Long-Lived Particles at Spallation Sources

In collaboration with C. Argüelles (Harvard) & S. Urrea (IFIC, Valencia)

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FNAL theory seminar

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$\mathscr{L}_{\rm SM}$

Incompleteness problems:

Dark matter

Neutrino masses and mixing

Predictivity problems:

Topological angle $\theta_{\rm QCD} \to 0$
(strong CP problem)

Fermion mass pattern

Higgs mass and naturalness

Matter-antimatter asymmetry

$\mathscr{L}_{\mathrm{SM}}$

DARK SECTOR (DS)

$\mathscr{L}_{\mathrm{DS}}$

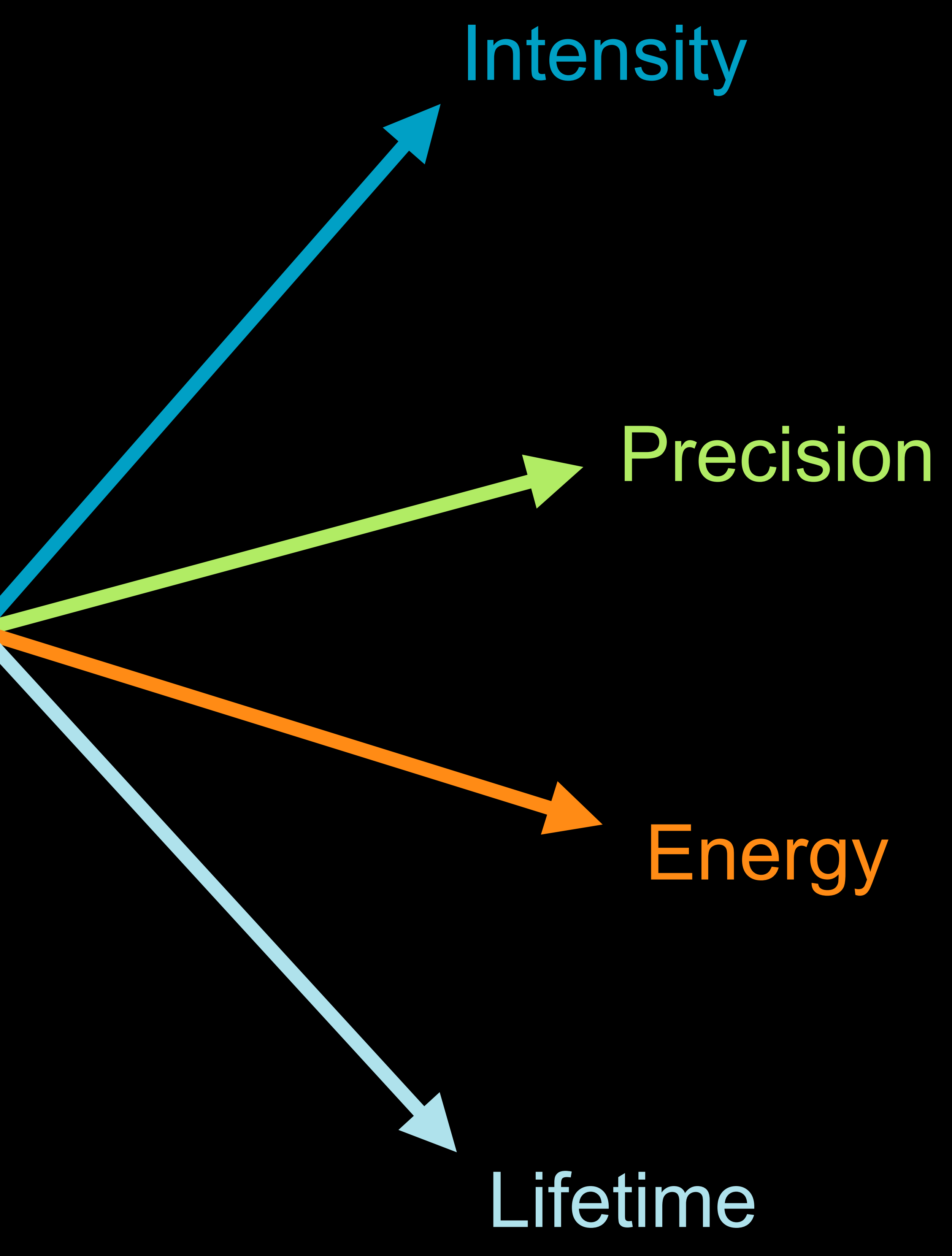
No SM charge

New fundamental mass scales

New particles can be light

Testable!

Prongs of intensity frontier



Long-lived particles (Intensity & Lifetime)

The existence of new light particles is not *mandatory* for solving the *predictivity and incompleteness* issues of the Standard Model.

But it sure would provide major hints of the direction forward.

Searching for new “dark sectors” is **cheap*** but also **exciting!**

*but not free, we do have to think about it.

Outline:

1) **Spallation (neutron) sources: what and why?**

2) Opportunities with neutrino detectors

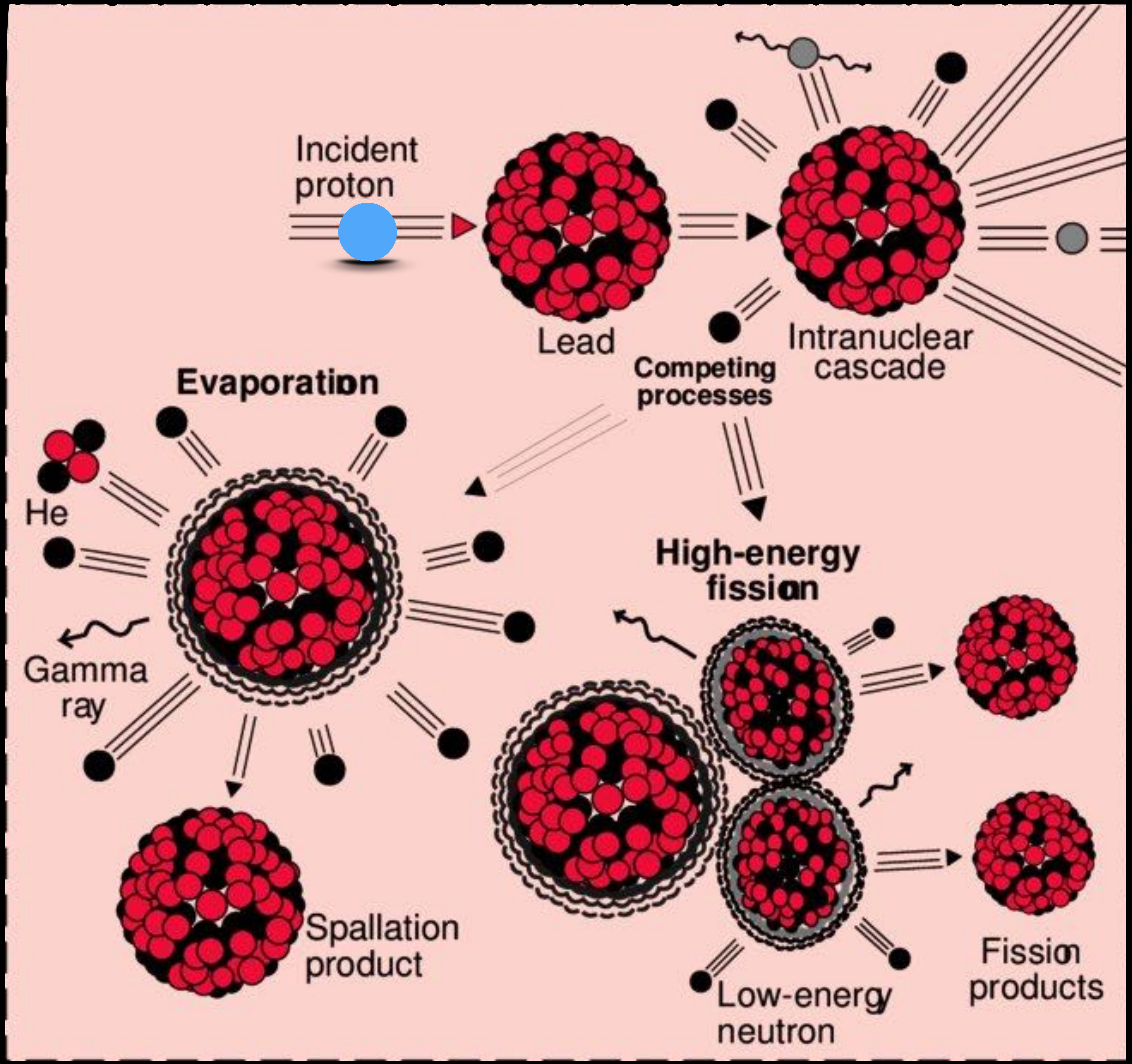
3) Long-lived particles below K, π, and μ masses

What is a Spallation (Neutron) **Source?**

$\mathcal{O}$(GeV) proton beam on dense targets

→ bright neutron sources

→ efficient pion (+ kaon) production



Why a Spallation (Neutron) **Source?**

Neutron science and applications…
lots of it.

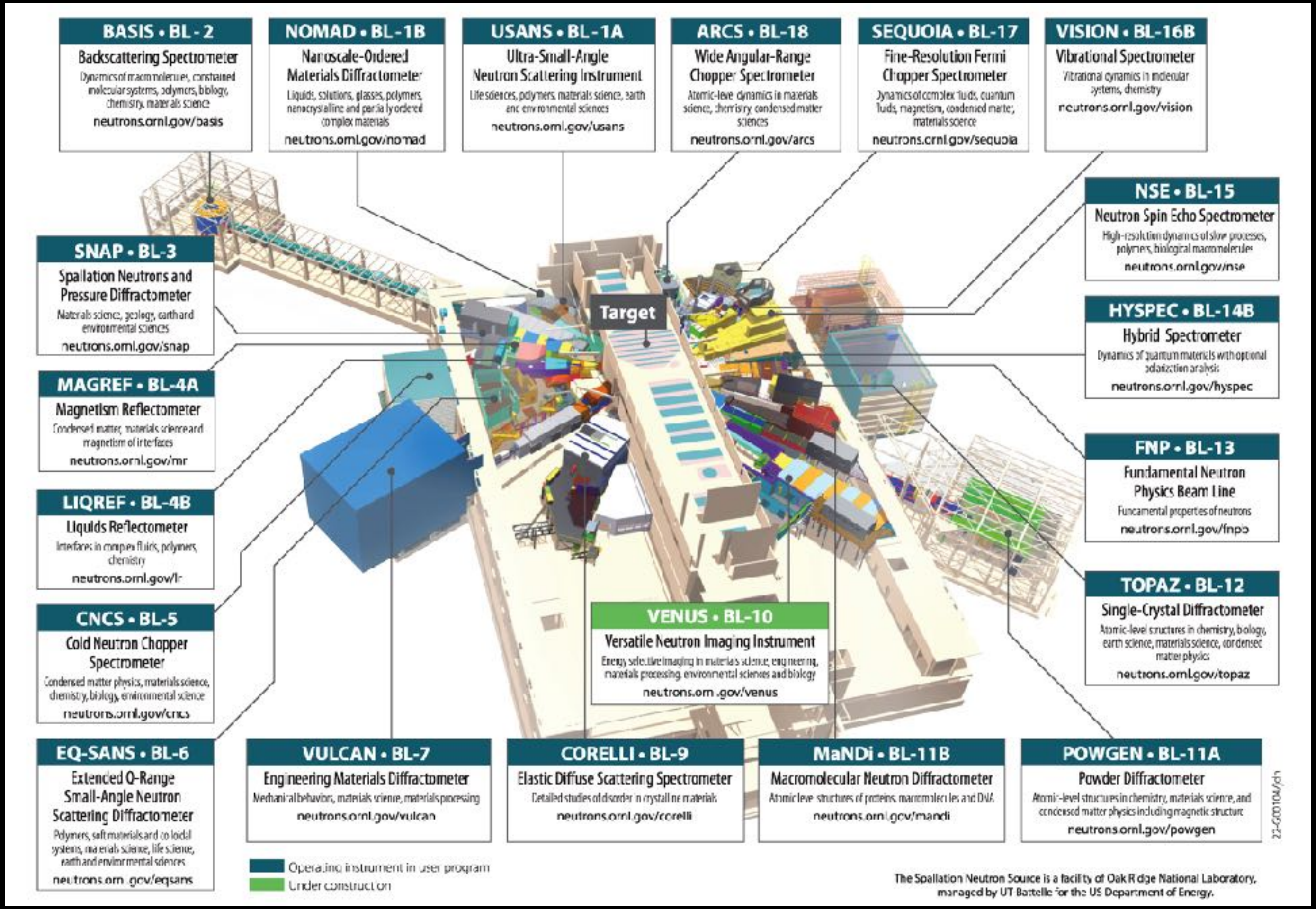
But why not, e.g., a reactor?

ILL reactor:
58 MW (1e15 neutrons/cm^2/s)

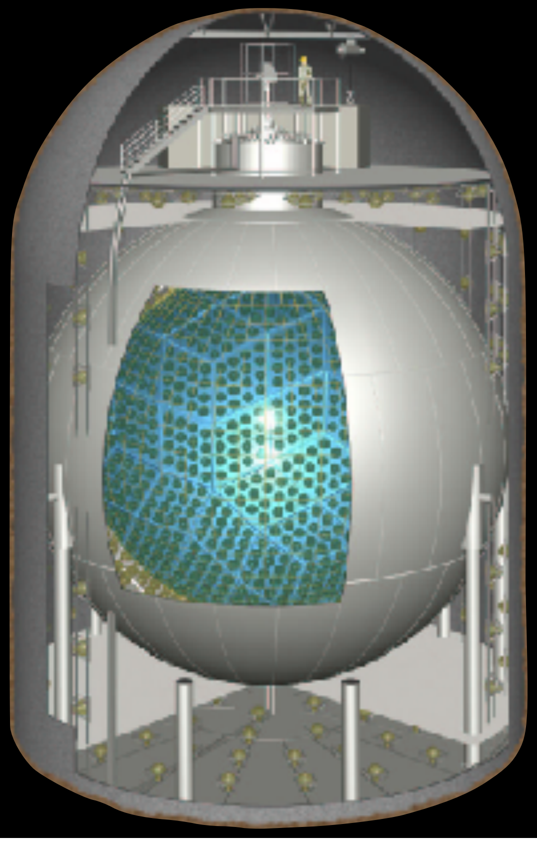
Oak Ridge Spallation:
1.4 MW (1e14 neutrons/cm^2/s — **Average**)

Atmosphere:
cosmic ray power (~0.1 neutrons/cm^2/s)

Oak Ridge Spallation Source instruments



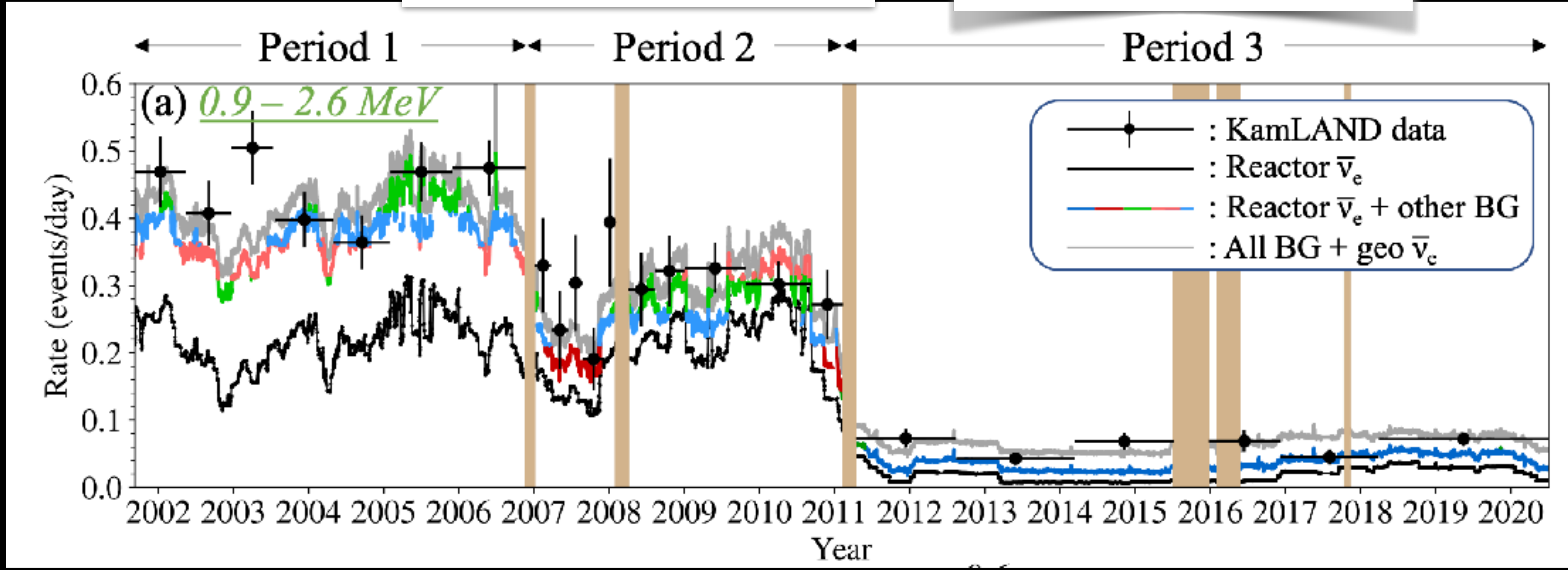
Why a Spallation (Neutron) **Source?**



KamLAND

Tōhoku Tsunami
Fukushima disaster

Purification periods



Impact of the reactor sutdown in Japan on the KamLAND program

Beams give you more control:

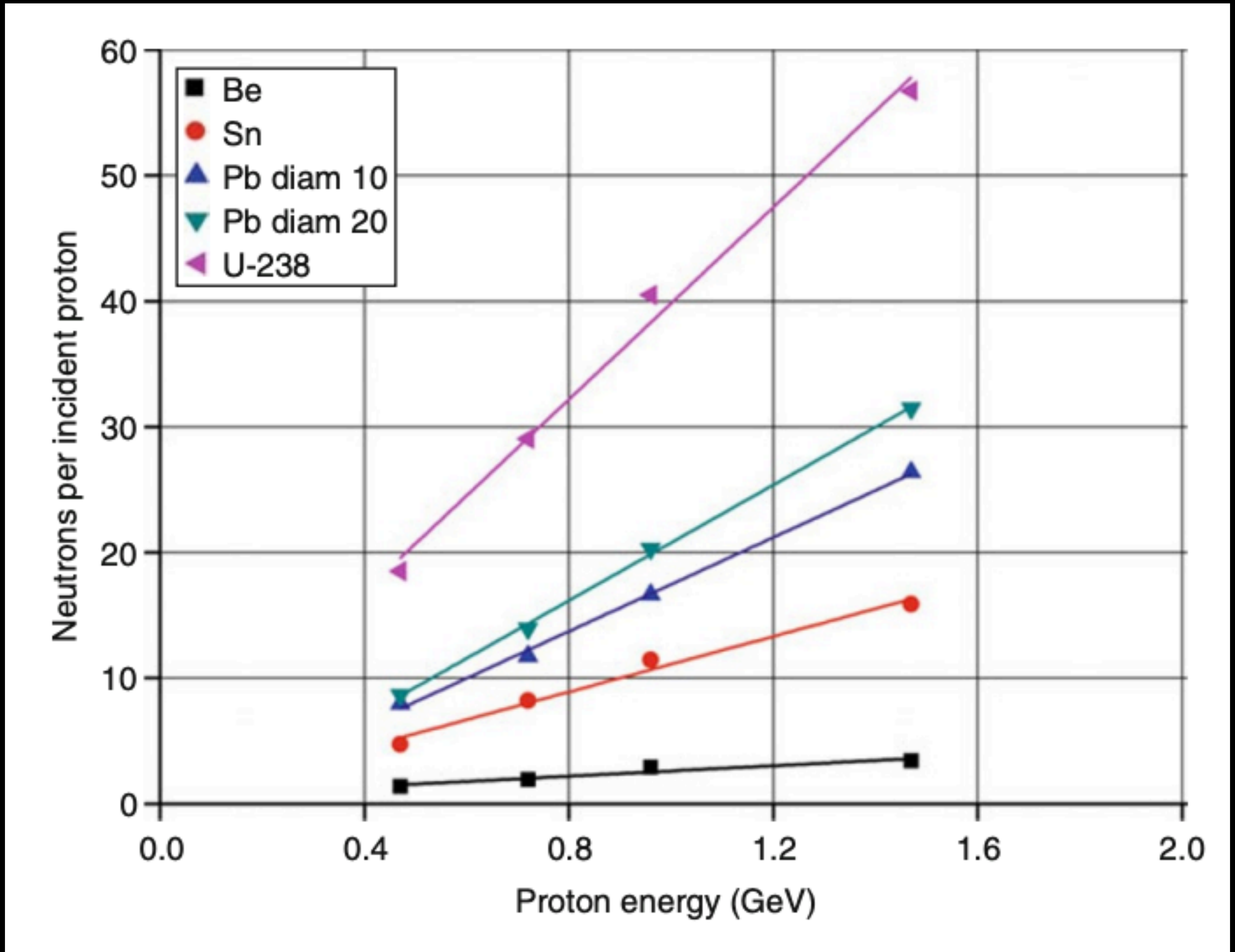
1) no **secondary** processes
(no criticality needed — *endo*thermic)

Why a Spallation (Neutron) **Source?**

Beams give you more control:

1) no **secondary** processes
   (no criticality needed — *endo*thermic)

2) **More neutrons per proton**



Why a Spallation (Neutron) **Source?**

Beams give you more control:

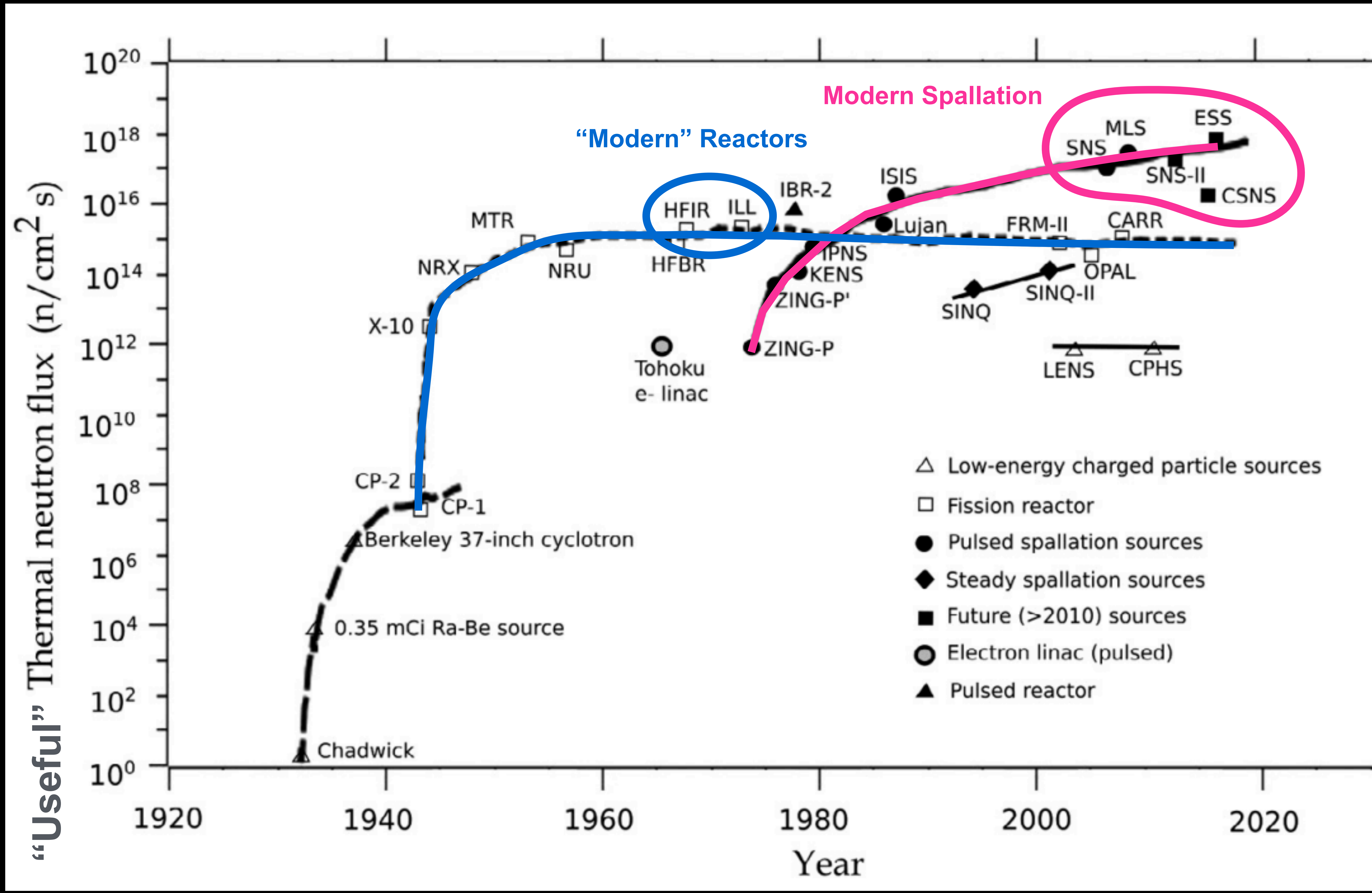
1) no **secondary** processes
   (no criticality needed — *endo*thermic)

2) **More neutrons per proton**

3) **Sources are pulsed**

We will continue to see development of spallation sources around the world.

This is an opportunity for fundamental physics.




ISIS (Rutherford, UK)
• 0.8 GeV p^+
• 0.16 MW and 0.2 mA
• 50 Hz
• 200 ns double-pulse (total 700 ns)
• About 4% πDAR/POT
SNS (Oak Ridge, USA)
• 1 GeV p^+
• 1.4 MW and 1.1 mA
• 60 Hz
• 400 ns single-pulse
• About 9% πDAR/POT
SINQ (PSI, Switzerland)
• 0.59 GeV p^+
• 1.4 MW and 2.4 mA
• Continuous
• Total of (—) πDAR/POT
LANSCE current (Los Alamos, USA)
• 0.8 GeV p^+
• 0.1 MW and 0.125 mA
• 20 Hz
• 290 ns single-pulse
• Total of 4.6% 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 10% πDAR/POT
• Total of 0.54% KDAR/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
Current sources w/ ν detectors
Past or no ν detectors
$\pi^+/\mu^+/K^+$ DAR sources


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
ISIS (Rutherford, UK)
• 0.8 GeV p^+
• 0.16 MW and 0.2 mA
• 50 Hz
• 200 ns double-pulse (total 700 ns)
• About 4% 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 (??)
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
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)
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• 0.8 GeV p^+
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• 20 Hz
• 290 ns single-pulse → 100 ns (LANSCE-PSR)
• Total of 4.6% πDAR/POT
LAMPF/LANSCE 93-98 (Los Alamos, USA)
• 0.8 GeV p^+
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• 120 Hz
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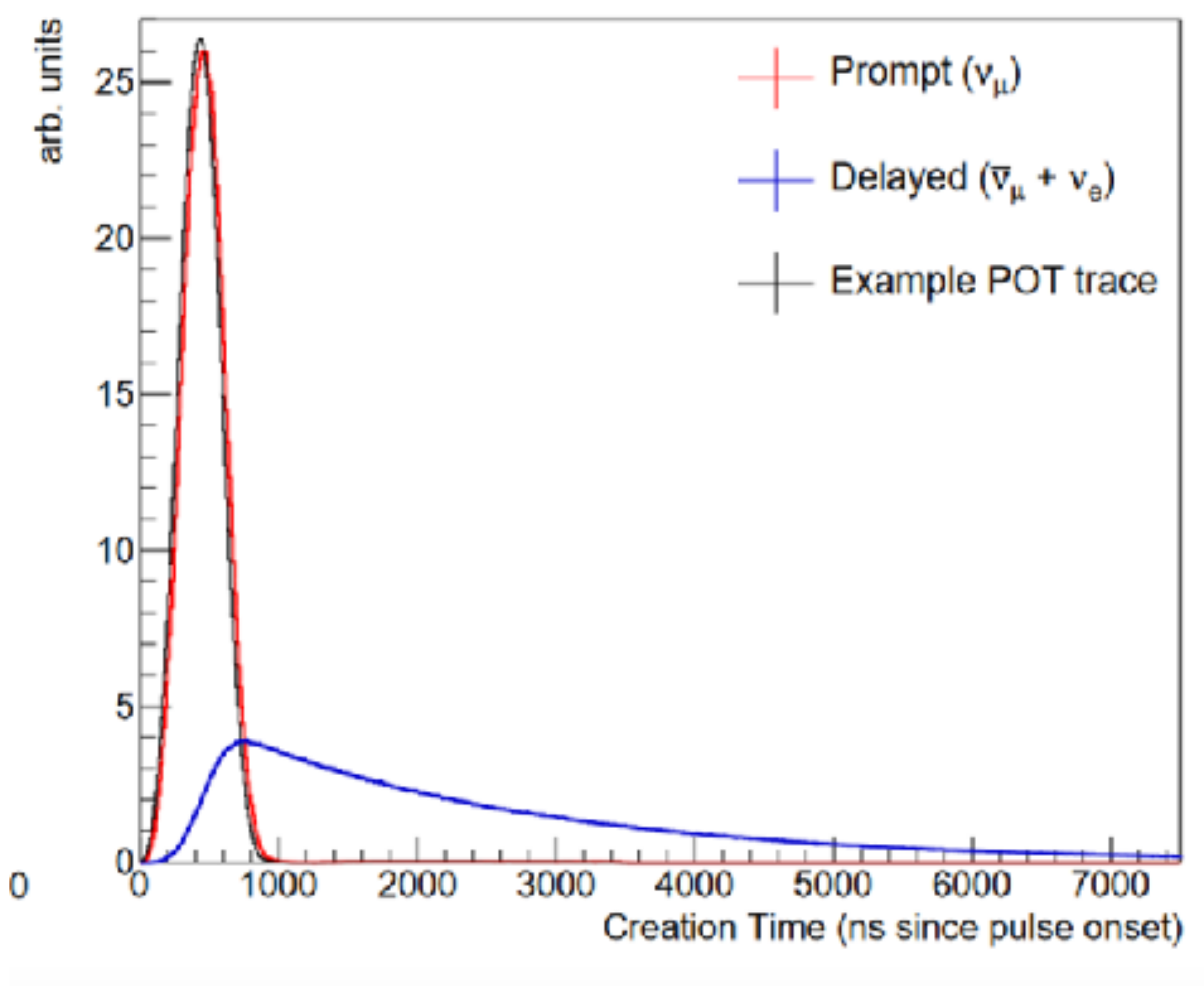
$\pi^+/\mu^+/K^+$ DAR sources
Current sources w/ ν detectors
Past or no ν detectors
Future sources w/ ν detector plans

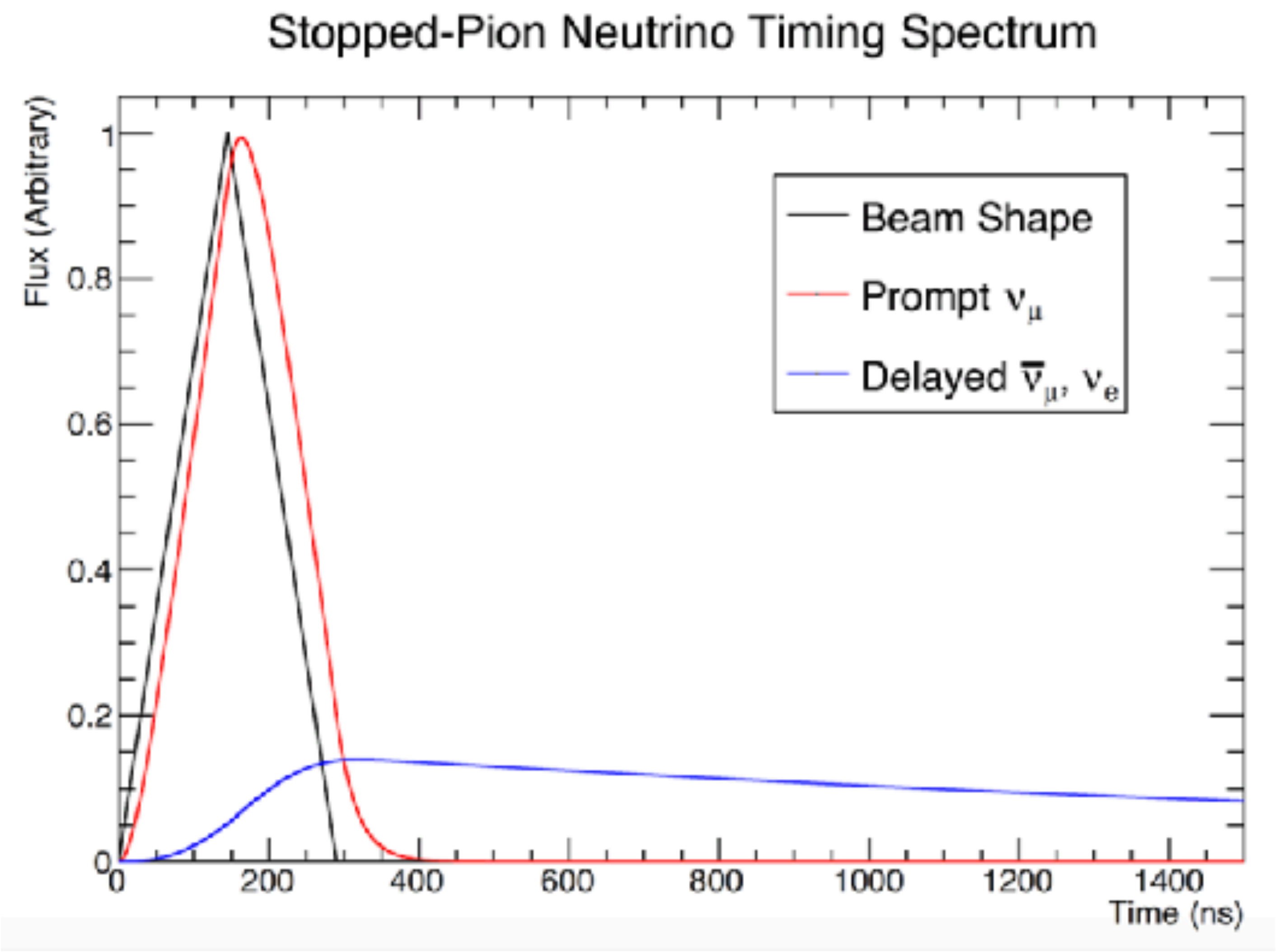
Pulse shape

Oak Ridge



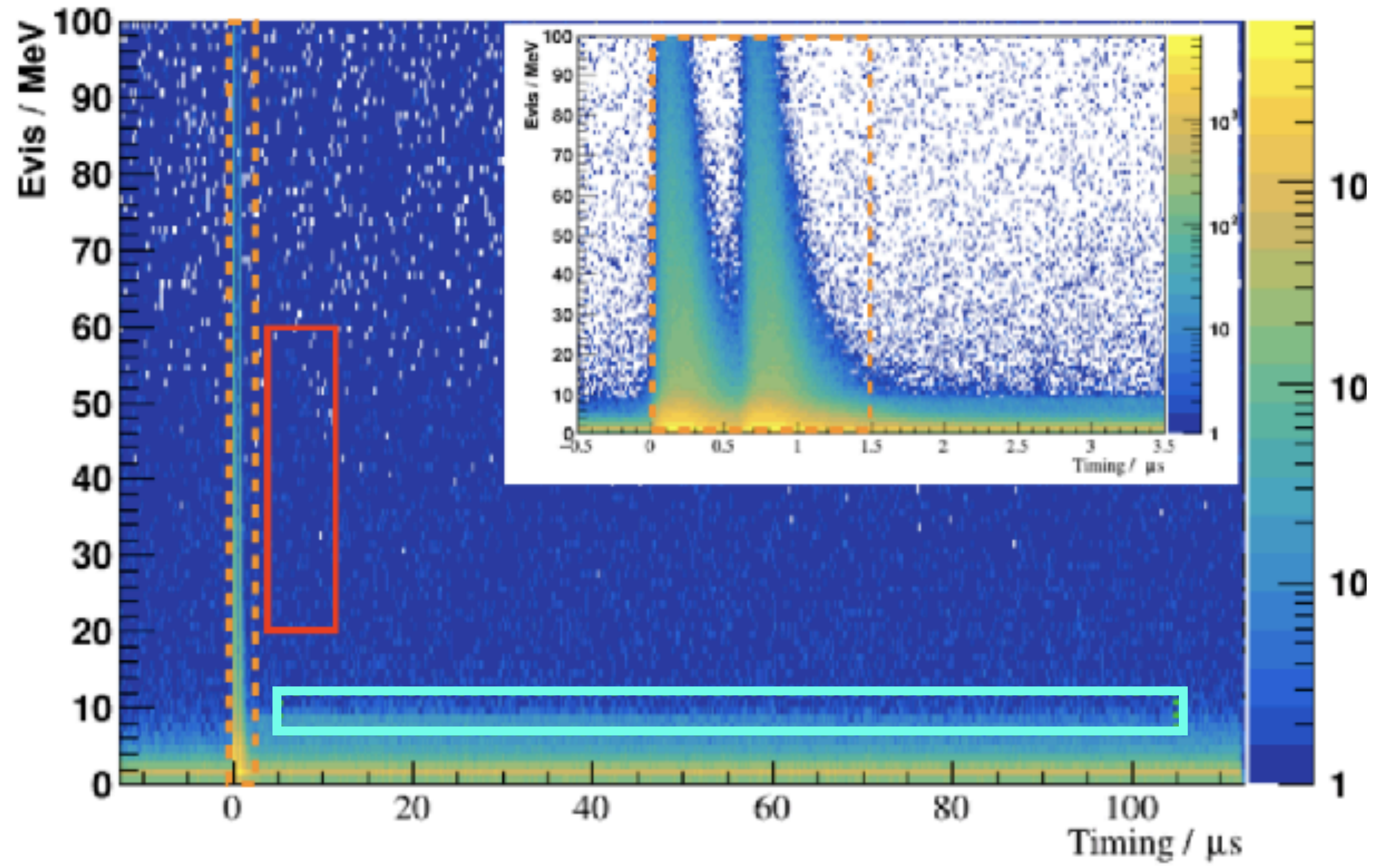
400 ns single-pulse

Los Alamos



290 ns single-pulse
Upgrade to 100 ns with LANSCE-PSR

J-PARC



100 ns double-pulse (total 800 ns)

Spallation sources as a neutrino source

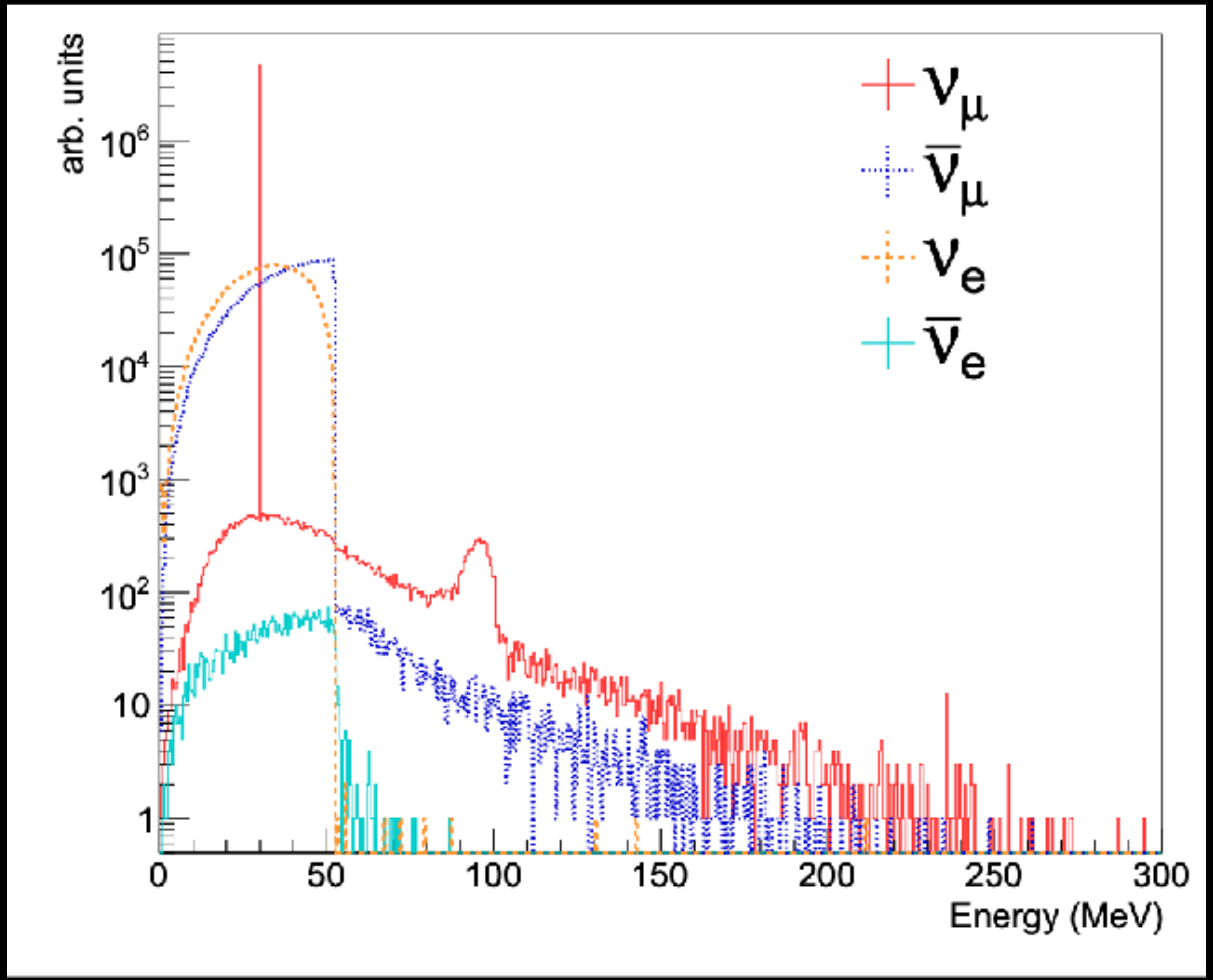
$10^{20} - 10^{22}$ π^+, K^+, and μ^+ decays at rest

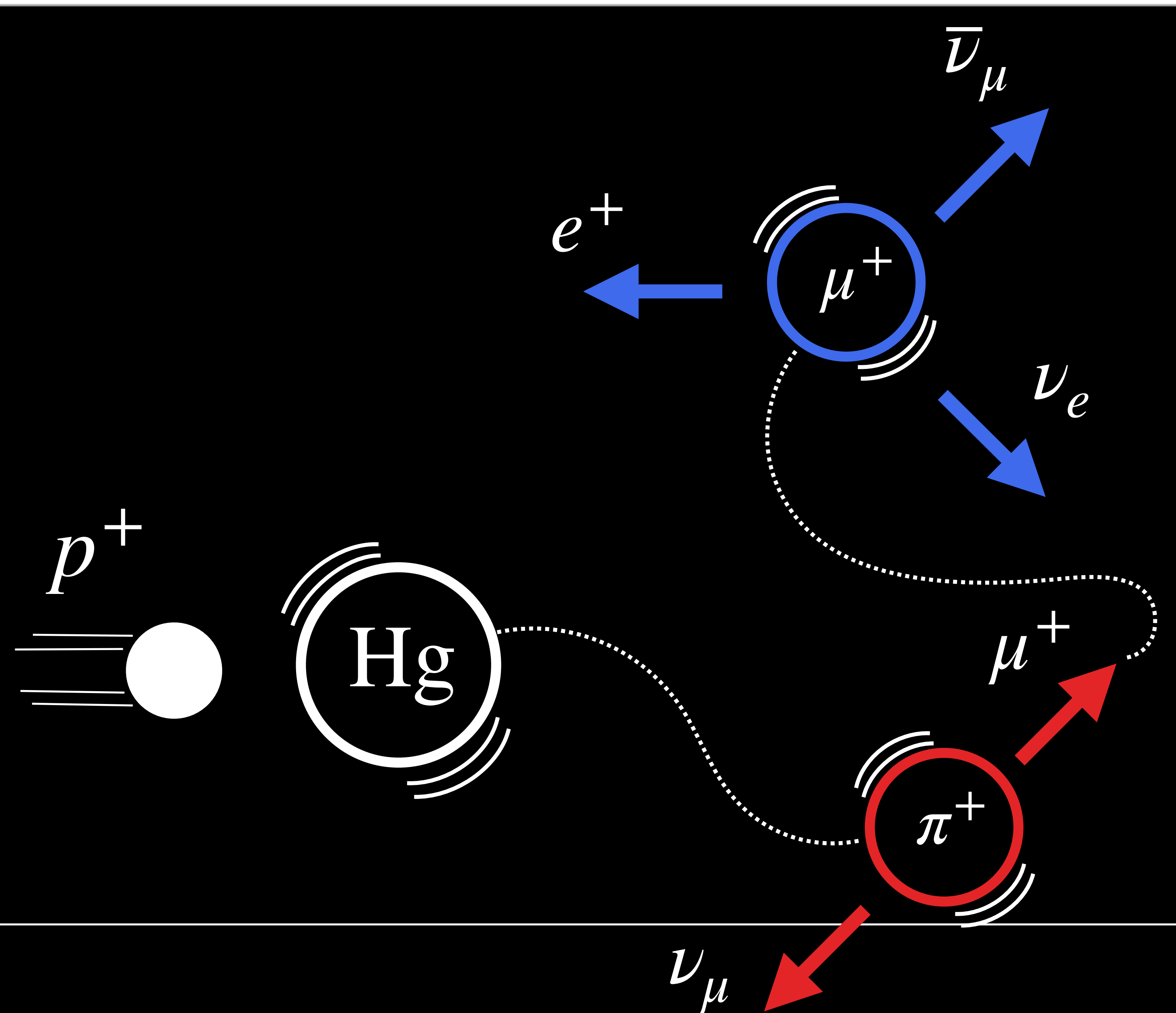
Production data on p+Be target...

Produced Hadron	Exclusive Reaction	M_X (GeV/c^2)	$\sqrt{s_{thresh}}$ (GeV)	E^{beam}_{thresh} GeV	KE of beam (MeV)
π^+	$pn\pi^+$	1.878	2.018	1.233	295
π^-	$pp\pi^+\pi^-$	2.016	2.156	1.54	602
π^0	$pp\pi^0$	1.876	2.011	1.218	280
K^+	$\Lambda^0 pK^+$	2.053	2.547	2.52	1582
K^-	ppK^+K^-	2.37	2.864	3.434	2496
K^0	$p\Sigma^+K^0$	2.13	2.628	2.743	1805

Very few locations!

J. Conrad

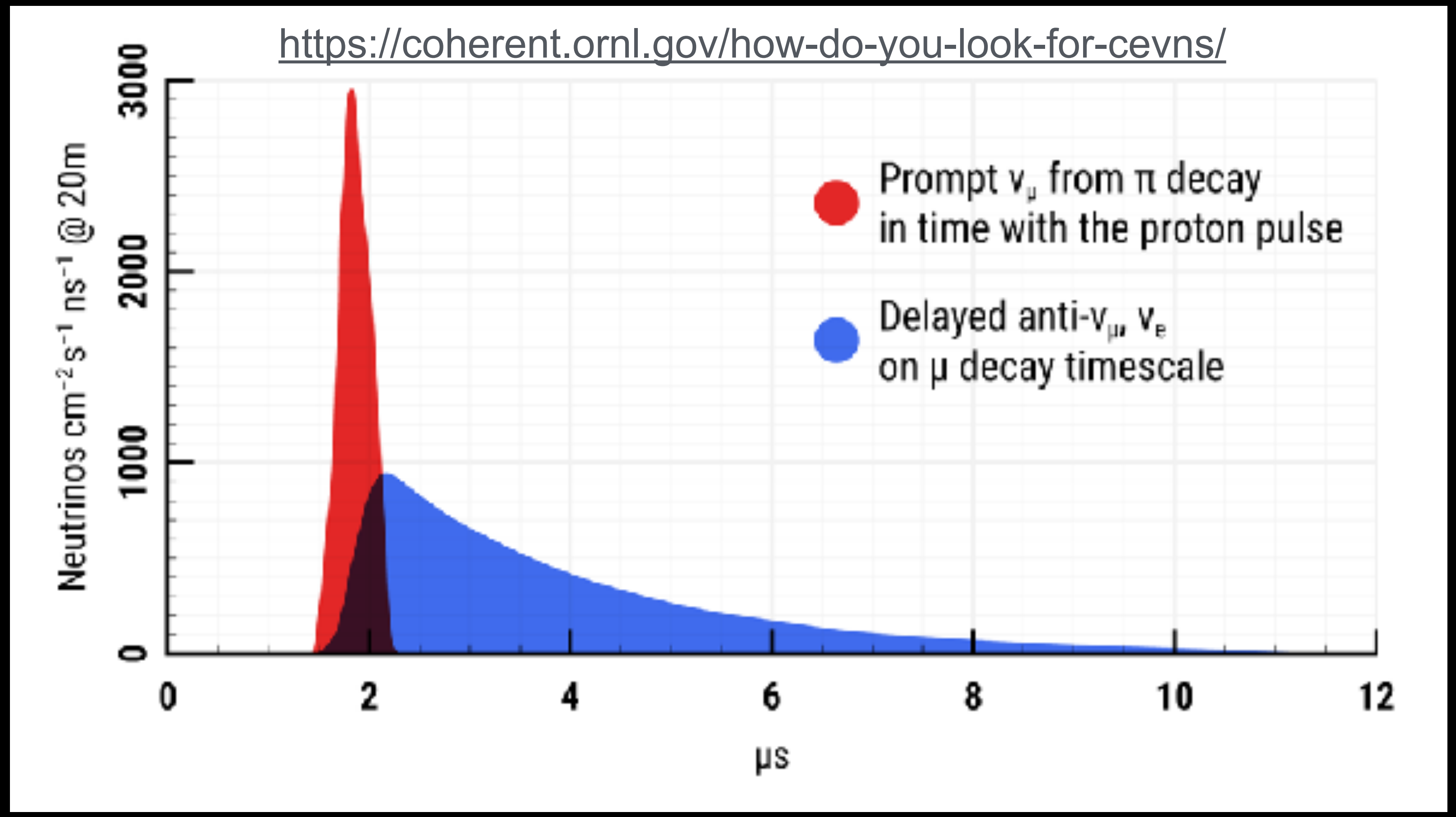


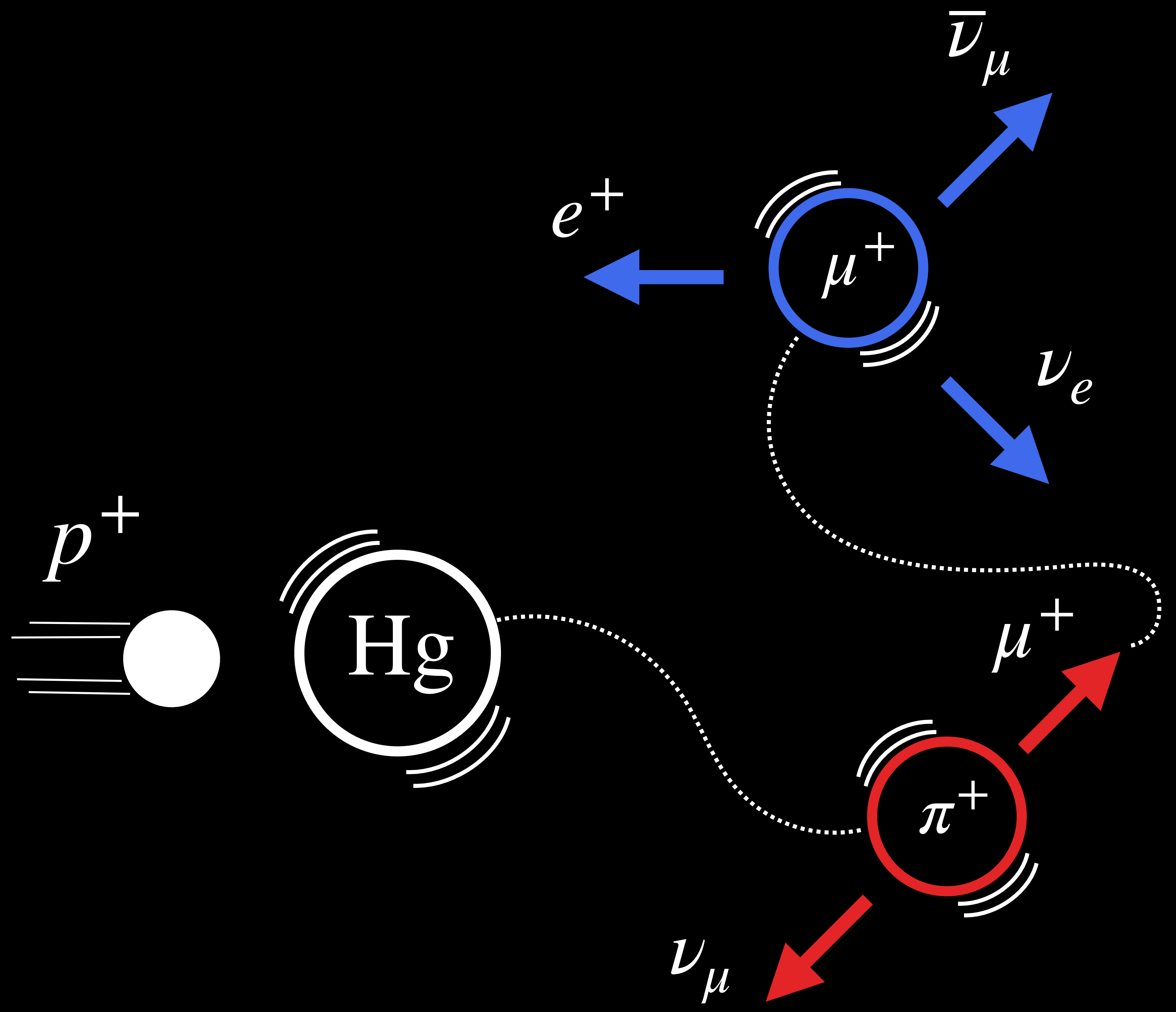


CEvNS and neutrino physics program

Long-lived particles at Spallation sources

$10^{20} - 10^{22}$ π^+, K^+, and μ^+ decays at rest

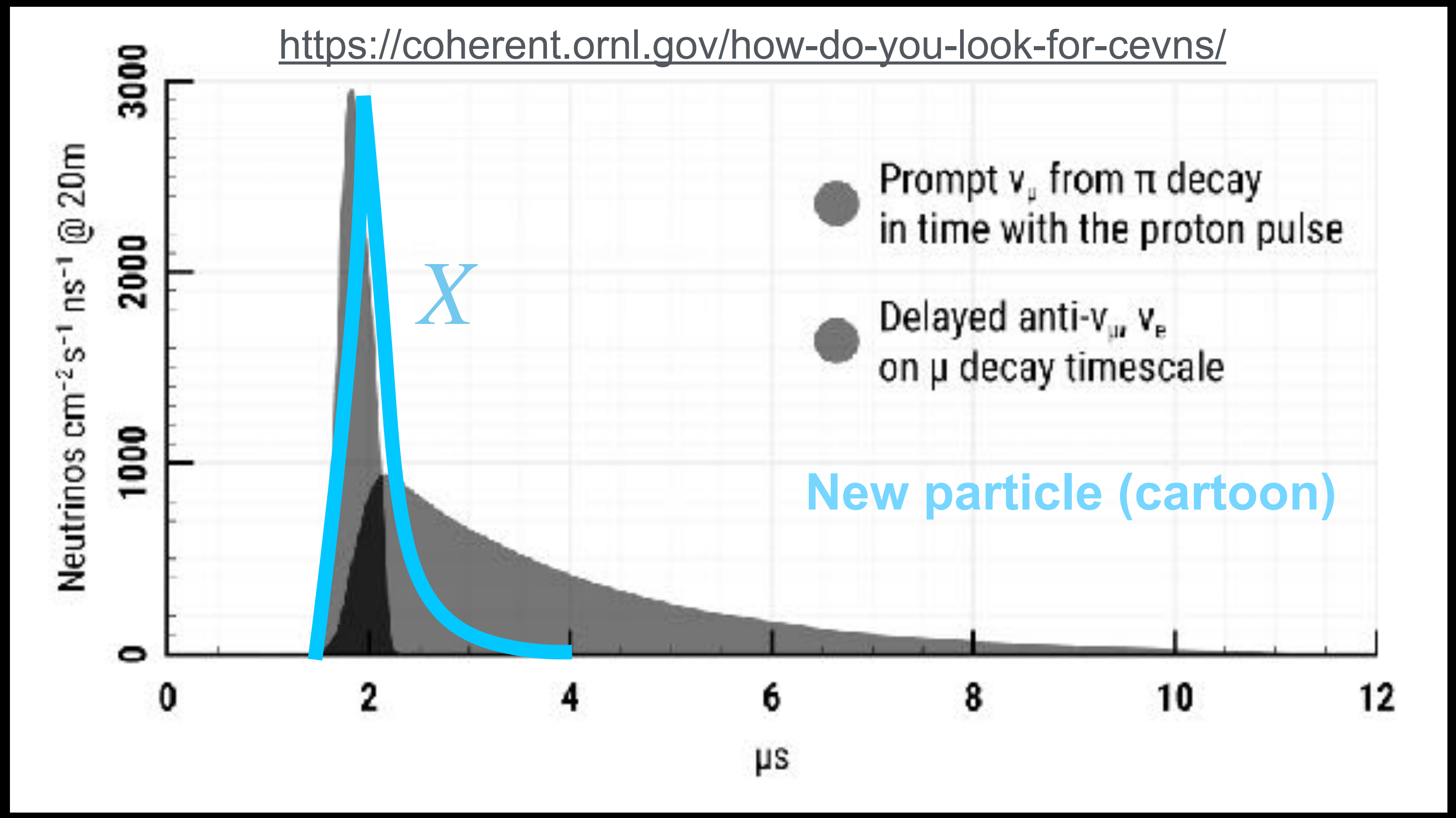


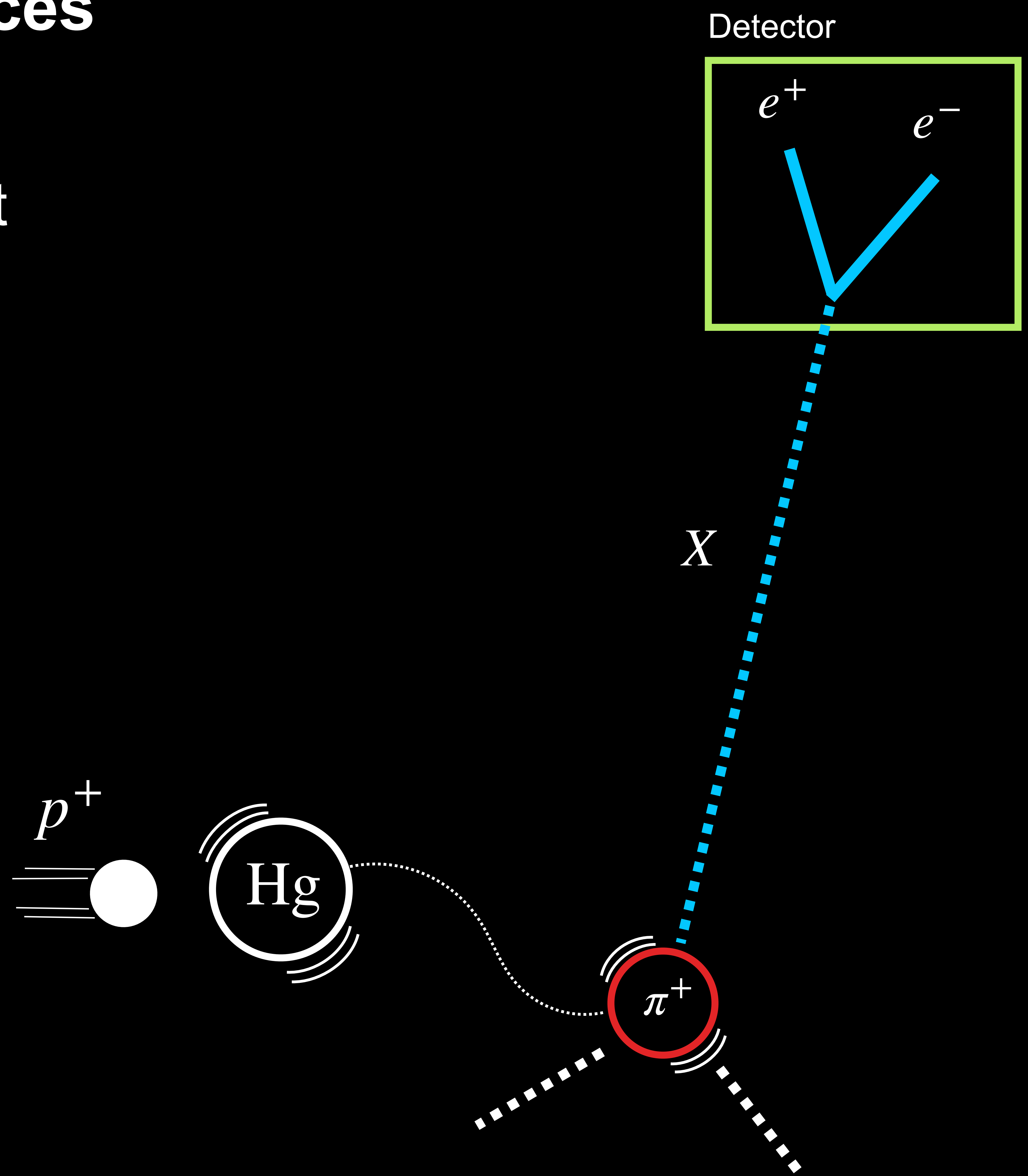


Long-lived particles at Spallation sources

$10^{20} - 10^{22}$ π^+, K^+, and μ^+ decays at rest

Can also search for a flux of new states.





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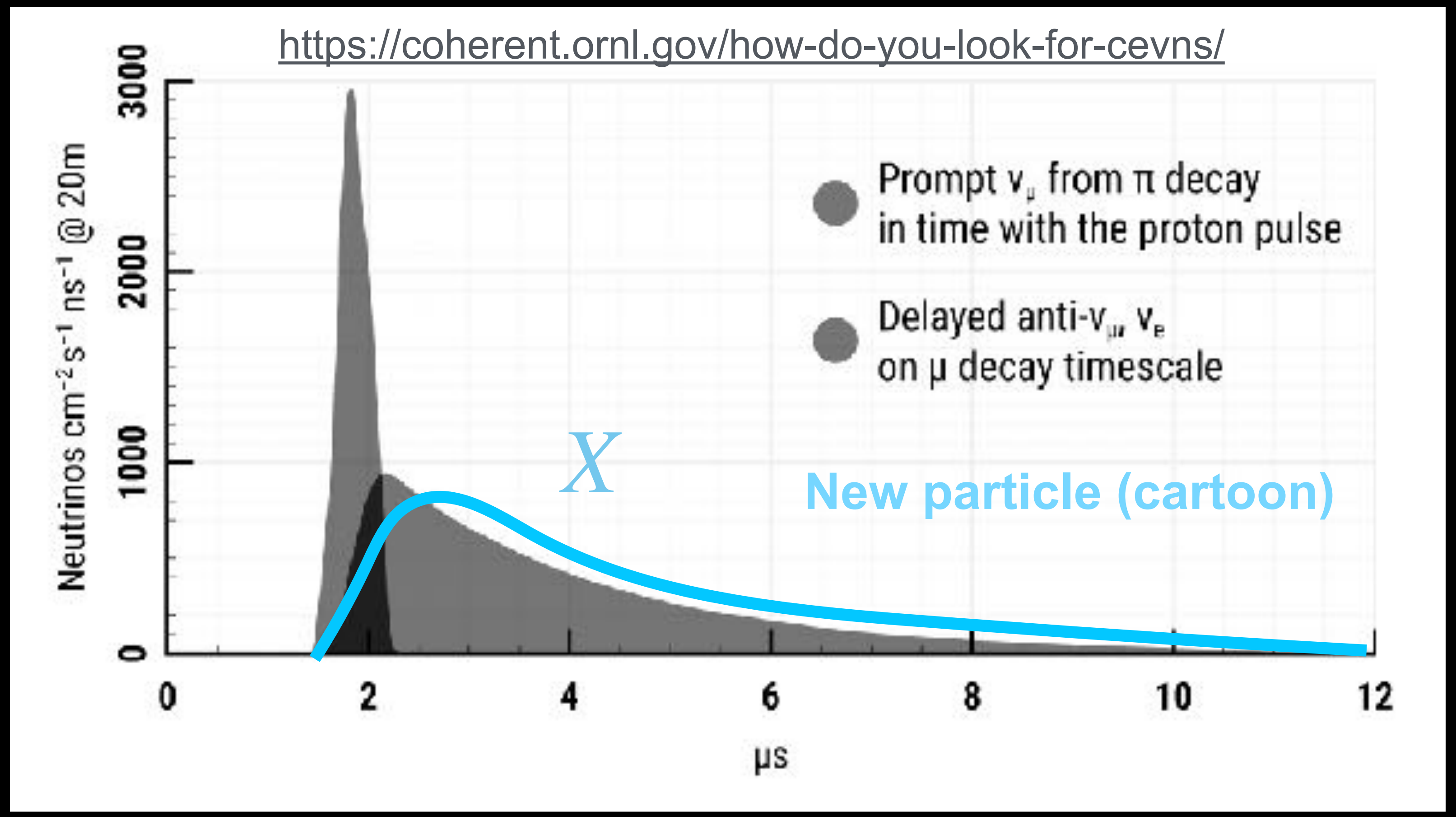
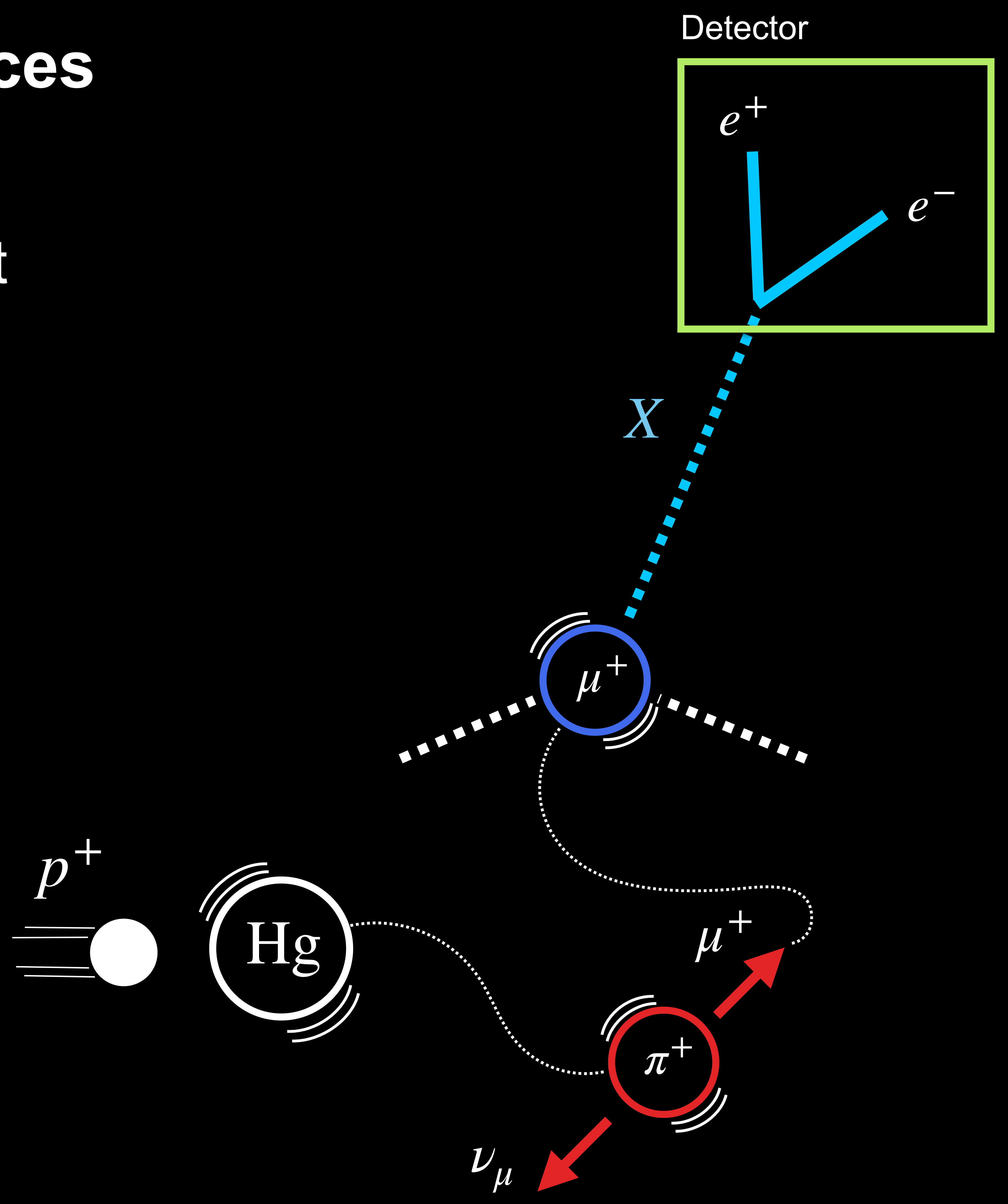




Outline:

1) **Spallation (neutron) sources: what and why?**

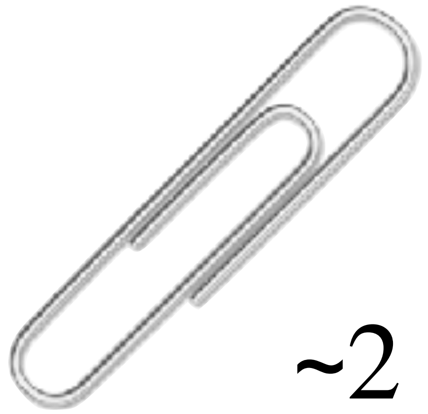
2) **Opportunities with neutrino detectors**

3) Long-lived particles below K, π, and μ masses

What do we already have?

The LSND $\nu - e$ scattering measurement

Extremely high intensity beam from ~93 - 98

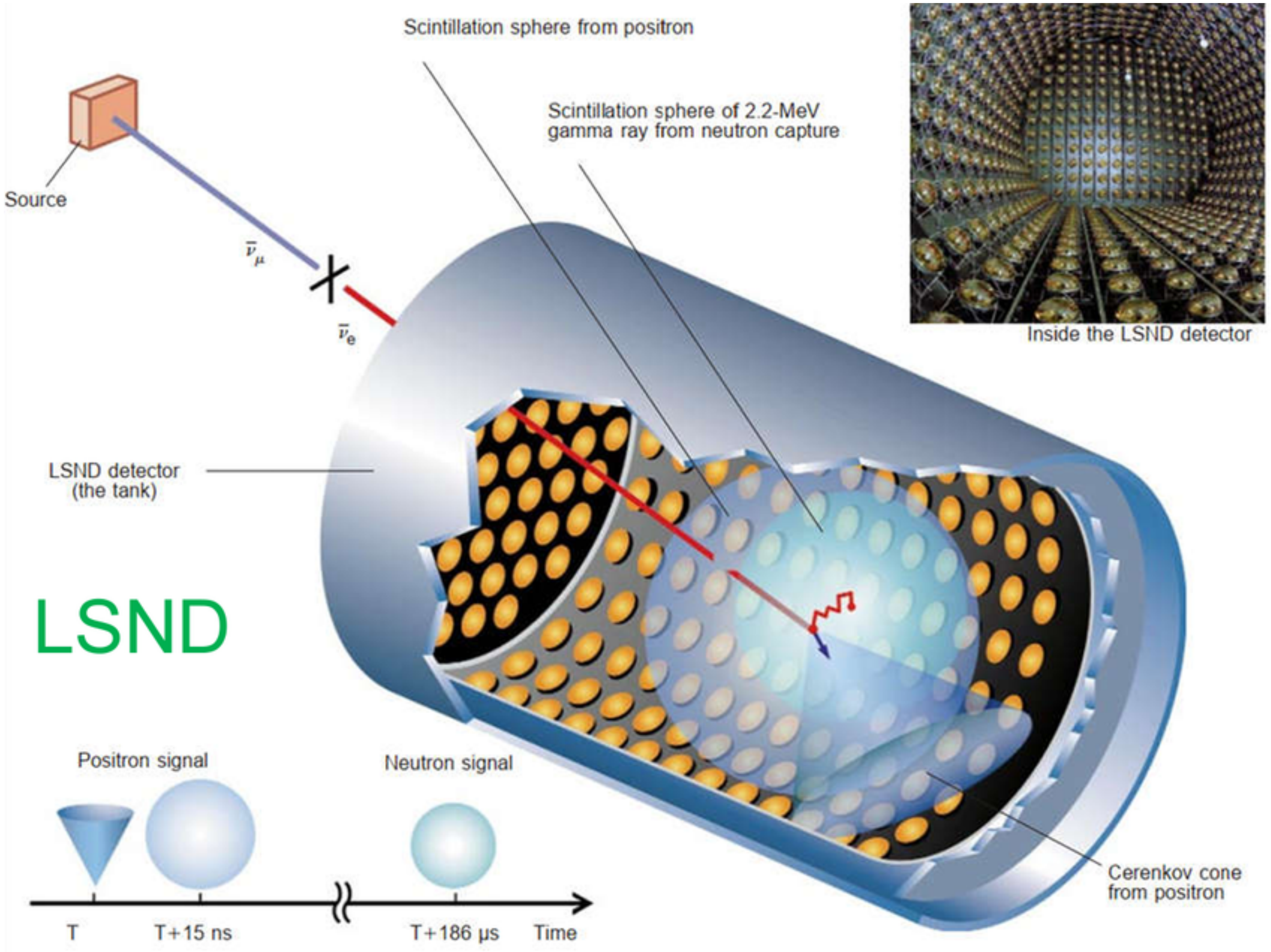


~160 ton of liquid scintillator

$\sim 2 \times 10^{23}$ POT (about a paperclip's worth of protons)

A striking measurement of $\nu + e \to \nu + e$ scattering with about 10% precision on the cross section.

(*not the same channel as the LSND anomaly.)



What do we already have?

The LSND $\nu - e$ scattering measurement

LSND: $\nu + e \to \nu + e$ scattering

(*not the same channel as the LSND anomaly.)

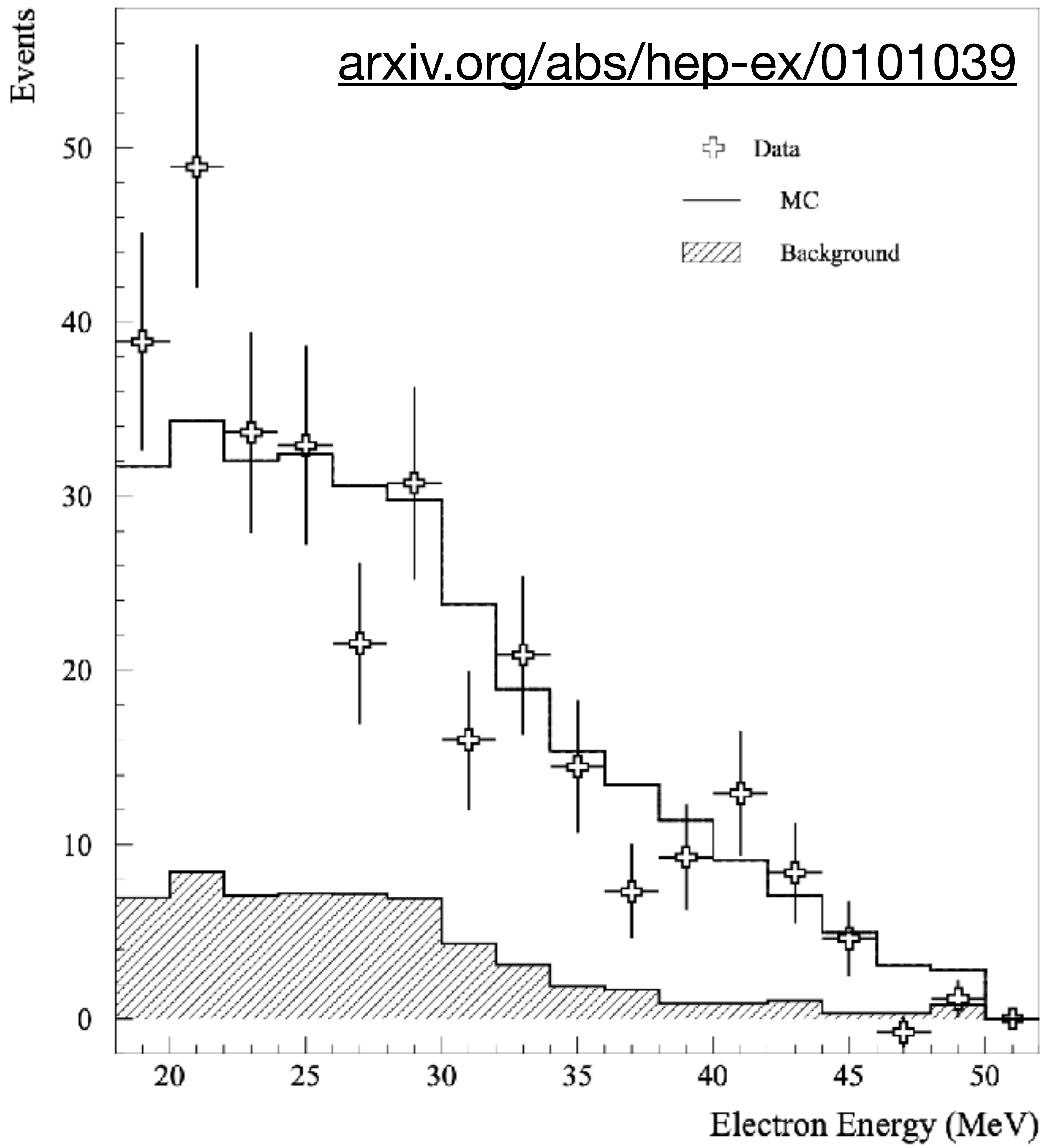
Very useful for BSM applications.

But is has its limitations:

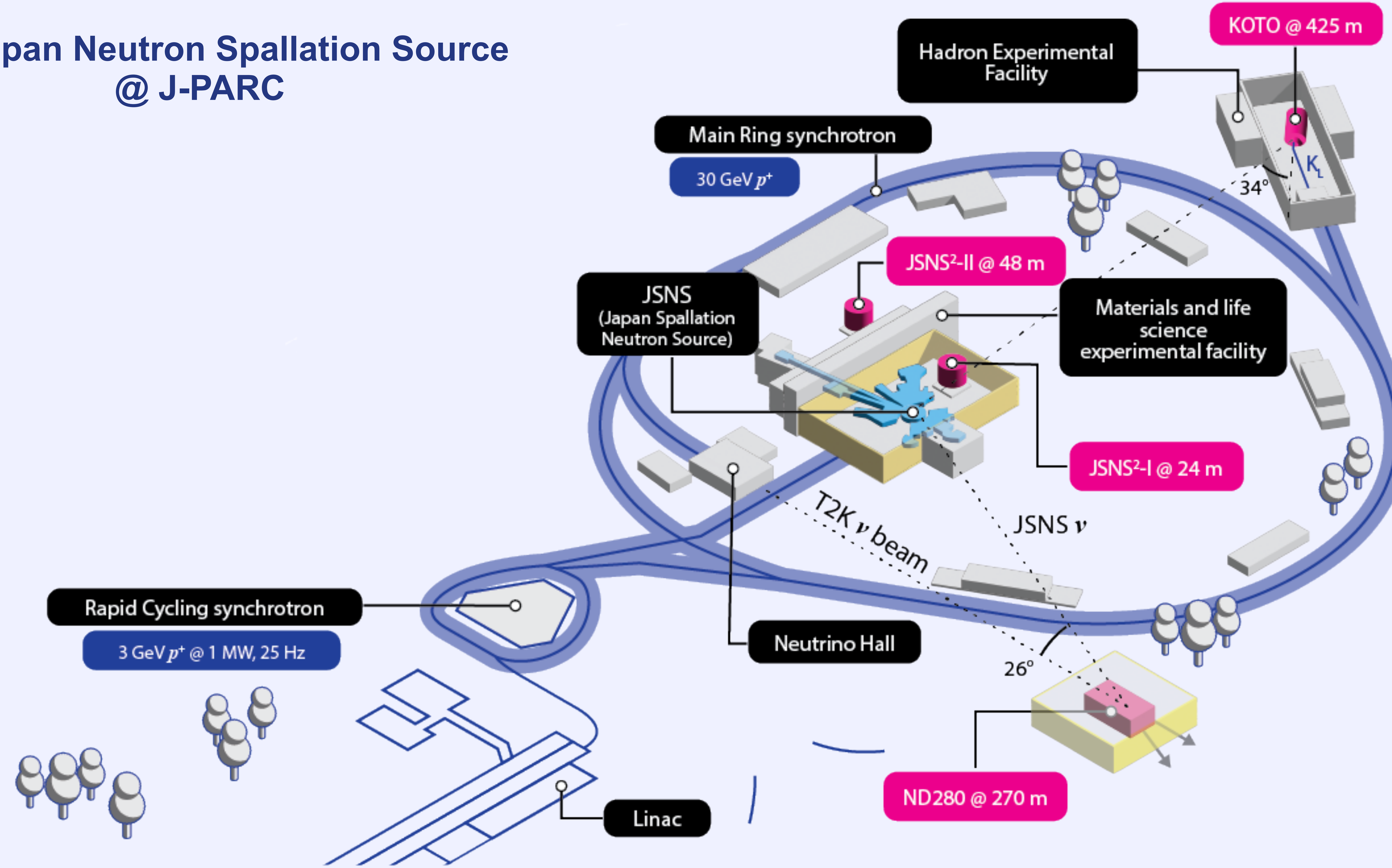
1) Very wide beam pulse (600 μs) and low E (π and μ only).
2) Only single EM showers (how to account for misID of e^+e^-?)
3) Limited energy range: 18 MeV $< E_{\rm vis} < 50$ MeV
4) Only the most forward electrons: $\cos\theta_{\rm vis} > 0.9$

No data release… how to model efficiencies?
All bounds come from theorists recast of this plot →

arxiv.org/abs/hep-ex/0101039



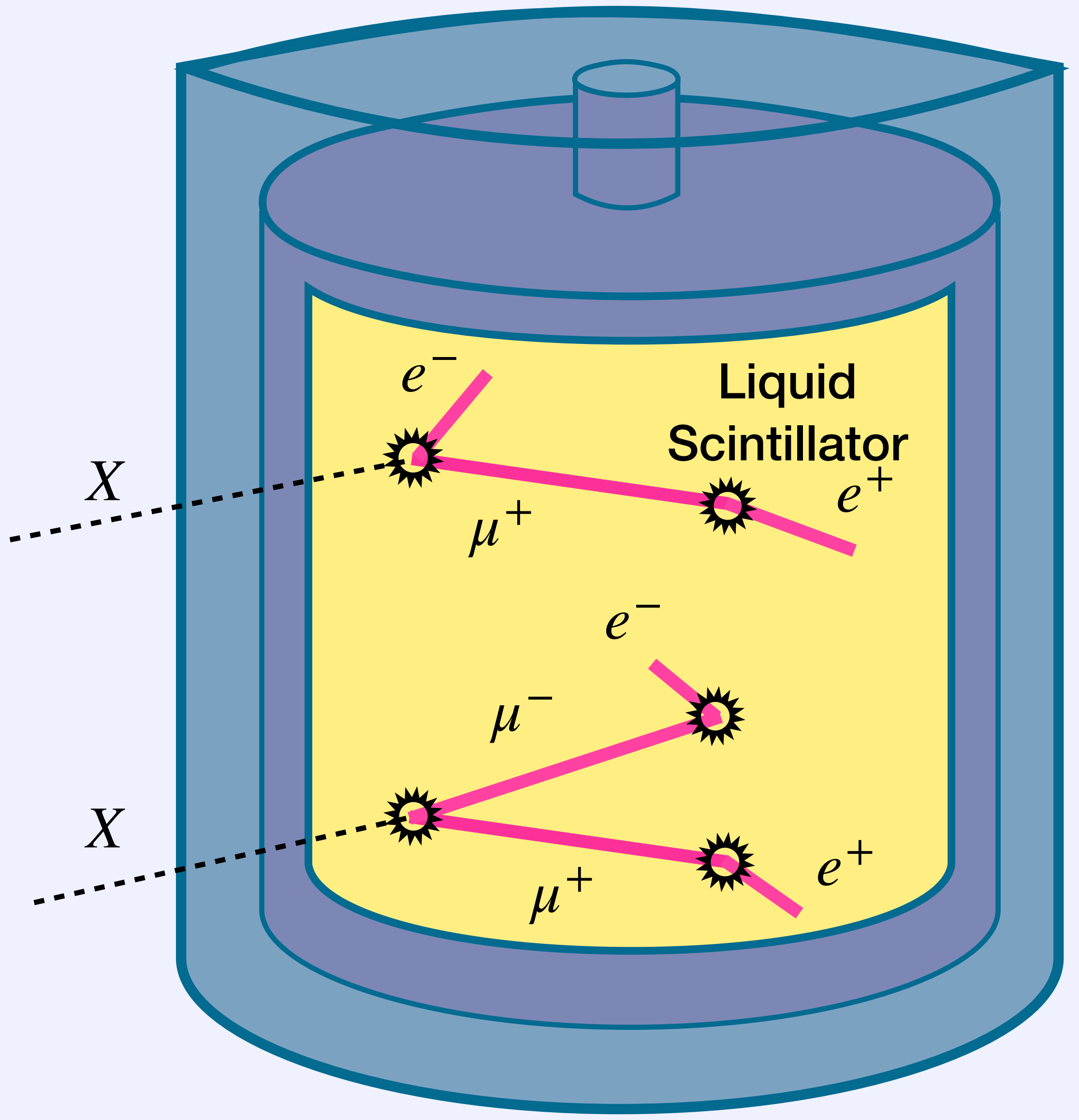
The Japan Neutron Spallation Source @ J-PARC



by J. Pairin

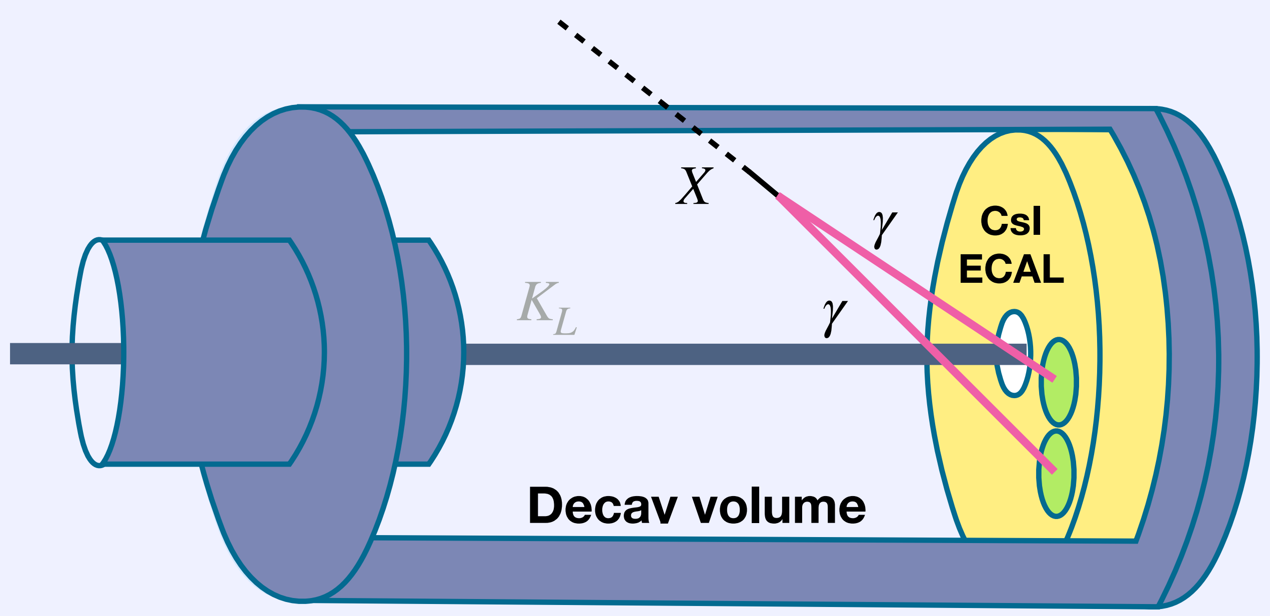
JSNS^2 (I and II):

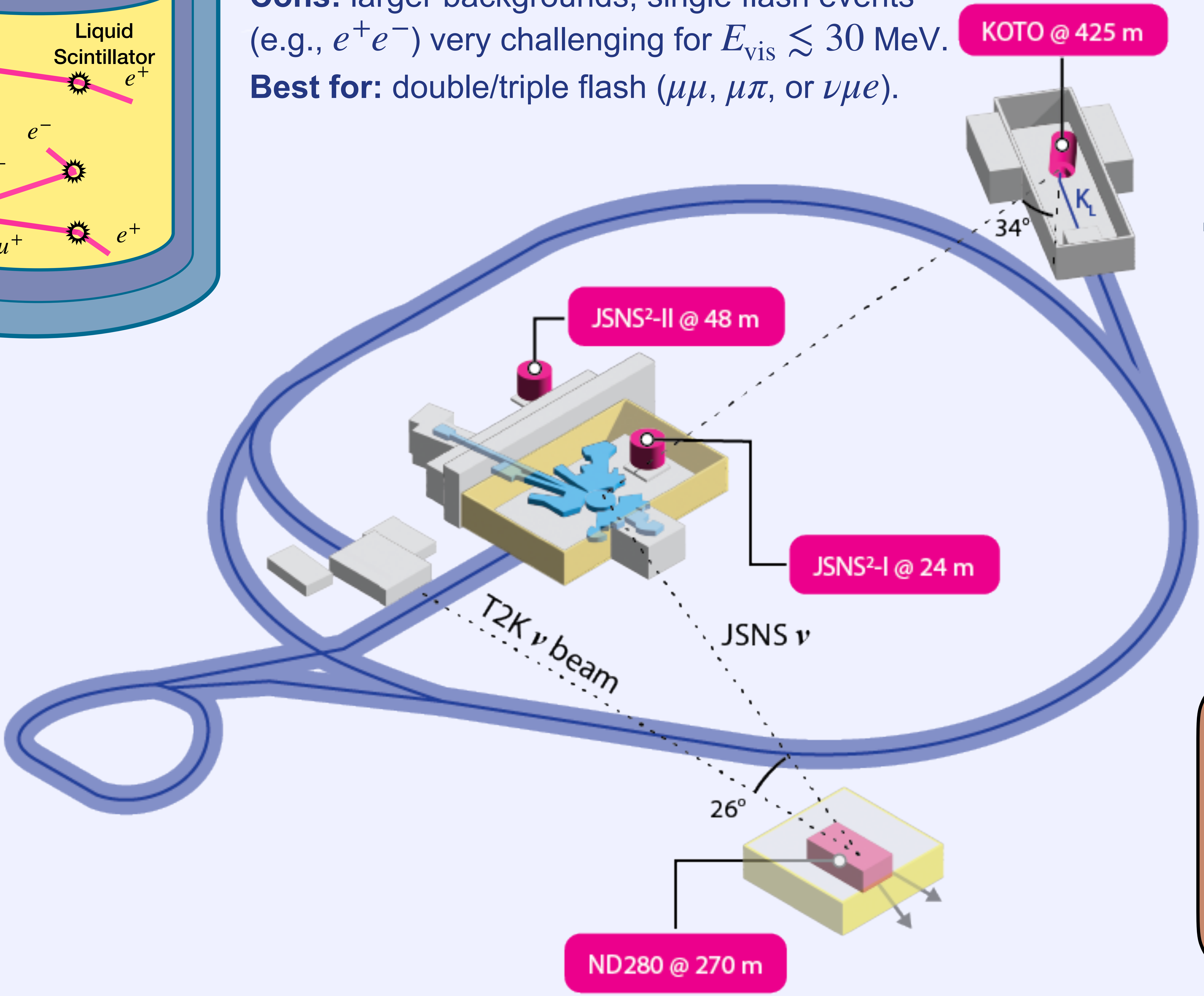
Pros: Closest to the source and largest vol
Cons: larger backgrounds, single flash events (e.g., e^+e^-) very challenging for $E_{\rm vis} \lesssim 30$ MeV.
Best for: double/triple flash ($\mu\mu$, $\mu\pi$, or $\nu\mu e$).



KOTO:

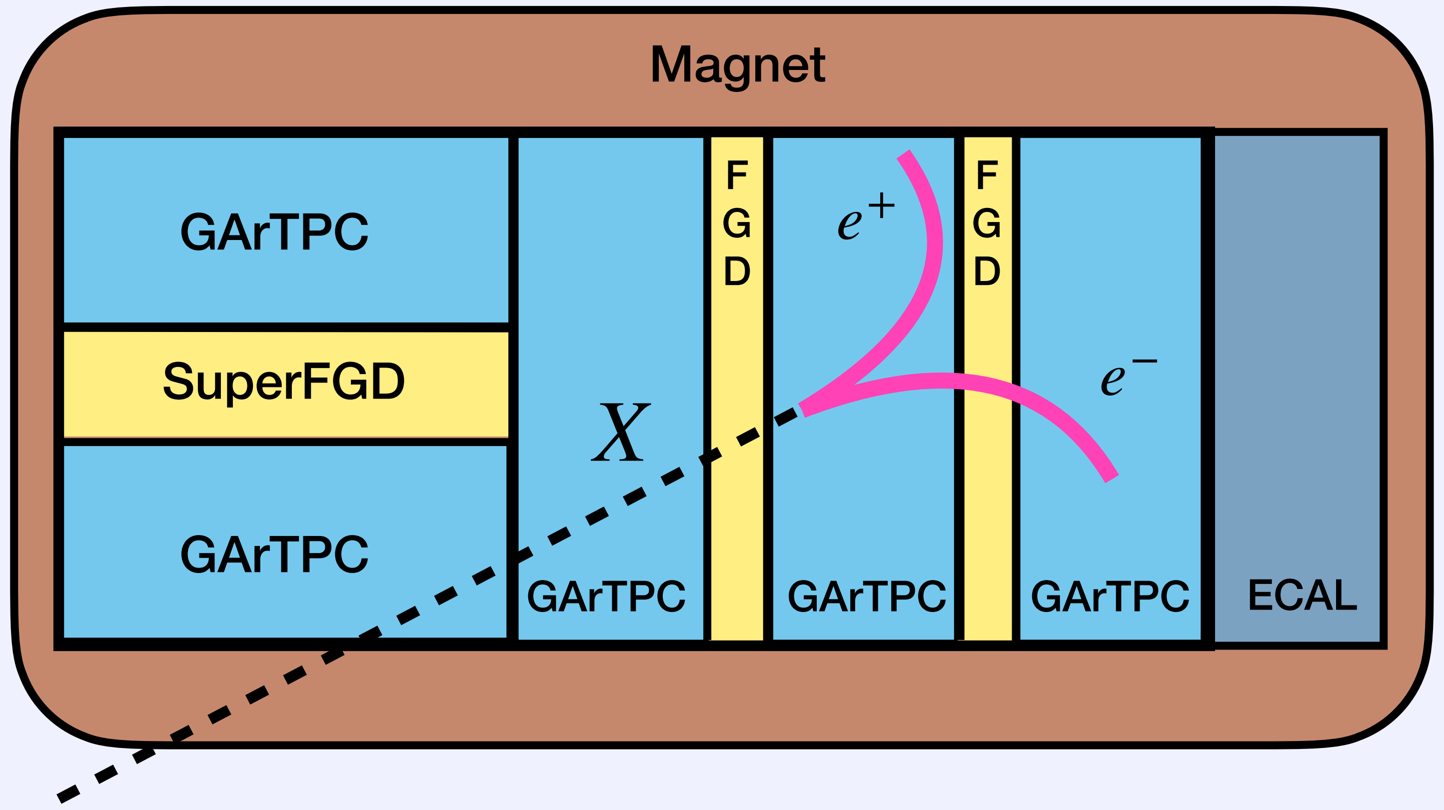
Pros: Low-density vol and low bkg
Cons: Further away
Best for: π^0 and $\gamma\gamma$

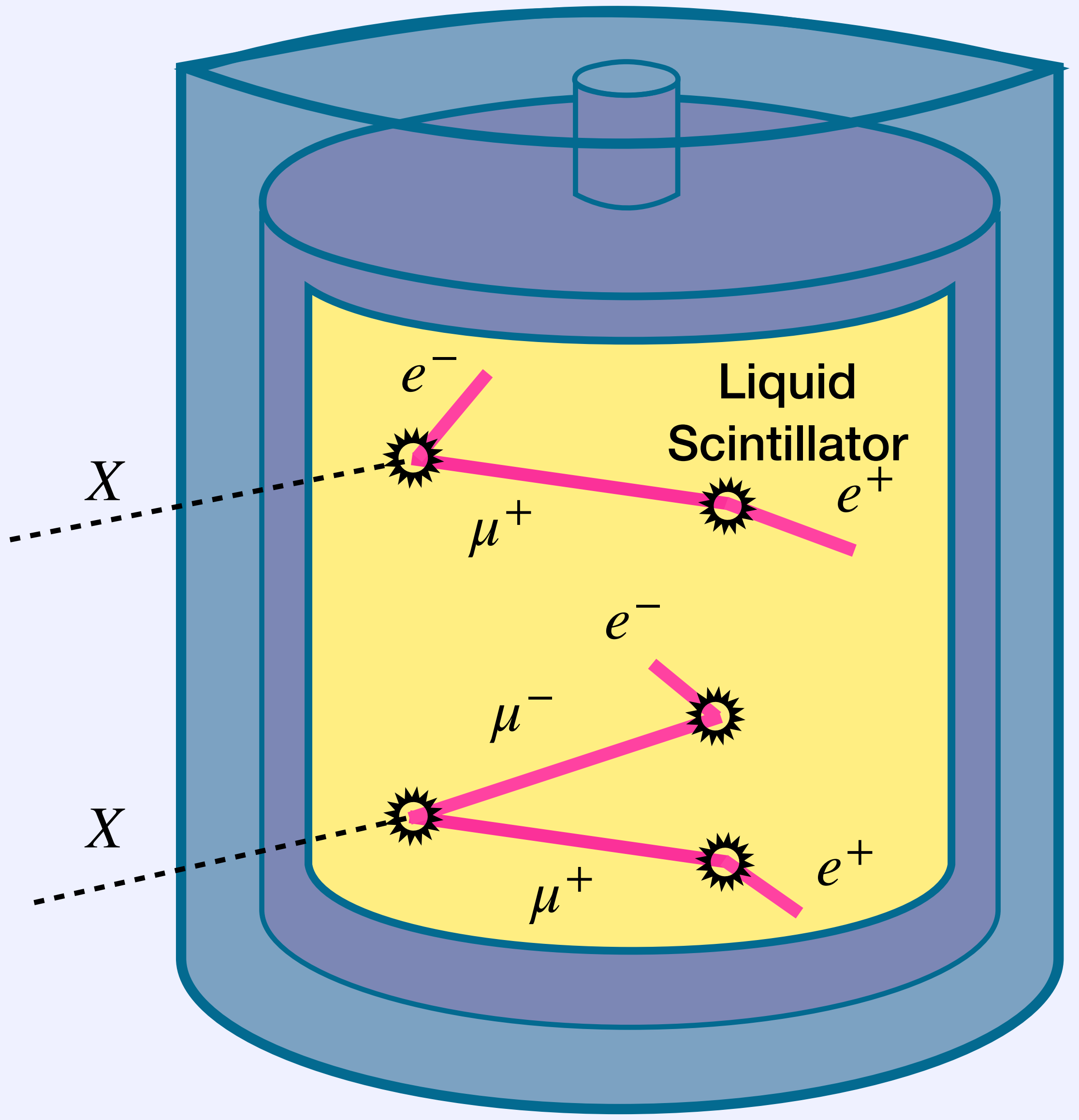




ND280:

Pros: Low-density and magnetized
Cons: Further away
Best for: any charged final state





JSNS^2 (I and II):

Pros: Closest to the source and largest vol
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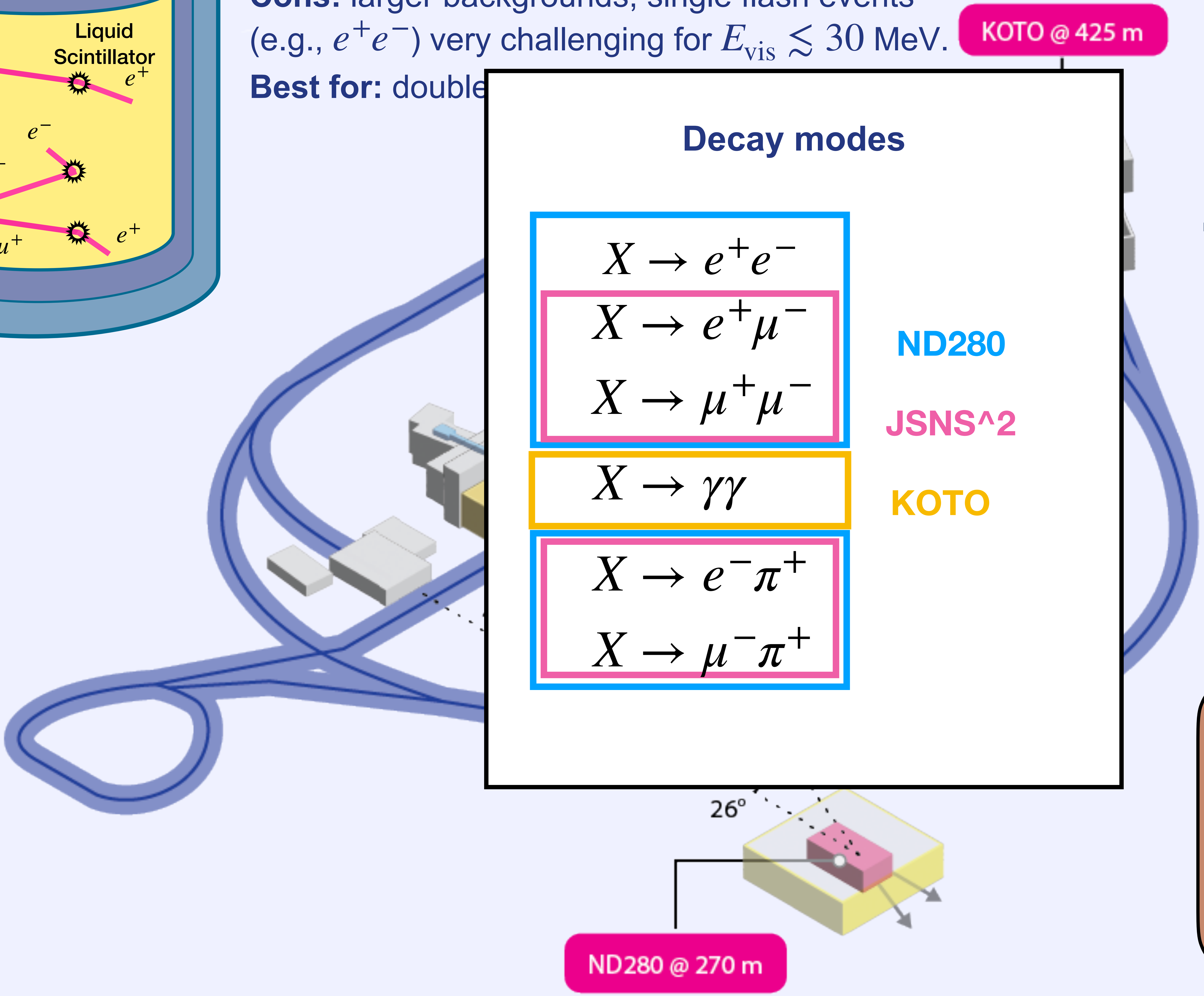
Best for: double



Decay modes

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

ND280
JSNS^2
KOTO

KOTO:
Pros: Low-density vol and low bkg
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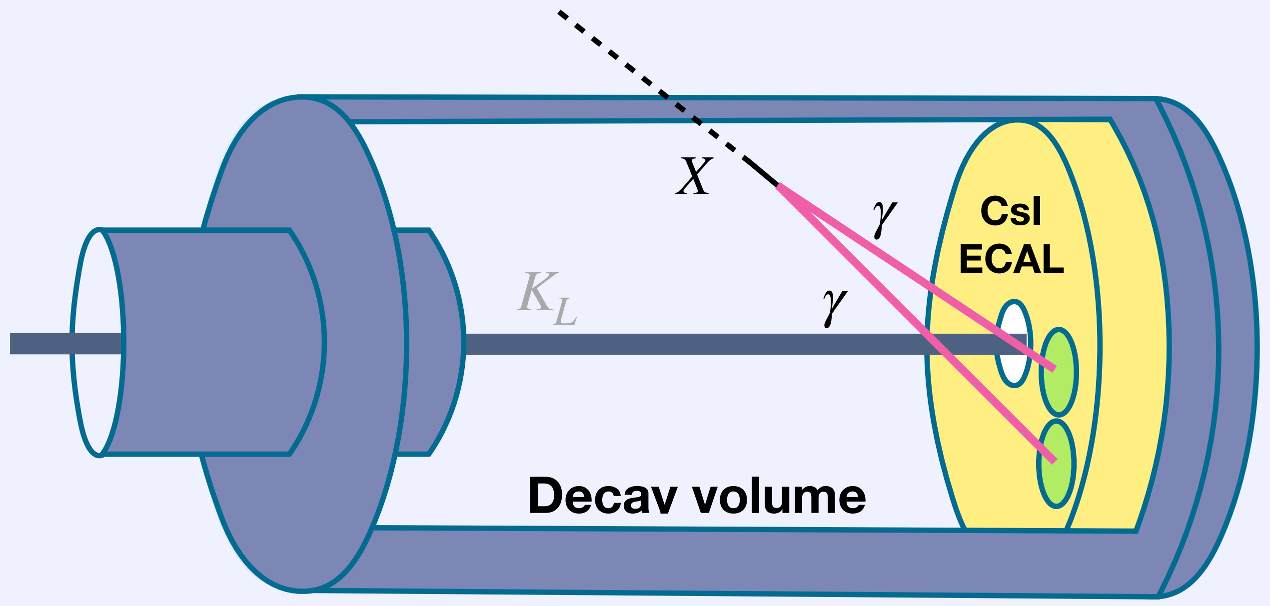
Best for: π^0 and $\gamma\gamma$



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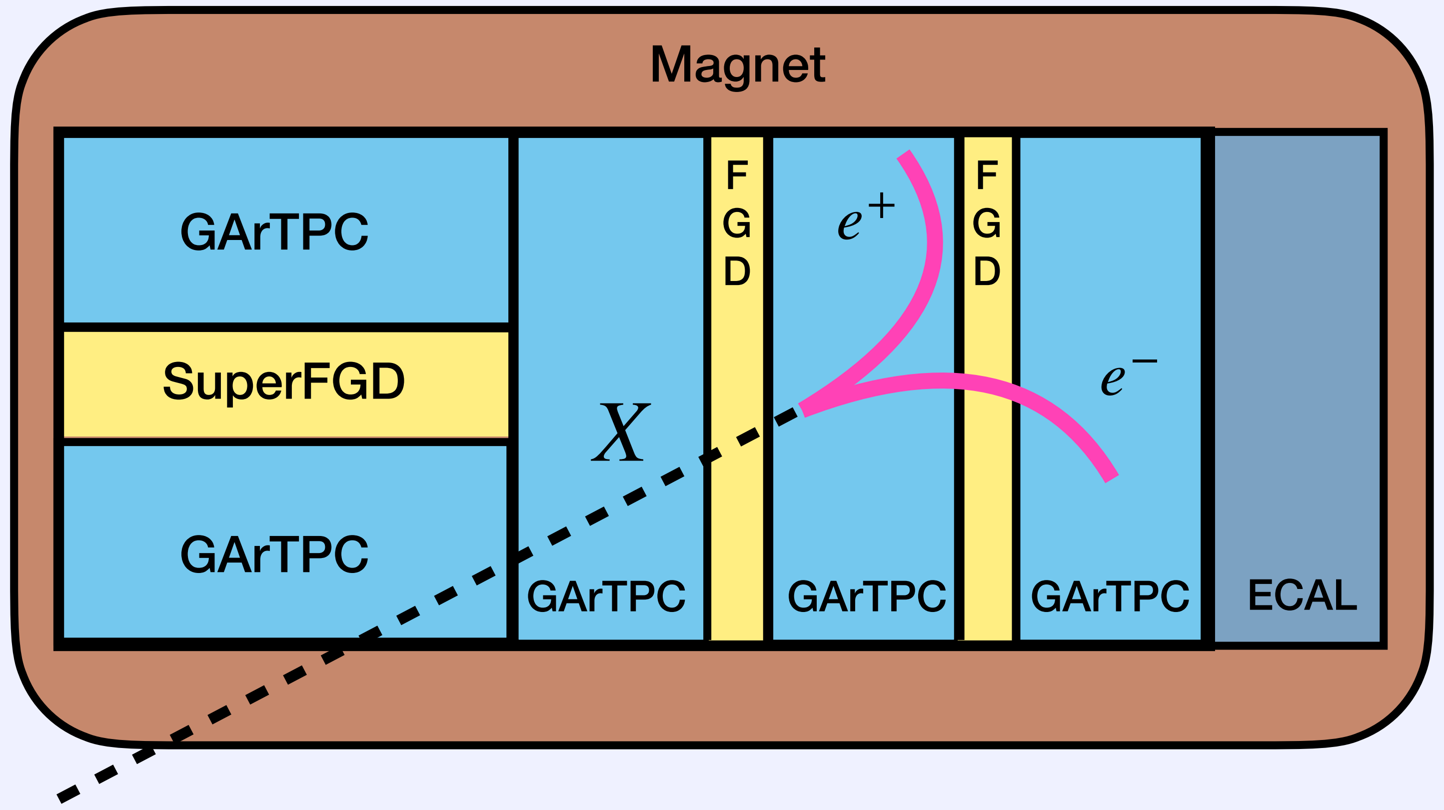
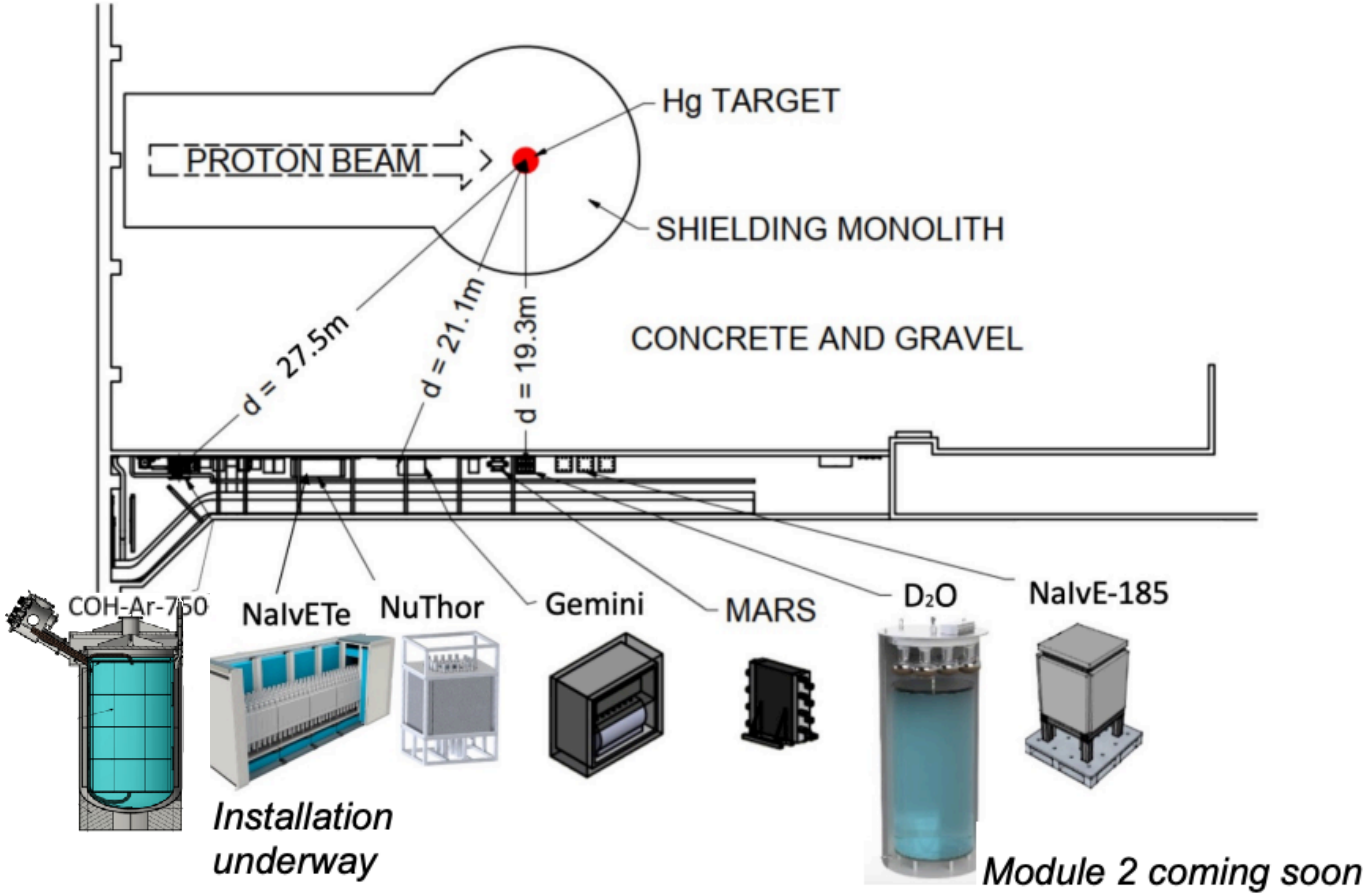


Opportunities at Oak Ridge

SNS COHERENT detectors



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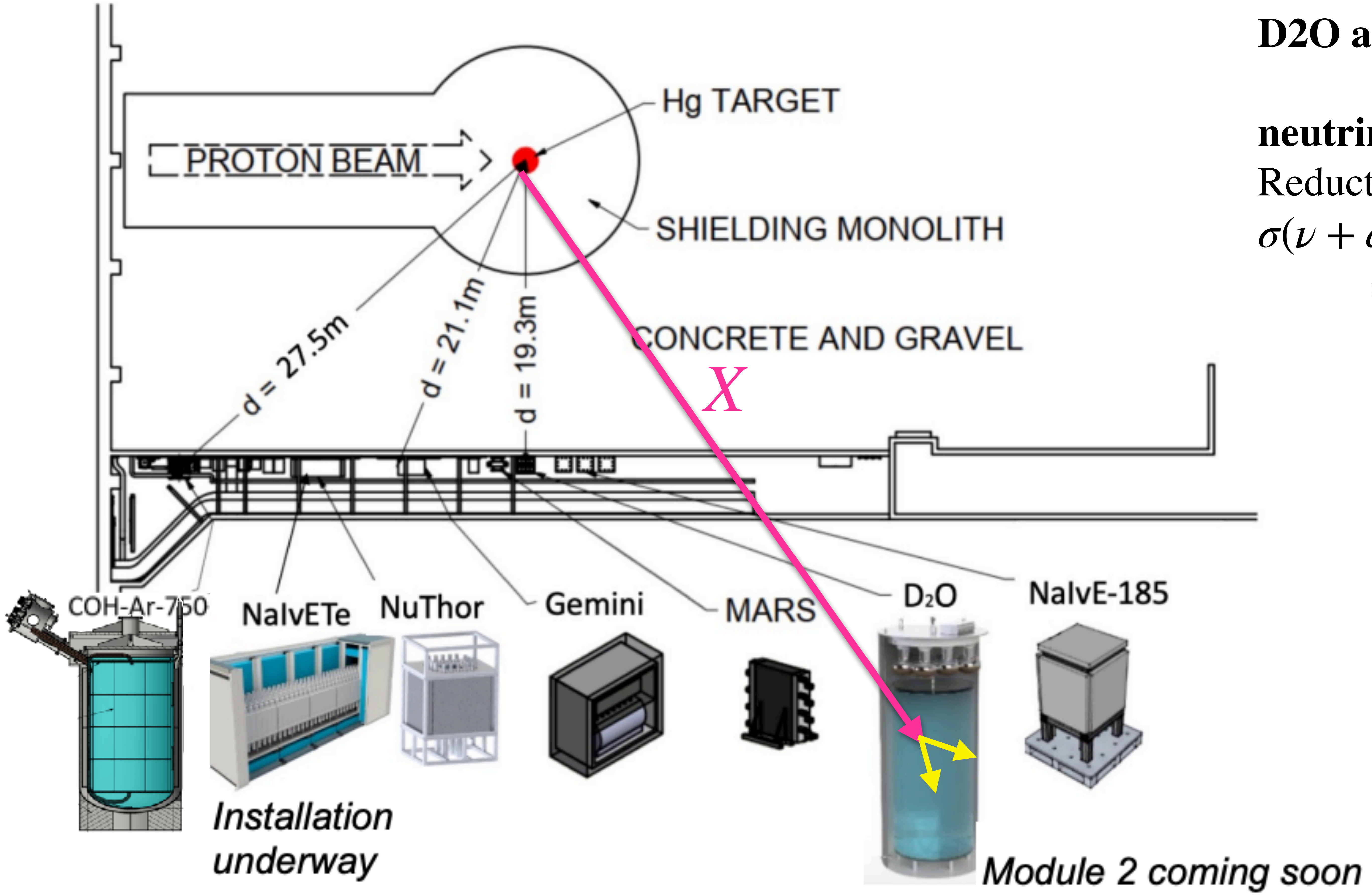


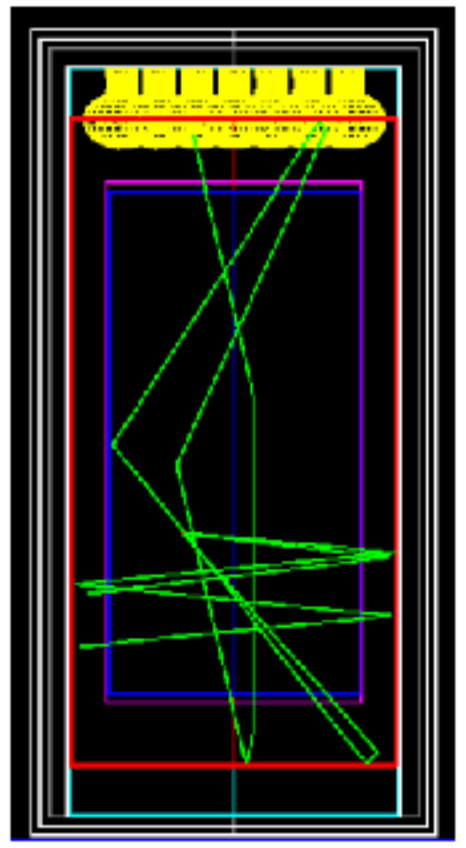
D2O and H2O modules:

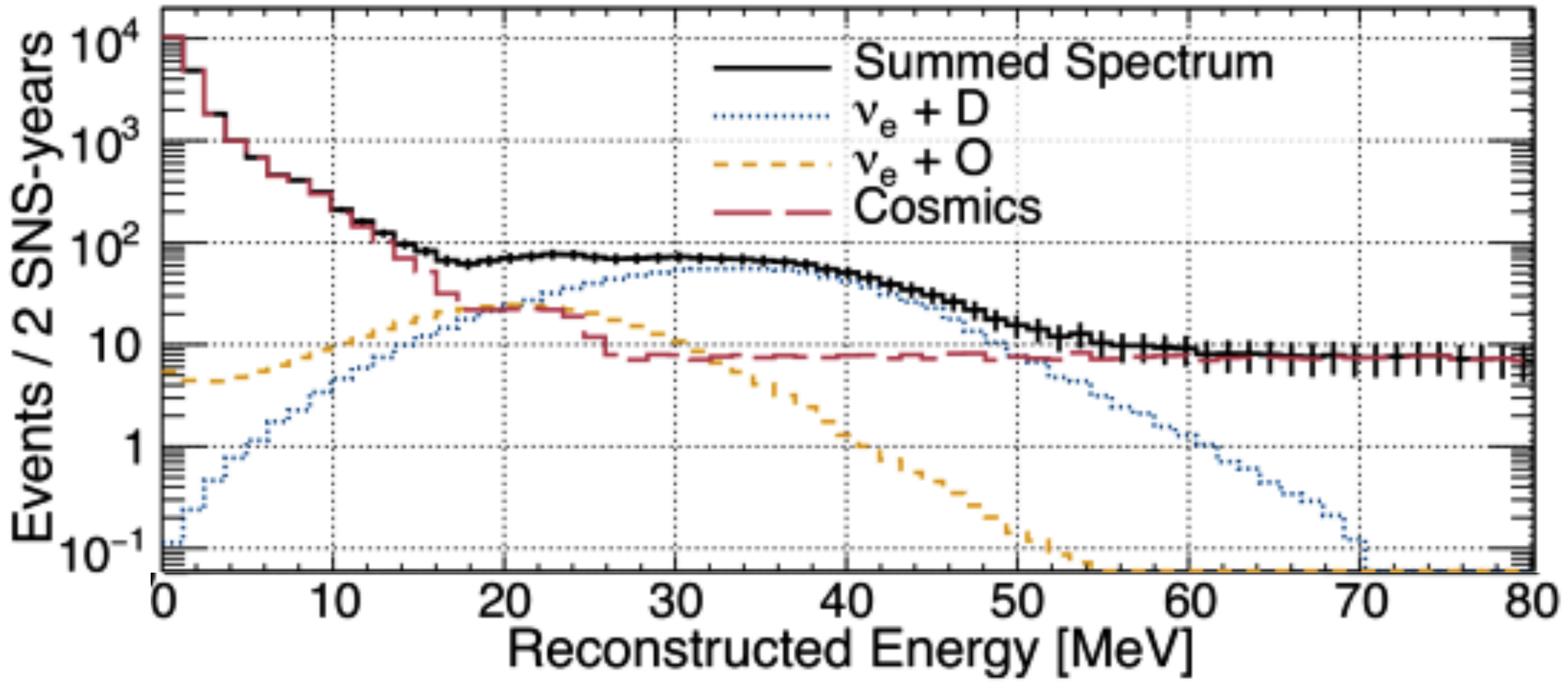
neutrino flux uncertainty :

Reduction of 10% → 2-3% in 5 years

$\sigma(\nu + d \to e + p + p)$ known to 2%).

d = deuterium

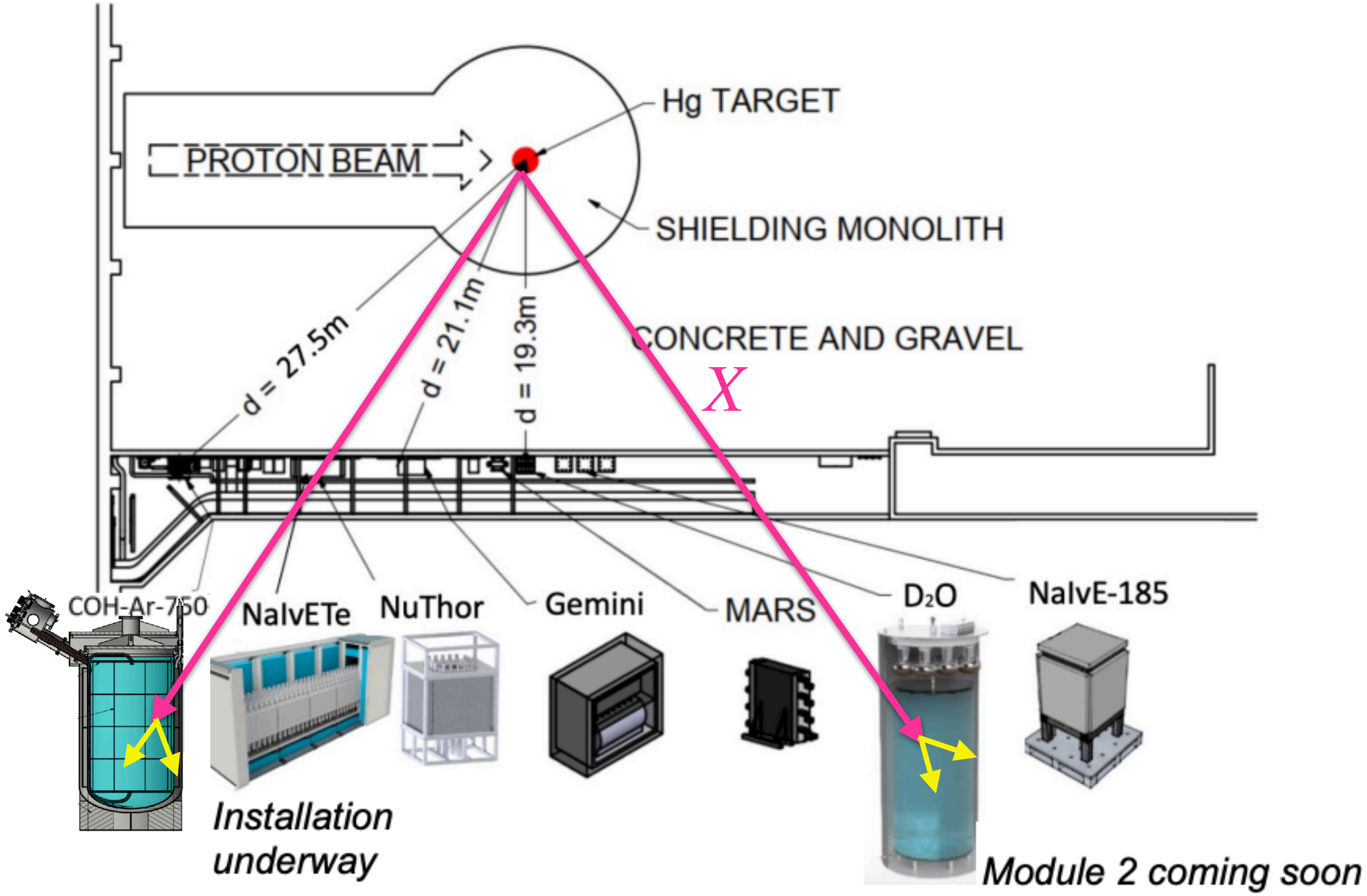




* D2O already has data and H2O is under construction.

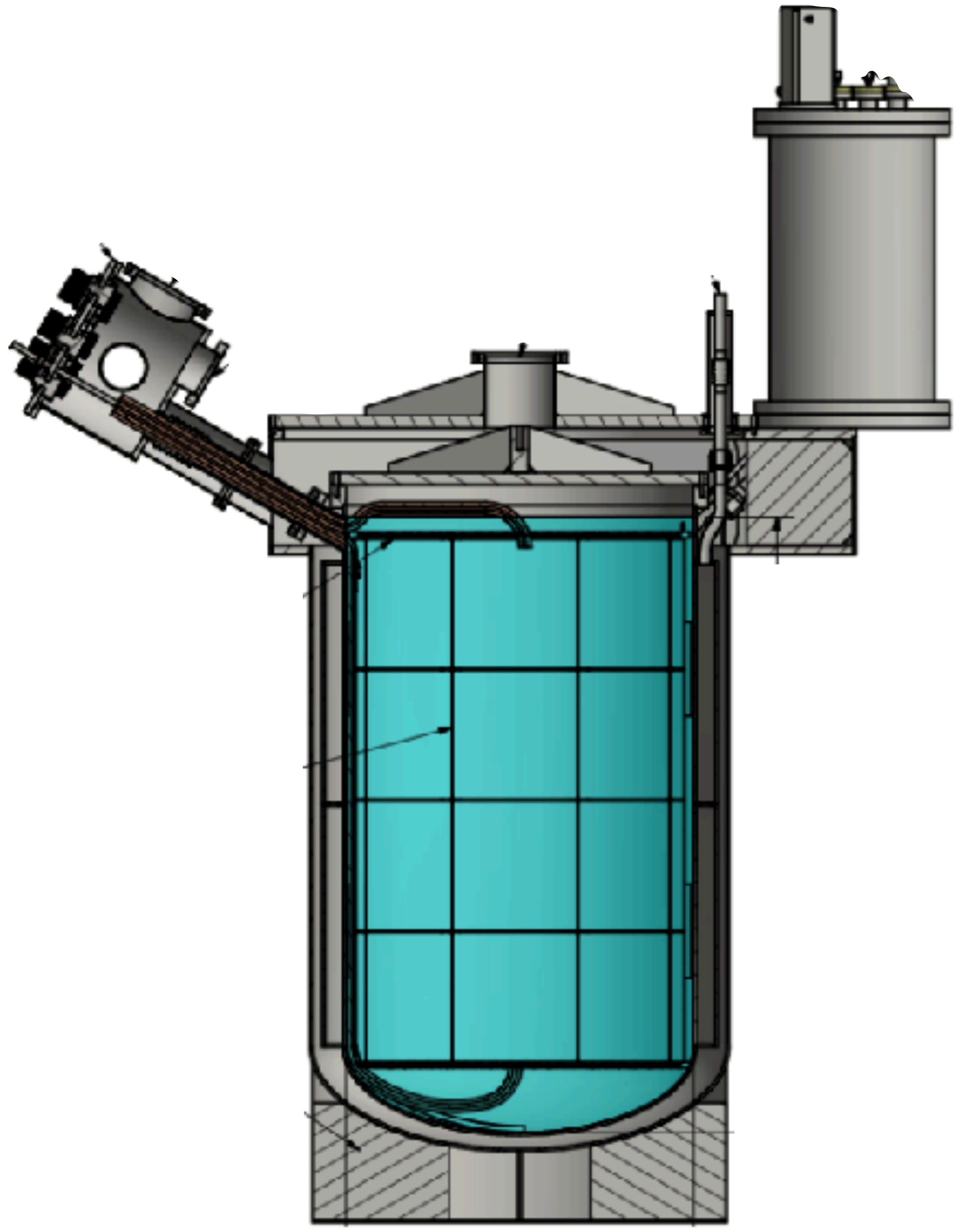
Opportunities at Oak Ridge

SNS COHERENT detectors



COH-Ar-750

- Scintillation calorimeter
- 750 kg of purified liquid Ar
- Measure ν_e Ar CEvNS



Opportunities at Oak Ridge

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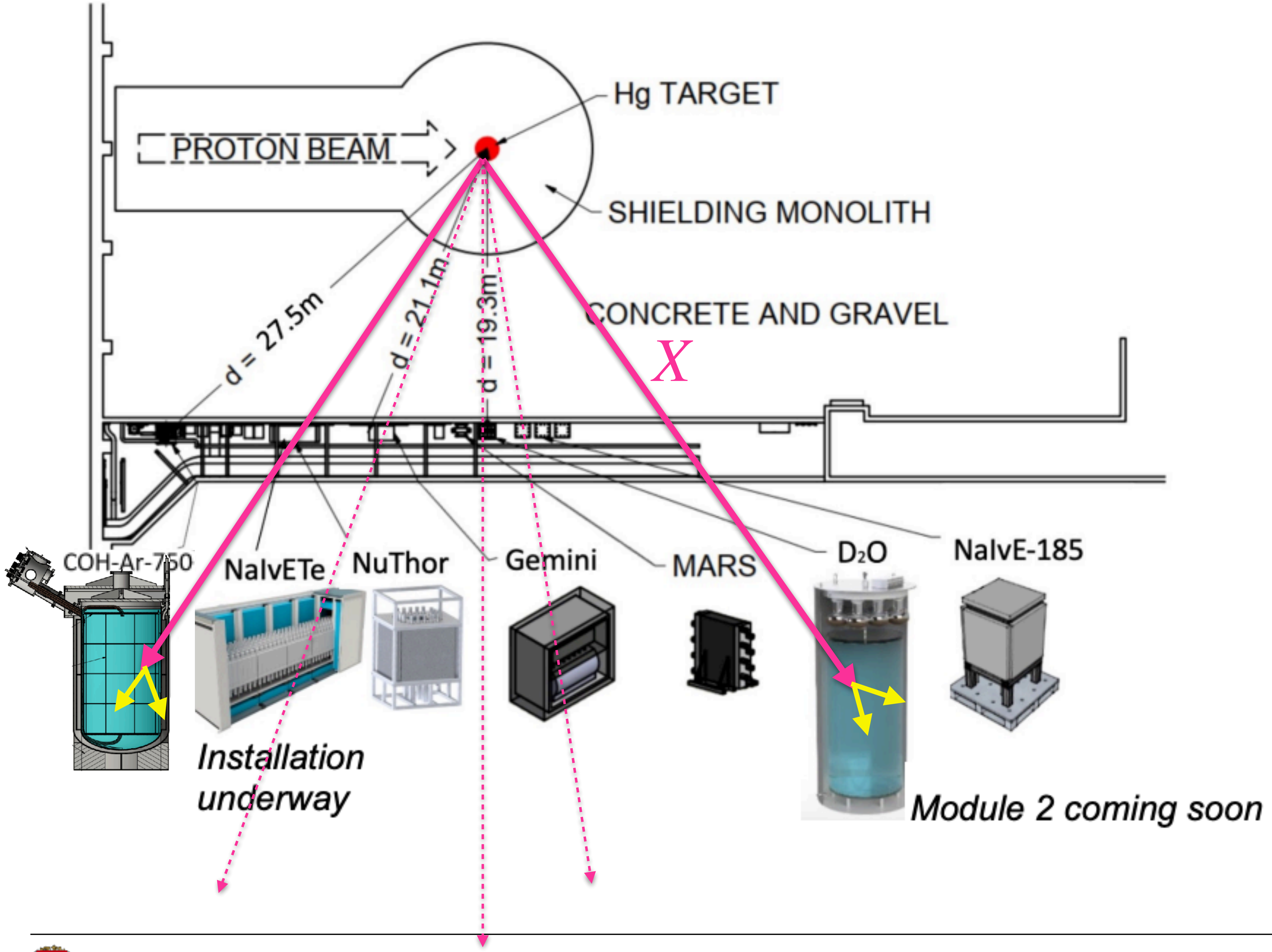


For this study, I will require:

50 events/3 years of operation:

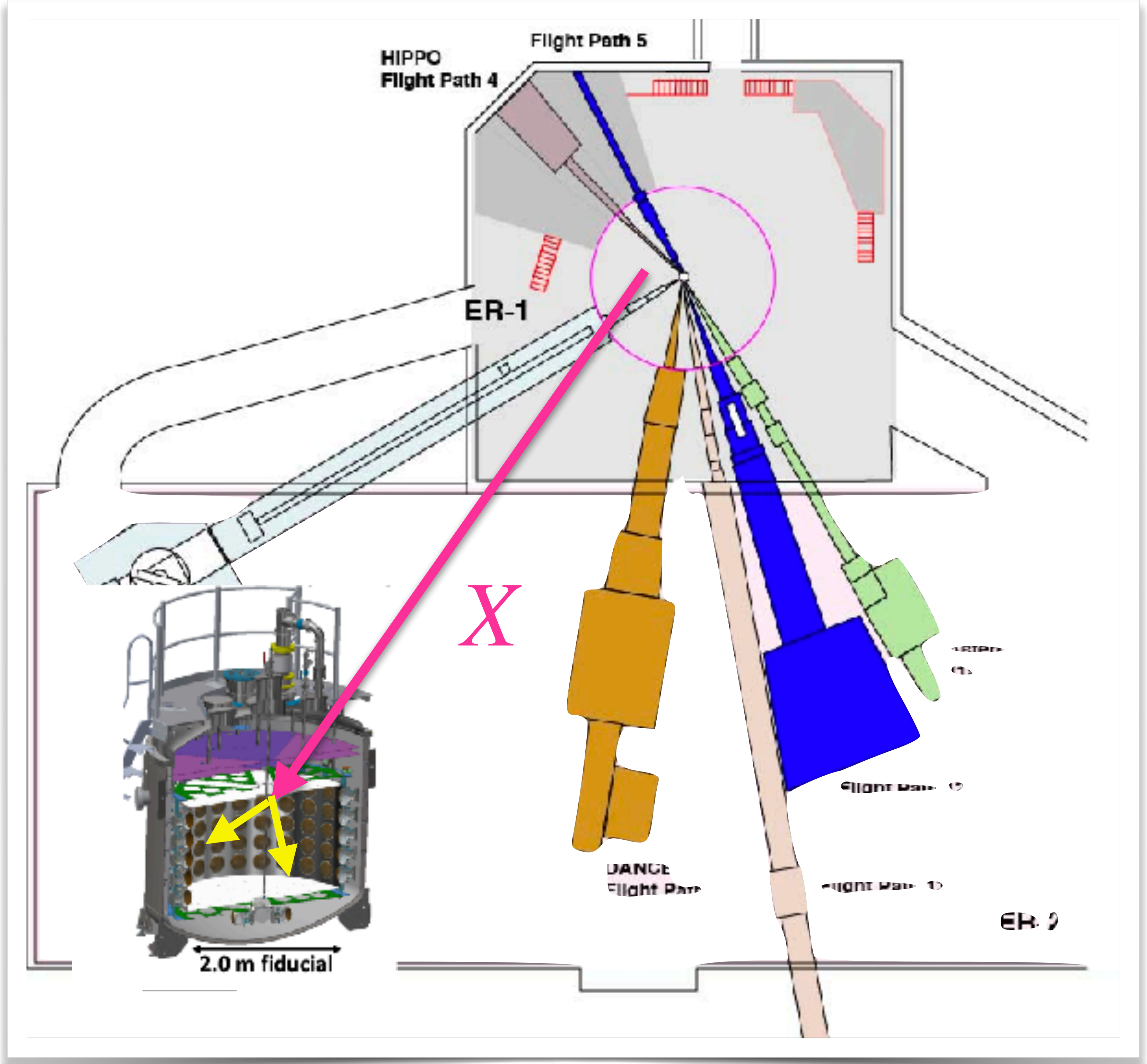
- 750 kg (LAr)
- 508 kg (H2O) + 549 kg (D2O)

Other detectors? For example:
Surface deployment of 4-ton detector possible with L ~ 22 m.

Possible for PROSPECT-II?
(under investigation with B. Littlejohn)

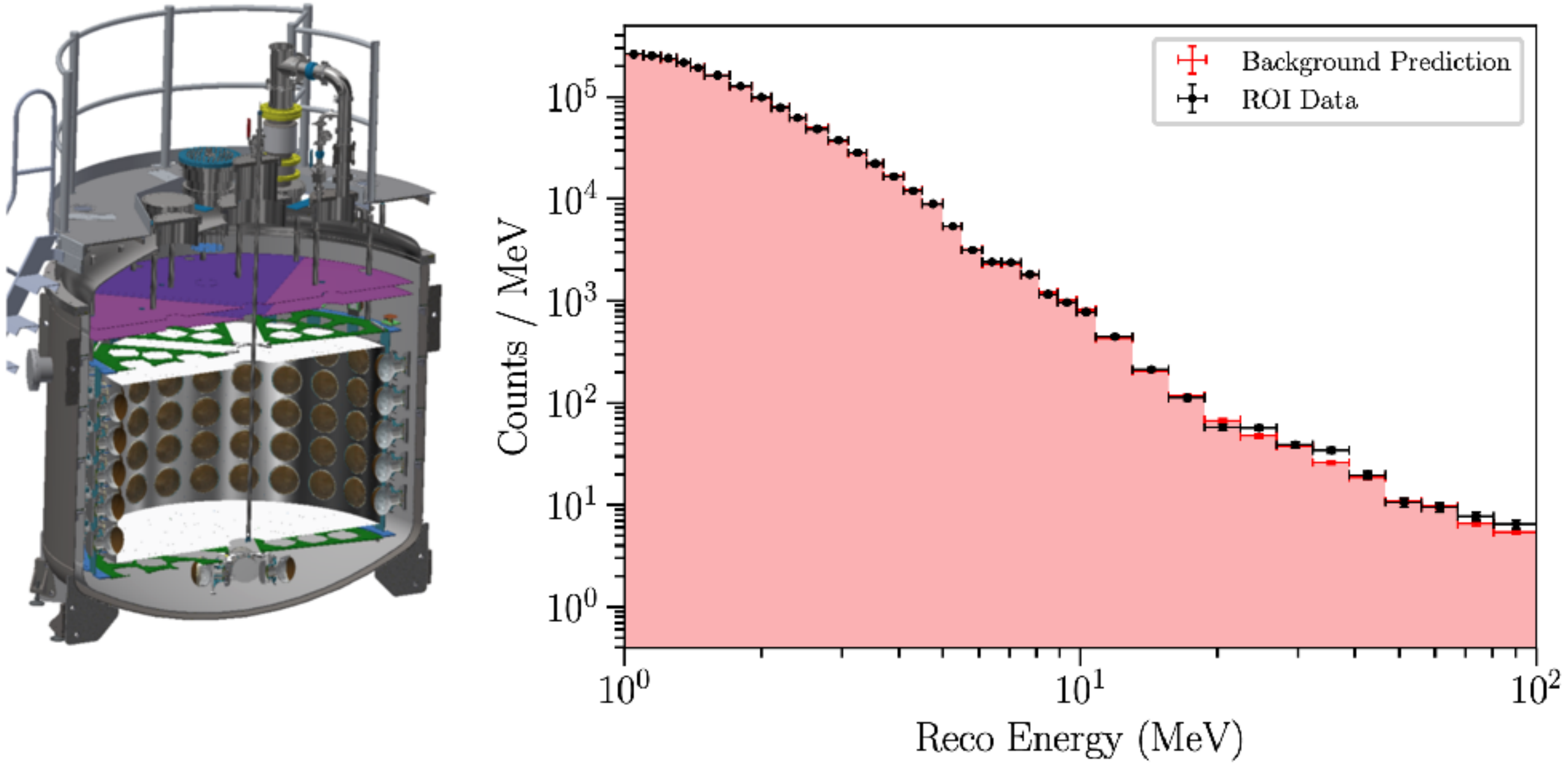
Opportunities at Los Alamos

LANSCE Coherent-Captain-Mills (CCM)



CCM: 7 tons of LAr
Detects scintillation of Ar

Rate of background events for CCM120 (120 inward pointing PMTs)



Projected 100 times smaller bkg rate for CCM200 (200 PMTs)

In this study, we project sensitivity for 40 events/3 years of operation

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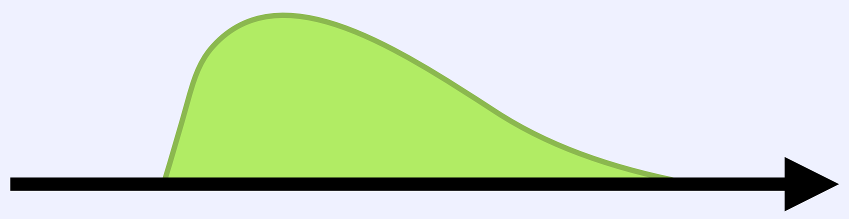
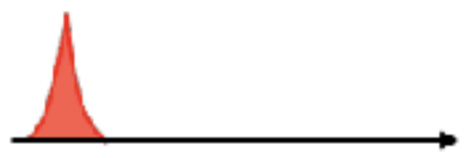
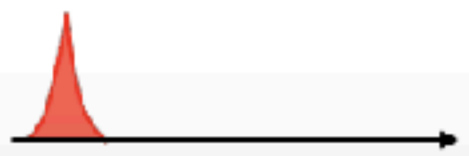
Timing profile of LLP signatures

Prompt $\mathcal{O}(100)$ ns (on time from π^+/K^+ decay)

$\mathcal{O}(2)$ μs delayed (μ^+ time)

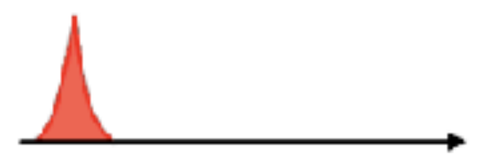
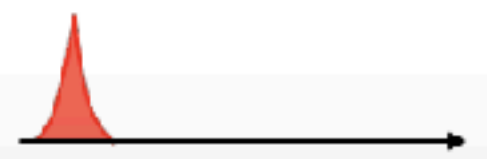


Model	Production	Decay	Timing signature	J-PARC Detector
Heavy Neutral Leptons	$\mu^+ \to e^+ \nu N$	$N \to \nu e^+ e^-$		ND280
	$\pi^+/K^+ \to \ell N$	$N \to \nu e^+ e^-$		ND280
		$N \to \nu \mu^+ e^- / \pi^+ e^-$		JSNS^2 and ND280
		$N \to \nu \mu^+ \mu^- / \pi^+ \mu^-$		JSNS^2 and ND280
		$N \to \nu \pi^0$		KOTO
Higgs Portal Scalar	$K^+ \to \pi^+ S$	$S \to e^+ e^-$		ND280
		$S \to \mu^+ \mu^- / \pi^+ \pi^-$		JSNS^2 and ND280
		$S \to \pi^0 \pi^0$		KOTO
Muon Portal Scalar	$\mu^+ \to e^+ \nu \nu S_M$	$S_M \to \gamma\gamma$		KOTO
ALP: Higgs Coupling	$K^+ \to \pi^+ a_\phi$	$a_\phi \to e^+ e^-$		ND280
		$a_\phi \to \mu^+ \mu^-$		JSNS^2 and ND280
ALP: Flavor Violating	$\mu^+ \to e^+ a_{\rm FV} (\gamma)$	$a_{\rm FV} \to e^+ e^-$		ND280
ALP: Weak Violating	$\pi^+ \to e^+ \nu_e a_{\rm WV}$	$a_{\rm WV} \to e^+ e^-$		ND280

Timing profile of LLP signatures

A lot of these come from μ^+ and π^+ decays.

~1 GeV p^+ beams are in the game.

Model	Production	Decay	Timing signature	J-PARC Detector
Heavy Neutral Leptons	$\mu^+ \to e^+ \nu N$	$N \to \nu e^+ e^-$		ND280
	$\pi^+/K^+ \to \ell N$	$N \to \nu e^+ e^-$		ND280
		$N \to \nu \mu^+ e^- / \pi^+ e^-$		JSNS^2 and ND280
		$N \to \nu \mu^+ \mu^- / \pi^+ \mu^-$		JSNS^2 and ND280
		$N \to \nu \pi^0$		KOTO
Higgs Portal Scalar	$K^+ \to \pi^+ S$	$S \to e^+ e^-$		ND280
		$S \to \mu^+ \mu^- / \pi^+ \pi^-$		JSNS^2 and ND280
		$S \to \pi^0 \pi^0$		KOTO
Muon Portal Scalar	$\mu^+ \to e^+ \nu \nu S_M$	$S_M \to \gamma\gamma$		KOTO
ALP: Higgs Coupling	$K^+ \to \pi^+ a_\phi$	$a_\phi \to e^+ e^-$		ND280
		$a_\phi \to \mu^+ \mu^-$		JSNS^2 and ND280
ALP: Flavor Violating	$\mu^+ \to e^+ a_{\mathrm{FV}} (\gamma)$	$a_{\mathrm{FV}} \to e^+ e^-$		ND280
ALP: Weak Violating	$\pi^+ \to e^+ \nu_e a_{\mathrm{WV}}$	$a_{\mathrm{WV}} \to e^+ e^-$		ND280

Outline:

1) Spallation (neutron) sources: what and why?

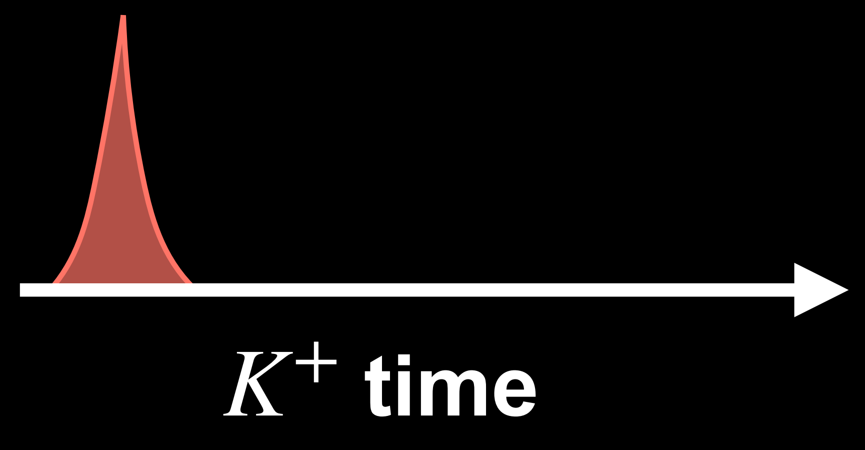
2) Opportunities with neutrino detectors

3) Long-lived particles below K, π, and μ masses

Higgs portal scalar: the simplest case

Long-lived particles at spallation sources

Higgs portal scalar



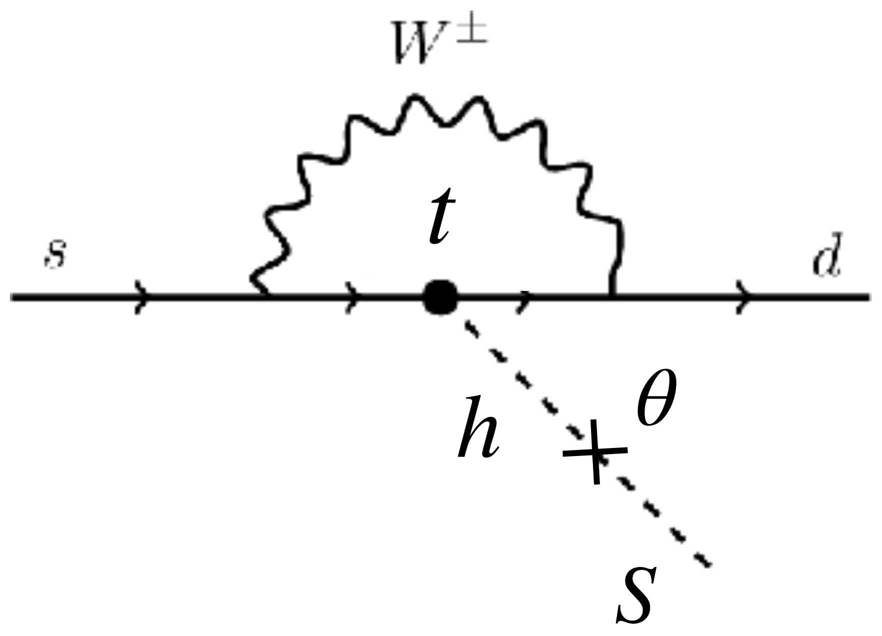
Arguably the simplest extension of the SM:

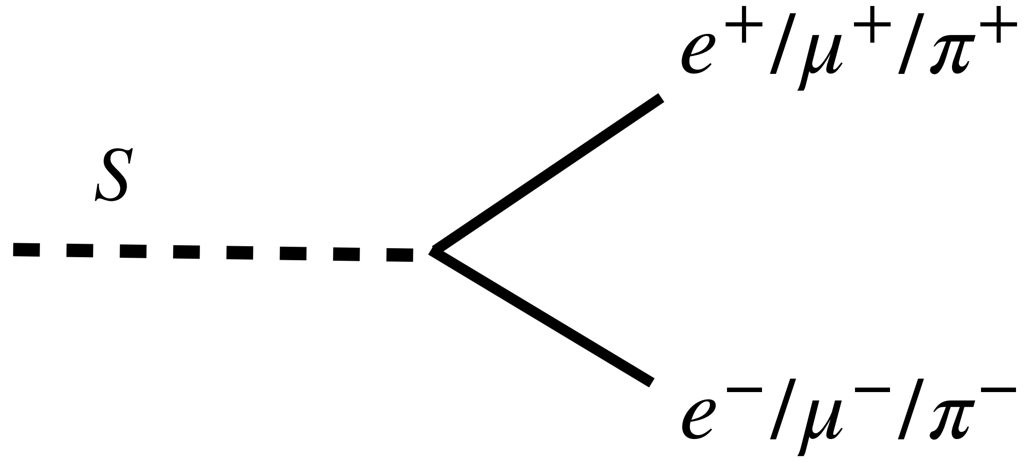
Singlet scalar particle S that mixes with the Higgs boson
a.k.a. Higgs Portal Scalar (HPS).

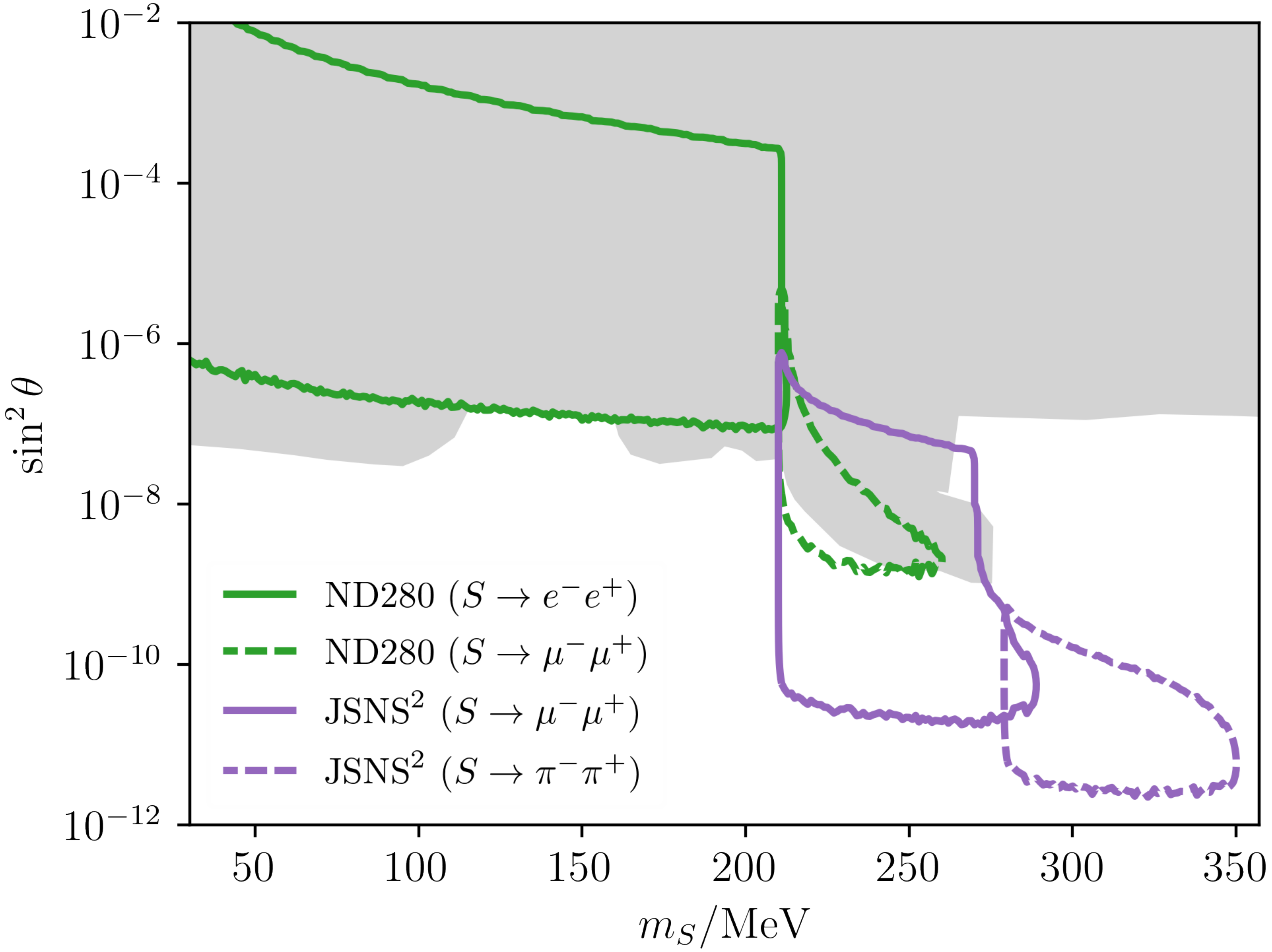
Production (almost) exclusively through K^+ **decays**.

J-PARC is most well suited for this.
(+ accelerators like T2K and FNAL's SBN program)

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







Outline:

1) Spallation (neutron) sources: what and why?

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Axion-like particle: flavor-violating couplings

Long-lived particles at spallation sources

A lepton-flavor-violating axion-like particle (LFV ALP)

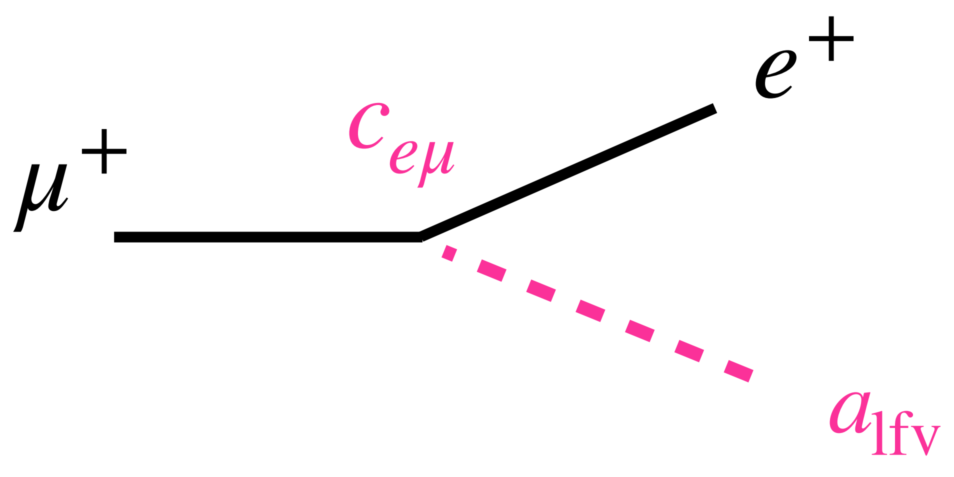
Light goldstone boson to probe lepton flavor violation

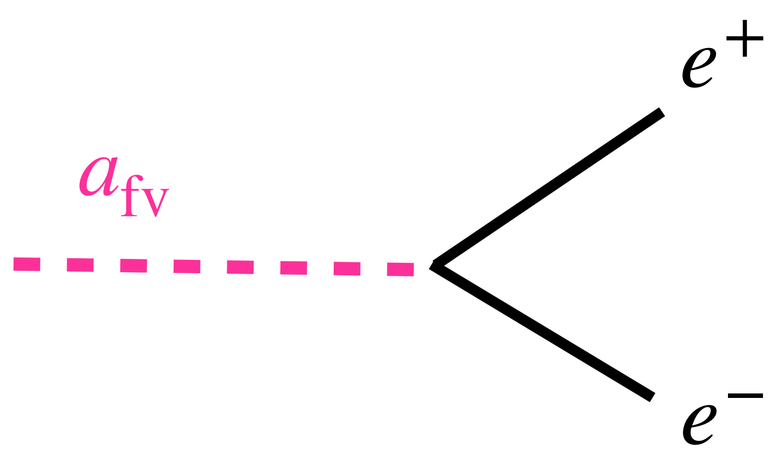
Complementary to $\mu \to e$ searches (Mu2e, Mu3e, MEG-II).

Indirect limits constraint products of couplings (not a killer).

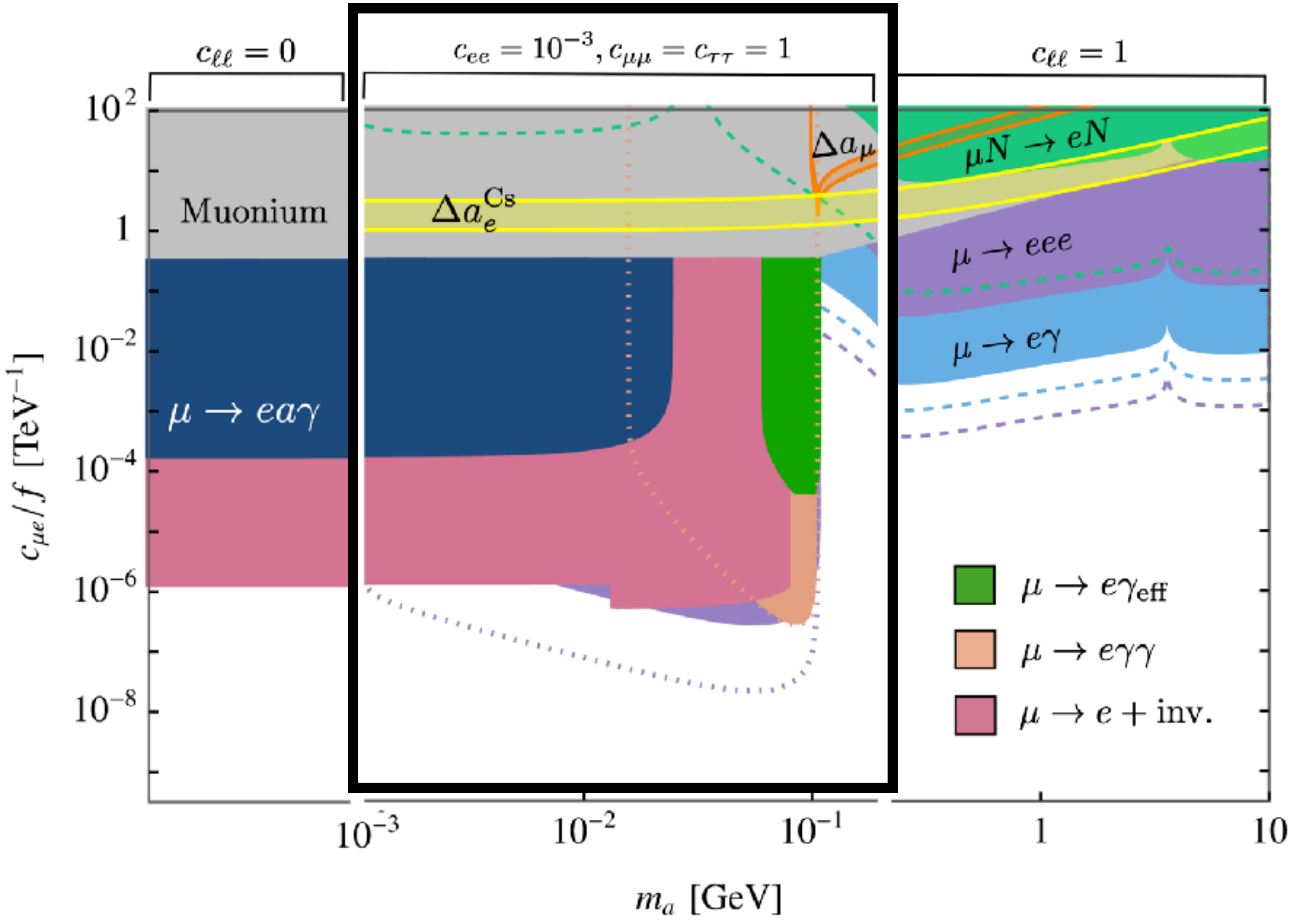
Direct limit: $\mathscr{B}(\mu^+ \to e^+ a_{\rm fv}) \lesssim 10^{-5}$ if a is long-lived.

That would lead to about $10^{14} - 10^{15}$ $a_{\rm fv}$ /year in typical spallation sources…

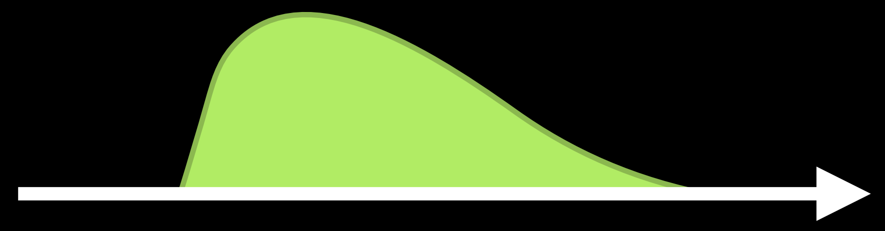




$$j^{\rho}_{\rm FV} = y^{L}_{e\mu} \frac{\overline{L_e H} \gamma^{\rho} H L_{\mu}}{\Lambda^2} + c^{R}_{e\mu} \bar{e}_R \gamma^{\rho} \mu_R \xrightarrow{\rm E\!\!\!/W} \bar{e}\gamma^{\rho}(c^{L}_{e\mu} P_L + c^{R}_{e\mu} P_R)\mu$$



M. Bauer et al, 2110.10698 and L. Calibbi et al 2006.04795

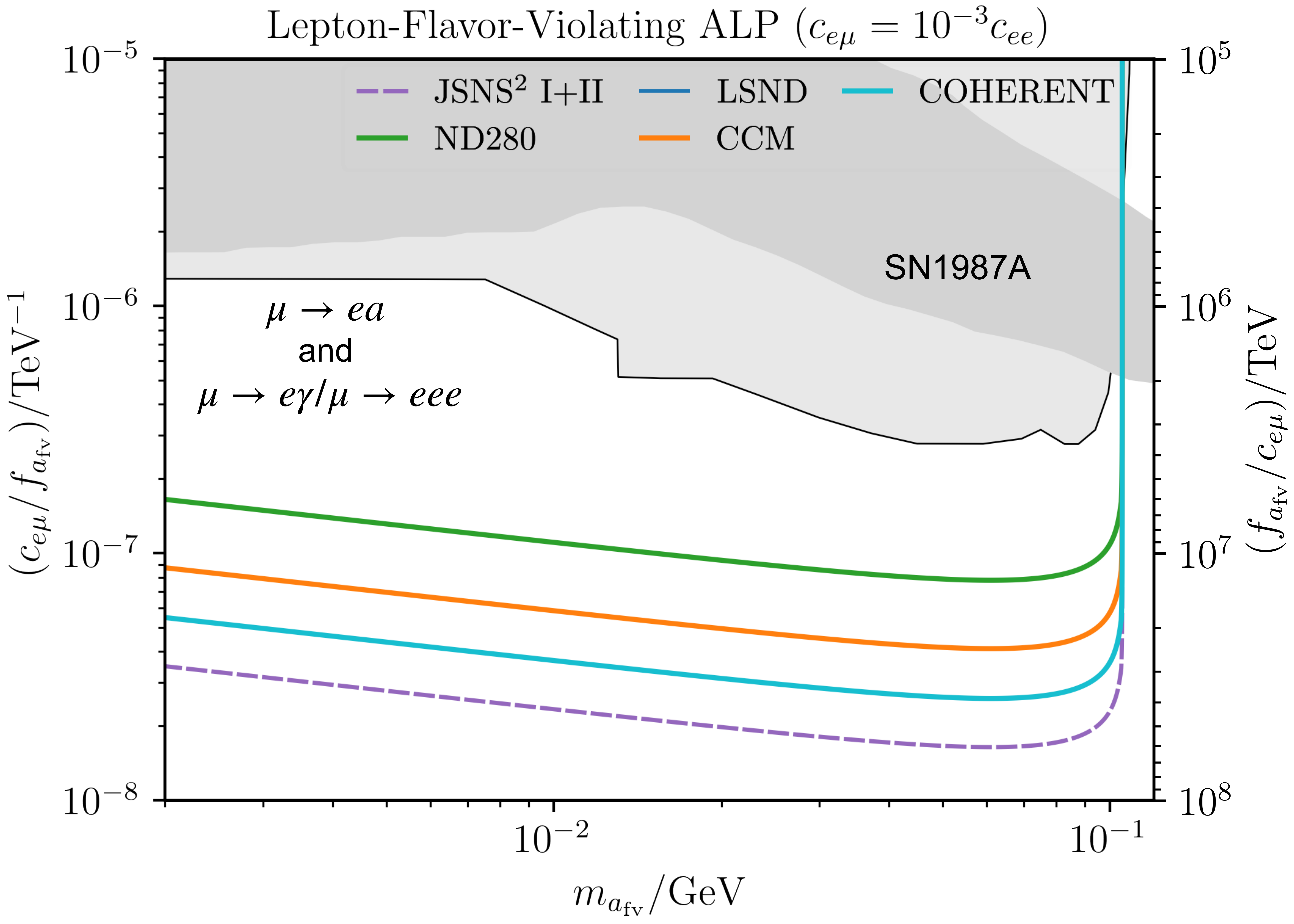


Light goldstone boson to probe lepton flavor violation

Far more sensitive than indirect probes in this region.

This is a high-energy final state $\simeq m_\mu/2$, so LSND "threw it away". Easy to see with new searches.

* Supernovae will also be impacted due to large μ content (afaik, this has not been worked out yet).



Outline:

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Minimal muonphilic scalars

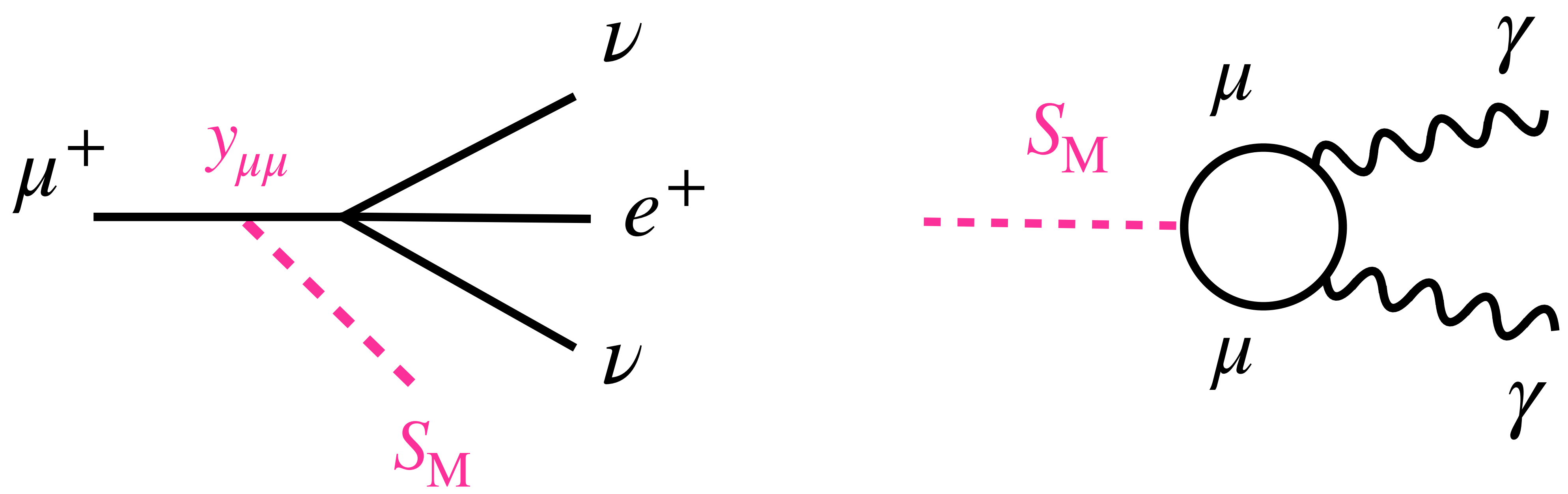
Exotic force that couples only to muons

A popular effective model for discrepancy(?) in $(g-2)_\mu$

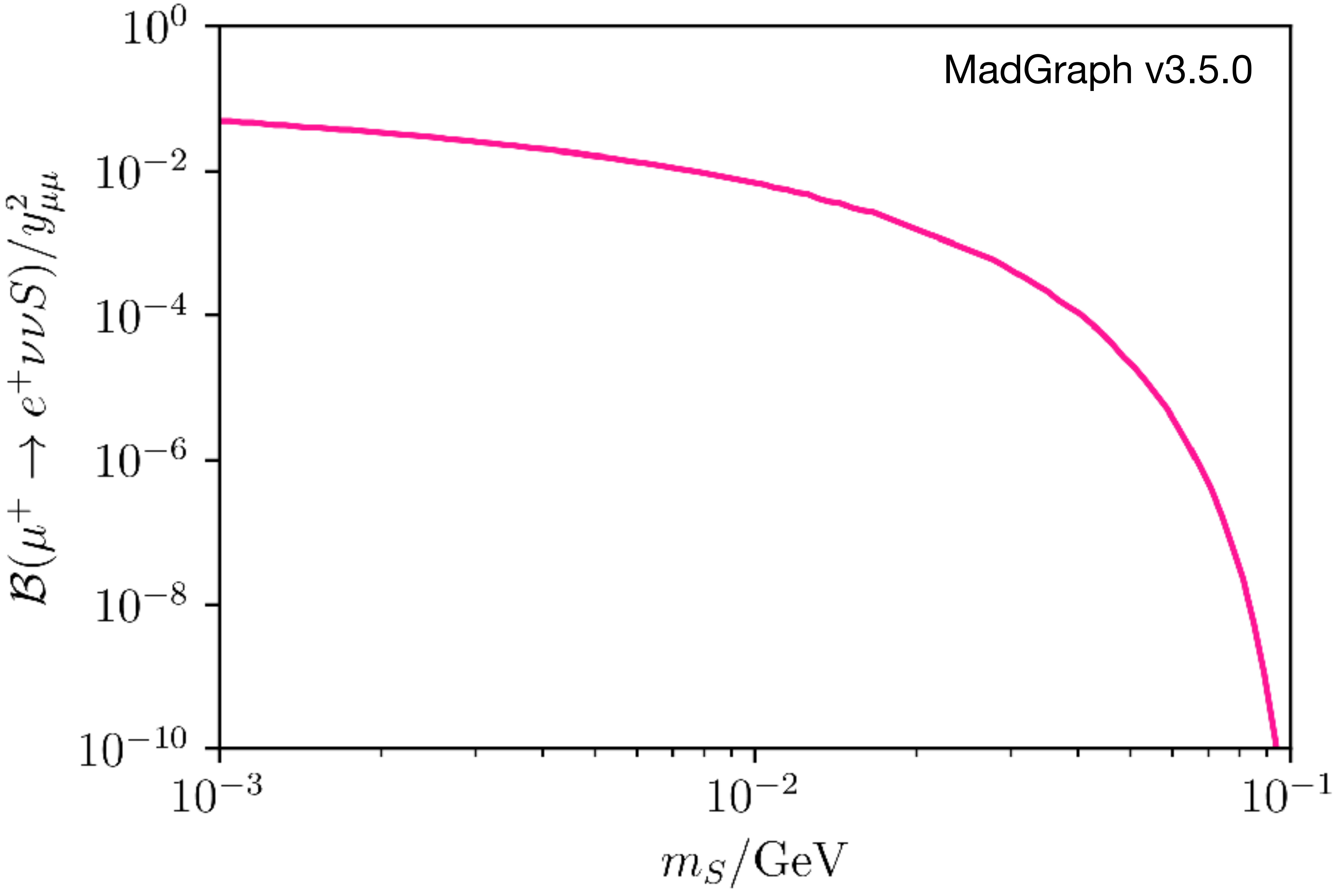
$$-\mathscr{L}_{\rm M} \supset \frac{Y_{\mu\mu}}{\Lambda} S_M \overline{L_\mu} H \mu_R + \text{ h.c.} \xrightarrow{\text{E\!\!\!/W}} y_{\mu\mu} S_M \overline{\mu}\mu$$

Very hard to constrain — no coupling to neutrinos.

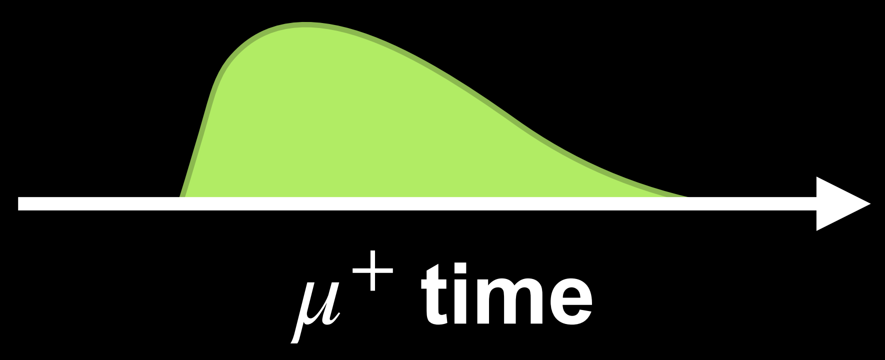
Below dimuon threshold ($m_S < 2m_\mu$), the scalar is long-lived:



Scalar production in 4-body muon decays:



Long-lived particles at spallation sources
Muonphilic scalar

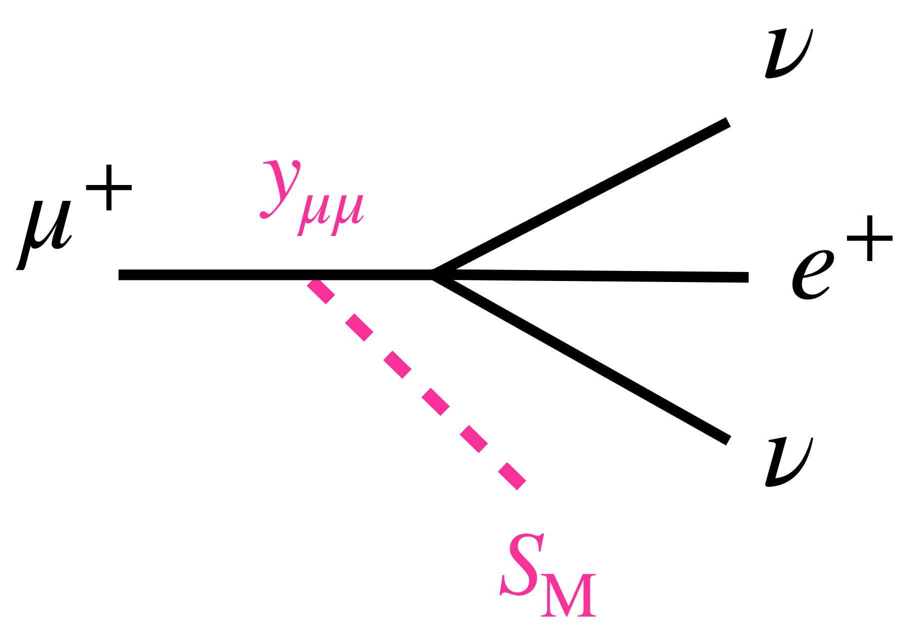


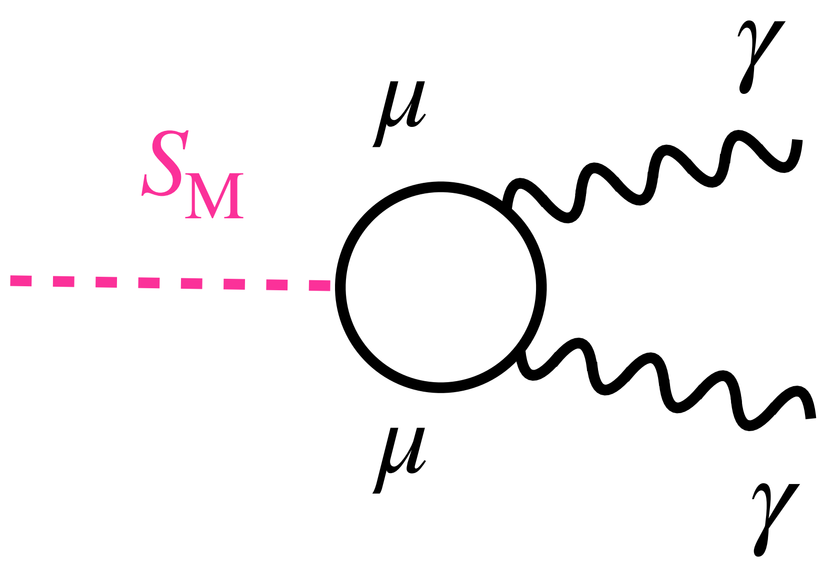
Exotic force that couples only to muons

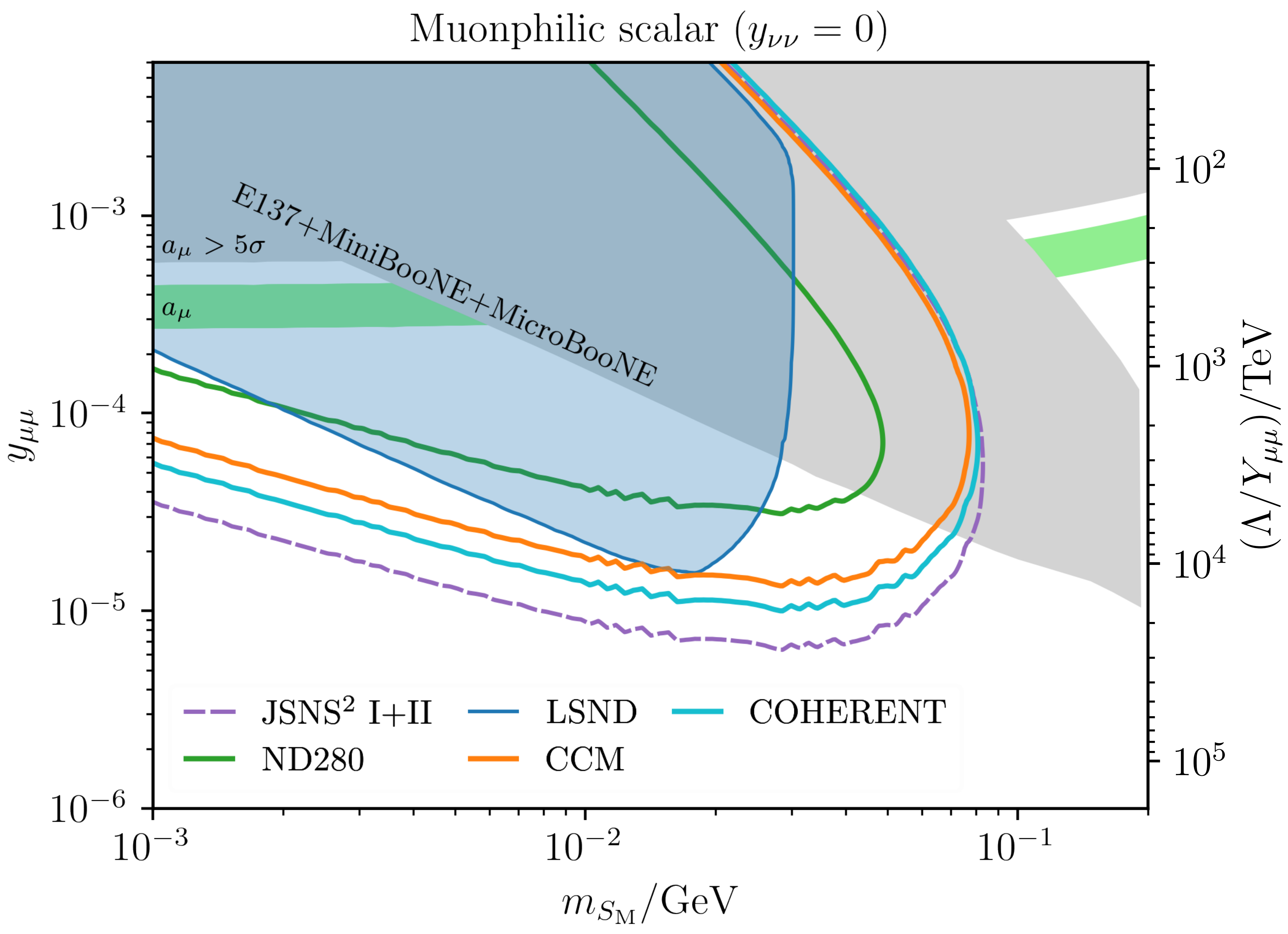
Setting new limits with LSND recast — no g-2 at low masses.

Improvements expected in all cases.

(Hard for JSNS^2 as it is only a single flash).







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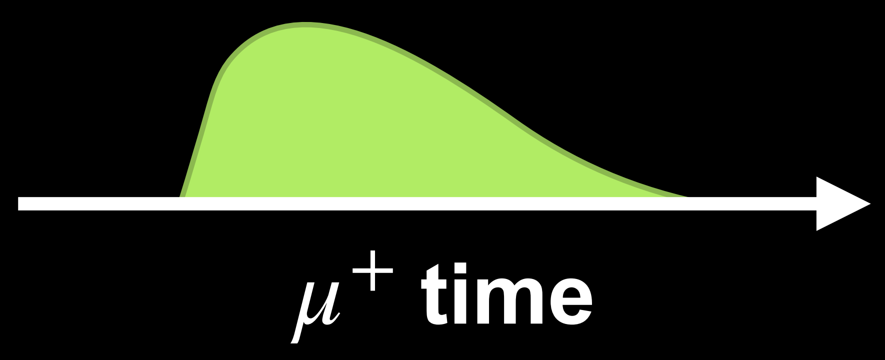
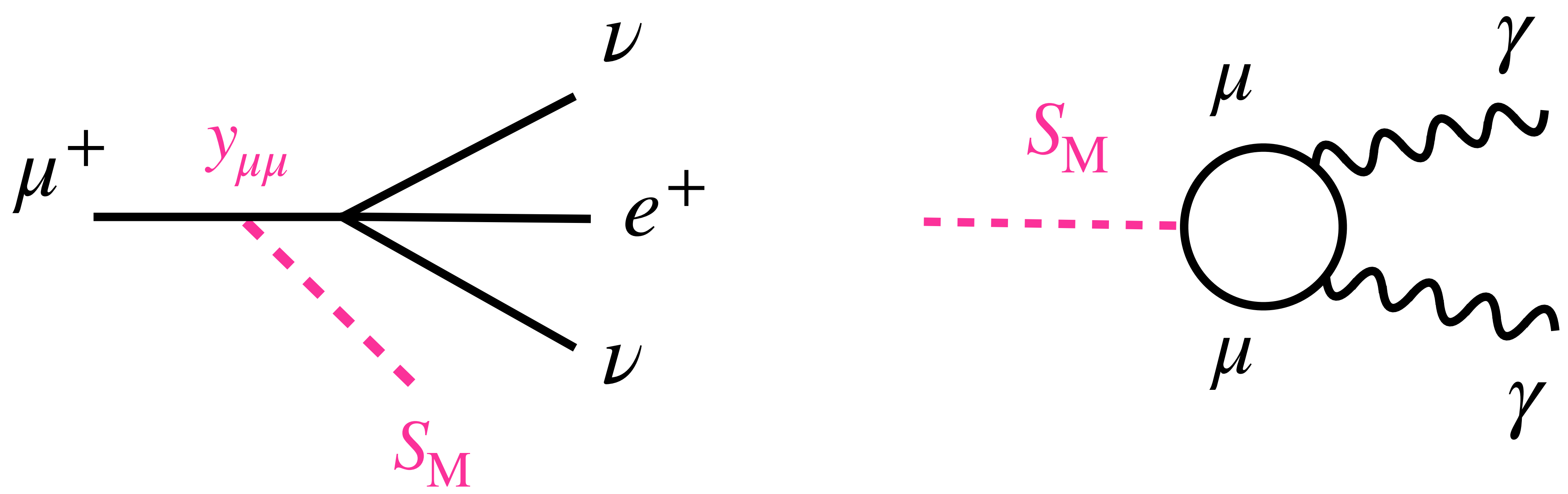
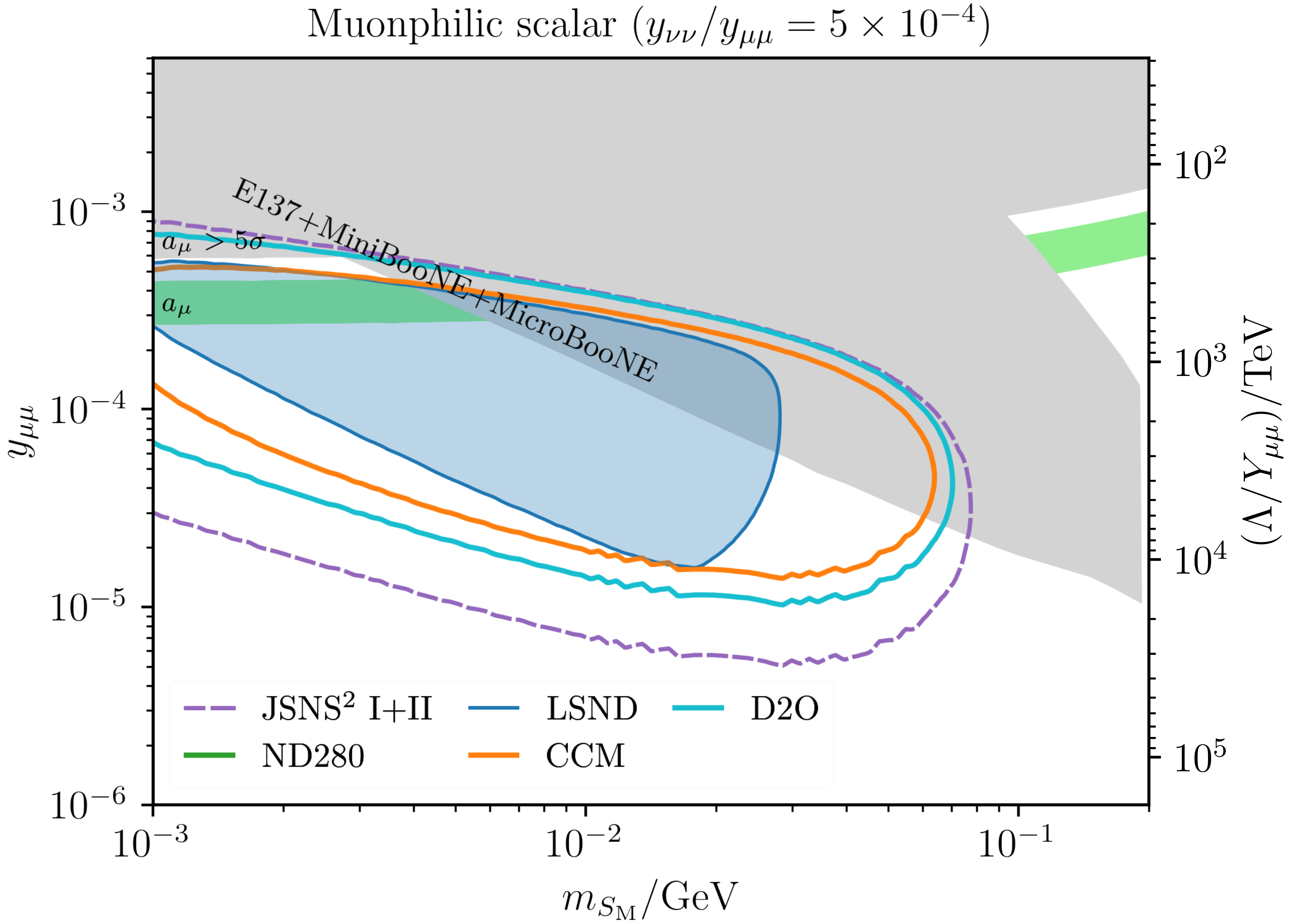
Muonphilic scalar



Exotic force that couples only to muons

Turning on an invisible branching ratio for S_M may be possible, but requires a very specific hierarchy of couplings.





Outline:

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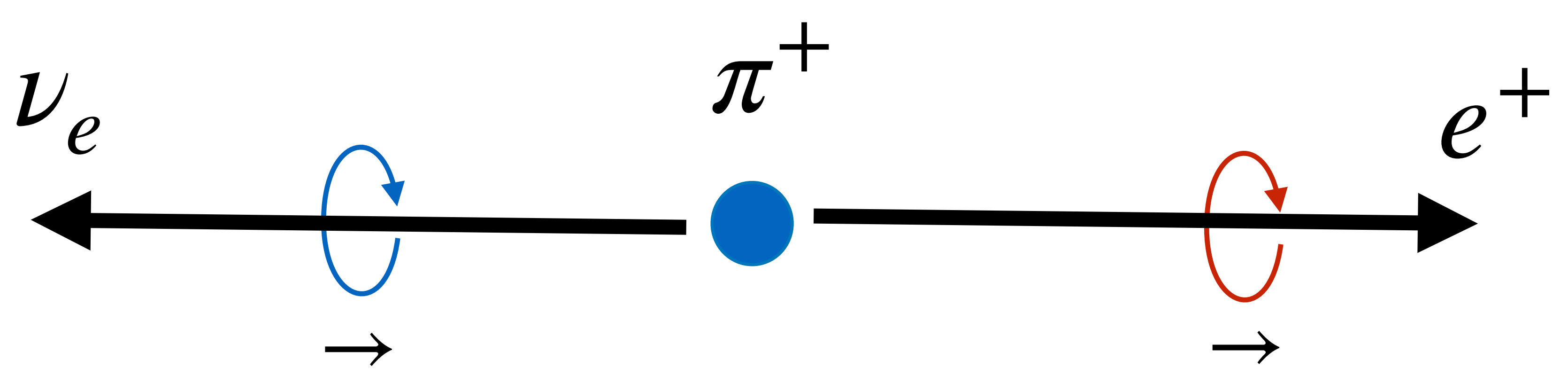
How about dark particle production in charged pion decay?

Radiative pion decay

Pion decays — helicity flip



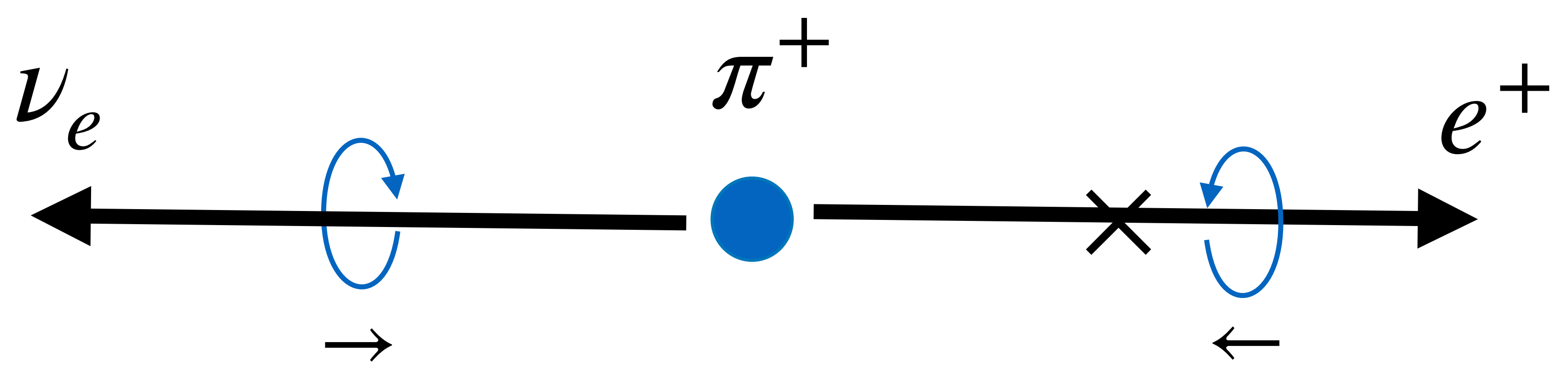
Weak interactions in the SM are left-handed.

Angular momentum needs to be conserved.

The pion is a spin-0 particle, so **neutrino and positron helicities have to be anti-aligned!**

Radiative pion decay

Pion decays — helicity flip



Weak interactions in the SM are left-handed.

Angular momentum needs to be conserved.

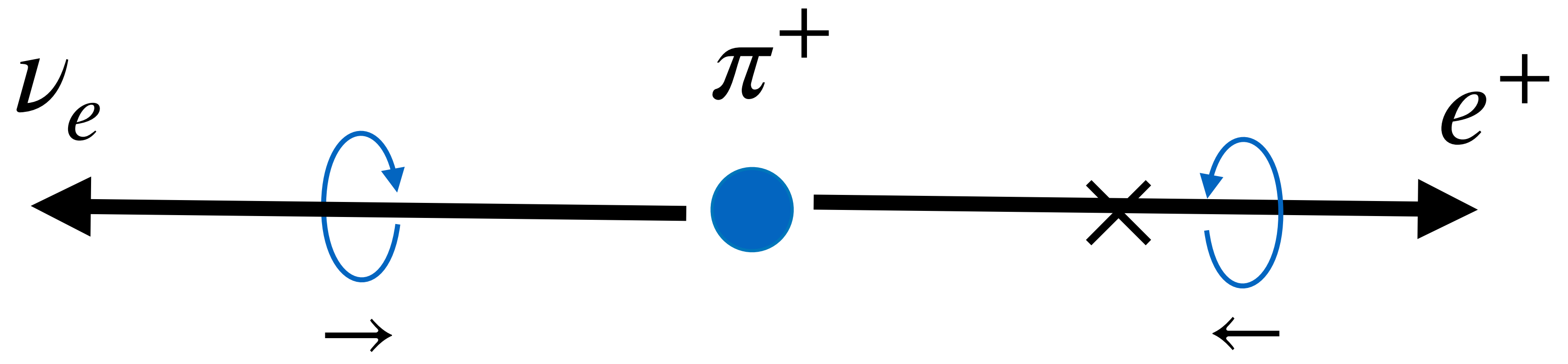
The pion is a spin-0 particle, so **neutrino and positron helicities have to be anti-aligned!**

Helicity suppression:

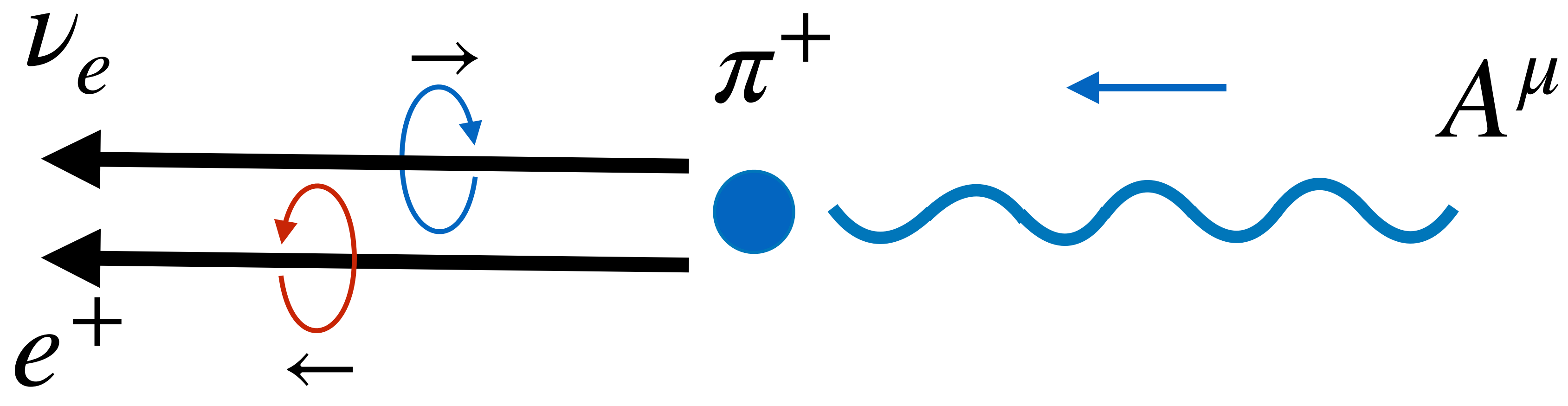
$$\Gamma \propto G_F^2 f_\pi^2 m_\pi^3 \times \left(\frac{m_e^2}{m_\pi^2}\right) \rightarrow \mathscr{B} \sim 10^{-4} \text{ branching ratio for } \pi^+.$$

Radiative pion decay

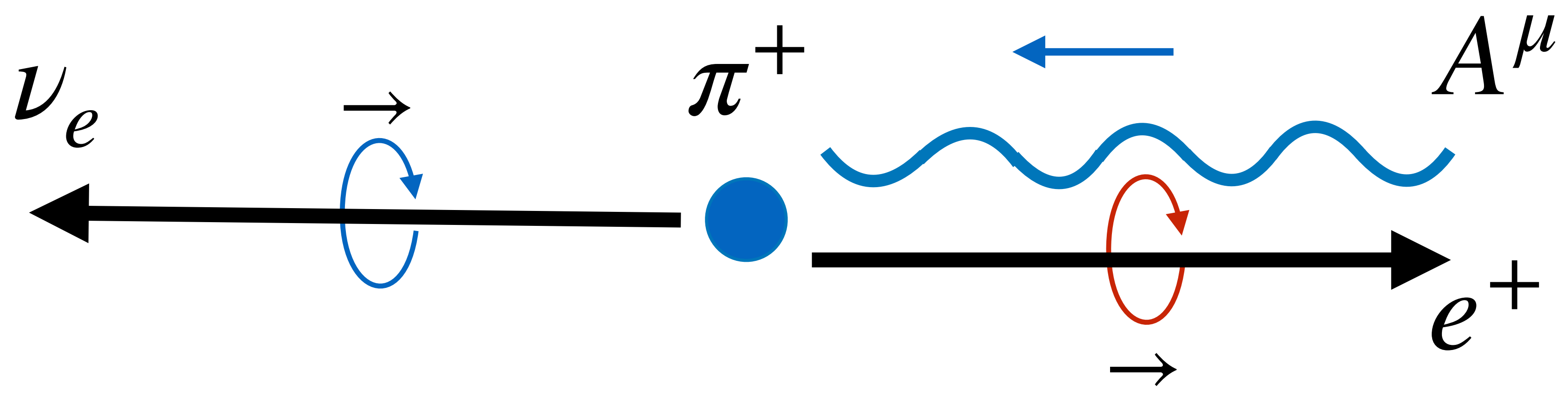
Pion decays — helicity flip



Well, there's an easy way out: make it a three-body decay! **Radiative pion decays:**



No helicity flip.



No helicity flip.

Radiative pion decay

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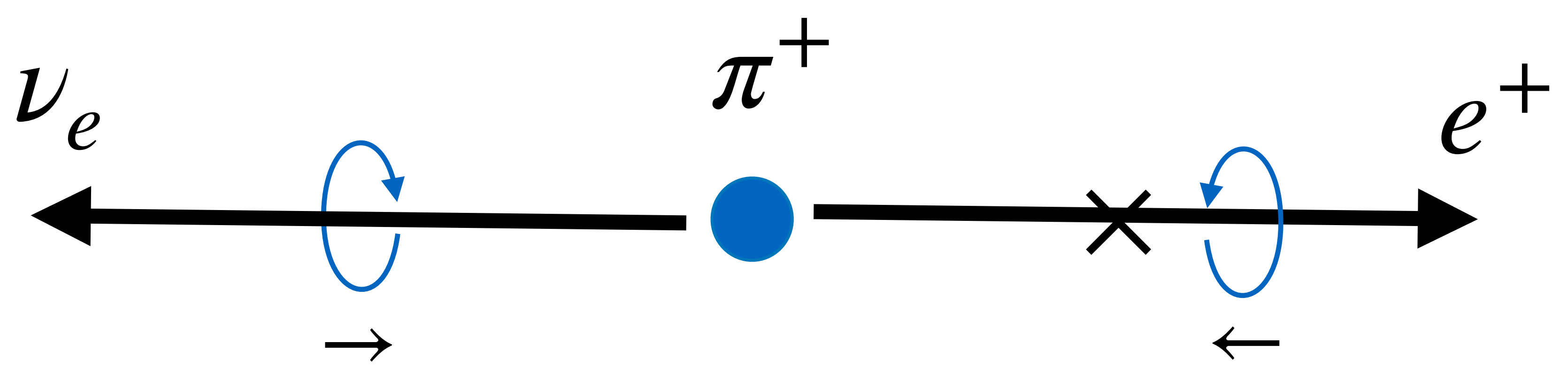

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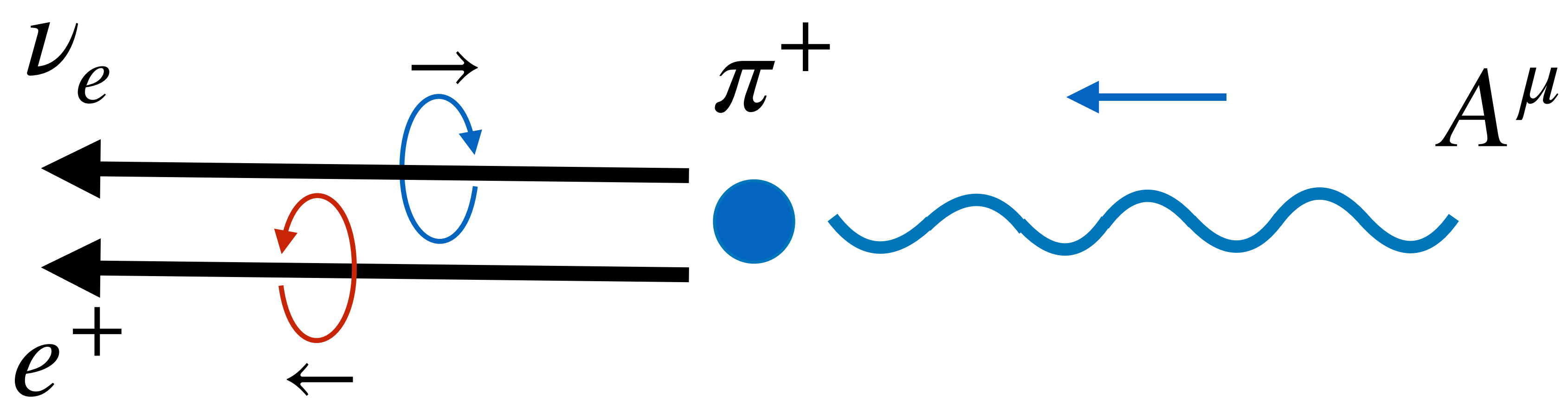
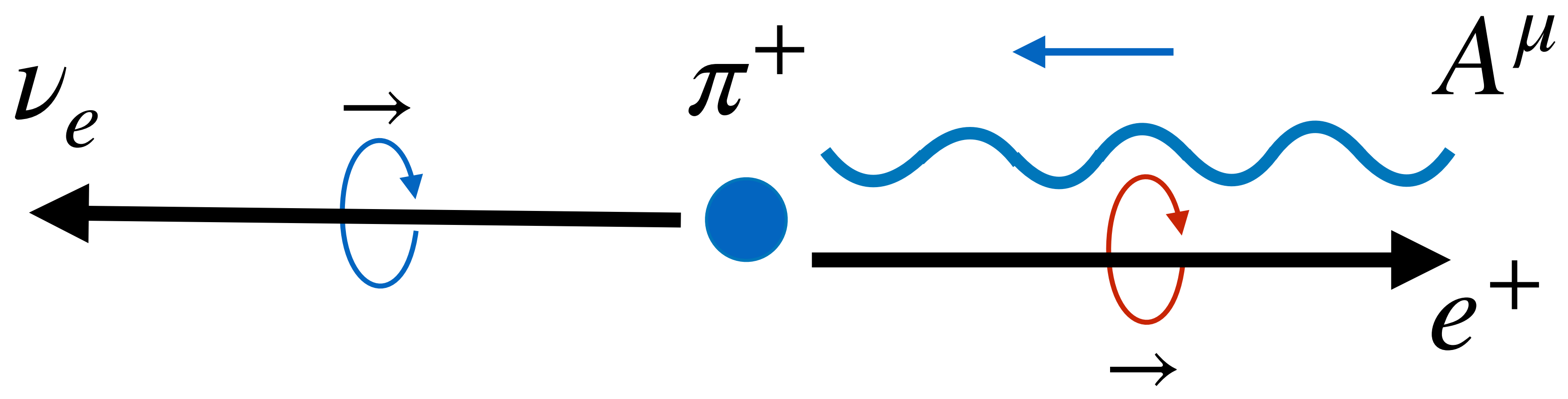


No helicity flip.



No helicity flip.

Feels like cheating…

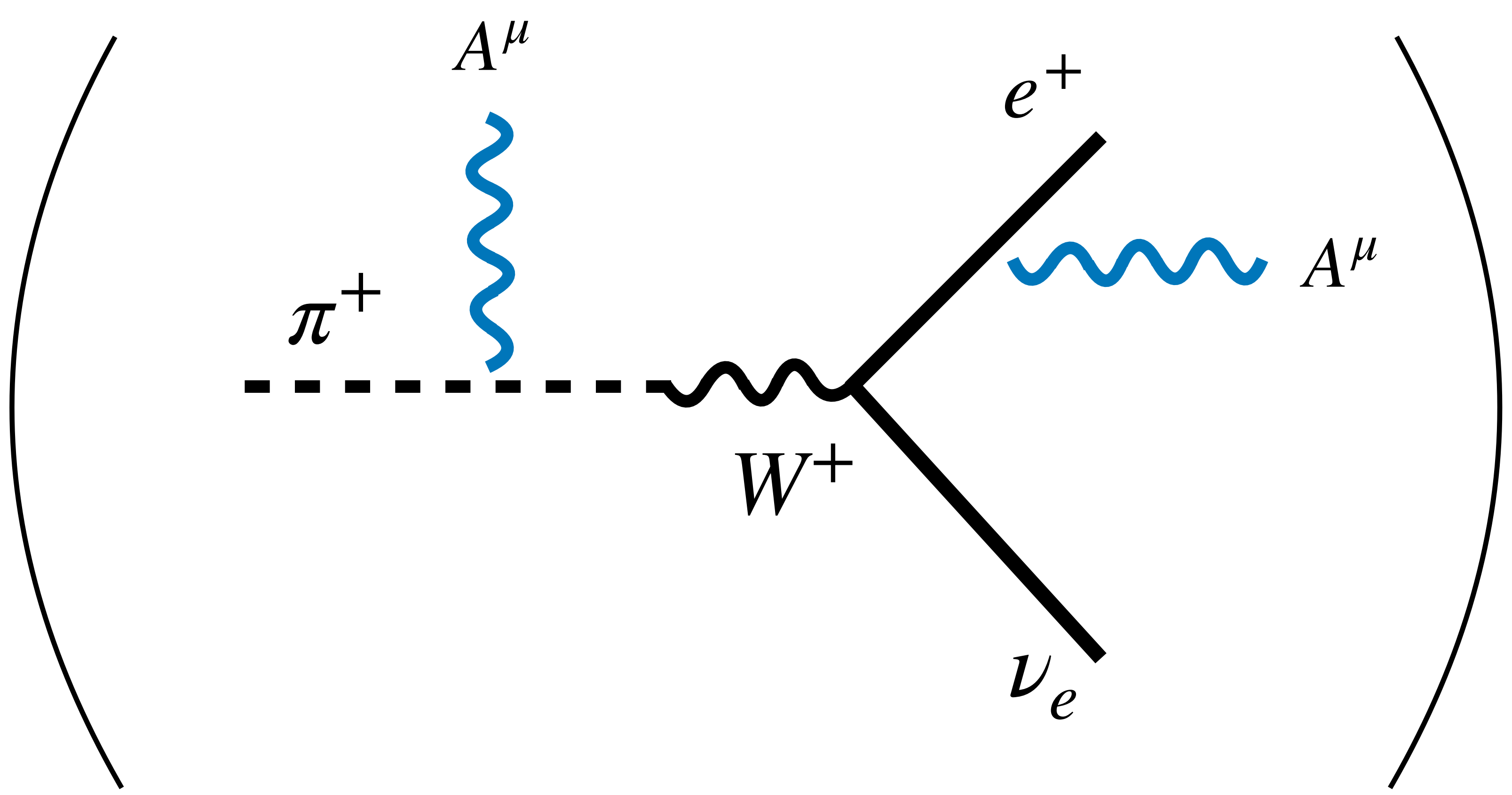
$$\frac{\Gamma_{e\gamma}}{\Gamma_e} \sim \left(\frac{m_\pi^2}{m_e^2}\right)\left(\frac{\alpha}{4\pi}\right) \sim 40$$

Can the radiative mode really be that much larger than the core leptonic process?

Radiative pion decay

Pion decays — helicity flip

Internal Bremsstrahlung 1 and 2



$\not\propto m_e$ Not helicity suppressed.

Primary vertex for pion decay:

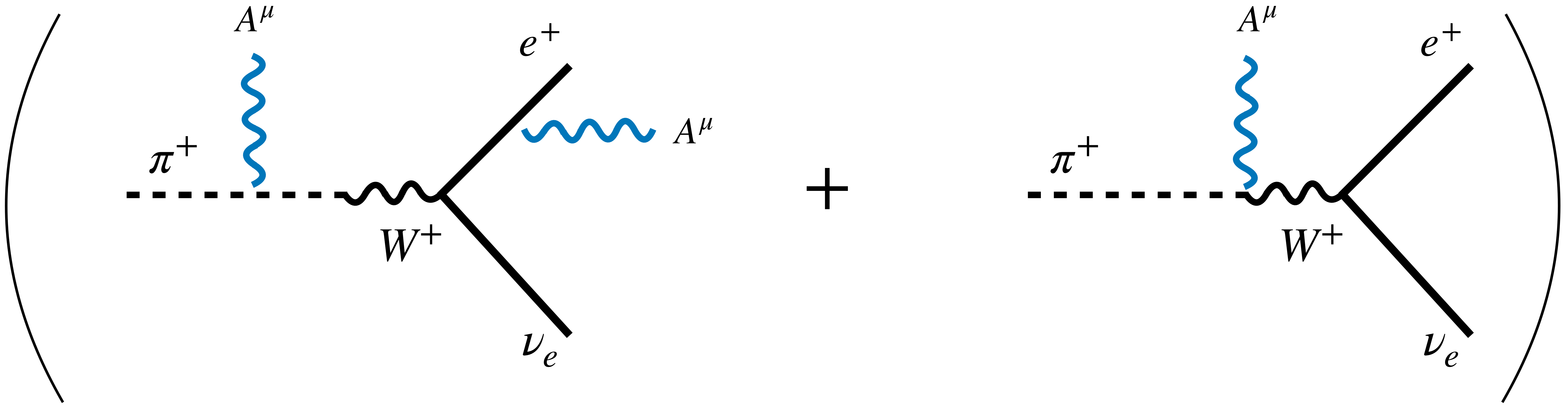
$$\mathscr{L} \supset G_F f_\pi \times \partial_\mu \pi \left(\overline{\ell} \gamma^\mu \nu_\ell\right)$$

Point-like pion & leptonic bremsstrahlung

Radiative pion decay

Pion decays — helicity flip

Internal Bremsstrahlung 1 and 2 | Internal Bremsstrahlung 3



$\propto \; m_e$

Still helicity suppressed!

Primary vertex for pion decay:

$$\mathscr{L} \supset G_F f_\pi \times \partial_\mu \pi \left(\overline{\ell}\gamma^\mu \nu_\ell\right)$$

Point-like pion & leptonic bremsstrahlung

Not gauge invariant. Need a replacement:

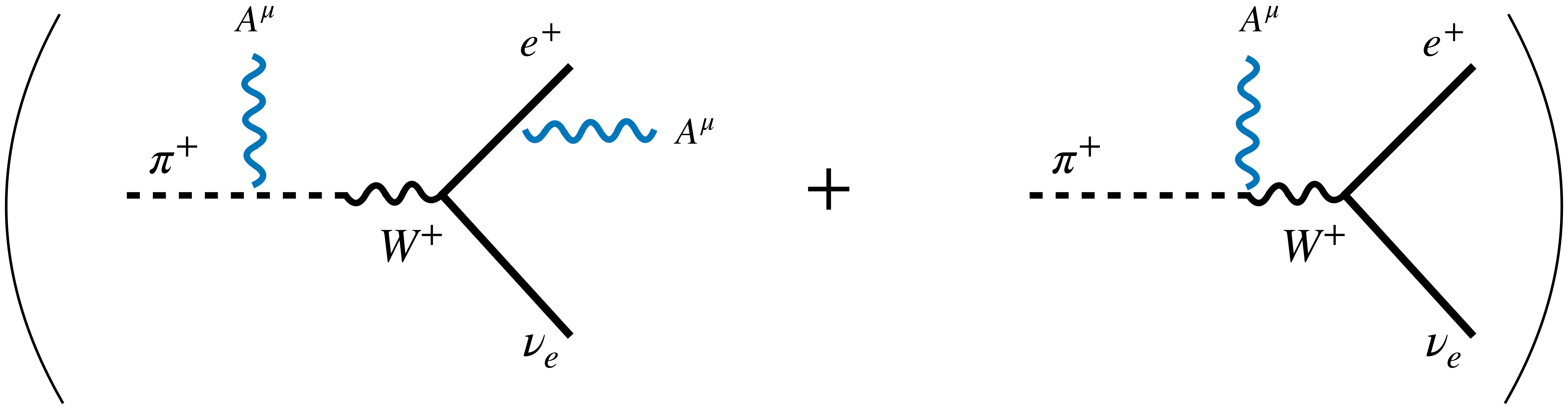
$$\partial_\mu \pi \left(\overline{\ell}\gamma^\mu \nu_\ell\right) \to (\partial_\mu - ieA_\mu)\pi \left(\overline{\ell}\gamma^\mu \nu_\ell\right)$$

Seagull diagram unavoidable in gauge invariant theory.

Radiative pion decay

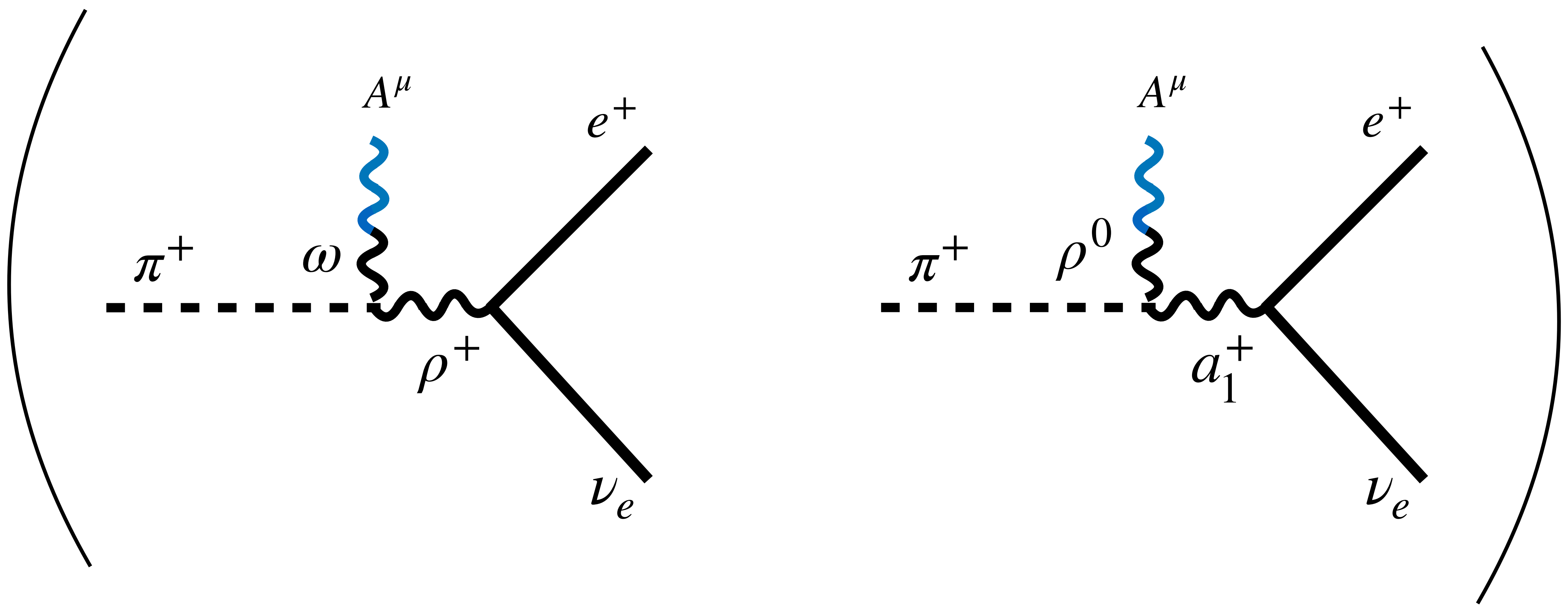
Pion decays — helicity flip

Internal Bremsstrahlung 1 and 2 | Internal Bremsstrahlung 3



$\propto \; m_e$

Still helicity suppressed!



$\not\propto m_e$

Structure Dependent V and A

π no longer "point-like"

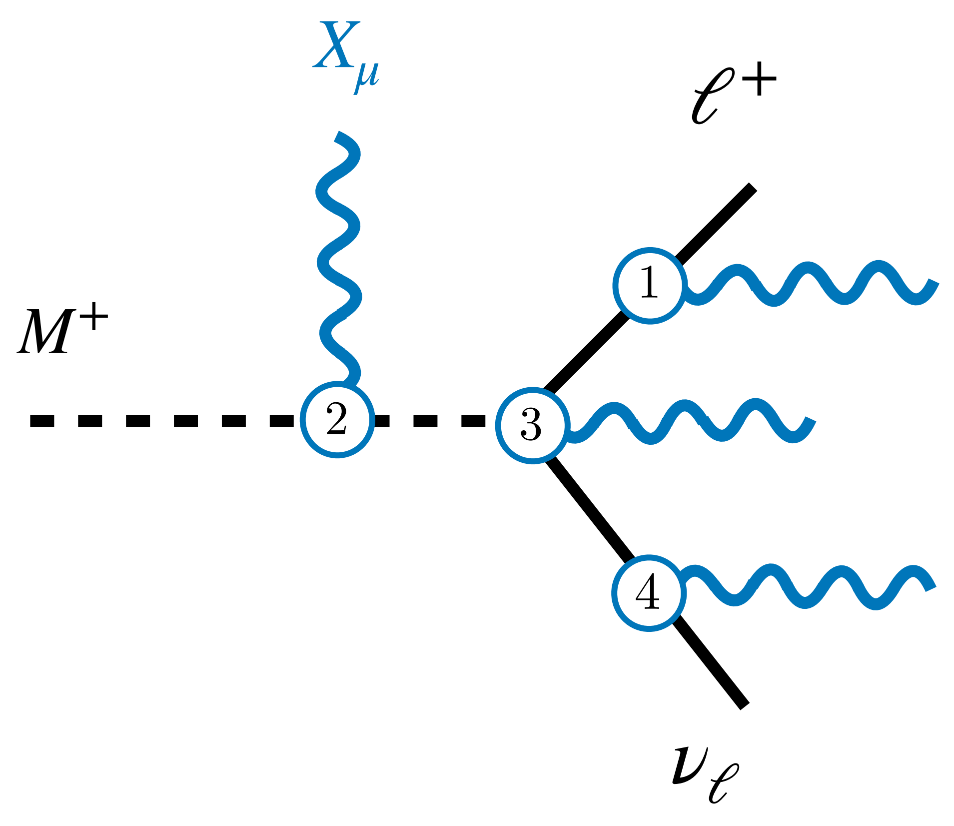
These are suppressed by M_ρ^{-1} instead

so can be safely neglected!

New vector bosons

Radiative pion decays

MH, M. Pospelov, PRD 108, 055011



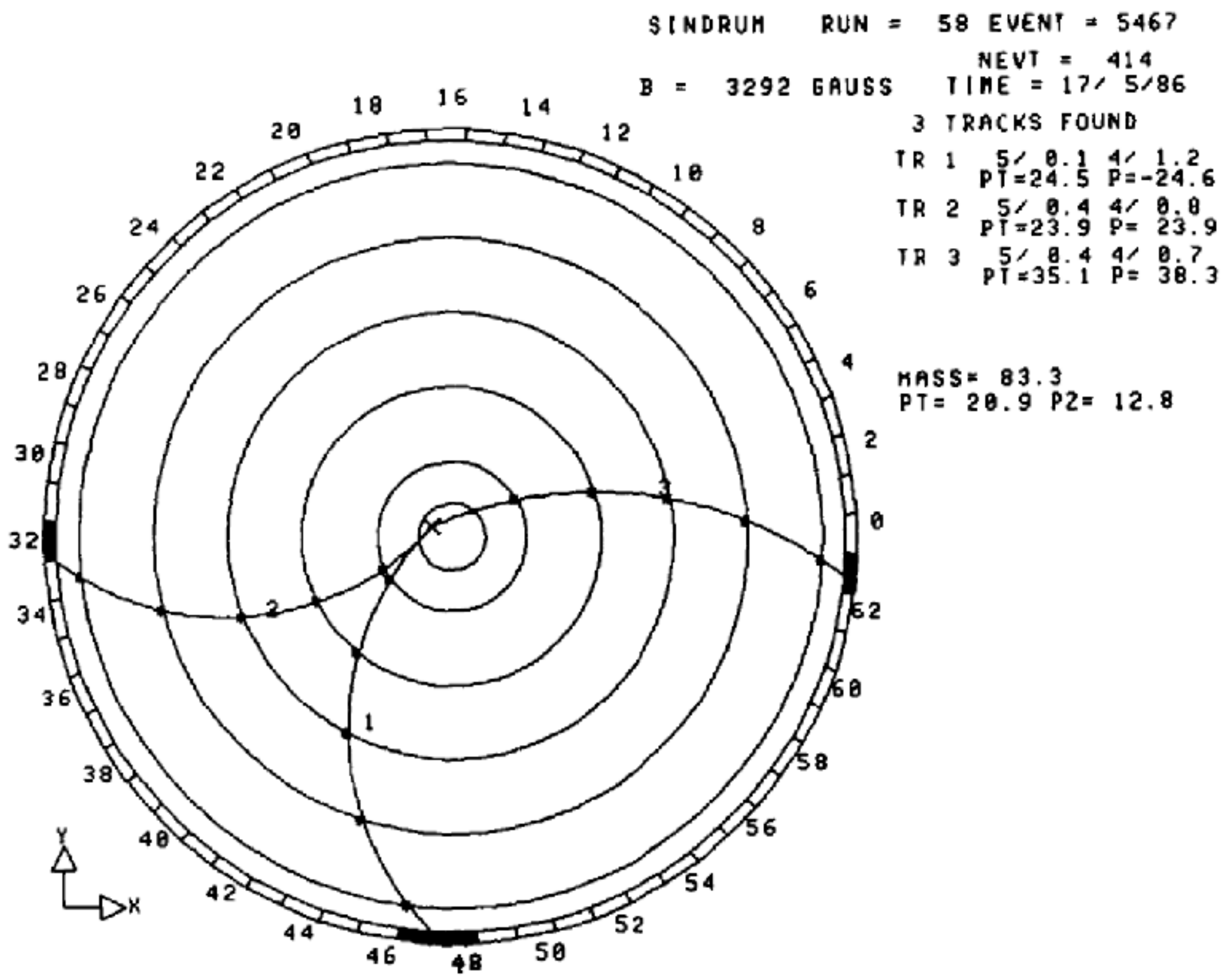
$$k^\mu \mathscr{M}_\mu \propto \left(Q_{\pi^+} - (Q_\nu - Q_e)\right)\, \overline{\nu_e} \left(k^\mu \gamma_\mu P_L - m_e P_R\right) e$$

Enhancement by:

1) helicity flip,

2) longitudinal mode emission.

$$\Gamma_{\text{protophobic}} \sim \Gamma_{\text{SM}} \times \left(\frac{m_\pi^4}{m_e^2 m_X^2}\right)$$

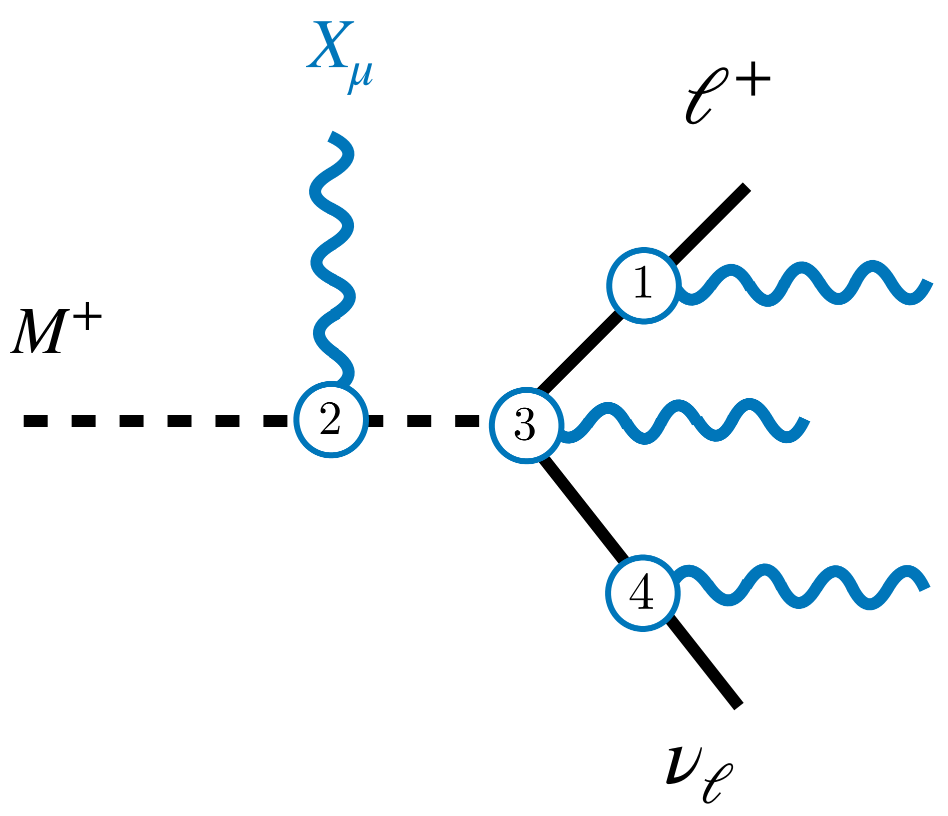


SINDRUM-I search for bumps in $\pi^+ \to e^+ \nu_e e^+ e^-$ decays.

New vector bosons

Radiative pion decays

MH, M. Pospelov, PRD 108, 055011



$$k^\mu \mathcal{M}_\mu \propto \left(Q_{\pi^+} - (Q_\nu - Q_e)\right)\, \overline{\nu_e}\left(k^\mu \gamma_\mu P_L - m_e P_R\right) e$$

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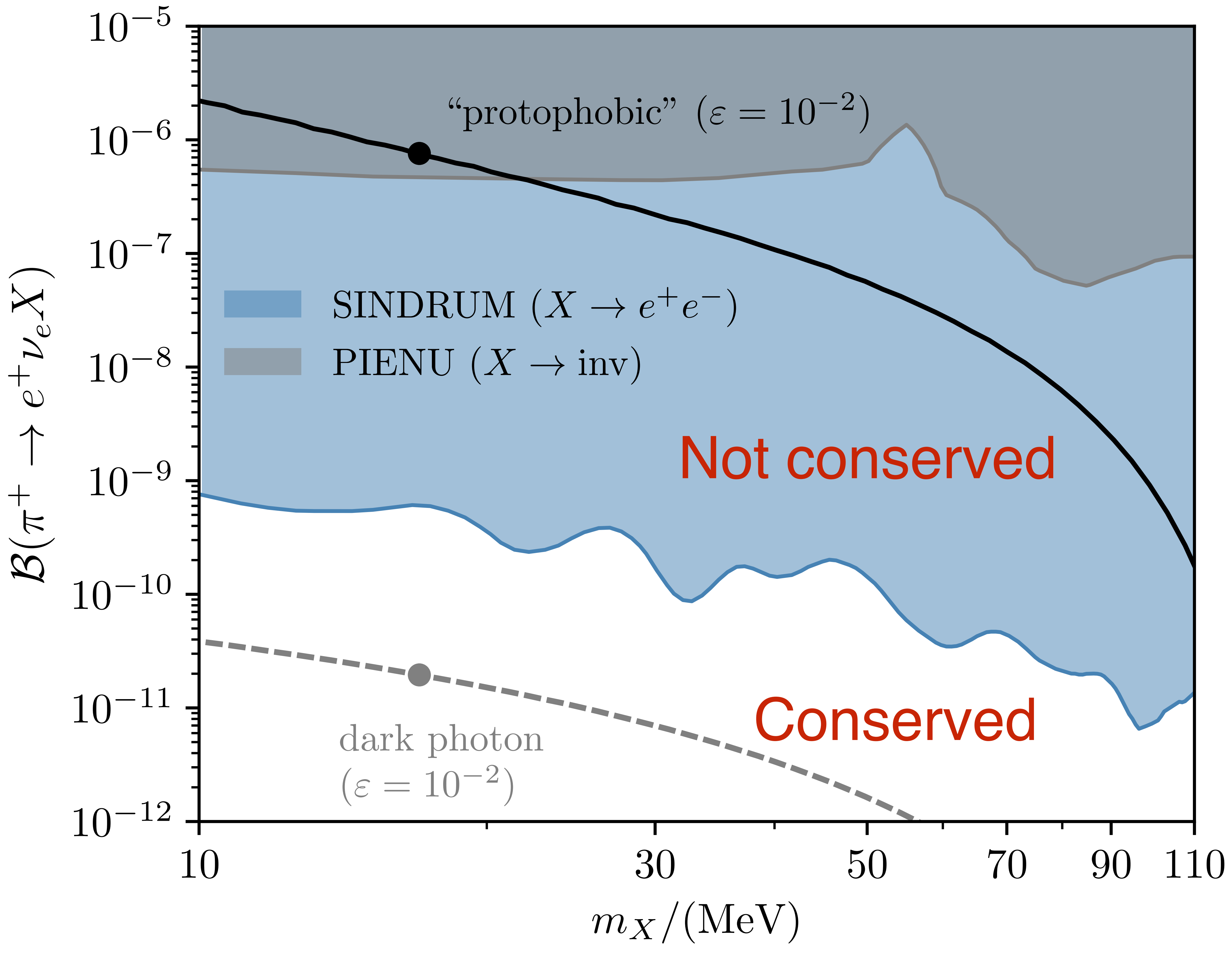
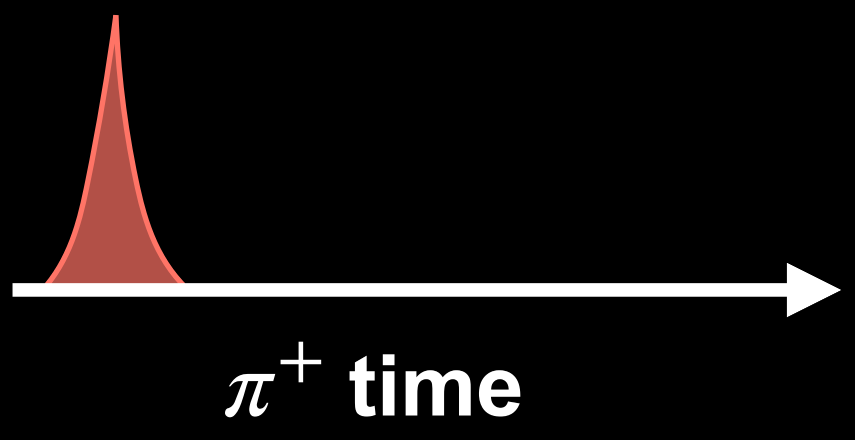


BTW: This basically excludes all exotic 17 MeV vector Boson explanations of ATOMKI anomaly

Long-lived particles at spallation sources
“Weak-violating” axion-like-particle (WV ALP)



Light goldstone boson that probes exotic electron couplings

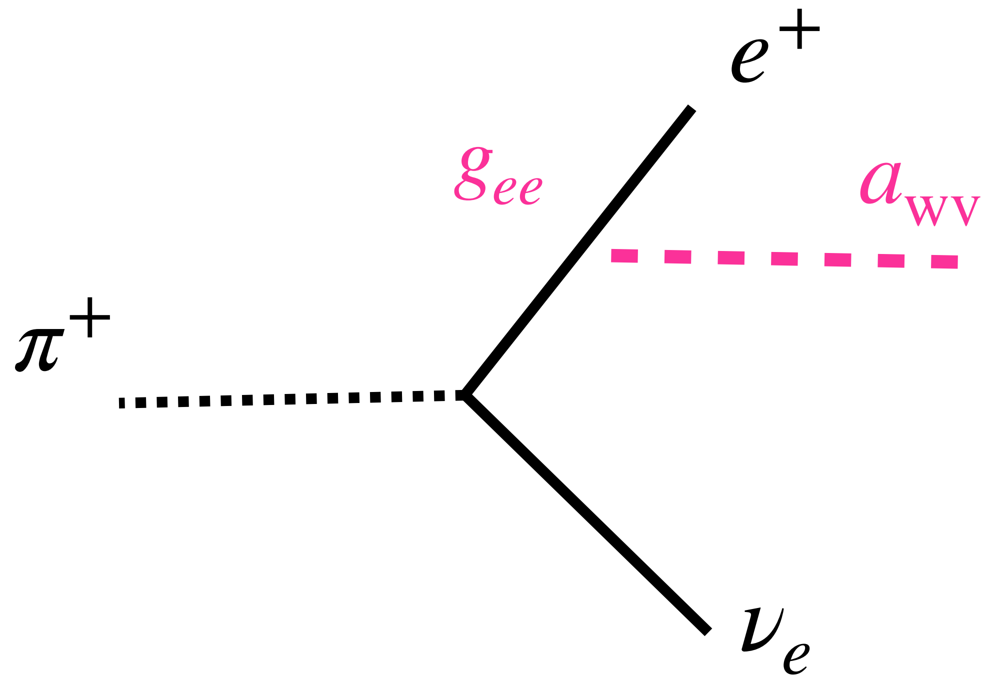
$$j^\mu_{\rm PQ} = \frac{\bar{g}_{\ell\ell}}{2m_\ell}\bar{\ell}\gamma^\mu \ell + \frac{g_{\ell\ell}}{2m_\ell}\bar{\ell}\gamma^\mu\gamma_5 \ell + \frac{g_{\nu_\ell}}{2m_\ell}\bar{\nu}_\ell\gamma^\mu P_L \nu_\ell\,.$$

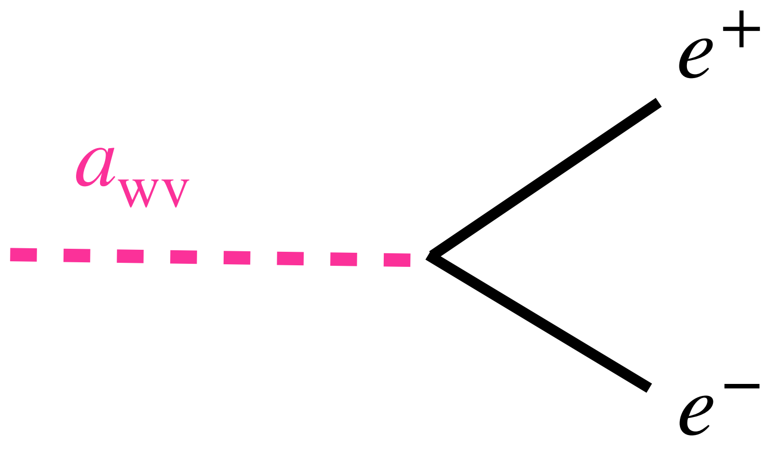
Lifting helicity suppression in 3-body π^+ decay is not easy, but can be done in a class of “weak-violating” ALP models.

This is an exception: underlying current is not gauged, so it is ok!

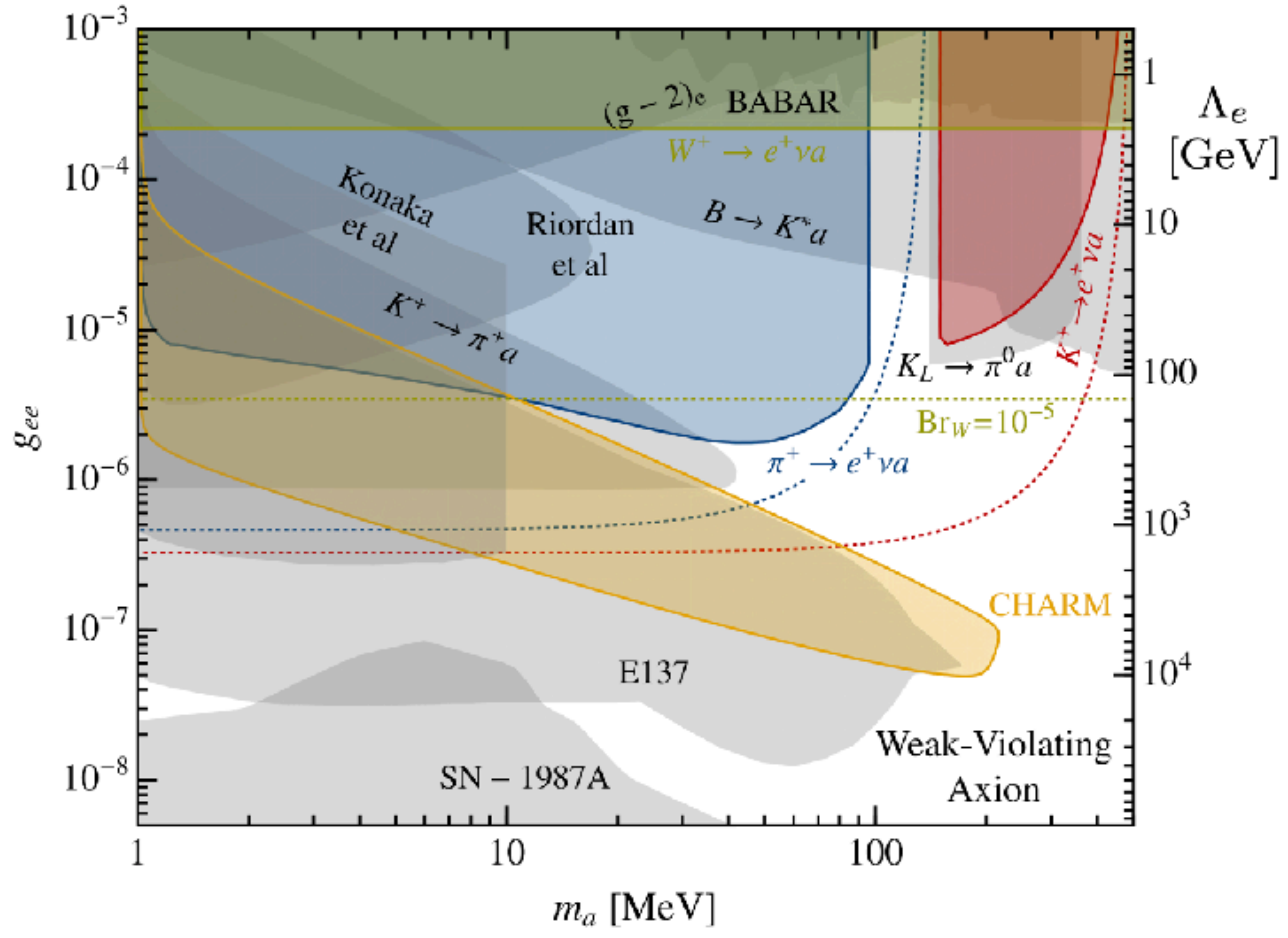
W. Altmannshoffer et al, arXiv:2209.00665

In this case, three-body decays of the pion are the dominant source of these ALPs at accelerators.

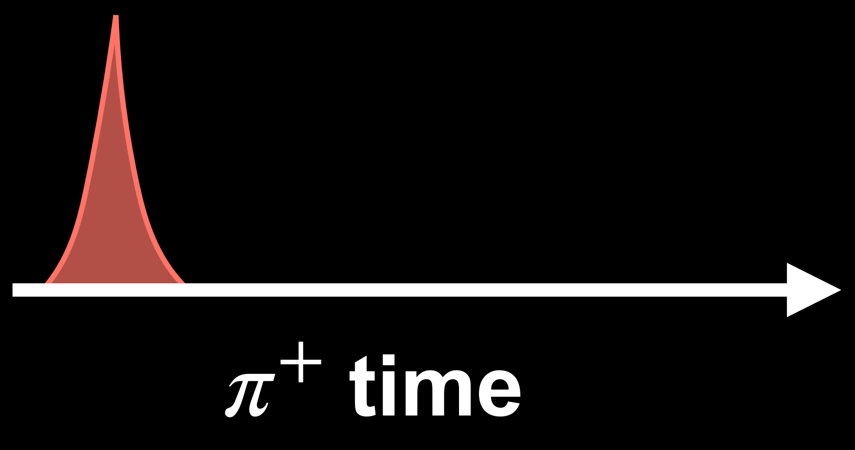




$$\frac{\mathcal{B}(P^+ \to \ell^+\nu_\ell a)}{\mathcal{B}(P^+ \to \ell'^+\nu_{\ell'})} \simeq \frac{1}{1536\pi^2}\frac{m_P^4}{m_\ell^2 m_{\ell'}^2}\left(1 - \frac{m_{\ell'}^2}{m_P^2}\right)^{-2} \times \left[(g_{\ell\ell} - \bar{g}_{\ell\ell} + g_{\nu_\ell})^2 f_0(x_P) + \frac{16 m_\ell^2}{m_P^2} g_{\ell\ell}^2 f_1(x_P)\right].$$



Long-lived particles at spallation sources
“Weak-violating” axion-like-particle (WV ALP)



Light goldstone boson that probes exotic electron couplings

Lifting helicity suppression in 3-body π^+ decay is not easy, but can be done in a class of ALP models with “weak-violating” (SU$(2)_L$-violating) couplings.

W. Altmannshoffer et al, arXiv:2209.00665

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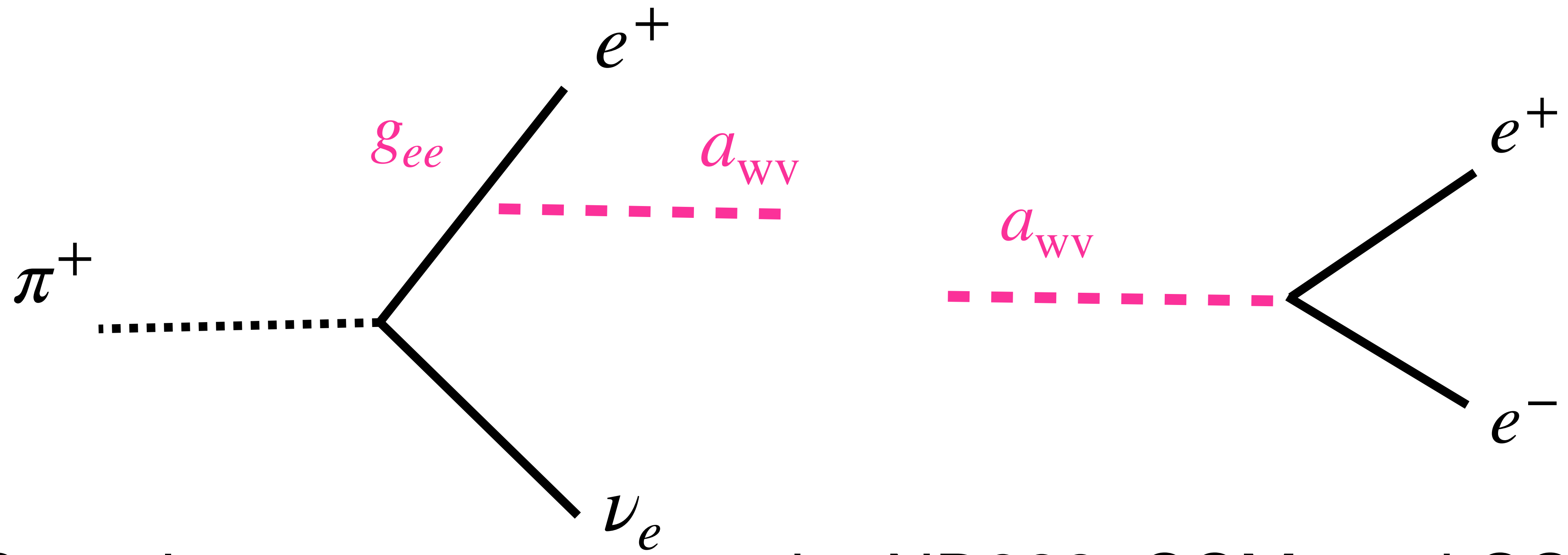

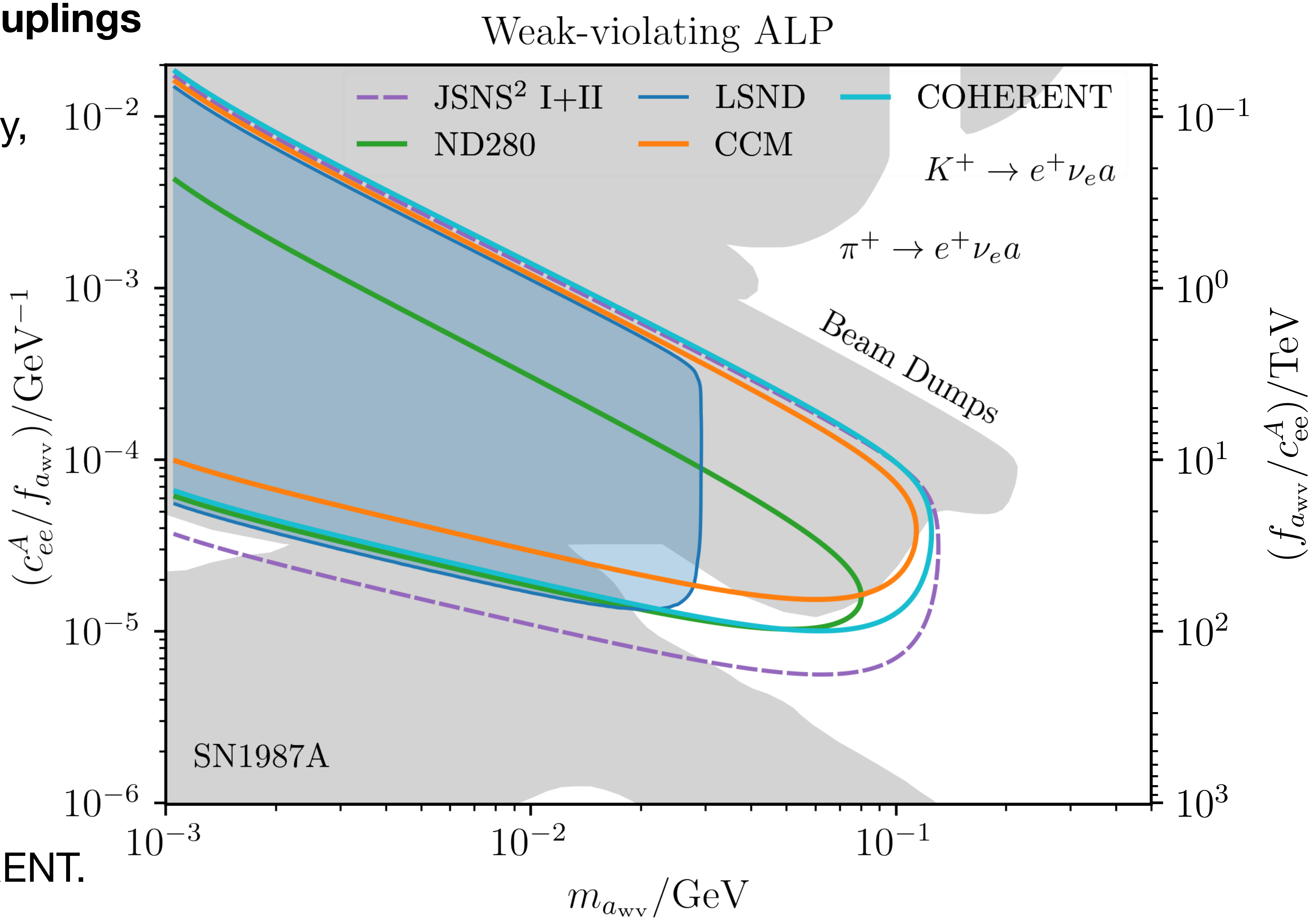

Complementary coverage by ND280, CCM, and COHERENT.

LSND more on par since $a_{\rm wv}$ is more energetic.

Outline:

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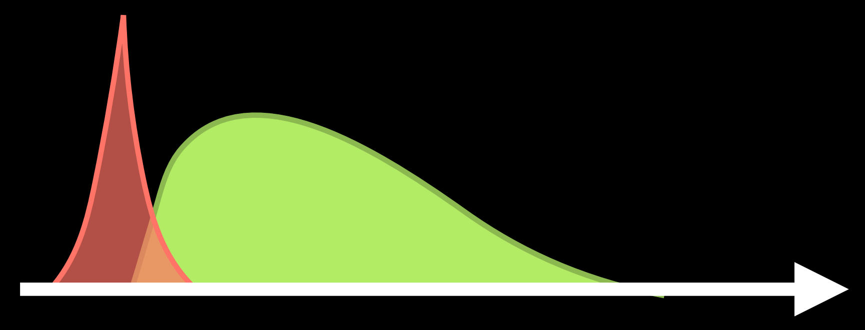
Heavy neutral leptons (low-scale seesaw)

Long-lived particles at spallation sources
Heavy neutral leptons

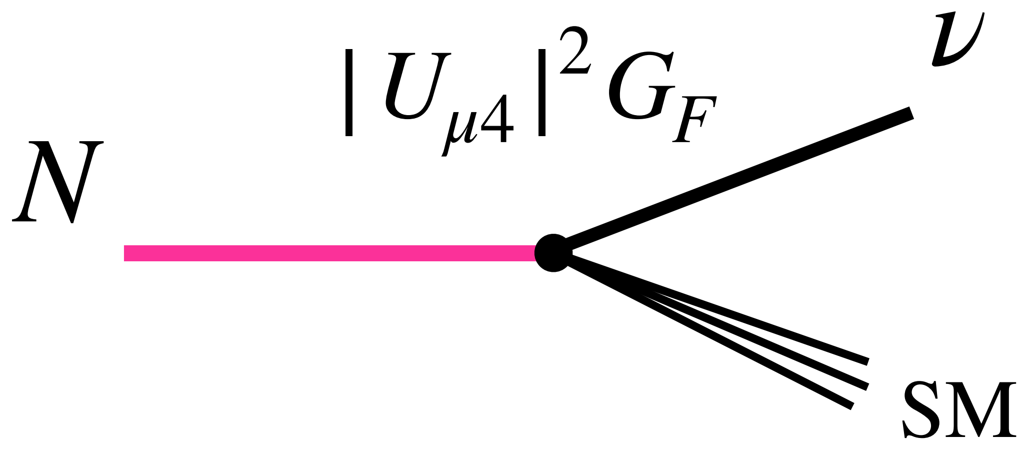


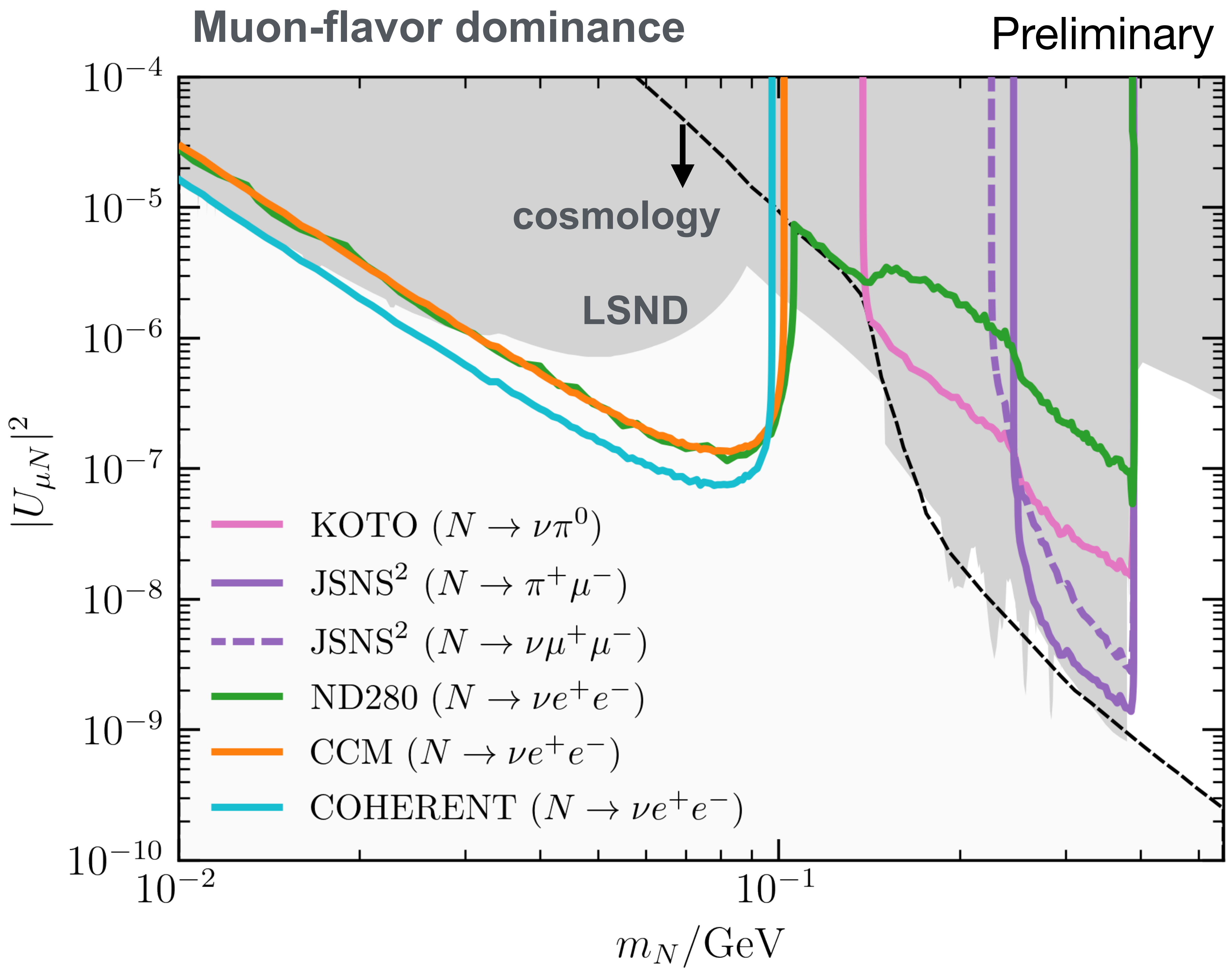
Low-scale neutrino mass model

Improvement over LSND because of the stringent signal selection criterion to fake $\nu - e$ scattering.

Most final states are relevant for K^+ parentage so they have limited sensitivity.

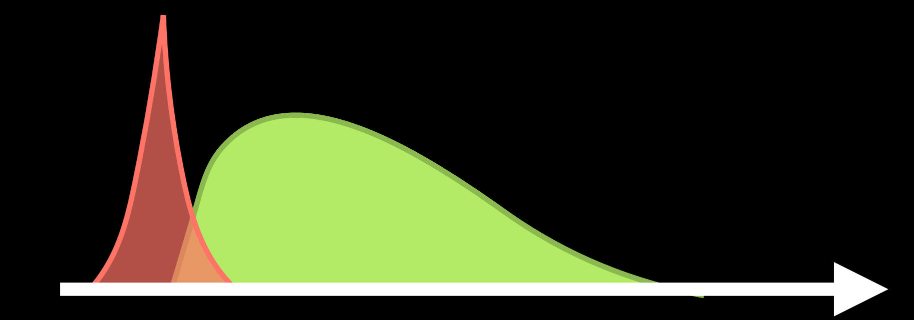
Competition with LSND and meson peak searches.





LSND limit derived in Y. Ema, Z. Liu, K. Lyu, M. Pospelov, arXiv:2306.07315

Long-lived particles at spallation sources
Heavy neutral leptons

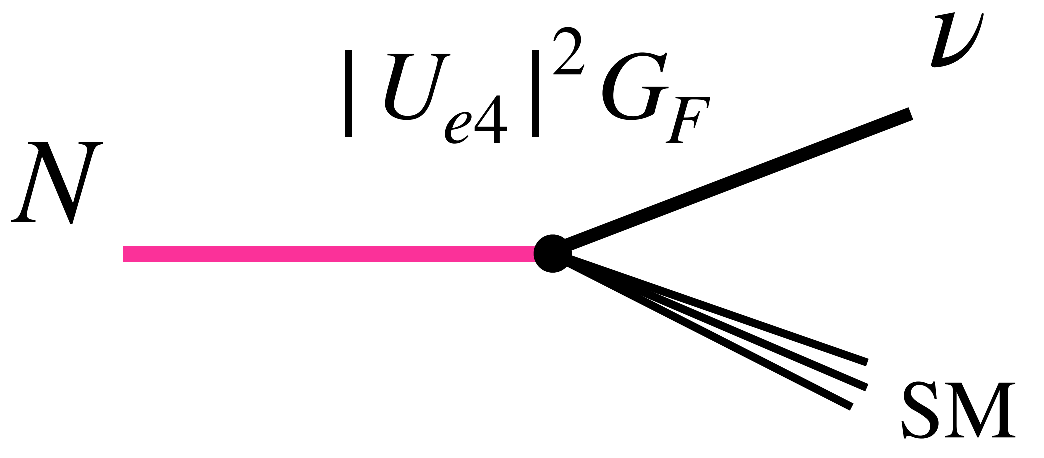


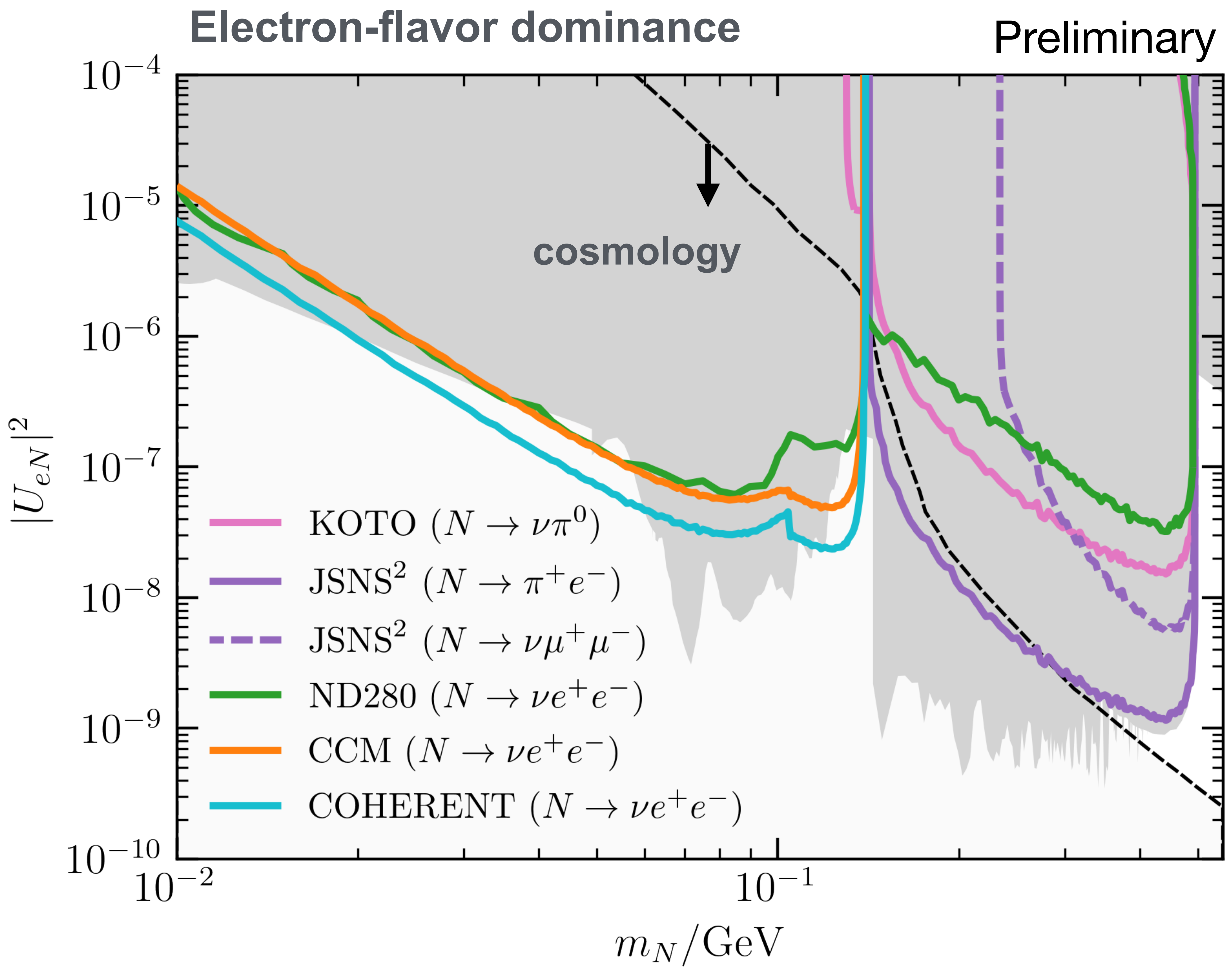
Low-scale neutrino mass model

Improvement over LSND because of the stringent signal selection criterion to fake $\nu - e$ scattering.

Most final states are relevant for K^+ parentage so they have limited sensitivity.

Competition with LSND and meson peak searches.

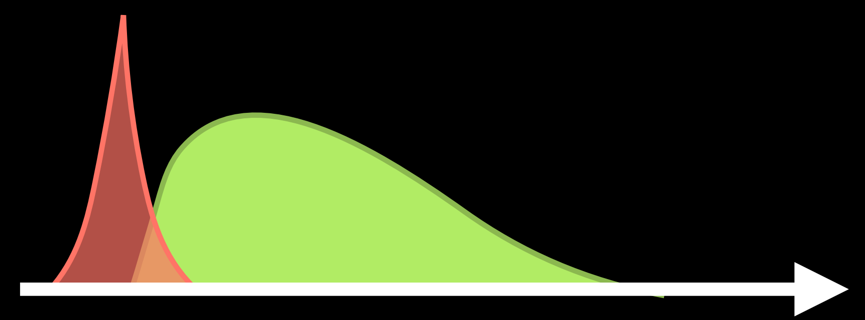




LSND limit derived in Y. Ema, Z. Liu, K. Lyu, M. Pospelov, arXiv:2306.07315

See E. Fernández-Martínez, M.González-López, J. Hernández-García, MH, J. Lópes-Pavón, 10.1007/JHEP09(2023)001

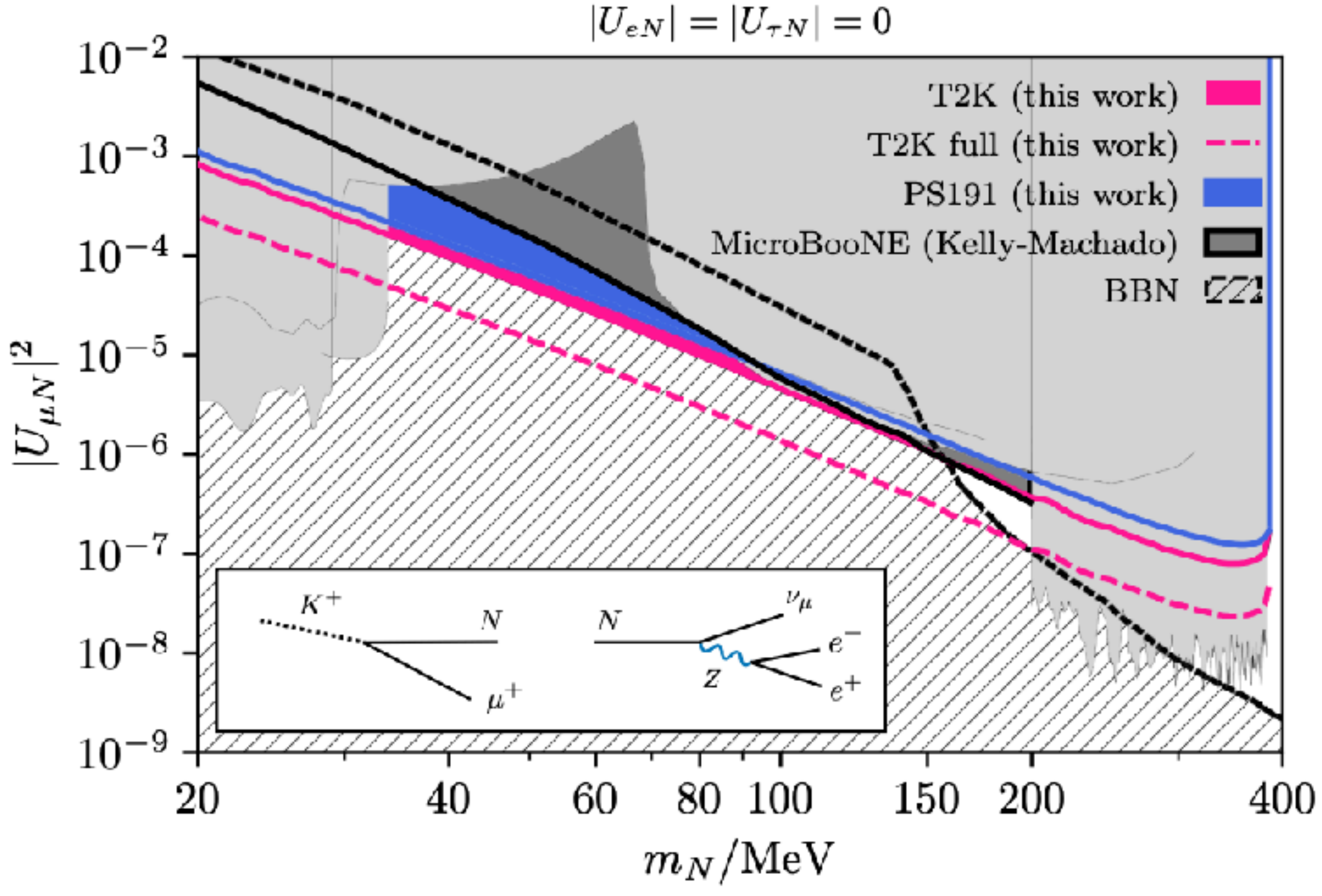
Long-lived particles at spallation sources
Heavy neutral leptons — avoiding cosmological limits?



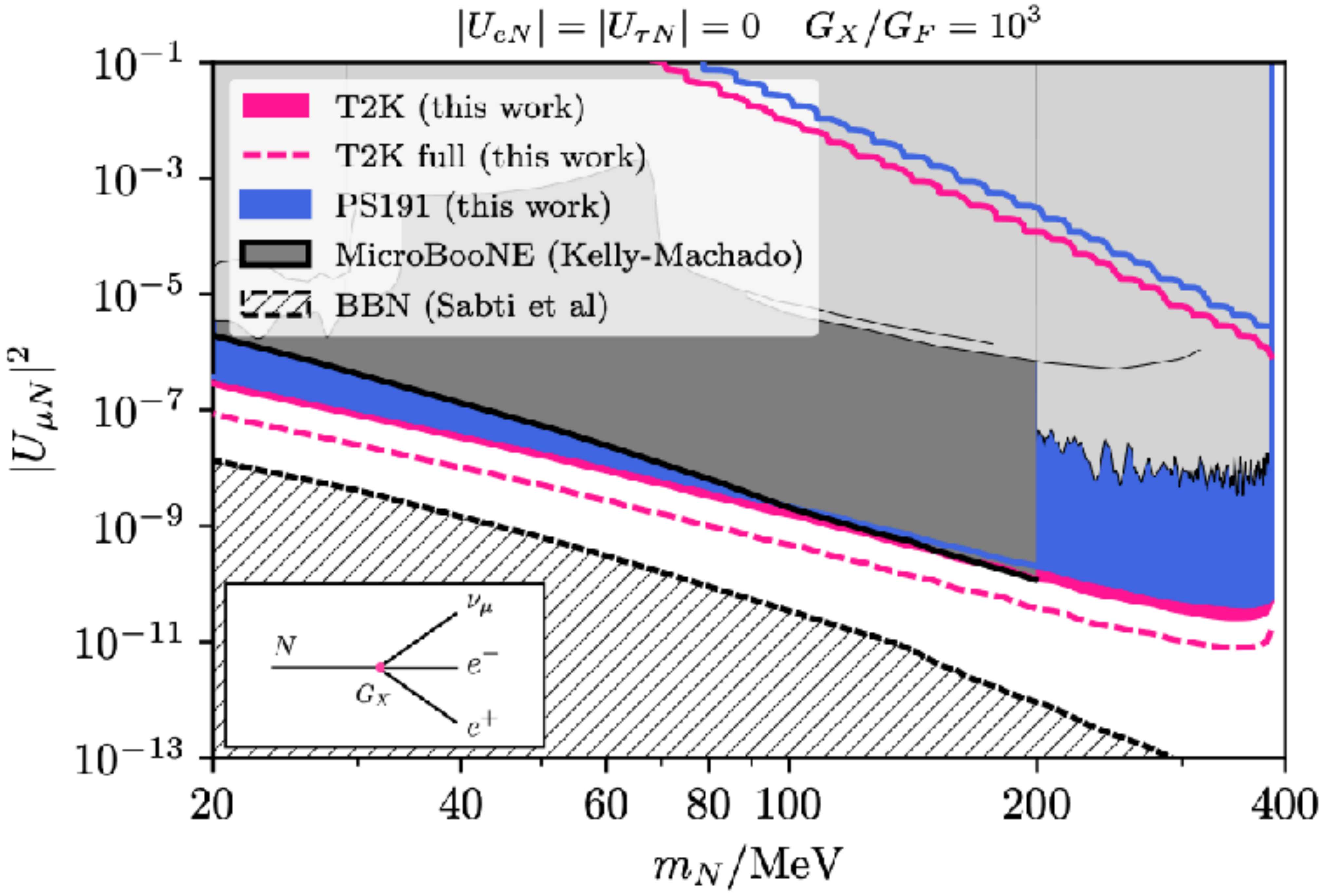
Cosmological limits typically make the sub-100 MeV region less interesting in minimal HNL models.

If new forces exist (e.g., magnetic moments or dark photons), decay-in-flight limits on LLPs quickly become the most important.

Spallation sources are useful for "non-minimal" HNL models. For example:



Minimal HNL



Dark force + HNL

Outline:

1) Spallation (neutron) sources: what and why?

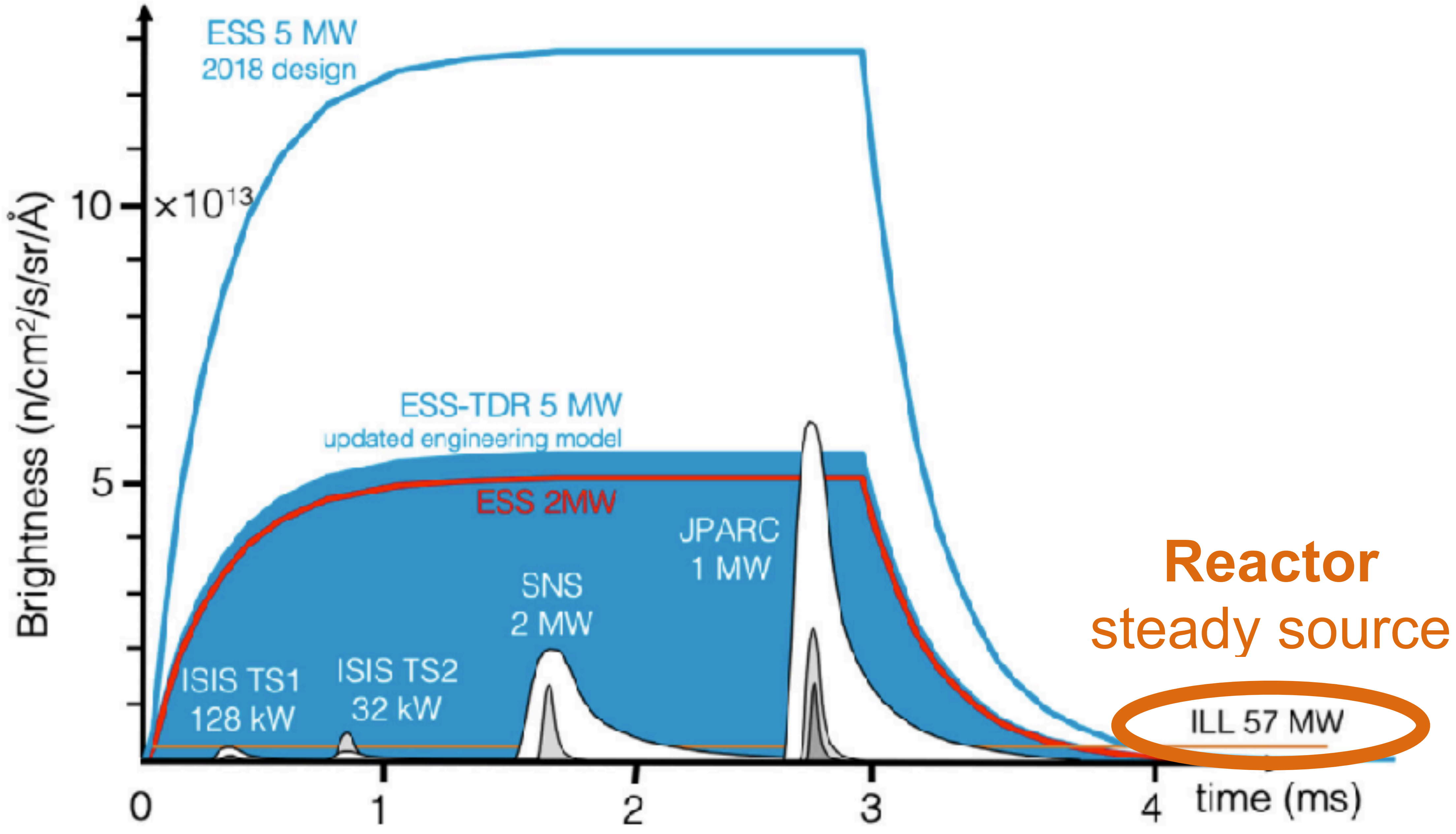
2) Opportunities with neutrino detectors

3) Long-lived particles below K, π, and μ masses

Bonus) Thoughts on future and next-generation facilities

Future facilities

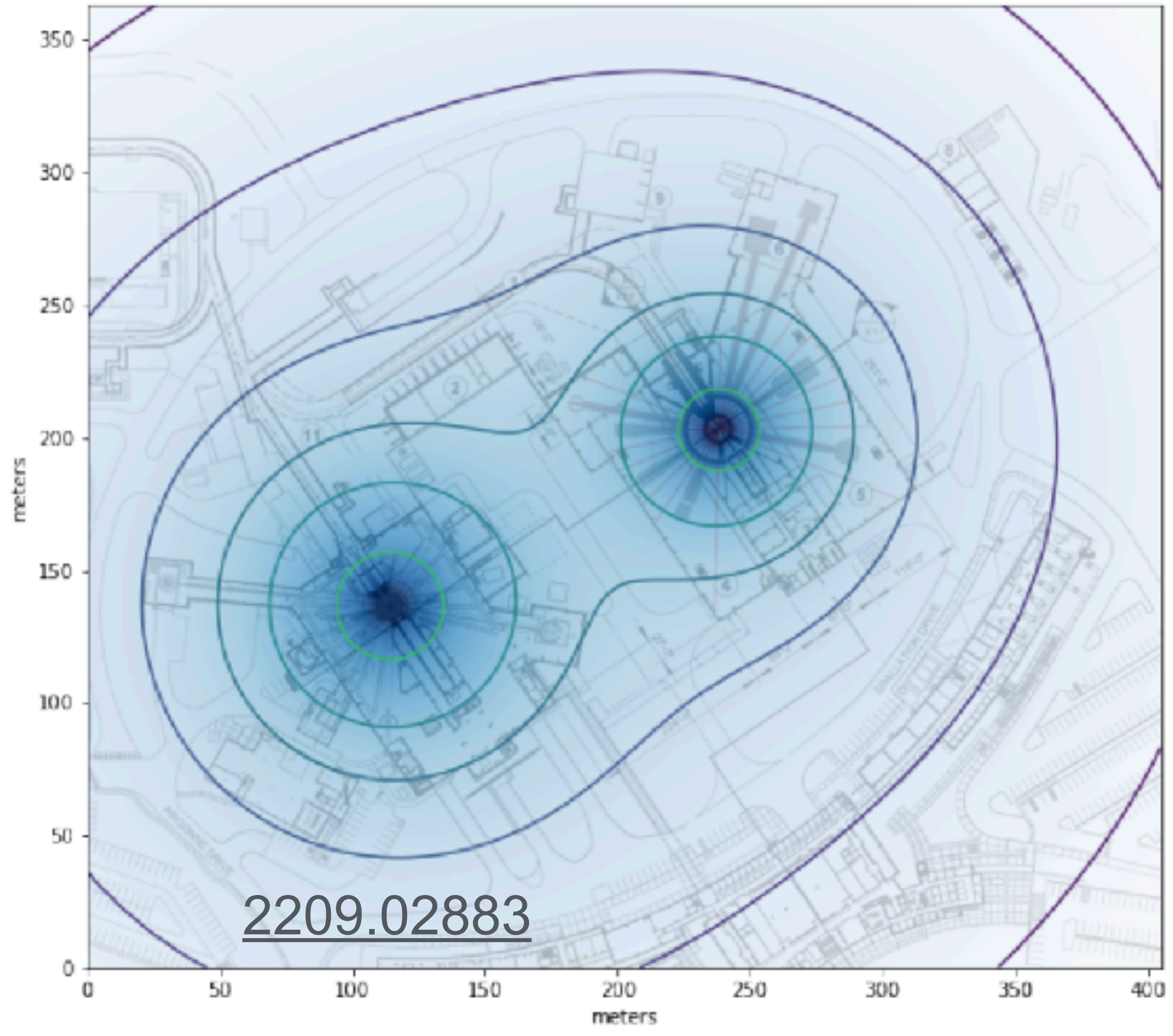
European Spallation Source
a “long” jump in intensity (rotating target)



https://doi.org/10.1016/j.nima.2020.163402

5 MW (1-2 GeV p^+) — huge intensity, but worse background rejection.

Second Target Station at SNS
More neutrinos (rotating target)



First target would receive 2.0 MW at 45 Hz
Second target would receive 0.7 MW at 15 Hz
Neutrino rate is actually the same

Summary

Thank you for listening!

Matheus Hostert (mhostert@g.harvard.edu)

1) Spallation targets are a very messy environment… but move a bit further out and build sufficiently large-volume detectors, and *extremely rare processes* from LLPs could appear.

2) Shown a non-exhaustive list of long-lived particle (LLP) models that can be constrained with existing spallation sources and detectors. Usually less minimal to survive other limits below π and μ masses.

3) A clear application for a well-shielded, low-density, large-volume, and fast detector close to the source.

Magnificent CEvNS 2024

Not all about POTs and volume: background rejection, timing, and people-power.

Lots of stones are left unturned.

Build bigger and away from the neutrino alley? Lower density CCM?

The future is bright and I look forward to the new searches!

Back-up slides

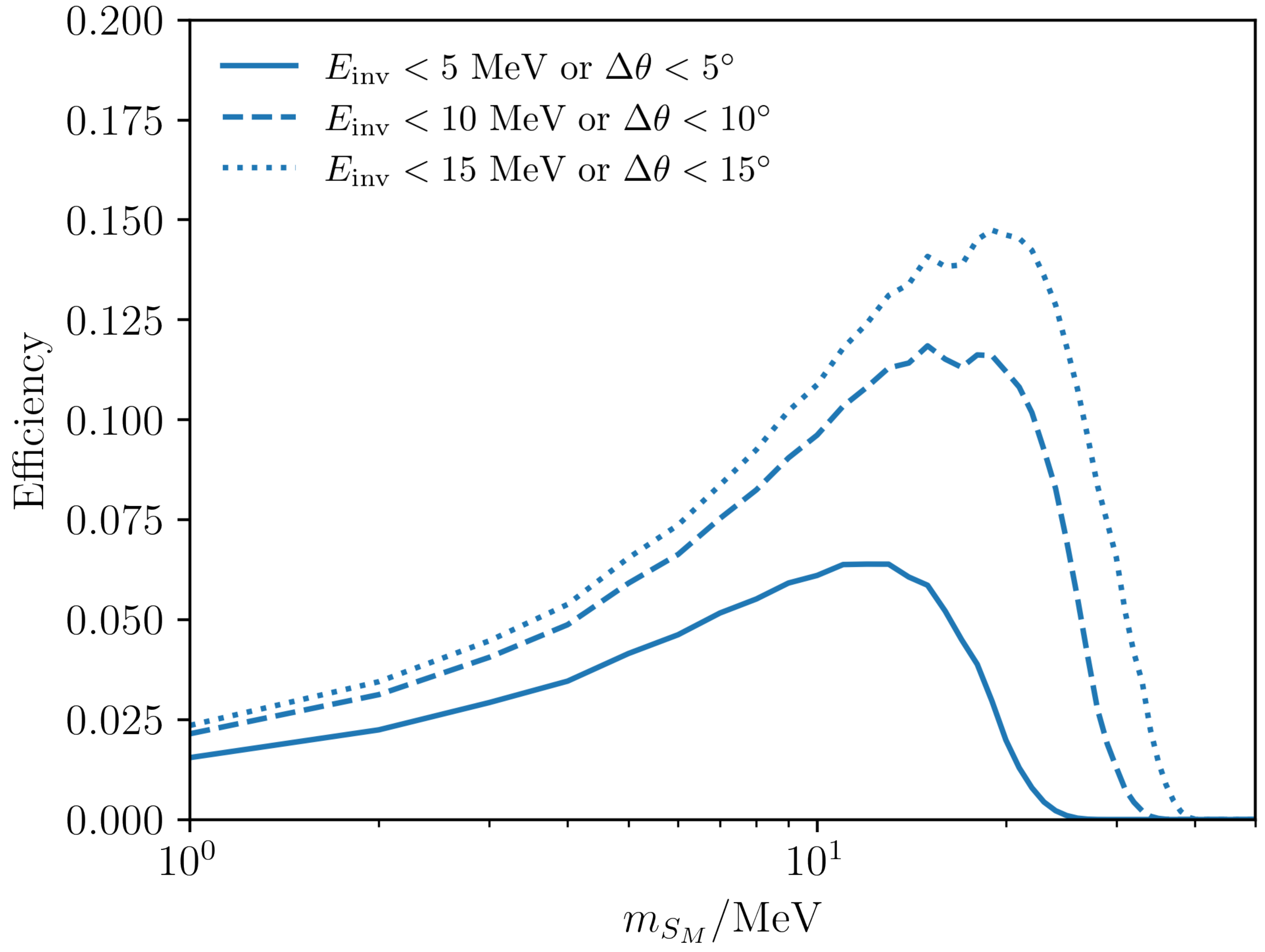
CEvNS — Coherent Elastic Neutrino Nucleus Scattering

Three examples for requiring $\gamma\gamma \leftrightarrow e^-$ mis-identification:

1) $E_{e_{inv}} < 5$ MeV or $\theta_{ee} < 5°$
2) $E_{e_{inv}} < 10$ MeV or $\theta_{ee} < 10°$
3) $E_{e_{inv}} < 15$ MeV or $\theta_{ee} < 15°$ (strongest limit)

All events must also satisfy signal selection criterion:

18 MeV $< E_{\rm vis} < 50$ MeV and $\cos\theta_{\rm vis} > 0.9$



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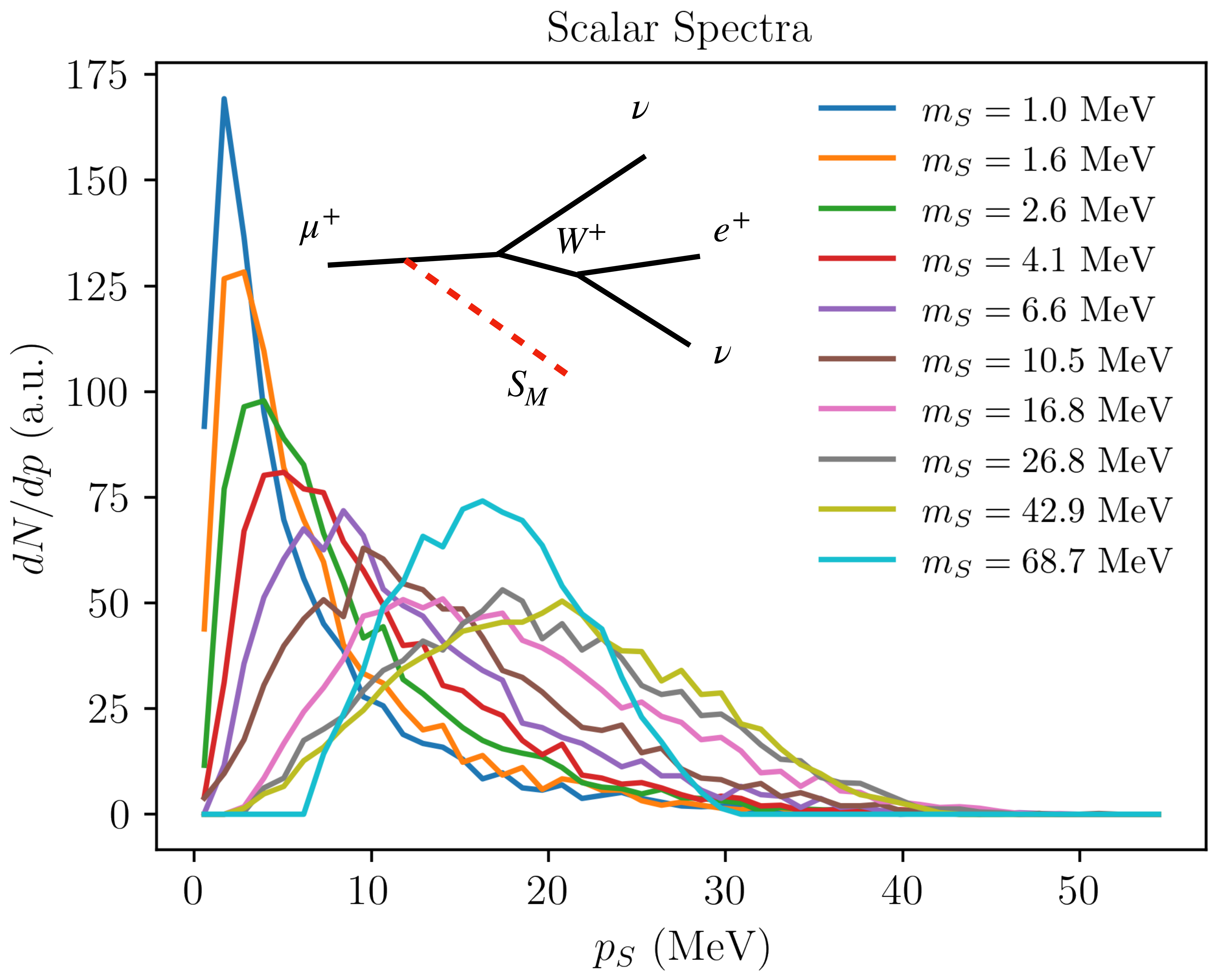


Heavy Neutral Leptons

E. Fernández-Martínez, M.González-López, J. Hernández-García, **MH**, J. Lópes-Pavón, 10.1007/JHEP09(2023)001

Axion-like particles with kaon decay at rest

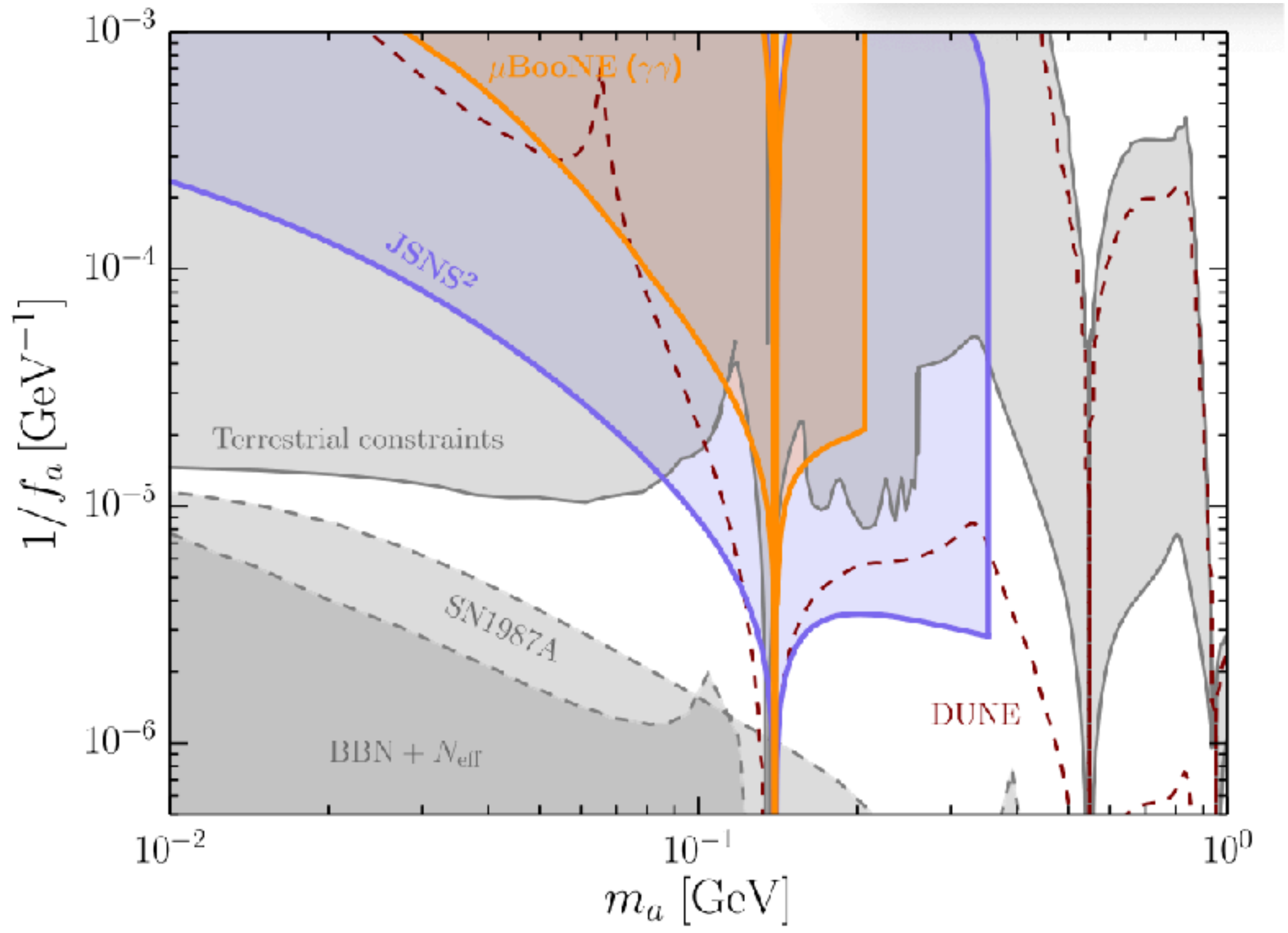


FIG. 2. (*Codominance*) The same figure as Fig. 1 but with $c_{WW} = c_{BB} = c_{GG}$. The sensitivity for $m_a \ll m_\pi$ is worse than the gluon dominance case since $|c^{\rm eff}_{\gamma\gamma}| \ll 1$ for this specific choice of the parameters.

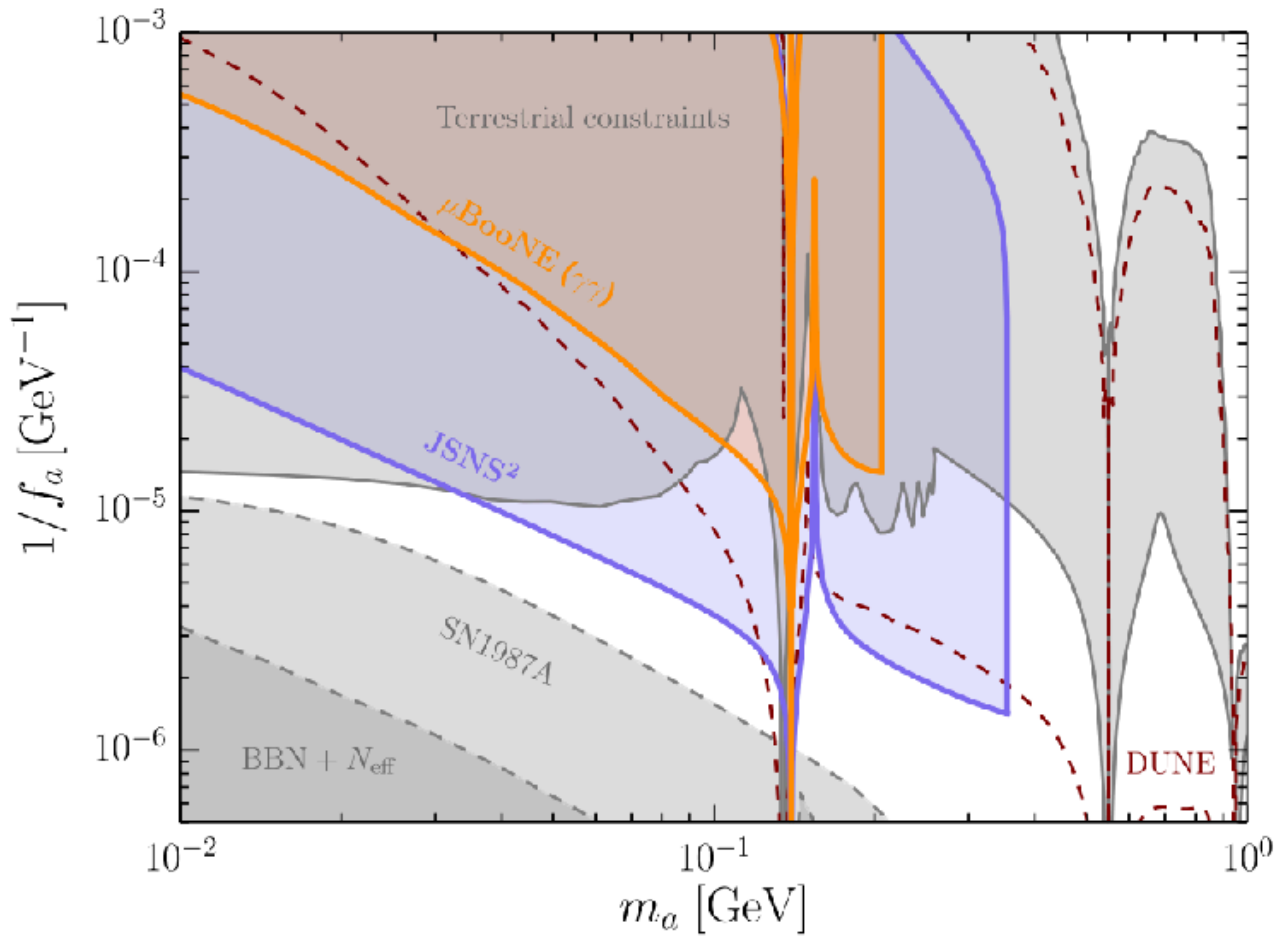
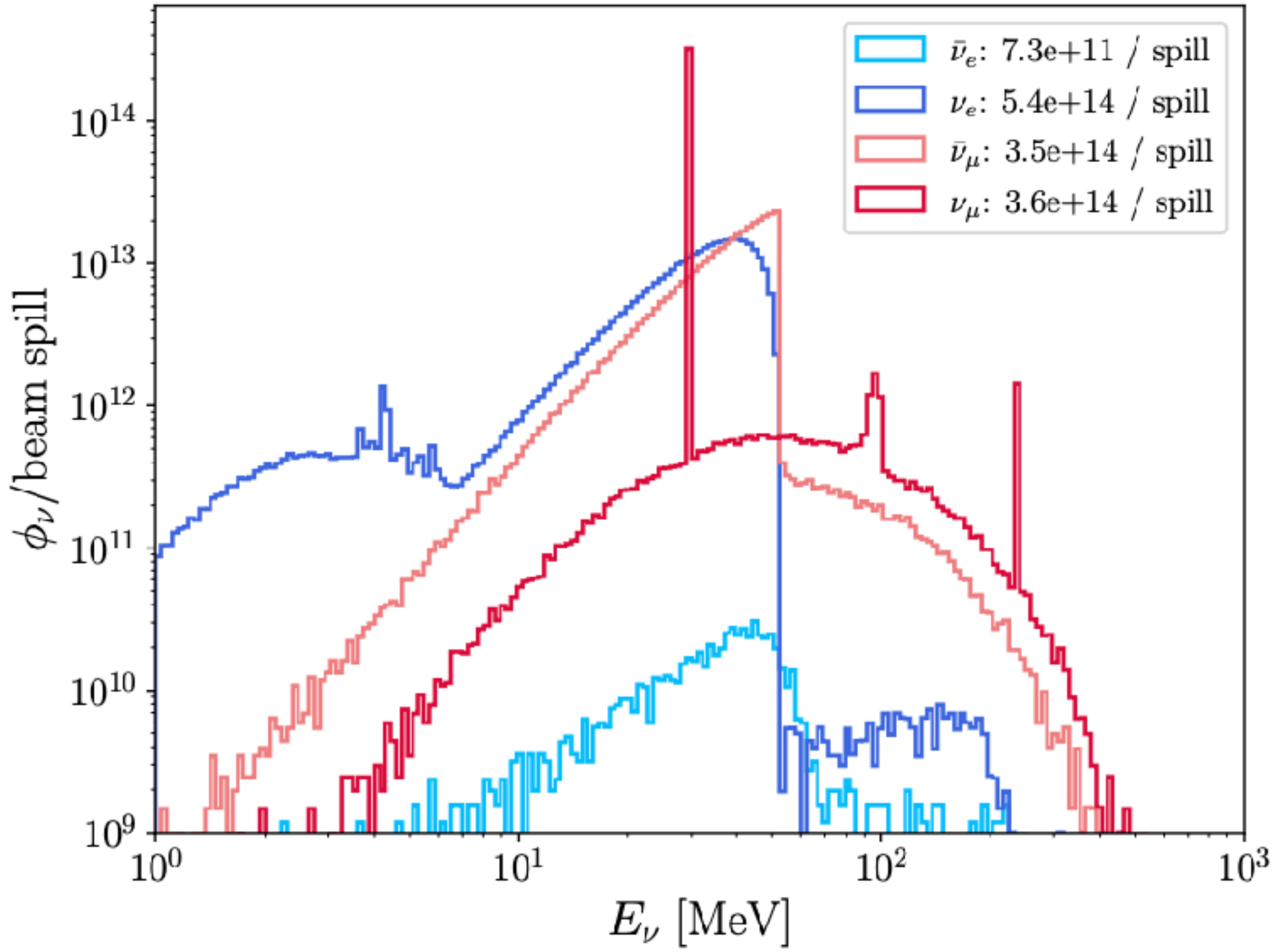
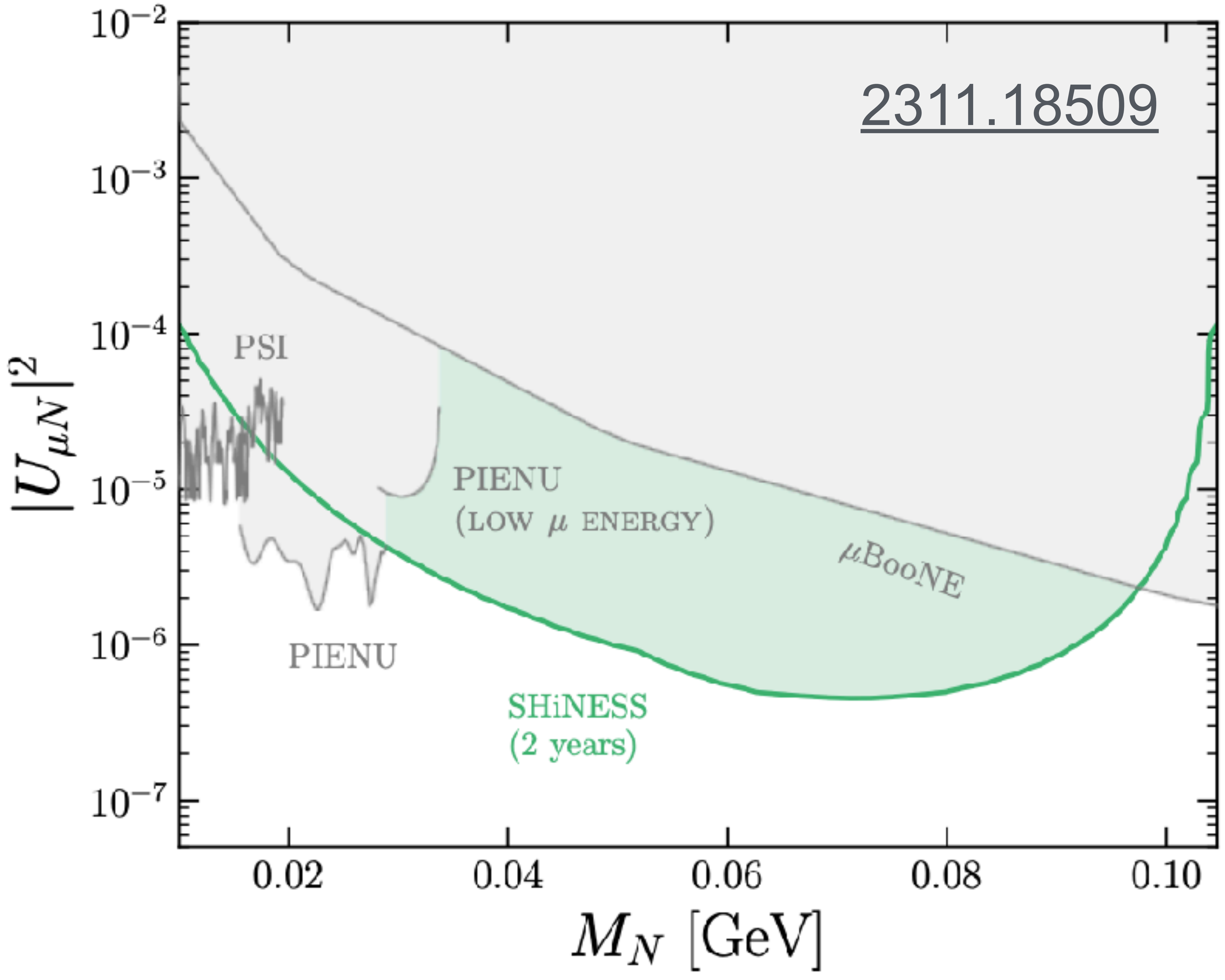


FIG. 1. (*Gluon dominance*) Sensitivities of MicroBooNE and JSNS^2 compared with existing limits and other projected sensitivities when all couplings are induced by a gluon coupling c_{GG} at a high scale. The MicroBooNE sensitivity is cut at 210 MeV

European Spallation Source: Hidden Neutrinos

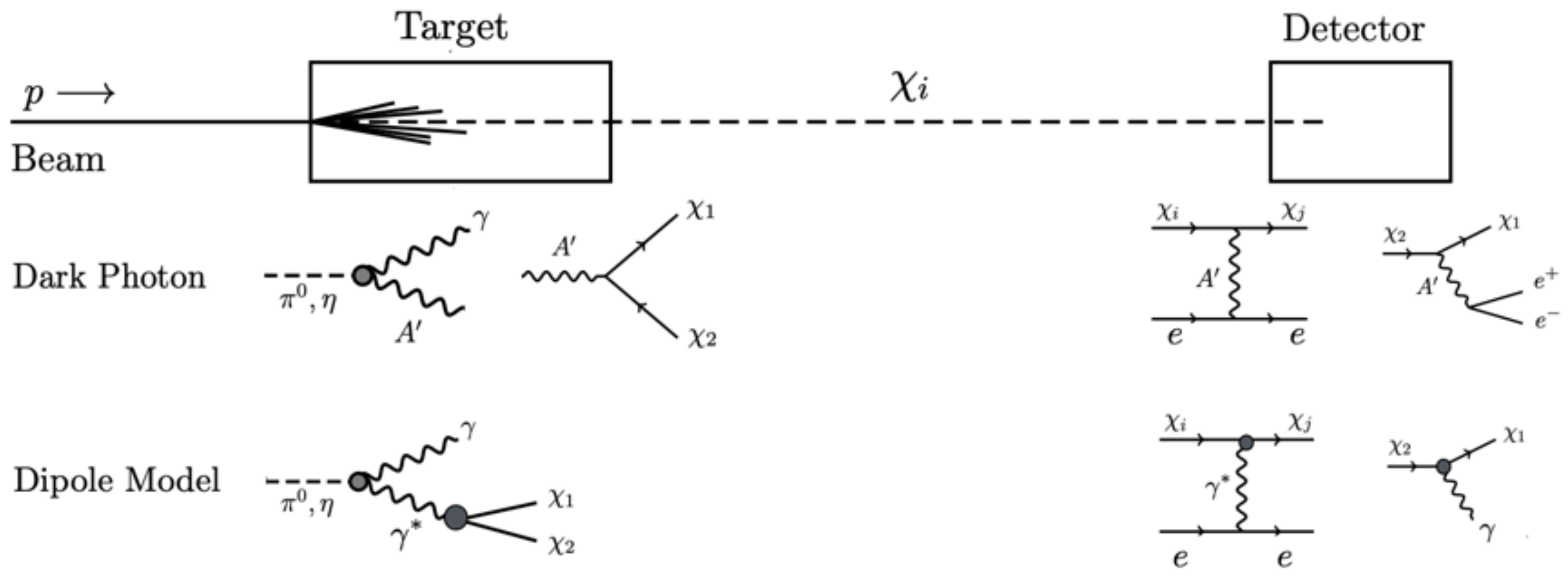
SHiNESS

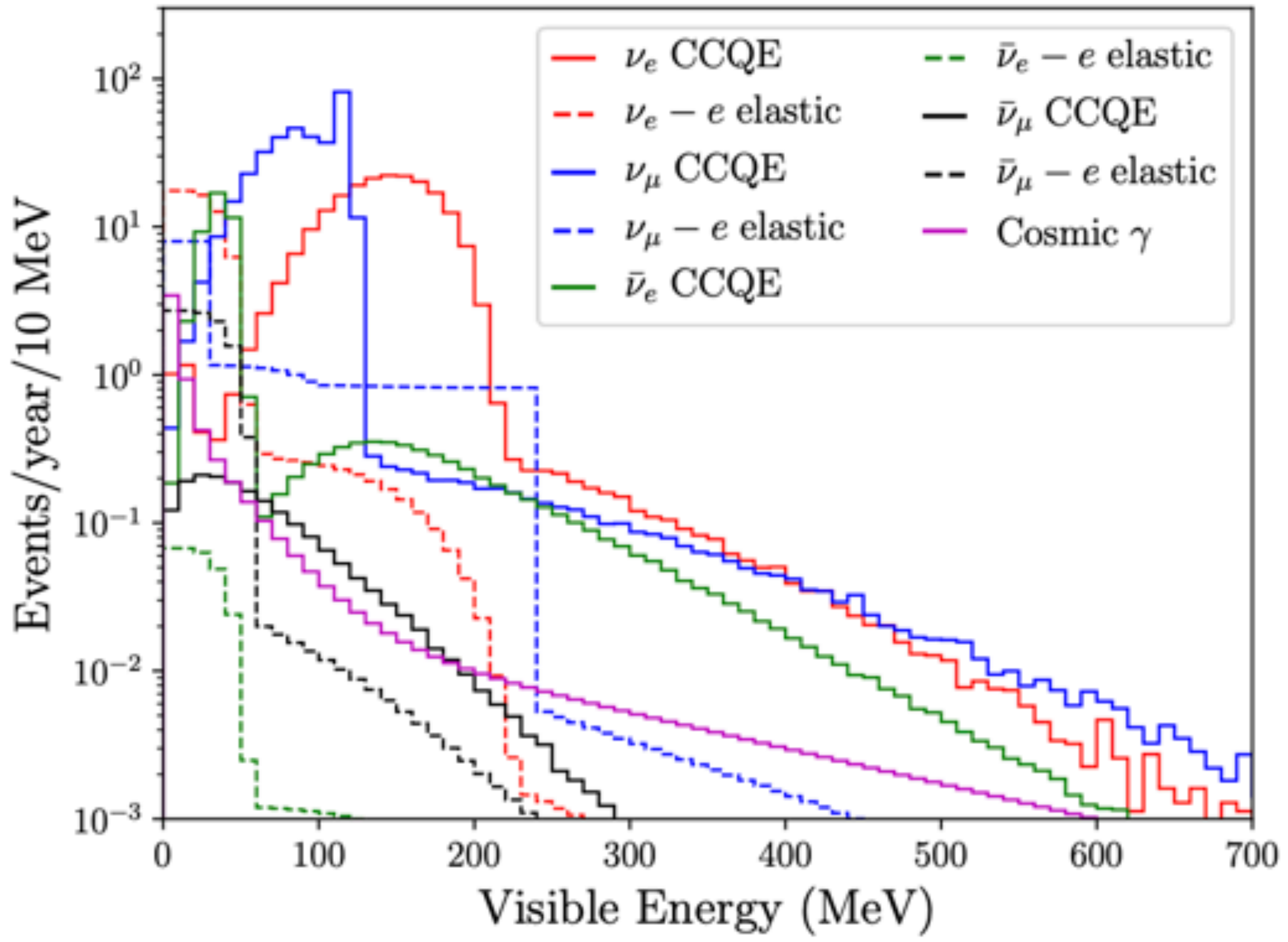


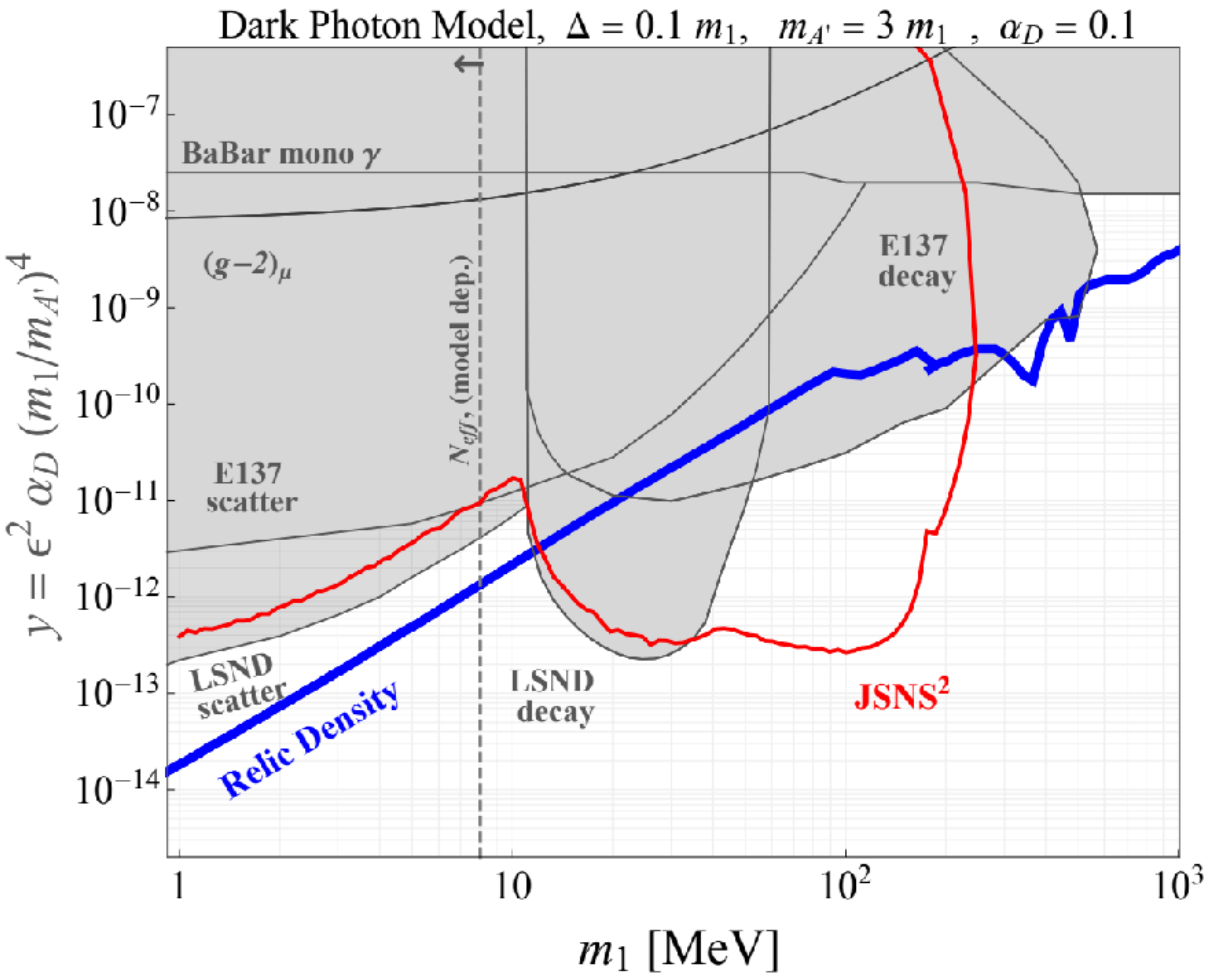


(b) Muon mixing.

Inelastic Dark Matter





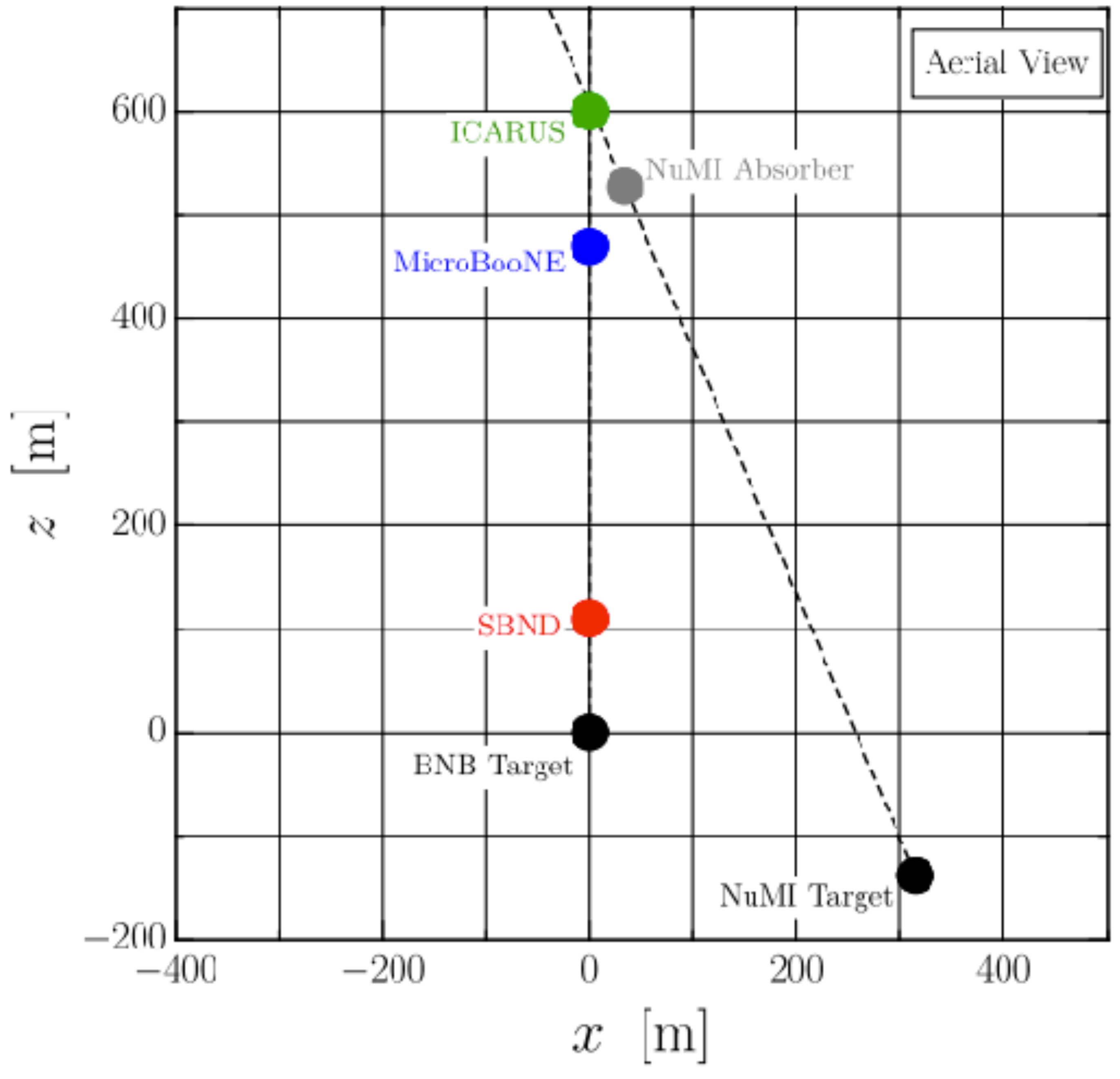


J.R. Jordan, Y. Kahn, G. Krnjaic, M. Moschella, and J. Spitz. arXiv:1806.05185

MicroBooNE and KDAR from NuMI absorber

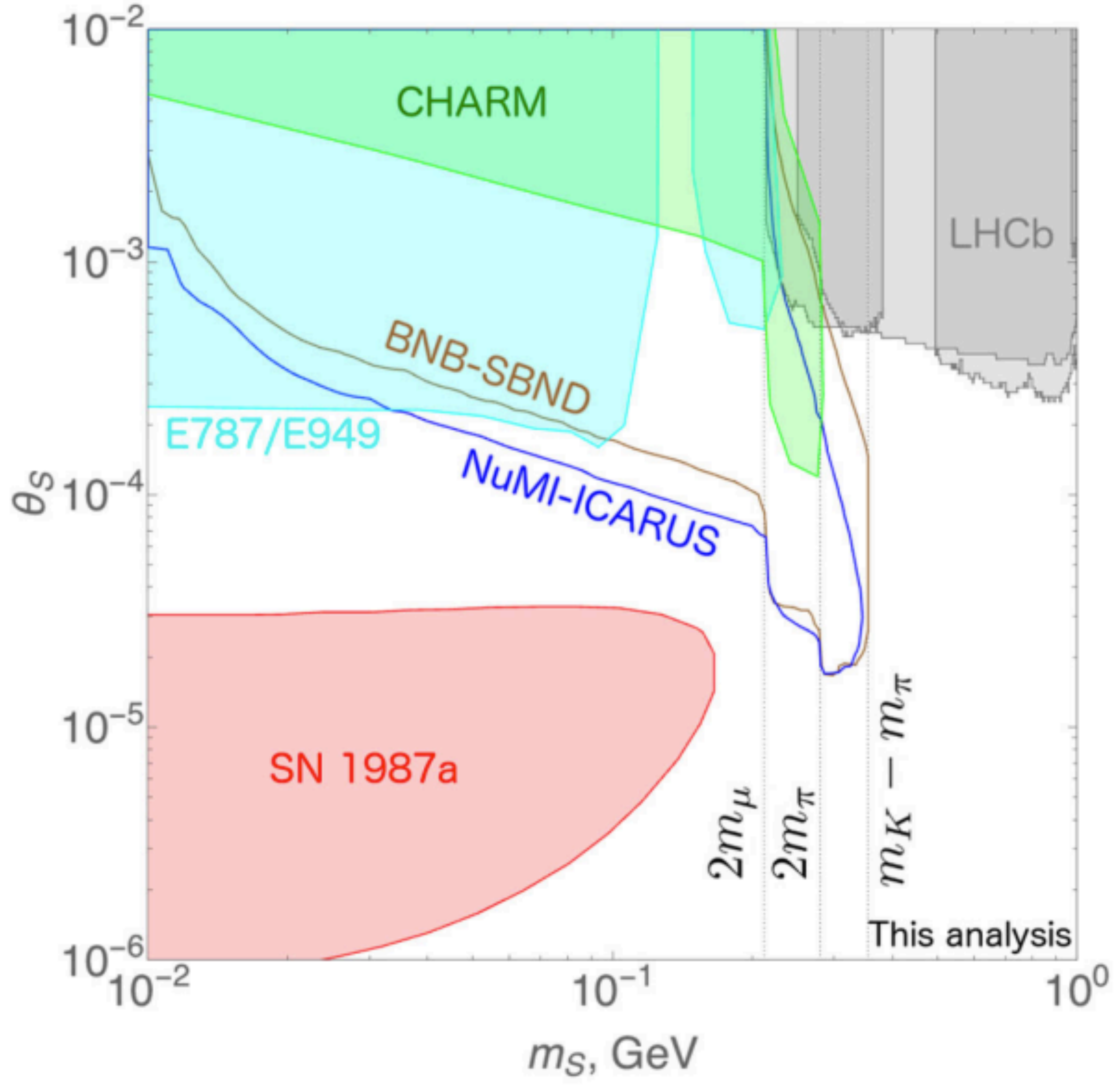
Fermilab’s fortunate coincidence:

SBN program detectors are close to a KDAR source:

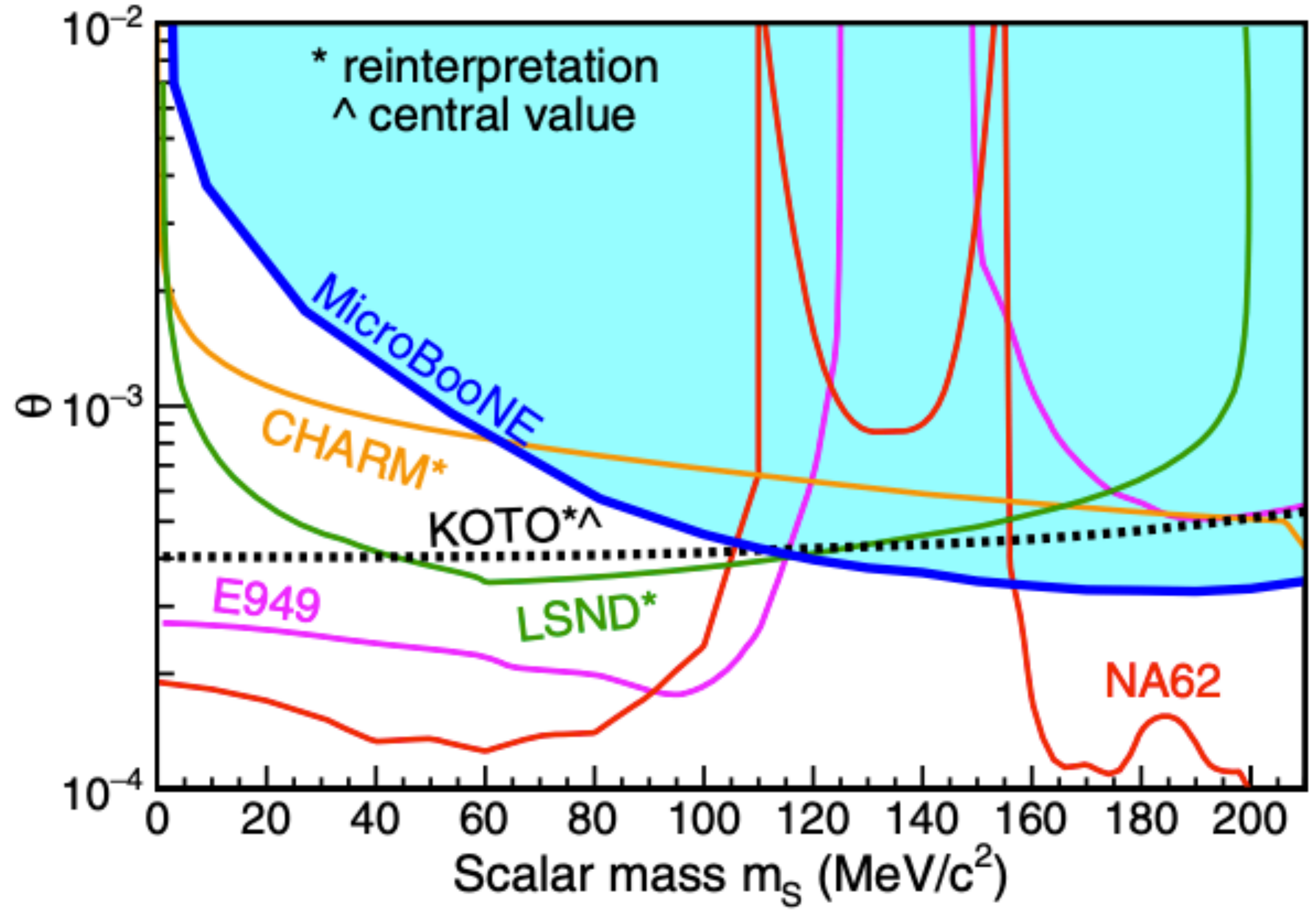


About 0.13 KDAR per NuMI POT.

Batell, Berger, Ismail PRD.100.115039



MicroBooNE PRL.127.151803



https://arxiv.org/pdf/2204.04575

TABLE I. Parameters of subsystems for CEvNS detection.

Nuclear target	Detector Technology	Target Mass (kg)	Distance from source	Energy threshold (keV†)	Deployment dates
CsI[Na]	Scintillating crystal	14	20 m	5	2015-2019
Ar	Single-phase LAr⋆	24	29 m	20	2016-2021
Ge	HPGe PPC‡	18	22 m	<5	2022
NaI[Tl]	Scintillating Crystal	3500	22 m	13	2022
Ar	Single-phase LAr⋆	750	29 m	20	2025
Ge	HPGe PPC‡	50	22 m	<5	2025
CsI	CsI+SiPM arrays at 40 K	10∼15	20 m	1.4	2025

Finished Planned, ⋆liquid argon, ‡p-type point-contact, †nuclear recoil energy, approximate threshold

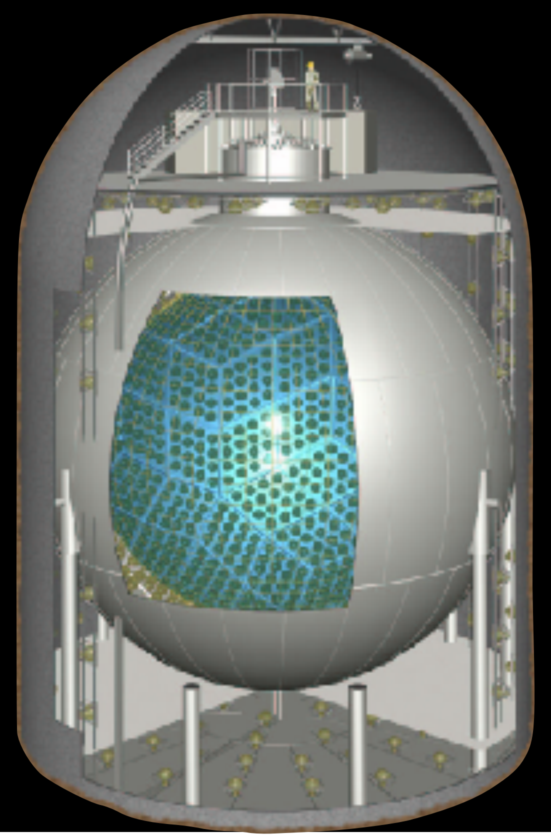
TABLE II. Additional detectors that broaden the physics reach of COHERENT.

Name	Detector Technology	Main purpose	Deployment dates
NaIvE	185 kg NaI[Tl] crystals	Measure ν_e+ I CC cross section & beam-related backgrounds	2016 - present
MARS	scintillation panels interleafed with Gd-painted foils	Measure beam-related neutrons in Neutrino Alley	2017 - present
NIN cubes	liquid scintillator cells in lead and iron shields	Measure neutrino-induced neutrons (NIN) in lead & iron	2015 - present
D_2O	heavy water Cherenkov detector	Measure neutrino flux precisely & ν_e+O inelastic cross section	2022
LAr TPC	liquid argon time-projection chamber	Measure ν_e+Ar inelastic cross section	2025

Current Planned

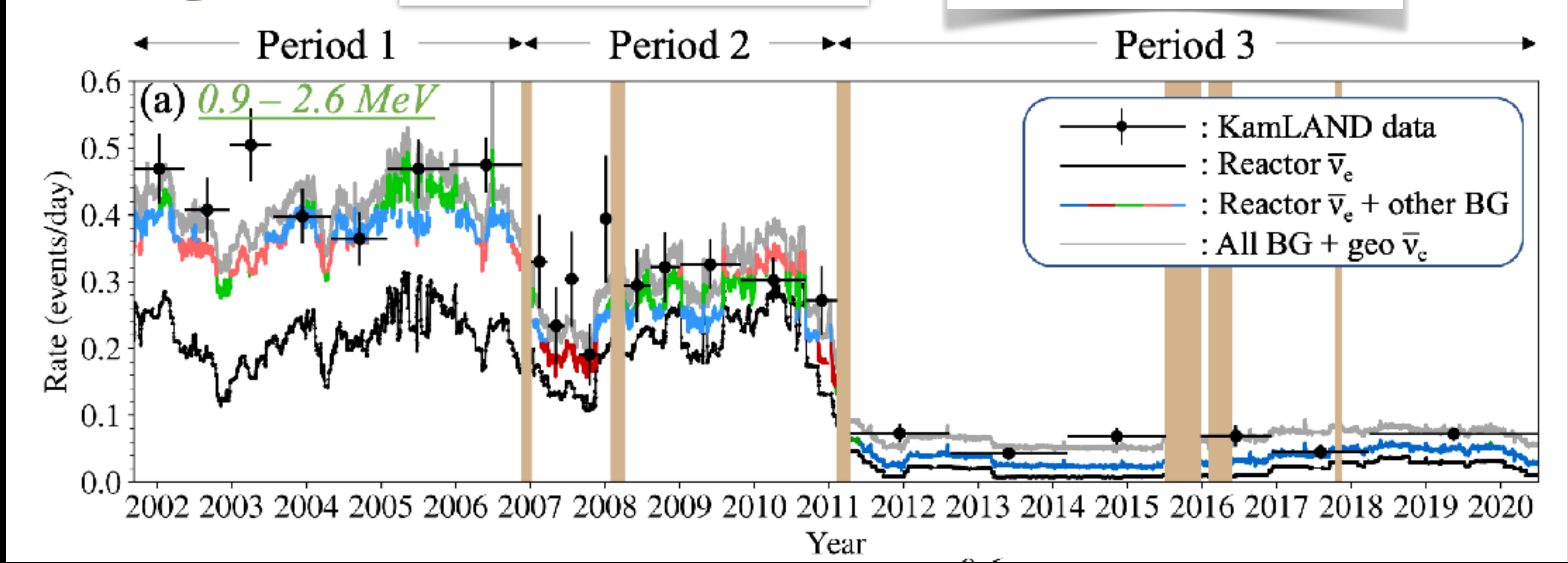
Exothermic sources have their drawback…

Impact of the reactor sutdown in Japan on the KamLAND neutrino experiment



Tōhoku Tsunami Fukushima disaster

Purification periods



KamLAND coll. 10.1029/2022GL099566