NEUTRINOLESS DOUBLE BETA DECAY AND STERILE NEUTRINOS

Jordy de Vries
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The plan of attack

1. **Motivations: neutrino masses/antimatter/EFTs**

2. Lepton number violation and neutrinoless double beta decay

    - *Exciting lecture on the recent history of nuclear physics*

3. Producing sterile neutrinos in the laboratory

Neutrino masses

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

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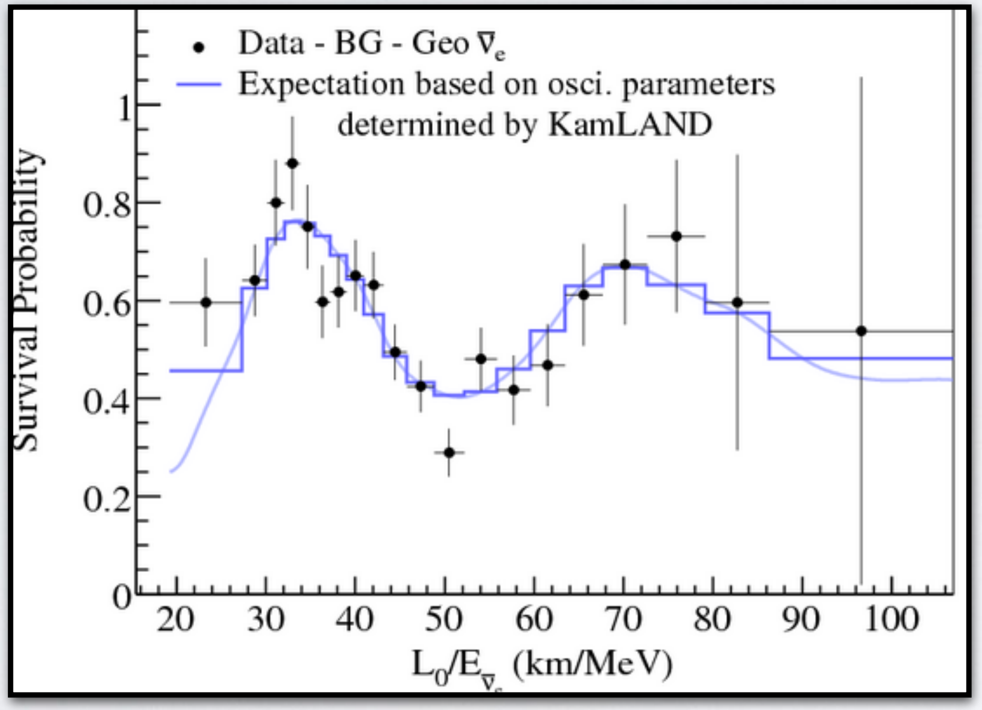
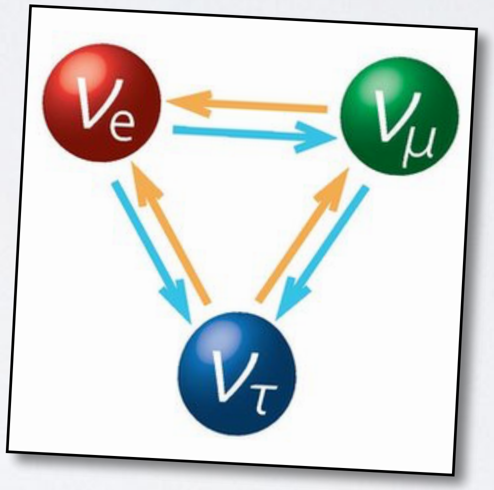
- Not crazy: from beta decay experiments $m_\nu \ll m_e \ll m_p$
- **But neutrinos do have mass !**



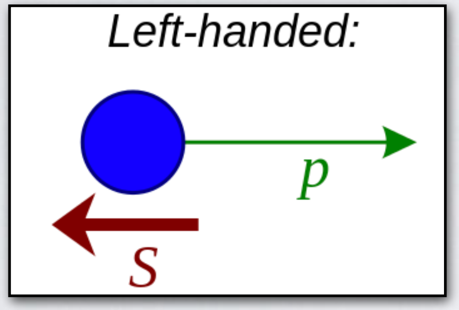
$$P(\nu_\mu \to \nu_e) \sim \sin \frac{\Delta m^2 L}{2E}$$

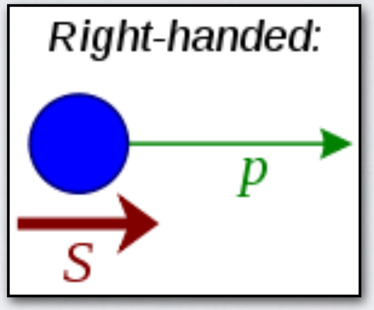


- Biggest mass splitting: $|\Delta m| \simeq 0.05\, eV$ Smallest: $|\delta m| \simeq 0.008\, eV$
- Direct limits: $m_{\nu_e} \leq 0.8\, eV$ **KATRIN experiment**
- Cosmology $\sum_{i=e,\mu,\tau} m_{\nu_i} \leq 0.12\, eV$

Mass generation in the Standard Model

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





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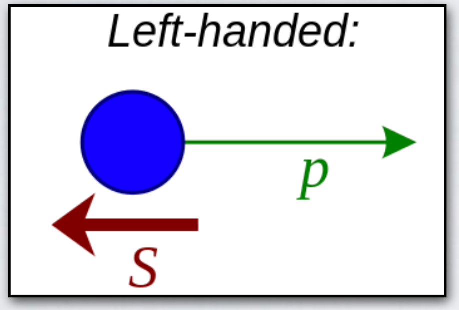

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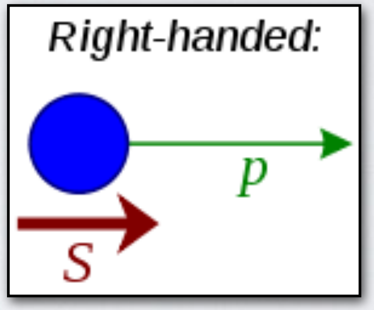

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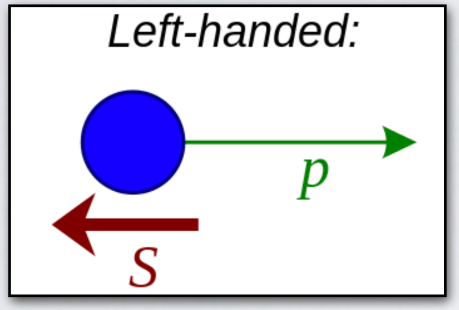

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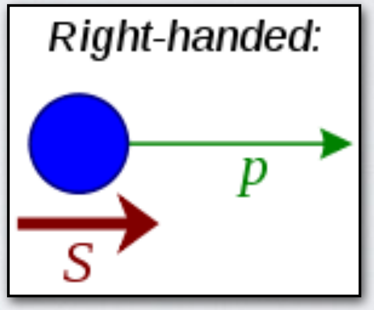

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- This would violate 'weak charge' conservation (or SU(2) gauge invariance)
- The Standard Model overcomes this problem through the **Higgs** mechanism

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

- 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 ν_R

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

- Nothing really wrong with this….

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- Nothing really wrong with this…. **But nothing forbids a Majorana Mass term**

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

'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**
- **Does this term exist in nature? How can we find out ?**
- 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)

The puzzle of the neutrino mass

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

Minkowski '77

- 1+1 case: diagonalization leads to **2 mass eigenstates**

$\nu_{1,2}$ describe 2 massive Majorana neutrinos $\nu_i^c = \nu_i$ **Particle = anti-Particle**

- A Majorana particle only has 2 degrees of freedom (Dirac particle has 4)

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  - If M_R is significantly larger than a **few eV**: see-saw mechanism

$$m_1 \simeq \left| \frac{y_\nu^2 v^2}{M_R} \right| \qquad m_2 \simeq M_R \qquad \begin{aligned} \nu_1 &\simeq \nu_L - \theta \nu_R^c + \ldots \\ \nu_2 &\simeq \nu_R + \theta \nu_L^c + \ldots \end{aligned} \qquad |\theta| \simeq \sqrt{\frac{m_1}{m_2}}$$

- The mixing angle determines **strength of weak interactions** of heavy neutrinos

- Possible to get **larger mixing angles** in scenarios with more sterile neutrinos

Mass ranges

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

M_R ?

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

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

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

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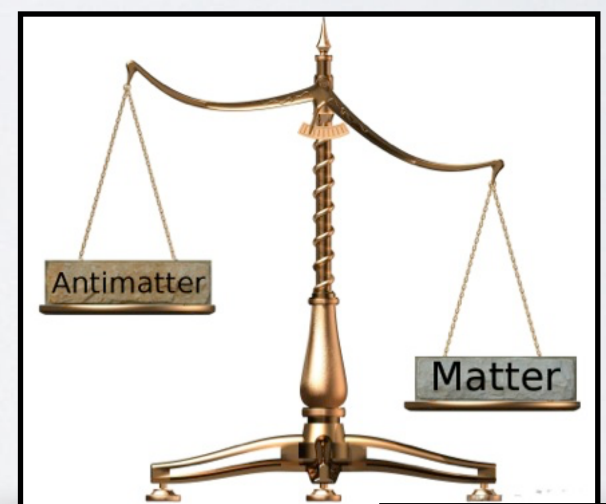
Fukugita, Yanagadi '86

- **Thermal leptogenesis possible** $M_R \geq 10^9\,\text{GeV}$ Davidson Ibarra '02

13.7 billion year →



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

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- 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

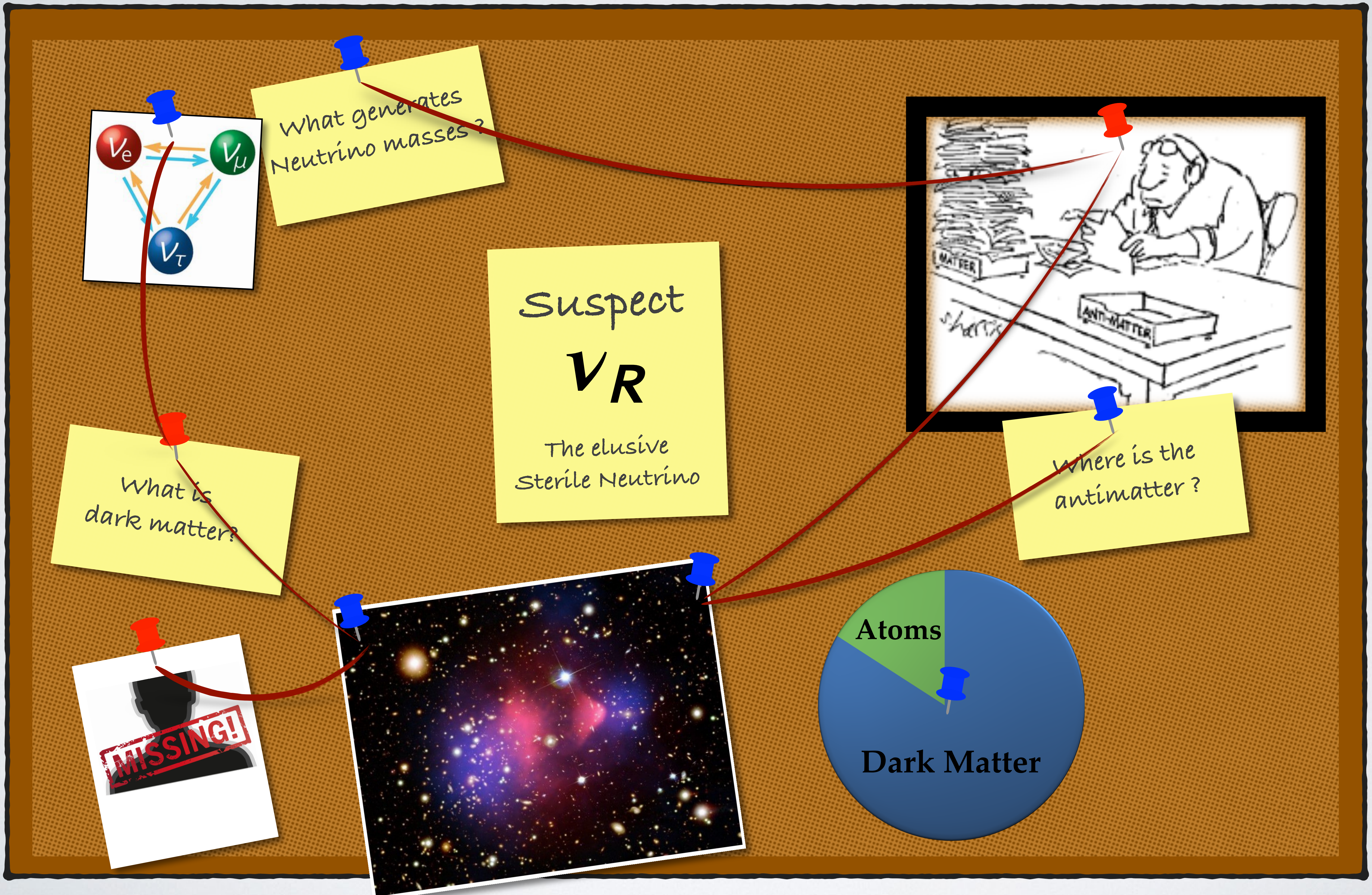
- KeV sterile neutrino could be Dark Matter (but getting more difficult) and essentially decoupled from neutrino mass generation

  Dodelson, Widrow '97
  Shaposhnikov et al '05

- eV sterile neutrinos potentially related to short base-line anomalies

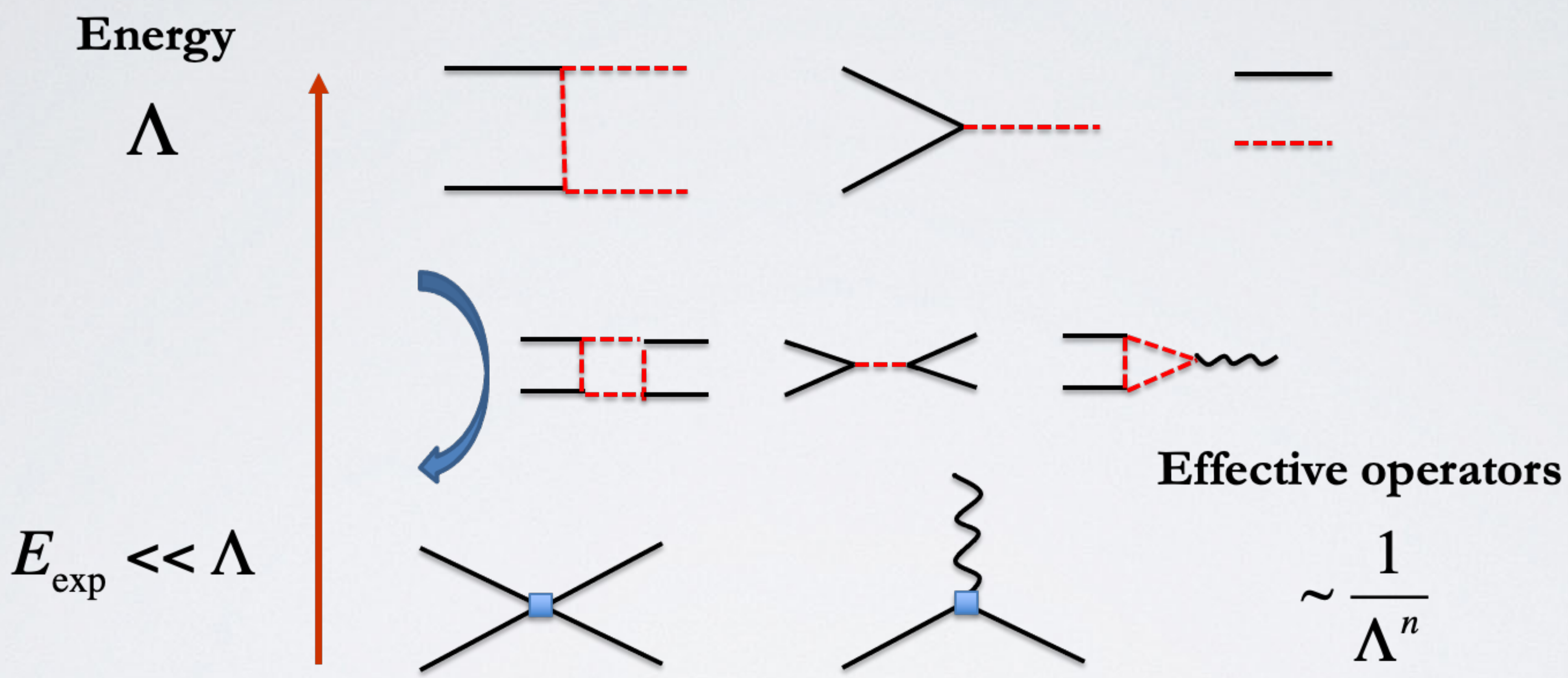
- **Clear motivation to look for a broad range of sterile neutrino masses**

The evidence board



The Standard Model as an EFT

- **Let's be more agnostic:** assume as little as possible about BSM
- Let's just assume BSM physics lives at high scales



- Extend SM with higher-dimensional operators (@Nikhef, mainly care about dim-6)

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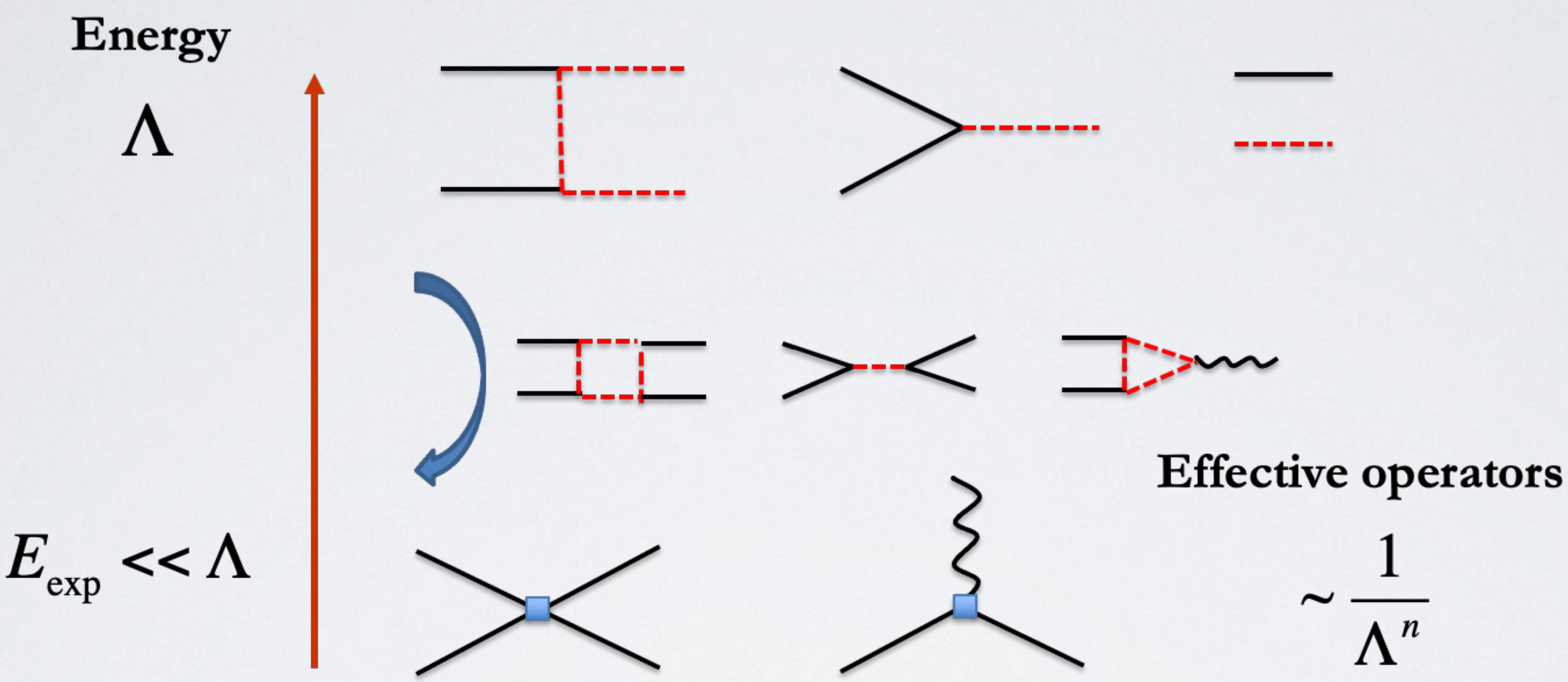

- Extend SM with higher-dimensional operators (@Nikhef, mainly care about dim-6)
- But first operator appears at dimension 5 $\mathscr{L}_5 = \frac{c_5}{\Lambda}\left(L^T C\tilde{H}\right)(\tilde{H}^T L)$ Weinberg ‘79
- **Neutrino Majorana masses are the first SM-EFT prediction !**

Heavy-weight neutrinos

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

First consider heavy states

- For $m_R \geq 50$ TeV or so, we'll not be able to produce them this century

Heavy-weight neutrinos

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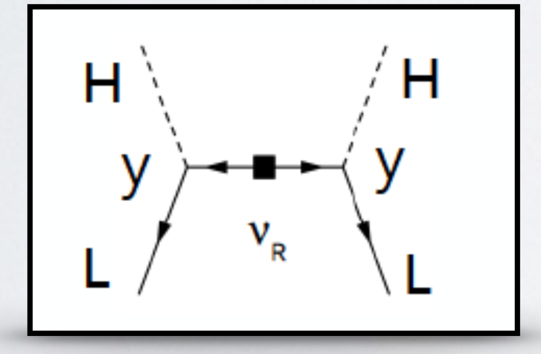
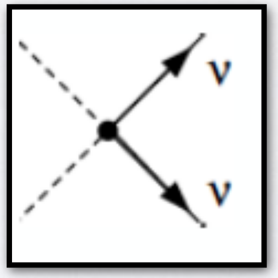
eV keV MeV GeV TeV ..... 10^{15} GeV → **M_R ?**

First consider heavy states

- For $m_R \geq 50$ TeV or so, we'll not be able to produce them this century
- But they leave a **footprint through quantum effects**





$$\mathscr{L}_5 = \frac{c_5}{\Lambda}\left(L^T C \tilde{H}\right)(\tilde{H}^T L)$$

$$c_5 = y_\nu^2$$
$$\Lambda = M_R$$

- **Violates an accidental SM symmetry: Lepton Number**

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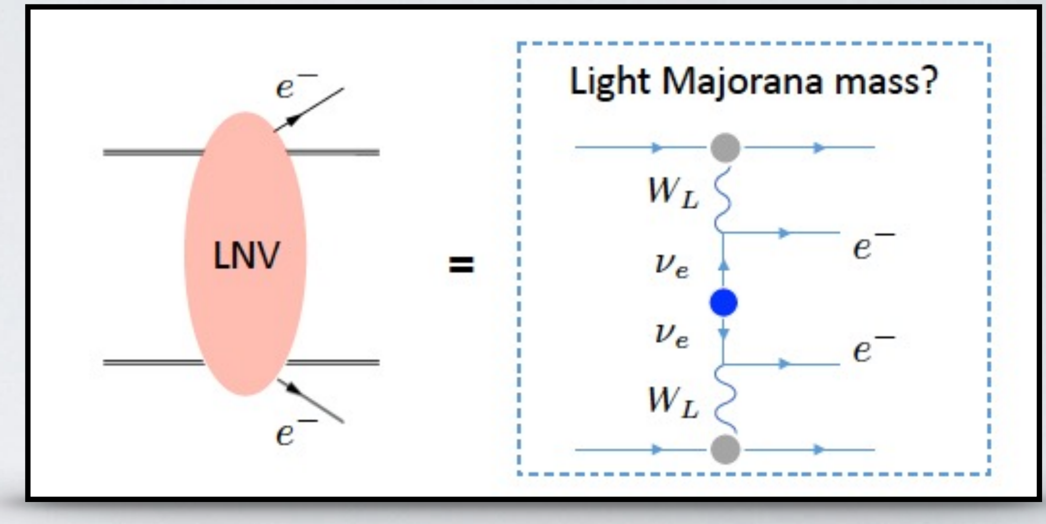
Low-energy probes of LNV

- 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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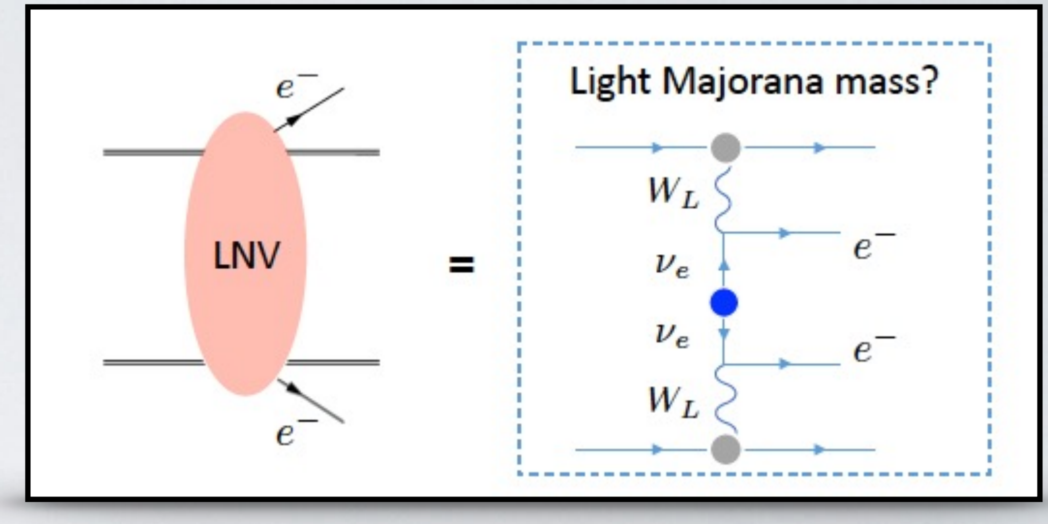

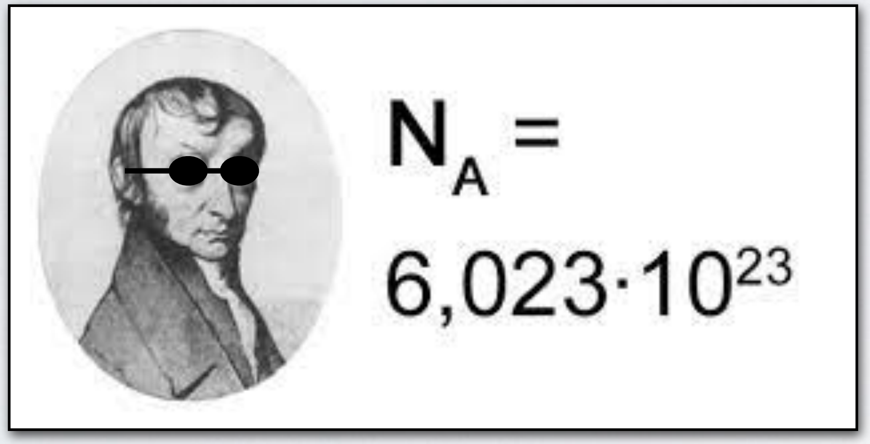

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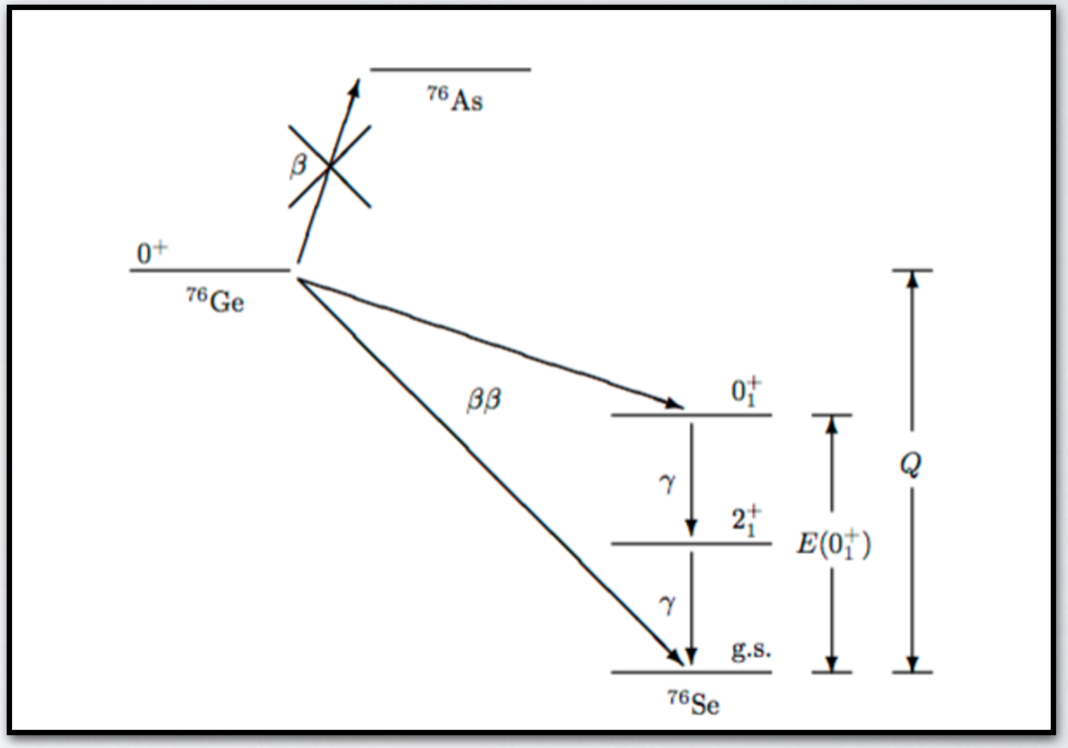
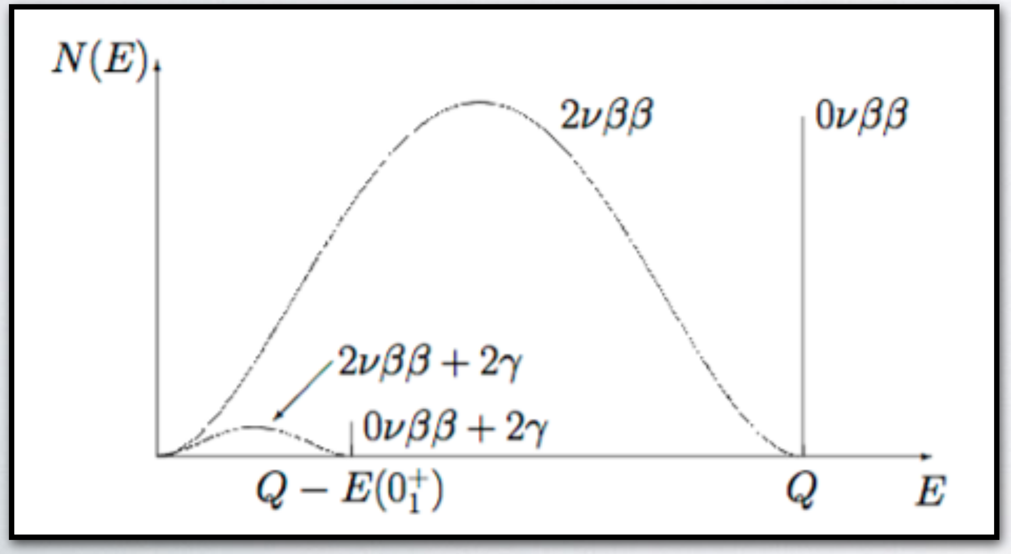
- Isotopes protected from single beta decay

- Neutrinofull double beta decay from Standard Model

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

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

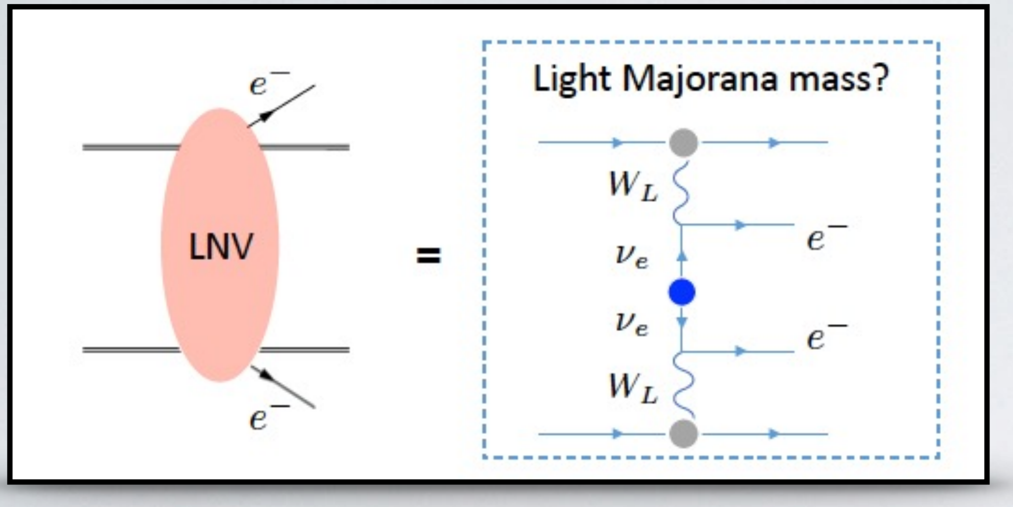




	Lifetime	Experiment	Year
76Ge	$8.0 \cdot 10^{25}\, y$	GERDA	2018
130Te	$3.2 \cdot 10^{25}\, y$	CUORE	2019
136Xe	$2.2 \cdot 10^{26}\, y$	KamLAND-Zen	2022

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

Interpreting 10^{26} years....



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

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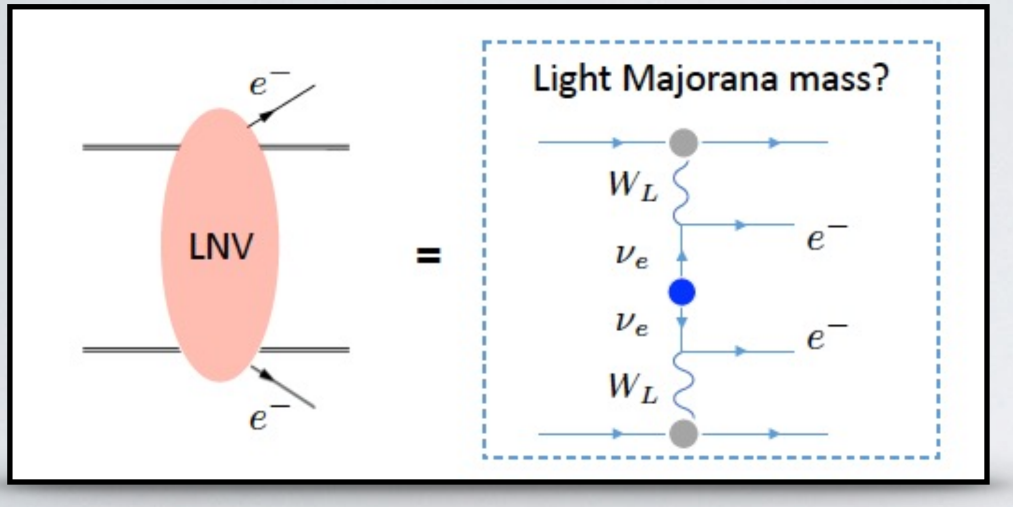

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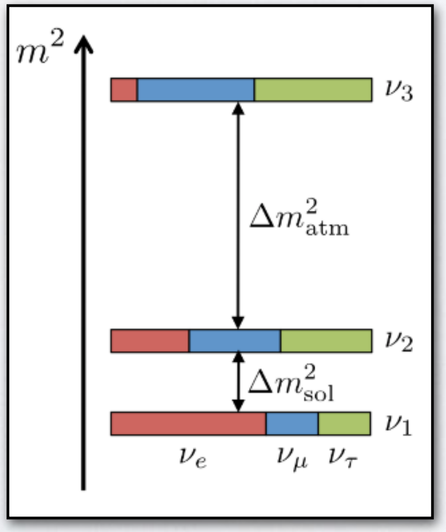
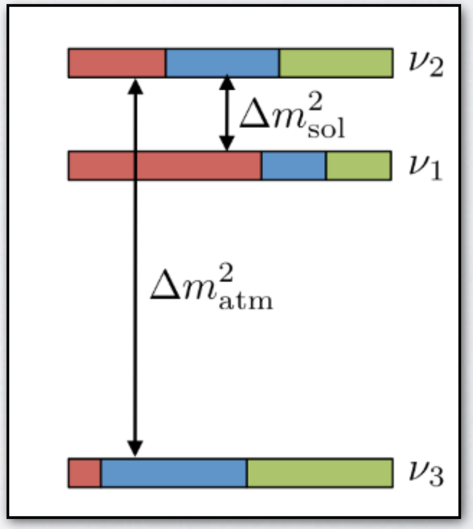
- c_{23} etc are neutrino mixing angles (**known** from oscillation experiments)
- Know the **mass splittings** but not the **absolute mass scale** nor **mass ordering**
- The **phases** are unknown (some hints for non-zero Dirac phase)

Normal Hierarchy (NH)



Inverted Hierarchy (NH)



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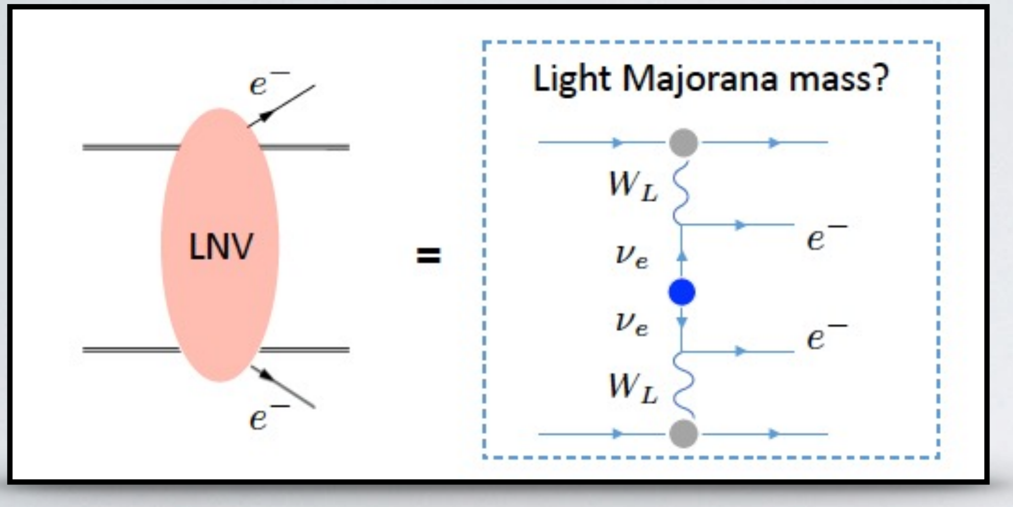

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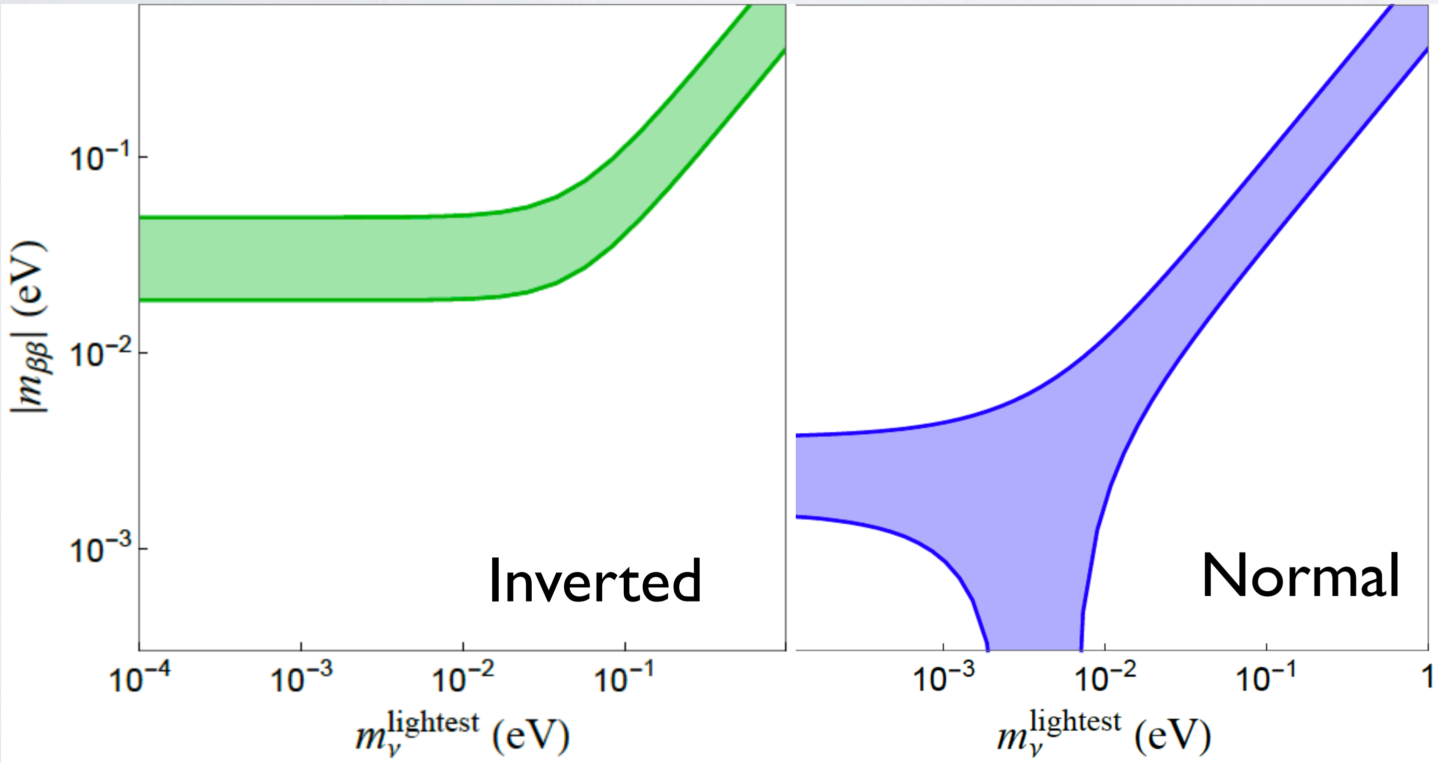

Vary the lightest mass and the ordering

Band from varying unknown phases

How close are experiments ?

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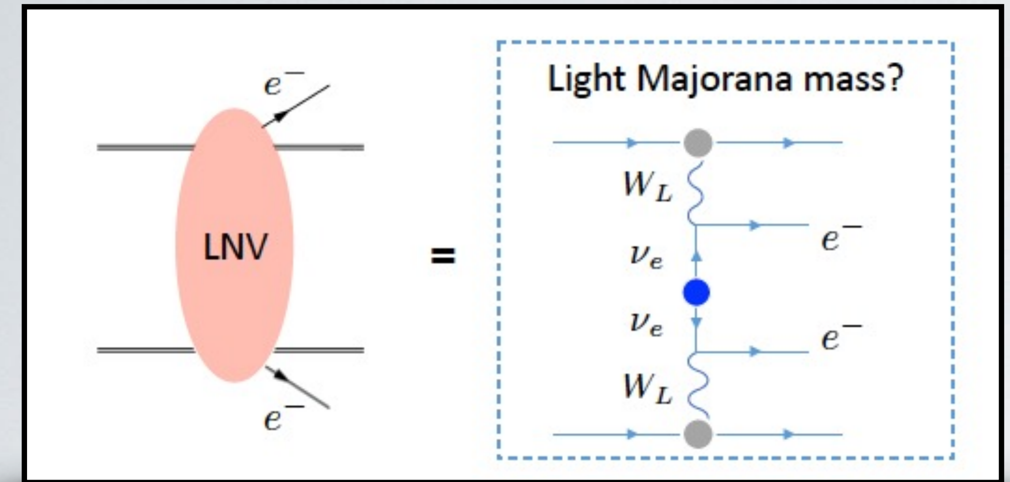

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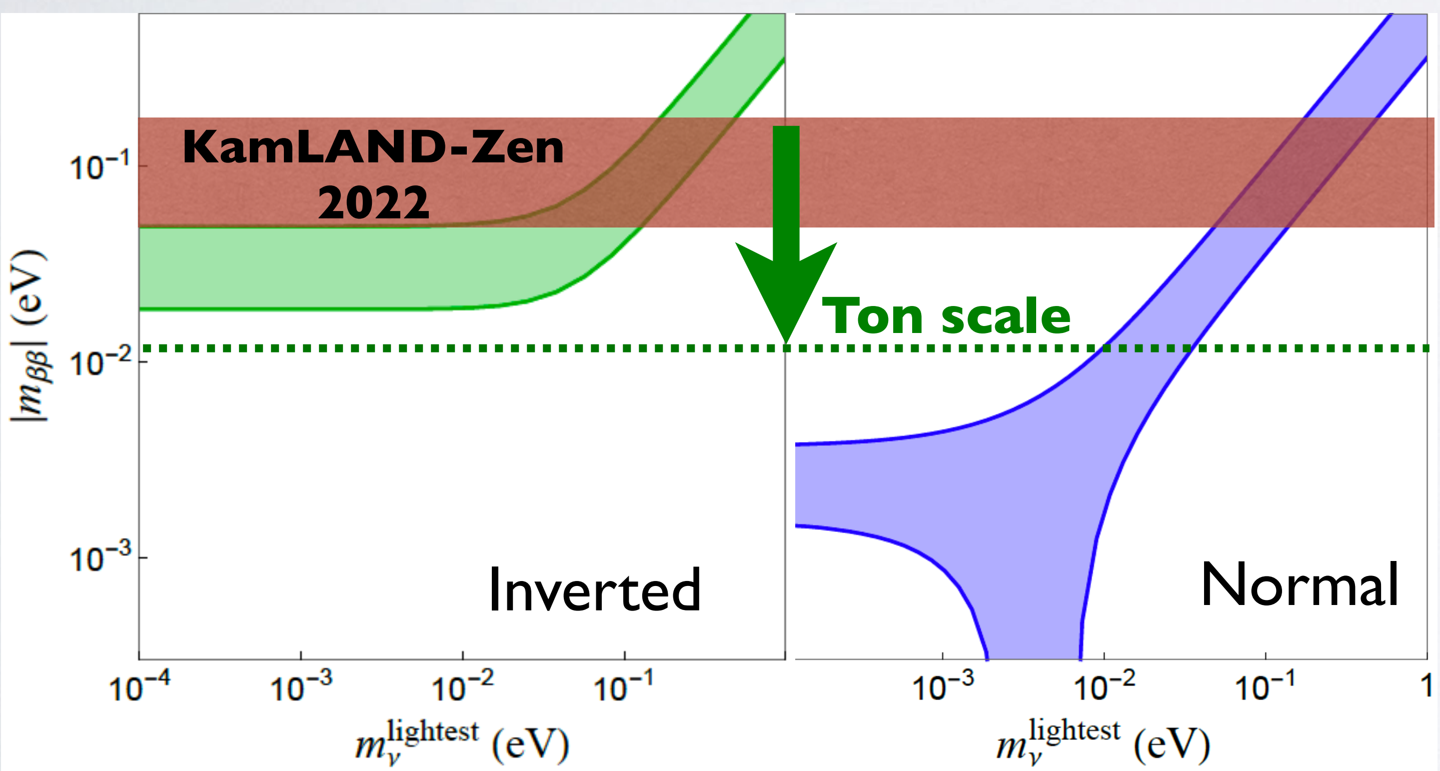


Very close !!

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

These experiments are probing energy scales up 10^{14} GeV

There is a clear **end-game** for this search ! But it will require ~ **10^{30}** years sensitivity

Anatomy of a decay

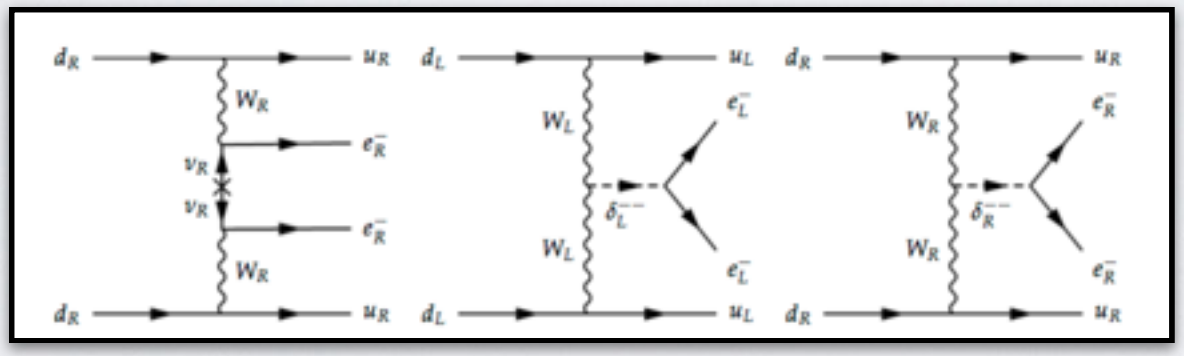
$$\Gamma^{0\nu} \sim m_{\beta\beta}^2 \cdot g_A^4 \cdot |M_{0\nu}|^2 \cdot G$$

Energy (↑)

?	$m_{\beta\beta}^2$	Lepton-number-violating source (*not necessarily neutrino mass*) ***(Particle Physics)***
GeV	g_A^4	From quarks to hadrons ***(Hadronic Physics)***
100 MeV	$\lvert M_{0\nu}\rvert^2 = \lvert\langle 0^+ \lvert V_\nu \rvert 0^+ \rangle\rvert^2$	Nuclear transition matrix element ***(Nuclear Physics… oh no)***
MeV	G	Phase space factor ***(Atomic Physics)***

Beyond neutrino masses

- Neutrinoless double beta decay can be caused through other mechanisms !
- For instance in *left-right symmetric models, supersymmetry, leptoquarks* ….



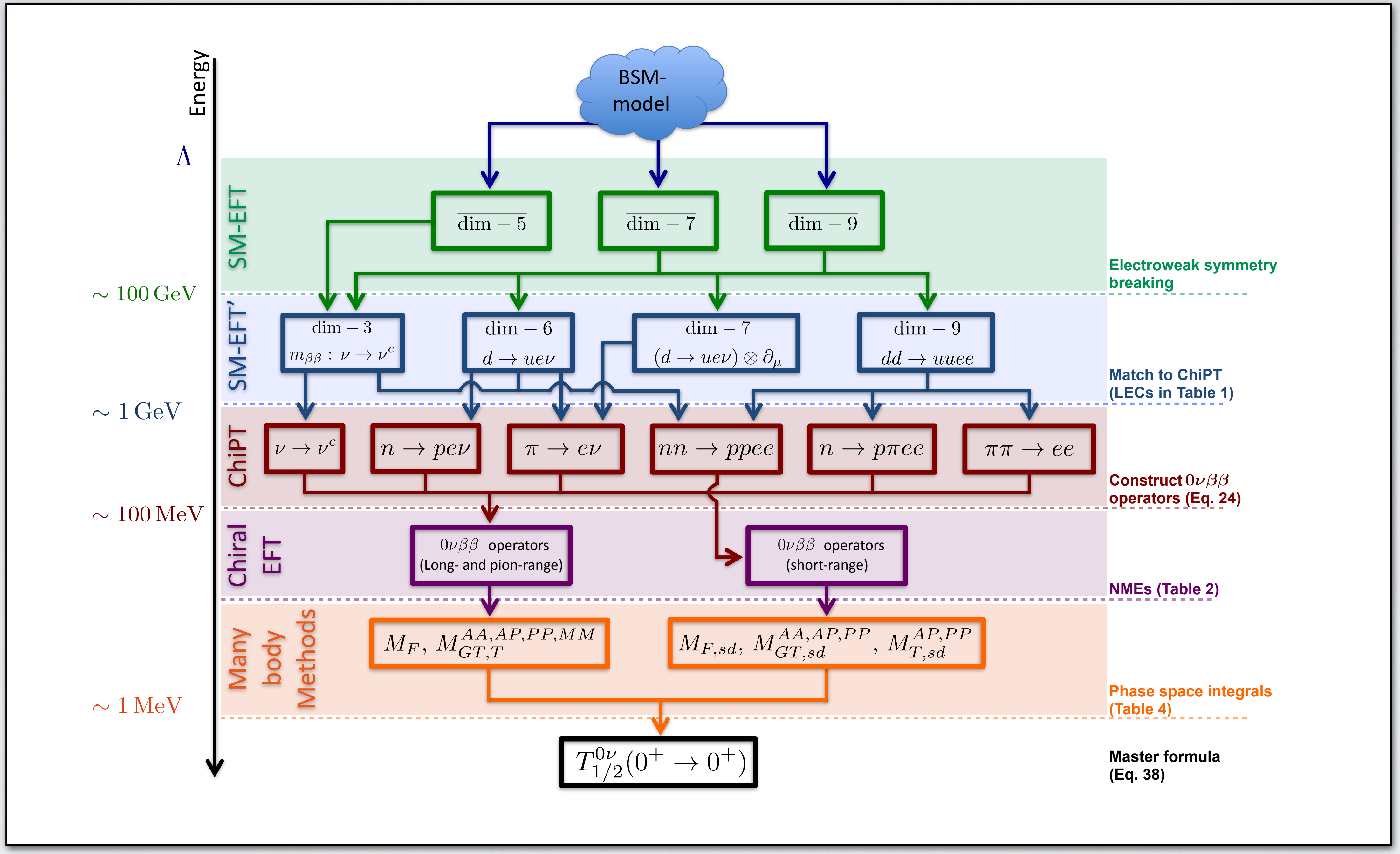
- No light neutrinos appear at all in these processes but **same observable signature**
- All these different processes can be captured by effective field theory techniques

$$\mathscr{L}_{LNV} = \frac{c_5}{\Lambda}\left(L^T C\tilde{H}\right)(\tilde{H}^T L) + \sum_i \frac{d_i}{\Lambda^3} O_{7i} + \sum_i \frac{f_i}{\Lambda^5} O_{9i} + \ldots$$

- Disentangling the origin from 0vbb measurements will be hard but a luxury problem

The 0vbb metro map

Cirigliano, Dekens, JdV, Graesser, Mereghetti'18

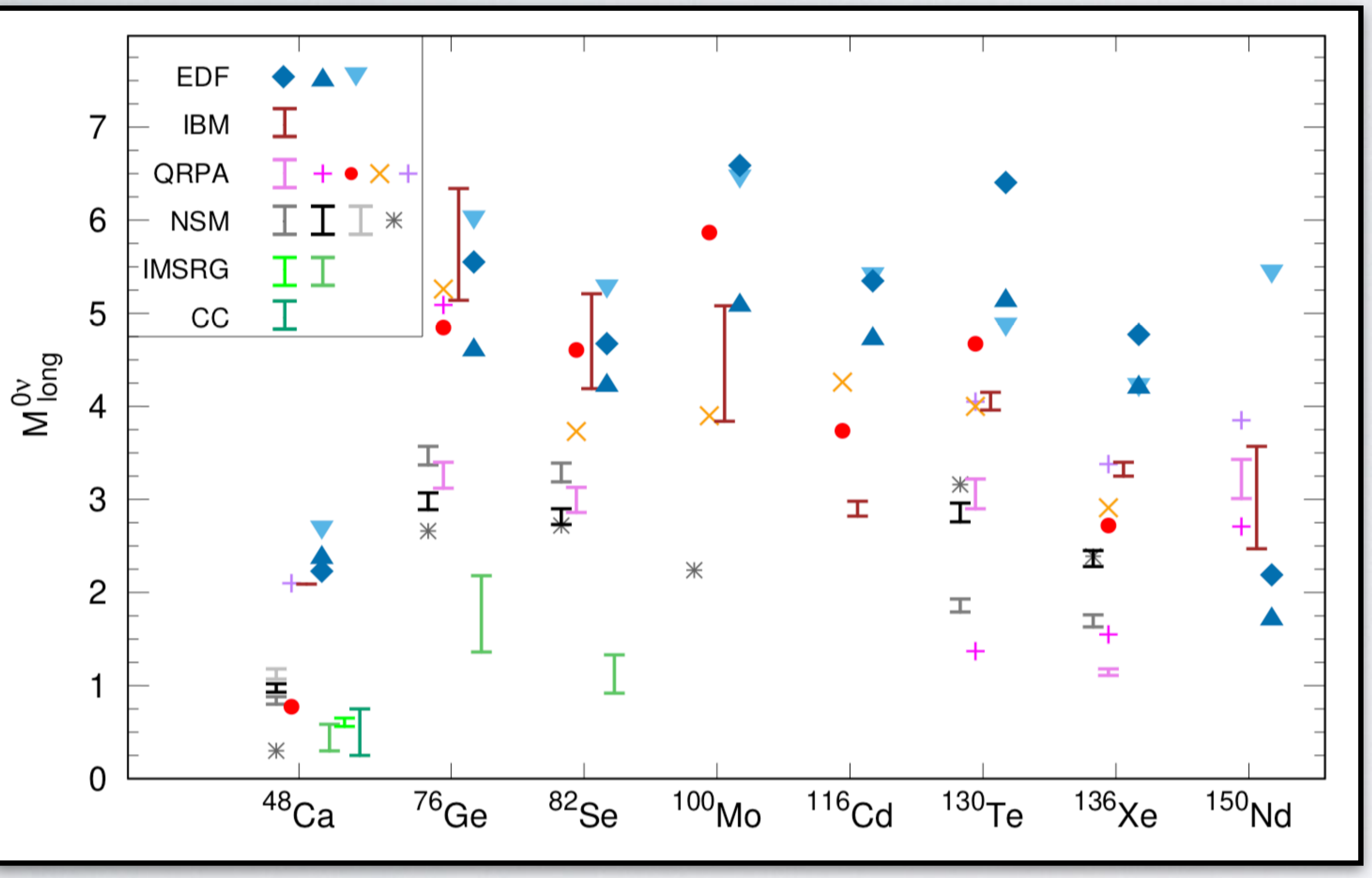


- Open-access Phyton tool (***NuDoBe***) that automizes all of this in SM-EFT framework

Scholer, Graf, JdV' 23

Predictions are hard, especially about the future

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 ?

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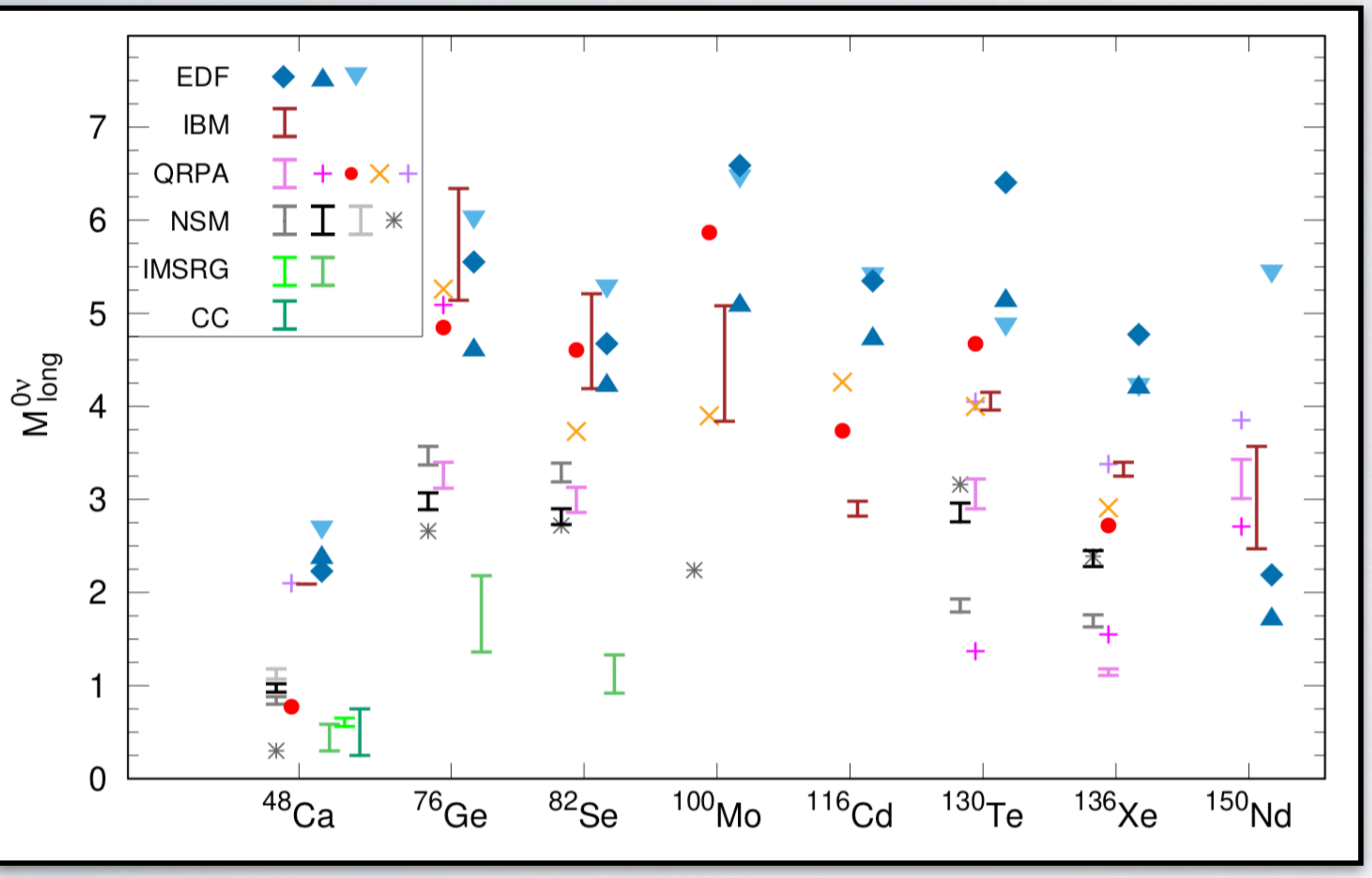

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Where is this coming from ?

- First of all: nuclear many-body physics is simply difficult
- Many approximations without a clear 'power counting'
- Nuclear methods and codes are benchmarked on 'single-nucleon-currents' physics
- **Recent developments: ab initio computations of 0vbb matrix elements**

How to get nuclear physics from QCD

- Nuclear physics historically data-driven model-building enterprise (*semi-emperical mass formula, nuclear shell model, Nijmegen potential,* ……)
- Successful description but hard to learn general lessons and make predictions for something new (such as neutrinoless double-beta decay)
- Nuclear physics = stamp collecting ?

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- In my mind, this changed in the 90's when Weinberg wrote 2 extremely 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

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

- This is now a mature and sizable field where people describe large nuclei from ChPT.

Chiral EFT in a nut-shell

$$\mathscr{L}_{QCD} = \bar{q}_L i\gamma^\mu D_\mu q_L + \bar{q}_R i\gamma^\mu D_\mu q_R + \text{masses} \qquad q = \begin{pmatrix} u \\ d \end{pmatrix}$$

- Neglect light-quark masses: QCD has a global $SU_L(2)\times SU_R(2)$ symmetry
- Spontaneously broken to $SU_{isospin}(2)$ in the ground-state -> **3 Goldstone bosons** (pions)
- Pions are not exactly massless due to quark masses (**Pseudo-Goldstone bosons**)

$$m_\pi^2 \sim (m_u + m_d)$$

Chiral EFT in a nut-shell

$$\mathscr{L}_{QCD} = \bar{q}_L i\gamma^\mu D_\mu q_L + \bar{q}_R i\gamma^\mu D_\mu q_R + \text{masses} \qquad q = \begin{pmatrix} u \\ d \end{pmatrix}$$

- Neglect light-quark masses: QCD has a global $SU_L(2)\times SU_R(2)$ symmetry
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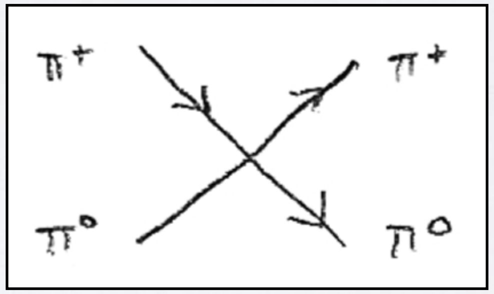
- Pions are not exactly massless due to quark masses (**Pseudo-Goldstone bosons**)

$$m_\pi^2 \sim (m_u + m_d)$$

- Chiral perturbation theory is **perturbative at low energies** due to Goldstone nature

$$\mathscr{L} = (\partial_\mu \pi)^2 + \frac{1}{f_\pi^2}(\pi\partial\pi)^2 + \ldots$$



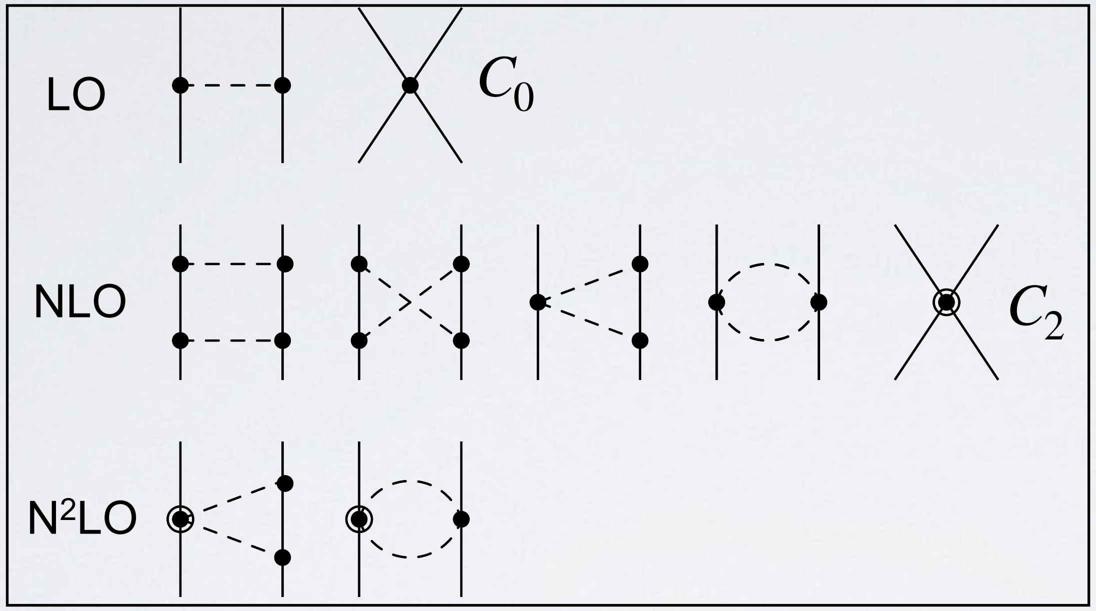
$$\sim (p \cdot p')$$

- Expansion parameter of chPT $\frac{p}{\Lambda_\chi}$ where $\Lambda_\chi \sim 1\,\text{GeV}$
- At higher-orders in the expansion more interactions appear $\mathscr{L} = L_4\,(\partial\pi)^4 \qquad L_4 \sim \frac{1}{f_\pi^2 \Lambda_\chi^2}$
- The coupling constants are **not predicted: fit to data or lattice QCD**

Towards nuclear physics

- Chiral perturbation theory can be extended to include nucleons
- Derive **nuclear potential** from the chiral Lagrangian

$$V_{NN} =$$



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

- Fit the coupling constants $C_{0,2}$ etc to **nucleon-nucleon data** --> predict the rest
- This describes an effective quantum field theory approach to nuclear physics

Towards nuclear physics

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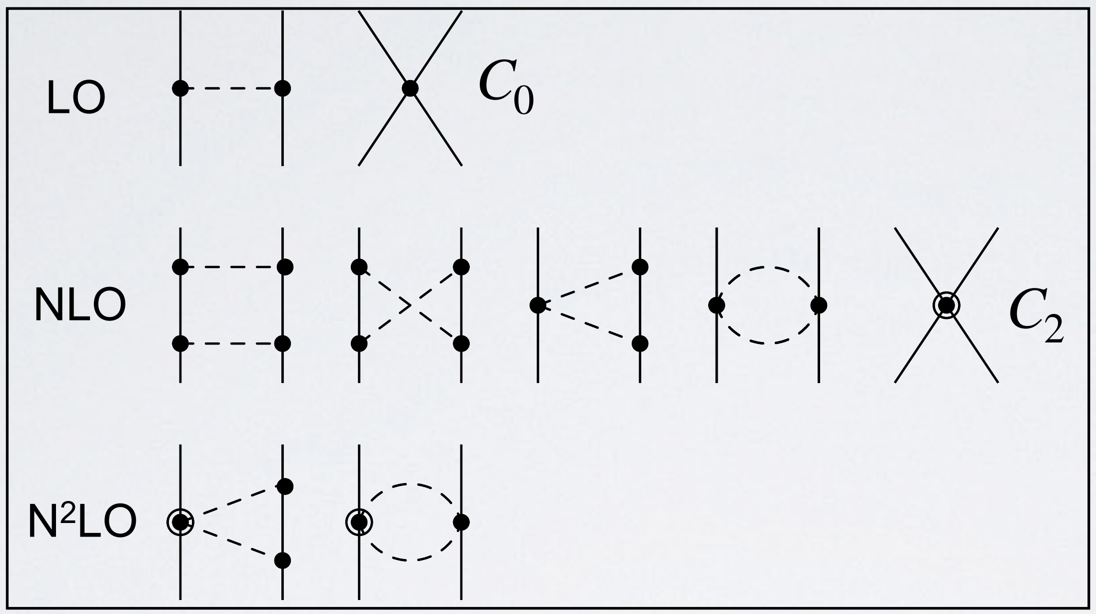

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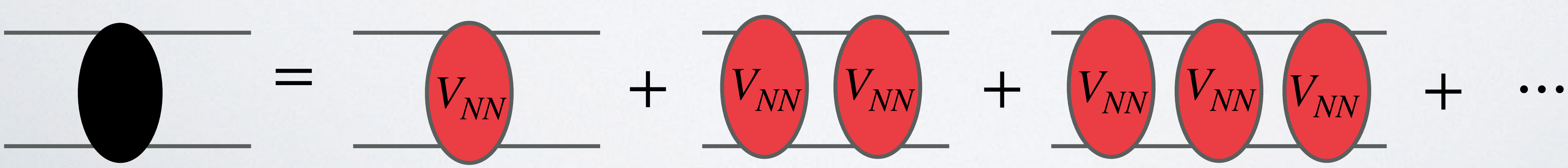
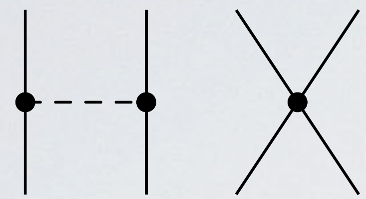
And many more…

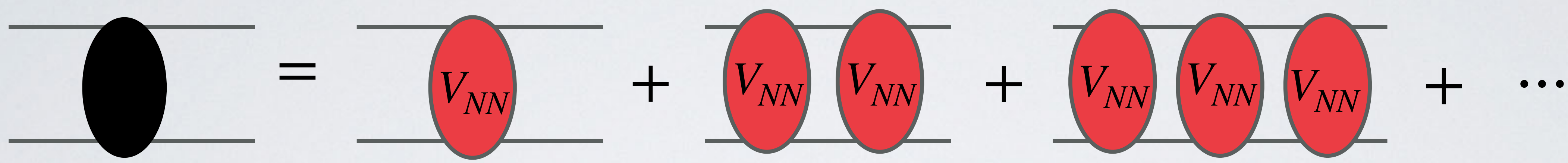
- Fit the coupling constants $C_{0,2}$ etc to **nucleon-nucleon data** --> predict the rest
- This describes an effective quantum field theory approach to nuclear physics
- Now nuclear forces are **not perturbative !** They lead to **bound states** !
- This is achieved by 'resumming' the potential (solving a Schrodinger equation)



Example at leading order

LO 

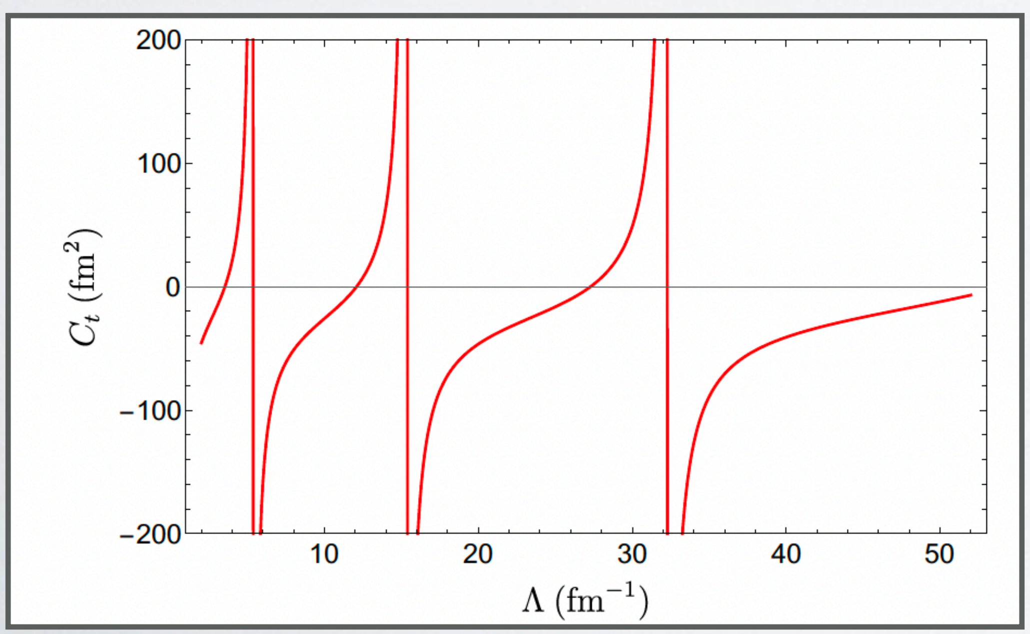
$$V_{\rm NN} = C_0 - \frac{g_A^2}{4f_\pi^2}\frac{m_\pi^2}{\mathbf{q}^2 + m_\pi^2}$$

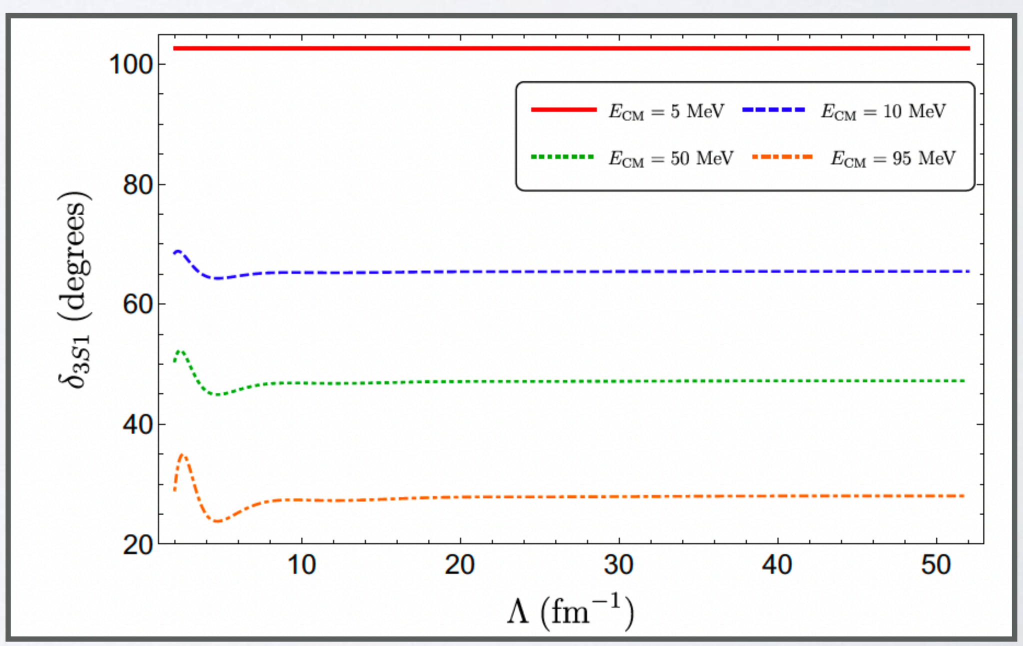


- Loops appearing here typically diverge and one has to **regulate**

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

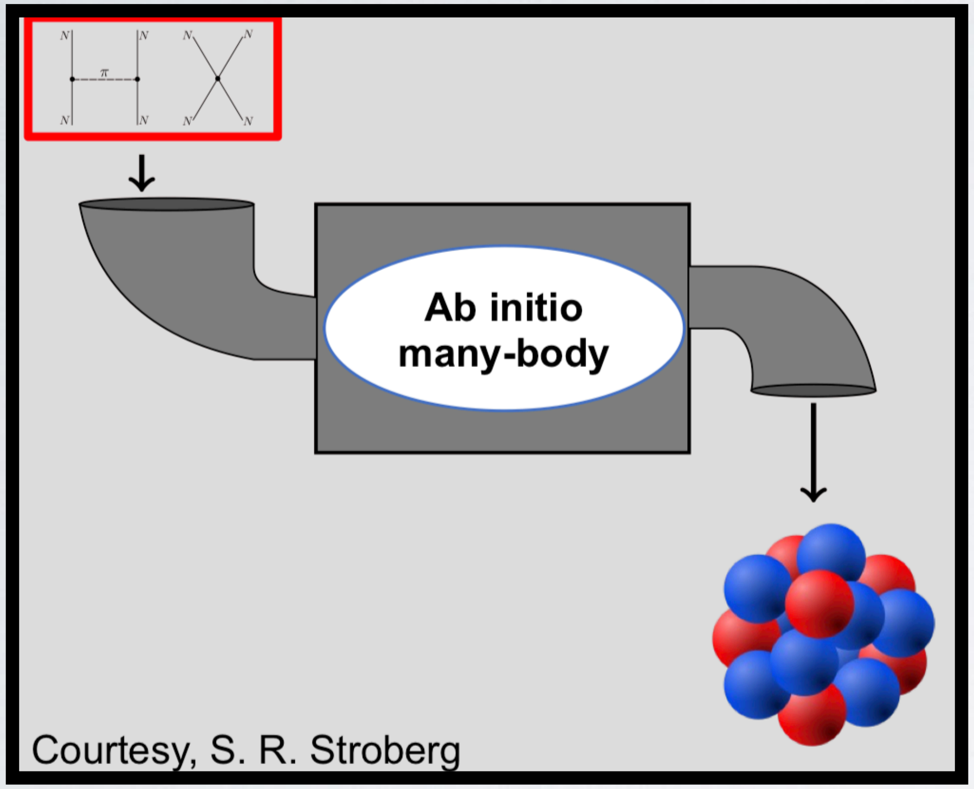
- Fit counter term C_0 to nucleon-nucleon scattering data for each Λ
- This is called 'non-perturbative renormalization' similar in spirit to what we do in any QFT





State of the art

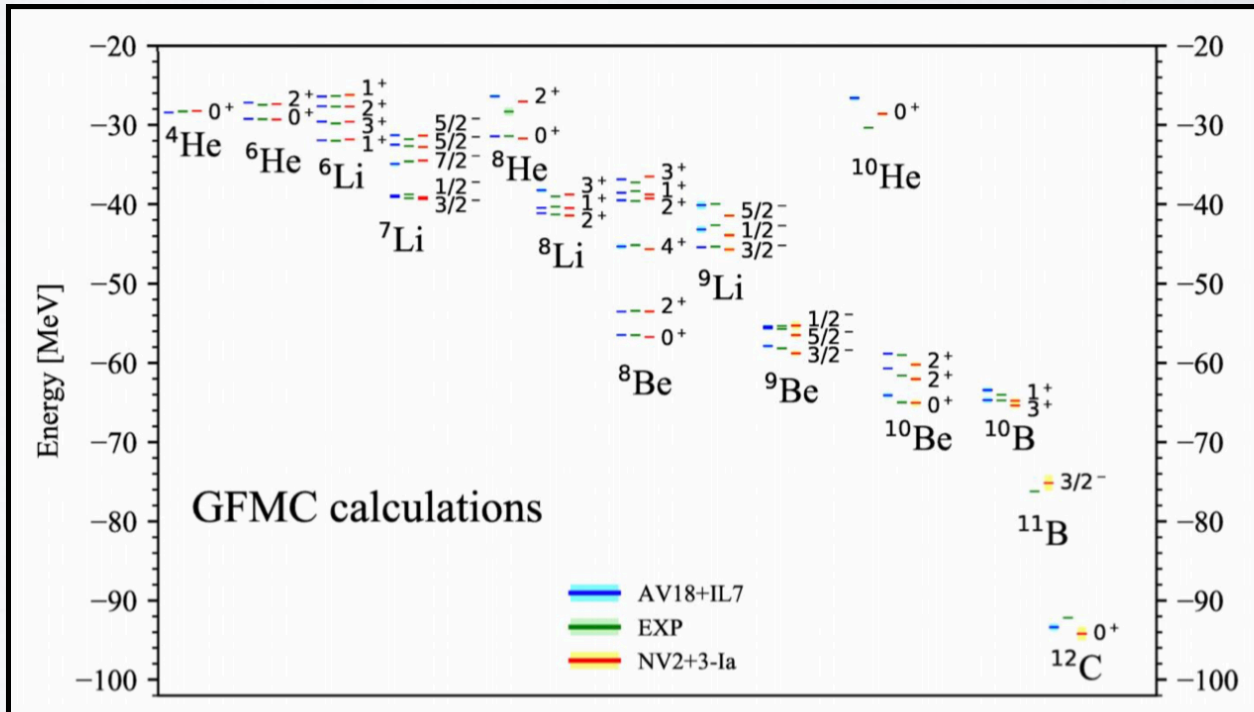
- Starting from chiral EFT —> derive nuclear properties + reactions



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

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

Gysbers et al '20



Piarulli et al. PRL 120, 052503 (2018)

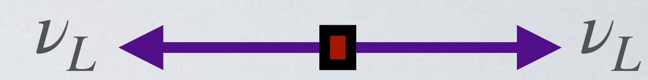
Ab Initio Calculation of the Hoyle State

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

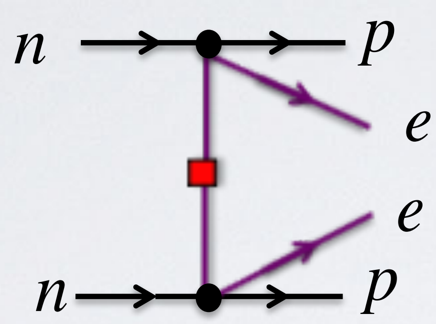
Physics See Viewpoint: The carbon challenge

Chiral EFT for 0vbb

- Neutrinos are still degrees of freedom in low-energy chiral EFT



- Compute neutrinoless double-beta decay processes in chiral expansion



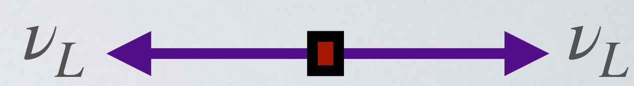
$$V_\nu \sim \frac{m_{\beta\beta}}{\mathbf{q}^2} \qquad \mathbf{q} \sim k_F \sim m_\pi$$

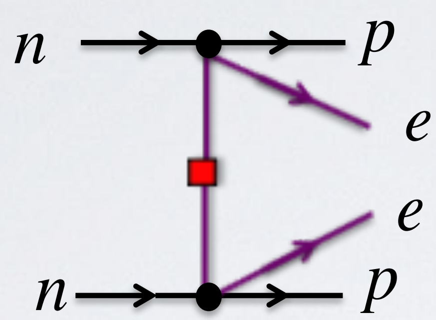
$$V_\nu = (2G_F^2 m_{\beta\beta})\tau_1^+\tau_2^+ \frac{1}{\mathbf{q}^2}\left[(1+2g_A^2) + \frac{g_A^2 m_\pi^4}{(\mathbf{q}^2+m_\pi^2)}\right] \otimes \bar{e}_L e_L^c$$

- Note: the nucleons appear in a bound state and **q** is a loop momentum

Chiral EFT for 0vbb

- Neutrinos are still degrees of freedom in low-energy chiral EFT
- Compute neutrinoless double-beta decay processes in chiral expansion





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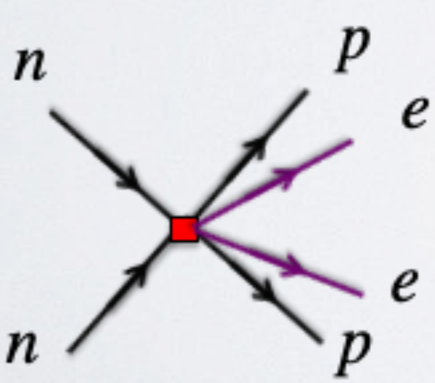
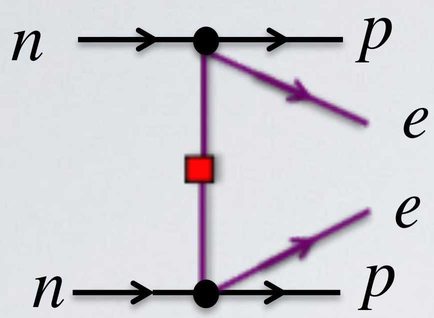


- Contributions from virtual hard neutrinos $\quad \mathbf{q} \sim \Lambda_\chi \sim 1\,\mathrm{GeV}$
- Weinberg power counting then puts this at higher order

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

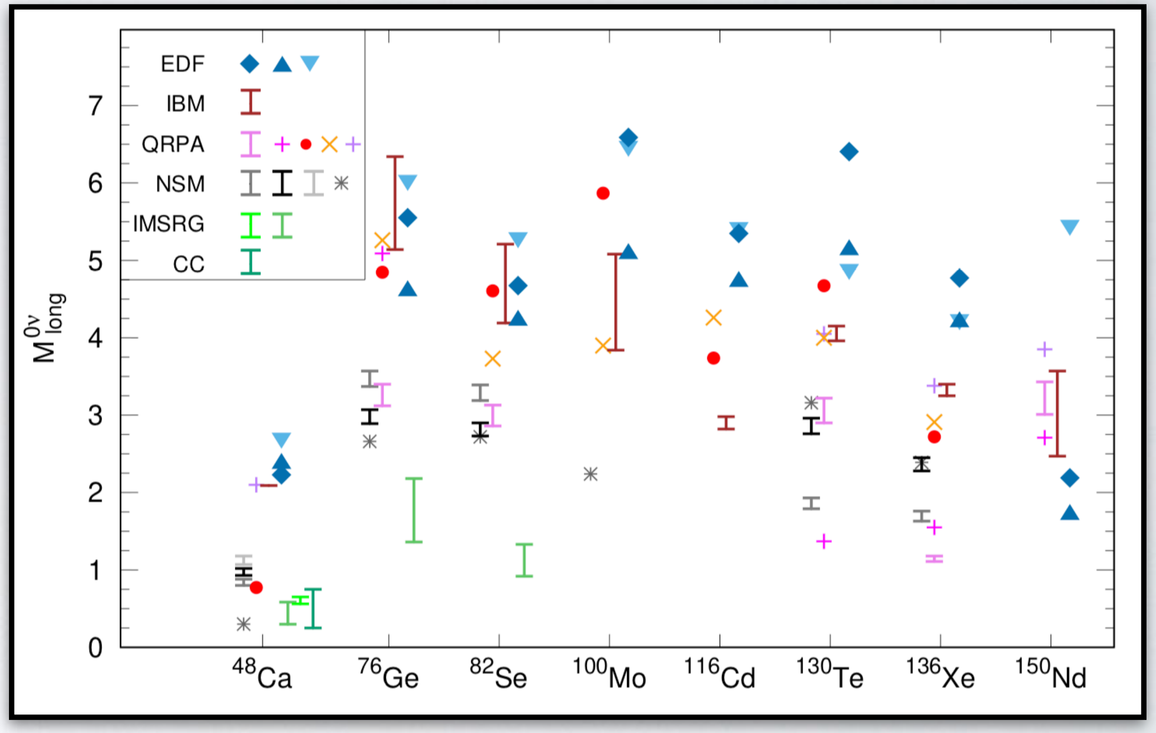
- Also loop diagrams etc at higher order (not today)

The leading order process



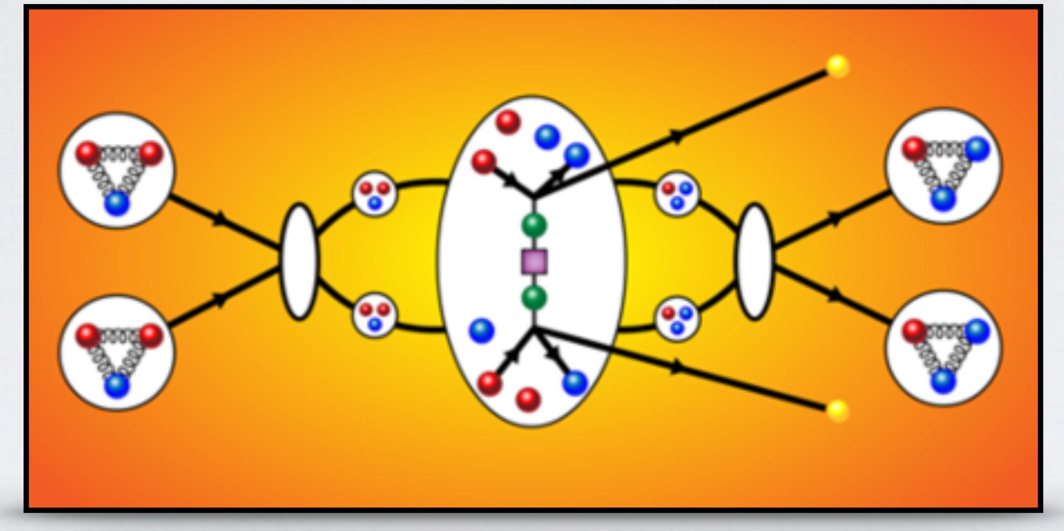
$$V_\nu = (2G_F^2 m_{\beta\beta})\tau_1^+\tau_2^+ \frac{1}{\mathbf{q}^2}\left[(1+2g_A^2) + \frac{g_A^2 m_\pi^4}{(\mathbf{q}^2+m_\pi^2)}\right] \otimes \bar{e}_L e_L^c$$

- Leading-order 0vbb current is very simple
- No unknown hadronic input ! Only unknown $m_{\beta\beta}$
- Many-body methods disagree significantly
- Idea: see what happens for lighter systems
- **Not relevant for experiments but as a theoretical laboratory**



Neutron-Neutron → Proton-Proton

- Study simplest nuclear process: nn → pp + ee

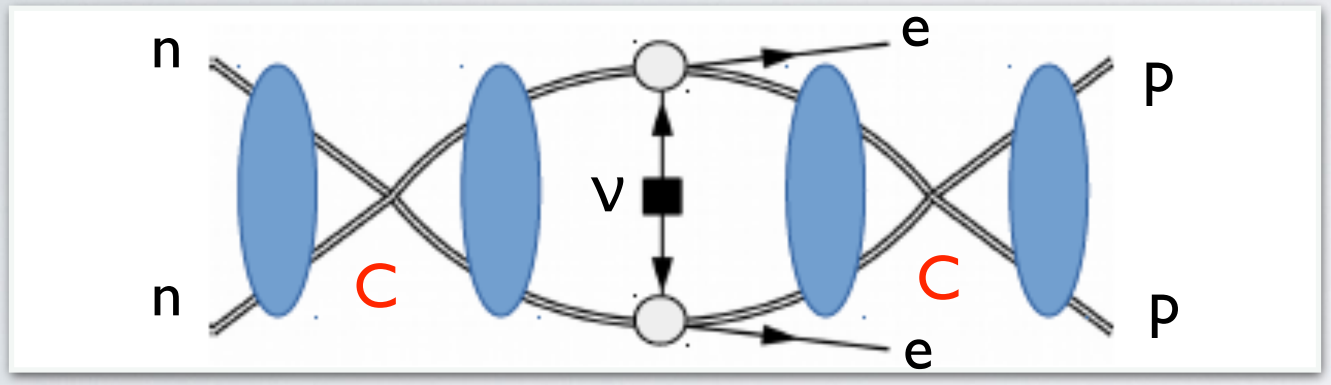


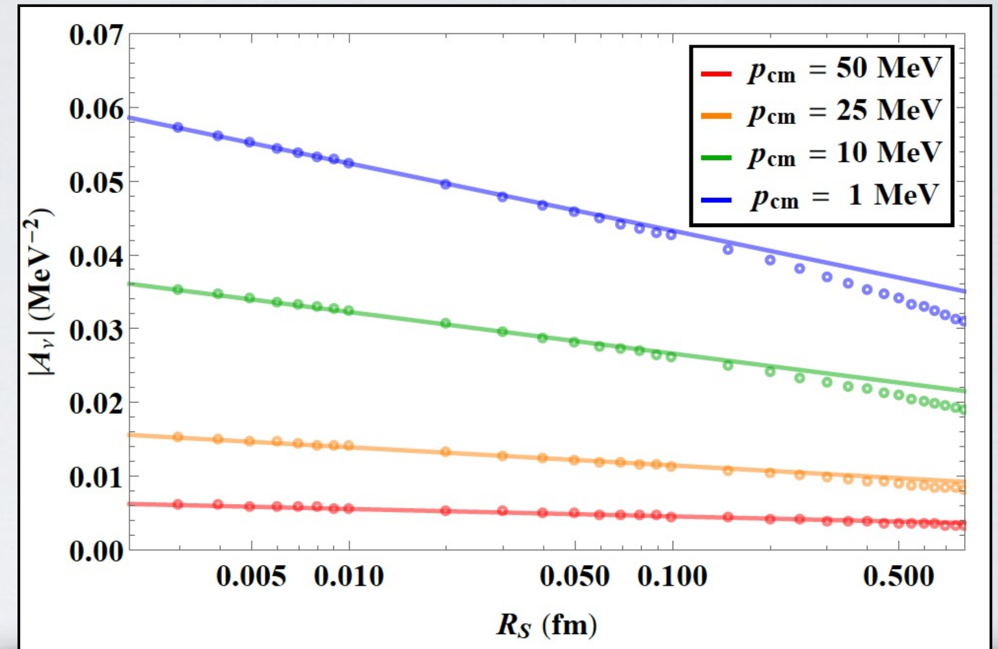
- Compute everything consistently from chiral EFT: wave function + currents

- Then insert the 0vbb potential in renormalized wave function —> **should be finite**

$$V_\nu \sim \frac{m_{\beta\beta}}{\mathbf{q}^2} \qquad A_\nu = \langle \Psi_{pp} | V_\nu | \Psi_{nn} \rangle$$

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 !

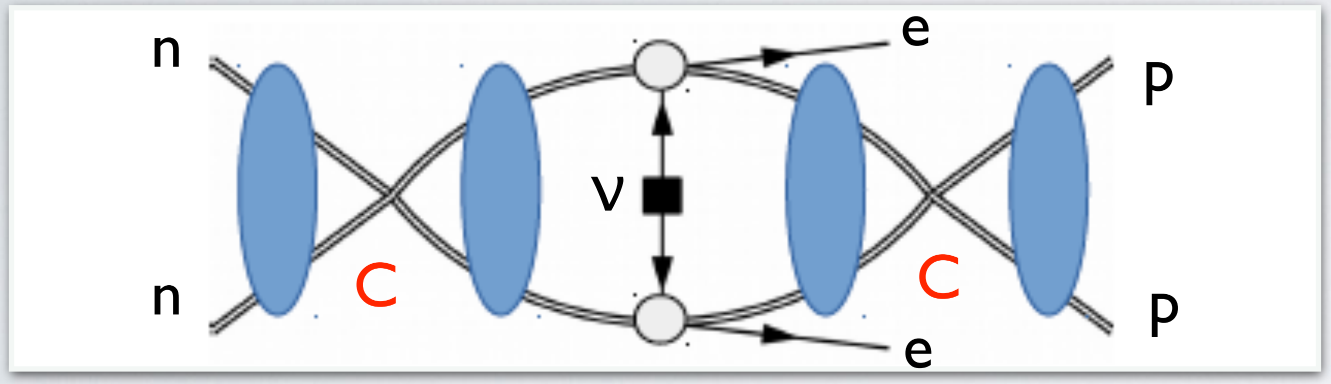
Featured in Physics | Editors' Suggestion | Open Access

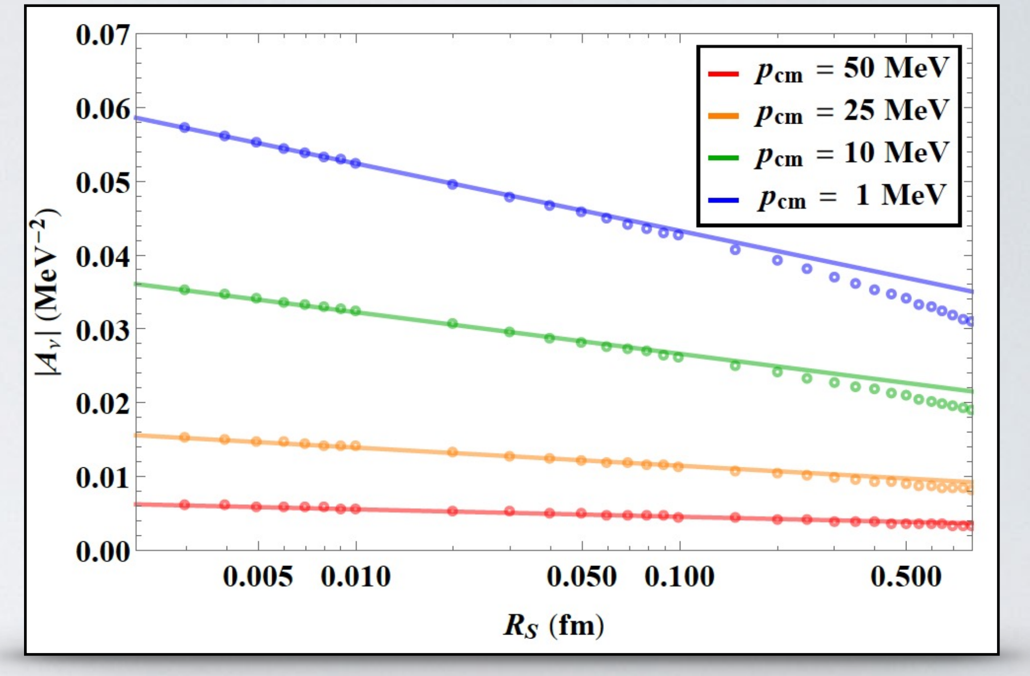
New Leading Contribution to Neutrinoless Double-β Decay

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

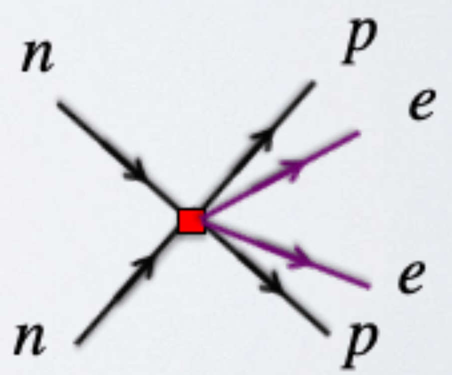




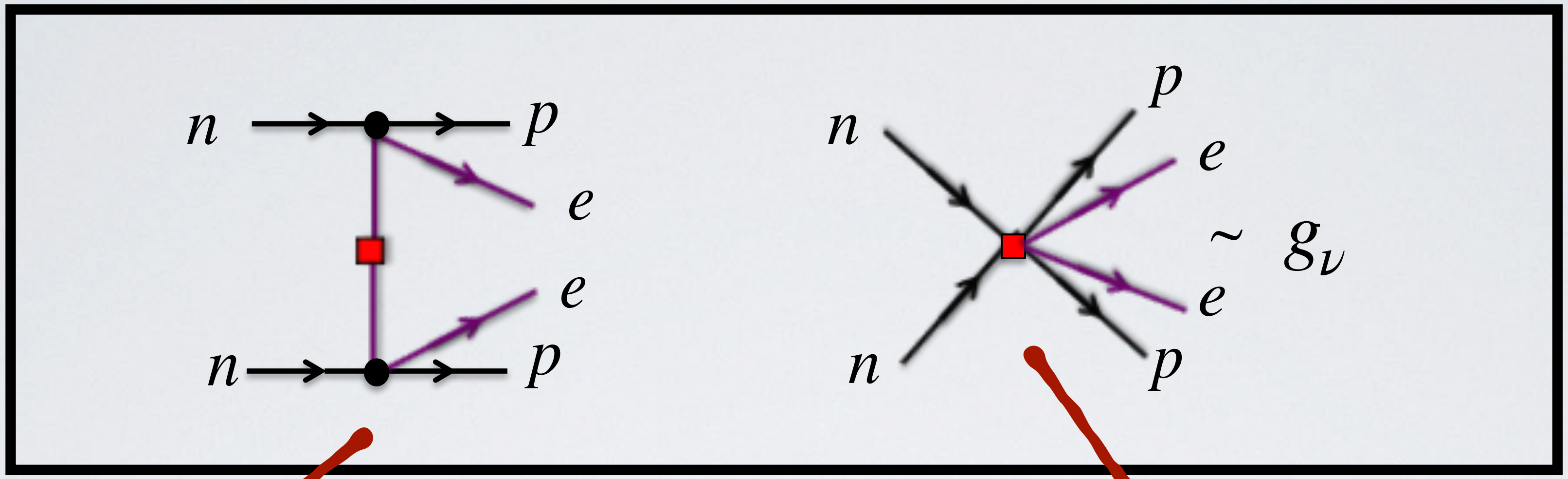
$$\sim (1 + 2g_A^2)\left(\frac{m_N C_0}{4\pi}\right)^2 \left(\frac{1}{\epsilon} + \log\frac{\mu^2}{p^2}\right)$$

New divergences

- Divergence indicates sensitivity to short-distance physics
- **Requires a leading order counter term**
- In the literature this is callled '*breakdown of Weinberg power counting*'



A new leading-order contribution



'Long-range' neutrino-exchange

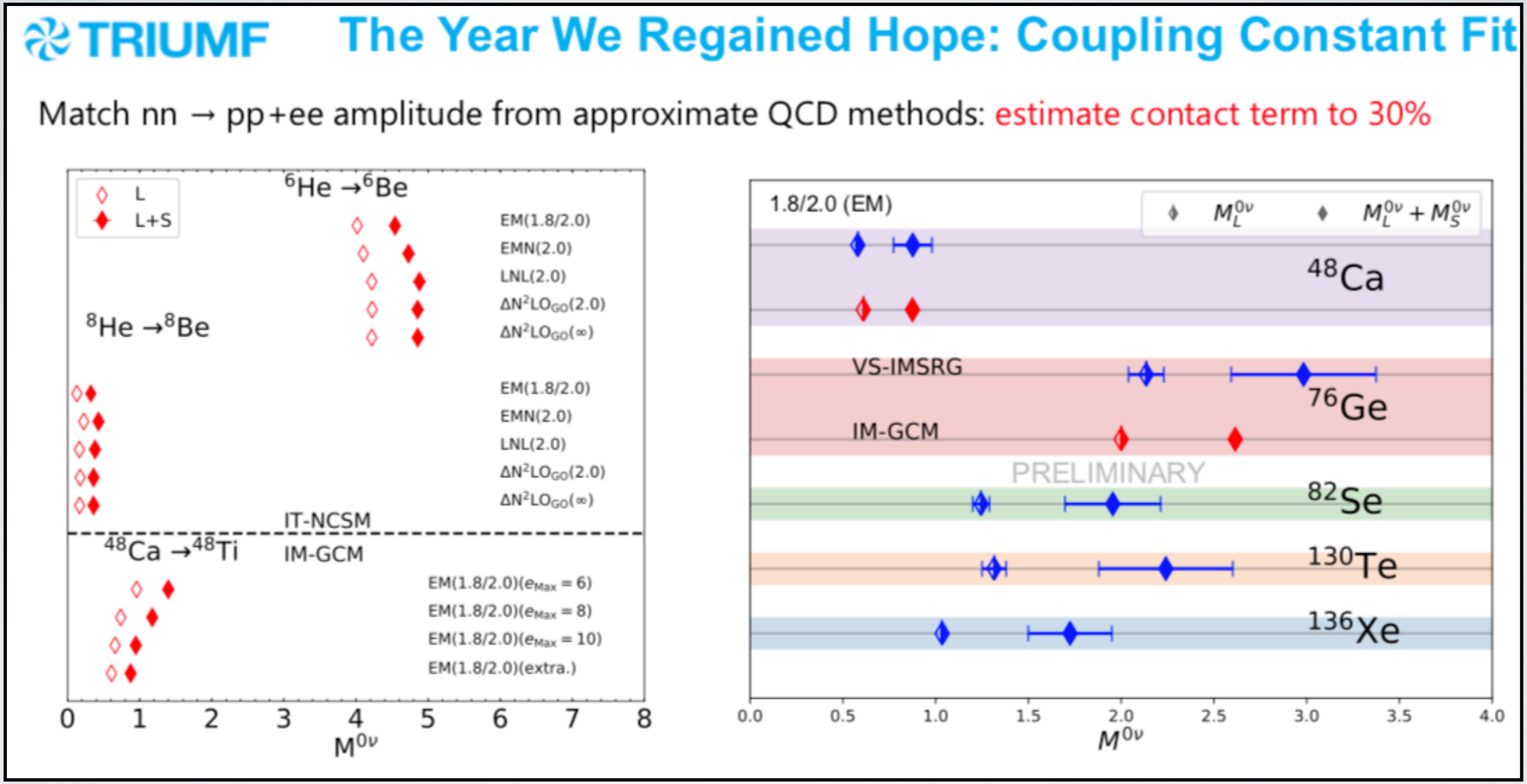
'Short-distance' neutrino exchange required by renormalization of amplitude

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

Cirigliano, Dekens, JdV, Hoferichter, Mereghetti PRC '19 PRL '21 JHEP '21 Richardson, Schindler, Pastore, Springer '21
Davoudi, Kadam PRL '21 Briceno et al '19 '20 Tuo et al. '19; Detmold, Murphy '20 '22

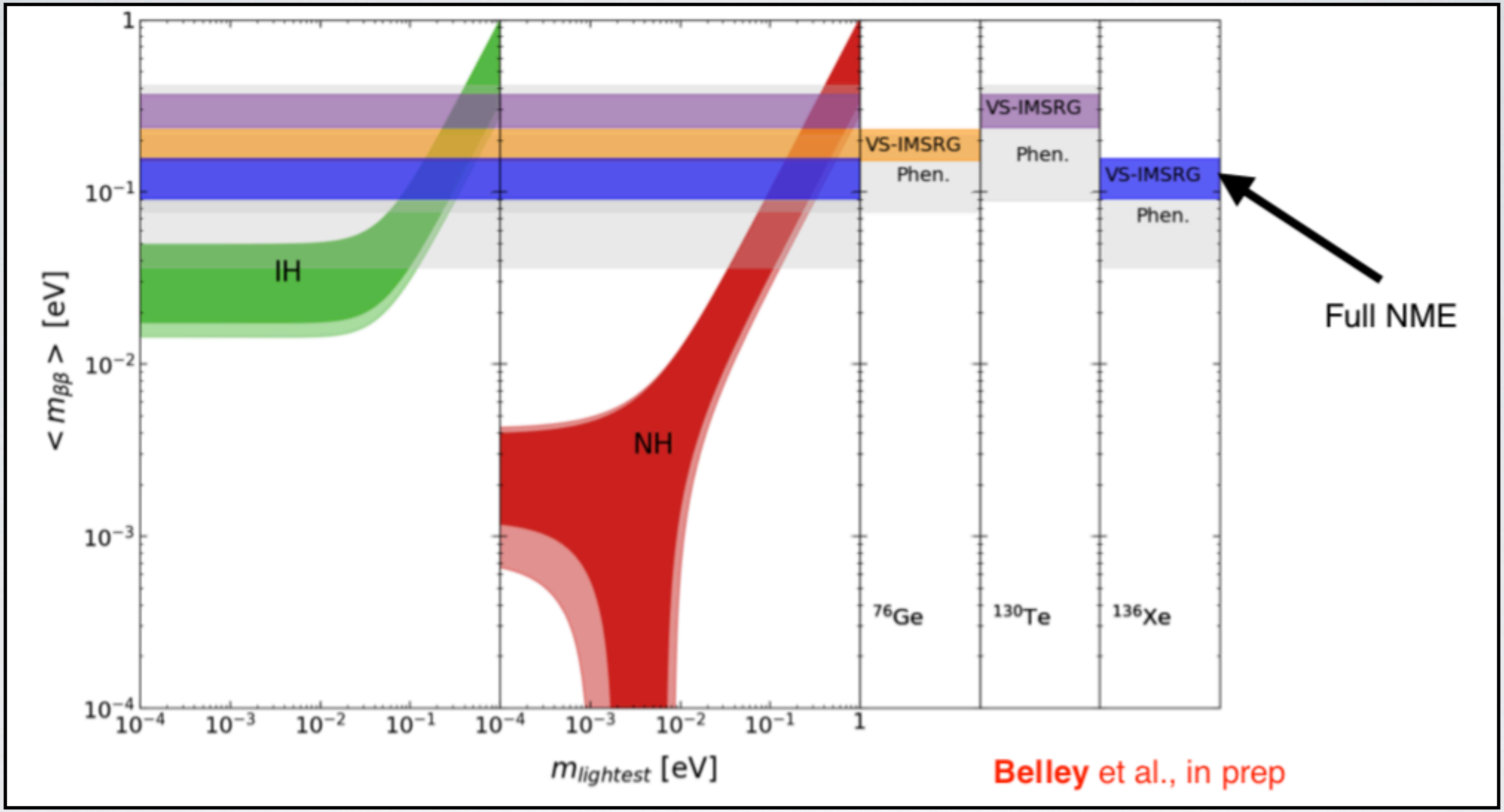
- 0vbb calculations have to be redone —> Took some convincing but is now happening !

Impact on realistic nuclei



- Slides from **Jason Holt** (TRIUMF) at Institute of Nuclear Physics Seattle (few weeks ago)
- The contact term enhances NMEs by 100% (Ca) to 70% (Xe) (factor 3-4 on the lifetime)
- Inclusion of contact term brings different computations **closer** together !

Impact on realistic nuclei



- Slides from **Jason Holt** (TRIUMF) at Institute of Nuclear Physics Seattle (few weeks ago)
- Ab initio (including short-distance) gives now the most accurate predictions
- **Still a lot to be done but there is now real path towards reliable predictions !**

Obese neutrinos

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

- For $m_R \geq 50$ TeV or so, we'll **not be able to produce them this century**

- **But good chance to see their quantum effects if they exist !!**

Feather-weight neutrinos

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

- For masses below a GeV, the 0vbb matrix elements become mass dependent

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

Feather-weight neutrinos

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

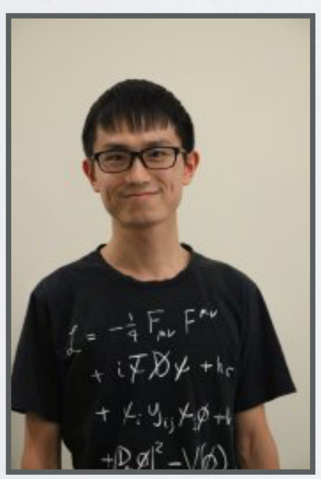
eV **keV** **MeV** **GeV** **TeV** **.....** **10^{15} GeV** **M_R ?**

What about here ?

- For masses below a GeV, the 0vbb matrix elements become mass dependent

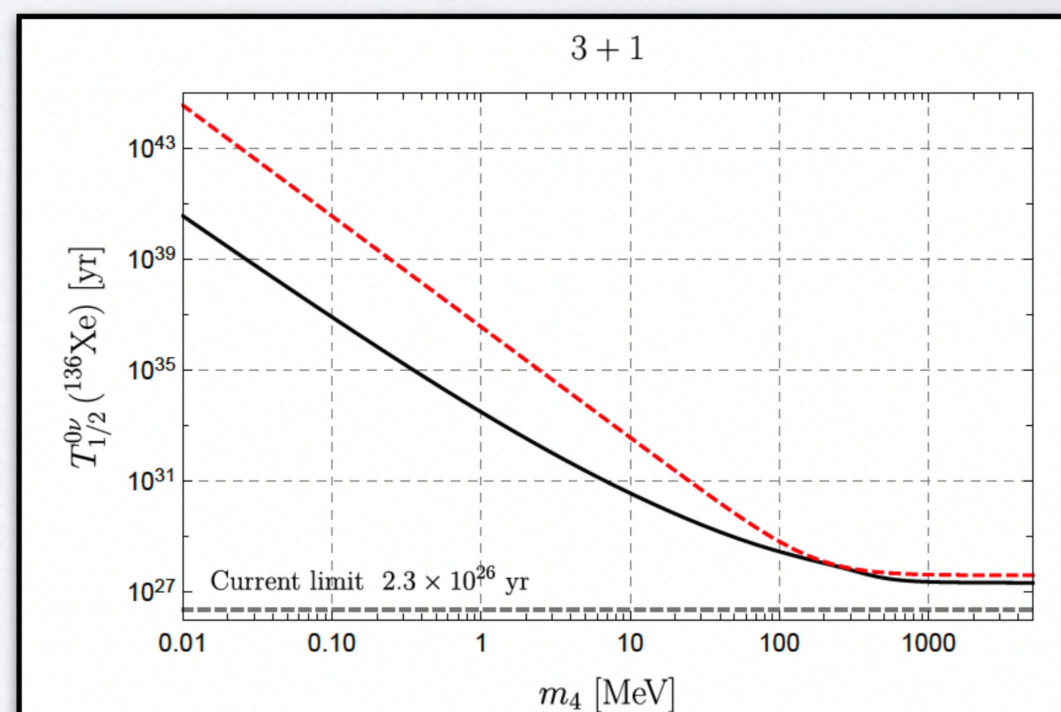
$$|M_{0\nu}(m_R)|^2 = |\langle 0^+|V_\nu(m_R)|0^+\rangle|^2$$

- Using EFT methods we find again large new contributions missed in earlier work



Guanghui Zhou

Vaisakh Plakkot



The plan of attack

1. Motivations: neutrino masses/antimatter/EFTs

2. Lepton number violation and neutrinoless double beta decay

   - *Exciting lecture on the recent history of nuclear physics*

3. **Producing sterile neutrinos in the laboratory**

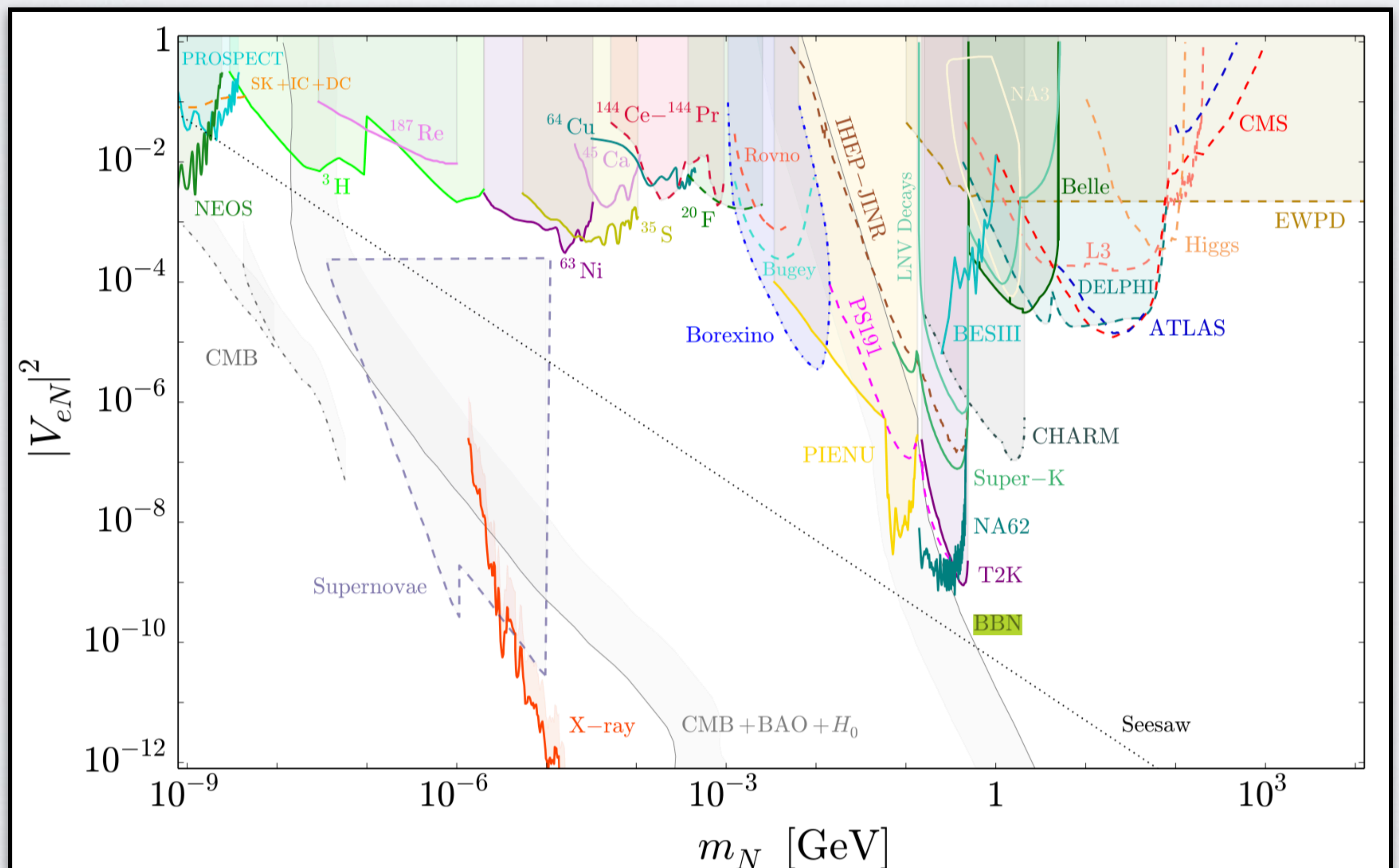
Feather-weight neutrinos

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

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

What about here ?

- We can now try to produce sterile neutrinos **directly** !



Bolton, Deppisch, Dev JHEP '20

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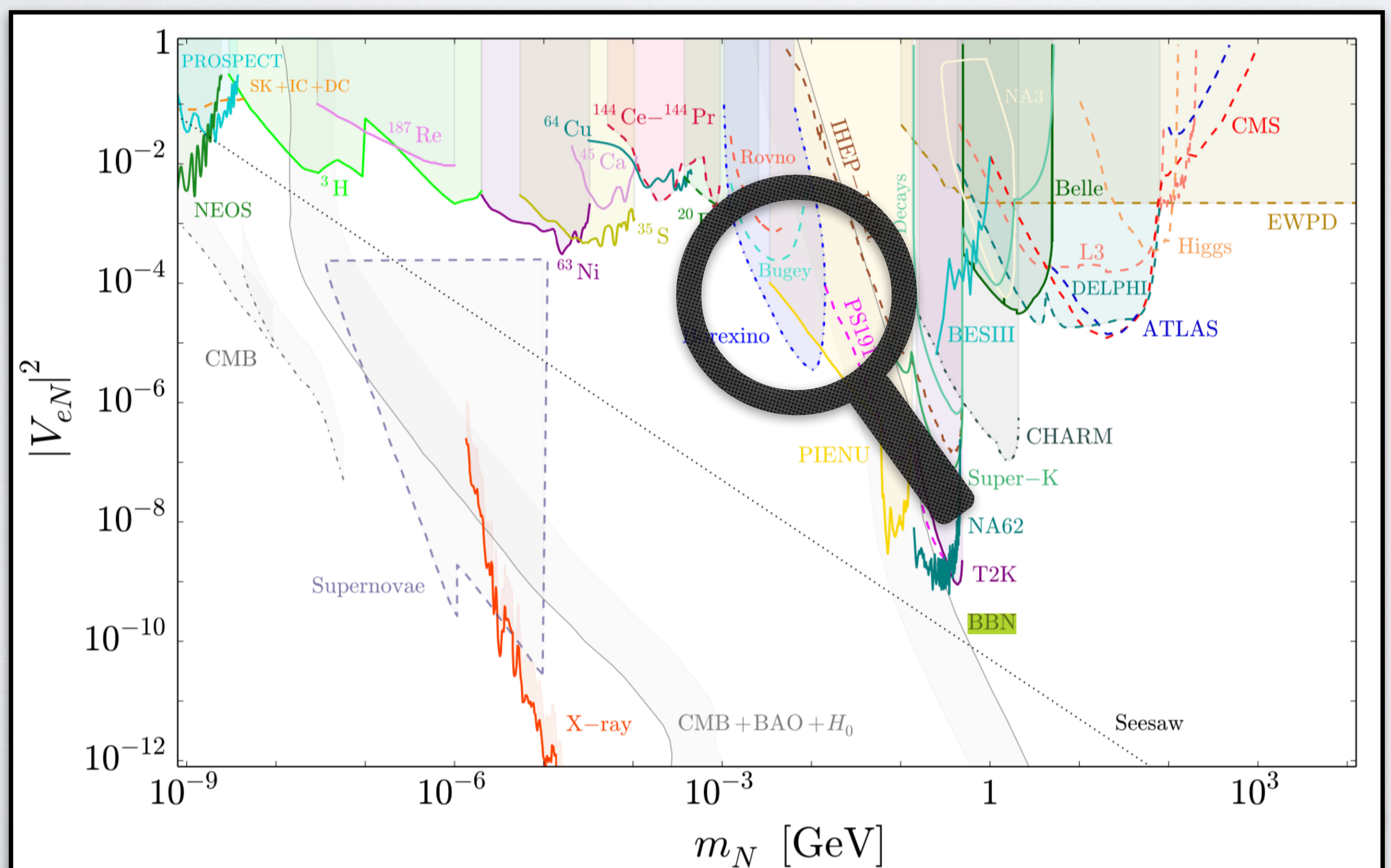

Heleen Mulder

$$K^0 \to \pi^+ + e^- + N$$

$$\pi^+ \to \mu^+ + N$$

Feather-weight neutrinos

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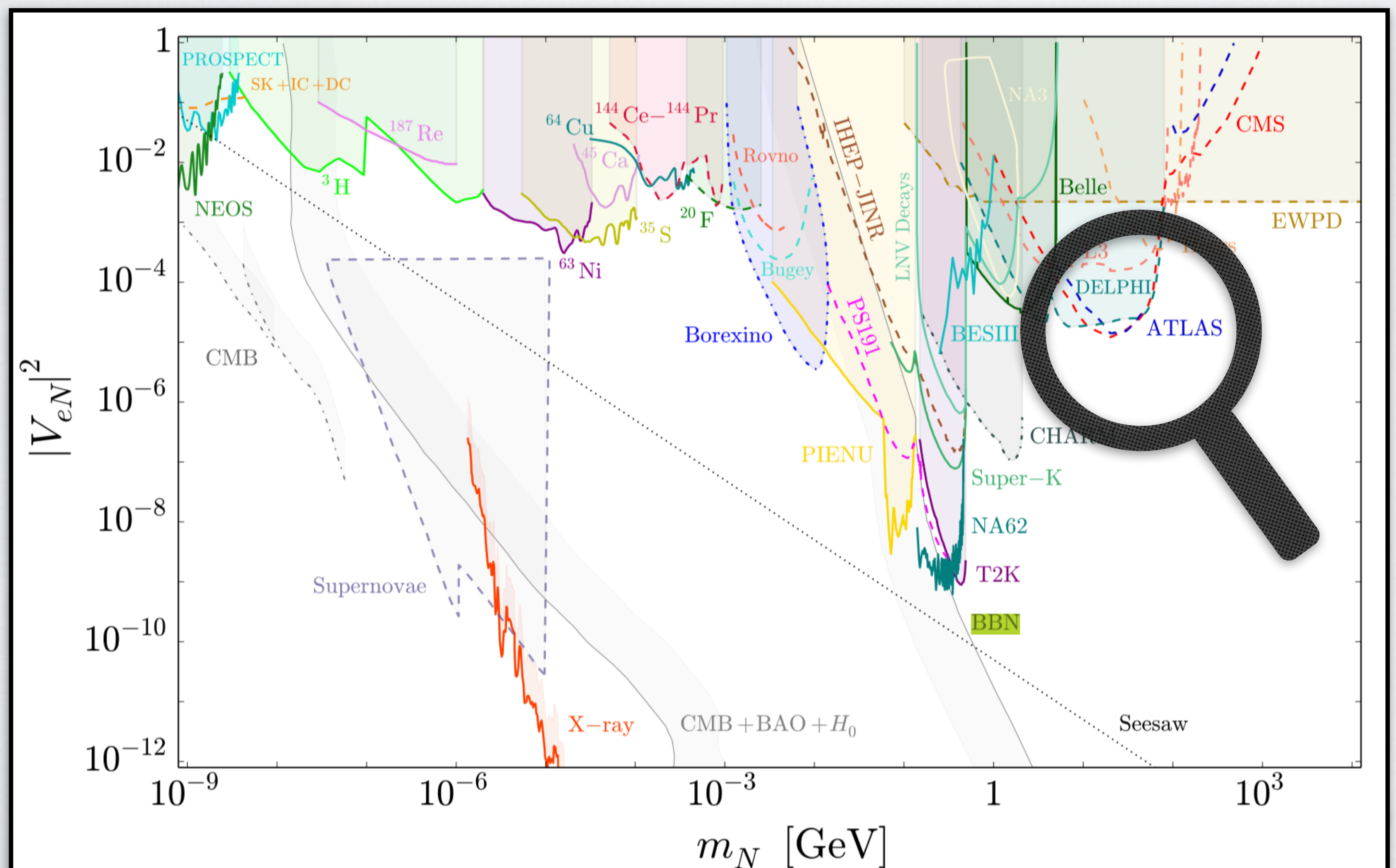

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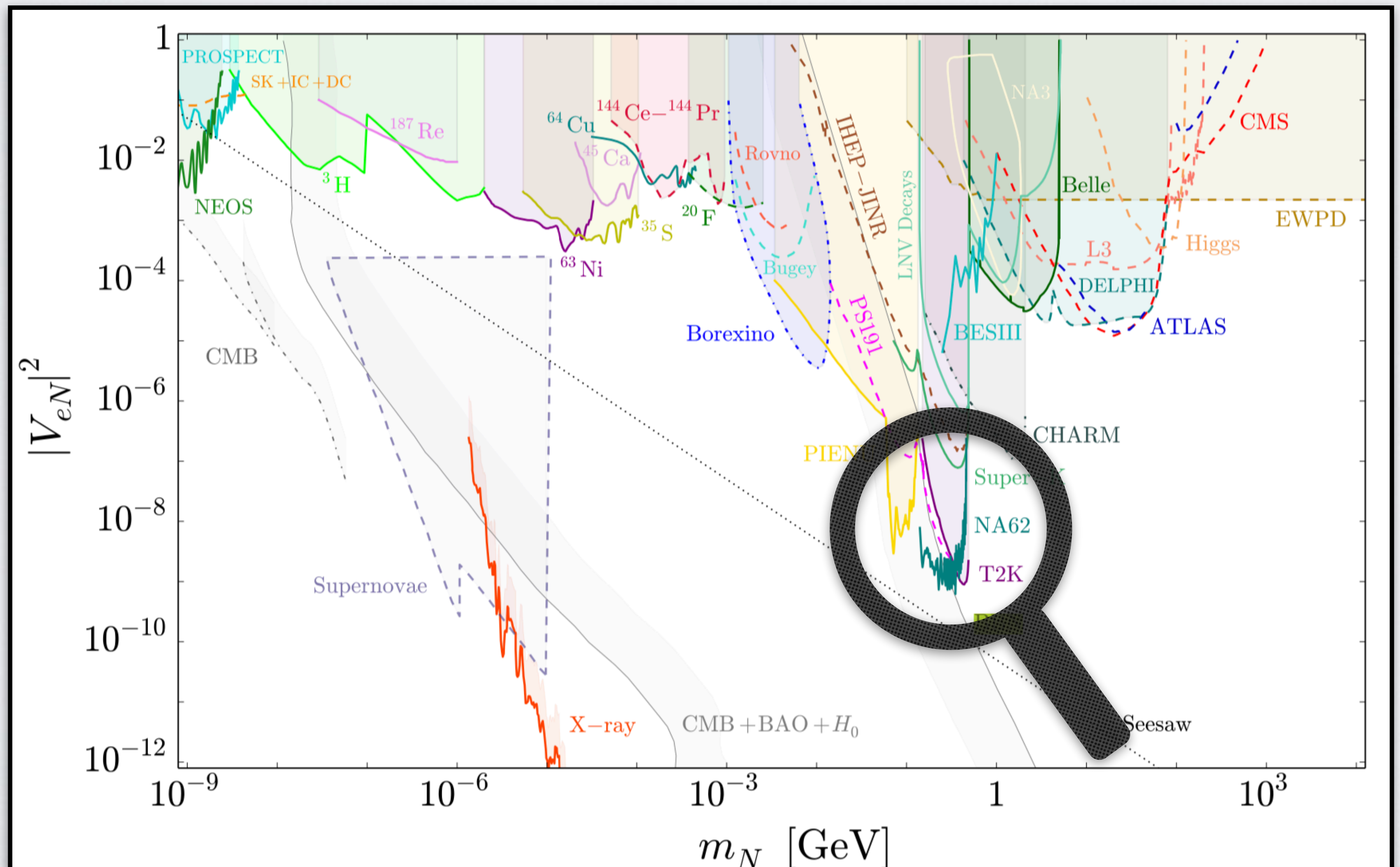

Jelle Groot

Bolton, Deppisch, Dev JHEP '20

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

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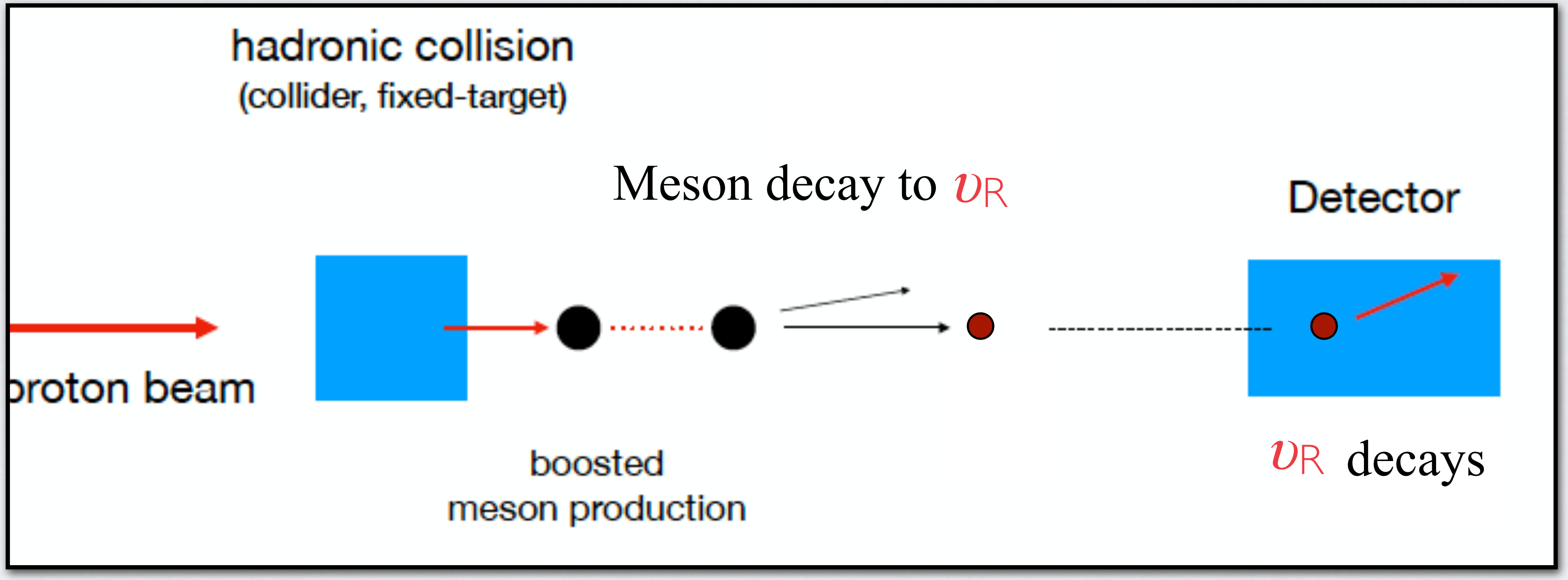
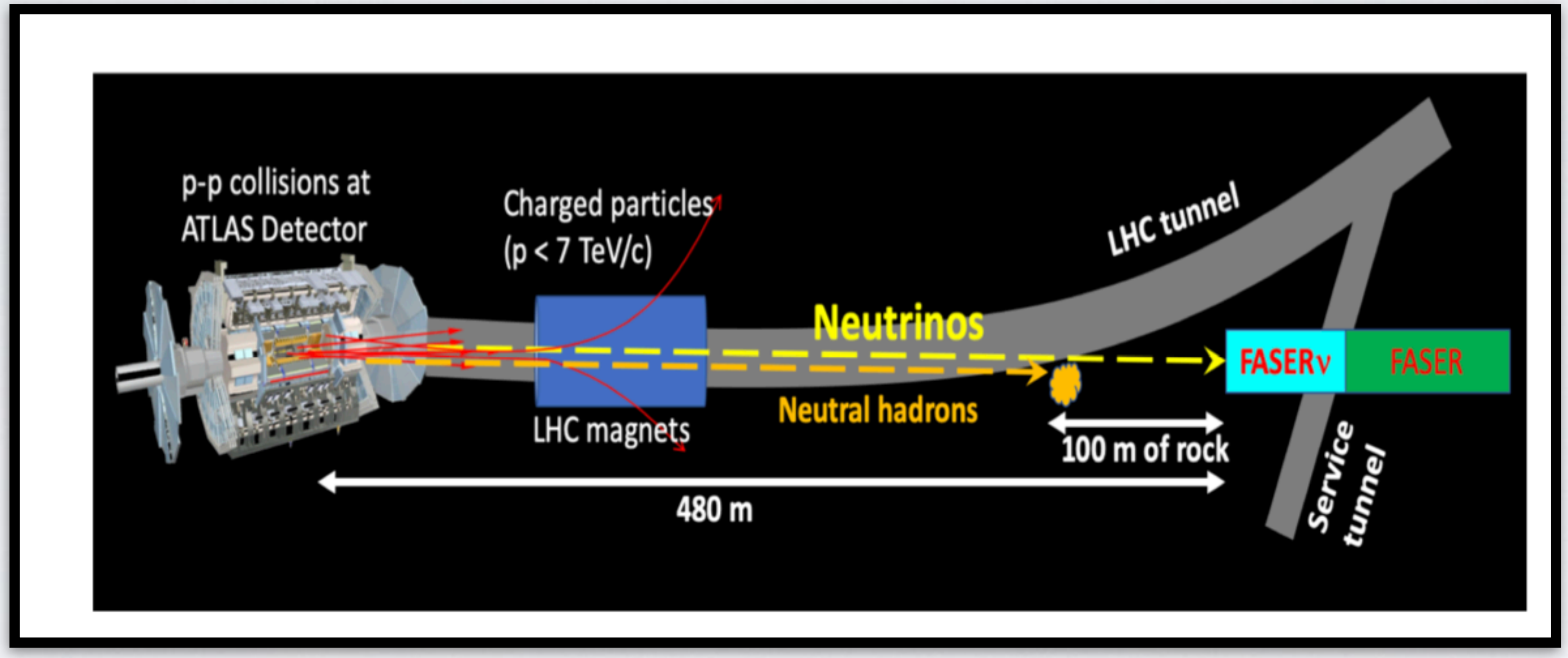


- Detector is placed far away from interaction point (tens to hundreds of meters)
- Space to install veto and shielding segments

Sterile neutrino from meson decay

- Idea: at colliders huge amount of **mesons** are produced (**strong interaction**)
- Some mesons only decay through **weak interaction -> chance to produce** ν_R



arXiv:2303.14185 (hep-ex)

[Submitted on 24 Mar 2023]

First Direct Observation of Collider Neutrinos with FASER at the LHC

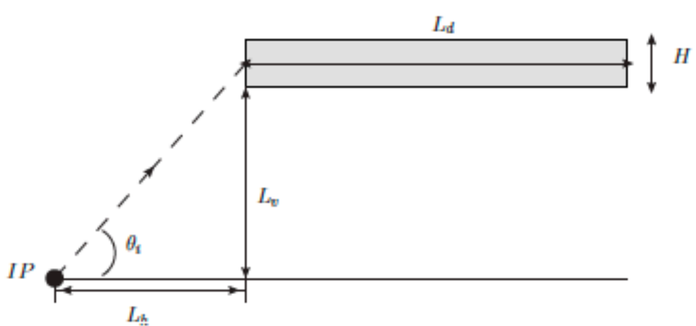
Sterile neutrino from meson decay

- Idea: at colliders huge amount of **mesons** are produced (**strong interaction**)
- Some mesons only decay through **weak interaction -> chance to produce** ν_R

Many more proposed experiments

MATHUSLA

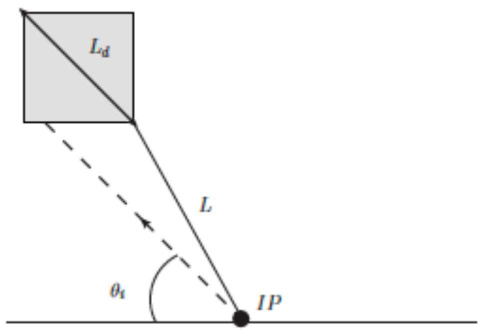
- MAssive Timing Hodoscope for Ultra Stable neutraL pArticles: a surface detector above the CMS IP: 100 m × 100 m ×25 m [2009.01693]



Extracted from [1810.03617]

L_d (m)	L_h (m)	L_v (m)	H (m)	$\phi/2\pi$	$\mathcal{L}$ (fb^{-1})
100	68	60	25	0.22	3000

CODEX-b



A Compact Detector for Exotics at LHCb: 10 m × 10 m × 10 m [1708.09395]

Extracted from [1810.03617]

L_d (m)	L (m)	$\phi/2\pi$	η	$\mathcal{L}$ (fb^{-1})
10	25	0.06	[0.2, 0.6]	300

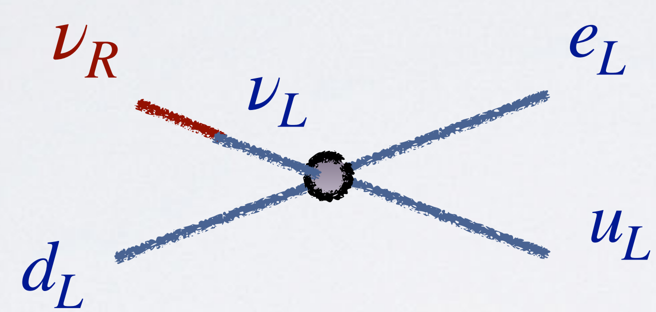
- **+ ANUBIS, MoEDAL-MAPP 1&2, AL3X , DUNE, ... etc**

Theoretical framework

- In mass basis, charged weak currents couple to 'sterile' states as well.

$$\mathscr{L} \sim U_{eR}\,\bar{e}_L\gamma^\mu\nu_R\,W_\mu$$

- Interactions suppressed by small mixing angles $U_{eR} \sim \sqrt{\frac{m_\nu}{m_R}}$ (but could be larger)



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

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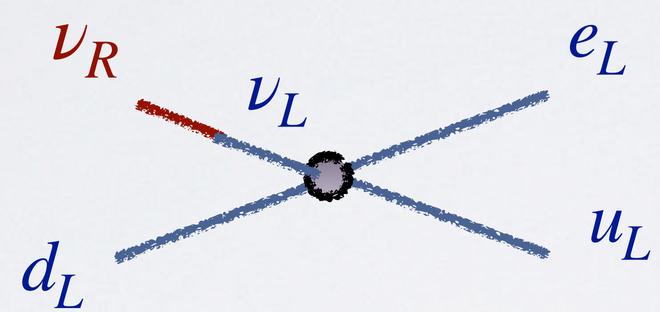
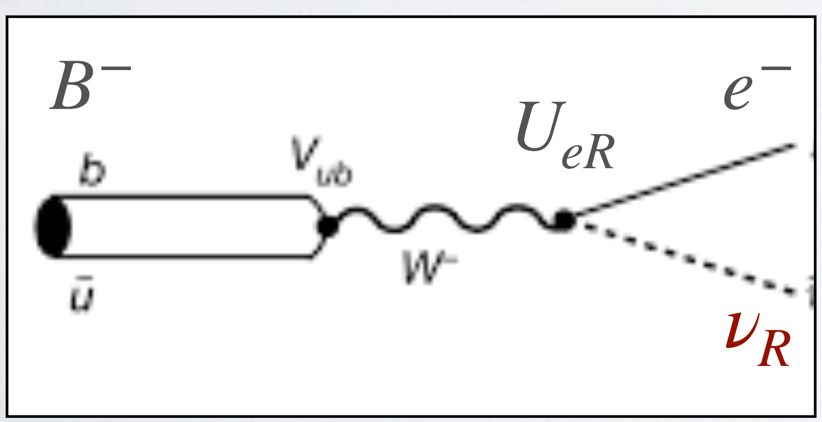
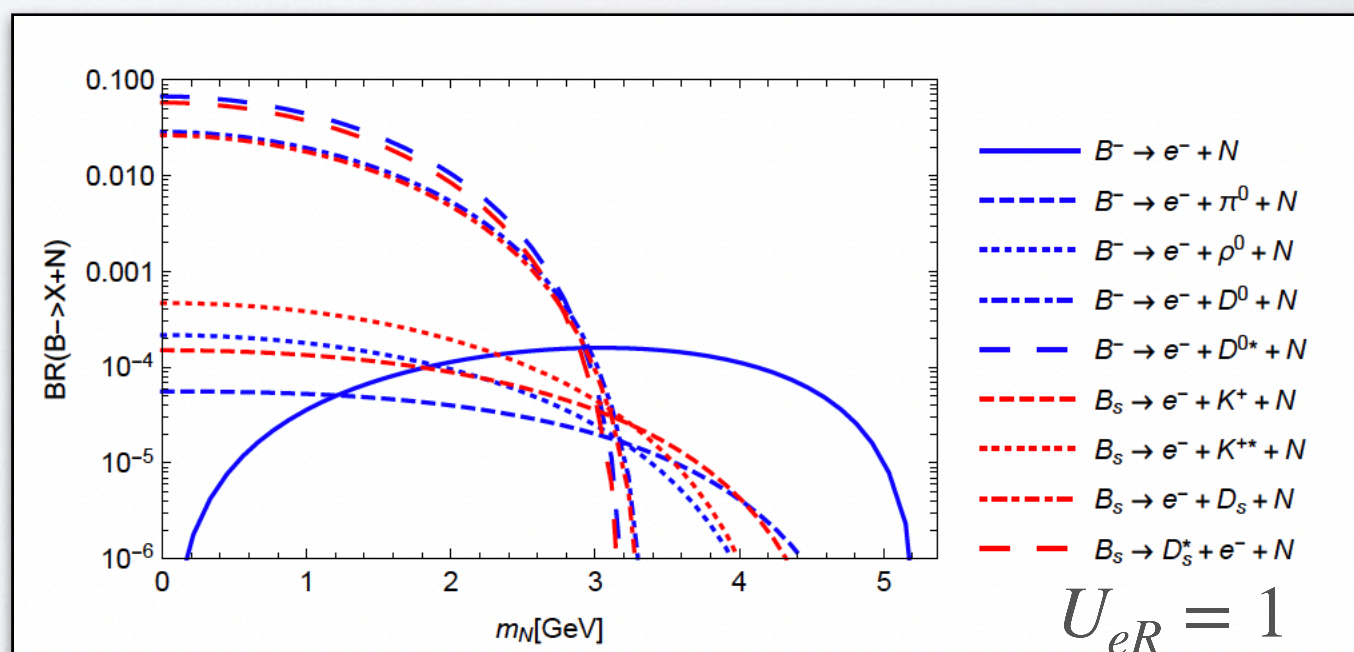


$$\sim \left(\frac{1}{M_W}\right)^2 U_{eR}$$

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



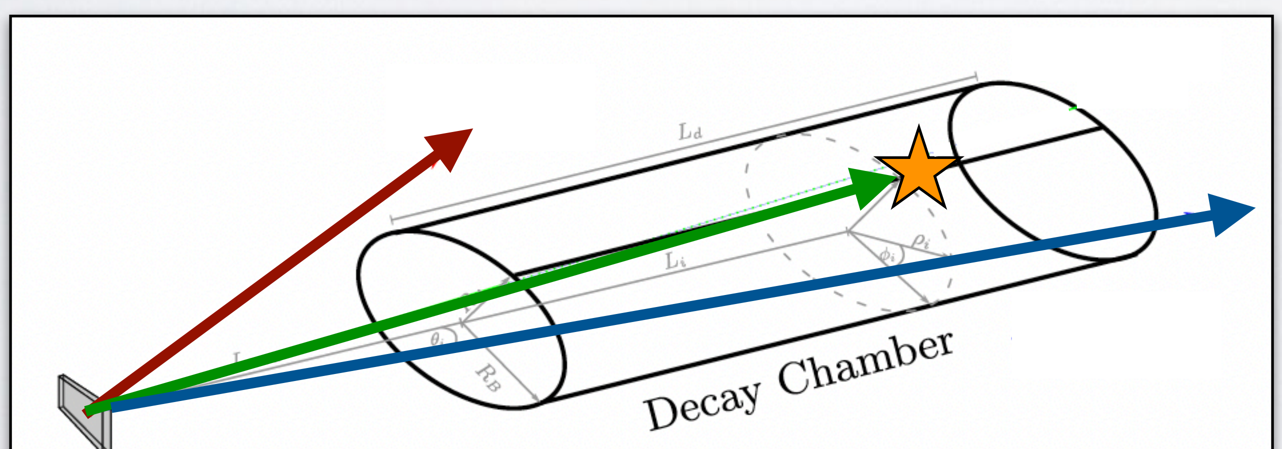


Simulation framework

- Simulate meson production/decay with Pythia 8 -> **Kinematics of sterile neutrinos**
- Simulate around 10^6 events and rescale to total number of producers mesons with 3 ab^{-1}

$$N_{D^\pm}^{\text{HL-LHC}} = 2.04 \times 10^{16}, \quad N_{D^0}^{\text{HL-LHC}} = 3.89 \times 10^{16}, \quad N_{D_s}^{\text{HL-LHC}} = 6.62 \times 10^{15},$$
$$N_{B^\pm}^{\text{HL-LHC}} = 1.46 \times 10^{15}, \quad N_{B^0}^{\text{HL-LHC}} = 1.46 \times 10^{15}, \quad N_{B_s}^{\text{HL-LHC}} = 2.53 \times 10^{14}.$$

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



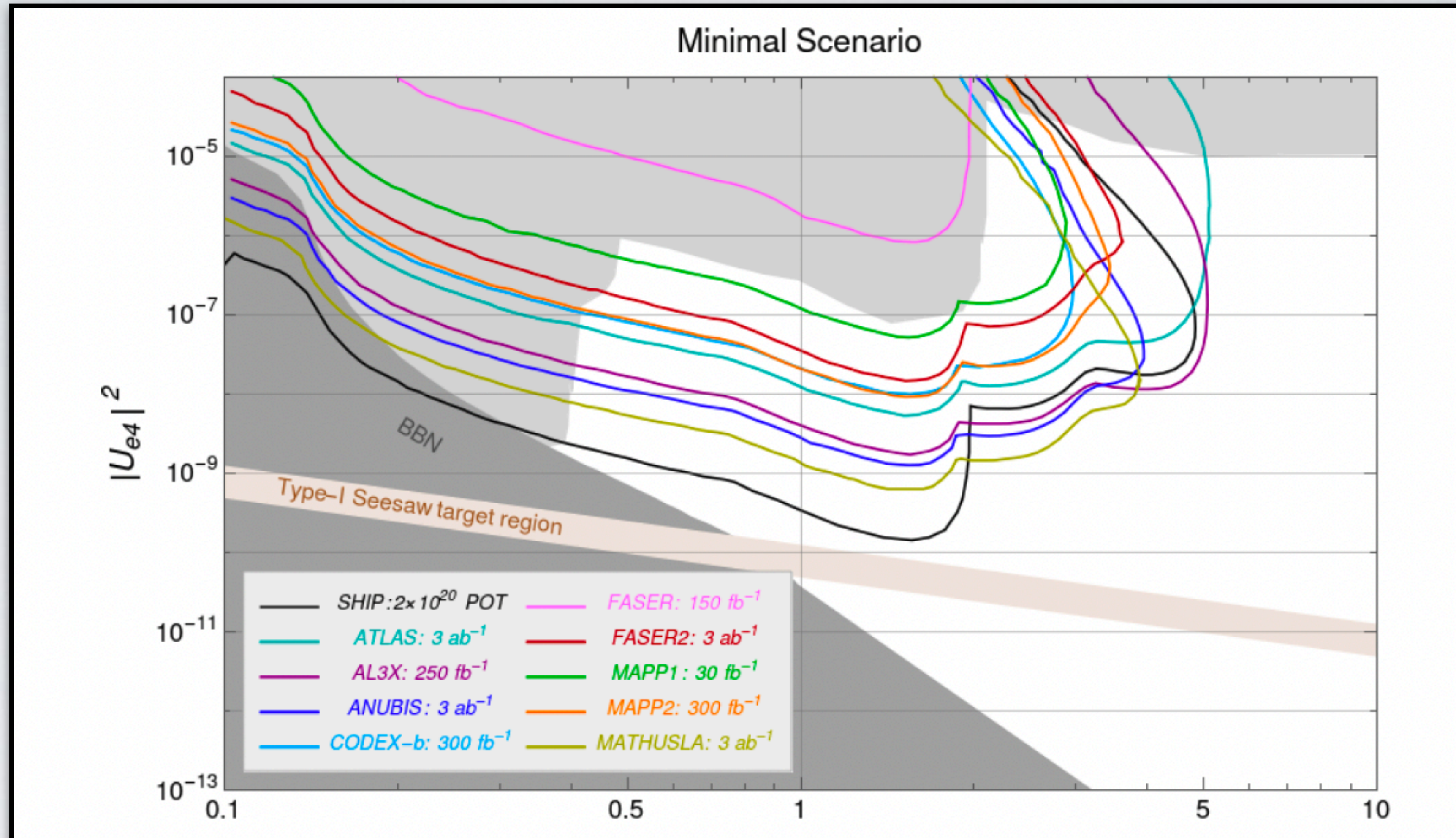
Miss !

Pass !

Success!

Sterile neutrino decay

Good prospects at colliders

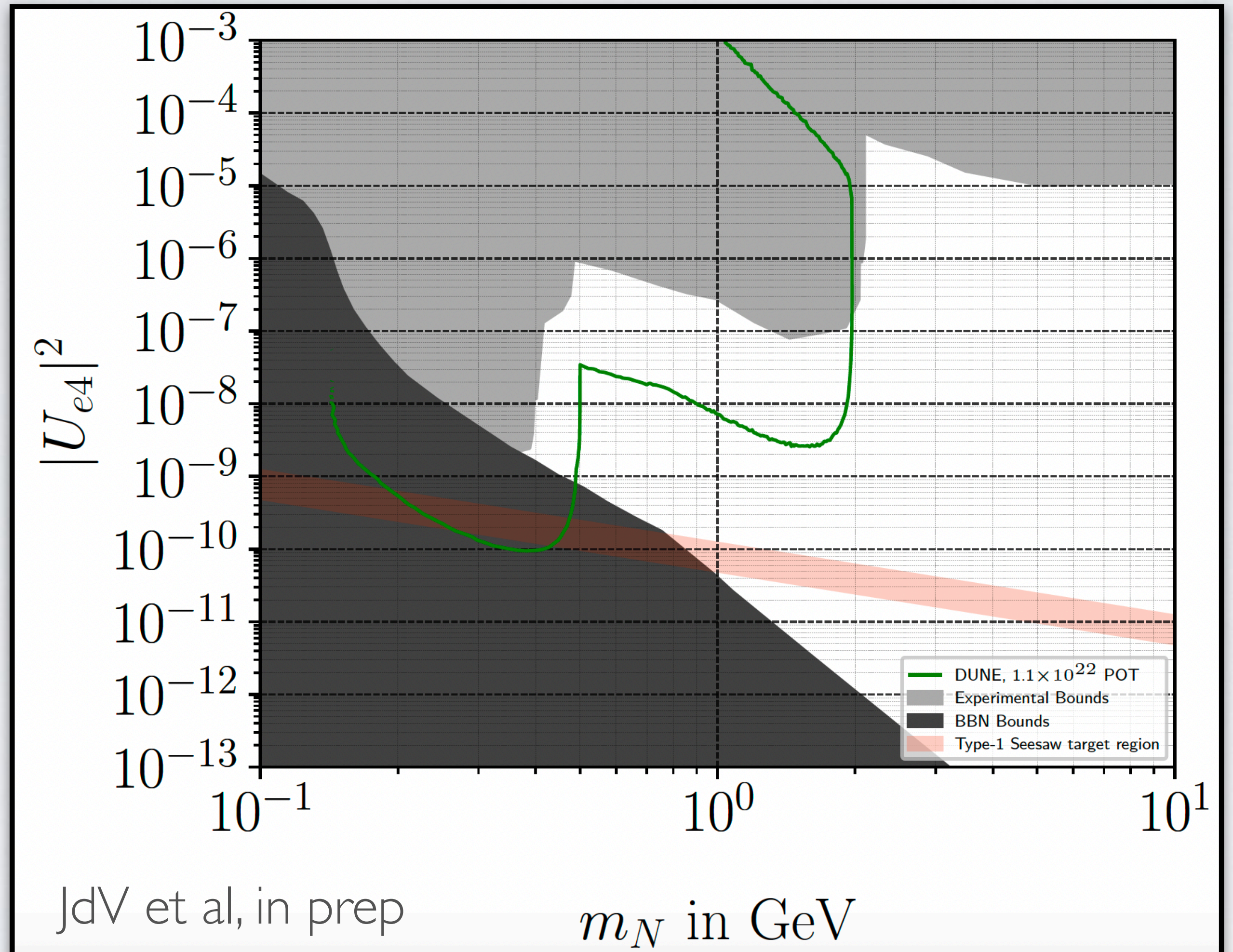


JdV et al JHEP '21

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

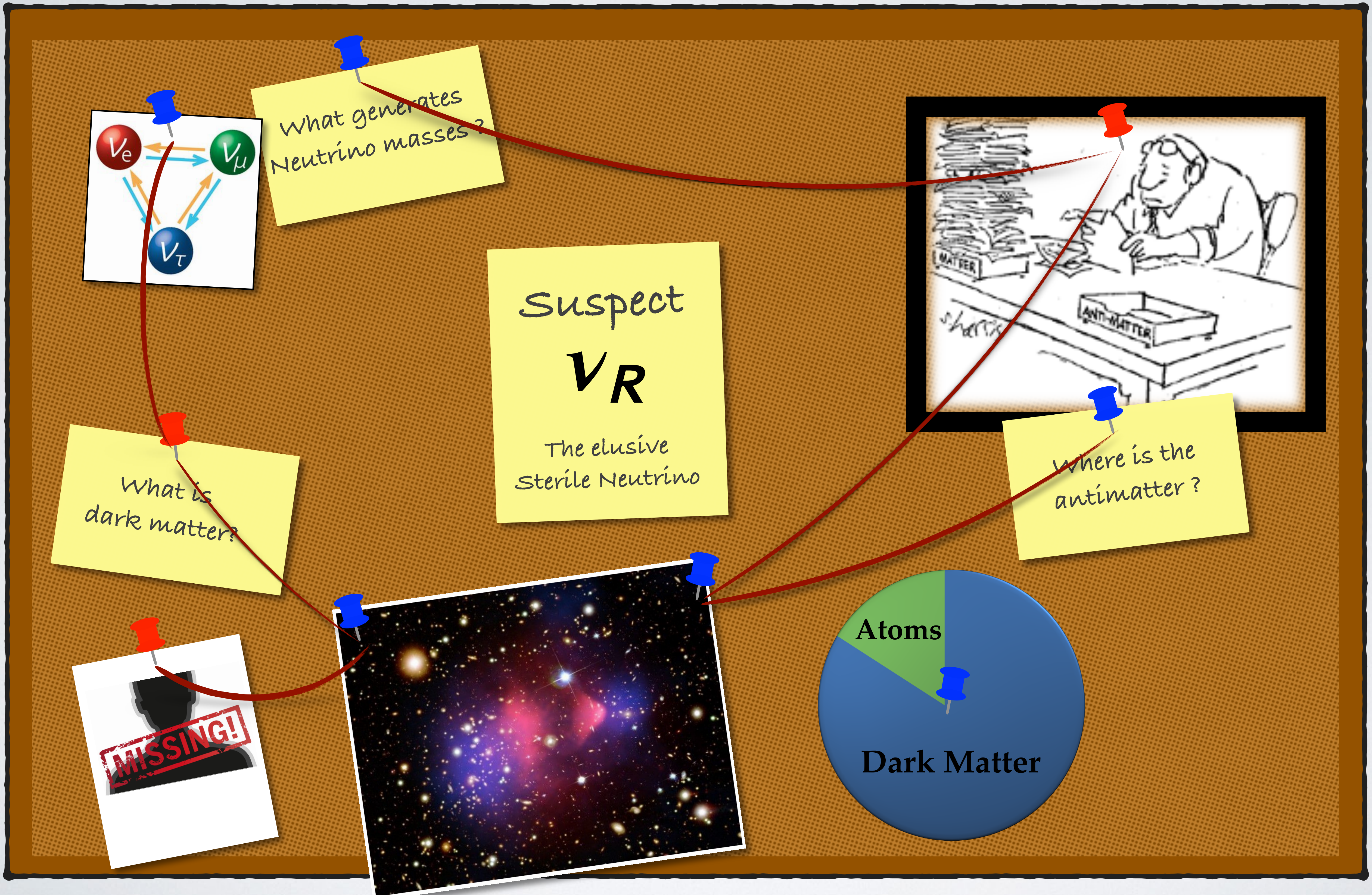
- **Current limits will improve significantly with new experiments**

Good prospects at neutrino experiments



- **DUNE will be very sensitive for sterile masses below 2 GeV**

The evidence board



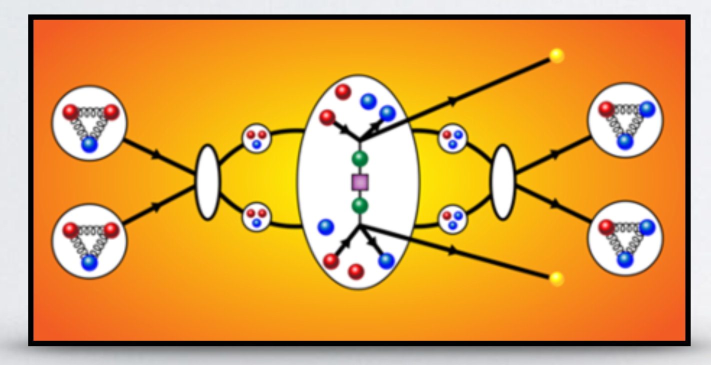
Summary and outlook

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

M_R ?

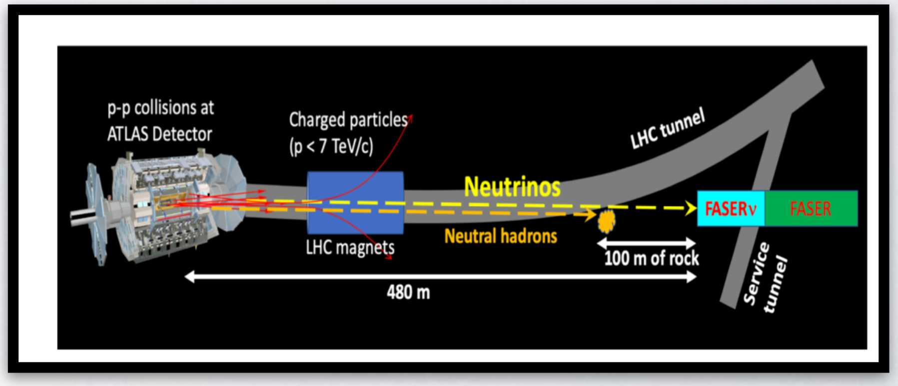
eV keV MeV GeV TeV ..... 10^{15} GeV

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



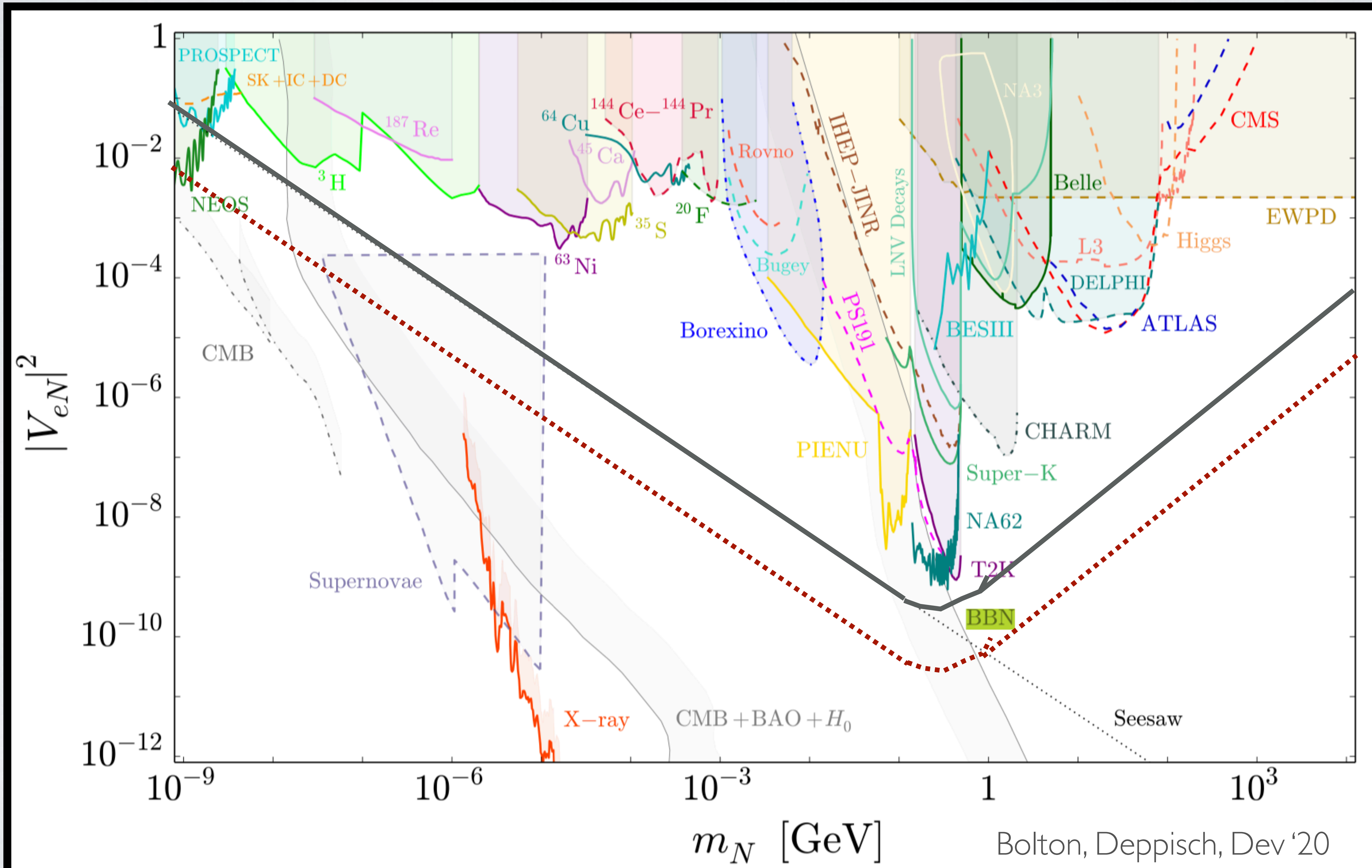
- **Exciting experimental program**
- Theory improvements needed but good progress last 5 years
- There is an end goal !

- **Great activity to find long-lived particles**
- We can detect sterile neutrinos at LHC and DUNE and other experiments (beta decay, oscillations)
- Unfortunately only in relative small mass range



Backup

Naive 0vbb limits



Bolton, Deppisch, Dev '20

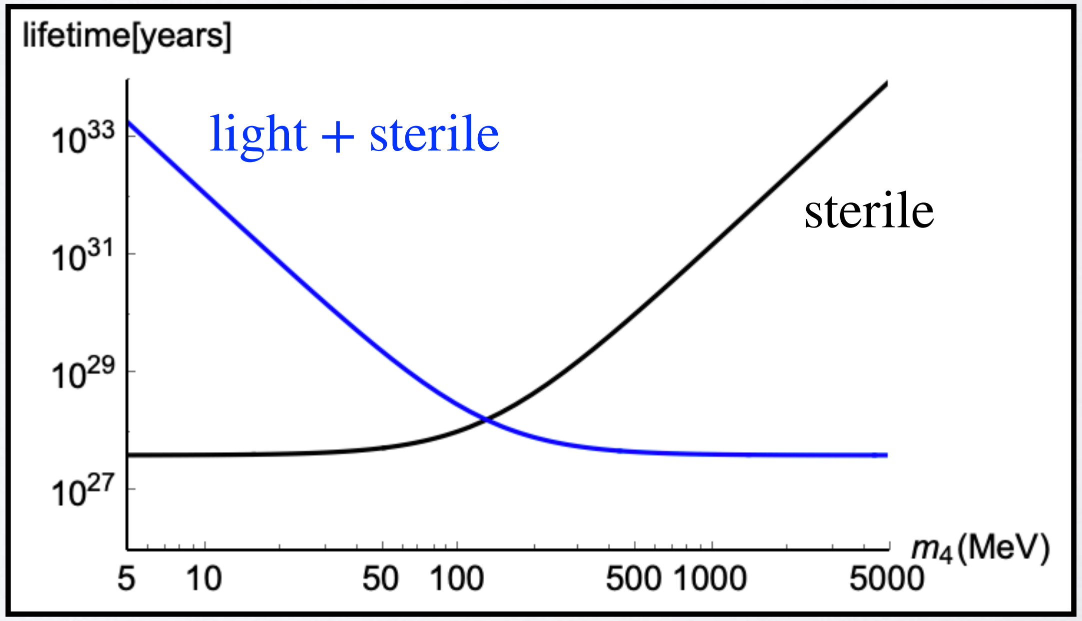
- Bounds can be weakened by considering **pseudo-Dirac** sterile neutrino pairs

Revisit the light regime

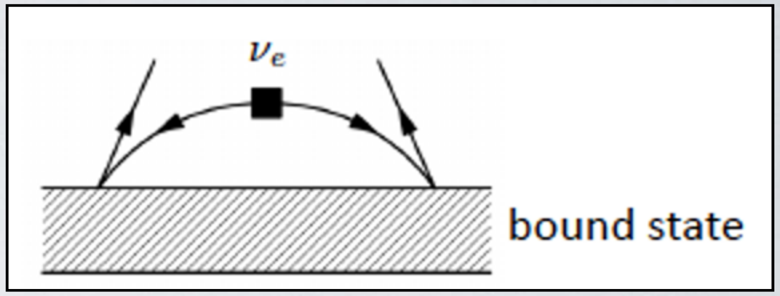
$$A_\nu \sim \sum_{i=1}^{3} U_{ei}^2 m_i \frac{1}{\langle p^2 \rangle} + U_{e4}^2 m_4 \frac{1}{\langle p^2 \rangle + m_4^2} \xrightarrow{m_4 \ll 100\,\mathrm{MeV}} A_\nu \sim \sum_{i=1}^{4} U_{ei}^2 m_i \frac{1}{\langle p^2 \rangle} + \mathcal{O}\left(\frac{m_i^3}{\langle p^2 \rangle^2}\right)$$

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

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



Light extra neutrinos



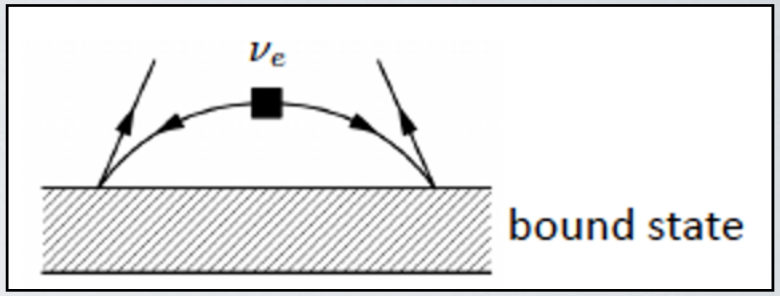
- Is there a way to avoid the GIM mechanism ?
- There are additional contributions from 'ultra-soft' neutrinos

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

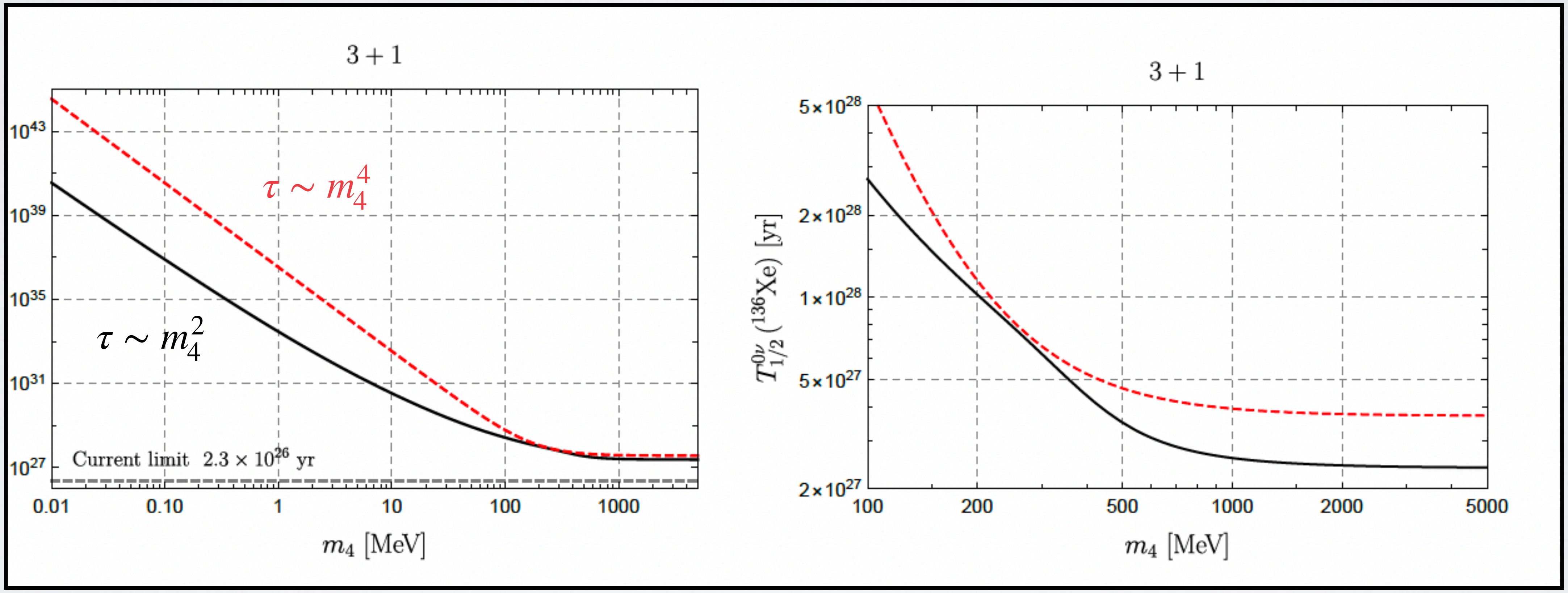
- Depends on nuclear excited states. Normally these are tiny effects (5%)
- But become dominant in the GIM mechanism ! $\sim U_{ei}^2 m_i^3$
- For $m_4 \sim$ MeV we get new contributions $\sim U_{ei}^2 m_i^2$
- For $m_4 <<$ MeV we get new contributions $\sim U_{ei}^2 m_i^3 \log \frac{(E_n - E_0)^2}{m_i^2}$
- These effects are not considered in any analysis of neutrinoless double beta decay
- Javier Menendez computed for us the necessary matrix elements

Light extra neutrinos

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



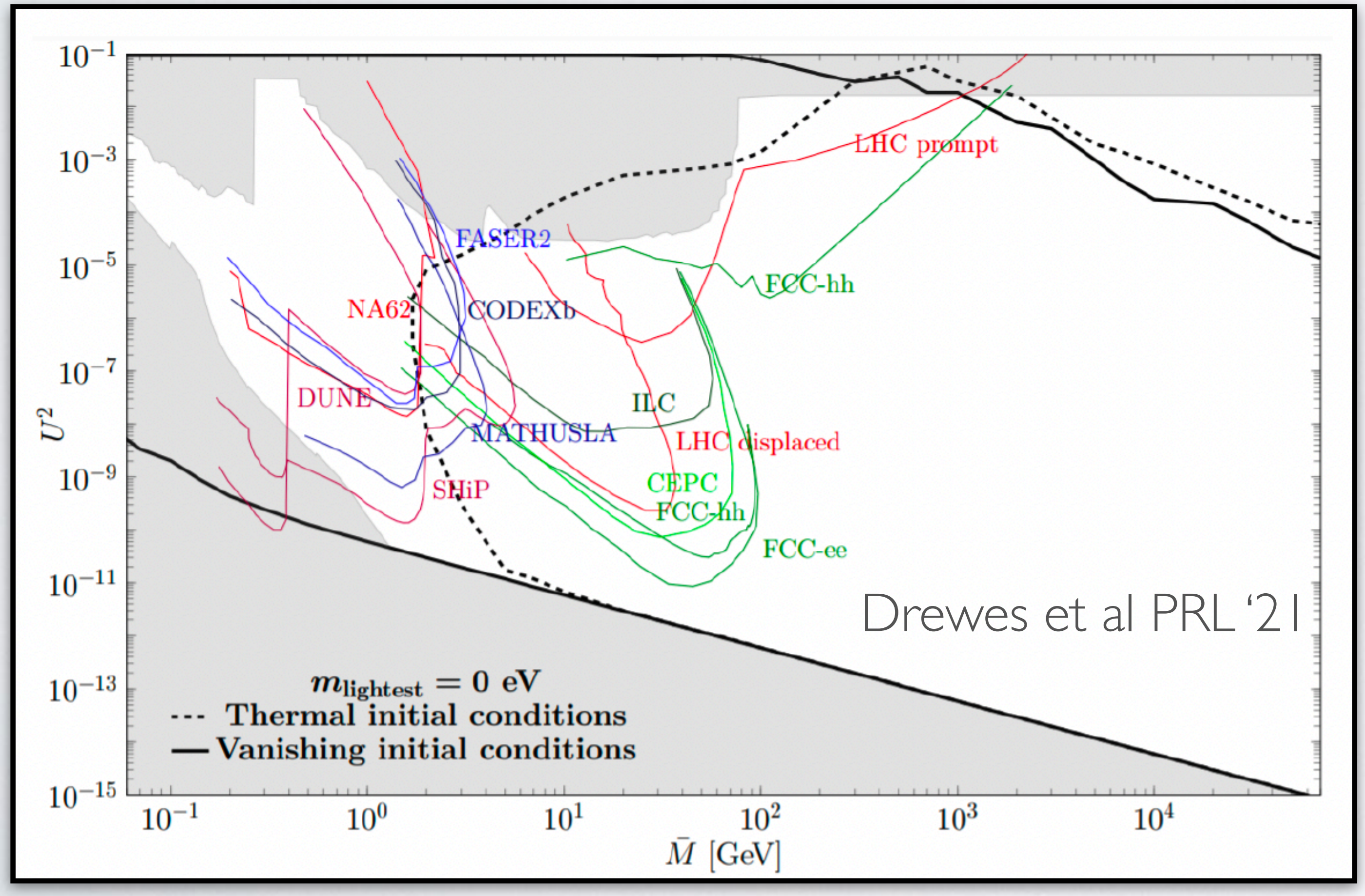
Lifetime in years



- **Work in progress: compute these corrections for realistic models**

Work in progress

- Our work has focused on hadronic/nuclear aspects: what drives 0vbb
- But we focused on toy neutrino models
- Ongoing work in collaboration with Marco Drewes (Louvain) and his group
- Use realistic 3+2 and 3+3 models + **leptogenesis**



- Compute 0vbb predictions for all viable points in parameter space

The associated symmetries

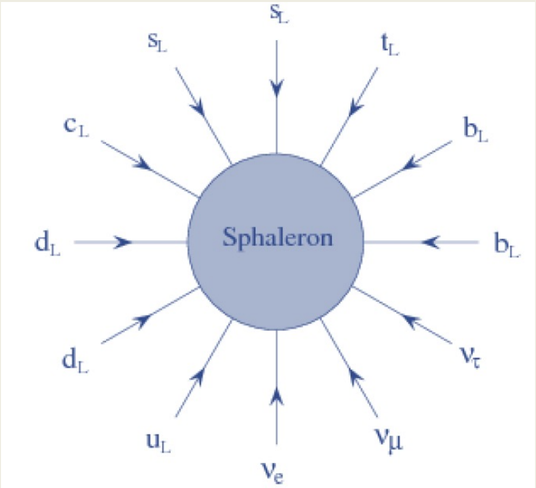
Important caveat II

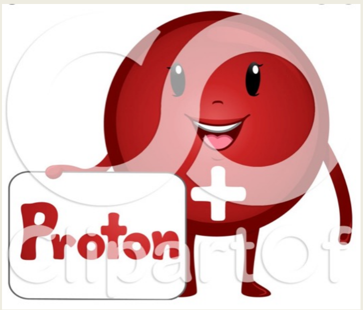
- Not all classical symmetries survive quantum mechanics
- **B+L** is an *anomalous* symmetry

$$\eth_\mu j^\mu_L = \eth_\mu j^\mu_B = 3\frac{g^2}{32\pi^2} W^a_{\mu\upsilon}\widetilde{W}^{a\,\mu\upsilon}$$

't Hooft 1976

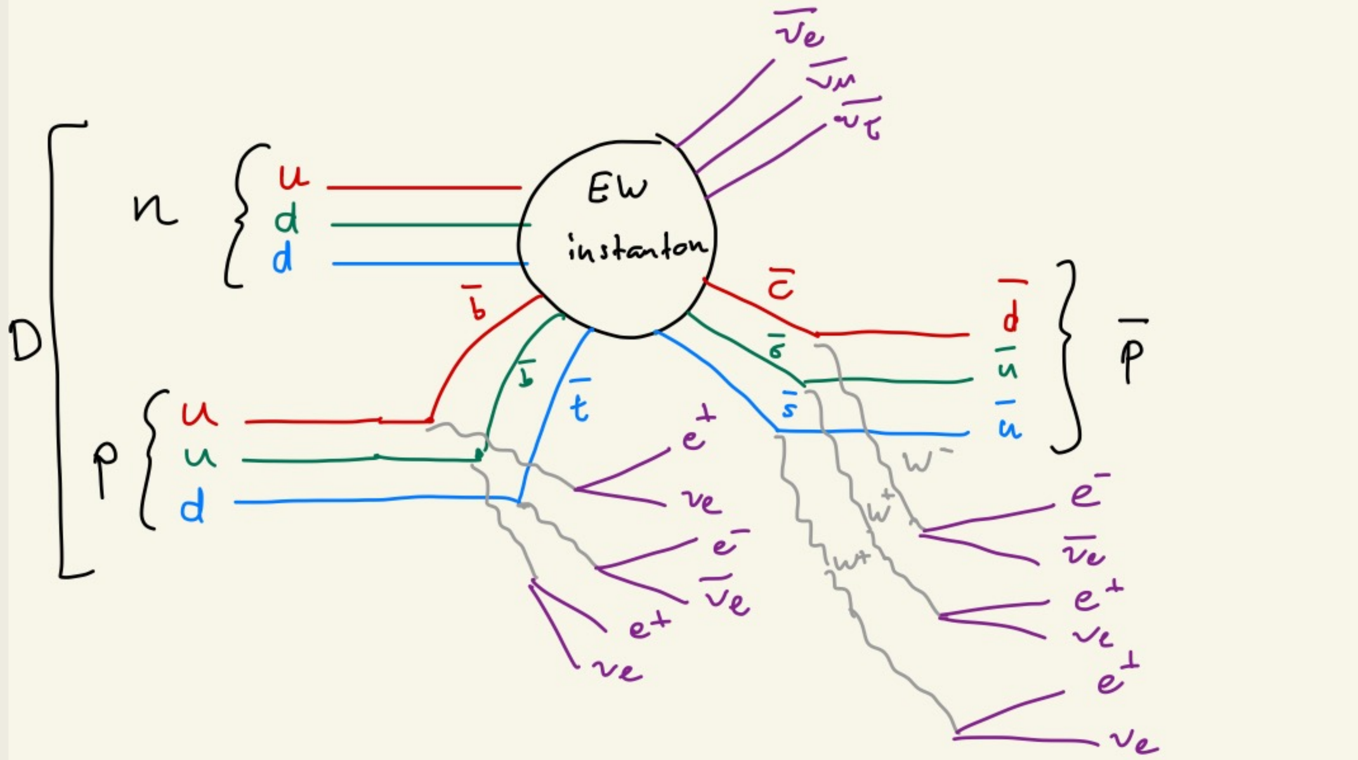
- These non-perturbative processes (aka electroweak instantons) cause **(B+L)-violating processes** (but conserve B-L) $\Delta B = \Delta L = \pm 3n$





A murder most foul

But we are saved !!



$$D \longrightarrow \bar{p} + 4e^+ + 2e^- + 4\nu_e + 3\bar{\nu}_e + \bar{\nu}_\mu + \bar{\nu}_\tau$$

$$\Gamma_D \sim G_F^{12} (m_D - m_{\bar{p}})^{25} V_{td}^2 V_{ub}^4 V_{cd}^2 V_{us}^4 \times e^{-16\pi^2/g^2}$$

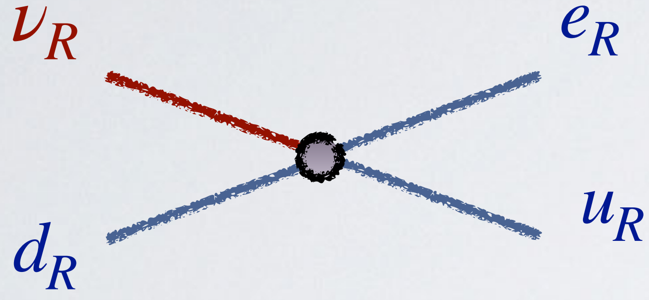
$$\tau_D = \Gamma_D^{-1} \sim 10^{184}\, y \sim 10^{174} \text{ Age of universe}$$

inspired by Andrew Long

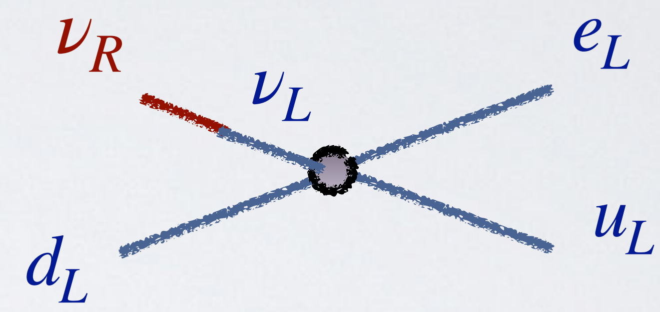
Non-sterile sterile neutrinos ?

- In various interesting scenarios sterile neutrinos only look sterile at low energies

- In left-right symmetric models: right-handed neutrinos charged under $SU_R(2)$



$$\sim \left(\frac{1}{M_{W_R}}\right)^2$$



$$\sim \left(\frac{1}{M_{W_L}}\right)^2 \sqrt{\frac{m_\nu}{m_R}}$$

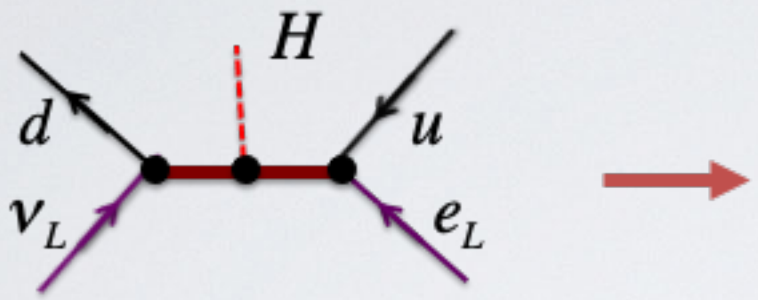
- For allowed right-handed scales (M_{WR} > 5 TeV) this can lead to much larger interactions

- This also happens in for instance Leptoquark scenarios and can even used in solutions to anomalies such as muon g-2 or flavor anomalies (not today)

e.g. Ruiz, JdV et al '21 e.g. Azatov, Barducci et al '18

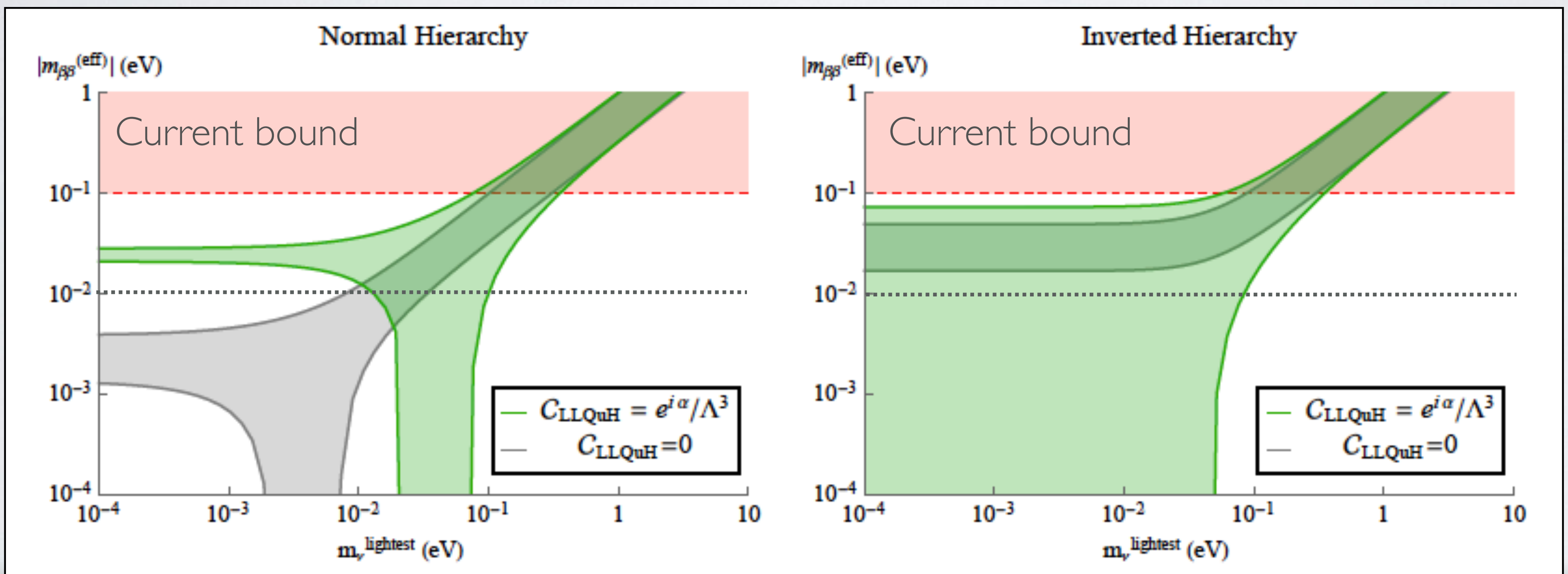
Using the framework

- Example: a model of heavy leptoquarks   (LHC probes 1 TeV leptoquarks roughly)



$C_7 \sim (v/\Lambda)^3$

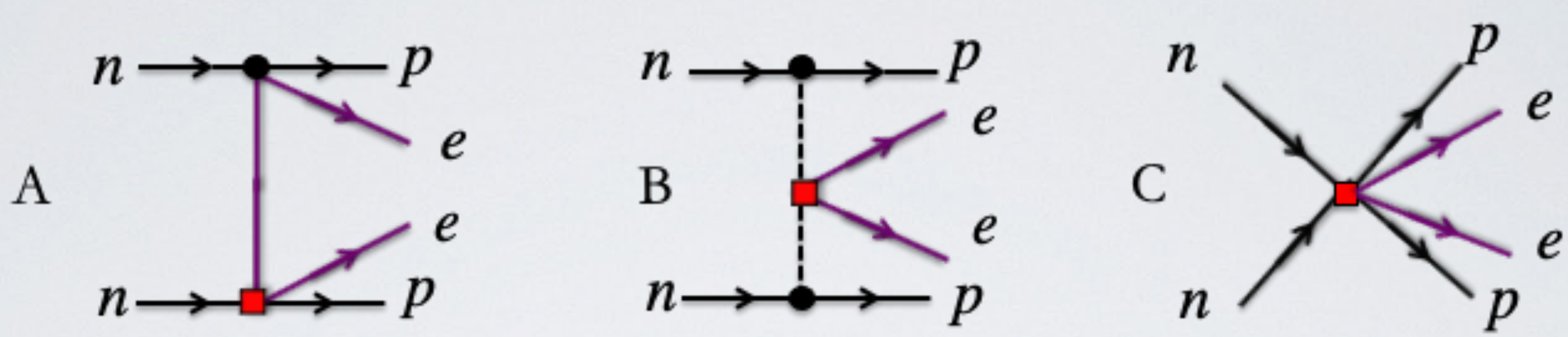
$\Lambda > 400\ TeV$



Ton-scale expectations

- Dramatic impact on 0vbb phenomenology !
- Sensitivity to 500-TeV new physics scales

New 0vbb topologies

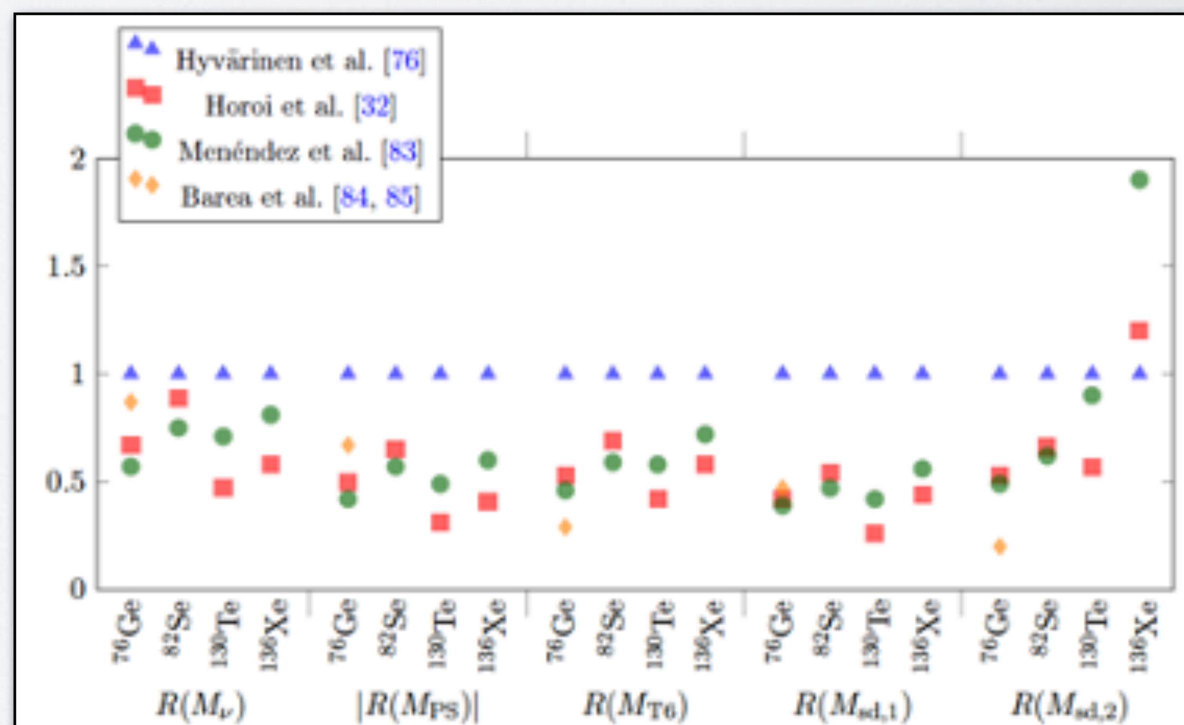


- Straightforward to calculate generalized 0vbb transition current — Cirigliano et al '17 '18
- Need additional nuclear matrix elements (NMEs)
- **At leading-order in Chiral-EFT: 15 NMEs (all in literature)**
- Similar uncertainties as before

NMEs	^{76}Ge [74]	[31]	[81]	[82,83]
M_F	-1.74	-0.67	-0.59	-0.68
M_{GT}^{AA}	5.48	3.50	3.15	5.06
M_{GT}^{AP}	-2.02	-0.25	-0.94	
M_{GT}^{PP}	0.66	0.33	0.30	
M_{GT}^{MM}	0.51	0.25	0.22	
M_T^{AA}	–	–	–	
M_T^{AP}	-0.35	0.01	-0.01	
M_T^{PP}	0.10	0.00	0.00	
M_T^{MM}	-0.04	0.00	0.00	

NMEs	^{76}Ge			
$M_{F,sd}$	-3.46	-1.55	-1.46	-1.1
$M_{GT,sd}^{AA}$	11.1	4.03	4.87	3.62
$M_{GT,sd}^{AP}$	-5.35	-2.37	-2.26	-1.37
$M_{GT,sd}^{PP}$	1.99	0.85	0.82	0.42
$M_{T,sd}^{AP}$	-0.85	0.01	-0.05	-0.97
$M_{T,sd}^{PP}$	0.32	0.00	0.02	0.38

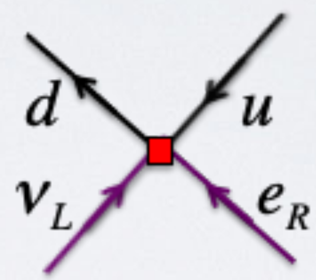
Hyvarinen/Suhonen '15
Menendez et al '17 '18
Barea et al '15 '18
Horoi/Neacsu '17



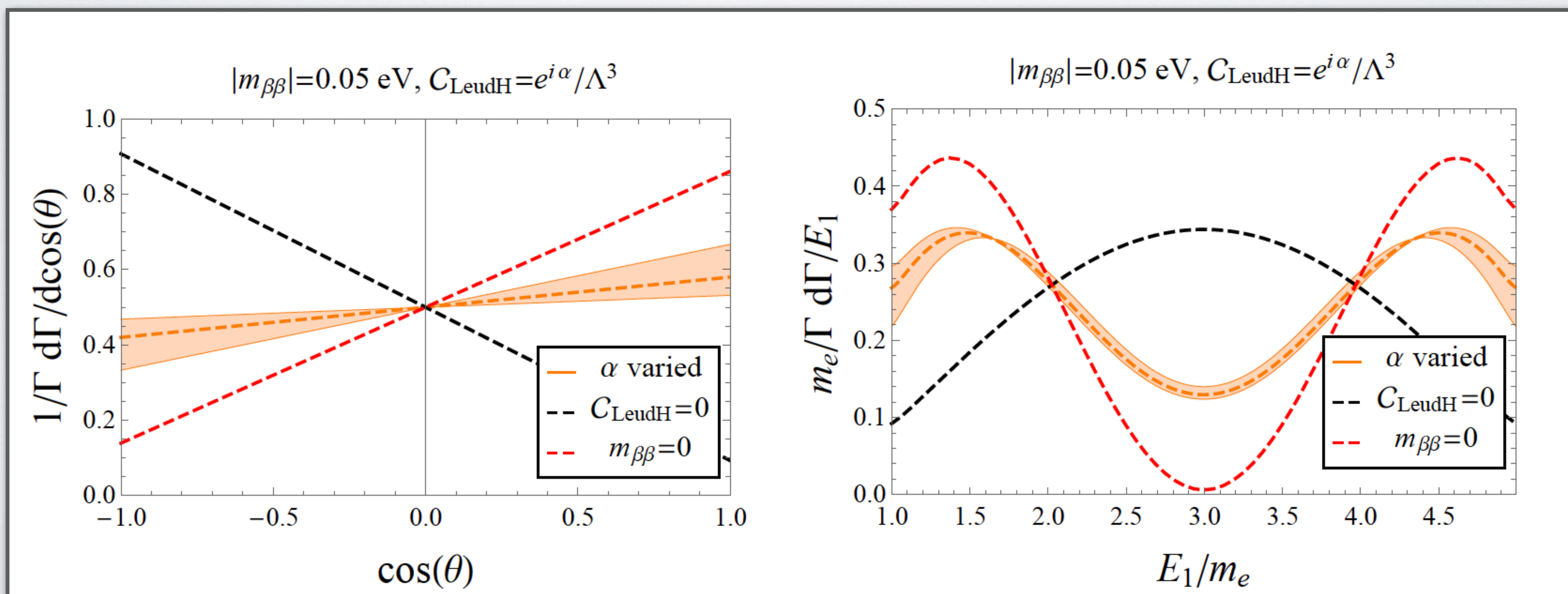
Disentangling the source of LNV

- A single measurement can be from any LNV operator
- Can we learn more from several measurements ?

- **One could in principle measure angular&energy electron distributions**

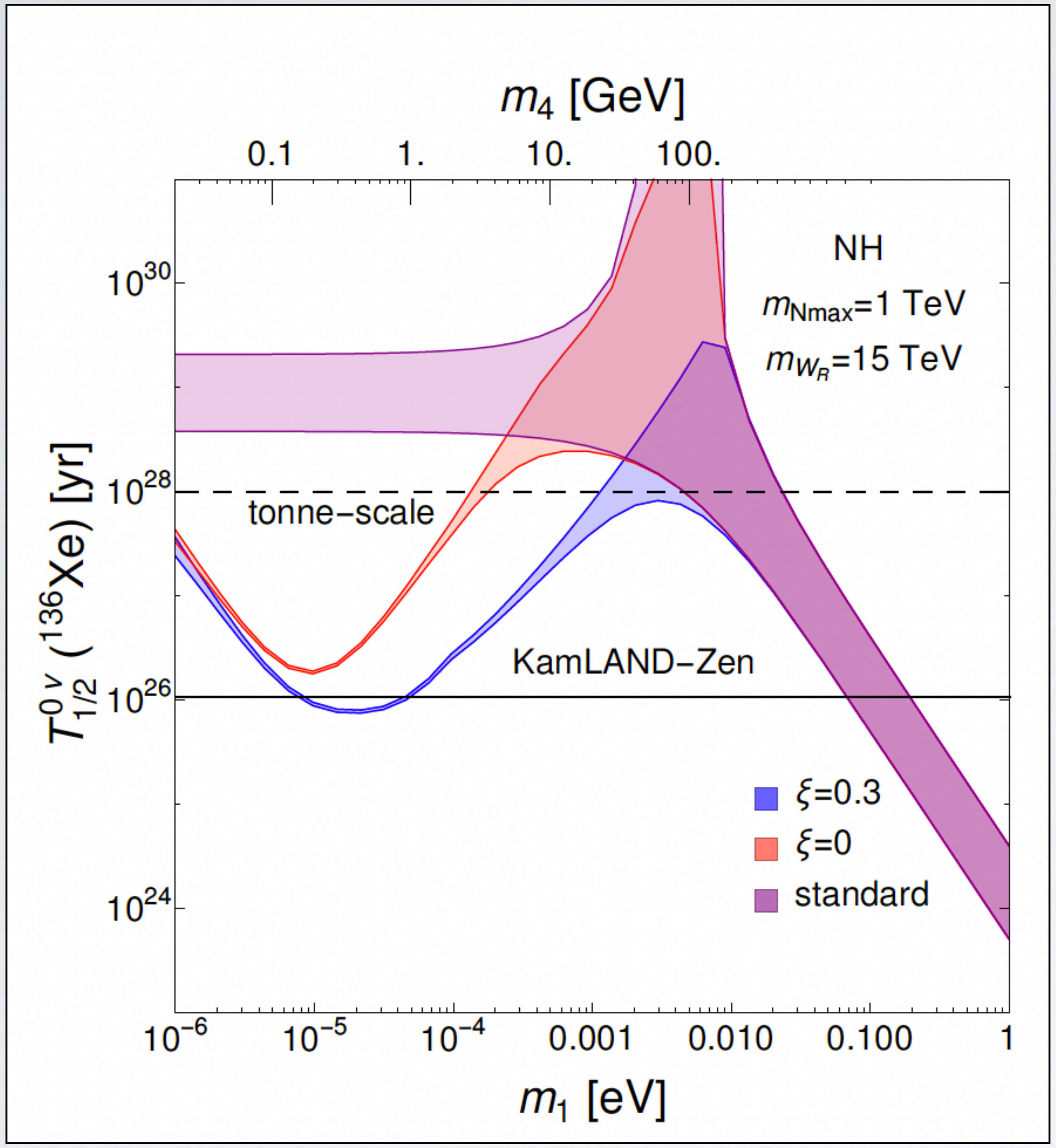


$C_7 \sim (v/\Lambda)^3 e^{i\alpha}$ $\Lambda \sim 50\,\mathrm{TeV}$



An example: mLRSM + light right-handed neutrinos

Li, Ramsey-Musolf, Vasquez PRL '20
JdV, Li, Ramsey-Musolf, Vasquez '22



$M_{W_R} \simeq 15\,\text{TeV}$

$M_N(\text{light}) \in (0.1 - 1000)\,\text{GeV}$

$\xi \sim W_L - W_R\,\text{mixing}$

Normal Hierarchy

- Large enhancements possible for 0vbb for parameter space not excluded elsewhere.
- Automizing more complicated due to more 'user input' (sterile masses + mixing)
- If someone is interested in helping out….