THE ~~(FRUSTRATING)~~ Exciting SEARCH FOR STERILE NEUTRINOS

Jordy de Vries
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Tiny masses

- In the original formulation of the Standard Model (Weinberg 1967) neutrinos were considered to be massless particles
- Not crazy: from beta decay experiments $m_\nu \ll m_e \ll m_p$

Neutrinos, they are very small.
They have no charge and have no mass
And do not interact at all.
The earth is just a silly ball
To them, through which they simply pass.

John Updike's Cosmic Gall
(1960)

Tiny masses

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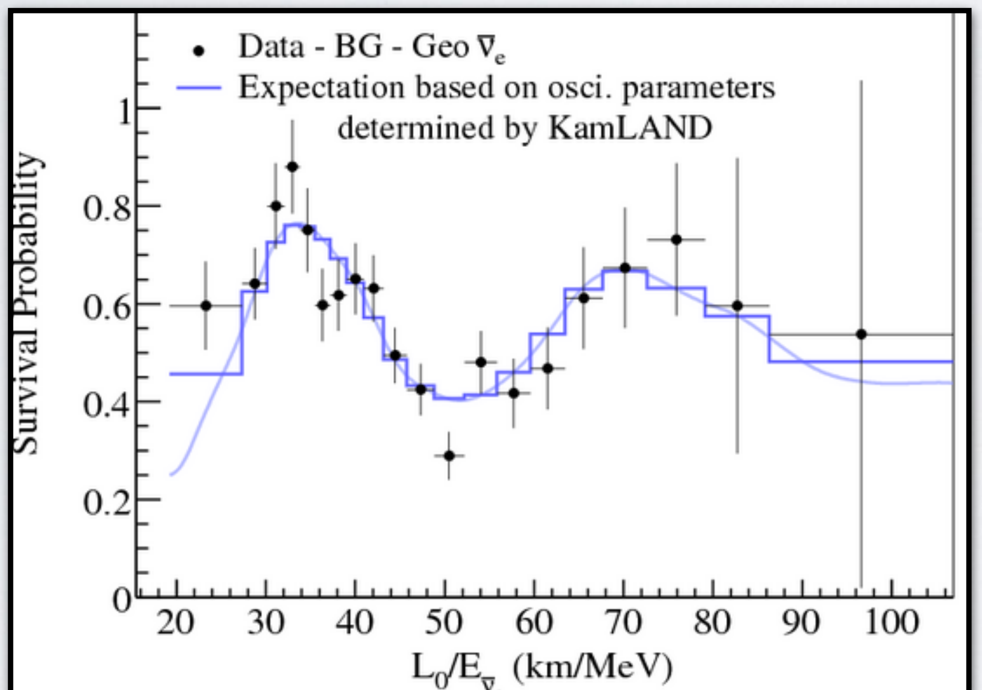
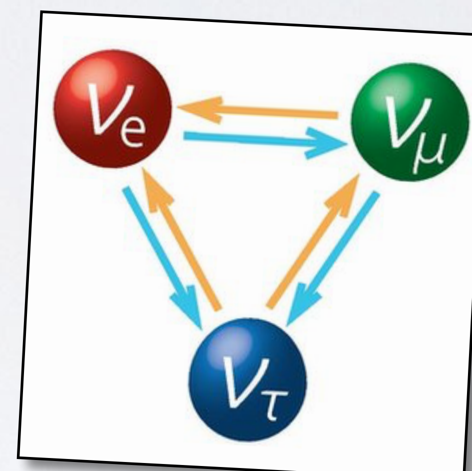
- **But neutrinos do have mass !**



$$P(\nu_\mu \to \nu_e) \sim \sin \frac{\Delta m^2 L}{2E}$$



- Biggest mass splitting: $|\Delta m| \simeq 0.05\, eV$ Smallest: $|\delta m| \simeq 0.008\, eV$
- Direct limits: $m_{\nu_e} \leq 0.8\, eV$
  KATRIN experiment
- Cosmology (DESI 2024) $\sum m_{\nu_i} \leq 0.15\, eV (IH)$
  $\sum m_{\nu_i} \leq 0.11\, eV (NH)$

Tiny masses

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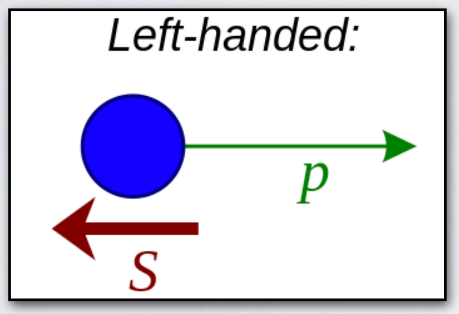
- **But neutrinos do have mass !**

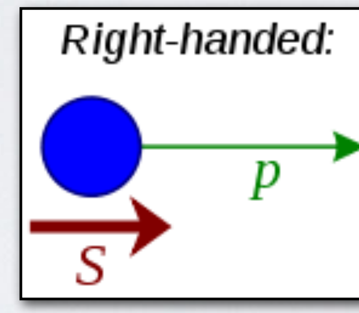
- **The problem of neutrino masses points towards new fields/new scales/new symmetries**

Mass generation in the Standard Model

- How does the electron get a mass in the Standard Model ?
- It's **tricky**: a mass term connects a left-handed to a right-handed field



Left-handed fields have a 'weak' charge



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- We cannot just write down a mass term: $\mathscr{L} = -m_e \bar{e}_L e_R$
- This would violate 'weak charge' conservation (or SU(2) gauge invariance)

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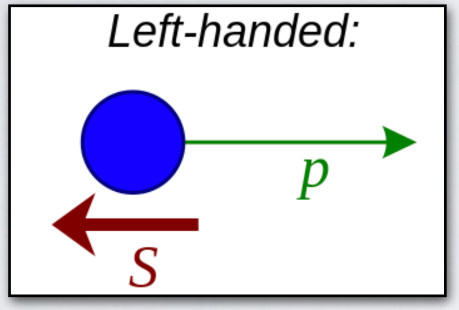

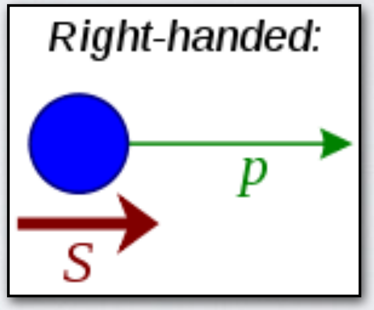

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- We cannot just write down a mass term: $\mathscr{L} = -m_e \bar{e}_L e_R$
- This would violate 'weak charge' conservation (or SU(2) gauge invariance)
- The Standard Model overcomes this problem through the **Higgs** mechanism

$$\mathscr{L} = -y_e \bar{e}_L e_R \varphi \longrightarrow \mathscr{L} = -y_e \bar{e}_L e_R \mathrm{v} \qquad m_e = y_e \mathrm{v}$$

- The scalar field has a weak charge and a nonzero value **v** in the vacuum (*spontaneous symmetry breaking*)

The puzzle of the neutrino mass

- **Easy fix:** Insert gauge-singlet right-handed neutrino υ_R

$$\mathscr{L} = -\, y_\nu \bar{\nu}_L \nu_R \varphi \qquad\qquad y_\nu \sim 10^{-12} \to m_\nu \sim 0.1\,\mathrm{eV}$$

- Nothing really wrong with this….
- **The υ-nightmare scenario**

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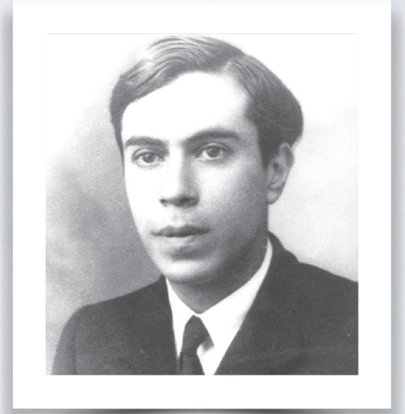
$$\mathscr{L} = -y_\nu \bar{\nu}_L \nu_R \varphi - M_R \nu_R{}^T C \nu_R$$

'Everything that is not forbidden is compulsary'



Ettore Majorana

- This is not allowed for any Standard Model particle !
- M_R not connected to electroweak scale: could be a **completely new scale**

- Footnote: by far not the only way to generate neutrino masses! Can be done without right-handed neutrino's (see e.g. type-II seesaw with a new triplet scalar field)

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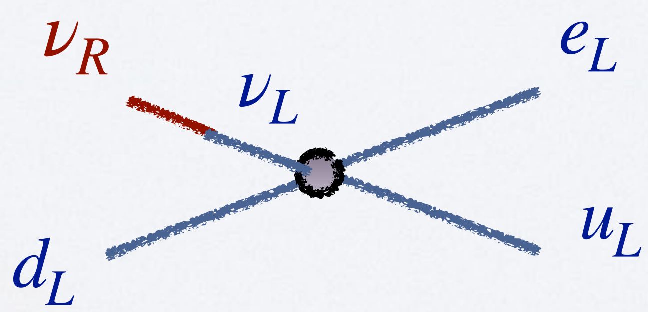
- 1+1 case: diagonalization leads to **Majorana** mass eigenstates $\qquad \nu_i^c = \nu_i$
- If M_R is significantly larger than active neutrino masses: **see-saw mechanism**

$$m_1 \simeq \left| \frac{y_\nu^2 v^2}{M_R} \right| \ll m_2 \simeq M_R$$

Active neutrino + heavier sibling (sterile neutrino)

- **Sterile neutrinos**



$$\sim G_F \sqrt{\frac{m_1}{m_2}} \ll G_F$$

The puzzle of the neutrino mass

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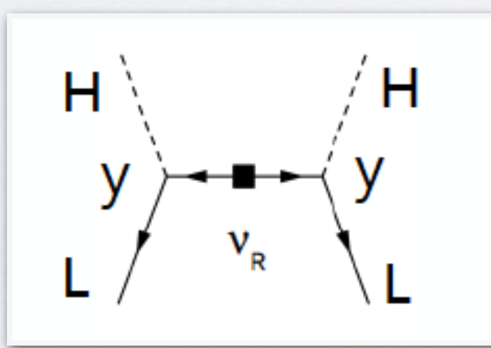
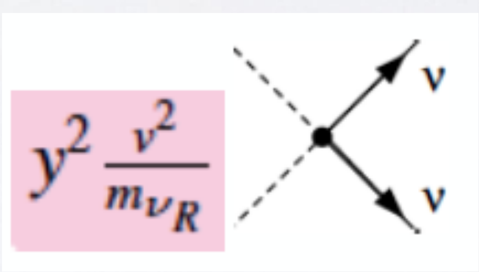
$$\mathscr{L} = -\, y_\nu \bar{\nu}_L \nu_R \varphi - M_R {\nu_R}^T C \nu_R$$

- If M_R is significantly larger than electroweak scale: **integrate it out**





- Obtain dimension-5 SMEFT operator that lead to **active neutrino Majorana mass**

$$\mathscr{L}_5 = C_5 \left(L^T C \tilde{H}\right)(\tilde{H}^T L)$$

Weinberg '79

- Weinberg operator describes many 'high-scale' mechanisms

Are neutrino masses BSM ?

- A question to fight about at lunch
- Not uncommon opinion: ***Standard Model can be redefined to include neutrino masses***

Are neutrino masses BSM ?

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- Not uncommon opinion: ***Standard Model can be redefined to include neutrino masses***

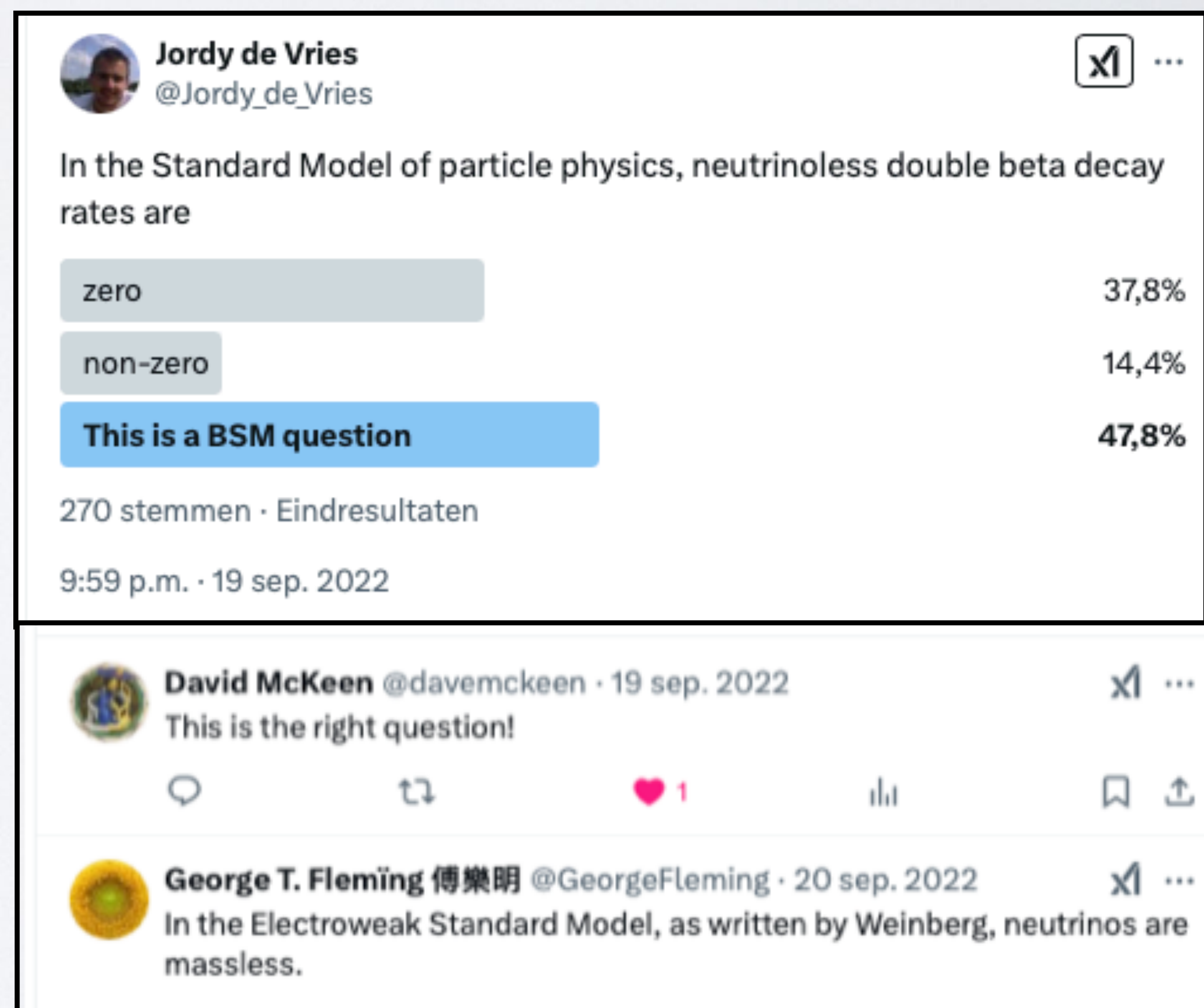
- ***But which mechanism?***

A) $\mathscr{L} = -y_\nu \bar{\nu}_L {\color{red}\nu_R} \varphi$

B) $\mathscr{L} = C_5 \left(L^T C \tilde{H}\right)(\tilde{H}^T L)$

C) $\mathscr{L} = -y_\nu \bar{\nu}_L {\color{red}\nu_R} \varphi - M_R {\color{red}\nu_R}^T C {\color{red}\nu_R}$

D) ....



- *Footnote: B and C/D are not exclusive*

The plan of attack

1. Motivation: the puzzle of neutrino masses

2. **Probing sterile neutrinos directly and indirectly**

    - *Effective field theory for 0vbb*

3. Connection to low-scale leptogenesis

In this talk: minimal option C setup

- **See-saw (variants) can work for essentially any right-handed scale**

$\longrightarrow$ **M_R ?**

eV **keV** **MeV** **GeV** **TeV** **.....** **10^{15} GeV**

- If Yukawa coupling order 1 then $$m_1 \simeq \left| \frac{v^2}{M_R} \right| \quad \rightarrow M_R \simeq 10^{15}\,\mathrm{GeV}$$

In this talk: minimal option C setup

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M_R ?

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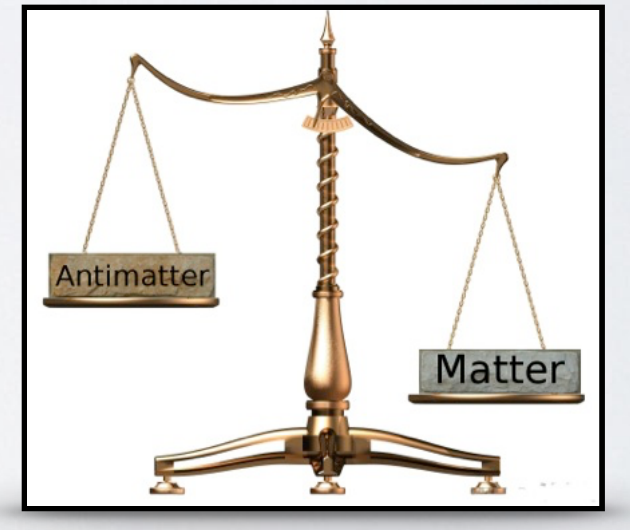
- If Yukawa coupling order 1 then $m_1 \simeq \left| \frac{v^2}{M_R} \right| \rightarrow M_R \simeq 10^{15}\,\text{GeV}$

- **Thermal leptogenesis possible** $M_R \geq 10^9\,\text{GeV}$

Fukugita, Yanagadi '86

Davidson Ibarra '02

13.7 billion year



- Hard to test directly but smoking gun evidence:
  neutrinos are Majorana + CPV in neutrino sector

Mass ranges

- **See-saw (variants) can work for essentially any right-handed scale**

eV keV MeV GeV TeV ..... 10^{15} GeV → M_R ?

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Fukugita, Yanagadi ‘86

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Davidson Ibarra ‘02

- But also leptogenesis possible with **TeV** sterile neutrinos!

Pilaftsis ’97, Akhmedov et al ’98

- And even in the **MeV-GeV** range

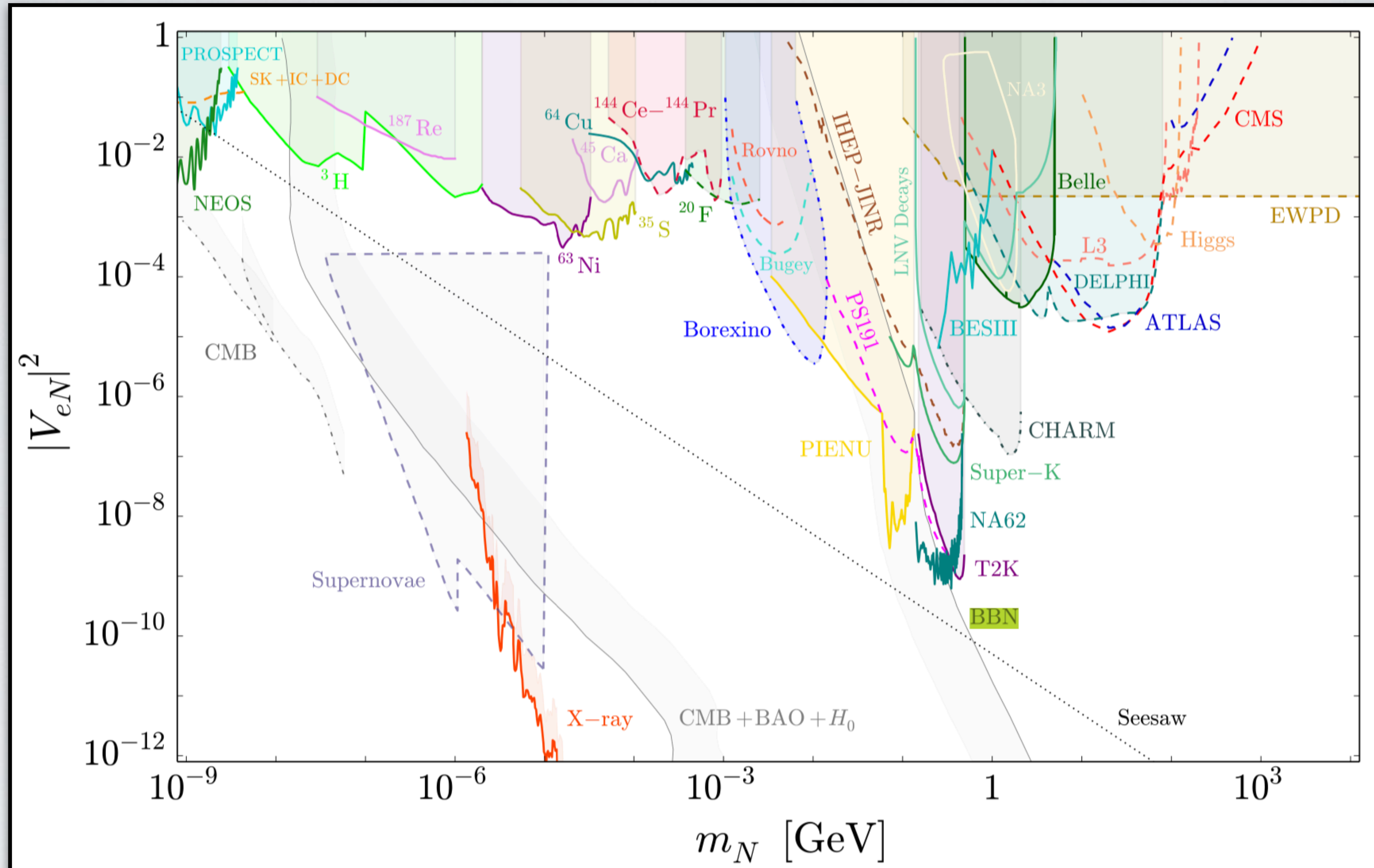
See e.g. Shaposhnikov et al (many works)
Drewes et al ‘21

- KeV sterile neutrino could be Dark Matter (but getting more difficult) and essentially decoupled from neutrino mass generation

Dodelson, Widrow ’97
Shaposhnikov et al ‘05

- **Motivation to look for a broad range of sterile neutrino masses**

We really want to find them....



Bolton, Deppisch, Dev JHEP '20

- If they exist with masses below 1 TeV or so, we might find them directly !
- Very interesting experimental signatures depending on the mass range

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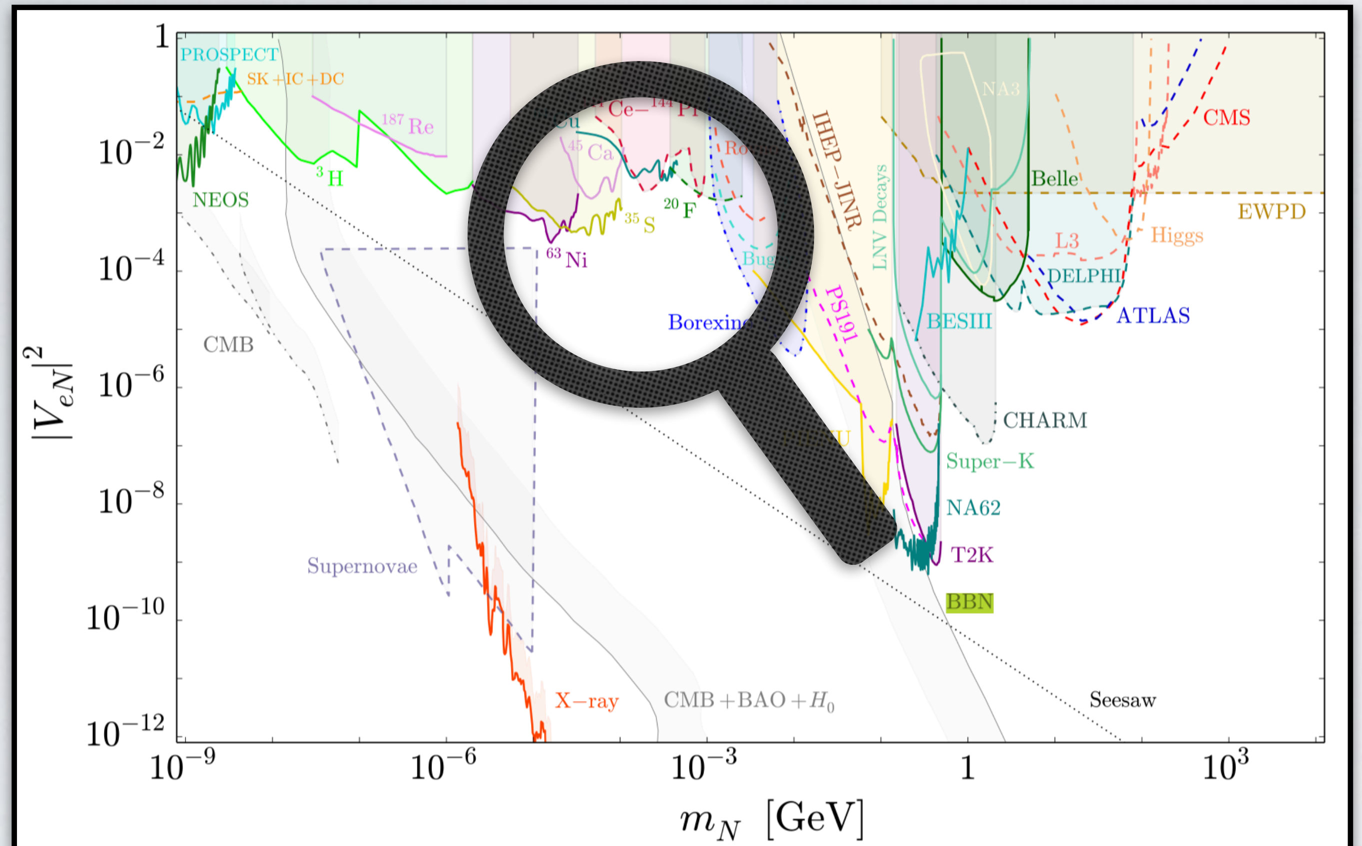

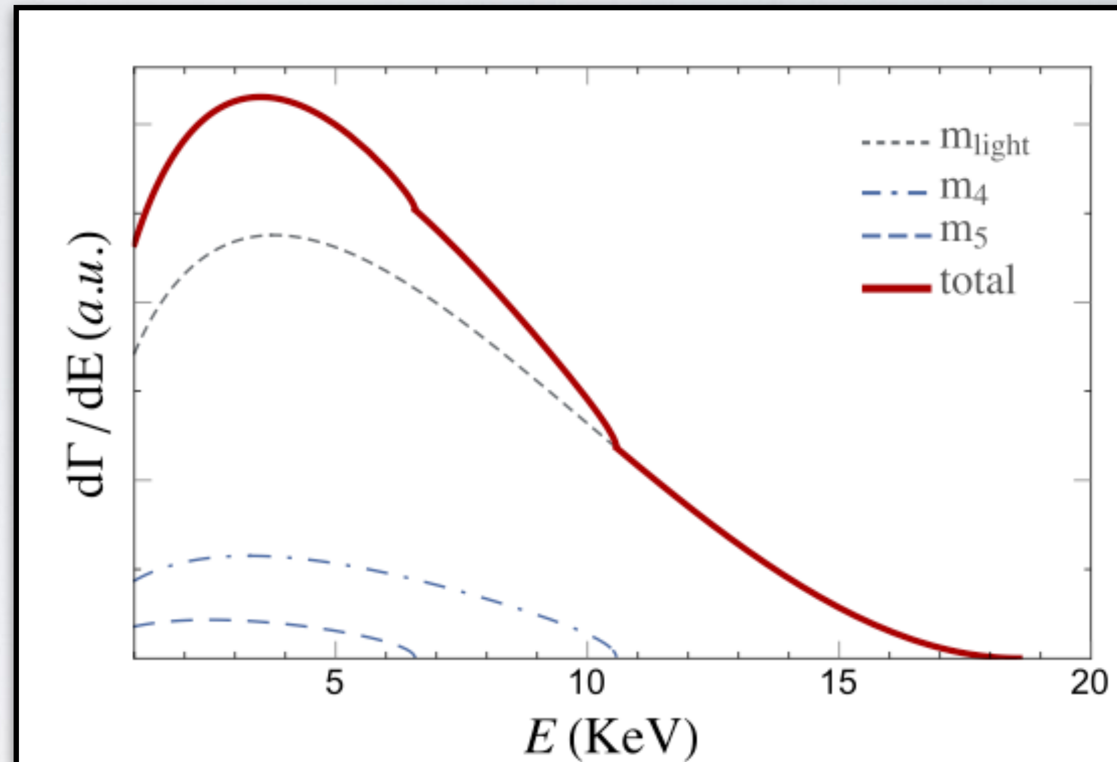

$m_4 = 8\,\text{keV}\,,\, U_{e4} = 0.1 \quad m_5 = 12\,\text{keV}\,,\, U_{e5} = 0.1$

- Light sterile neutrinos can be produced in beta-decays $\quad {}^{A}_{Z}X \to {}^{A}_{Z+1}Y + e^- + \nu$
- Measure the sum of decay rates, for example: $$\frac{d\Gamma}{dE_e} = \frac{d\Gamma_\nu}{dE_e} + U_{e4}^2 \frac{d\Gamma_4}{dE_e} + U_{e5}^2 \frac{d\Gamma_5}{dE_e}$$
- Sensitivity limited by experimental accuracy and ***theoretical control of spectral shape***

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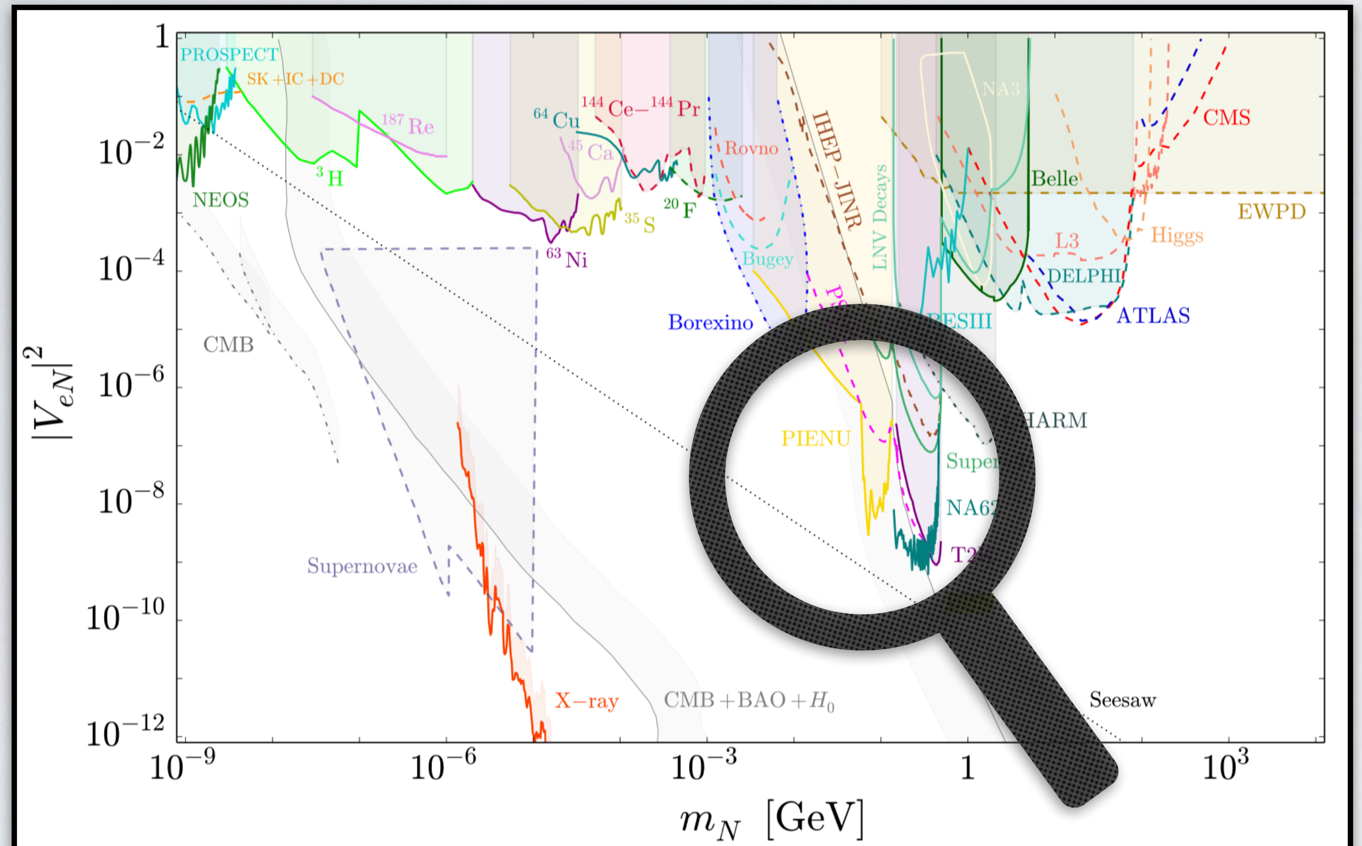
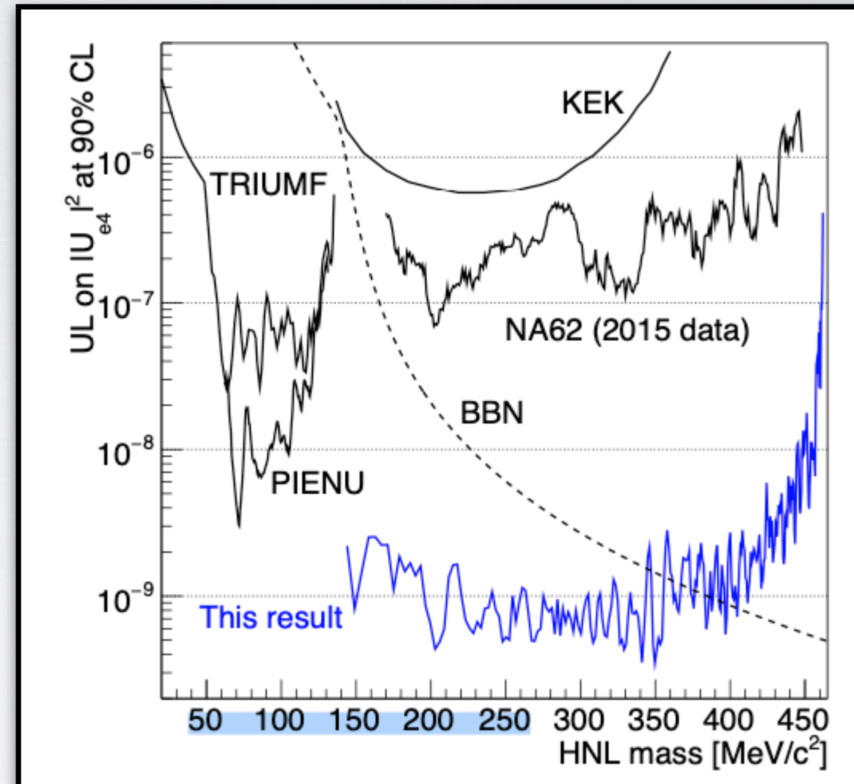
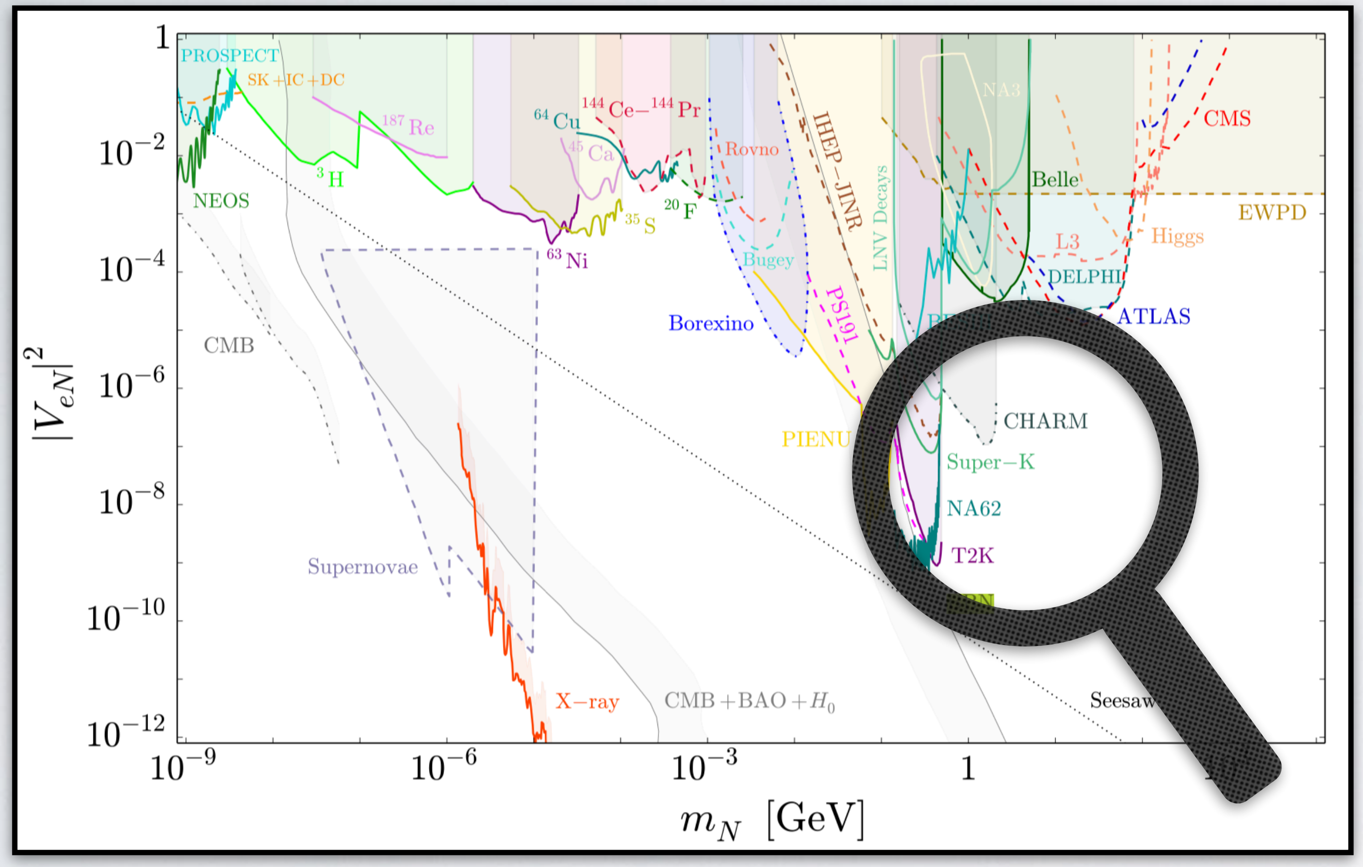




NA62 ‘20

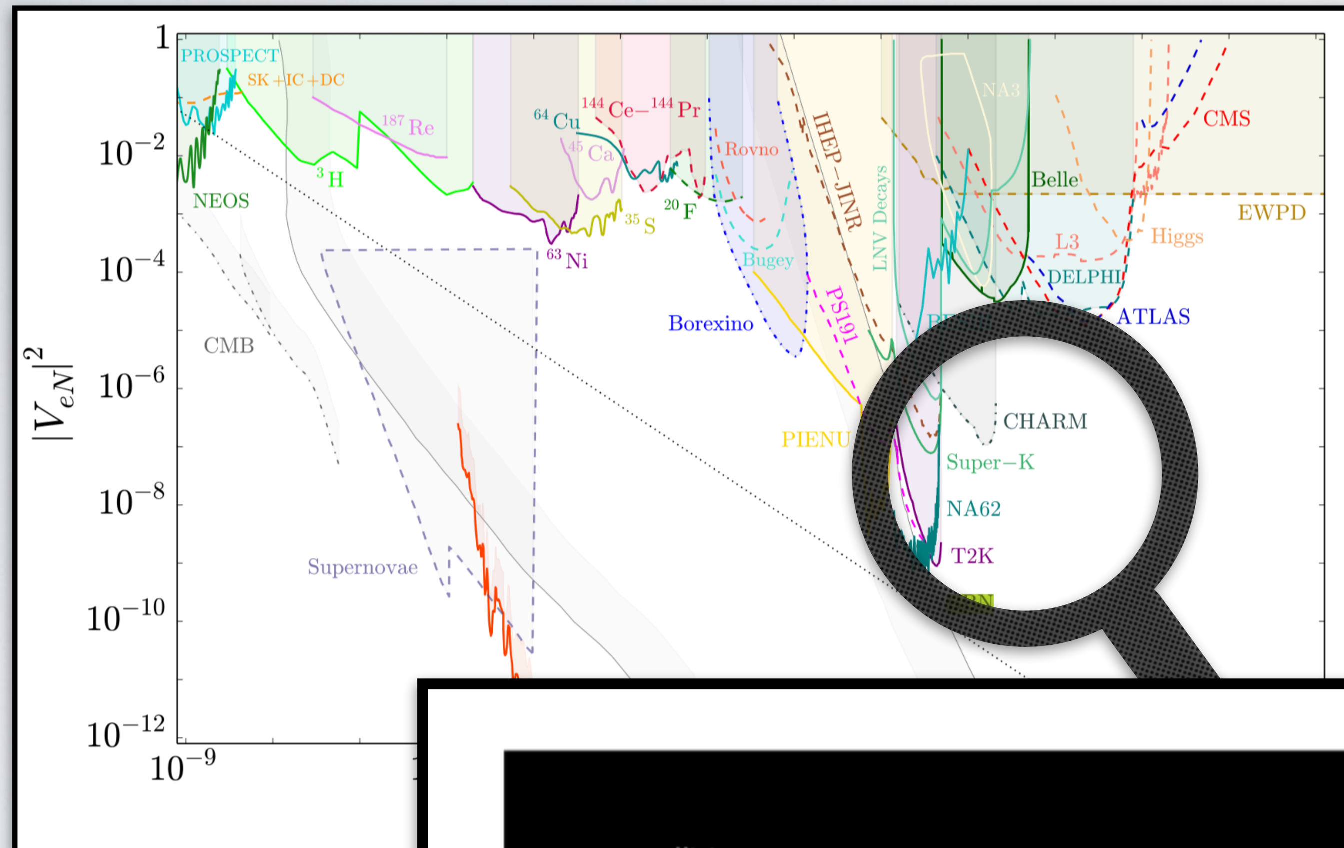
- Light sterile neutrinos can be produced in meson-decays $K^{\pm}, \pi^{\pm} \rightarrow e^{\pm} + N$
- Much cleaner than beta-decay and much more phase space —> **Stronger limits**
- Works up to Kaon mass threshold ~ 450 MeV.
- Sensitivity limited by statistics (number of mesons)/background control

We really want to find them....



- There is a gap after the kaon threshold
- New experiments are being developed
- `Displaced vertex searches ‘

We really want to find them....



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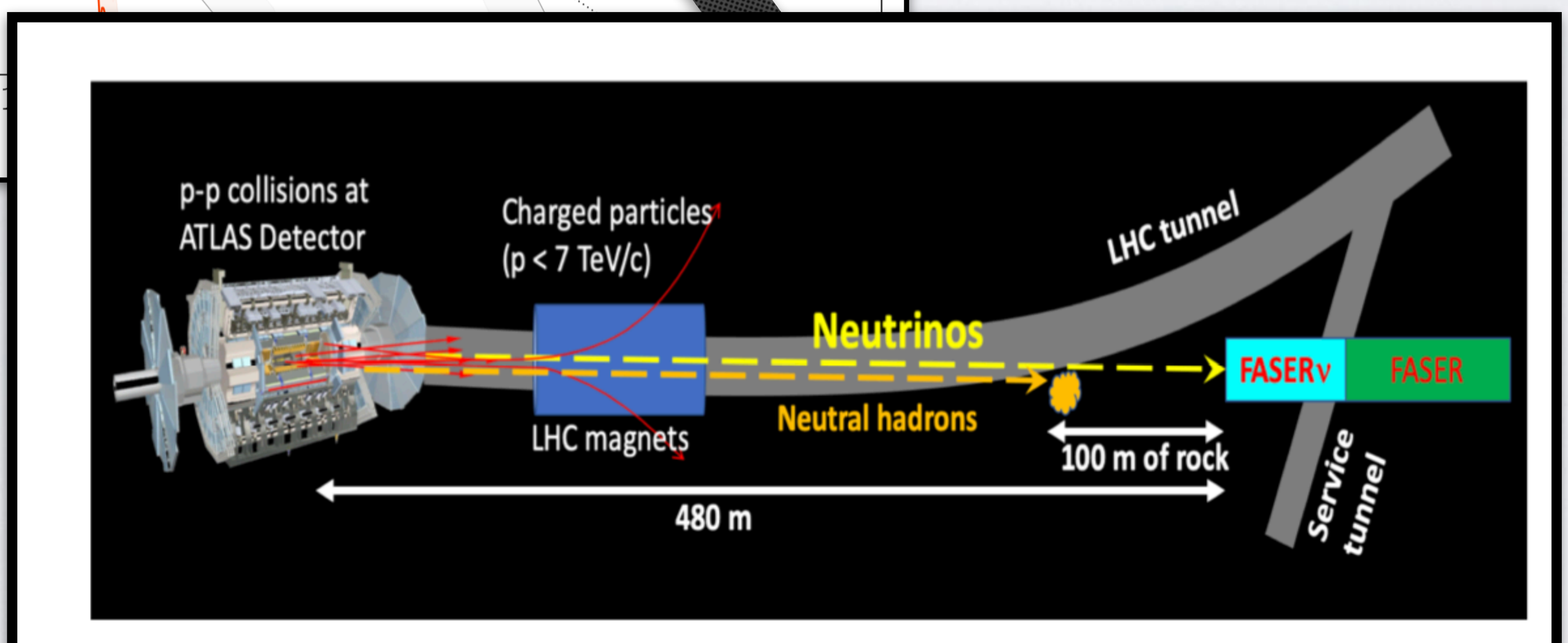


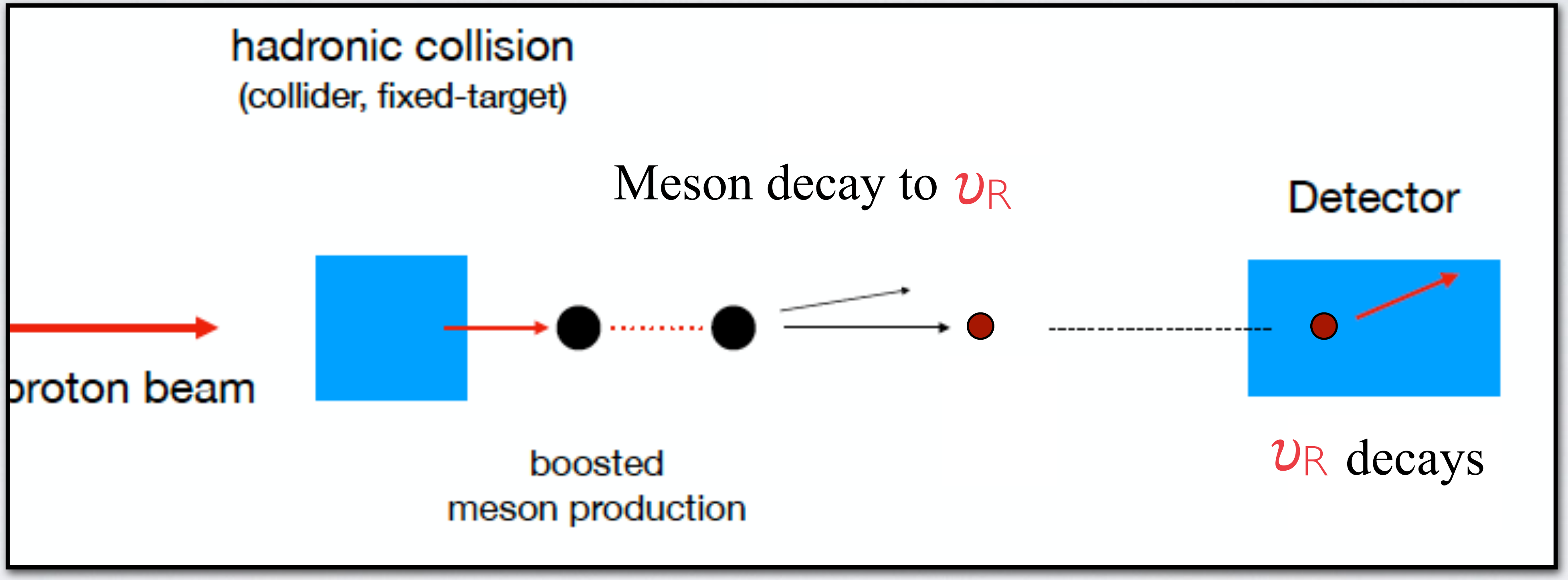
arXiv:2303.14185 (hep-ex)

[Submitted on 24 Mar 2023]

First Direct Observation of Collider Neutrinos with FASER at the LHC

Sterile neutrino from meson decay

- Idea: at colliders huge amount of **mesons** are produced (**strong interaction**)
- Some mesons decay through **weak interaction -> better chance** to produce ν_R
- Sterile neutrinos are relatively **long-lived:** escape conventional detectors

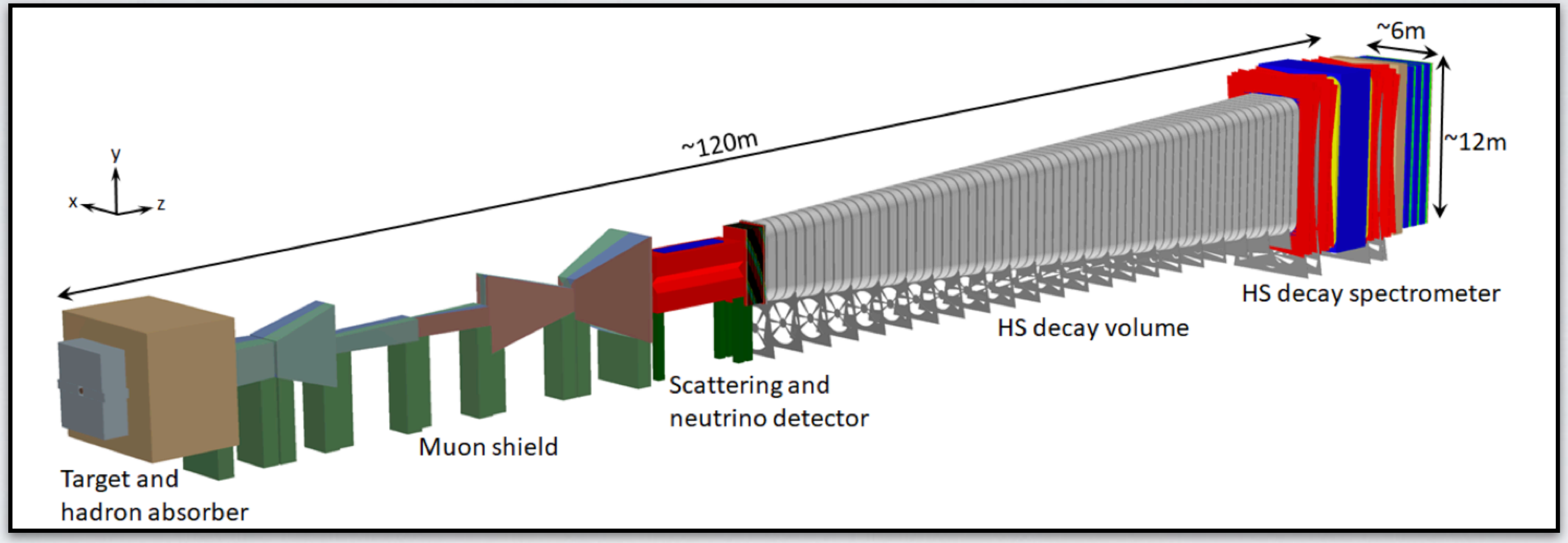


- Detector is placed far away from interaction point (tens to hundreds of meters)
- Space to install veto and shielding segments

New experiments

Many proposed experiments (MATHUSLA, CODEX-b, ANUBIS, MoEDAL)….

ShiP (Search for hidden Particles)

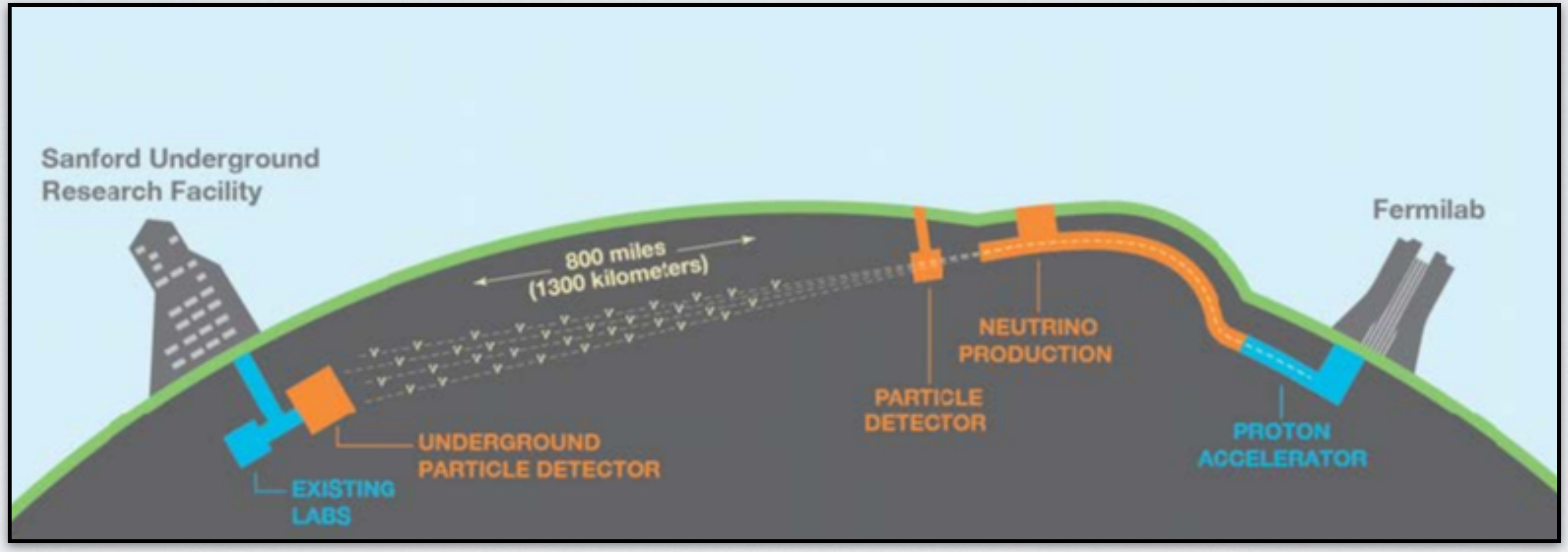


- Dump the SPS CERN beam (Super Proton Synchrotron) (400 GeV) on a dense target
- Huge amount of charm (10^{17}) and beauty (10^{13}) mesons produced in 4 year of running
- Data-taking to start in 2030.

New experiments

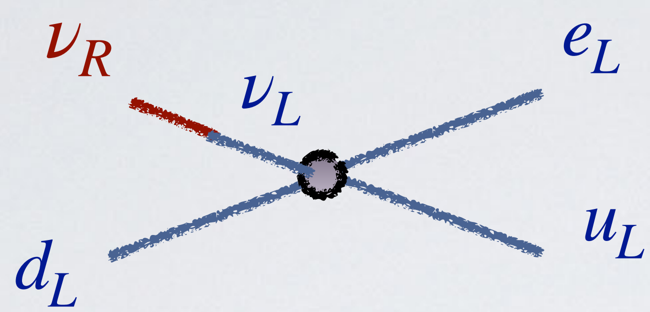
Many proposed experiments (MATHUSLA, CODEX-b, ANUBIS, MoEDAL)….

DUNE (Deep Underground Neutrino Experiment)



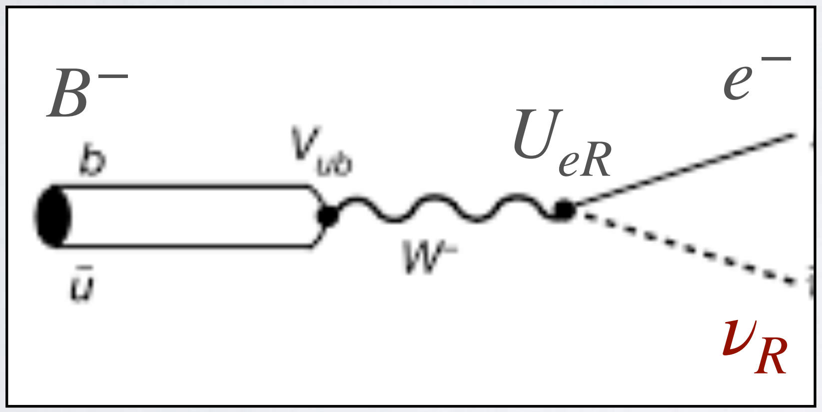
- 120 GeV proton beam on target to produce a neutrino beam
- 'Near'-detector roughly 574 m away
- Experiment operational end of this decade

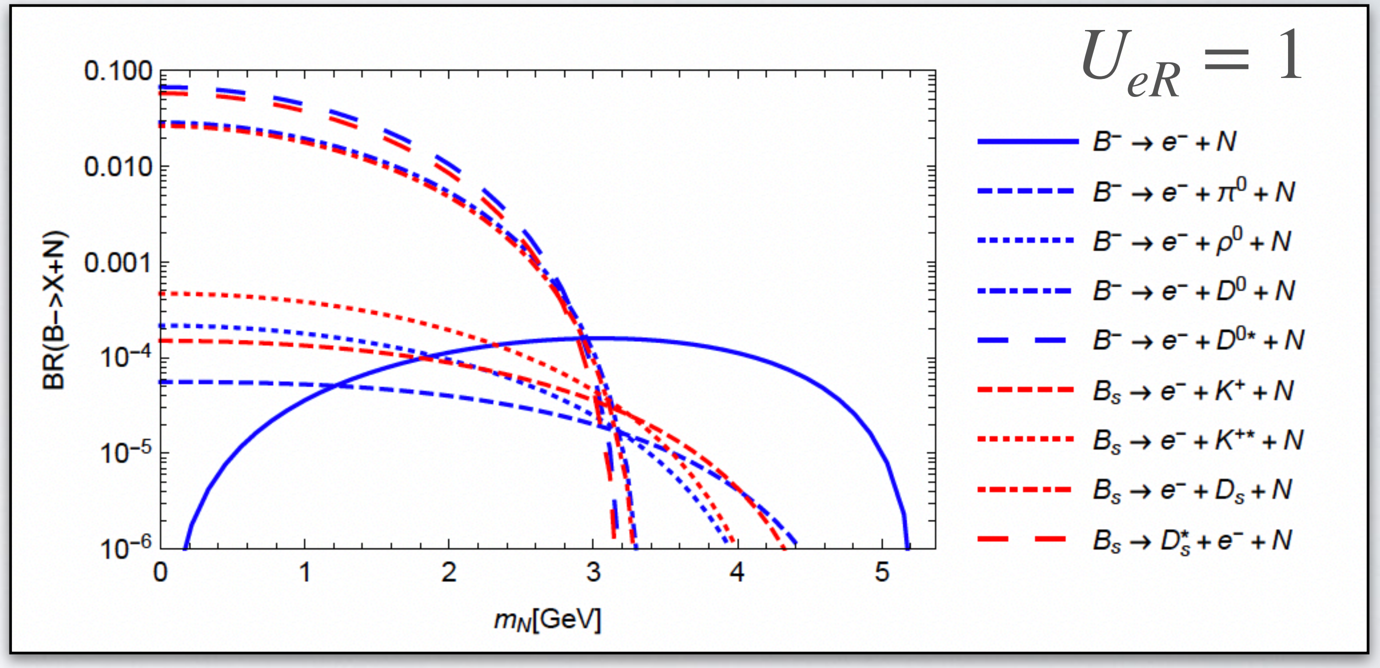
Production and decay of sterile neutrinos



$$\sim \left(\frac{1}{M_W}\right)^2 U_{eR}$$

Example: Sterile neutrino production from beauty (B) meson decays





In turn sterile neutrino decays to visible or invisible final states

$$\nu_R \to e^- + \pi^+ \qquad \nu_R \to \nu_L + K^0$$

$$\nu_R \to e^- + e^+ + \nu_L \qquad \nu_R \to \nu_L + \bar{\nu}_L + \nu_L$$

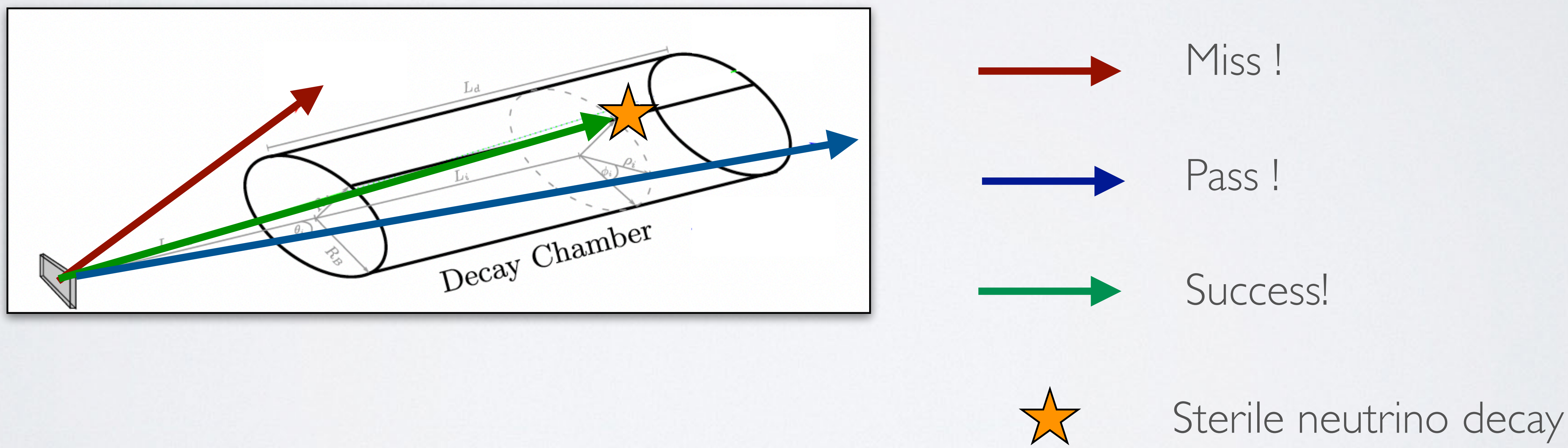
Simulations

- Compute meson production at experiments with Pythia simulations

$$N_N^{\mathrm{prod}} = \sum N_{M_i} \cdot \mathrm{Br}(M_i \to N + X)$$

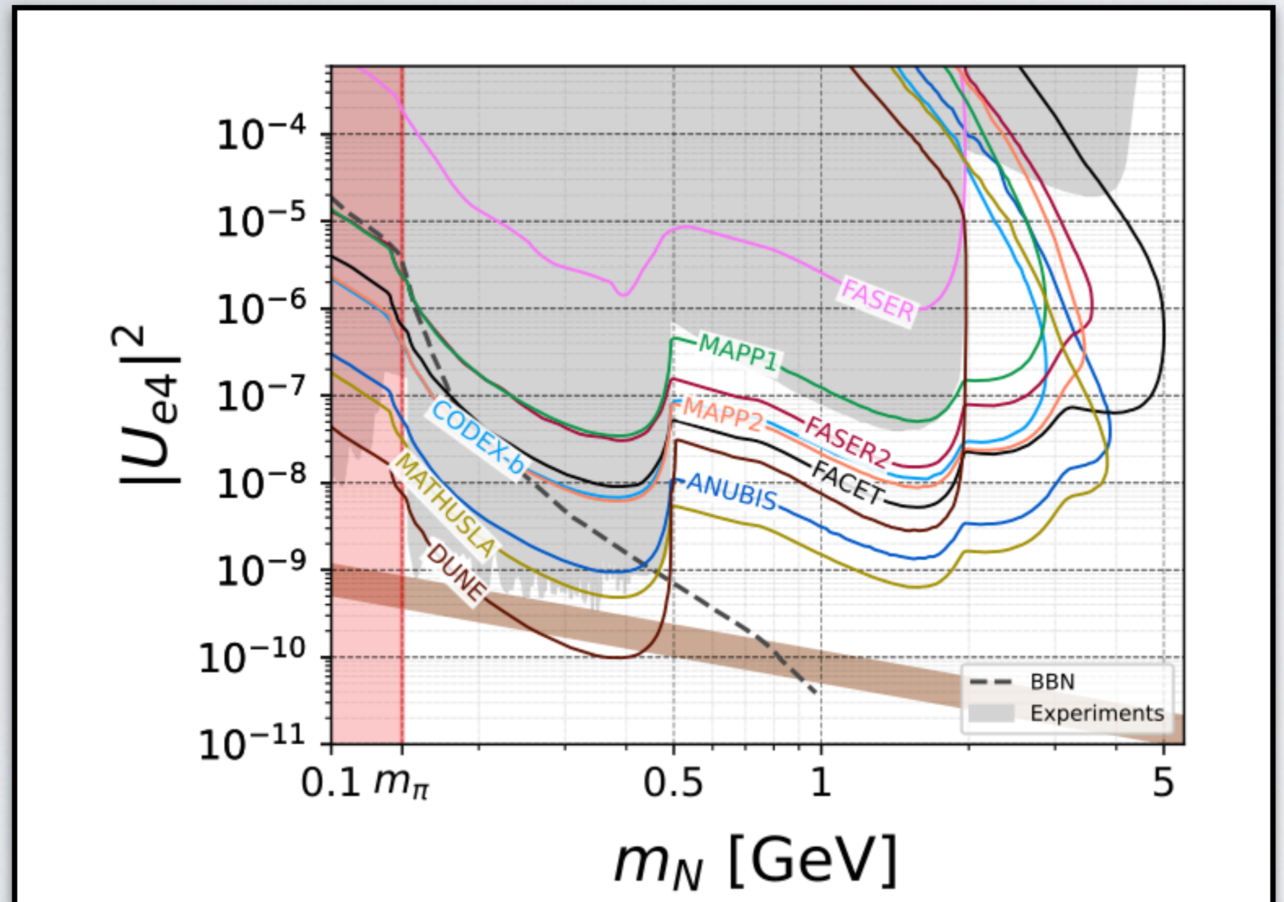
- Simulate around 10^6 events and rescale to total number of produced mesons in experiment

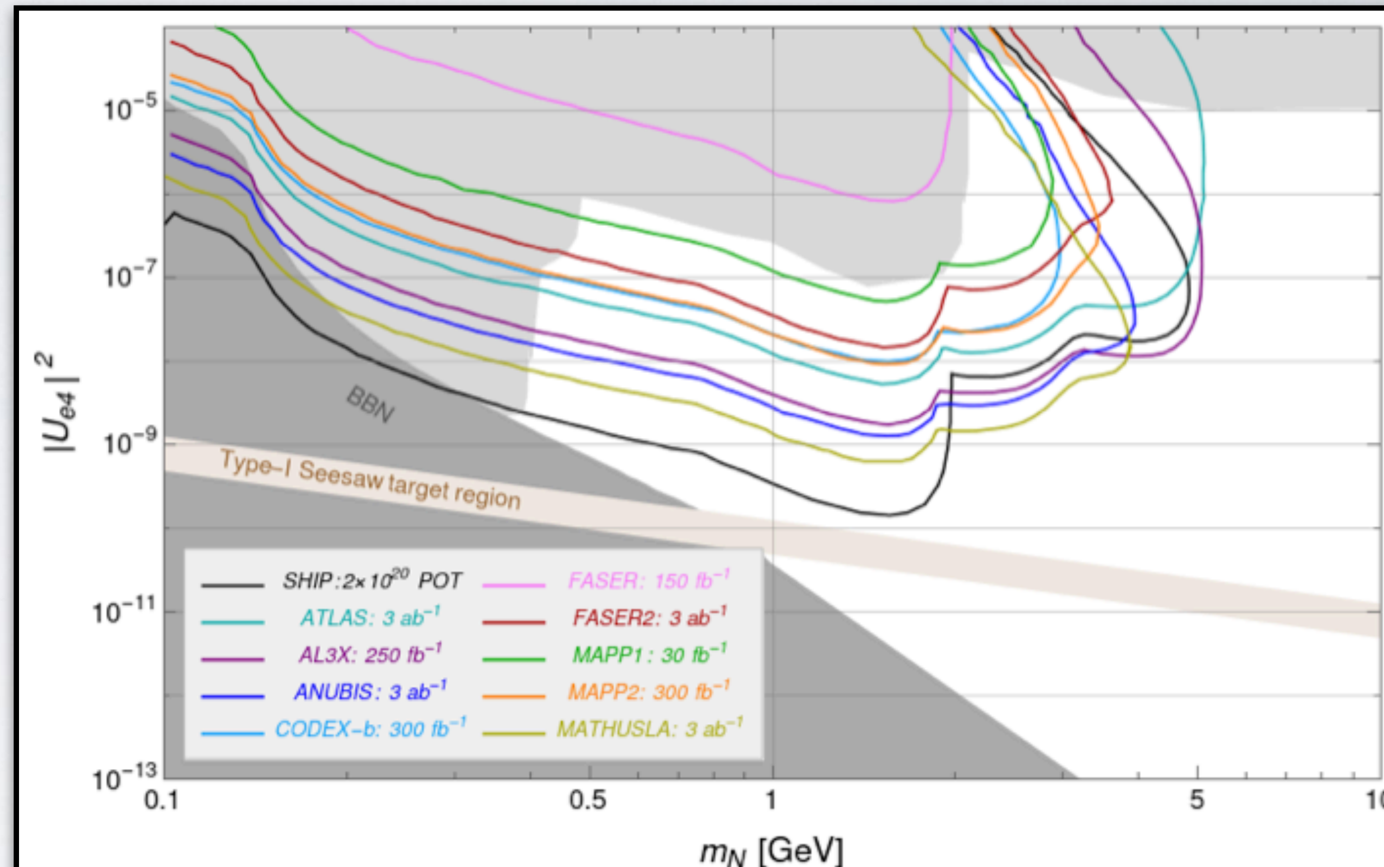
- For each proposed experiment then determine **probability of decay in detector**



Minimal scenarios

- **Current limits will improve significantly with new experiments**



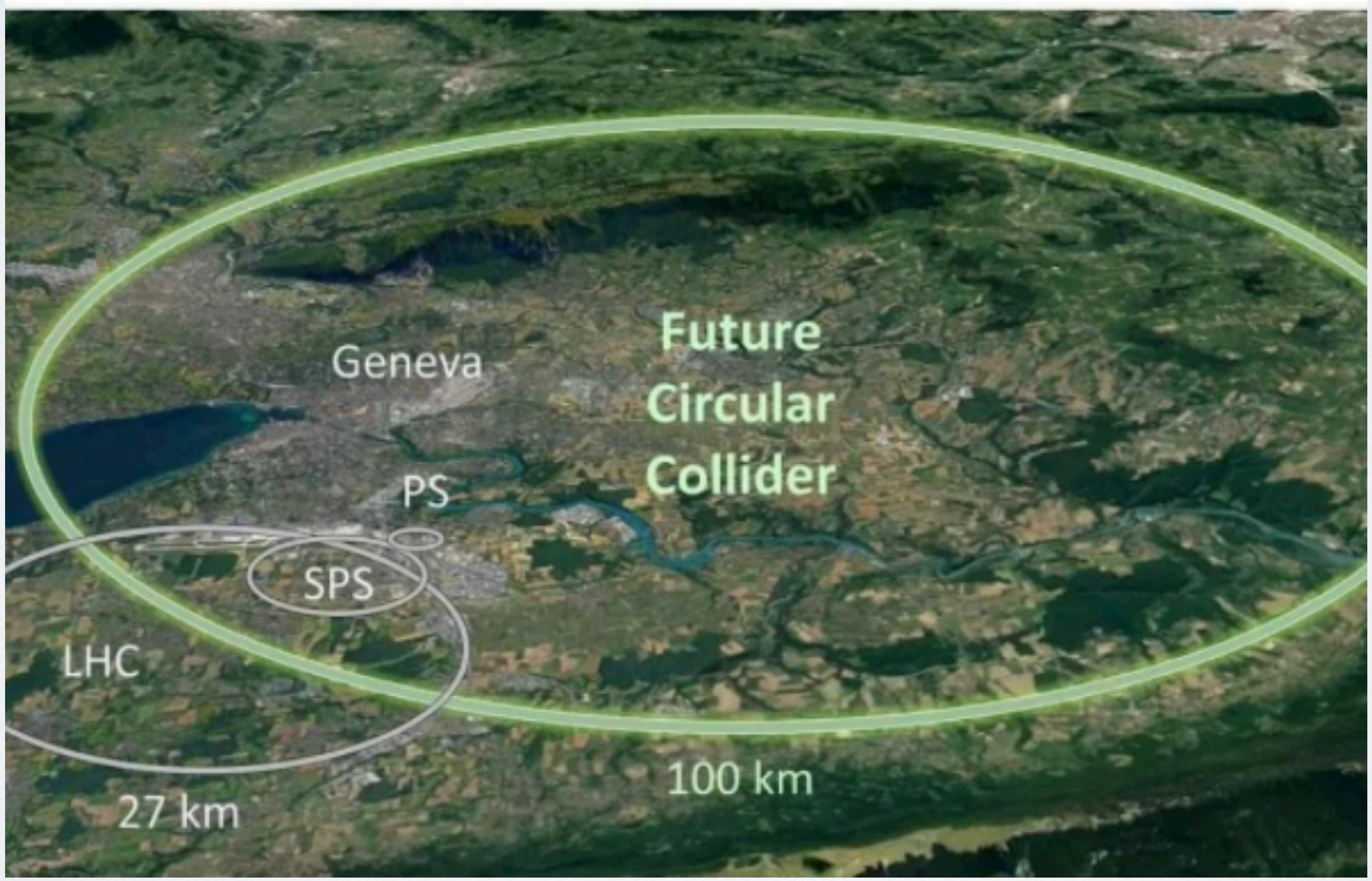


JdV et al JHEP '21 '23

See also many other works: Bondarenko et al, Shaposhnikov et al, Drewes et al, Pascoli et al

- Proposed experiments can come pretty close or even cover the seesaw band
- Unfortunately only works in mass range MeV-GeV.

just one more collider bro. i promise bro just one more collider and we'll find all the particles bro. it's just a bigger collider bro. please just one more. one more collider and we'll figure out dark matter bro. bro cmon just give me 22 billion dollars and we'll solve physics i promise bro. bro bro please we just need to build one more collider t

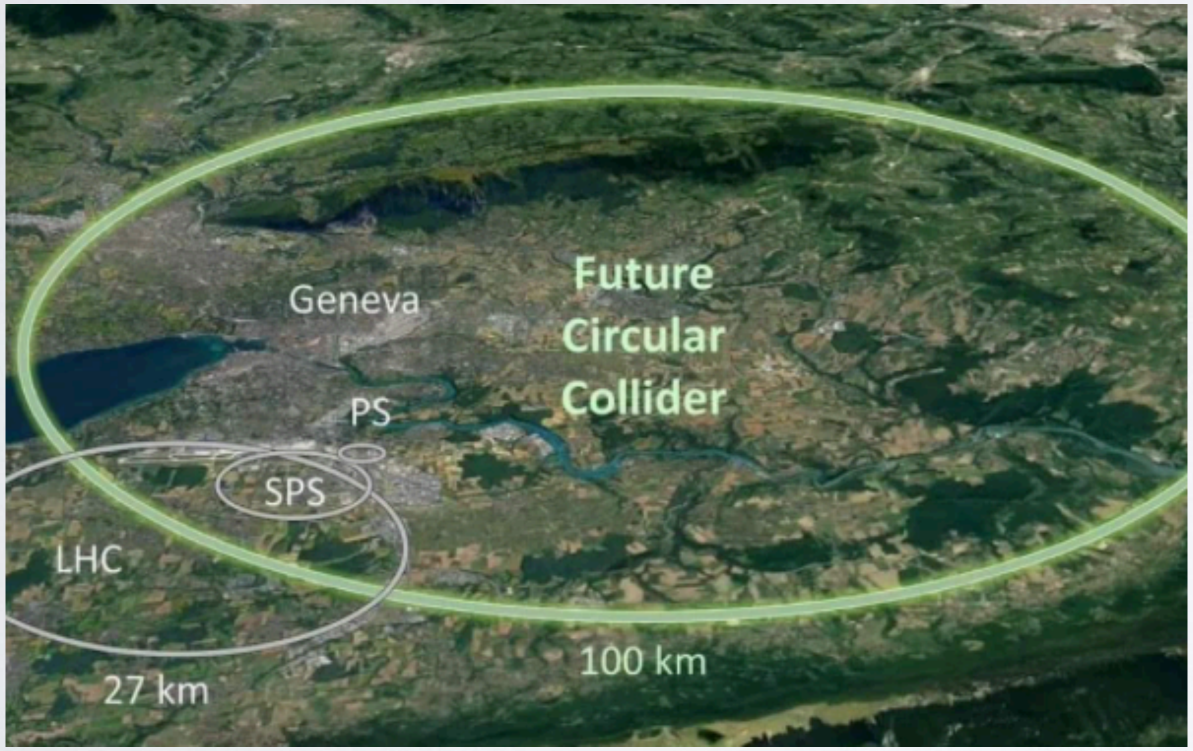


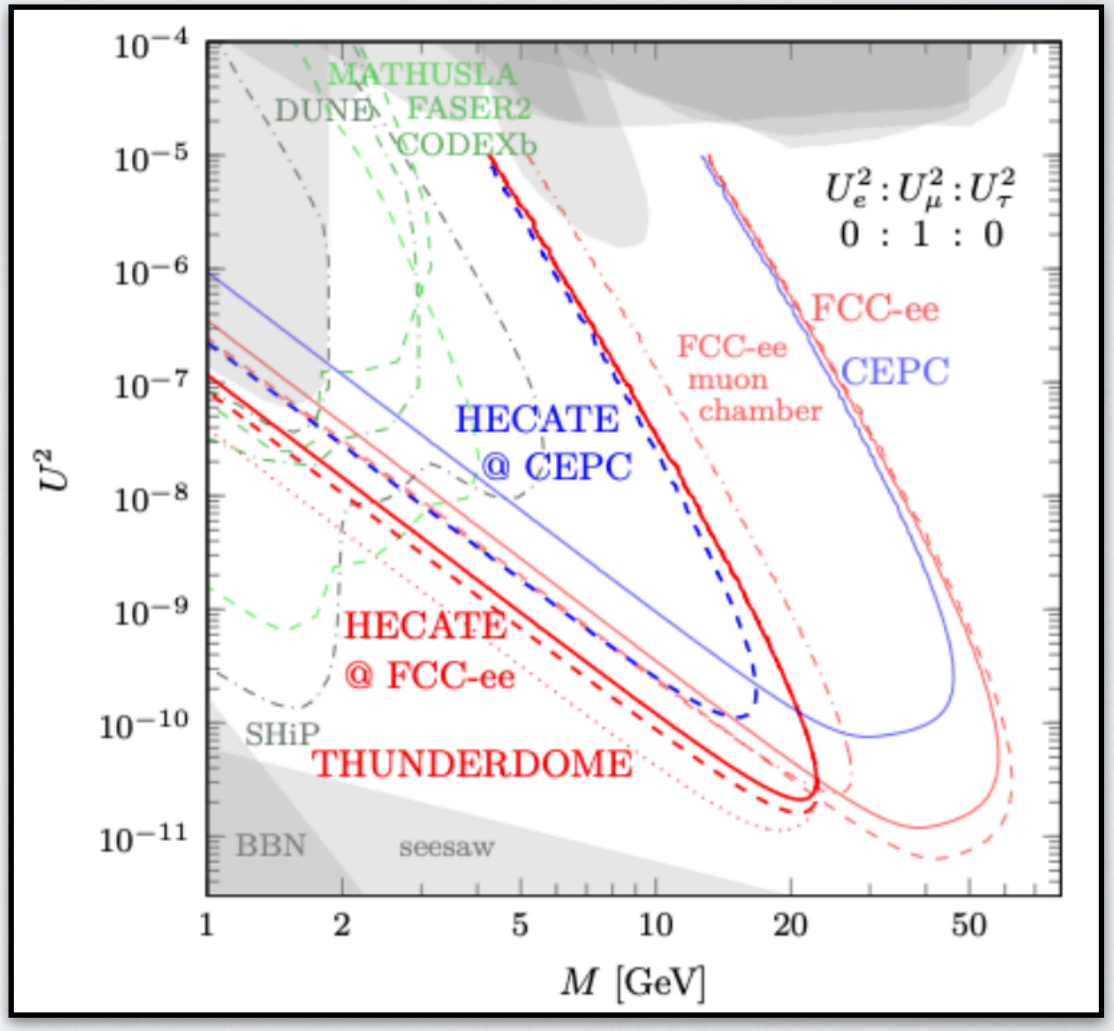
The future is now

- FCC-ee running at the Z-pole would produce huge amounts of on-shell Z bosons

$$e^- + e^+ \to Z \to \nu_L + \nu_R$$

- Then perform a displaced vertex search of the sterile neutrino decay

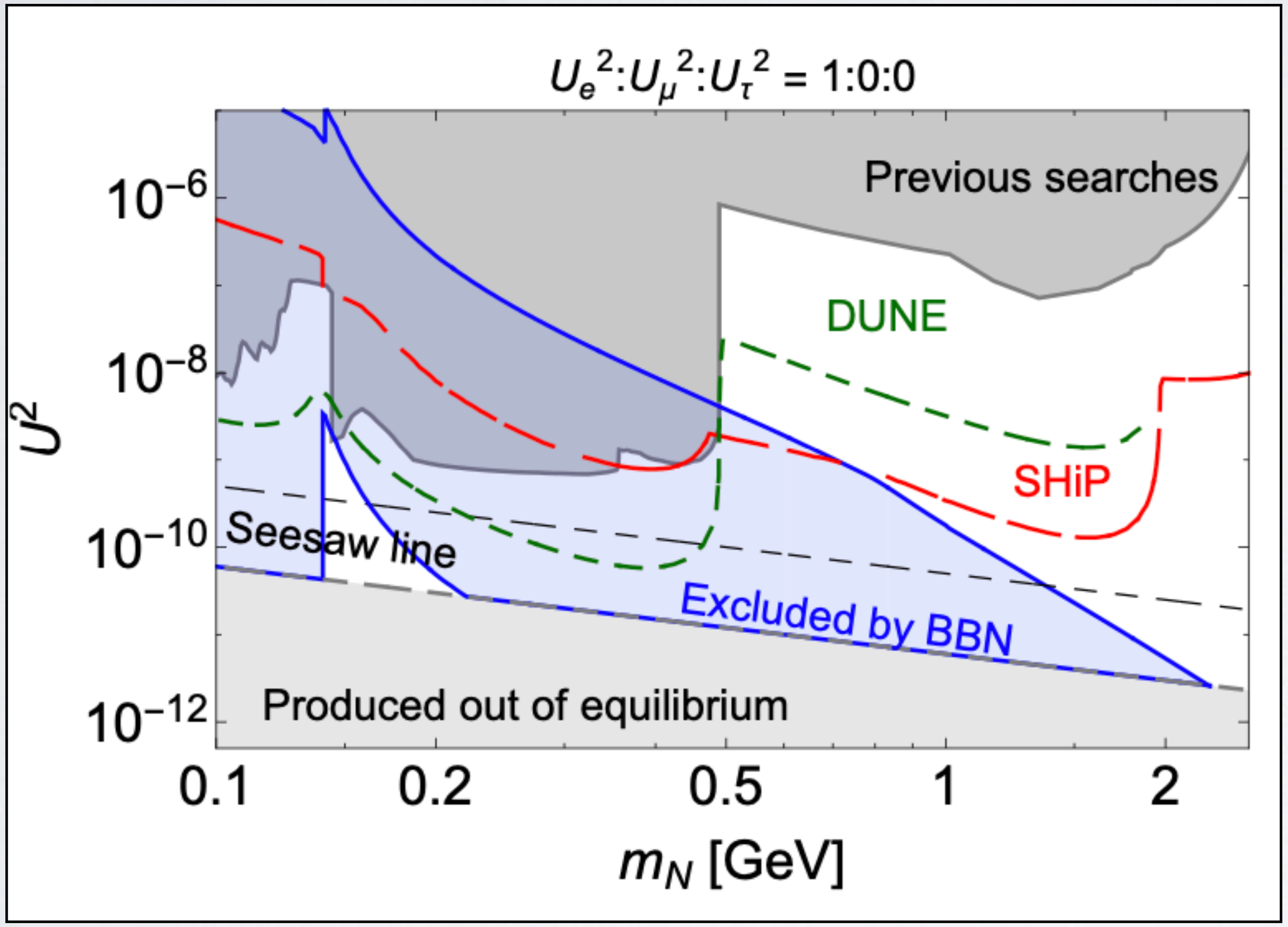


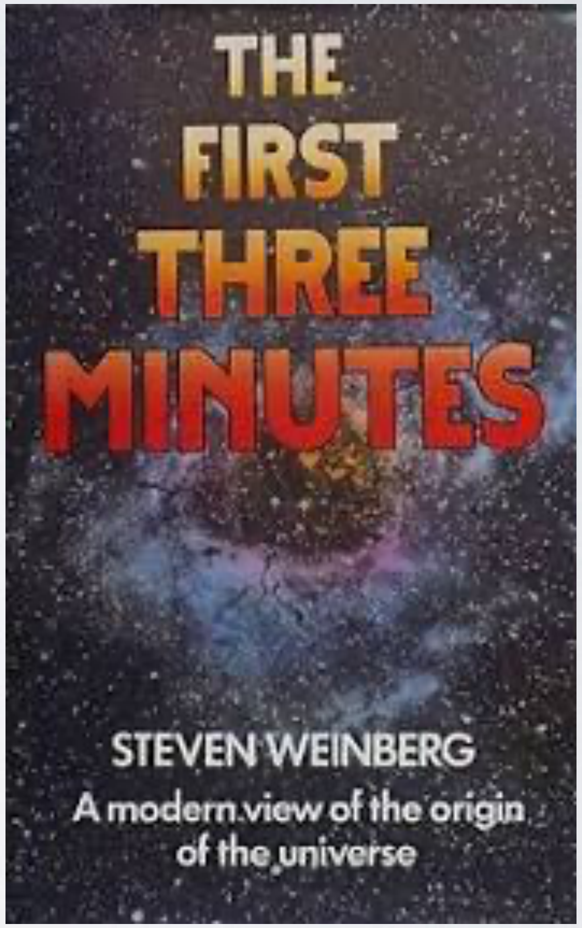


Big Bang Nucleosynthesis

- Sterile neutrinos with can modify BBN

- Most couplings lead to thermal equilibrium in early universe —> relativistic freeze out
- Require that they decay before BBN times (~ 1 sec)





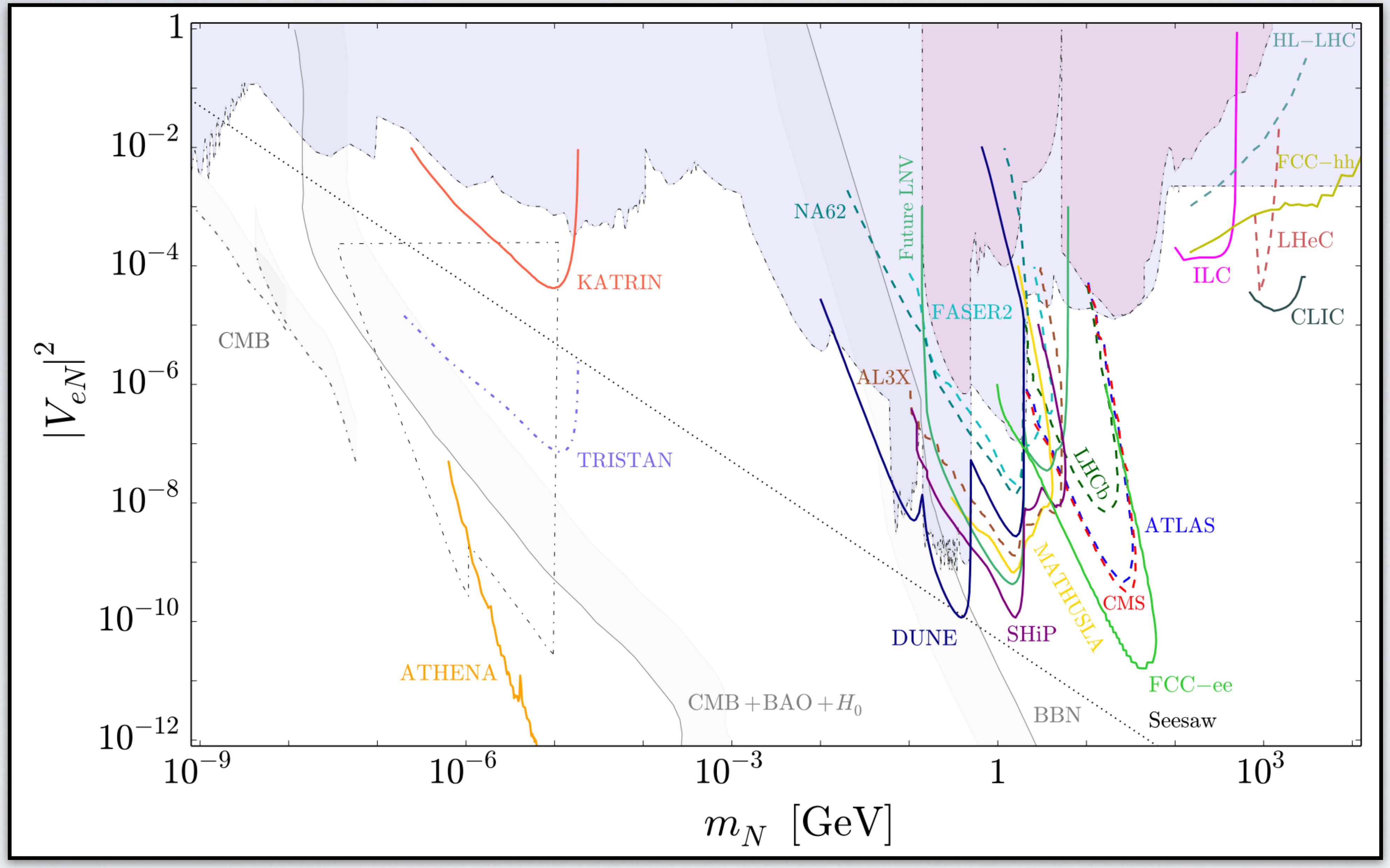
Boyarsky et al '20

- BBN bounds can be avoided in more complicated cosmological models

- Minimal models essentially require masses above MeV scale

Dolgov et al '00
Ruchayskiy et al '12
Pospelov/Pradler '10

Summary of future prospects



- Sterile neutrinos below 1 TeV : **we can really discover them !**

Heavy-weight neutrinos

- **See-saw (variants) can work for essentially any right-handed scale ...**

eV keV MeV GeV TeV ..... 10^{15} GeV M_R ?

Many decades are untouched...

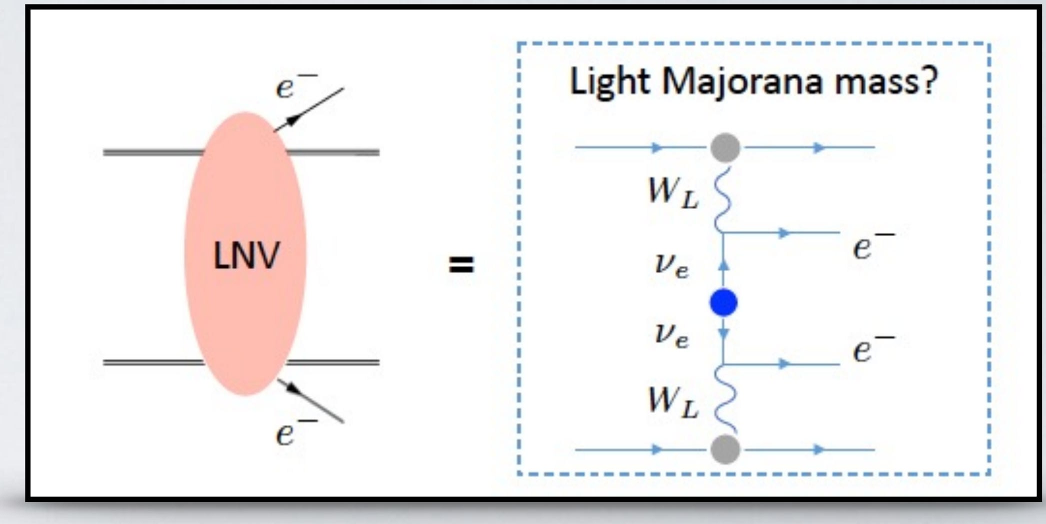
- For $m_R \geq 10$ TeV or so, we'll probably not be able to produce them this century

Probes of lepton number violation

- Most promising way: look at `neutrinoless' processes

$$K^- \to \pi^+ + e^- + e^- \qquad pp \to e^+ + e^+ + \text{jets}$$

$$X(Z,N) \to Y(Z+2,N-2) + e^- + e^-$$



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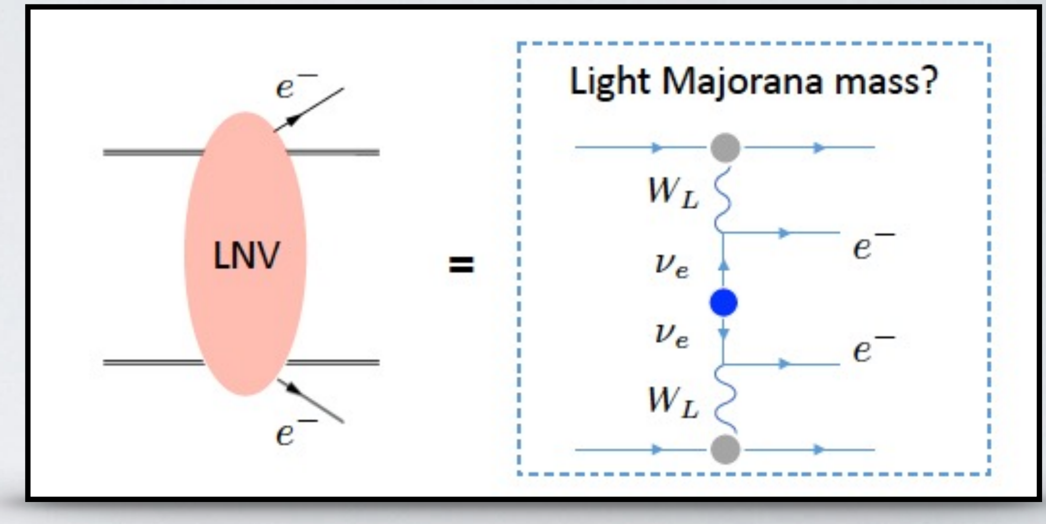

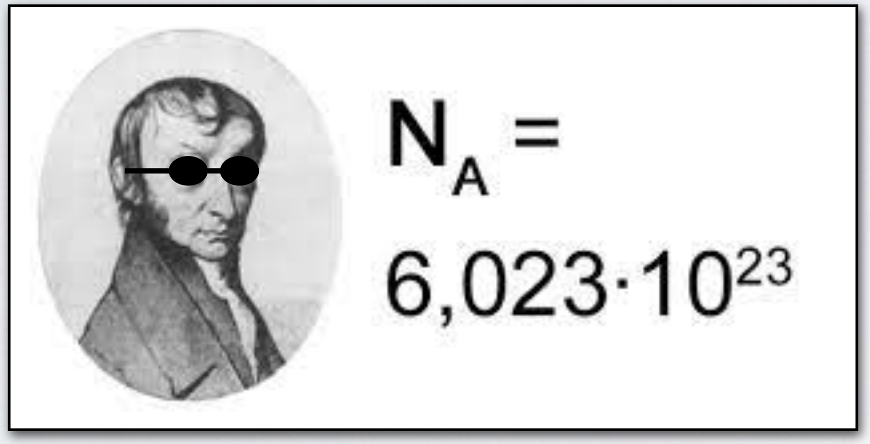

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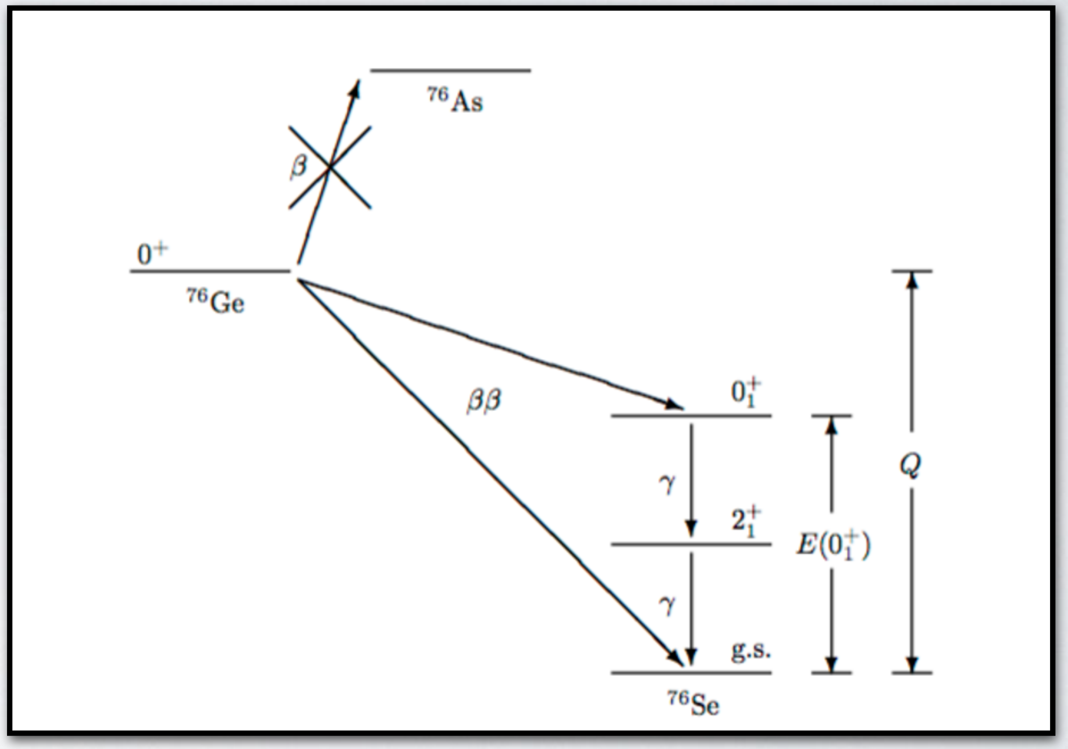
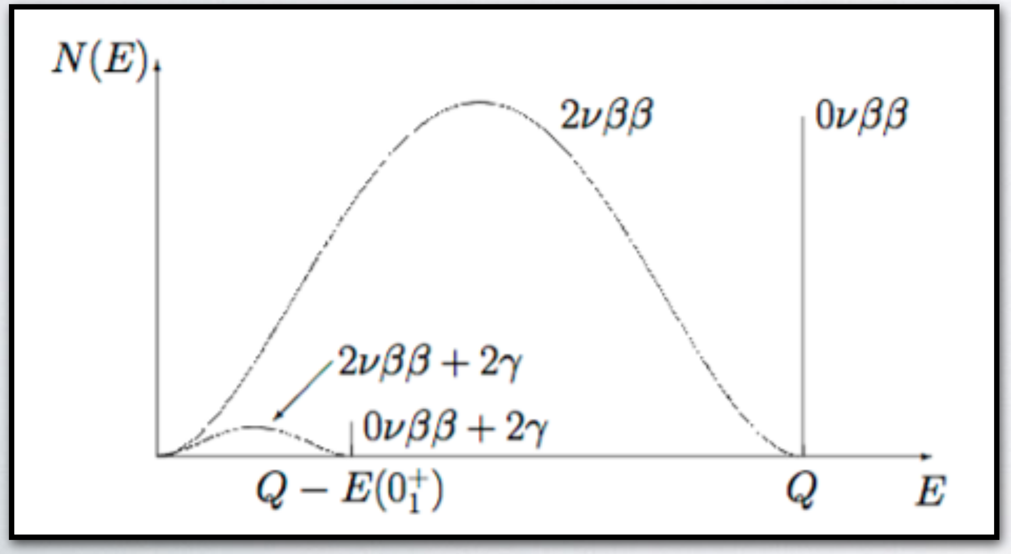


- Isotopes protected from single beta decay

- Neutrinofull double beta decay from Standard Model

$$X(Z,N) \to Y(Z+2, N-2) + 2e^- + 2\bar{\nu}_e$$

$$T_{1/2}^{2\nu}\left({}^{76}Ge \to {}^{76}Se\right) = \left(1.84^{+0.14}_{-0.10}\right) \times 10^{21}\ yr$$



	Lifetime	Experiment	Year
76Ge	$8.0 \cdot 10^{25}\,y$	GERDA	2018
130Te	$3.2 \cdot 10^{25}\,y$	CUORE	2019
136Xe	$3.8 \cdot 10^{26}\,y$	KamLAND-Zen	2024

Note: age of universe ~ 10^{10} year

Probes of lepton number violation

- Most promising way: look at `neutrinoless' processes

$$K^- \to \pi^+ + e^- + e^- \qquad pp \to e^+ + e^+$$

$$X(Z,N) \to Y(Z+2,N-2) + e^- + e$$

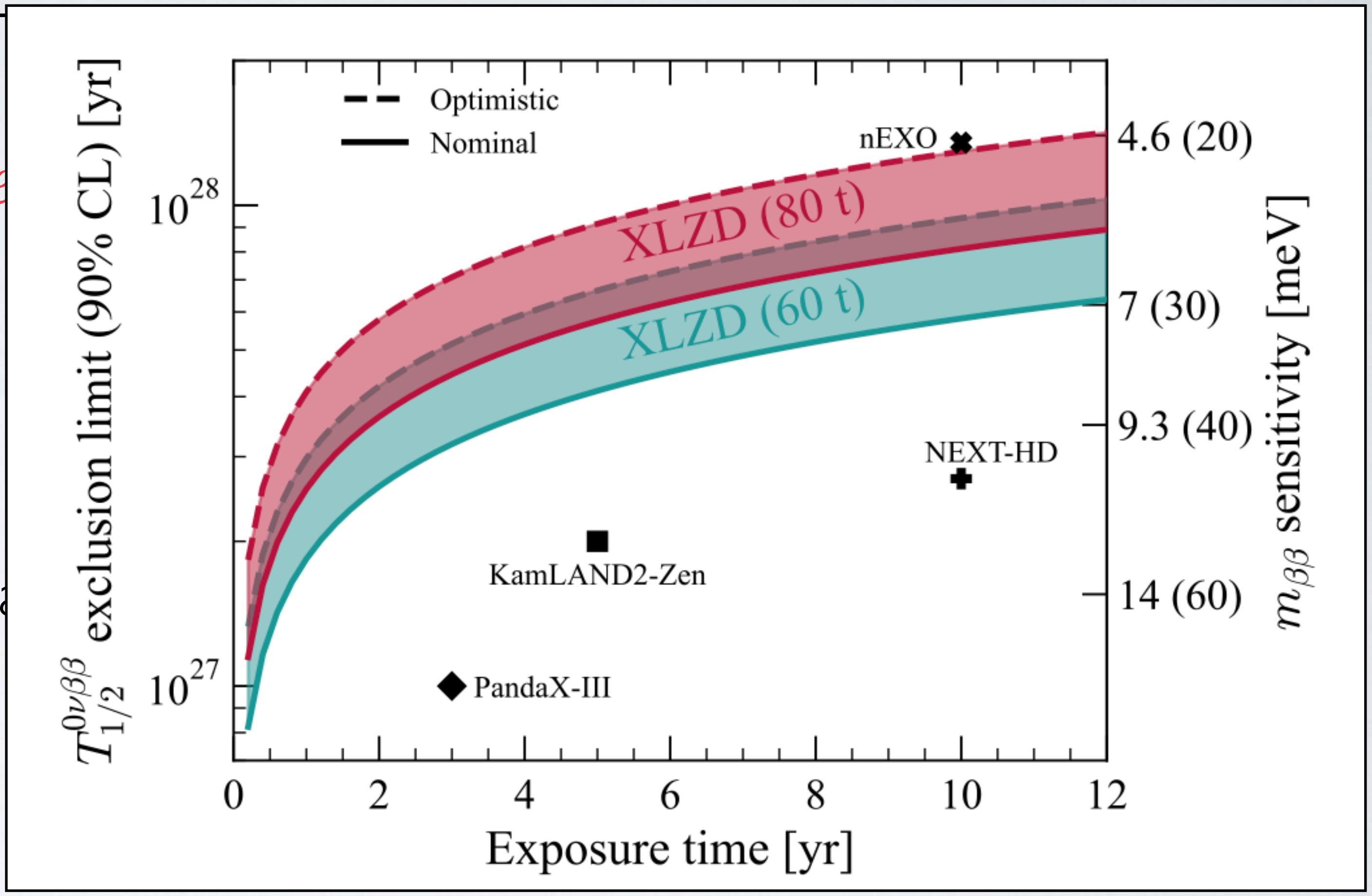


Figure from XLZD collaboration, 2410.19016

- Isotopes protected from single beta decay
- Neutrinofull double beta decay from Standa

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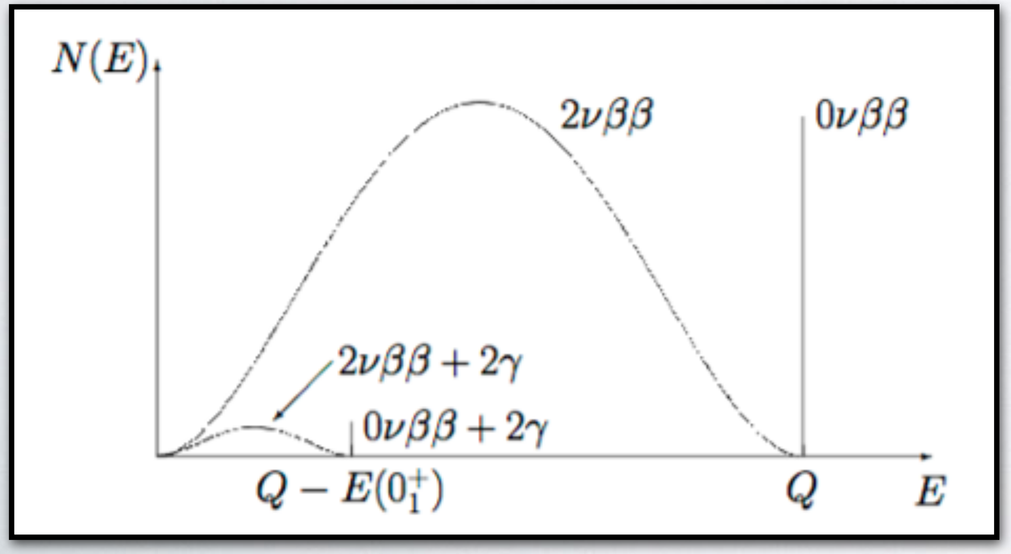

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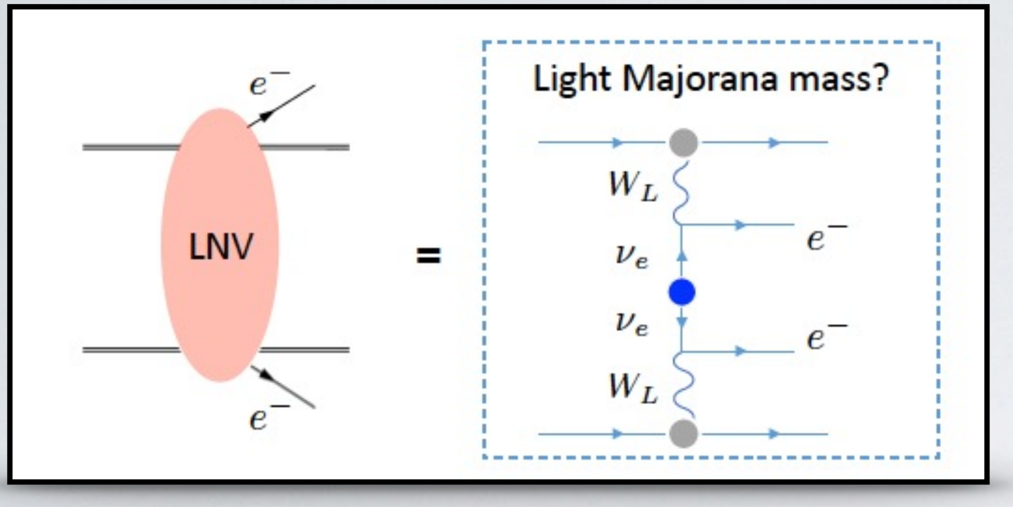
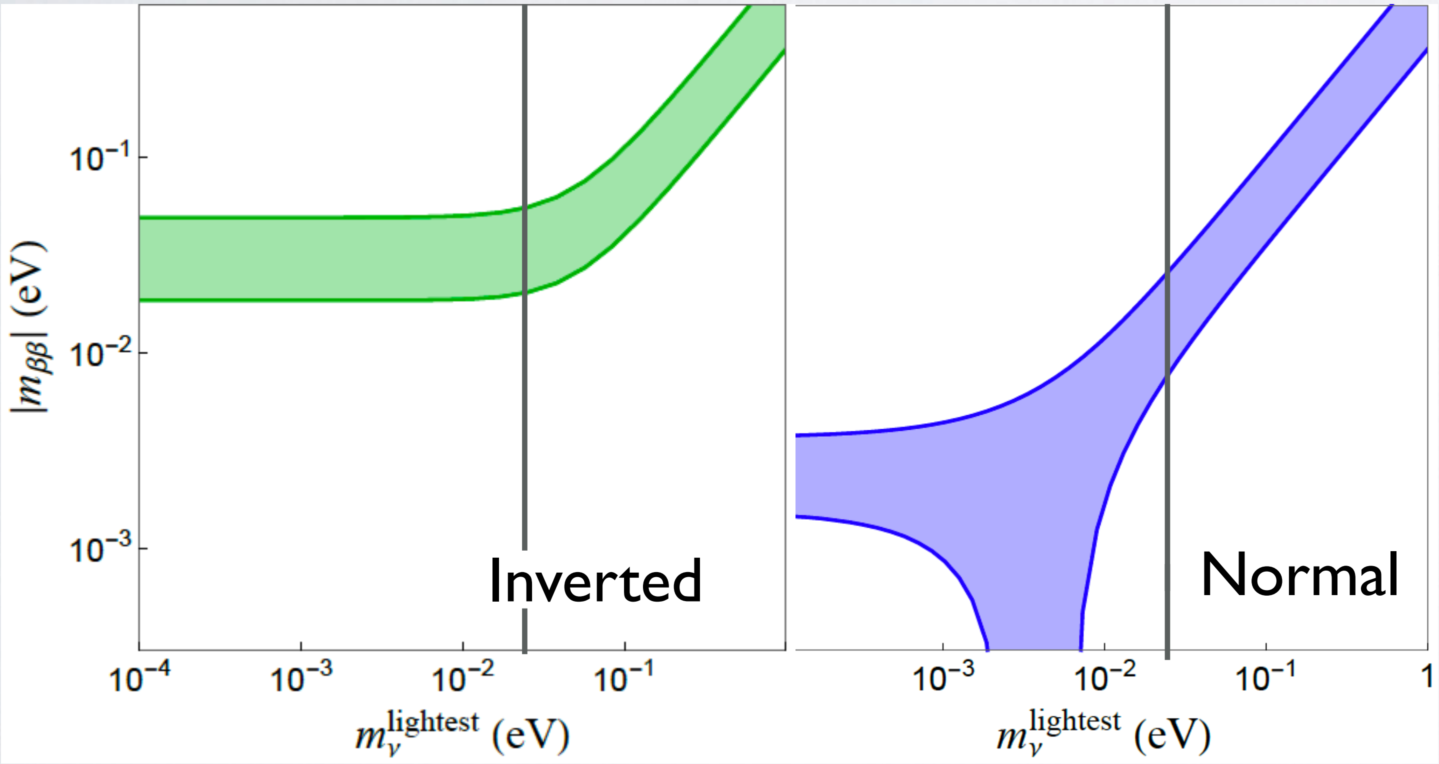
Interpreting 10^{26} years....



$$1/\tau \sim |M_{0\nu}|^2 m_{\beta\beta}^2 \qquad m_{\beta\beta} = \sum_i U_{ei}^2 m_i$$

$$m_{\beta\beta} = m_1\, c_{12}^2 c_{13}^2 + m_2\, s_{12}^2 c_{13}^2 e^{2i\lambda_1} + m_3\, s_{13}^2 e^{2i(\lambda_2 - \delta_{13})}$$ = Effective neutrino mass

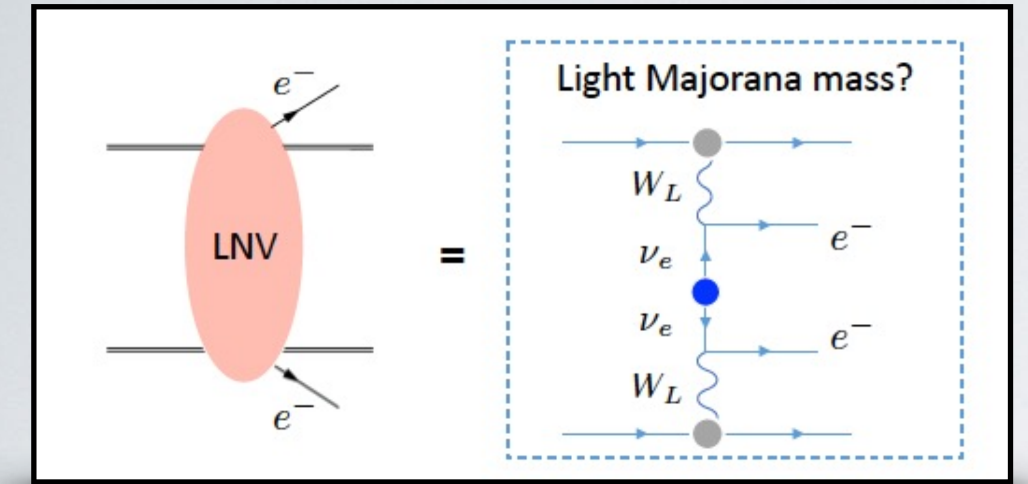


Vary the lightest mass and the ordering

Band from varying unknown phases

How close are experiments ?

Interpreting 10^{26} years....



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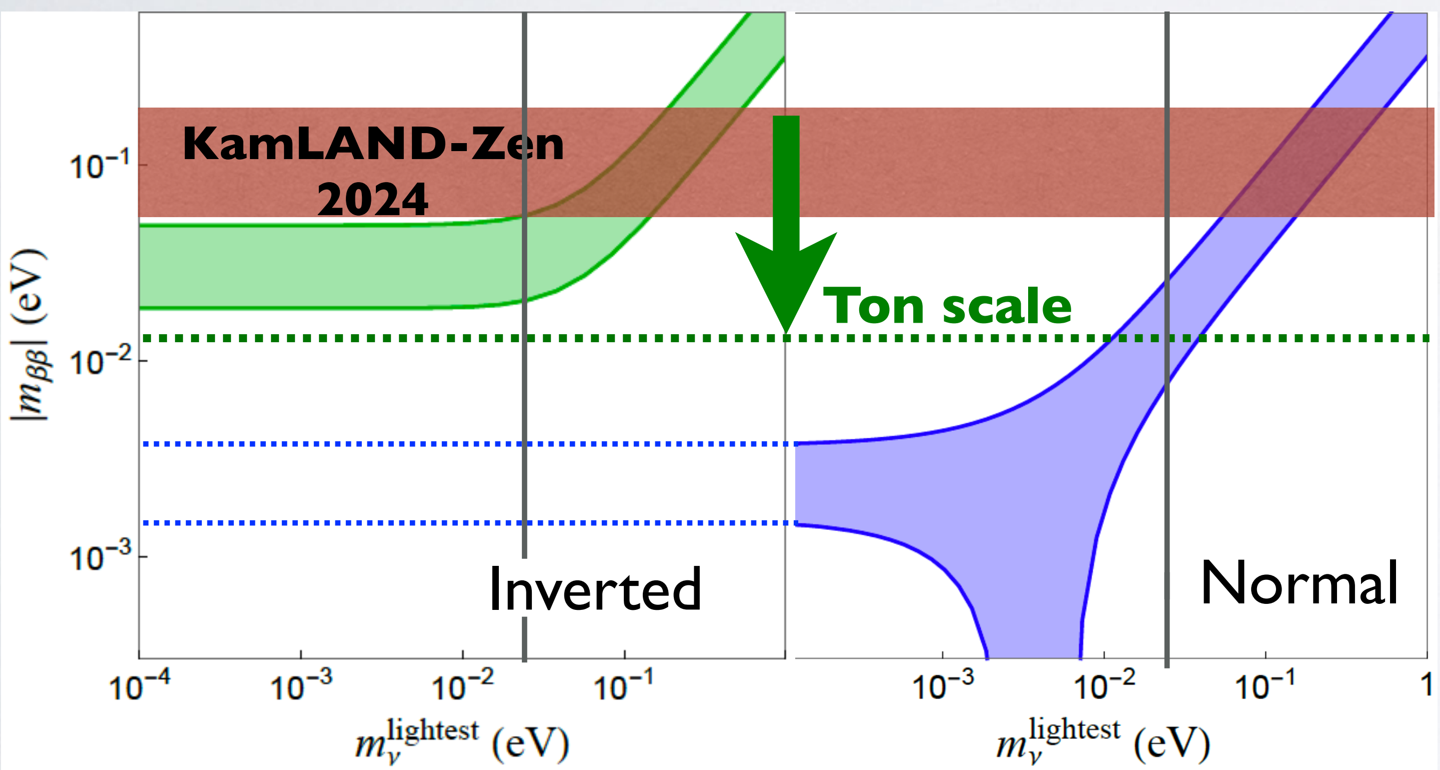


Quite close !!

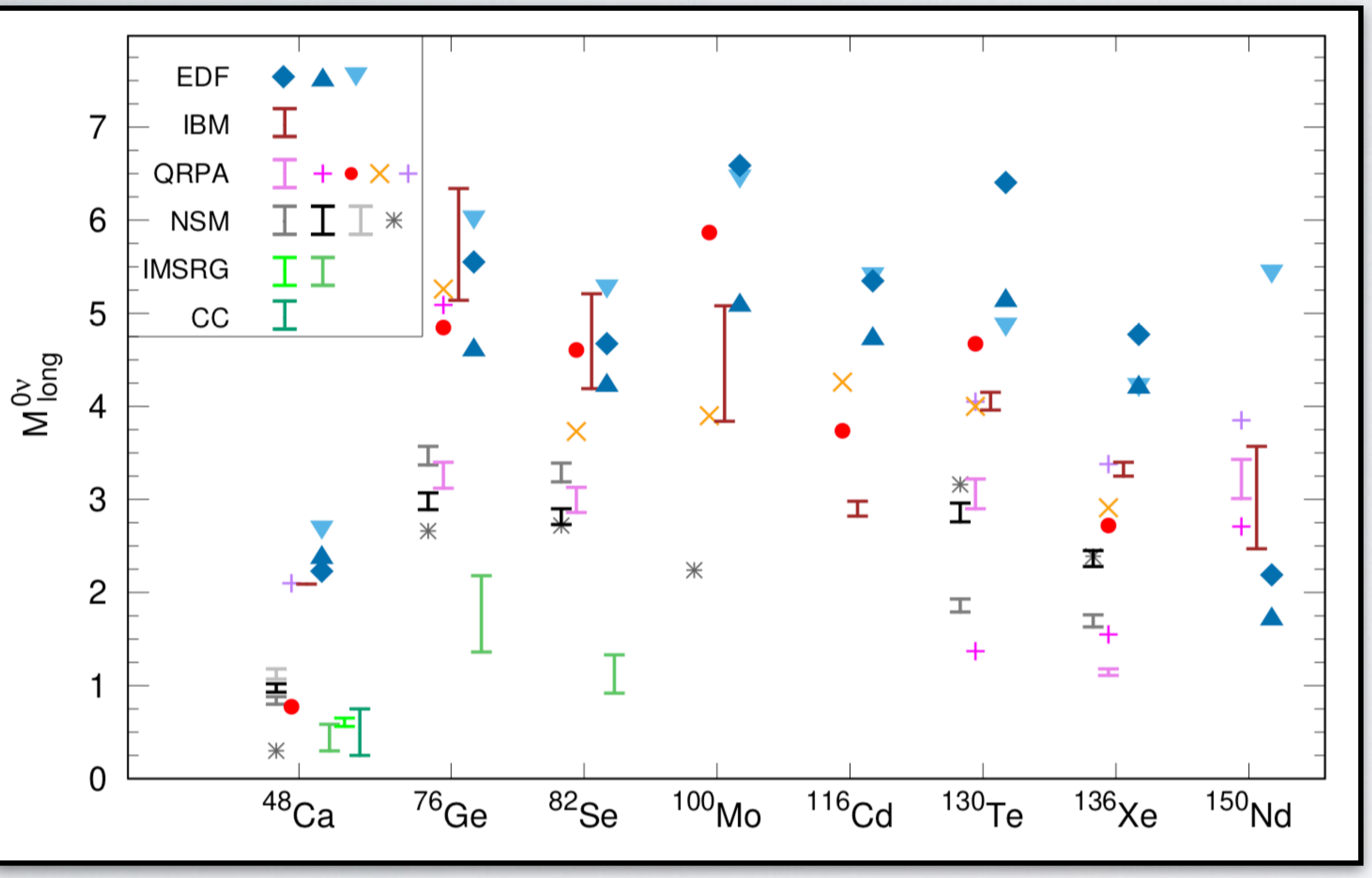
Next-generation discovery possible if inverted hierarchy or m_{lightest} >0.01 eV

Note: **FUNNEL OF DESPAIR** and **THE DEAD ZONE**

See Denton & Gehrlein '23 for the likelihood that we live in the funnel

Predictions are hard, especially about ~~the future~~ nuclei

From: Menendez et al review '22



$$1/\tau \sim |M_{0\nu}|^2 m_{\beta\beta}^2$$

Uncertainties factor 5 !
So factor 25 on the life time !

Where is this coming from ?

Predictions are hard, especially about ~~the future~~ nuclei

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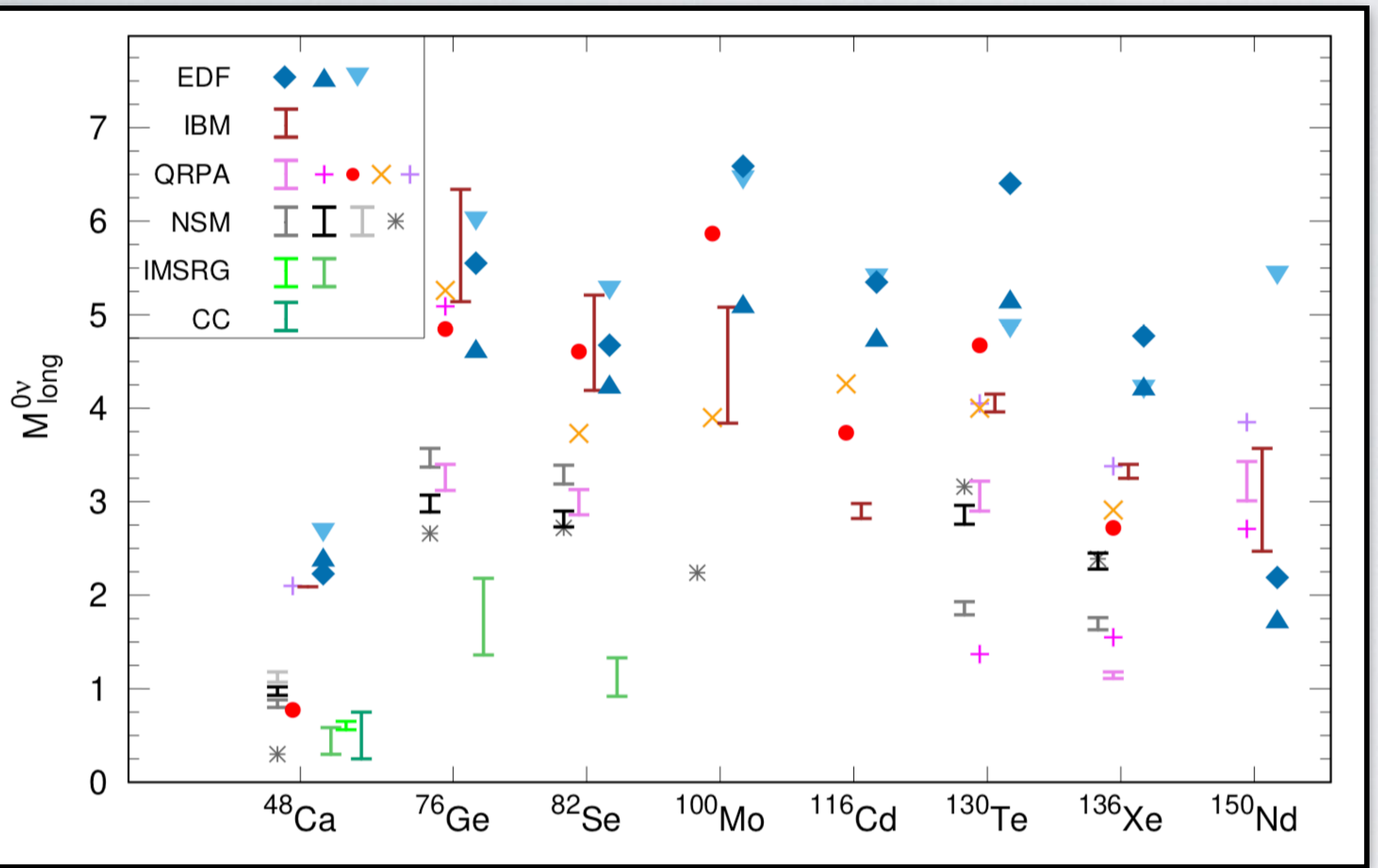

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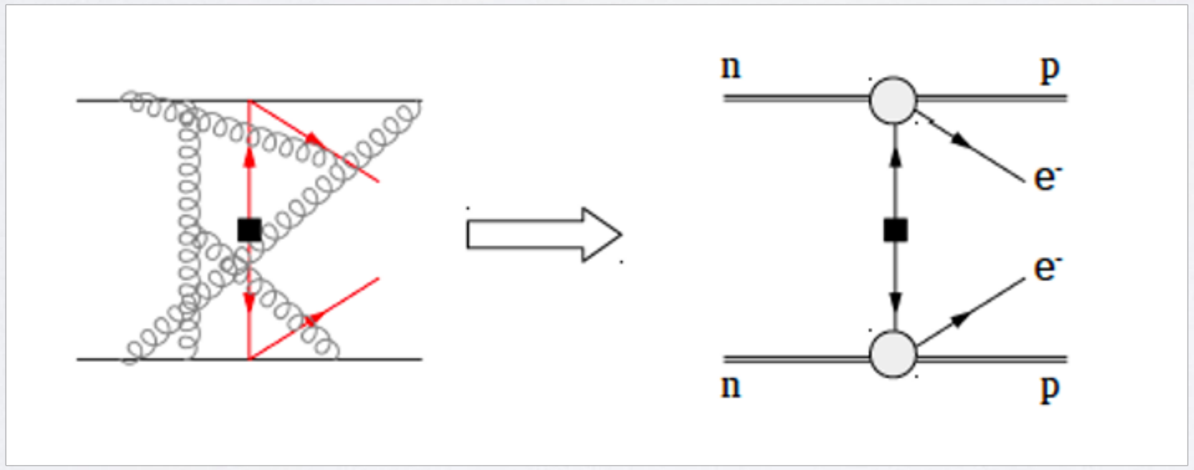

- Large nuclei —> complicated many-body nuclear matrix elements
- Nuclear methods and codes are benchmarked on 'single-nucleon-currents' physics

Nuclear physics from QCD

- In the 90's Weinberg (who else) wrote 2 very nice papers

Effective chiral Lagrangians for nucleon - pion interactions and nuclear forces #3
Steven Weinberg (Texas U.) (Apr 1, 1991)
Published in: *Nucl.Phys.B* 363 (1991) 3-18
pdf DOI cite claim reference search 1,442 citations

Nuclear forces from chiral Lagrangians #4
Steven Weinberg (Texas U.) (Oct 9, 1990)
Published in: *Phys.Lett.B* 251 (1990) 288-292
DOI cite claim reference search 1,529 citations

[Submitted on 16 Feb 2025]

Steven Weinberg: A Scientific Life

C.P. Burgess, F. Quevedo

Weinberg used similar tools to compute the inter-nucleon forces implied at low energies by generalizing the effective theory governing low-energy pion interactions to include nonrelativistic nucleons [85–87] (see also [88]). By so doing he enabled the calculation of *ab initio* nuclear energy levels for the first time, at least for light nuclei involving comparatively few protons and neutrons. Nuclear physicists at the time were instead fitting data from nuclear measurements with models in which meson exchange between nucleons assumed phenomenological couplings.

Nuclear physics from QCD

- In the 90's Weinberg (who else) wrote 2 very nice papers

Effective chiral Lagrangians for nucleon - pion interactions and nuclear forces #3
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Published in: *Nucl.Phys.B* 363 (1991) 3-18
pdf DOI cite claim reference search 1,442 citations

Nuclear forces from chiral Lagrangians #4
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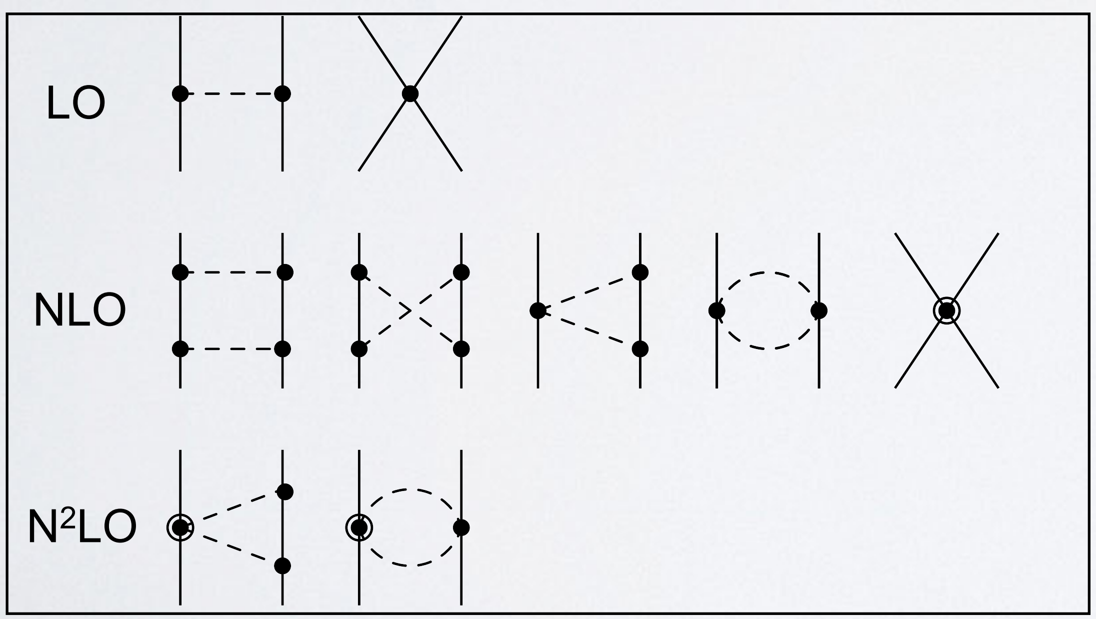
Published in: *Phys.Lett.B* 251 (1990) 288-292
DOI cite claim reference search 1,529 citations

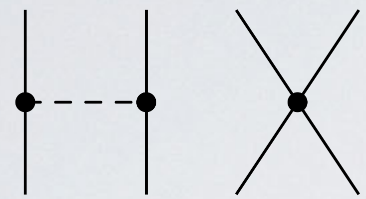
- Describe the **nucleon-nucleon** force from **chiral perturbation theory**



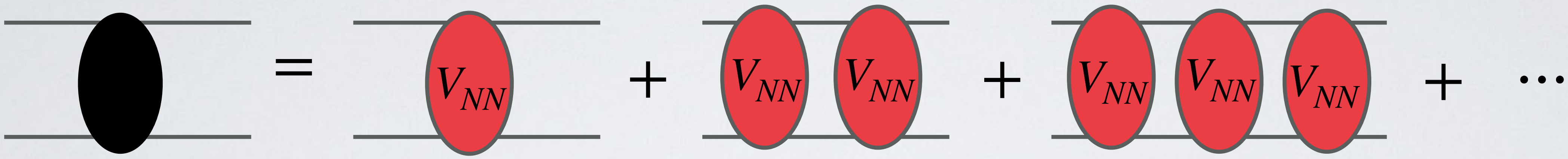
- Effective field theory description of nuclear forces and currents
- Systematic expansion
- Nuclei from solving Schrodinger-like equations
- Wilson coefficient (low-energy constants fitted to few-nucleon data) -> predict larger systems

Developed by van Kolck, Meißner, Epelbaum, Machleidt and many others ….

Example at leading order

LO 

$$V_{\rm NN} = C_0 - \frac{g_A^2}{4f_\pi^2}\frac{m_\pi^2}{\mathbf{q}^2 + m_\pi^2}$$

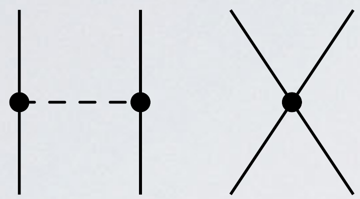


- Loops appearing here typically diverge and one has to **regulate** (typically numerically)

$$V_{\rm NN} \to e^{-p^6/\Lambda^6} \times V_{\rm NN} \times e^{-p'^6/\Lambda^6}$$

- Fit counter term C_0 to nucleon-nucleon scattering data for each Λ

Example at leading order

LO 

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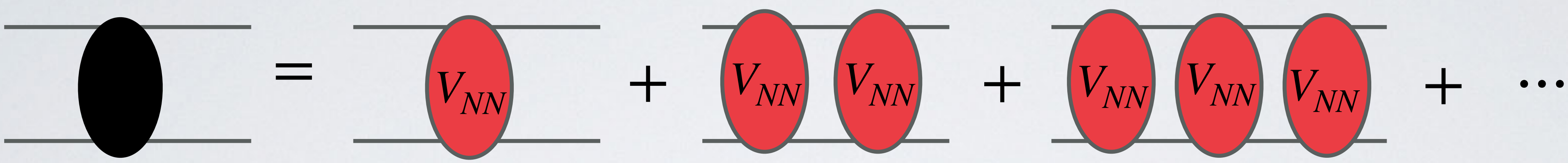

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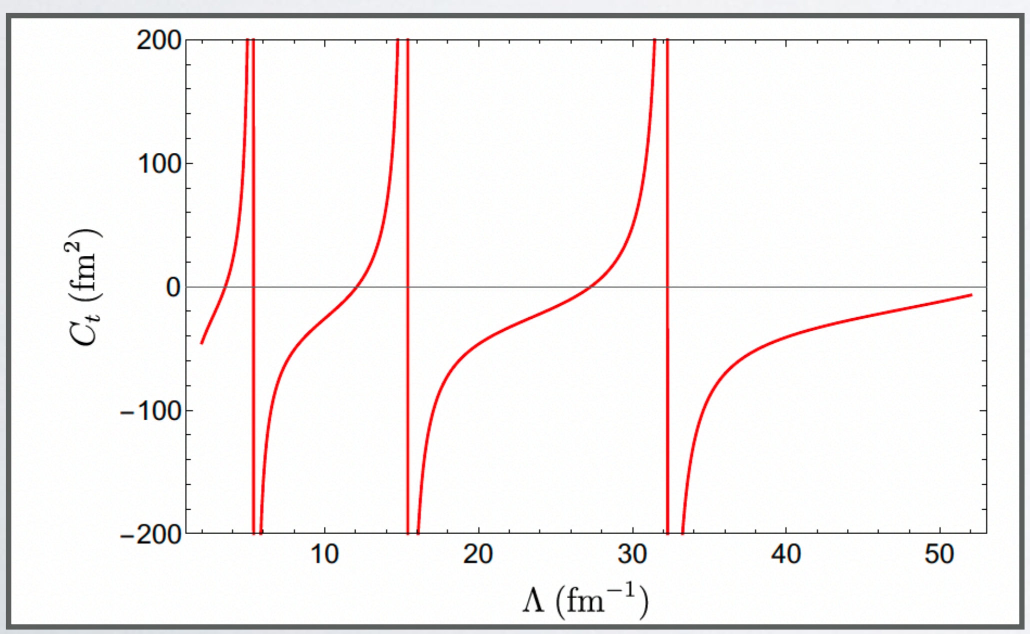
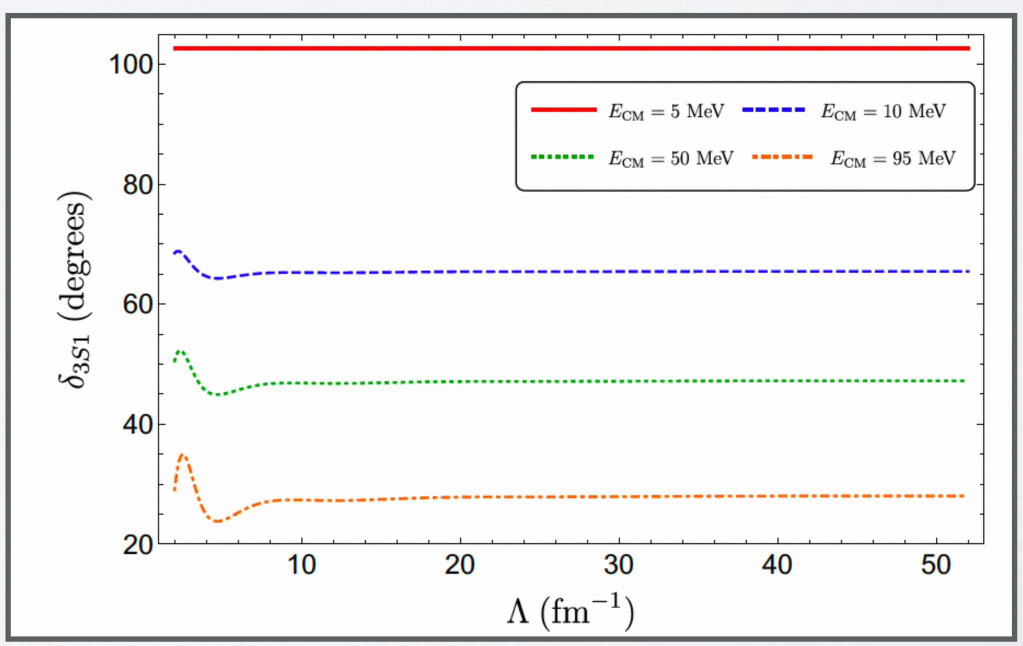
$$V_{\rm NN} \rightarrow e^{-p^6/\Lambda^6} \times V_{\rm NN} \times e^{-p'^6/\Lambda^6}$$

- Fit counter term C_0 to nucleon-nucleon scattering data for each Λ
- This is called 'non-perturbative renormalization'. This is now down at very high order.
- Use nucleon-nucleon + three-nucleon data to fit constants —> predict nuclear physics





Nogga, Timmermans, van Kolck '05

Some successes (not by me)

- Chiral EFT —> derive nuclear properties + reactions —> equation of state + neutron stars

LETTERS
nature physics
https://doi.org/10.1038/s41567-019-0450-7

Discrepancy between experimental and theoretical β-decay rates resolved from first principles

Gysbers et al '20

ARTICLES
nature physics
https://doi.org/10.1038/s41567-022-01715-8
Check for updates

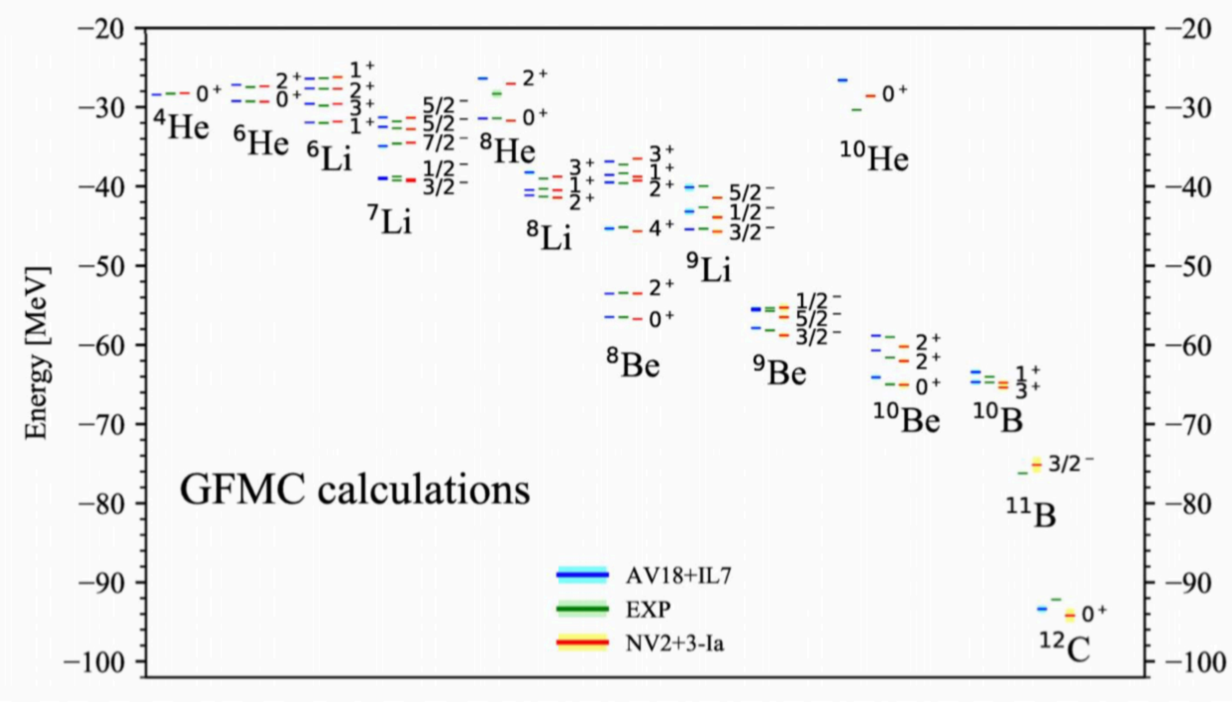
OPEN
Ab initio predictions link the neutron skin of ^{208}Pb to nuclear forces

Hu et al '22

Ab Initio Calculation of the Hoyle State

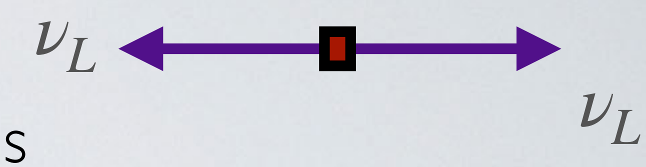
Evgeny Epelbaum, Hermann Krebs, Dean Lee, and Ulf-G. Meißner
Phys. Rev. Lett. **106**, 192501 – Published 9 May 2011

Physics See Viewpoint: The carbon challenge

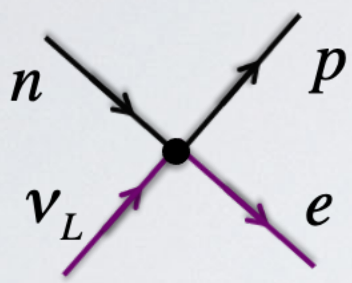


Piarulli et al. PRL 120, 052503 (2018)

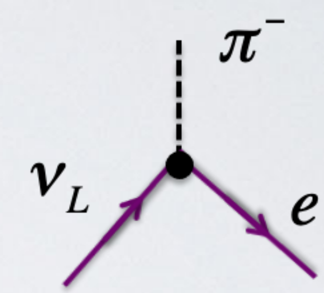
Light Majorana neutrinos (standard mechanism)



- Neutrinos are still degrees of freedom in low-energy chiral EFT
- Basically just use low-energy chiral Lagrangian with weak interactions



$$L_{\chi,Fermi} = G_F f_\pi \left(\partial_\mu \pi^- \, \bar{e}_L \gamma^\mu \nu_L \right)$$
$$+ G_F \, \bar{p}\left(\gamma^\mu - g_A \gamma^\mu \gamma^5\right) n \, \bar{e}_L \gamma^\mu \nu_L + \cdots$$



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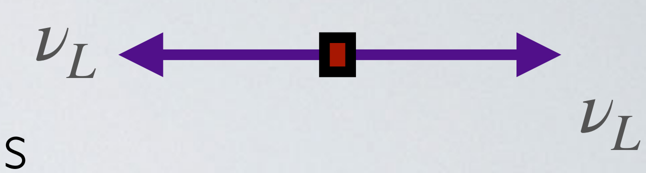

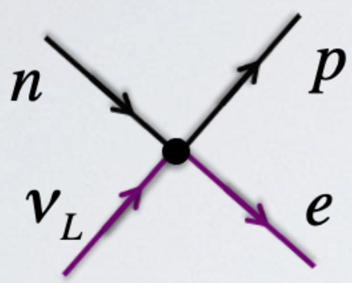

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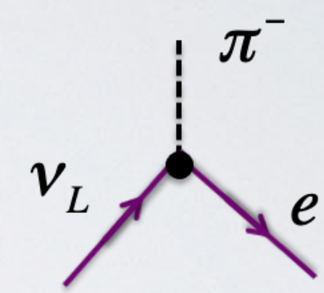
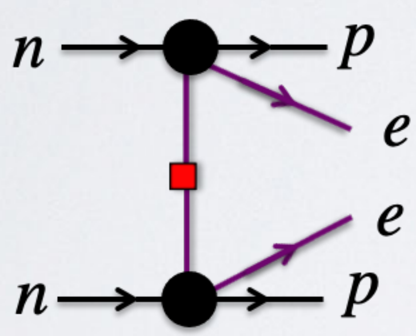


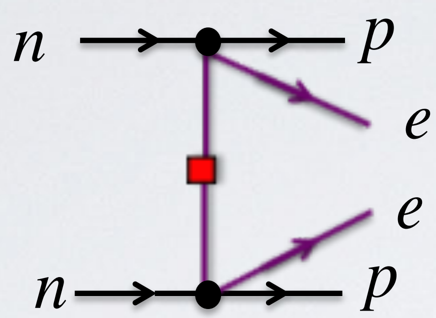


$$V_\nu(^1S_0) = (2G_F^2 m_{\beta\beta})\tau_1^+\tau_2^+ \frac{1}{\mathbf{q}^2}\left[(1+2g_A^2) + \frac{g_A^2 m_\pi^4}{(\mathbf{q}^2 + m_\pi^2)}\right] \otimes \bar{e}_L e_L^c$$

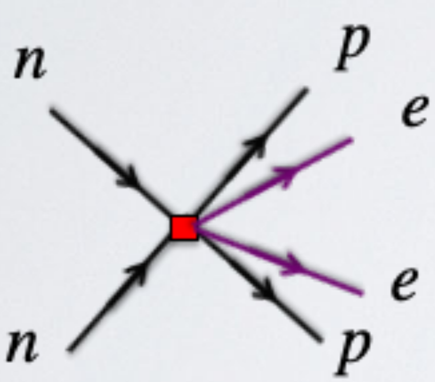
- This is the leading-order 'neutrino potential'.
- Then insert this 'potential' between nuclear wave functions $A_\nu = \langle \Psi_f | V_\nu | \Psi_i \rangle$
- Note: the nucleons appear in a bound state and **q** is a loop momentum

Light Majorana neutrinos (standard mechanism)

- Leads to 'long-range' nn ➞ pp + ee



$$V_\nu \sim \frac{m_{\beta\beta}}{\mathbf{q}^2} \qquad \mathbf{q} \sim k_F \sim m_\pi$$

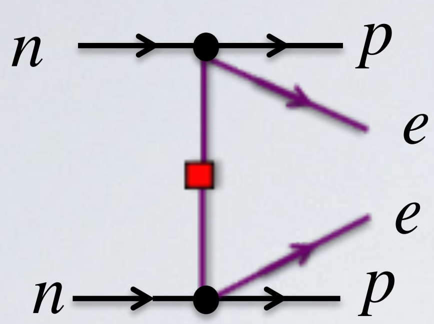


- Contributions from virtual hard neutrinos $\mathbf{q} \sim \Lambda_\chi \sim 1\,\mathrm{GeV}$
- Naive-dimensional analysis tells us this is NNLO

$$V_\nu^{short} \sim \frac{m_{\beta\beta}}{\Lambda_\chi^2}$$

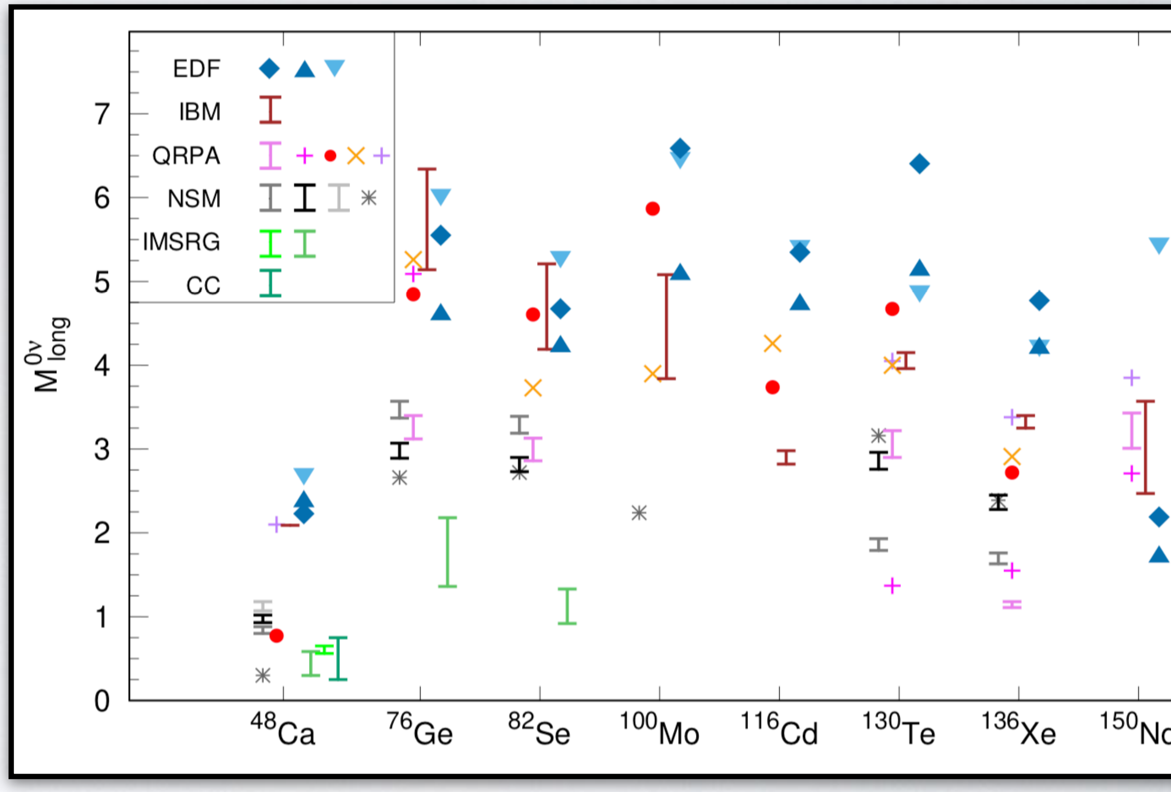
- Loops and other corrections at higher order in chiral EFT expansion

Leading-order transition currents



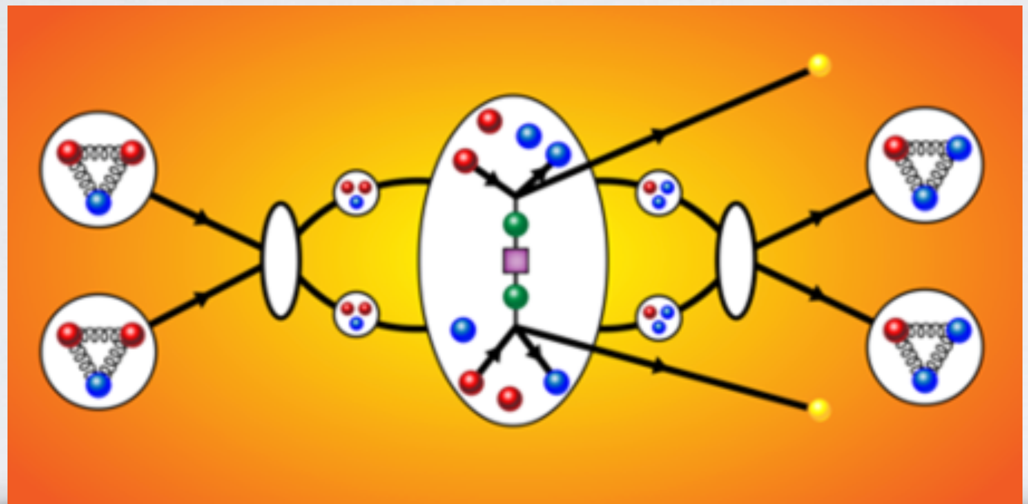
$$V_\nu = (2G_F^2 m_{\beta\beta})\tau_1^+\tau_2^+ \frac{1}{\mathbf{q}^2}\left[(1+2g_A^2) + \frac{g_A^2 m_\pi^4}{(\mathbf{q}^2+m_\pi^2)}\right] \otimes \bar{e}_L e_L^c$$

- Leading-order 0vbb current is very simple
- No unknown hadronic input ! Only unknown is $m_{\beta\beta}$
- ***Many-body methods disagree significantly***
- Original idea: study simpler nuclear systems
- **Not relevant for experiments but as a theoretical laboratory**



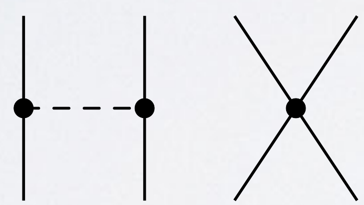
Neutron-Neutron → Proton-Proton

- Study simplest nuclear process: nn → pp + ee



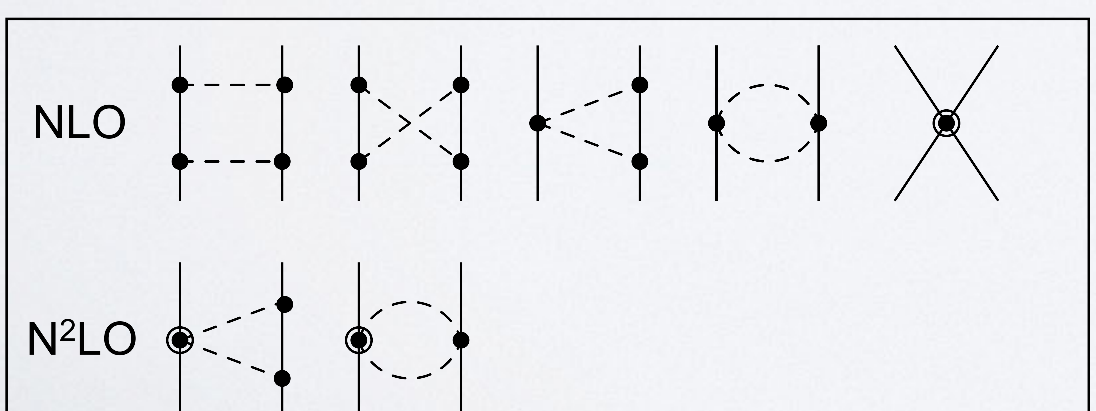
- Derive wave functions from chiral effective field theory

LO



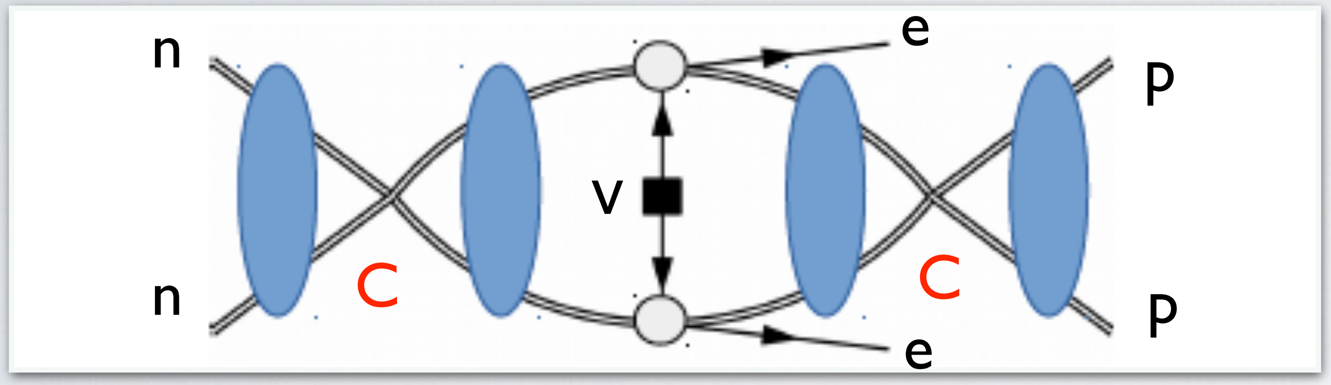
$$V_{\text{strong}} = C_0 - \frac{g_A^2}{4f_\pi^2}\frac{m_\pi^2}{\mathbf{q}^2 + m_\pi^2}$$

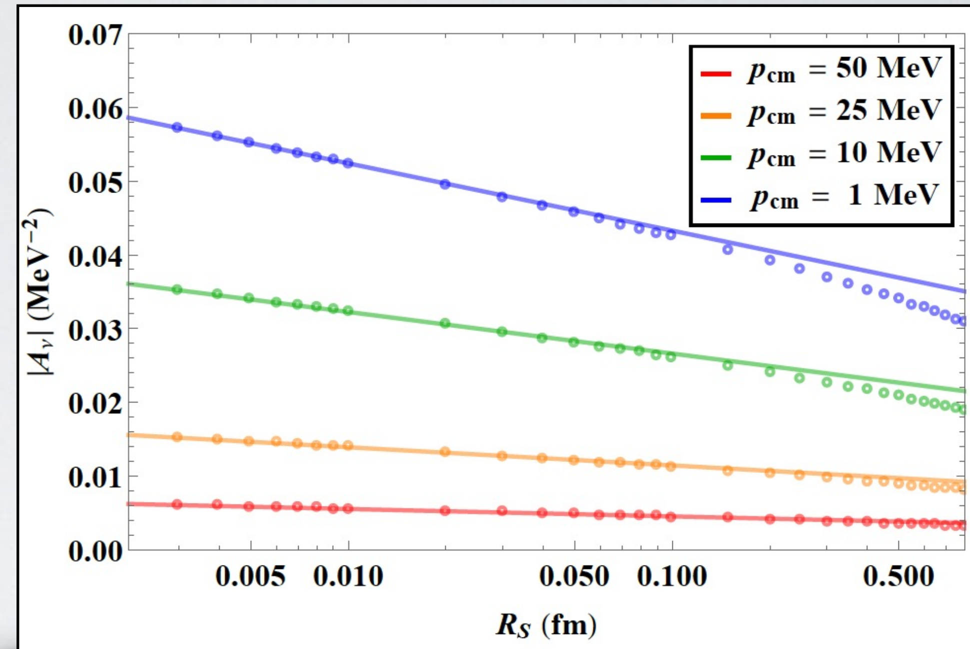
Weinberg 90' 91'



Weinberg
Van Kolck et al,
Epelbaum et al,
Machleidt et al,
And many more…

It doesn’t work





$$\sim (1+2g_A^2)\left(\frac{m_N C_0}{4\pi}\right)^2\left(\frac{1}{\epsilon}+\log\frac{\mu^2}{p^2}\right)$$

New divergences

The leading order amplitude is not renormalized !

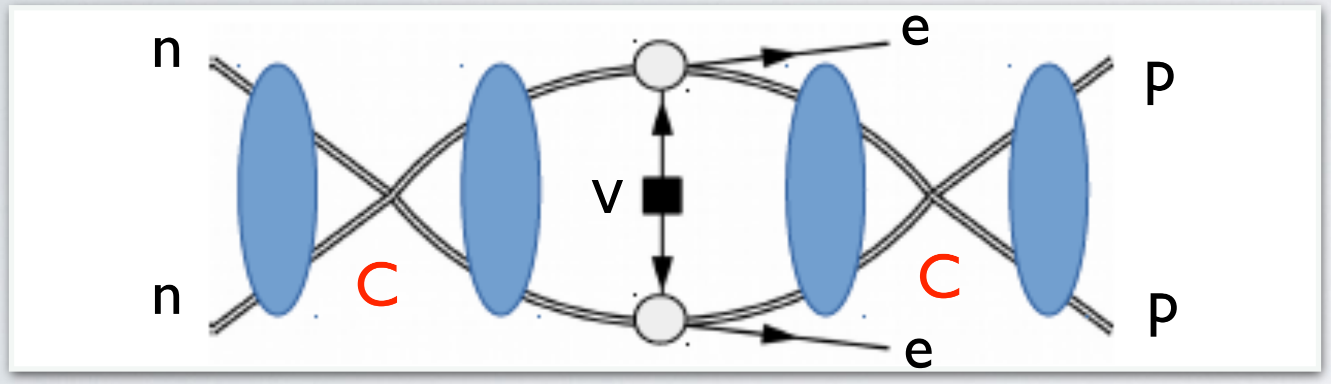
Featured in Physics | Editors' Suggestion | Open Access

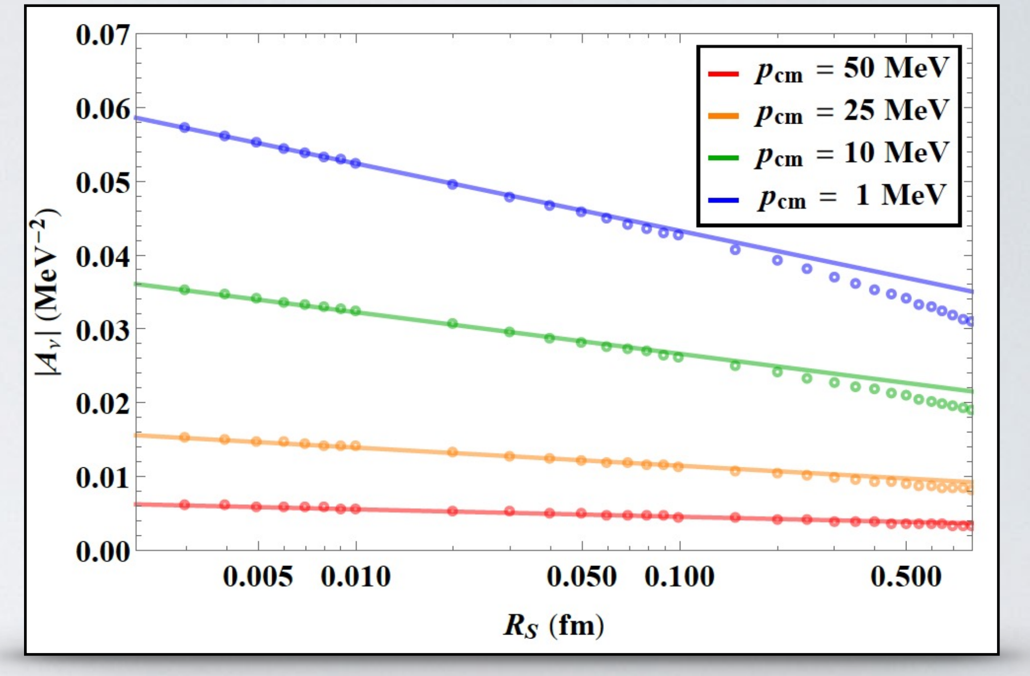
New Leading Contribution to Neutrinoless Double-β Decay

Vincenzo Cirigliano, Wouter Dekens, Jordy de Vries, Michael L. Graesser, Emanuele Mereghetti, Saori Pastore, and Ubirajara van Kolck

Phys. Rev. Lett. **120**, 202001 – Published 16 May 2018

It doesn't work

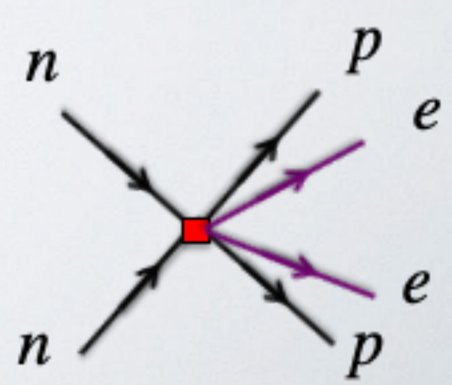




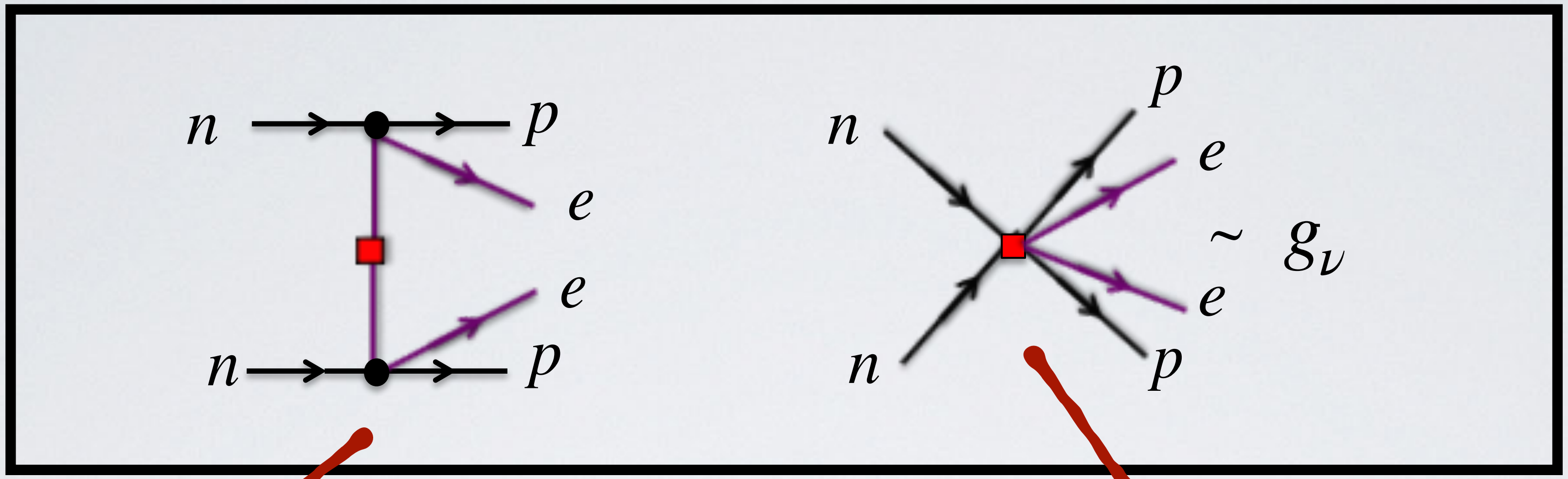
$$\sim (1 + 2g_A^2)\left(\frac{m_N C_0}{4\pi}\right)^2 \left(\frac{1}{\epsilon} + \log\frac{\mu^2}{p^2}\right)$$

New divergences

- **Logarithmic regulator dependence**
- Divergence indicates sensitivity to short-distance physics (hard-neutrino exchange)
- Suggest to add a counter term: a short-range nn → pp + ee operator
- Literature: *'breakdown of Weinberg power counting'*



A new leading-order contribution



'Long-range' neutrino-exchange

'Short-distance' neutrino exchange required by renormalization of amplitude

- **Short-distance piece depends on QCD matrix element** g_ν
- This was initially unknown but has now been determined (long story for a technical talk)

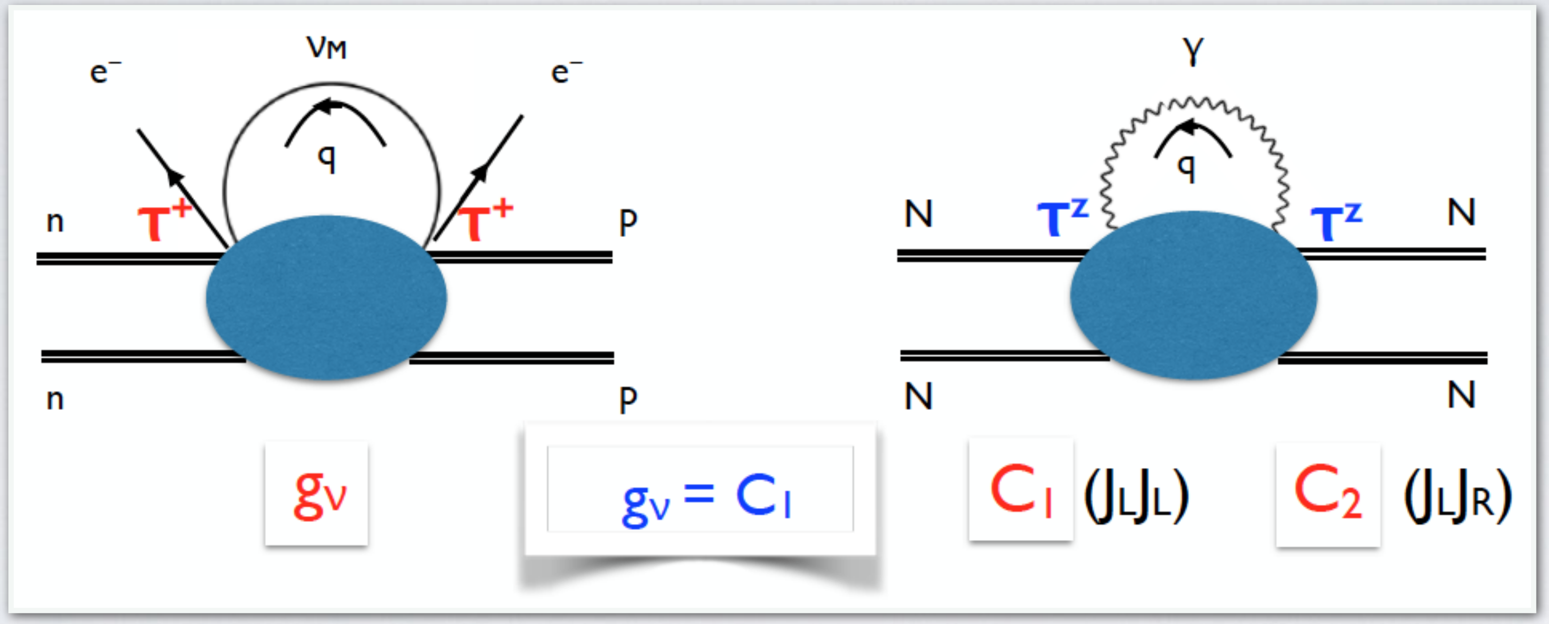
Cirigliano, Dekens, JdV, Hoferichter, Mereghetti PRC '19 PRL '21 JHEP '21
Davoudi, Kadam PRL '21 Briceno et al '19 '20
Van Groffier '24

Richardson, Schindler, Pastore, Springer '21
Tuo et al. '19; Detmold, Murphy '20 '22
Yang, Zhao '23 '24

- 0vbb calculations have to be redone —> This is now happening by many groups

A connection to electromagnetism

- A neutrino-exchange process looks like a photon-exchange process



Cirigliano et al '19

Walzl, Meißner, Epelbaum '01

- **Chiral** connection between double-weak and double-EM NN interactions

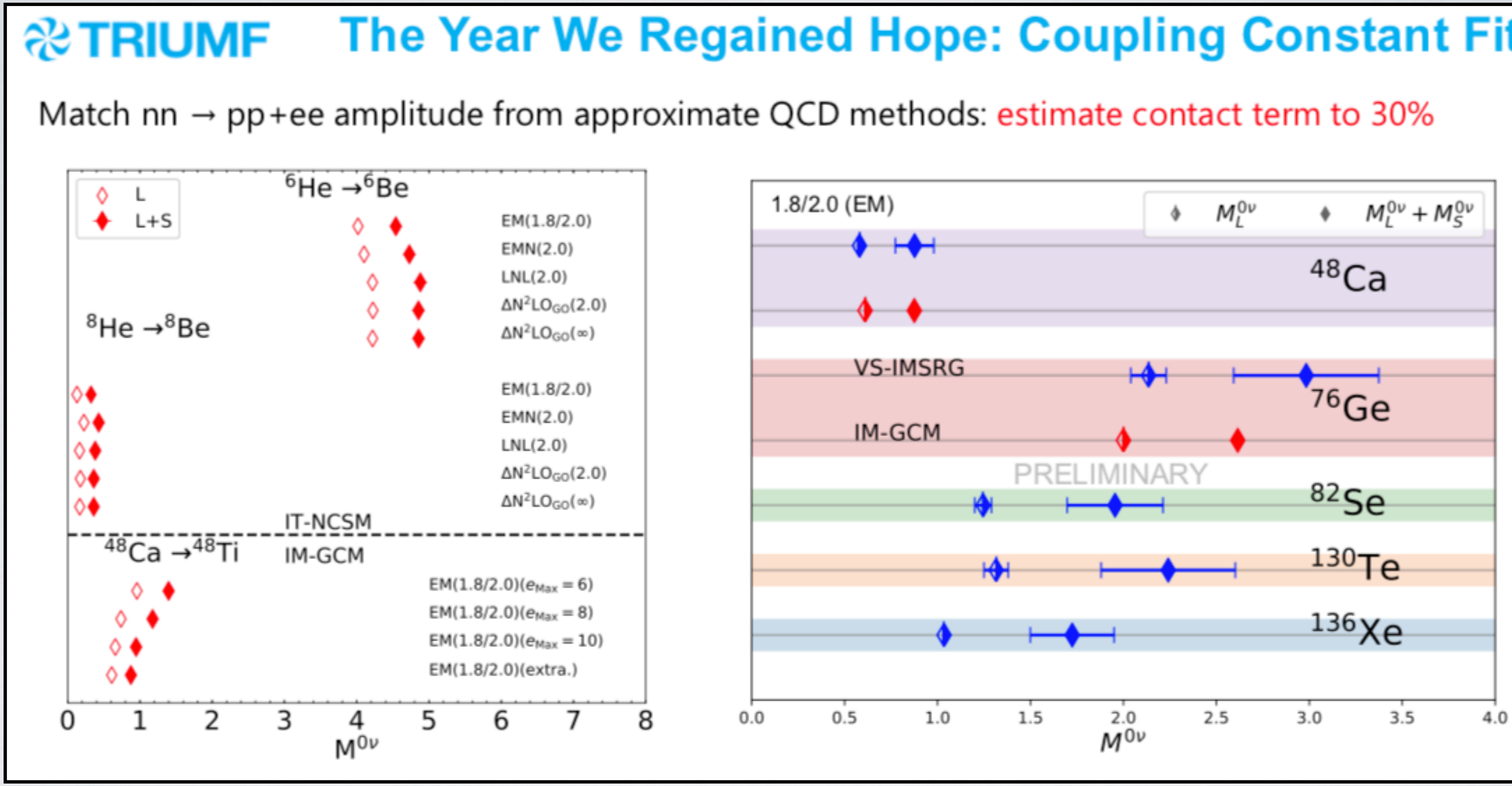
- Isospin-breaking nucleon-nucleon scattering data determines **C_1+C_2**
- Electromagnetism conserves **parity** coupling and **g_ν~C_1** only

- Large-Nc arguments indicates $C_1 + C_2 \gg C_1 - C_2$ Richardson, Schindler, Pastore, Springer PRC'21

- This seems to work surprisingly well Cirigliano, Dekens, JdV, Hoferichter, Mereghetti PRL '21

Van Groffier '24 Yang, Zhao PLB '23 '24

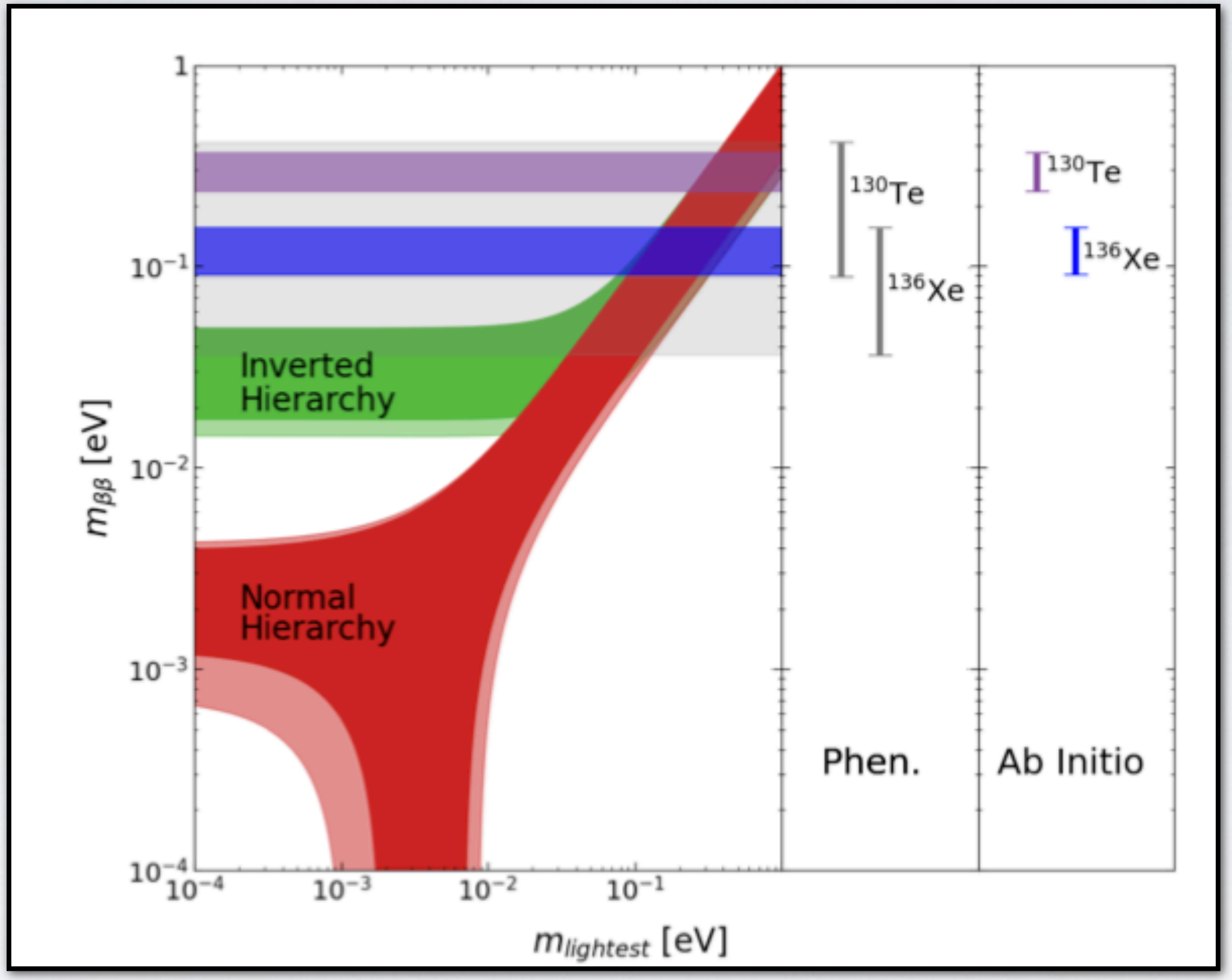
Impact on realistic nuclei



- Slides from **Jason Holt** (TRIUMF) at Institute of Nuclear Physics Seattle (2024)
- The contact term enhances NMEs by 100% (Ca) to 70% (Xe) (factor 3-4 on the lifetime)

Impact on realistic nuclei

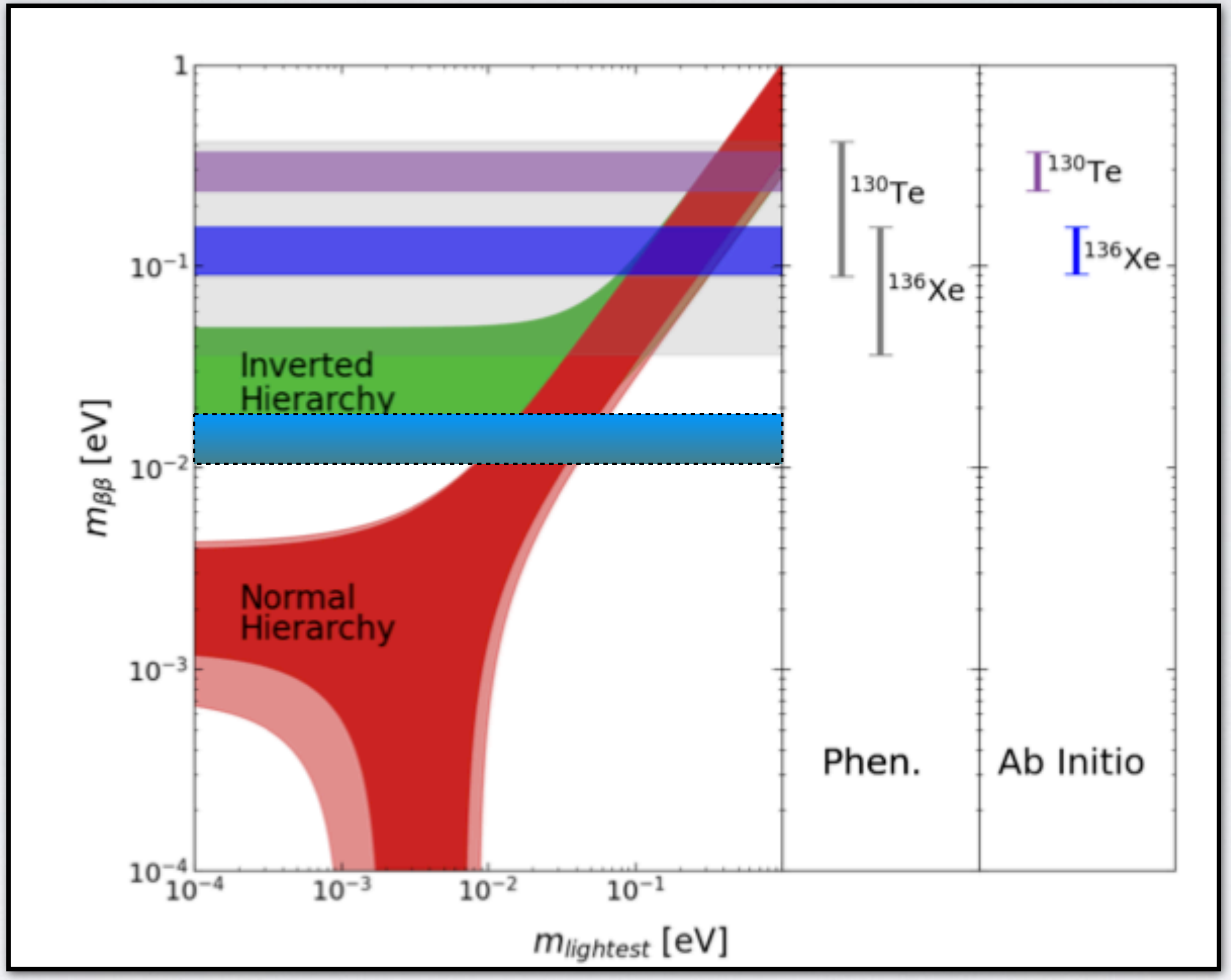
- Results from 2307.15156 (Belley et al) and PRL 132, 182502 (2024) + papers from '21 '22



- Ab initio calculations find rather small NME **compensated** by contact term
- Counter term leads to smaller model dependence: uncertainties at 30-40% level

- Not clear to me how to connect chiral EFT to phenomenological nuclear models

Intermediate summary



- NMEs are still a big problem but there has been progress
- ***Next-gen experiments to reach inverted hierarchy but normal hierarchy remains difficult (unless m_l ~ 0.01 eV)***

The plan of attack

1. Motivation: the puzzle of neutrino masses

2. Probing sterile neutrinos directly and indirectly

    - *Effective field theory for 0vbb*

3. **Connection to low-scale leptogenesis**

Impact of light sterile neutrinos ?

M_R ?

eV — keV — MeV — GeV — TeV — ..... — 10^{15} GeV

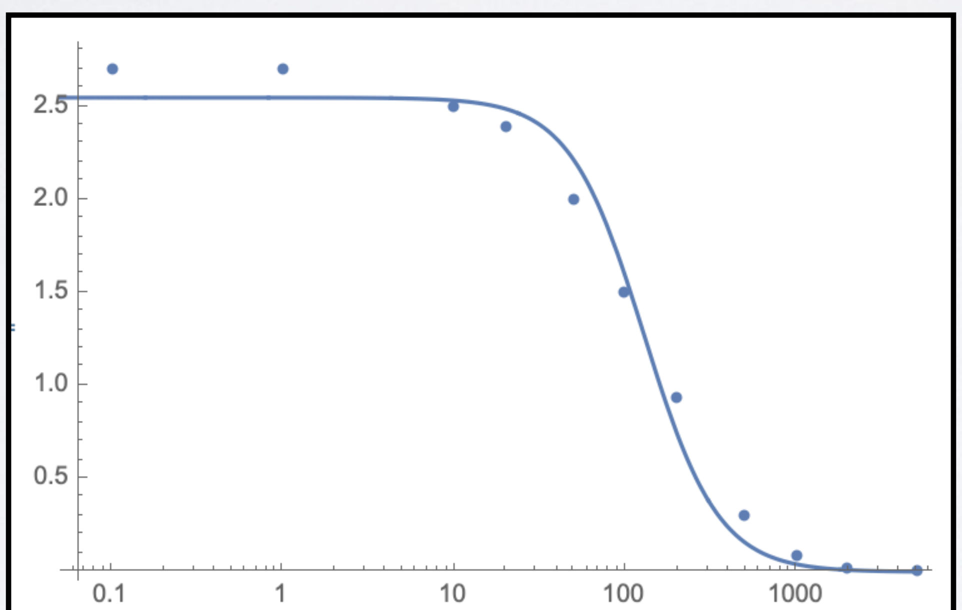
What about here ?

- For masses below a GeV, the sterile neutrinos become explicit degrees of freedom

$$|M_{0\nu}(m_R)|^2 = |\langle 0^+ | V_\nu(m_R) | 0^+ \rangle|^2$$

Shell model Xe (Menendez)

$M(m_4)$



m_4(MeV)

$$M(m_4) \sim \frac{1}{\langle p^2 \rangle + m_4^2}$$

$$\langle p^2 \rangle \simeq (100\,\mathrm{MeV})^2$$

Revisit the light regime

$$A_\nu \sim \sum_{i=1}^{3} U_{ei}^2 m_i \frac{1}{\langle p^2 \rangle} + U_{e4}^2 m_4 \frac{1}{\langle p^2 \rangle + m_4^2} \xrightarrow{m_4 \ll 100\,\mathrm{MeV}} A_\nu \sim \sum_{i=1}^{4} U_{ei}^2 m_i \frac{1}{\langle p^2 \rangle} + \mathcal{O}\left(\frac{m_i^3}{\langle p^2 \rangle^2}\right)$$

- The first term depends on $\sum_{i=1}^{4} U_{ei}^2 m_i = M_{ee} = 0$ $\quad M = \begin{pmatrix} 0 & v y_\nu \\ v y_\nu & M_R \end{pmatrix}$
- **The 'GIM' mechanism for neutrinos !** (only valid if all steriles are light)
- The amplitude is strongly suppressed $A_\nu \sim \sum_{i=1}^{4} U_{ei}^2 m_i^3$ Blennow et al '10 JHEP

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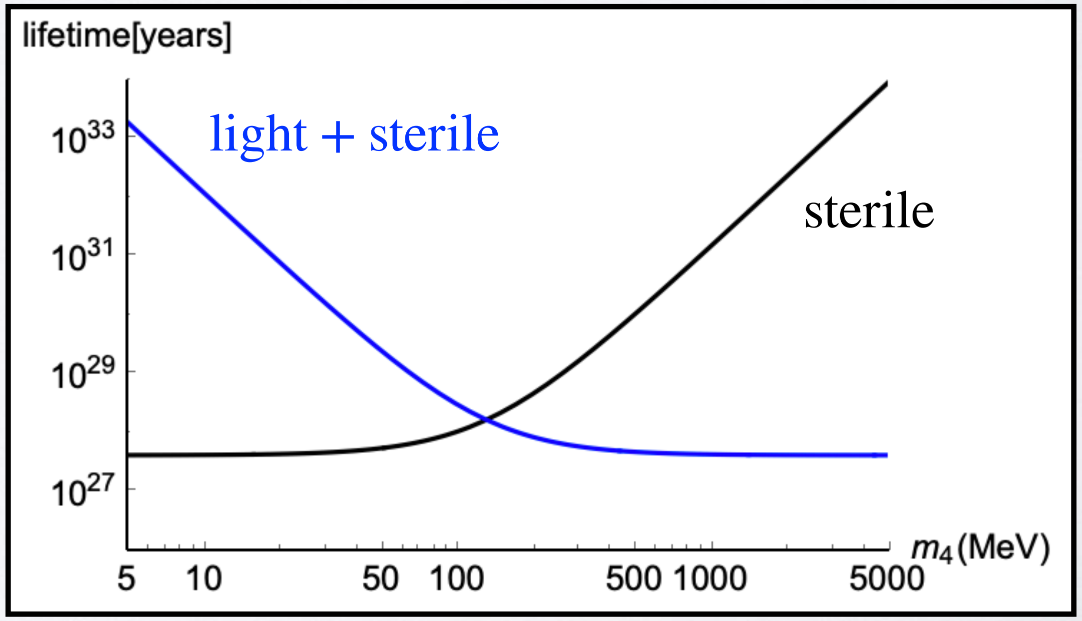
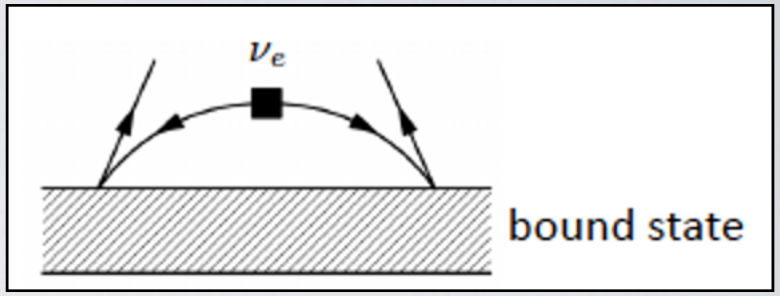
- Example in 3+1model
- Cancellation between light + sterile contributions leads to

$$\tau_{1/2} \sim m_4^4$$



Light extra neutrinos



- Is there a way to avoid the GIM mechanism ?
- There are additional contributions from '***ultra-soft***' neutrinos

$$\sum_n \langle f | J_\mu | n \rangle \langle f | J^\mu | i \rangle \times \int \frac{d^3k}{(2\pi)^3} \frac{1}{E_\nu [E_\nu + (E_n - E_0) - i\epsilon]} \qquad E_\nu = \sqrt{k^2 + m_i^2}$$

- The neutrinos see the nucleus as a whole and becomes sensitive to nuclear structure effects
- Depends on nuclear excited states. Normally these are tiny effects (5%)

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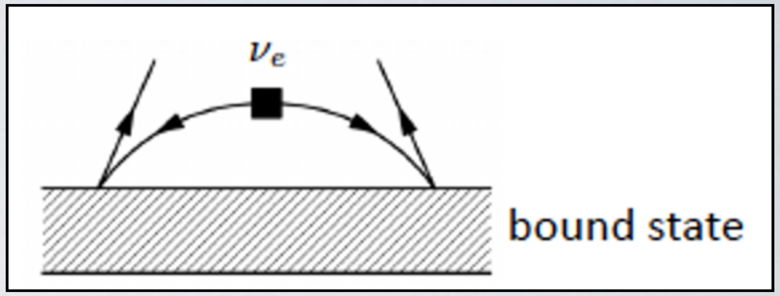

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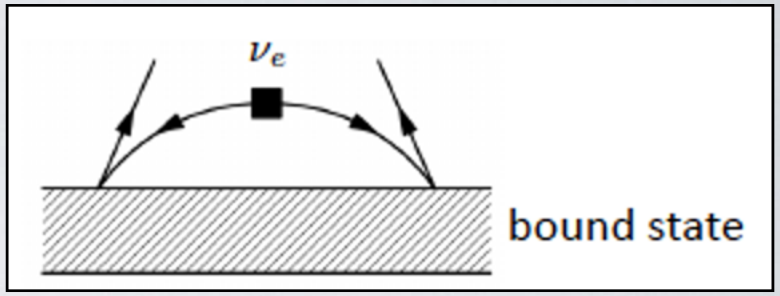
$\frac{E_n-E_i}{\text{MeV}}$	$\langle 1_n^+\|\boldsymbol{\sigma}\tau^+\|0_i^+\rangle$	$\langle 0_f^+\|\boldsymbol{\sigma}\tau^+\|1_n^+\rangle$	$\frac{E_n-E_i}{\text{MeV}}$	$\langle 1_n^+\|\boldsymbol{\sigma}\tau^+\|0_i^+\rangle$	$\langle 0_f^+\|\boldsymbol{\sigma}\tau^+\|1_n^+\rangle$	$\frac{E_n-E_i}{\text{MeV}}$	$\langle 1_n^+\|\boldsymbol{\sigma}\tau^+\|0_i^+\rangle$	$\langle 0_f^+\|\boldsymbol{\sigma}\tau^+\|1_n^+\rangle$
0.17	1.	0.13	3.3	0.39	-0.0013	9.1	0.8	0.0038
0.63	-0.19	-0.0063	3.6	0.39	0.0021	9.4	0.59	0.0014
0.89	-0.25	-0.016	3.8	0.45	-0.013	9.8	-0.5	0.0027
1.02	0.3	0.036	4.0	-0.44	-0.0032	10.1	0.35	-0.0027
1.05	0.23	0.025	4.3	-0.35	-0.0038	10.5	0.26	-0.00053
1.1	-0.13	-0.00076	4.6	-0.36	-0.0067	10.9	-0.22	-0.00021
1.2	0.12	-0.0052	4.8	0.44	0.0083	11.3	0.17	-0.00037
1.3	0.16	-0.0028	5.1	0.44	0.0066	11.7	-0.16	-0.00054
1.4	-0.23	-0.0098	5.4	-0.55	-0.0093	12.0	-0.16	-0.001
1.5	0.2	-0.012	5.7	0.63	0.012	12.4	0.14	0.00092
1.6	-0.36	0.0084	6.1	0.85	0.013	12.8	0.12	-0.00014
1.7	-0.24	0.00058	6.3	-1.2	-0.016	13.1	0.092	-0.0004
1.9	0.22	0.011	6.7	-1.3	-0.014	13.5	-0.079	-0.00019
2.0	0.34	0.007	7.0	-1.9	-0.016	13.9	0.071	-0.00026
2.2	0.35	0.006	7.3	3.1	0.023	14.2	-0.07	0.000031
2.3	-0.49	-0.0086	7.5	-4.	-0.028	14.6	-0.035	0.00021
2.6	0.62	0.021	7.7	2.6	0.017	15.1	-0.051	-0.00015
2.7	-0.91	-0.024	8.1	1.4	0.0091	16.2	-0.039	0.00011
2.9	0.37	0.0064	8.4	-1.	-0.0057	17.3	-0.043	-0.000091
3.1	0.3	0.0013	8.8	-0.93	-0.0064	17.7	0.11	-0.000029

- Javier Menendez and his group computed the transition matrix elements for us

Light extra neutrinos



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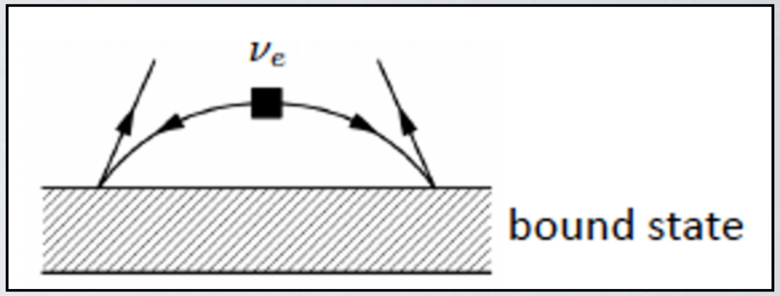
- The neutrinos see the nucleus as a whole and becomes sensitive to nuclear structure effects
- Depends on nuclear excited states. Normally these are tiny effects (5%)
- This becomes dominant in the GIM mechanism ! $\sim U_{ei}^2 m_i^3$
- For m_i ~ MeV: new contributions $\sim U_{ei}^2 m_i^2$ Dekens, JdV et al '23 '24
- For m_i << MeV: new contributions $\sim U_{ei}^2 m_i^3 \log \frac{(E_n - E_0)^2}{m_i^2}$

Light extra neutrinos



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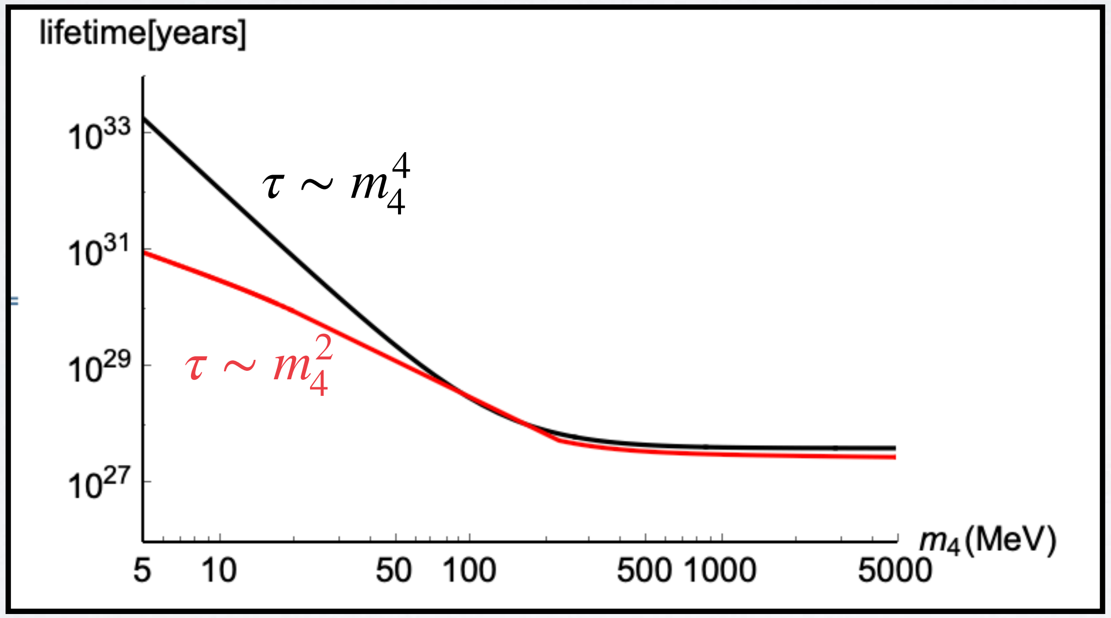


100x larger decay rates

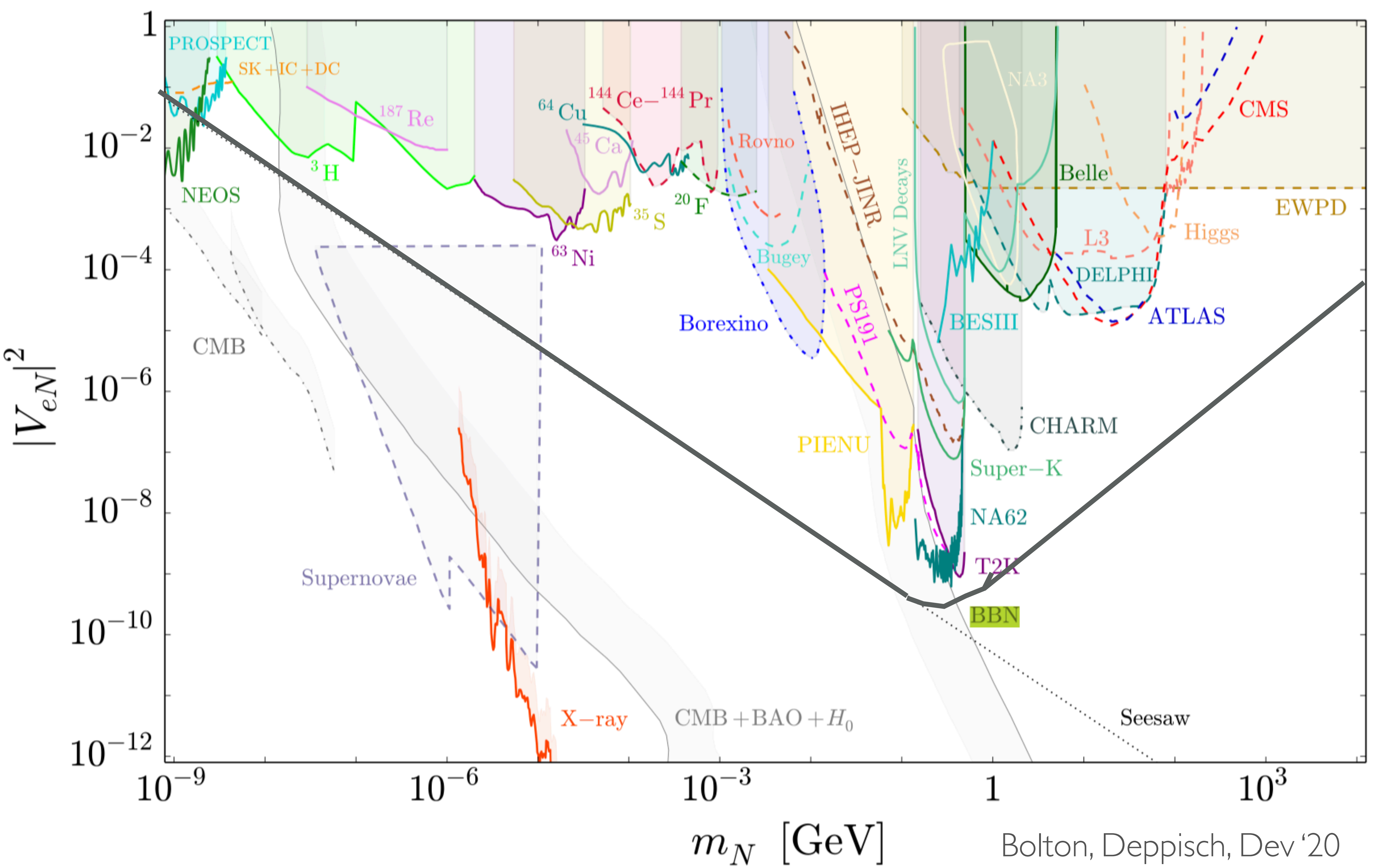
Dekens, JdV et al '23 '24

- Lifetimes are still suppressed for small sterile neutrino masses but not as much
- Not today: short-distance piece becomes mass dependent too $\mathbf{g}_\nu^{\mathbf{NN}}(m_i)$

Cirigliano et al '24

Compared to 0vbb

- **Naively saturate** the 0vbb lifetime with just the m4 contribution



Bolton, Deppisch, Dev '20

- Bounds can be weakened by considering **pseudo-Dirac** sterile neutrino pairs

This is perhaps not fair

- Consider **minimal 3+2 extension** (lightest active neutrino is massless)

$$m_4 = \bar{M} - \Delta M/2\,, \qquad m_5 = \bar{M} + \Delta M/2\,, \qquad \mu = \frac{\Delta M}{\bar{M}}$$

- For small mass splittings, the heavy neutrino pair can form a **pseudo-Dirac neutrino**

- 0vbb amplitude proportional to $\bar{m}_{\beta\beta} = m_{\beta\beta}\left[1 - \frac{M(\bar{M})}{M(0)}\right] + f(\bar{M})\,\mu\,U_e^2 + \mathcal{O}(\mu^2)$

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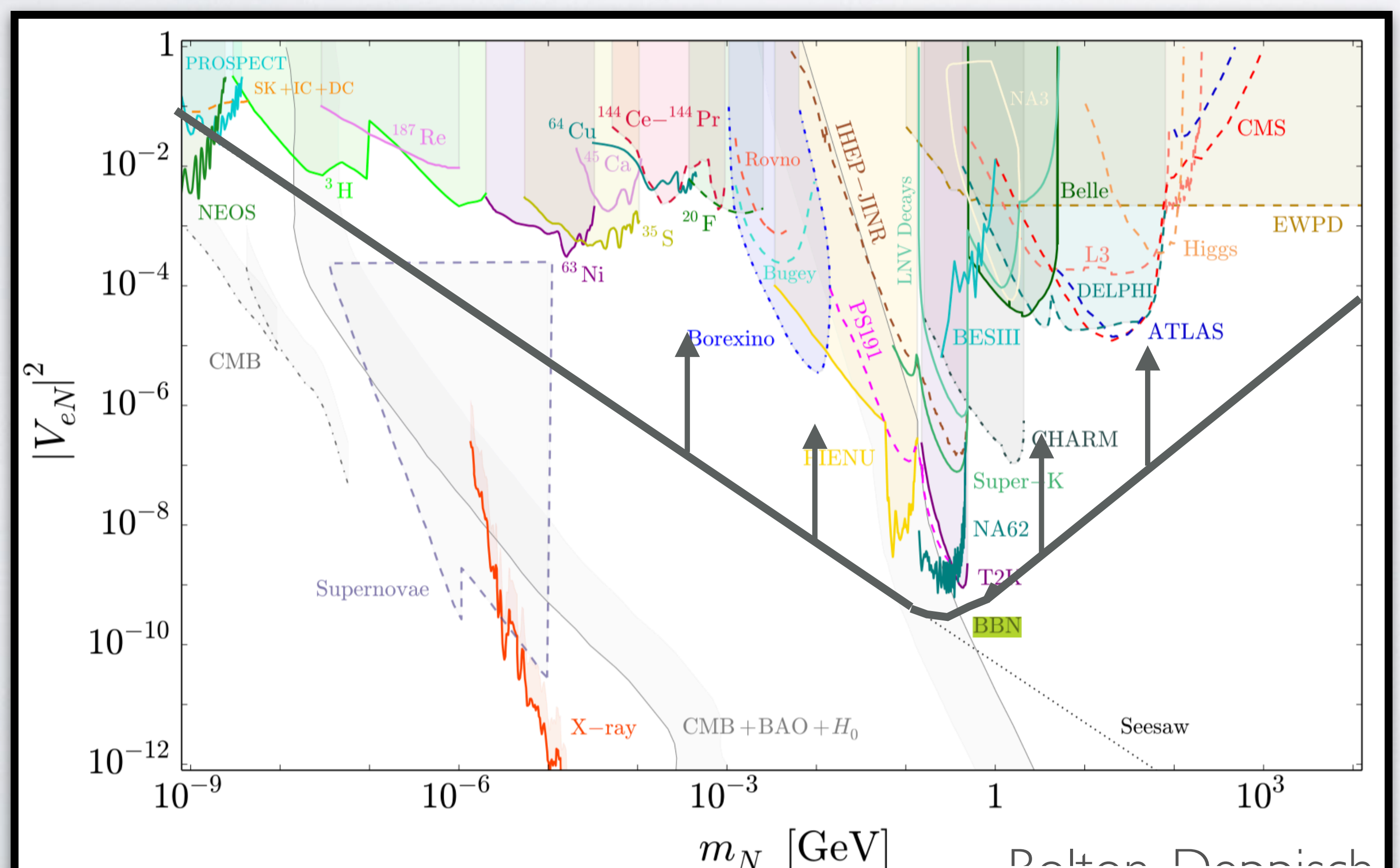
- Bounds can be moved up for small and/or degenerate masses.



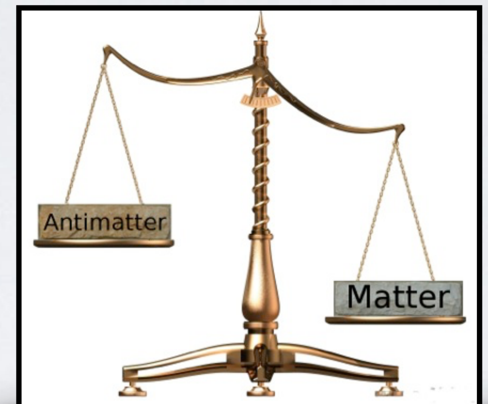
- **0vbb becomes weak for (pseudo-)Dirac sterile neutrinos**
- **Need an independent handle on the mass splitting**

Low-scale leptogenesis

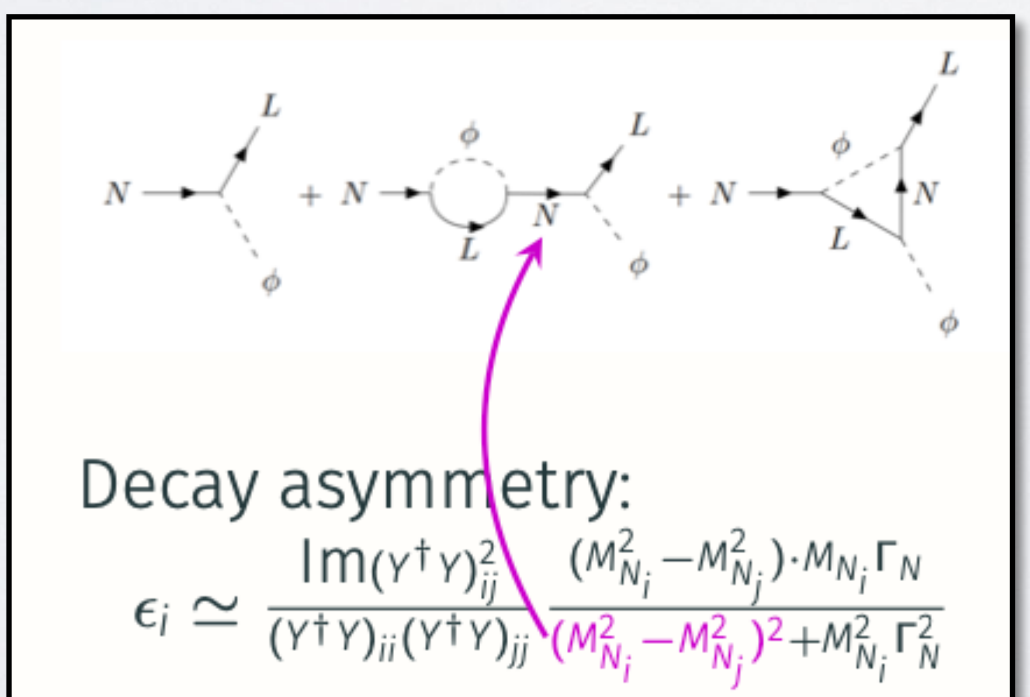
Arxiv:2407.10560

- Low-scale leptogenesis requires a small mass splitting as well !
- We can do leptogenesis at the same time in the **minimal 3+2 extension**

13.7 billion year



- Production of asymmetries enhanced by small mass splittings



Akhmedov/Rubakov/Smirnov '98
Pilaftsis/Underwood '03
Asaka/Shaposhnikov '05

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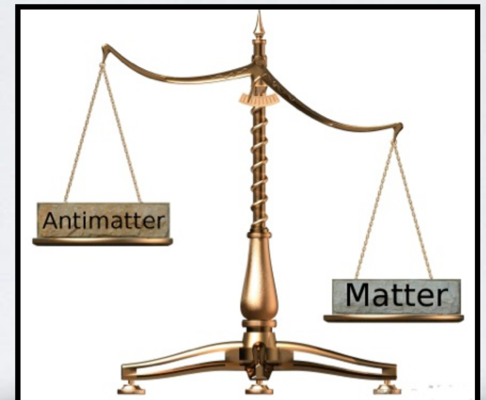


- Production of asymmetries enhanced by small mass splittings
- Scan over parameters in the 3+2 extension (masses, angles, phases ~ O(10))

☑ Neutrino masses

☑ Matter/Antimatter asymmetry

☑ Consistent with all current experiments

☑ Sterile neutrino masses below 10 GeV

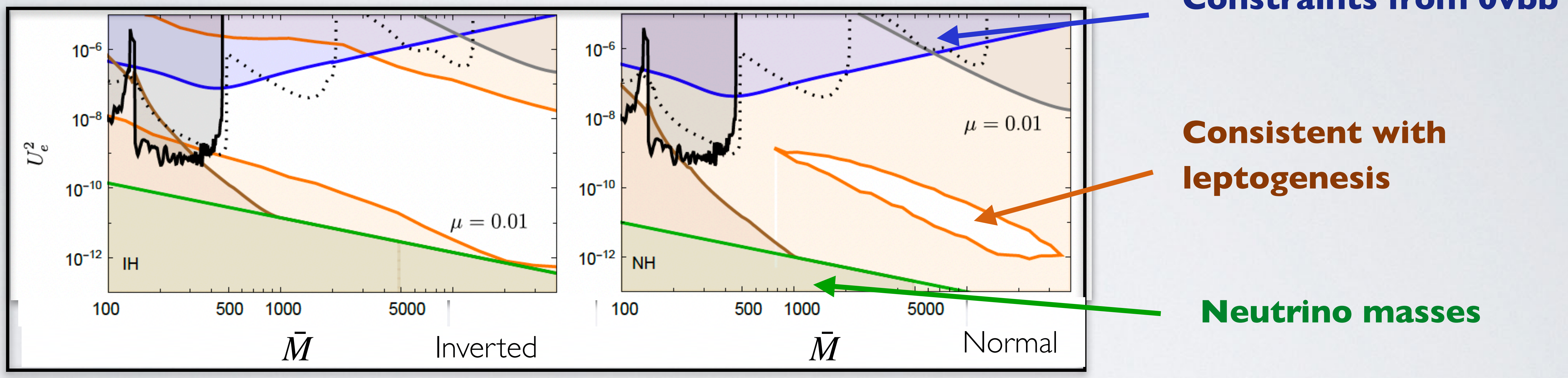
Juraj Klaric, Vaisakh Plakkot, Yannis Georis

Low-scale leptogenesis

Leptogenesis contours calculated by Drewes/Georis/Klaric

Arxiv:2407.10560

- Simplest solution to neutrino masses + matter/antimatter asymmetry
- Scans give contours like this (fixed mass splitting at 1%)



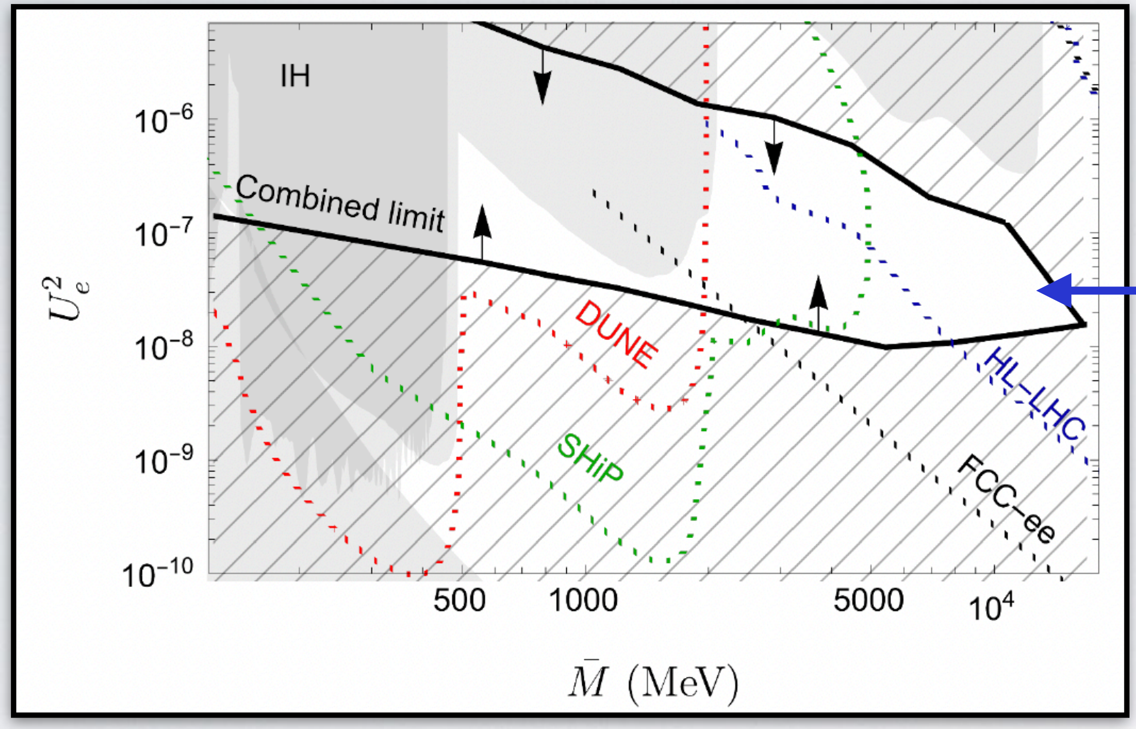
- For inverted hierarchy, 0vbb is ruling out part of the space

$$\bar{m}_{\beta\beta} = m_{\beta\beta}\left[1 - \frac{M(\bar{M})}{M(0)}\right] + f(\bar{M})\,\mu\,U_e^2$$

- In inverted hierarchy, next-gen should see something unless we have a **cancellation !**

Low-scale leptogenesis

- **The IH scenario can be falsified if we don't see 0vbb in next-gen**



Arxiv:2407.10560

Consistent with no signal in next-gen 0vbb

Inverted hierarchy

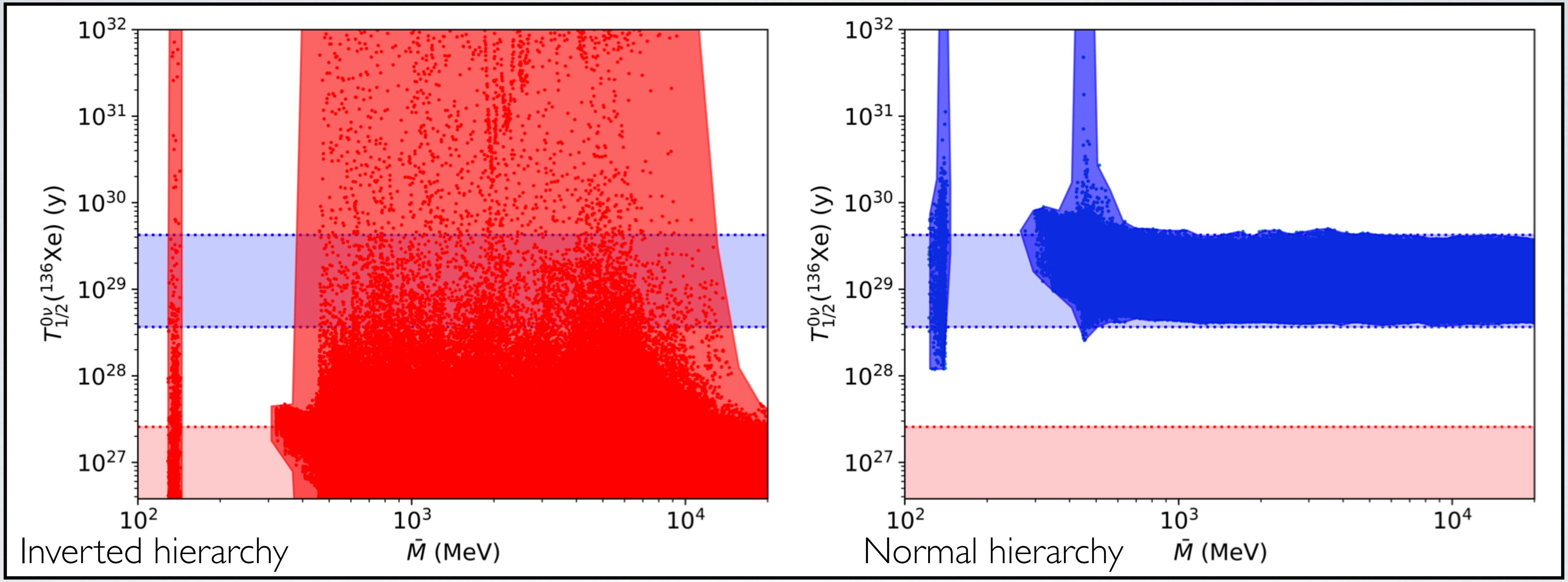
- If we do see a signal —> Nobel prize, neutrinos are Majorana, but….. **not clear if light sterile neutrinos were involved. Need more tests**

- Normal hierarchy: similar to IH but requires 10x better 0vbb experiments then IH.

- Analysis much harder for 3+3 (see e.g. Chrzaszcz, Weniger et al' 19) 18 parameters ….

Is the signal 'outside' the band

- If we do see a 0vbb signal, Question: is it different from the 'standard mechanism'



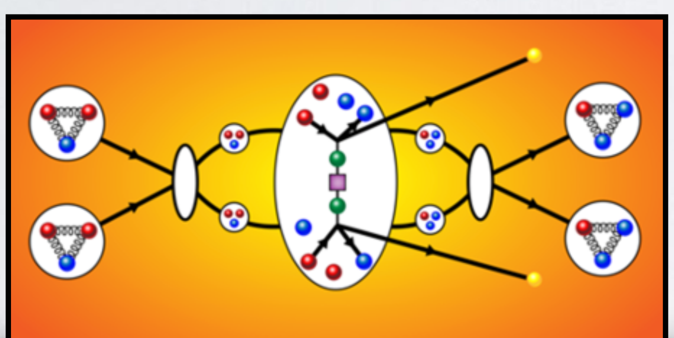
- **Unfortunately:** within 3+2 leptogenesis it is hard to **enhance** 0vbb rates in normal hierarchy
- **Key lessons: we should all hope we live in the Inverted Hierarchy**

Summary and outlook

- Neutrino masses requires an explanation !!
- Good motivation for sterile neutrinos (also leptogenesis) but mass range unclear

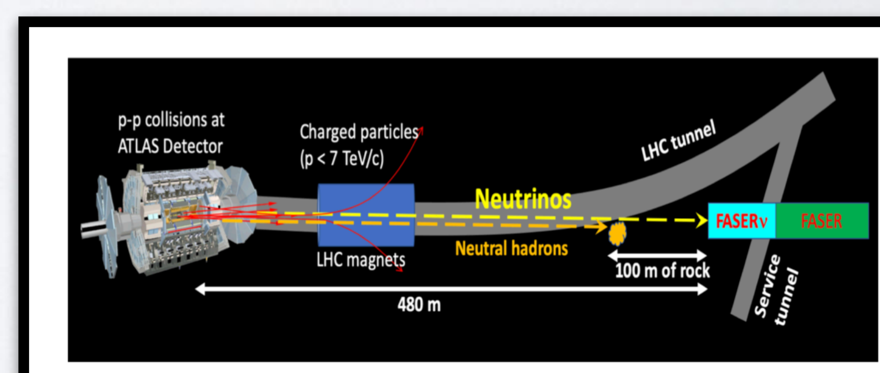
eV — keV — MeV — GeV — TeV — ..... — 10^{15} GeV → M_R ?

- **Excellent experimental prospects for large chunk of mass range**
- Neutrinoless double beta decay important for entire mass range



- **Exciting experimental program**
- Theory improvements needed but good progress last 5 years
- Crucial to test leptogenesis at all scales

- **Great activity to find long-lived particles**
- New experiments Ship/Dune/Faser very promising
- Low-scale leptogenesis can be tested by the combined experimental program !



Backup