^{76}Ge Double Beta Decay in Context

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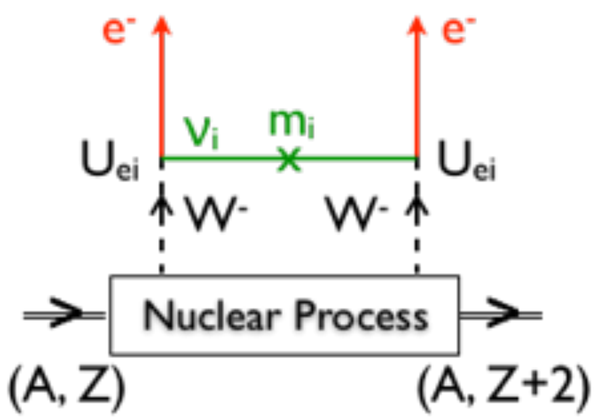
Meeting on the Next Generation ^{76}Ge Experiment
Munich, Germany, Apr. 25, 2016

Outline

- $0\nu\beta\beta$ searches in the context of “vanilla” Majorana Standard Model neutrinos and the global effort to measure the neutrino mass ordering
- $0\nu\beta\beta$ searches in the context of “non-vanilla” models and accelerator searches
- Reaching the required sensitivity in next generation experiments

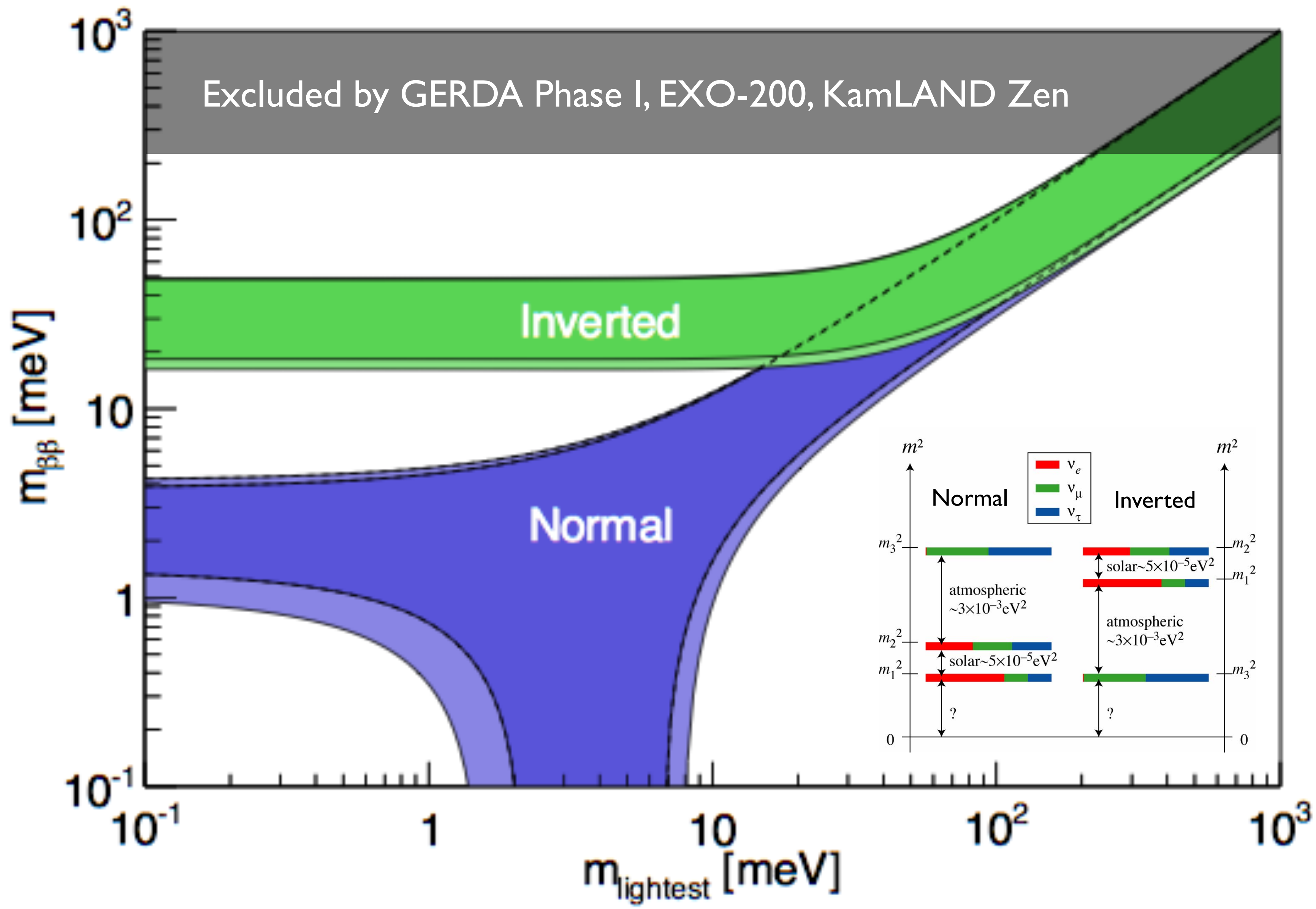
SM Neutrino = Majorana



$m_{\beta\beta} = | \Sigma\, m_i\, U_{ei}^2 |$

Goal 1: $m_{\beta\beta}$ ~ 15 meV

Goal 2: $m_{\beta\beta}$ ~ 1 meV



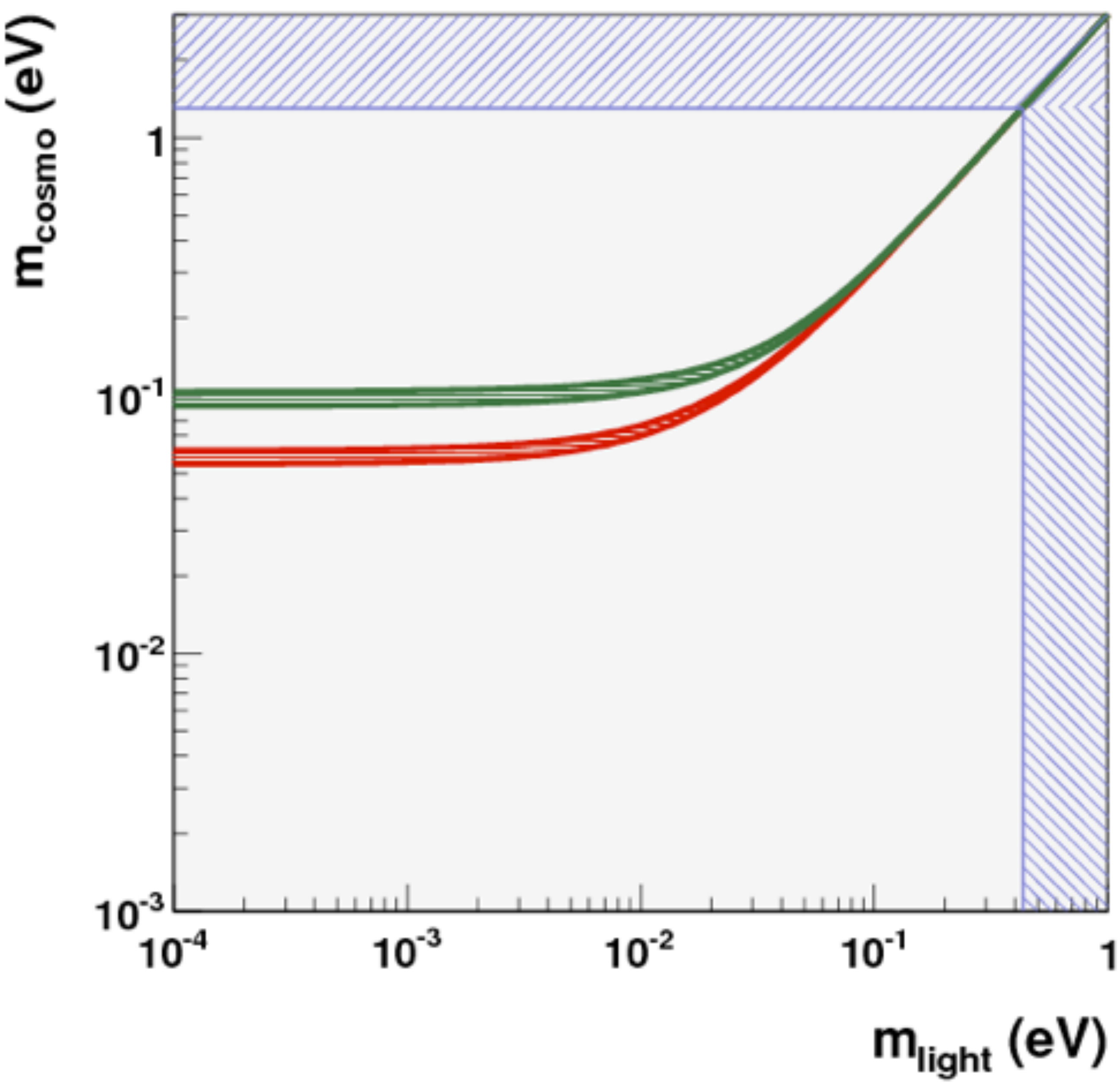
0νββ is the best probe at present

ν Hierarchy Vs. Ordering

- Ordering: do the ν masses have a normal or inverted ordering?
  - Relevant for 0νββ only if ν masses are hierarchical

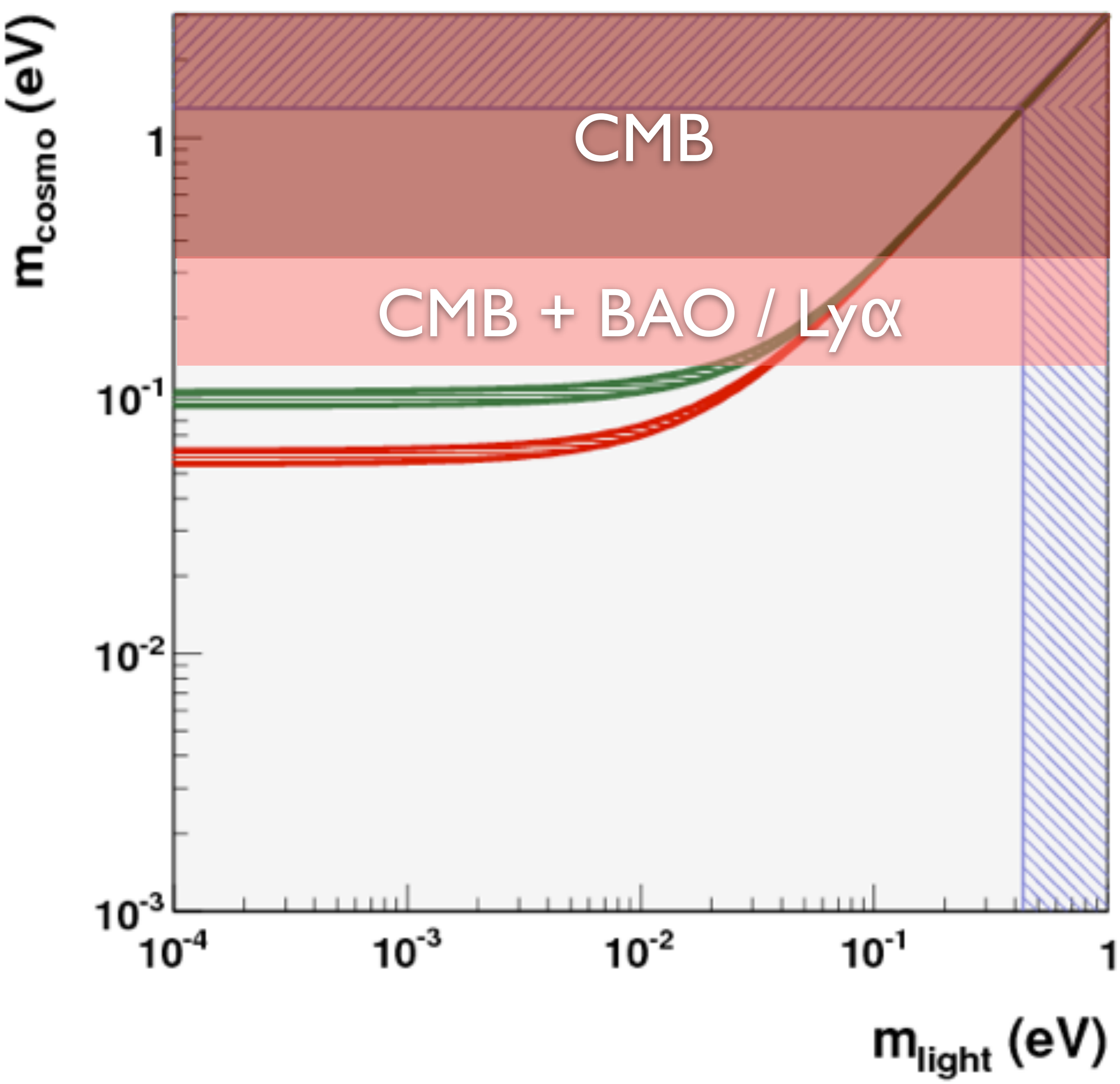
- Hierarchy: are ν masses similar (quasi-degenerate) or very different (“hierarchical”)
  - To be addressed definitively by KATRIN soon
  - Model dependent preference for hierarchical neutrinos (Normal Ordering) from cosmology

Cosmological Limits on Σm_i



 Gomez-Cadenas *et al*. Riv. Nuovo Cim. **35**, 29 (2012).

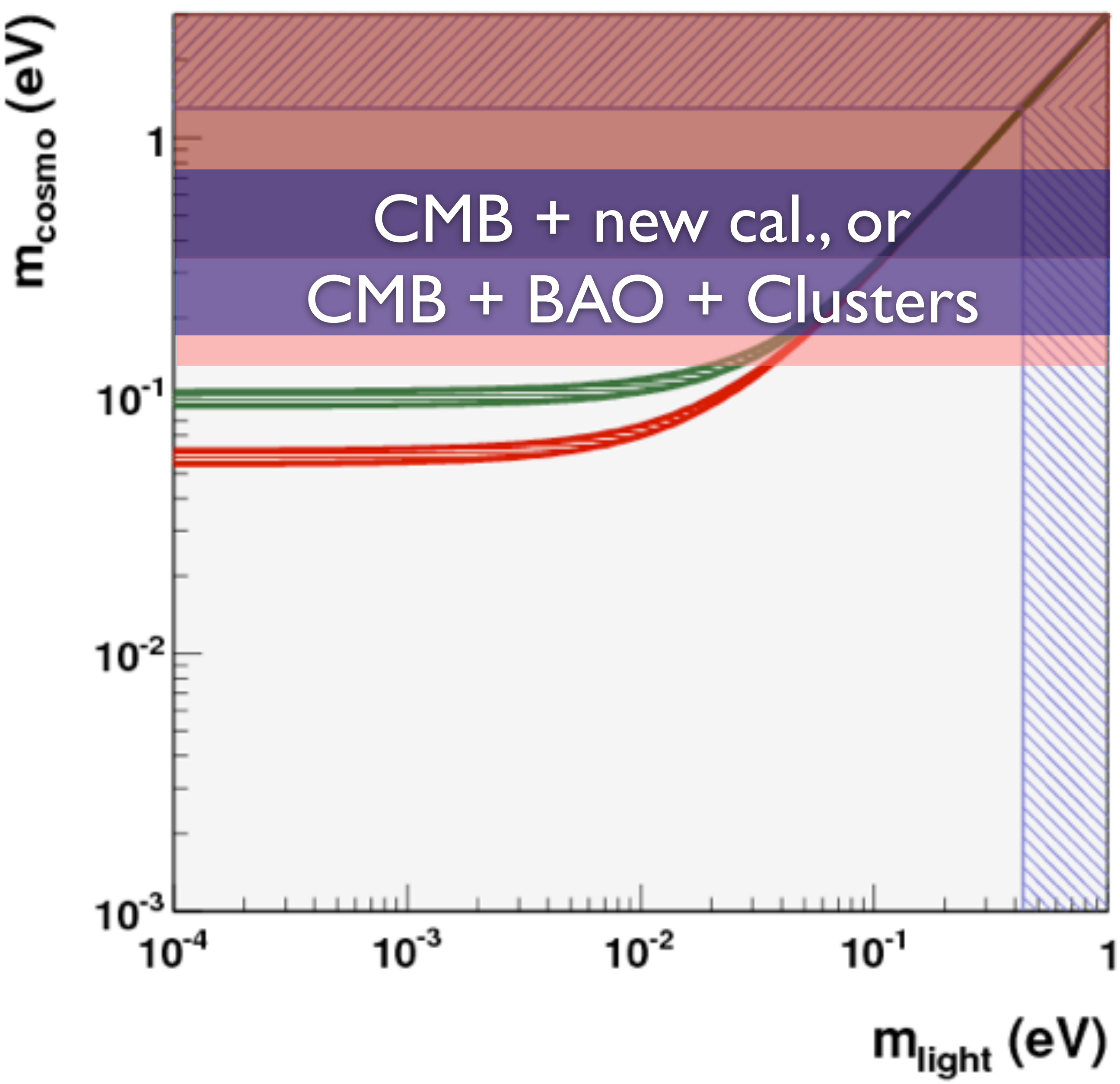
Cosmological Limits on Σm_i



Exclusion

e.g. Palanque-Delabrouille *et al.*, JCAP **1502** 045 (2015).

Cosmological Limits on Σm_i



Exclusion

Inclusion

e.g. Böhringer and Chon, A&A 574, L8 (2015).

Cosmological Limits on Σm_i

- Rely on vanilla ΛCDM and tensions between correlated parameters with large systematics.
  - Can go from from strong exclusions to evidence of neutrino mass at 3x limit e.g. by letting a calibration systematic float

- Preference for NO over IO in exclusions is parametric: due to lack of evidence for ν masses in those exclusions
  - IF nothing is seen, Inverted Ordering will always “look” more excluded
  - Must *see* something by 50 meV while definitively excluding something at 100 meV to “decide” ordering and impact 0νββ searches

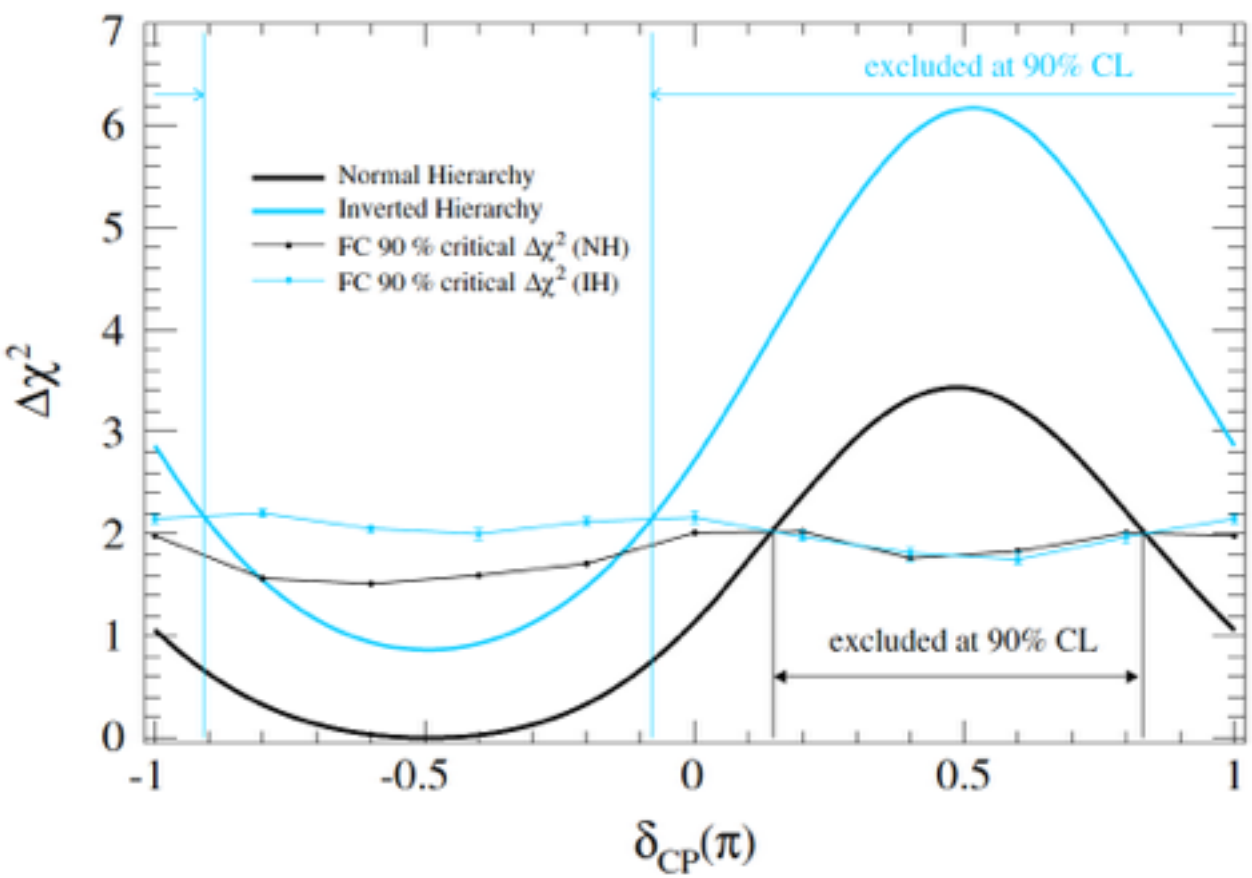
- Multi-$B cosmology experiments over the next decade would benefit greatly from cheap ν mass parameter measurements on Earth

Terrestrial ν Hierarchy Tests

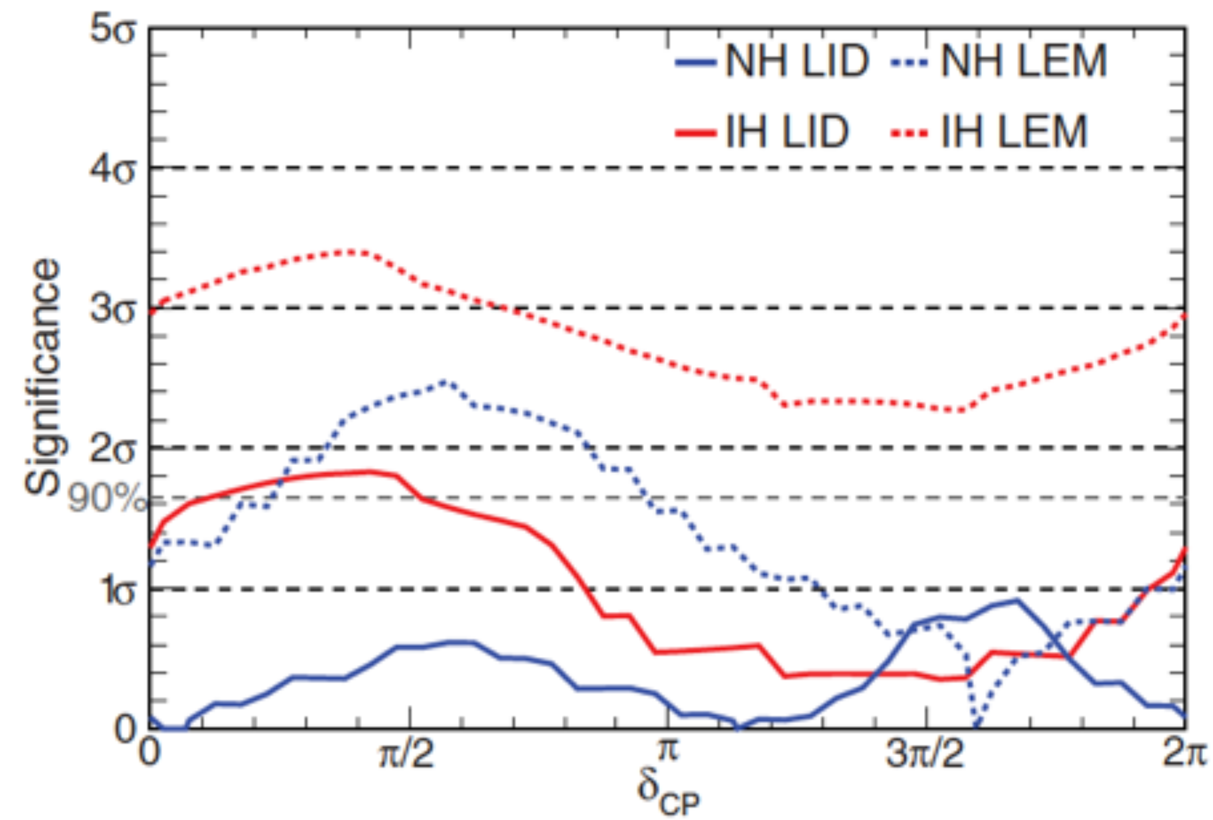
- Neutrino Beams
  - T2K + NOνA
  - DUNE / HyperK
- Reactor Neutrinos
  - JUNO
  - RENO-50
- Atmospheric Neutrinos
  - PINGU
  - DUNE / HyperK
  - SuperK, INO

ν Beams

T2K



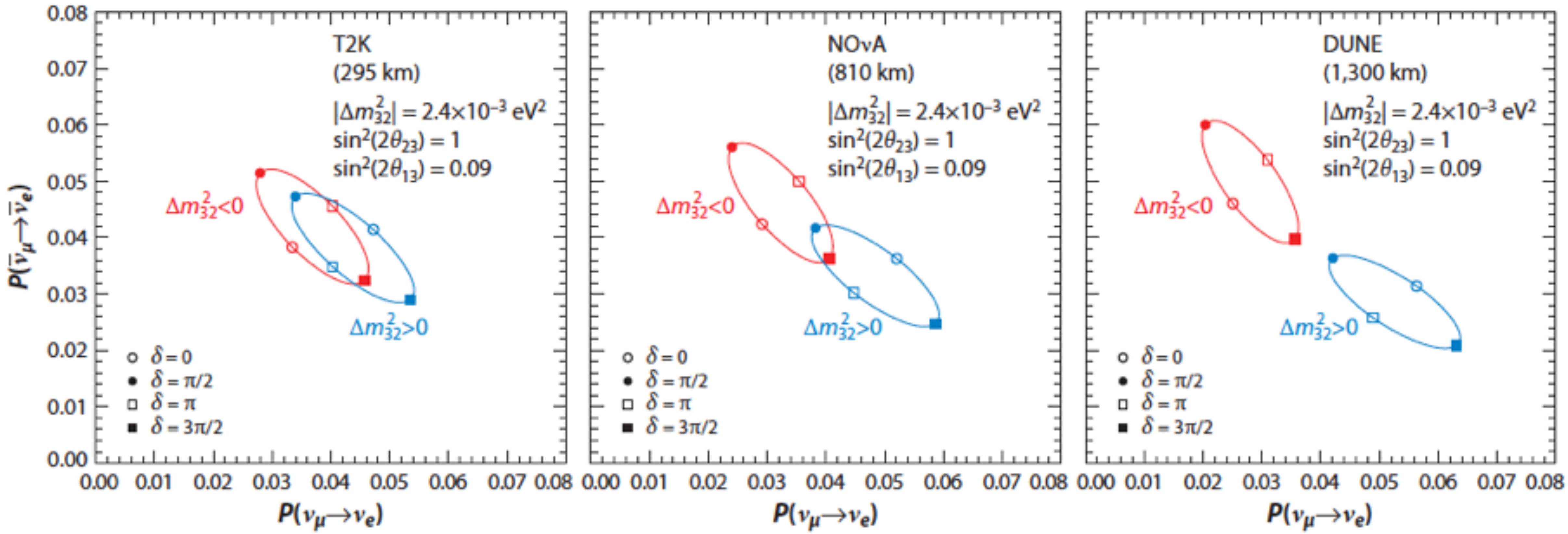
NOvA



T2K Collab., Phys. Rev. D **91**, 072010 (2015).
NOvA Collab., Phys. Rev. D **116**, 151806 (2016).

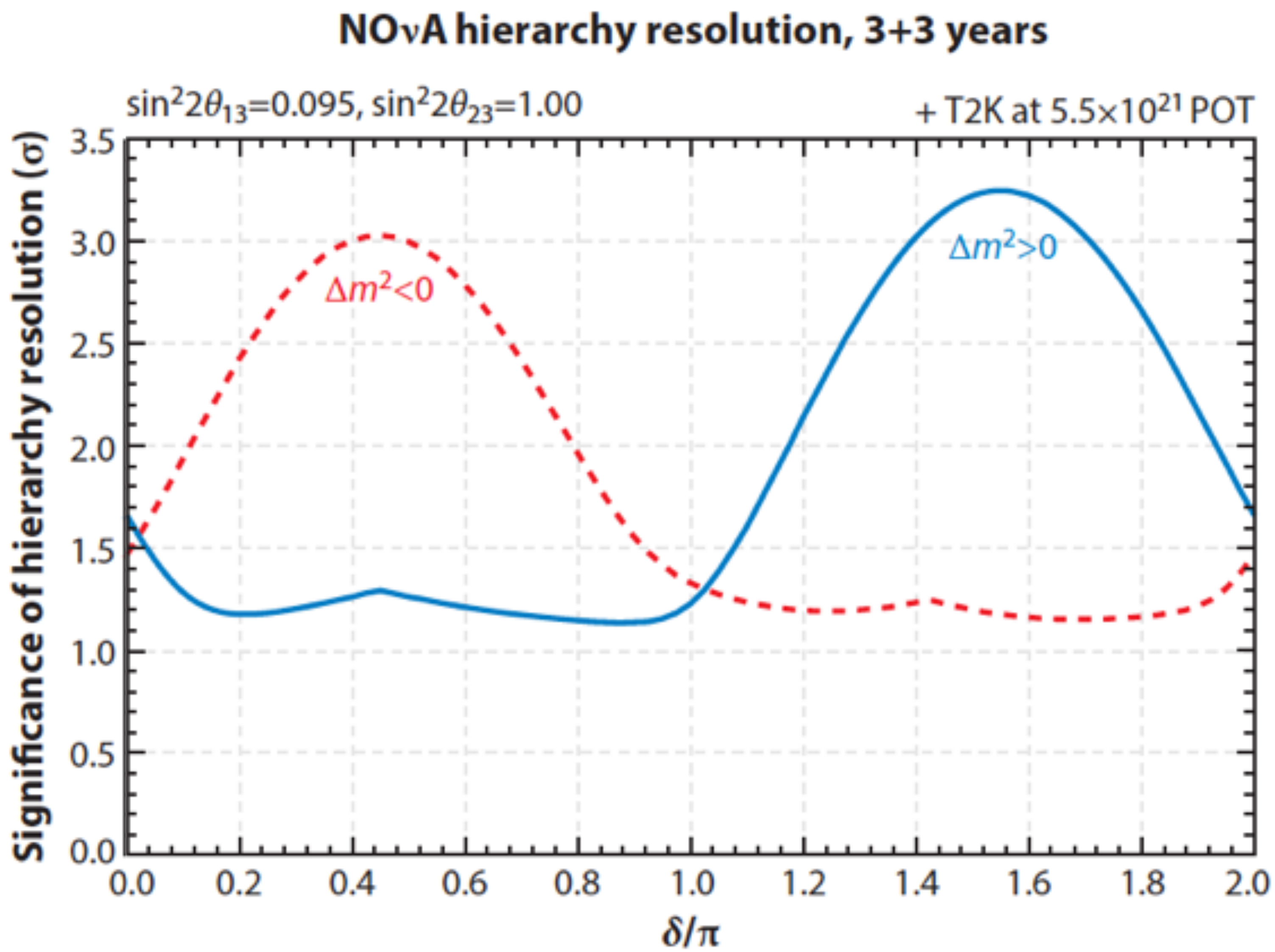
ν Beams

E.g. for L/E = 400 km/GeV:



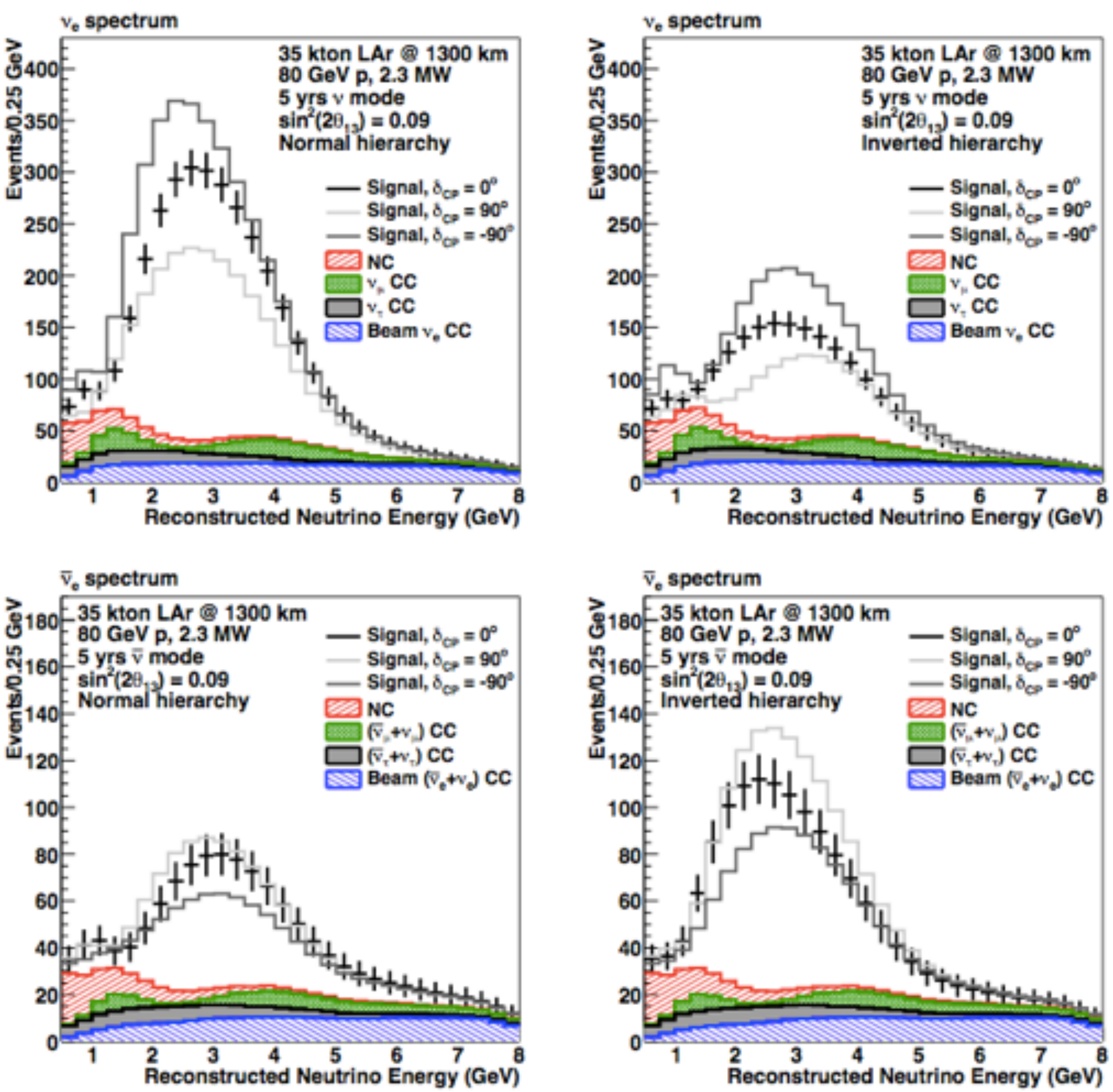
 Patterson, Annu. Rev. Nucl. Part. Sci. **65**, 177 (2015).

T2K + NOvA Sensitivity



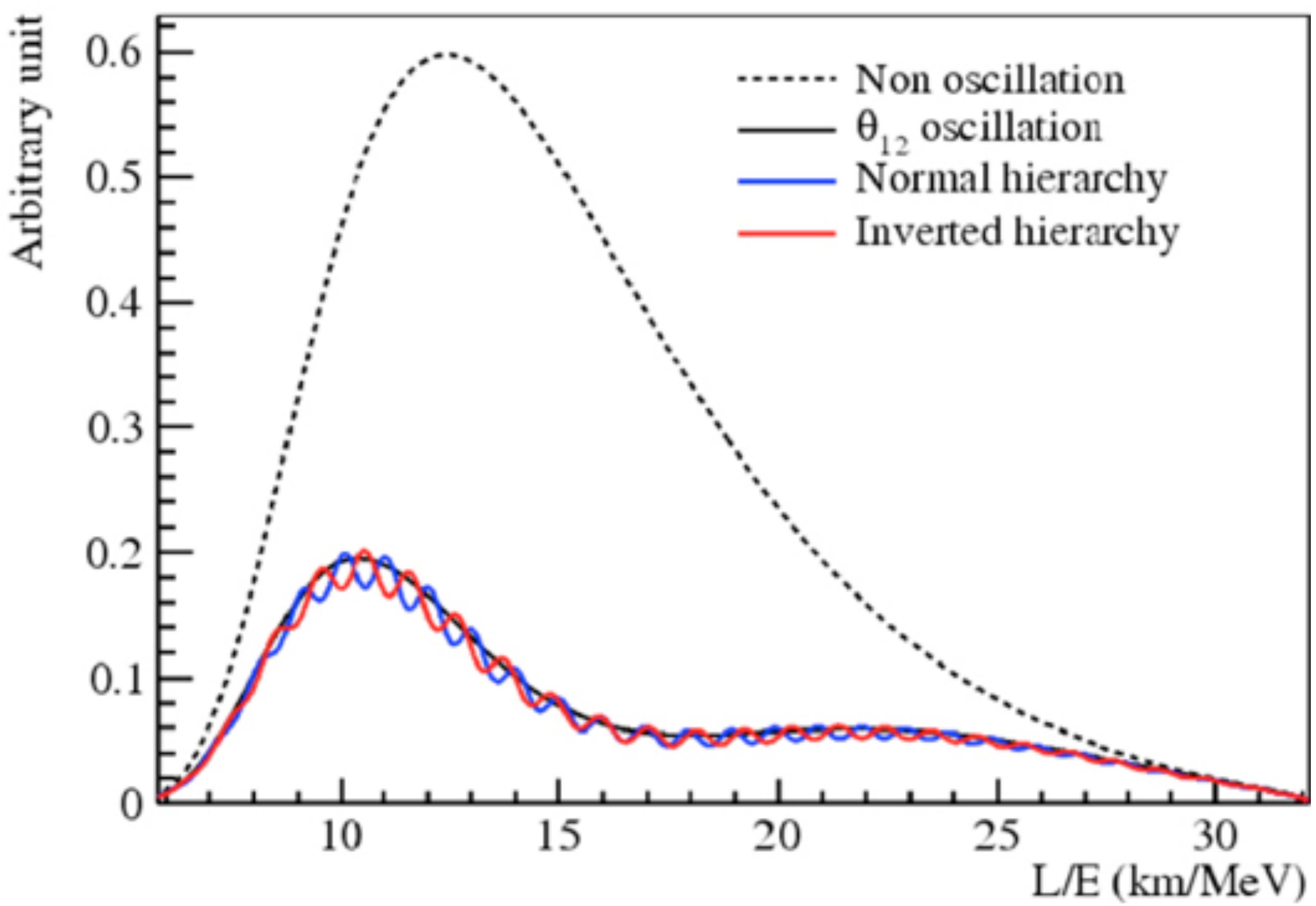
Patterson, Annu. Rev. Nucl. Part. Sci. **65**, 177 (2015).

Future ν Beams



- Whenever a difference is seen at low statistics, parametric dependence points to $\delta_{CP} = \pm\pi/2$ and preference for a hierarchy
- A definitive claim from future ν beams requires high statistics: more than a decade and O($B) from now

Reactor ν's



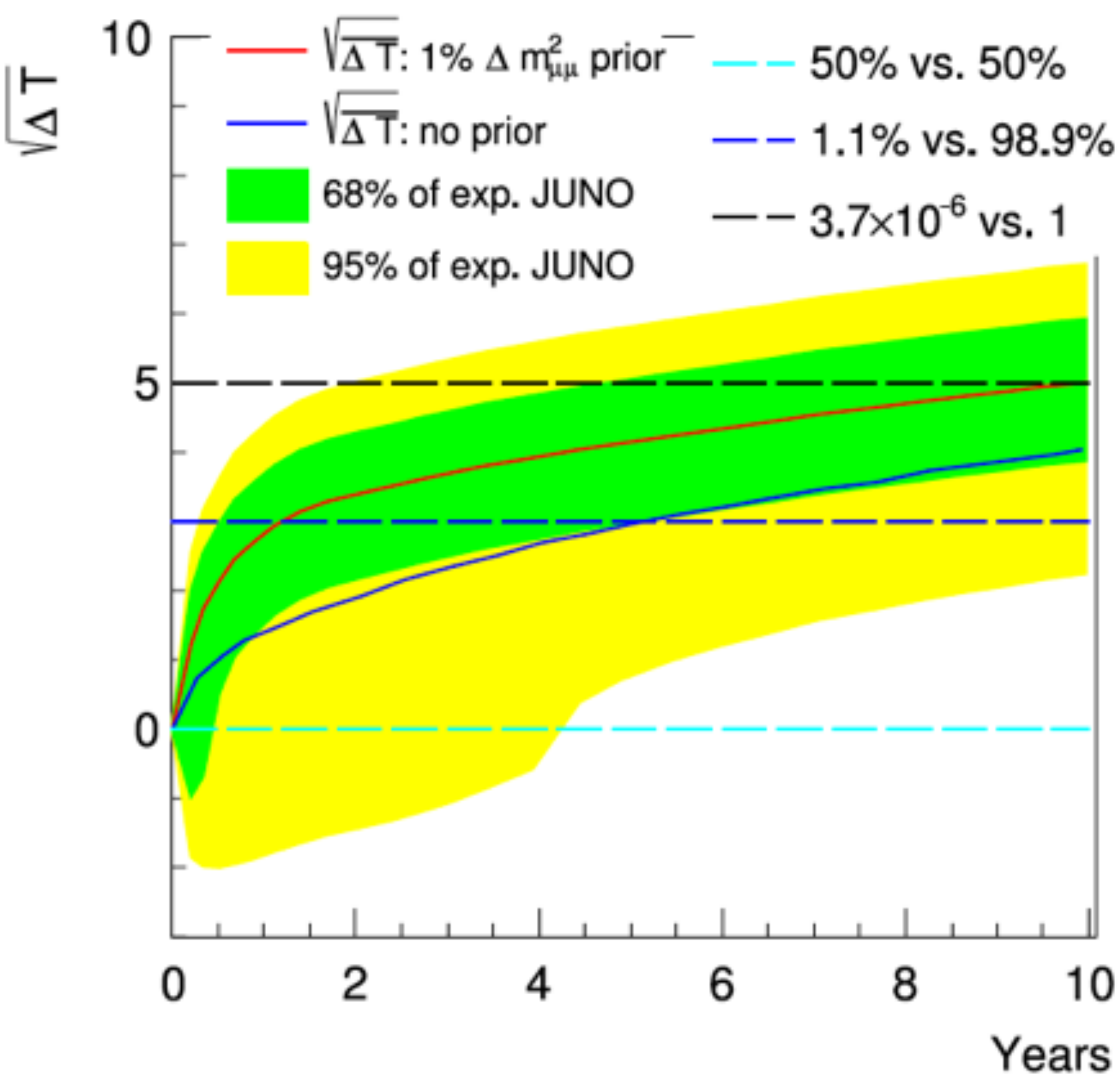
Challenges:

- Energy resolution
  - Photocathode coverage
  - PMT quantum ε
  - LS light yield
  - LS attenuation
- Degeneracies
  - E scale calibration
  - E scale non-linearity

JUNO Collab., J. Phys. G **43**, 030401 (2016).
See also e.g. Qian *et al.*, PRD **87**, 033005 (2013).

JUNO

(#σ)



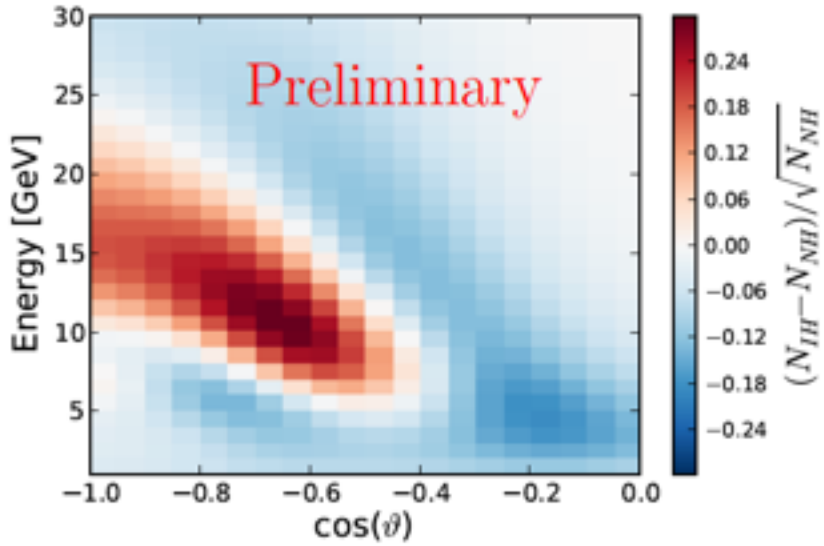
With LBL osc. results

JUNO alone

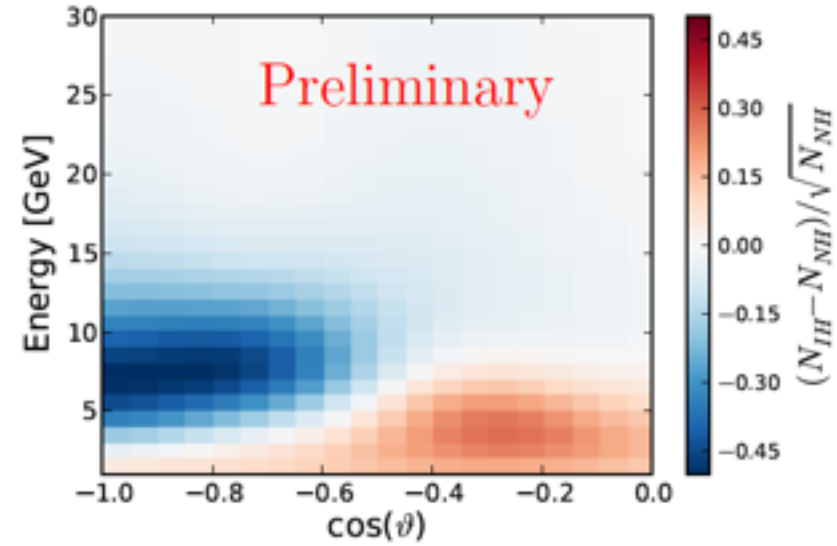
- Challenging experiments
- Definitive results 3-10 years after construction

Qian and Vogel, Prog. Part. Nucl. Phys. **83**, 1 (2015).

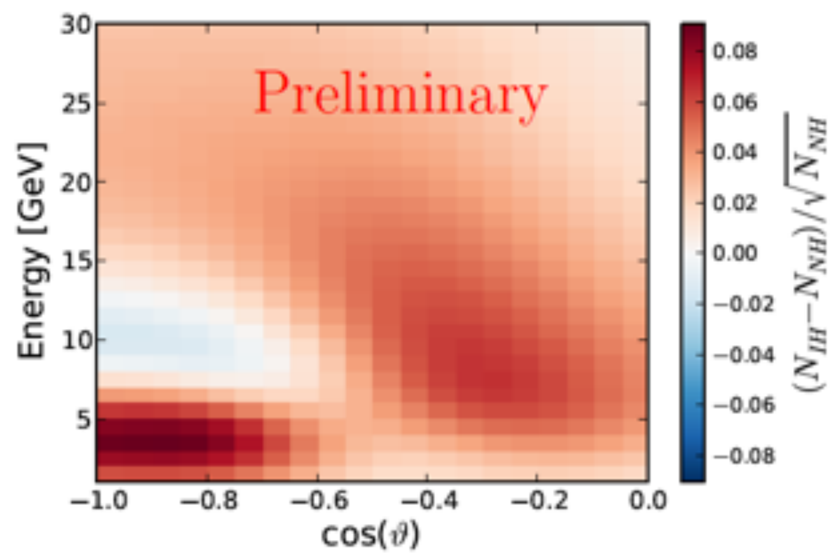
Atmospheric ν: PINGU



(a) ν_μ CC events.



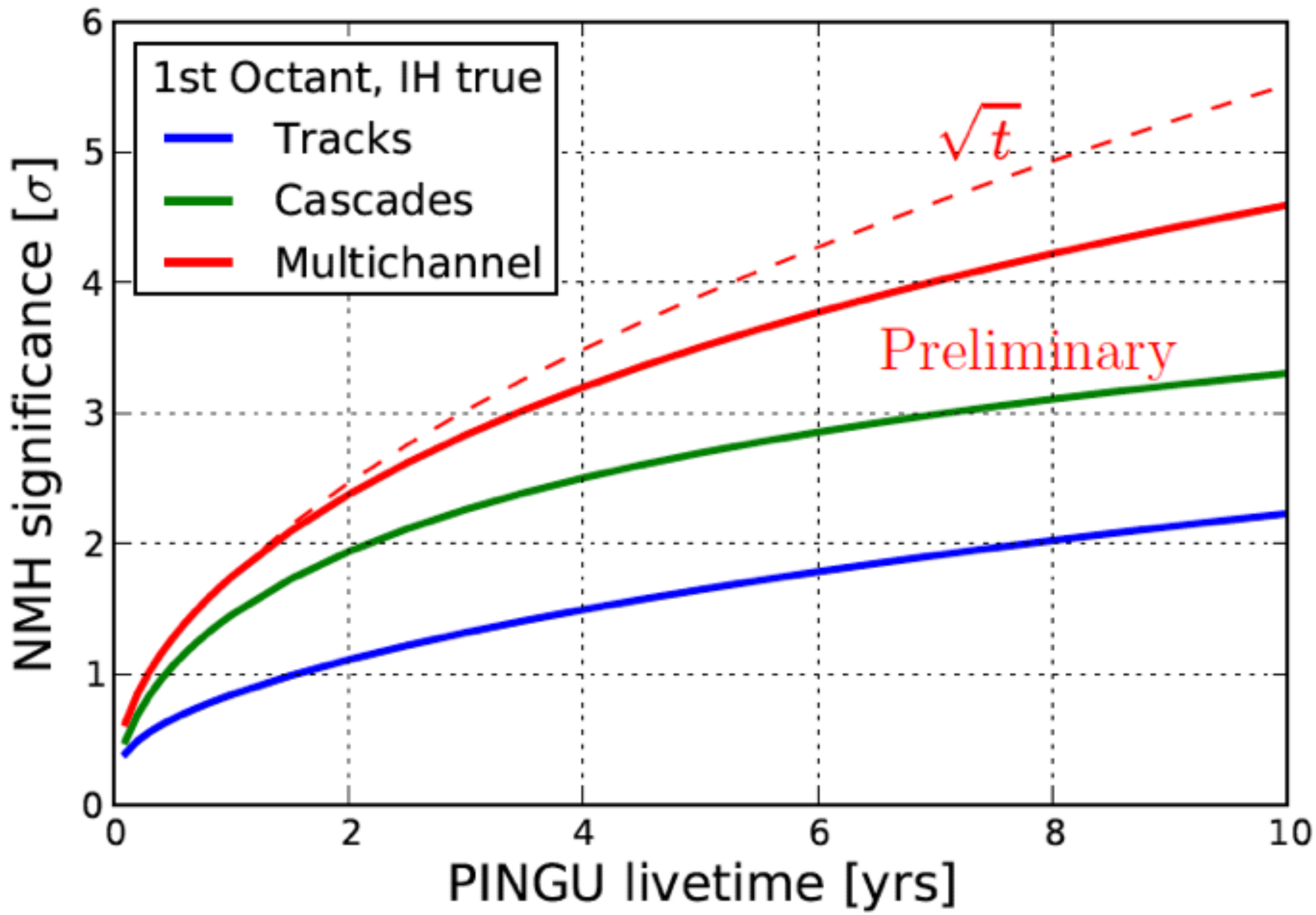
(b) ν_e CC events.



(c) ν_τ CC events.

 PINGU Collab., arXiv:1401.2046 (2014).

Atmospheric ν: PINGU



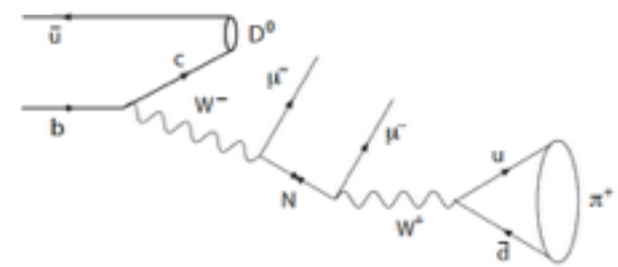
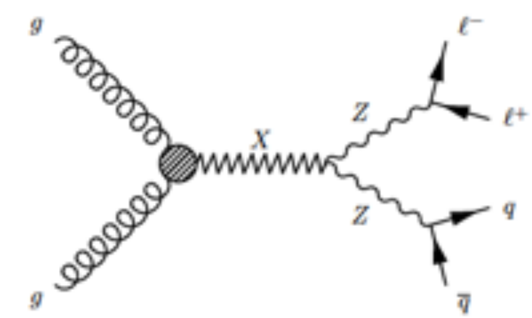
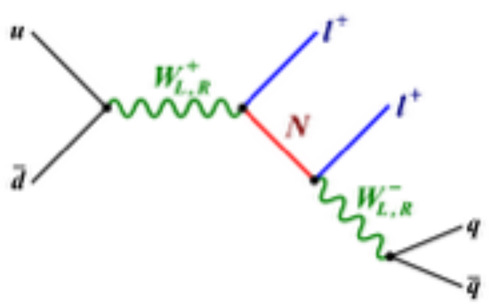
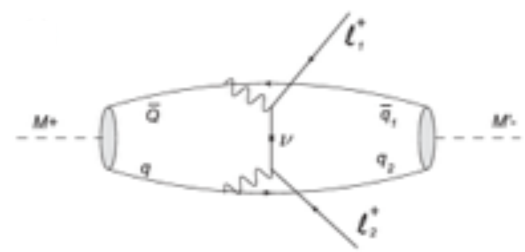
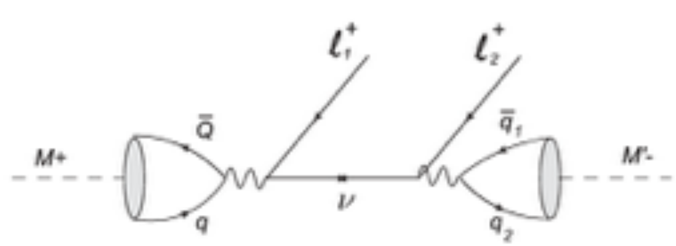
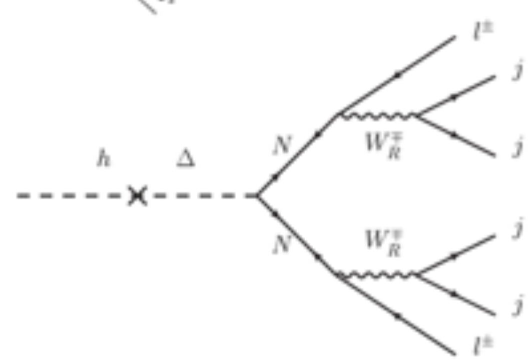
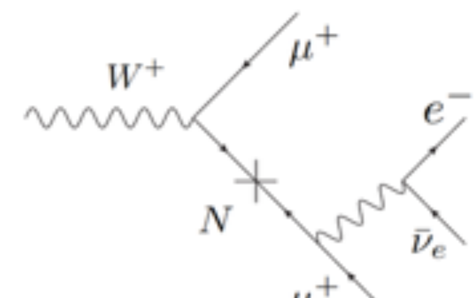
PINGU Collab., arXiv:1401.2046 (2014).

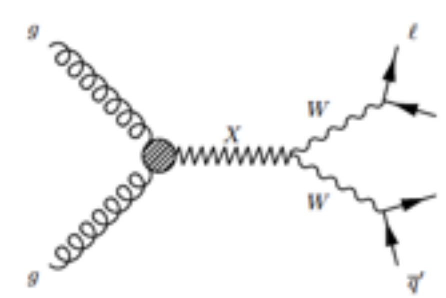
Summary So Far

- Cosmological limits have less to give to ν physics than they have to gain from terrestrial experiments
- Definitive ordering determination is not likely to come any time soon, in my opinion
- Even if ν are demonstrated to be normal and hierarchical, Inverted Ordering $m_{\beta\beta}^{min}$ still represents an order-of-magnitude improvement over current $0\nu\beta\beta$ limits.
- So: For the “vanilla” SM extension, IO $m_{\beta\beta}^{min}$ is a good goal for the next ~decade in any scenario

Non-Vanilla L Violation

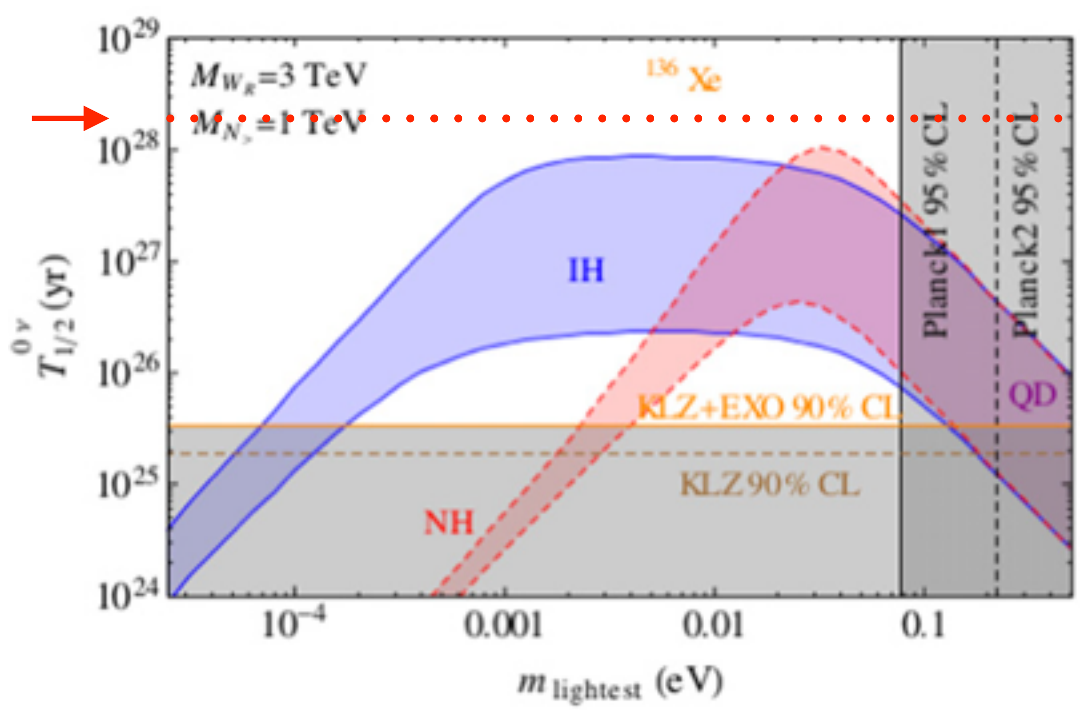
- Many theories predict new particles / interactions that can generate LNV and 0vββ decay
  - See Hirsch talk!

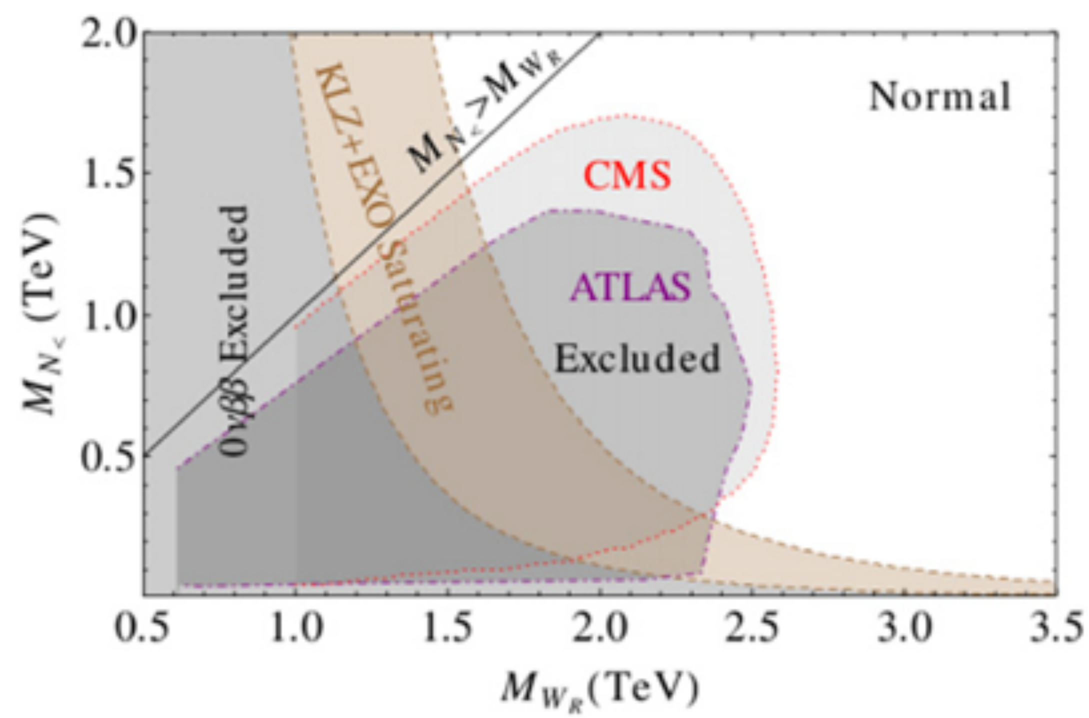










Ex: LR-Symmetric Models

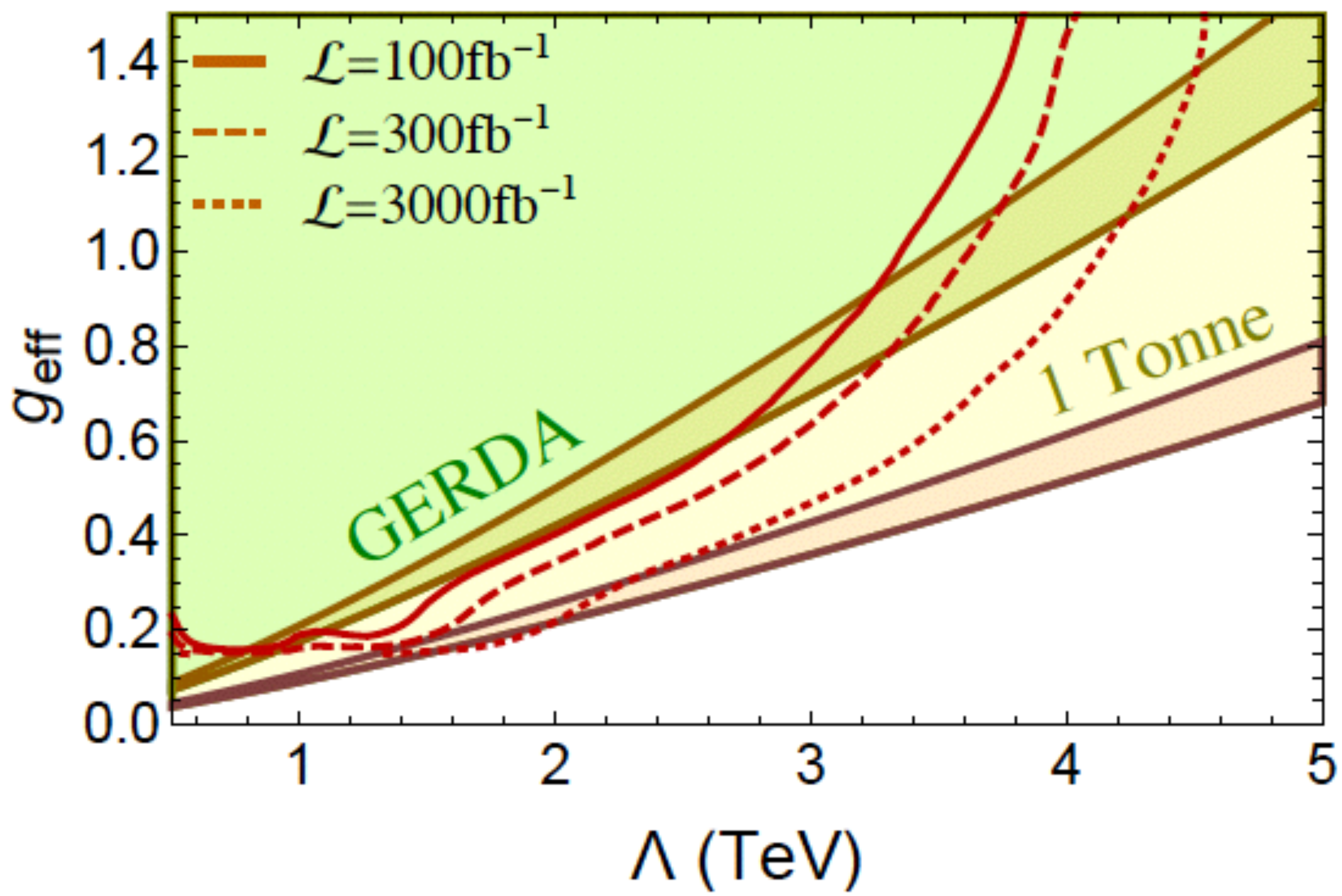
IO $m_{\beta\beta}^{min}$





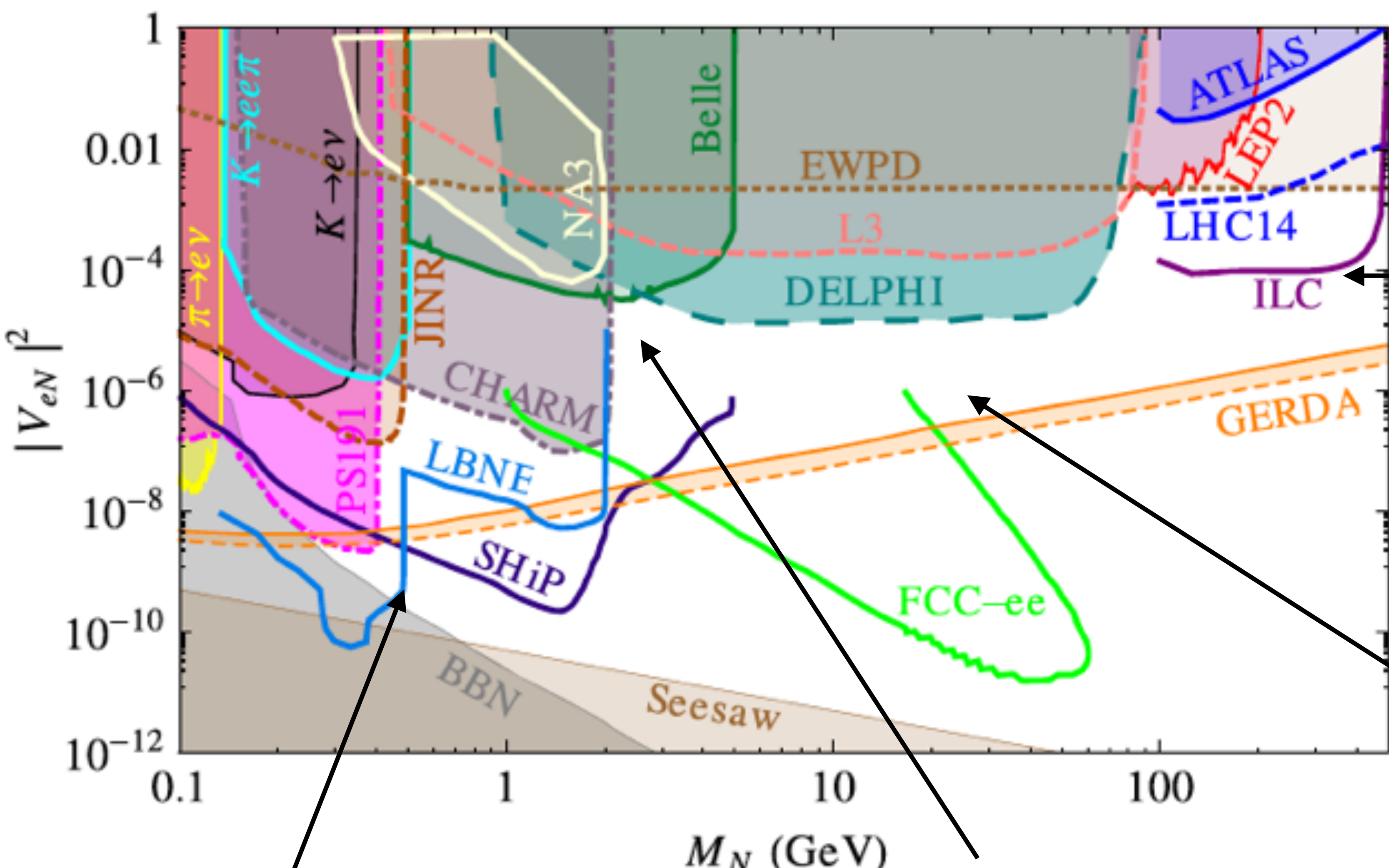
Päs and Rodejohann, New J. Phys. J. **17**, 115010 (2015)

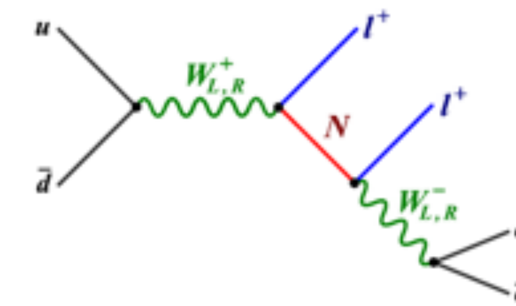
Generic TeV LNV interaction



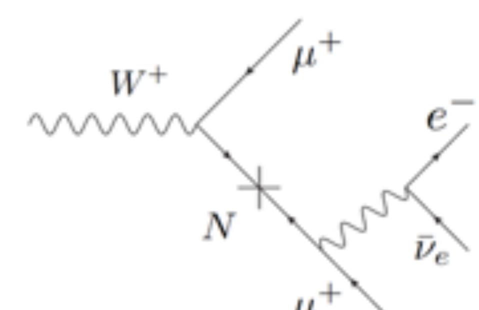
Peng *et al.*, arXiv:1508.04444 (2015).

Type-I Seesaw with Sterile ν

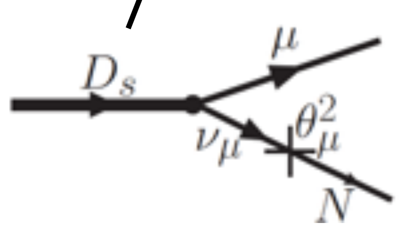




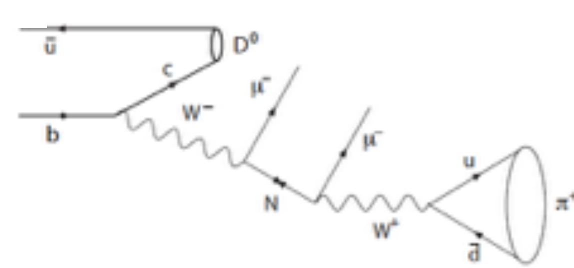
dilepton



trilepton



D decays



B decays

Deppisch *et al.*, New J. Phys. **17** 075019 (2015).

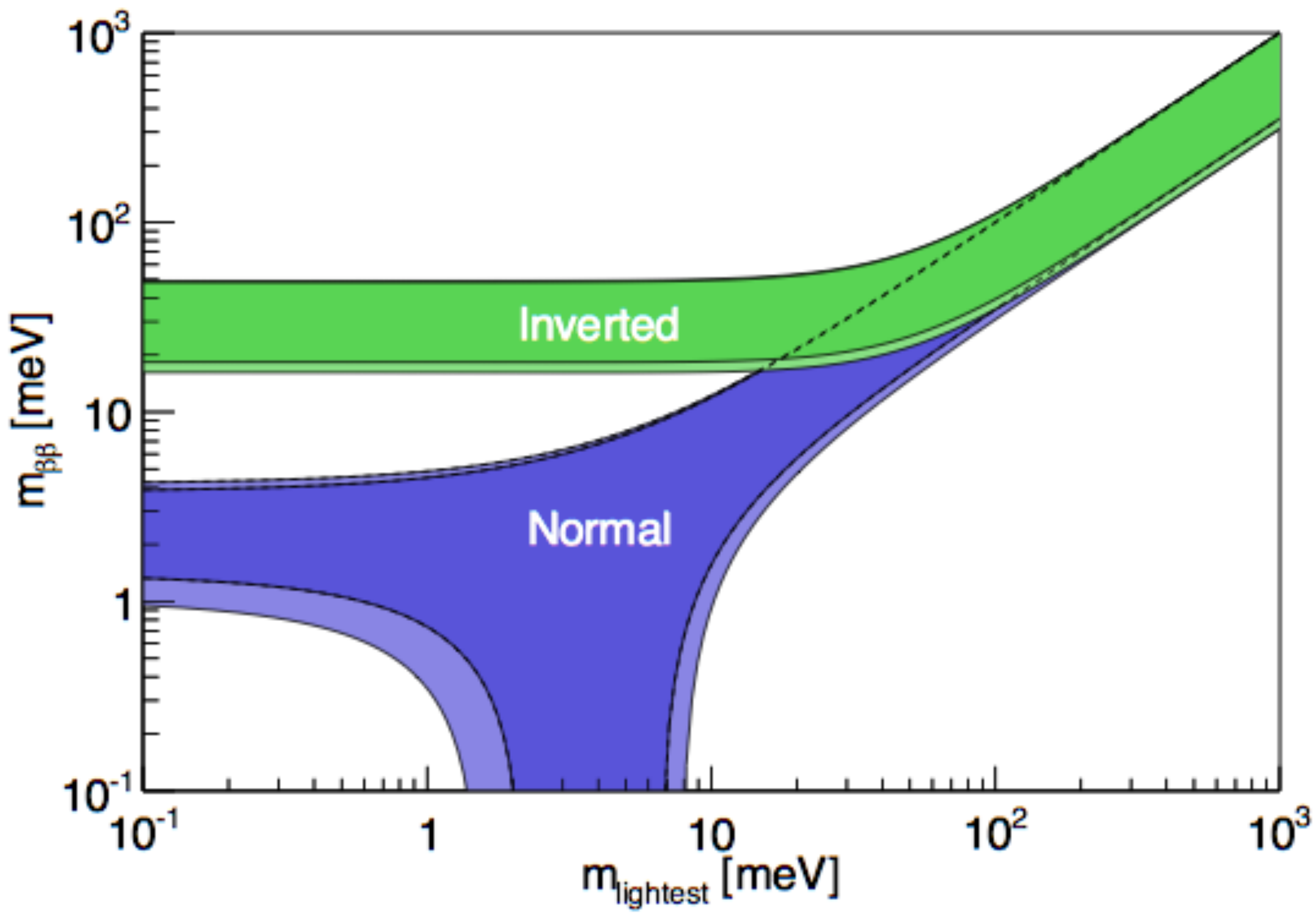
Implications of Non-Vanilla Models

- Alternative mechanisms open up the entire phase space for 0νββ
  - "Constraints" from ν mass are irrelevant for many models
- 0νββ searches are highly complementary to searches at LHC and elsewhere
- So: For non-"vanilla" SM extensions, IO $m_{\beta\beta}^{min}$ is an extra order-of-magnitude improvement: a good goal for the next ~decade in any scenario

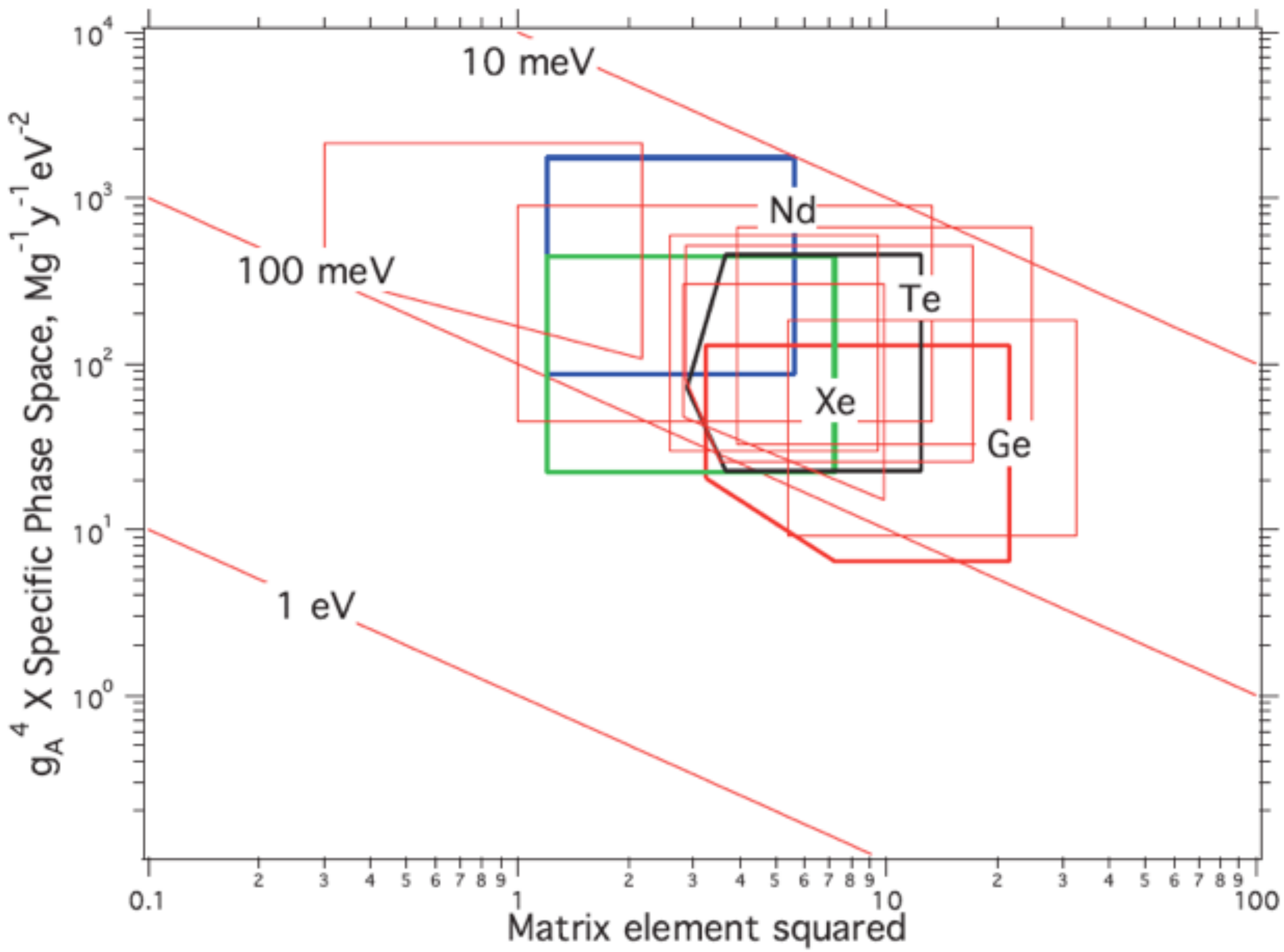
Getting to IO $m_{\beta\beta}^{min}$

From $m_{\beta\beta}$ to Decay Rate

$$\Gamma_{1/2}^{0\nu} = G^{0\nu}\,|M^{0\nu}|^2\, m_{\beta\beta}^{\;2} = NT\varepsilon/S(C,B)$$



No Isotope Preference *a priori*



R.G.H. Robertson, Mod. Phys. Lett. A **28**, 1350021 (2013).

Sensitivity and Discovery Level

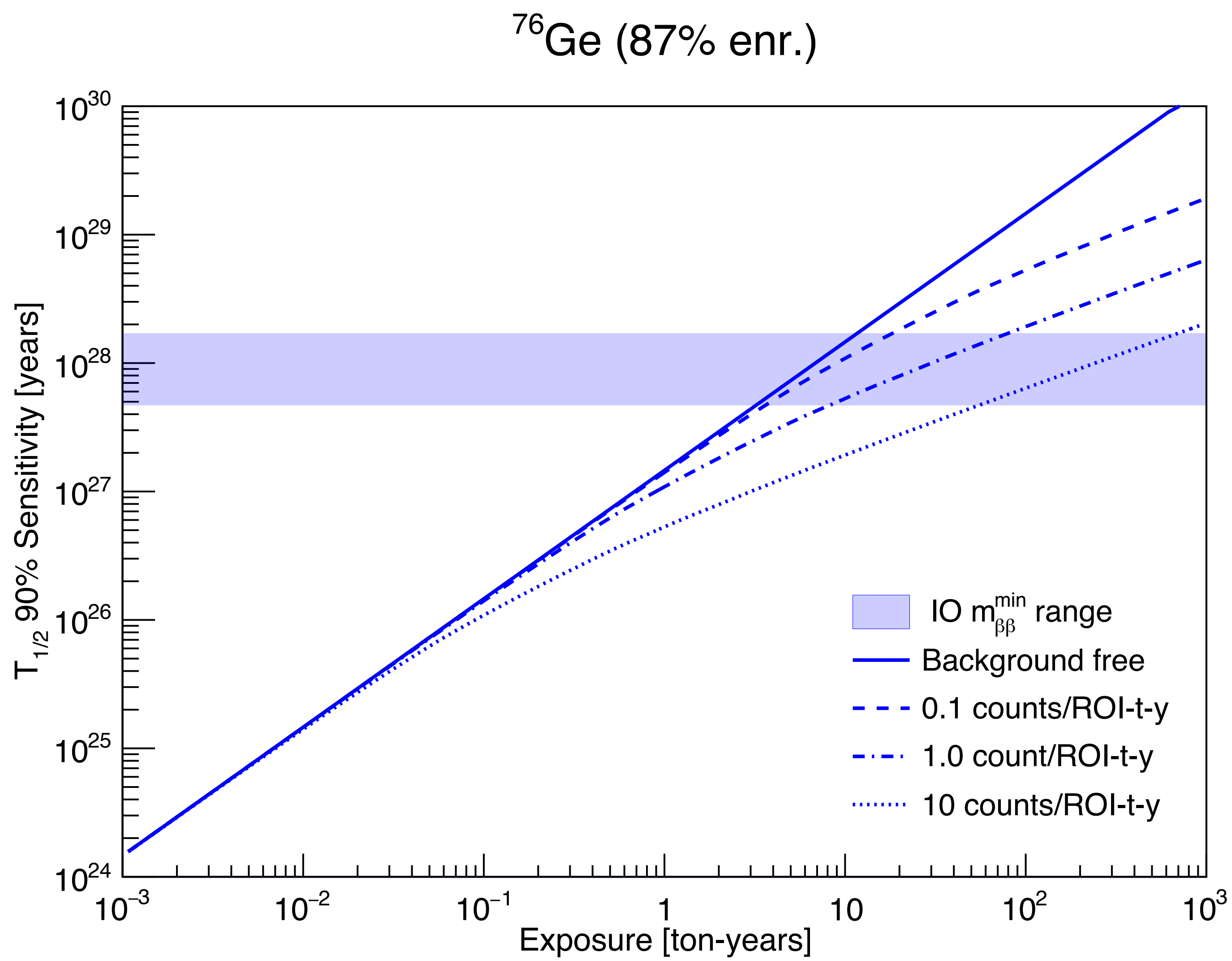
- Sensitivity: "typical" UL on $S(C,B)$ assuming zero signal.
  - I use $\langle \mathrm{UL}(S\,|B)\rangle$ from Feldman and Cousins to vary smoothly between the background-free and background limited regimes
- Nσ Discovery Level: signal level such that on average an Nσ excess above B is observed

$$C_{3\sigma} : \mathrm{CDF}_{\mathrm{Poisson}}(C_{3\sigma}|B) = 3\sigma$$

$$S_{3\sigma} : 1 - \mathrm{CDF}_{\mathrm{Poisson}}(C_{3\sigma}|S_{3\sigma} + B) = 50\%$$

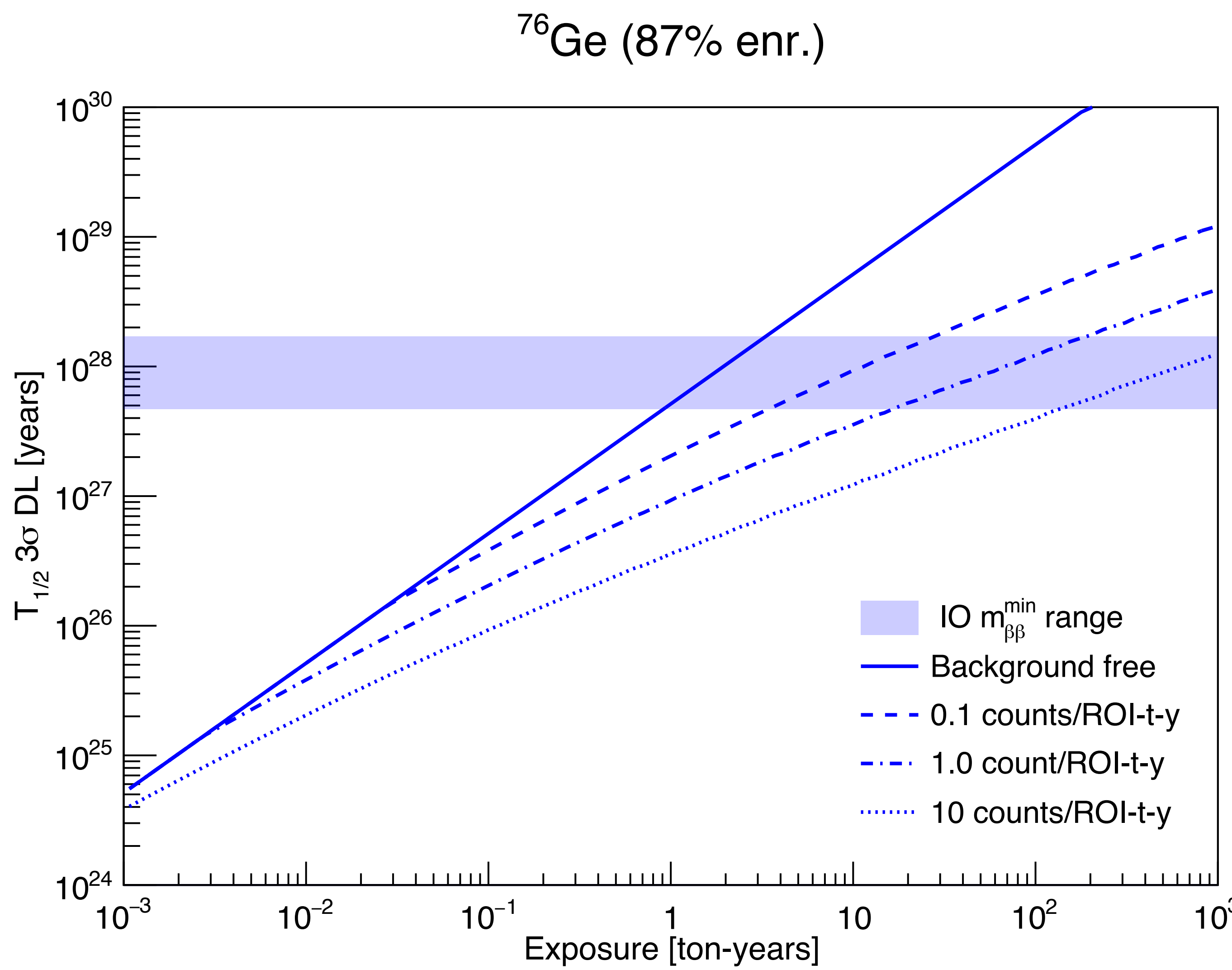
$$\mathrm{CDF}_{\mathrm{Poisson}}(C|\mu) = \frac{\Gamma(C+1,\mu)}{\Gamma(C+1)}$$

Sensitivity: ^{enr}Ge



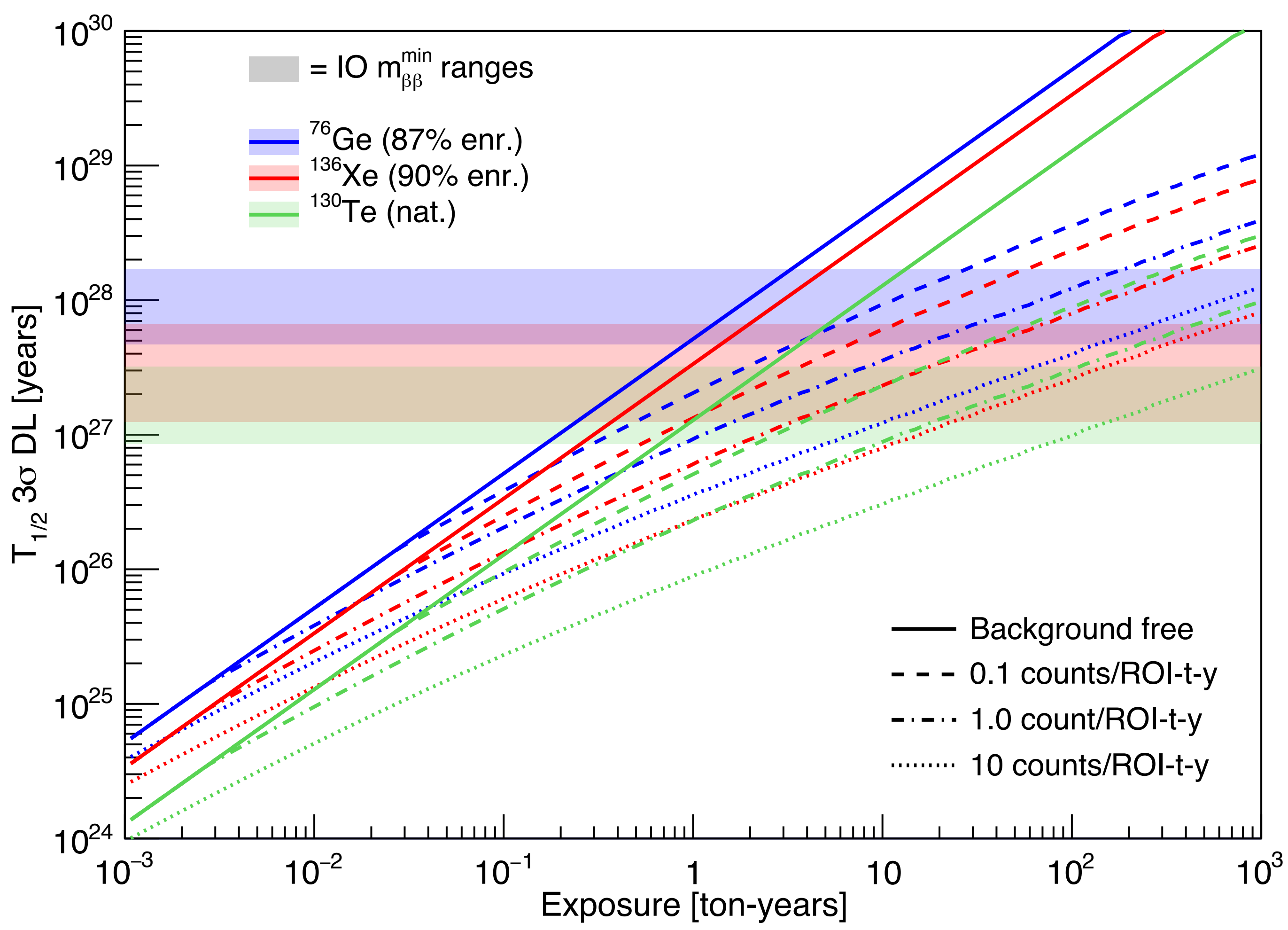
 ε, abundance factors taken from GERDA Phase I

Discovery Level: ^{enr}Ge



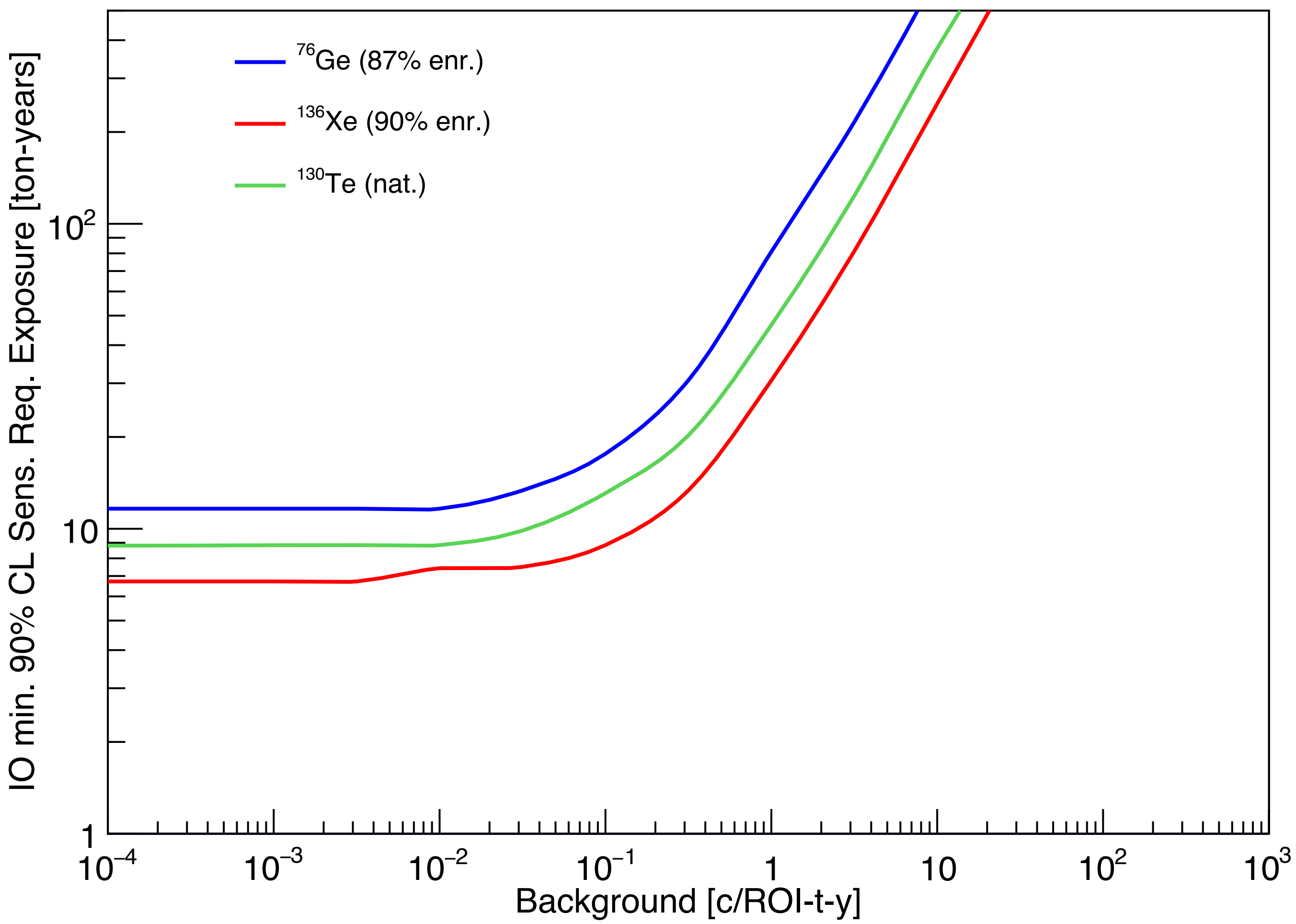
ε, abundance factors taken from GERDA Phase I

DL Comparison

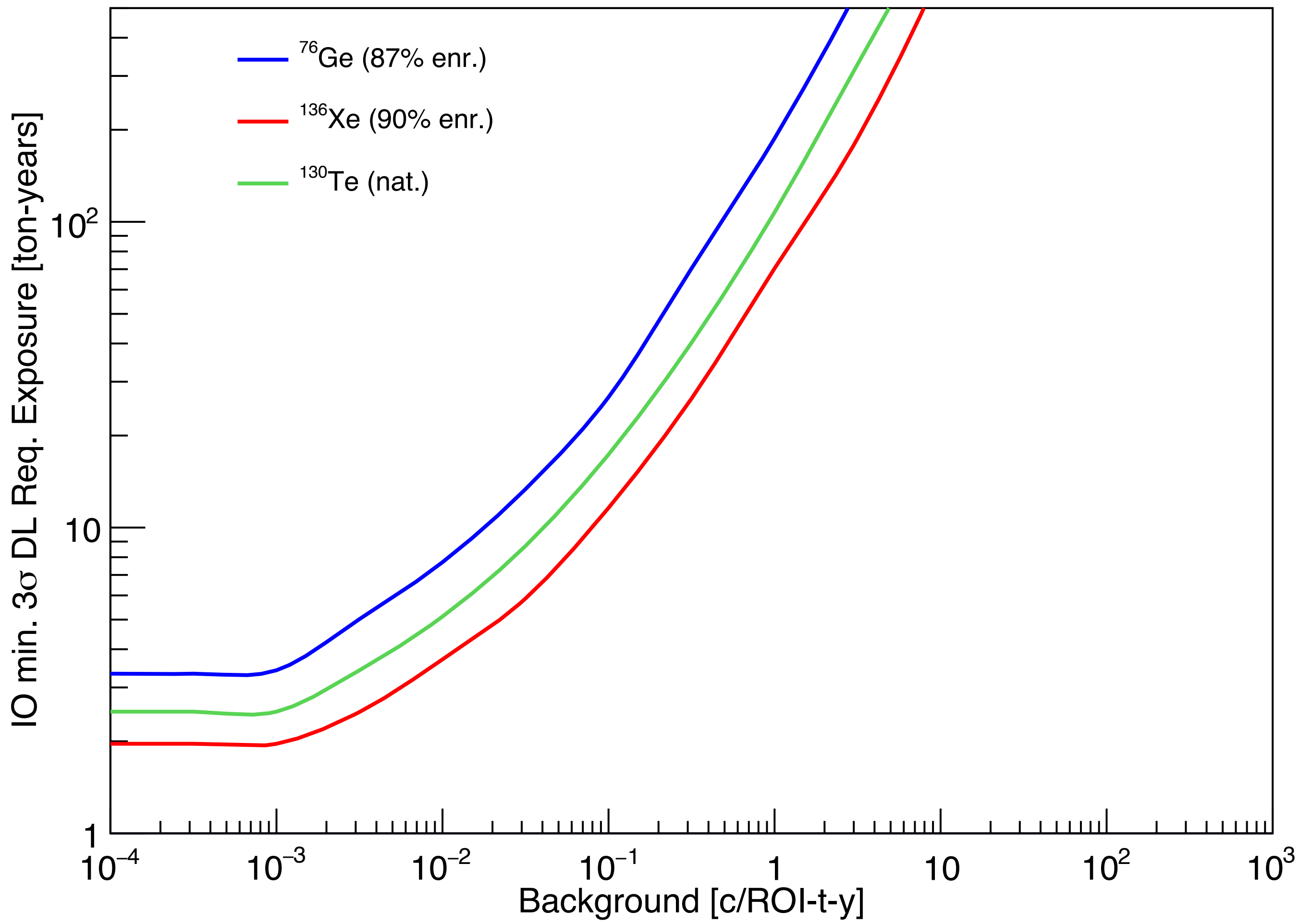


ε, abundance factors taken from GERDA Phase I, EXO-200, and CUORE-0

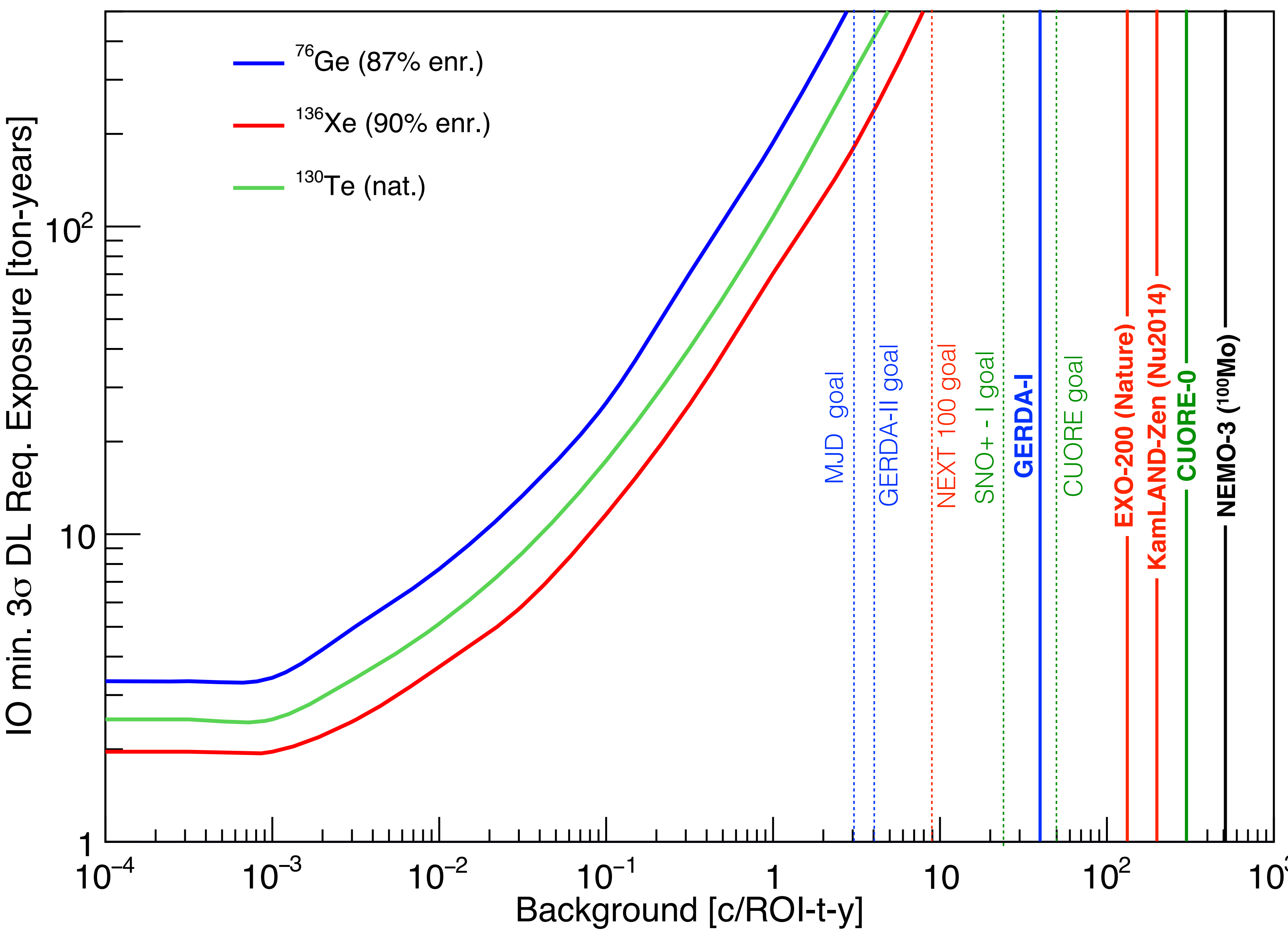
Exposure to reach IO $m_{\beta\beta}^{min}$: Sensitivity



Exposure to reach IO $m_{\beta\beta}^{\text{min}}$: Discovery Level



Exposure to reach IO $m_{\beta\beta}^{min}$: Discovery Level



Summary

- Inverted Ordering $m_{\beta\beta}^{min}$ has a large phase space for discovery, irrespective of what else is measured between now and then
- It's going to take exposure ≥10 t-y and/or background ≤ 0.1 c/ROI/t/y to get there
- ^{76}Ge is the closest to achieving this background goal
    - We expect this argument will only become stronger!