Fundación "la Caixa"

SHiNESS: search for hidden neutrinos at the ESS

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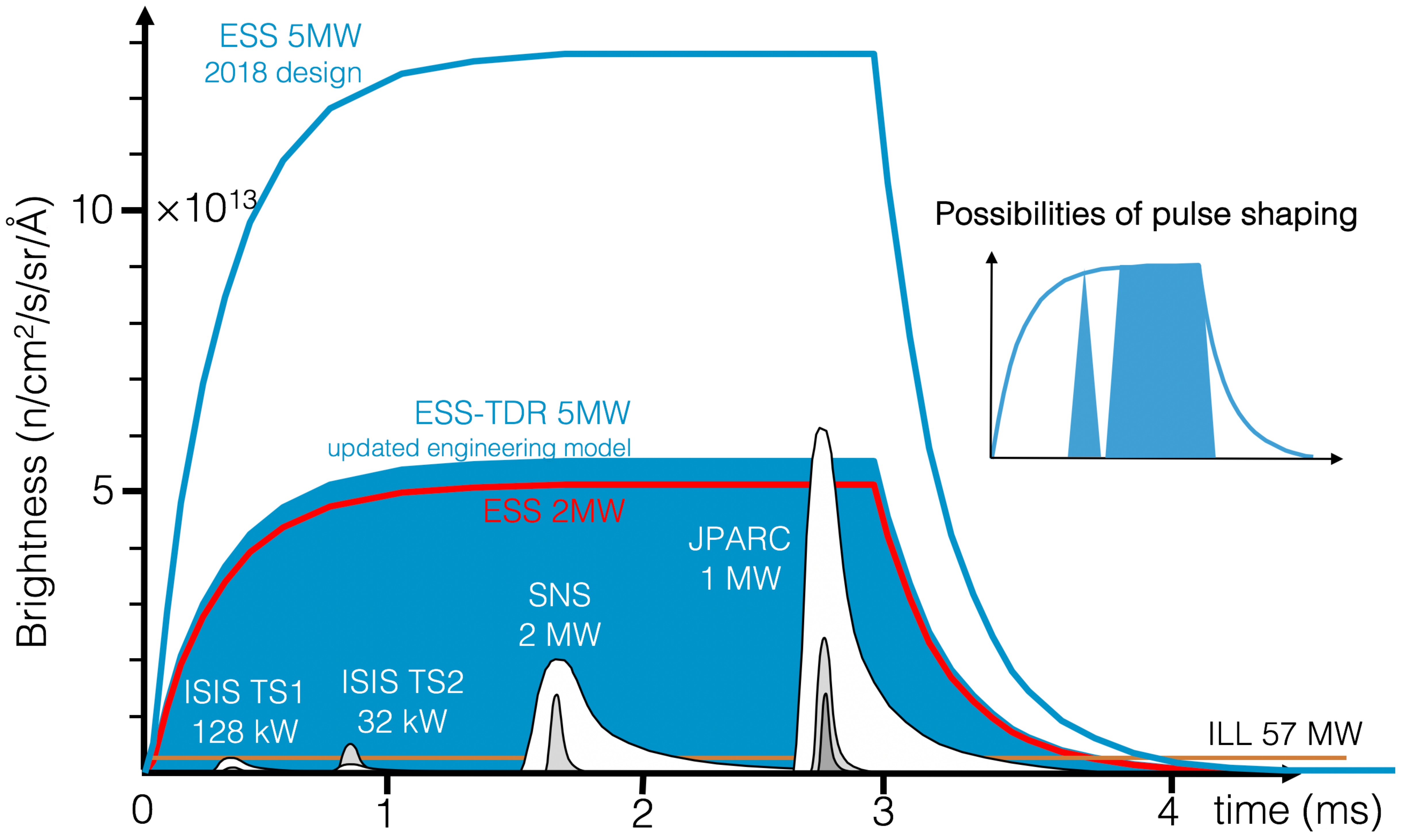
The European Spallation Source

SHiNESS

- The ESS will produce the **most intense neutron beam in the world** via nuclear spallation.
- A proton beam will impinge on a rotating target wheel made of Tungsten bricks:
  - **2 GeV energy**
  - 14 Hz rate
  - 2.8 ms long spills
  - 3.92×10^{-2} duty factor
- Approximately **one order of magnitude more intense** than the Spallation Neutron Source at Oak Ridge.



The ESS as a neutrino source

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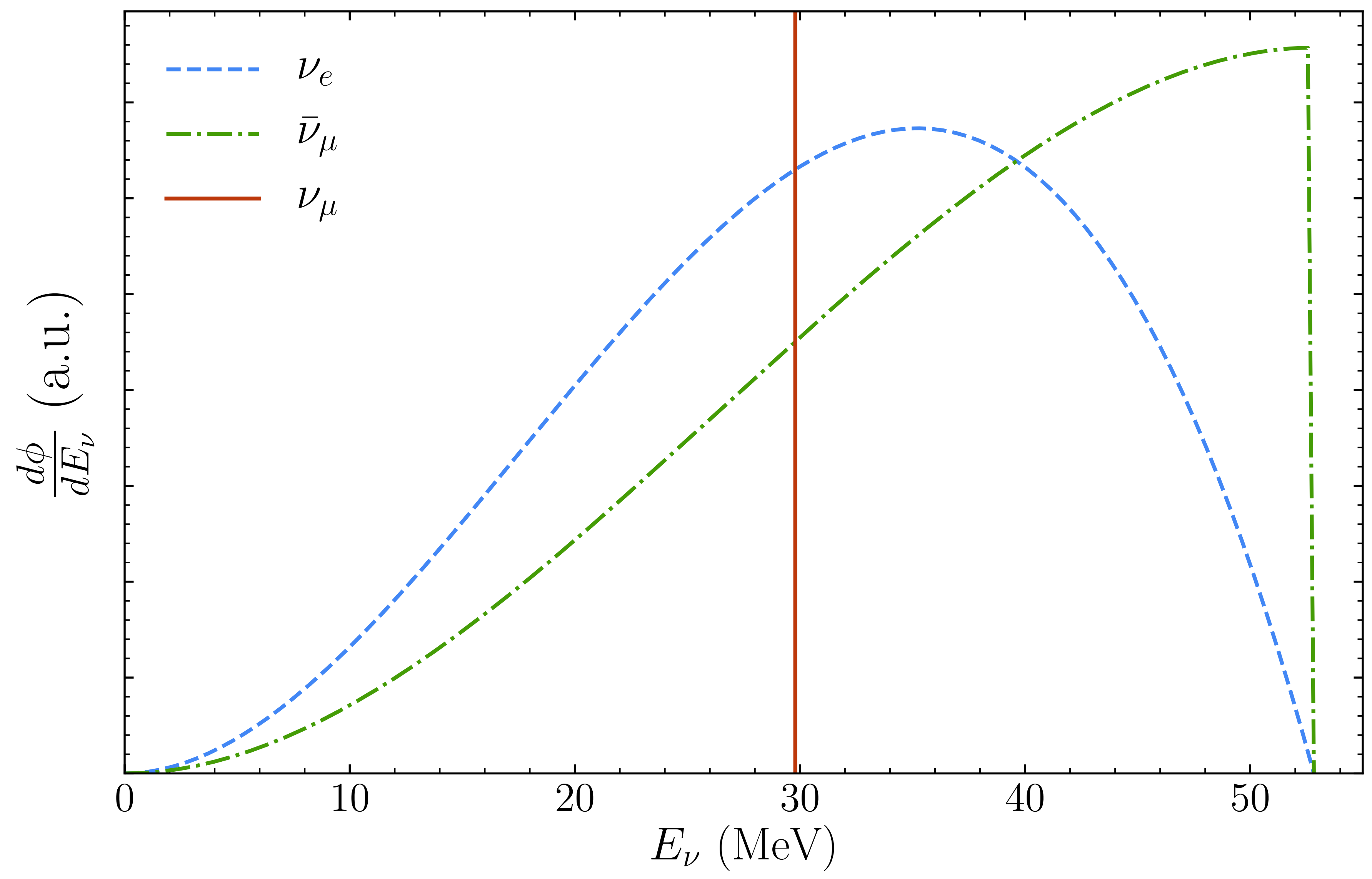
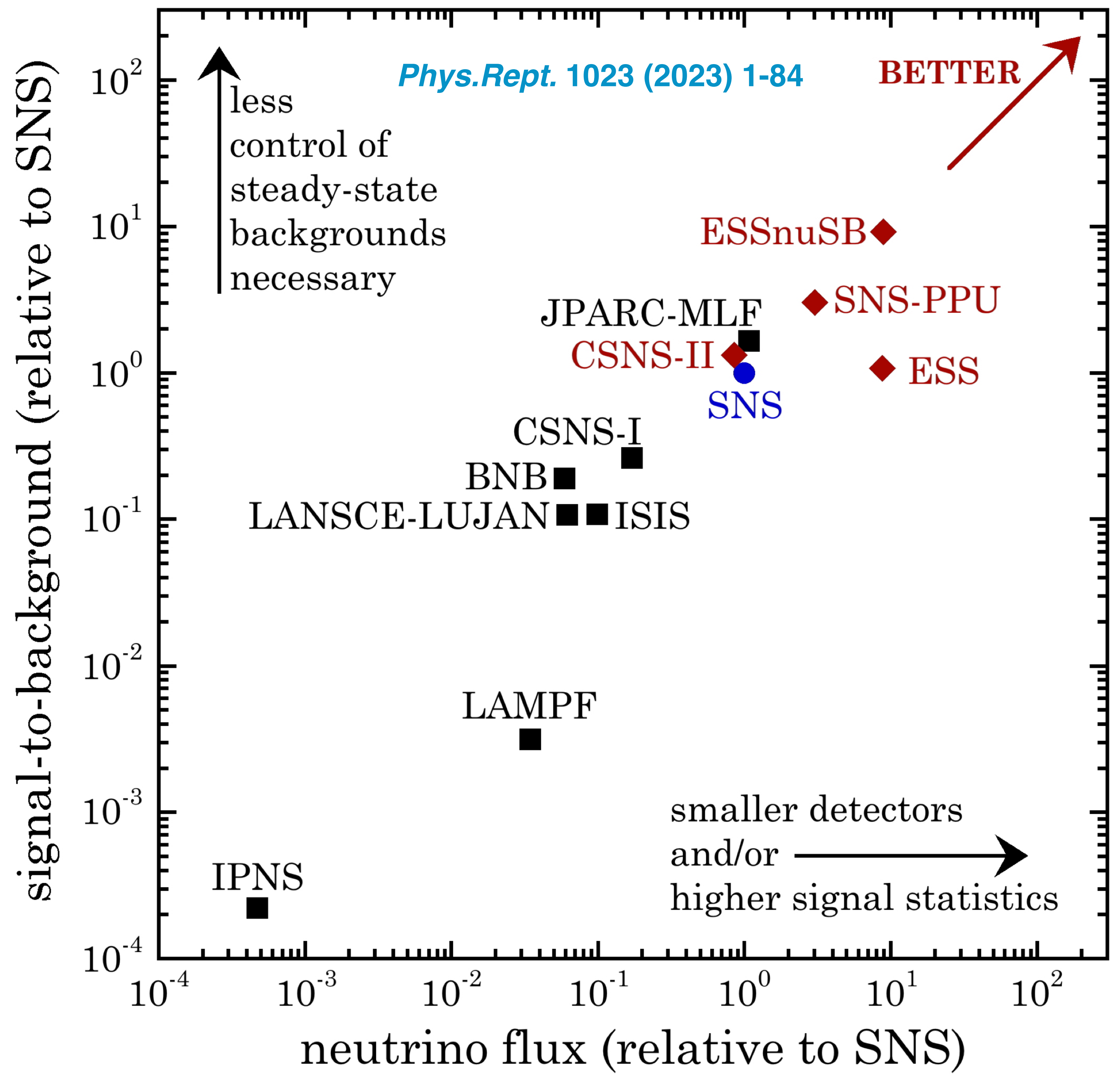
- Spallation sources produce an intense flux of neutrinos as a *byproduct* through π^+ **decay at rest** (DAR) and subsequent μ^+ decay

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

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

- The energy spectra of π^+DAR neutrinos is well known (in contrast with conventional neutrino beams), making spallation sources an excellent tool to probe for **new physics**.





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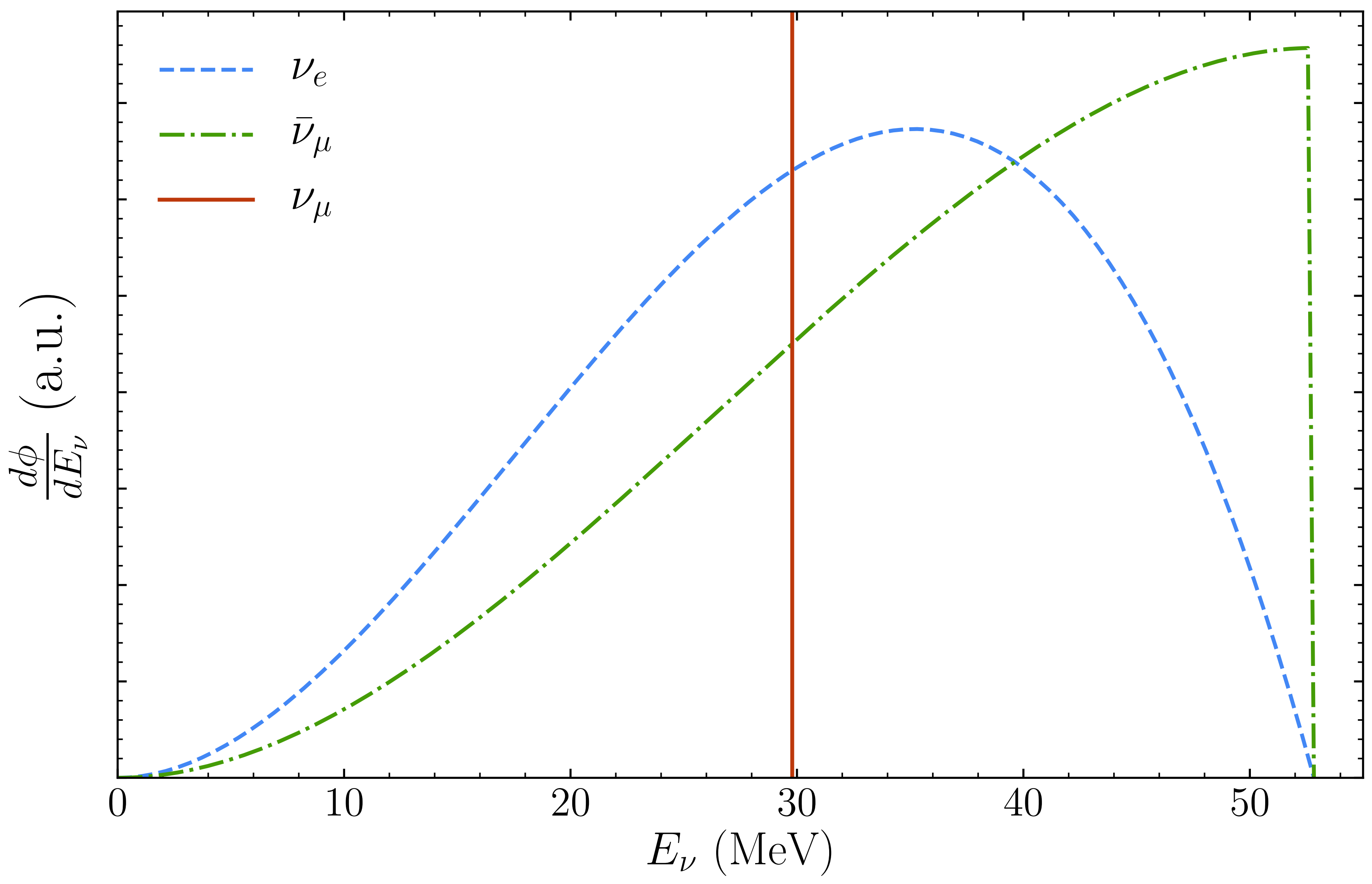

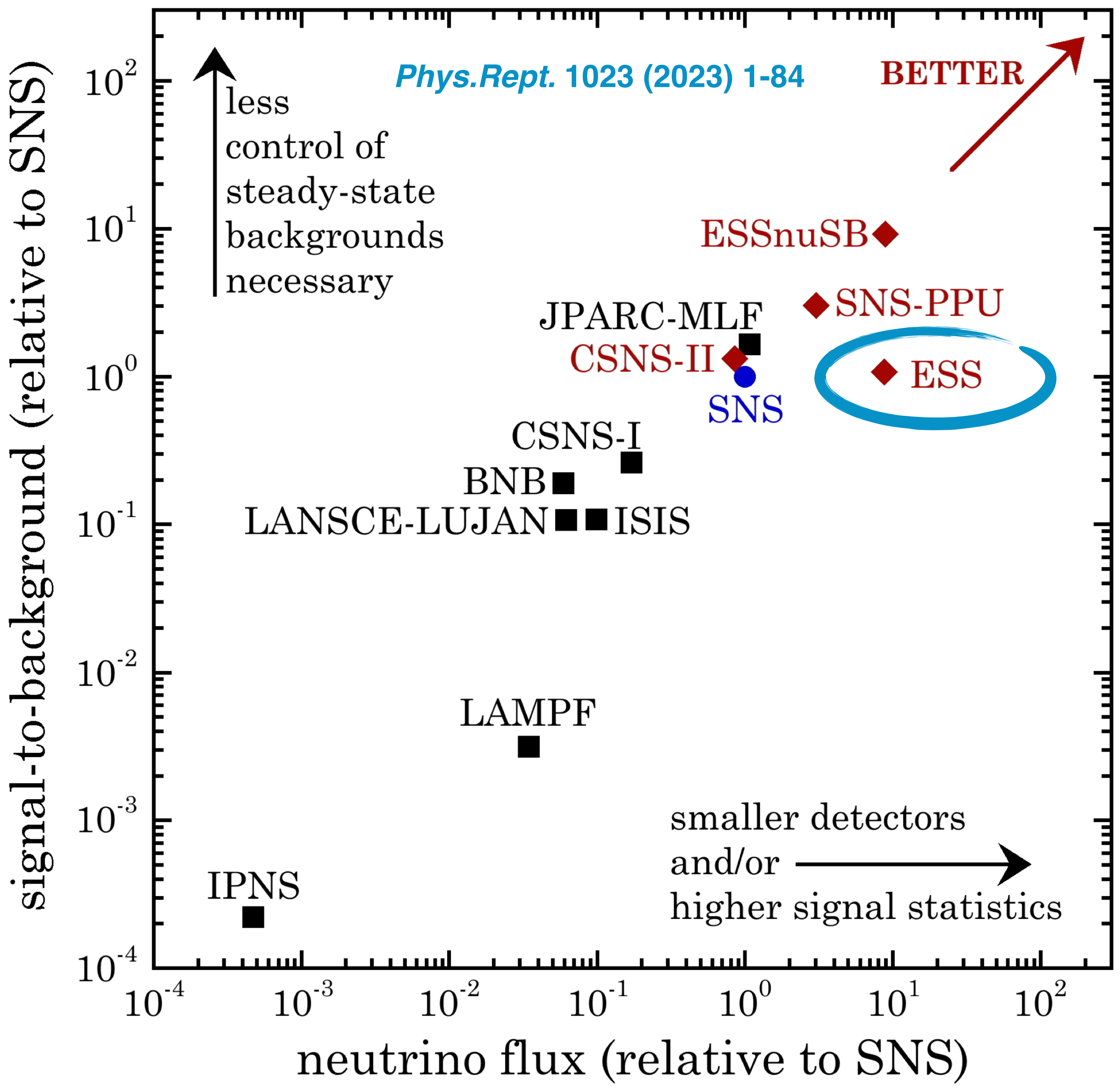

New physics at the ESS

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- Searching for **new physics at spallation sources** is not a novel idea: LSND at LAMPF, KARMEN at ISIS, JSNS^2 at J-PARC, etc.
- However, the exceptional intensity of the ESS beam allows to reach **unprecedented sensitivities** for several new physics scenarios:

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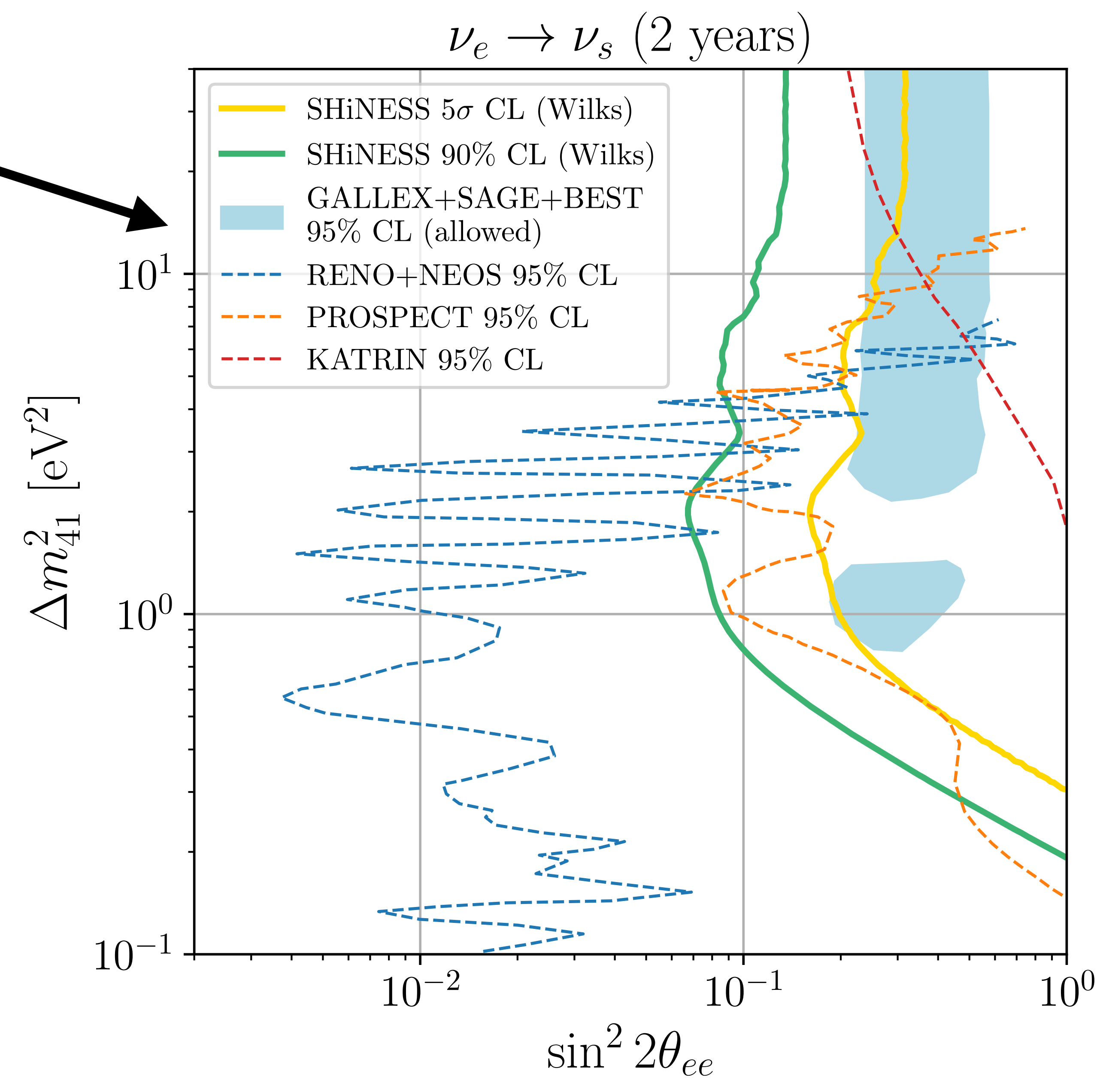
  - **Light sterile neutrino** (LSND/MiniBooNE anomaly, gallium anomaly)



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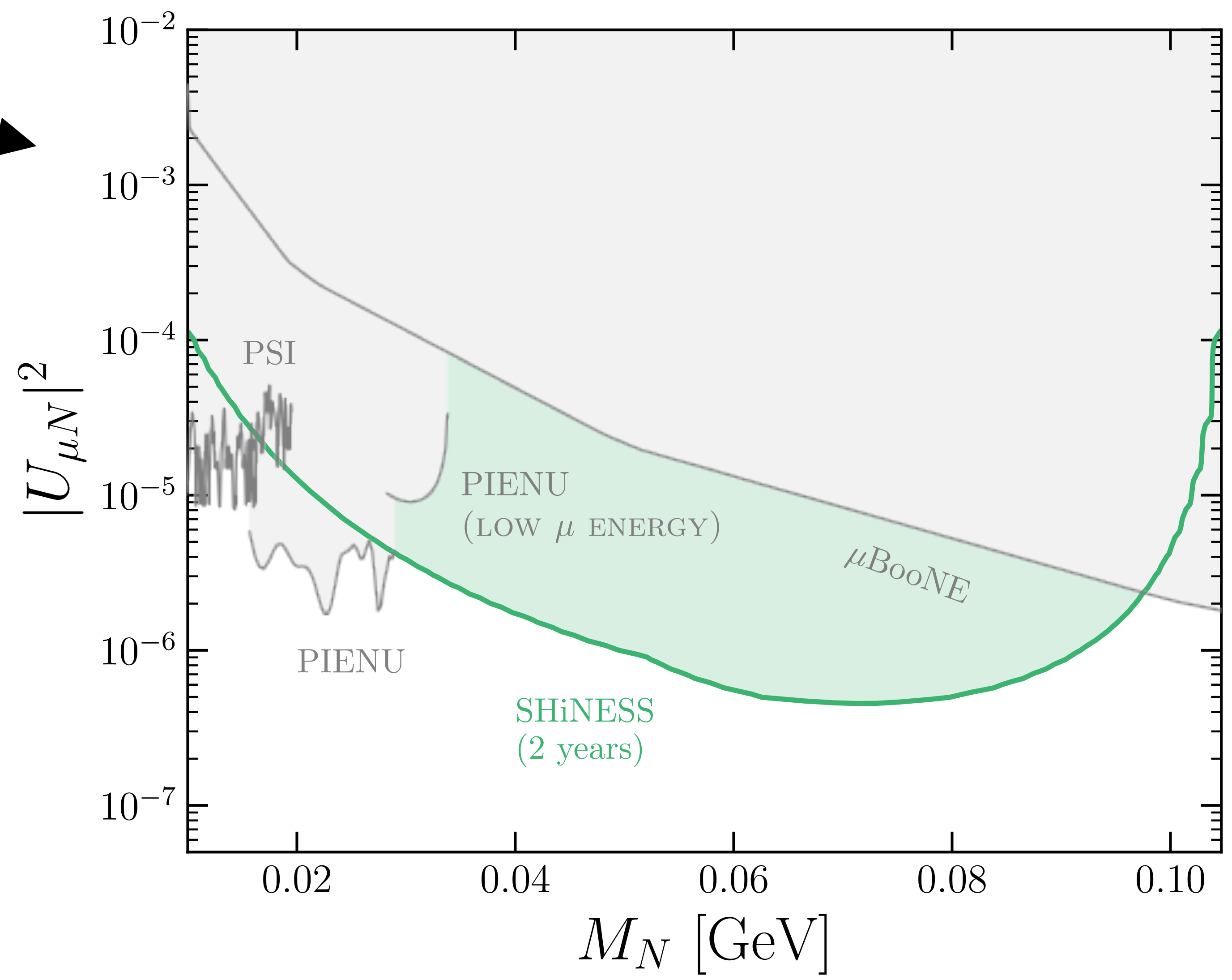

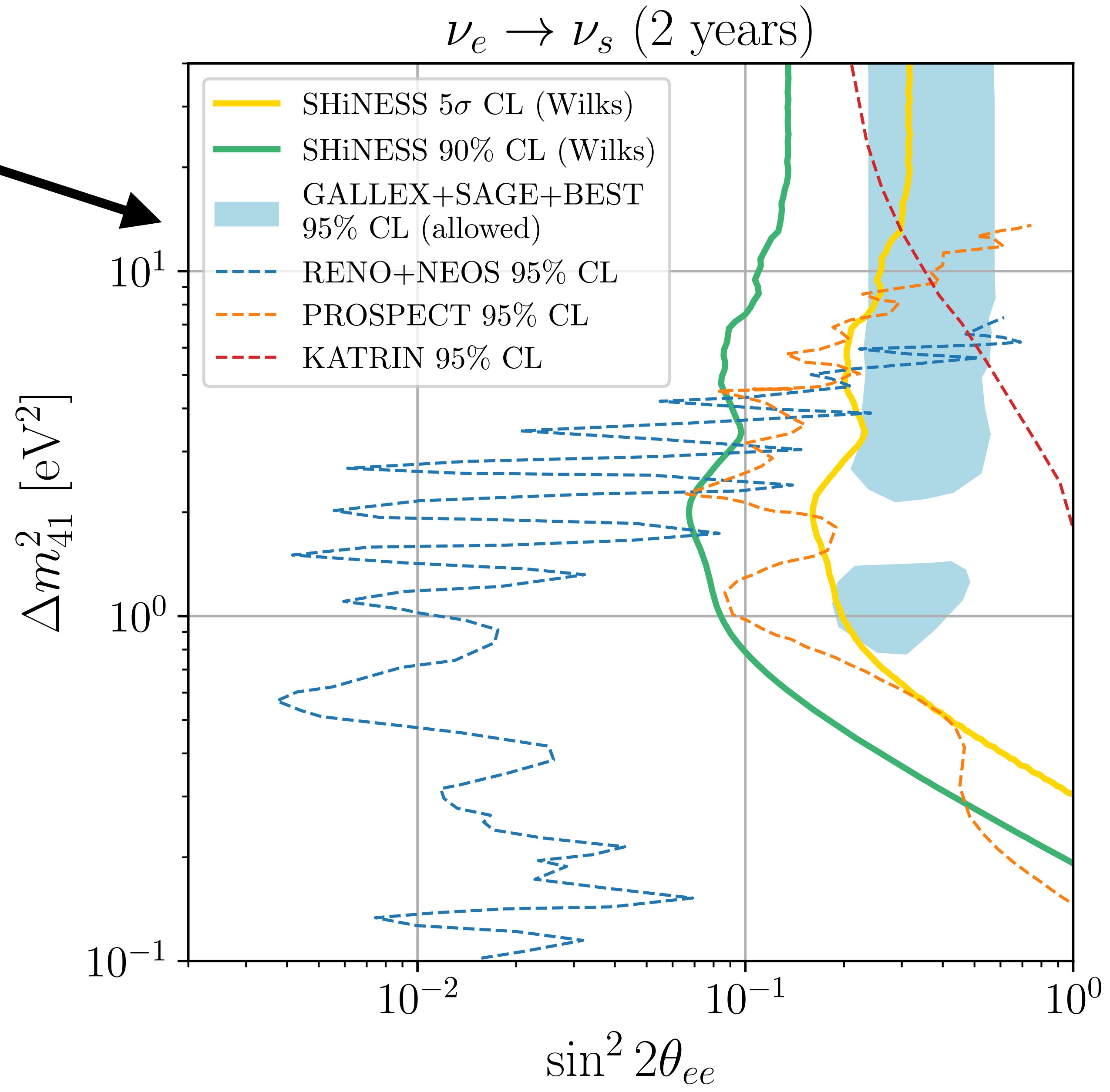

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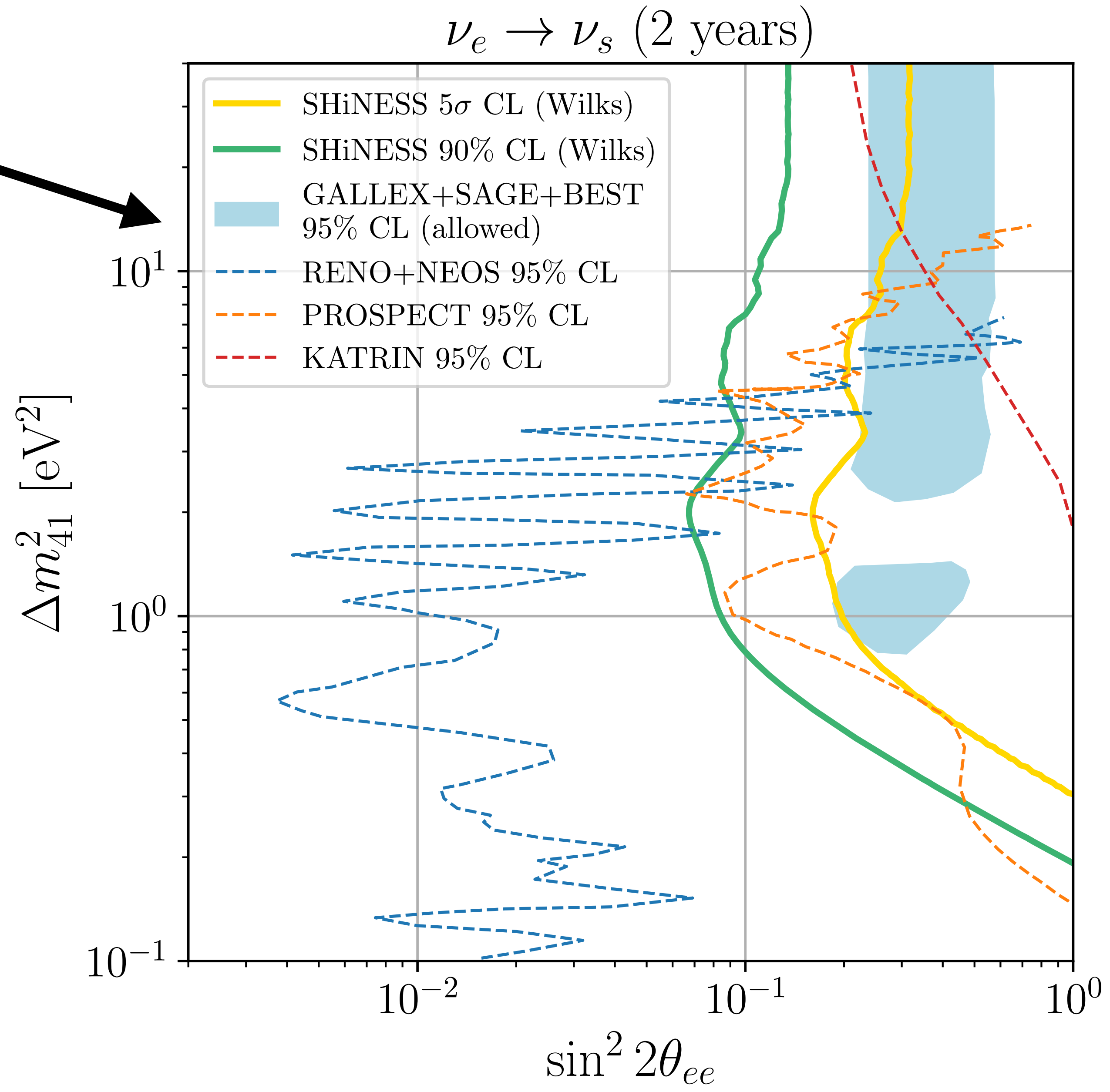
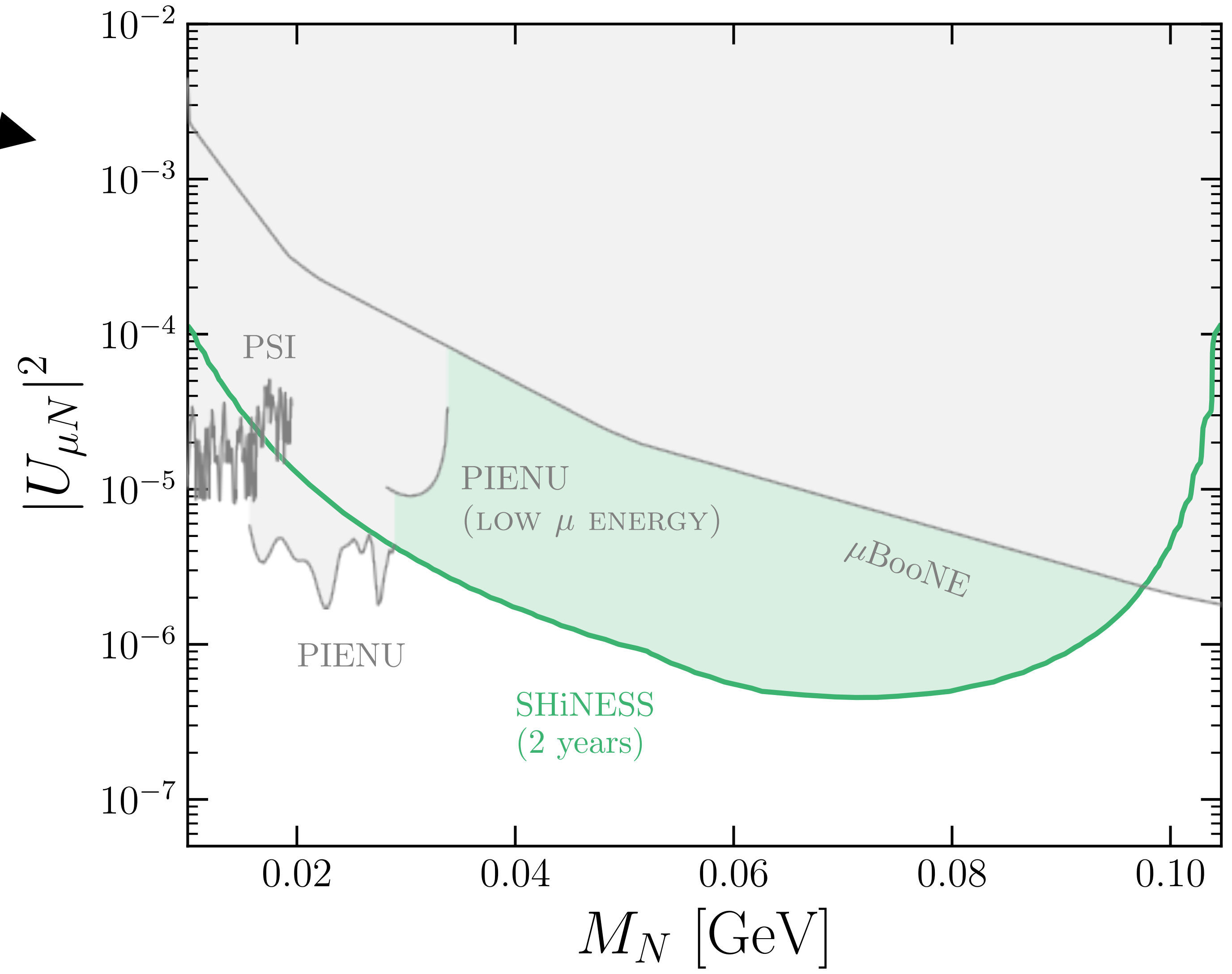
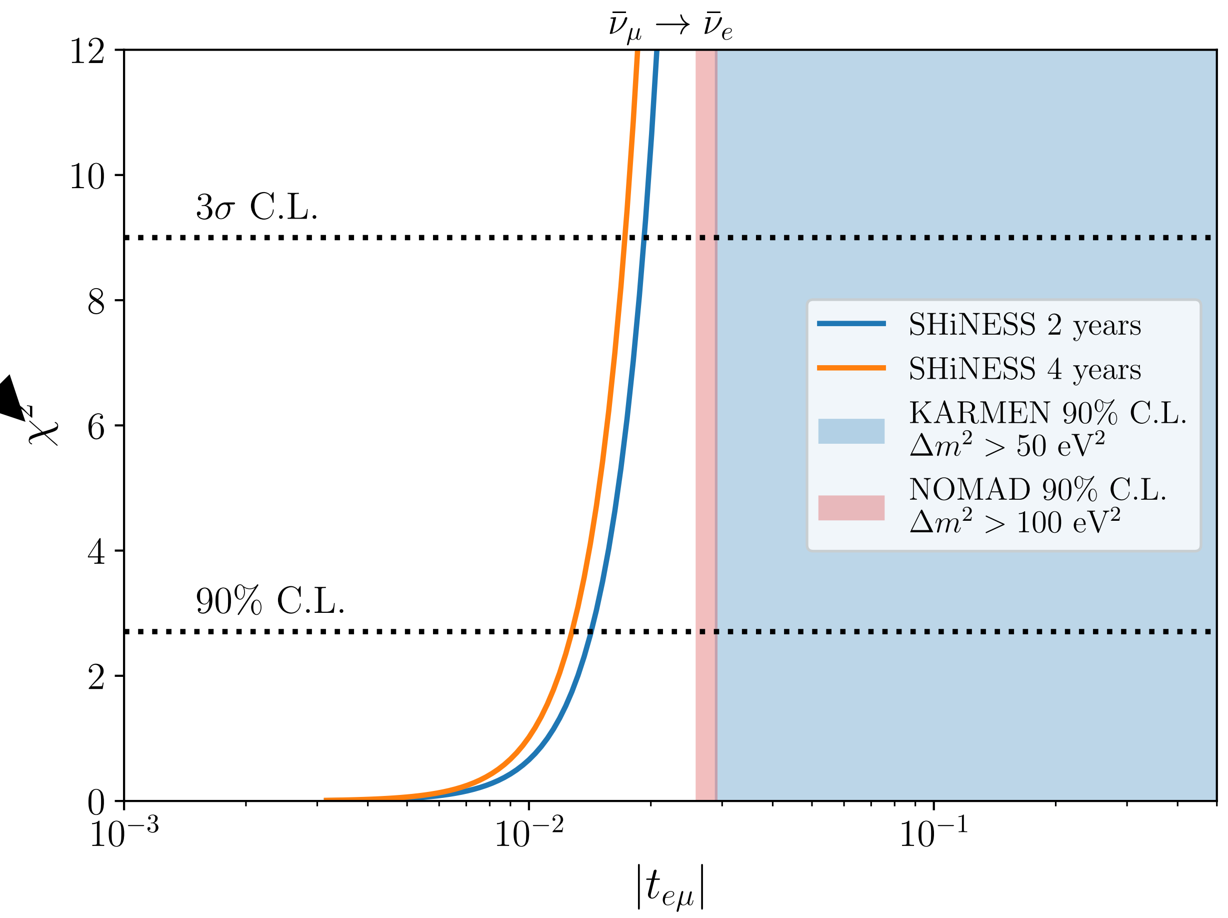
  - **Heavy neutral leptons**
  - **Neutrino mixing matrix unitarity**

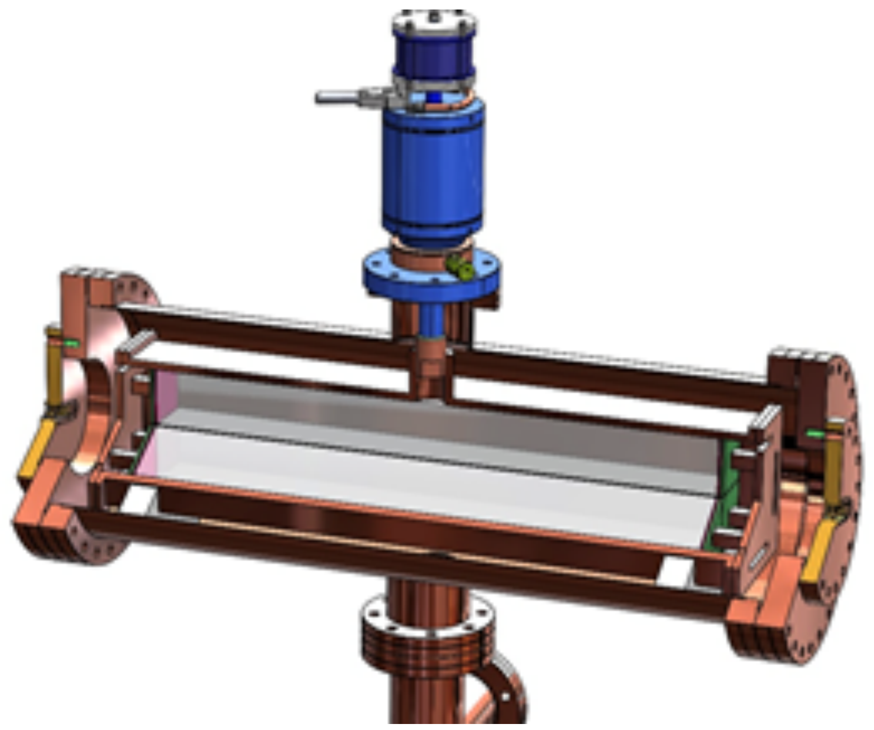




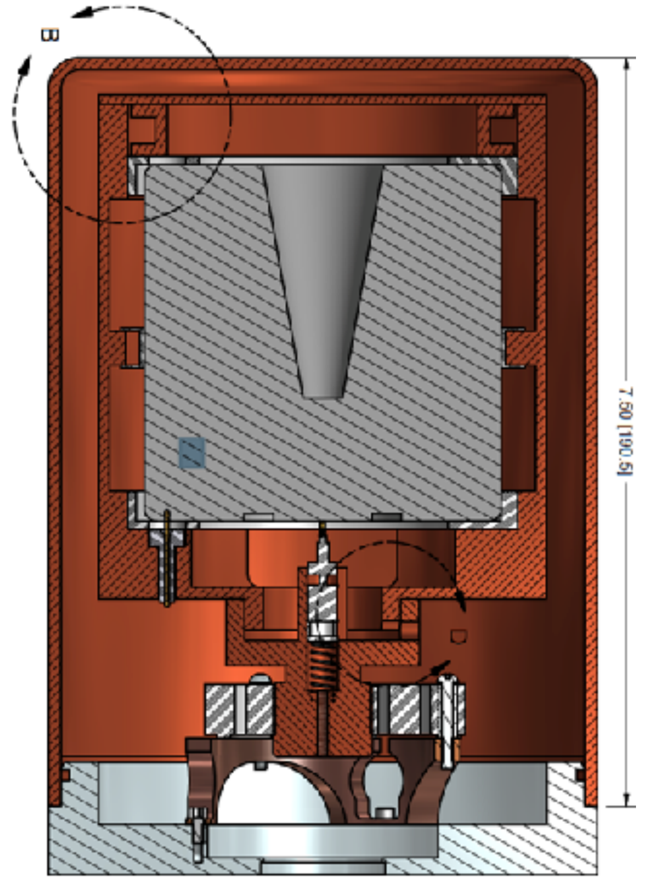


Particle physics at the ESS

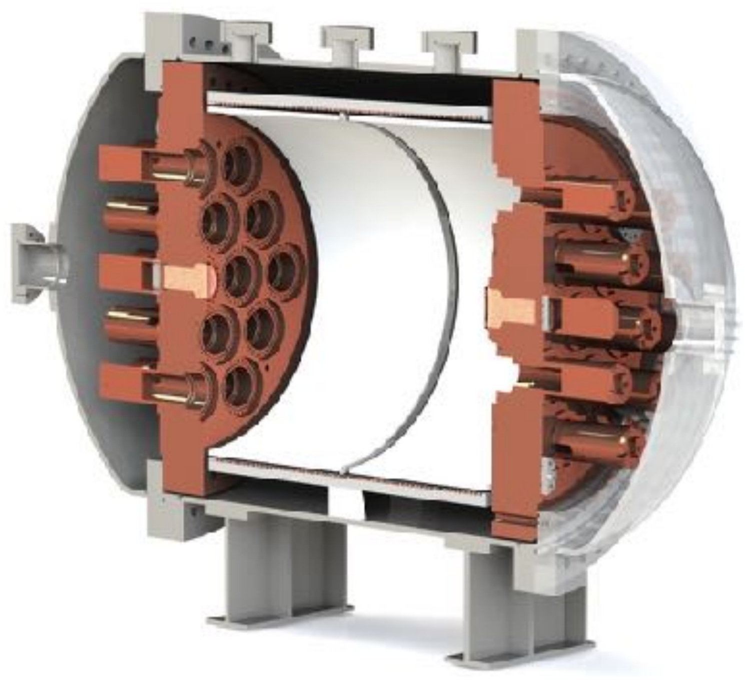
- Although the ESS is a facility focused on spallation neutrons, a **comprehensive particle physics program** has been proposed.
- In particular, our group at DIPC is focused on the **detection of coherent elastic neutrino-nucleus scattering** (CEvNS) with three different technologies (cryogenic CsI, p-type point contact Ge, high pressure gas TPC).
- **Clear synergy with a π^+ DAR experiment**: having a complementary neutrino measurement can reduce the flux uncertainty (which is ~10% at SNS).



Cryogenic undoped CsI



p-type point contact Ge



high pressure gas TPC

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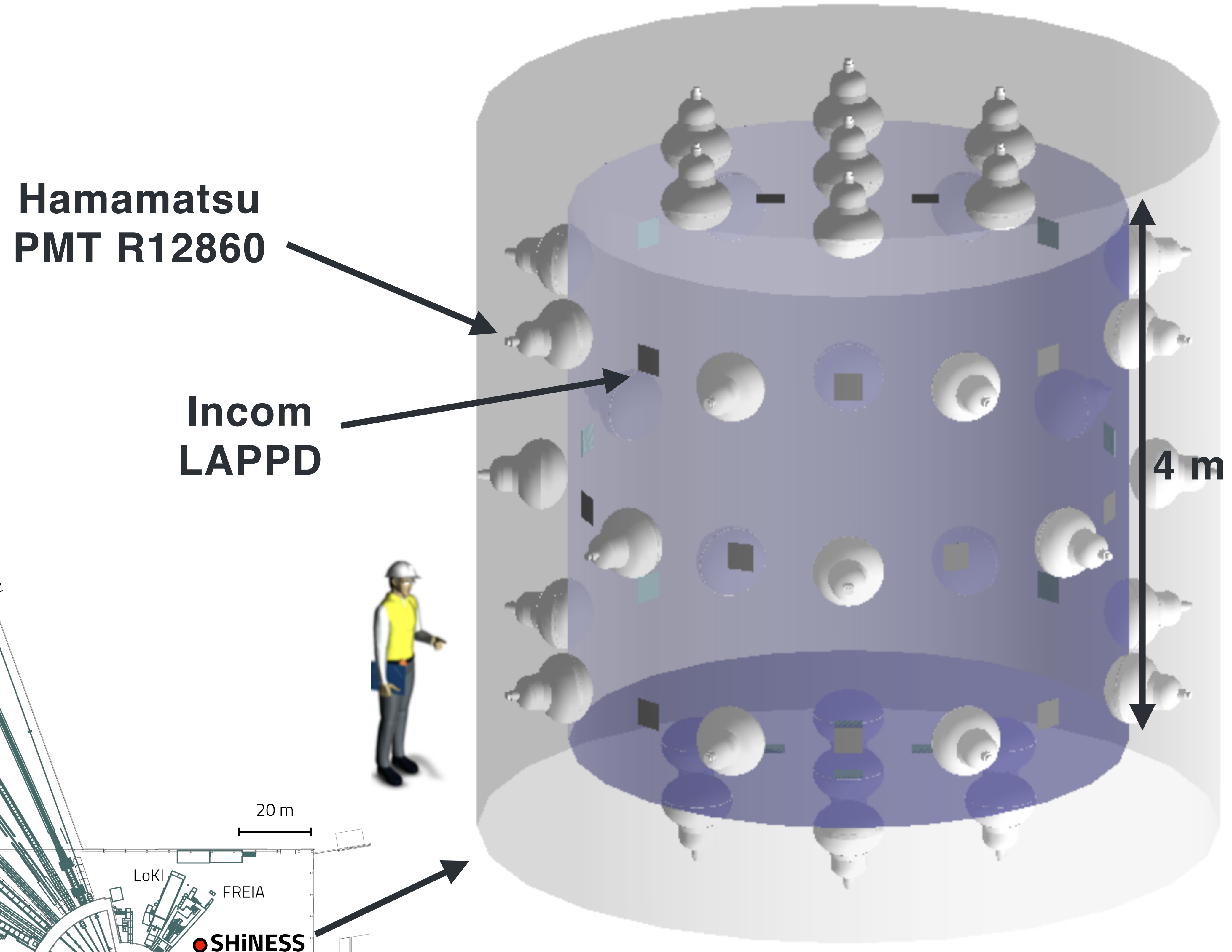
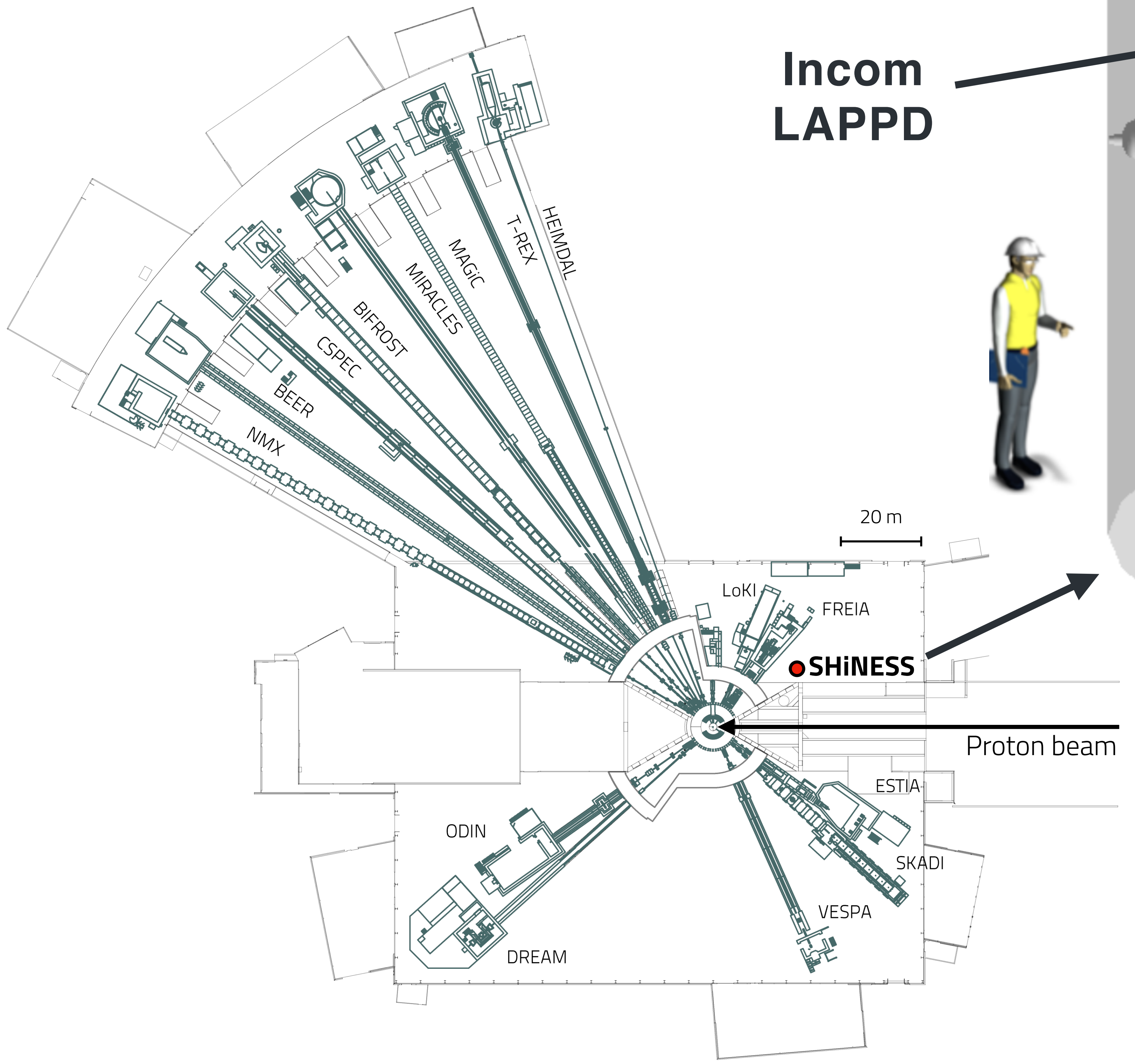
European Research Council
Established by the European Commission

SHiNESS proposal

JHEP 03 (2024) 148 [arXiv:2311.18509 [hep-ex]]

- We propose a **liquid scintillator tank** (42 ton active volume) to detect neutrino interactions and HNL decays.
- Detector is placed **25 m far from the beam target** off-axis in the backward direction (to suppress backgrounds).
- Light is detected by **large-area PMTs** and **Incom LAPPDs**, which allow to distinguish between Cherenkov and scintillation, **enabling directionality**.





Detector performances

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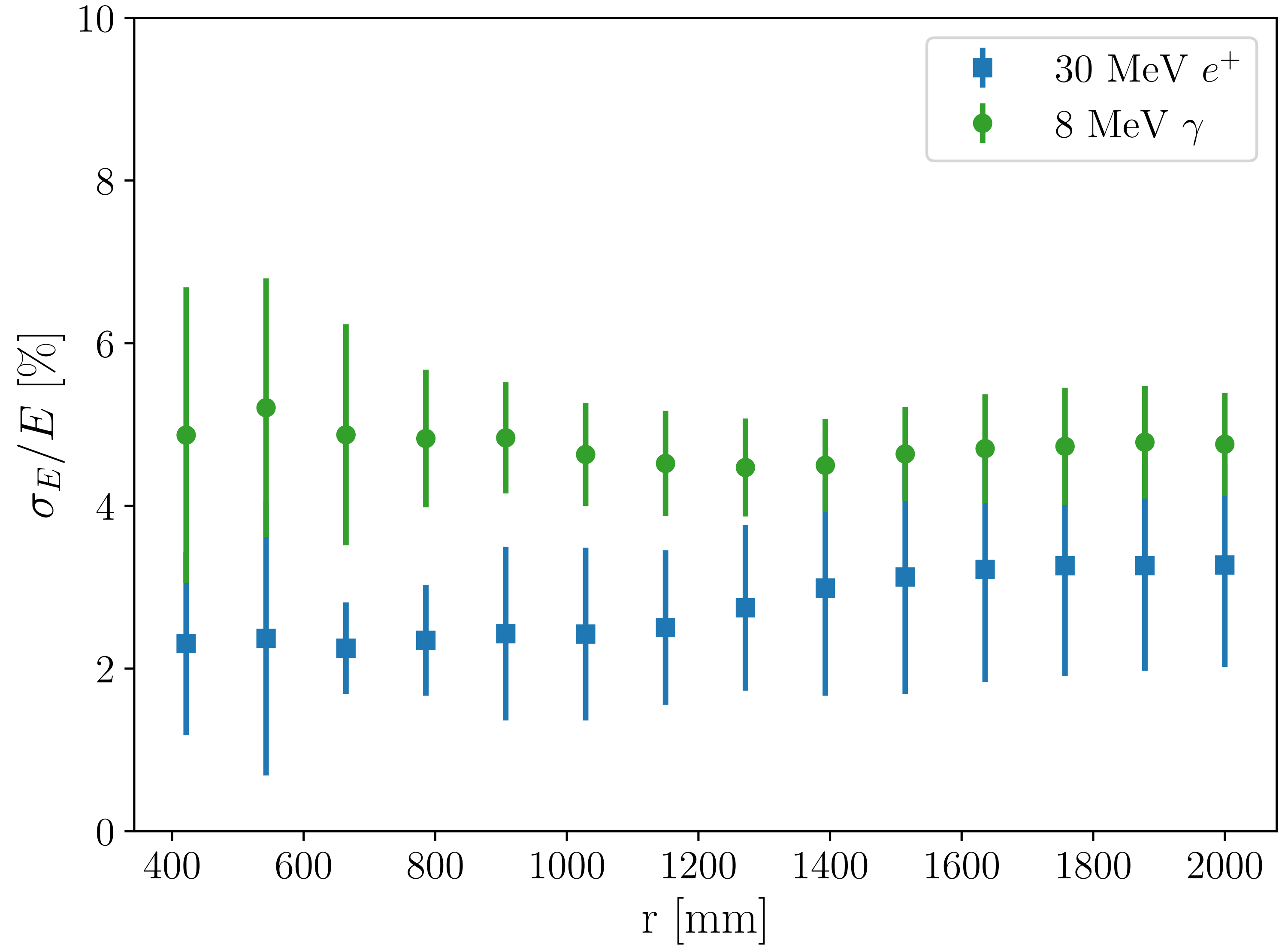
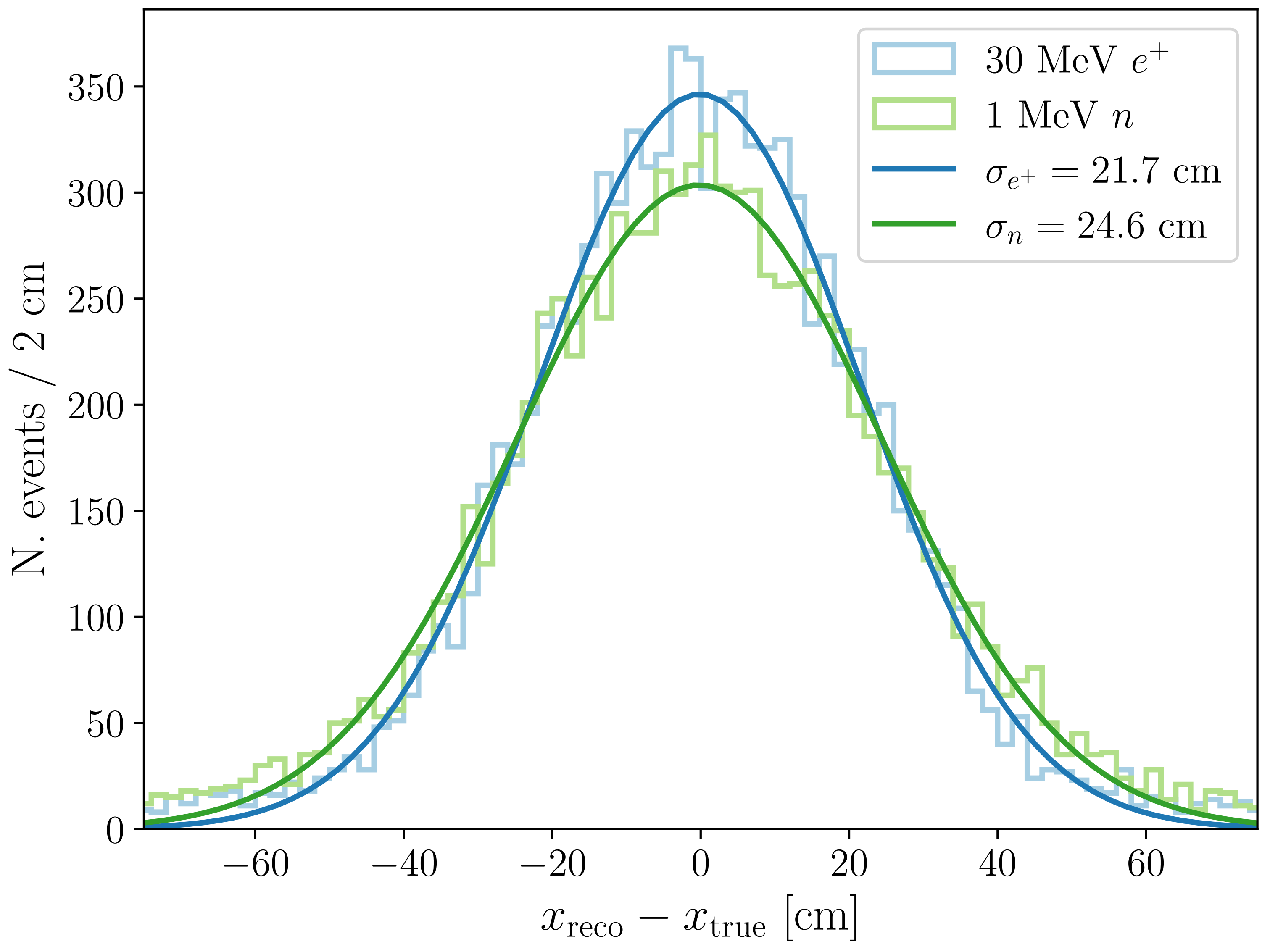
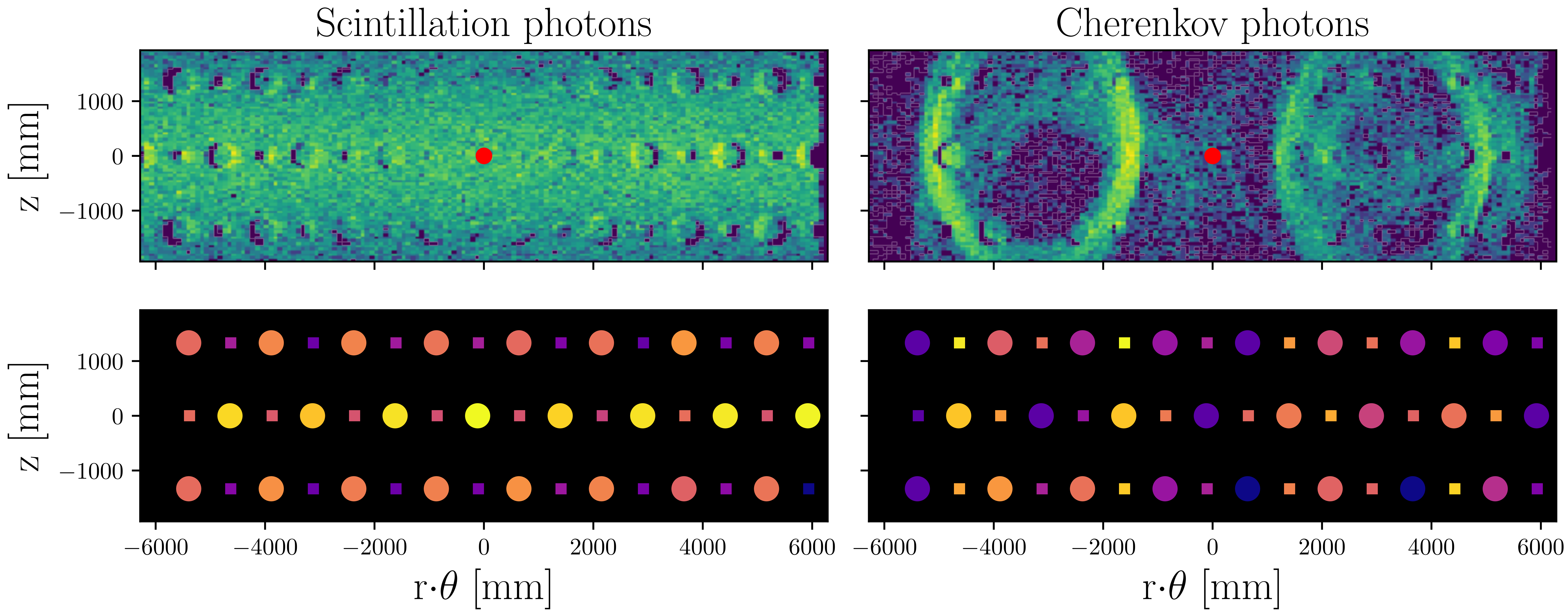
- The baseline designs includes a 42-ton tank filled with a **LAB/PPO cocktail**, proving a good light yield (~11,000 photons/MeV) and a long attenuation length (14 m at 430 nm). Largely used in neutrino physics (SNO+, RENO, etc.)
- **Gadolinium loading** to enhance neutron absorption (useful for inverse beta decay detection). Solution adopted by Daya Bay.
- Better than **5% energy resolution** for O(10 MeV) electrons.
- Vertex resolution **only with PMTs ~20 cm**.





Scintillation/Cherenkov discrimination

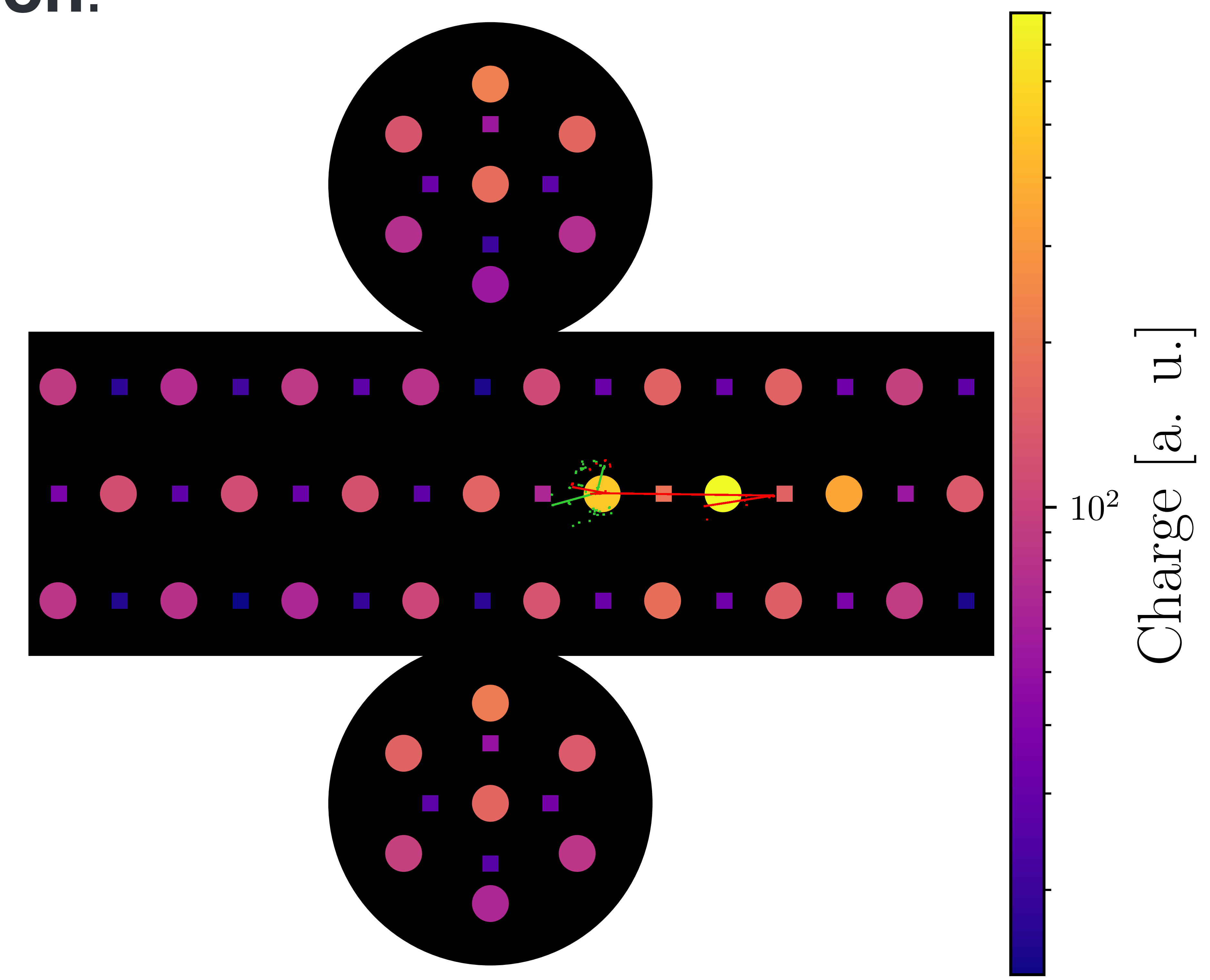
- **Scintillation photons** are abundant and allow to measure the **energy** of the event.
- However, they are produced ~isotropically and with a certain emission time constant, giving **no information on the directionality**.
- **Cherenkov photons**, on the other hand, are emitted **promptly** and **along the direction** of the particle, producing the typical Cherenkov rings.

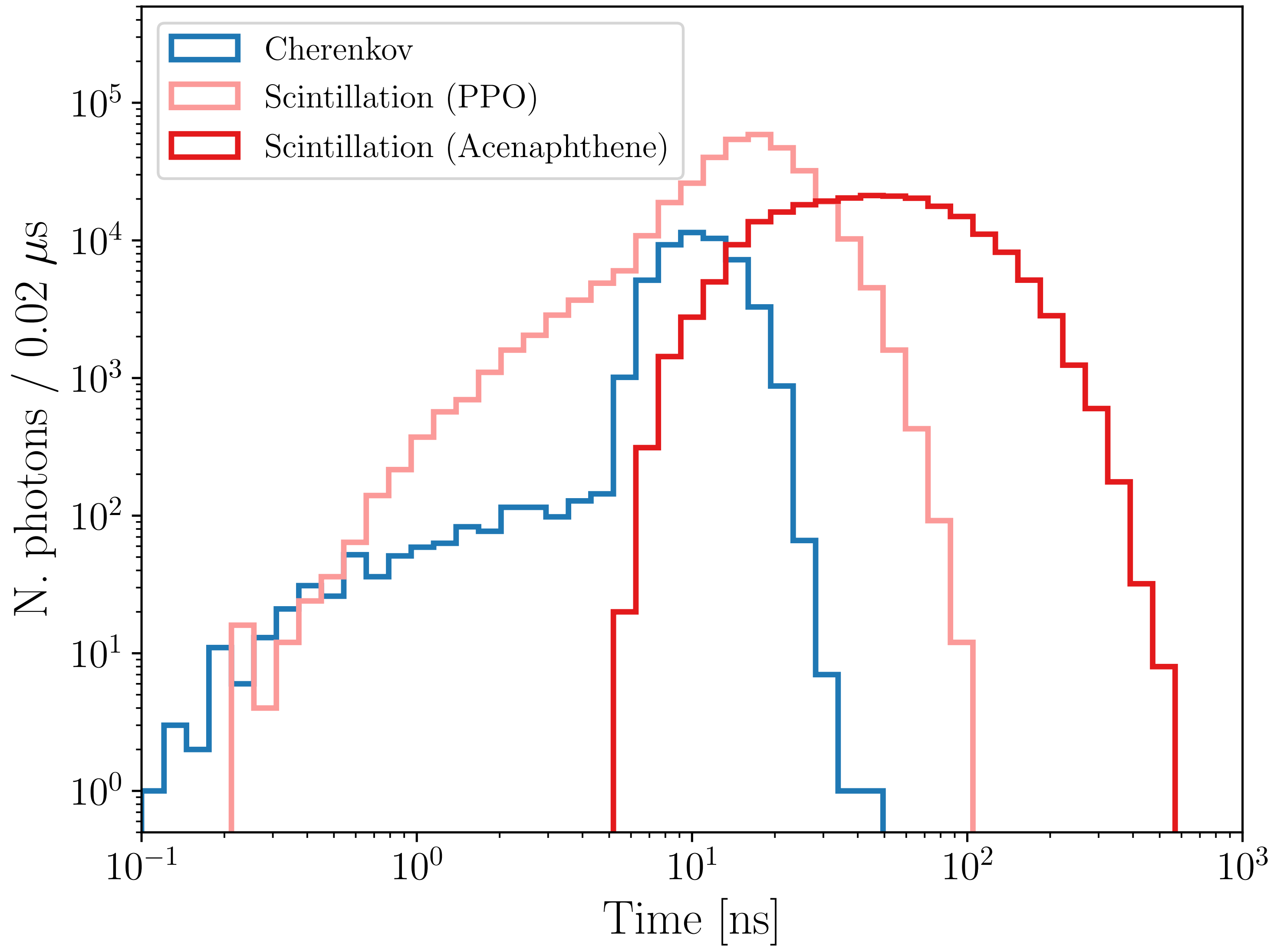


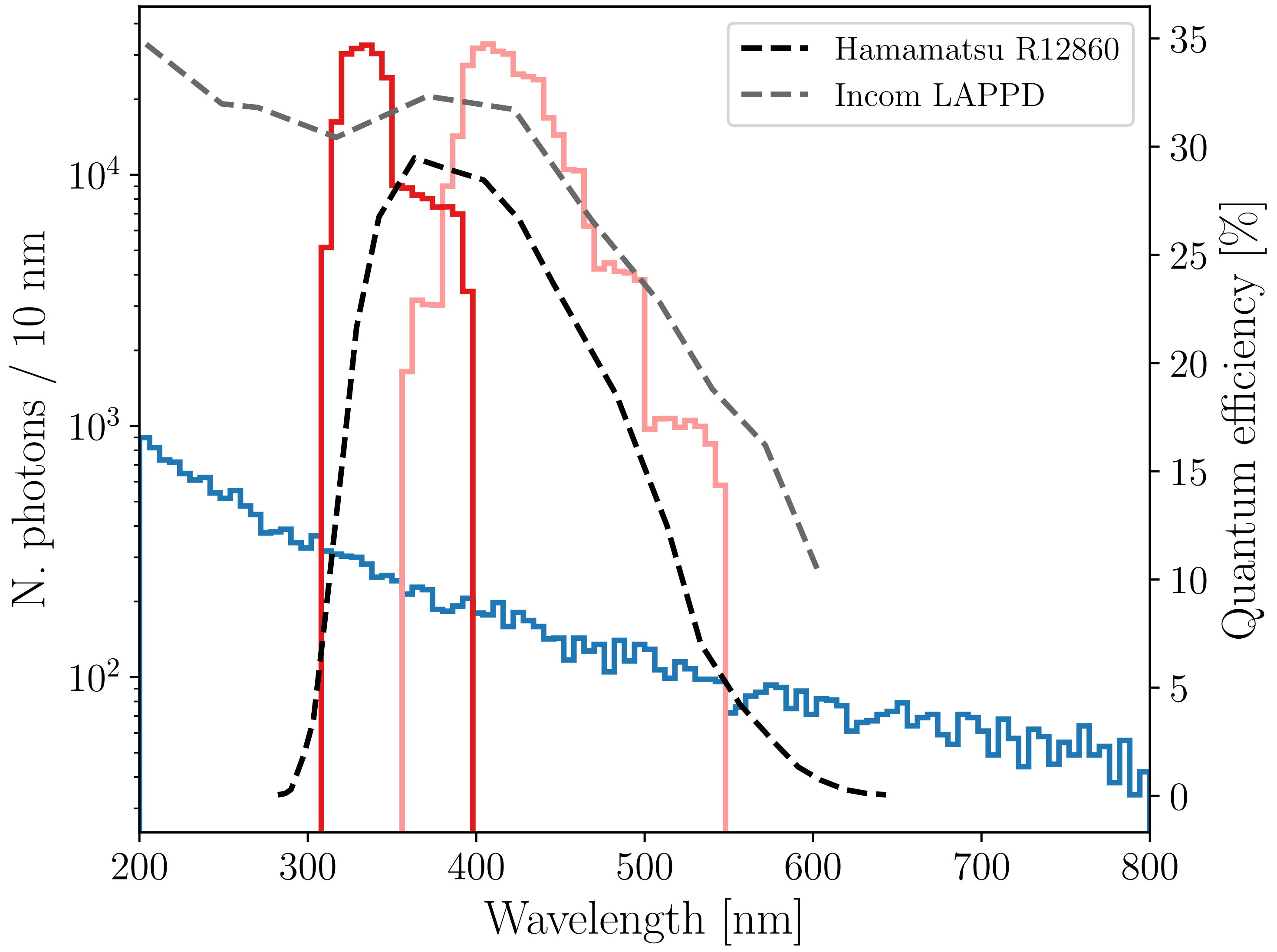
Isolating Cherenkov events

- Isolating Cherenkov photons allows to reconstruct particle direction.
- This is achieved with the **LAPPDs**, providing **50 ps time resolution**.
- Further discrimination could be achieved with ***slow flours***, which increase the scintillation time constant, and ***quantum dots***, which could shifts the UV component of the Cherenkov towards the visible.

Inverse beta decay event display







Neutrino detection

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	Process	Events/year	Detection
Inverse beta decay	$\bar{\nu}_e + p \to e^+ + n$ $\bar{\nu}_e + ^{12}\mathrm{C} \to e^+ + n + ^{11}\mathrm{B}$	$(1.48 \pm 0.15) \times 10^5$	Positron detection in delayed coincidence with neutron absorption
CC interaction	$\nu_e + ^{12}\mathrm{C} \to ^{12}\mathrm{N}_{\mathrm{gs}} + e^-$ $^{12}\mathrm{N}_{\mathrm{gs}} \to ^{12}\mathrm{C} + e^+ + \nu_e$	$(2.19 \pm 0.22) \times 10^3$	Electron detection in delayed coincidence with N-12 beta decay
NC interaction	$^{12}\mathrm{C} + \nu \to ^{12}\mathrm{C}^* + \nu$ $^{12}\mathrm{C}^* \to ^{12}\mathrm{C} + \gamma$	$(7.33 \pm 0.73) \times 10^4$	Detection of monochromatic gamma of 15.11 MeV.

Neutrino mixing matrix

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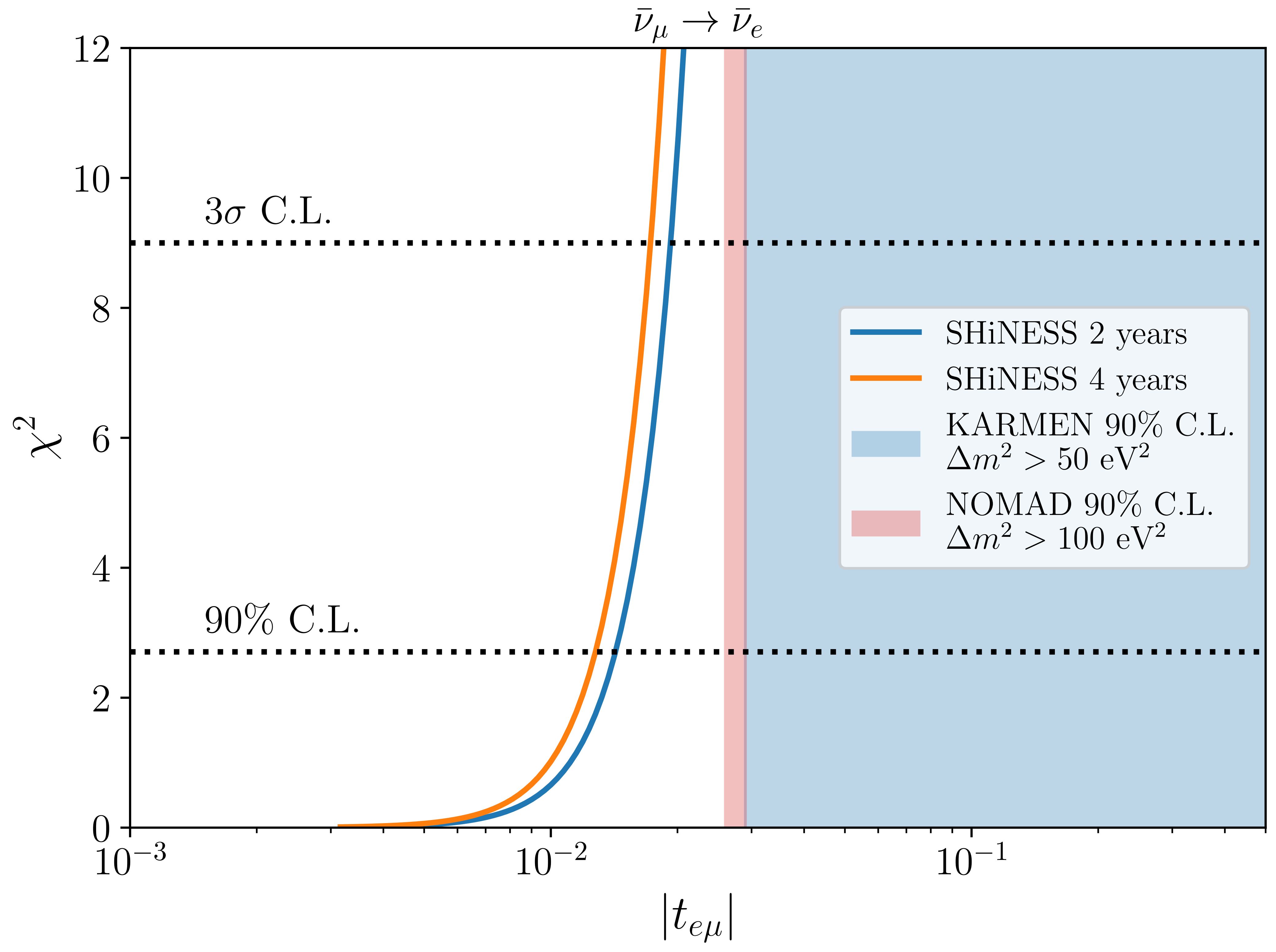
- Neutrino oscillations generally assume a **unitary 3 × 3 lepton mixing matrix** U (using e.g. the PMNS parametrization).
- The unitarity of the matrix, however, only holds in a limited amount of neutrino mass models.
- In general, in the presence of n additional neutrinos, the mass Lagrangian in the extended neutrino sector is diagonalized by a **(n + 3) × (n + 3) mixing matrix**.
- SHiNESS is expected to be sensitive to the closure of the **unitarity triangle in the eμ sector**, by comparing the measured number of **IBD events** and the expected one.



MiniBooNE/LSND anomaly

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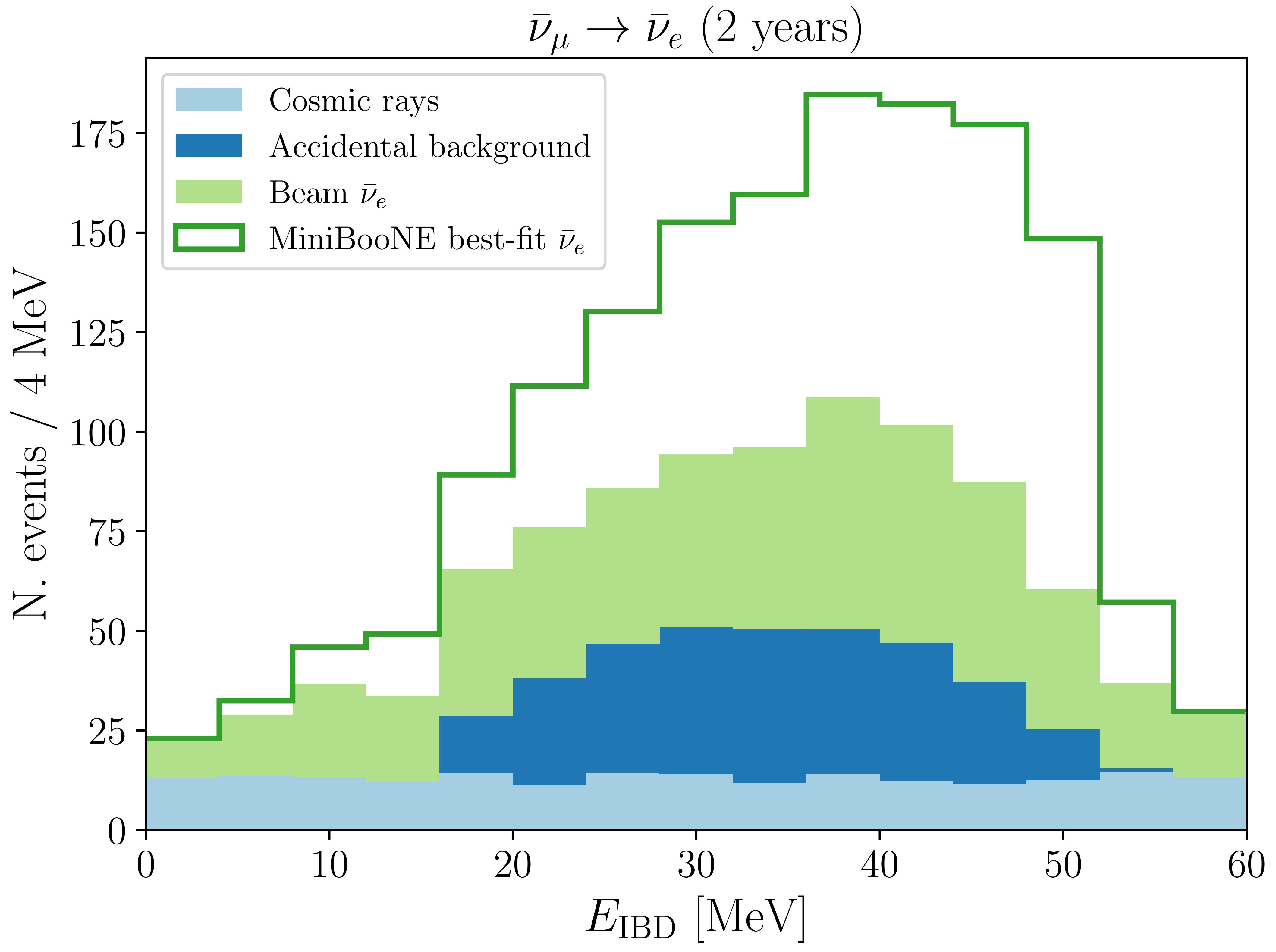
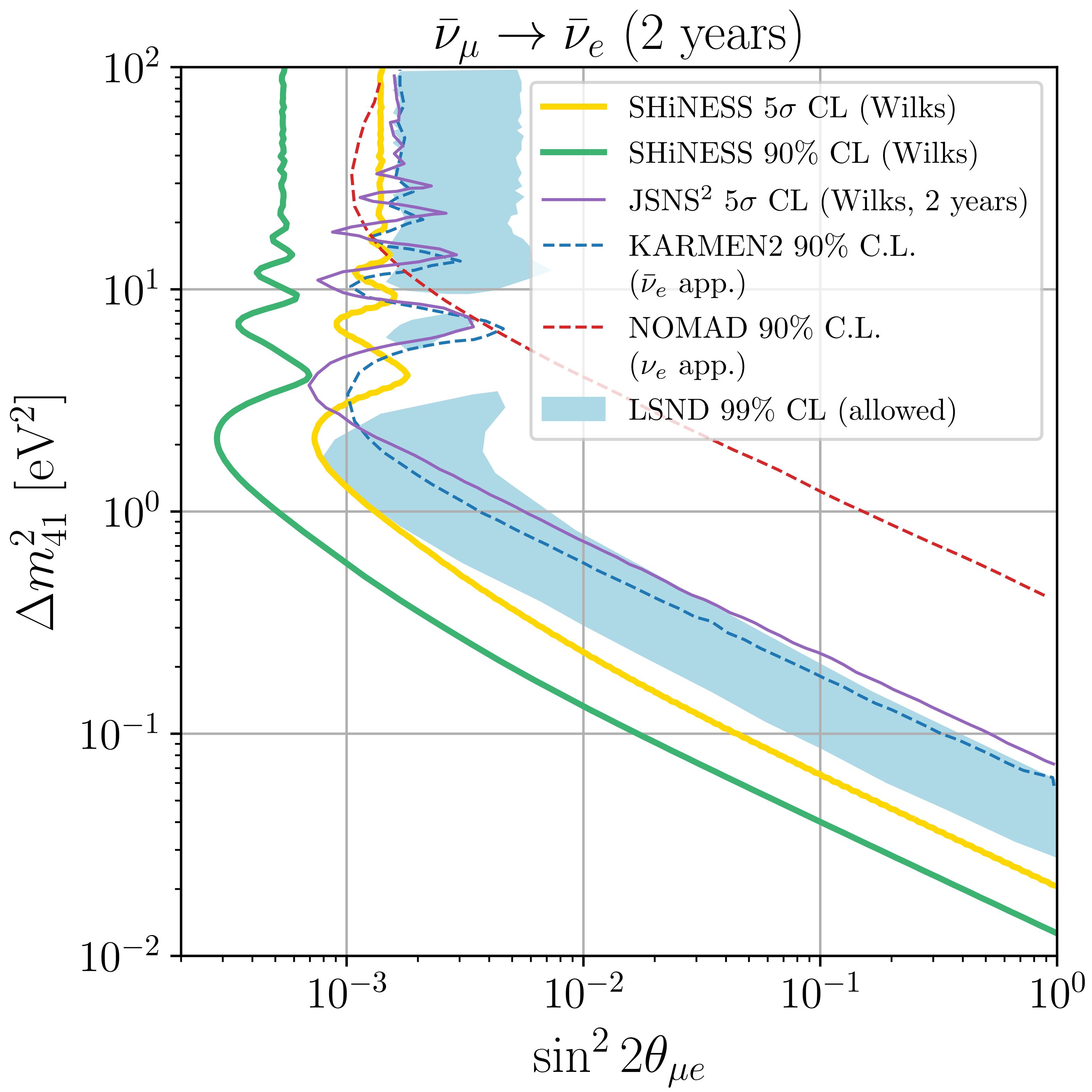
- The MiniBooNE and LSND experiments observed an **excess of electron (anti)neutrino interactions**, which could be compatible with the existence of a light sterile neutrino (~1 eV²).
- SHiNESS can **definitely rule out** this scenario through the IBD channel.
- Main background is the $\bar{\nu}_e$ intrinsic beam component (which comes with a large uncertainty).





Gallium anomaly

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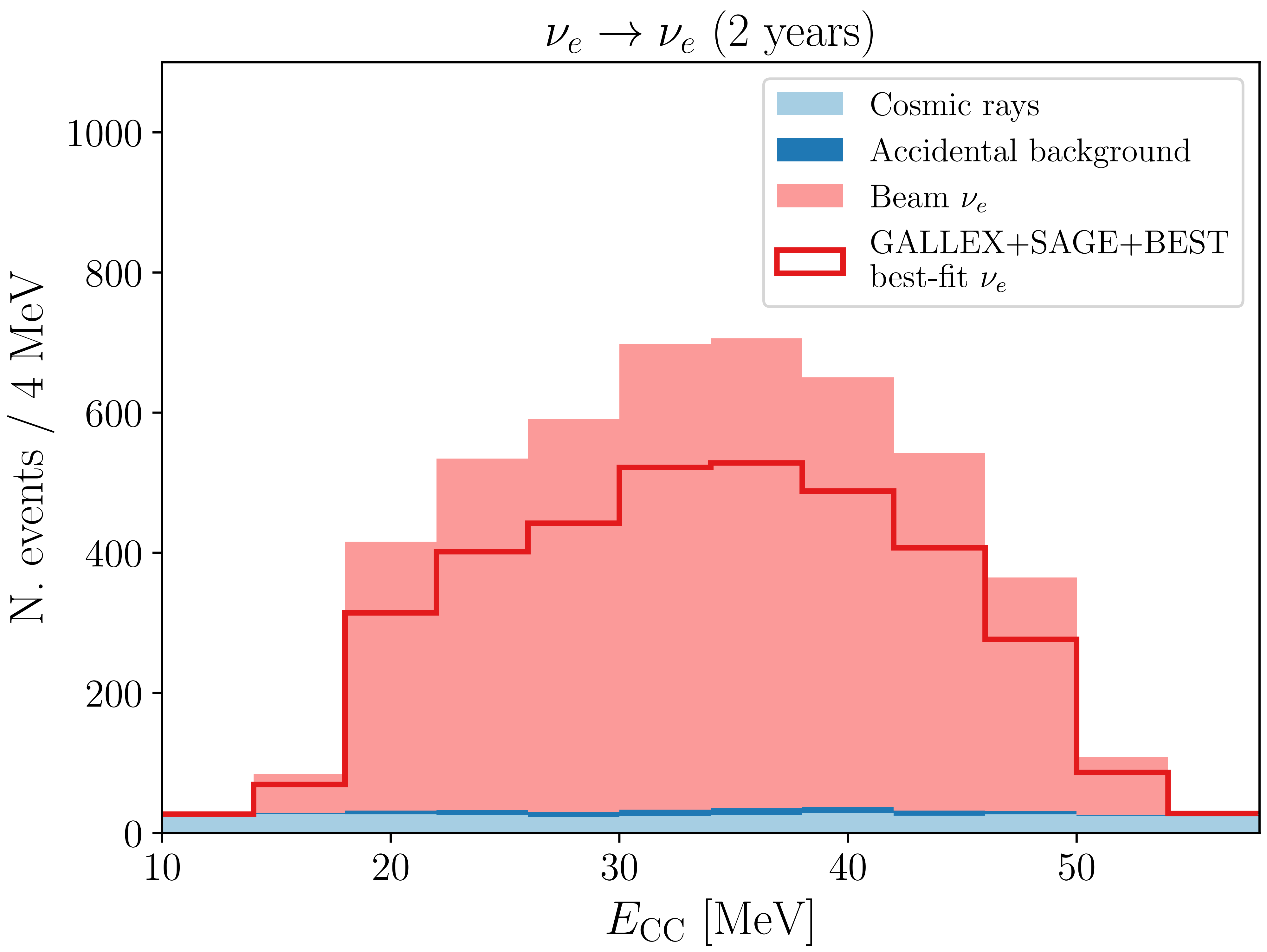
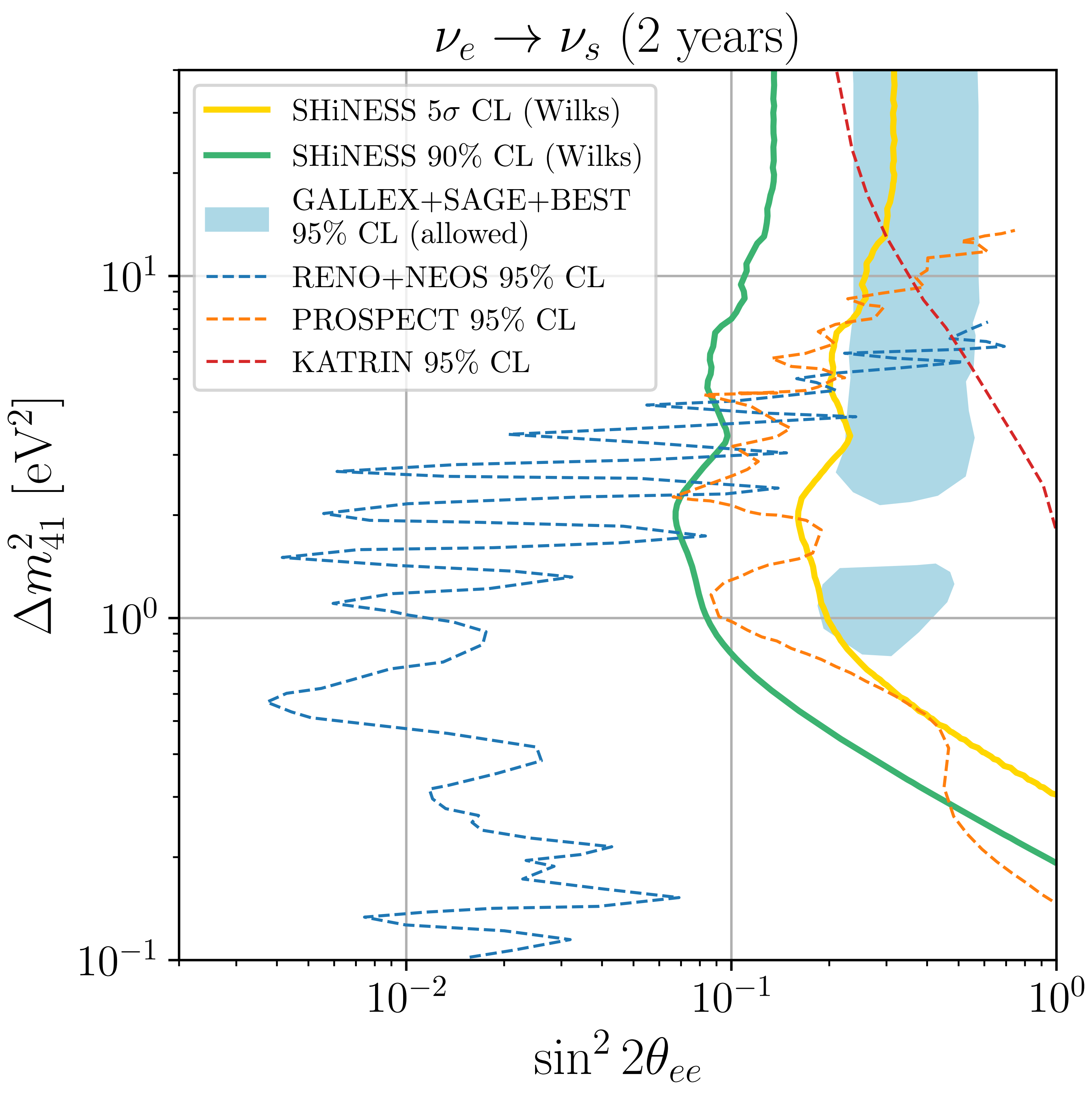
- GALLEX, SAGE and BEST experiments observed a **deficit of electron neutrino events** when exposed to radioactive sources.
- Also in this case, a possible explanation could be the **presence of a light sterile neutrino**.
- SHiNESS can also definitely exclude the parameter space for this anomaly using the **CC channel**.





Heavy neutral leptons

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- The detector can be used also to search for **long-lived particles produced near the beam target**.
- We explored the sensitivity for **heavy neutral leptons** (HNLs), but other scenarios are being investigated (e.g. axion-like particles, ALPs).
- For HNLs, two possible cases are possible:
  - **Electron mixing**, with the HNL being produced from the decay of muons and pions:

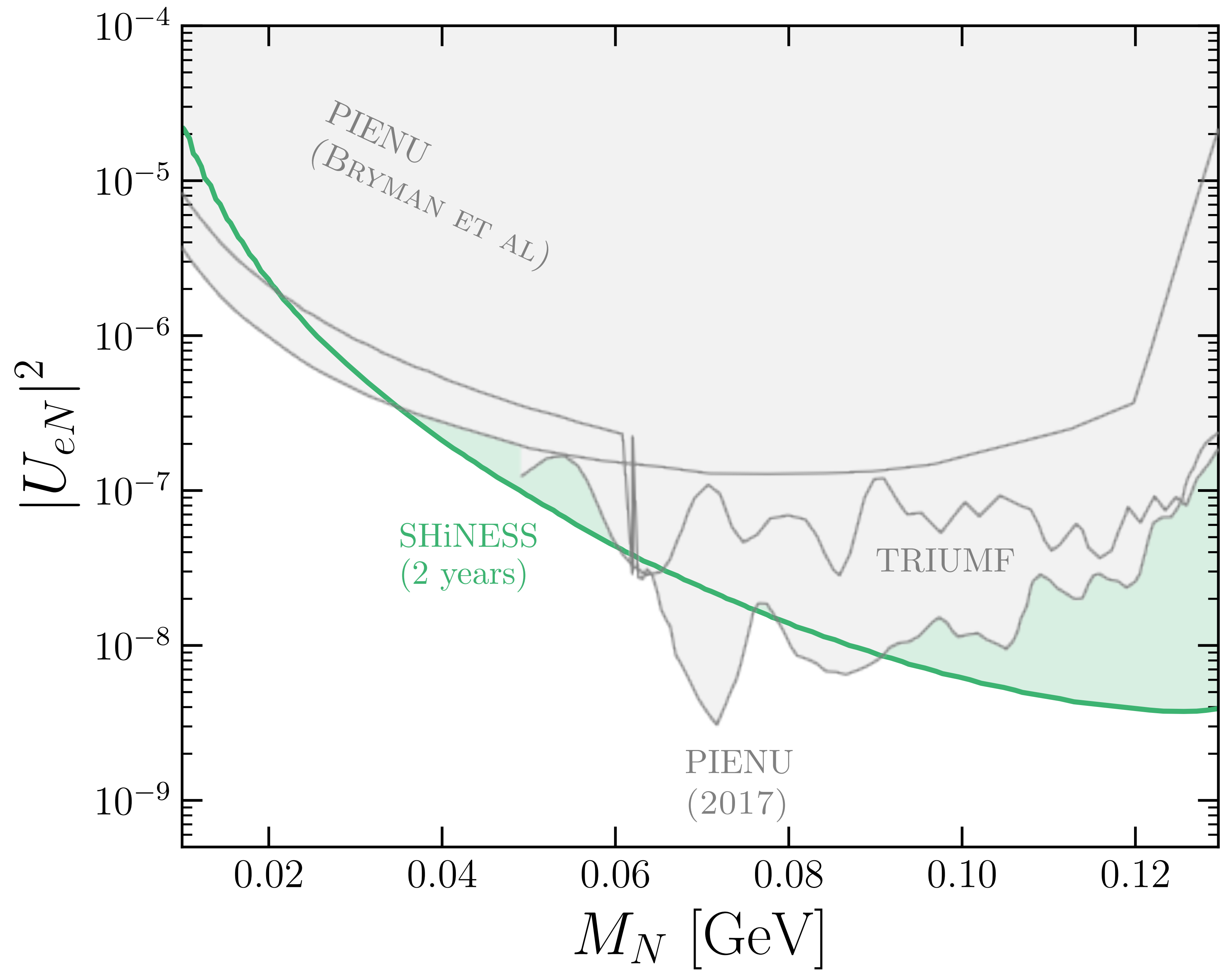
$$\Gamma(N \to e^+e^-\nu_e) = \frac{G_F^2 m_N^5}{768\pi^3} |U_{eN}|^2 \left(1 + 4\sin^2\theta_W + 8\sin^4\theta_W\right)$$

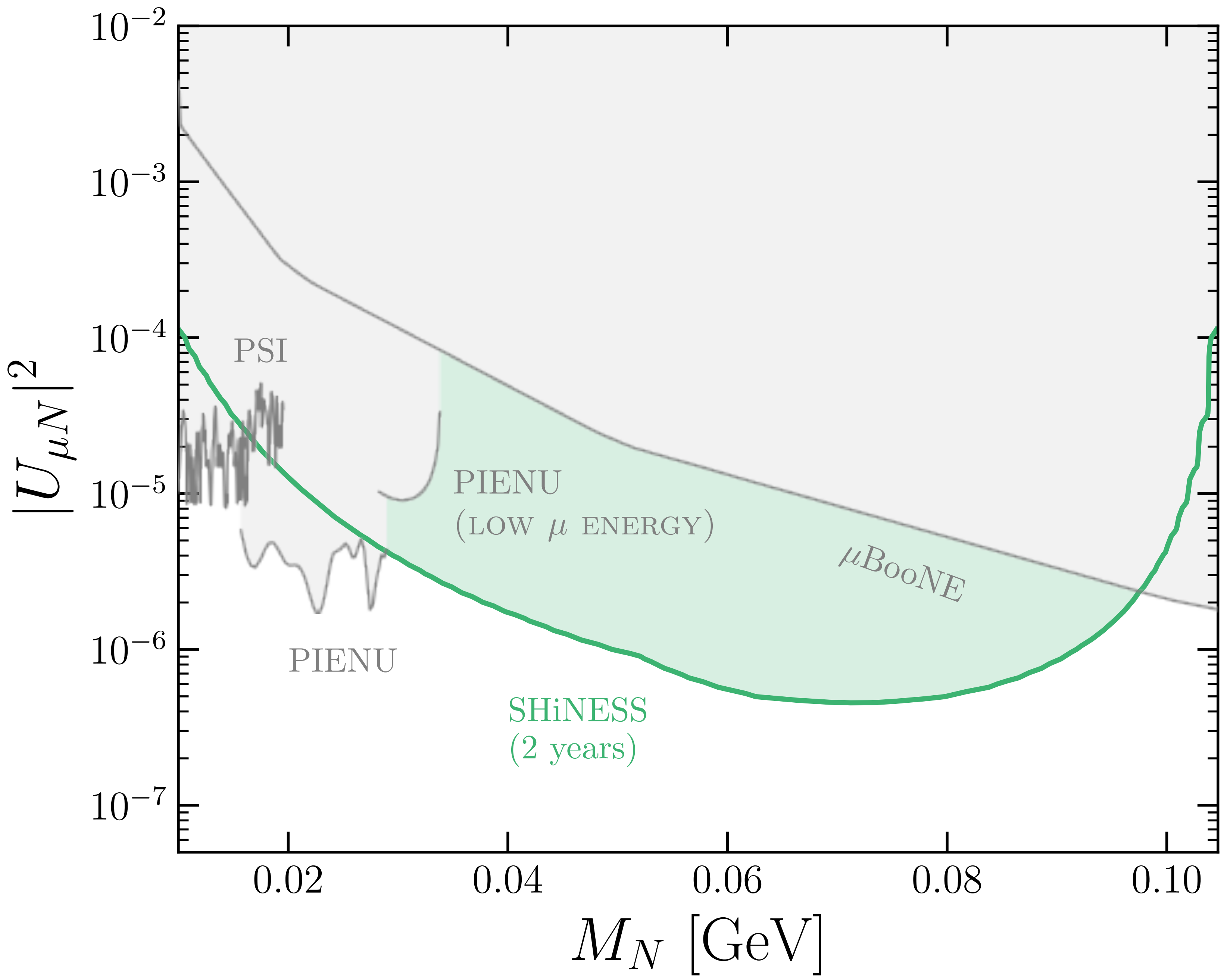
  - **Muon mixing**, with the HNL being produced from the decay of muons and, for $m_N < m_\pi - m_\mu$, from pions:

$$\Gamma(N \to e^+e^-\nu_\mu) = \frac{G_F^2 m_N^5}{768\pi^3} |U_{\mu N}|^2 \left(1 - 4\sin^2\theta_W + 8\sin^4\theta_W\right)$$

HNL sensitivity

- The e^+e^- can be detected in the liquid scintillator tank by looking for compatible **energy depositions** and **Cherenkov cones**.
- Analogous studies have been conducted for other π^+DAR experiments (e.g. LSND, JSNS²), but the **directionality capabilities of SHiNESS**, enabled by the LAPPDs, allow to reach **world-leading sensitivities** in the 10-100 MeV mass range.





Summary

SHiNESS

- **SHiNESS** is a **relatively cheap** and small-scale experiment using proven technologies.
- It will exploit the intense flux of well-characterized π^+DAR neutrinos produced as a byproduct of the spallation beam at the ESS.
- It does not require any update to the current ESS beam (**no need for ESS Neutrino Super Beam**).
- It has the potential to set world-leading sensitivities for several new physics scenarios: **light sterile neutrinos**, **neutrino mixing unitarity**, **heavy neutral leptons** have been explored.
- Interested in collaborating? **Contact me**!