Probing Long-Lived Particle Production in Muon Decays at the SNS with a Highly Capable Hydrocarbon Detector

Salvador Urrea

Based on arXiv:2509.14085 in collaboration with Matheus Hostert

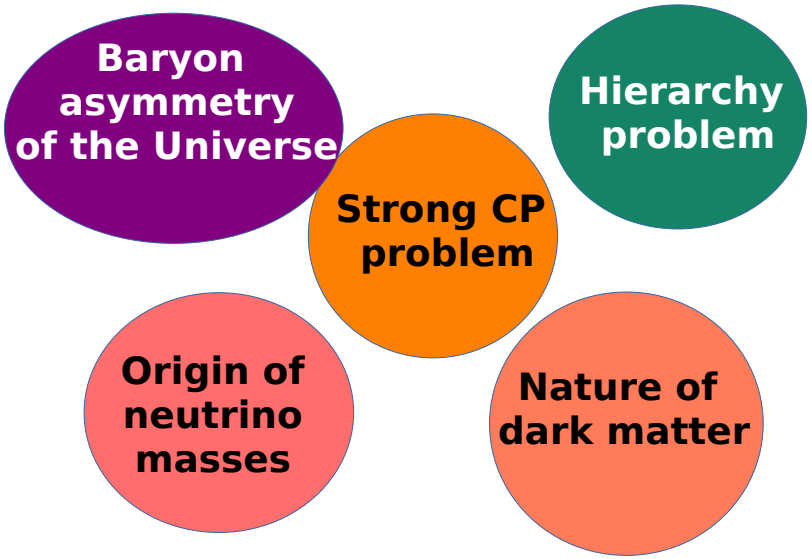
and arXiv:2606.19299 with the PROSPECT collaboration

DMLab October 21, 2026



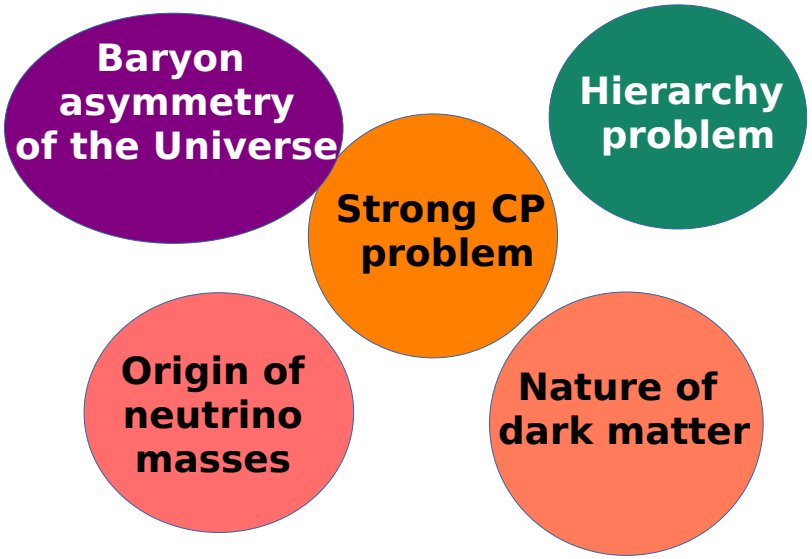


Open problems



Call for new physics

Open problems



Call for new physics

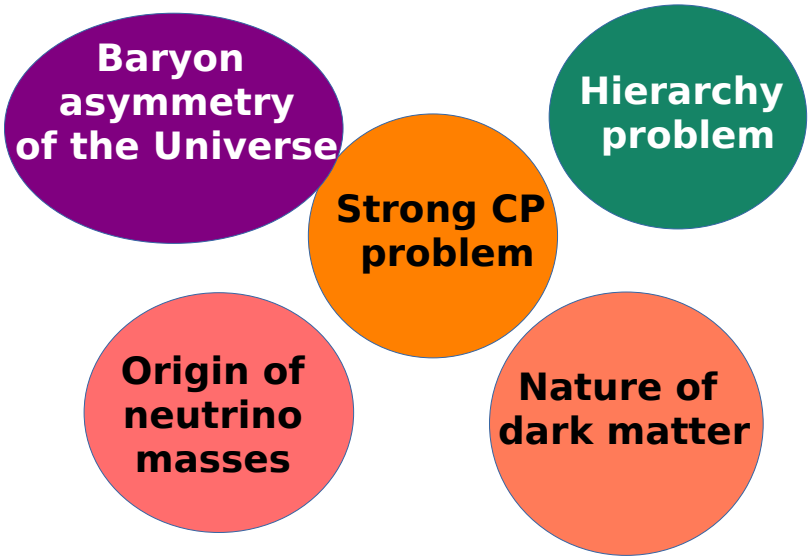
New Physics

Heavy

Light

Difficult to probe directly

Open problems



Call for new physics

New Physics

Heavy

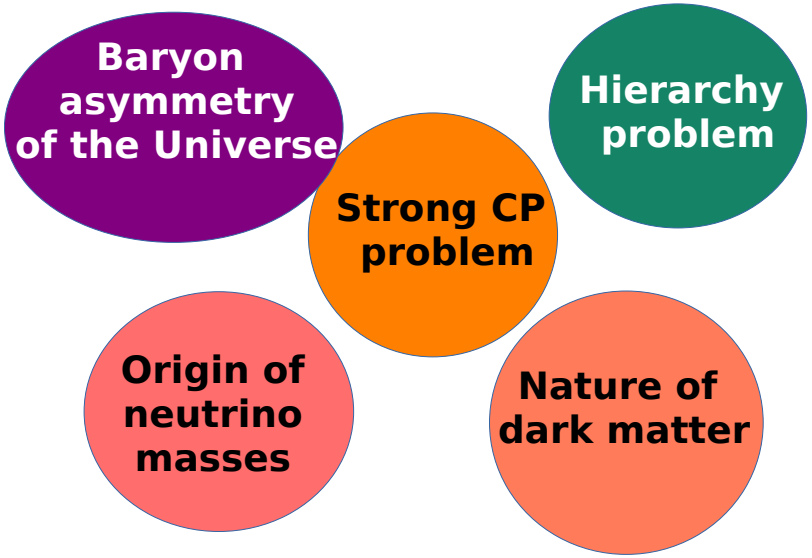
Difficult to probe directly

Light

In this talk

FIPs

Open problems



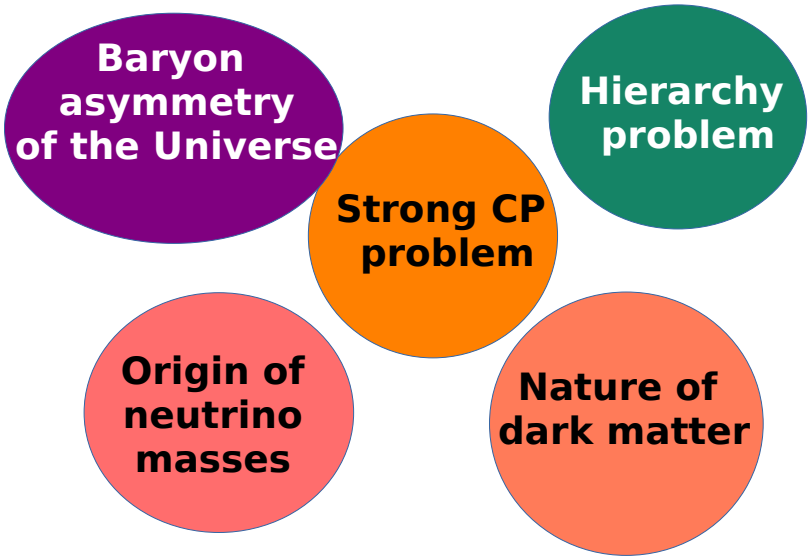
Call for new physics

- **Scalar : Dark Higgs, Muon scalar etc**
- **Pseudoscalar: Axions, ALPs**
- **Vector: Dark Photon, etc**
- **Fermions: Heavy neutral leptons (HNLs)**

Long lived particles

FIPs

Open problems

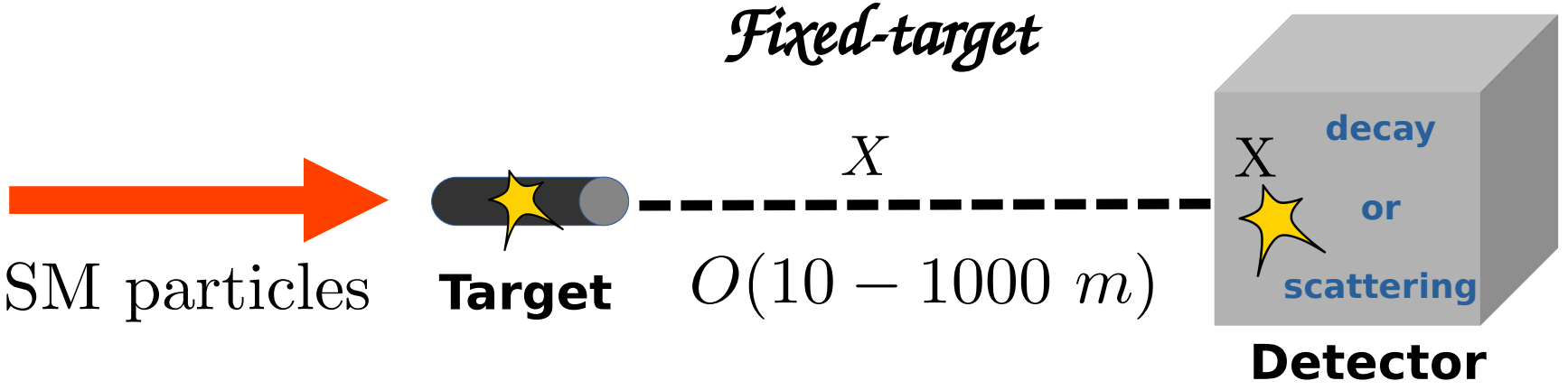


- **Scalar : Dark Higgs, Muon scalar etc**
- **Pseudoscalar: Axions, ALPs**
- **Vector: Dark Photon, etc**
- **Fermions: Heavy neutral leptons (HNLs)**

Long lived particles

Call for new physics

Fixed-target



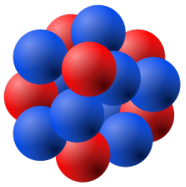
$m_{\rm NP} \sim (1\ \text{MeV-}2\ \text{GeV})$

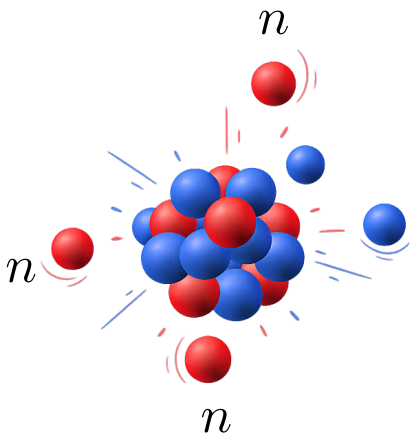
What is a spallation neutron source?

Intense beam

p

$O(1-3\mathrm{GeV})$





- **Nuclear Physics**
- **Material studies**

$pp \to pn\pi^+ \, (pp\pi^0)$

$pp \to pp\pi^+\pi^-$

$pp \to pp\eta$

$pp \to p\Lambda^0 K^+$

$pp \to p\Sigma^+ K^0$

$pp \to ppK^+K^-$

Meson production

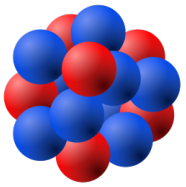
Lose energy and decay at rest	**Captured**
$\pi^+/K^+ \to \mu^+\nu_\mu$	π^-, K^-

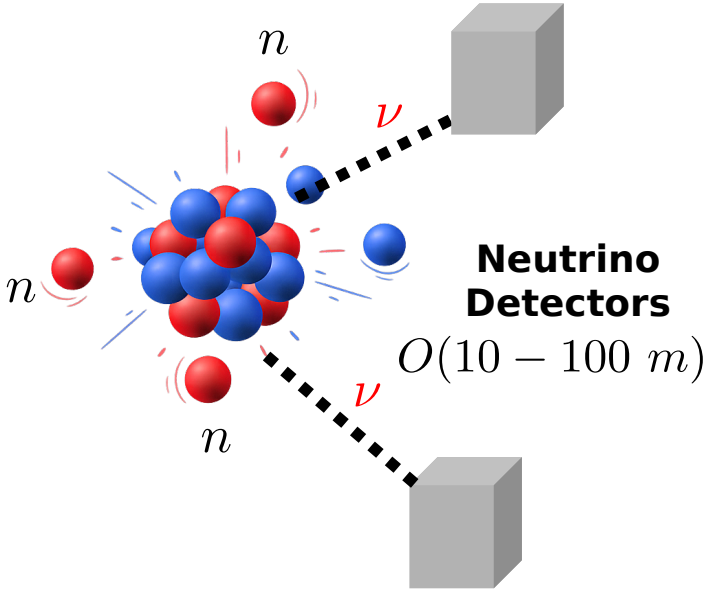
What is a spallation neutron source?

Intense beam

p

$O(1-3\text{GeV})$





- **Nuclear Physics**
- **Material studies**
- **Neutrino Physics**

$$pp \to pn\pi^+ \left(pp\pi^0\right)$$
$$pp \to pp\pi^+\pi^-$$
$$pp \to pp\eta$$
$$pp \to p\Lambda^0 K^+$$
$$pp \to p\Sigma^+ K^0$$
$$pp \to ppK^+K^-$$

Meson production

$$\pi^+/K^+ \to \mu^+\nu_\mu$$

$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

Sterile neutrinos **CEvNS**

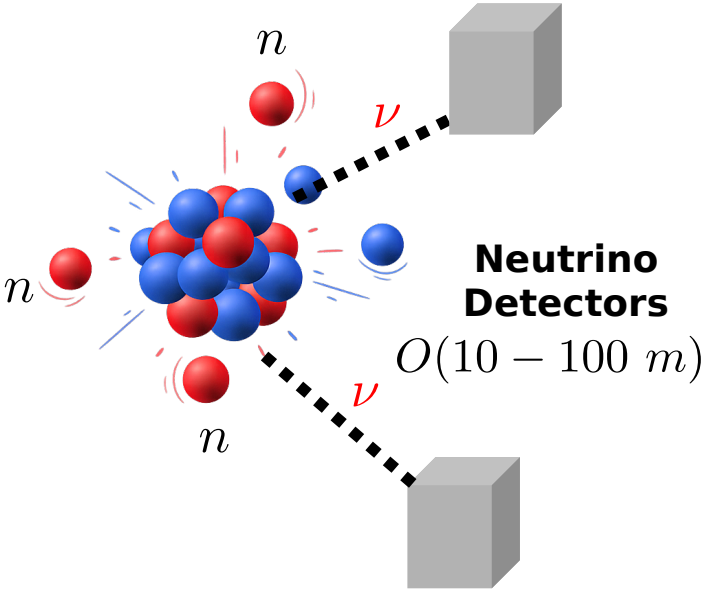
Lose energy and decay at rest	**Captured**
$\pi^+/K^+ \to \mu^+\nu_\mu$	π^-, K^-

What is a spallation neutron source?

Intense beam

p

$O(1-3\text{GeV})$



Neutrino Detectors

$O(10-100\ m)$

- **Nuclear Physics**
- **Material studies**
- **Neutrino Physics**

$$\pi^+/K^+ \to \mu^+\nu_\mu$$

$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

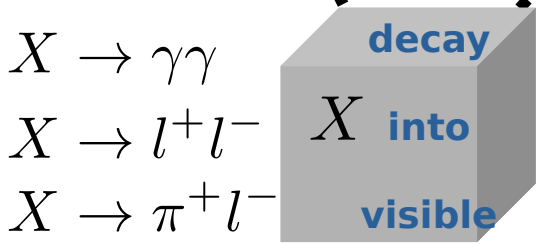
Sterile neutrinos **CEvNS**

$$pp \to pn\pi^+ \,(pp\pi^0)$$
$$pp \to pp\pi^+\pi^-$$
$$pp \to pp\eta$$
$$pp \to p\Lambda^0 K^+$$
$$pp \to p\Sigma^+ K^0$$
$$pp \to ppK^+K^-$$

Meson production

- **FIPs searches**

$\pi^+/K^+ \to X$ $\qquad$ $\mu^+ \to X$



$X \to \gamma\gamma$

$X \to l^+l^-$

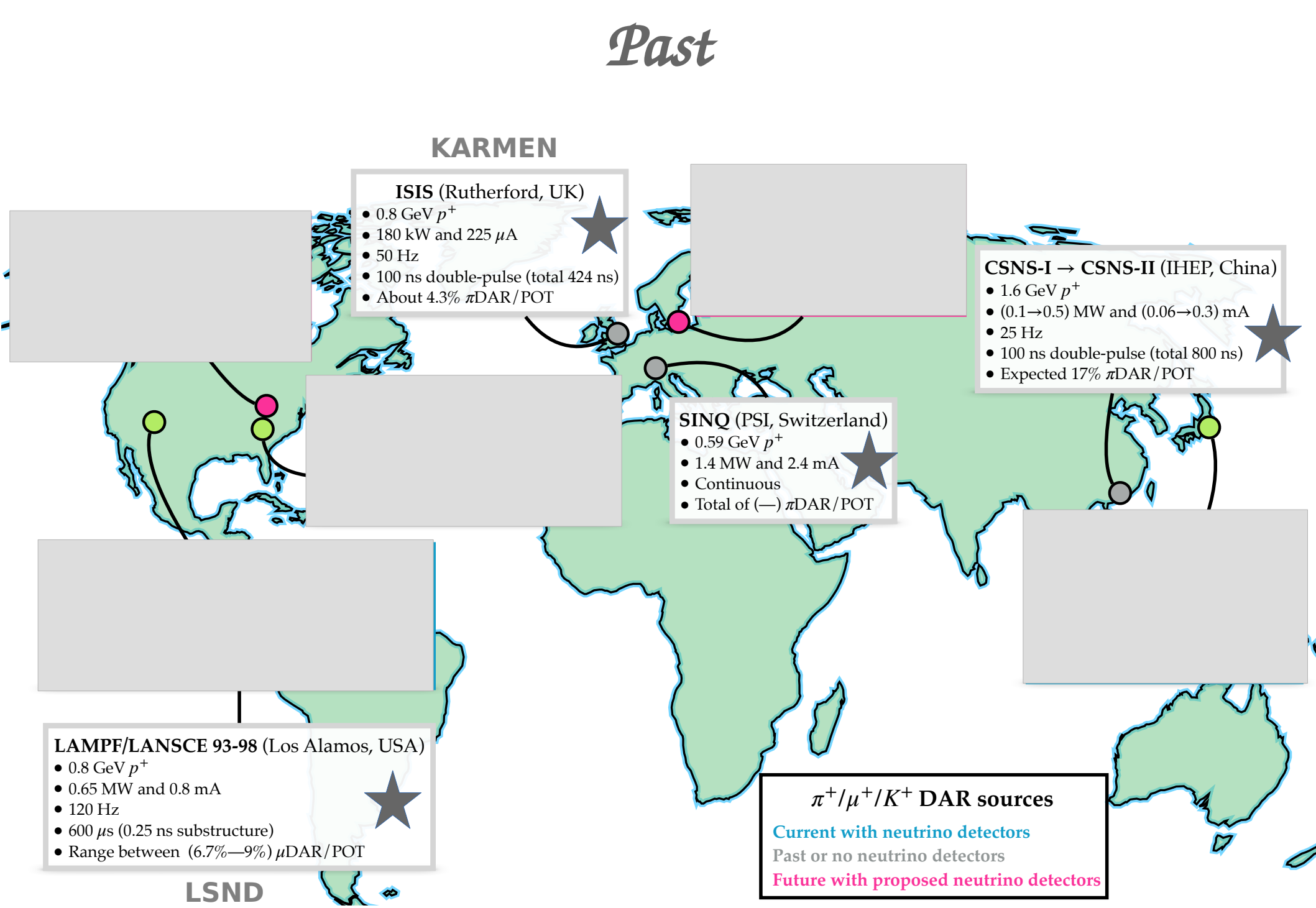
$X \to \pi^+l^-$

Neutrino Detectors

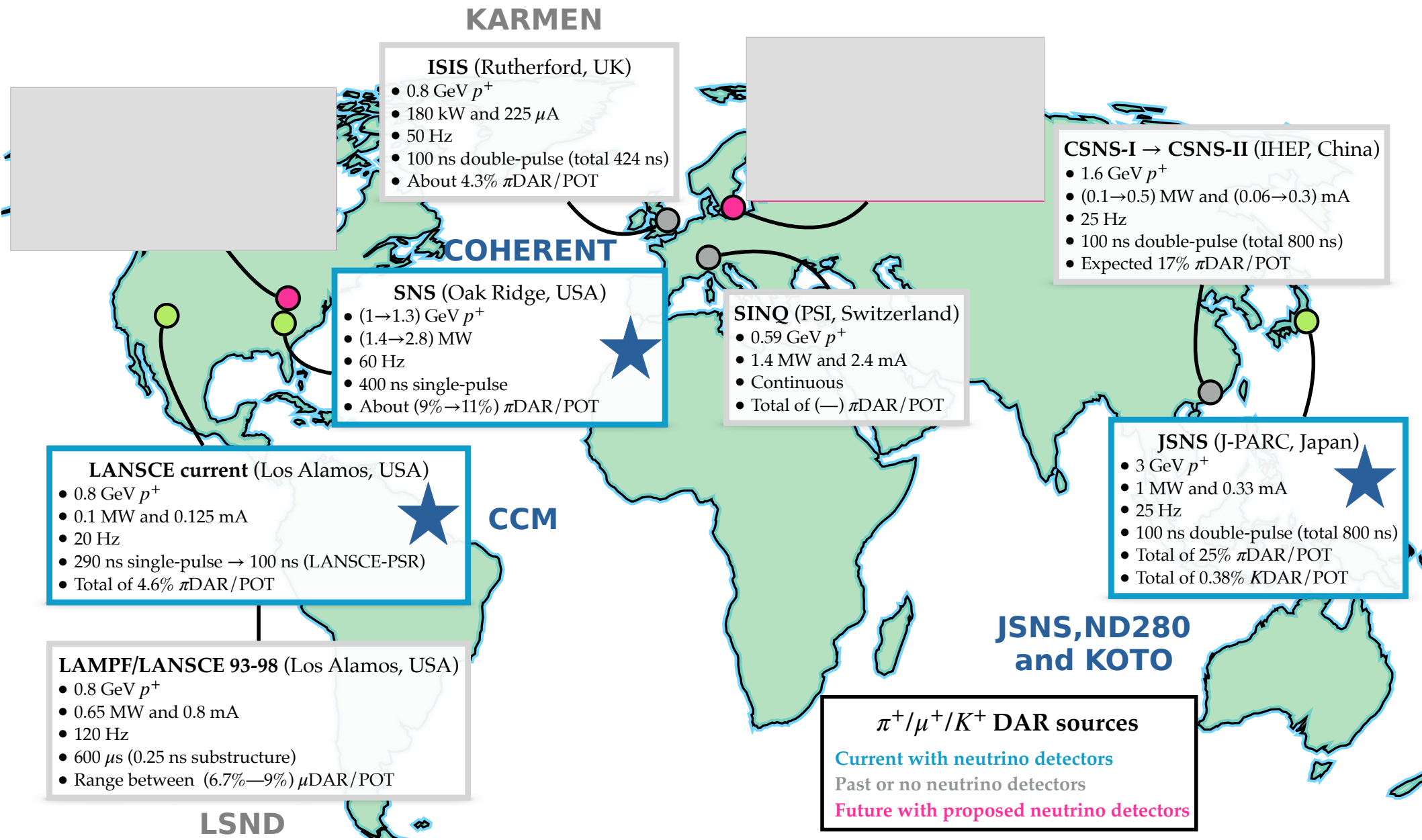
Lose energy and decay at rest	**Captured**
$\pi^+/K^+ \to \mu^+\nu_\mu$	π^-, K^-

Overview of facilities

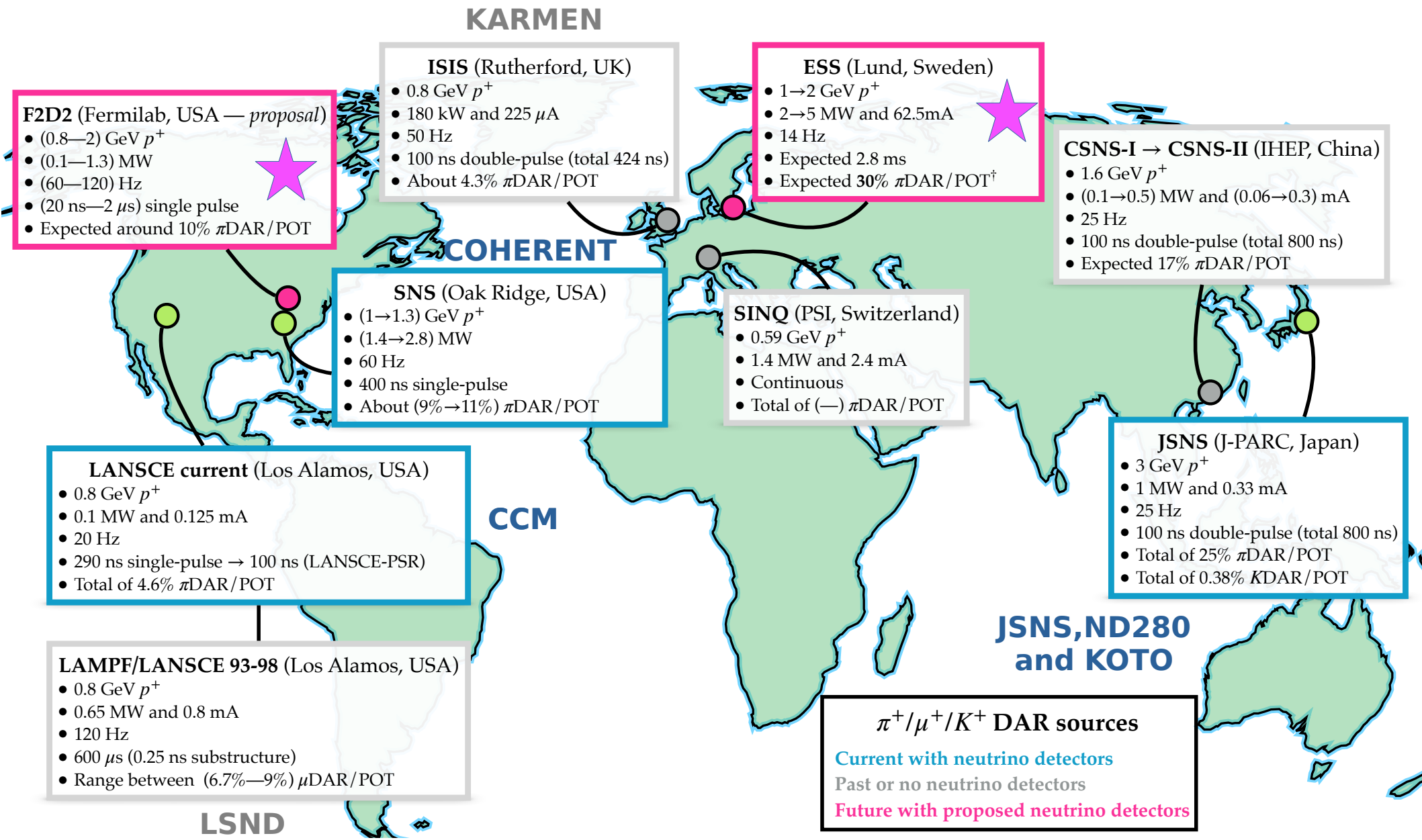
Past


KARMEN
ISIS (Rutherford, UK)
• 0.8 GeV p^+
• 180 kW and 225 μA
• 50 Hz
• 100 ns double-pulse (total 424 ns)
• About 4.3% πDAR/POT
CSNS-I → CSNS-II (IHEP, China)
• 1.6 GeV p^+
• (0.1→0.5) MW and (0.06→0.3) mA
• 25 Hz
• 100 ns double-pulse (total 800 ns)
• Expected 17% πDAR/POT
SINQ (PSI, Switzerland)
• 0.59 GeV p^+
• 1.4 MW and 2.4 mA
• Continuous
• Total of (—) πDAR/POT
LAMPF/LANSCE 93-98 (Los Alamos, USA)
• 0.8 GeV p^+
• 0.65 MW and 0.8 mA
• 120 Hz
• 600 μs (0.25 ns substructure)
• Range between (6.7%—9%) μDAR/POT
LSND
$\pi^+/\mu^+/K^+$ DAR sources
Current with neutrino detectors
Past or no neutrino detectors
Future with proposed neutrino detectors

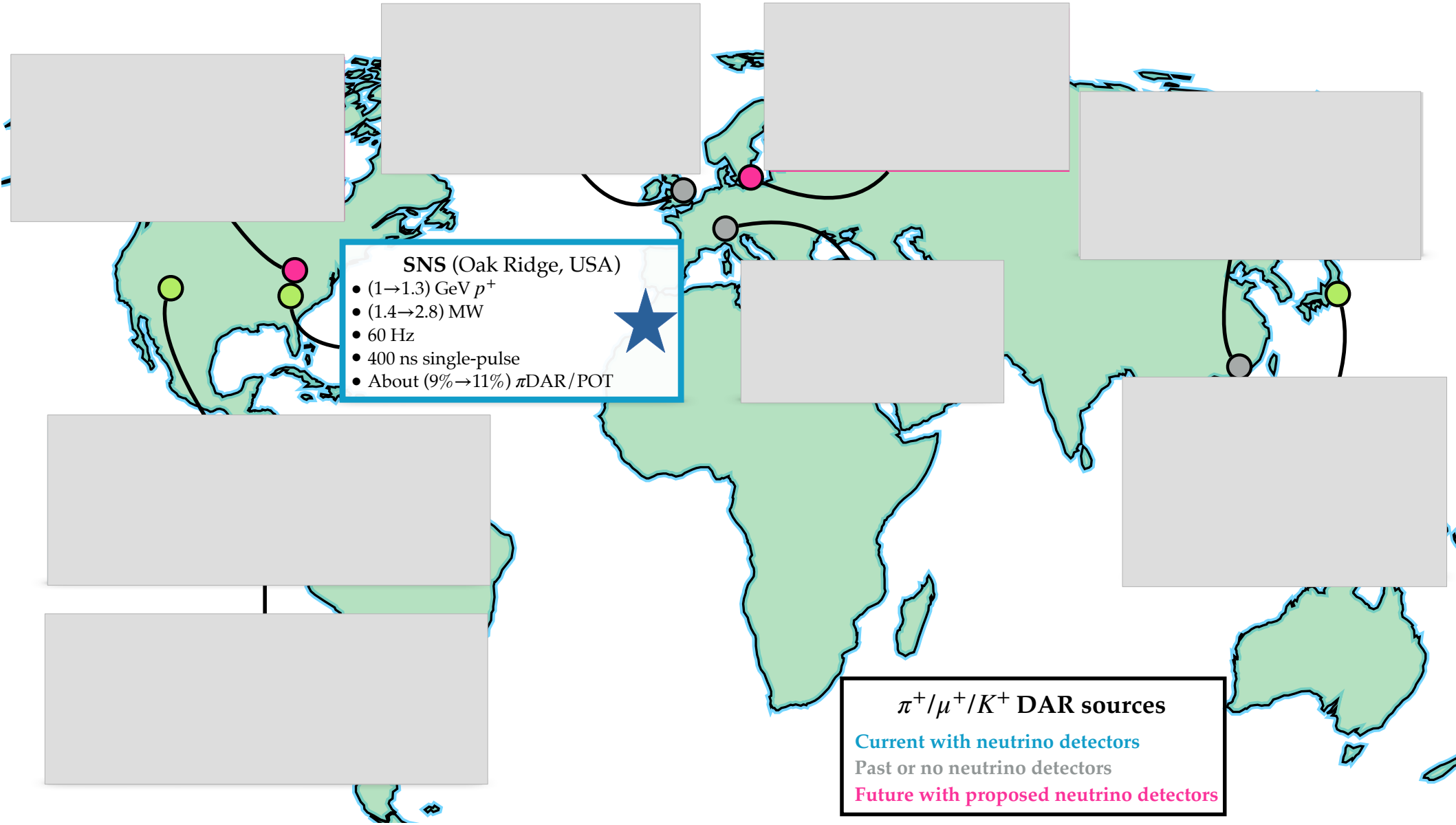
Current


KARMEN
ISIS (Rutherford, UK)
• 0.8 GeV p^+
• 180 kW and 225 μA
• 50 Hz
• 100 ns double-pulse (total 424 ns)
• About 4.3% πDAR/POT
COHERENT
SNS (Oak Ridge, USA)
• (1→1.3) GeV p^+
• (1.4→2.8) MW
• 60 Hz
• 400 ns single-pulse
• About (9%→11%) πDAR/POT
SINQ (PSI, Switzerland)
• 0.59 GeV p^+
• 1.4 MW and 2.4 mA
• Continuous
• Total of (—) πDAR/POT
CSNS-I → CSNS-II (IHEP, China)
• 1.6 GeV p^+
• (0.1→0.5) MW and (0.06→0.3) mA
• 25 Hz
• 100 ns double-pulse (total 800 ns)
• Expected 17% πDAR/POT
LANSCE current (Los Alamos, USA)
• 0.8 GeV p^+
• 0.1 MW and 0.125 mA
• 20 Hz
• 290 ns single-pulse → 100 ns (LANSCE-PSR)
• Total of 4.6% πDAR/POT
CCM
JSNS (J-PARC, Japan)
• 3 GeV p^+
• 1 MW and 0.33 mA
• 25 Hz
• 100 ns double-pulse (total 800 ns)
• Total of 25% πDAR/POT
• Total of 0.38% KDAR/POT
JSNS,ND280 and KOTO
LAMPF/LANSCE 93-98 (Los Alamos, USA)
• 0.8 GeV p^+
• 0.65 MW and 0.8 mA
• 120 Hz
• 600 μs (0.25 ns substructure)
• Range between (6.7%—9%) μDAR/POT
LSND
$\pi^+/\mu^+/K^+$ DAR sources
Current with neutrino detectors
Past or no neutrino detectors
Future with proposed neutrino detectors

Future


KARMEN
ISIS (Rutherford, UK)
• 0.8 GeV p^+
• 180 kW and 225 μA
• 50 Hz
• 100 ns double-pulse (total 424 ns)
• About 4.3% πDAR/POT
ESS (Lund, Sweden)
• 1→2 GeV p^+
• 2→5 MW and 62.5mA
• 14 Hz
• Expected 2.8 ms
• Expected 30% πDAR/POT†
F2D2 (Fermilab, USA — proposal)
• (0.8—2) GeV p^+
• (0.1—1.3) MW
• (60—120) Hz
• (20 ns—2 μs) single pulse
• Expected around 10% πDAR/POT
CSNS-I → CSNS-II (IHEP, China)
• 1.6 GeV p^+
• (0.1→0.5) MW and (0.06→0.3) mA
• 25 Hz
• 100 ns double-pulse (total 800 ns)
• Expected 17% πDAR/POT
COHERENT
SNS (Oak Ridge, USA)
• (1→1.3) GeV p^+
• (1.4→2.8) MW
• 60 Hz
• 400 ns single-pulse
• About (9%→11%) πDAR/POT
SINQ (PSI, Switzerland)
• 0.59 GeV p^+
• 1.4 MW and 2.4 mA
• Continuous
• Total of (—) πDAR/POT
JSNS (J-PARC, Japan)
• 3 GeV p^+
• 1 MW and 0.33 mA
• 25 Hz
• 100 ns double-pulse (total 800 ns)
• Total of 25% πDAR/POT
• Total of 0.38% KDAR/POT
LANSCE current (Los Alamos, USA)
• 0.8 GeV p^+
• 0.1 MW and 0.125 mA
• 20 Hz
• 290 ns single-pulse → 100 ns (LANSCE-PSR)
• Total of 4.6% πDAR/POT
CCM
JSNS,ND280 and KOTO
LAMPF/LANSCE 93-98 (Los Alamos, USA)
• 0.8 GeV p^+
• 0.65 MW and 0.8 mA
• 120 Hz
• 600 μs (0.25 ns substructure)
• Range between (6.7%—9%) μDAR/POT
LSND
$\pi^+/\mu^+/K^+$ DAR sources
Current with neutrino detectors
Past or no neutrino detectors
Future with proposed neutrino detectors

Used in this work

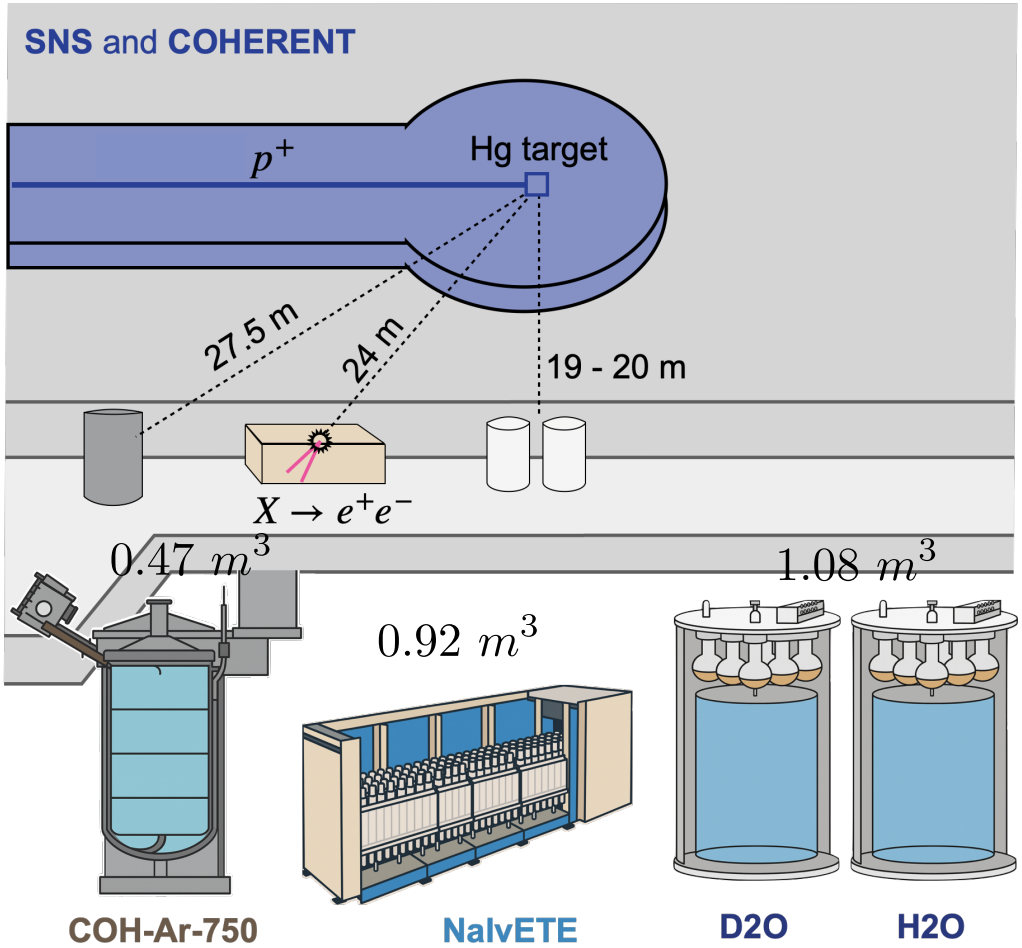


SNS

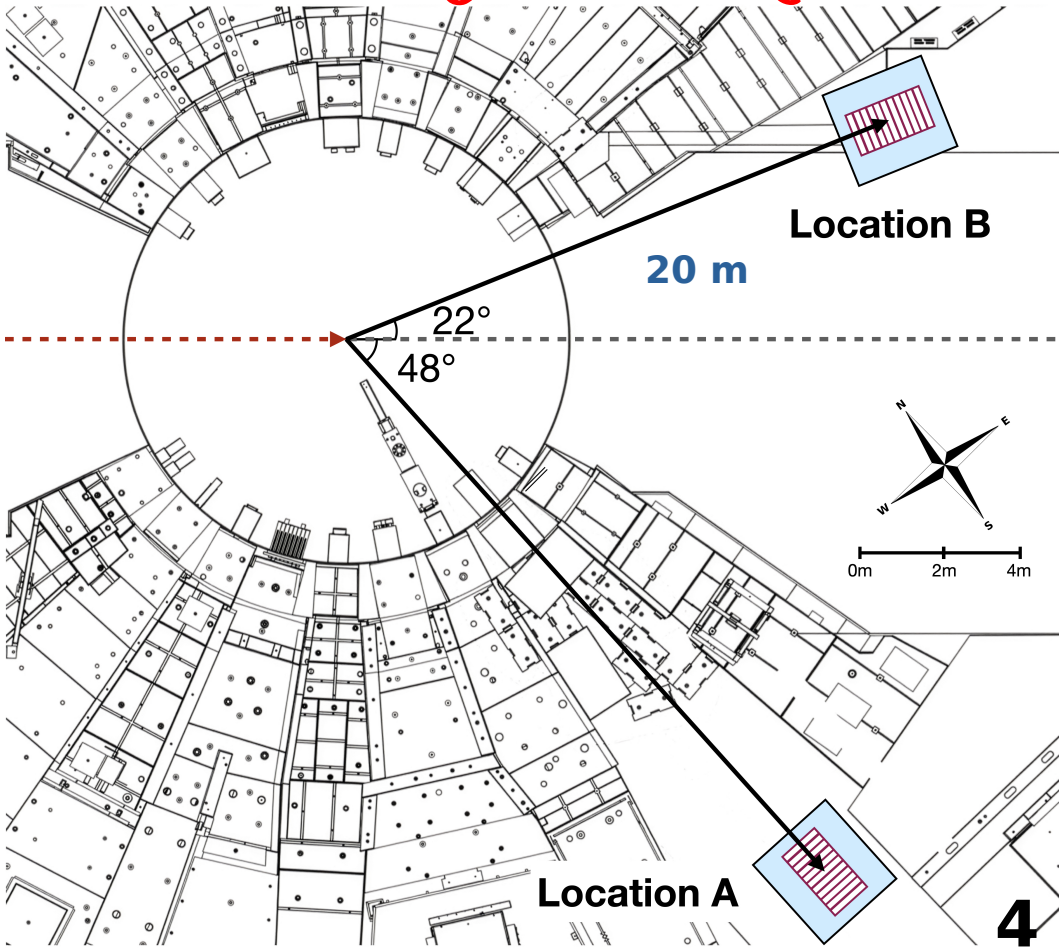
$$\pi^+ \to X \qquad \mu^+ \to X \qquad X \to e^+e^-, \gamma\gamma$$

1 GeV protons

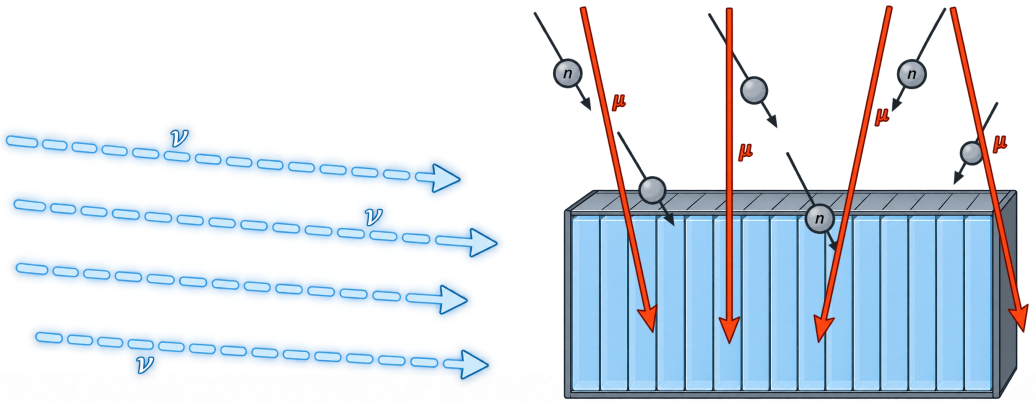
$4.5 \cdot 10^{23}$ PoT (3 years)



PROSPECT-like detector



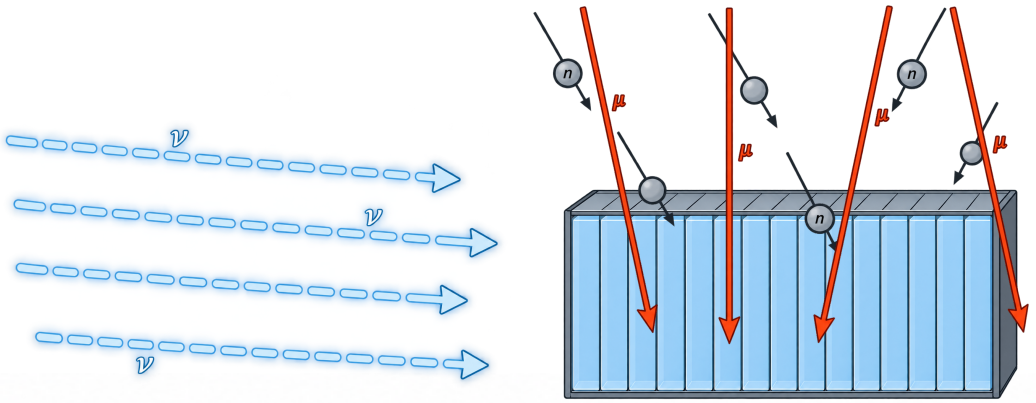
Detector PROSPECT-LIKE



3.7 t

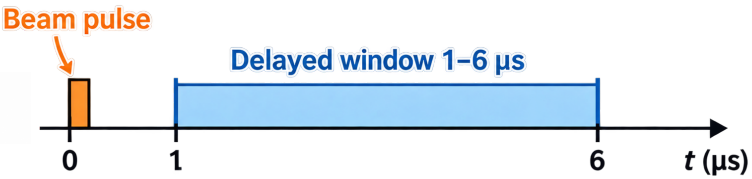
Segmented liquid scintillator

Detector PROSPECT-LIKE



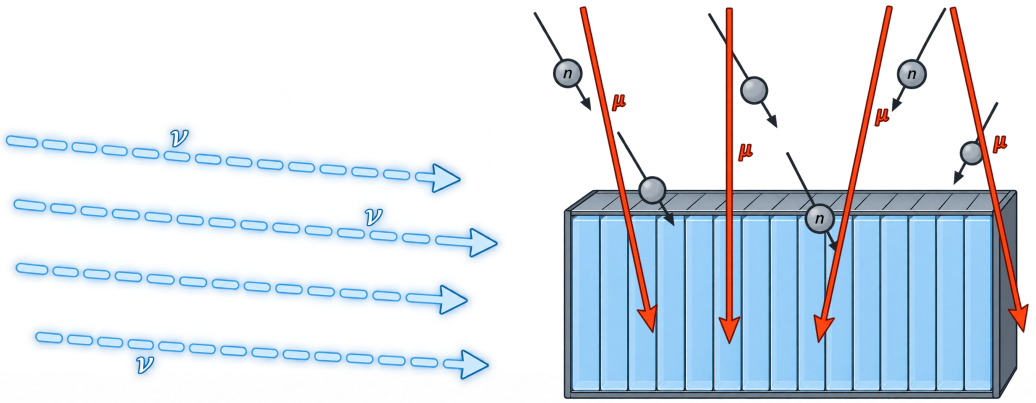
3.7 t

Reduce neutrino background

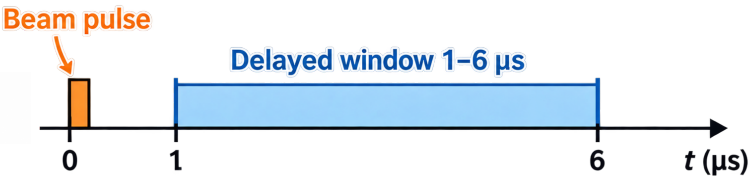


Segmented liquid scintillator

Detector PROSPECT-LIKE

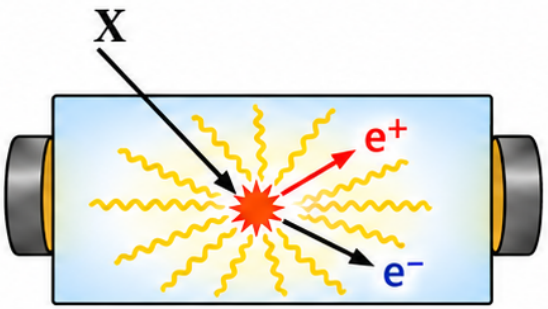


Reduce neutrino background



Segmented liquid scintillator

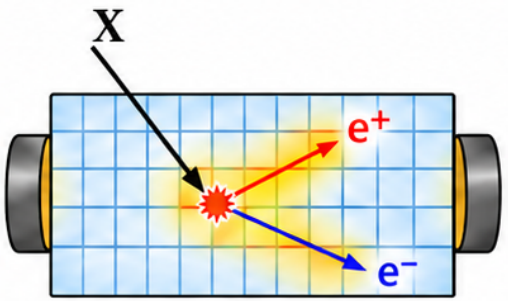
1. No segmentation



Only total light

topology

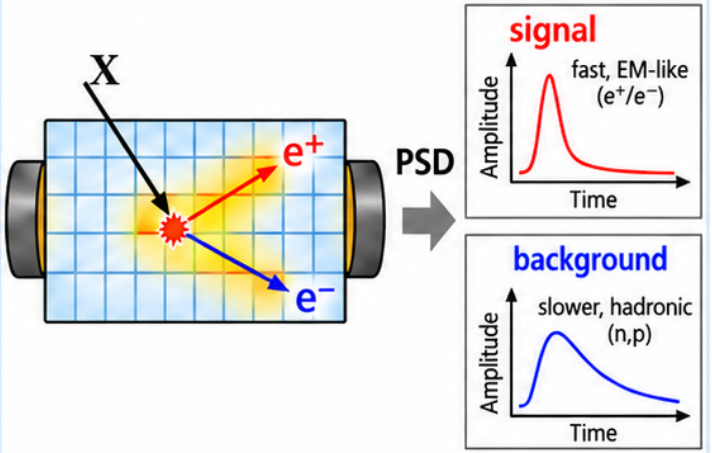
2. With segmentation



Topology is visible

+ PSD

3. Add pulse-shape discrimination



Distinguish signal from background

Maybe muon veto?

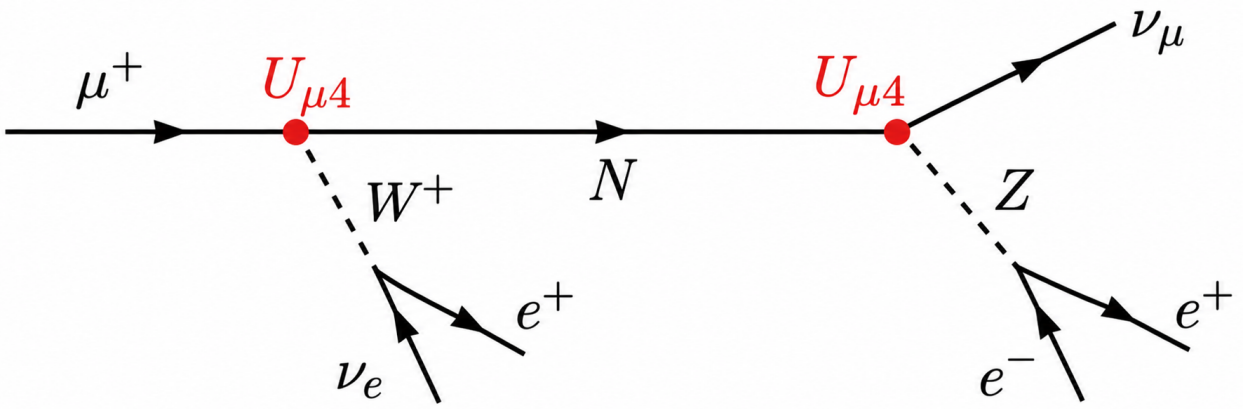
HNLs

HNL

$$\mathcal{L} \supset -\frac{g}{\sqrt{2}} \left(W_\mu^- \bar{l}_{L\alpha} \gamma_\mu U_{\alpha 4} N + \text{h.c.} \right) - \frac{g}{\cos\theta_W} \left(Z_\mu \bar{N} \gamma^\mu U_{\alpha 4}^* \nu_{L\alpha} + \text{h.c.} \right)$$

We consider simplified phenomenological benchmarks with one HNL mixing with one SM neutrino flavour.

U_{e4}	$U_{\mu 4}$
$K^+ \to e^+ N$ $\quad \pi^+ \to e^+ N$	$K^+ \to \mu^+ N$ $\quad \pi^+ \to \mu^+ N$
$\mu \to e \nu_e N$	$\mu \to e \nu_\mu N$



HNL

$$\mathcal{L} \supset -\frac{g}{\sqrt{2}} \left(W_\mu^- \bar{l}_{L\alpha} \gamma_\mu U_{\alpha 4} N + \text{h.c.} \right) - \frac{g}{\cos\theta_W} \left(Z_\mu \bar{N} \gamma^\mu U_{\alpha 4}^* \nu_{L\alpha} + \text{h.c.} \right)$$

We consider simplified phenomenological benchmarks with one HNL mixing with one SM neutrino flavour.

U_{e4}

Not enough production

~~$K^+ \to e^+ N$~~

$\pi^+ \to e^+ N$

$\mu \to e \nu_e N$

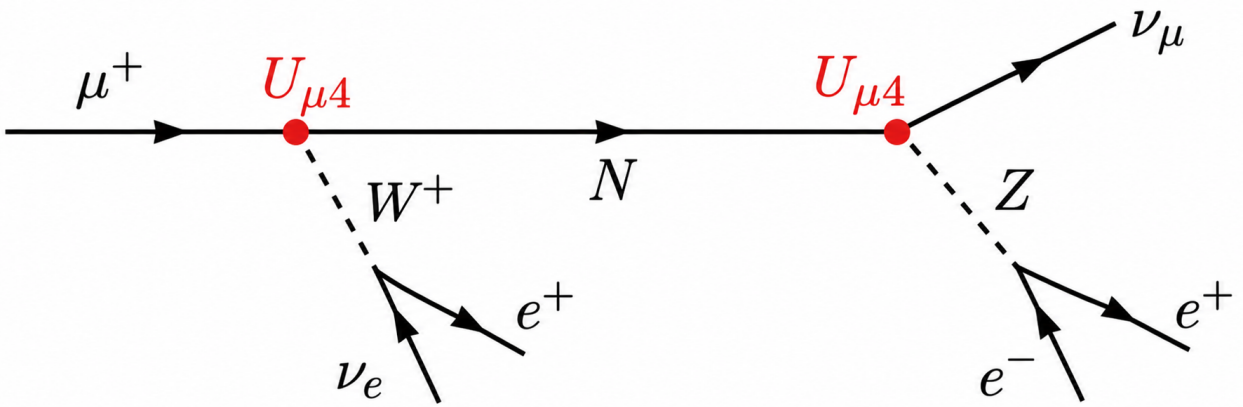
$U_{\mu 4}$

Not enough production

~~$K^+ \to \mu^+ N$~~

$\pi^+ \to \mu^+ N$

$\mu \to e \nu_\mu N$



HNL

$$\mathcal{L} \supset -\frac{g}{\sqrt{2}} \left(W_\mu^- \bar{l}_{L\alpha} \gamma_\mu U_{\alpha 4} N + \text{h.c.} \right) - \frac{g}{\cos\theta_W} \left(Z_\mu \bar{N} \gamma^\mu U_{\alpha 4}^* \nu_{L\alpha} + \text{h.c.} \right)$$

We consider simplified phenomenological benchmarks with one HNL mixing with one SM neutrino flavour.

U_{e4}

Not enough production $K^+ \to e^+ N$

More neutrino bkg $\pi^+ \to e^+ N$

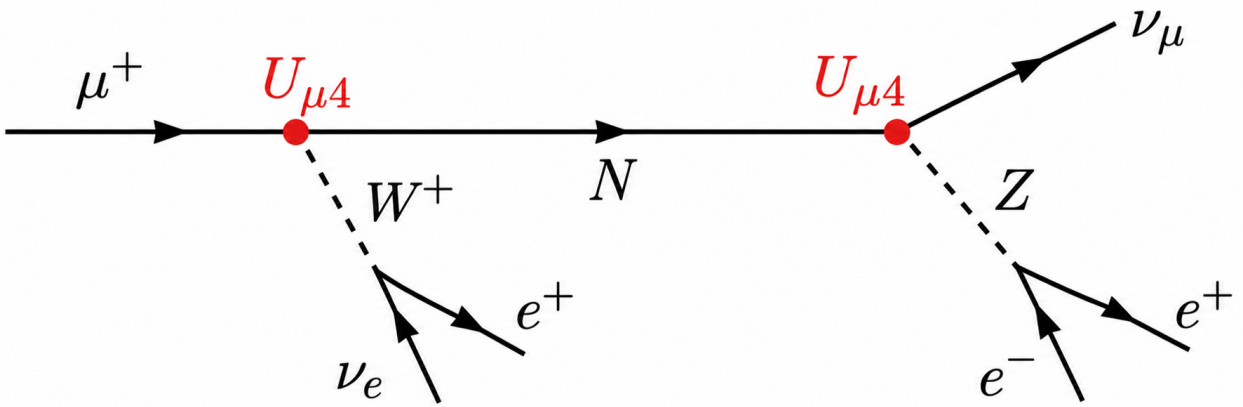
$\mu \to e \nu_e N$

$U_{\mu 4}$

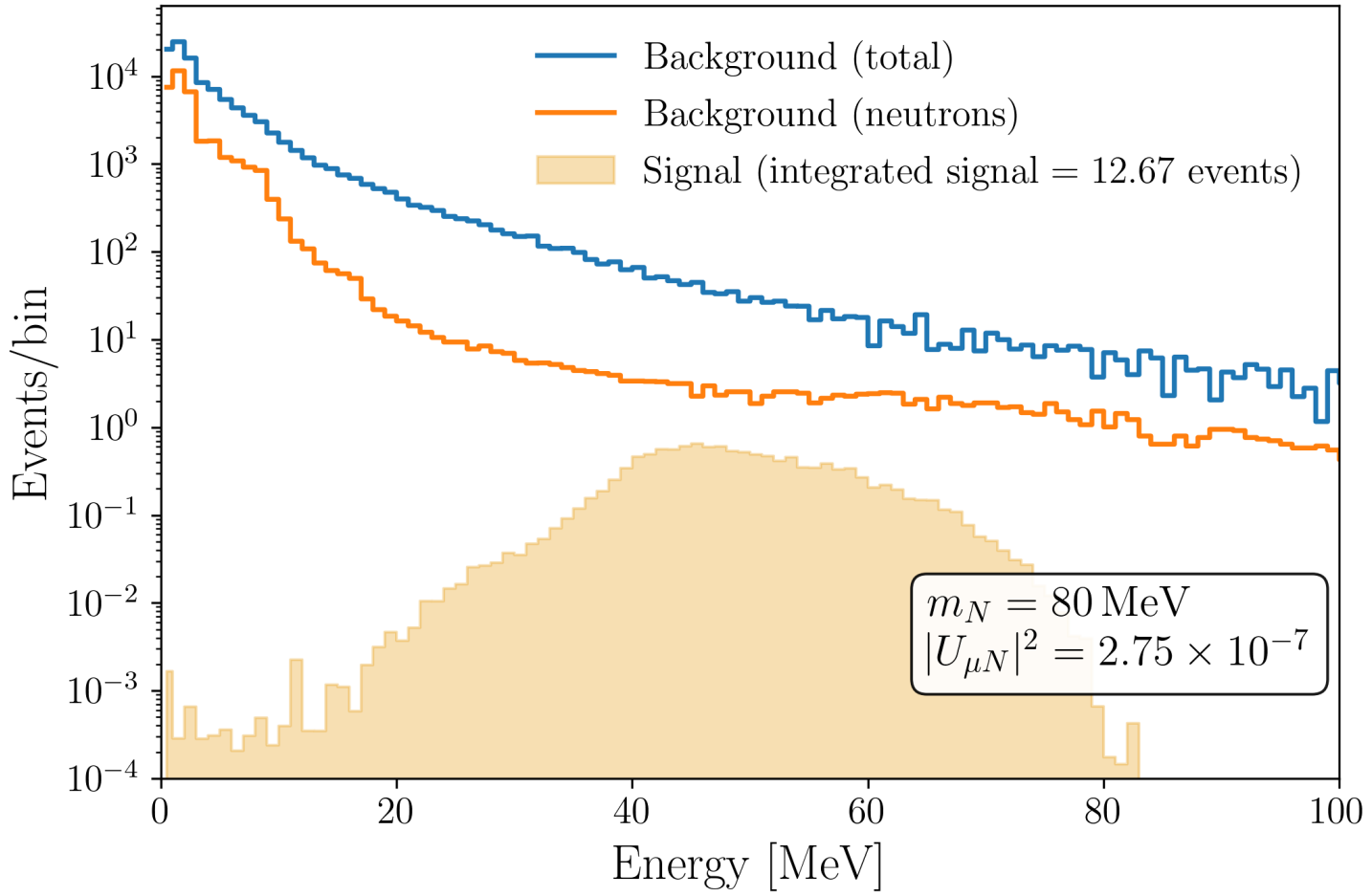
Not enough production $K^+ \to \mu^+ N$

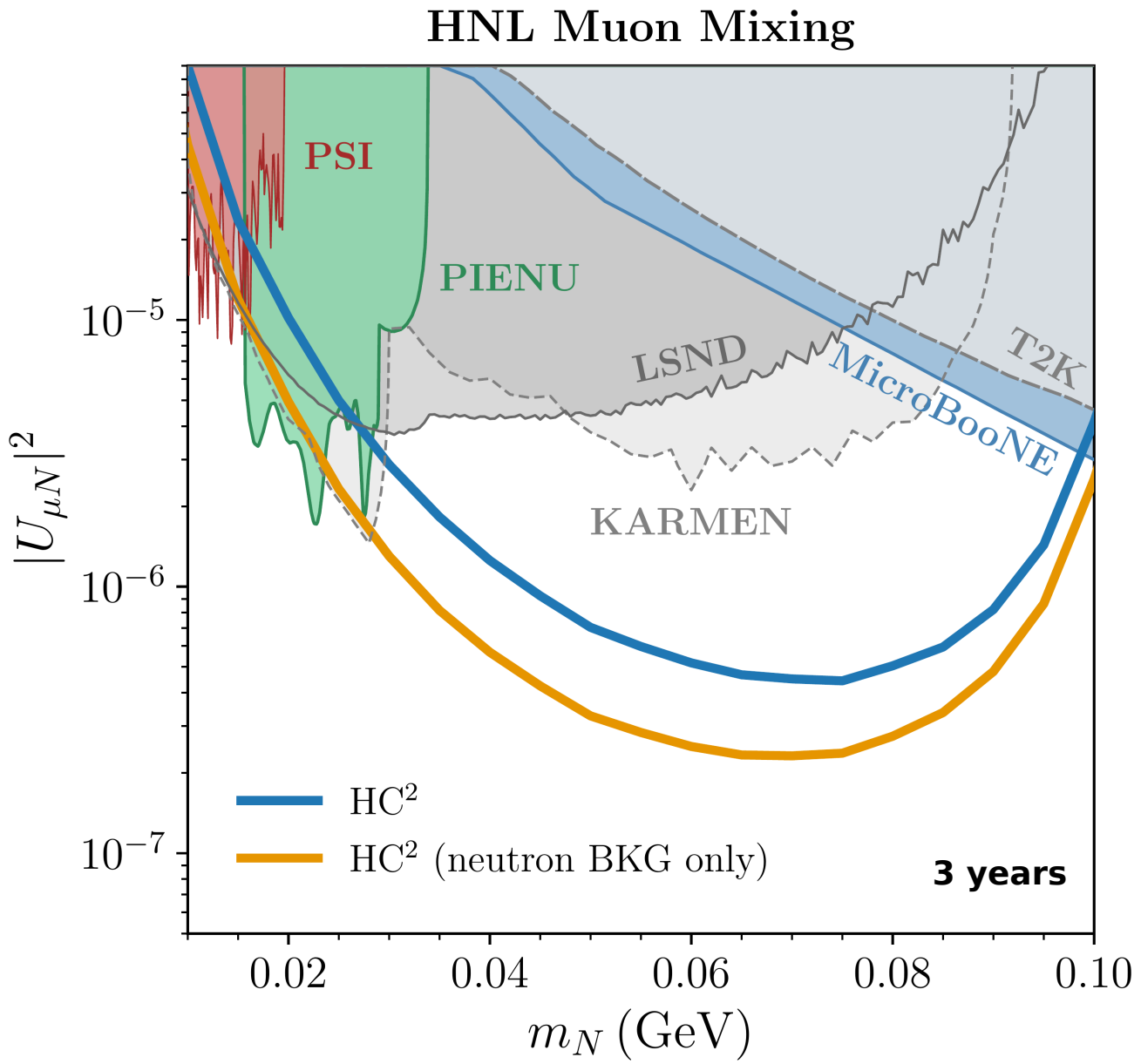
More neutrino bkg $\pi^+ \to \mu^+ N$

$\mu \to e \nu_\mu N$



Cosmogenic background




HNL Muon Mixing
PSI
PIENU
LSND
MicroBooNE
T2K
KARMEN
HC²
HC² (neutron BKG only)
3 years
$|U_{\mu N}|^2$
10^{-5}
10^{-6}
10^{-7}
0.02
0.04
0.06
0.08
0.10
m_N (GeV)

Leptophilic LFV ALPs

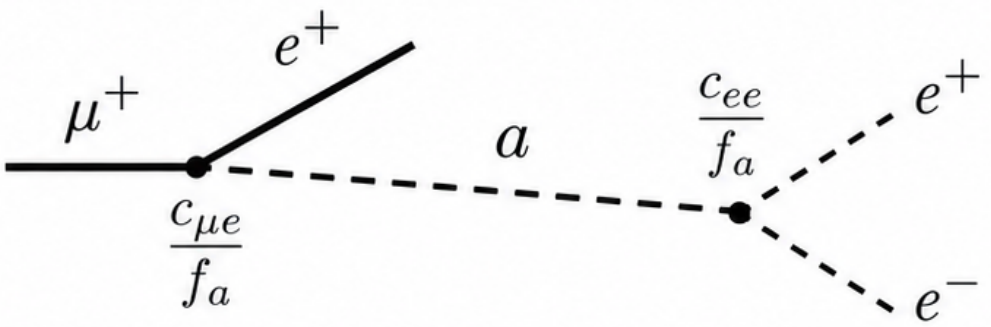
ALPs: Leptophilic

$$\mathcal{L}_{\rm ALP} \supset \frac{1}{2}\left(\partial_\mu a\right)\left(\partial^\mu a\right) - \frac{m_a^2}{2}a^2 + \frac{\partial_\mu a}{2f_a}\, j^\mu,$$

$$j_\ell^\mu = \sum_{i,j}^{e,\mu,\tau}\left(c_{ij}^L\,\overline{\ell}_L^i\gamma^\mu\ell_L^j + c_{ij}^\nu\,\overline{\nu}_L^i\gamma^\mu\nu_L^j + c_{ij}^R\,\overline{\ell}_R^i\gamma^\mu\ell_R^j\right).$$

Lepton Flavour violating (LFV)

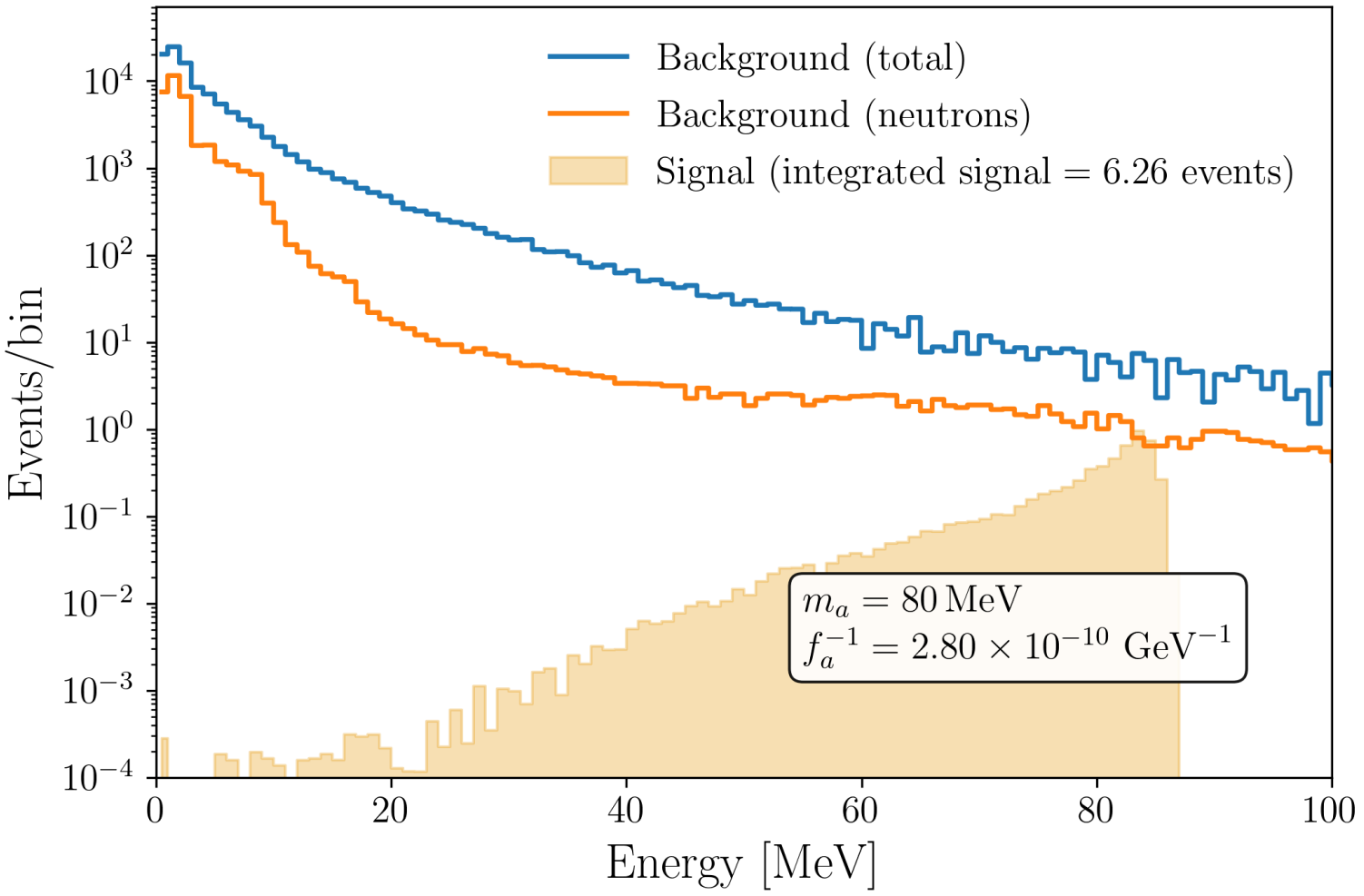
$c_{ij}^{L,R,\nu}$

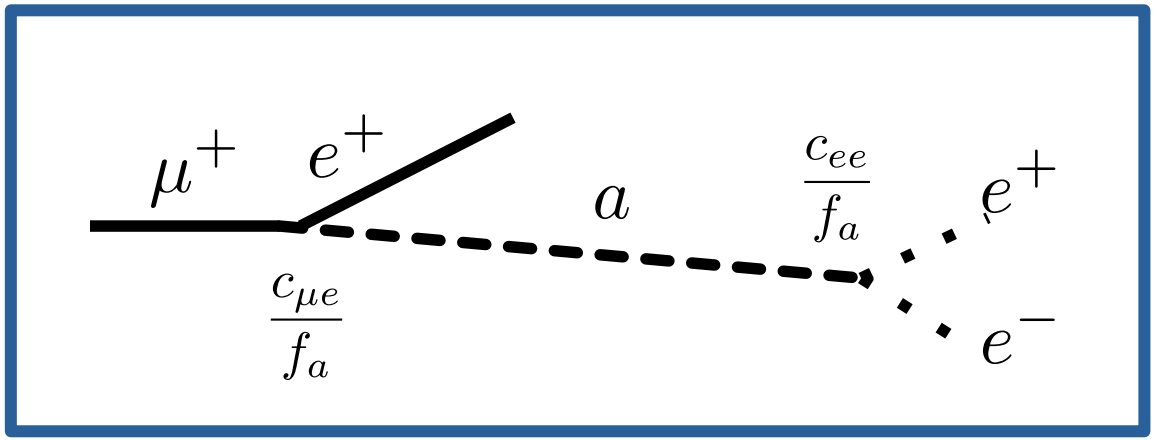


$$\Gamma\left(\mu^+ \to e^+ a_\ell\right) \simeq \left(\left|c_{e\mu}^L\right|^2 + \left|c_{e\mu}^R\right|^2\right)\frac{m_\mu^3}{32\pi f_a^2}\, f\left(r_e, r_a\right),$$

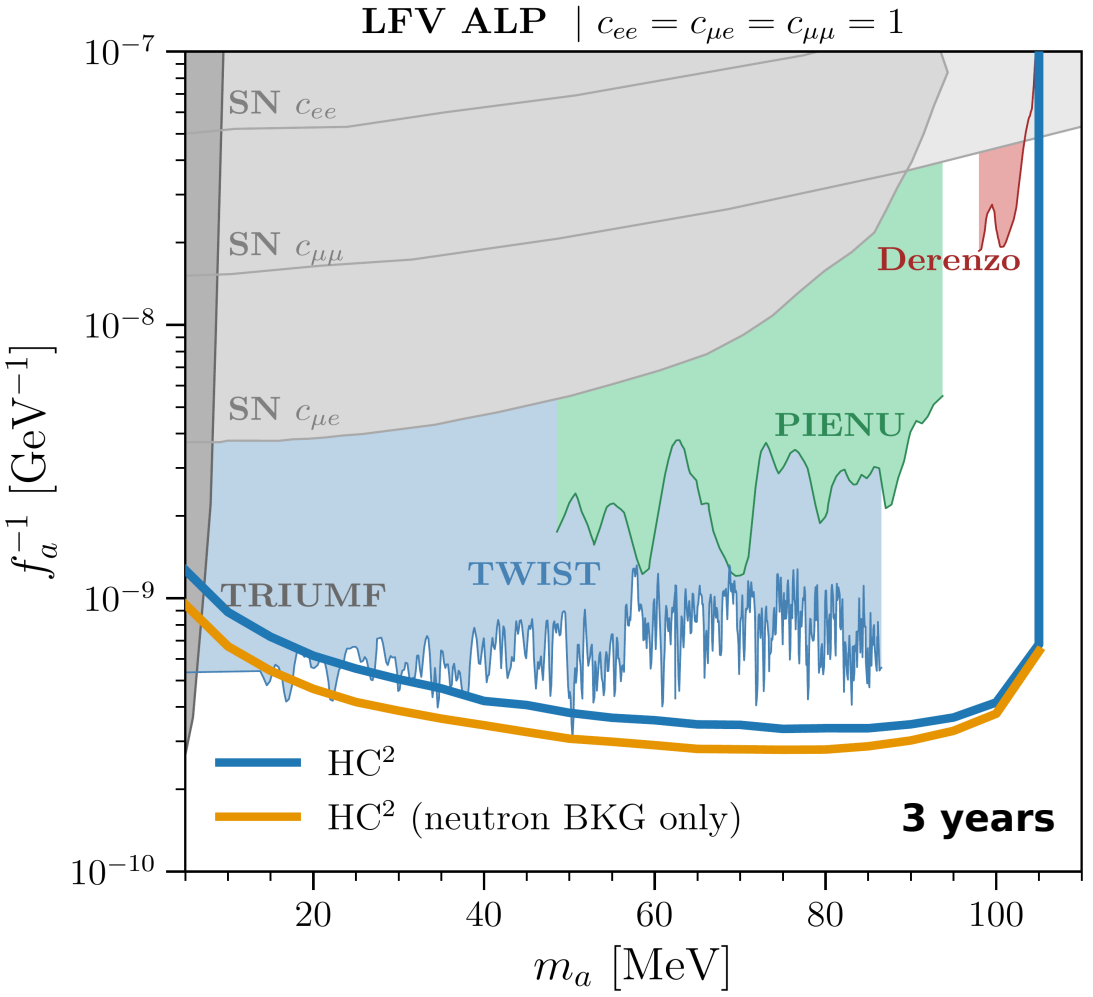
where $f(r_e, r_a) = (1+r_e)^2\left[(1-r_e)^2 - r_a^2\right]\lambda^{1/2}\left(1, r_e, r_a\right)$ with $r_i = m_i^2/m_\mu^2$.

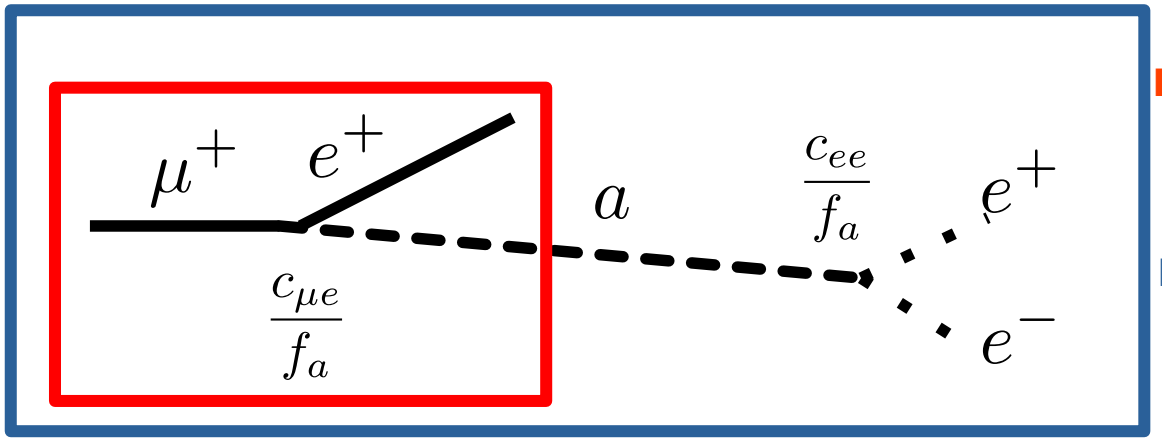
Cosmogenic background





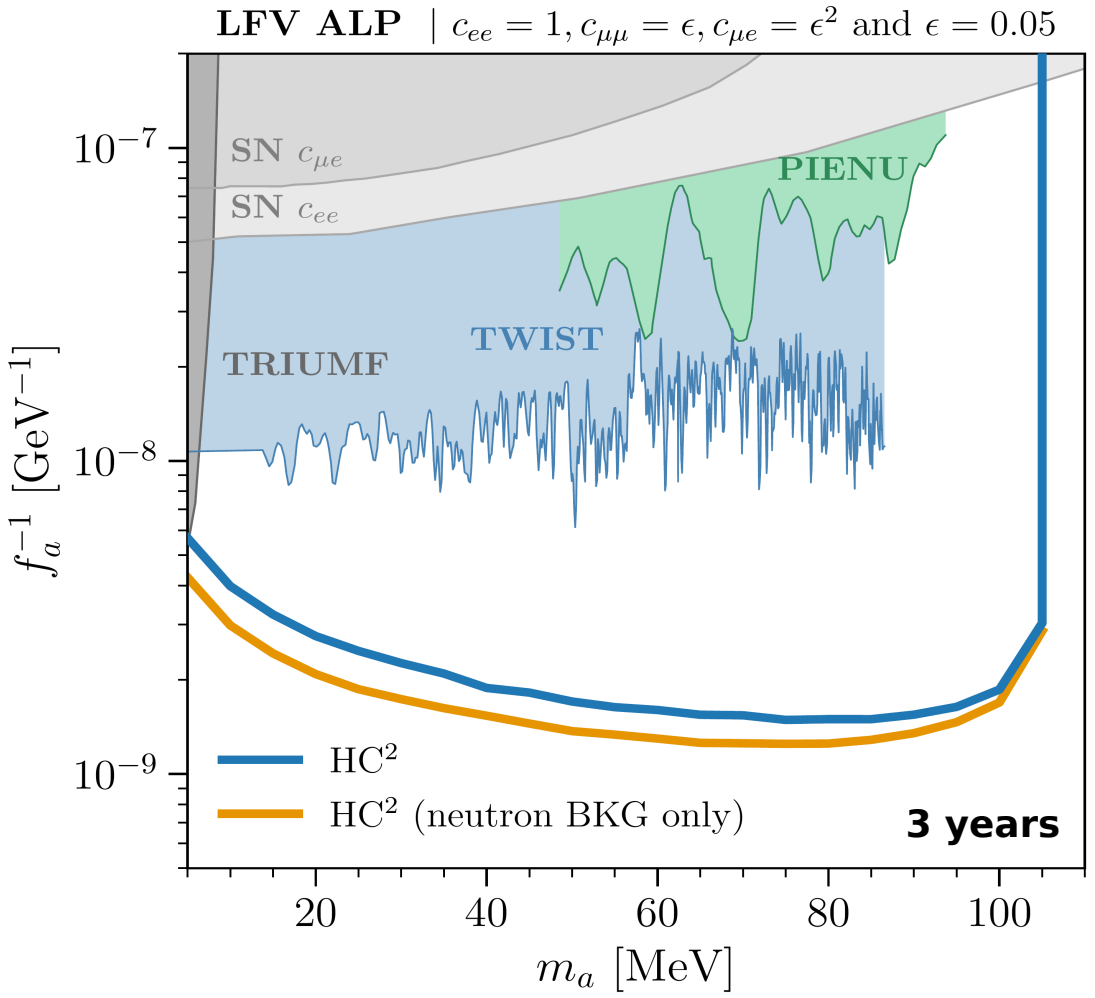
Decay in flight $\propto \frac{c_{\mu e}^2 c_{ee}^2}{f_a^4}$.





Rare muon decays $\propto \frac{c_{\mu e}^2}{f_a^2}$.

Decay in flight $\propto \frac{c_{\mu e}^2 c_{ee}^2}{f_a^4}$.



Summary

- **Spallation sources** offer a complementary opportunity to search for light, long-lived particles produced in meson and muon decays.

- A **segmented hydrocarbon scintillator** at the SNS can exploit topology, pulse-shape discrimination, and beam timing to suppress backgrounds.

- Our study demonstrates promising sensitivity to **HNLs** and **lepton-flavour-violating ALPs**, extending the reach of existing experiments.

Thank you

Back up

ALPs

Appear in many new Physics models

Warm dark matter

QCD Axion solution and Strong CP problem

$$\mathcal{L}_{\mathrm{QCD}} + \frac{\theta g_s^2}{32\pi^2}\epsilon_{\mu\nu\alpha\beta}G_a^{\mu\nu}G^{\alpha\beta}$$

Neutron electric dipole moment

$$d_n = \left(5.2 \times 10^{-16} e \cdot \mathrm{cm}\right)\theta.$$

Why so small?

$$\theta < 10^{-10}$$



$$\frac{a g_s^2}{32\pi^2}\epsilon_{\mu\nu\alpha\beta}G_a^{\mu\nu}G_a^{\alpha\beta}$$

Solves dynamically the Strong CP problem

Peccei, Quinn 1977

Weinberg 1978

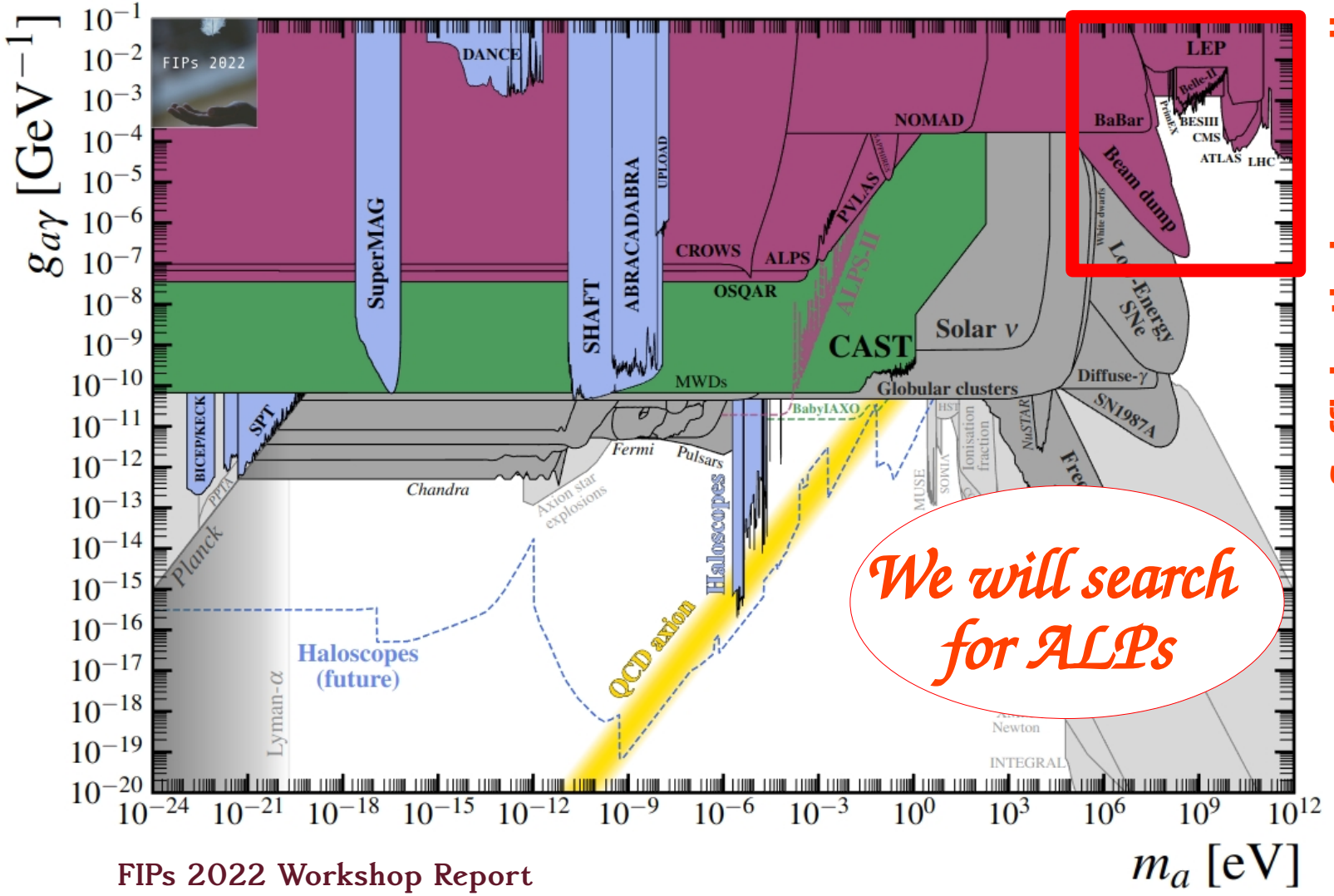
Abel, C., & Others. (2020). Measurement of the Permanent Electric Dipole Moment of the Neutron. Phys. Rev. Lett.

How do we search for ALPs?

Neutrino Detectors

50MeV-2GeV

Sufficiently large coupling



FIPs 2022 Workshop Report

ALPs: Higgs coupled

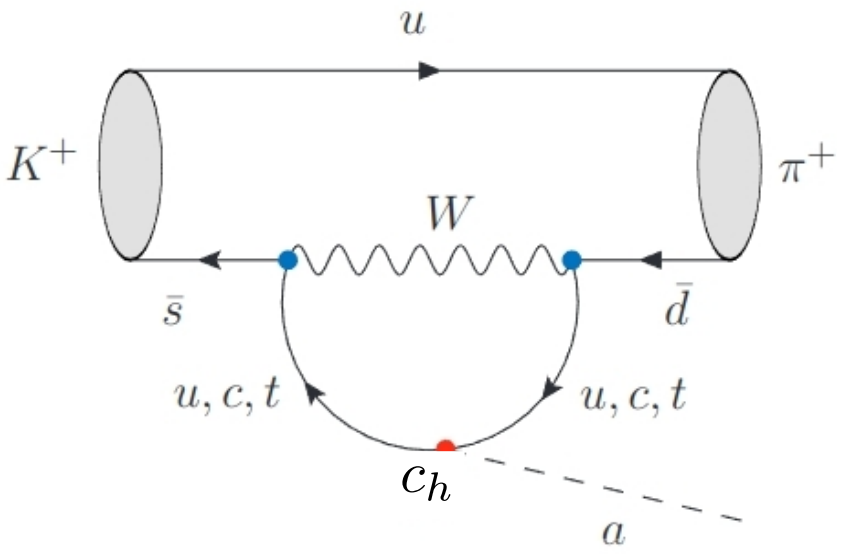
$$L_{\rm ALP} \supset \frac{1}{2}\left(\partial_\mu a\right)\left(\partial^\mu a\right) - \frac{m_a^2}{2}a^2 + \frac{\partial_\mu a}{f_a} c_h \left(H^\dagger i \overleftrightarrow{D^\mu} H \right)$$

Hypercharge rotation

$$c_h \left(H^\dagger i \overleftrightarrow{D^\mu} H \right) \quad \Rightarrow \quad c_{ff} \sum_f \bar{f}\gamma^\mu\gamma_5 f$$

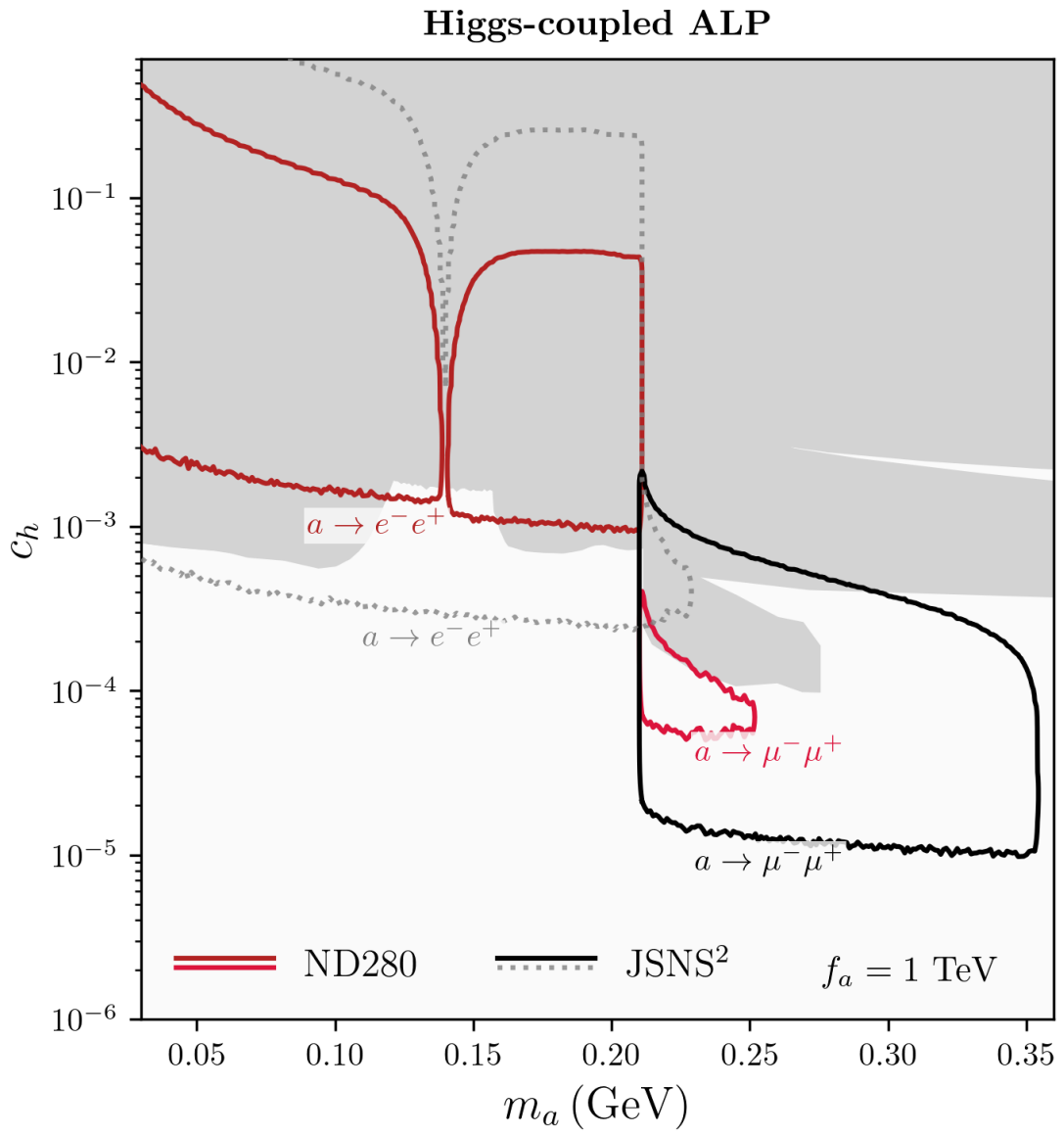
Production

$$K^+ \to \pi^+ a_h$$

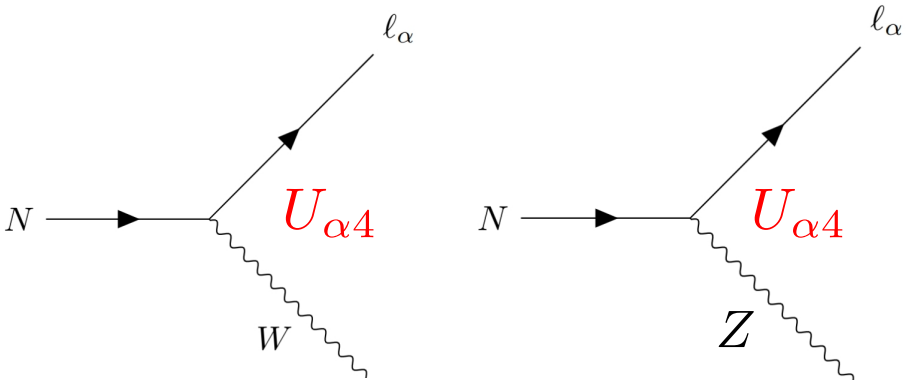


ALPs: Higgs coupled

$$\Gamma_{a_h \to \ell^+\ell^-} = |c_h|^2 \frac{m_a m_\ell^2}{8\pi f_a^2} \sqrt{1 - 4r_\ell^2} \text{ where } r_\ell = m_\ell / m_a$$

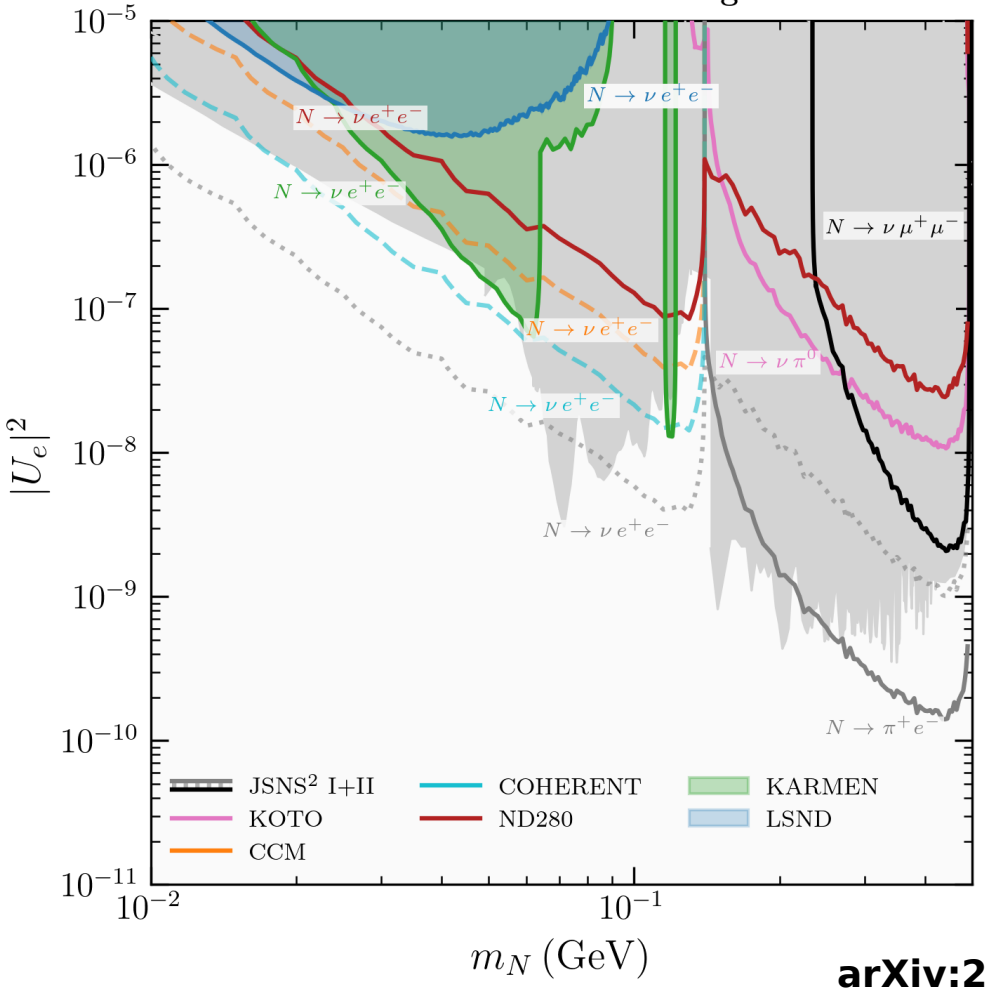


HNL

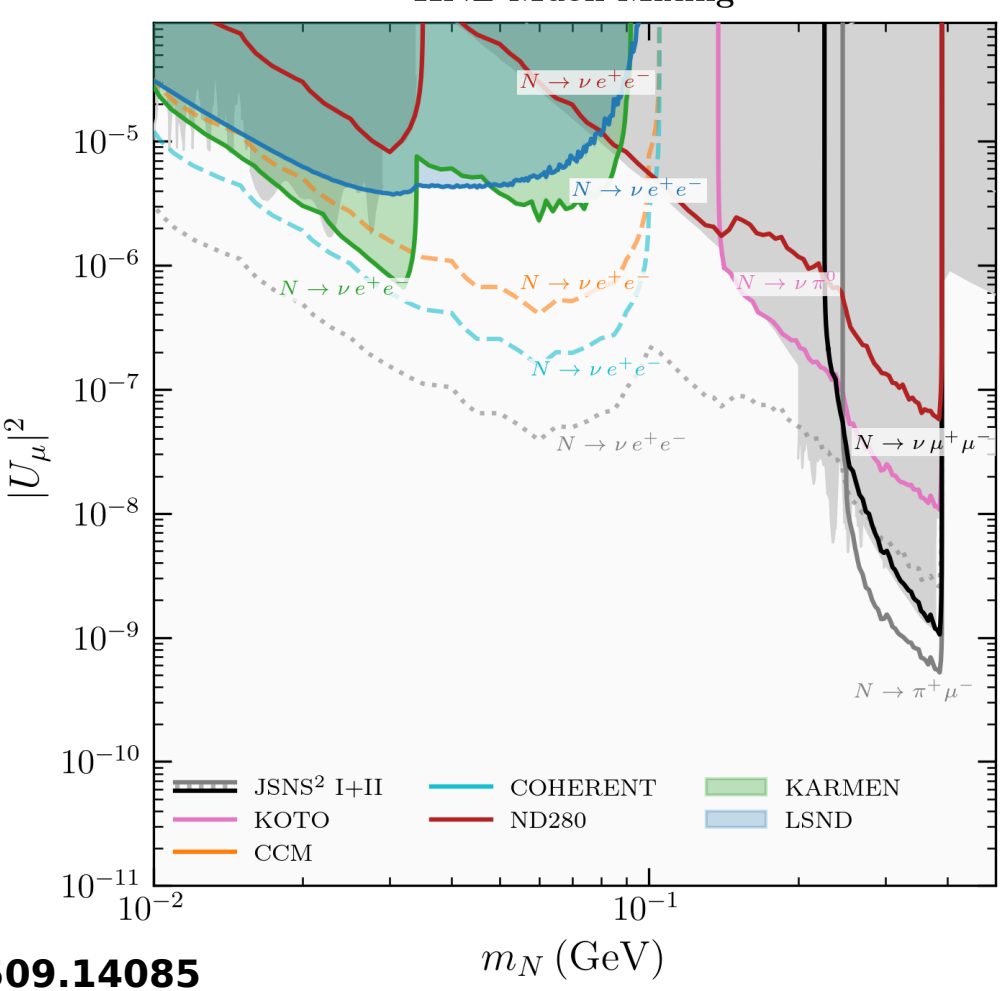


$$
\begin{aligned}
N &\to \nu e^+ e^- && \text{(NC and CC)},\\
N &\to \nu e^\pm \mu^\mp && \text{(CC)},\\
N &\to \nu \mu^+ \mu^- && \text{(NC and CC)},\\
N &\to \nu \pi^0 && \text{(NC)},\\
N &\to e^- \pi^+ && \text{(CC)},\\
N &\to \mu^- \pi^+ && \text{(CC)},
\end{aligned}
$$

HNL Electron Mixing

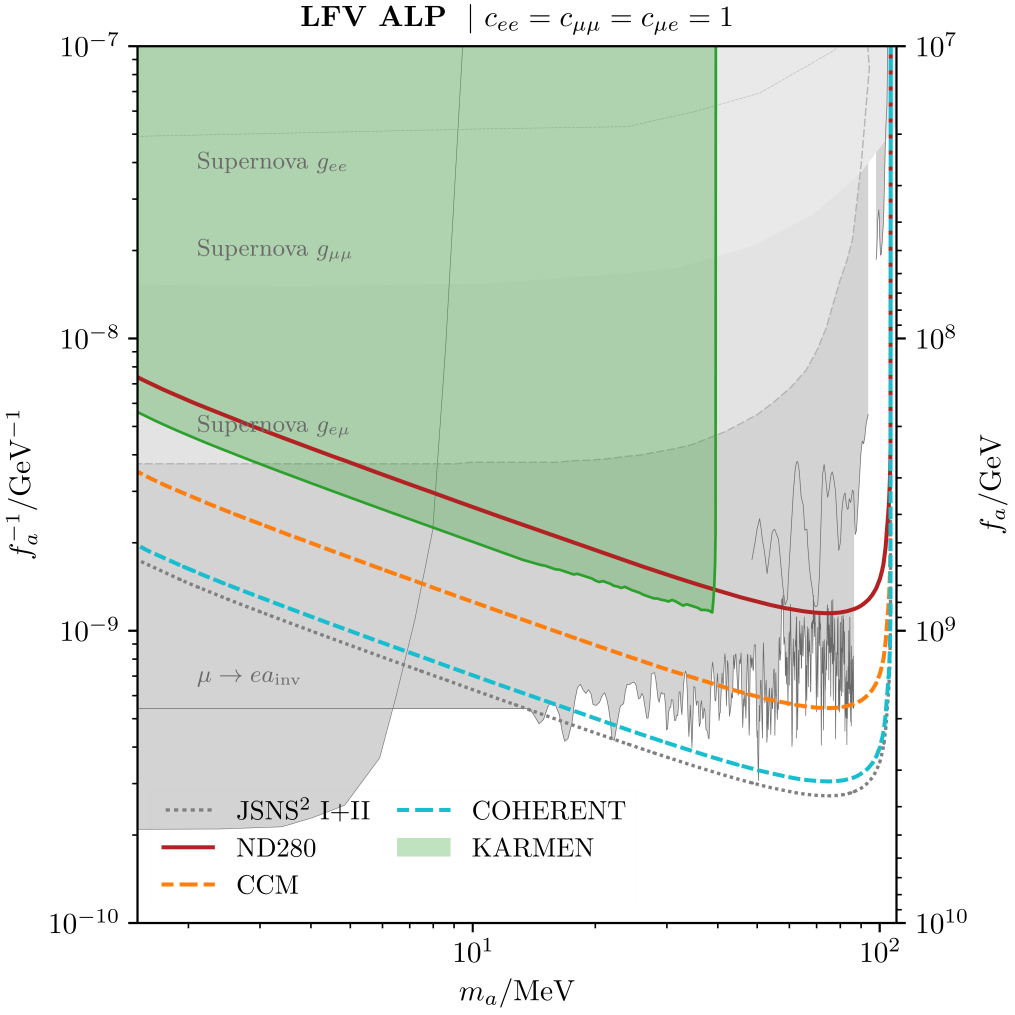


HNL Muon Mixing

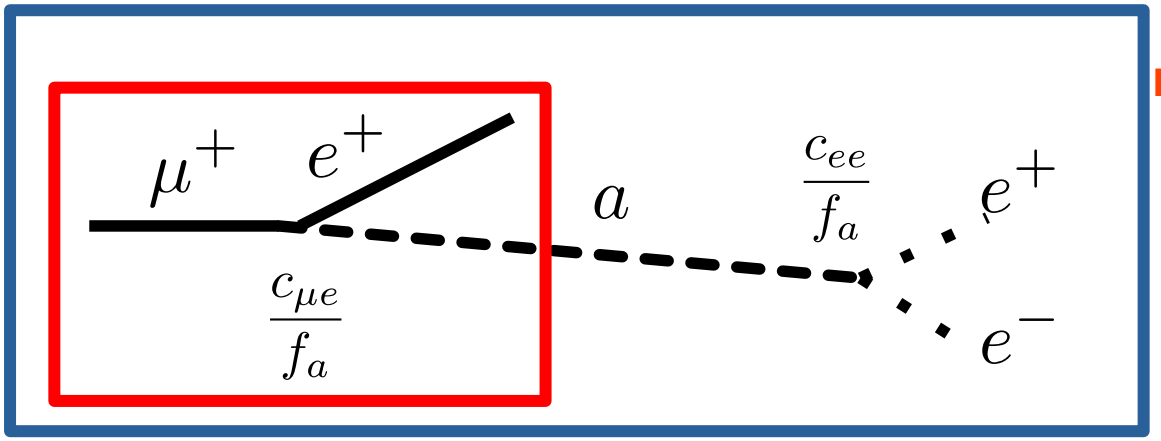


arXiv:2509.14085

Lepton Flavour violating (LFV)

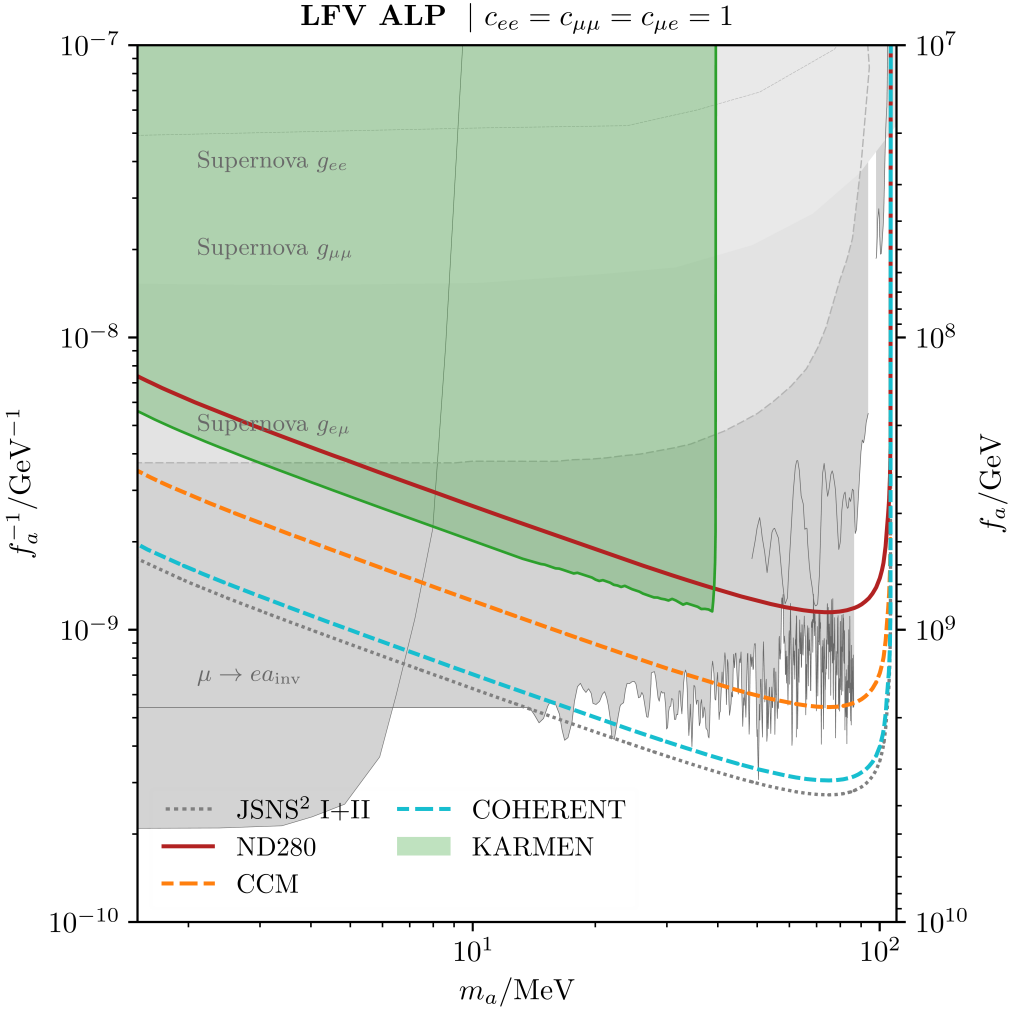


Lepton Flavour violating (LFV)

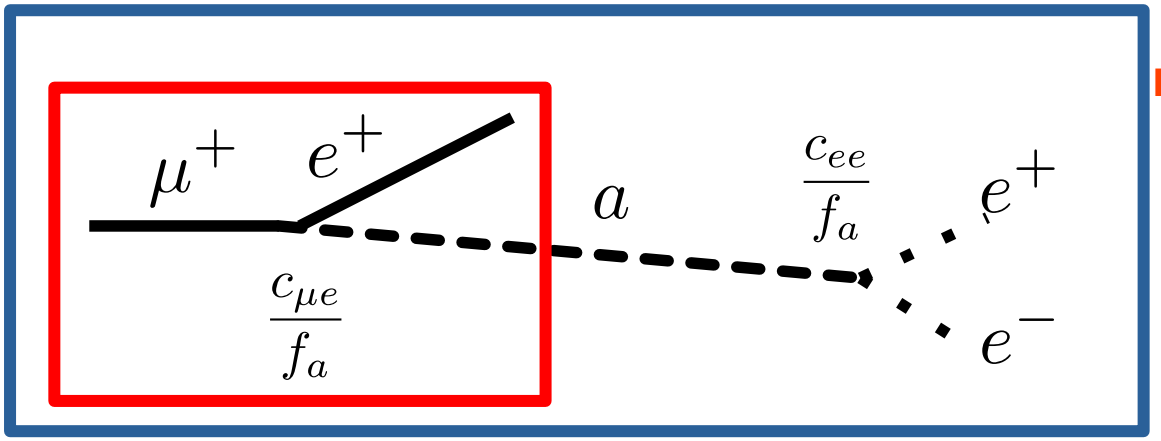


Rare muon decays $\propto \frac{c_{\mu e}^2}{f_a^2}$.

Decay in flight $\propto \frac{c_{\mu e}^2 c_{ee}^2}{f_a^4}$.

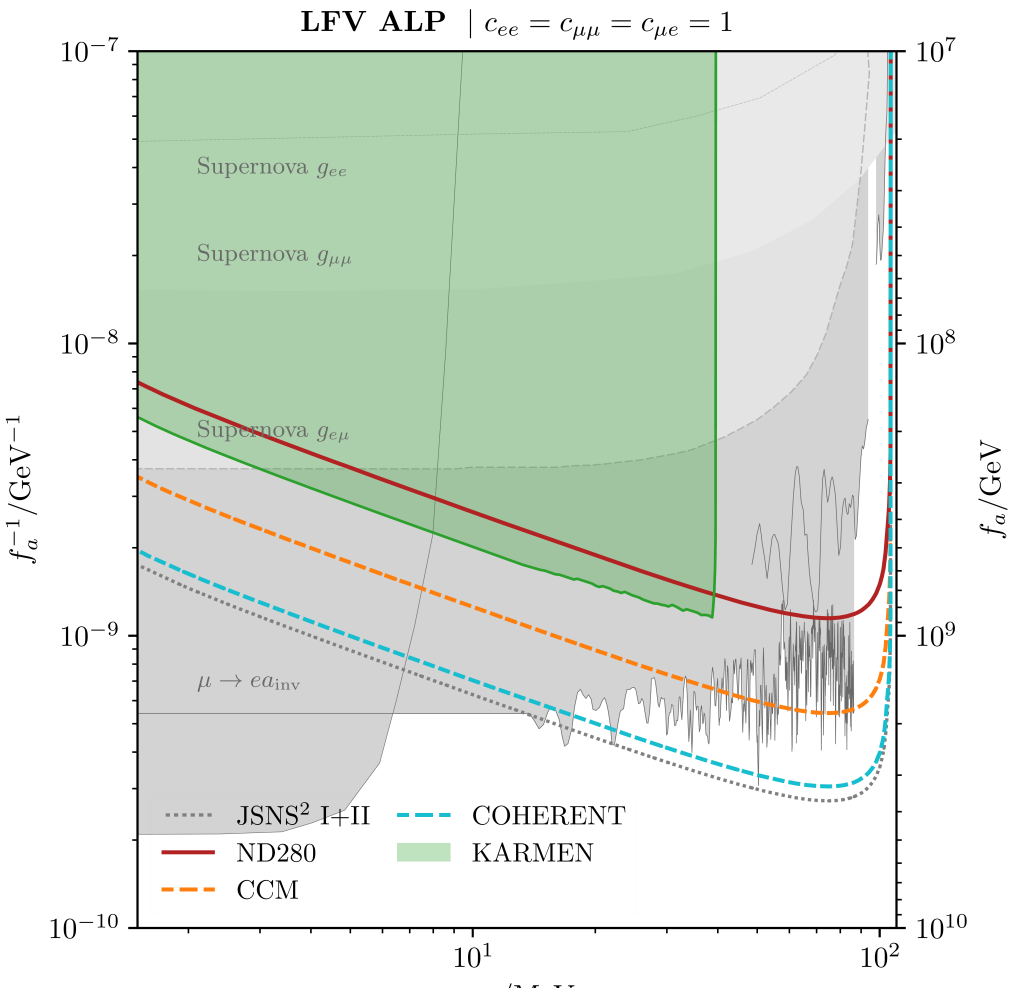


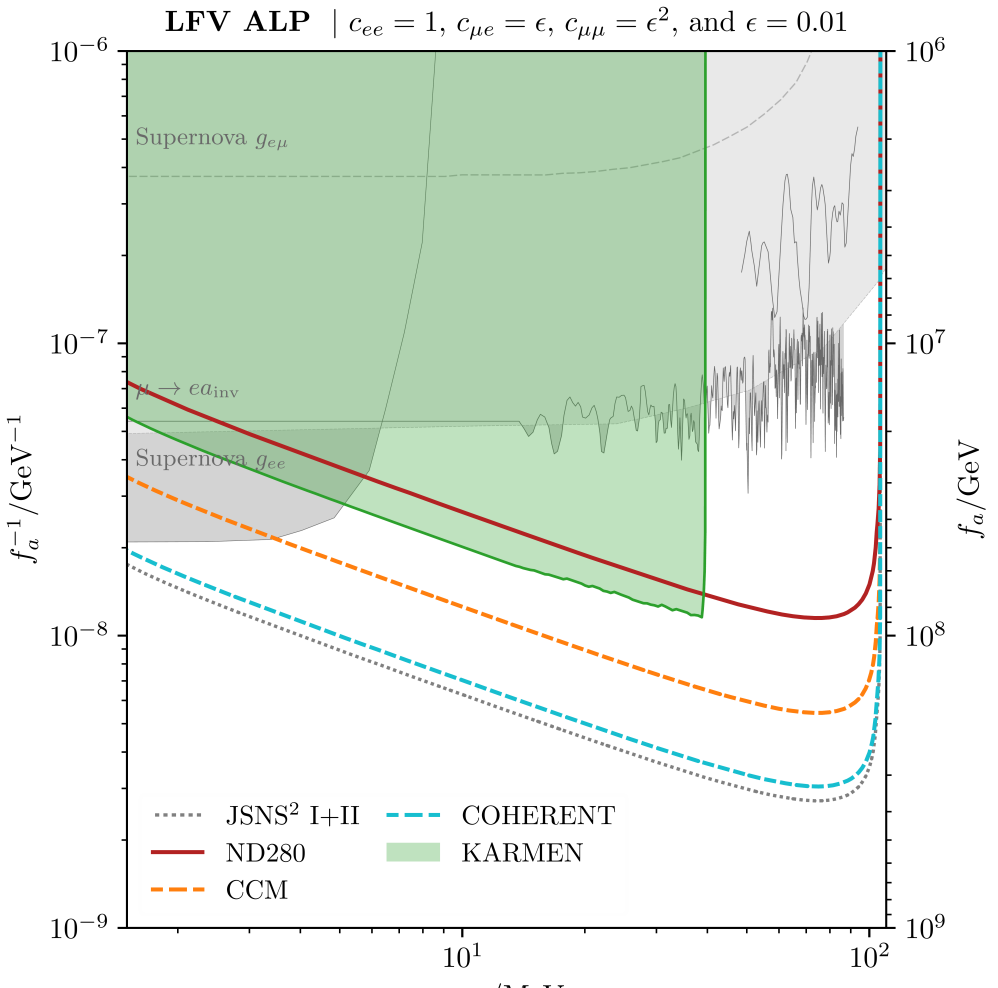
Lepton Flavour violating (LFV)



Rare muon decays $\propto \frac{c_{\mu e}^2}{f_a^2}$.

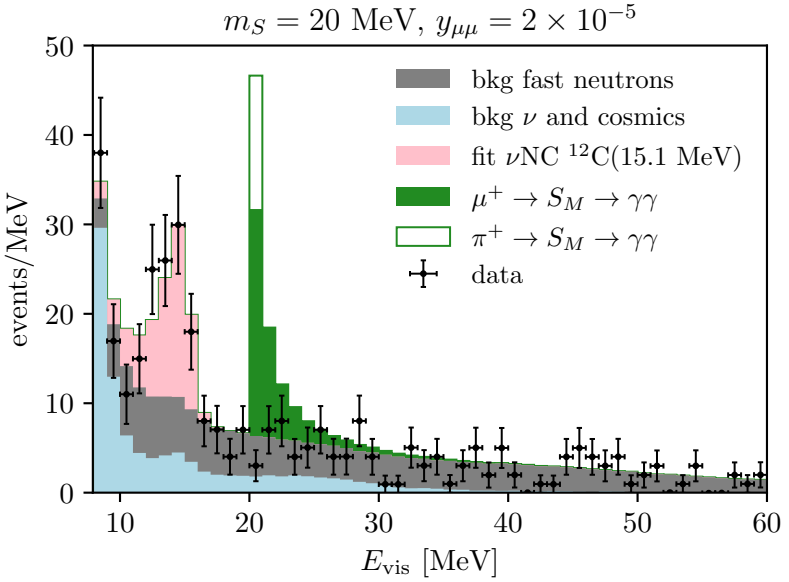
Decay in flight $\propto \frac{c_{\mu e}^2 c_{ee}^2}{f_a^4}$.

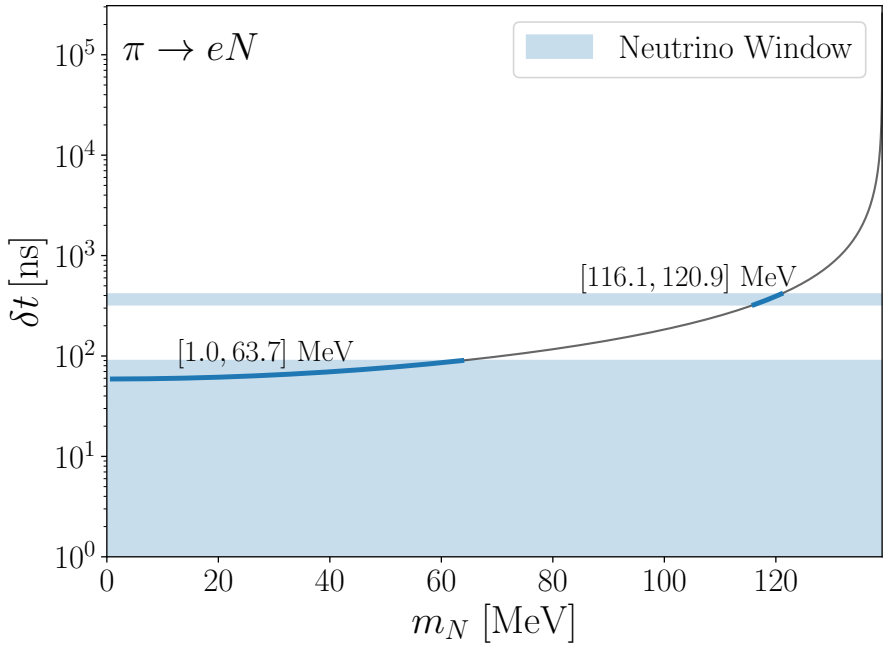


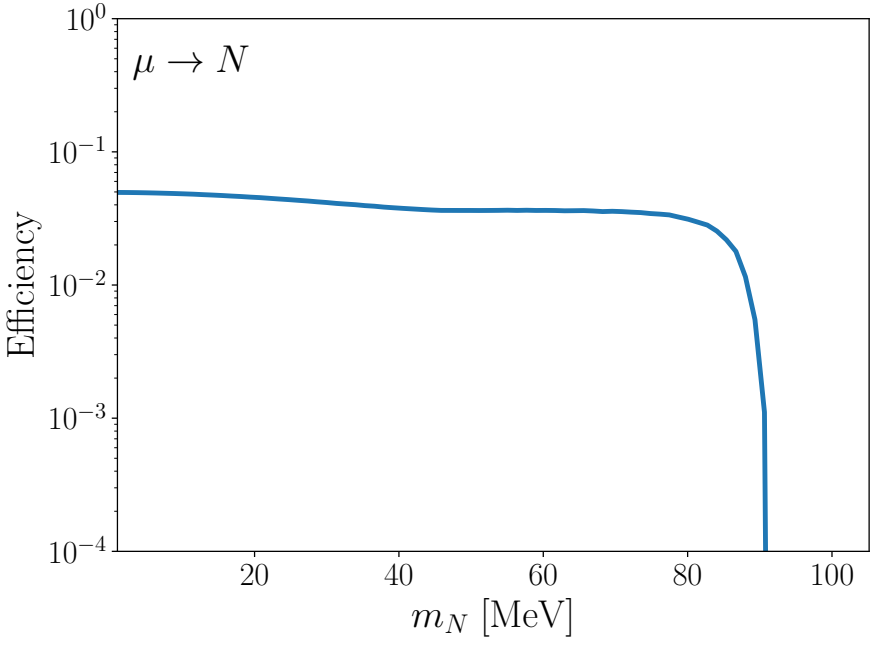


arXiv:2509.14085

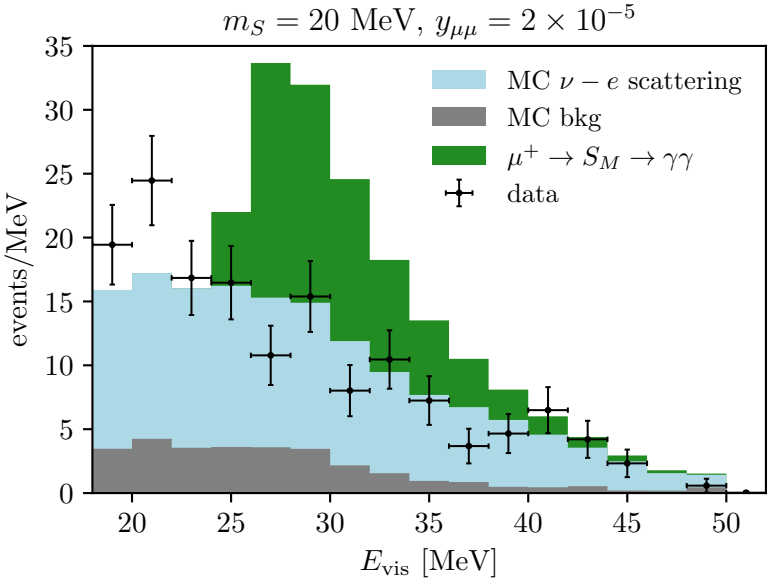
KARMEN

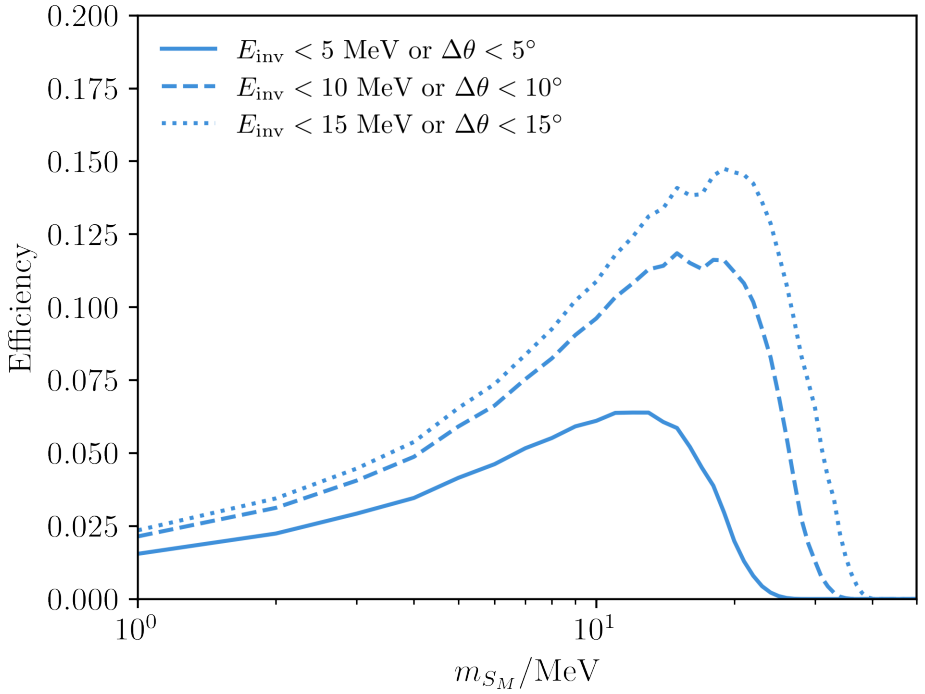

$m_S = 20$ MeV, $y_{\mu\mu} = 2 \times 10^{-5}$
bkg fast neutrons
bkg ν and cosmics
fit νNC ^{12}C(15.1 MeV)
$\mu^+ \to S_M \to \gamma\gamma$
$\pi^+ \to S_M \to \gamma\gamma$
data
events/MeV
$E_{\rm vis}$ [MeV]


$\pi \to eN$
Neutrino Window
[116.1, 120.9] MeV
[1.0, 63.7] MeV
δt [ns]
m_N [MeV]


$\mu \to N$
Efficiency
m_N [MeV]

LSND


$m_S = 20$ MeV, $y_{\mu\mu} = 2 \times 10^{-5}$
MC $\nu - e$ scattering
MC bkg
$\mu^+ \to S_M \to \gamma\gamma$
data
events/MeV
E_{vis} [MeV]


$E_{\text{inv}} < 5$ MeV or $\Delta\theta < 5°$
$E_{\text{inv}} < 10$ MeV or $\Delta\theta < 10°$
$E_{\text{inv}} < 15$ MeV or $\Delta\theta < 15°$
Efficiency
m_{S_M}/MeV

How do we give mass to neutrinos?

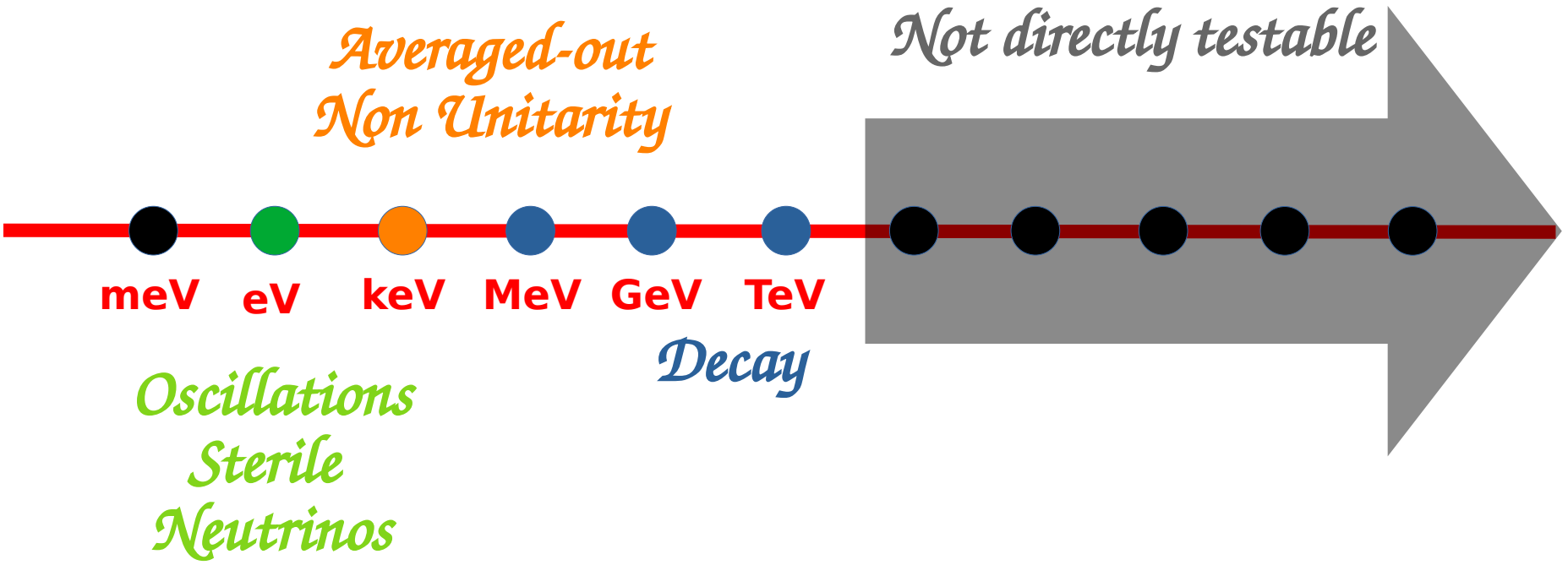
ΔL conserved	ΔL largely violated	ΔL approximately conserved
Higgs mechanism	**High scale See-saw**	**Low scale see-saw**
$m_\nu \sim y_\nu \frac{v}{\sqrt{2}}$	$m_\nu \sim \frac{y_\nu^2 v^2}{M}$	$m_\nu \sim \frac{v^2}{M^2}\mu$
$y_\nu < 6.5 \cdot 10^{-13}$	If $y_\nu^2 \sim O(1) \rightarrow M \sim 10^{11}\text{GeV}$,	$\mu \ll 1$
Why so small?	If $y_\nu^2 \sim O(y_e^2) \rightarrow M \sim 1\text{GeV}$,	**Symmetry protected scenarios**
	Schechter and Valle 1980; Mohapatra and Senjanovic 1979; Minkowski 1977; Gell-Mann, Ramond and Slansky 1979; Yanagida 1980	Mohapatra, & Valle 1986 ; Akhmedov, Lindner, Schnapka, and Valle 1996; Gonzalez-Garcia and Valle 1989; Gavela, Hambye, Hernandez 2009; Bernabéu, Santamaria, Vidal, Mendez, and Valle 1987; Mohapatra 1986

How do we give mass to neutrinos?

ΔL conserved	ΔL largely violated	ΔL approximately conserved
Higgs mechanism	**High scale See-saw**	**Low scale see-saw**
		This work
$m_\nu \sim y_\nu \dfrac{v}{\sqrt{2}}$	$m_\nu \sim \dfrac{y_\nu^2 v^2}{M}$	$m_\nu \sim \dfrac{v^2}{M^2}\mu$
$y_\nu < 6.5 \cdot 10^{-13}$	If $y_\nu^2 \sim O(1) \rightarrow M \sim 10^{11}\text{GeV}$,	$\mu \ll 1$
Why so small?	If $y_\nu^2 \sim O(y_e^2) \rightarrow M \sim 1\text{GeV}$,	**Symmetry protected scenarios**
	Schechter and Valle 1980; Mohapatra and Senjanovic 1979; Minkowski 1977; Gell-Mann, Ramond and Slansky 1979; Yanagida 1980	Mohapatra, & Valle 1986 ; Akhmedov, Lindner, Schnapka, and Valle 1996; Gonzalez-Garcia and Valle 1989; Gavela, Hambye, Hernandez 2009; Bernabéu, Santamaria, Vidal, Mendez, and Valle 1987; Mohapatra 1986

How do we give mass to neutrinos?

New Physics scale M



How do we give mass to neutrinos?

New Physics scale M

