Long-Lived Particles at Spallation Neutron Sources

Salvador Urrea

arXiv:2509.14085 in collaboration with Matheus Hostert (Univ. Iowa)

and work in progress

in collaboration with PROSPECT

(thanks B. Littlejohn (IIT), F. Machado (IIT), T. Haugen (NIST))

Rencontres de Physique des Particules 2026

March 11, 2026

IJCLab Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis

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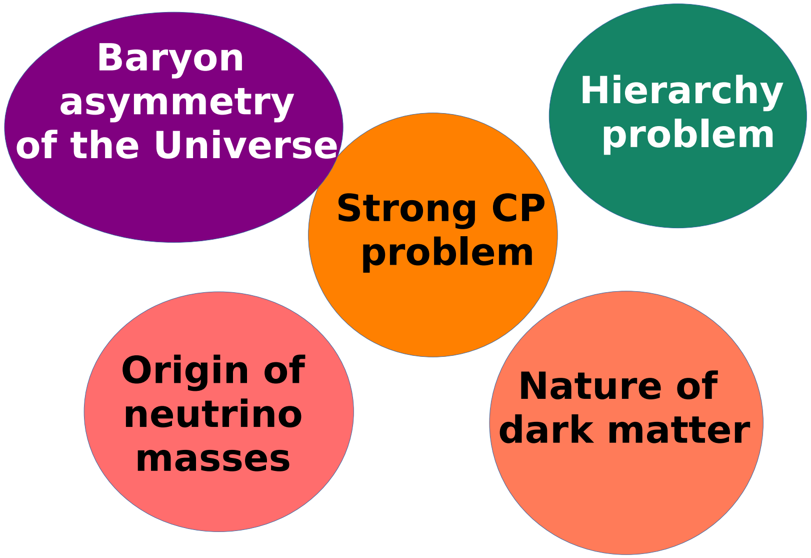
Open problems



Call for new physics

Open problems

Baryon asymmetry of the Universe

Hierarchy problem

Strong CP problem

Origin of neutrino masses

Nature of dark matter

Call for new physics

New Physics

Heavy

Light

Difficult to probe directly

Open problems

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In this talk

FIPs

Open problems

- Baryon asymmetry of the Universe
- Strong CP problem
- Hierarchy problem
- Origin of neutrino masses
- Nature of dark matter

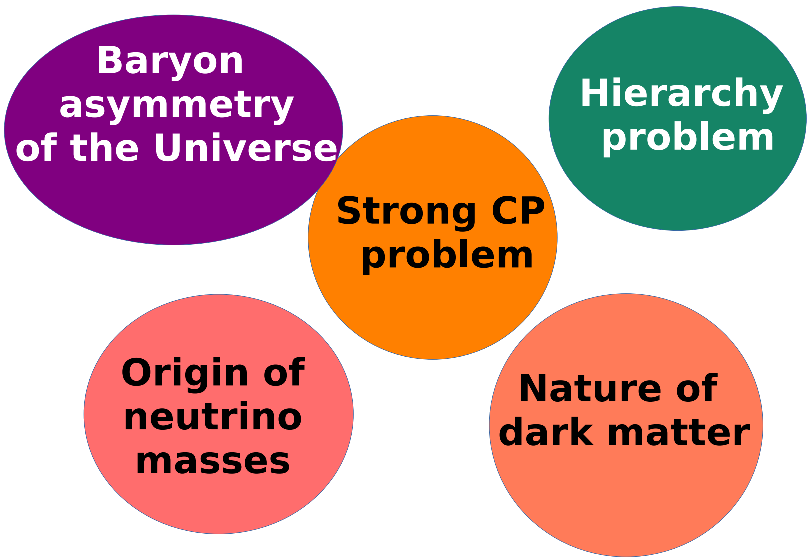
Call for new physics

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

Long lived particles

FIPs

Open problems



Call for new physics

- **Scalar : Dark Higgs, Muon scalar etc**
- **Pseudoscalar: Axions, ALPs**
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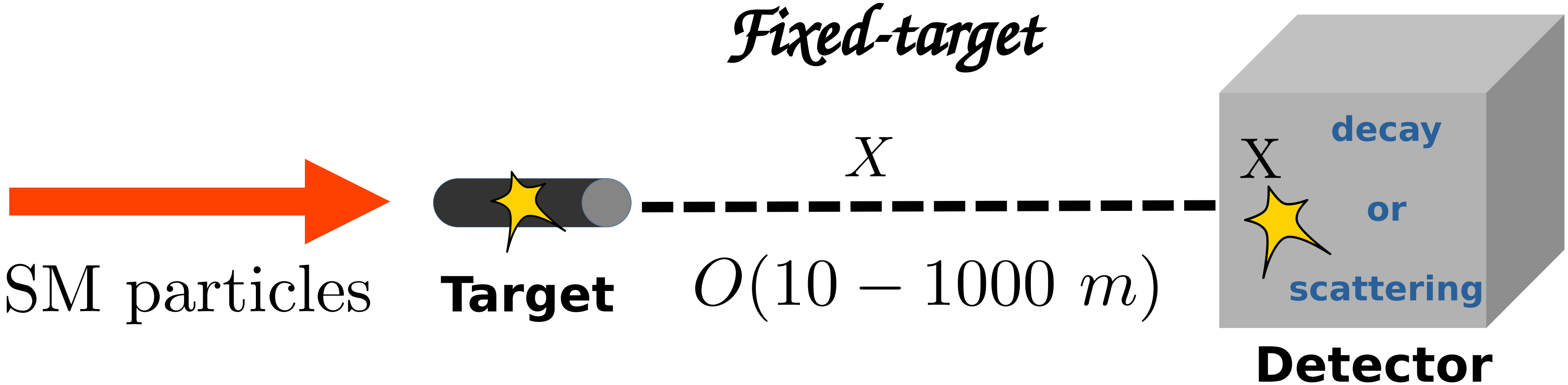
Long lived particles

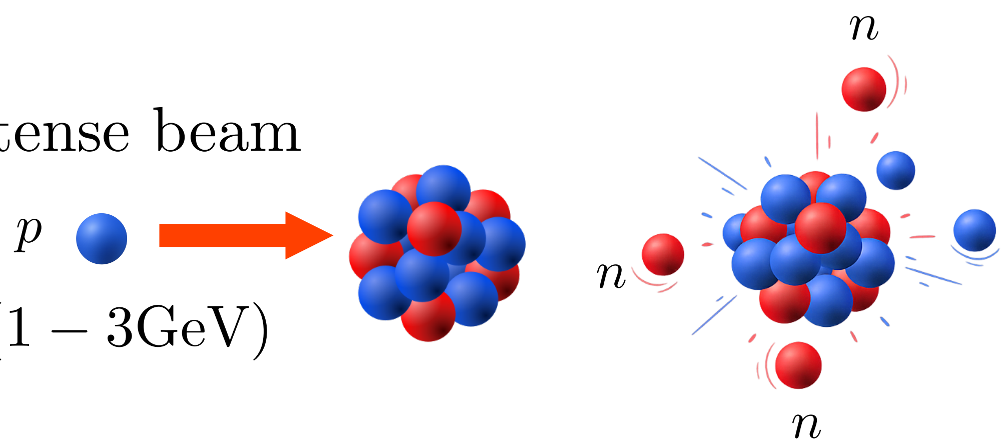
Fixed-target



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

What is a spallation neutron source?

Intense beam



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

- **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

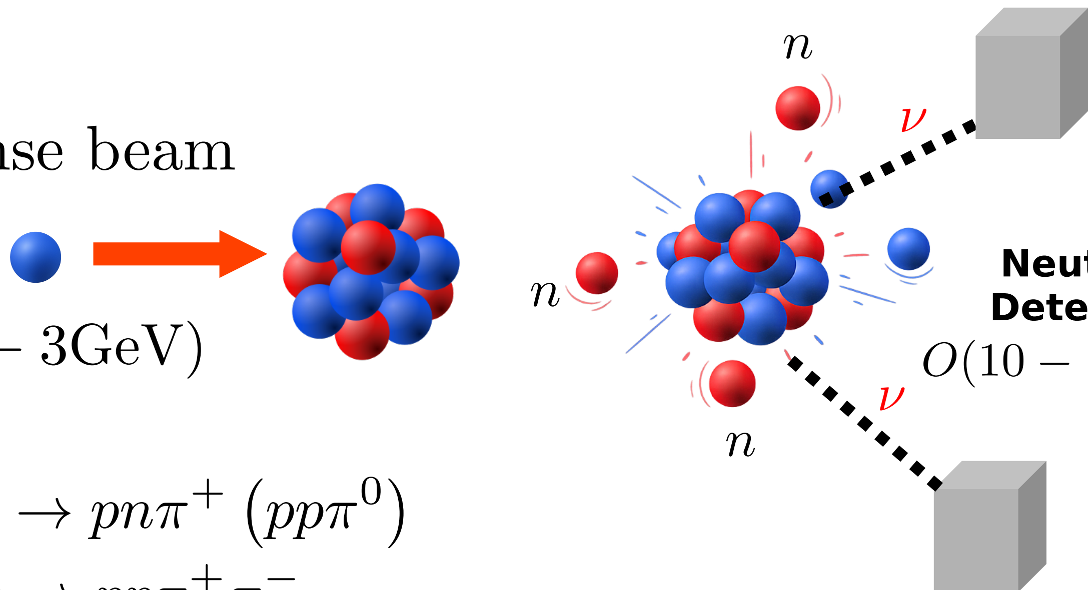
Lose energy and decay at rest	Captured
$\pi^+/K^+ \to \mu^+\nu_\mu$	π^-, K^-

What is a spallation neutron source?

Intense beam

p

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



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

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

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

Sterile neutrinos **CEvNS**

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

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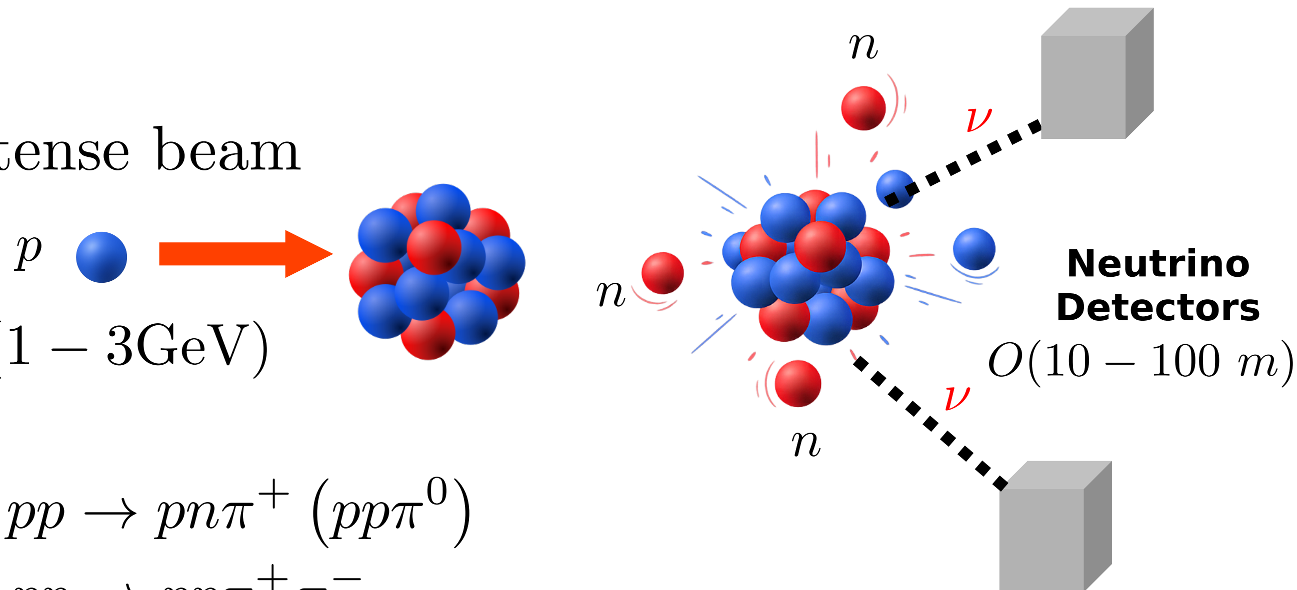

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Meson production

Lose energy and decay at rest

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

Captured

π^-, K^-

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

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

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

Sterile neutrinos **CEvNS**

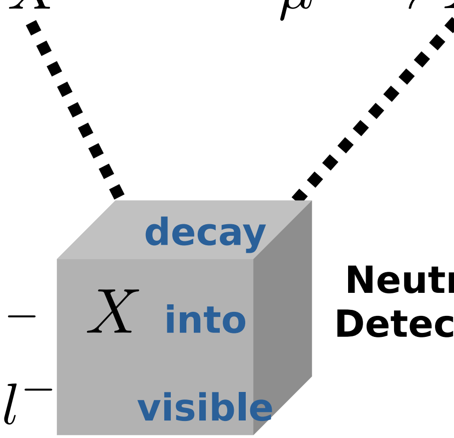
- **FIPs searches**

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

$X \to \gamma\gamma$

$X \to l^+l^-$

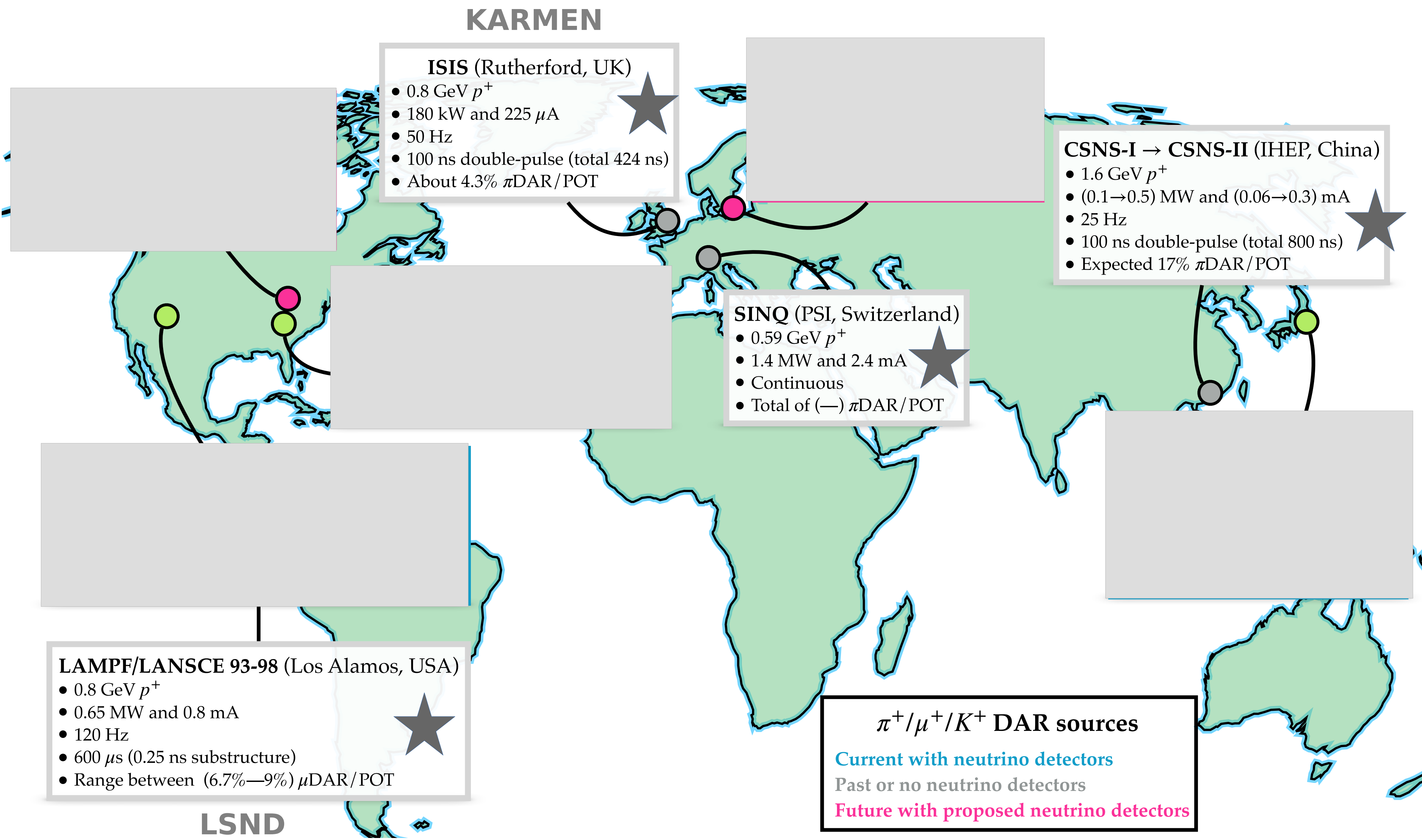
$X \to \pi^+l^-$



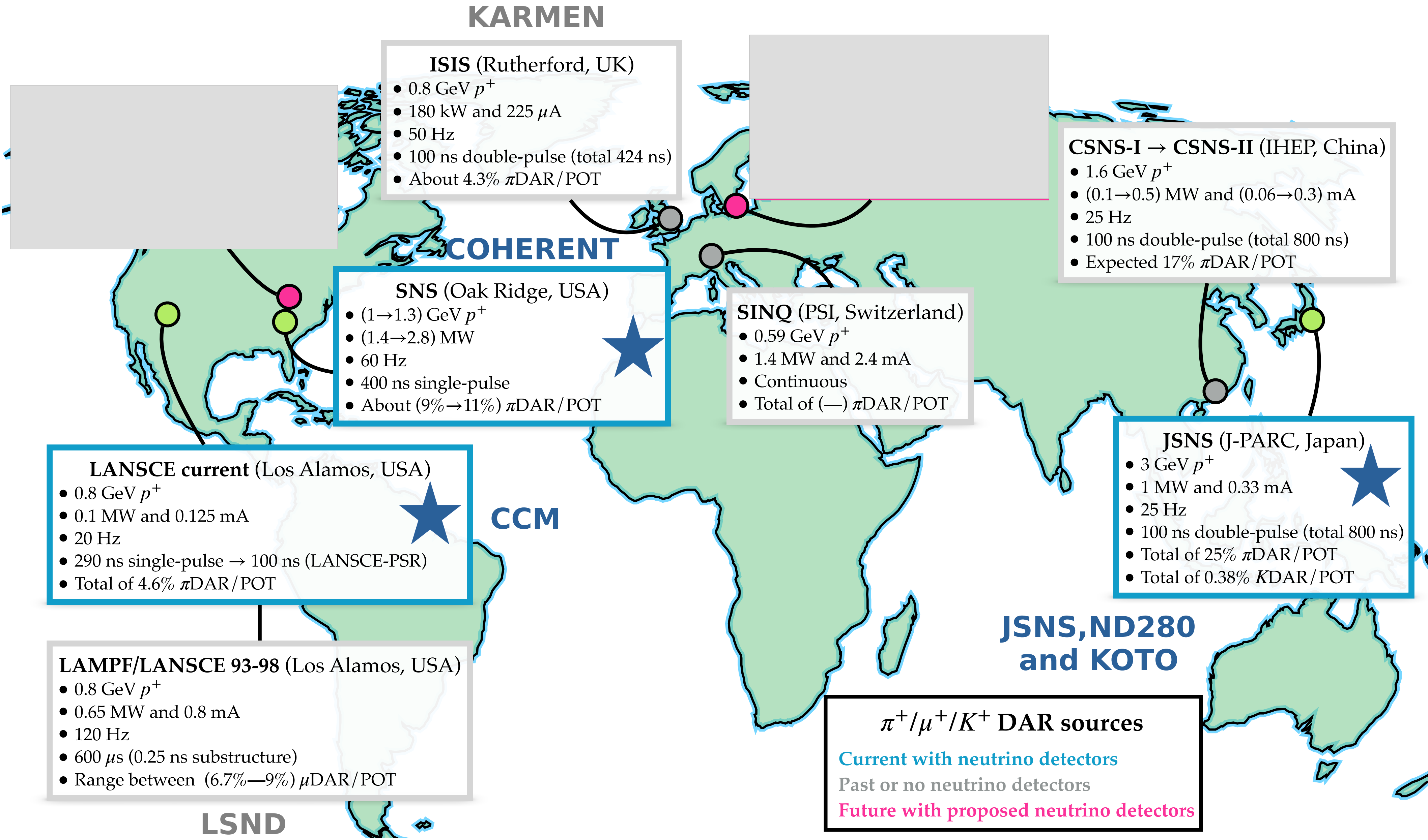
Neutrino Detectors

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



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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
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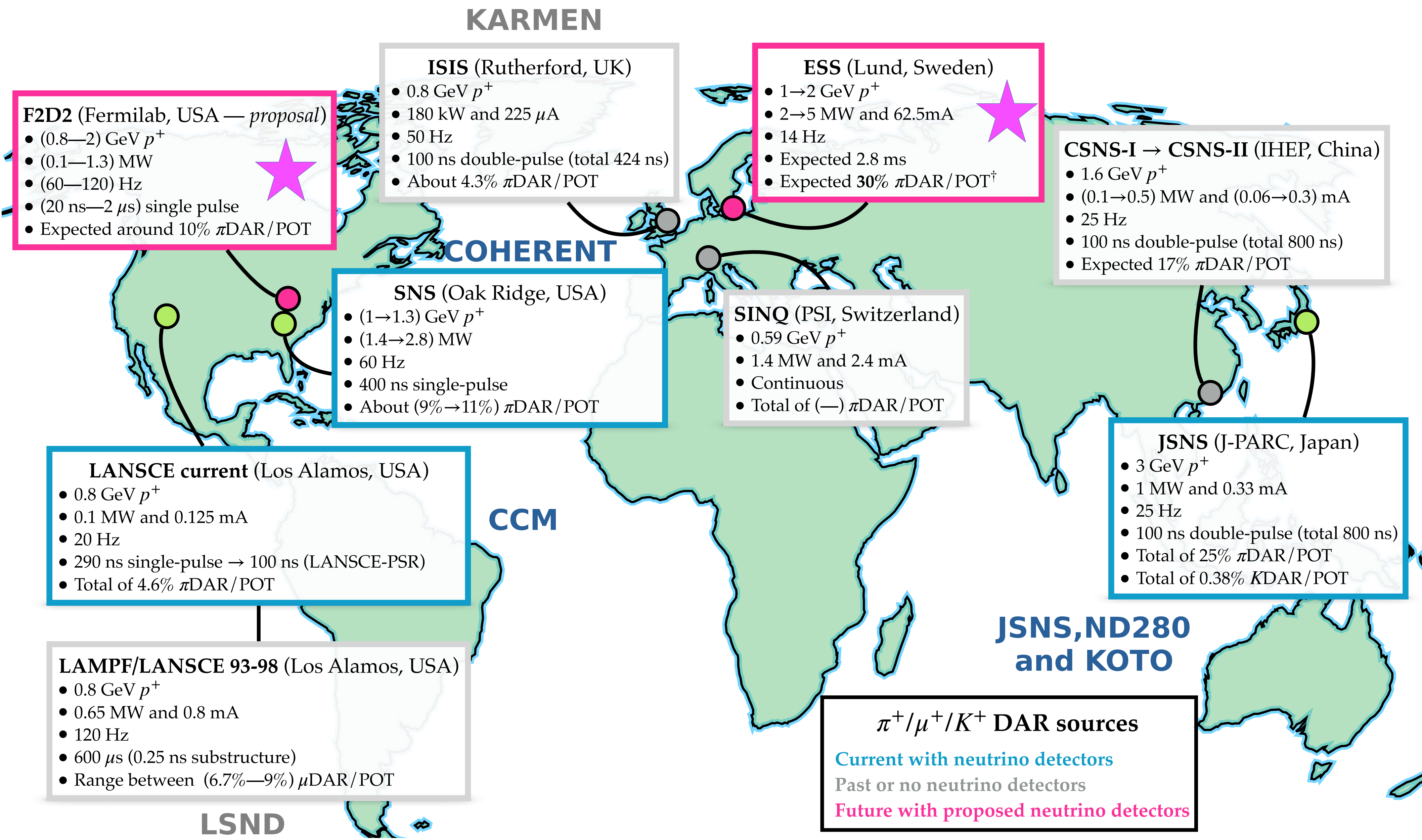
Future


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
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$\pi^+/\mu^+/K^+$ DAR sources
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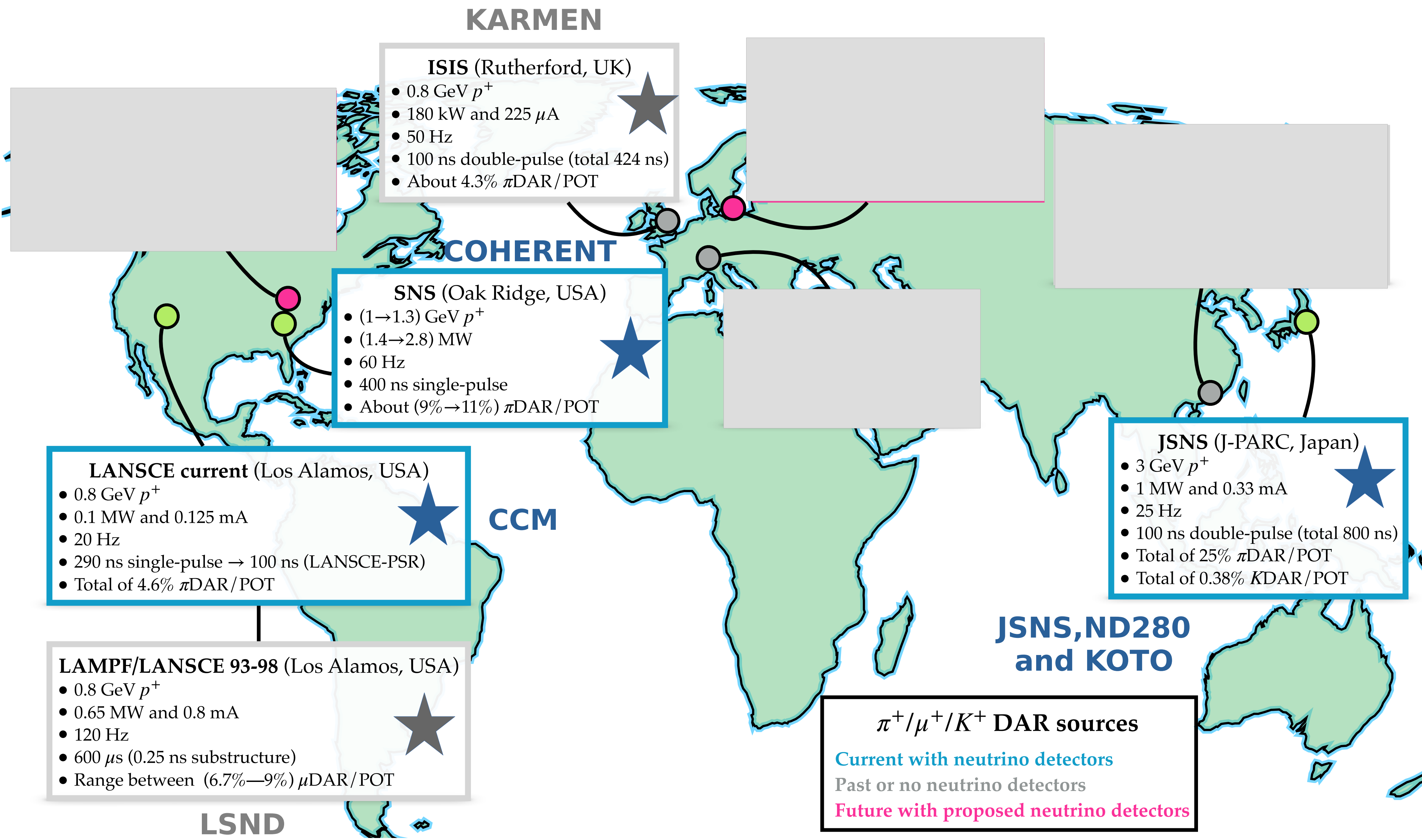
LSND

Used in this work

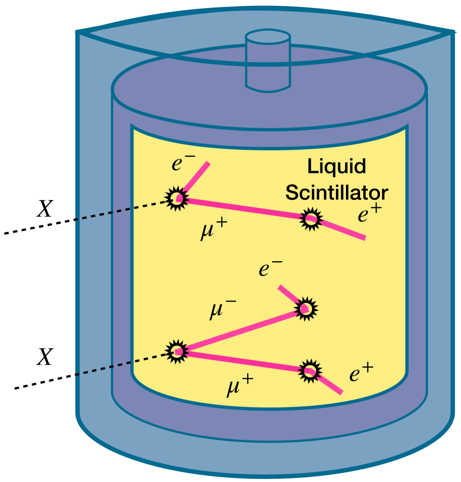
$\nu_\mu + {}^{12}\mathrm{C} \rightarrow \nu_\mu + {}^{12}\mathrm{C}^*(15.1\mathrm{MeV})$ NC data



$\nu_e e^- \rightarrow \nu_e e^-$ Elastic Scattering data

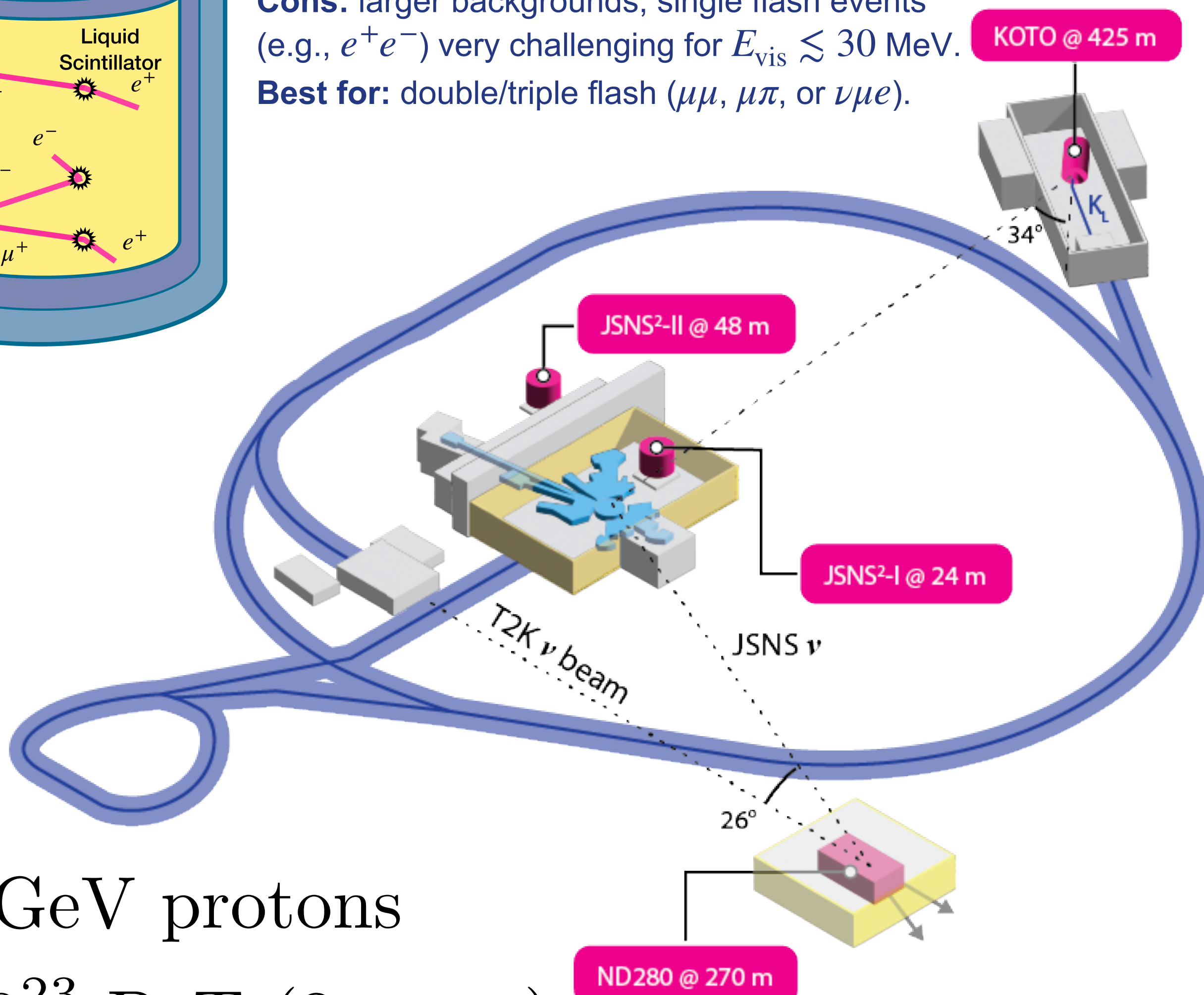
J-PARC

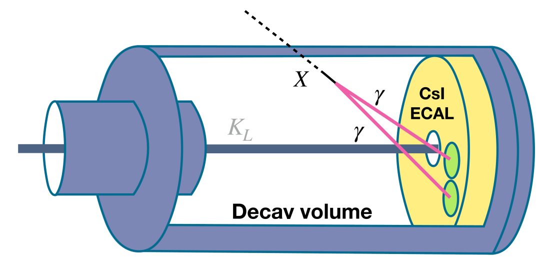
$$\pi^+/K^+ \to X \qquad \mu^+ \to X \qquad\qquad X \to e^+e^-, \gamma\gamma, \mu^+\mu^-, \pi^+\mu^-, etc$$



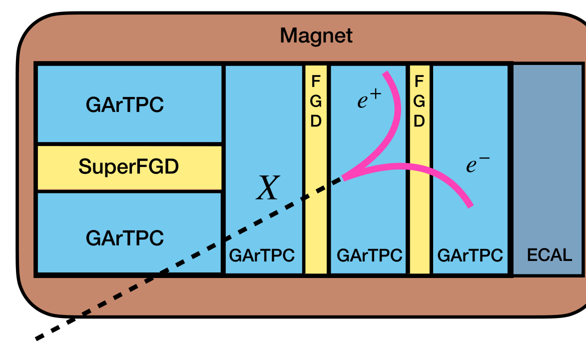
JSNS^2 (I and II): $20\ m^3, 36\ m^3$
Pros: Closest to the source and largest vol
Cons: larger backgrounds, single flash events (e.g., e^+e^-) very challenging for $E_{\rm vis} \lesssim 30$ MeV.
Best for: double/triple flash ($\mu\mu$, $\mu\pi$, or $\nu\mu e$).

KOTO: $13\ m^3$
Pros: Low-density vol and low bkg
Cons: Further away
Best for: π^0 and $\gamma\gamma$





ND280: $11.7\ m^3$
Pros: Low-density and magnetized
Cons: Further away
Best for: any charged final state



3 GeV protons

$1.1 \cdot 10^{23}$ PoT (3 years)

SNS and LANSCE

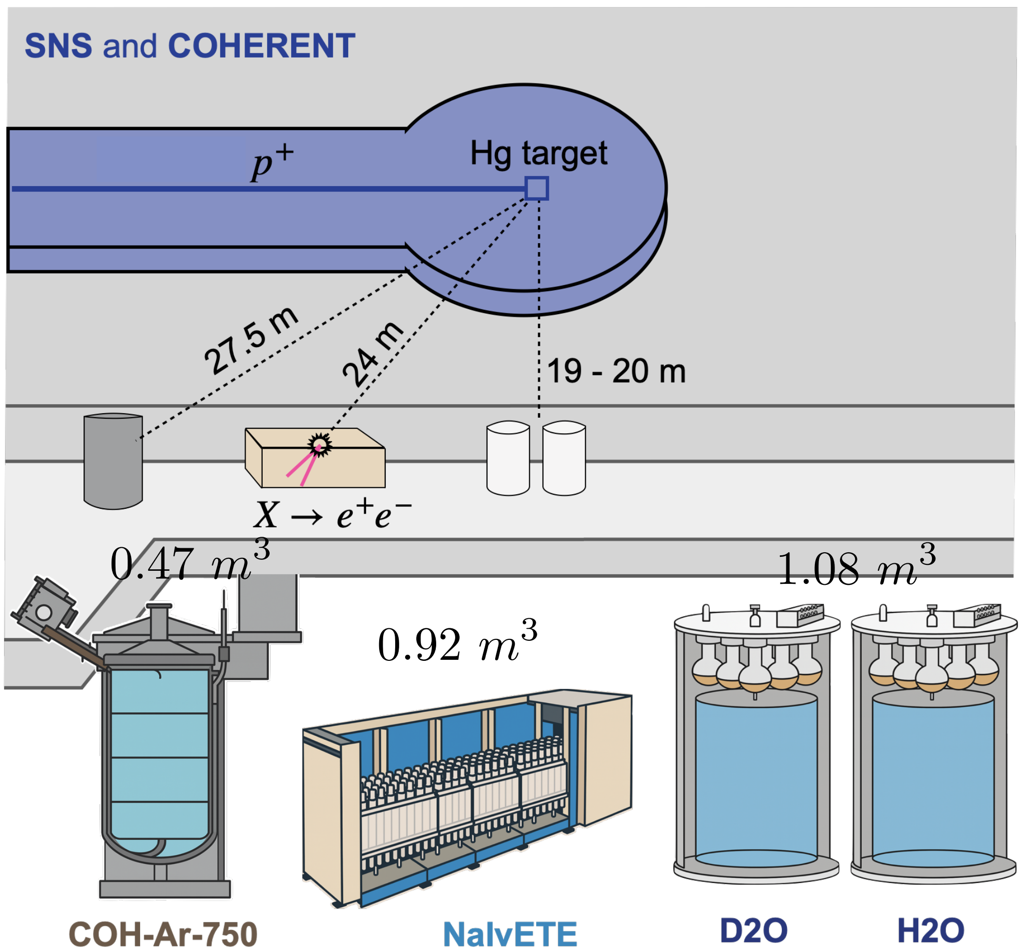
$$\pi^+ \to X \qquad \mu^+ \to X \qquad X \to e^+e^-, \gamma\gamma$$

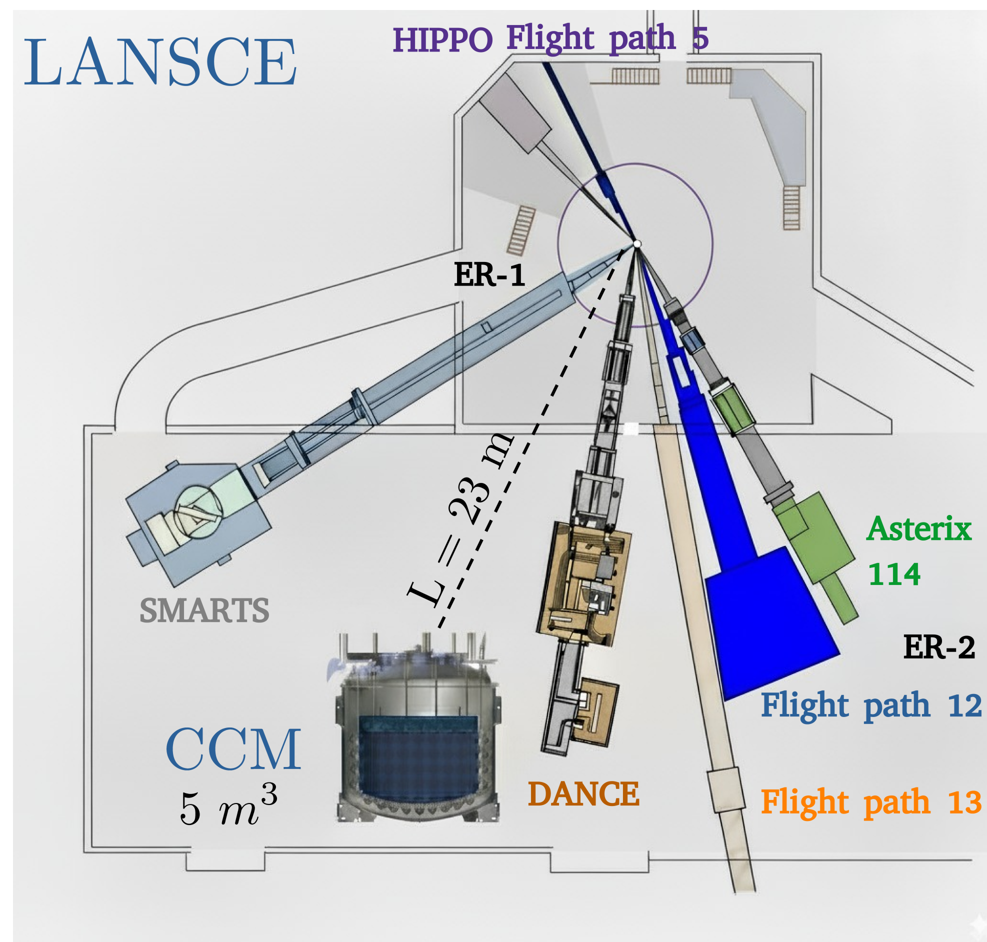
1 GeV protons

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

0.8 GeV protons

$2.25 \cdot 10^{22}$ PoT (3 years)





Results

Models studied in this work

- **Scalar : Higgs portal scalar, Muon scalar**
- **Pseudoscalars: ALPs**
- **Fermions: Heavy neutral leptons**

Models studied in this work

- **Scalar : Higgs portal scalar, Muon scalar**
- **Pseudoscalars: ALPs**
- **Fermions: Heavy neutral leptons**

In this talk

HNLs

HNL

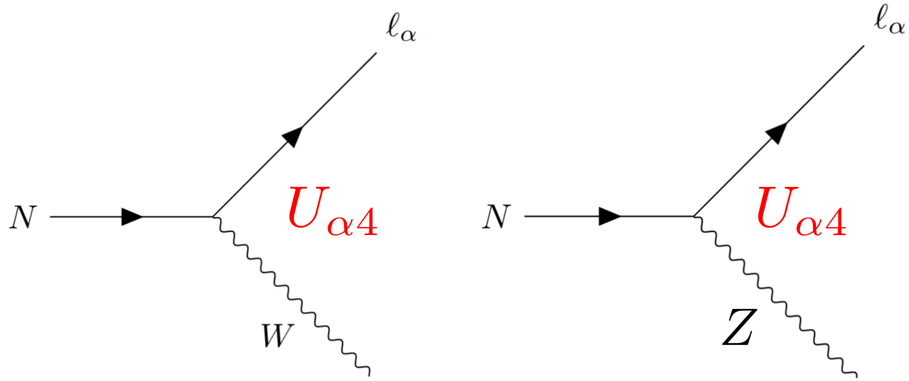
$$\mathcal{L} \supset -\frac{g}{\sqrt{2}}\left(W_\mu^- \bar{l}_{L\alpha}\gamma_\mu U_{\alpha 4} N + \text{h.c.}\right) - \frac{g}{\cos\theta_W}\left(Z_\mu \bar{N}\gamma^\mu U^*_{\alpha 4}\nu_{L\alpha} + \text{h.c.}\right)$$

We consider the simplified phenomenological benchmarks of one HNL mixing with one SM neutrino of a given flavour

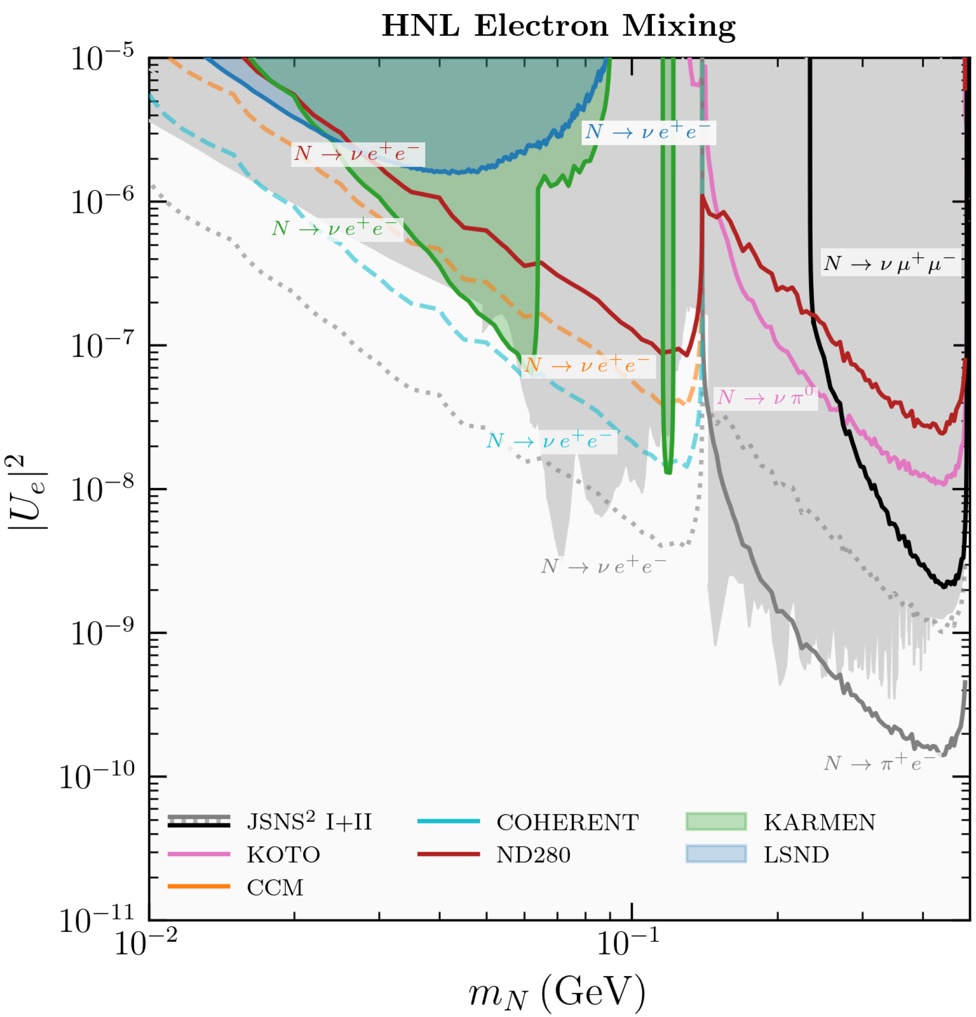
Production

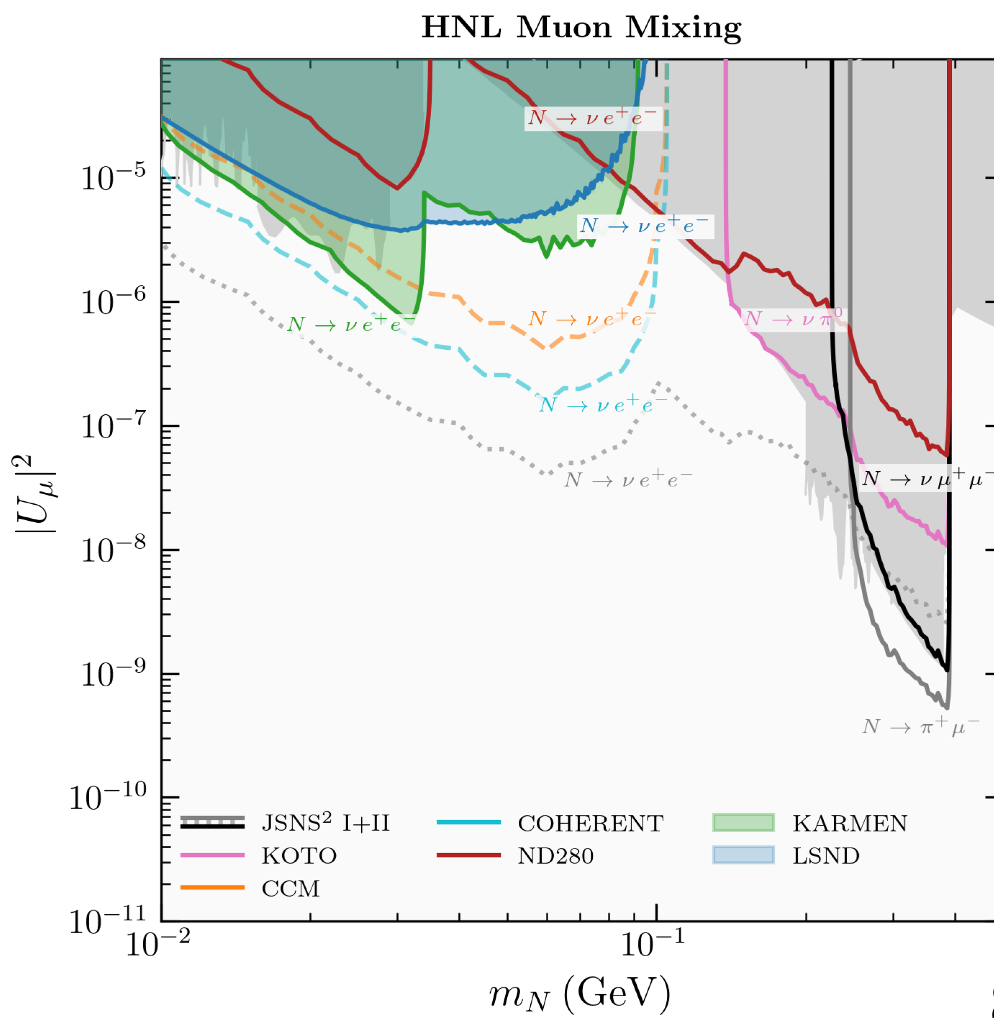
U_{e4}	$U_{\mu 4}$
$K^+ \to e^+ N$	$K^+ \to \mu^+ N$
$\pi^+ \to e^+ N$	$\pi^+ \to \mu^+ N$
$\mu \to e \nu_e N$	$\mu \to e \nu_\mu N$

HNL



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





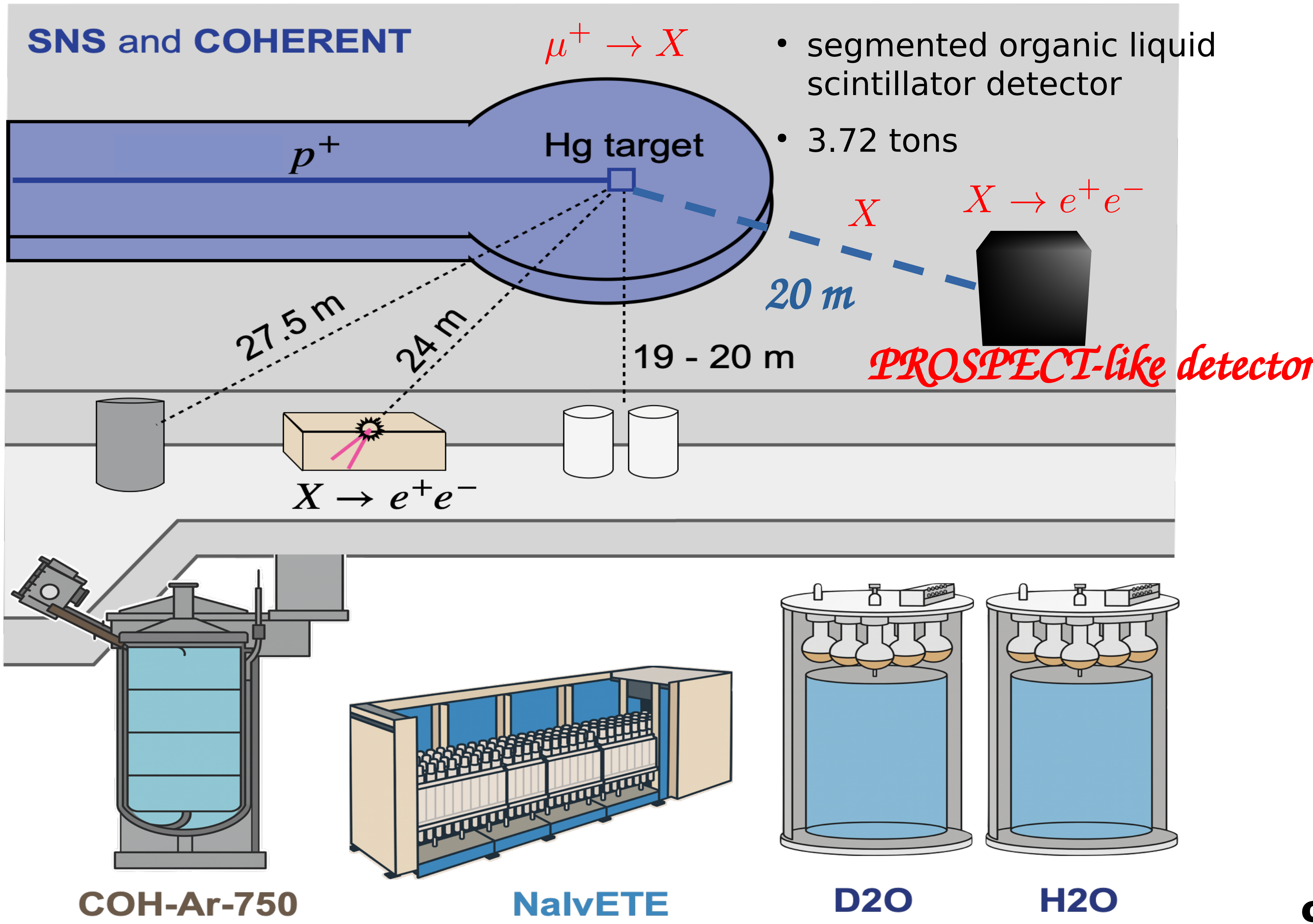
Work in progress

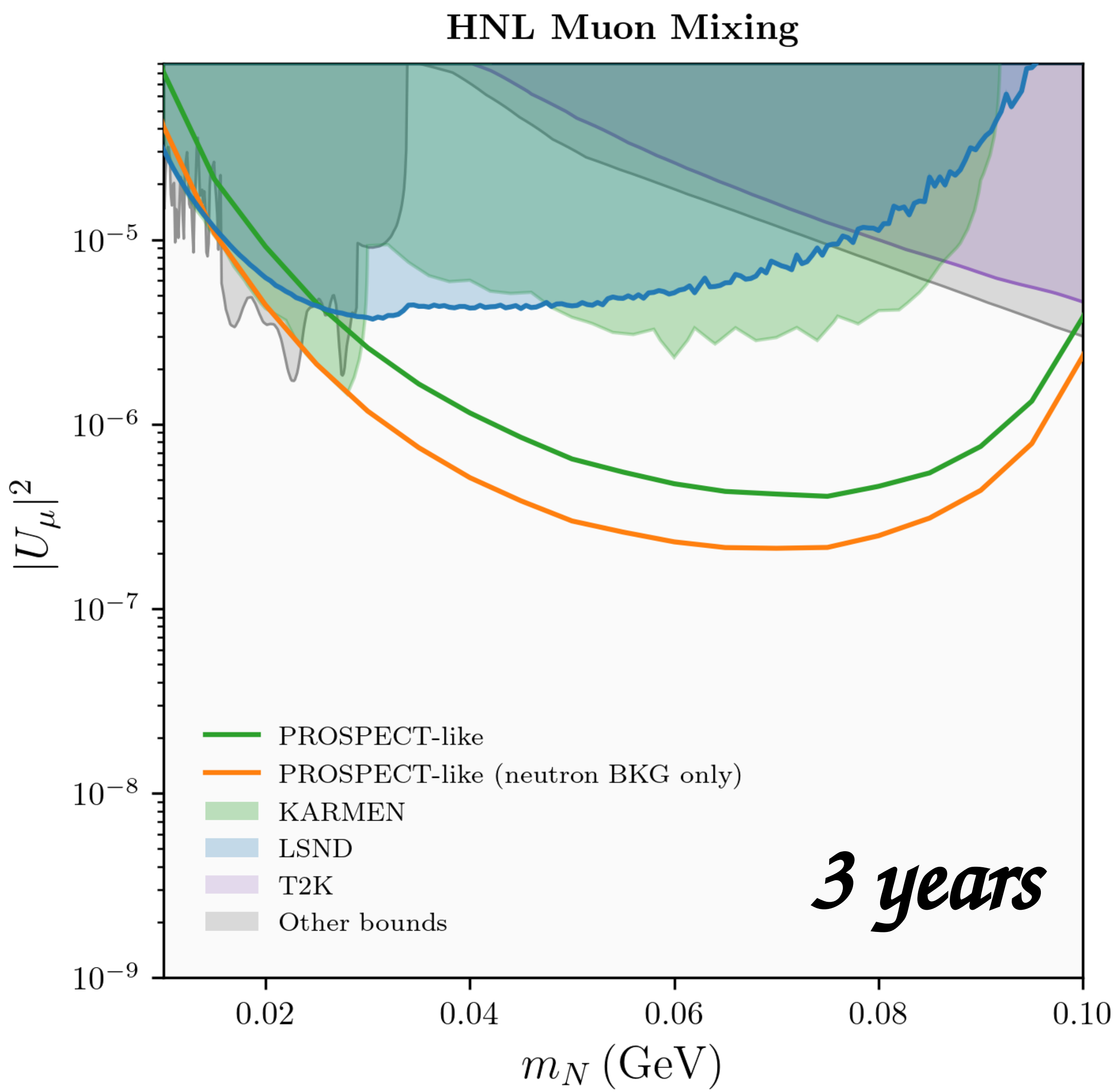
collaborating with PROSPECT

(thanks B. Littlejohn (IIT), F. Machado (IIT), T. Haugen (NIST))

Investigating a new experimental configuration at SNS

- segmented organic liquid scintillator detector
- 3.72 tons





These lines have into account:

- Efficiencies with realistic cuts
- Cosmogenic backgrounds (muons and neutrons)
- Energy reconstruction effects

Summary

- Past experimental data keeps giving us nice surprises, such as those from KARMEN and LSND.

- Spallation sources provide a valuable complementary venue to search for FIPs, particularly those produced in muon and pion decays.

- A PROSPECT-like detector at SNS would be a very promising and realistic way to probe these models.

Thank you

Back up

ALPs

ALPs

Appear in many new Physics models

Warm dark matter

QCD Axion solution and Strong CP problem

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

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

Neutron electric dipole moment

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

Why so small?

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

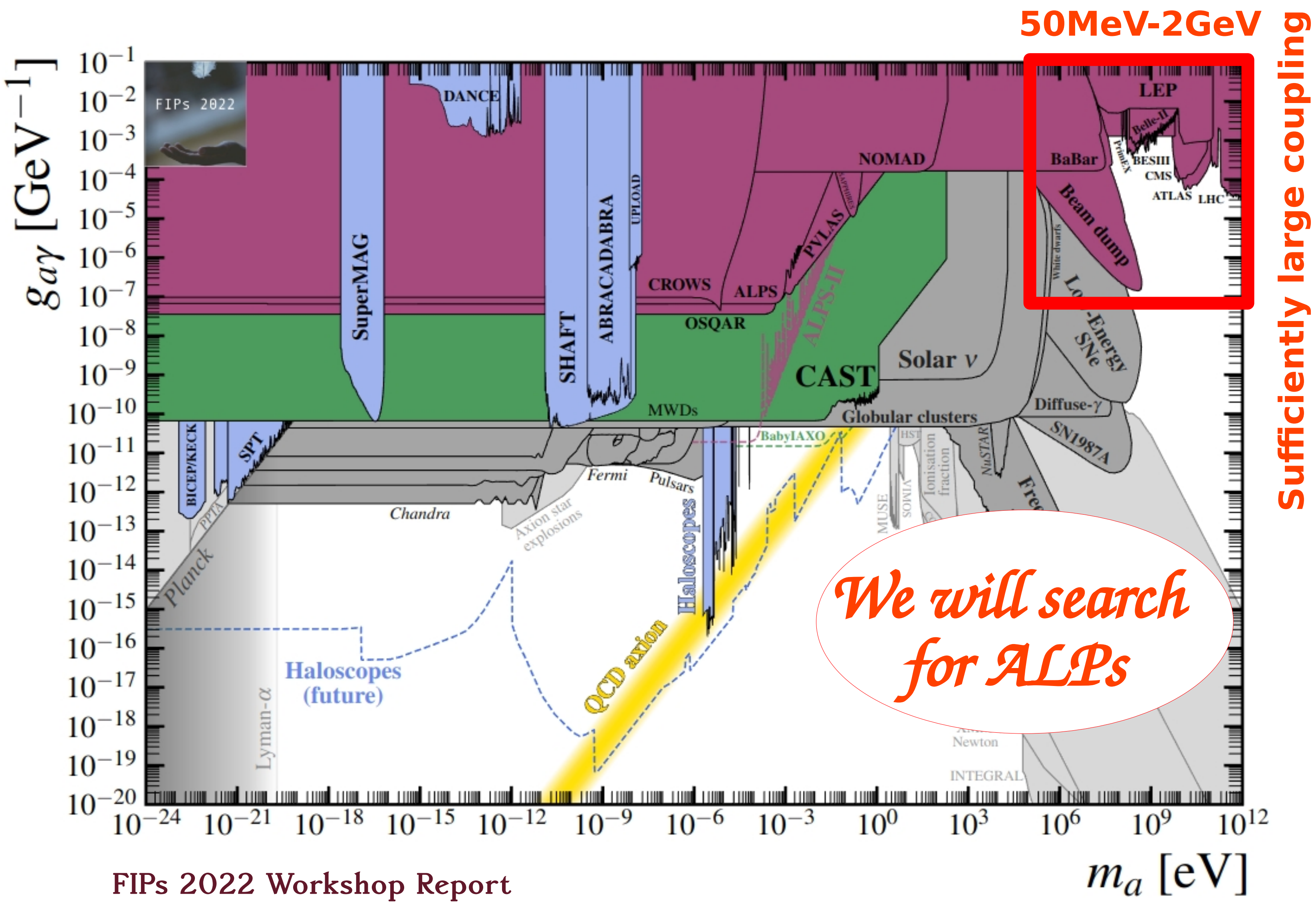
Abel, C., & Others. (2020). Measurement of the Permanent Electric Dipole Moment of the Neutron. Phys. Rev. Lett.

Solves dynamically the Strong CP problem

Peccei, Quinn 1977

Weinberg 1978

How do we search for ALPs?



FIPs 2022 Workshop Report

ALPs: Higgs coupled

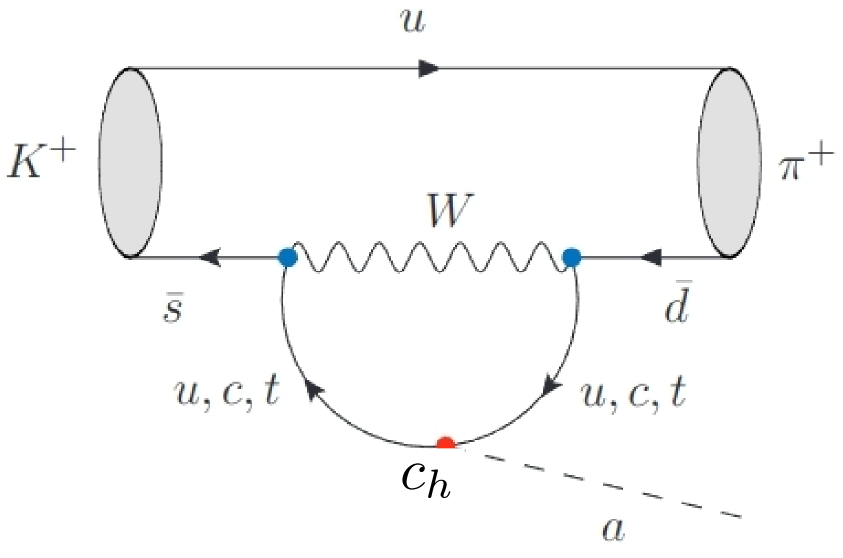
$$L_{\text{ALP}} \supset \frac{1}{2}\left(\partial_\mu a\right)\left(\partial^\mu a\right) - \frac{m_a^2}{2}a^2 + \frac{\partial_\mu a}{f_a}c_h\left(H^\dagger i \overleftrightarrow{D}^\mu H\right)$$

Hypercharge rotation

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

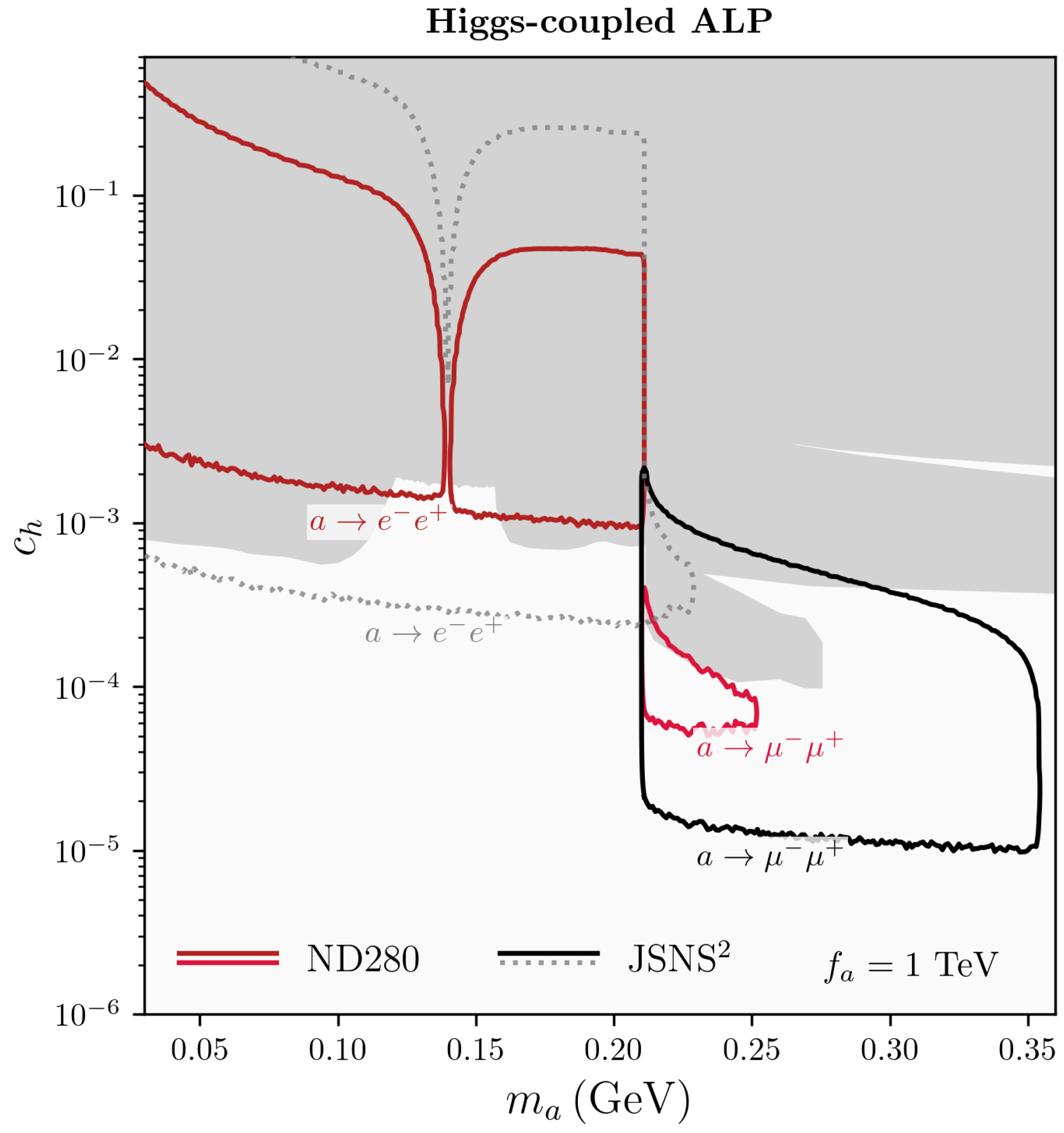
Production

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



ALPs: Higgs coupled

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



ALPs: Leptophilic

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

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

Lepton Flavour conserving (LFC)

$$c_{ij}^{L,R,\nu} = \delta_{ij} \times c_j^{L,R,\nu},$$

- **Weak conserving (WC)**

$$c_{ii}^L = -c_{ii}^R, \quad c_{ii}^\nu = -c_{ii}^L.$$

- **Weak violating (WV)**

$$c_{ii}^L = -c_{ii}^R,, \quad c_{ii}^\nu = 0.$$

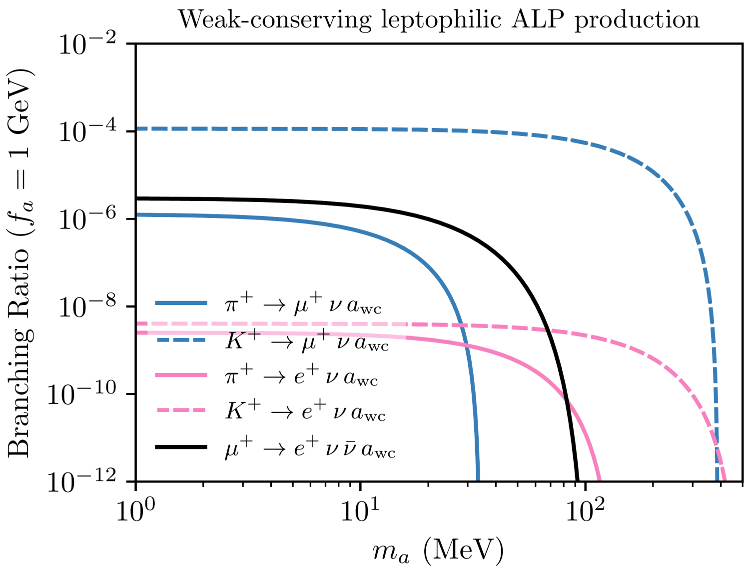
Lepton Flavour violating (LFV)

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

$$c_{ij}^L = -c_{ij}^R \text{ and } c_{ij}^\nu = -c_{ij}^L.$$

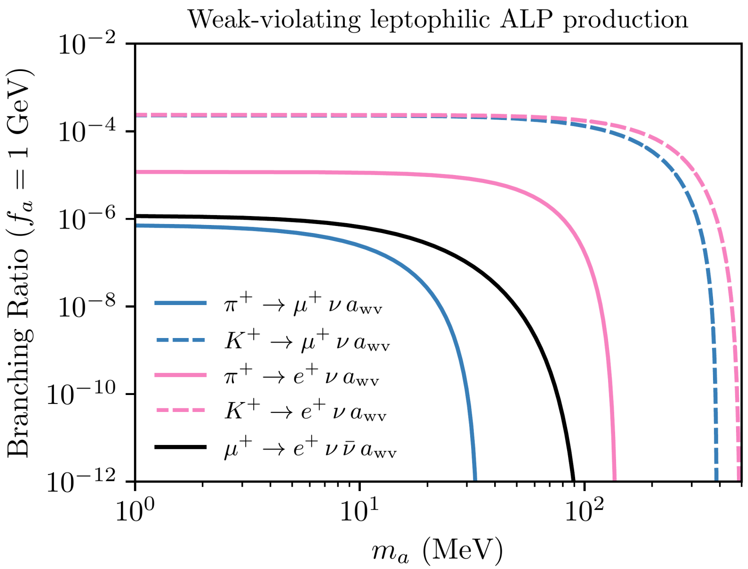
Production

Lepton Flavour conserving (LFC)



Helicity suppression lifted

$$M^+ \to e^+ \nu_e a_\ell$$



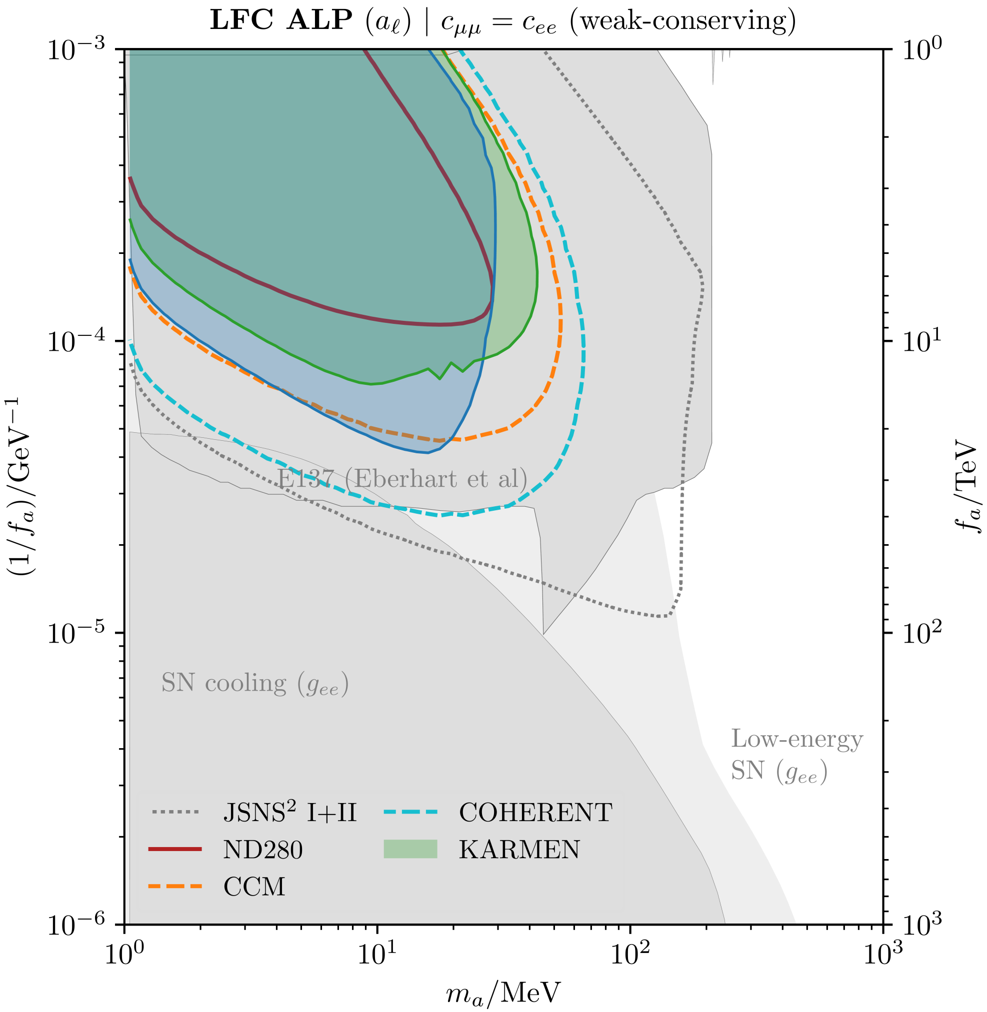
Lepton Flavour violating (LFV)

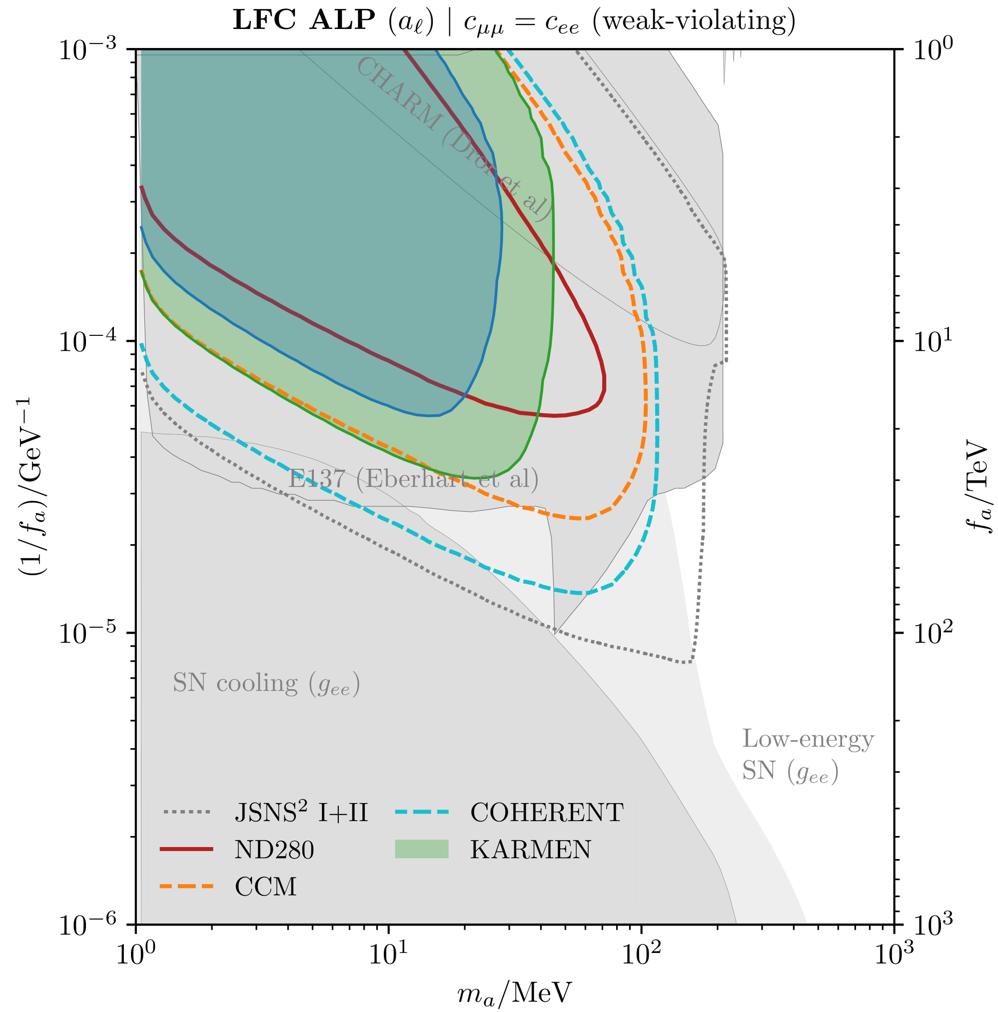
$$\Gamma\left(\mu^+ \to e^+ a_\ell\right) \simeq \left(\left|c^L_{e\mu}\right|^2 + \left|c^R_{e\mu}\right|^2\right) \frac{m_\mu^3}{32\pi f_a^2} f\left(r_e, r_a\right),$$

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

Lepton Flavour conserving (LFC): universal

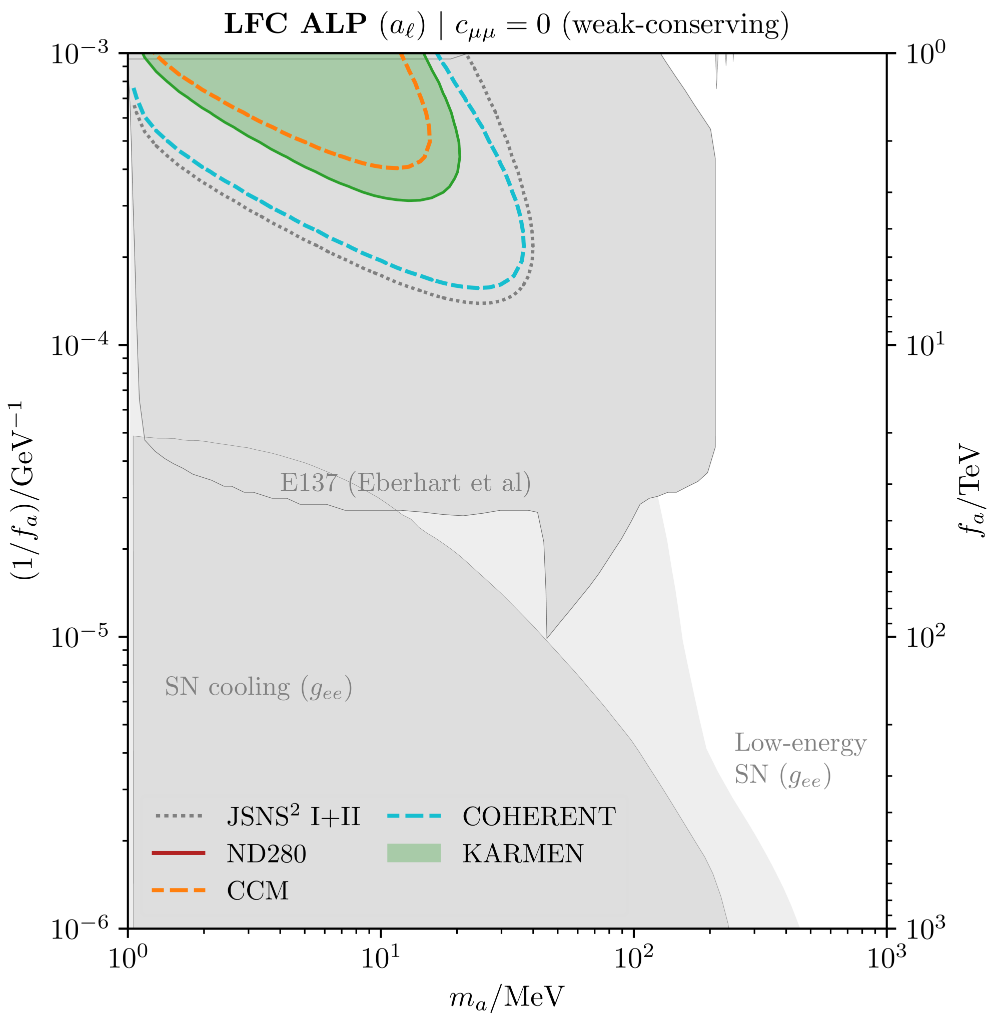
$$a_\ell \to e^+e^-$$

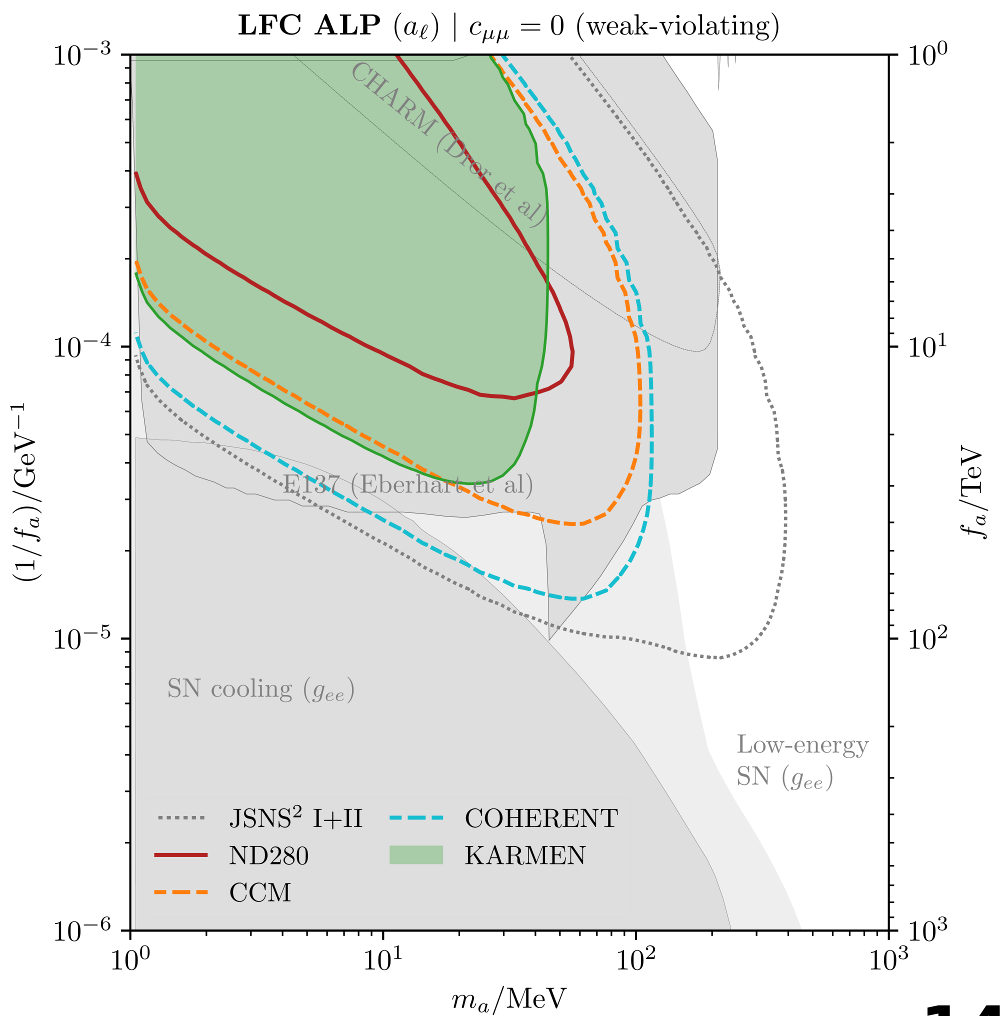




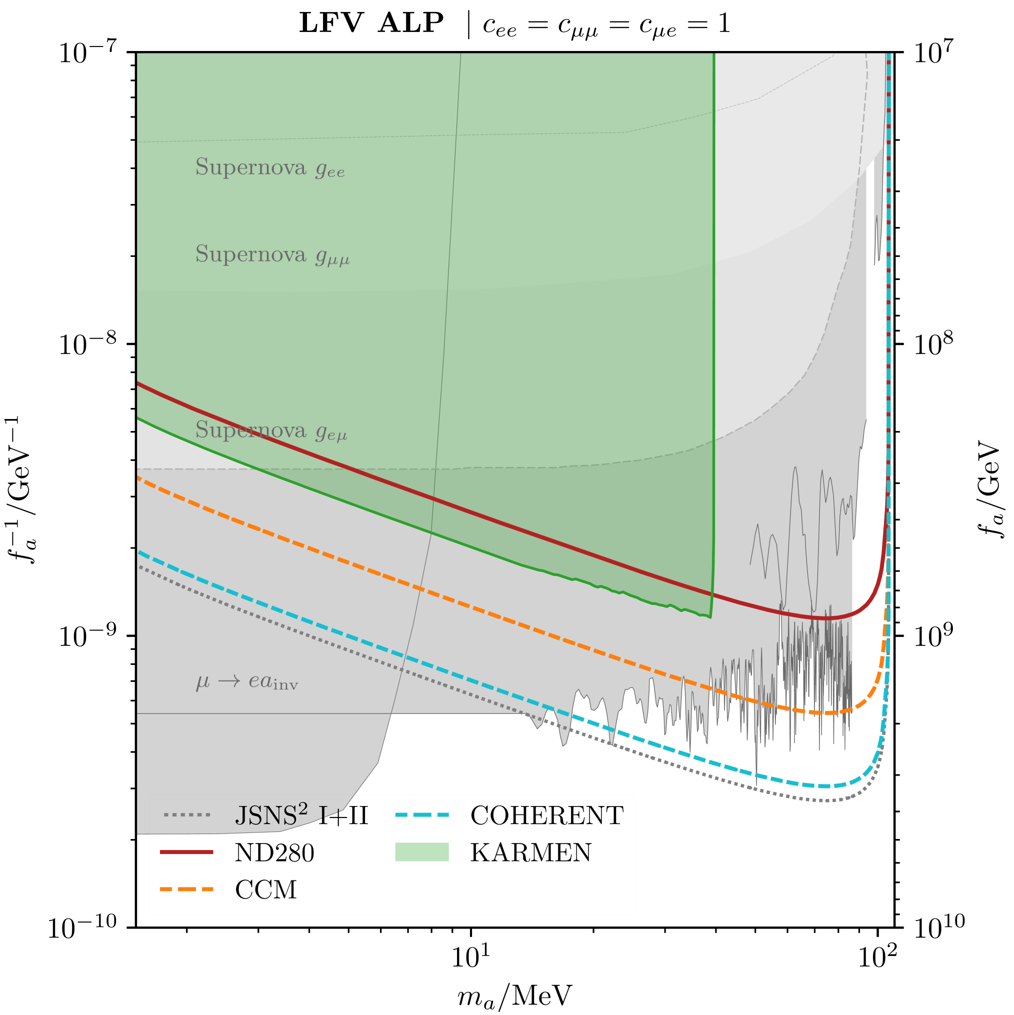
Lepton Flavour conserving (LFC): electron dominance

$$a_\ell \to e^+e^-$$

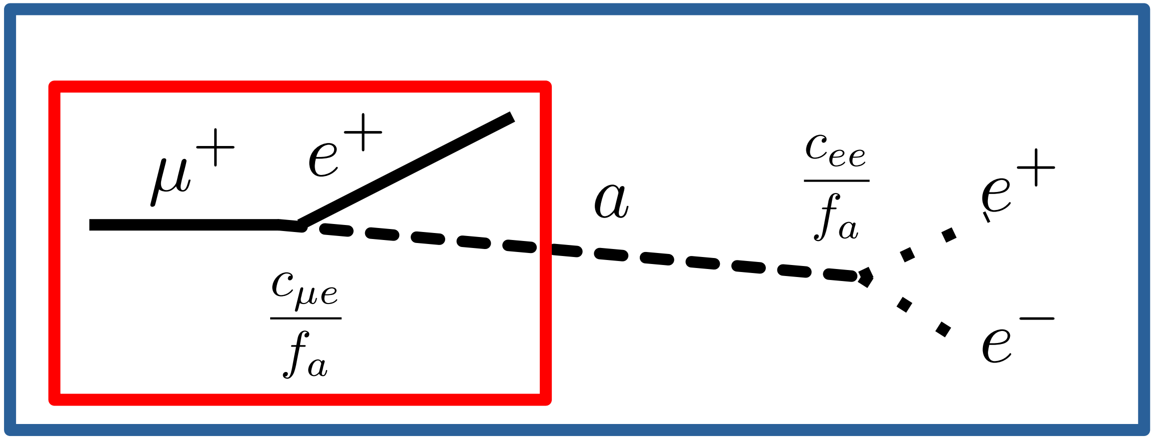




Lepton Flavour violating (LFV)

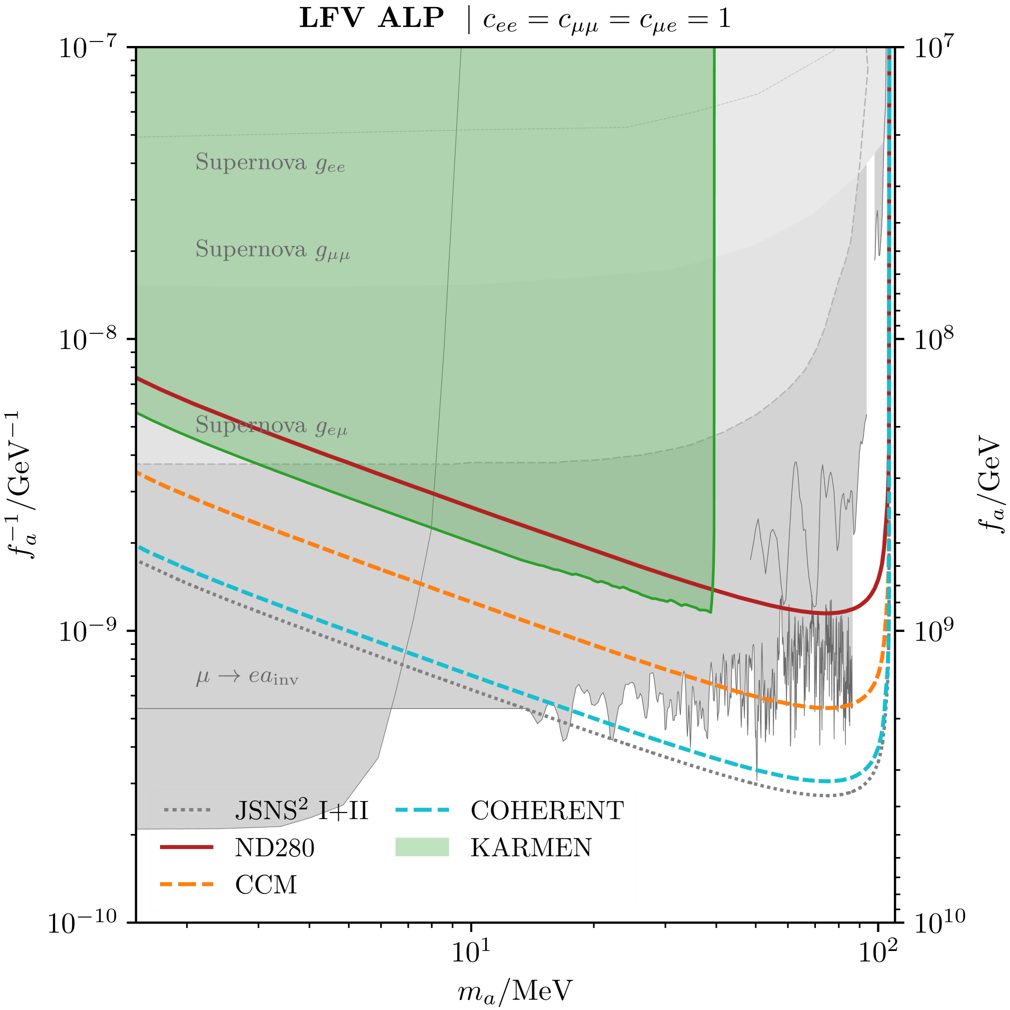


Lepton Flavour violating (LFV)

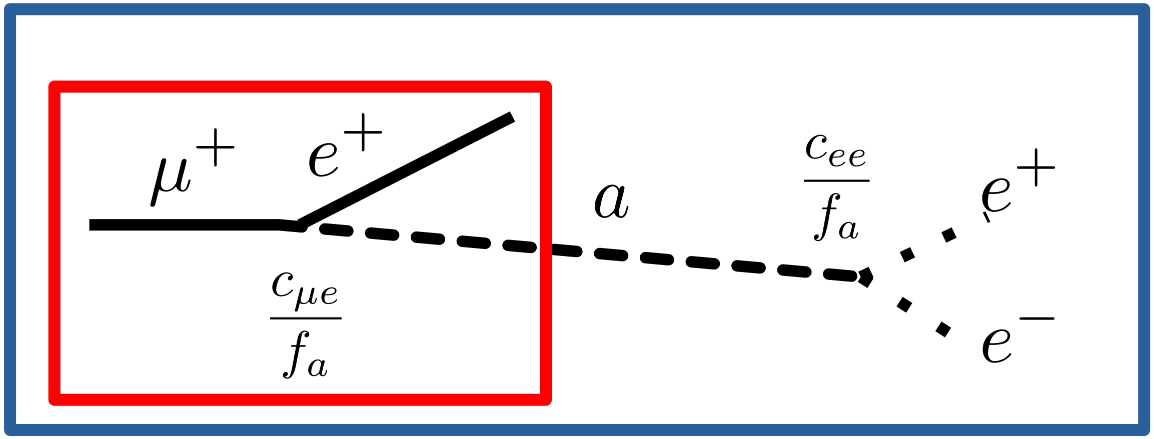


Rare muon decays $\propto \frac{c_{\mu e}^2}{f_a^2}.$

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



Lepton Flavour violating (LFV)



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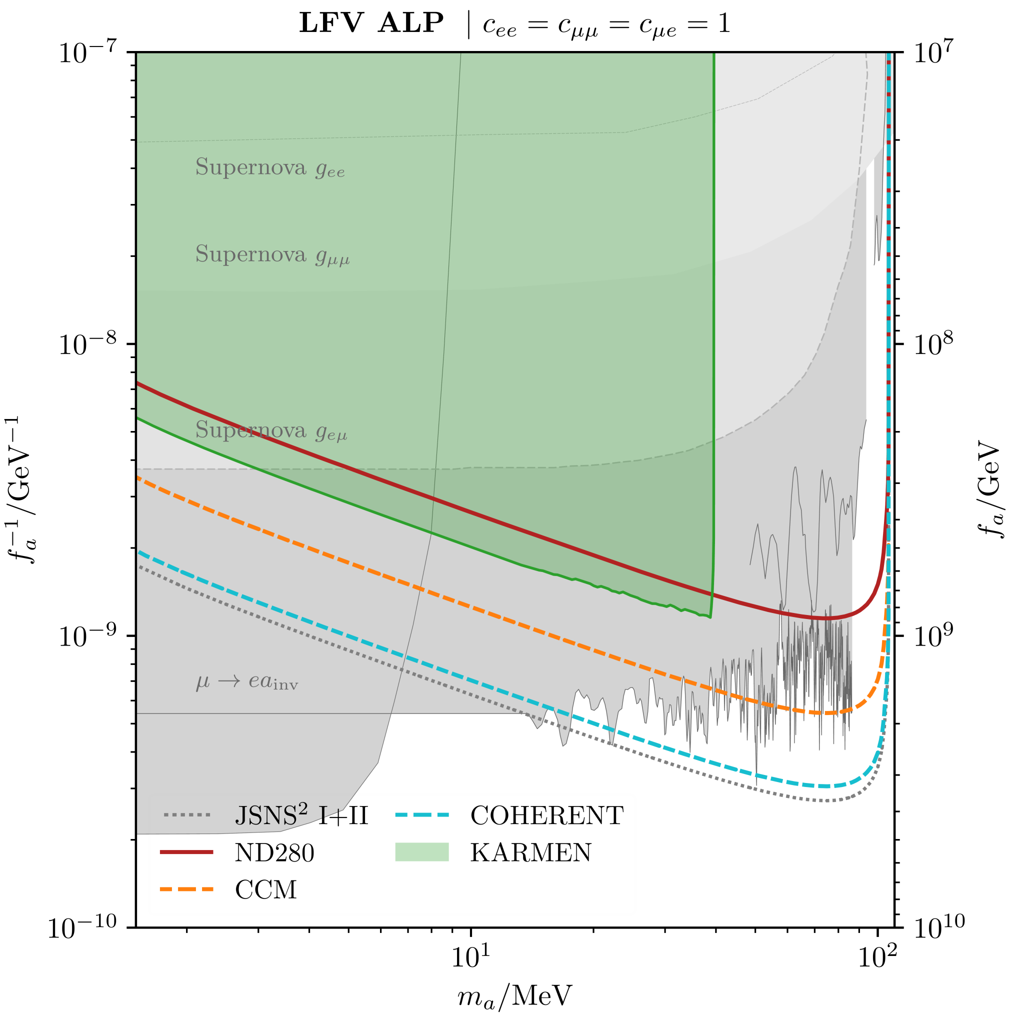
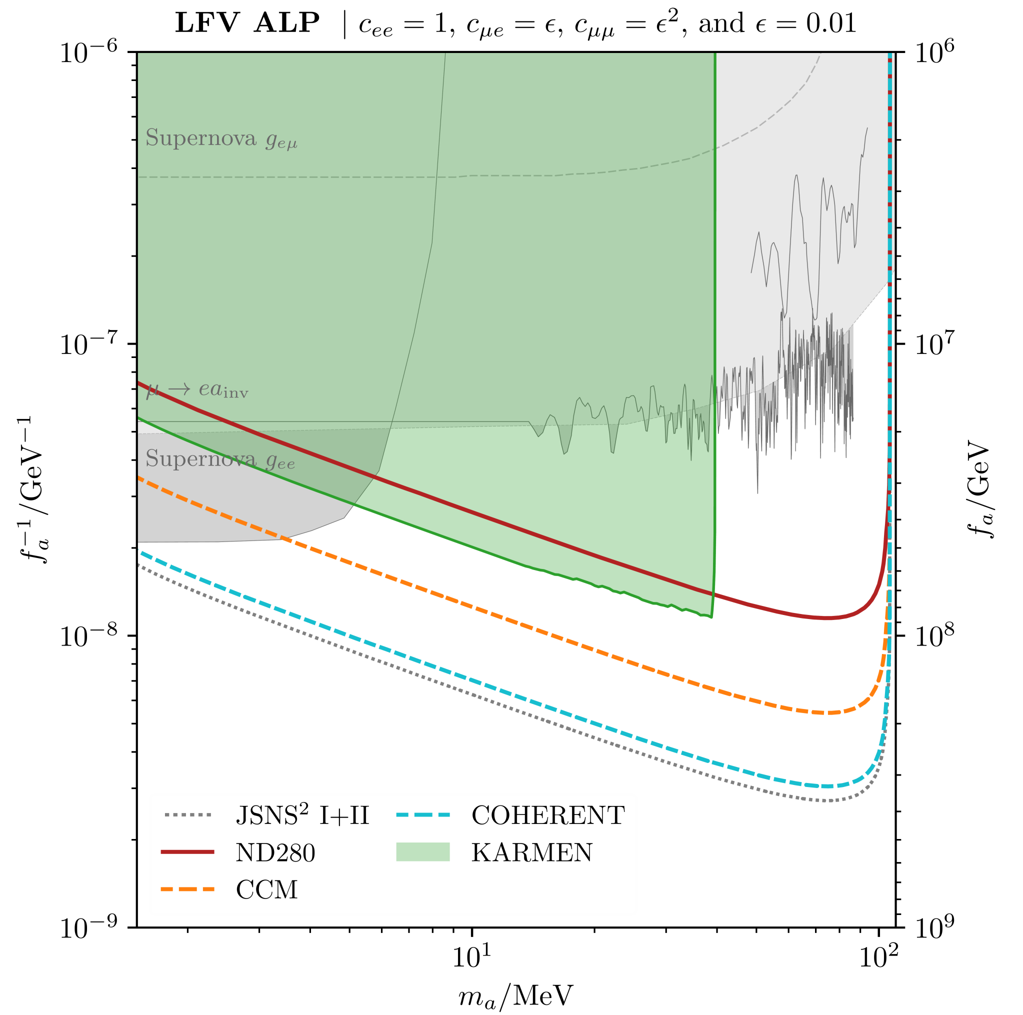
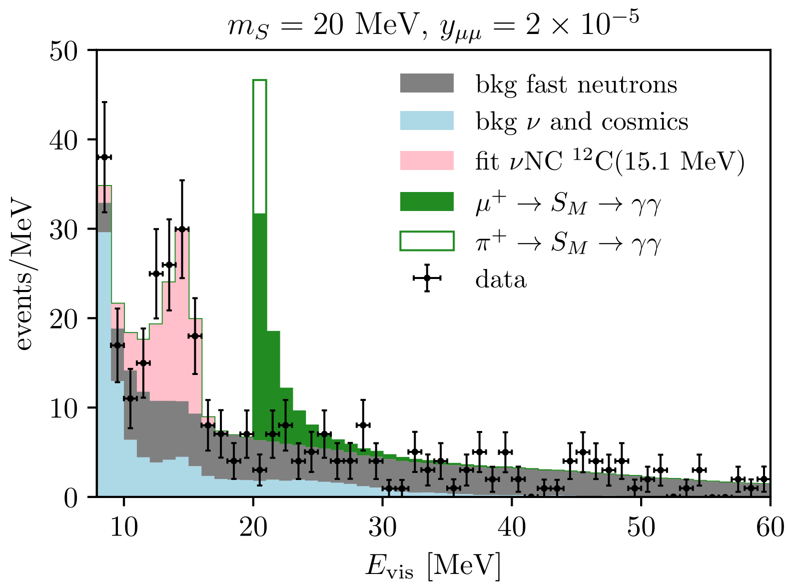
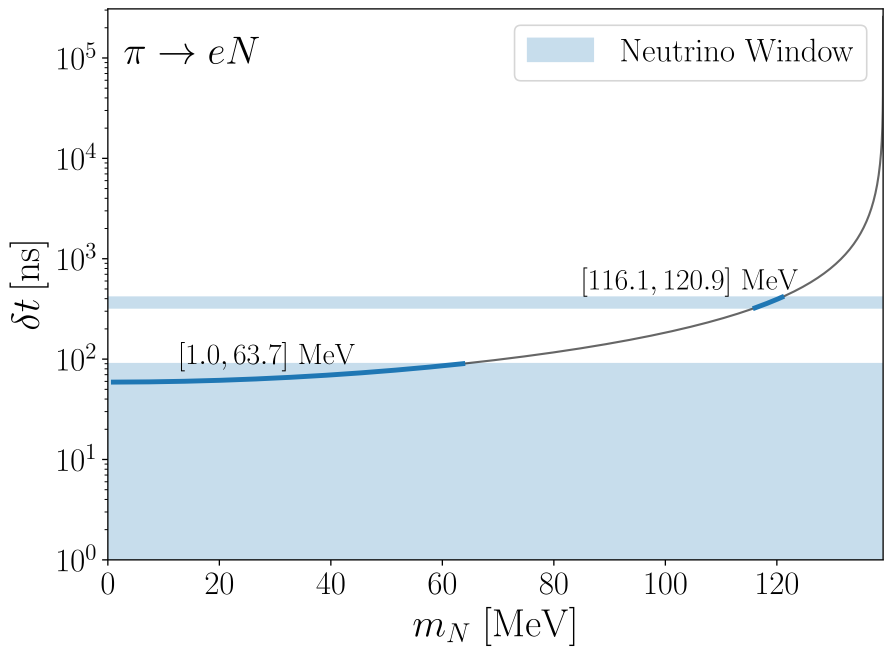




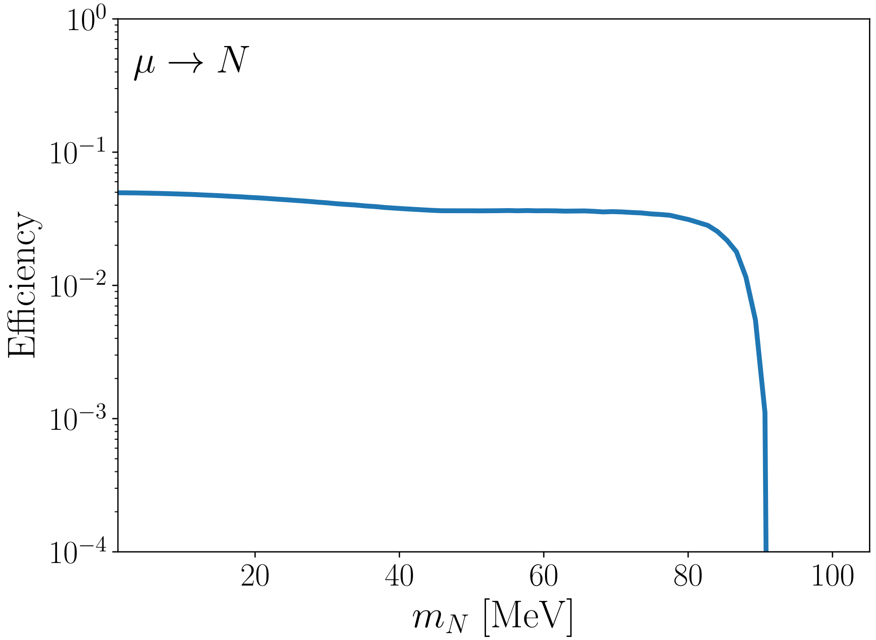
KARMEN



$m_S = 20$ 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_{vis} [MeV]

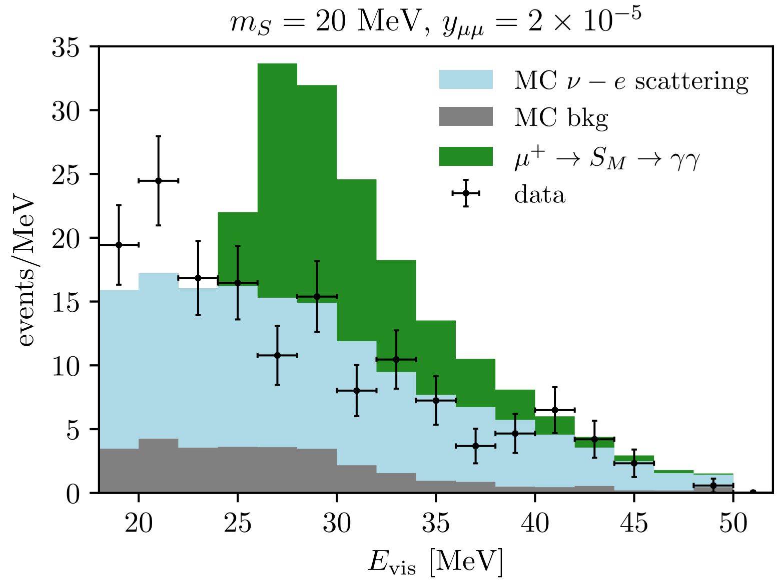


$\pi \to eN$
Neutrino Window
[116.1, 120.9] MeV
[1.0, 63.7] MeV
δt [ns]
m_N [MeV]

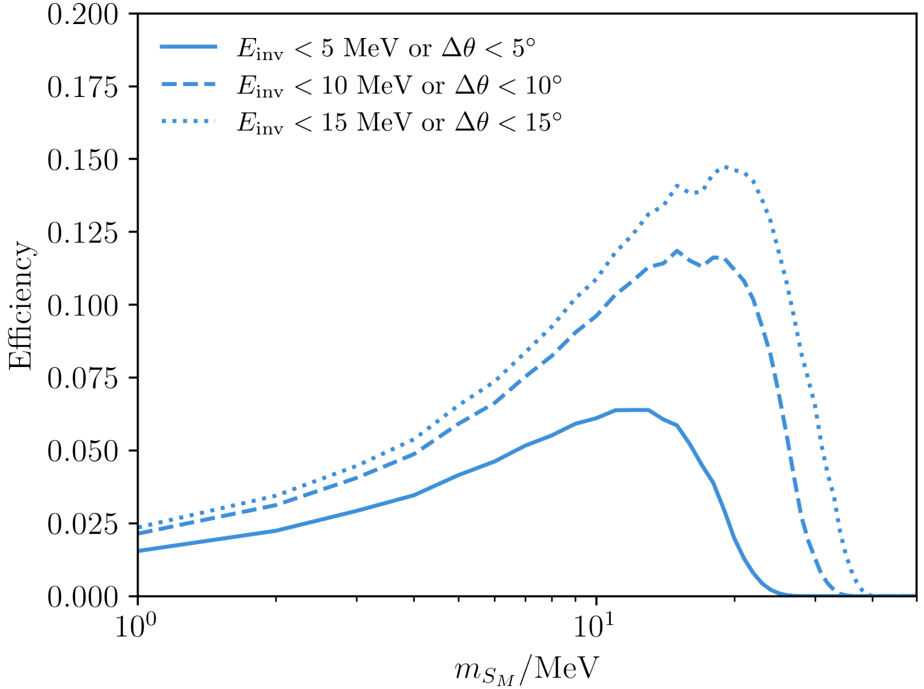


$\mu \to N$
Efficiency
m_N [MeV]

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

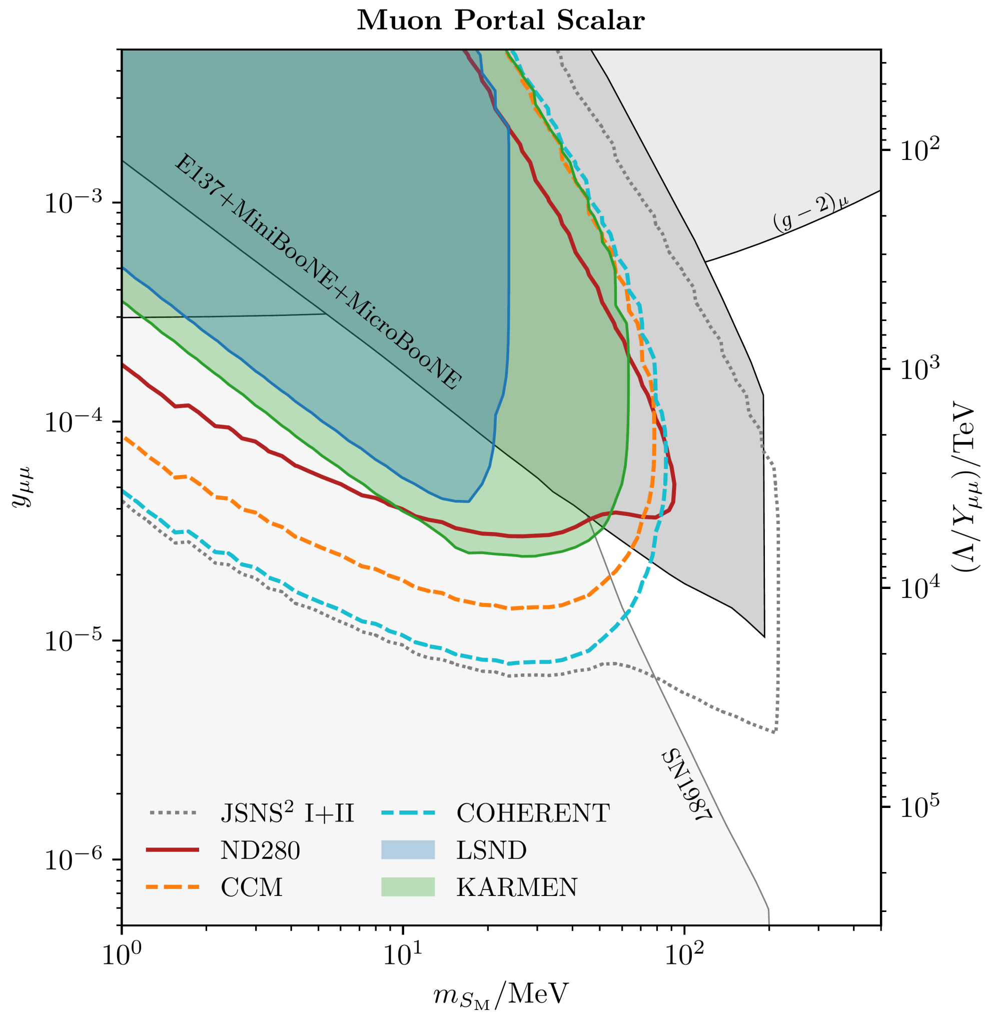
Muon scalar

$$\mathrm{L}_{S_M} \supset \frac{1}{2}\partial_\mu S_M \partial^\mu S_M - \frac{m_{S_M}^2}{2} S_M^2 - y_{\mu\mu} S_M \bar{\mu}\left(c_S + c_P \gamma_5\right)\mu$$

$$\Gamma_{S_M\to\gamma\gamma} = \frac{\alpha^2 m_{S_M}^3}{64\pi^3}\left|\frac{y_{\mu\mu}}{m_\mu} x[1+(1-x)f(x)]\right|^2,$$

with the loop function

$$f(x) = \begin{cases} \arcsin^2\left(\sqrt{x^{-1}}\right), & x > 1 \\ -\frac{1}{4}\left[\ln\left(\frac{1+\sqrt{1-x}}{1-\sqrt{1-x}}\right) - i\pi\right]^2, & x \le 1 \end{cases}$$



Higgs portal scalar

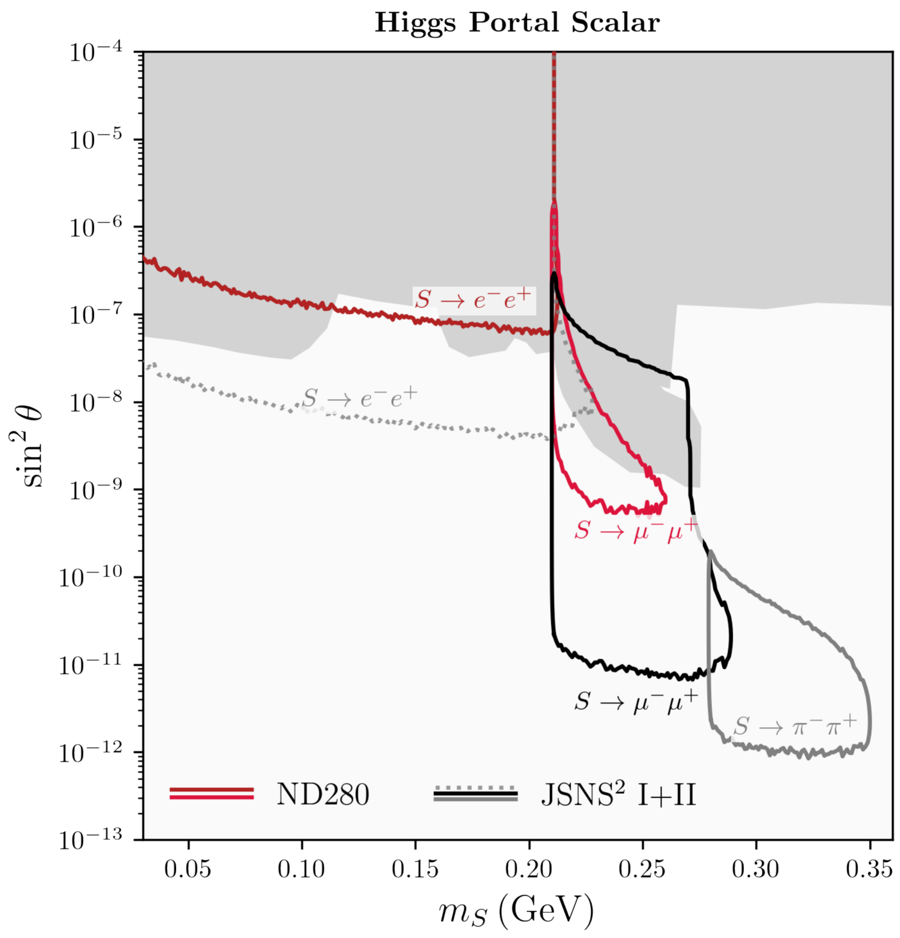
$$L_S \supset \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{m_{S_M}^2}{2} S^2 - \sin\theta S \sum_f \left(\frac{m_f}{v}\bar{f}f\right)$$

$$K^+ \to \pi^+ S$$

$$\Gamma_{S\to\ell^+\ell^-} = \sin^2\theta \frac{m_\ell^2 m_S}{v^2 8\pi}\left(1-\frac{4m_\ell^2}{m_S^2}\right)^{3/2}.$$

$$\Gamma_{S\to\pi\pi} = \sin^2\theta \frac{3\left|G_\pi\left(m_S^2\right)\right|^2}{32\pi v^2 m_S}\left(1-\frac{4m_\pi^2}{m_S^2}\right)^{1/2},$$

where $G_\pi(s) = \left(2s + m_\pi^2\right)/9$



We add two new neutrinos to the SM particle content

N_R^1 $\quad$ N_R^2

$L = 1$ $\quad$ $L = -1$

$$\mathcal{L} \supset -\left(Y_\alpha \, \bar{\ell}_\alpha \, \tilde{\phi} \, N_R^1 + \underline{\epsilon \, Y'_\alpha \, \bar{\ell}_\alpha \, \tilde{\phi} \, N_R^2} + \frac{\Lambda}{2} \, \bar{N}_R^{1c} \, N_R^2 + \underline{\frac{\mu}{2} \, \bar{N}_R^{2c} \, N_R^2} \right) + \text{h.c.}$$

Sources of lepton number violation

$$\mathrm{M} = \begin{pmatrix} \mathbf{0} & \mathbf{Y} v & \epsilon \, \mathbf{Y}' v \\ \mathbf{Y}^T v & 0 & \Lambda \\ \epsilon \, \mathbf{Y}'^T v & \Lambda & \mu \end{pmatrix}$$

Linear-inverse seesaw (LISS) = Linear seesaw + Inverse seesaw

$$|Yv|\,,|\epsilon Y'v|,|\mu| \ll \Lambda$$

$$\mathrm{U}_B^T M_{\mathrm{LISS}} U_B = \begin{pmatrix} m_{\mathrm{light}}^{3\times 3} & 0_{3\times 1} & 0_{3\times 1} \\ 0_{1\times 3} & \multicolumn{2}{c}{\multirow{2}{*}{$M_{\mathrm{heavy}}^{2\times 2}$}} \\ 0_{1\times 3} & & \end{pmatrix}$$

$$m_\nu \equiv m_{\mathrm{light}} \simeq \frac{1}{\Lambda}\left(\mu\,\frac{Y_N Y_N^T v^2}{\Lambda} - \left(\epsilon v^2 Y_N Y_N'^T + \epsilon v^2 Y_N' Y_N^T\right)\right)$$

$$\mathrm{M}_{\mathrm{heavy}} \simeq \begin{pmatrix} 0 & \Lambda \\ \Lambda & \mu \end{pmatrix} \qquad m_{4,5} \simeq \Lambda \pm \frac{1}{2}|\mu|$$

The two heavy neutrinos form a pseudo-Dirac pair

How do we give mass to neutrinos?

ΔL conserved

Higgs mechanism

$$m_\nu \sim y_\nu \frac{v}{\sqrt{2}}$$

$y_\nu < 6.5 \cdot 10^{-13}$

Why so small?

ΔL largely violated

High scale See-saw

$$m_\nu \sim \frac{y_\nu^2 v^2}{M}$$

If $y_\nu^2 \sim O(1) \to M \sim 10^{11}\mathrm{GeV}$,

If $y_\nu^2 \sim O(y_e^2) \to M \sim 1\mathrm{GeV}$,

Schechter and Valle 1980; Mohapatra and Senjanovic 1979; Minkowski 1977; Gell-Mann, Ramond and Slansky 1979; Yanagida 1980

ΔL approximately conserved

Low scale see-saw

$$m_\nu \sim \frac{v^2}{M^2}\mu$$

$\mu \ll 1$

Symmetry protected scenarios

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
$$m_\nu \sim y_\nu \frac{v}{\sqrt{2}}$$	$$m_\nu \sim \frac{y_\nu^2 v^2}{M}$$	$$m_\nu \sim \frac{v^2}{M^2}\mu$$
$y_\nu < 6.5 \cdot 10^{-13}$	If $y_\nu^2 \sim O(1) \rightarrow M \sim 10^{11}\mathrm{GeV}$,	$\mu \ll 1$
Why so small?	If $y_\nu^2 \sim O(y_e^2) \rightarrow M \sim 1\mathrm{GeV}$,	**Symmetry protected scenarios**
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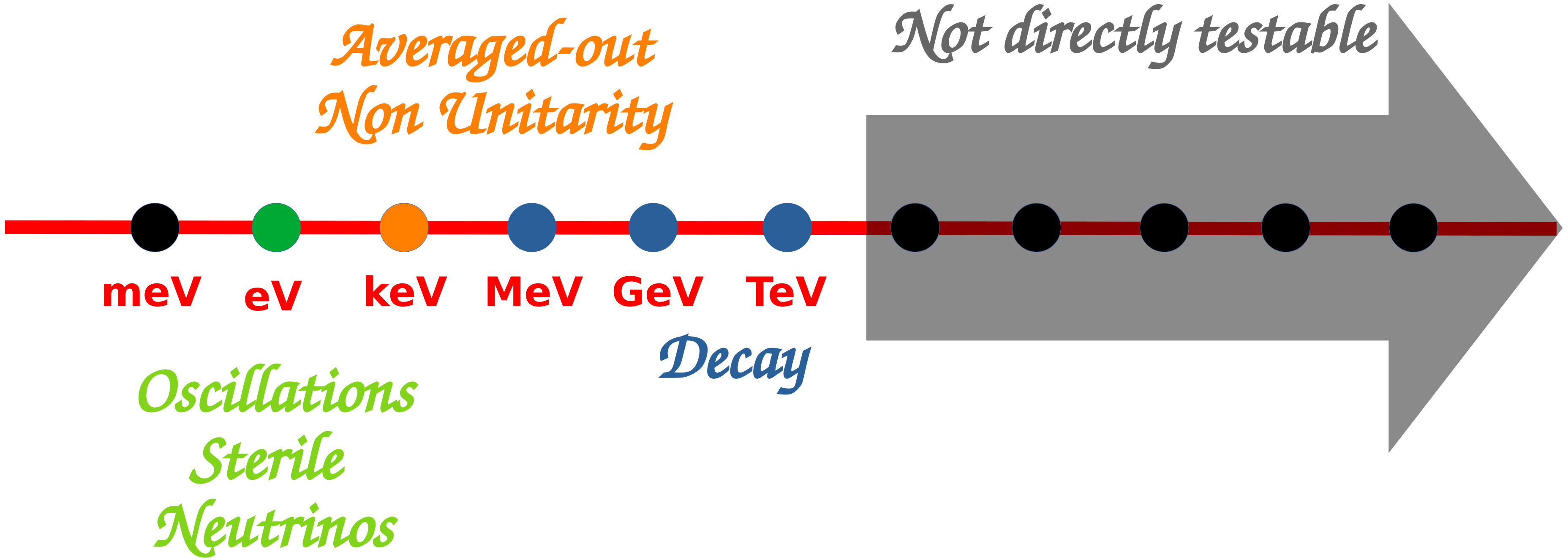
How do we give mass to neutrinos?

New Physics scale M



How do we give mass to neutrinos?

New Physics scale M