Long-Lived Particles at Spallation Neutron Sources

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This week on arXiv

in collaboration with Matheus Hostert

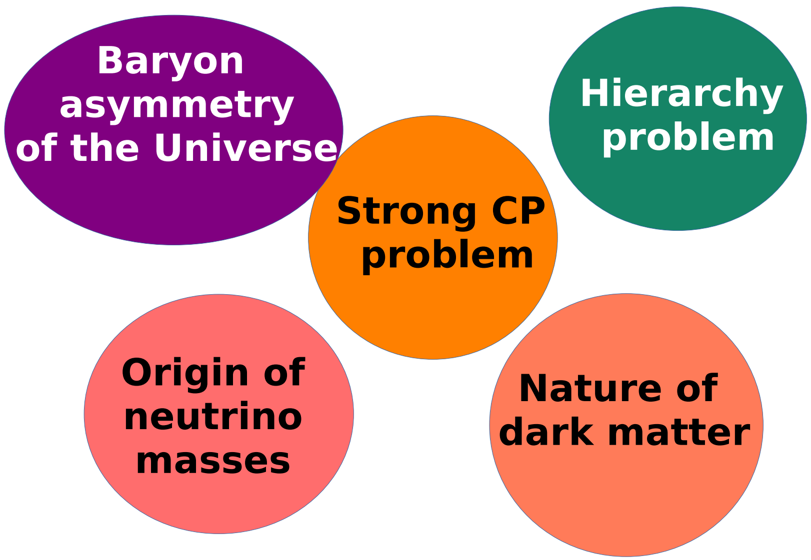
Light Dark World September 17, 2025

IJCLab Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis

cnrs

FIPs

Open problems

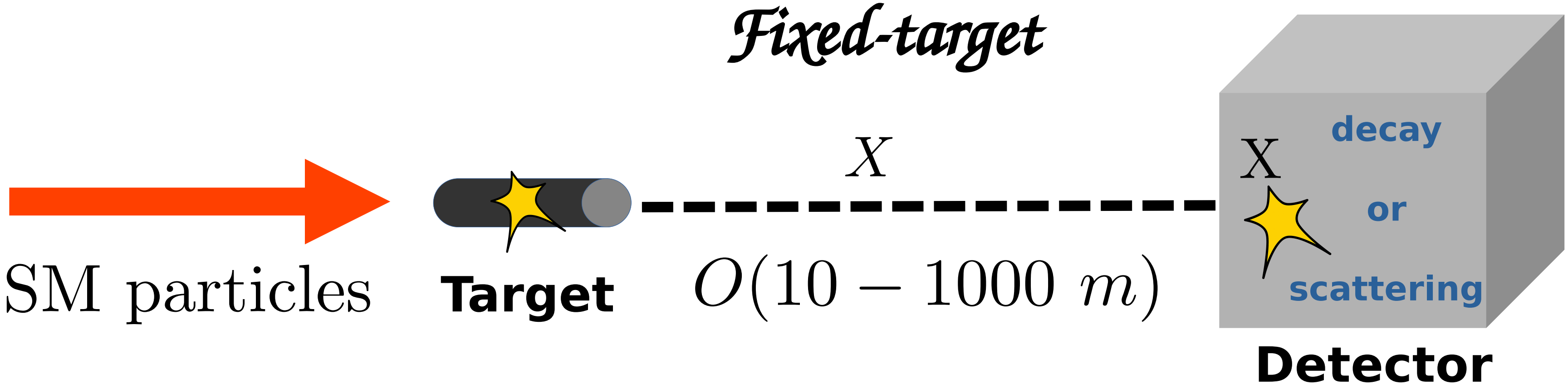


Call for new physics

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

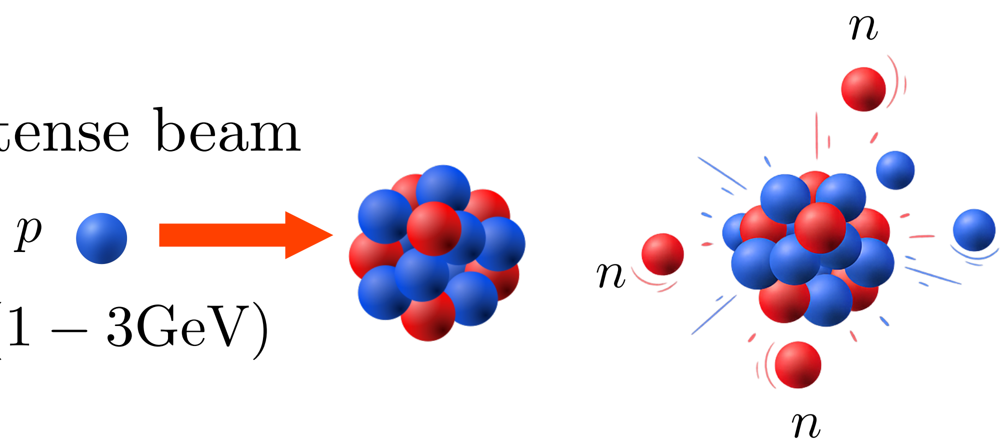
Long lived particles

Fixed-target



What is a spallation neutron source?

Intense beam



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

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

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

Meson production

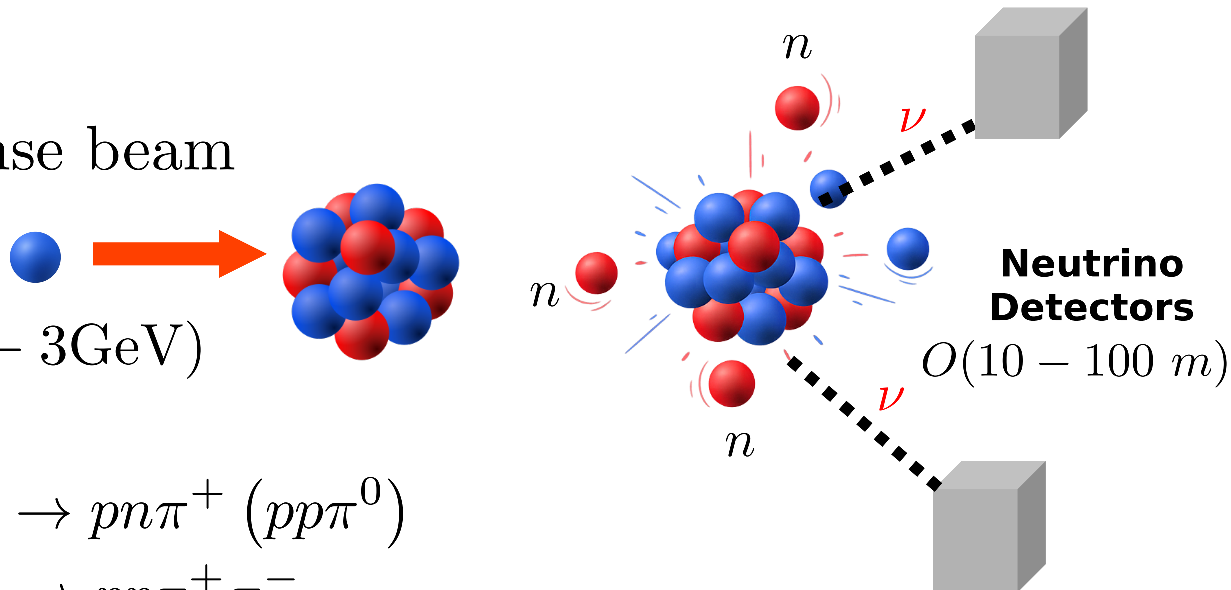
Lose energy and decay at rest	**Captured**
$\pi^+/K^+ \to \mu^+\nu_\mu$	π^-, K^-

What is a spallation neutron source?

Intense beam

p

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



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

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

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

Sterile neutrinos **CEvNS**

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

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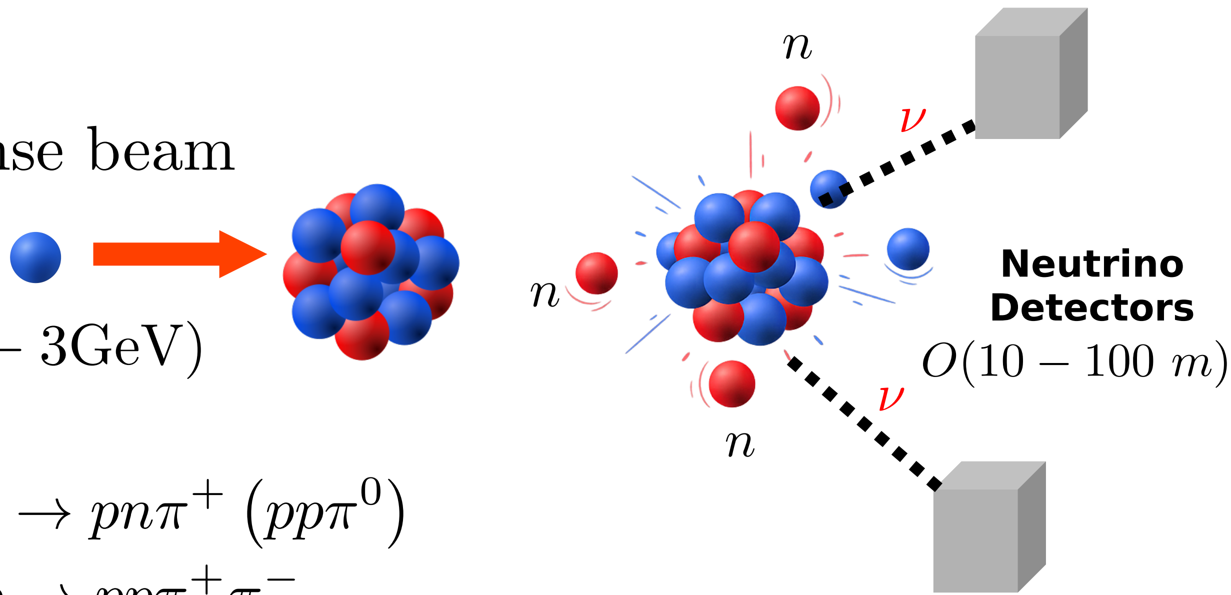

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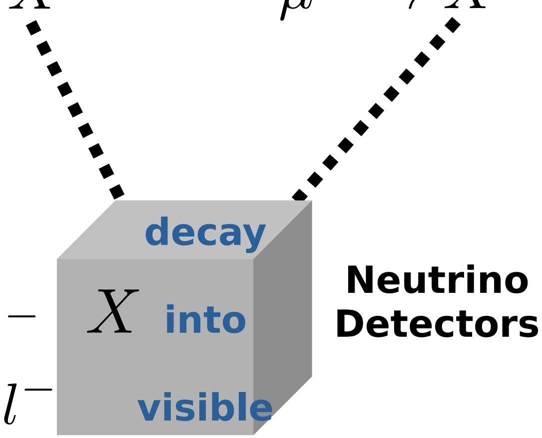
Meson production

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

- **FIPs searches**

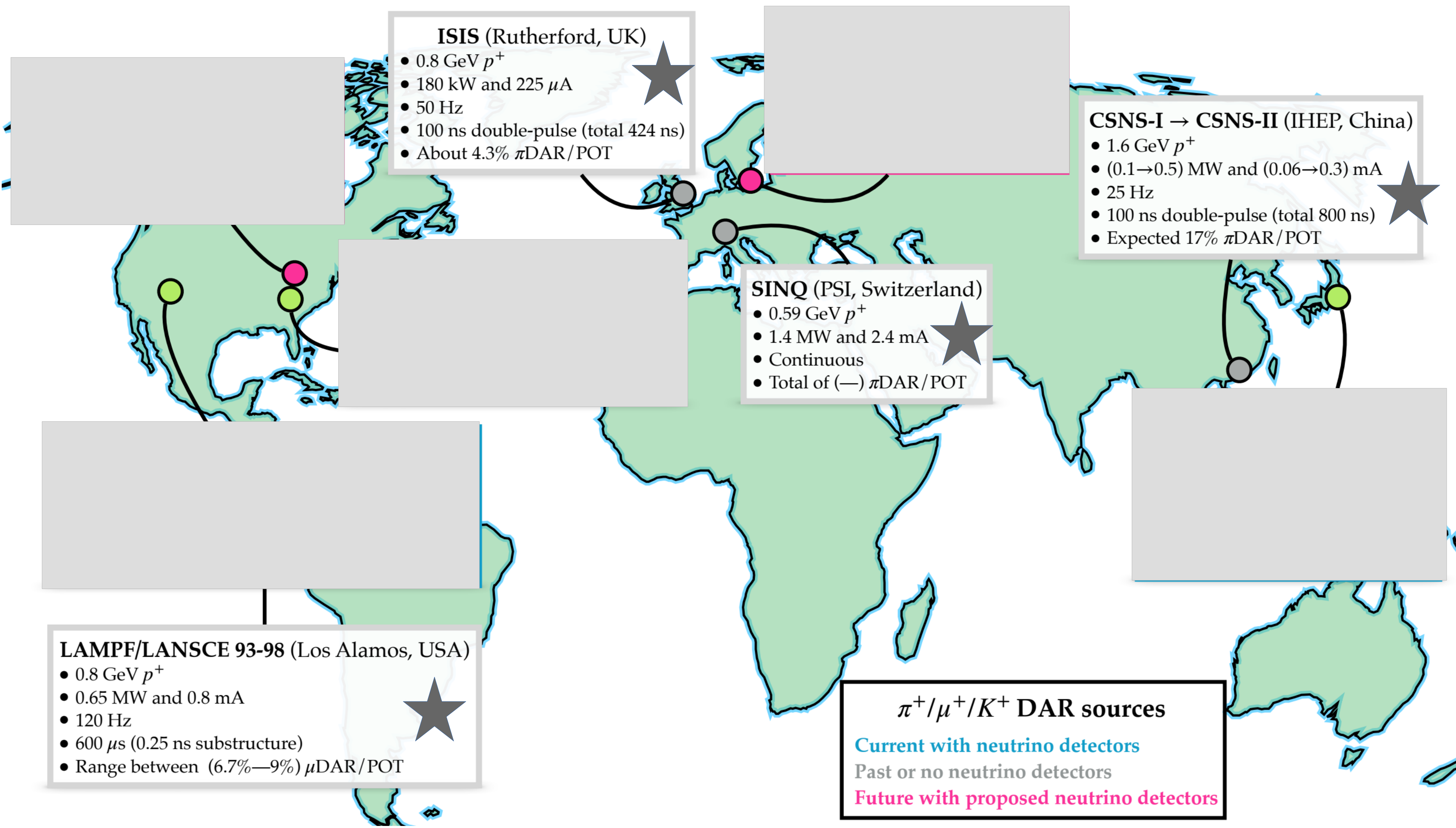
$\pi^+/K^+ \to X$ $\mu^+ \to X$

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

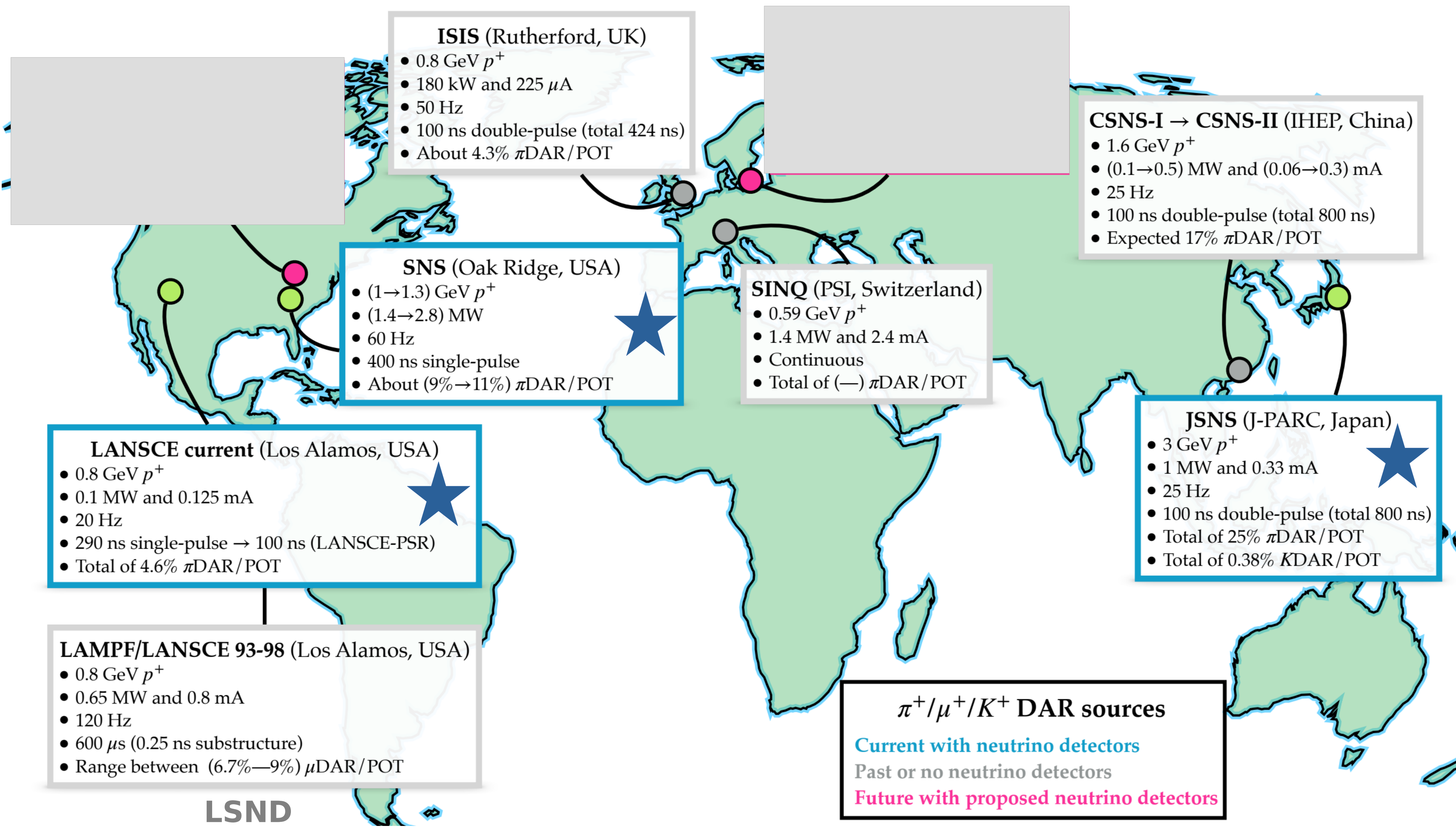


Overview of facilities

Past


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
$\pi^+/\mu^+/K^+$ **DAR sources**
Current with neutrino detectors
Past or no neutrino detectors
Future with proposed neutrino detectors

Current



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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
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• 0.8 GeV p^+
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$\pi^+/\mu^+/K^+$ DAR sources
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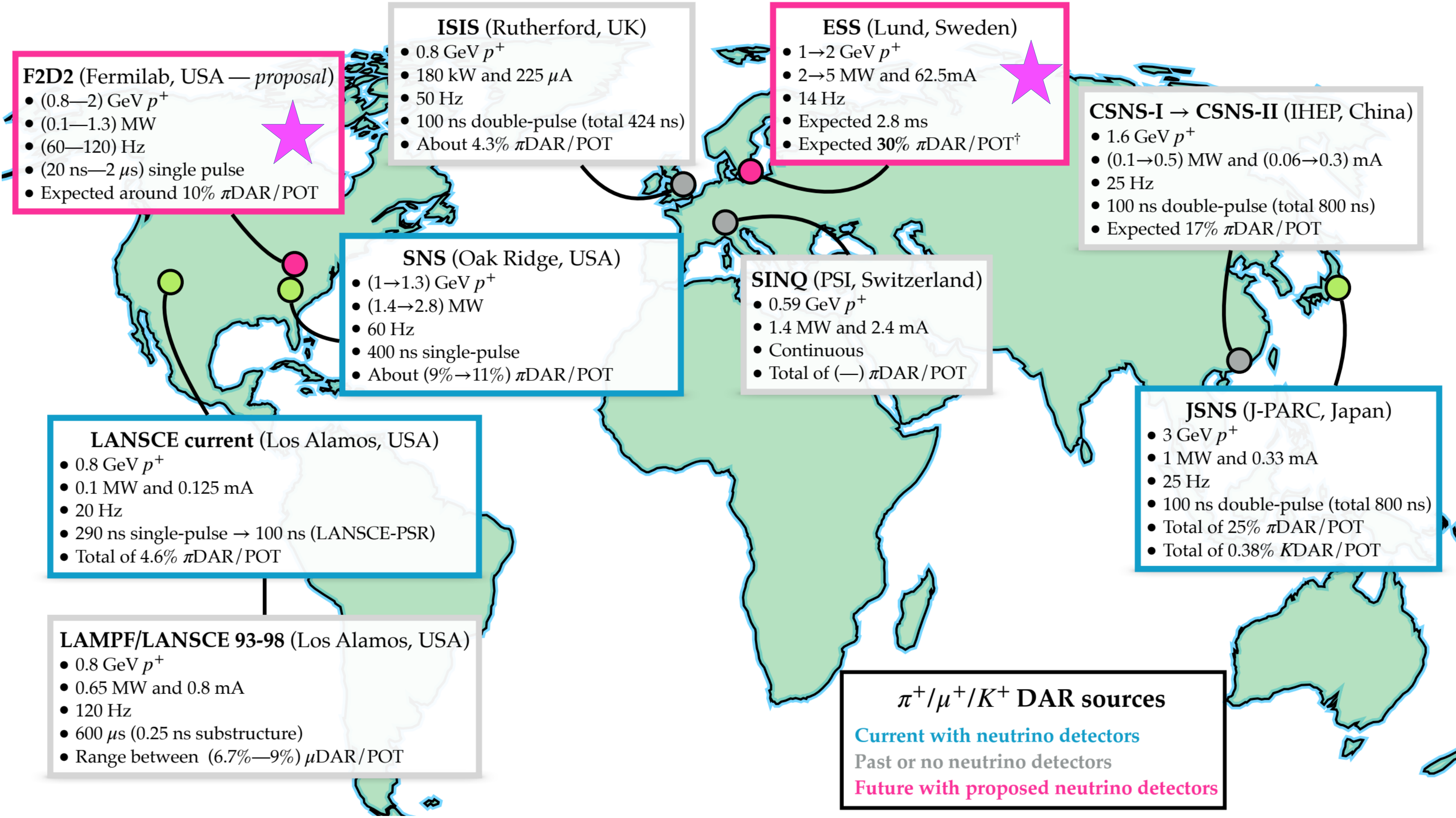
Future



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
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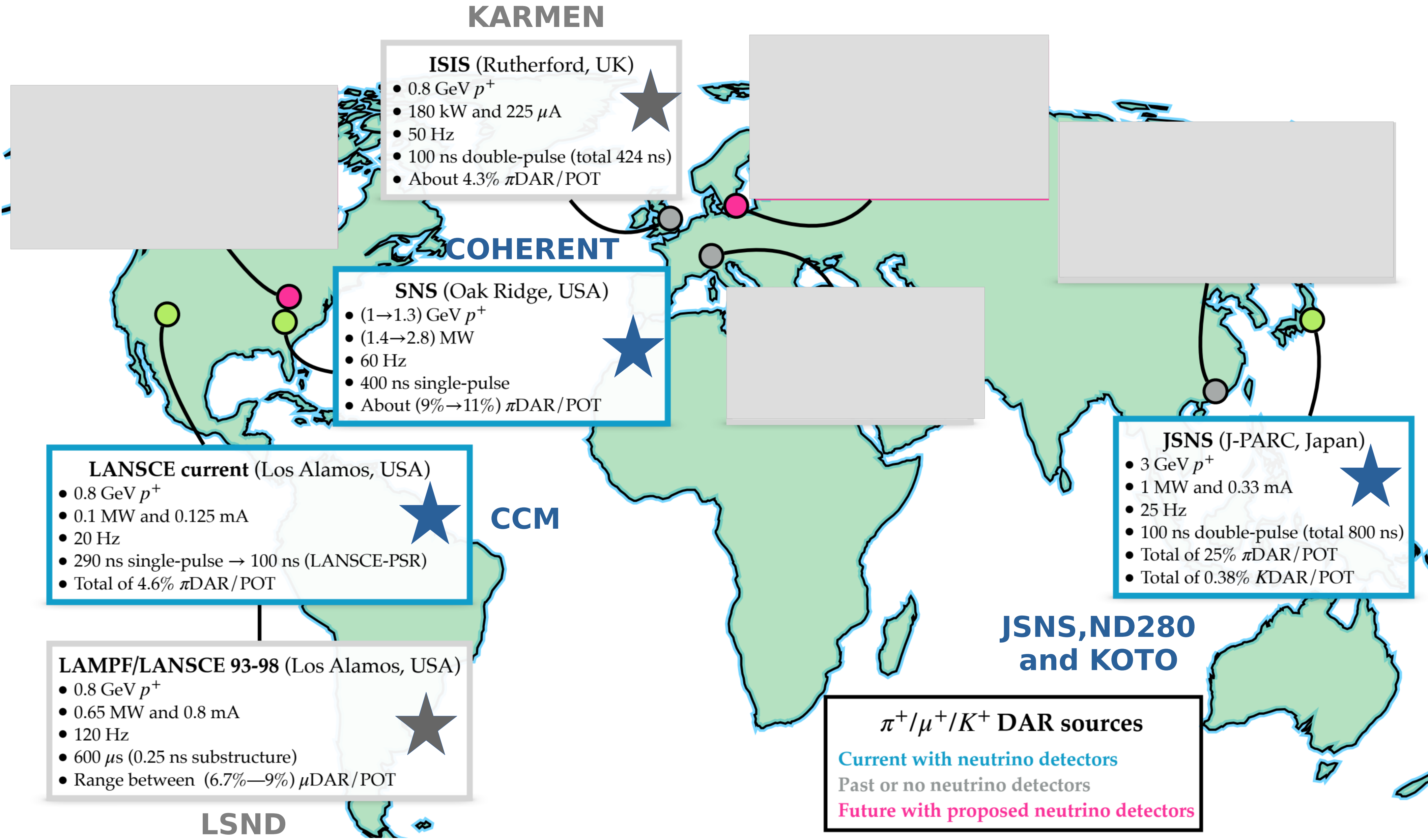
$\pi^+/\mu^+/K^+$ DAR sources
Current with neutrino detectors
Past or no neutrino detectors
Future with proposed neutrino detectors

Used in this work

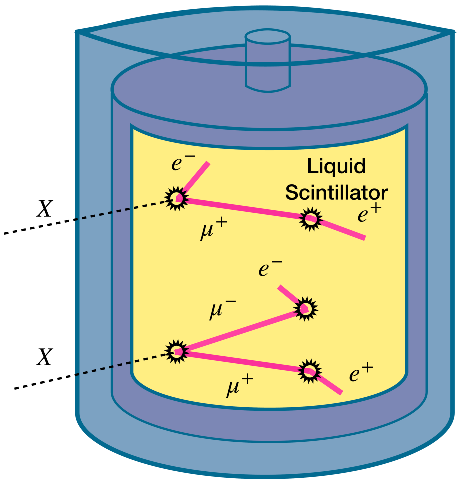
$\nu_\mu + {}^{12}\mathrm{C} \rightarrow \nu_\mu + {}^{12}\mathrm{C}^*(15.1\mathrm{MeV})$ NC data



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

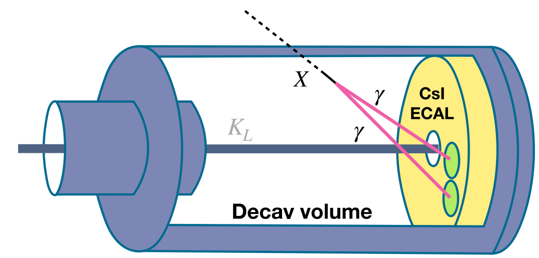
J-PARC

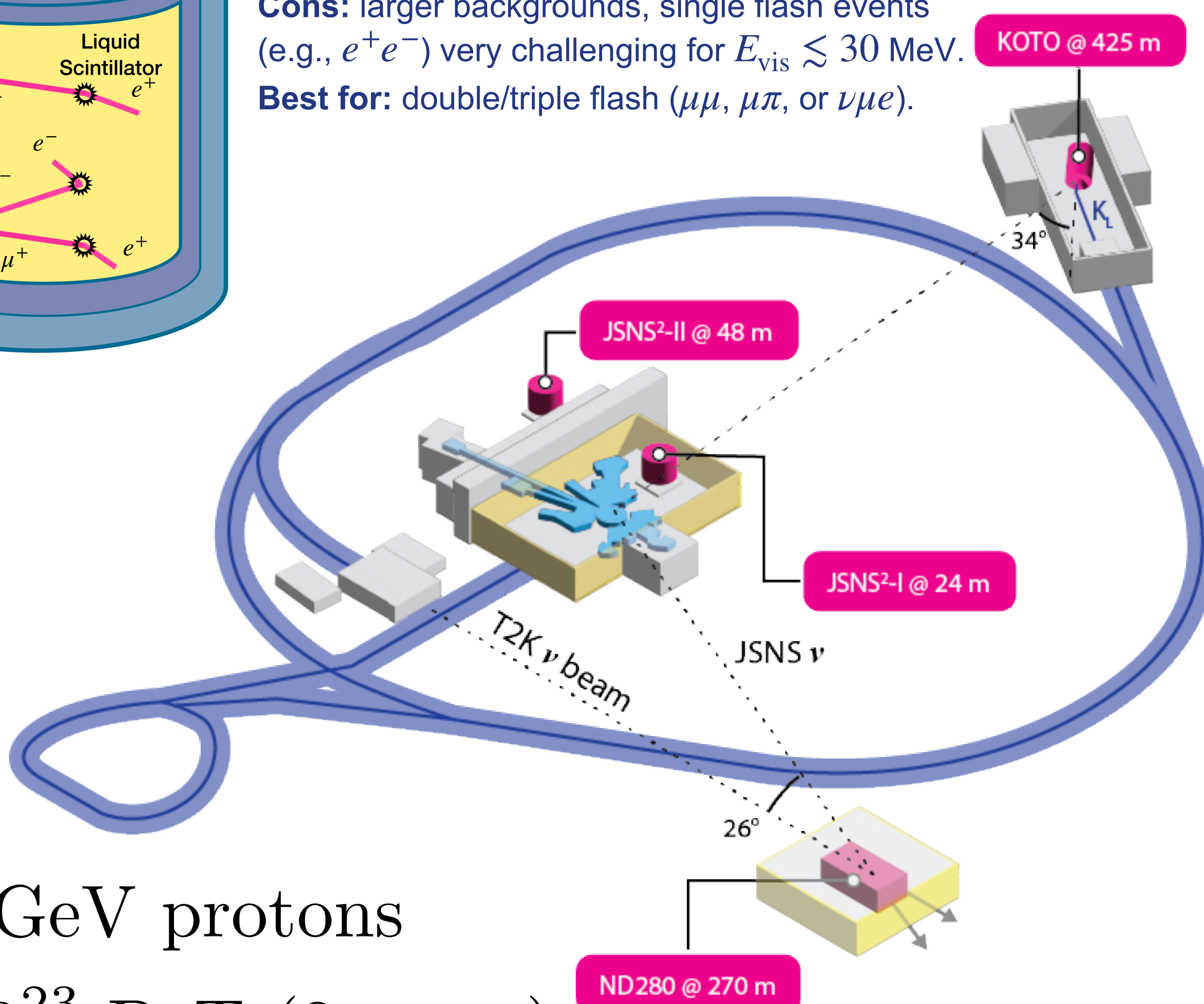
$$\pi^+/K^+ \to X \qquad \mu^+ \to X \qquad\qquad X \to e^+e^-, \gamma\gamma, \mu^+\mu^-, \pi^+\mu^-, etc$$



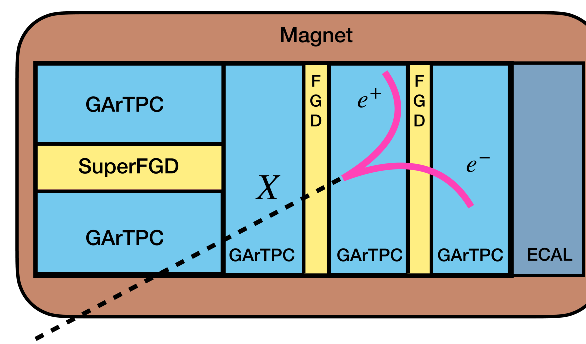
JSNS^2 (I and II): $20\ m^3, 36\ m^3$
Pros: Closest to the source and largest vol
Cons: larger backgrounds, single flash events (e.g., e^+e^-) very challenging for $E_{\rm vis} \lesssim 30$ MeV.
Best for: double/triple flash ($\mu\mu$, $\mu\pi$, or $\nu\mu e$).

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

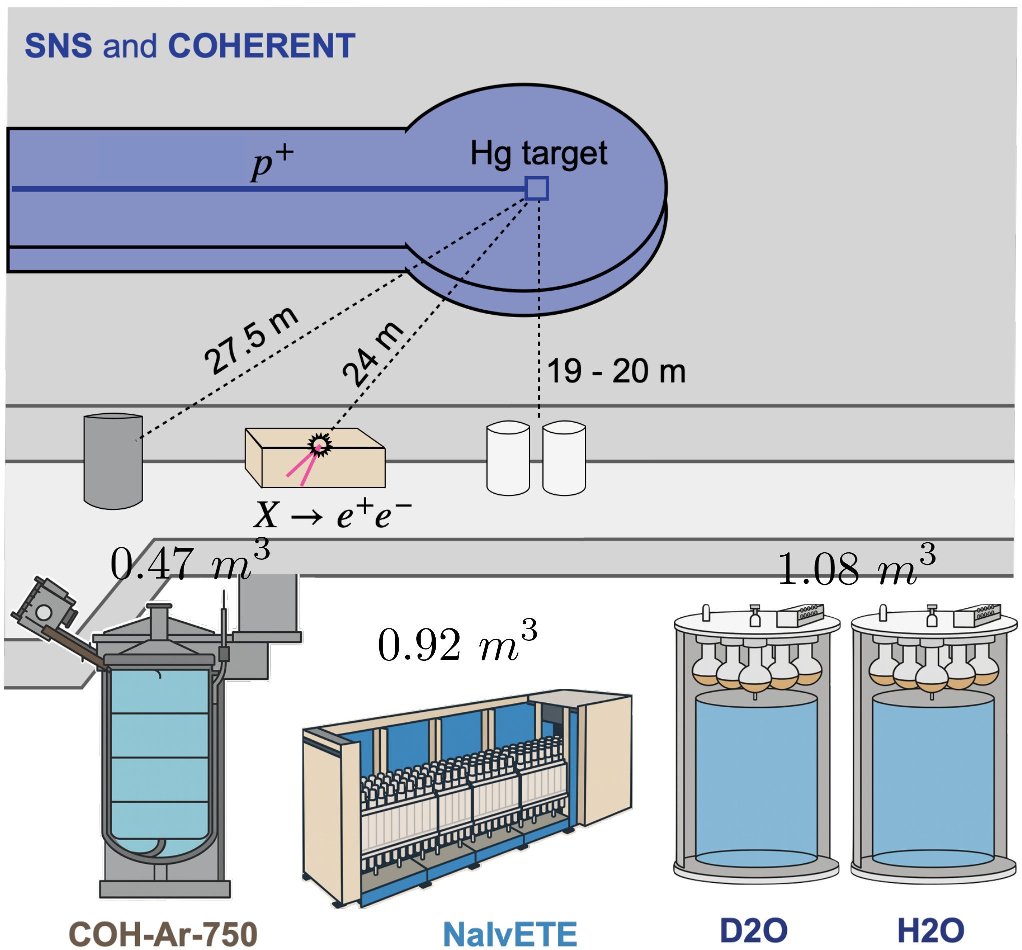
$$\pi^+ \to X \qquad \mu^+ \to X \qquad X \to e^+e^-, \gamma\gamma$$

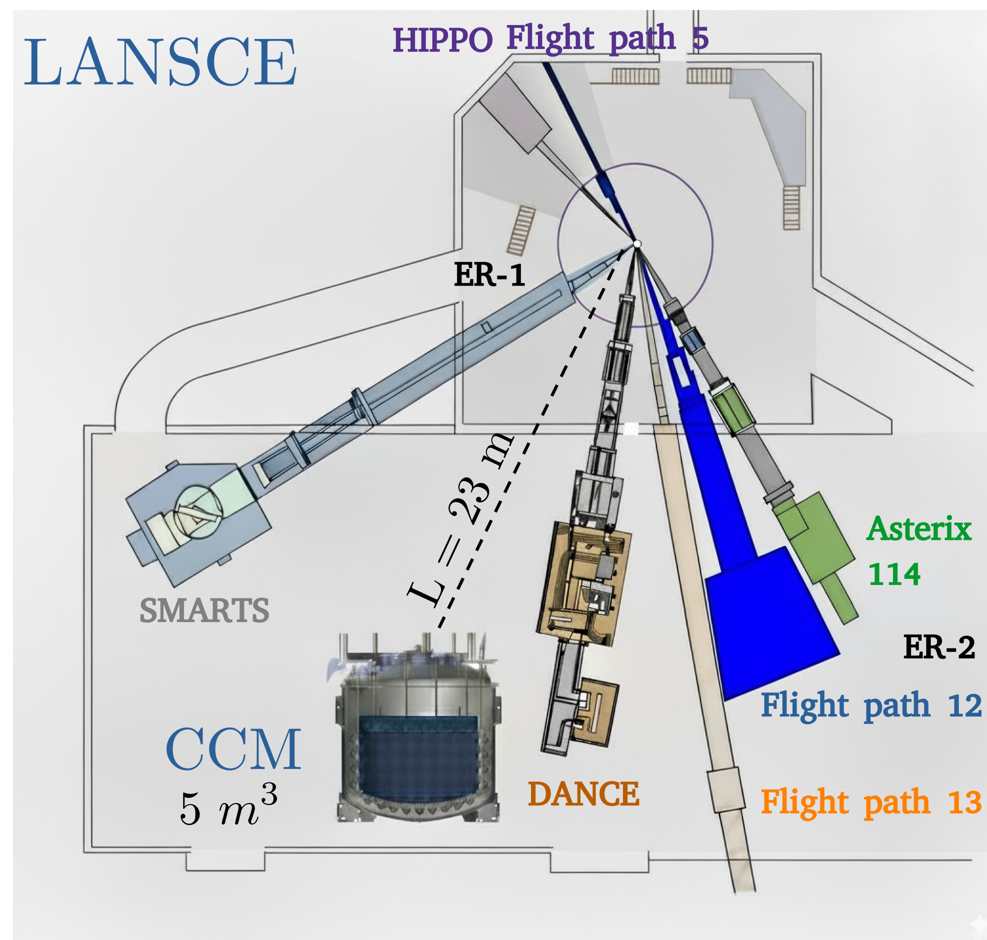
1 GeV protons

$4.5 \cdot 10^{23}$ 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: Higgs-coupled ALPs, Leptophilic ALPs**

- **Fermions: Heavy neutral leptons**

Models studied in this work

- **Scalar : Higgs portal scalar, Muon scalar**

- **Pseudoscalars: Higgs-coupled ALPs, Leptophilic ALPs**

- **Fermions: Heavy neutral leptons**

In this talk

HNLs

HNL

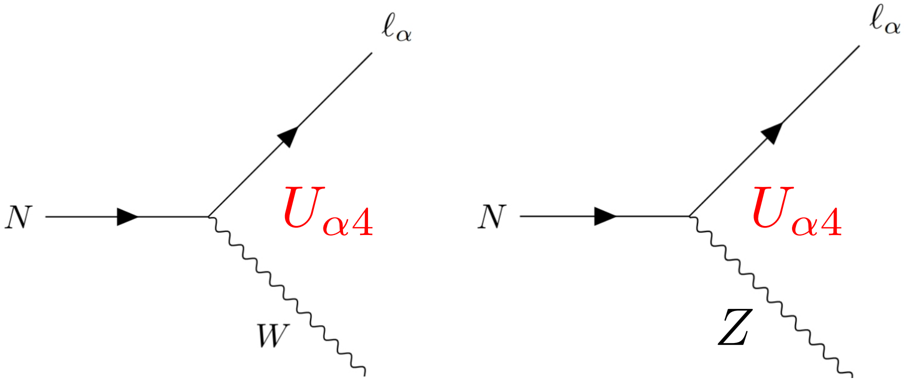
$$\mathcal{L} \supset -\frac{g}{\sqrt{2}} \left(W_\mu^- \bar{l}_{L\alpha} \gamma_\mu U_{\alpha 4} N + \text{h.c.} \right) - \frac{g}{\cos\theta_W} \left(Z_\mu \bar{N} \gamma^\mu U_{\alpha 4}^* \nu_{L\alpha} + \text{h.c.} \right)$$

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

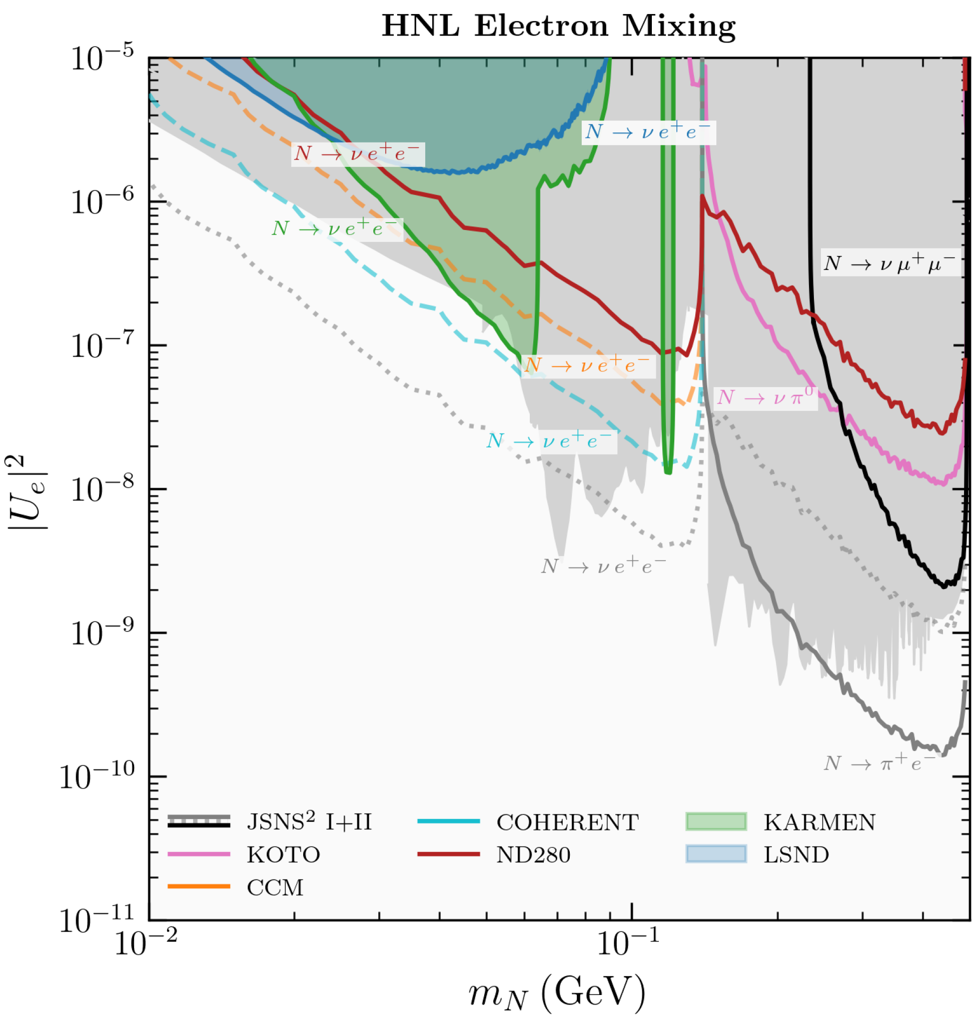
Production

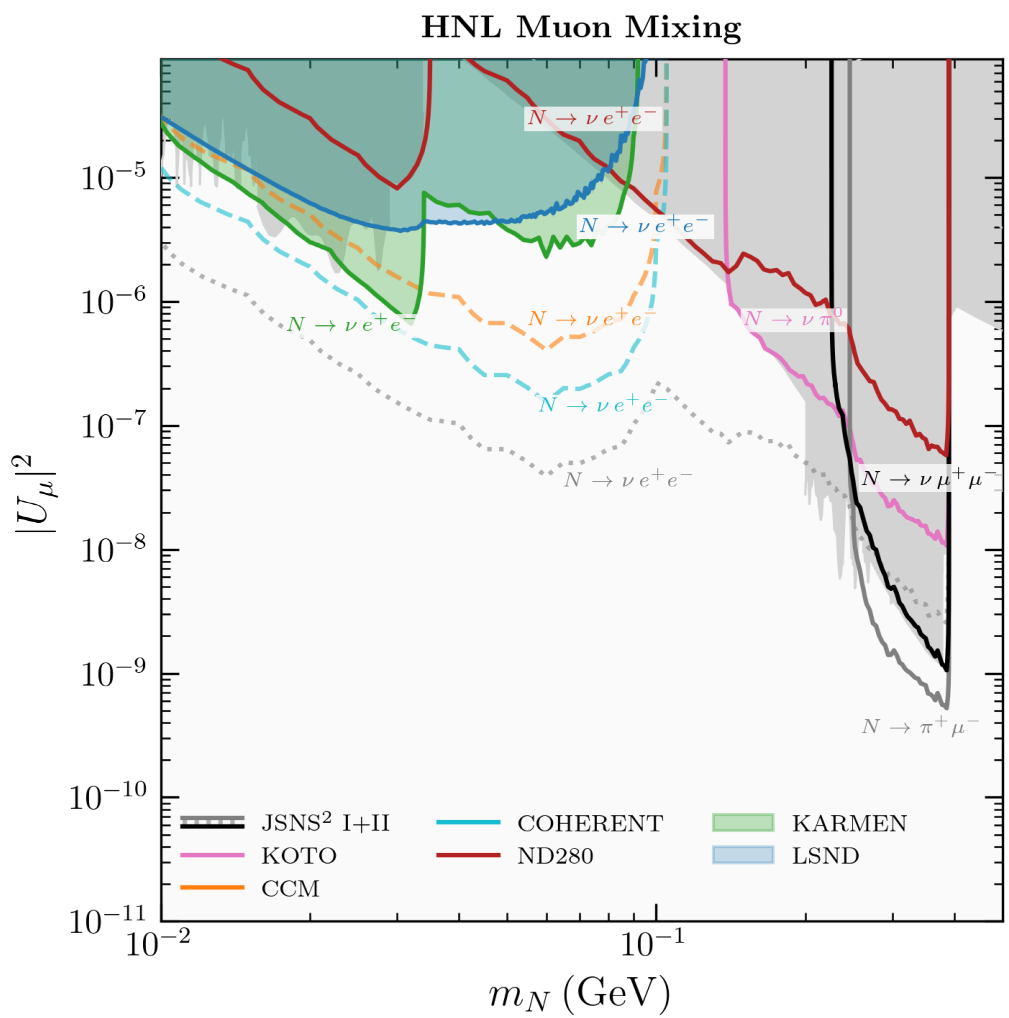
U_{e4}	$U_{\mu 4}$
$K^+ \to e^+ N$	$K^+ \to \mu^+ N$
$\pi^+ \to e^+ N$	$\pi^+ \to \mu^+ N$
$\mu \to e \nu_e N$	$\mu \to e \nu_\mu N$

HNL



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





ALPs

ALPs: Higgs coupled

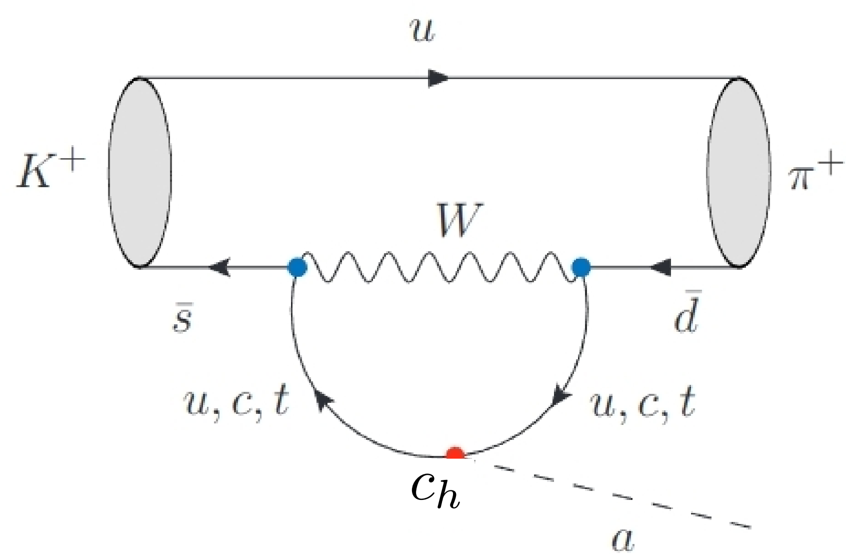
$$L_{\text{ALP}} \supset \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_a^2}{2}a^2 + \frac{\partial_\mu a}{f_a} c_h \left(H^\dagger i \overleftrightarrow{D}^\mu H \right)$$

Hypercharge rotation

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

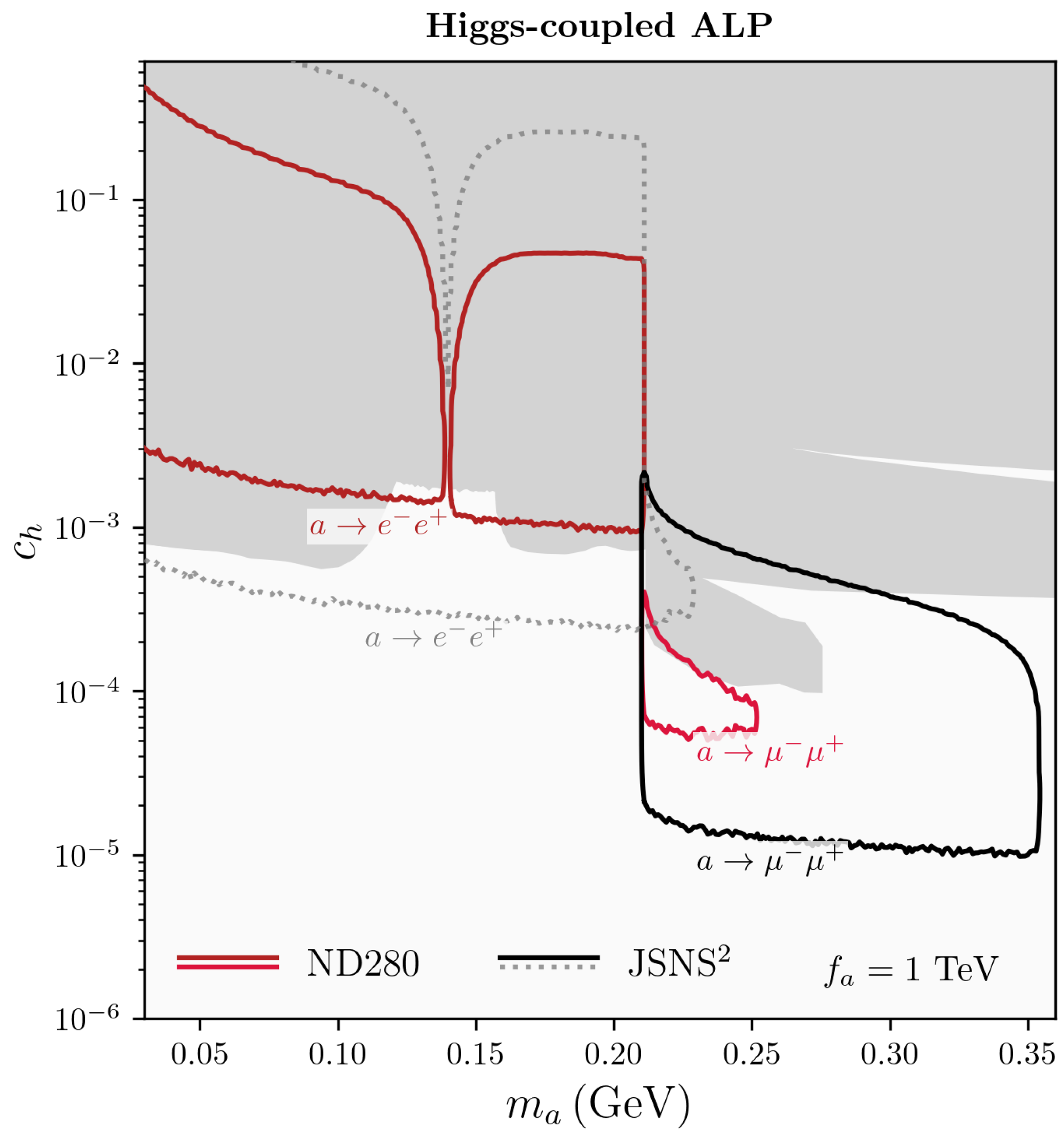
Production

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



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

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

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

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)**

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

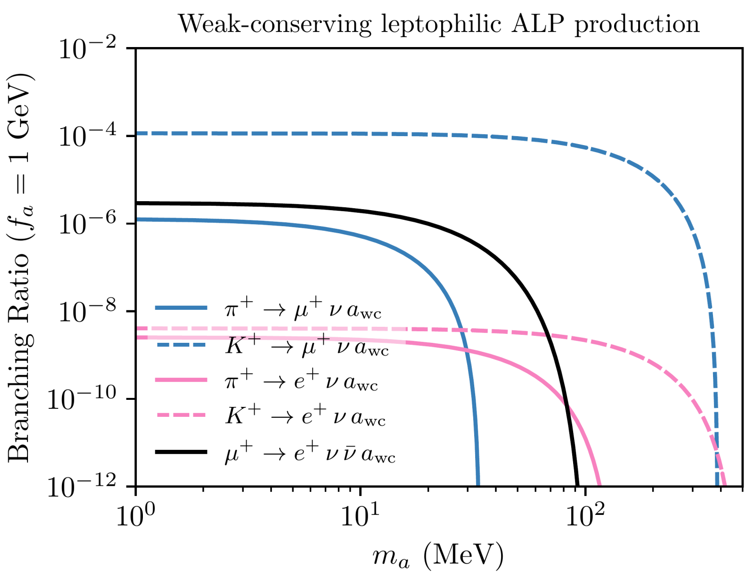
Lepton Flavour violating (LFV)

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

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

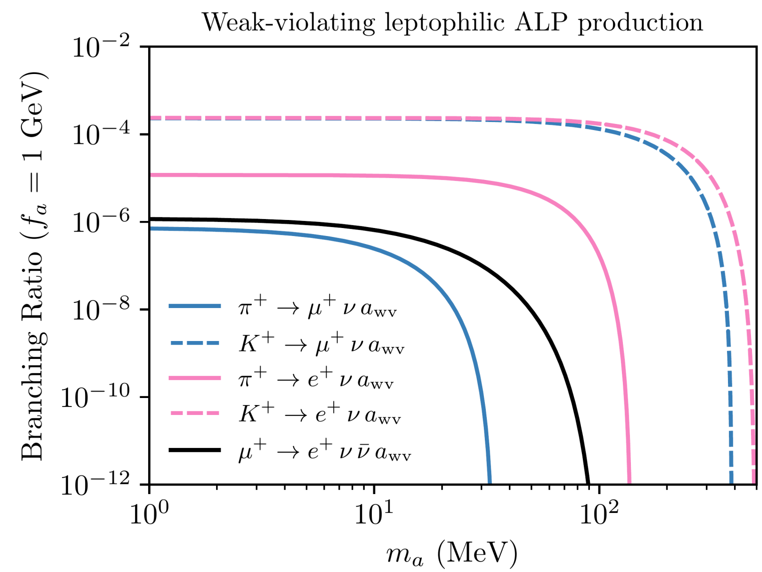
Production

Lepton Flavour conserving
(LFC)



Helicity suppression lifted

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



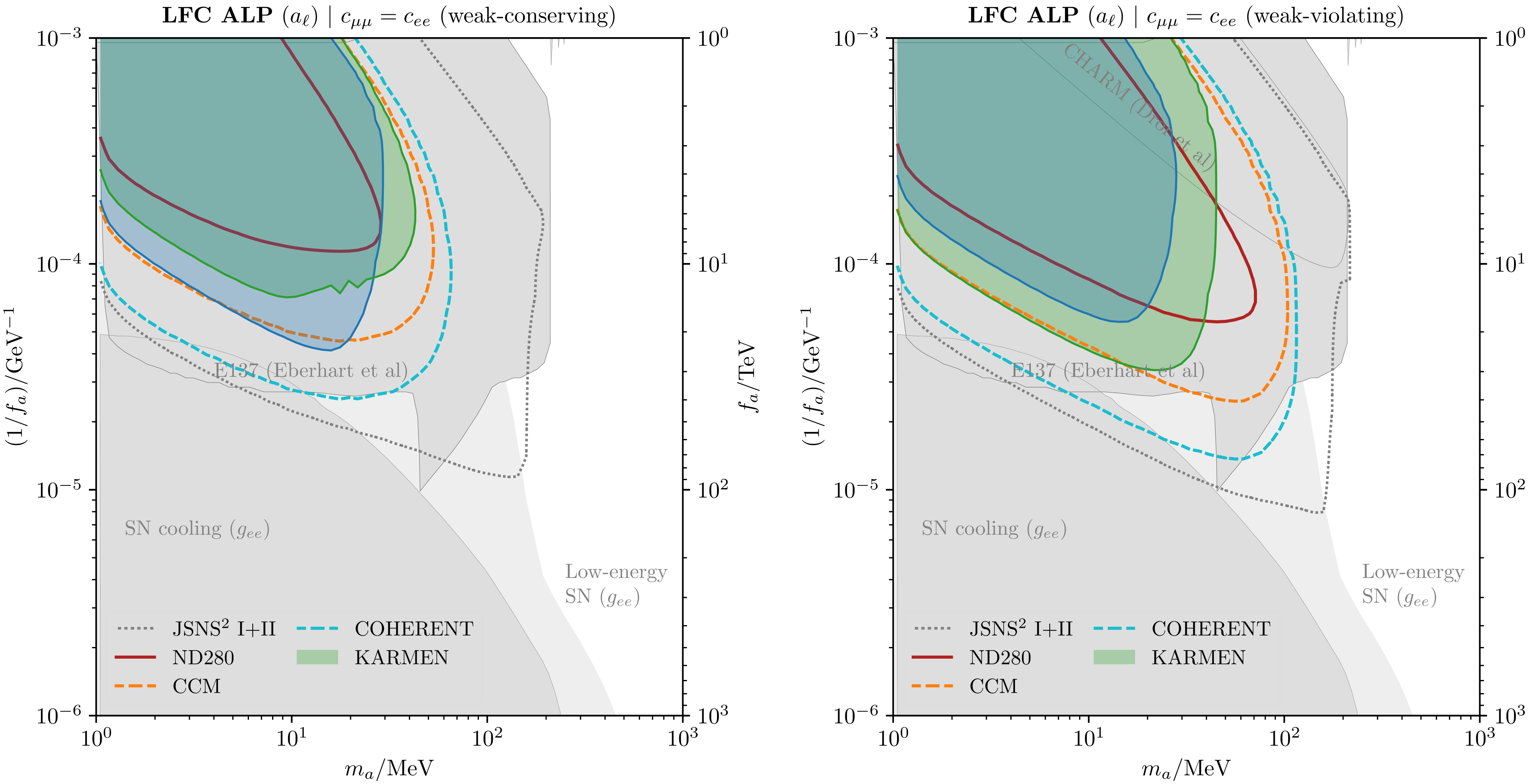
Lepton Flavour violating
(LFV)

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

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

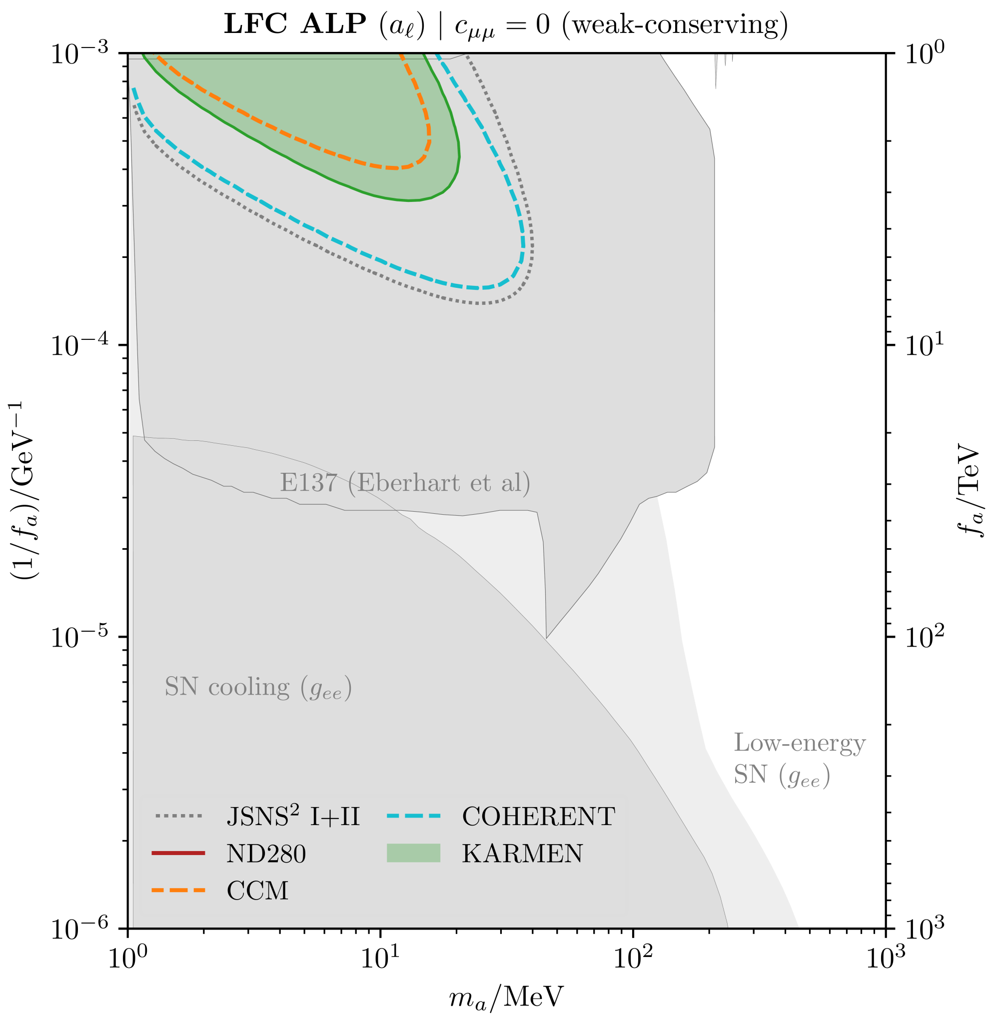
Lepton Flavour conserving (LFC): universal

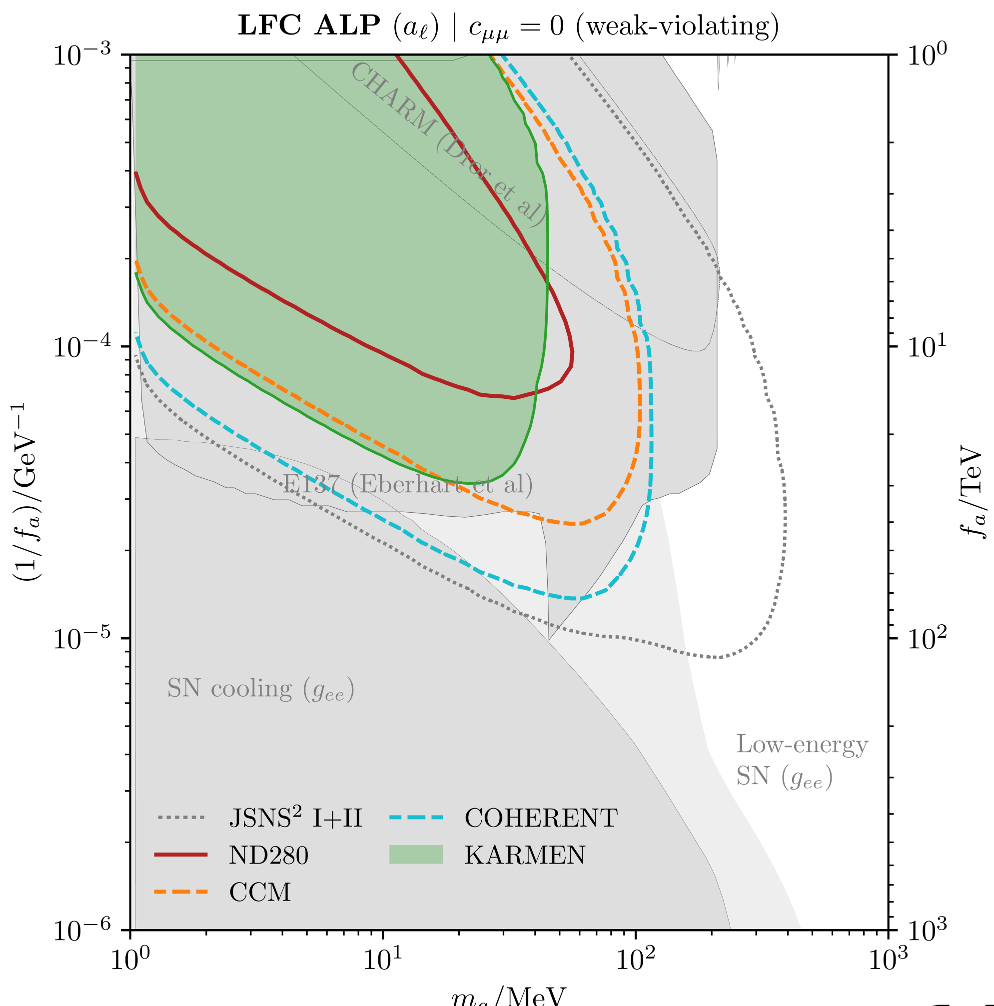
$$a_\ell \to e^+ e^-$$



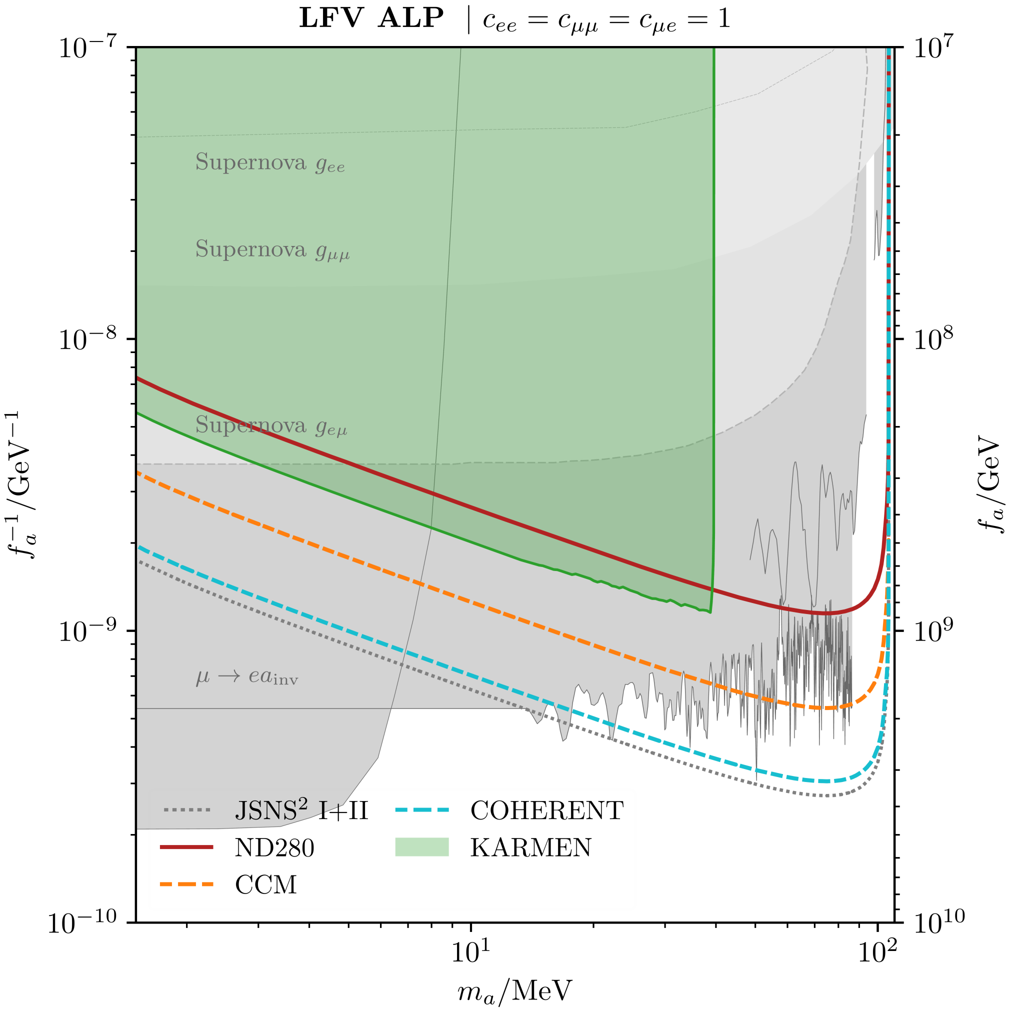
Lepton Flavour conserving (LFC): electron dominance

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

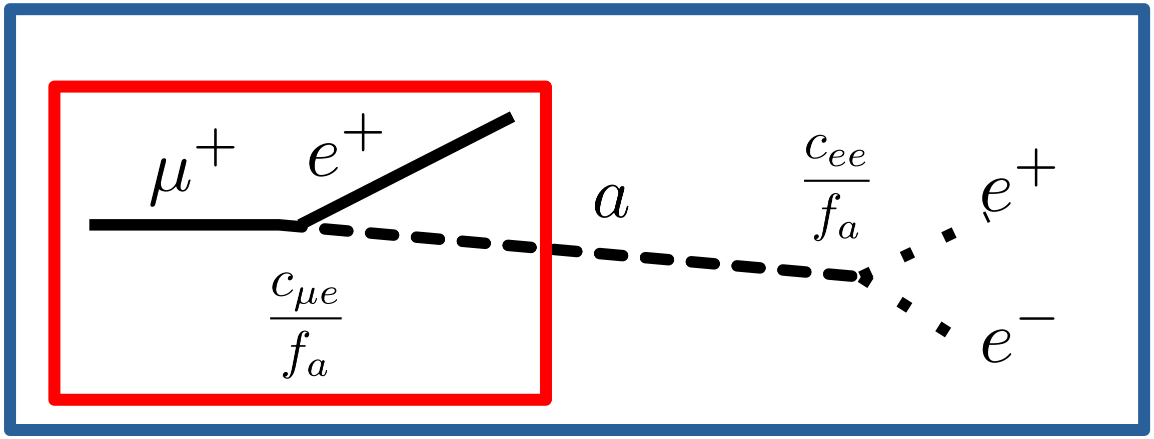




Lepton Flavour violating (LFV)

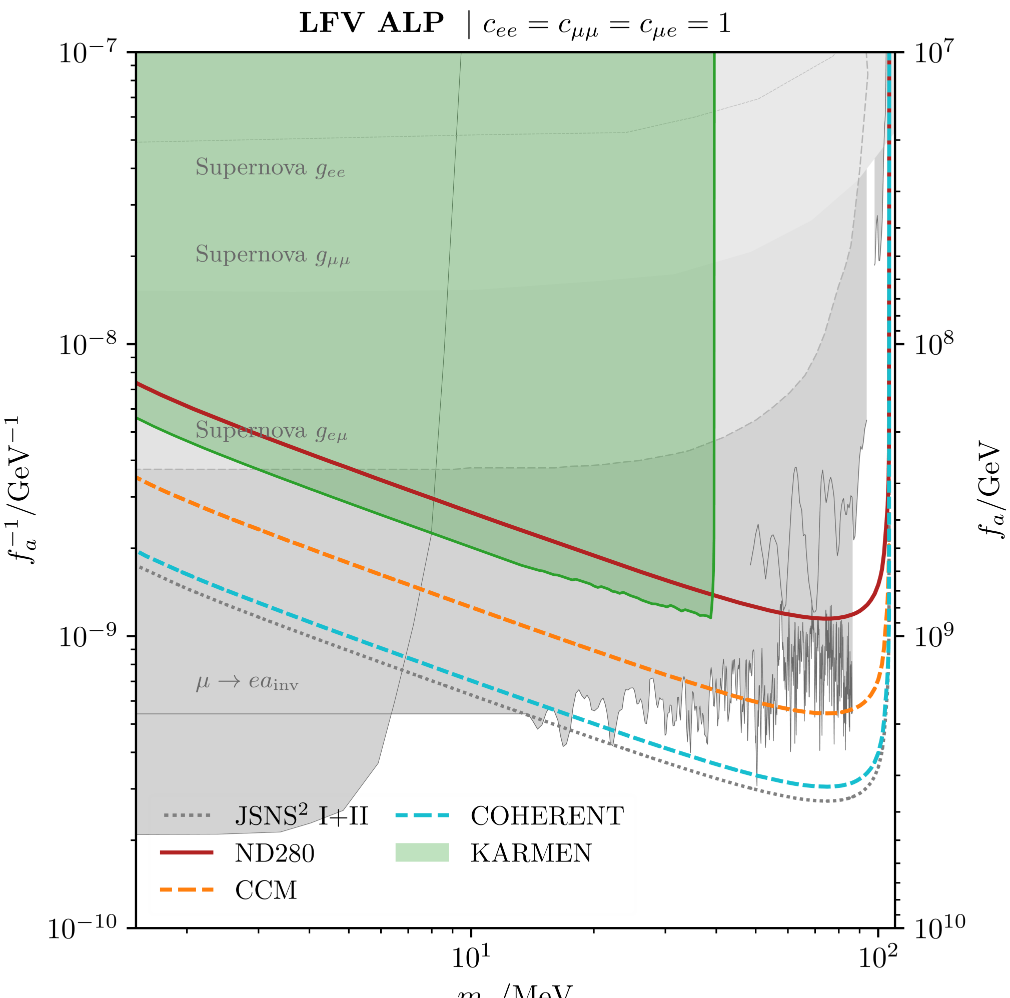


Lepton Flavour violating (LFV)

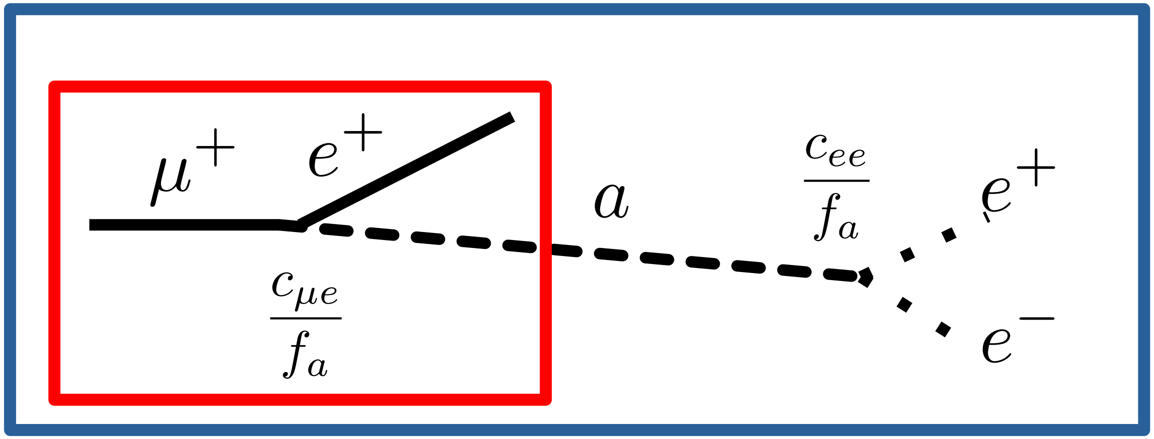


Rare muon decays $\propto \frac{c_{\mu e}^2}{f_a^2}.$

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



Lepton Flavour violating (LFV)



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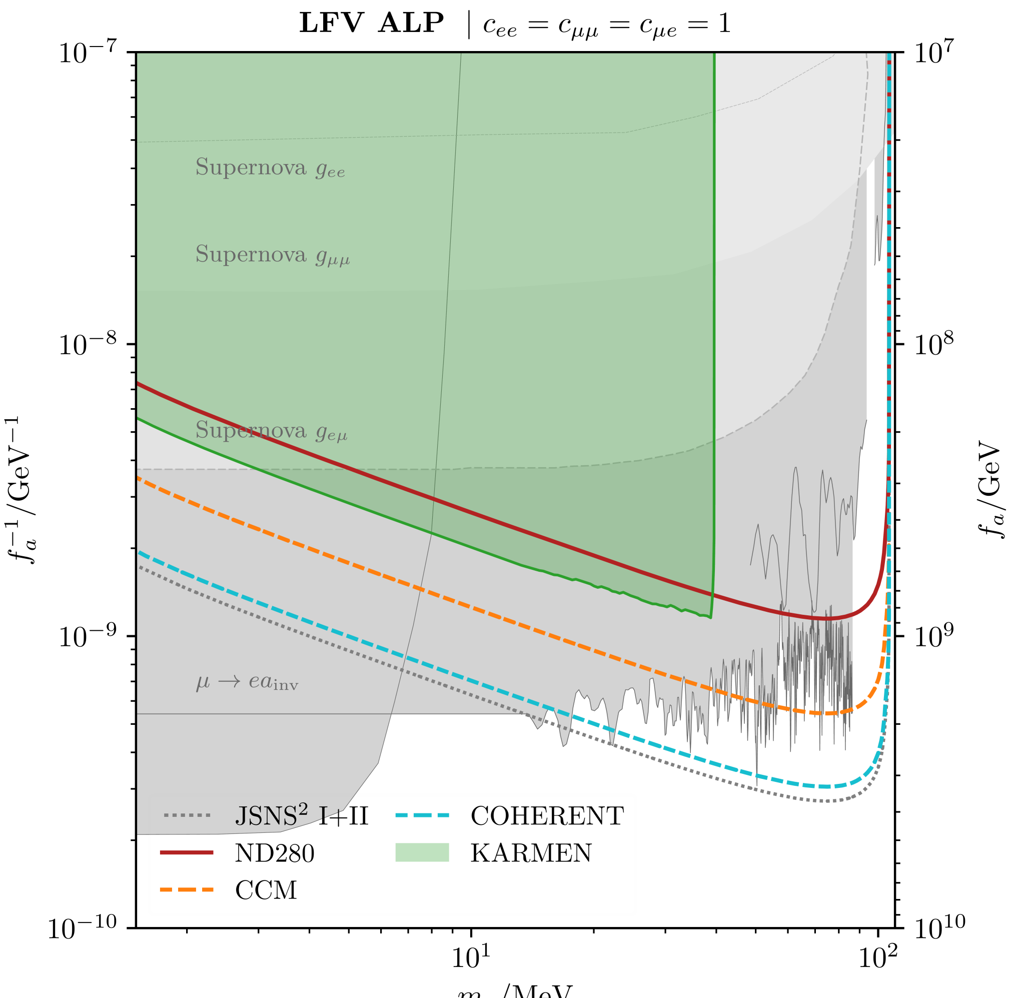
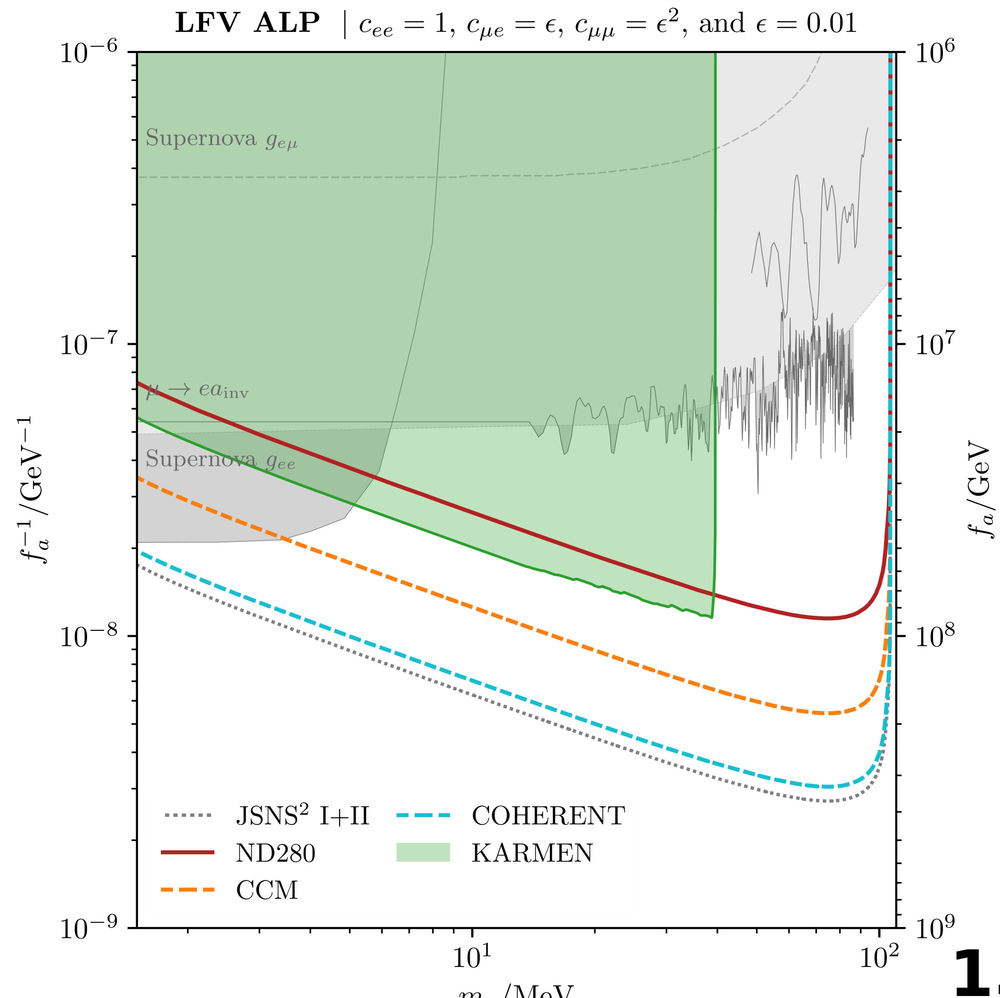




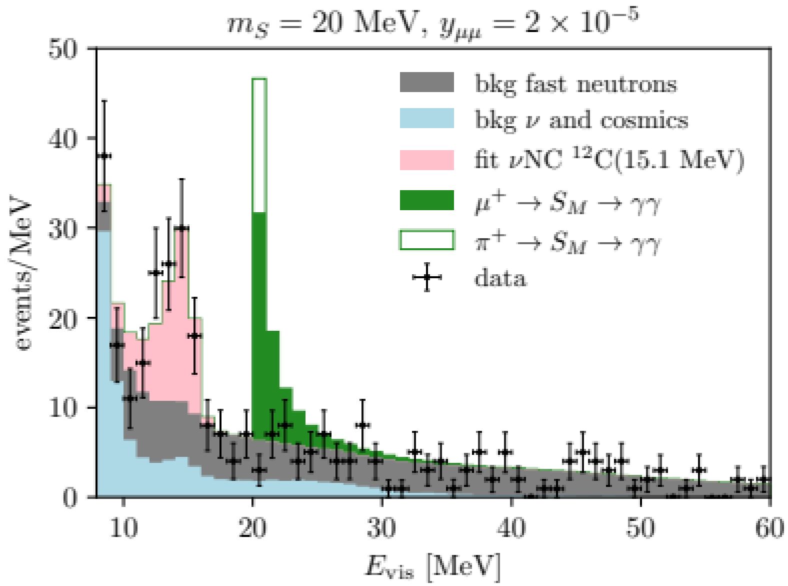
Summary

- 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.
- Reducing backgrounds will greatly enhance the ultimate reach of these facilities.

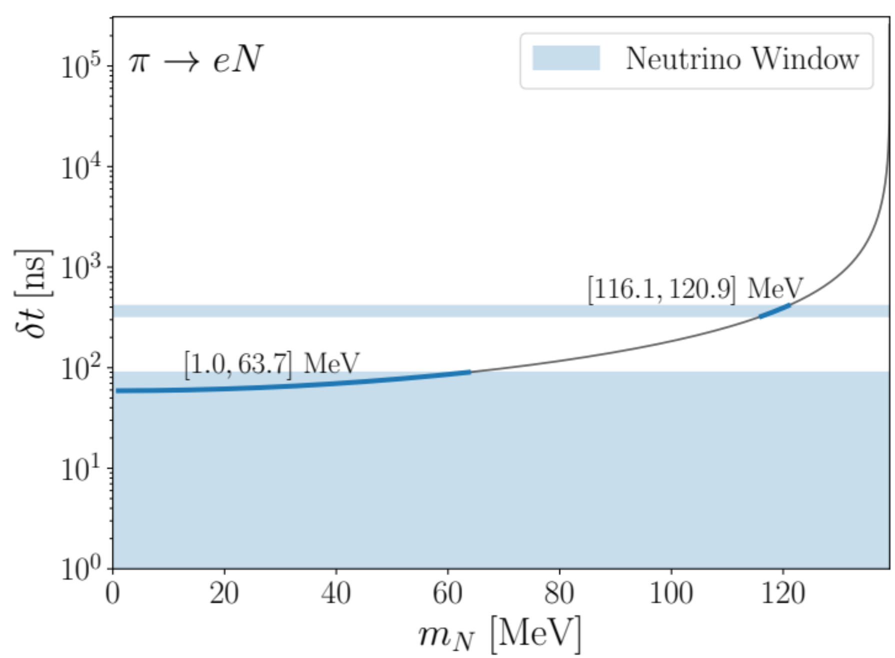
Thank you

Back up

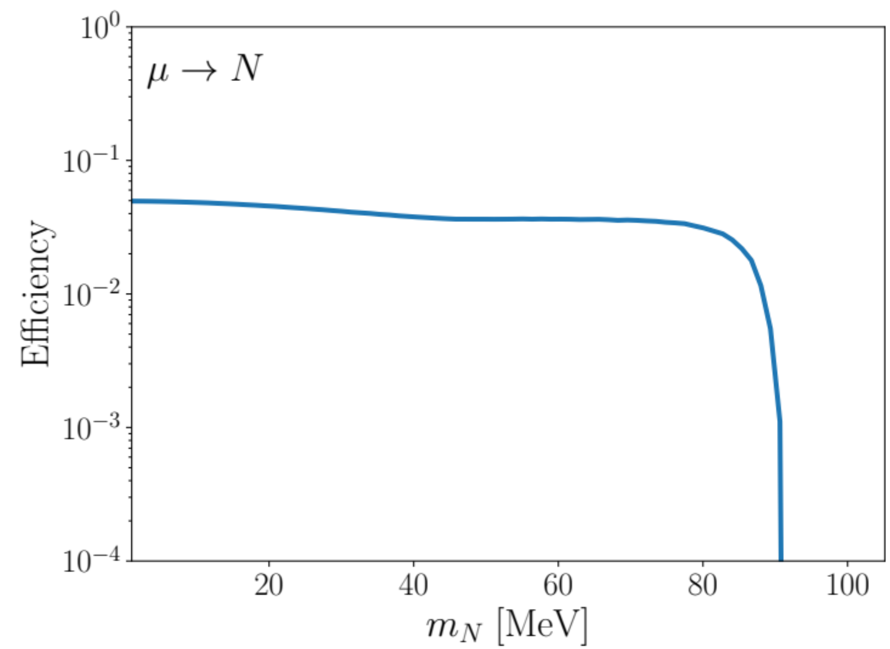
KARMEN



$m_S = 20$ 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
0
10
20
30
40
50
60
$E_{\rm vis}$ [MeV]

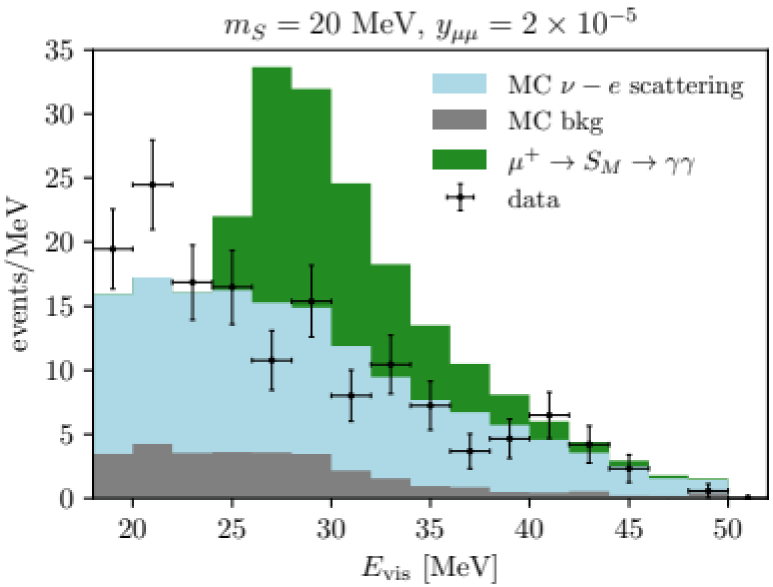


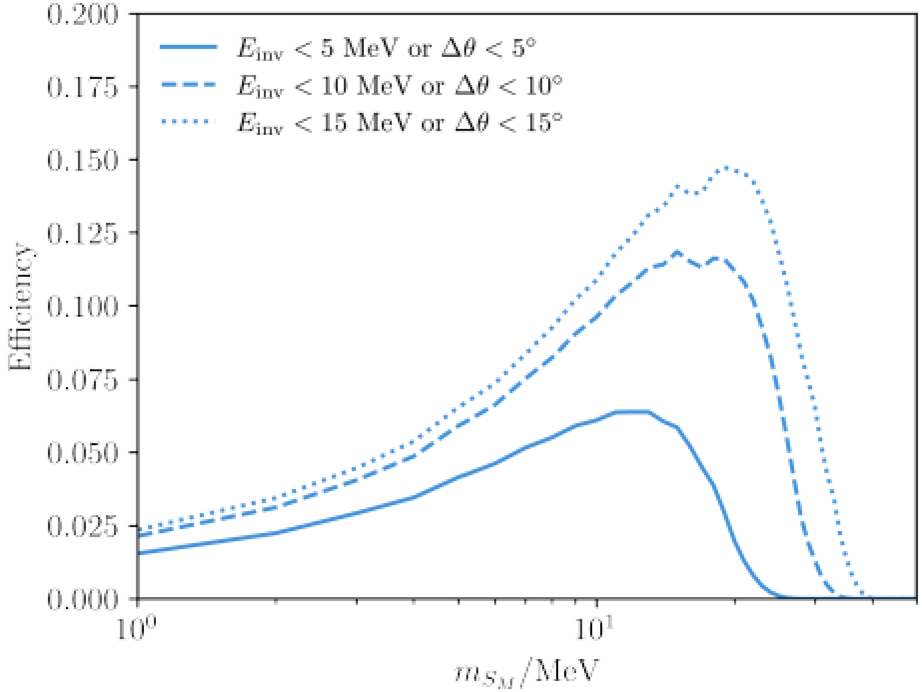
$\pi \to eN$
Neutrino Window
[116.1, 120.9] MeV
[1.0, 63.7] MeV
δt [ns]
10^0
10^1
10^2
10^3
10^4
10^5
0
20
40
60
80
100
120
m_N [MeV]



$\mu \to N$
Efficiency
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
20
40
60
80
100
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
$E_{\rm vis}$ [MeV]
0
5
10
15
20
25
30
35
20
25
30
35
40
45
50


$E_{\rm inv} < 5$ MeV or $\Delta\theta < 5°$
$E_{\rm inv} < 10$ MeV or $\Delta\theta < 10°$
$E_{\rm inv} < 15$ MeV or $\Delta\theta < 15°$
Efficiency
0.000
0.025
0.050
0.075
0.100
0.125
0.150
0.175
0.200
10^0
10^1
m_{S_M}/MeV

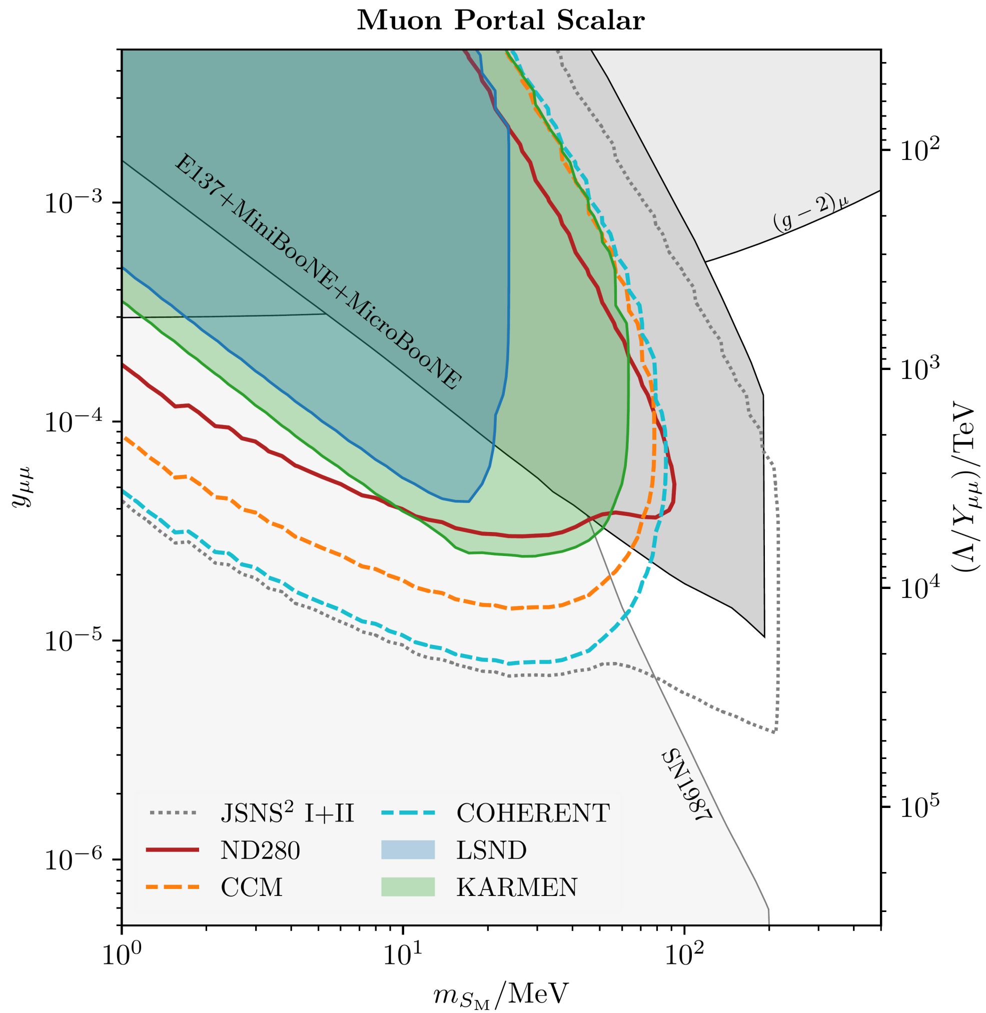
Muon scalar

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

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

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