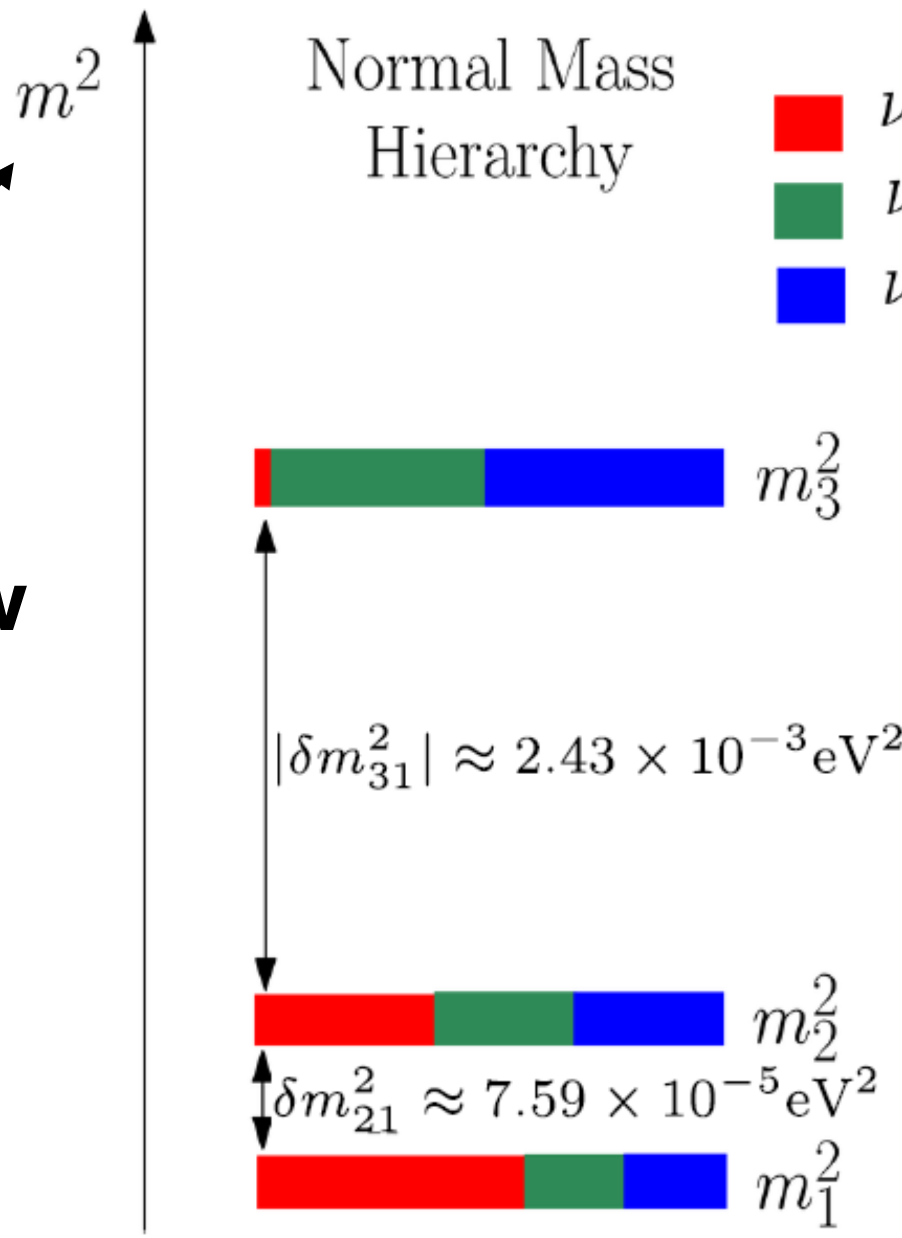
UK Activities in Neutrinoless ββ Decay

S. Biller, Oxford University
PPAP Community Meeting 2019

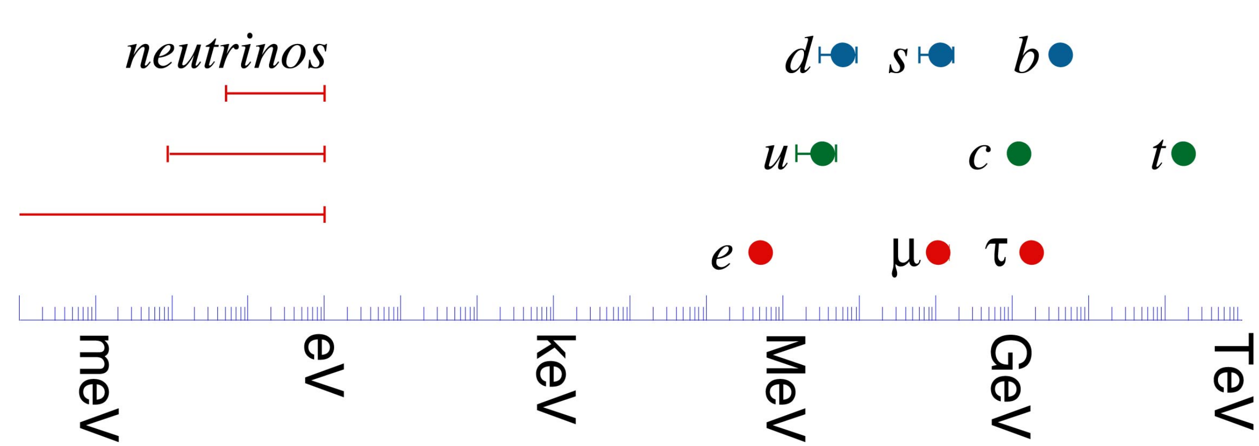
We don't know why

We don't know how



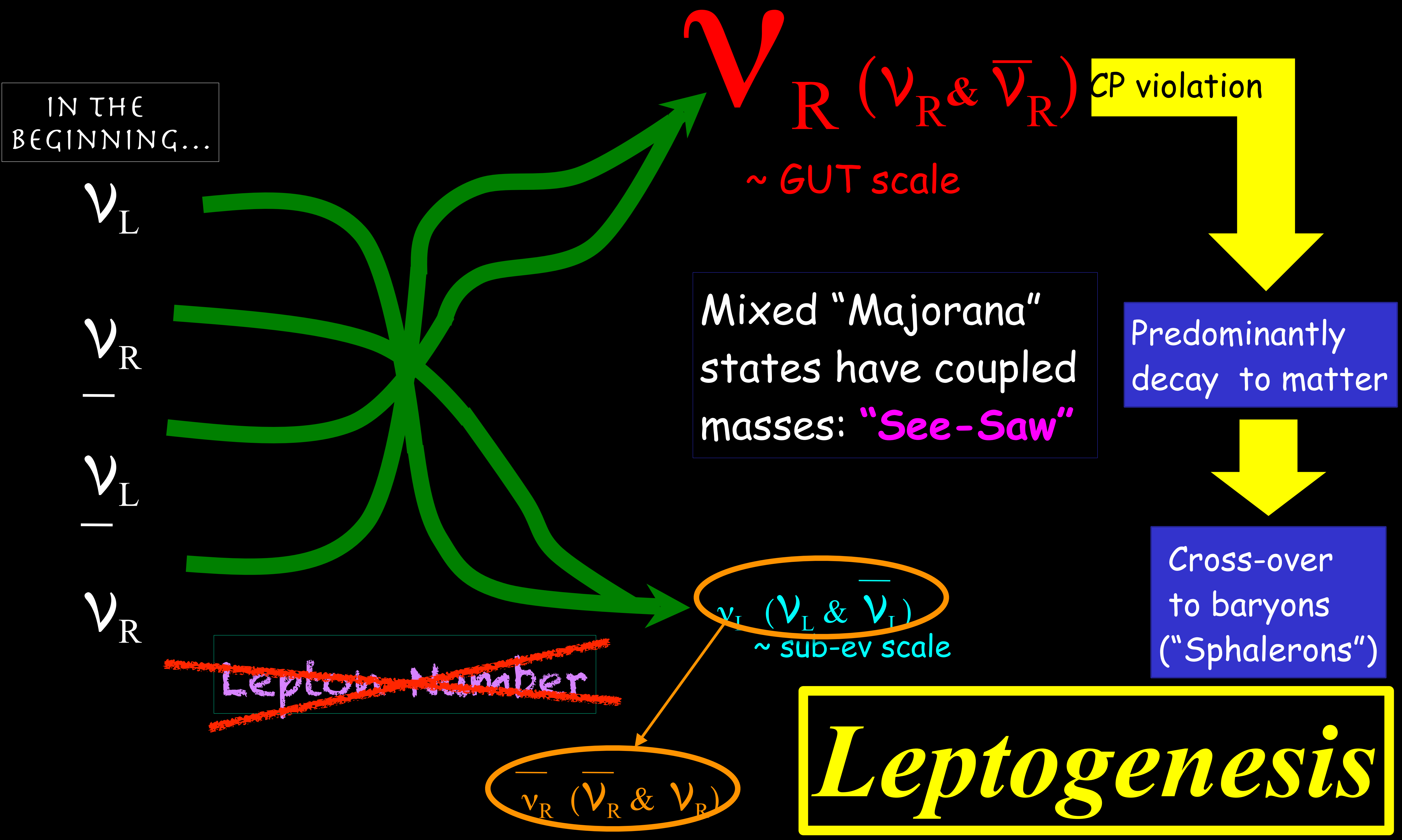
We don't know which

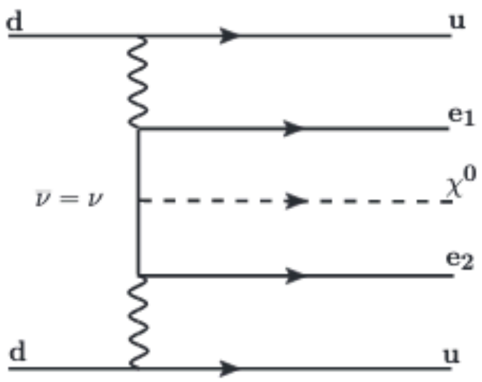
We don't know what

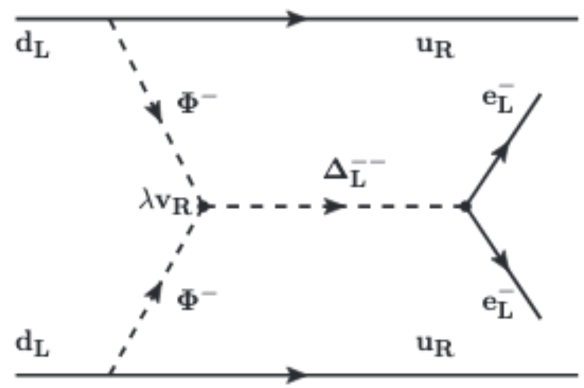


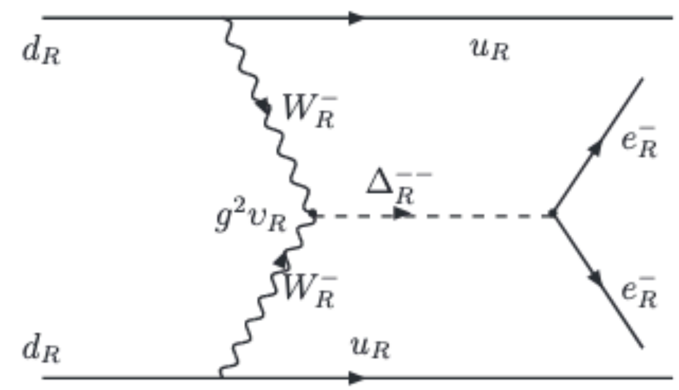
- **Why are all ν's left-handed?**
- **What is the mass ordering of ν states?**
- **What are the absolute neutrino masses?**
- **Why are ν masses so small?**
- **How do ν's get mass in the first place?**
- **Is helicity the only difference between ν's and $\bar{\nu}$'s?**
- **To what extent do ν's violate symmetries such as CP?**

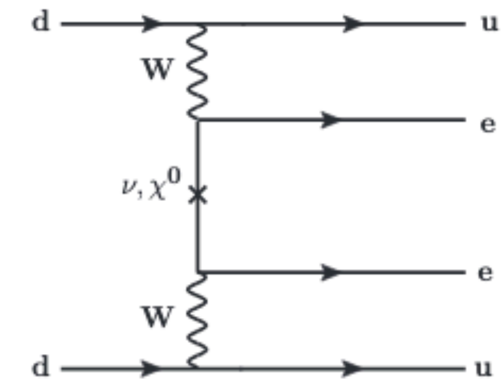
The Paradigm:

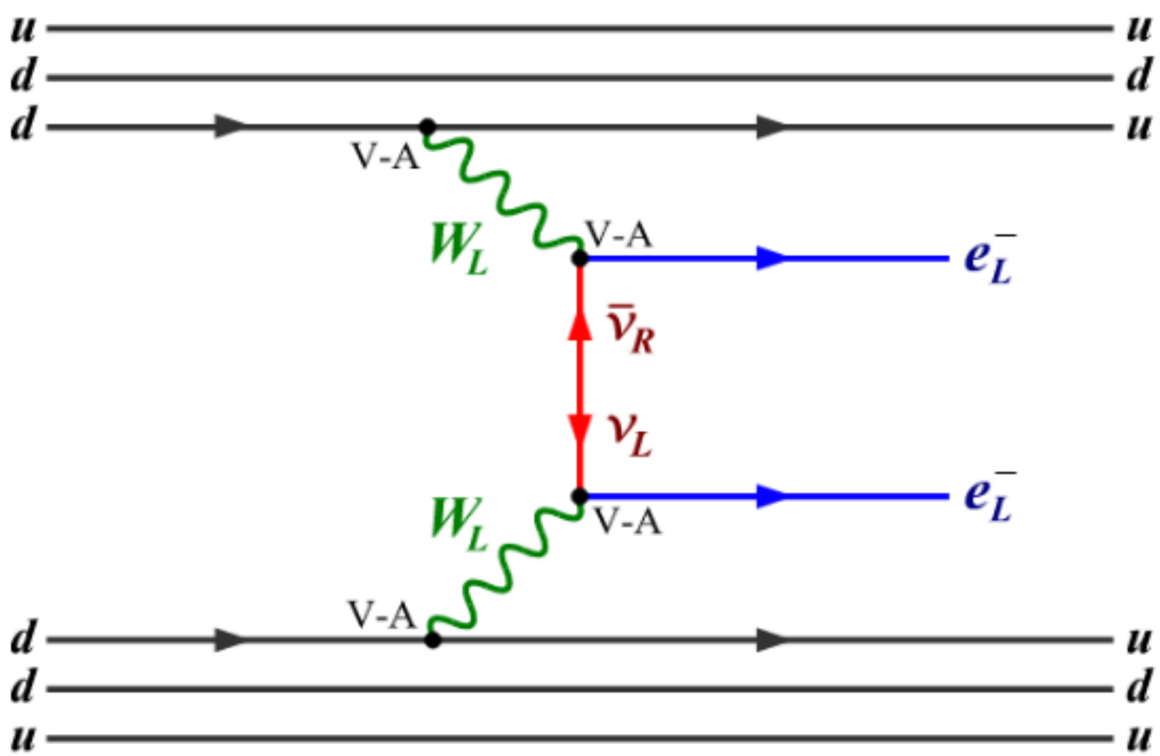


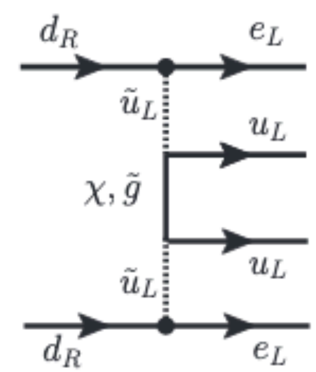

d
u
e_1
$\bar{\nu} = \nu$
χ^0
e_2
d
u

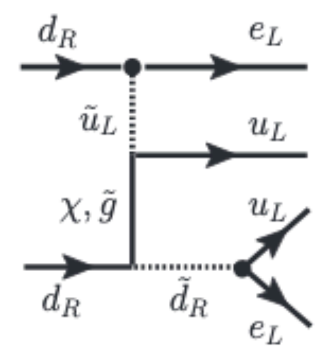

d_L
u_R
Φ^-
e_L^-
λv_R
Δ_L^{--}
Φ^-
e_L^-
d_L
u_R

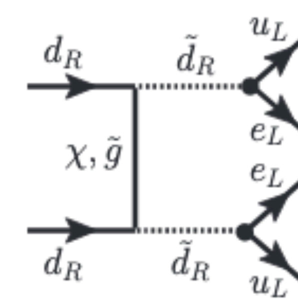

d_R
u_R
W_R^-
e_R^-
$g^2 v_R$
Δ_R^{--}
W_R^-
e_R^-
d_R
u_R

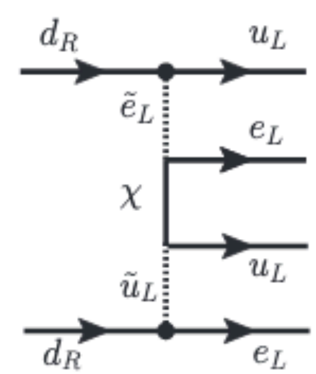

d
u
W
e
ν, χ^0
e
W
d
u

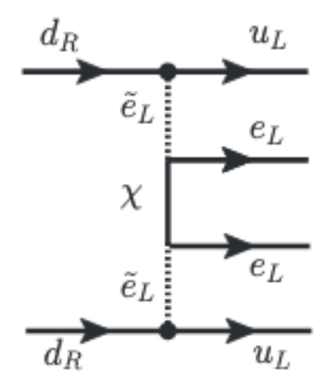

u
d
d
u
d
u
V-A
W_L
V-A
e_L^-
$\bar{\nu}_R$
ν_L
W_L
V-A
e_L^-
V-A
d
u
d
d
u
u

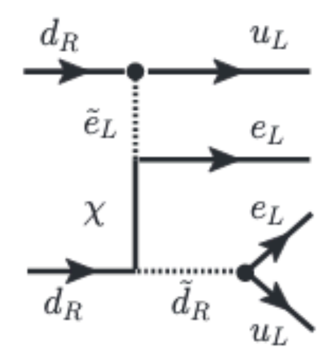

d_R
e_L
$\tilde{u}_L$
u_L
$\chi, \tilde{g}$
u_L
$\tilde{u}_L$
d_R
e_L

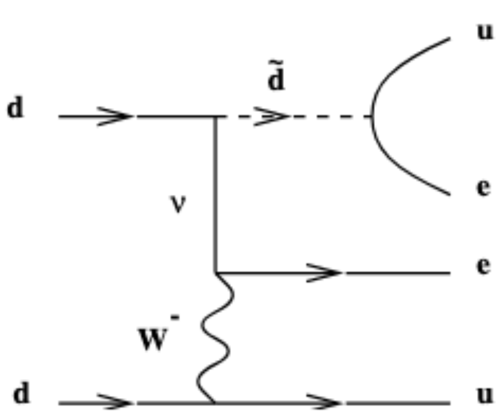

d_R
e_L
$\tilde{u}_L$
u_L
$\chi, \tilde{g}$
u_L
d_R
$\tilde{d}_R$
e_L

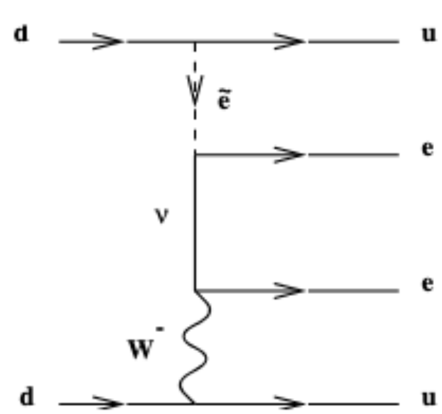

u_L
d_R
$\tilde{d}_R$
e_L
$\chi, \tilde{g}$
e_L
d_R
$\tilde{d}_R$
u_L

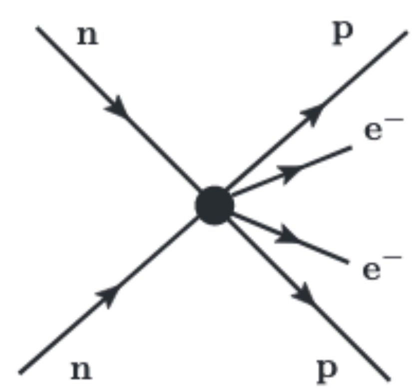

d_R
u_L
$\tilde{e}_L$
e_L
χ
u_L
$\tilde{u}_L$
d_R
e_L

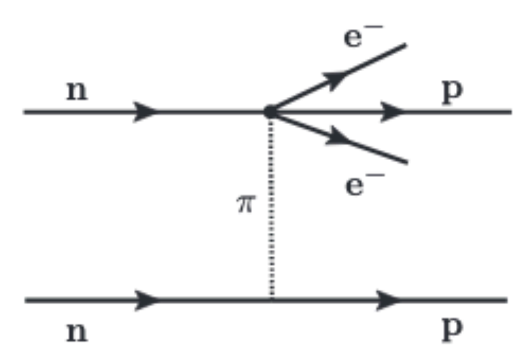

d_R
u_L
$\tilde{e}_L$
e_L
χ
e_L
$\tilde{e}_L$
d_R
u_L

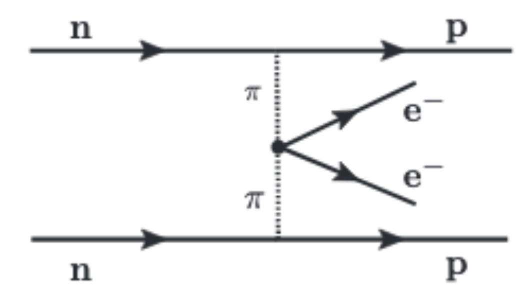

d_R
u_L
$\tilde{e}_L$
e_L
χ
e_L
d_R
$\tilde{d}_R$
u_L

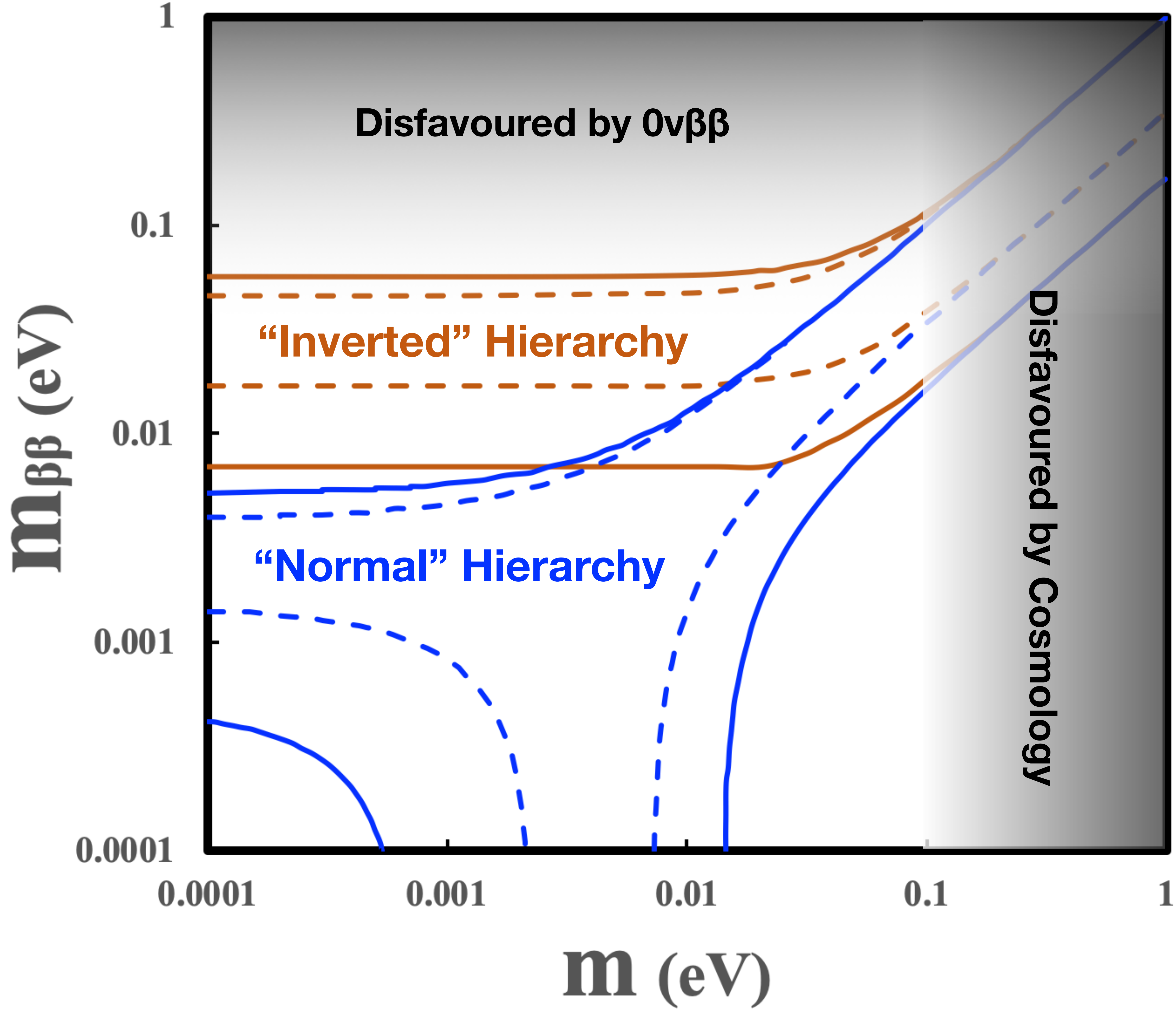

u
$\tilde{d}$
d
e
ν
e
W^-
d
u


d
u
$\tilde{e}$
e
ν
e
W^-
d
u

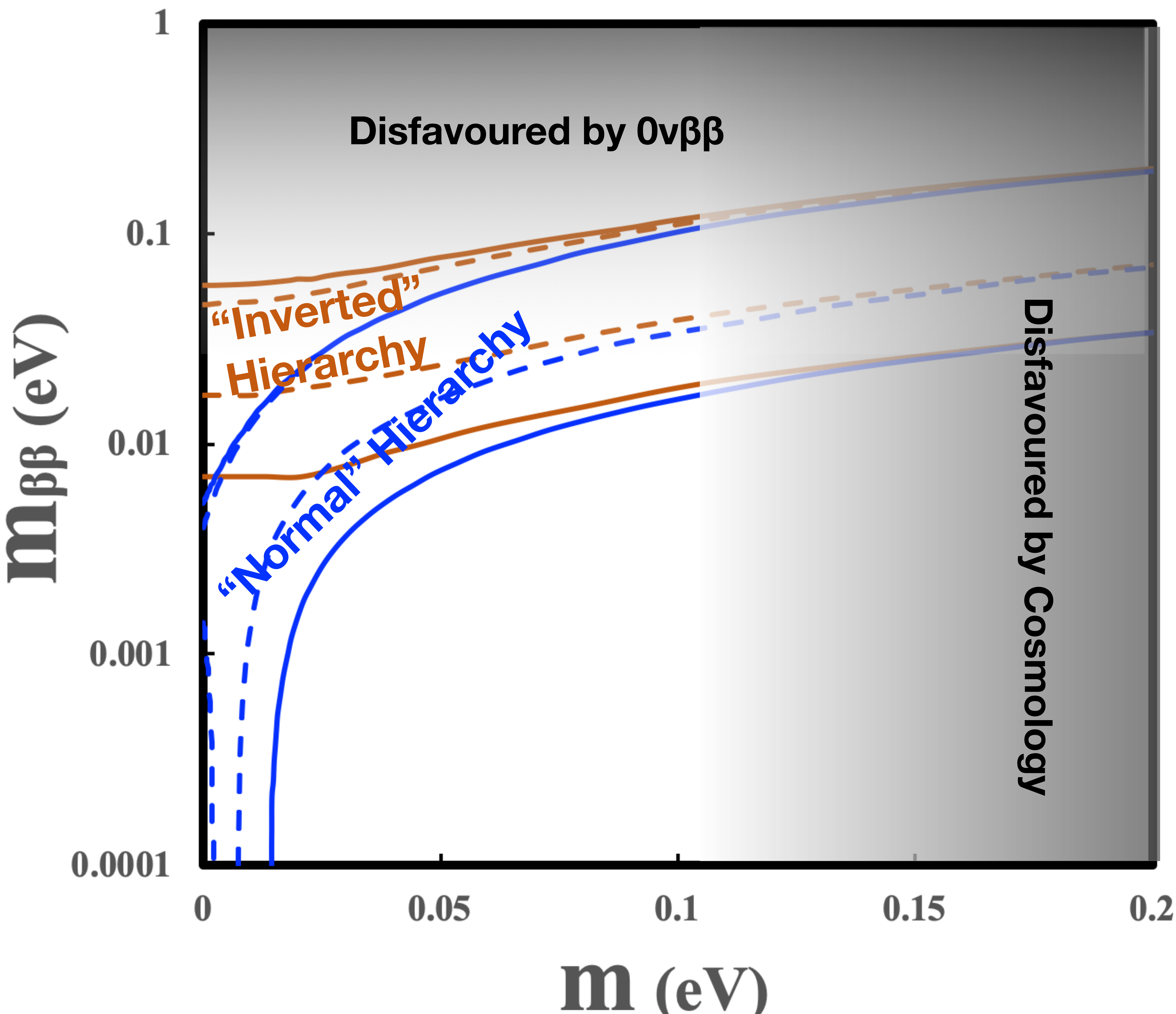

n
p
e^-
e^-
n
p

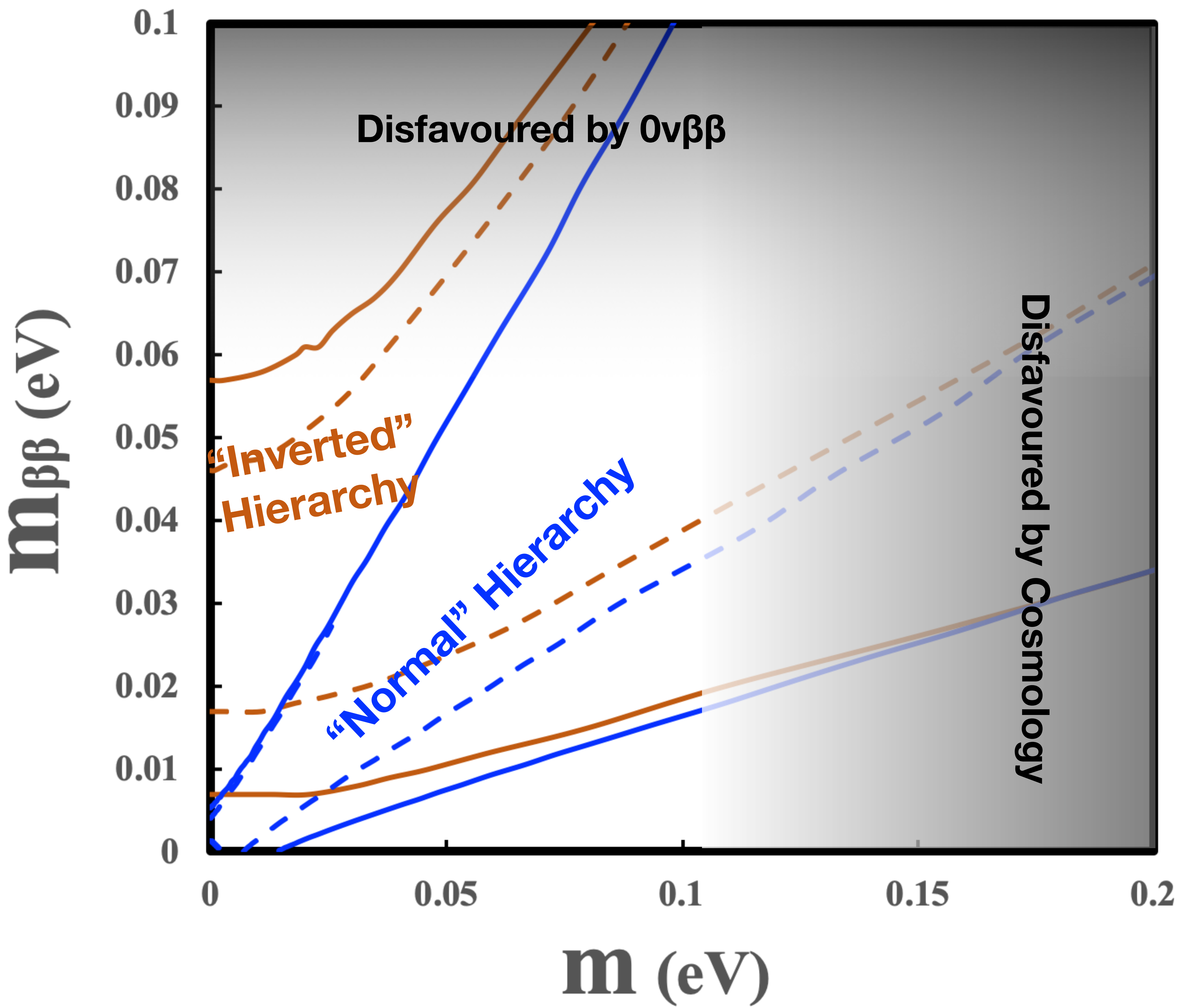

e^-
n
p
e^-
π
n
p


n
p
π
e^-
e^-
π
n
p



Disfavoured by 0νββ
"Inverted" Hierarchy
"Normal" Hierarchy
Disfavoured by Cosmology
$m_{\beta\beta}$ (eV)
m (eV)
1
0.1
0.01
0.001
0.0001
0.0001
0.001
0.01
0.1
1


Disfavoured by 0νββ
"Inverted" Hierarchy
"Normal" Hierarchy
Disfavoured by Cosmology
1
0.1
0.01
0.001
0.0001
$m_{\beta\beta}$ (eV)
0
0.05
0.1
0.15
0.2
m (eV)



Disfavoured by 0νββ
Disfavoured by Cosmology
"Inverted" Hierarchy
"Normal" Hierarchy
$m_{\beta\beta}$ (eV)
m (eV)
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0.05
0.1
0.15
0.2

Effective Majorana mass

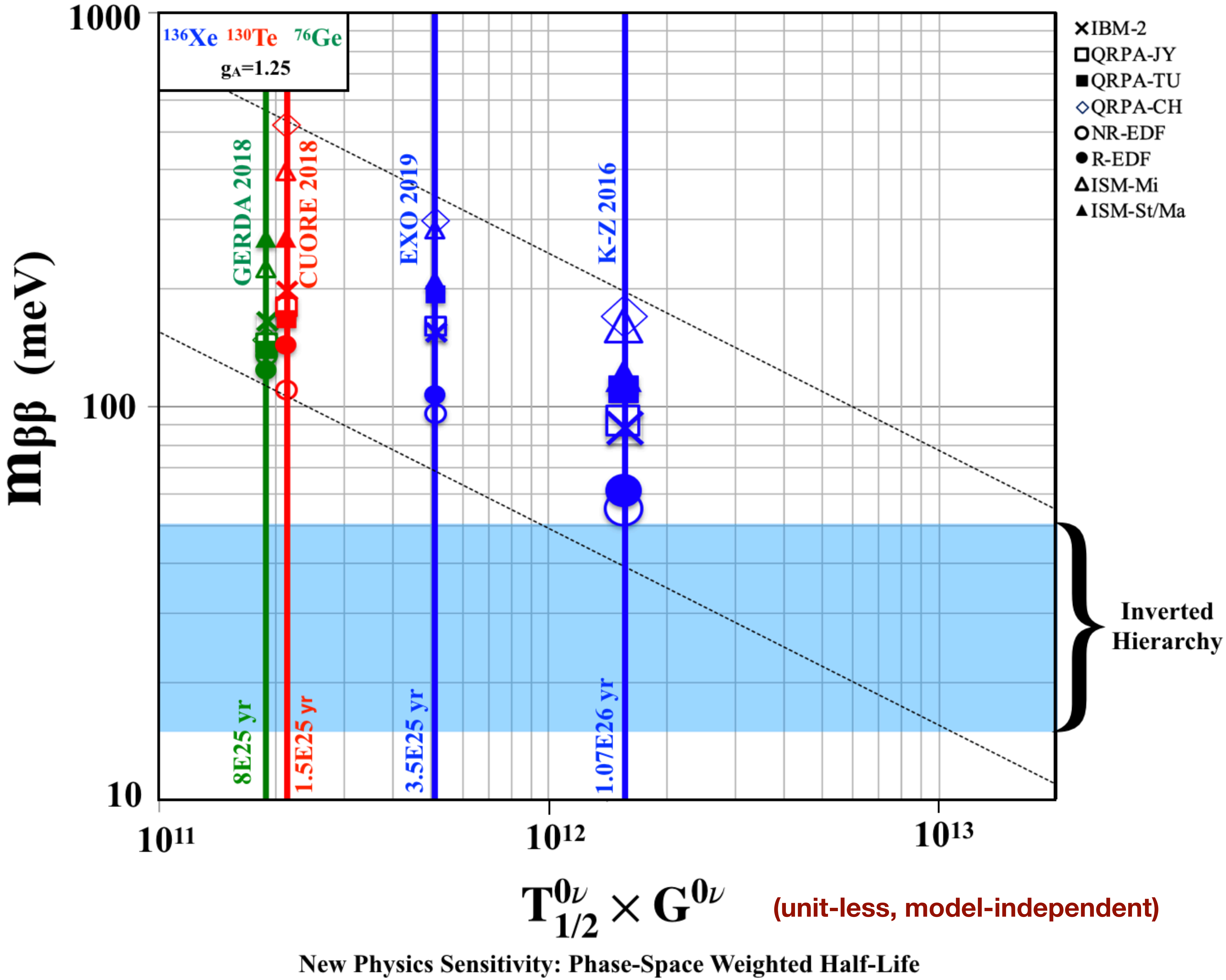
$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}\left|M^{0\nu}\right|^2\left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

Exactly calculable, <u>model-independent</u> phase space factor accounting for different momentum distributions corresponding to different isotope endpoints and the impact of the nuclear charge on the produced electrons.

Not so exactly calculable, <u>model-dependent</u> matrix element for the transition. Many different estimations, even for the "standard mechanism." Proportional to g_A^2, which might entail an effective "quenching."

What is the best way to represent this and to fairly compare across different isotopes when presenting experimental results?

Current Leading Bounds



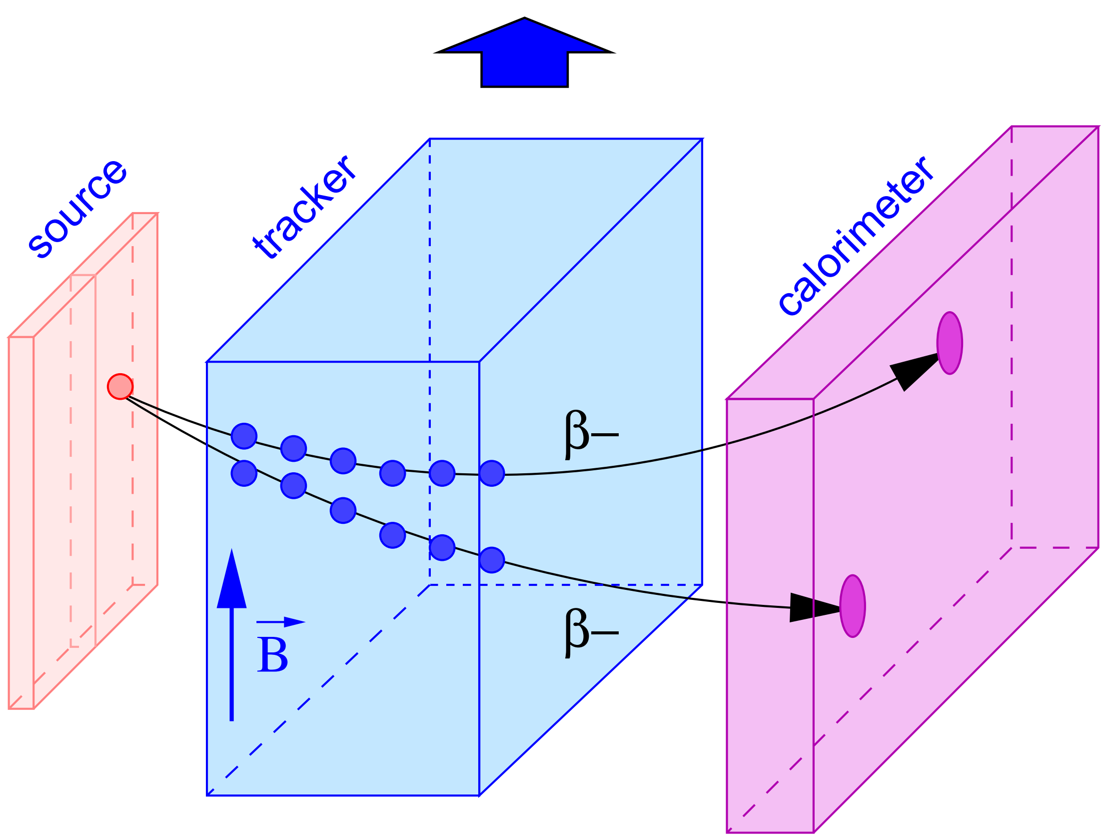

OCOG

supernemo collaboration

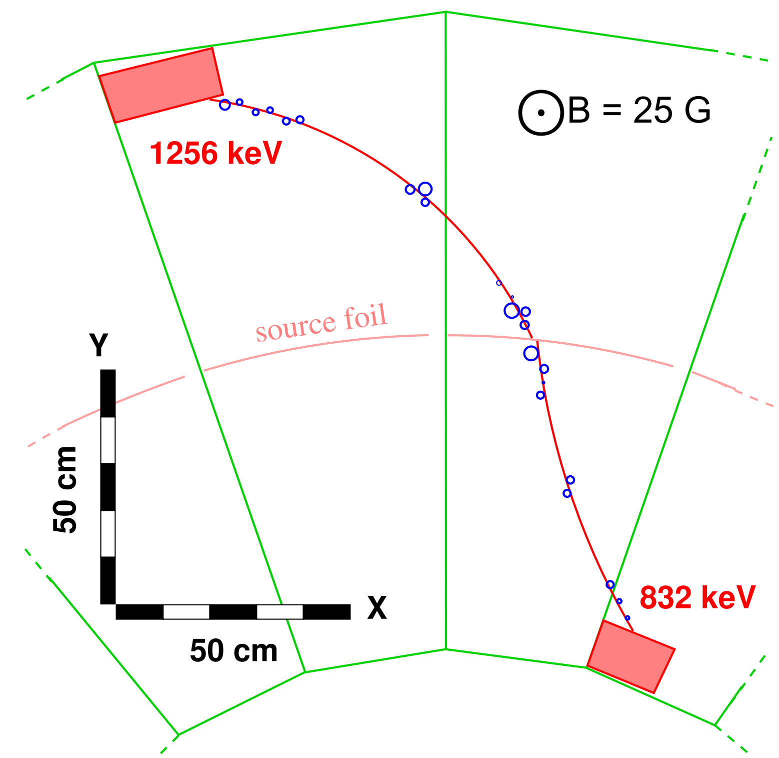
Imperial, Manchester, UCL, UCL-MSSL, Warwick

Tracker-Calorimeter Technique

- Source separated from detector: (almost) any solid isotope can be hosted.
- Generally poorer energy resolution than “homogeneous” detectors such as HPGe and bolometers.
- Full topological event reconstruction including $e^{\pm}$, γ-ray and α-particle identification.

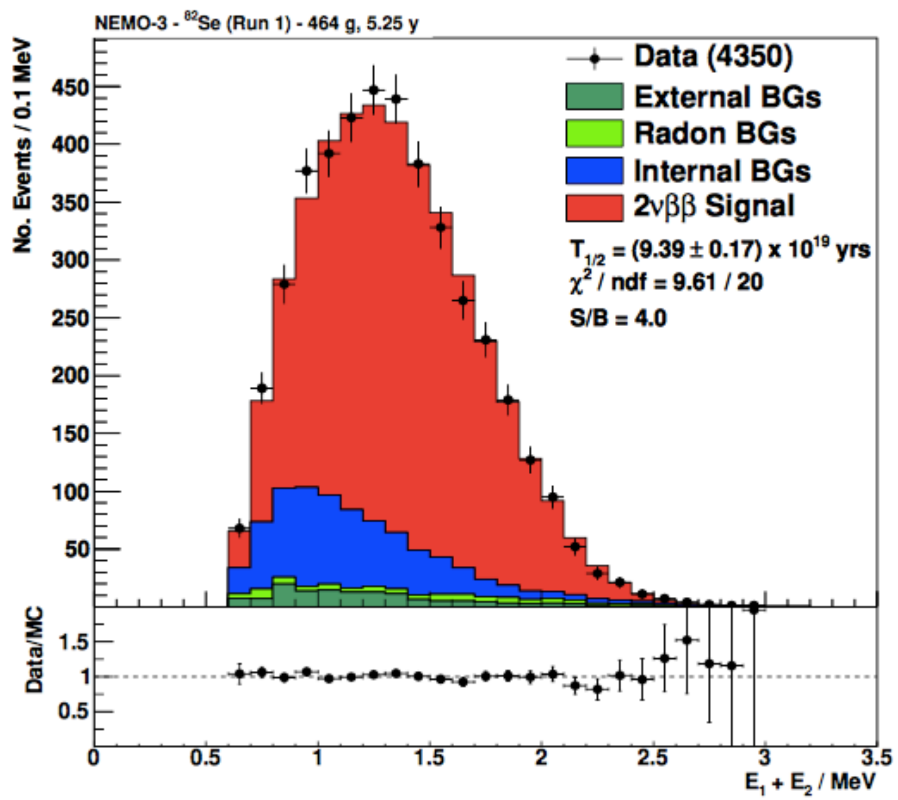


Candidate ^{100}Mo Double-Beta Decay Event in NEMO-3



- Strong background suppression by particle identification, event characterisation & timing.
- Ability to disentangle different mechanisms for $0\nu\beta\beta$, by looking at variables other than ΣE.

Recent NEMO-3 Highlight: ^{82}Se



- Final results on ^{82}Se (SuperNEMO isotope):

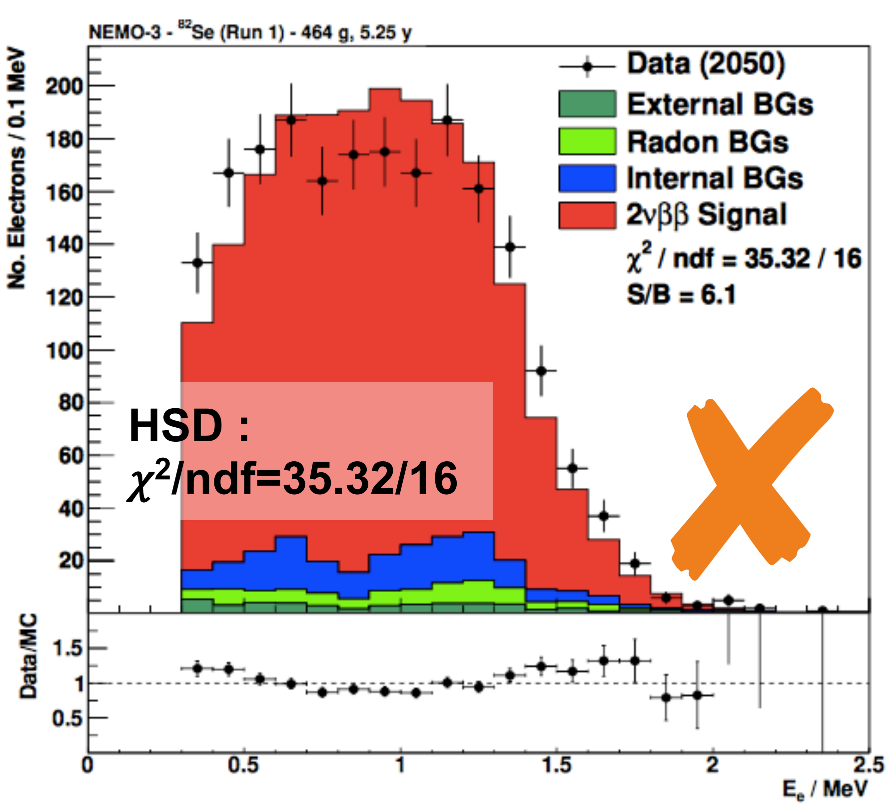
$$T_{1/2}^{2\nu\beta\beta} = 9.39 \pm 0.17(\mathrm{stat.}) \pm 0.58(\mathrm{syst.}) \times 10^{19} \text{ years}$$

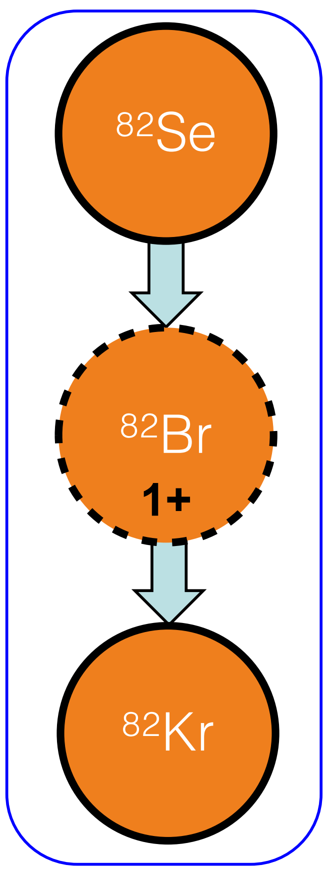
Assuming **SSD**. World' most precise measurement.

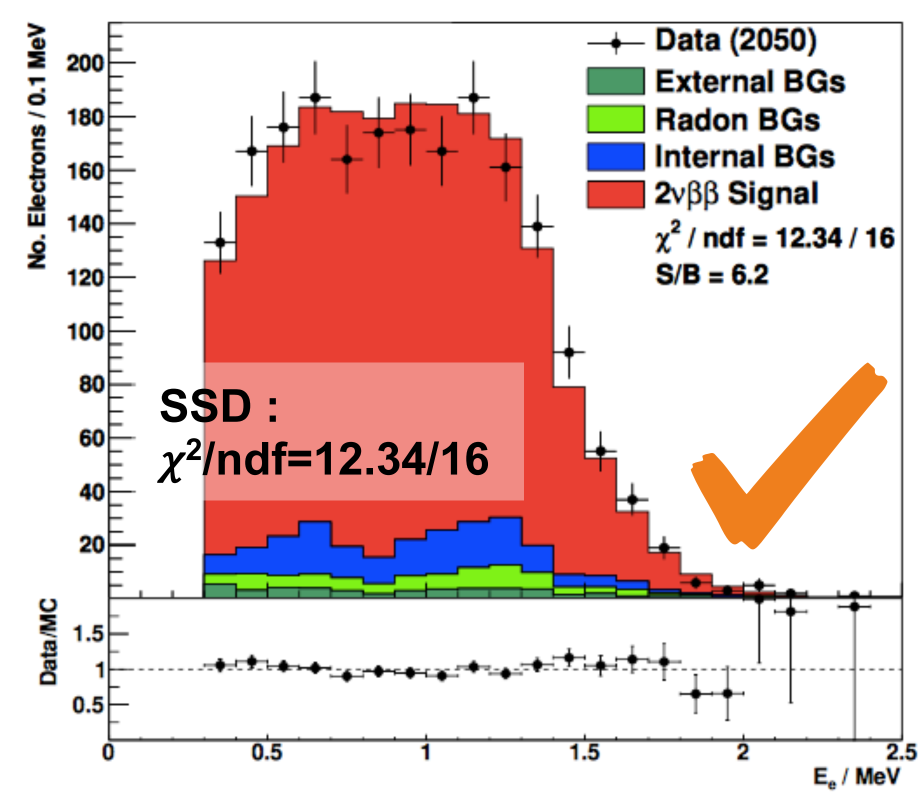
$$T_{1/2}^{0\nu\beta\beta} > 2.5 \times 10^{23} \text{ years } (90\%\mathrm{C.L.})$$

EPJ C78, 821 (2018)

- Discovering the mechanism behind $2\nu\beta\beta$:





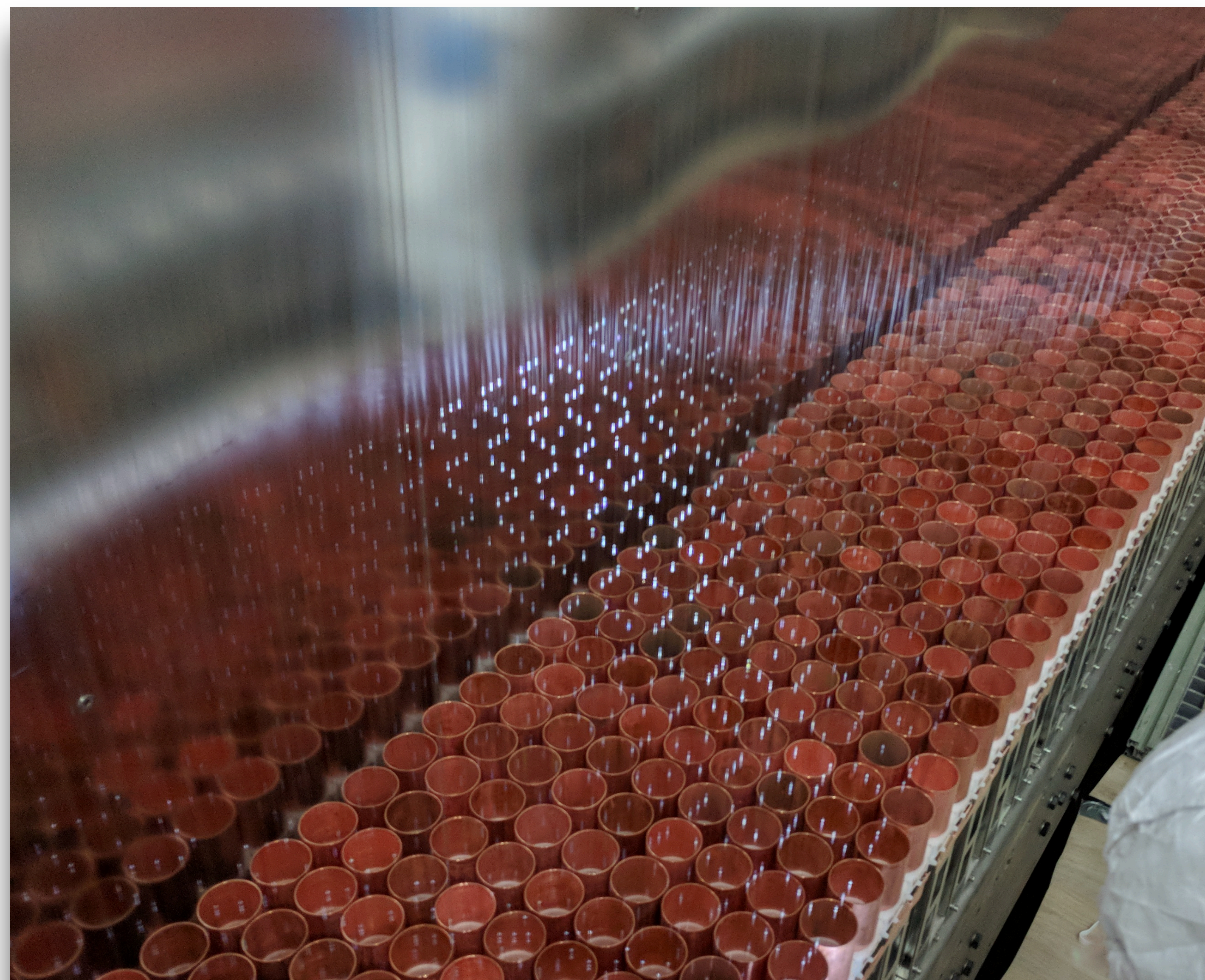


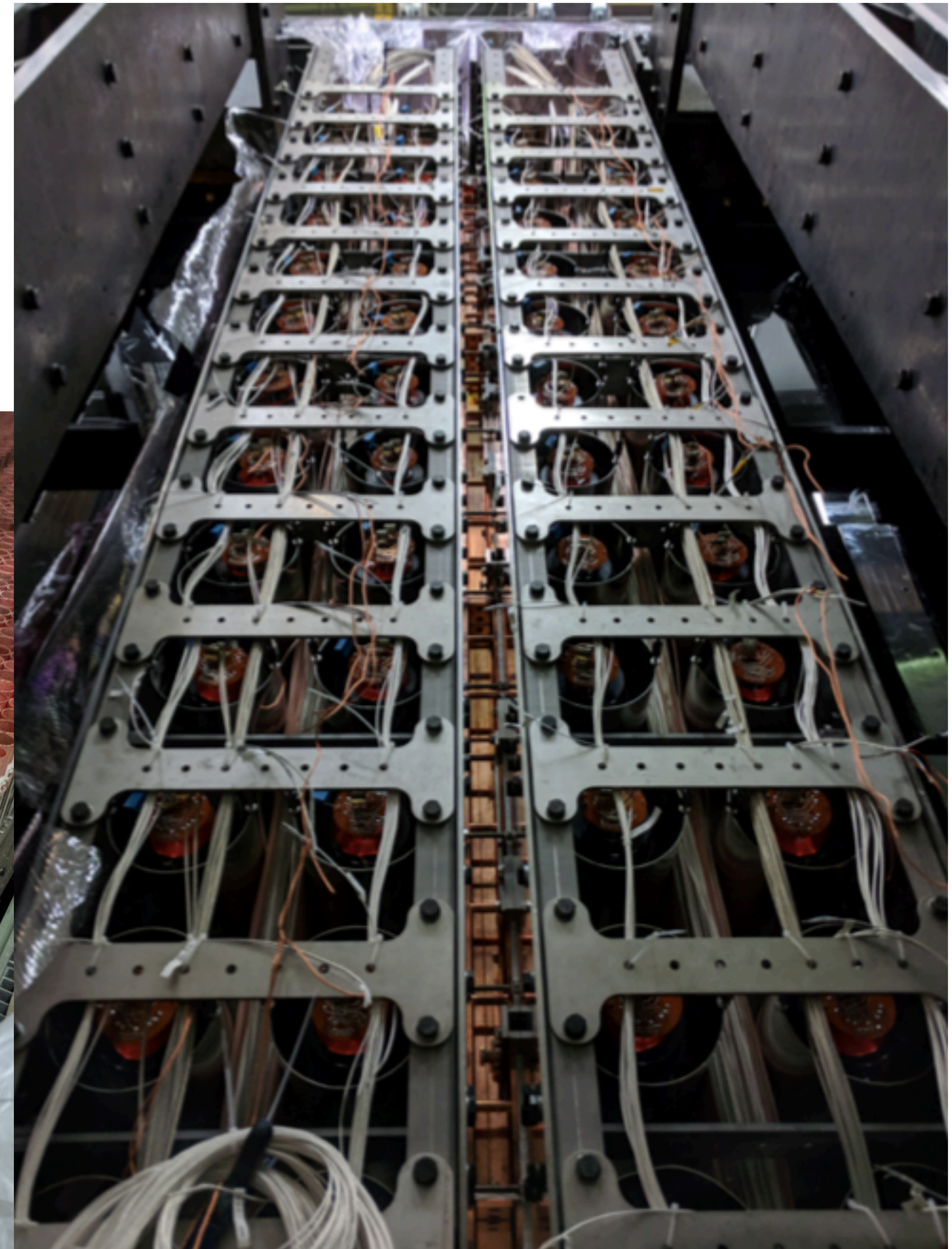
HSD : many intermediate excited states contribute

SSD : single intermediate 1+ state dominates

SuperNEMO Prototype Status

- Source foils & calibration system installed.
- Detector closed and fully cabled.
- Calorimeter commissioning is advanced.
- Full detector turn-on later in 2019.





SuperNEMO prospects

Physics in the next 3—4 years

$0\nu\beta\beta$: $T_{1/2} > 6 \times 10^{24}$ years; $\langle m_\nu \rangle <$ 160-400 meV

Exotic $0\nu\beta\beta$ mechanisms

Lorentz invariance violation test

$2\nu\beta\beta$: SSD/HSD discrimination at 5σ level

Probe nuclear physics by investigating g_A

Alternative isotopes: ^{150}Nd and ^{96}Zr

$0\nu4\beta$: for ^{150}Nd

In case of a discovery of $0\nu\beta\beta$ at $\langle m_\nu \rangle \sim 50$ meV, SuperNEMO technology is

- Essential to determine the $0\nu\beta\beta$ mechanisim
- The best way to verify the observation in multiple isotopes

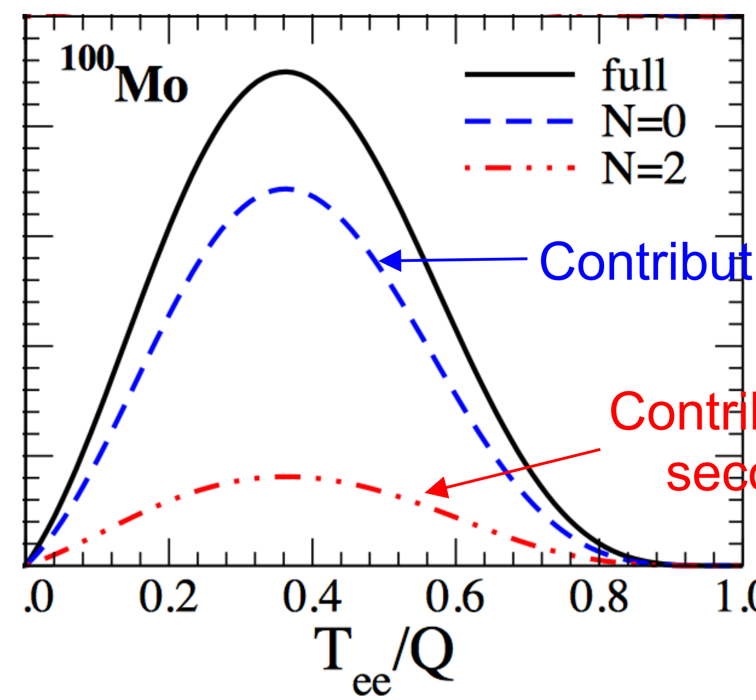
Quenching of axial vector coupling constant g_A in heavy nuclei

- Not well understood, and a hot topic in the field
- $2\nu\beta\beta$ rate has a strong g_A dependence

$$\left(T^{2\nu}_{1/2}\right)^{-1} \simeq \left(g_A^{\mathrm{eff}}\right)^4 \left|M^{2\nu}_{\mathrm{GT}}\right|^2 G^{2\nu}_0$$

Include second term in expression for decay rate

$$(T^{2\nu}_{1/2})^{-1} \simeq (g_A^{\mathrm{eff}})^4 |(M^{2\nu}_{GT})^2 G^{2\nu}_0 + M^{2\nu}_{GT} M^{2\nu}_{GT-3} G^{2\nu}_2|$$



Can study in NEMO-3 ^{100}Mo data, and in SuperNEMO with ^{82}Se

LEGEND

arXiv:1709.01980

- Collaboration formed in 2016.
- UK invited to join based on :
  - HPGe expertise (in nuclear physics community).
  - Low background screening capability.
  - Detector development and $0\nu\beta\beta$ expertise.

Current members:

UCL

UNIVERSITY OF LIVERPOOL

Lancaster University

+ SoI signatories:

THE UNIVERSITY OF WARWICK

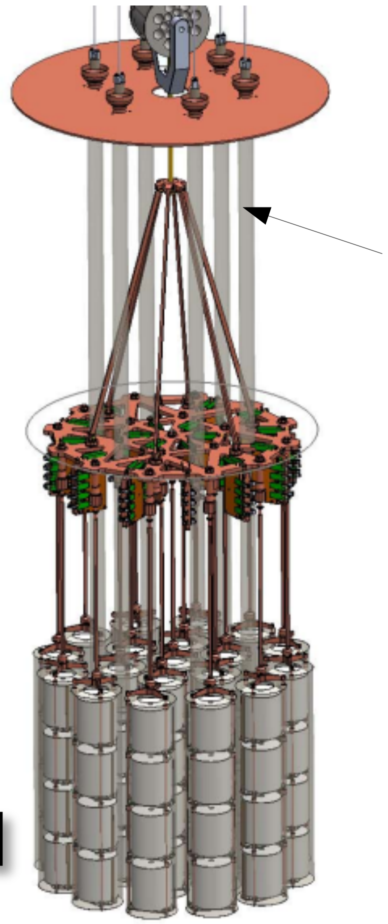
MANCHESTER 1824 The University of Manchester

Large Enriched Germanium Experiment for $0\nu\beta\beta$ Decay

Current GERDA array

Sensitivity Goals

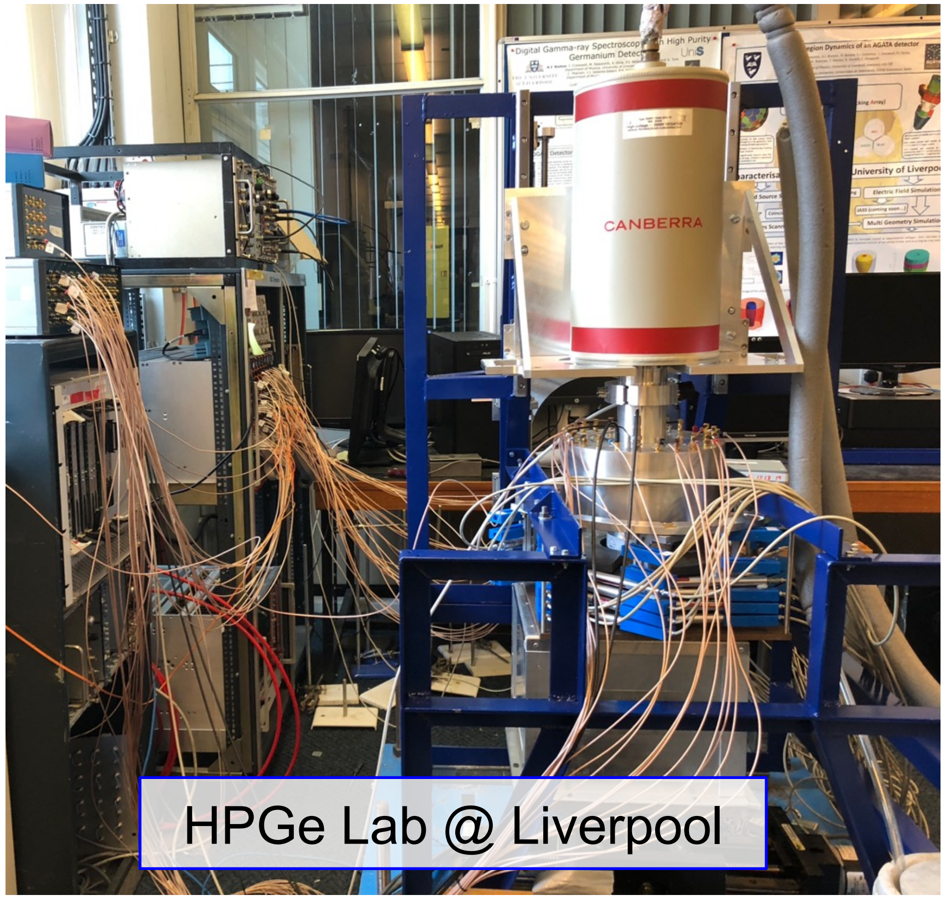
- 10^{27} yrs: 200kg (requires bkgd reduction factor of 3 from GERDA)
- 10^{28} yrs: 1000kg (requires further bkgd reduction factor of 6 from LEGEND 200)

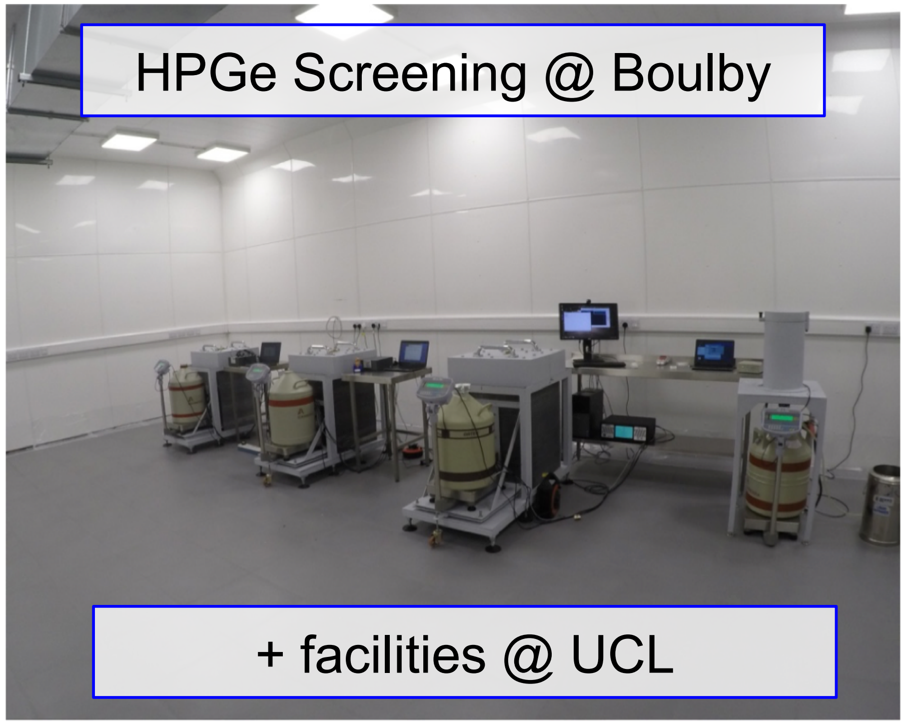


LEGEND-200 in GERDA cryostat. Deployment 2021.

Large Enriched Germanium Experiment for $0\nu\beta\beta$ Decay

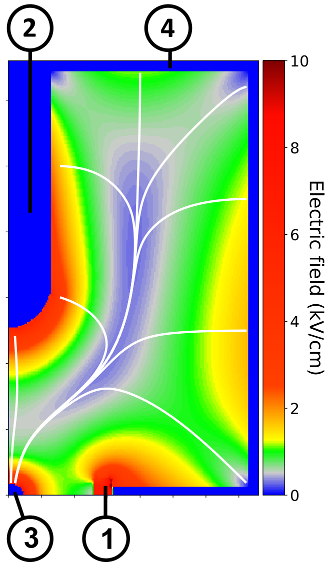
LEGEND-200 *will* be one of the (few) next-generation $0\nu\beta\beta$ experiments :
  - Exciting and experimentally plausible discovery potential.
  - Strong momentum with LEGEND-200 timetable already secure.
- The UK has played an important role already :
  - Early ^{76}Ge vendor assays.
  - IB Chair.
  - Innovative detector & holder designs.
- Opportunity for interdisciplinary UK team (NP & PP) to make a major impact.

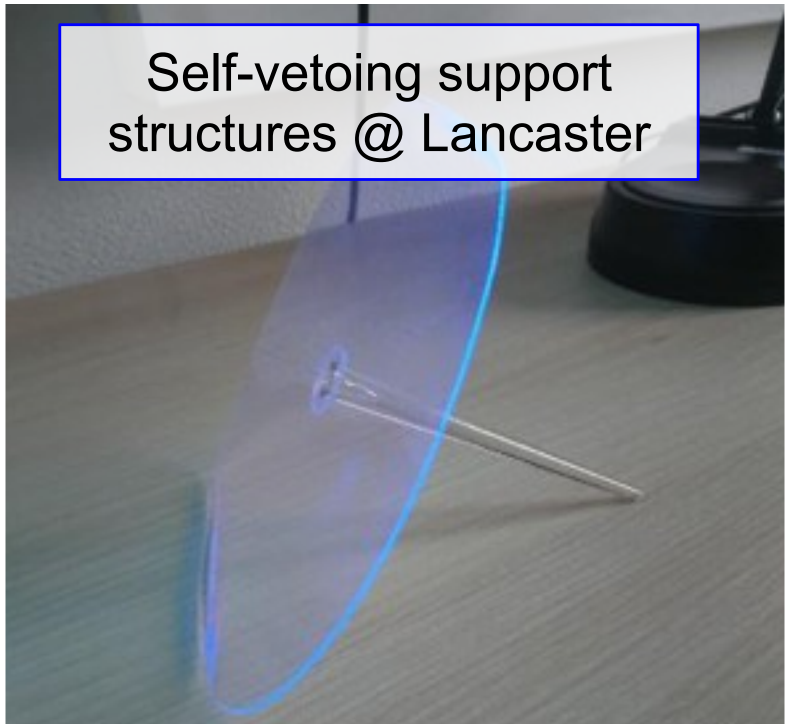

HPGe Lab @ Liverpool


HPGe Screening @ Boulby

+ facilities @ UCL

Very Large Mass Detector R&D




Self-vetoing support structures @ Lancaster

SNO+

Lancaster
Liverpool
Oxford
KCL
Sussex

$0\nu\beta\beta$

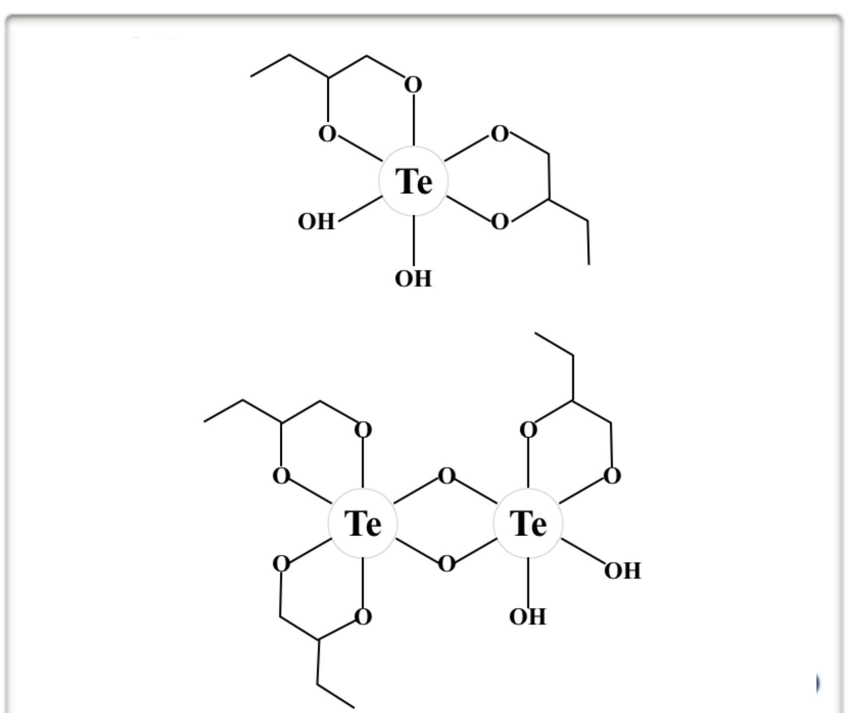
- Reactor neutrinos (will resolve Δm^2_{12} tension)
- Low energy solar neutrinos
- Geo neutrinos
- Supernova neutrinos
- Invisible modes of nucleon decay
-
-
-

^{130}Te-loaded scintillator

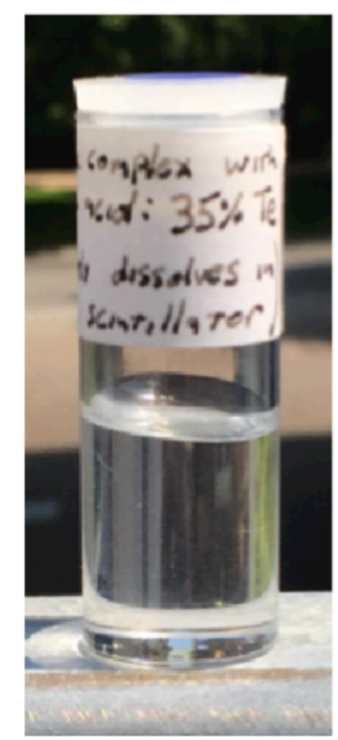
Concept originated in UK (Biller & Chen, 2012)

- ^{130}Te is the most cost effective isotope:
  - Enriched ^{136}Xe ~ \$20,000 /kg of isotope
  - Natural Te (34.5% ^{130}Te) ~ \$ 150 /kg of isotope
- ^{130}Te has good predicted matrix element values (better than ^{136}Xe) and a good phase space factor (comparable to ^{136}Xe and ~6 times better than ^{76}Ge)
- Liquid scintillator is the most cost effective and scalable $0\nu\beta\beta$ detection technology

New loading method also developed in UK: Te-diol complex



- Simple synthesis
- Single safe, distillable chemical
- Low radioactivity levels
- Minimal optical absorption
- High light levels at 0.5% Te Loading



LAB arrival at site

Scintillator purification system operational

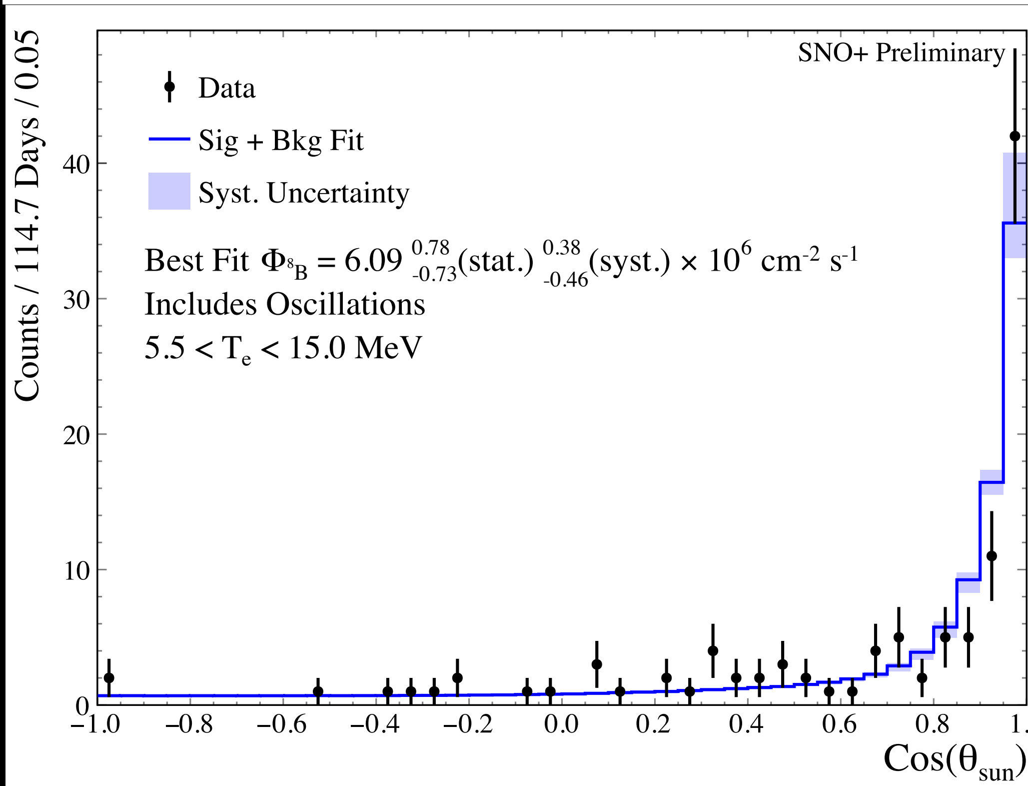
All of the Te needed for Phase I is now underground

Te purification and loading plants construction finished (starting commissioning)

Recent Water Results

PHYSICAL REVIEW D **99**, 012012 (2019)

Measurement of the ^{8}B solar neutrino flux in SNO+ with very low backgrounds



PHYSICAL REVIEW D **99**, 032008 (2019)

Search for invisible modes of nucleon decay in water with the SNO+ detector

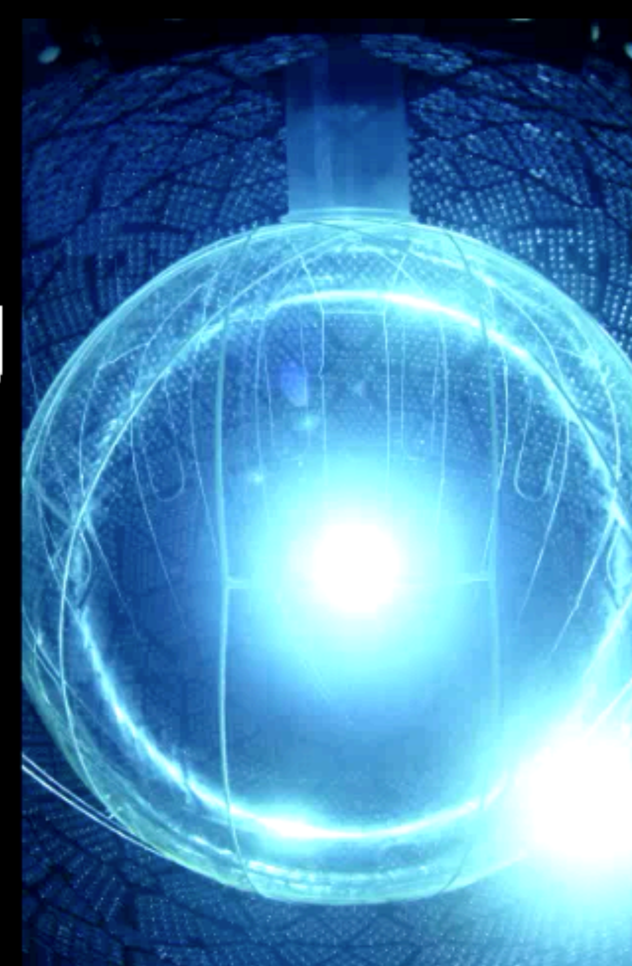
	Spectral analysis	Counting analysis	Existing limits
n	2.5×10^{29} y	2.6×10^{29} y	5.8×10^{29} y [9]
p	3.6×10^{29} y	3.4×10^{29} y	2.1×10^{29} y [10]
pp	4.7×10^{28} y	4.1×10^{28} y	5.0×10^{25} y [11]
pn	2.6×10^{28} y	2.3×10^{28} y	2.1×10^{25} y [13]
nn	1.3×10^{28} y	0.6×10^{28} y	1.4×10^{30} y [9]

Several other papers in preparation

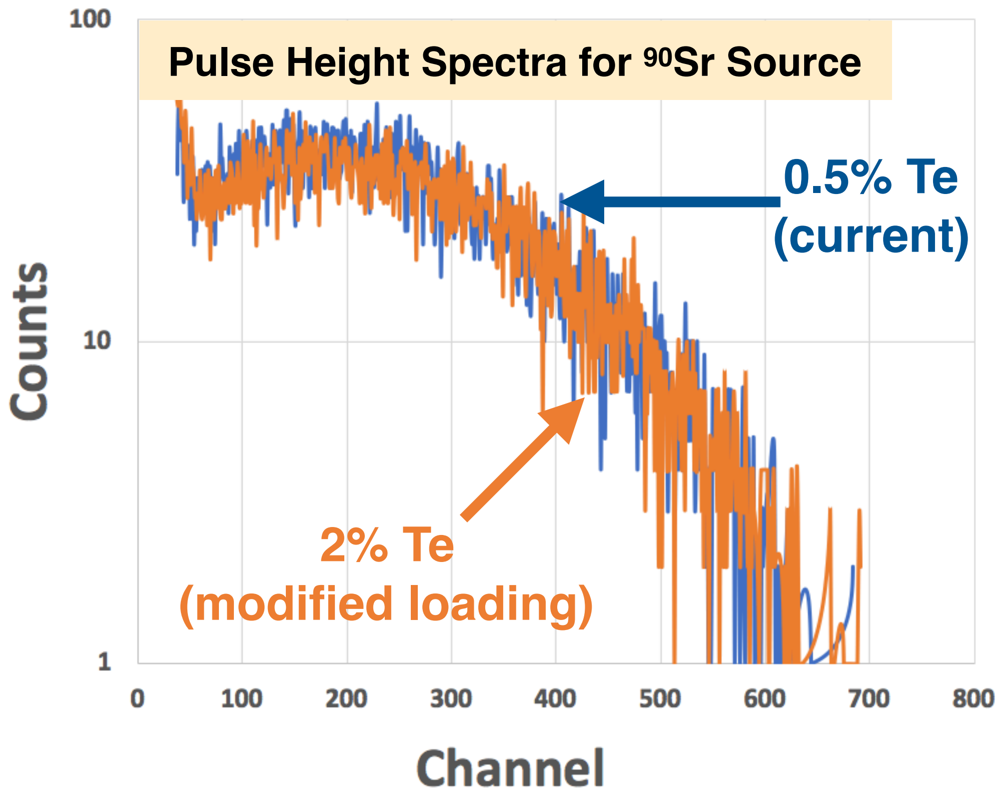
LAB fill in progress

Ready for Te loading next year

6200kg



Improved Loading Protocol to Move Beyond Phase I

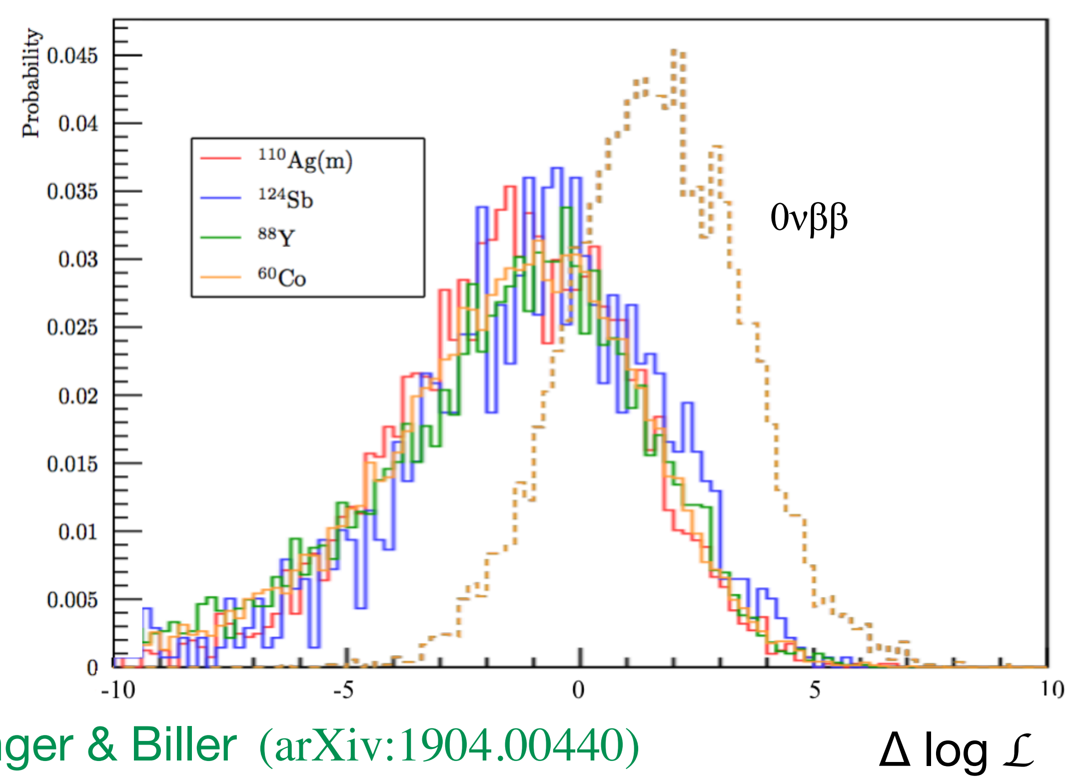


The Future:
Simply increase loading from Phase I <u>without any major hardware upgrade</u> to move adiabatically to "Phase II"
(~4 times higher half-life sensitivity to cover the majority of the IH region)

cost ~ $15M

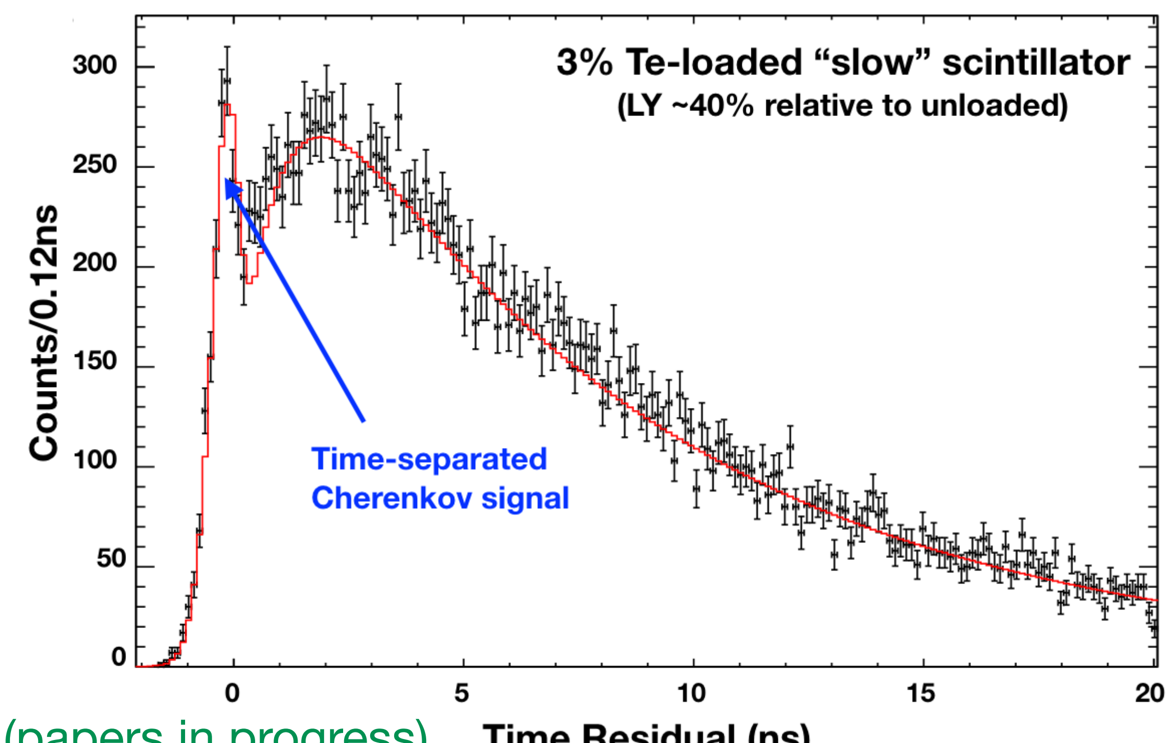
Other technical advances:

Multi-site discrimination in LS detectors



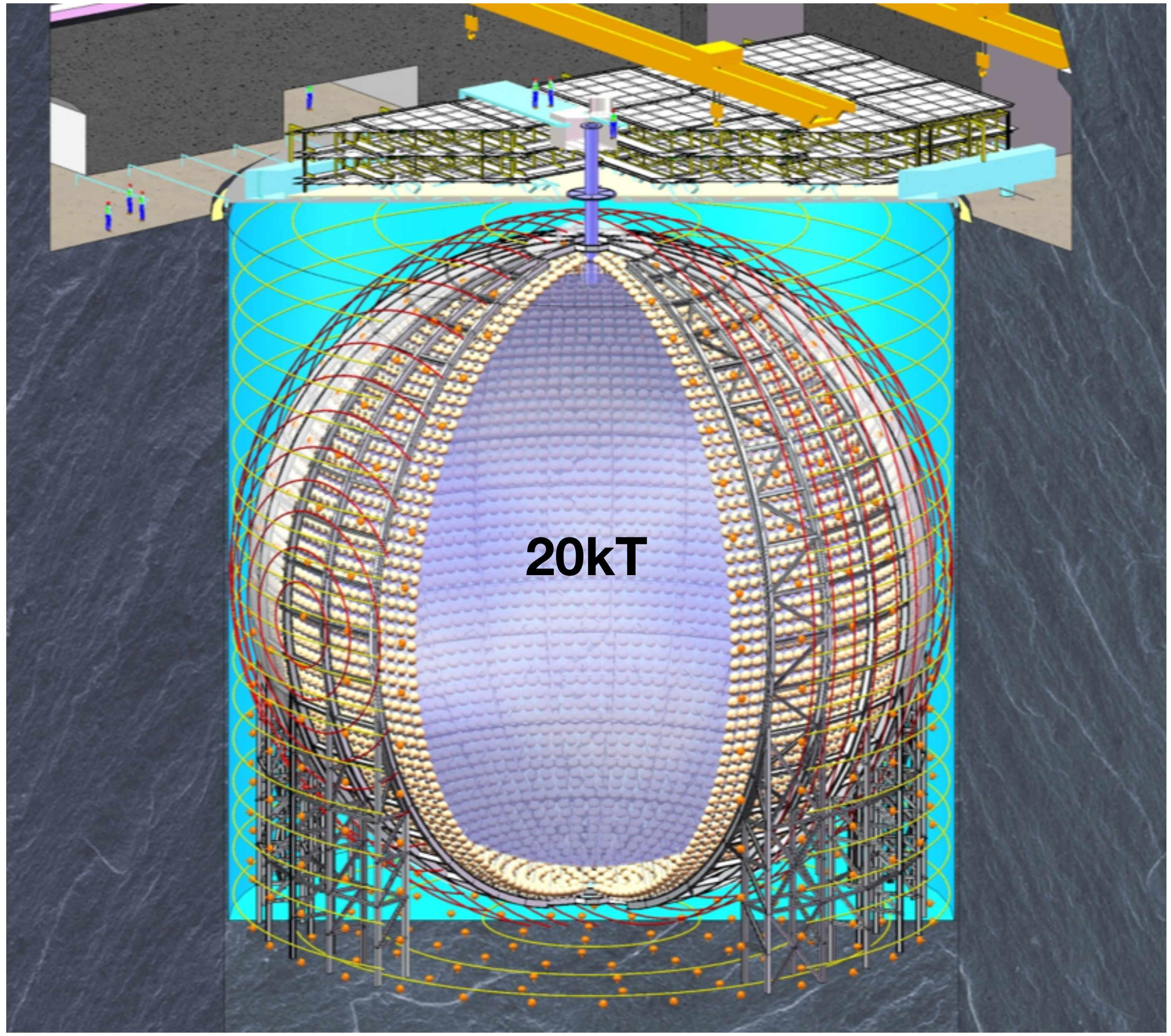
Dunger & Biller (arXiv:1904.00440)

Cherenkov separation using slow fluors



(papers in progress)

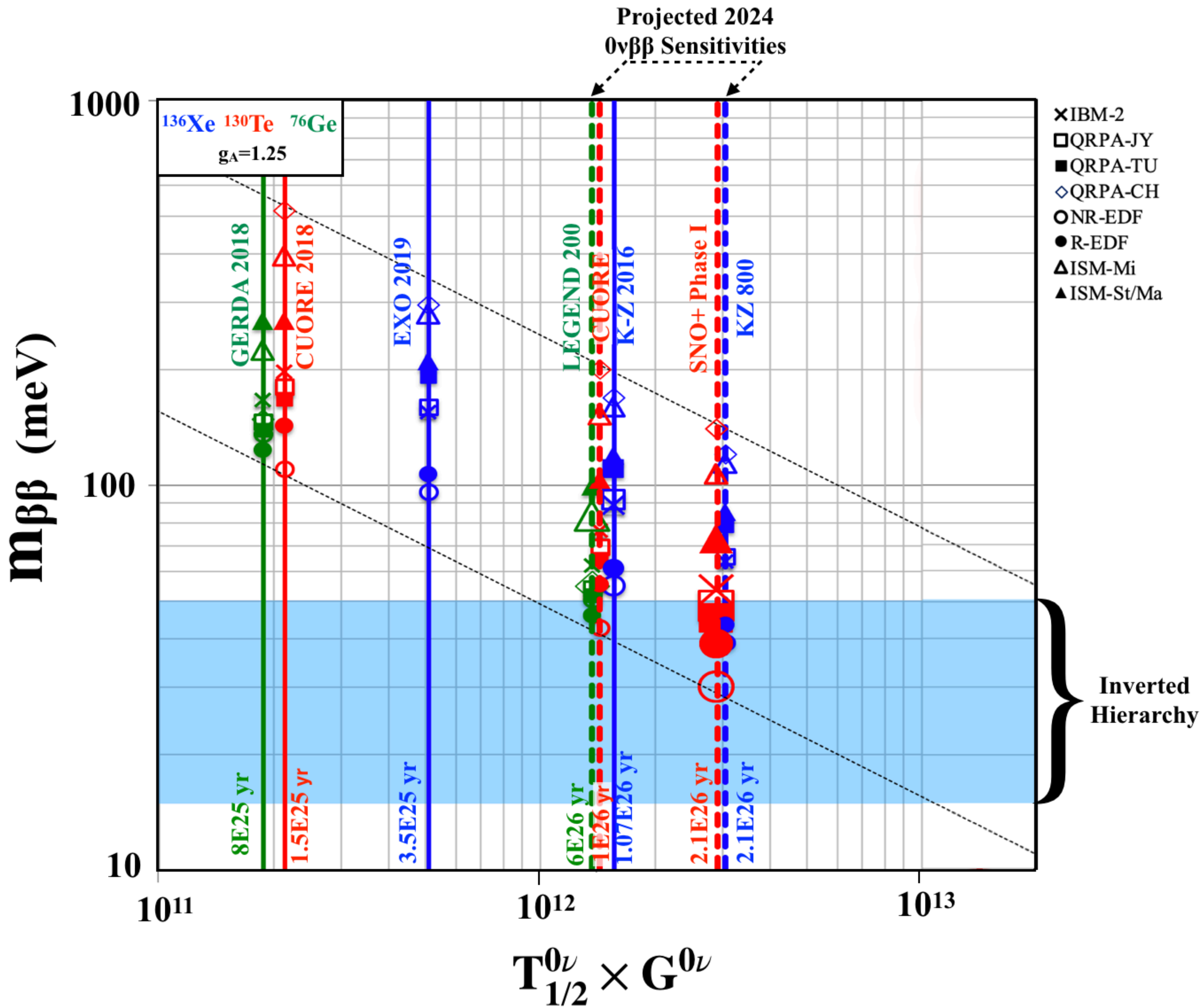
Possible Future Beyond SNO+ Phase II:



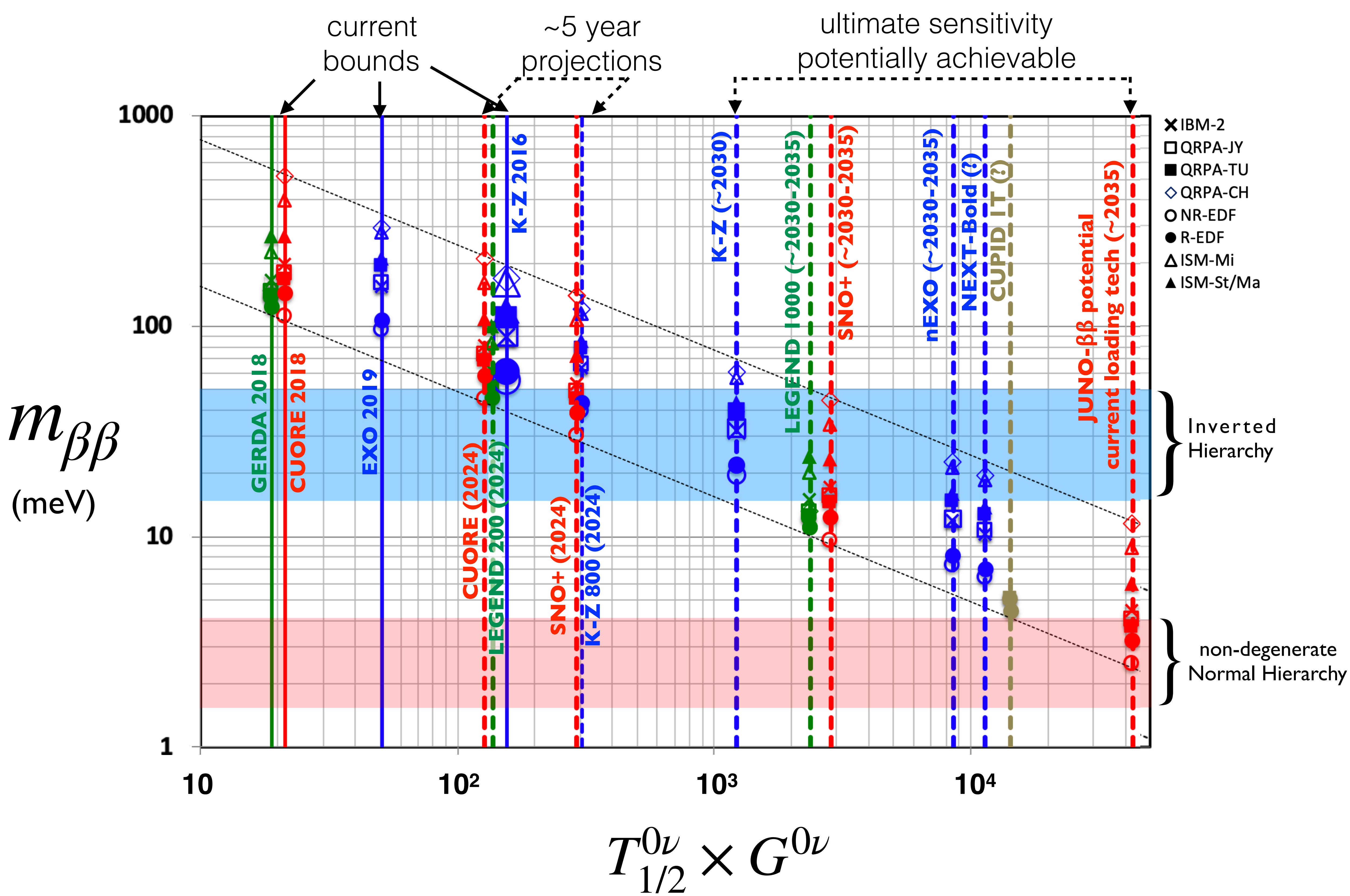
In discussions with group about possible future deployment of Te in JUNO

Potential to have greatest reach of any experiment and begin to probe non-degenerate normal hierarchy!

So How Do The Future Prospects Look?



New Physics Sensitivity: Phase-Space Weighted Half-Life


current bounds
~5 year projections
ultimate sensitivity potentially achievable
1000
100
10
1
$m_{\beta\beta}$
(meV)
10
10^2
10^3
10^4
$T_{1/2}^{0\nu} \times G^{0\nu}$
GERDA 2018
CUORE 2018
EXO 2019
CUORE (2024)
LEGEND 200 (2024)
K-Z 2016
SNO+ (2024)
K-Z 800 (2024)
K-Z (~2030)
LEGEND 1000 (~2030-2035)
SNO+ (~2030-2035)
nEXO (~2030-2035)
NEXT-Bold (?)
CUPID IT (?)
JUNO-ββ potential
current loading tech (~2035)
IBM-2
QRPA-JY
QRPA-TU
QRPA-CH
NR-EDF
R-EDF
ISM-Mi
ISM-St/Ma
Inverted Hierarchy
non-degenerate Normal Hierarchy