Snowmass Rare and Precision Measurements Frontier Spring Meeting
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Lepton Number Violation and Neutrinoless Double Beta Decay

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Outline

- Introduction
  - Lepton number violation: $0\nu\beta\beta$ and other probes
  - Effective Field Theory framework for $0\nu\beta\beta$

- Survey of $0\nu\beta\beta$ reach in classes of LNV models
  - High scale seesaw (dim 5)
  - TeV-scale LNV (dim 7, 9, ….)
  - Low-scale LNV (`light' ν_R, …)
  - Unraveling the mechanism?

- Outlook

For a comprehensive discussion see the 'theory-oriented' WP 2203. 21169

Why Lepton Number Violation?

- L is an accidental symmetry of the SM (up to anomalies which induce ΔB=ΔL=3, highly suppressed): unique window on BSM dynamics

- Connected with big questions: unification, origin of matter-antimatter asymmetry, origin of neutrino mass

Dirac mass:

$$\boxed{m_D \, \bar{\nu}_R \nu_L + \mathrm{h.c.}}$$

Violates $L_{e,\mu,\tau}$, conserves L

Majorana mass:

$$\boxed{\frac{1}{2} m_M \, \nu_L^T C \nu_L + \mathrm{h.c.}}$$

Violates $L_{e,\mu,\tau}$ and L (ΔL=2)

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$$\mathcal{L}_{\nu \mathrm{SM}} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\nu-\mathrm{mass}} + \ldots$$

- Key question: is Lepton Number a good symmetry of the new dynamics?

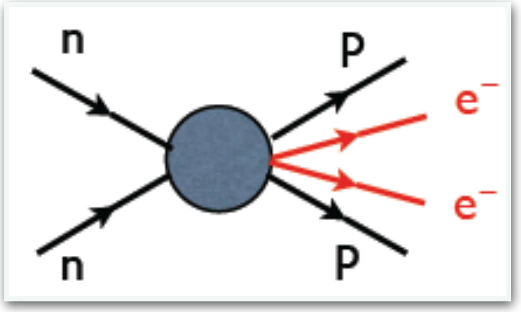
- Smallness of ν mass and chiral nature of the weak interactions implies that *neutrino-less* processes are the best probes of ΔL=2 interactions

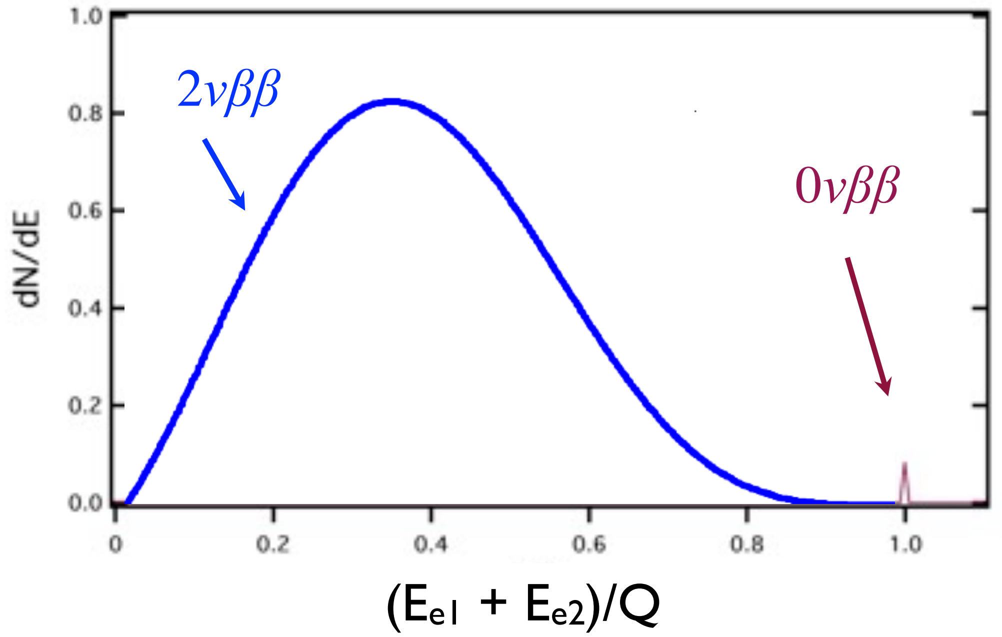
Probes of $\Delta L=2$ dynamics

- Neutrinoless double beta decay

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

$$\boxed{T_{1/2} > \#\, 10^{25} \mathrm{yr}}$$





Observable in certain even-even nuclei for which single beta decay is energetically forbidden

Probes of ΔL=2 dynamics

- Neutrinoless double beta decay

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

$$\boxed{T_{1/2} > \# 10^{25}\text{yr}}$$

- Decays of mesons or charged leptons

$$K^+ \to \pi^- \ell_1^+ \ell_2^+$$

$\ell_{1,2} = e, \mu$

$$B^+ \to h^- \ell_1^+ \ell_2^+$$

$h = \pi, K \quad \ell_{1,2} = e, \mu$

$$\tau^- \to \ell^+ h_1^- h_2^-$$

$\ell = e, \mu \quad h_{1,2} = \pi, K$

$$\boxed{\text{BRs} < \#10^{-10}}$$

$$\boxed{\text{BR } (\pi^- \mu^+ \mu^+) < \#10^{-9}}$$

$$\boxed{\text{BRs} < \#10^{-8}}$$

($\mu^- \to e^+$ conversion BR at 10^{-12} level)

Probes of ΔL=2 dynamics

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- Collider processes, e.g. same sign di-lepton production at LHC

$$pp \to \ell\ell + 2\ \mathrm{jets}$$

$\ell = e, \mu, \tau$

Probes of ΔL=2 dynamics

- Neutrinoless double beta decay

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

$$T_{1/2} > \# 10^{25} \mathrm{yr}$$

- 0νββ provides in many scenarios the strongest sensitivity to `ee' LNV couplings ("Avogadro's number wins", P. Vogel)
- Other processes can be competitive for `ee' couplings in certain scenarios and probe flavorful LNV couplings beyond `ee', inaccessible in 0νββ

Given our ignorance of the mechanism and scale of LNV

⬇

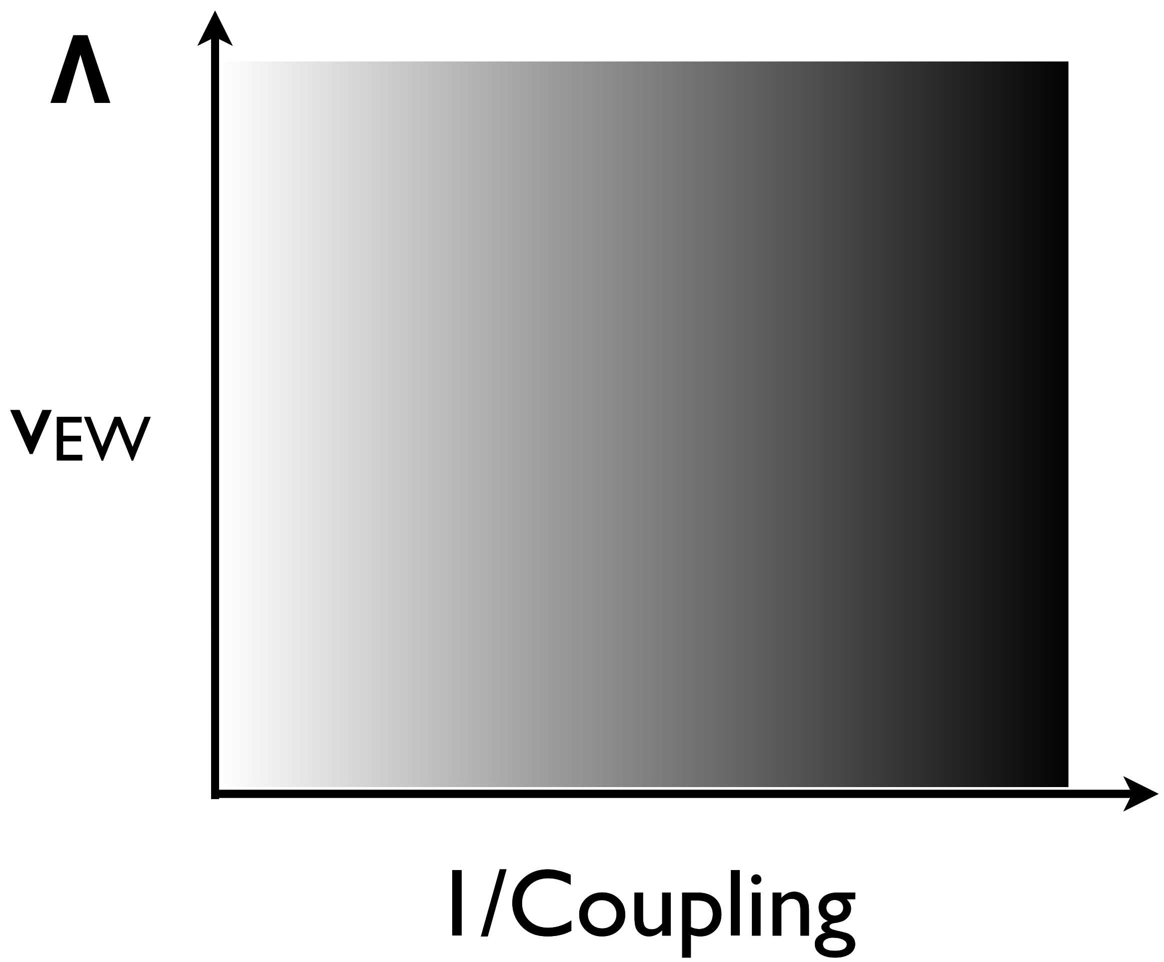
Pursuing many probes is essential. While LNV discovery may come from 0νββ, all probes will be essential to reconstruct LNV origin.
This requires an ambitious theoretical program [WP 2203. 21169]

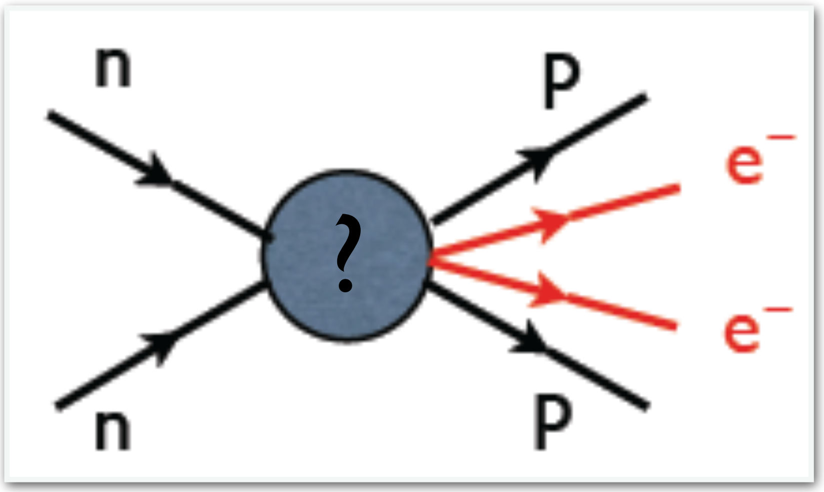
$$pp \to \ell\ell + 2 \text{ jets}$$

$$\ell = e, \mu, \tau$$

0νββ physics reach

- Ton-scale 0νββ searches ($T_{1/2} > 10^{27\text{-}28}$ yr) will probe at unprecedented levels LNV from a broad range of mechanisms





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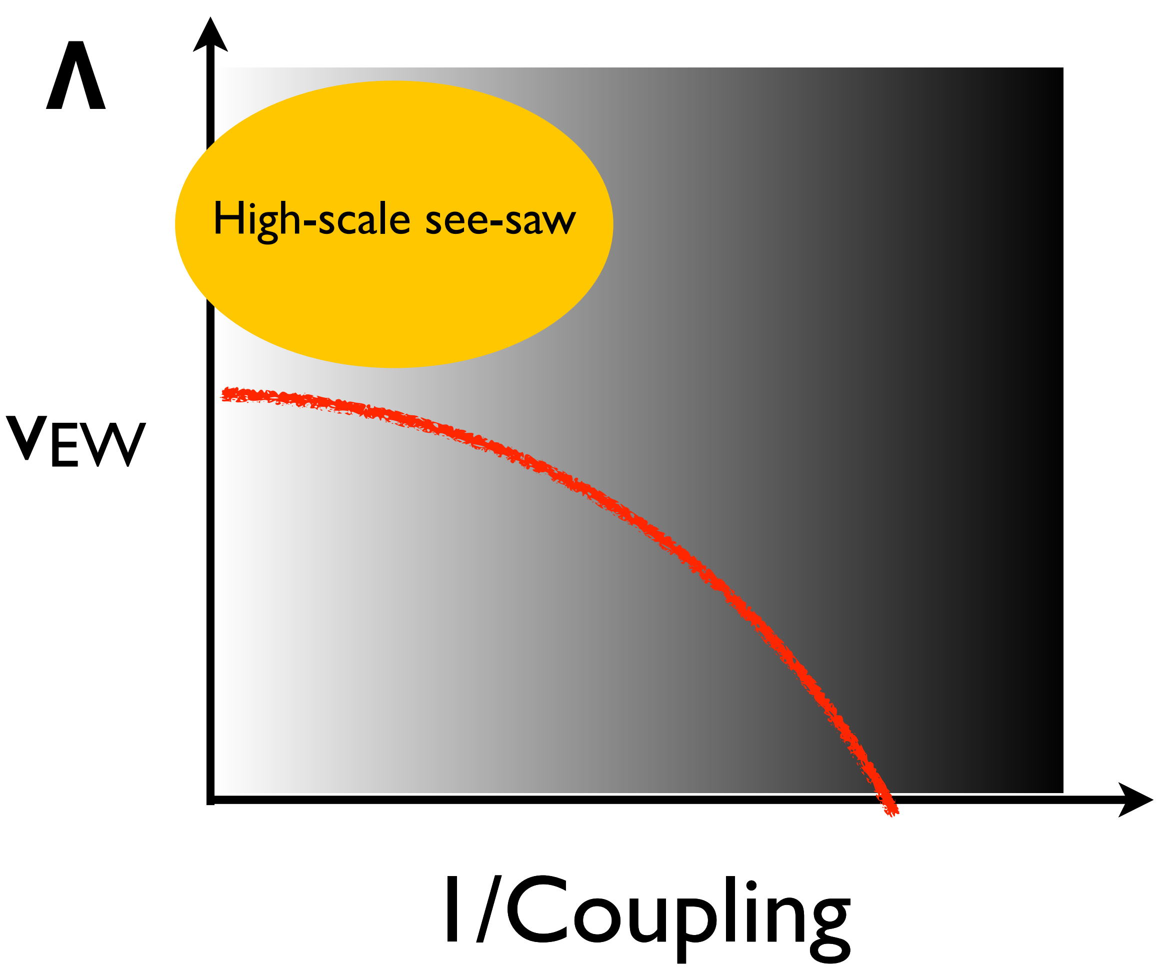

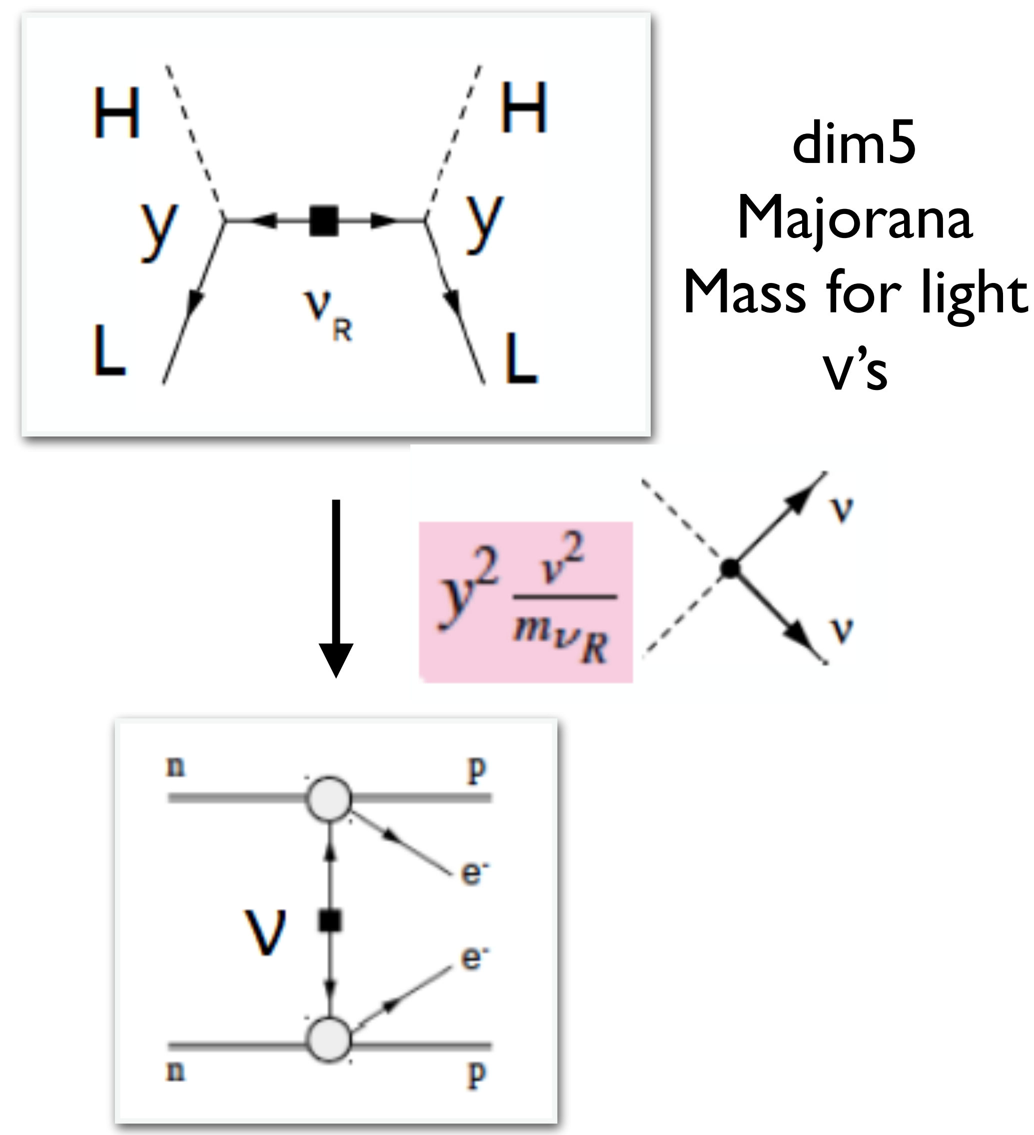

Only low-E remnant of LNV
is the neutrino mass

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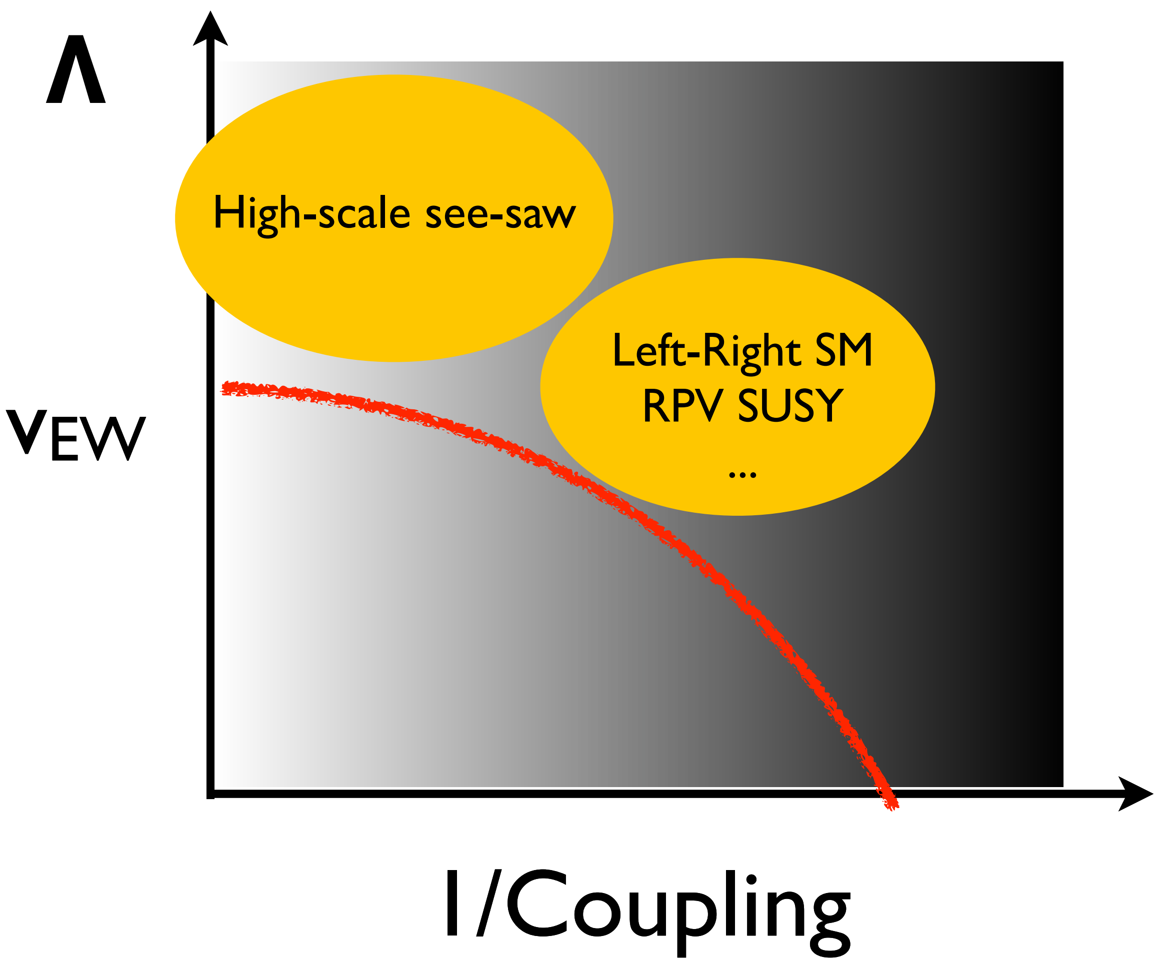
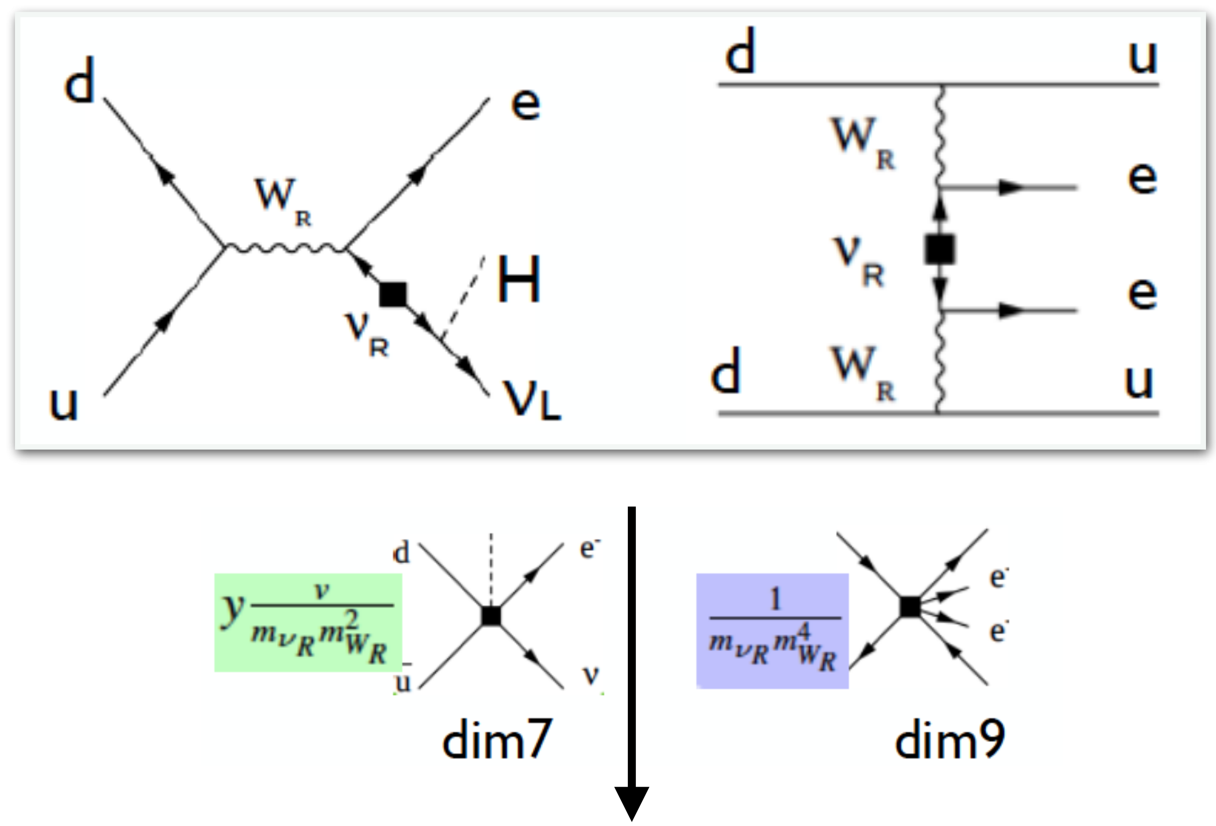
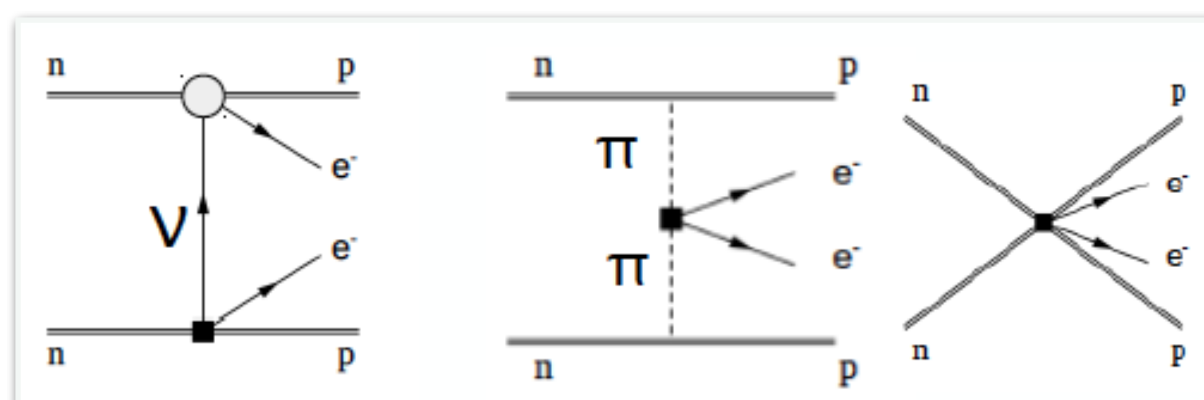


These contributions can compete with if scale is not too high and lead to new mechanisms at the nuclear scale





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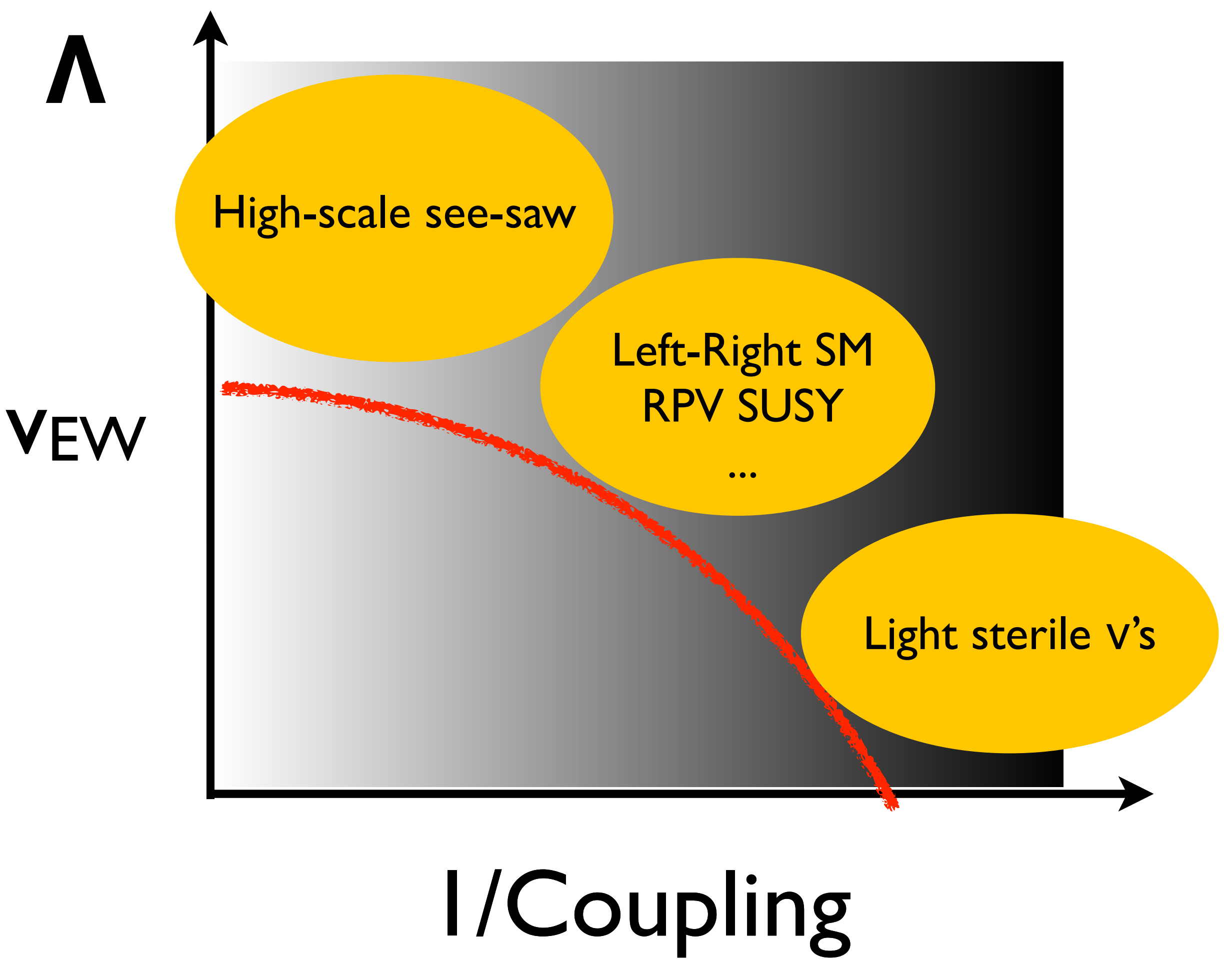
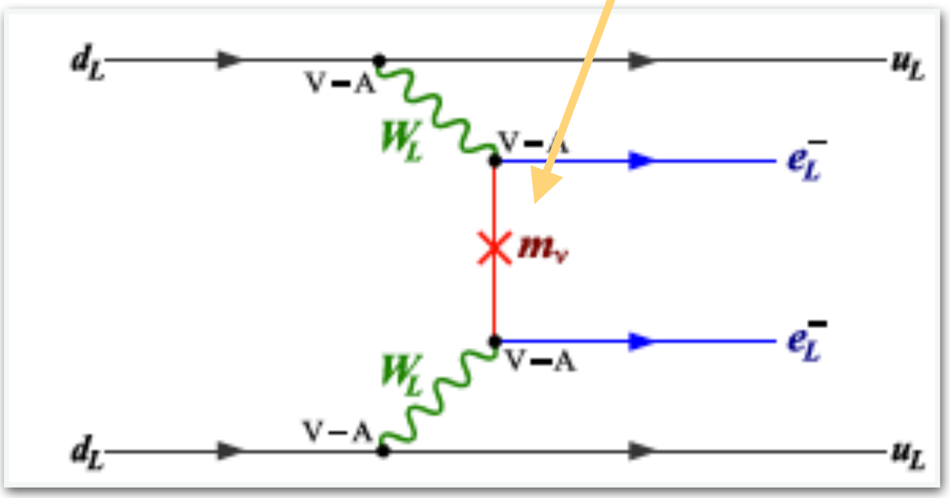


Light (nearly sterile) Majorana neutrinos:
M_R ~ eV → GeV:



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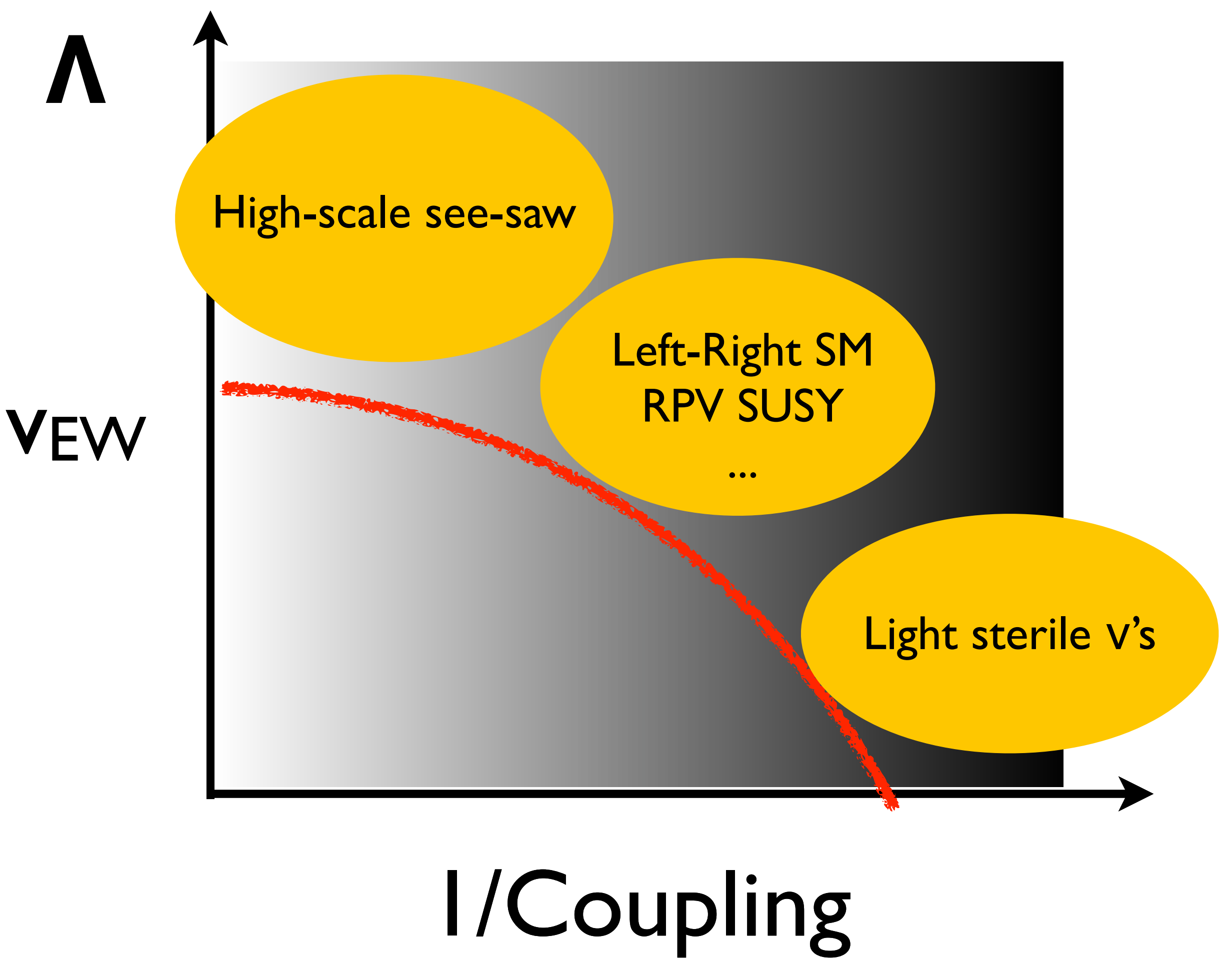


0νββ's impact and relation to other probes of LNV is best analyzed through a tower of EFTs that connect LNV scale Λ to nuclear scales, with controllable uncertainties

See VC-Dekens-deVries-Graesser-Mereghetti 1806.02780 and references therein

EFT framework

E

Λ
(> TeV)

Quarks

Λ_χ
(~GeV)

Nucleons, pions

Nuclei

$$\mathcal{L}_{\rm BSM}$$

$\downarrow$ Integrate out heavy particles

$$\mathcal{L}_{\rm eff} = \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(7)}}{\Lambda^3} O_i^{(7)} + \sum_i \frac{C_i^{(9)}}{\Lambda^5} O_i^{(9)}$$

Standard Model EFT
+ light d.o.f. (ν_R, ..):
v/Λ

$\downarrow$ *Hadronic* matrix elements

$$\mathcal{L}_{\pi,N} = \sum_i \tilde{C}_i(C_i)\, \tilde{O}_i$$

Chiral EFT:
Q/Λ_χ ($Q \sim k_F \sim m_\pi$)

$\downarrow$ *Nuclear* matrix elements

$T_{1/2}[\, \tilde{C}_i\, [C_j]]$

Chain of EFTs +

Hadronic matrix elements
& many-body methods

$\Rightarrow$ $T_{1/2}[\, \tilde{C}_i\, [C_j]\,] \sim (v/\Lambda)^A\, (\Lambda_\chi/v)^B\, (k_F/\Lambda_\chi)^C$

Main themes

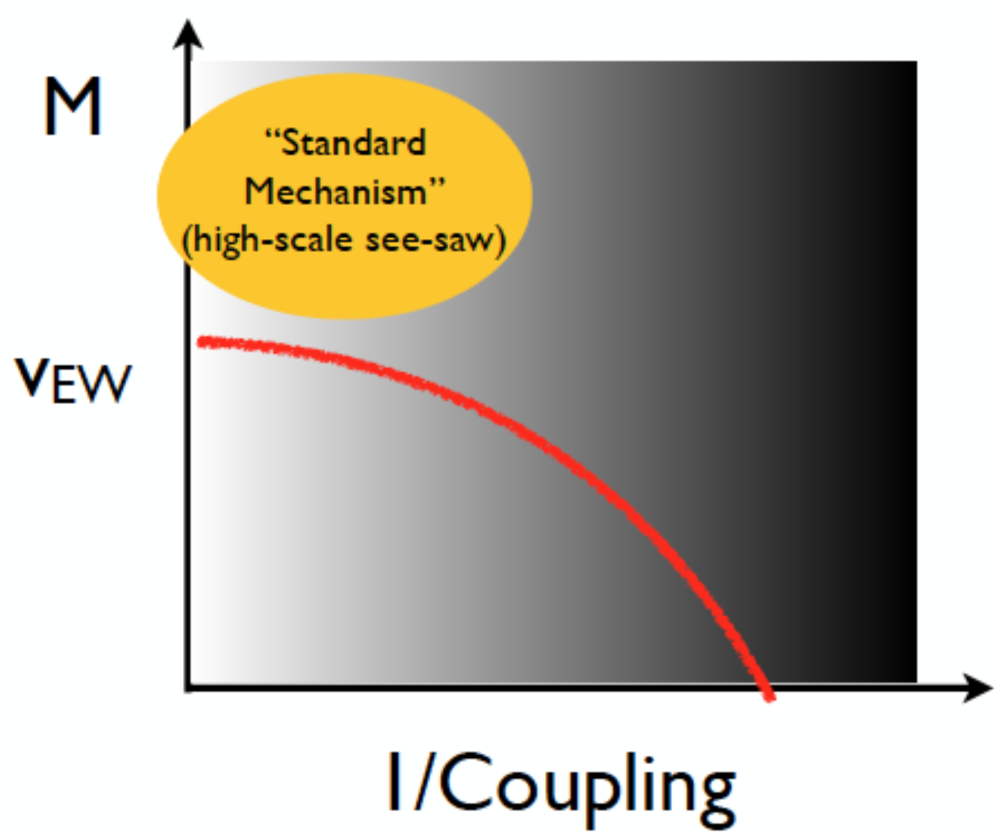
WP 2203. 21169

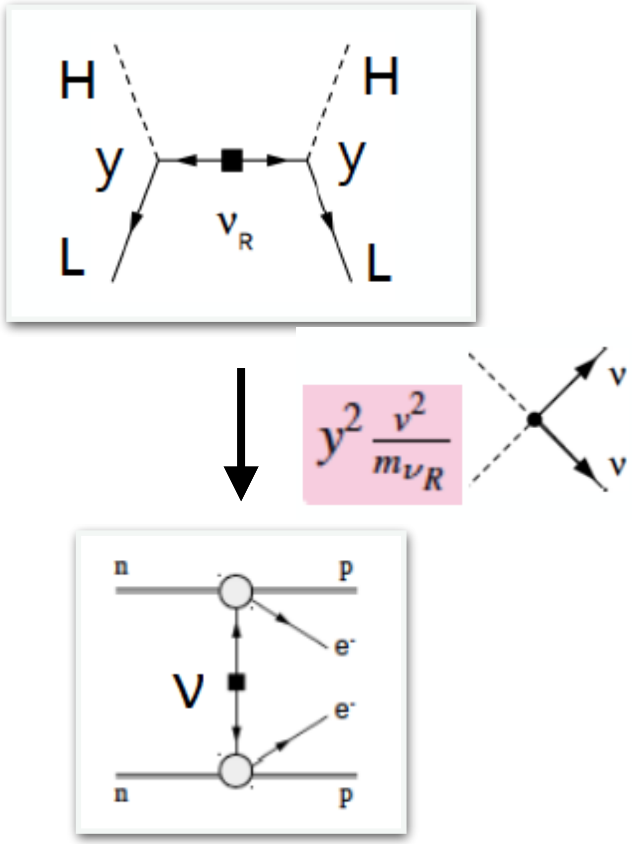
- Model building and phenomenology:
  - Investigate correlated signals of TeV (and lower) scale LNV across multiple phenomena and experiments, from cosmology to colliders to nuclei
- The "hadronic threshold":
  - Somewhat overlooked in the past. EFT methods have revealed that this is relevant even for light ν exchange mechanism
  - Requires two-nucleon matrix elements from LQCD: decadal program
- Nuclear matrix elements:
  - Shift from phenomenological approaches to nuclear "ab-initio" methods, with EFT-based nucleon interactions rooted in QCD.
  - First results for ^{48}Ca decay. Ambitious & challenging program ahead

In the rest of this talk

- Survey classes of models by LNV scale (op. dimension), highlighting:
    - phenomenological interest
    - theoretical developments and challenges
      (EFT, hadronic / nuclear matrix elements, …)

High-scale seesaw (LNV at dim-5)

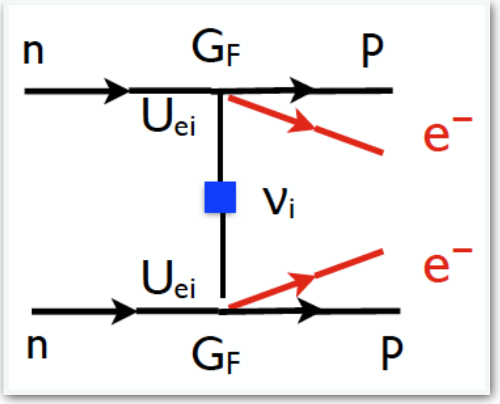




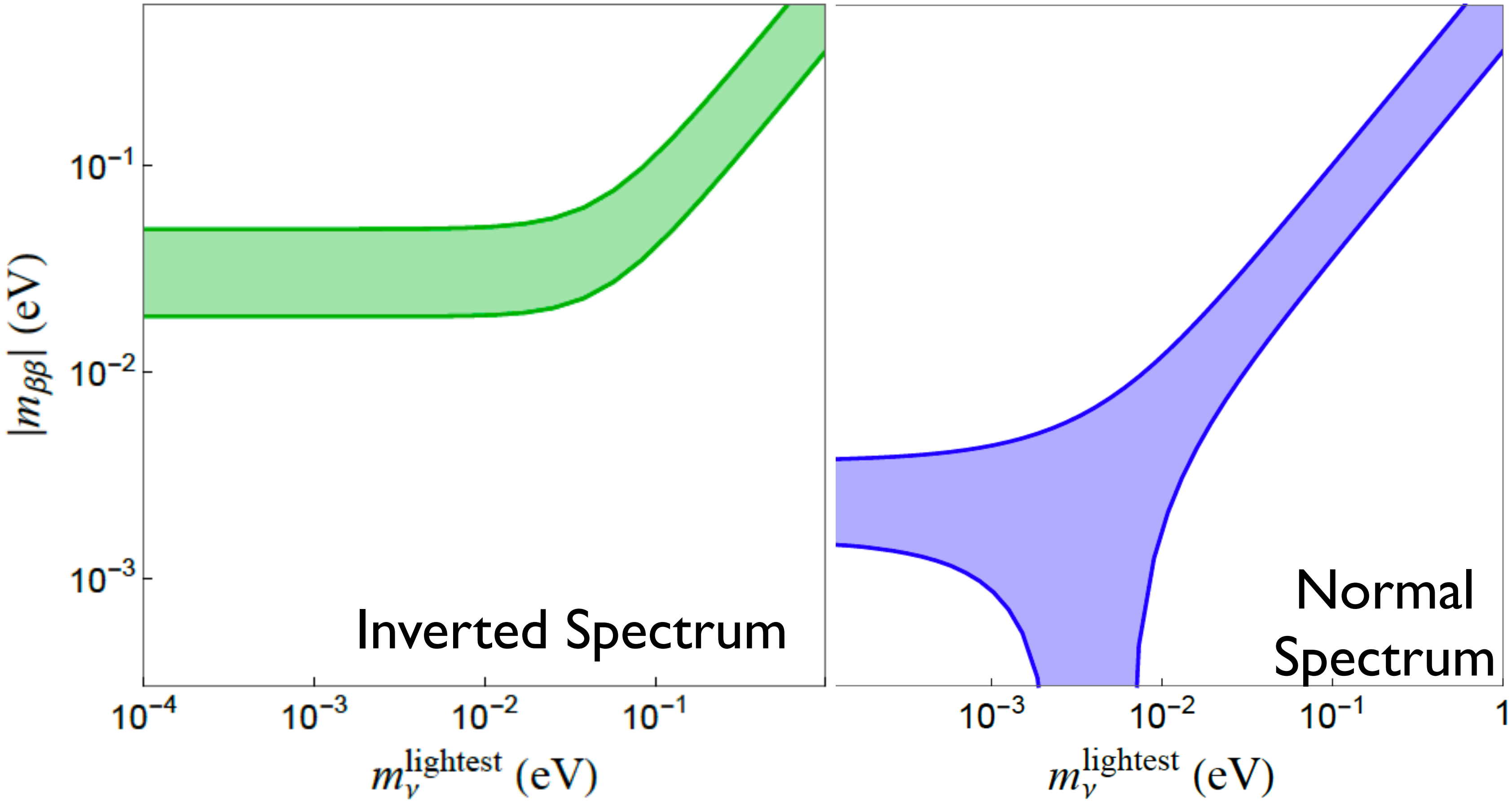
Discovery potential / target

- In this case $0\nu\beta\beta$ is a *direct* probe of ν Majorana mass: $\Gamma \propto |M_{0\nu}|^2 (m_{\beta\beta})^2$

$$\langle m_{\beta\beta}\rangle^2 = |\sum_i U_{ei}^2 m_{\nu i}|^2$$



Bands: unknown Majorana phases



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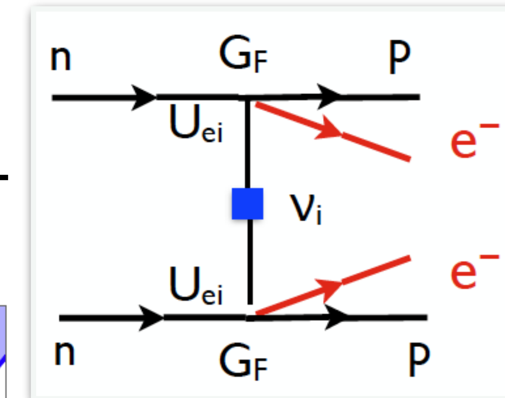

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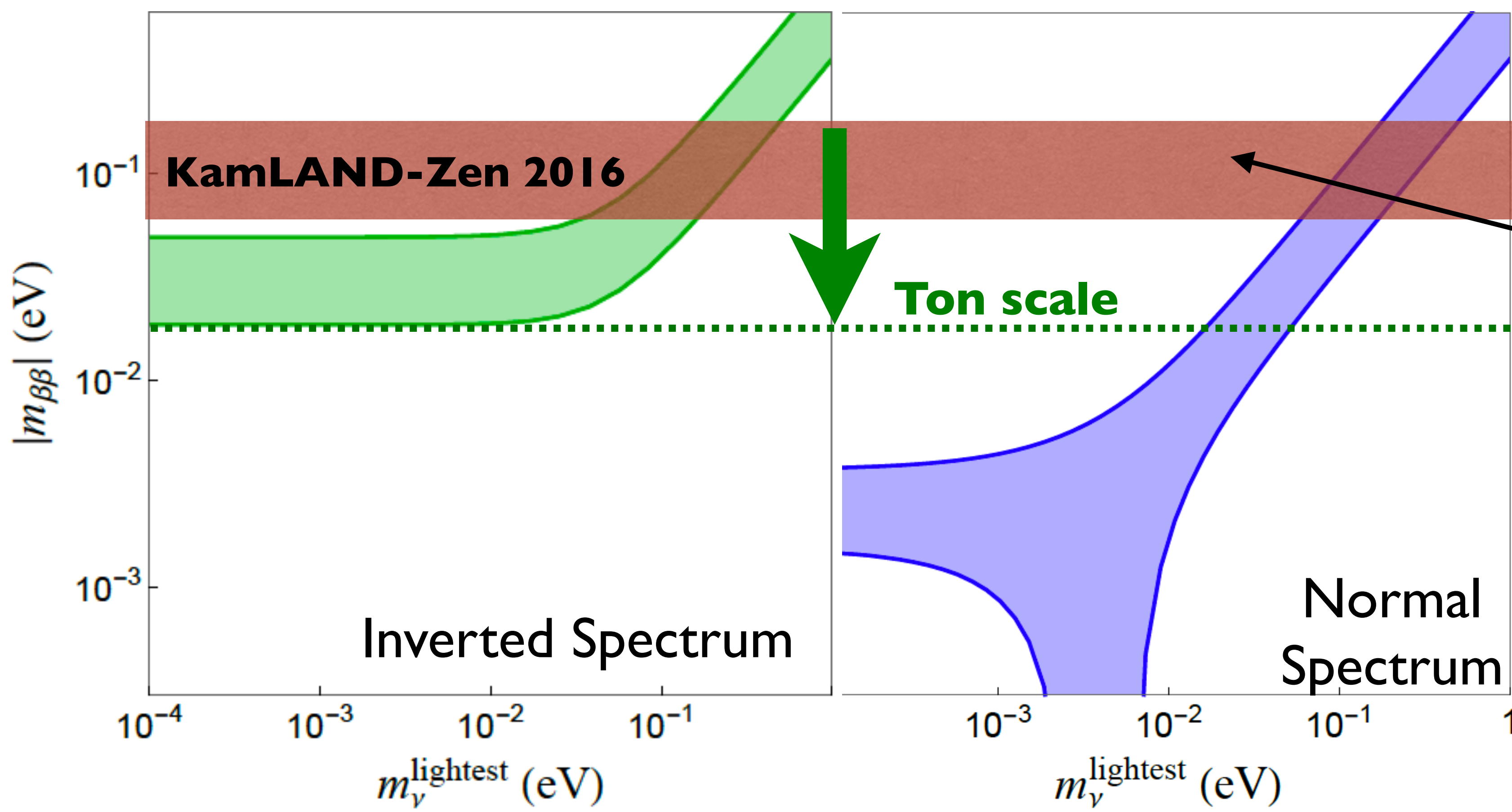

Assume range for nuclear matrix elements from different many-body methods

Assuming current range for matrix elements, discovery @ ton-scale *possible* for inverted spectrum or $m_{lightest}$ > 50 meV

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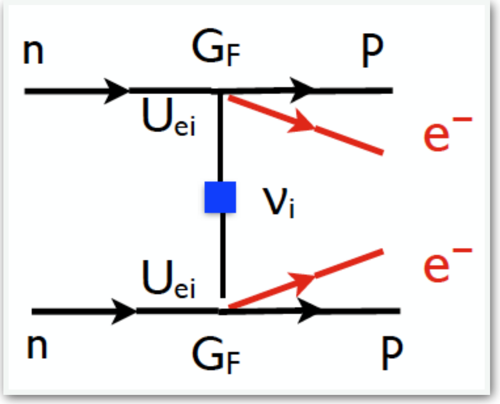
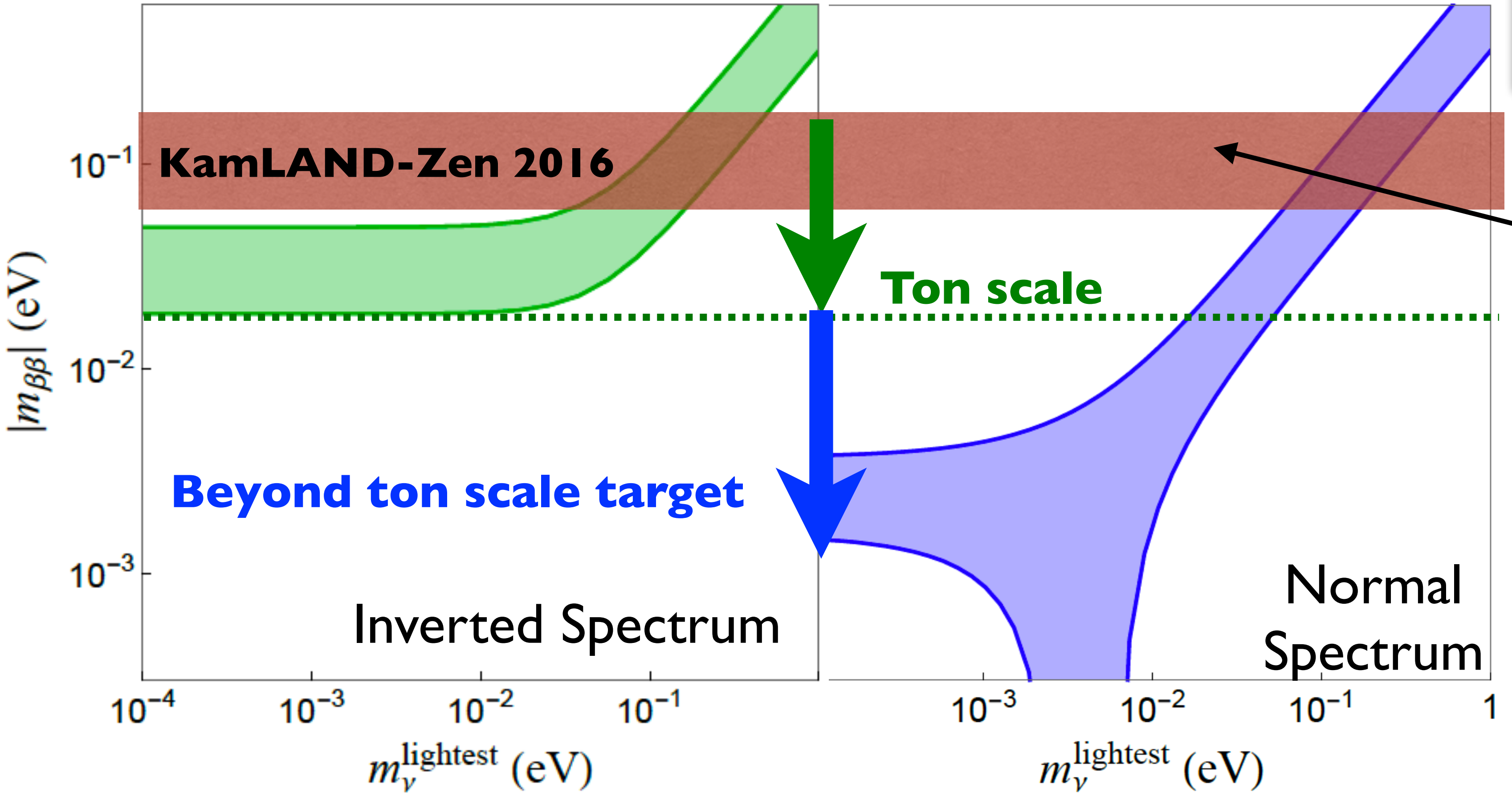




Bands: unknown Majorana phases

Assume range for nuclear matrix elements from different many-body methods

Natural (but challenging!) beyond ton-scale target seems $m_{\beta\beta} \sim$ meV

Diagnosing power

- High scale seesaw implies falsifiable correlation with other ν mass probes. Future data can unravel new LNV sources or physics beyond "ΛCDM + m_ν"

$$m_{\beta\beta} = \left| \sum_i U_{ei}^2 \, m_i \right|$$

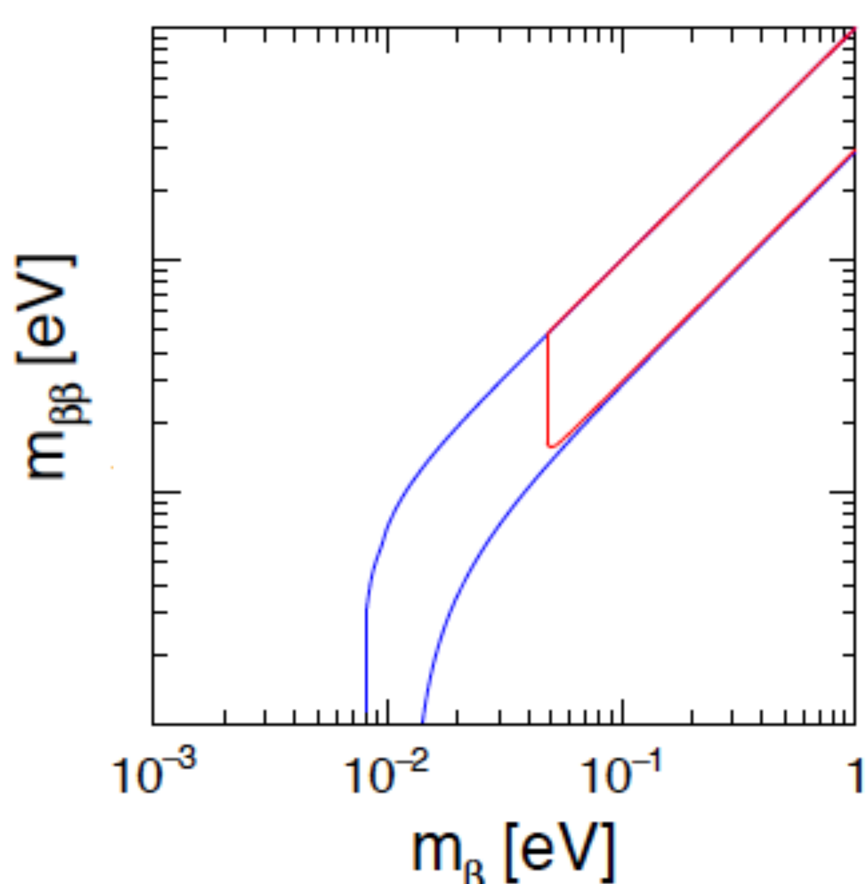
0νββ decay

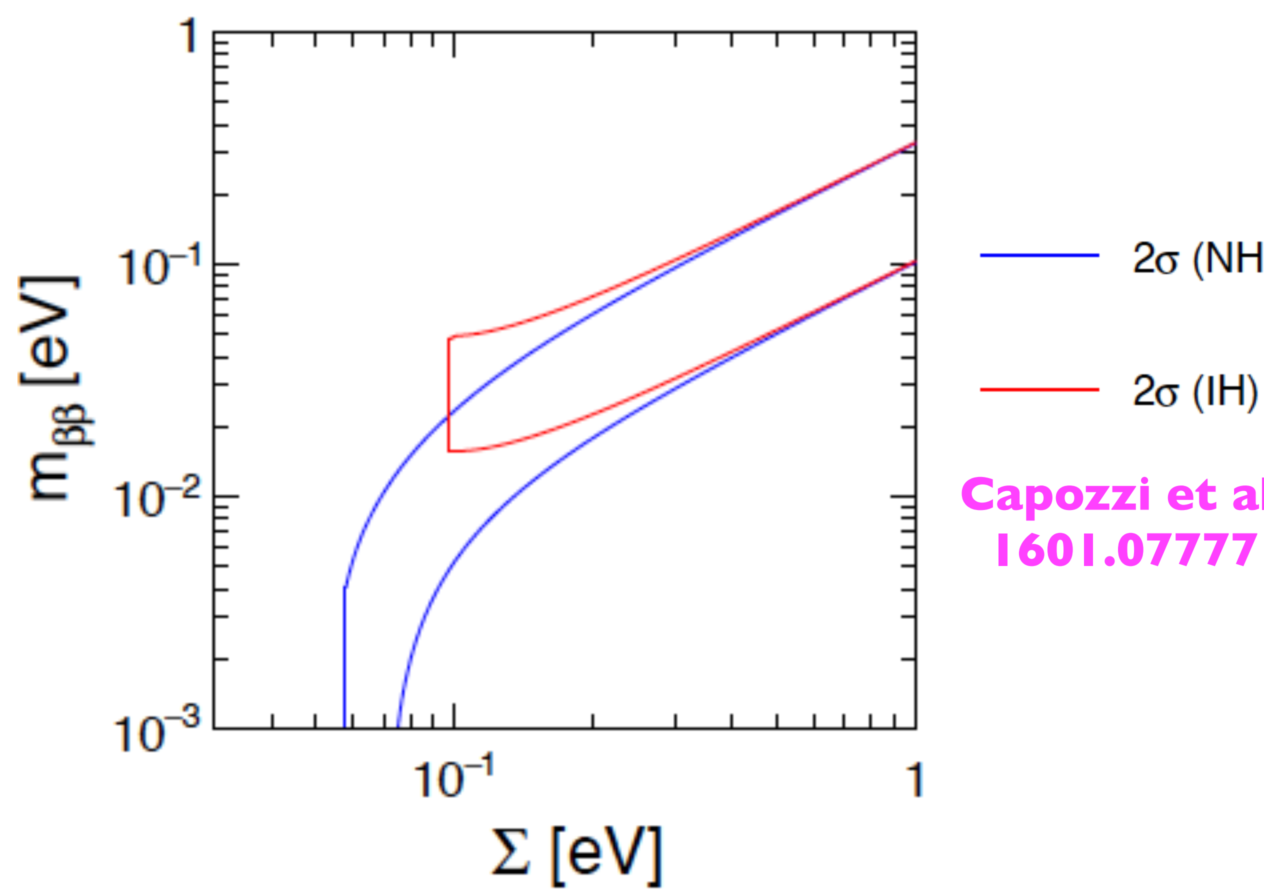
$$m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2}$$

Tritium β decay

$$\Sigma = \sum_i m_i$$

Cosmology





Capozzi et al, 1601.07777

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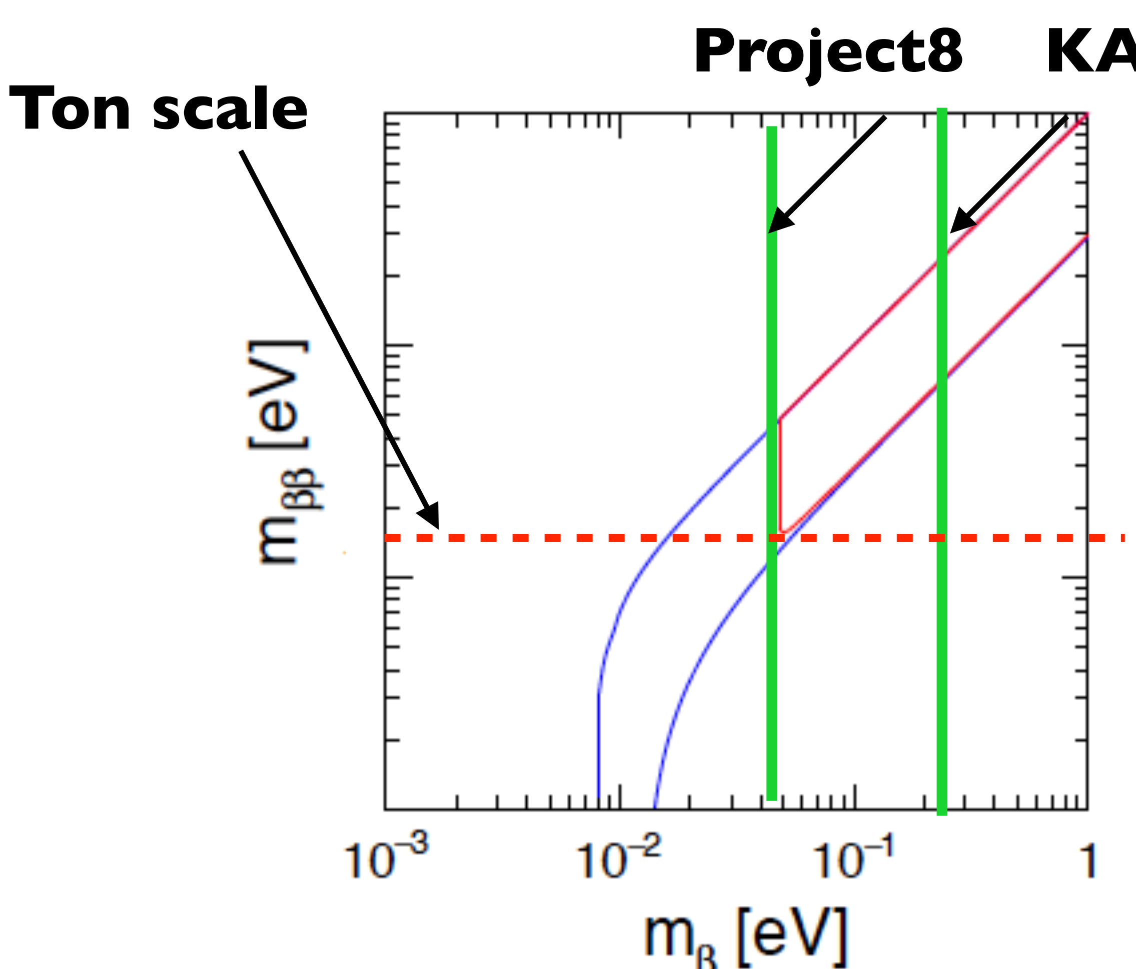

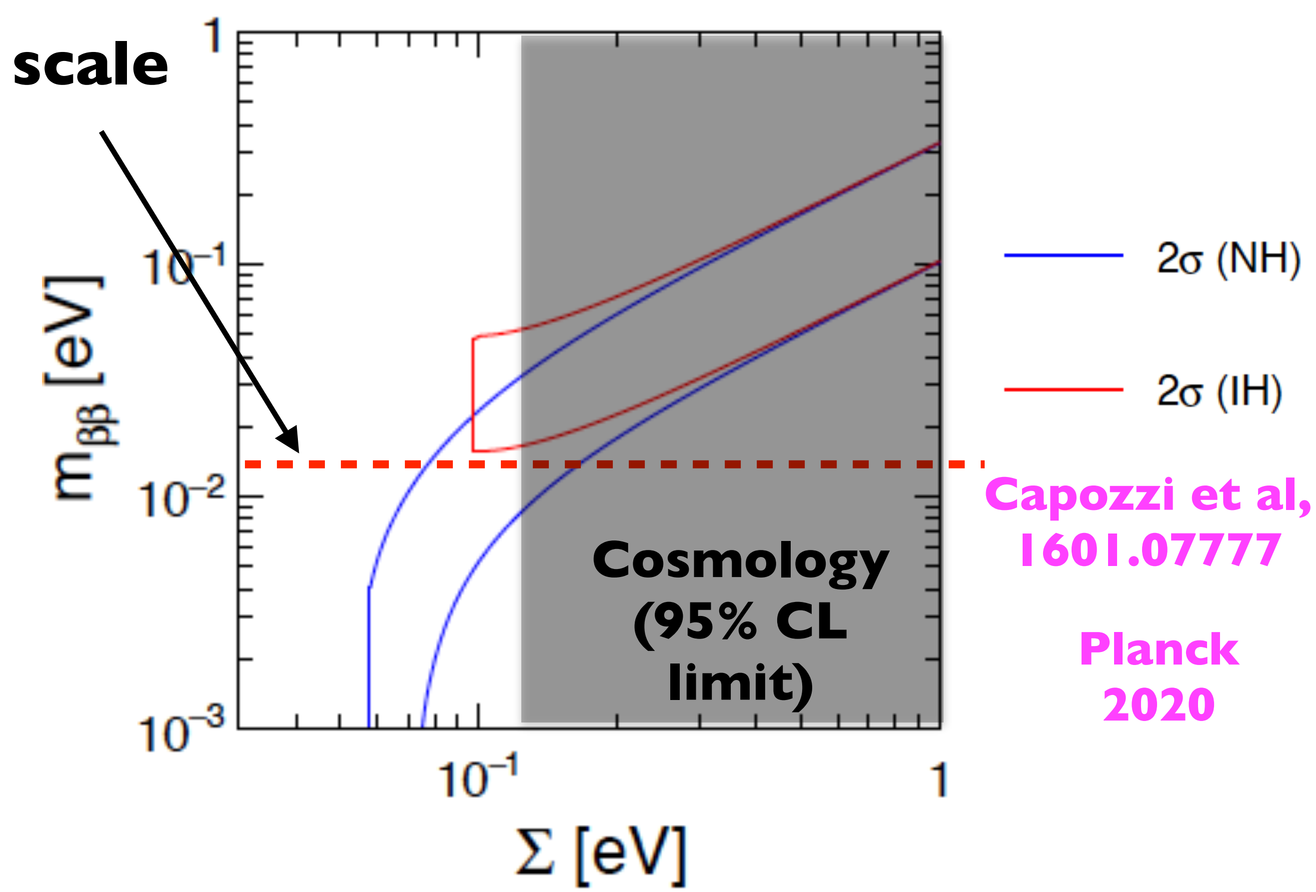

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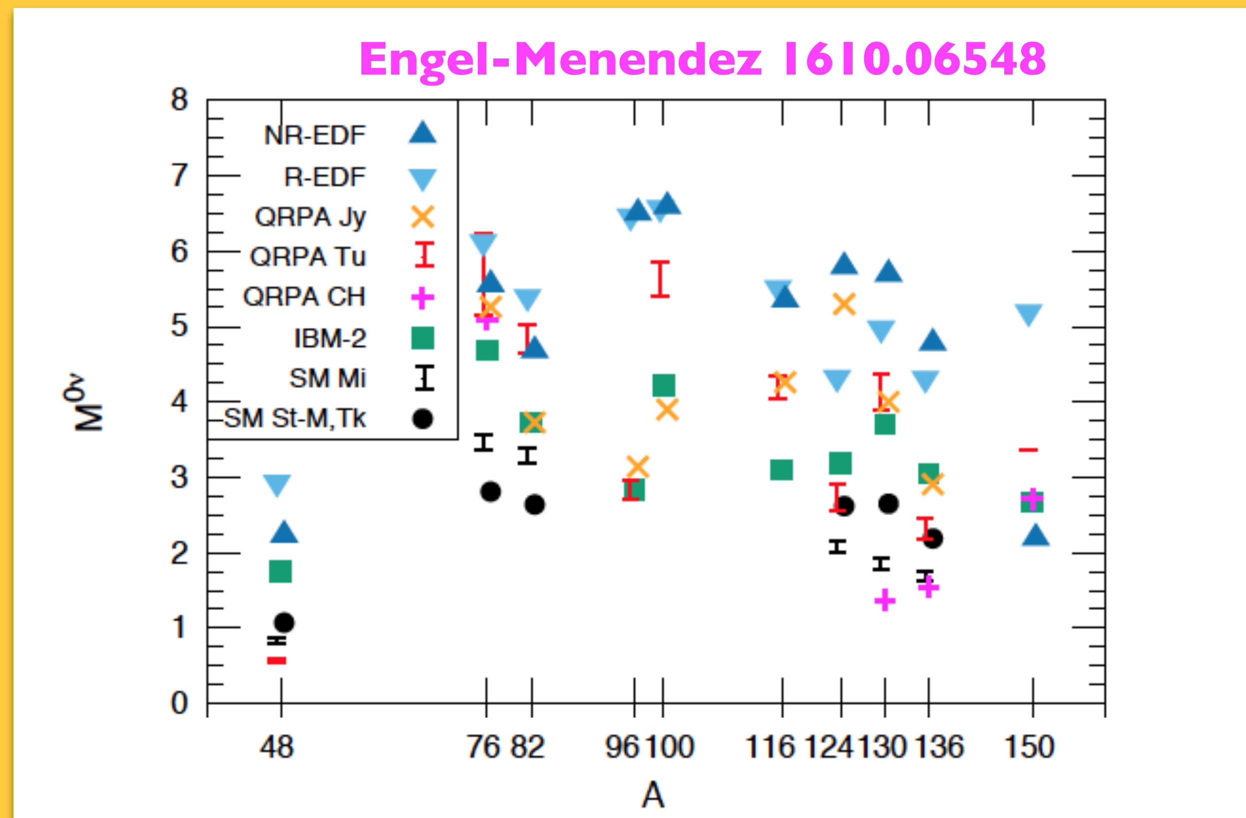
Cosmology

But these important *quantitative* connections require knowing nuclear matrix elements and their uncertainties!

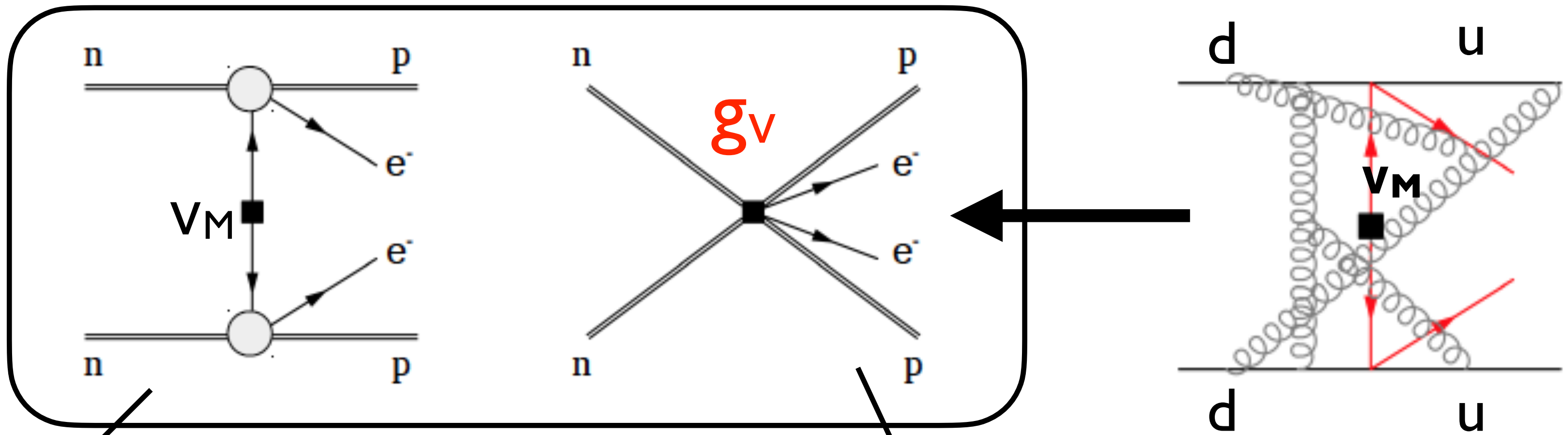


New insights from EFT

VC, W. Dekens, E. Mereghetti, A. Walker-Loud, 1710.01729

VC, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, S. Pastore, U. van Kolck 1802.10097

- Transition operator to leading order in Q/Λ_χ ($Q \sim k_F \sim m_\pi$, $\Lambda_\chi \sim$ GeV)



'Usual' ν_M exchange $\sim 1/Q^2$
Coulomb-like potential

'New': short-range coupling $g_\nu \sim 1/Q^2$

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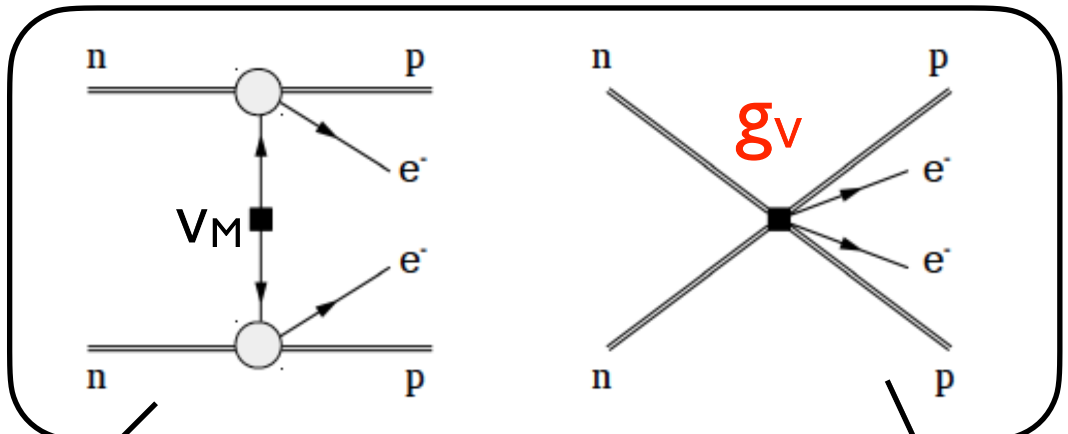
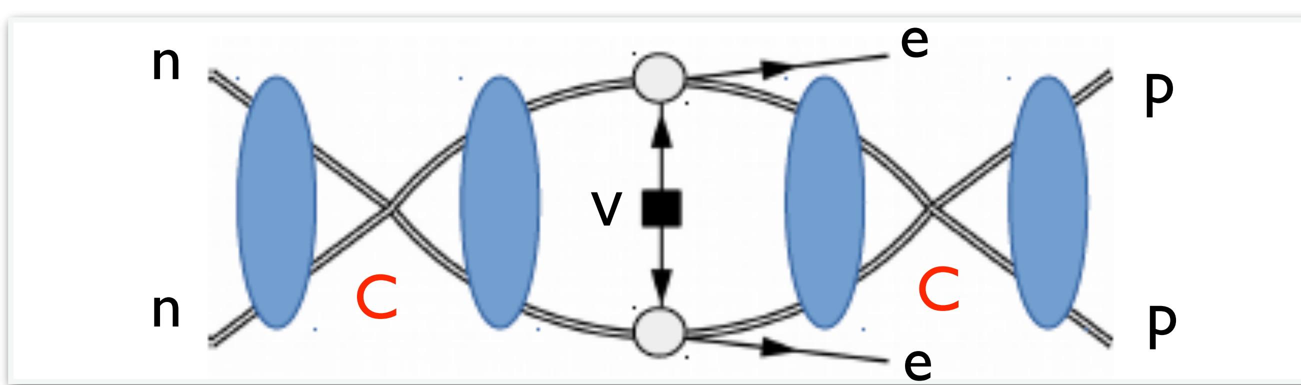


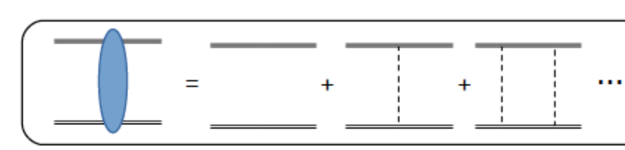
'Usual' v_M exchange $\sim 1/Q^2$
Coulomb-like potential

'New': short-range coupling $g_V \sim 1/Q^2$
Required by renormalization of $nn \rightarrow ppee$ amplitude in presence of strong interactions

UV divergence $\propto$ $C^2 \sim 1/Q^2$

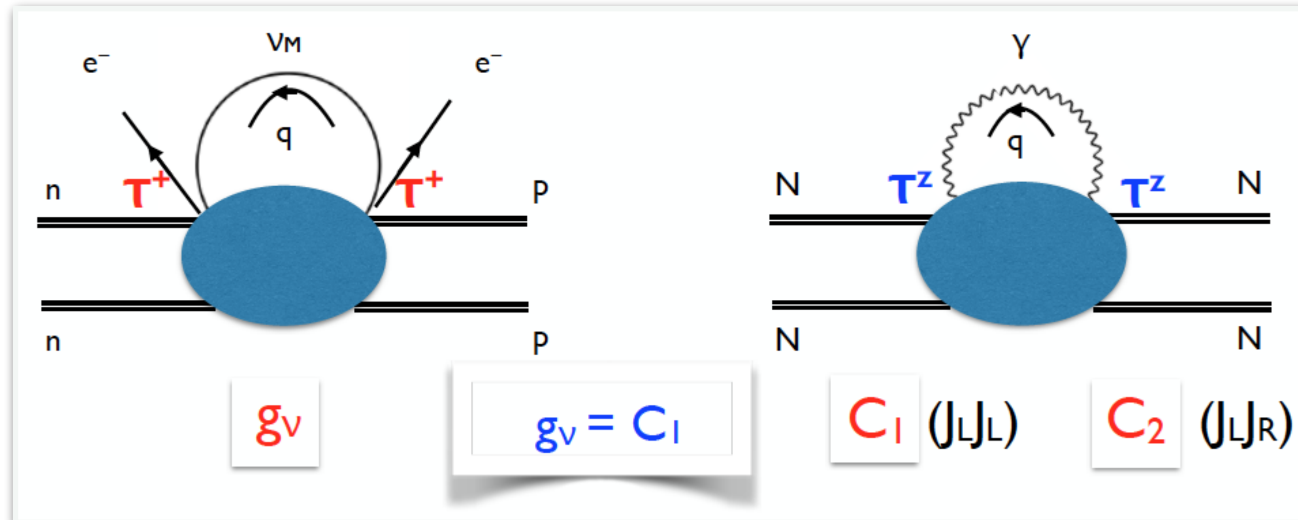
$C \sim 4\pi/(m_N Q)$
Strong $^1S_0$ short-range interaction





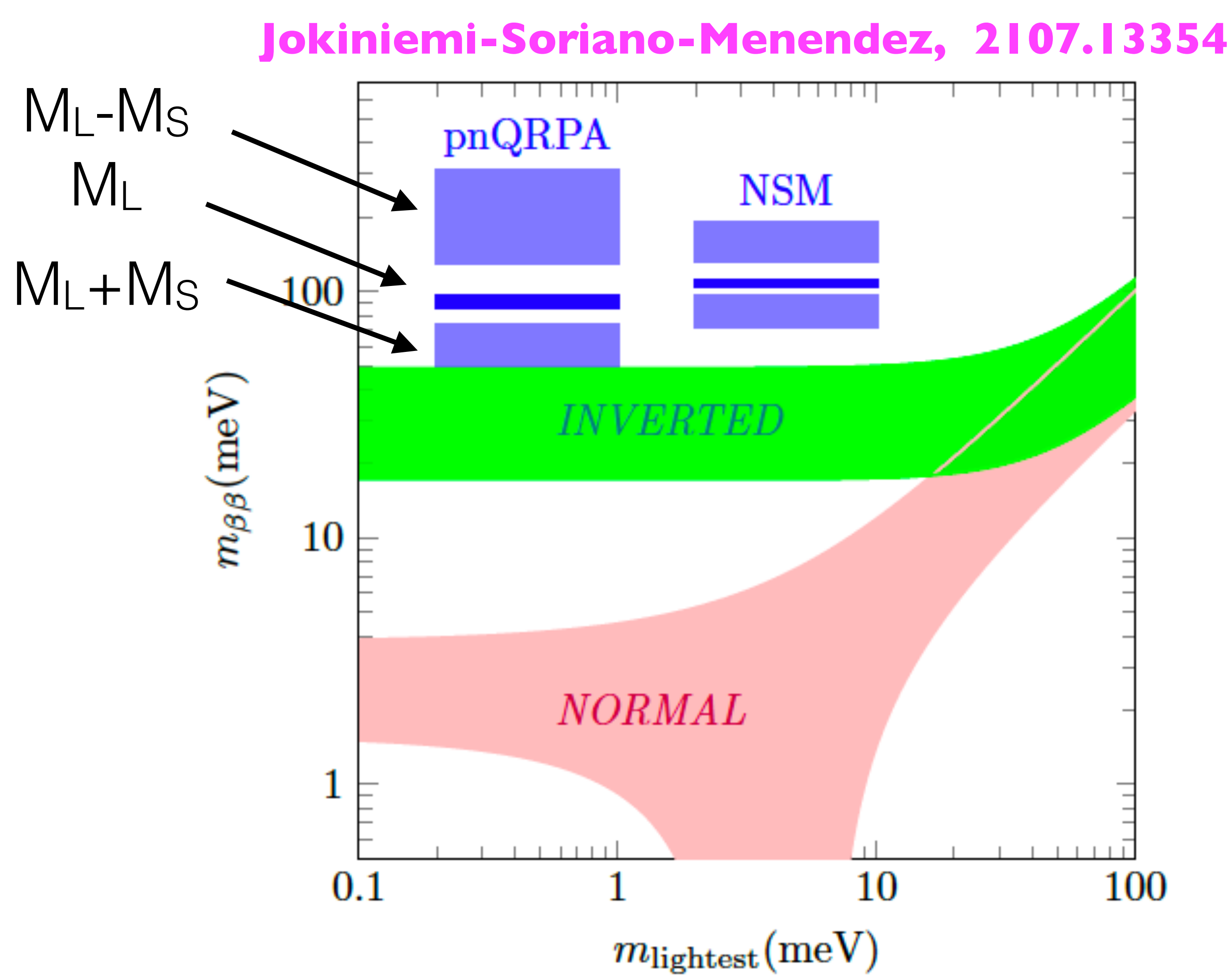
Impact on nuclear matrix elements

- Chiral+isospin symmetry relates g_V to one of two I=2 e.m. couplings (hard γ's & ν's)



- NN data ($a_{nn}+a_{pp}-2a_{np}$) determine C_1+C_2, confirming LO scaling

- *Assuming* $g_V \sim (C_1+C_2)/2$ → O(1) impact on m.e. and $m_{\beta\beta}$ extraction



Towards determining g_V

- Large-N_C arguments point to $g_V \sim (C_1 + C_2)/2$

Richardson, Shindler, Pastore, Springer, 2102.02814

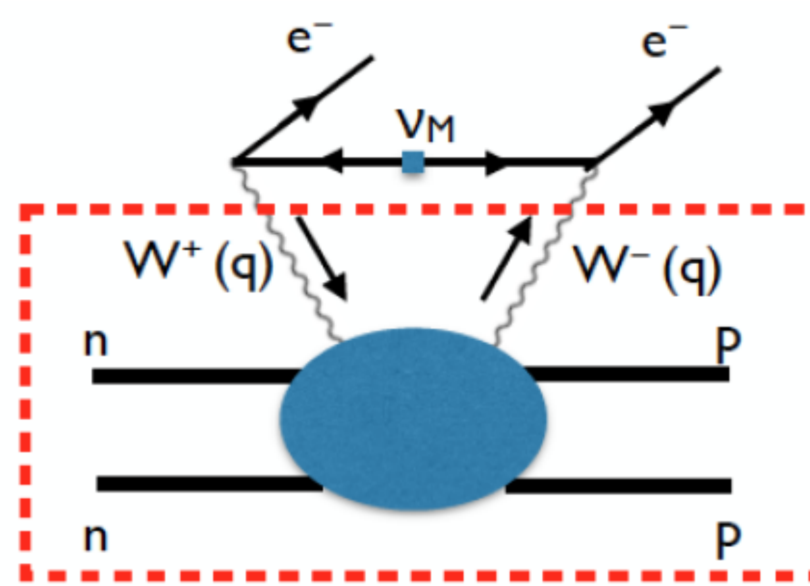
- Lattice QCD
  - $\pi^- \to \pi^+ e^- e^-$ precisely known

Tuo et al. 1909.13525; Detmold, Murphy 2004.07404

  - Formalism for NN developed

Davoudi, Kadam, 2012.02083
Feng, Jin, Wang, Zhang, 2005.01956

- Analytic approach inspired by Cottingham formula for $\delta m_{p,n}$ (EM)



VC, Dekens, deVries, Hoferichter, Mereghetti, 2012.11602, 2102.03371

Towards determining g_V

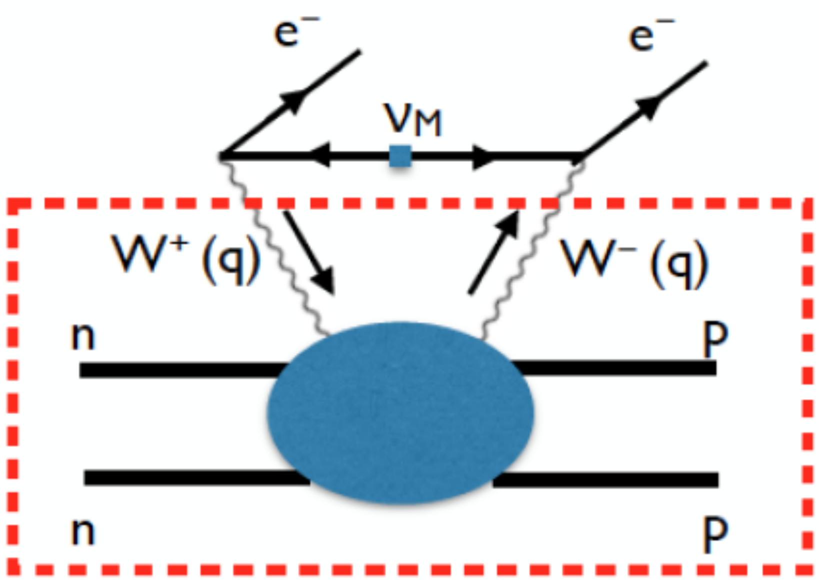
- Dispersive approach provides $C_{1,2}$ and can be validated by data:
$C_1+C_2 \Rightarrow (a_{nn}+a_{pp})/2 - a_{np}$ = 15.5(4.5) fm versus 10.4(2) fm (exp)

- Ab initio (IMSRG) calculation of $^{48}Ca \to {}^{48}Ti$ with dispersive $g_V=C_1$
$\Rightarrow$ contact term enhances nuclear matrix element by (43±7)%

Wirth, Yao, Hergert, 2105.05415

- Lattice QCD results expected in the next few years

- Analytic approach inspired by Cottingham formula for $\delta m_{p,n}$ (EM)

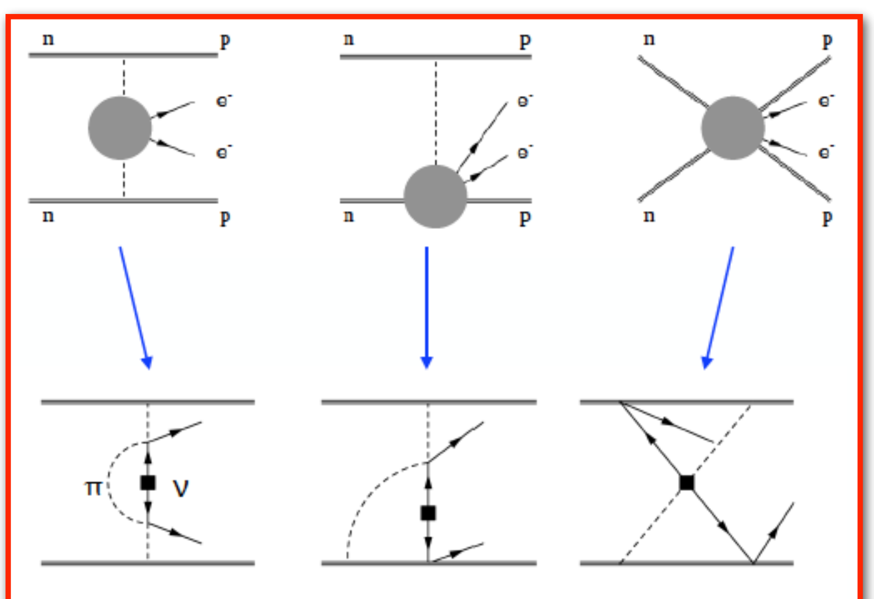


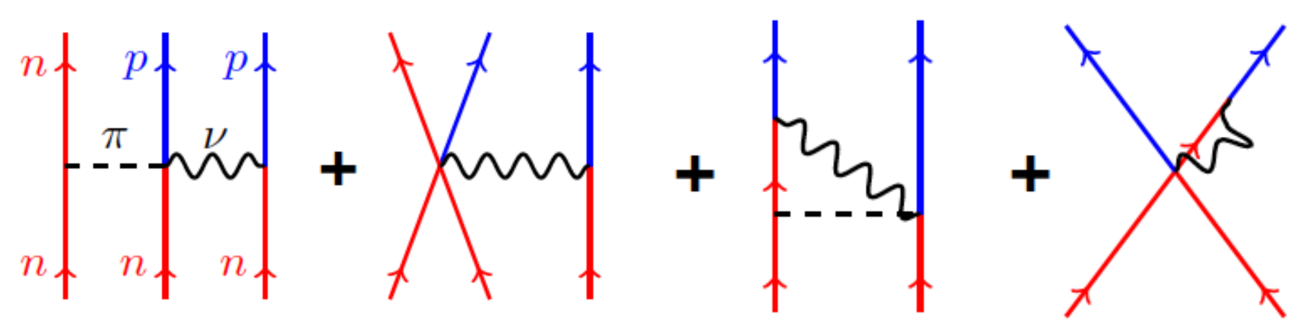
VC, Dekens, deVries, Hoferichter, Mereghetti, 2012.11602, 2102.03371

What about higher orders?

- N2LO
  - πN loops + new contact — VC, W. Dekens, E. Mereghetti, A. Walker-Loud, 1710.01729
  - 2-body **x** 1-body current (and a new contact) — Wang-Engel-Yao 1805.10276
  - Neglecting contact terms, calculations in light and heavy nuclei find O(10%) corrections: encouraging!

S. Pastore, J. Carlson, V.C., W. Dekens, E. Mereghetti, R. Wiringa 1710.05026
J. Engel, private communication





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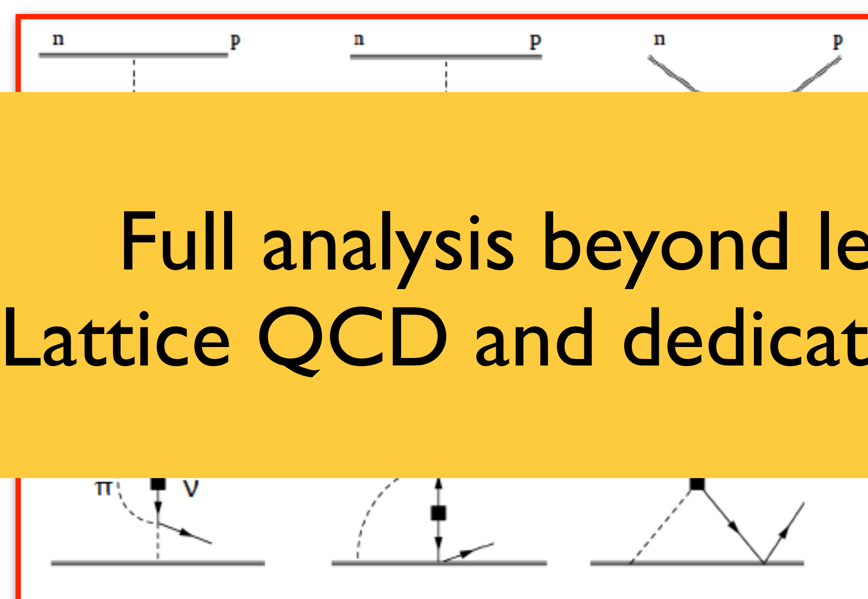
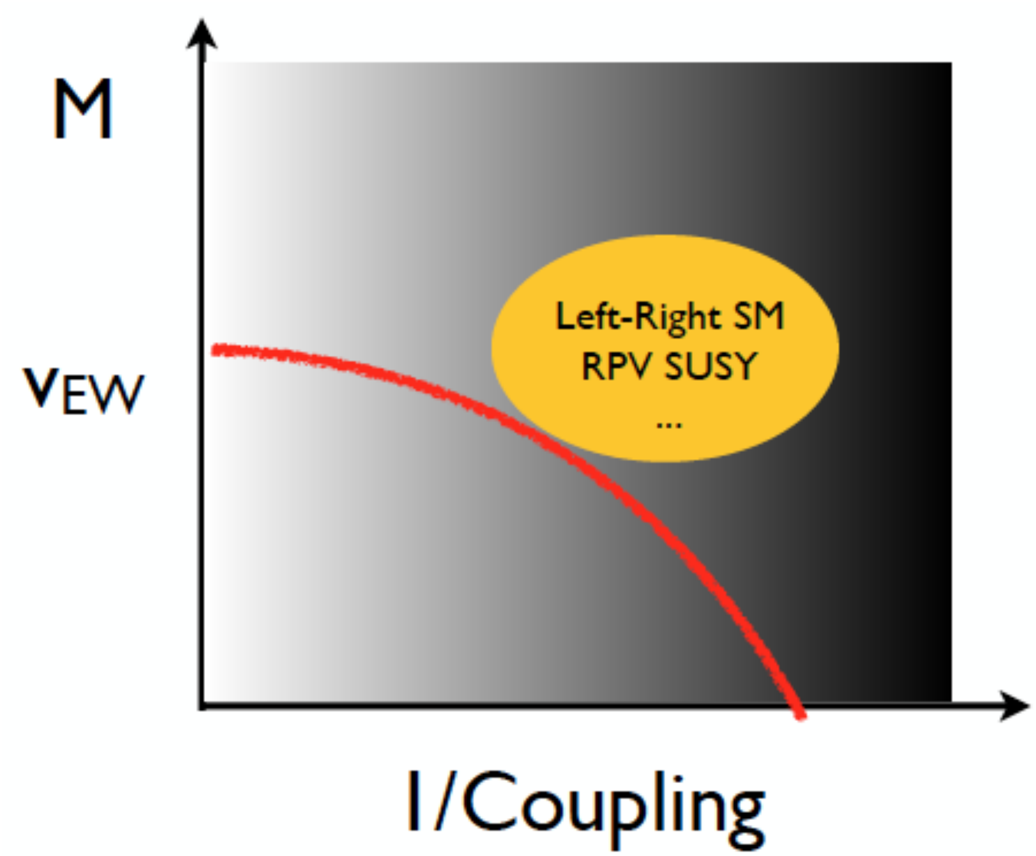
S. Pastore, J. Carlson, V.C., W. Dekens, E. Mereghetti, R. Wiringa 1710.05026
J. Engel, private communication



Full analysis beyond leading order requires again matching to Lattice QCD and dedicated many body calculations — decadal goal

0νββ from multi-TeV scale dynamics (dim-7, 9, ...operators)



Phenomenological interest

- Induce contributions to 0νββ *not directly related to the exchange of light neutrinos,* within reach of current experiments

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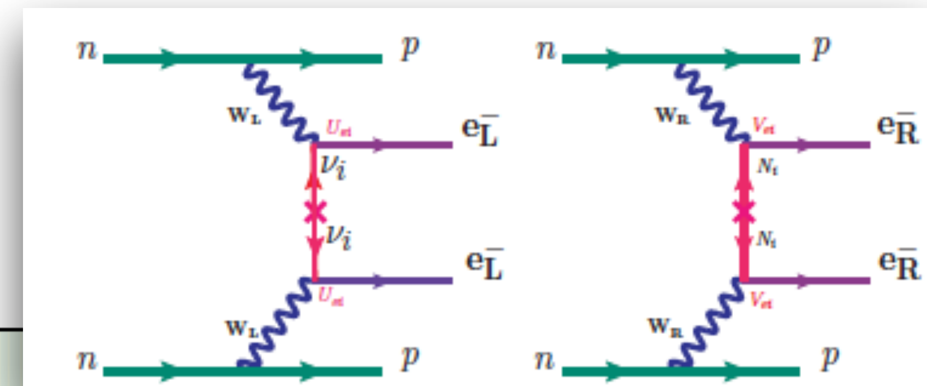
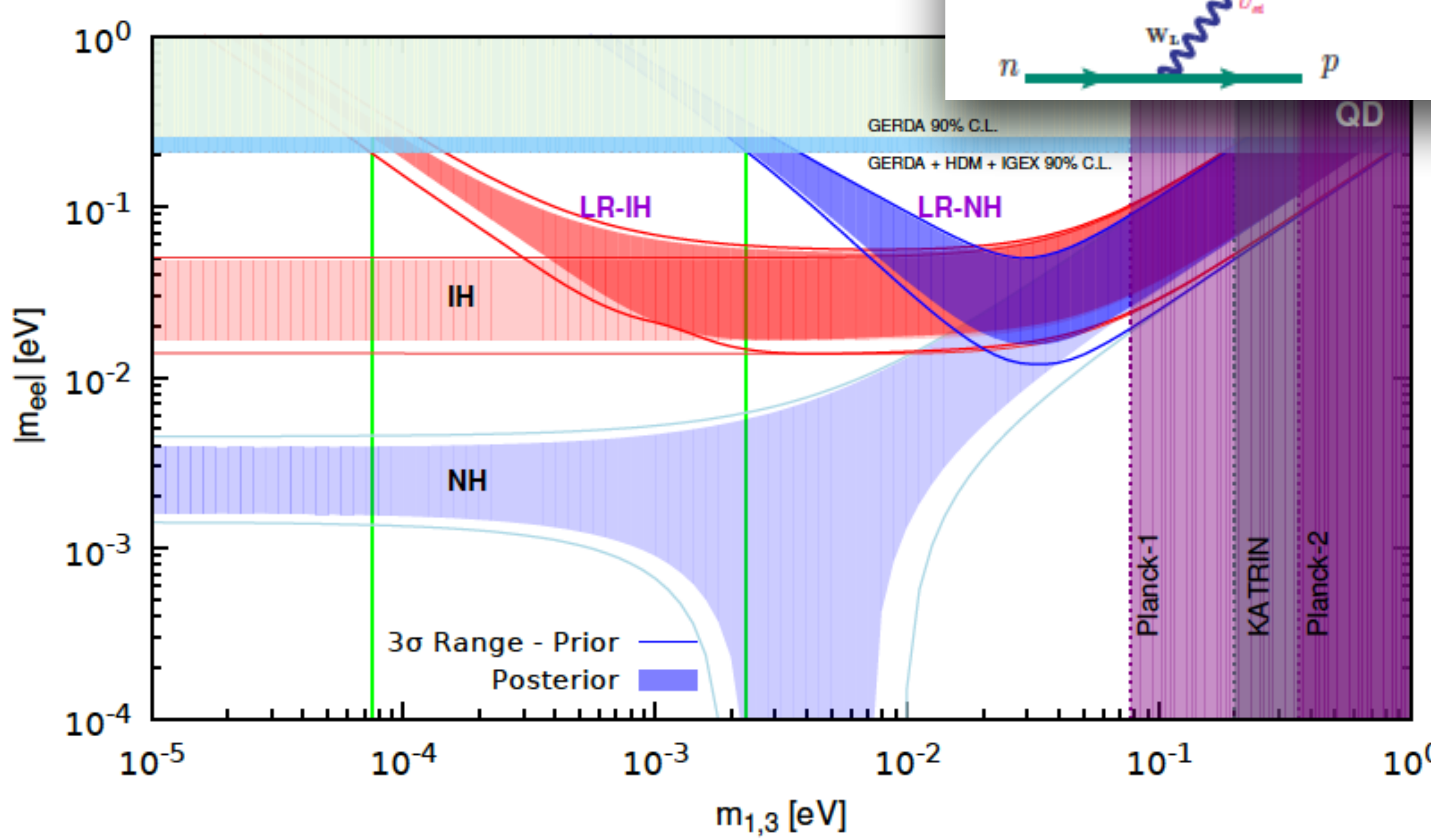
Example: left-right symmetric model with type-II seesaw





$$M_i \propto m_i$$

$$V_R^{PMNS} = V_L^{PMNS}$$

$$M_i = \frac{m_1}{m_3} M_3, \text{ for NH}$$
$$M_i = \frac{m_1}{m_2} M_2, \text{ for IH.}$$

$M_{2,3}$ = 1 TeV

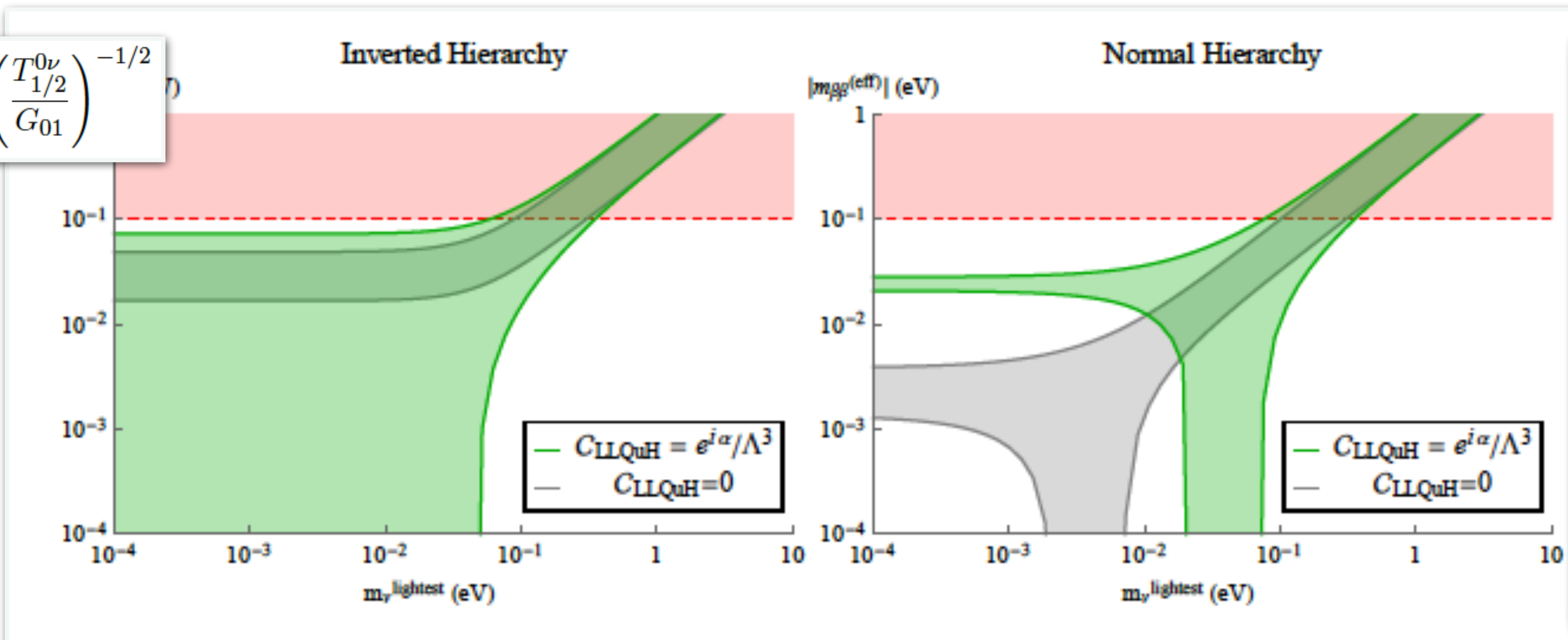
Tello-Nemevesek-Nesti-Senjanovic-Vissani 1011.3522
Ge-Lindner-Patra 1508.07286. **
...

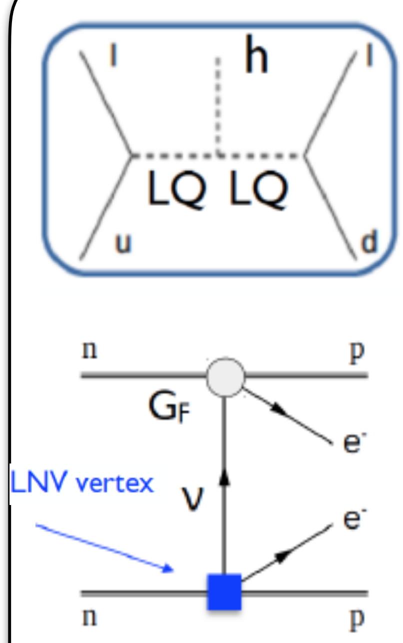
Phenomenological interest

- Induce contributions to $0\nu\beta\beta$ *not directly related to the exchange of light neutrinos,* within reach of current experiments

New contributions can add incoherently *or interfere with* $m_{\beta\beta}$, significantly affecting the interpretation of experimental results

$$m_{\beta\beta}^{(\mathrm{eff})} = \frac{m_e}{g_A^2 M_\nu}\left(\frac{T_{1/2}^{0\nu}}{G_{01}}\right)^{-1/2}$$





$\Lambda = 600$ TeV

VC, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, 1708.09390

Phenomenological interest

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- May lead to correlated (or precursor!) signal at LHC: pp →ee jj

Keung-Senjanovic '83

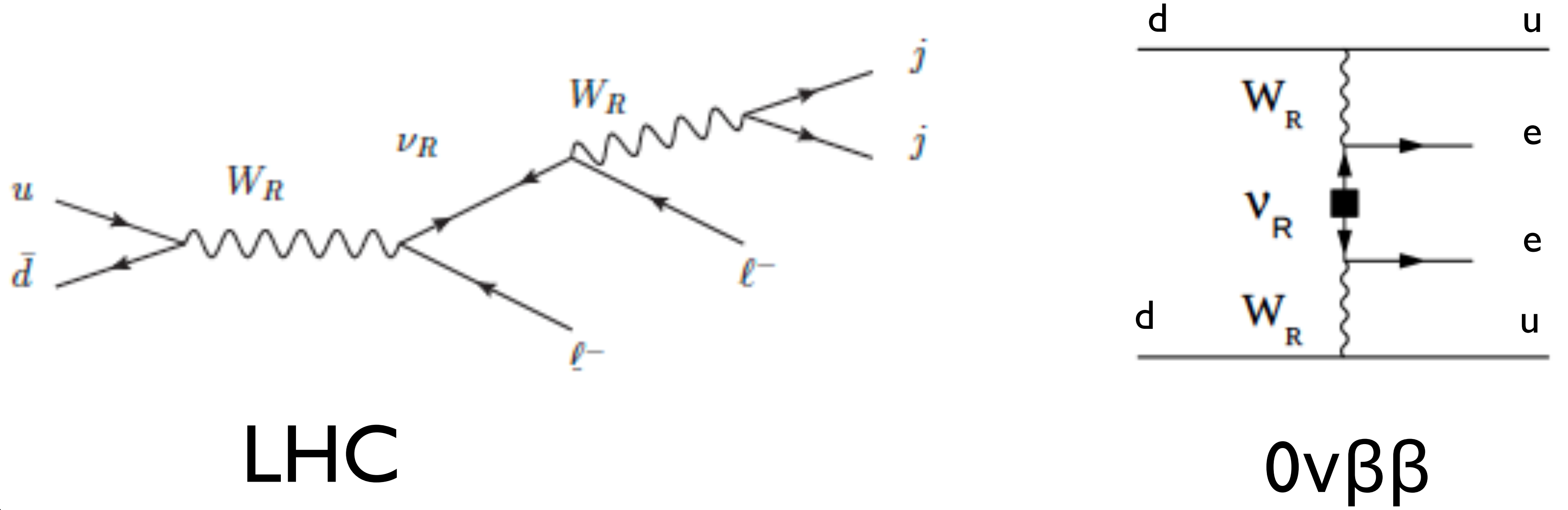
Maiezza-Nemevesek-Nesti- Senjanovic 1005.5160

Helo-Kovalenko-Hirsch-Pas 1303.0899, 1307.4849

Cai, Han, Li, Ruiz 1711.02180

…

Classic LRSM example



Phenomenological interest

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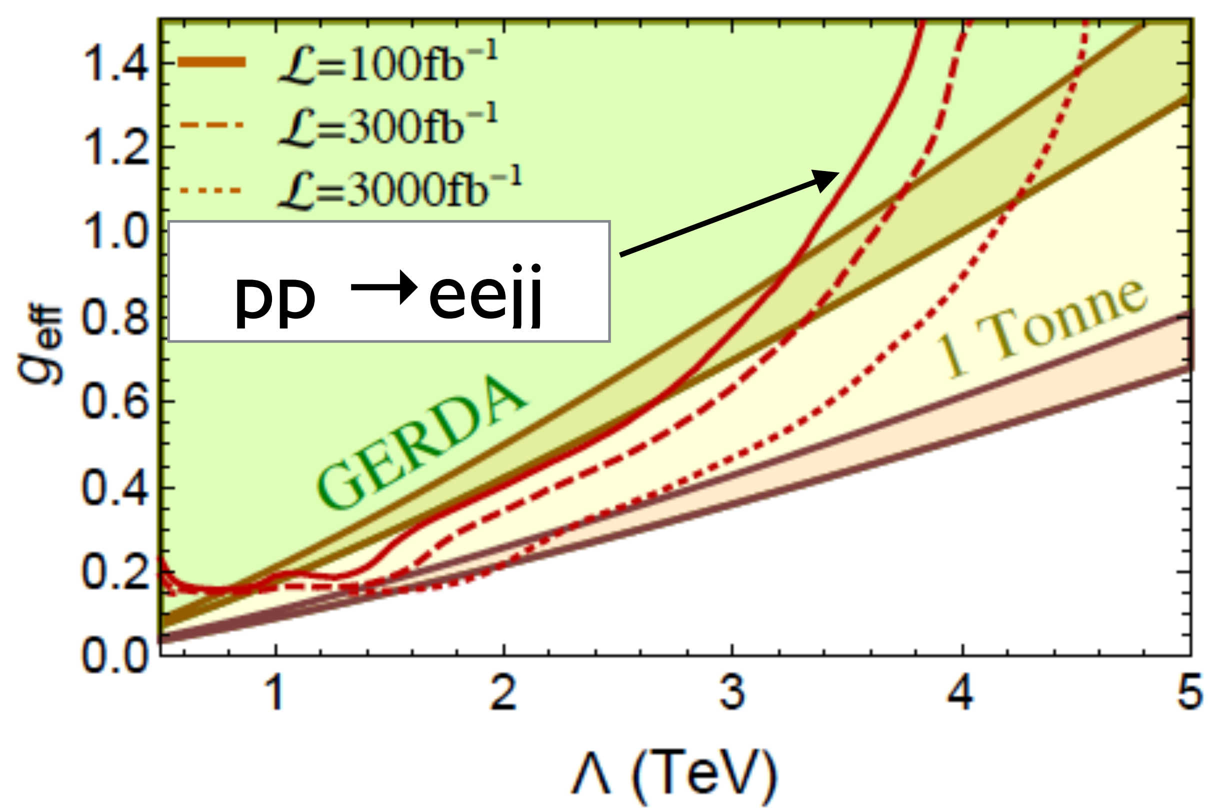
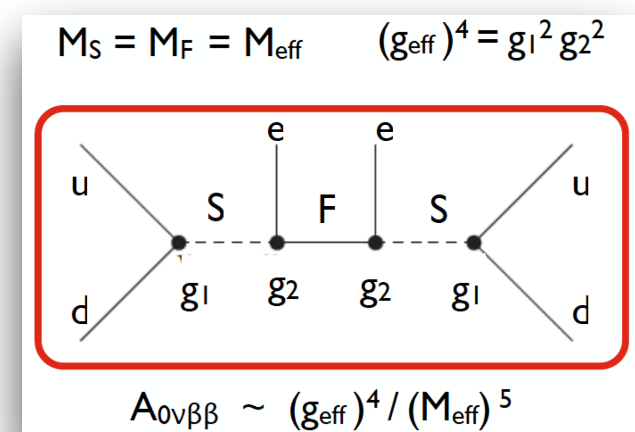
Cai, Han, Li, Ruiz 1711.02180

Peng, Ramsey-Musolf, Winslow, 1508.0444

...

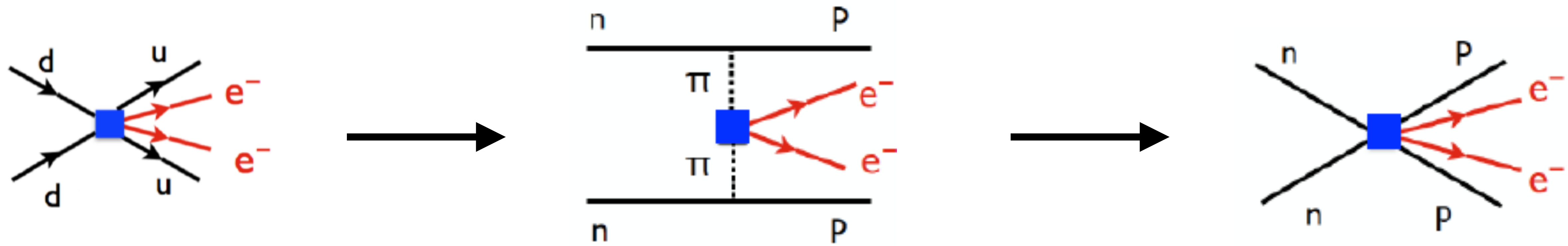


Simplified model



Hadronic theory developments

- Chiral EFT & Lattice QCD



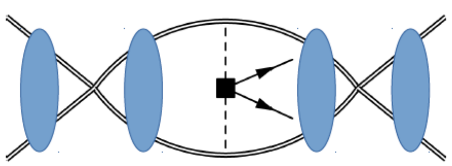
In Weinberg's counting, pion contribution dominates

Prezeau, Ramsey-Musolf, Vogel hep-ph/0303205

ππ matrix element known from LQCD at <10%

Nicholson et al (CalLat), 1805.02634

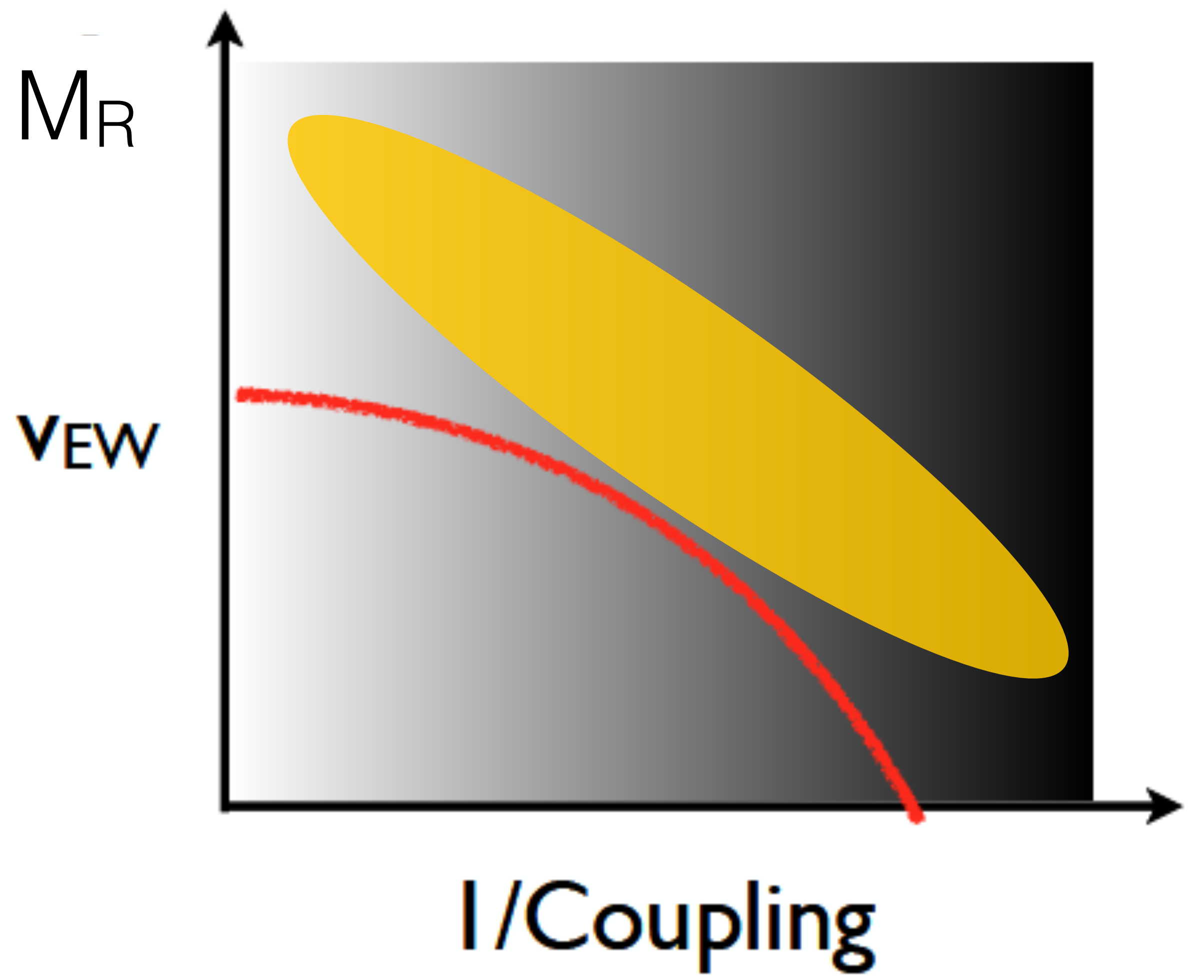
Renromalization requires a contact at the same order!



V.C, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti [1806.02780]

- Several unknown LO NN contact couplings. Opportunity for LQCD

0νββ and sterile neutrinos

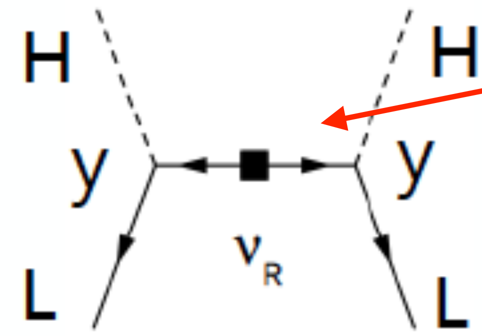


Phenomenological interest

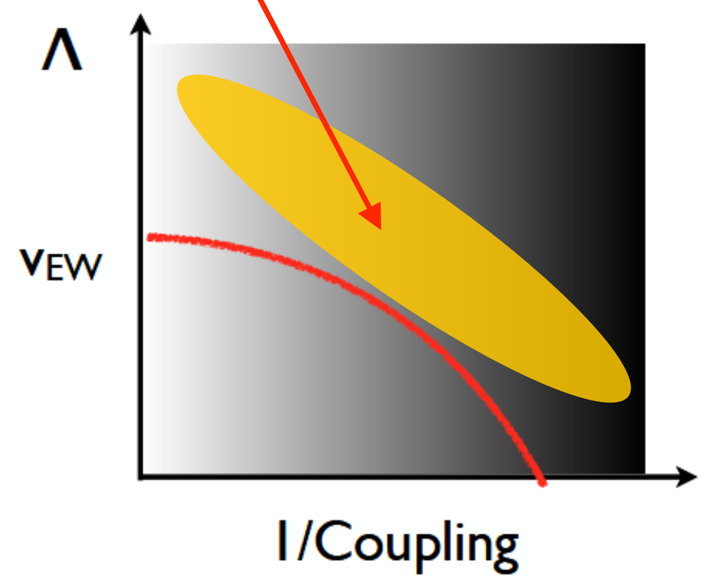
Akhmedov. Rubakov, Smirnov
hep-ph/9803255

Canetti, Drewes, Shaposhnikov
1204.3902

...



Arbitrary scale $M_R \leftrightarrow \Lambda$



- Attractive class of "minimal" models
  - ν_R can give rise to light neutrino masses
  - ν_R can provide a dark matter candidate
  - ν_R can generate the baryon asymmetry through leptogenesis

- In general $m_{\beta\beta} \neq (m_{\beta\beta})_{active}$, with strong dependence on ν_R spectrum

- Can be probed at colliders, beam dump, semileptonic decays, EWPO, …

See e.g. Bolton, Deppisch, Dev 1912.03058

EFT developments and challenges

- νSMEFT + chiral EFT analysis

Dekens et al. 2002.07182

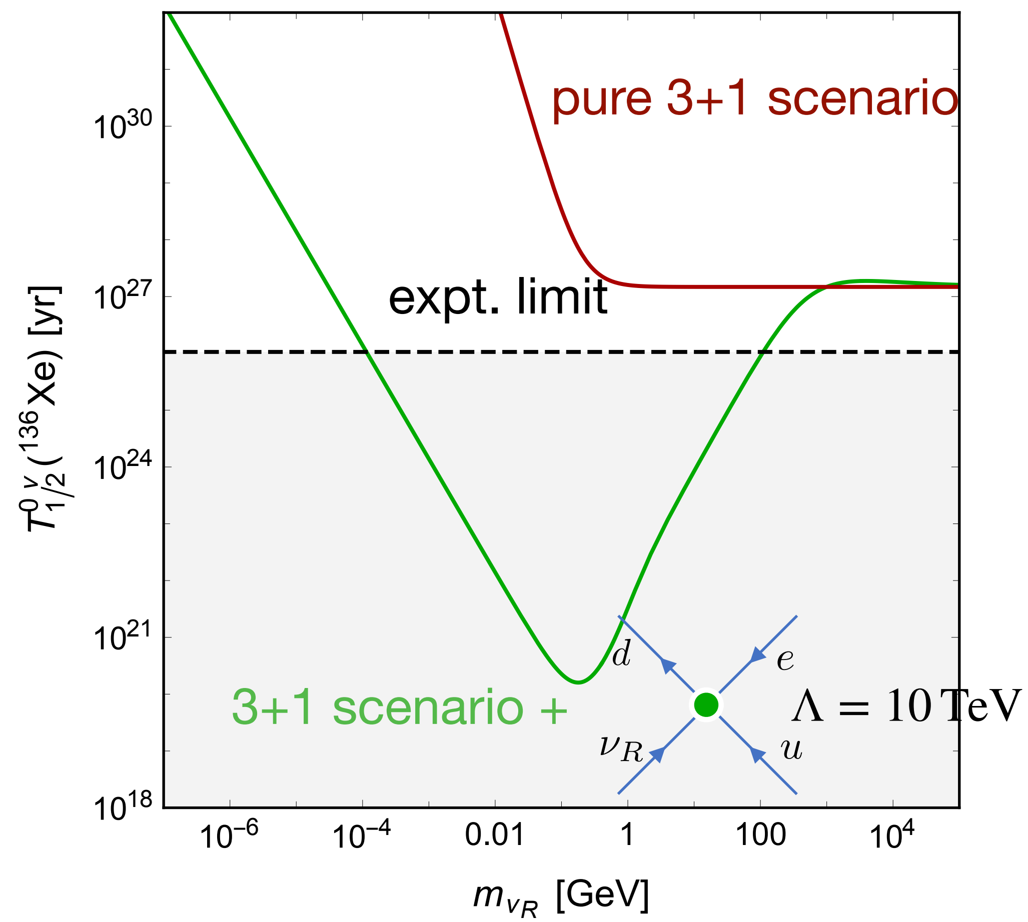
$$\mathcal{L}_{\nu_R} = i\bar{\nu}_R \partial\!\!\!/ \nu_R - \frac{1}{2}\bar{\nu}^c_R M_R \nu_R - \bar{L}\tilde{H}Y_D\nu_R + \mathcal{L}^{(6)}_{\nu_R} + \mathcal{L}^{(7)}_{\nu_R} + \dots$$

- ν_R's interaction beyond Yukawa can have large impact

- Challenges:
    - New LECs in hadronic EFT
    - Dependence of m.e. and LECs on ν_R mass

...
deGouvea et al hep-ph/0608147
Faessler et al, 1408.6077
Dekens et al. 2002.07182
...

O(100%) uncertainties not shown



Plot courtesy of Wouter Dekens

Unraveling $0\nu\beta\beta$ mechanisms?

Graf, Lindner, Scholer 2204.10845

- 32 operators below weak scale @ dim=3, 6, 7, 9 contribute to $0\nu\beta\beta$

- Can they be distinguished by

1. Isotope-dependence of the decay rates?

3. Phase space observable? (single electron spectra, relative angle of outgoing electrons)

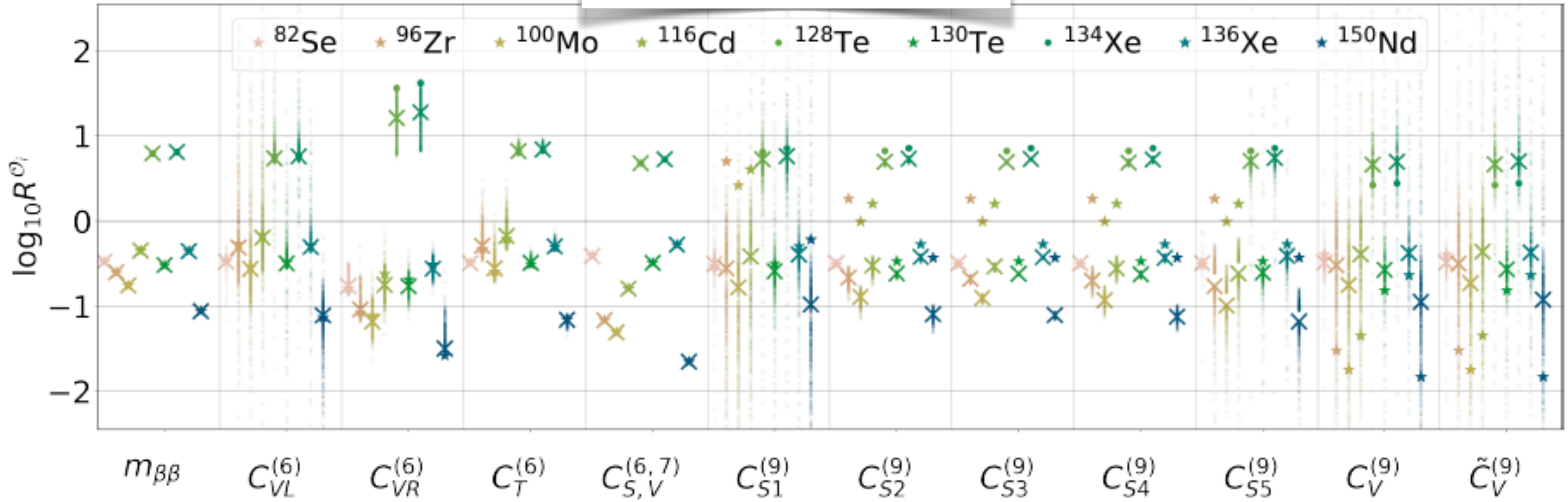
Despite degeneracies, useful diagnosing tools 'within' $0\nu\beta\beta$

Isotope dependence

Graf, Lindner, Scholer 2204.10845

- Only 12 groups of operators can be distinguished by taking ratios of decay rates
- Quite sensitive to LECs (varied around reference values denoted by larger markers)
- Distinguishing classes of operators will require combined theoretical uncertainty of ~10% , due to LEC + NME (here only IBM used)

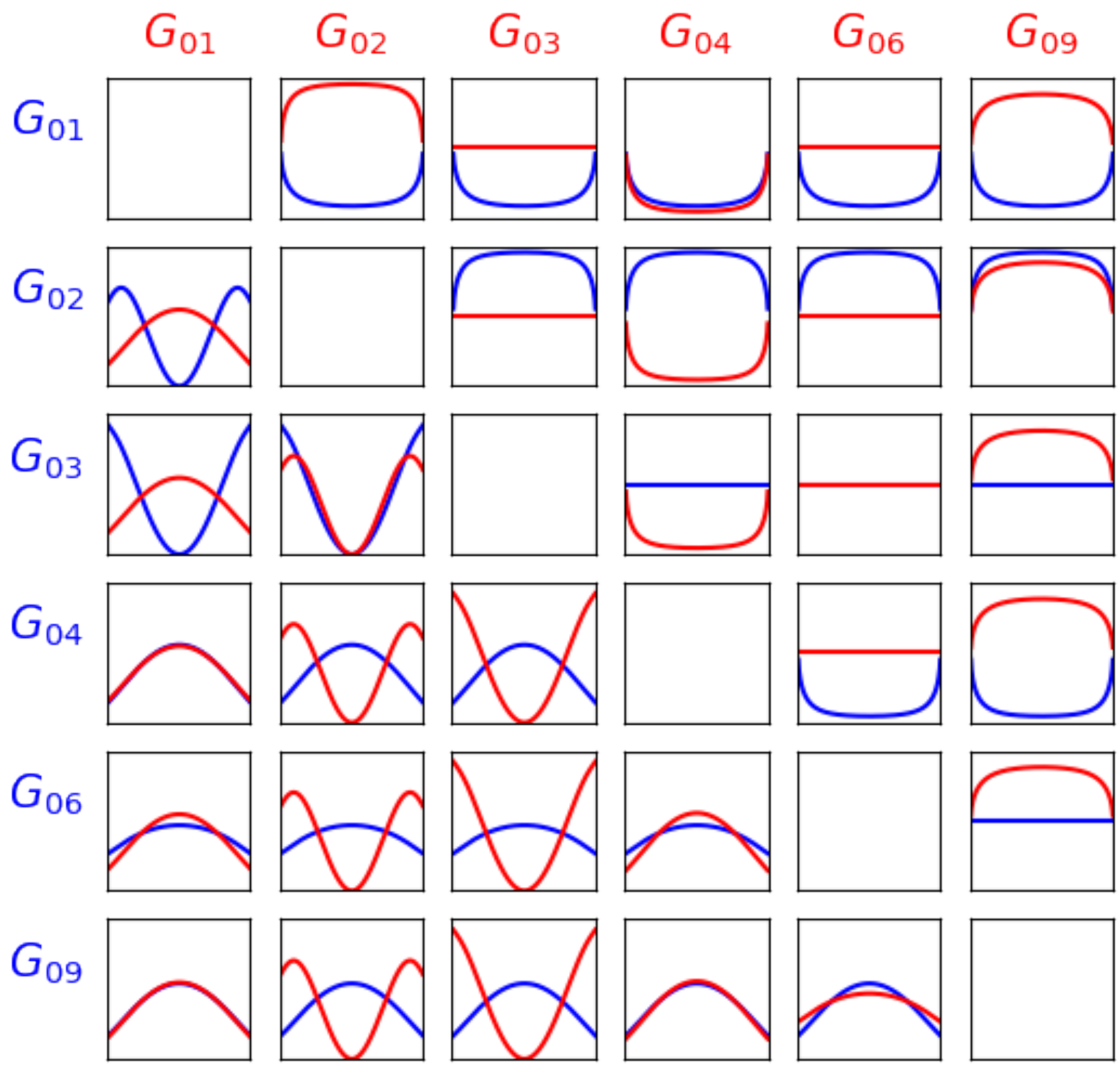
$$R^{\mathcal{O}_i}({}^{A}\mathrm{X}) \equiv \frac{T_{1/2}^{\mathcal{O}_i}({}^{A}\mathrm{X})}{T_{1/2}^{\mathcal{O}_i}({}^{76}\mathrm{Ge})}$$



Phase space observables

Graf, Lindner, Scholer 2204.10845

- Six phase space structures G_{0k}, after including interference terms



$\propto a_1(\tilde{\varepsilon})$

$\propto a_0(\tilde{\varepsilon})$

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta\,\mathrm{d}\tilde{\epsilon}_1} = a_0\left(1 + \frac{a_1}{a_0}\cos\theta\right)$$

$$\tilde{\epsilon}_i = \frac{\epsilon_i - m_e}{Q_{\beta\beta}} \in [0, 1]$$

Phase space observables

Graf, Lindner, Scholer 2204.10845

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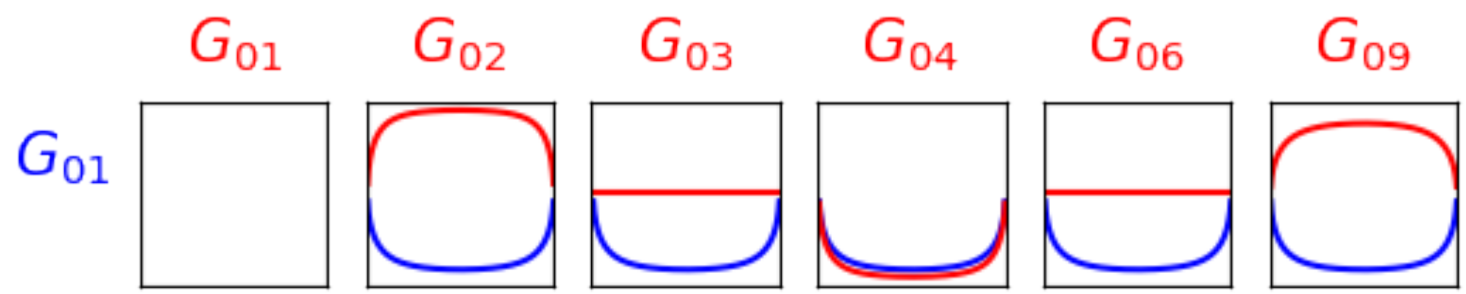
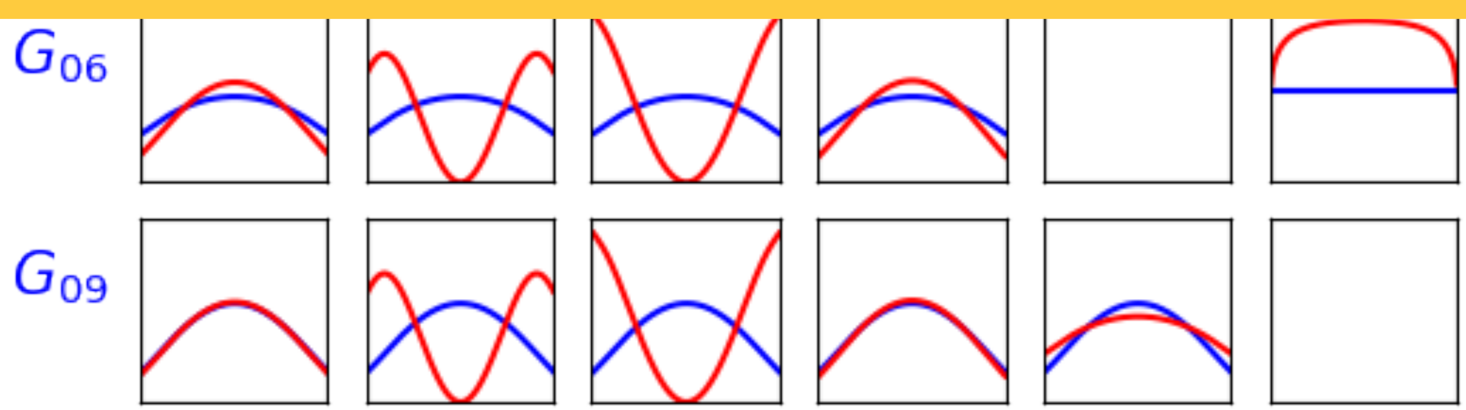


$\propto a_1(\tilde{\varepsilon})$

- Despite degeneracies, useful diagnosing tools 'within' $0\nu\beta\beta$
- This analysis reiterates two important points:
  - Need much improved matrix elements, with O(10%) uncertainty
  - Unraveling the mechanism of LNV will also require other probes (cosmology, collider, …)



$\propto a_0(\tilde{\varepsilon})$

LNV & 0νββ outlook

- Ton-scale 0νββ searches have great discovery potential — we simply don't know the origin of m_ν and the scale Λ associated with LNV

- Model diagnosing: what is the underlying source of LNV?
  - Within 0νββ: rate variation with isotope; single electron spectra and electron's angle distribution
  - 0νββ + other probes: oscillations, direct m_ν measurements, cosmology, meson & lepton decays, LNV @ colliders, LFV, …

- Exciting prospects thanks to synergy of model building, cosmology, collider physics, EFT, lattice QCD, and nuclear structure + (of course) experiment!