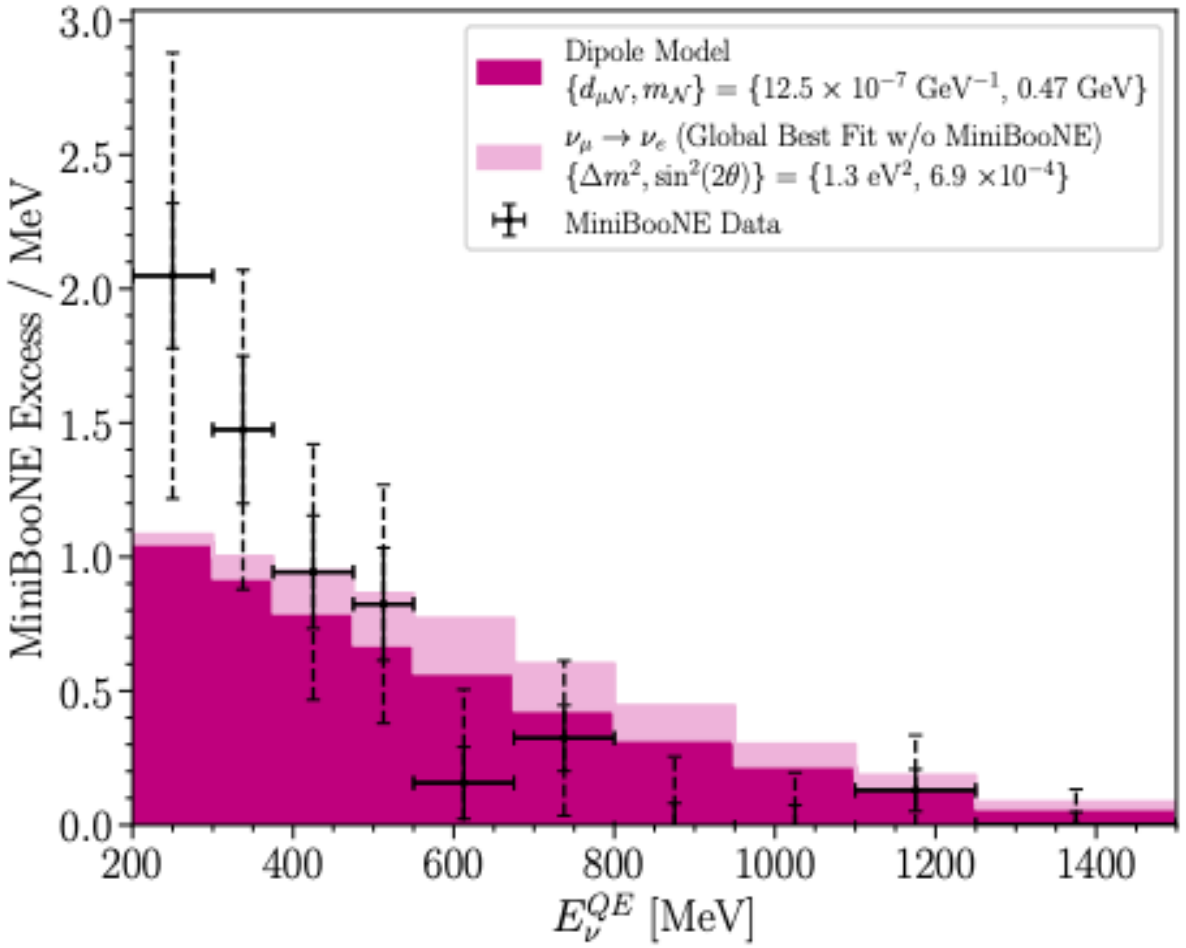
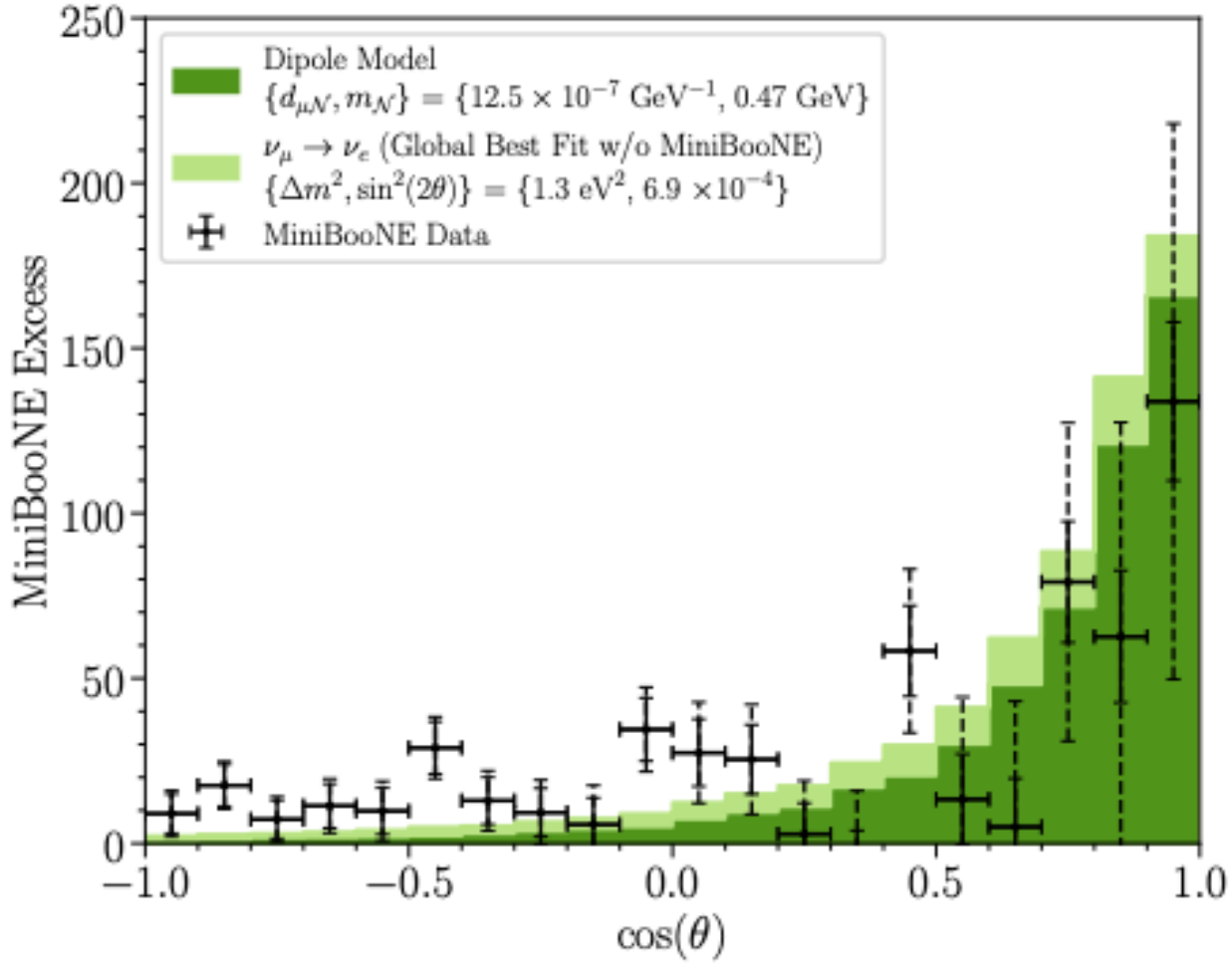
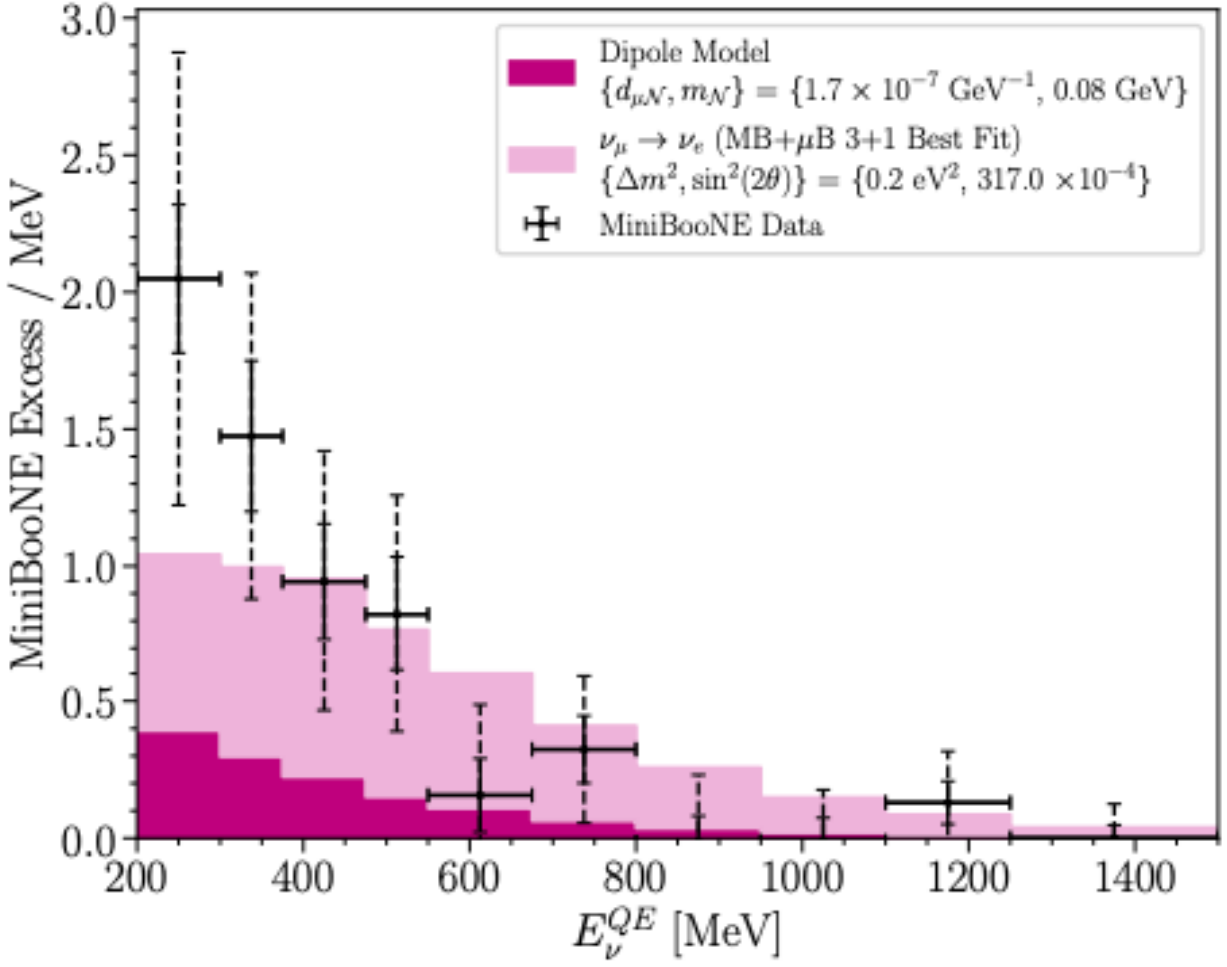
Mass and Coupling for MiniBooNE Excess Explanation I

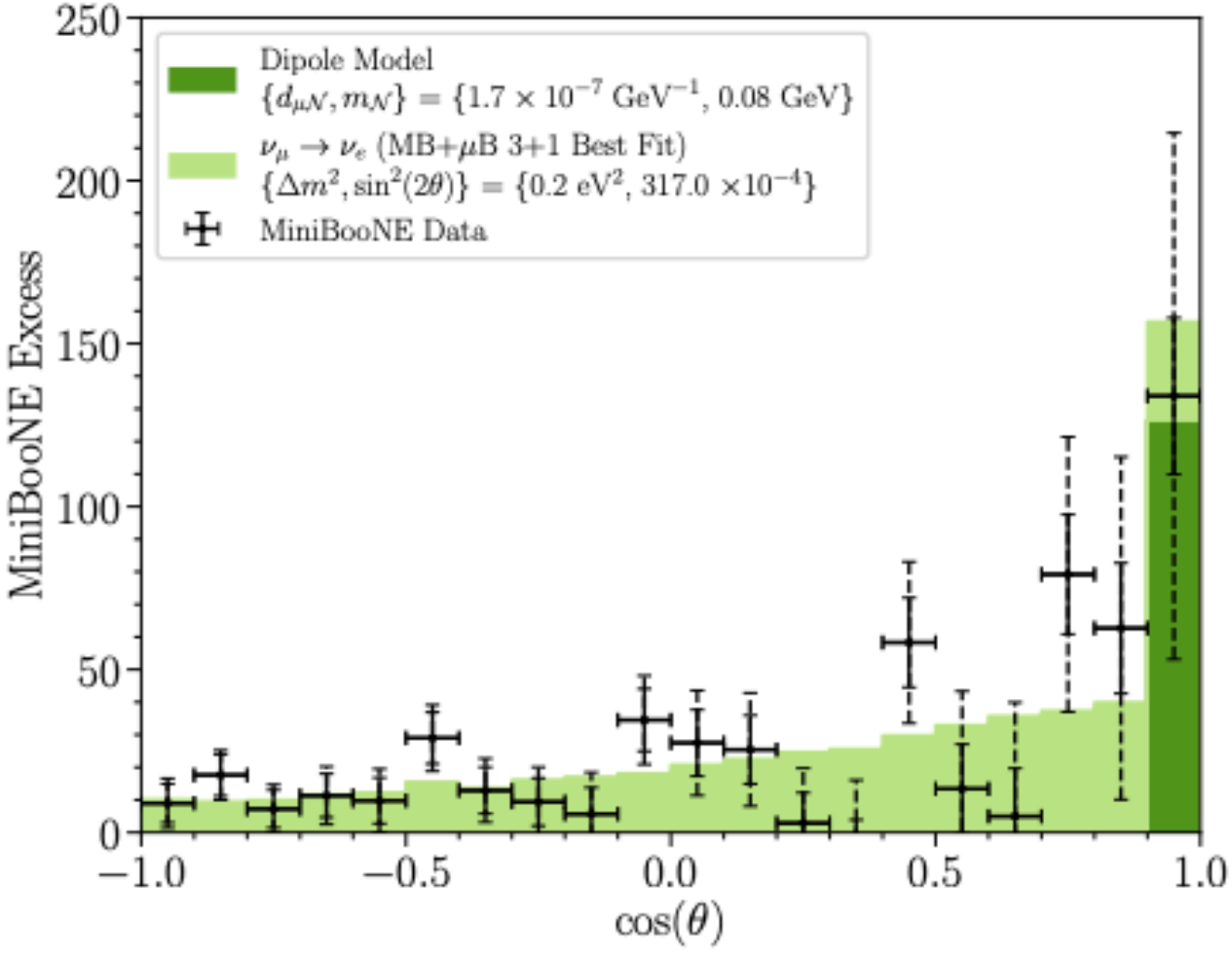




- N W. Kamp, M Hostert, A Schneider, S Vergani, C A. Argüelles, J M. Conrad, M H. Shaevitz, M A. Uchida, Phys. Rev. D 107, 055009 (References therein)

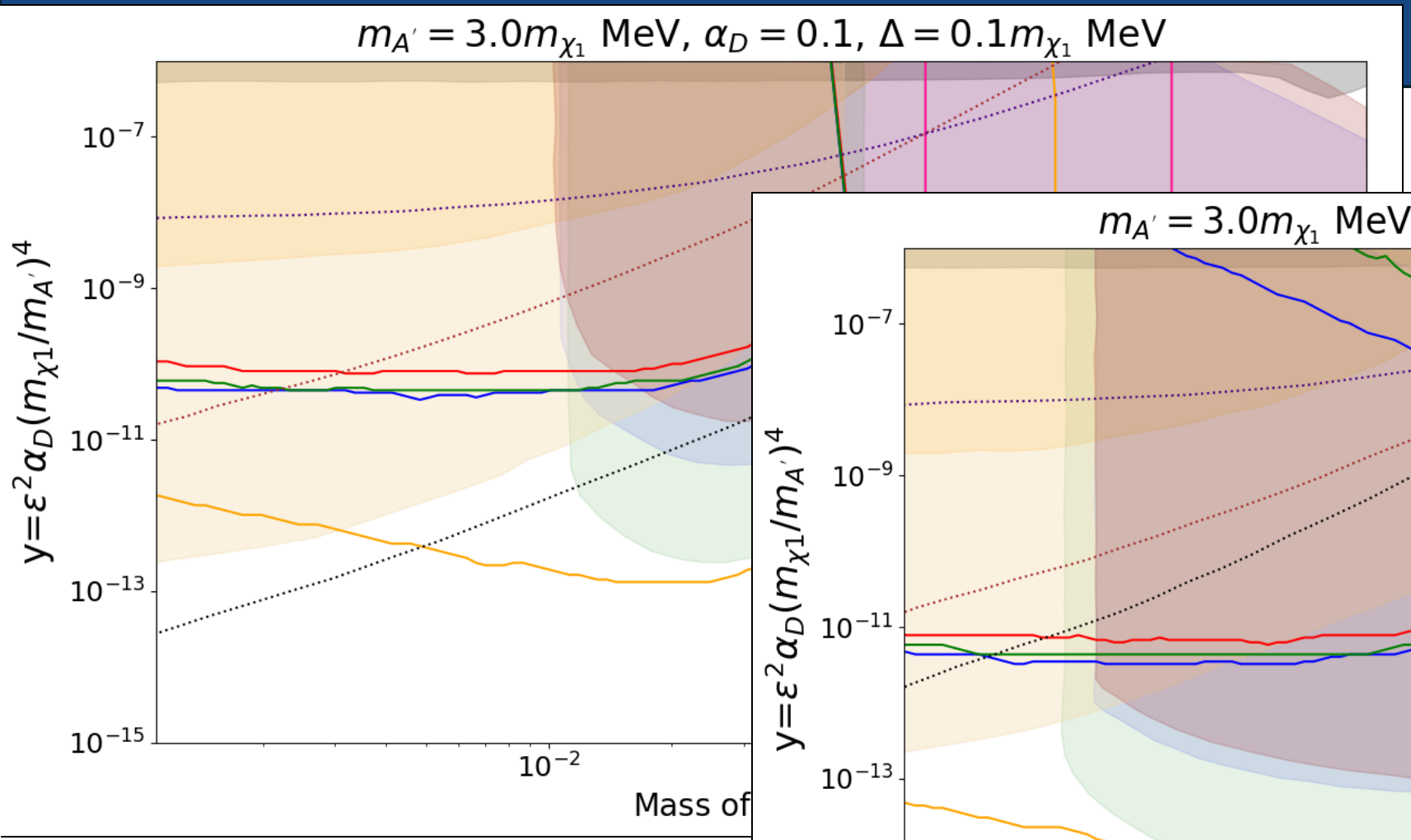
Mass and Coupling for MiniBooNE Excess Explanation II





- N W. Kamp, M Hostert, A Schneider, S Vergani, C A. Argüelles, J M. Conrad, M H. Shaevitz, M A. Uchida, Phys. Rev. D 107, 055009 (References therein)

SBND Inelastic Dark Matter Sensitivity Plots



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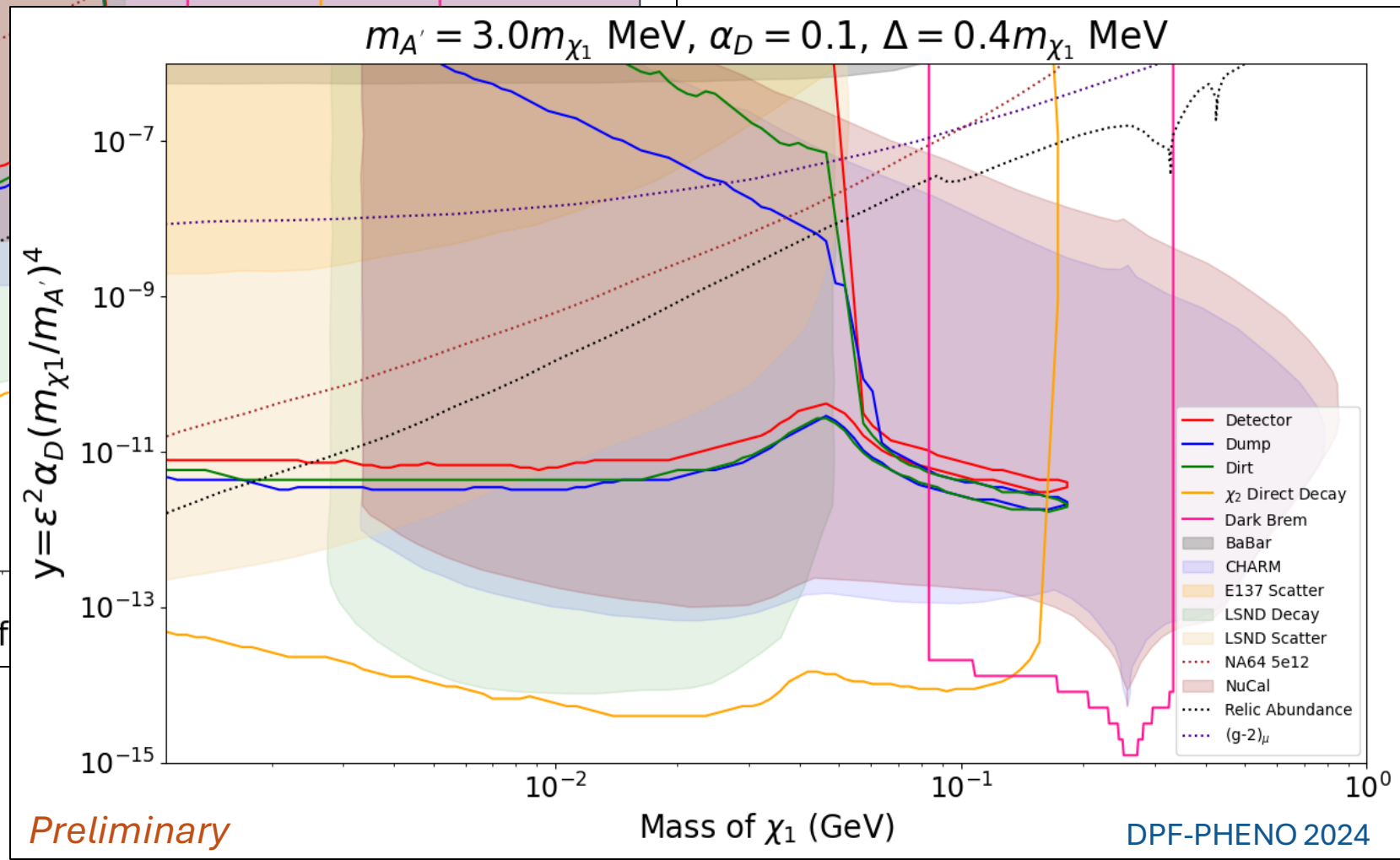

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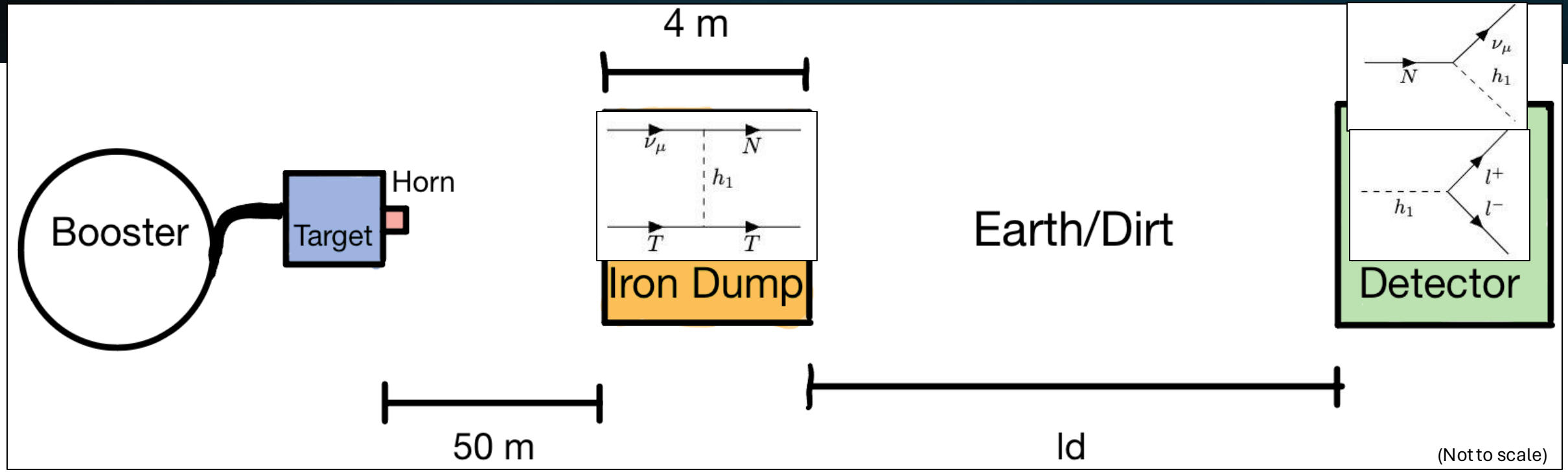
Preliminary

DPF-PHENO 2024

Model: Complex Scalar Extension of 2HDM

$$\mathcal{L} \supset d(\bar{\nu}_\mu N h_1) + y_{eh_1} \bar{f}_i f_j h_1 + h.c.$$



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