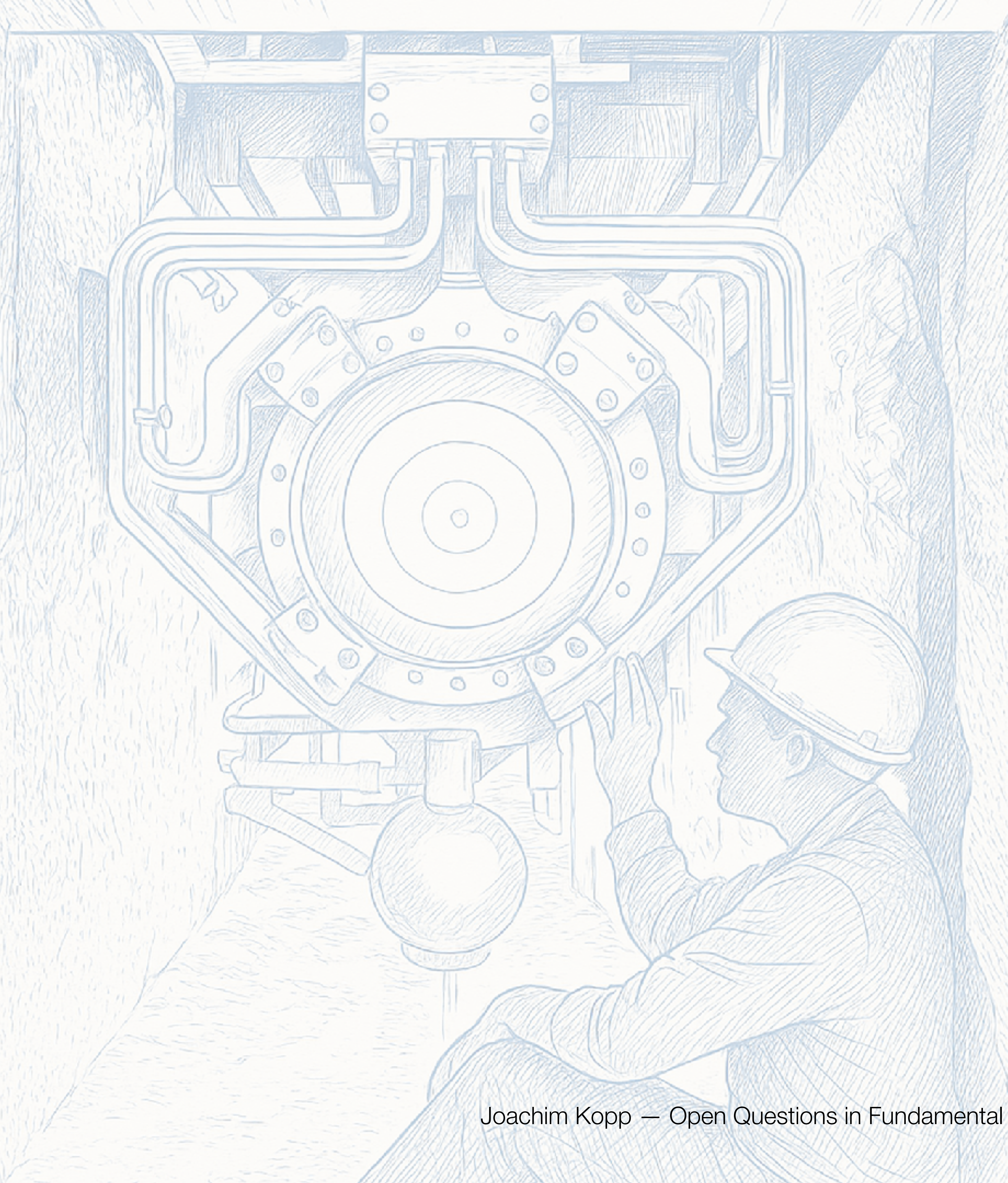
European Strategy for Particle Physics

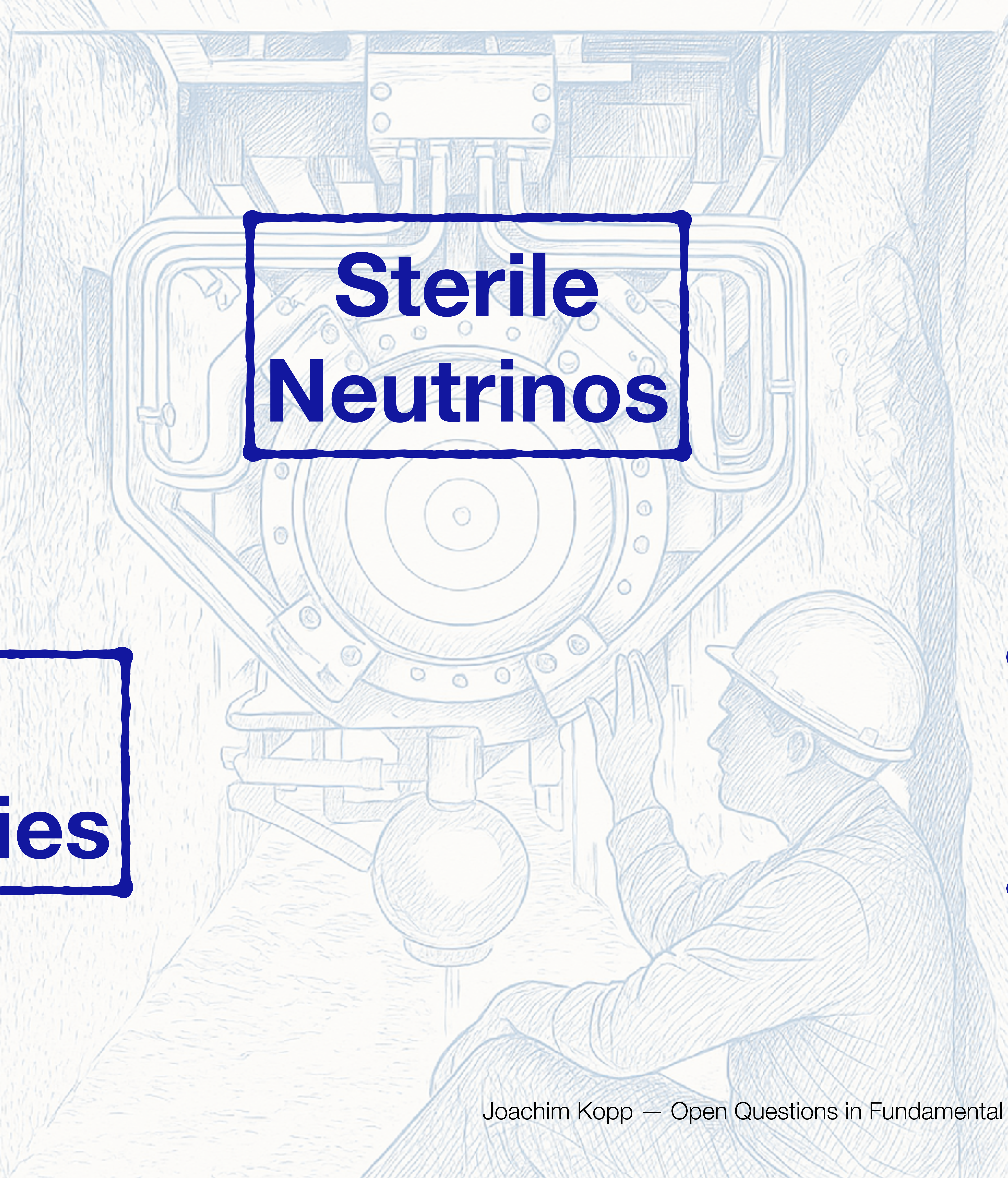
PARALLEL 3 / **NEUTRINOS AND COSMIC MESSENGERS**

BSM Searches in Neutrino Experiments

Joachim Kopp (CERN and JGU Mainz)

23-27 JUNE 2025 Lido di Venezia





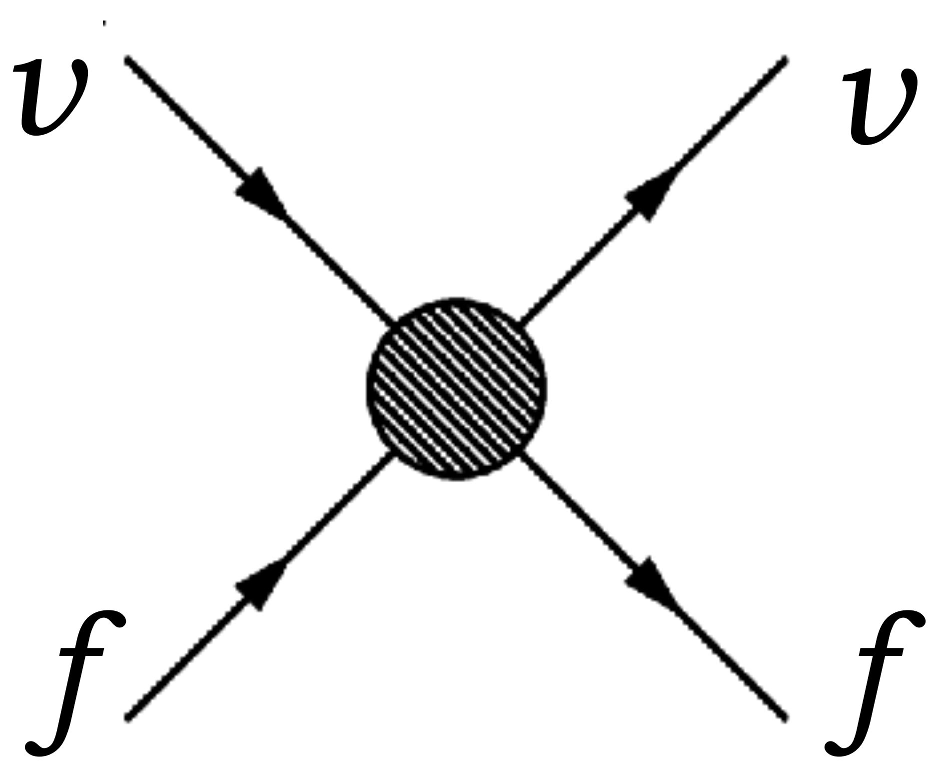
Sterile Neutrinos

Effective Field Theories

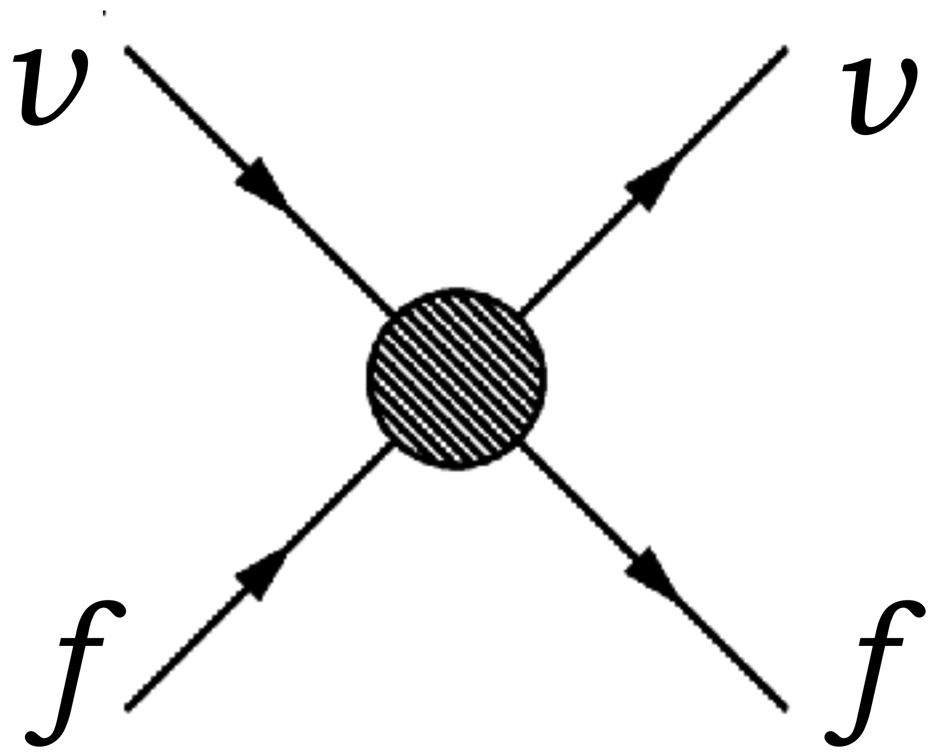
Dark Sectors

Effective Field Theories

Effective Field Theories



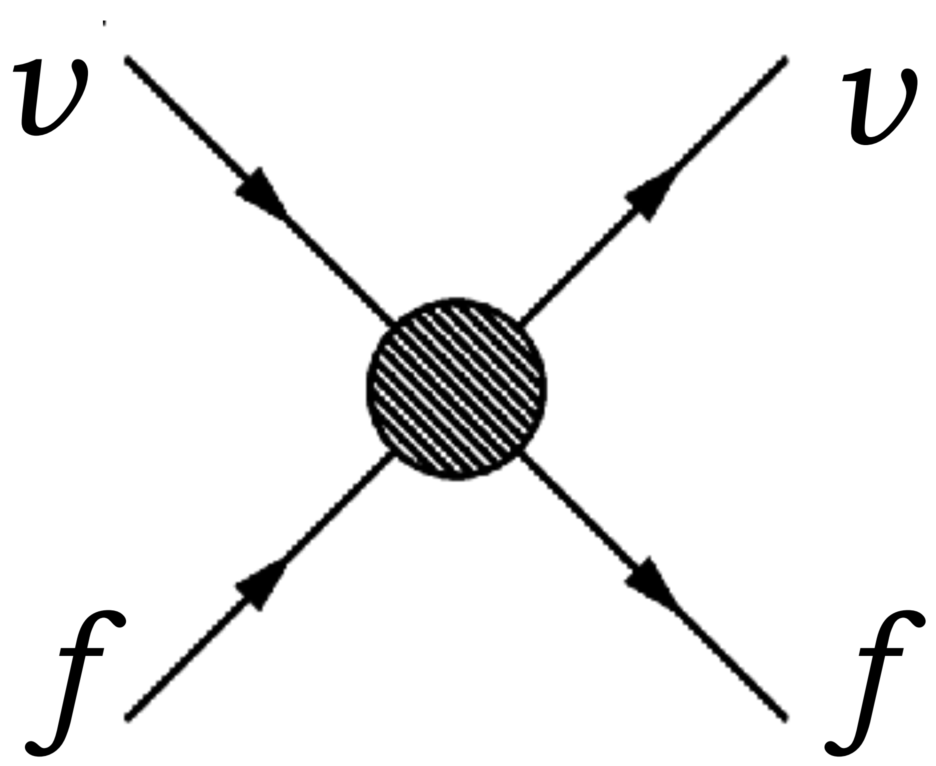
Effective Field Theories



- Standard Model Effective Field Theory (SMEFT) parameterises new physics above the electroweak scale

$$\mathcal{L}_{\mathrm{SMEFT}} = \sum_i \frac{c_i^{(5)}}{\Lambda} \mathcal{O}_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} + \ldots$$

Effective Field Theories



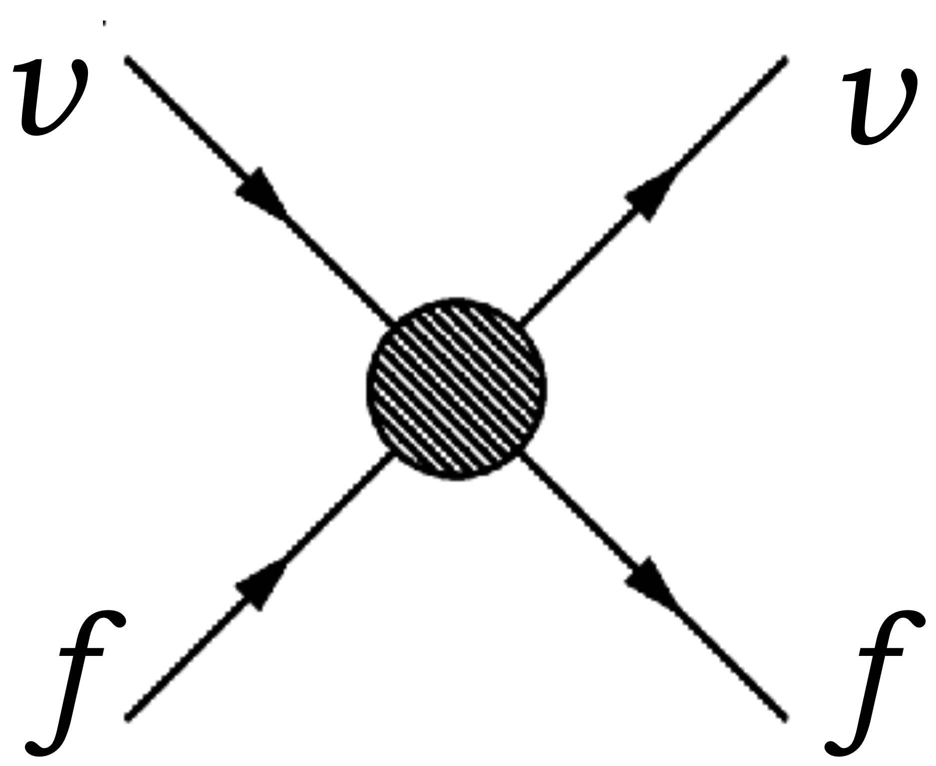
- Standard Model Effective Field Theory (SMEFT) parameterises new physics above the electroweak scale

$$\mathcal{L}_{\mathrm{SMEFT}} = \sum_i \frac{c_i^{(5)}}{\Lambda}\mathcal{O}_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \ldots$$

1 operator
(Majorana neutrino mass)

2499 operators

Effective Field Theories



- Standard Model Effective Field Theory (SMEFT) parameterises new physics above the electroweak scale

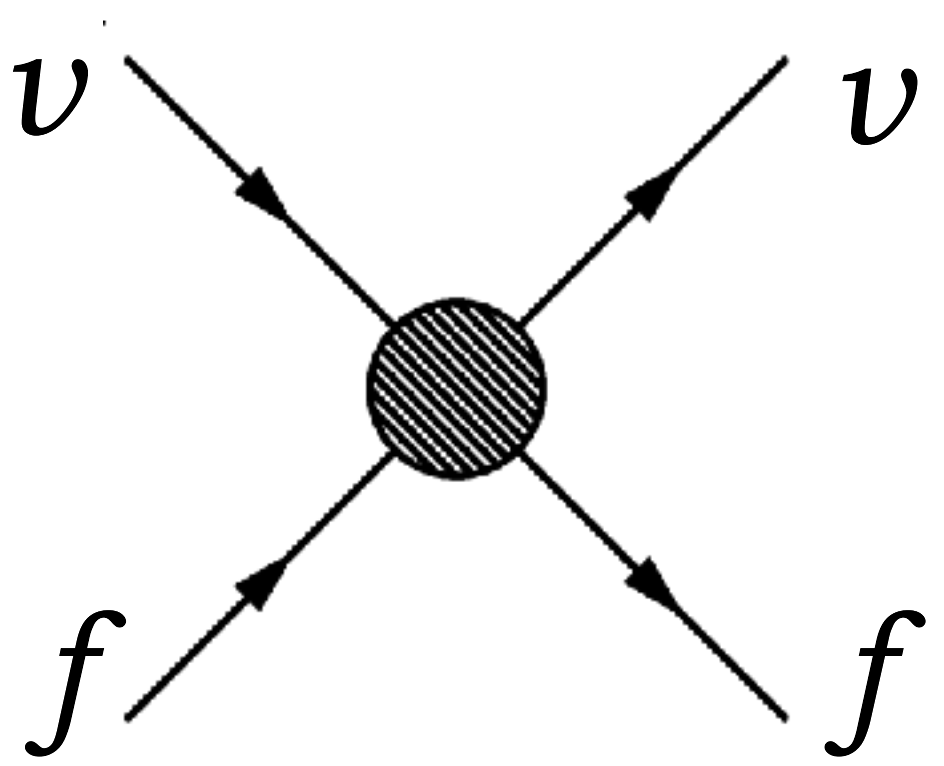
$$\mathcal{L}_{\text{SMEFT}} = \sum_i \frac{c_i^{(5)}}{\Lambda} \mathcal{O}_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} + \ldots$$

- For low-energy experiments (like neutrino experiments): map onto Weak Effective Field Theory (WEFT): "Non-Standard Interactions" (NSI) (EFT valid below the electroweak scale)

$$\mathcal{L}_{\text{NC}} = \sum 2\sqrt{2} G_F \epsilon_{\alpha\beta}^{q,XY} \left(\bar{\nu}_\alpha \Gamma_X P_L \nu_\beta\right) \left(\bar{q} \Gamma_Y q\right)$$

$$\mathcal{L}_{\text{CC}} = \sum 2\sqrt{2} G_F \epsilon_{\alpha\beta}^{qq',XY} \left(\bar{\ell}_\alpha \Gamma_X P_L \nu_\beta\right) \left(\bar{q}' \Gamma_Y q\right)$$

Effective Field Theories



- Standard Model Effective Field Theory (SMEFT)
  parameterises new physics above the electroweak scale

$$\mathcal{L}_{\mathrm{SMEFT}} = \sum_i \frac{c_i^{(5)}}{\Lambda}\mathcal{O}_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \ldots$$

- For low-energy experiments (like neutrino experiments):
  map onto Weak Effective Field Theory (WEFT): "Non-Standard Interactions" (NSI)
  (EFT valid below the electroweak scale)

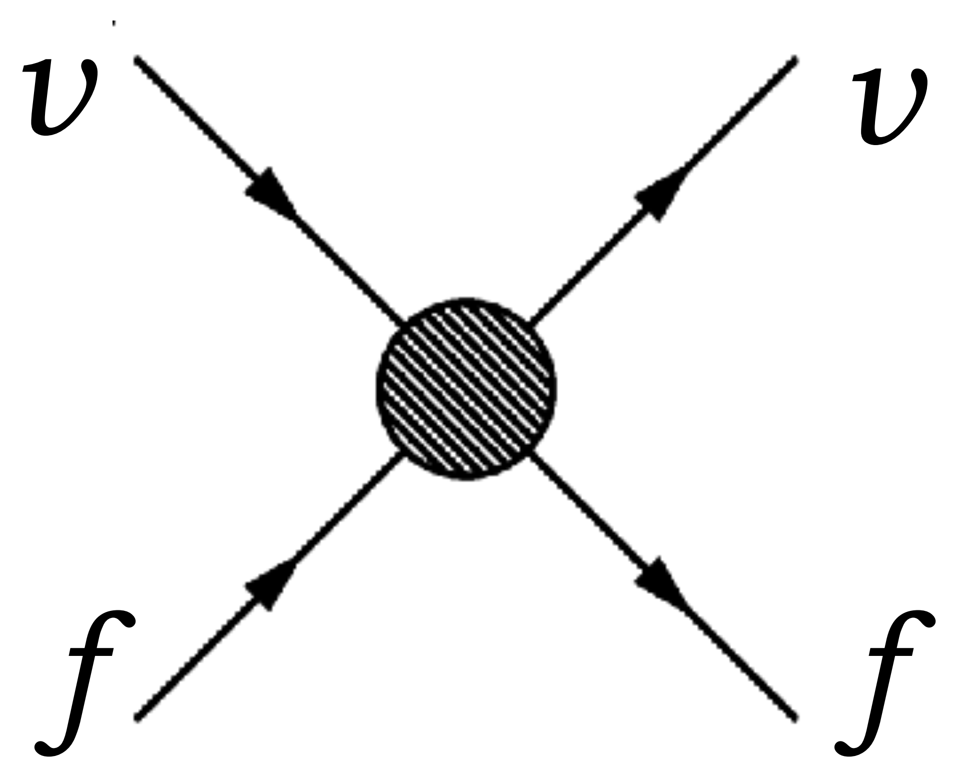
$$\mathcal{L}_{\mathrm{NC}} = \sum 2\sqrt{2}G_F \underline{\epsilon_{\alpha\beta}^{q,XY}}\, \underline{\left(\bar{\nu}_\alpha \Gamma_X P_L \nu_\beta\right)\left(\bar{q}\Gamma_Y q\right)}$$

$$\mathcal{L}_{\mathrm{CC}} = \sum 2\sqrt{2}G_F \underline{\epsilon_{\alpha\beta}^{qq',XY}}\, \underline{\left(\bar{\ell}_\alpha \Gamma_X P_L \nu_\beta\right)\left(\bar{q}'\Gamma_Y q\right)}$$

dim-6 operators
with different Lorentz structures

dimensionless coefficients
(interaction strength relative to SM weak interactions)

Effective Field Theories



- Standard Model Effective Field Theory (SMEFT)
  parameterises new physics above the electroweak scale

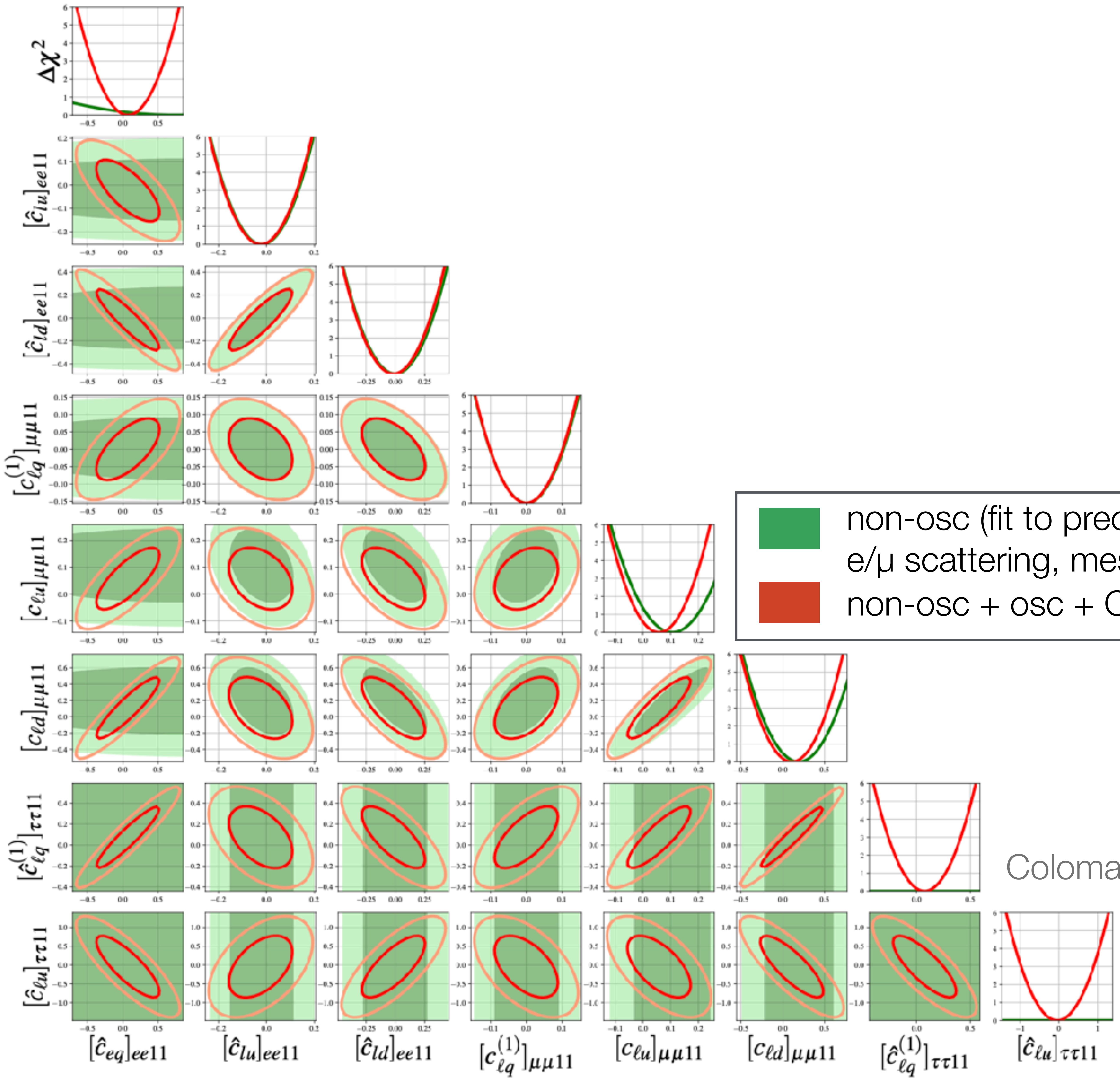
$$\mathcal{L}_{\text{SMEFT}} = \sum_i \frac{c_i^{(5)}}{\Lambda}\mathcal{O}_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \ldots$$

- For low-energy experiments (like neutrino experiments):
  map onto Weak Effective Field Theory (WEFT): "Non-Standard Interactions" (NSI)
  (EFT valid below the electroweak scale)

$$\mathcal{L}_{\text{NC}} = \sum 2\sqrt{2}G_F\epsilon_{\alpha\beta}^{q,XY}\left(\bar{\nu}_\alpha\Gamma_X P_L\nu_\beta\right)\left(\bar{q}\Gamma_Y q\right)$$ (new matter effects in oscillations)

$$\mathcal{L}_{\text{CC}} = \sum 2\sqrt{2}G_F\epsilon_{\alpha\beta}^{qq',XY}\left(\bar{\ell}_\alpha\Gamma_X P_L\nu_\beta\right)\left(\bar{q}'\Gamma_Y q\right)$$ (new ν production/detection processes)

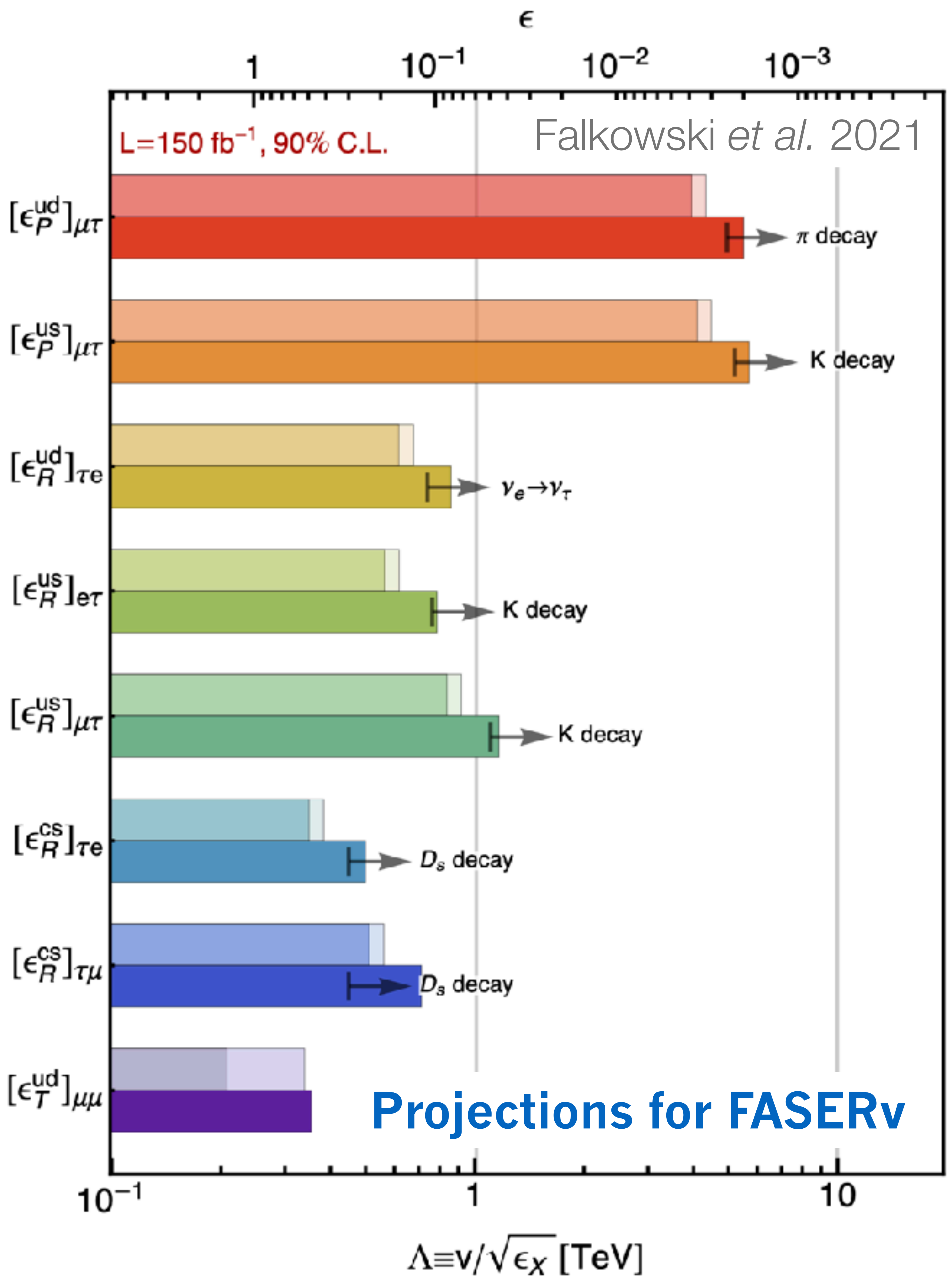
EFTs: Importance of Neutrino Constraints



non-osc (fit to precision ewk data, e/μ scattering, meson decays, …)

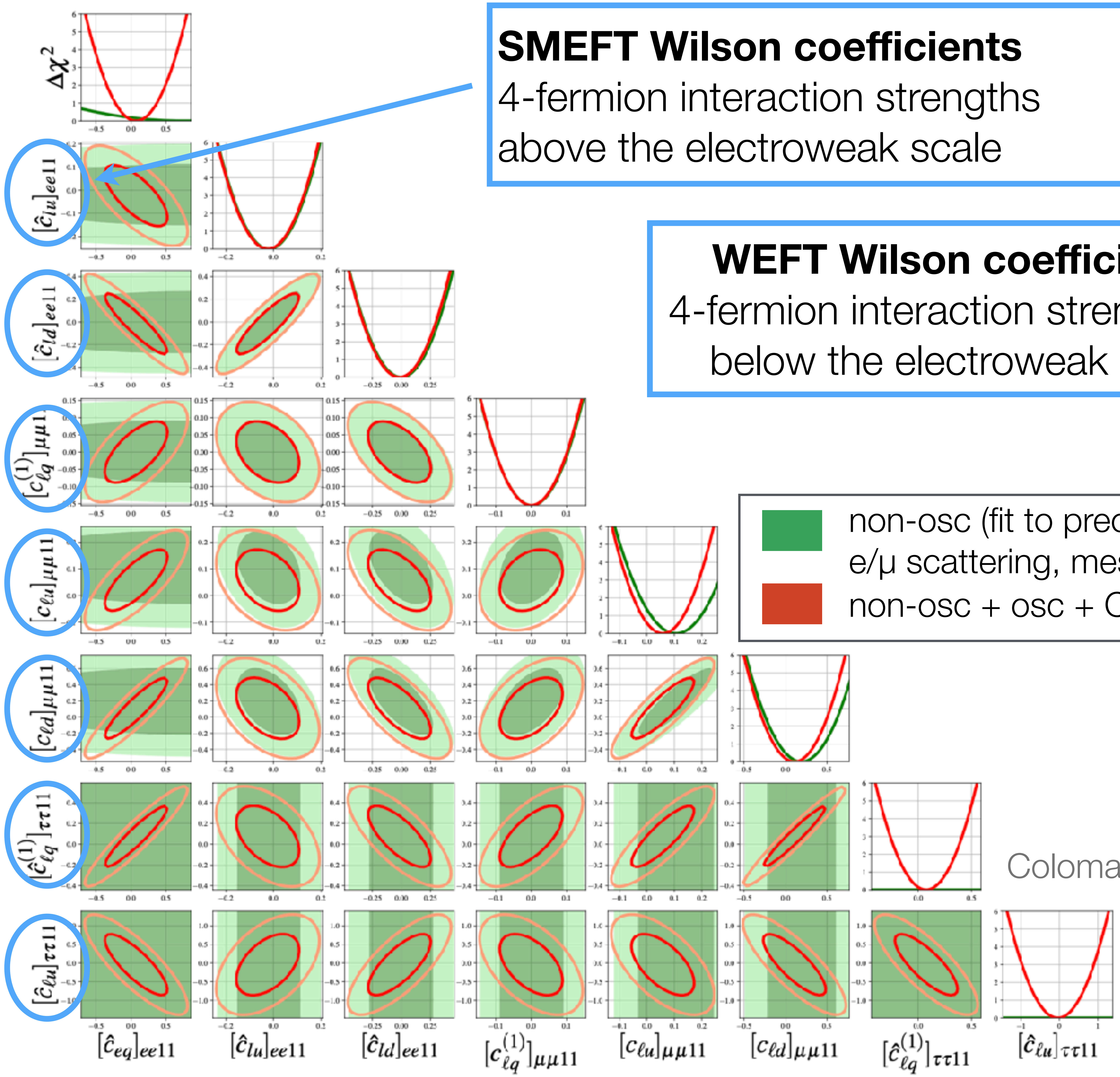
non-osc + osc + CEvNS

Coloma et al. 2024



Projections for FASERν

EFTs: Importance of Neutrino Constraints

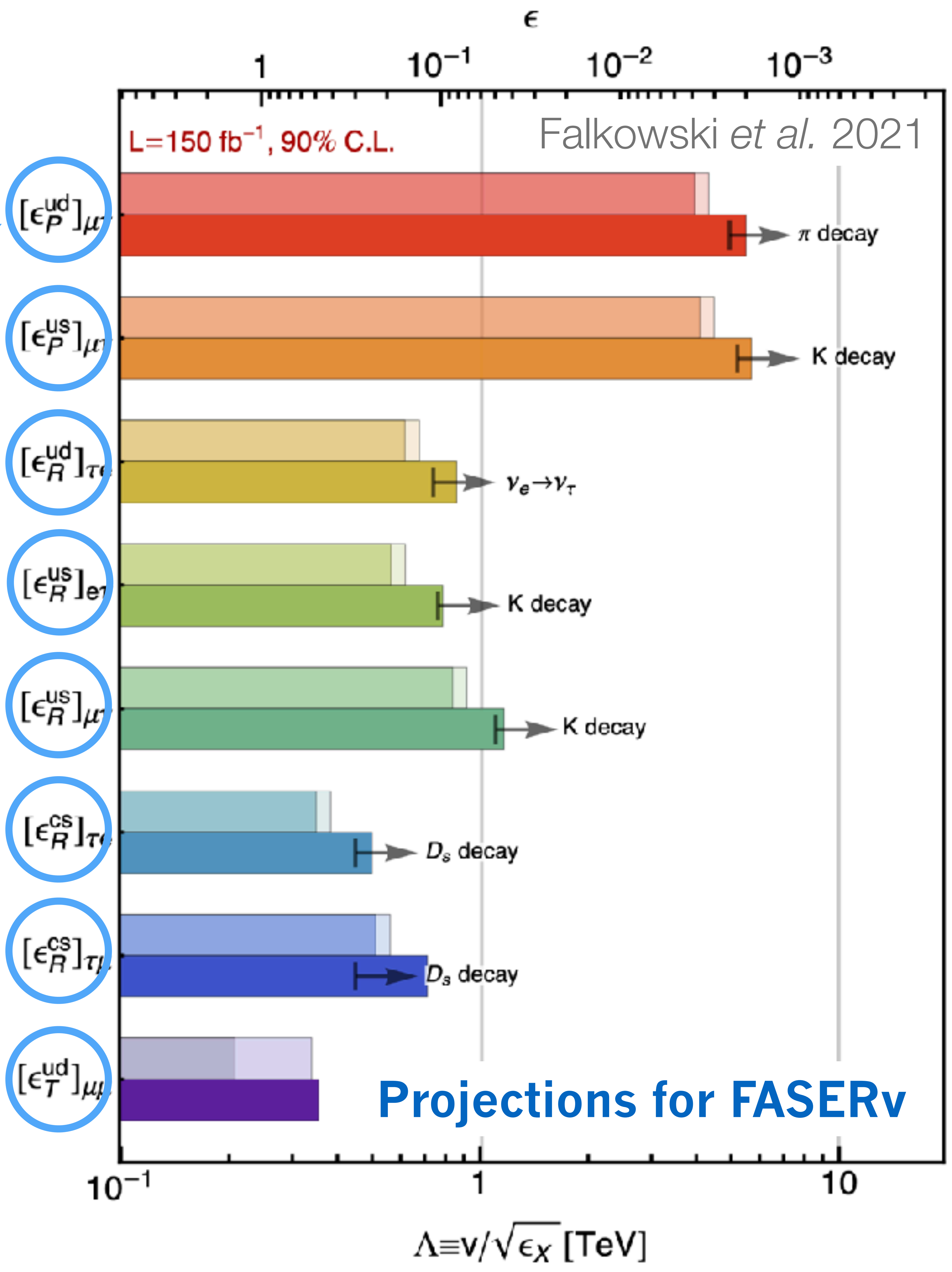


SMEFT Wilson coefficients
4-fermion interaction strengths
above the electroweak scale

WEFT Wilson coefficients
4-fermion interaction strengths
below the electroweak scale

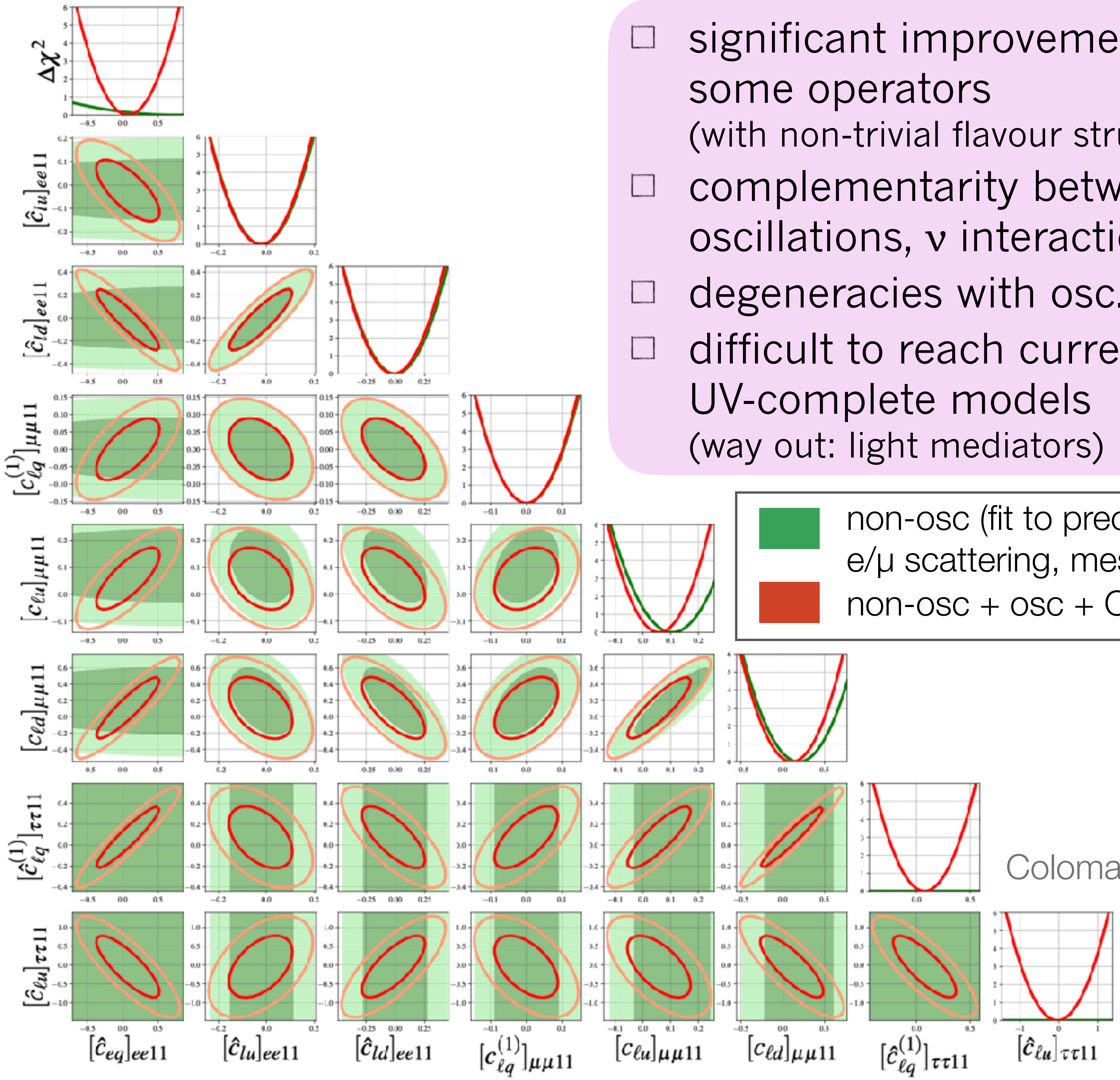
non-osc (fit to precision ewk data, e/μ scattering, meson decays, …)
non-osc + osc + CEvNS

Coloma et al. 2024



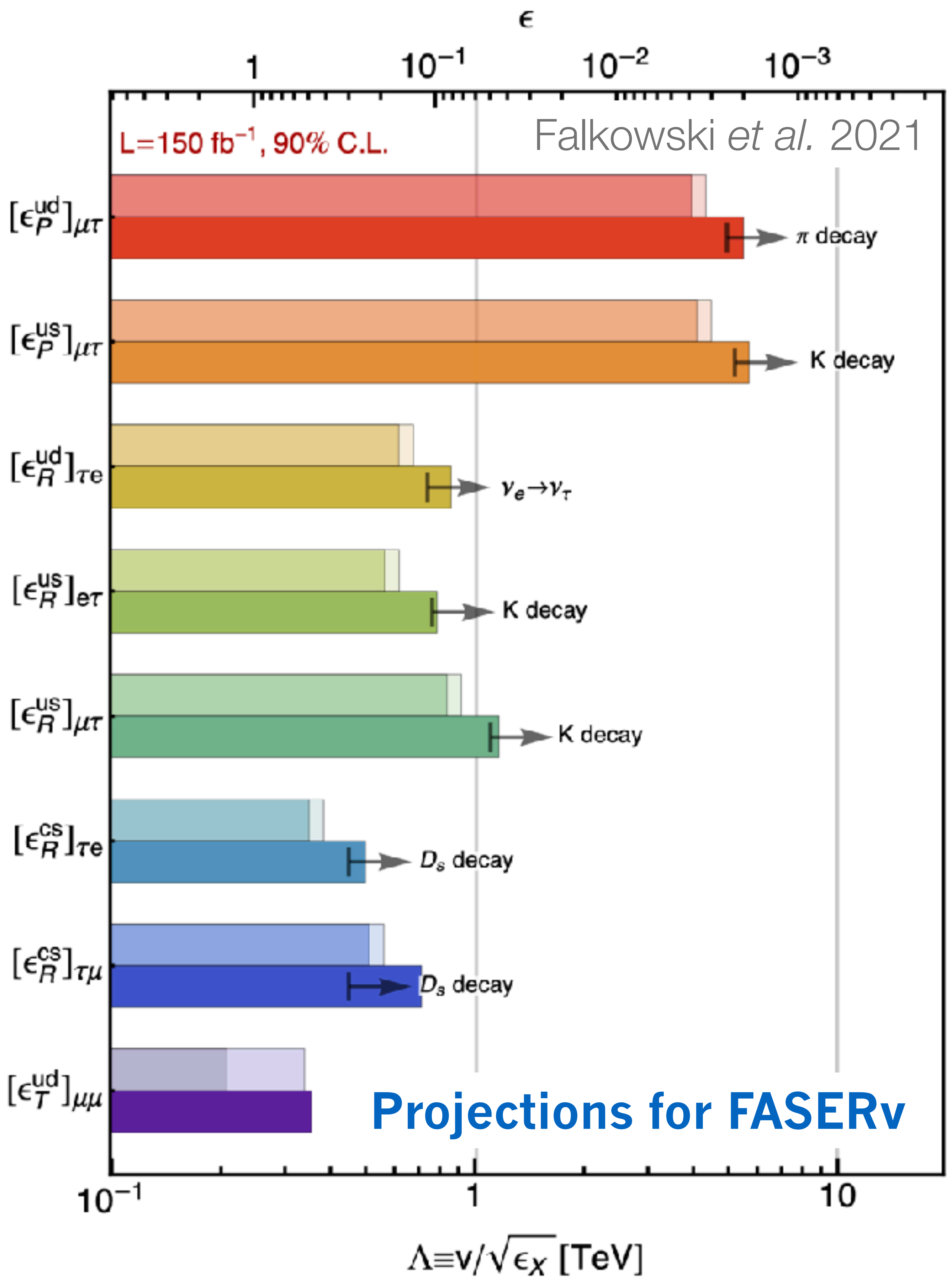
EFTs: Importance of Neutrino Constraints

- significant improvement for some operators
  (with non-trivial flavour structures)
- complementarity between oscillations, ν interactions, CEvNS
- degeneracies with osc. params
- difficult to reach current bounds in UV-complete models
  (way out: light mediators)



non-osc (fit to precision ewk data, e/μ scattering, meson decays, …)
non-osc + osc + CEvNS

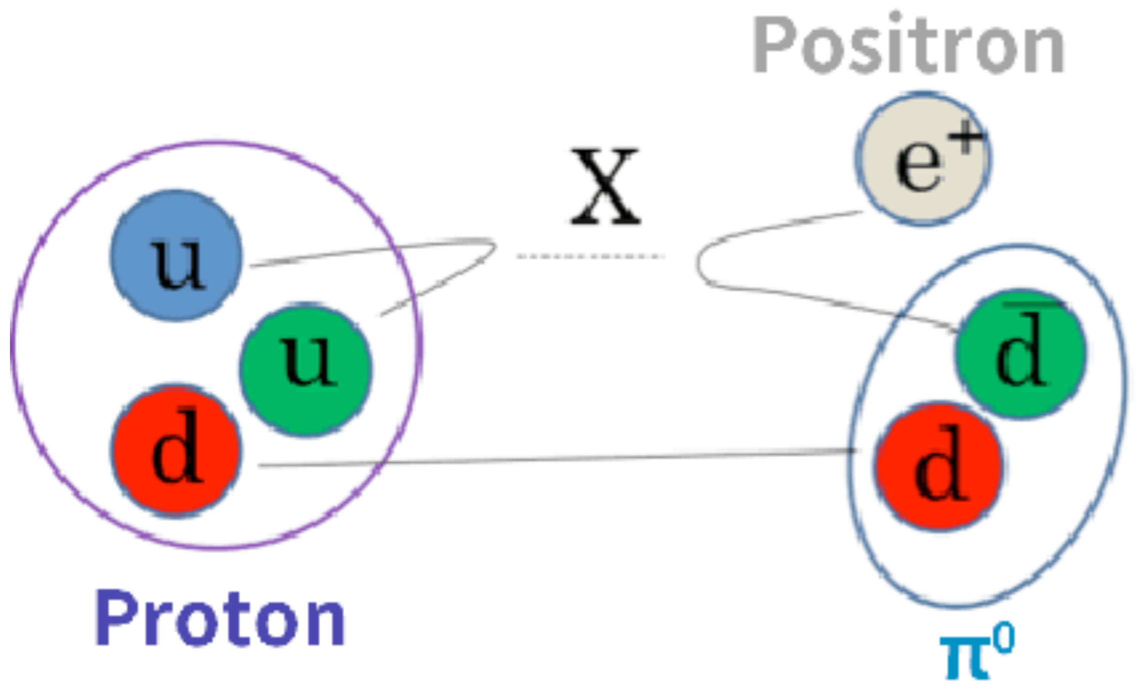
Coloma et al. 2024



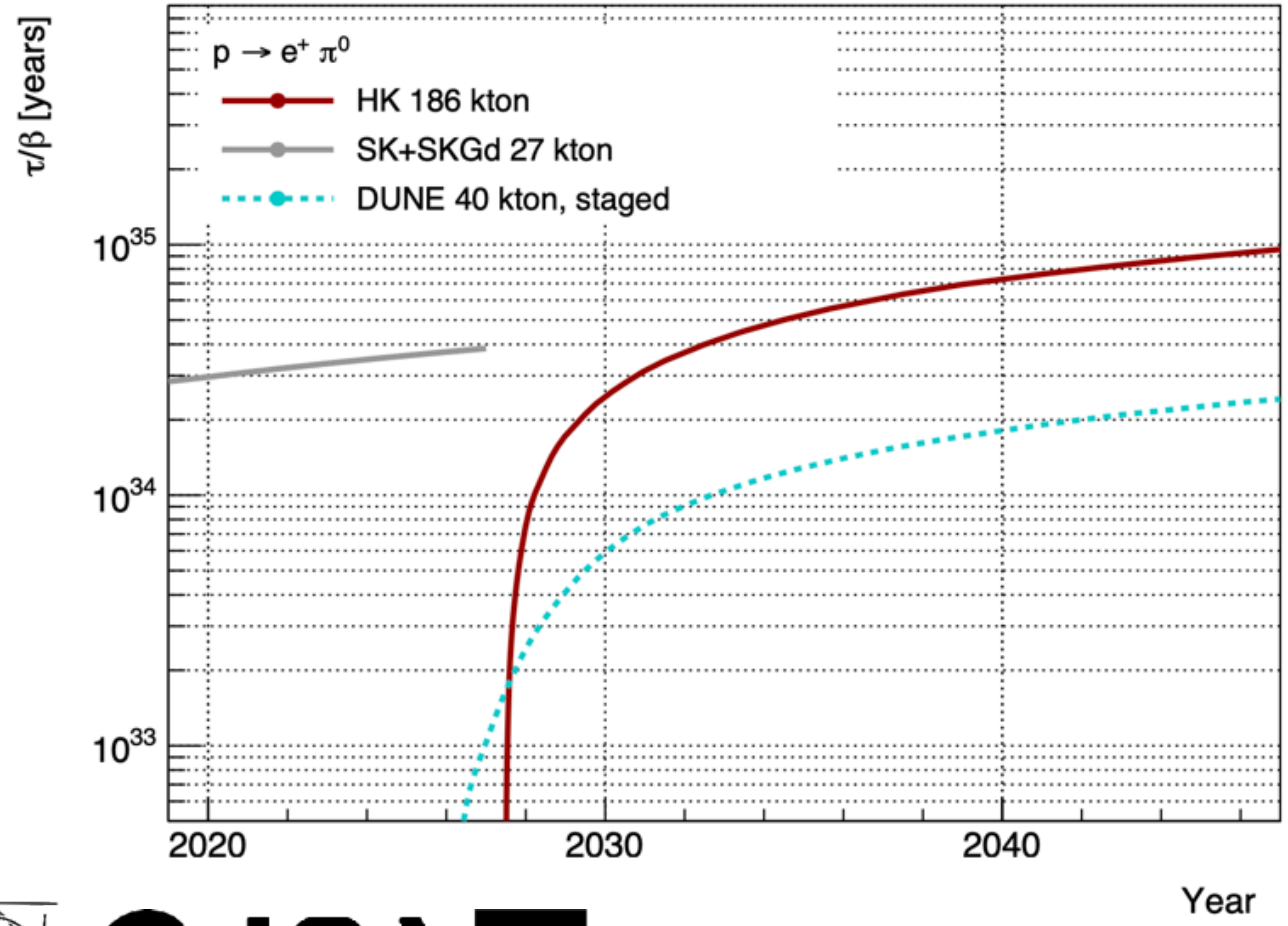
Projections for FASERν

Nucleon Decay

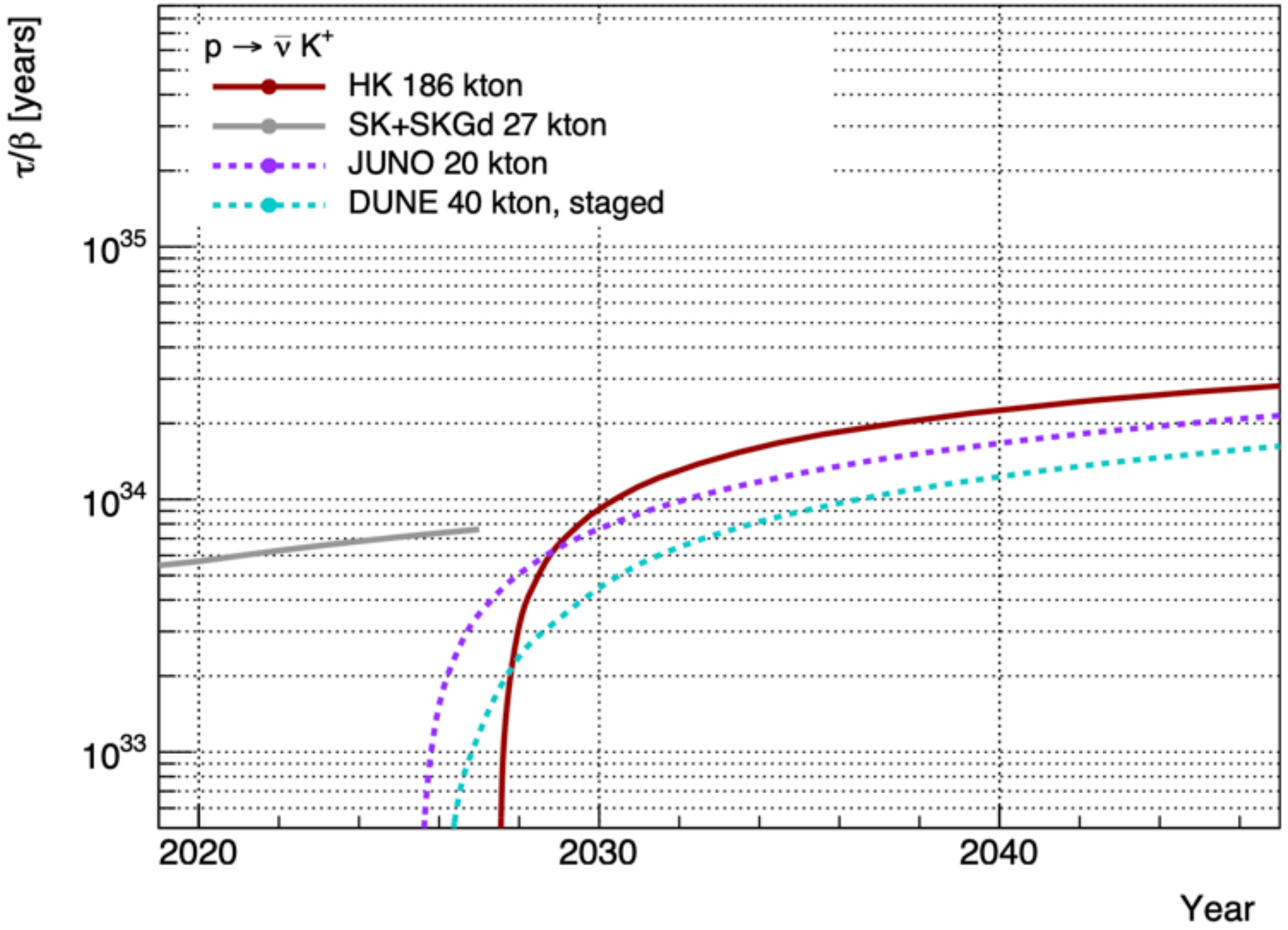
- Hallmark signature of Grand Unification
- HyperK: lots of protons, kaon ID only via decay products
  DUNE: excellent particle ID, lots of *neutrons*

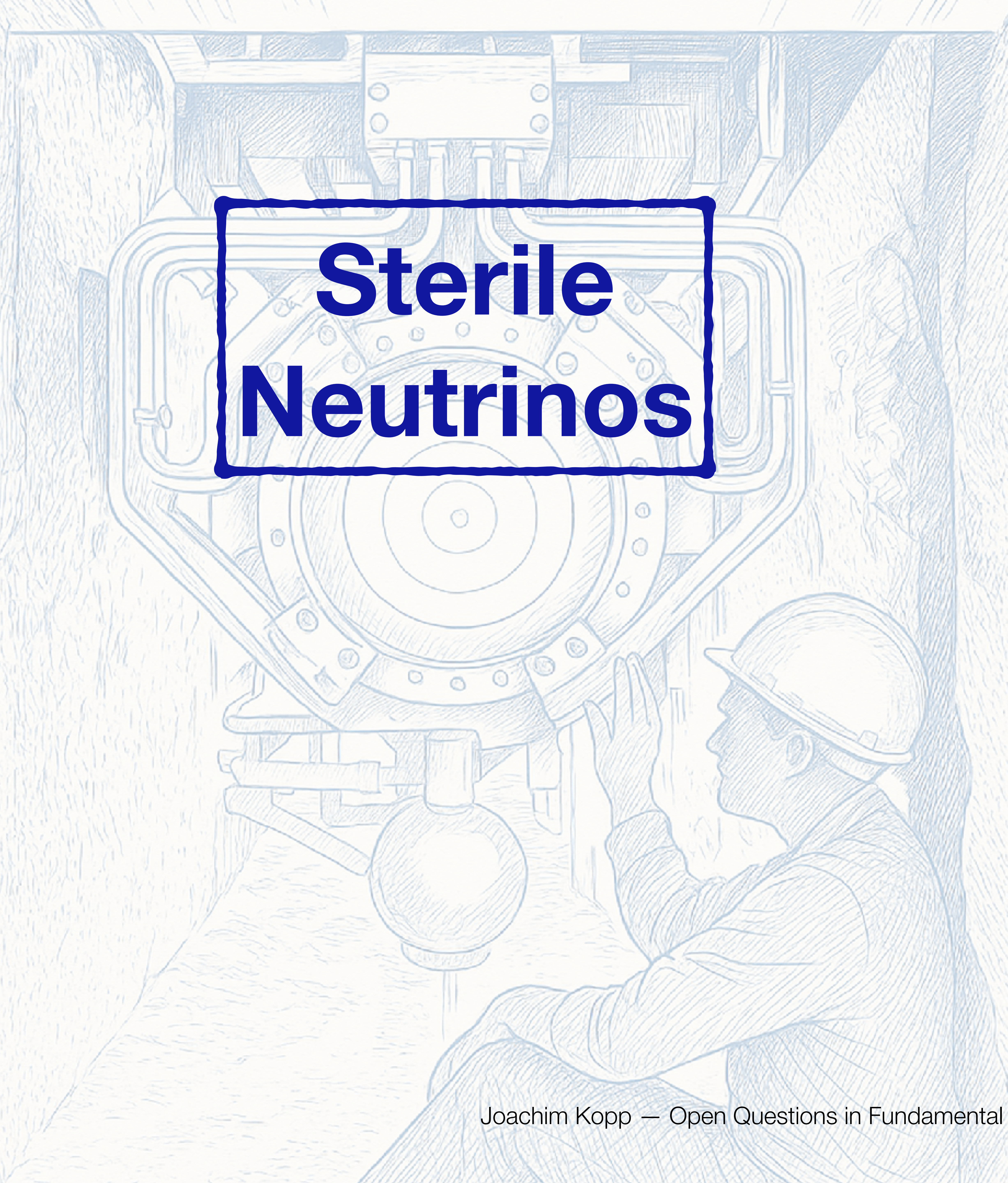


$p \to e^+ \pi^0$



$p \to \bar{\nu} K^+$

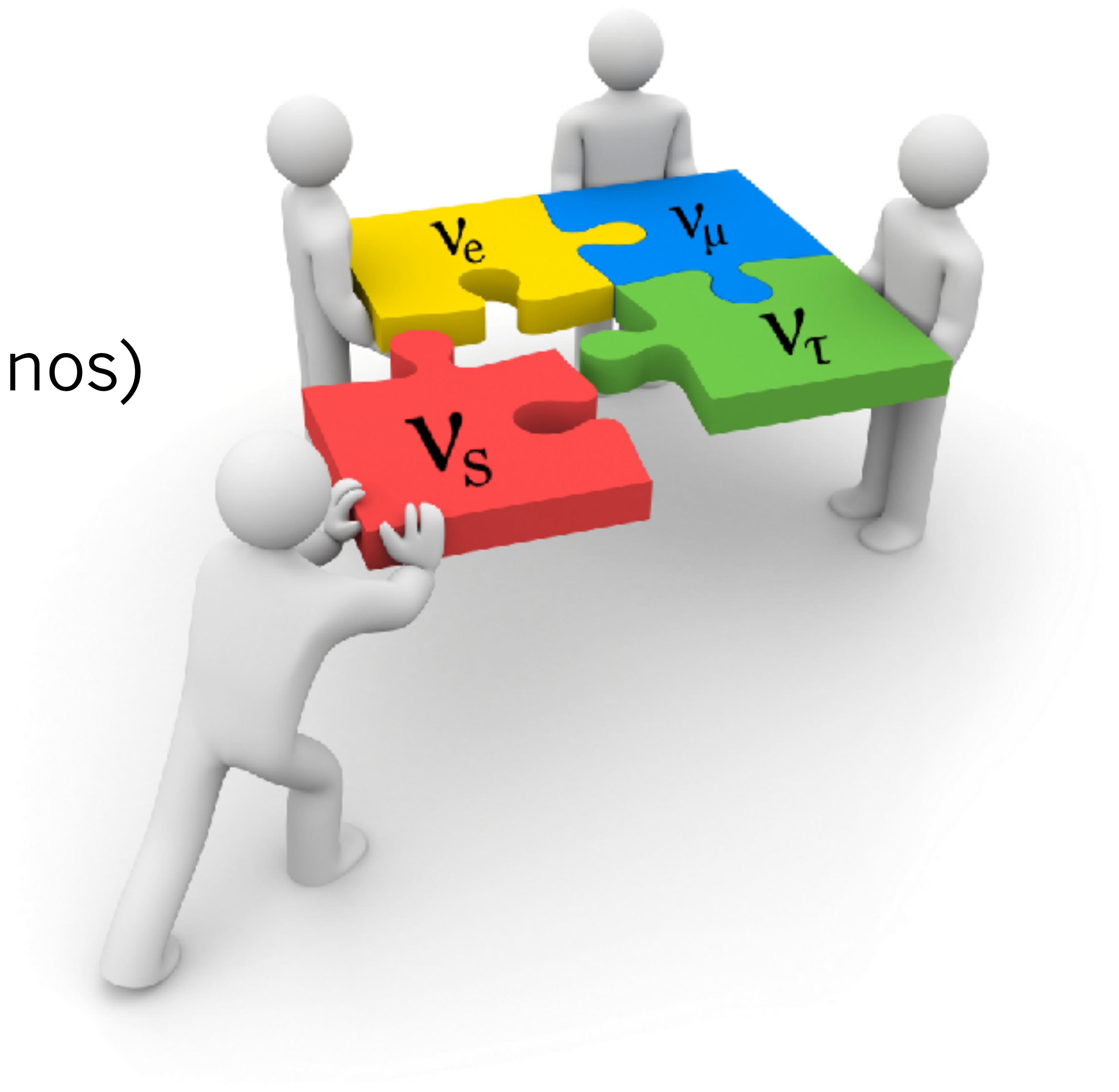




Sterile Neutrinos

Sterile Neutrinos

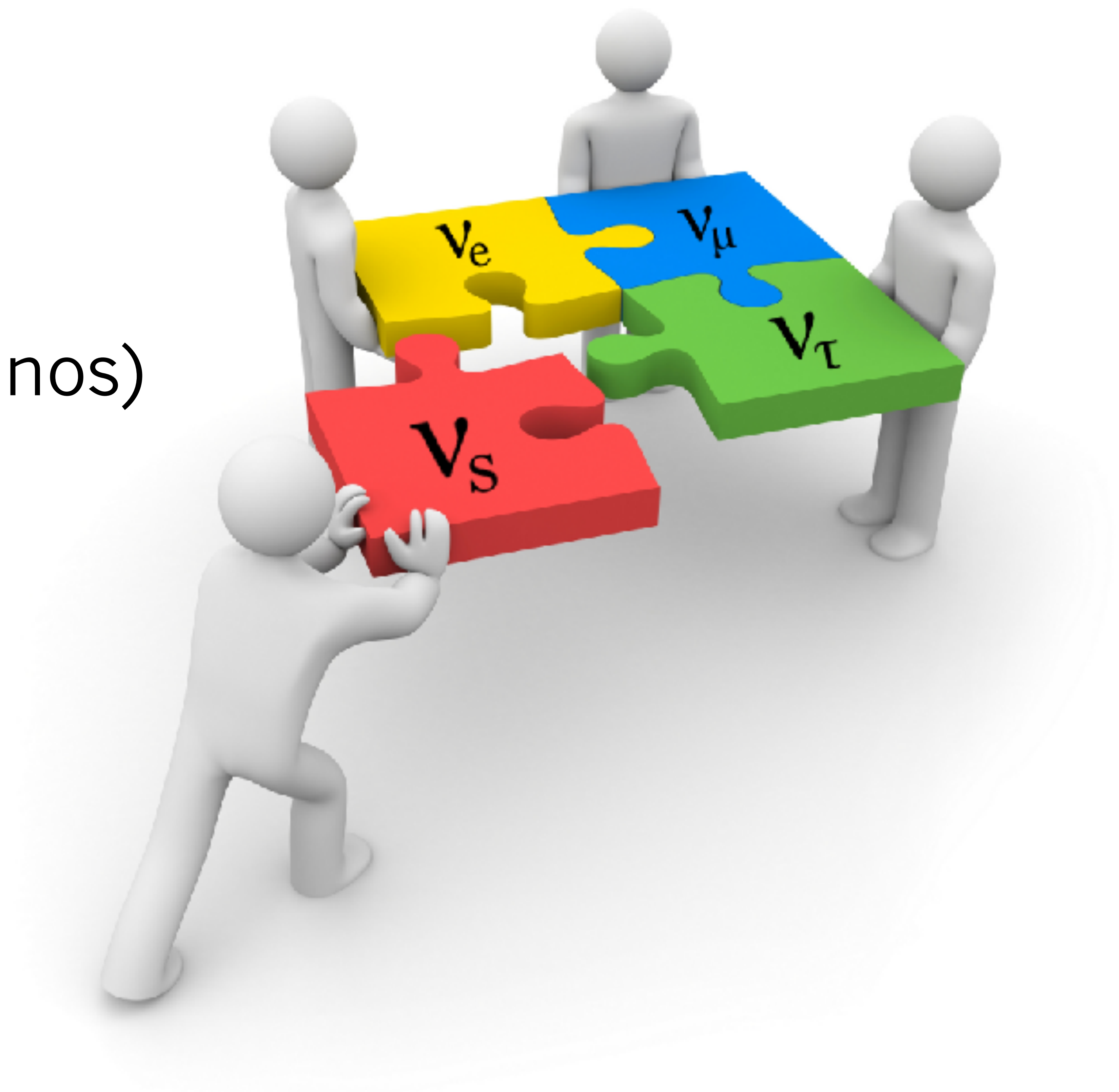
- Neutrino Portal: SM ν can mix with singlet fermions
  (sterile neutrinos = heavy neutral leptons = right-handed neutrinos)
  ➠ the only renormalisable SM coupling to singlet fermions
  (dark matter?)



$$\mathcal{L} \supset y\, \bar{L}\, (i\sigma^2 H^*)\, N$$

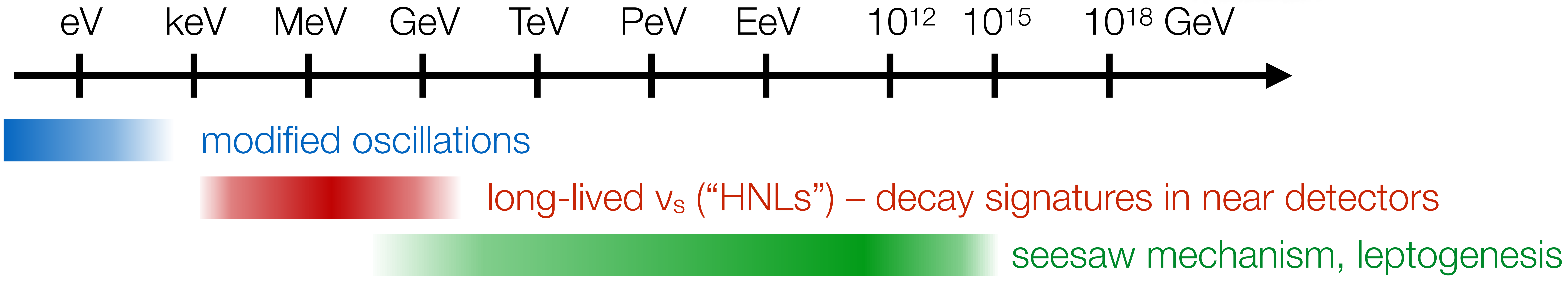
SM lepton doublet — SM Higgs doublet — sterile neutrino

Sterile Neutrinos



- Neutrino Portal: SM ν can mix with singlet fermions
  (sterile neutrinos = heavy neutral leptons = right-handed neutrinos)
  ➠ the only renormalisable SM coupling to singlet fermions
  (dark matter?)

$$\mathcal{L} \supset y\, \bar{L}\, (i\sigma^2 H^*)\, N$$



eV-Scale Sterile Neutrinos

- long-standing anomalies, no consistent explanation

LSND	$> 3\sigma$
MiniBooNE	$\sim 5\sigma$
reactor rates	resolved
gallium / radioactive source	$\sim 5\sigma$

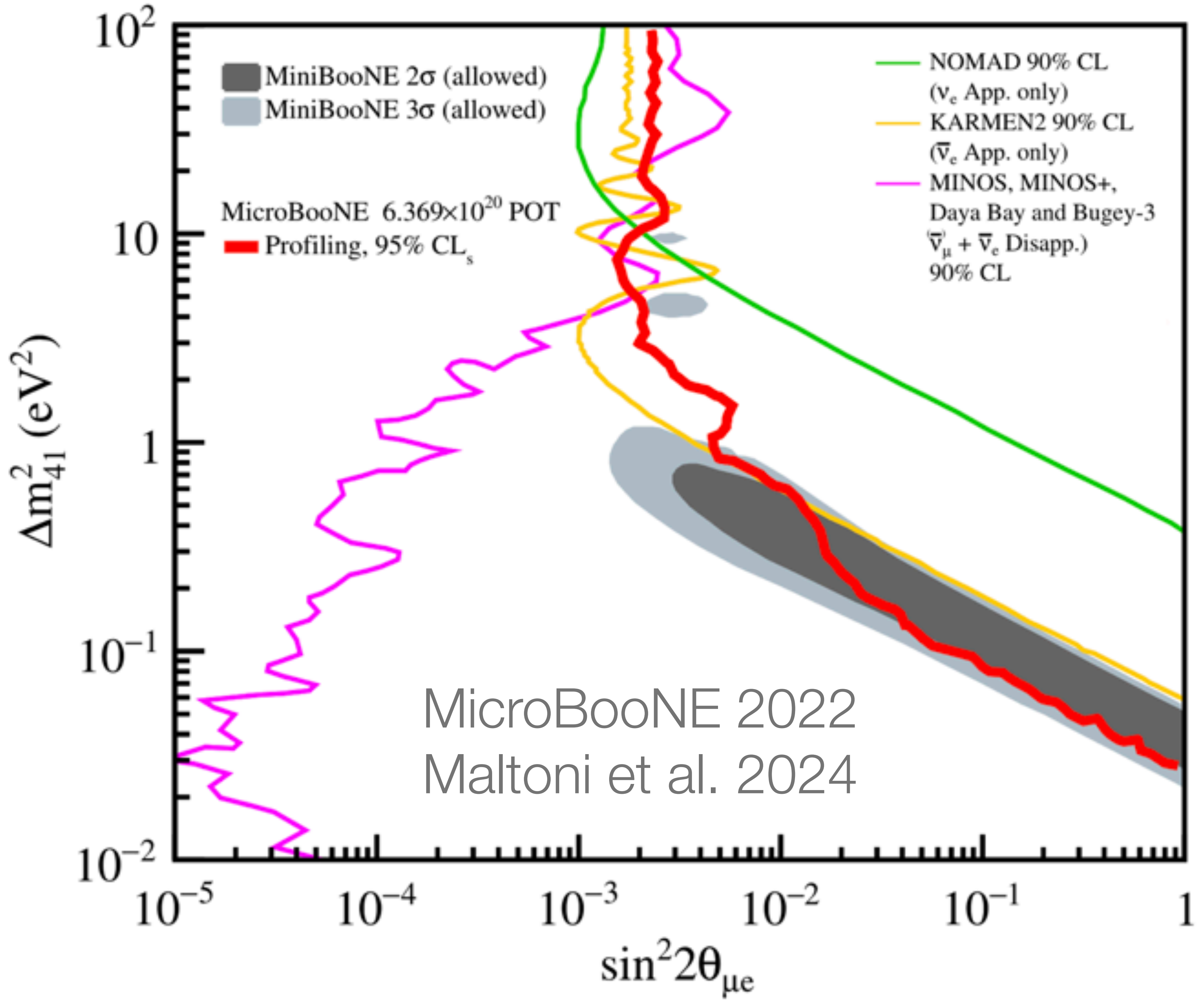
sterile ν interpretation
in tension with MicroBooNE

- vigorous experimental programme underway to resolve anomalies (SBN at FNAL)
  - expect important insights into ν interaction physics (or discover new physics)
- independent of anomalies sterile neutrinos remain an interesting possibility
  - integral part of BSM programme at upcoming experiments (DUNE, HyperK, JUNO, ...)
  - target windows in specific models

eV-Scale Sterile Neutrinos

- long-standing anomalies, no consistent explanation

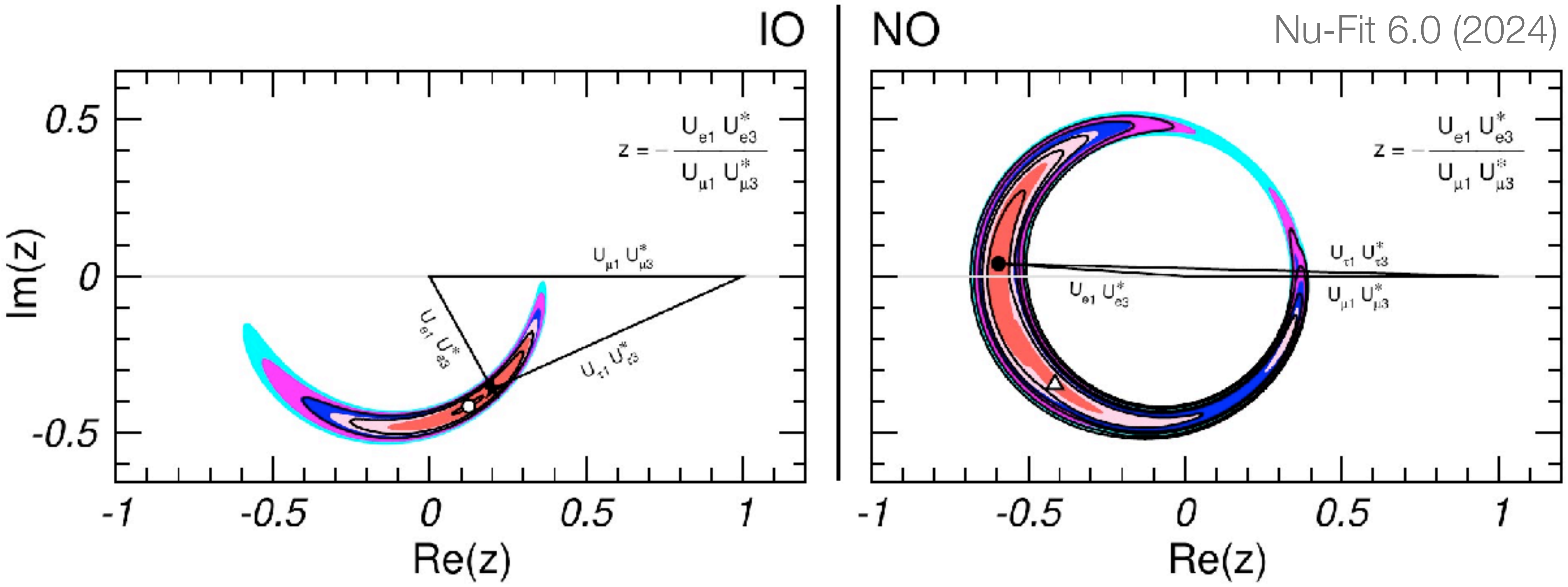
LSND	> 3σ
MiniBooNE	~ 5σ
reactor rates	resolved
gallium / radioactive source	~ 5σ



- vigorous experimental programme underway to resolve anomalies (SBN at FNAL)
  - expect important insights into ν interaction physics (or discover new physics)
- independent of anomalies sterile neutrinos remain an interesting possibility
  - integral part of BSM programme at upcoming experiments (DUNE, HyperK, JUNO, ...)
  - target windows in specific models

Heavy Neutral Leptons

- sterile neutrinos with $m \gtrsim$ MeV
- can be produced in meson decays
- long-lived ➠ detection via downstream decay
- inaccesible in oscillation experiments ➠ effective PMNS matrix non-unitary

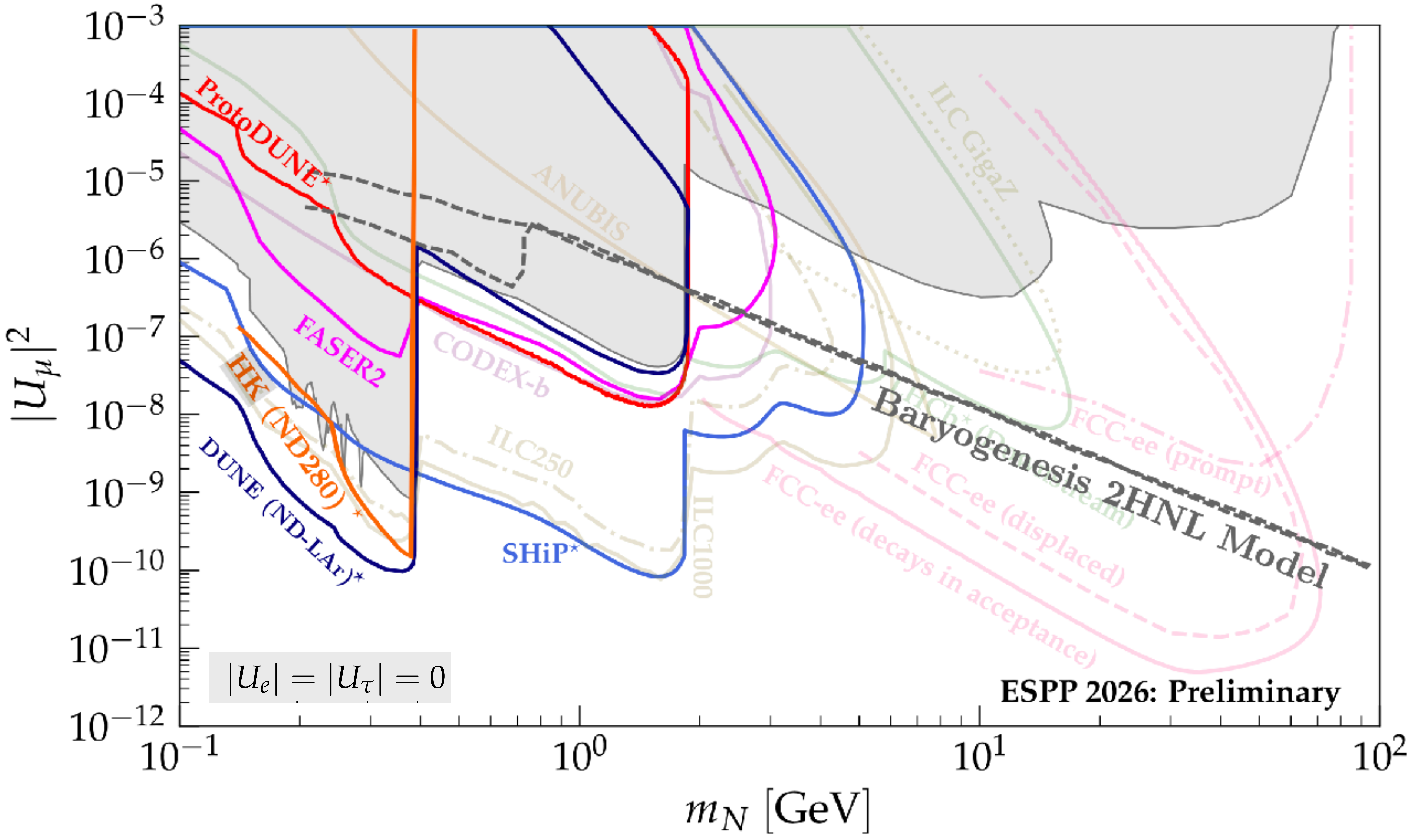


Heavy Neutral Leptons

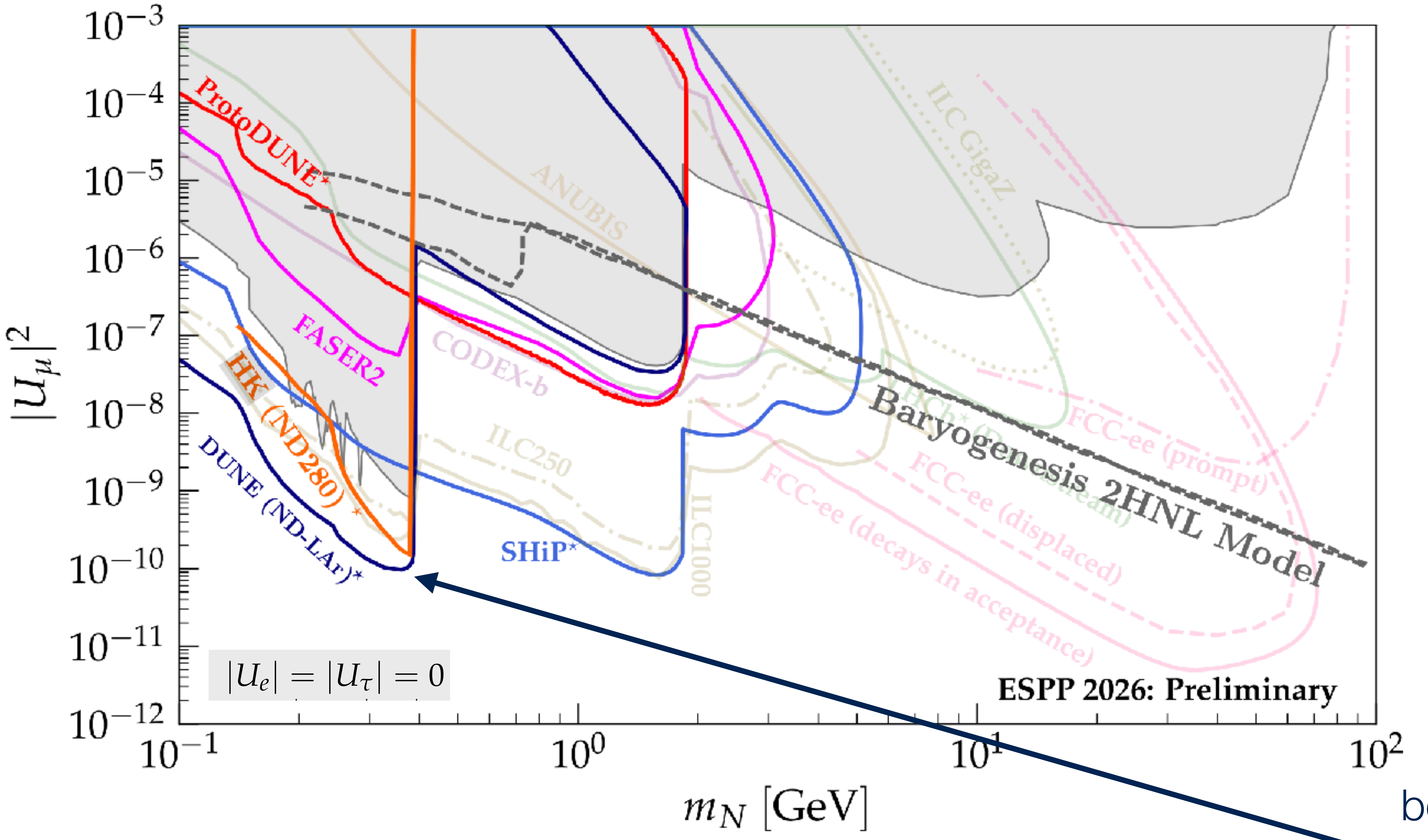
Fernandez-Martinez et al. 2023 / Hostert 2025 (GitHub)

- vast open parameter space
- target windows in specific models

Heavy Neutral Leptons

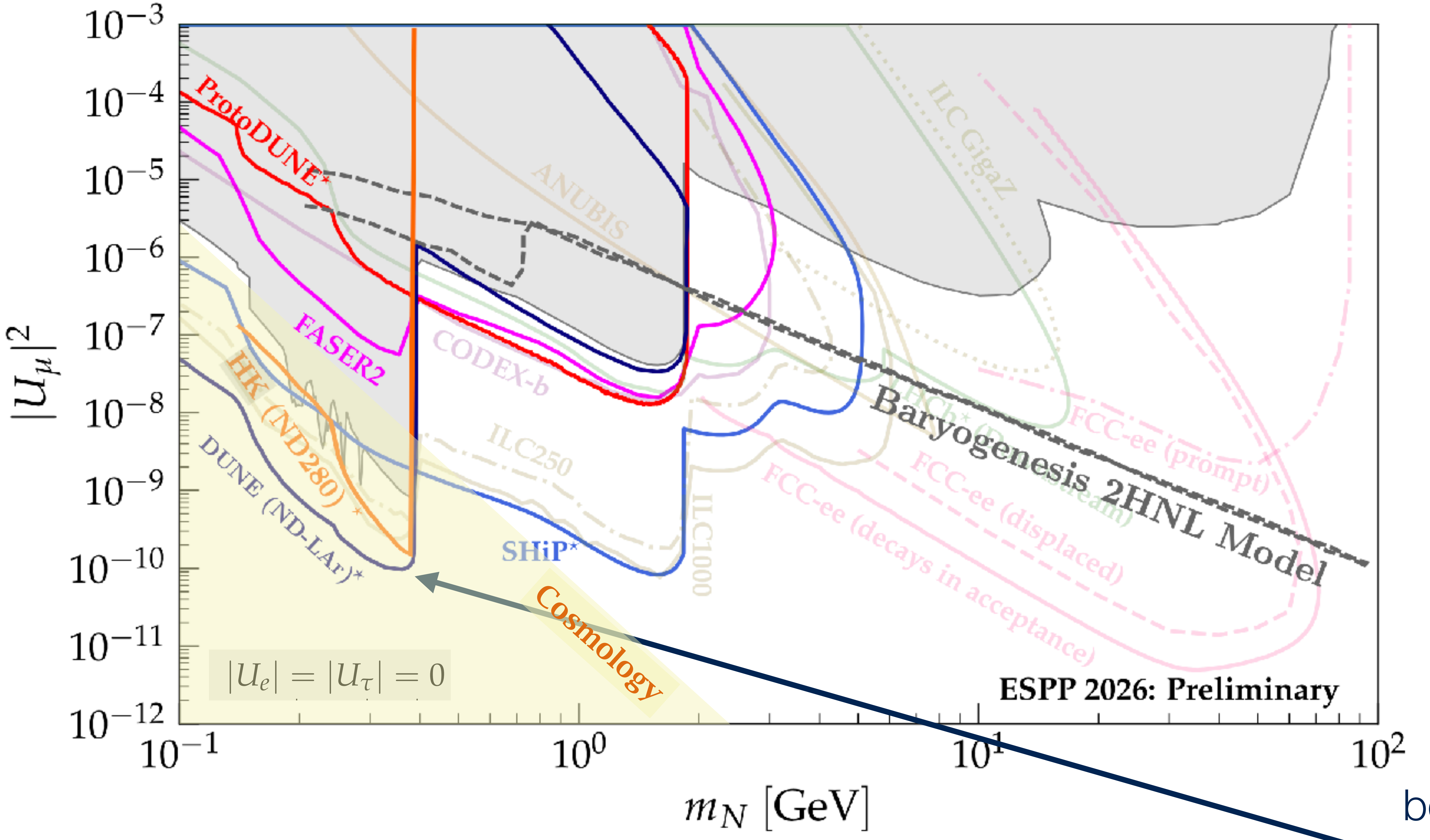


Heavy Neutral Leptons



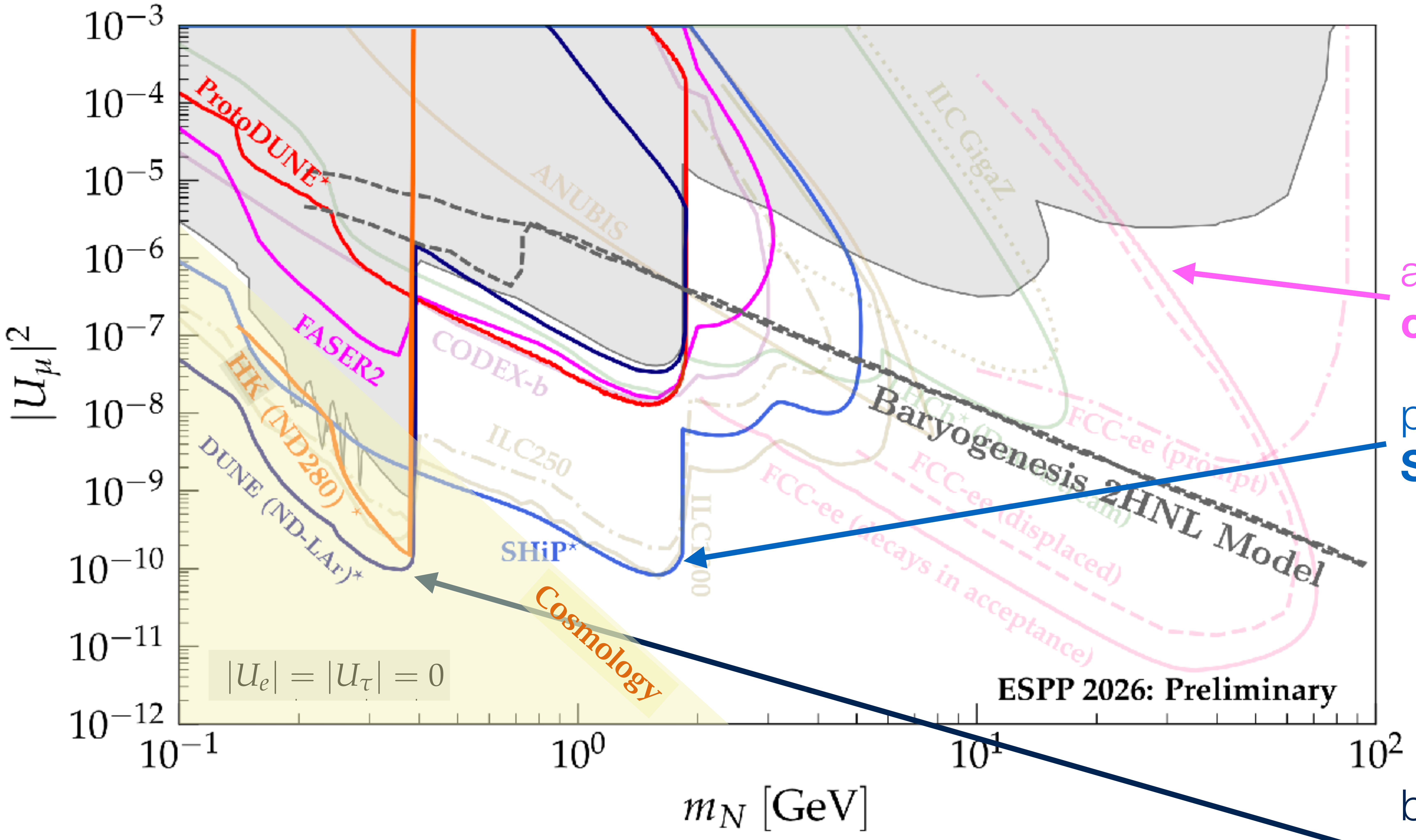
below kaon threshold:
neutrino beams dominate
(but cosmologically disfavoured)

Heavy Neutral Leptons



below kaon threshold:
neutrino beams dominate
(but cosmologically disfavoured)

Heavy Neutral Leptons



at the highest masses
colliders

production in charm/bottom decay:
SHiP / SPS dominate

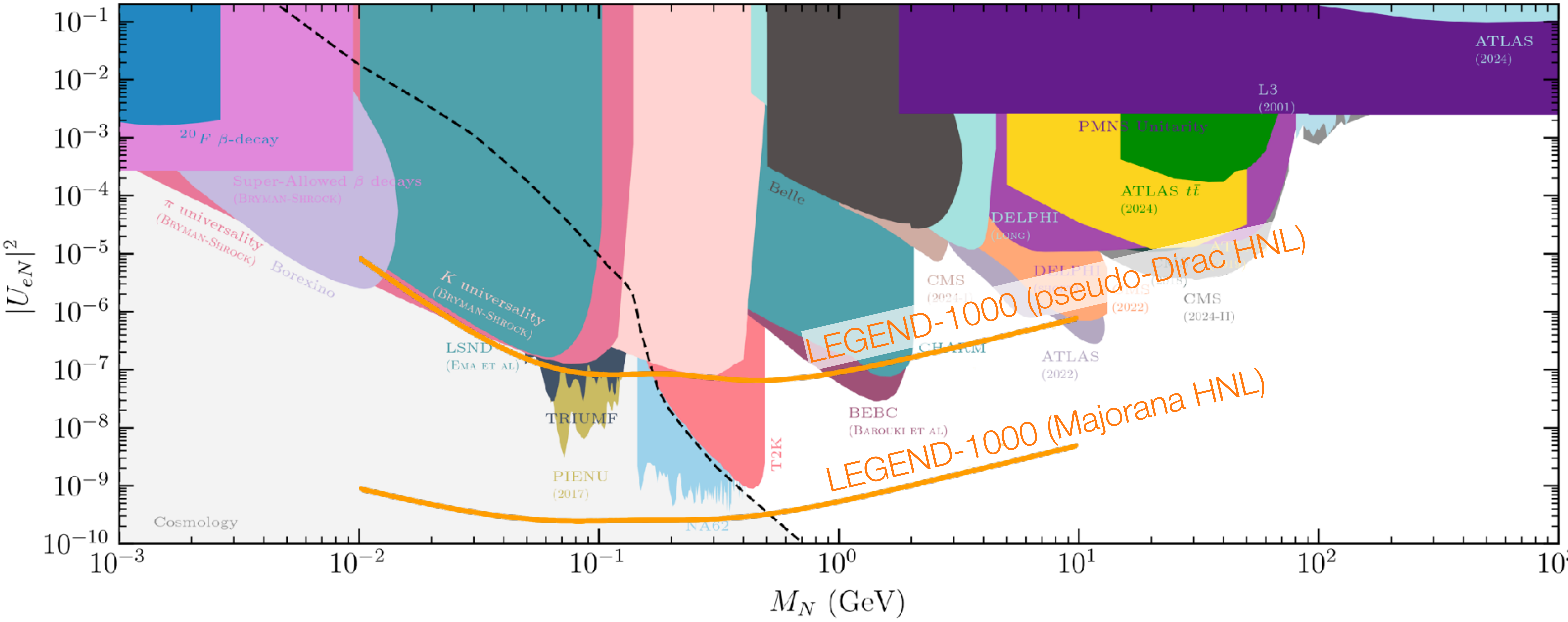
below kaon threshold:
neutrino beams dominate
(but cosmologically disfavoured)

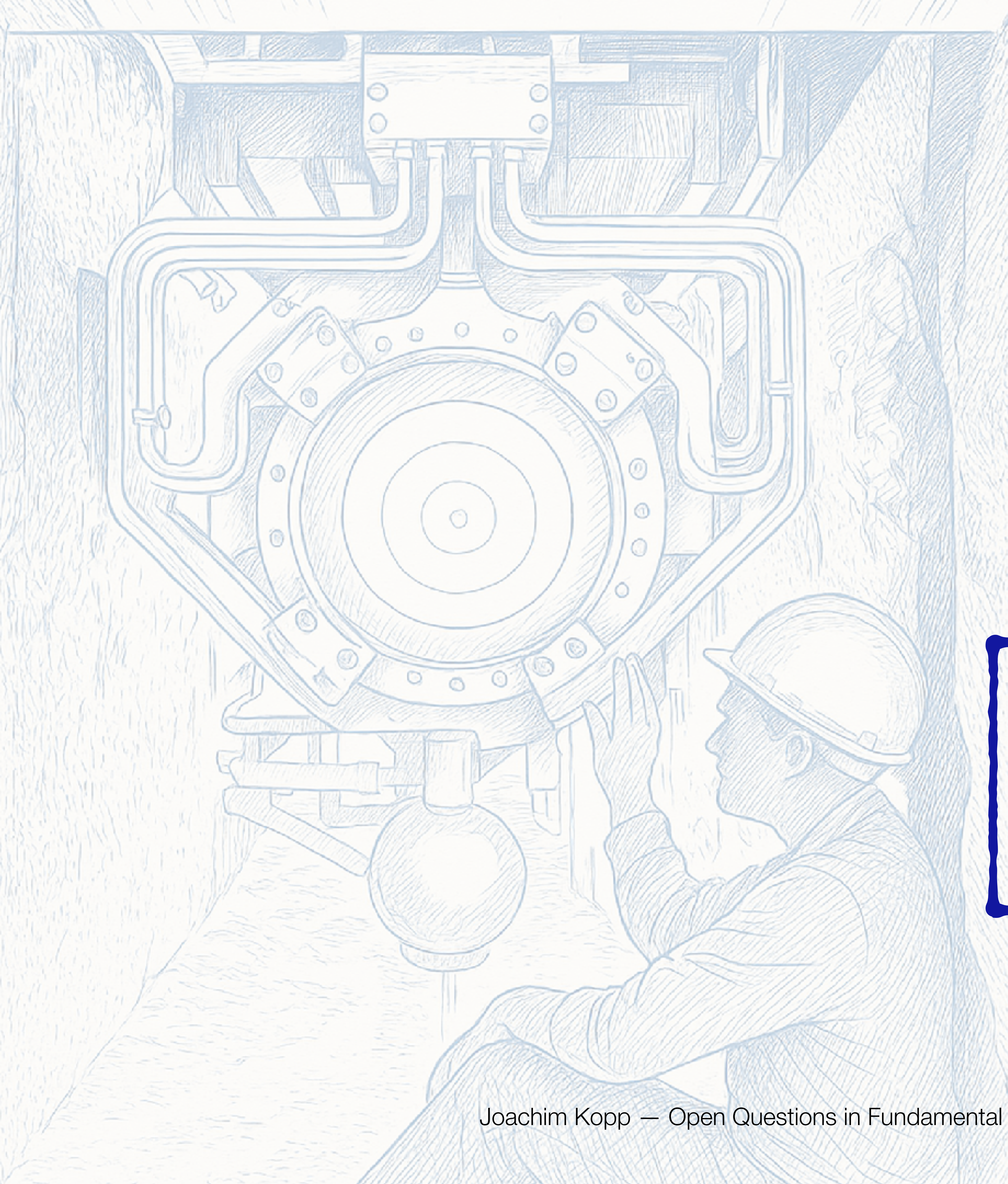
Heavy Neutral Leptons (coupling to electrons)

Fernandez-Martinez et al. 2023 / Hostert 2025 (GitHub) / Bolton et al. 2022

Heavy Neutral Leptons (coupling to electrons)

Fernandez-Martinez et al. 2023 / Hostert 2025 (GitHub) / Bolton et al. 2022





Dark Sectors

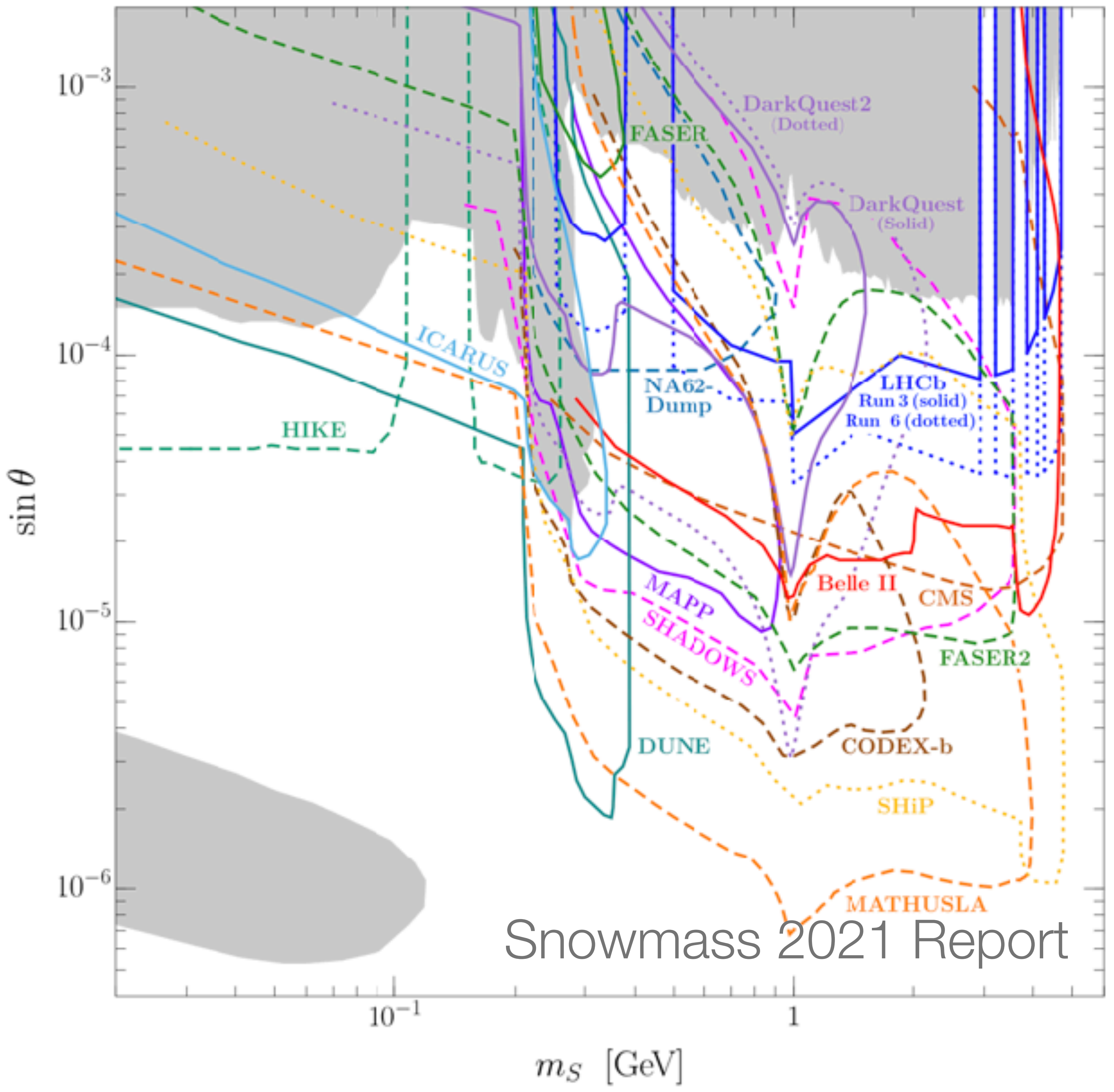
Long-Lived Particles at Neutrino Beams

- huge luminosities ➠ great for producing feebly interacting particles
- large detectors which excel in
  - event reconstruction
  - timing
  - spatial resolution
  - background suppression
- main players
  - DUNE (1.2–2.3 MW beam, 60–120 GeV)
  - T2K / SuperK / HyperK (0.8–1 MW beam, 30 GeV)
  - Fermilab short-baseline programme (0.05 MW, 8 GeV, currently taking data)
  - SPS @ CERN (0.35 MW, 400 GeV)
  - FASER / SND@LHC / FPF (~ TeV neutrinos)
  - CEvNS

Decay Signatures: Examples

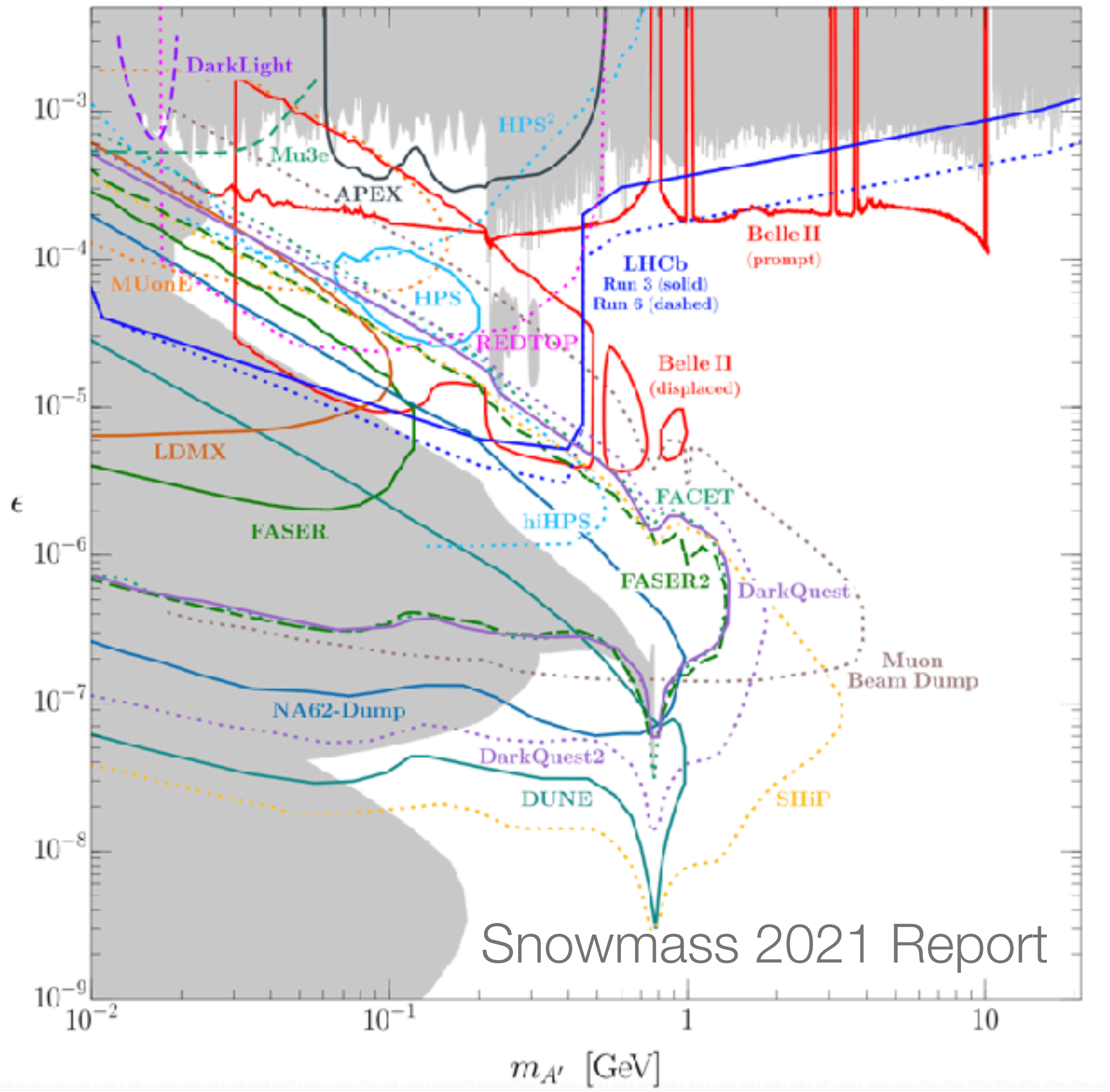
Higgs Portal Scalar

(production via meson decay, bremsstrahlung, Drell–Yann; decay to SM pairs)



Dark Photons

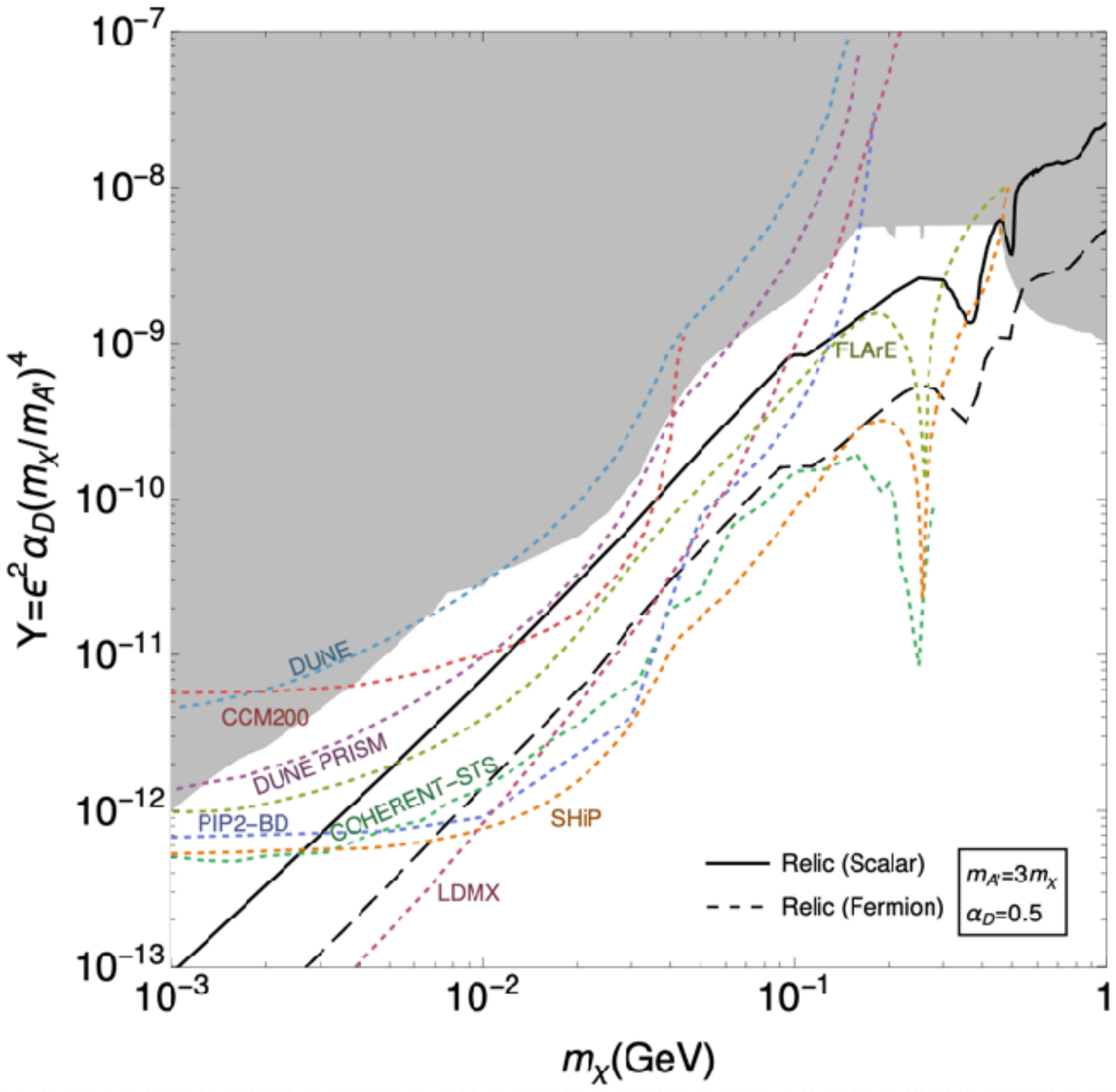
(production via meson decay, bremsstrahlung, Drell–Yann; detection via decay, tridents)



Scattering Signatures: Examples

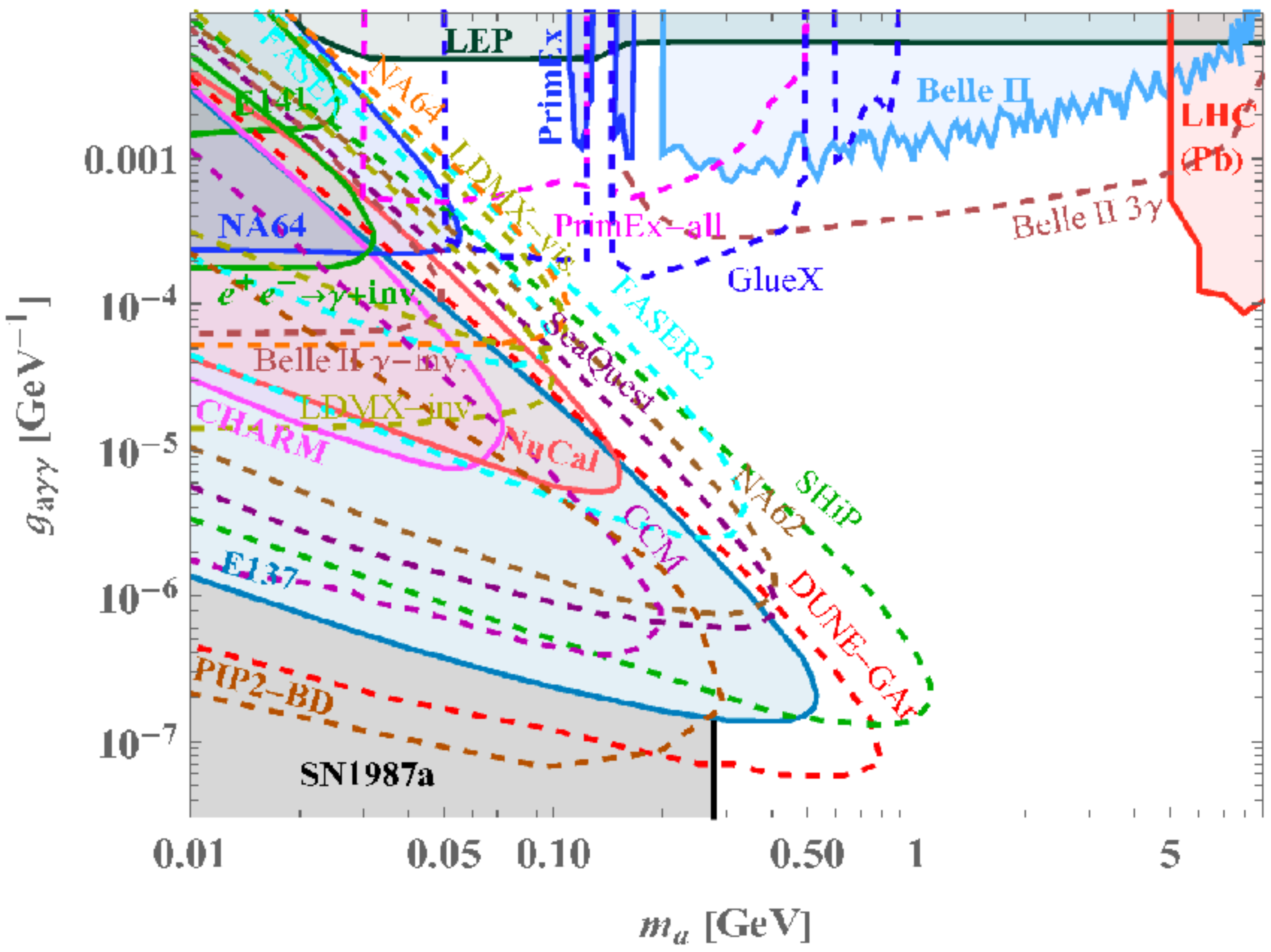
Vector Portal DM

(production via A' decay in the target
detection via scattering)



Axion-Like Particles

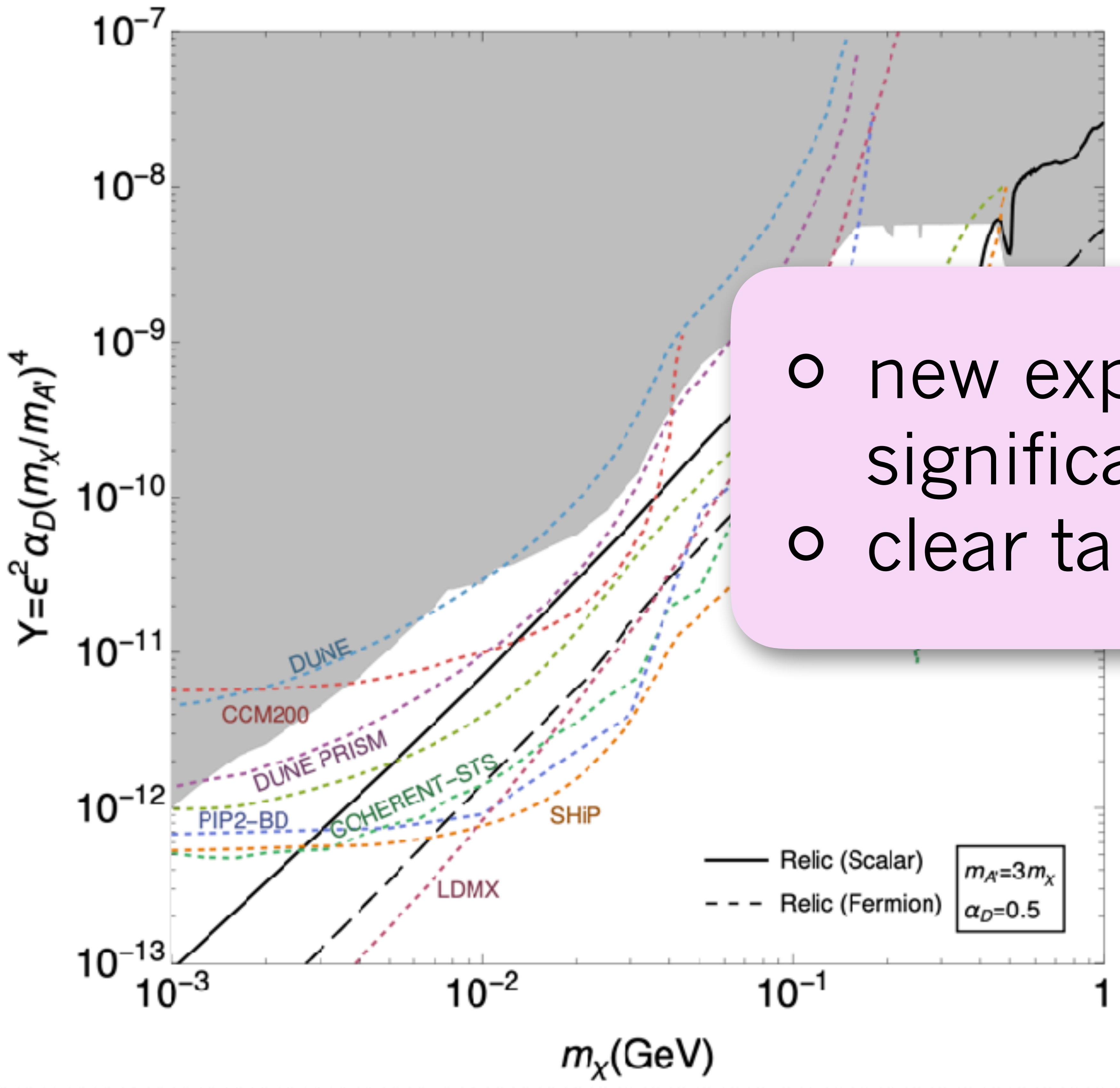
(production via Primakoff, Compton, nuclear reactions;
detection via decay, scattering)



Scattering Signatures: Examples

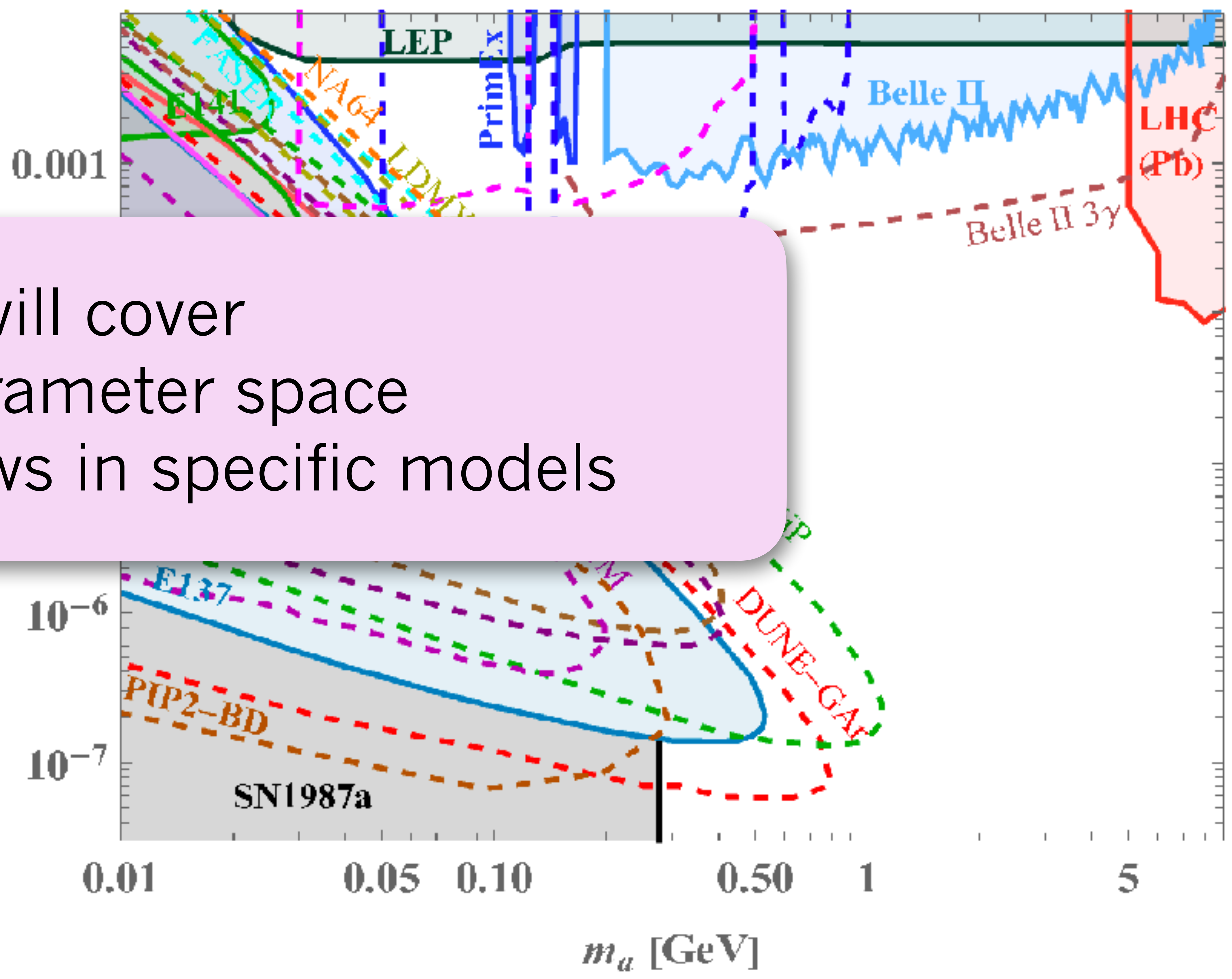
Vector Portal DM

(production via A' decay in the target detection via scattering)



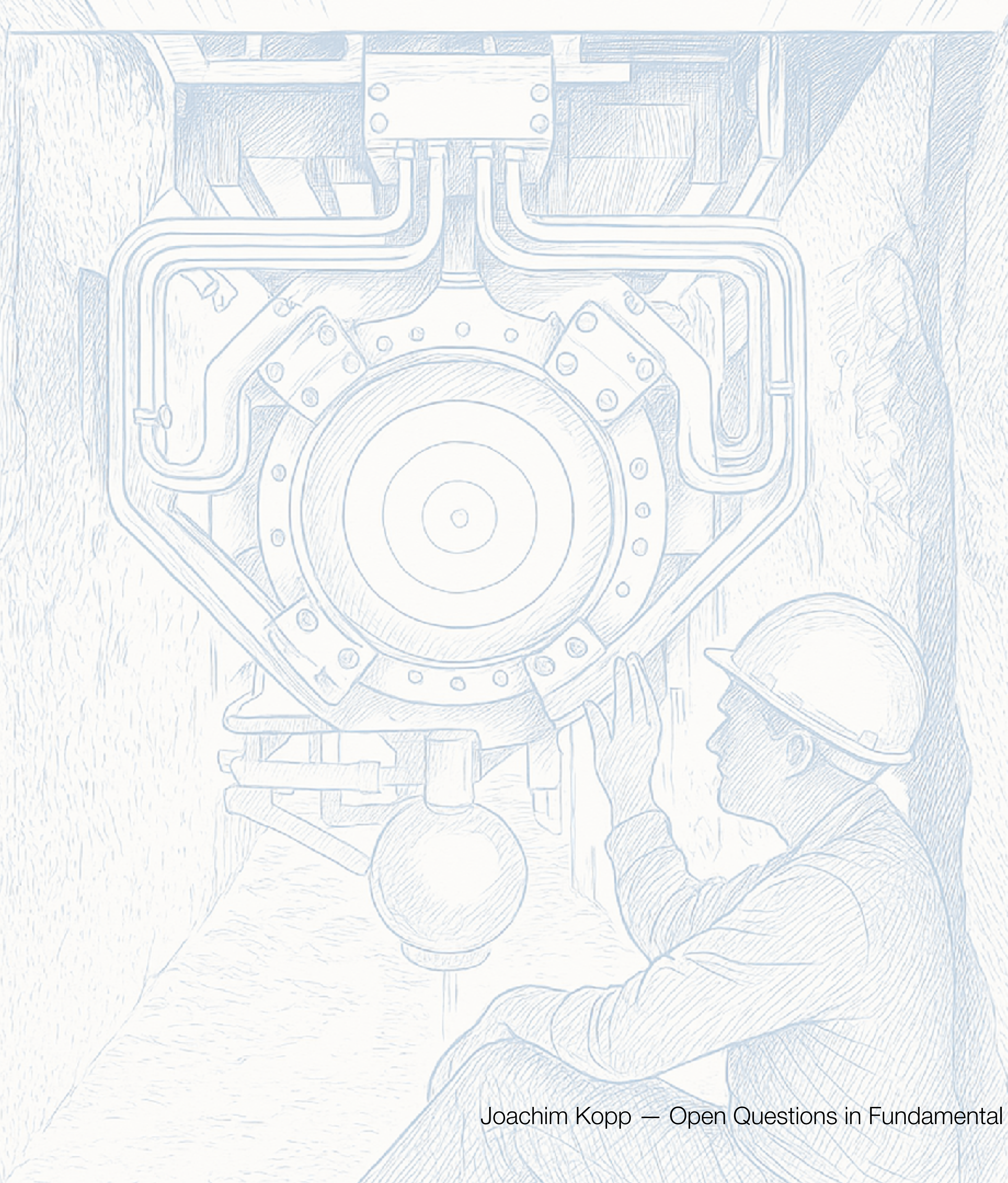
Axion-Like Particles

(production via Primakoff, Compton, nuclear reactions; detection via decay, scattering)



- new experiments will cover significant new parameter space
- clear target windows in specific models

Summary



Summary

Sterile Neutrinos

- very generic (➠ part of dark sector)
- target windows in specific models
- only detectable in neutrino experiments via oscillation or decay ("HNLs")

Effective Field Theories

- highly competitive constraints on some (flavourful) operators
- model-dependent constraints more challenging

Dark Sectors

- MW-scale neutrino beams uniquely positioned
- cover broad range of motivated models