1 Generator in a Bottle

Walking along the Isla Vista beach, you find a mysterious bottle with a note and a floppy disk inside. The note reads:

Dear friend,
After many years of isolation and research, I have finally devised the perfect neutrino interaction generator. I was able to solve QCD and electroweak interactions exactly all the way from neutrino energies of 1 meV up to 100 TeV. The only limitations are the values of the fundamental coupling constants, which I have fixed to the best known values today.

My generator takes in a neutrino flux model and a detector geometry file and includes all Standard Model effects to simulate interactions with any target material, including reinteractions of secondary particles.

I have also included a new physics module that allows you to simulate interactions with any new physics model you can think of by simply typing in the Lagrangian of your model.

Use it wisely.

Yours truly,
Dr. X. Boson

With such tremendous power at your fingertips, your team becomes a leader in neutrino physics and obtains unlimited resources to carry out your research.

What experiment would you build and how would you use this mysterious generator to discover new physics?

Some questions to consider:

- What is the physics case for your experiment? What new physics model are you trying to probe?
- What kind of neutrino energy, beam, and detector would you use?
- How could you use your generator to bypass the remaining uncertainties?
- What are the main backgrounds to your signal and how would you mitigate them?
- Can you derive the sensitivity of your experiment to a specific new physics model?
- What couplings strengths and mass ranges can you probe?

Variable Interacting Neutrino beam for Discovery of Interactions, Exotic States, and Effective Lagrangians

Henry Truelson, River Govin, Jason Chapman

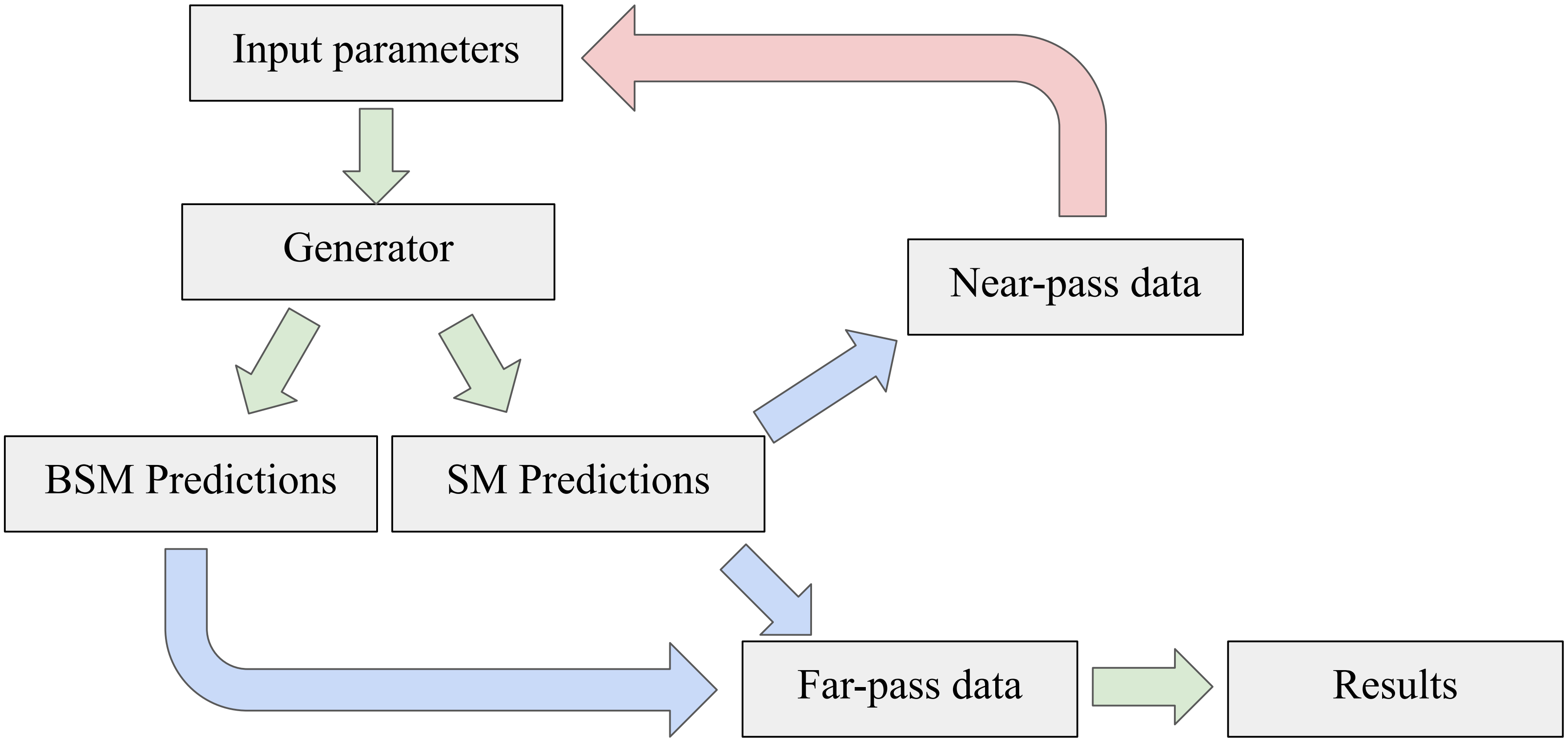
Variable **I**nteracting **N**eutrino beam for **D**iscovery of **I**nteractions, **E**xotic **S**tates, and **E**ffective **L**agrangians

(VIN DIESEL)

Henry Truelson, River Govin, Jason Chapman

Goals

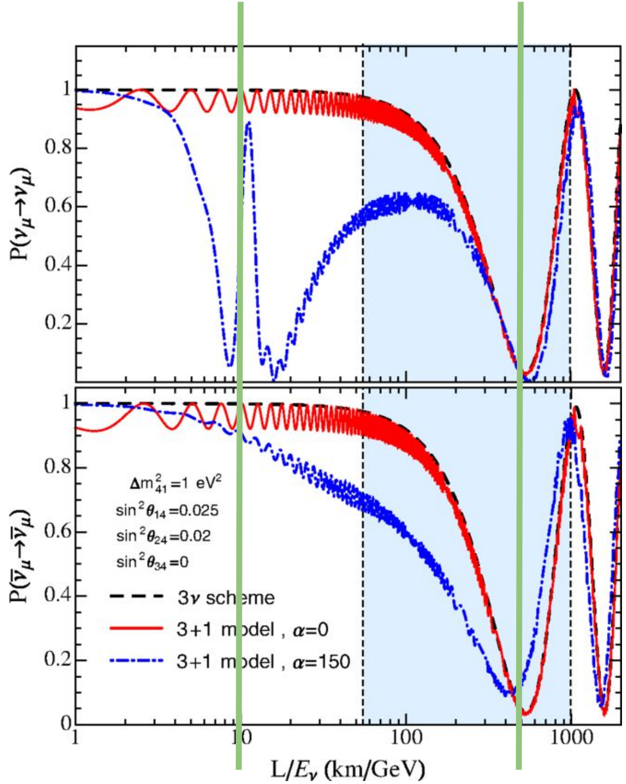
- Design an ideal neutrino experiment enabled by a **perfect neutrino interaction generator**
- Target a specific **beyond-the-Standard-Model physics** scenario
- Optimize the **beam, detector, and analysis** using exact interaction modeling
- Demonstrate **discovery reach** through projected sensitivity to new physics parameters



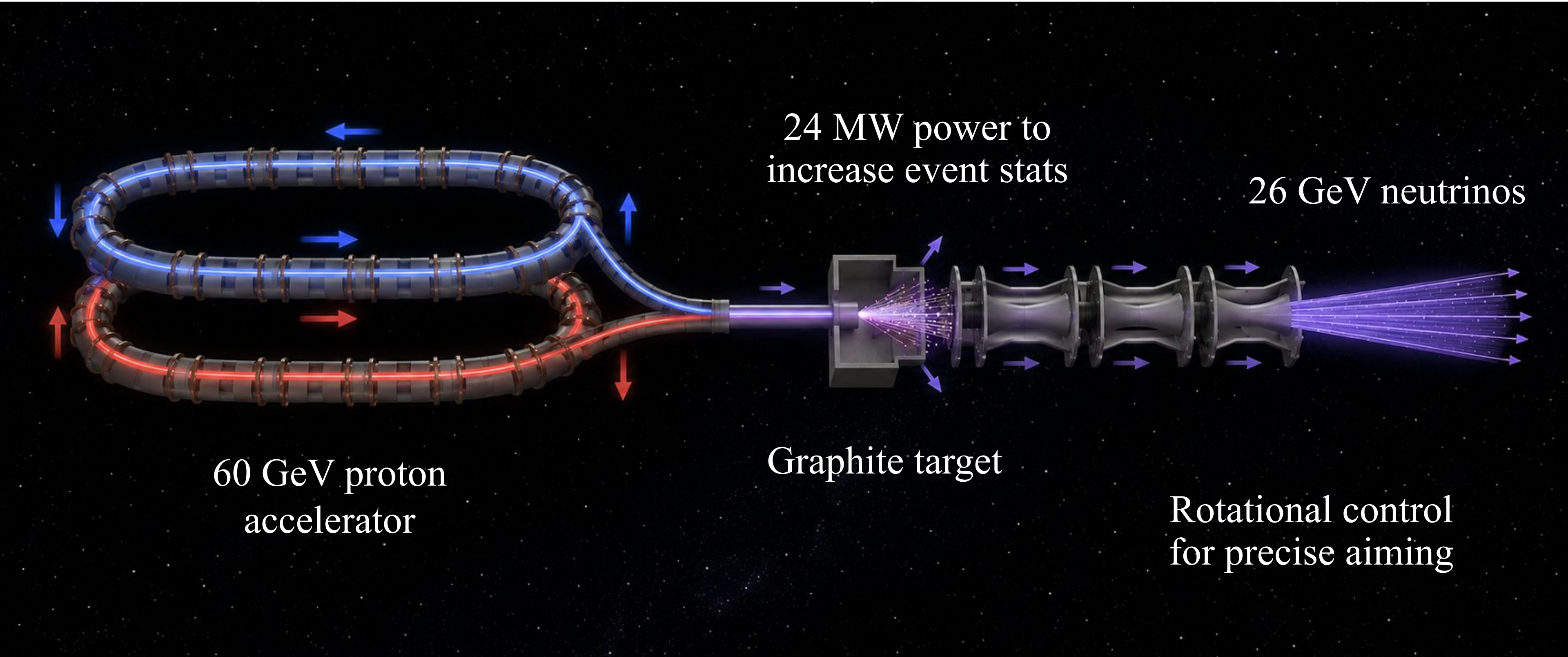
Input parameters
Generator
BSM Predictions
SM Predictions
Near-pass data
Far-pass data
Results

Experimental Concept

26 GeV beam
Near L/E =
Far L/E = 490 km/GeV



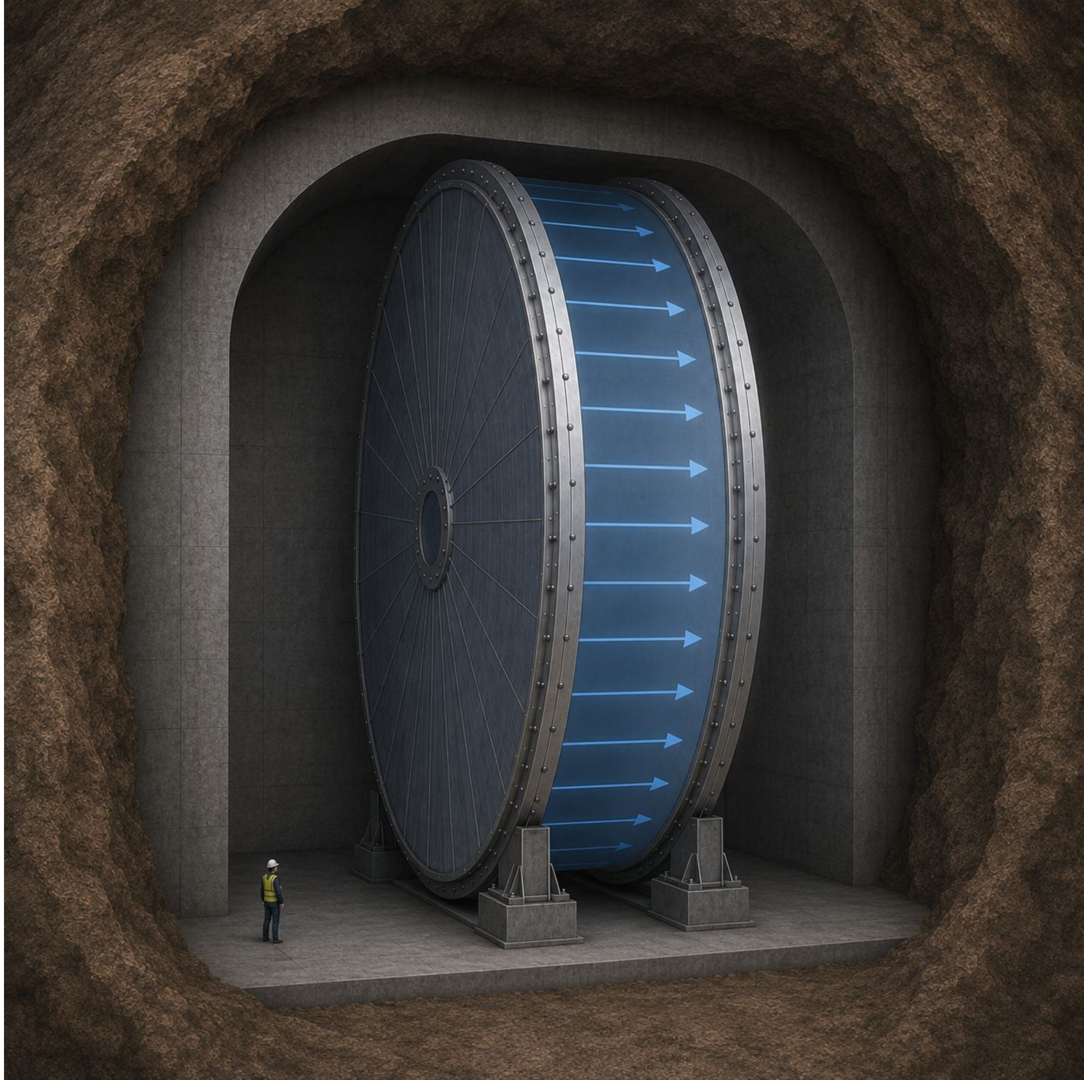
Accelerator



Neutrino In-orbit Source for Standard, Astro, and New physics with a Global Trajectory-adjustable Relativistic beam (**NISSAN GTR**)

Detector

- **F**lavor **A**ccessible **M**ass with **I**ncreased **L**epton **Y**ield (FAMILY)
- Large-volume LAr TPC
- Sanford Underground Research Facility (SURF)
- Wheel shape to accommodate variable beam direction



BSM 1: Axion-Like Particles

Neutrinophilic Axion-Like Dark Matter

Huang and Nath, arxiv:1809.01111

- Incredibly light particles ($\sim 10^{-20}$ - 10^{-25} eV) with incredibly high number density ($\sim 10^{30}$ / cm^3)
- All oscillate coherently as a single classical field:

$$a(t,x) = a_0 \cos\left(m_a t - \vec{p}\cdot\vec{x}\right),$$

- Consider exclusively ALP-Neutrino Interactions:

$$-\mathcal{L}_{\text{int}} = g_{\alpha\beta}\partial_\mu a\, \overline{\nu}_\alpha \gamma^\mu \gamma_5 \nu_\beta,$$

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Axion Pseudoscalar (Kinetic Term)

Neutrino Fields

$$4 \stackrel{?}{=} 1 + 1 \quad + \quad 3/2 + 3/2$$

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$g_{\alpha\beta}$ *has mass dimension -1!*

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Axion Pseudoscalar (Kinetic Term)

Neutrino Fields

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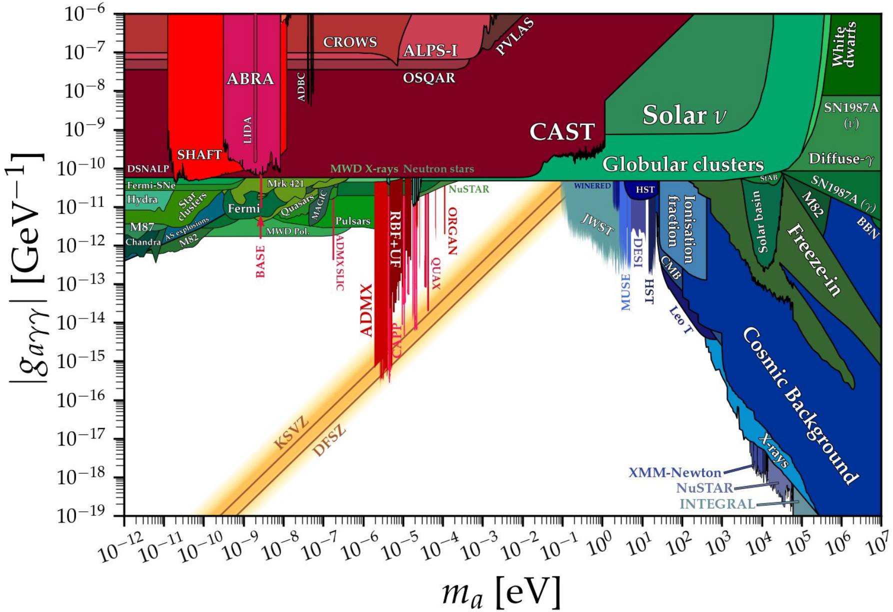
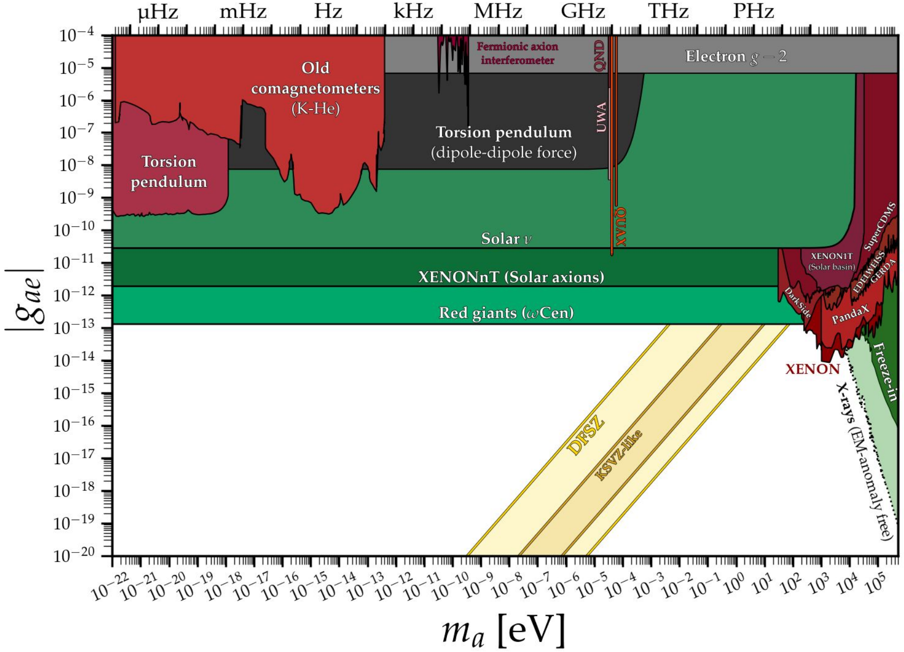
BSM 1: Axion-Like Particles

https://cajohare.github.io/AxionLimits/





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Huang and Nath, arxiv:1809.01111

$$H(t) = \frac{1}{2E_\nu} U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} U^\dagger + \begin{pmatrix} V + \xi_{ee}(t) & \xi_{e\mu}(t) & \xi_{e\tau}(t) \\ \xi^*_{e\mu}(t) & \xi_{\mu\mu}(t) & \xi_{\mu\tau}(t) \\ \xi^*_{e\tau}(t) & \xi^*_{\mu\tau}(t) & \xi_{\tau\tau}(t) \end{pmatrix}$$

$$\Big\downarrow \quad P(\nu_\mu \to \nu_e)$$

$$\boxed{g \lesssim \frac{\Delta m^2}{2\pi E_\nu} \frac{\sigma}{\sqrt{2\rho}} \max\left(2\pi, m_a t_{\text{flt}}\right)}$$

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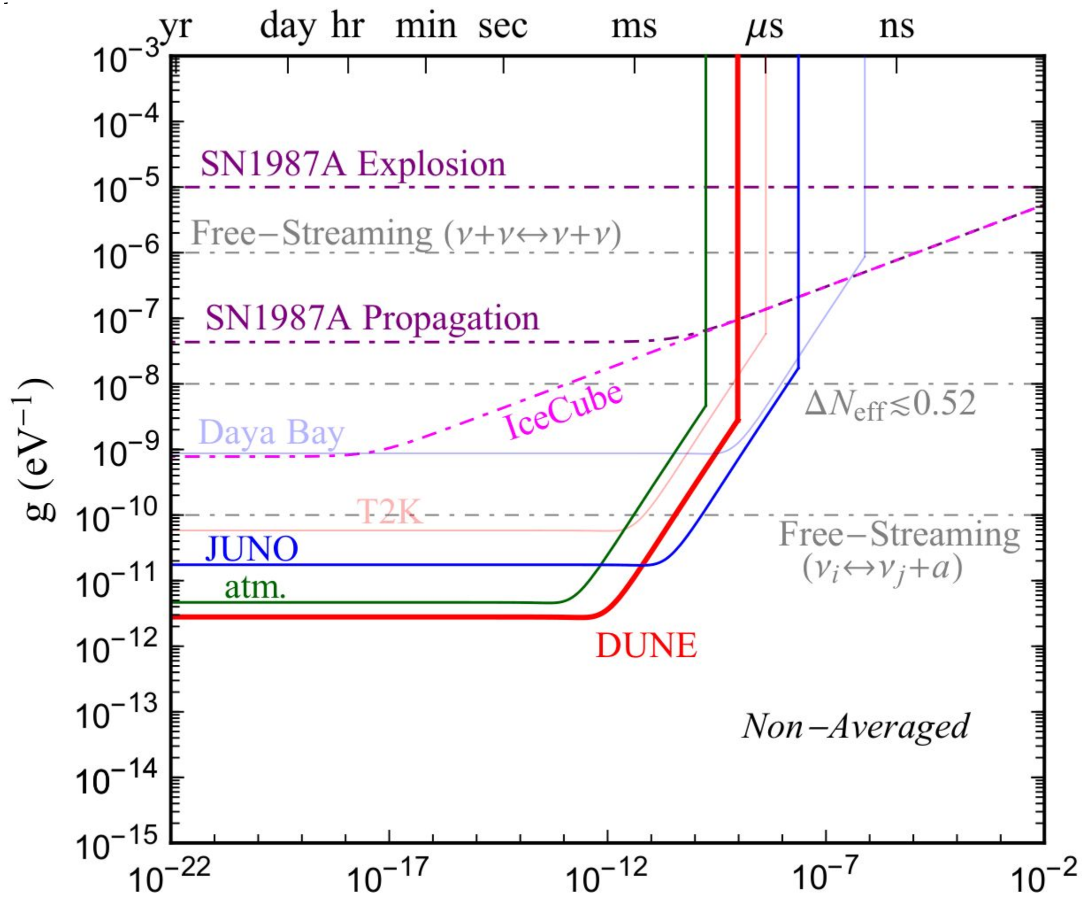

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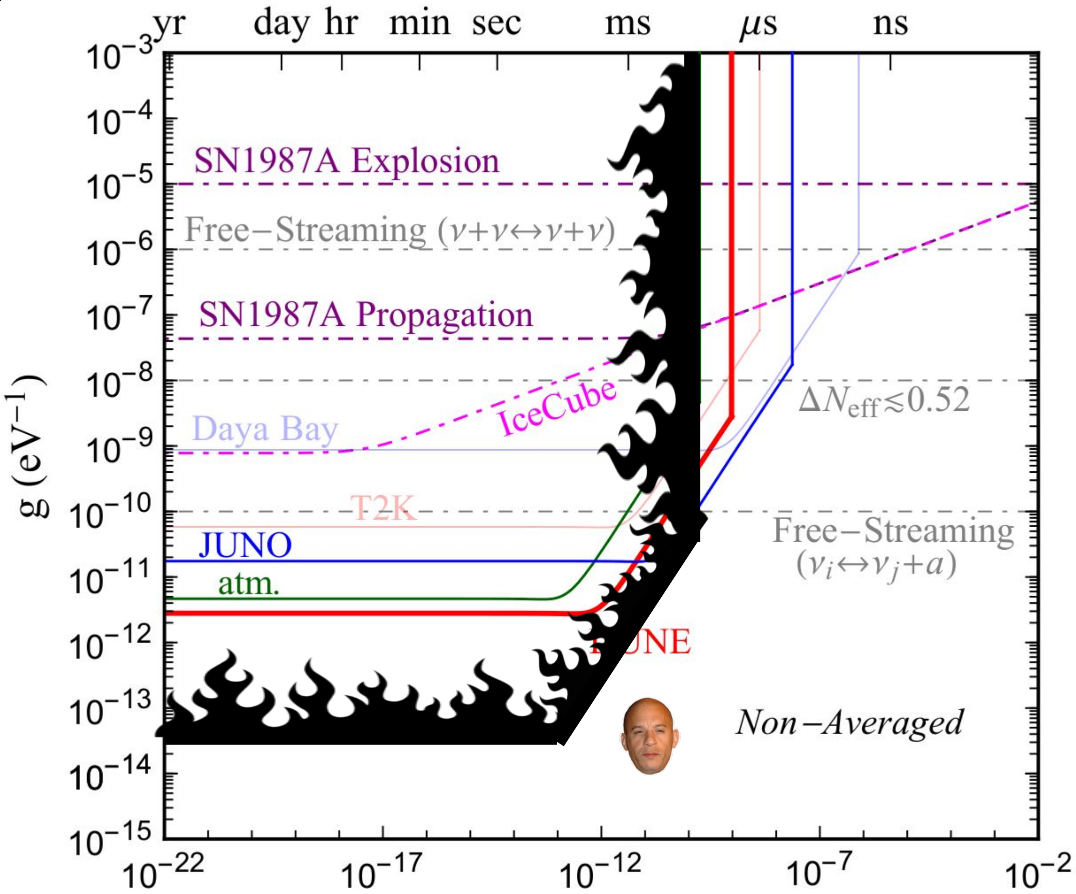


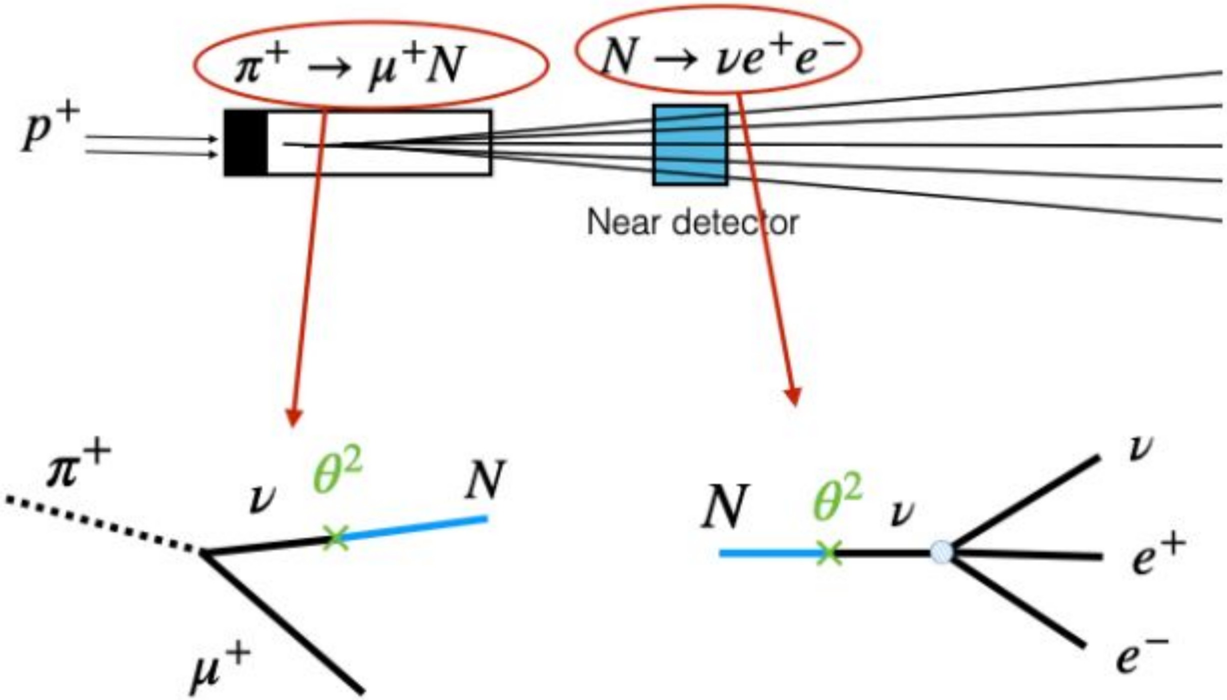
BSM 2: Heavy Neutral Lepton (HNL) Search

- Construct a Lagrangian that includes HNL

$$-\mathscr{L}_{\mathrm{HNL}} \supset \frac{g}{2c_W} U^*_{\alpha N} \overline{\nu_\alpha} \not{Z} P_L N + \frac{g}{\sqrt{2}} U^*_{\alpha N} \bar{\ell}_\alpha \not{W} P_L N + \text{ h.c.},$$

Long-Lived Particles from Meson and Muon Decays at Rest at Spallation Sources
Matheus Hostert and Salvador Urrea, arXiv:2509.14085

Search for HNL in the MeV to GeV range



Note: There are other decay channels, but we would search for this specific outcome.

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Diagram Credit: Matheus Hostert's online notes


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