

Broad Perspective on the Future of $0\nu\beta\beta$ Experiments: Opportunities and Risks:

Subtitle: Recent progress and implications for $0\nu\beta\beta$

Manfred Lindner



Physics Opportunities of Large Liquid Scintillator Detectors (II)
Oct. 13-15, 2026, Helmholtz Institute Mainz

Hints for the Neutrino Mass Hierarchy

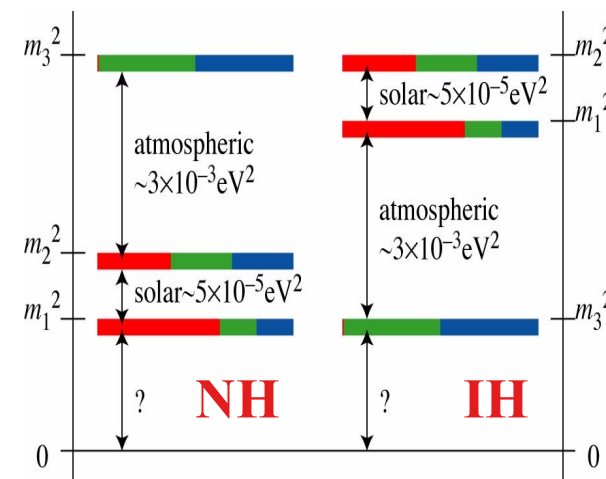
Neutrino masses and mixings constraint by:

- **absolute mass measurements:**
 $m_\nu < 0.45 \text{ eV @90\%CL (KATRIN)}$
- **oscillations – dominated by two flavor contributions**

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta) \cdot \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

→ dominant two flavour picture:

- normal hierarchy (**NH**) → $\Sigma m_\nu \gtrsim 50 \text{ meV}$
- inverted hierarchy (**IH**) → $\Sigma m_\nu \gtrsim 100 \text{ meV}$
- mass ordering is $\approx$ a small sub-leading effect
- excellent global fits; sterile neutrino evidences $\approx$ gone



QUANTITATIVELY: Combining JUNO+Daya-Bay (Reactor) with MINOS, NoVA, T2K (LBL)

Global fits:

Combining all data → preference for NH; e.g.:

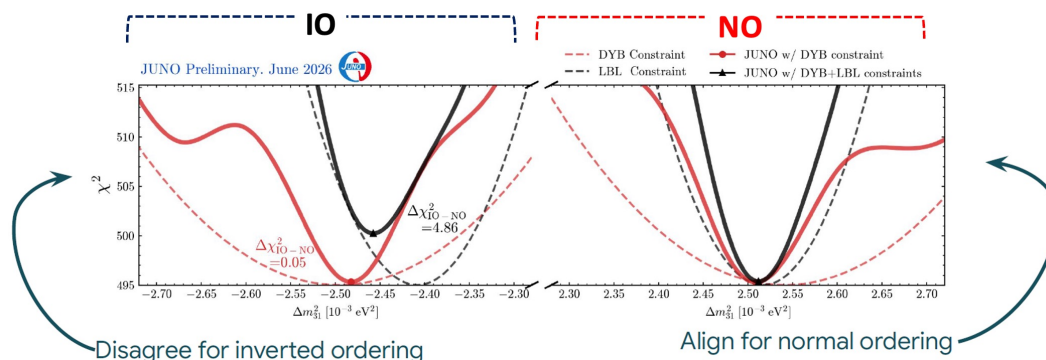
I. Martínez Soler, NOW 2026

F. Marcone, NOW 2026

B. Caccianiga (on behalf of JUNO), NOW2026 →

Remaining tension:

Dirac CP phase δ from T2K and NOvA



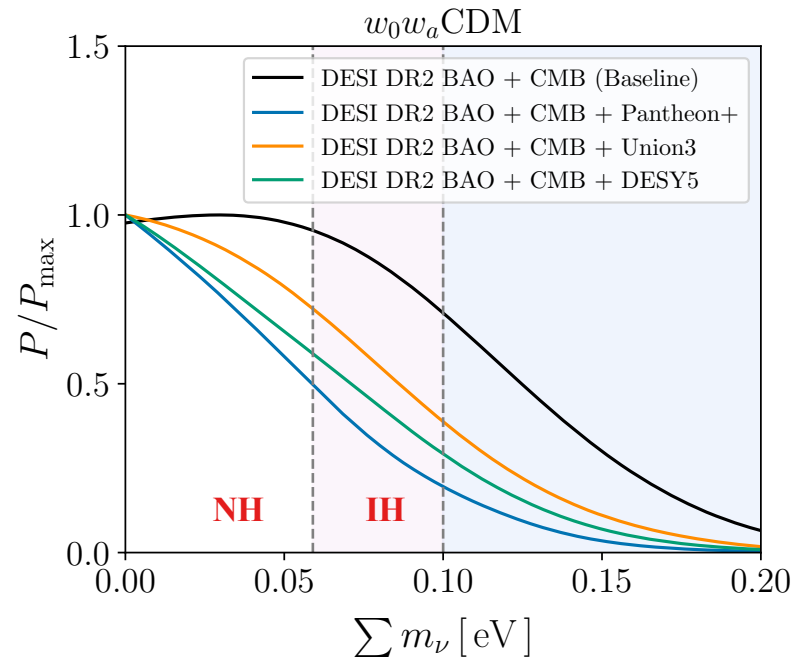
Normal Ordering is preferred with $\Delta\chi^2=4.86$

* NuFit 6.0 - JHEP 12 (2024) 216 [arXiv:2410.05380]; www.nu-fit.org

more data → further improvements to come

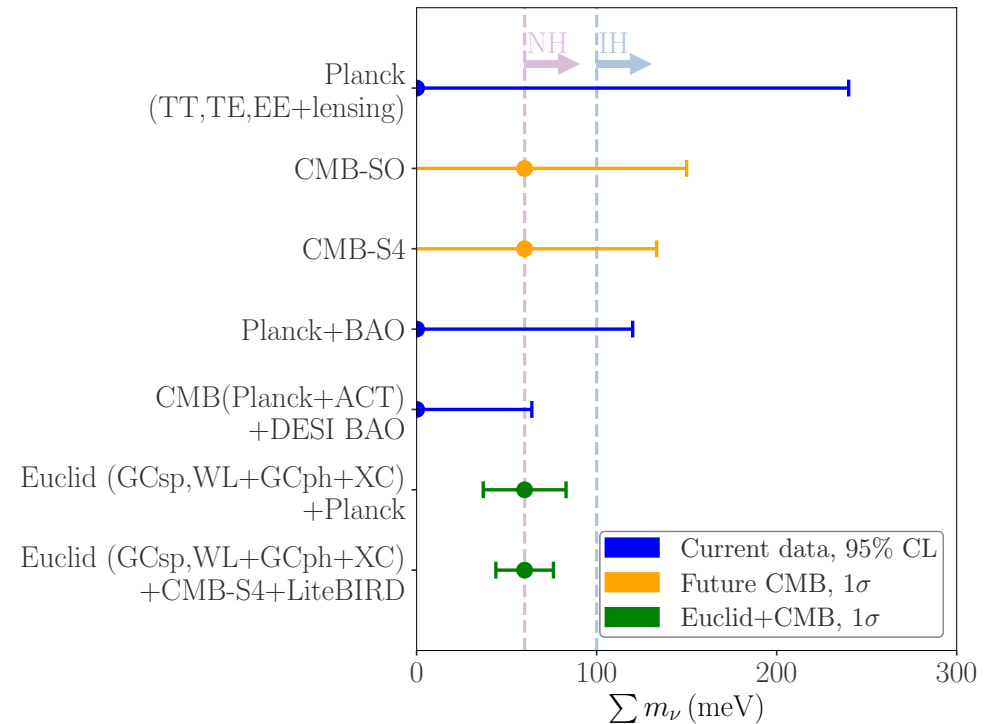
Cosmology: Σm_ν – Now & Future

M. Archidiacono, Erice 09/2026



Now:

- a certain tendency towards NH



Future (within in a few years...):

- significantly reduced error bars
- note: assumes $\Lambda_{\text{CDM}} = \text{SM of cosmology}$
- $\text{BS}_{\text{cosmology}}$ M: other cosmologies...
- central value: NH, IH else?
- consistent with lab results?
- yes: both SM's OK $\rightarrow$ NH or IH
- no: $\rightarrow$ BSM $\rightarrow$ particles/cosmolog?

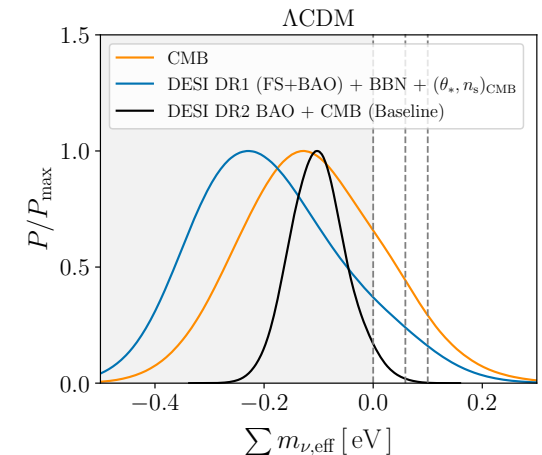
The Situation within a few Years...

If cosmology and lab results are inconsistent:

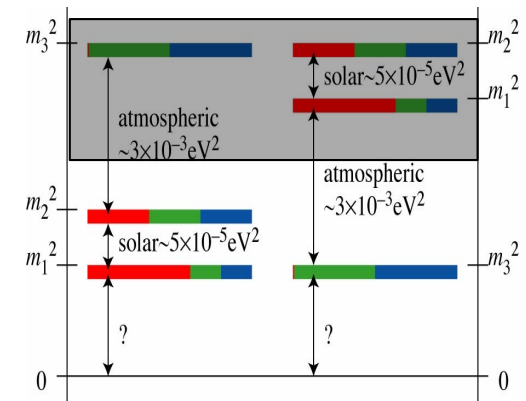
- BSM (or systematics) in either (or both) cosmology and particle physics
- examples:
 - * cosmology:
 - dynamical dark energy ; $p_{\text{DE}} = w(a) \rho_{\text{DE}}$, ...
 - systematics... $\leftrightarrow$ negative fit parameter $\Sigma m_{\nu, \text{eff}}$?
 - * particle physics:
 - if both NH and IH were 'excluded'? $\rightarrow$ decay?
 - * many more things one could think of...

If cosmology and lab results are consistent:

- indicates that both SM's work even better $\rightarrow$ IH or NH
- limits BSM ideas (less if no directly effect on neutrino masses)
 - * cosmology: free streaming, ...
 - * particle physics: neutrino mass models



DESI Collaboration, Elbers et al., 2025

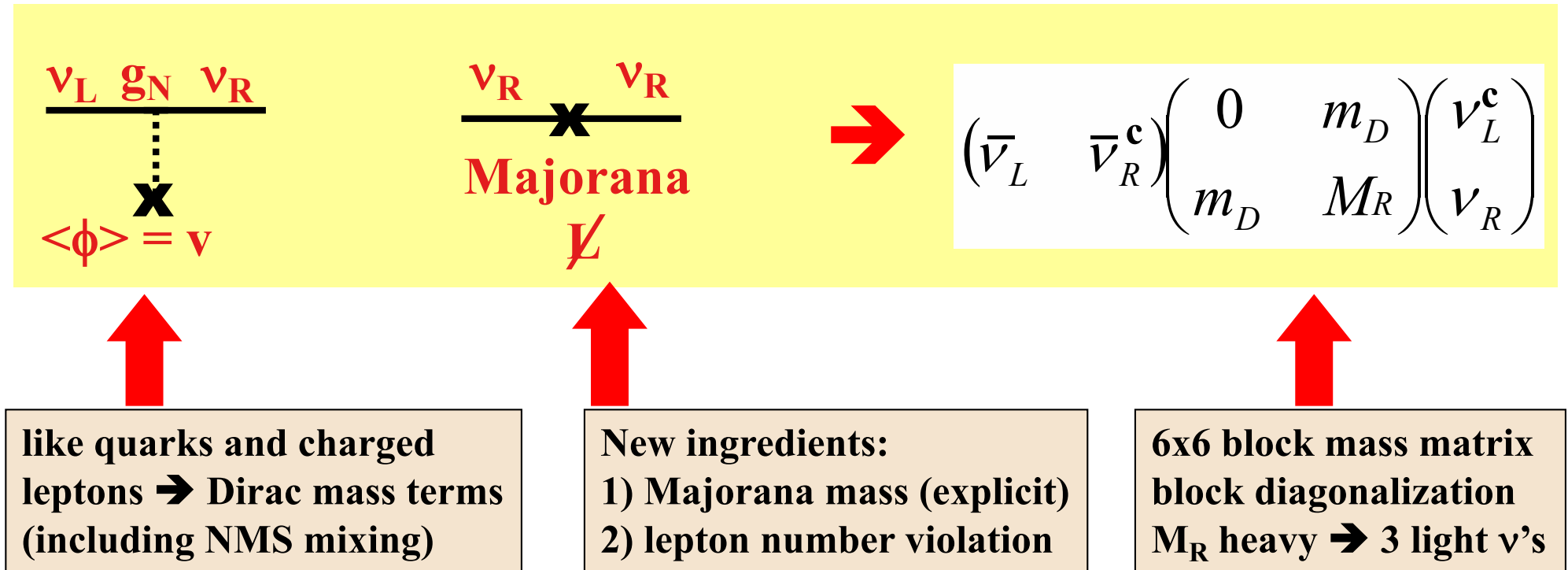


Planned $0\nu\beta\beta$ projects test IH; IH is challenging and all new projects require many years...

$\rightarrow$ time to think about consequences for $0\nu\beta\beta$ if the current trend to NH persists?

Adding Neutrino Masses to the SM

Simplest possibility: add 3 right handed neutrino fields



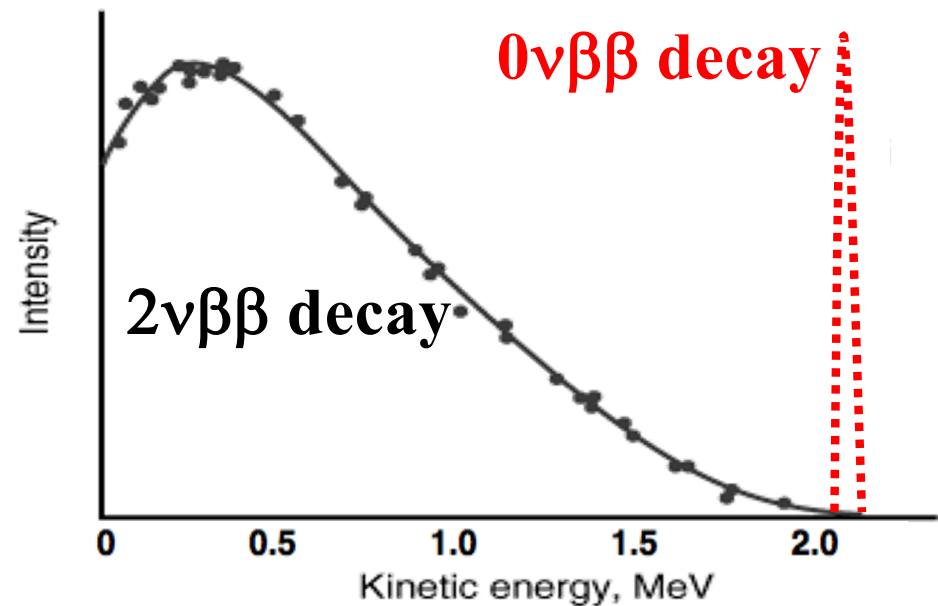
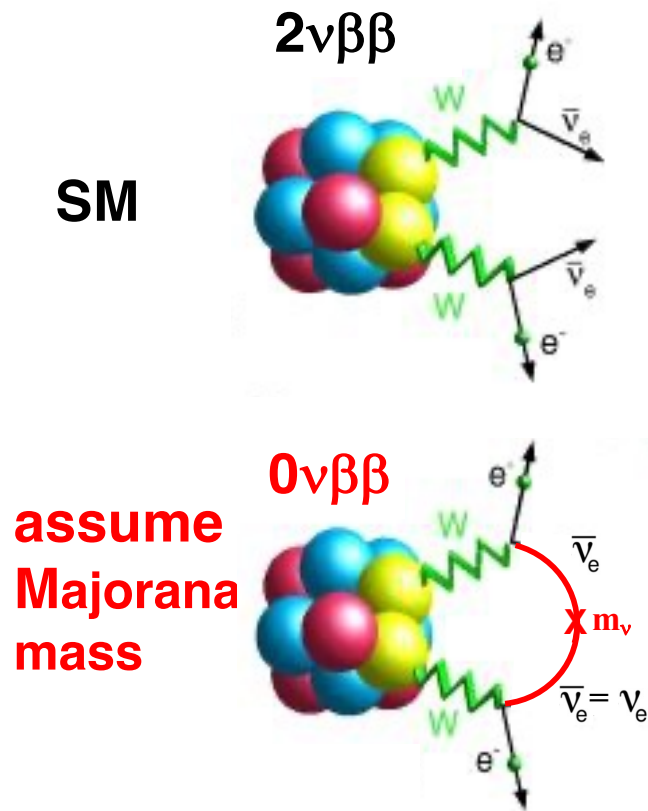
significant NEW ingredients:

- SM=1-scale theory $\rightarrow$ multi-scale theory
- modified global symmetries (L, henn – egg)
- 9 more parameters

$\rightarrow$ call it at least SM+

$\rightarrow$ see-saw: $m_\nu = (m_D)^2/M_R$ mass $\equiv$ L violation

Majorana Neutrino Interpretation of $0\nu\beta\beta$



$$1/\tau = G(Q,Z) |M_{\text{nucl}}|^2 \langle m_{ee} \rangle^2$$

lifetime τ

NMEs have
uncertainties...

- observe expected $2\nu\beta\beta$ signal
- look for a line at $Q_{\beta\beta}$

interpret signal **as Majorana mass**

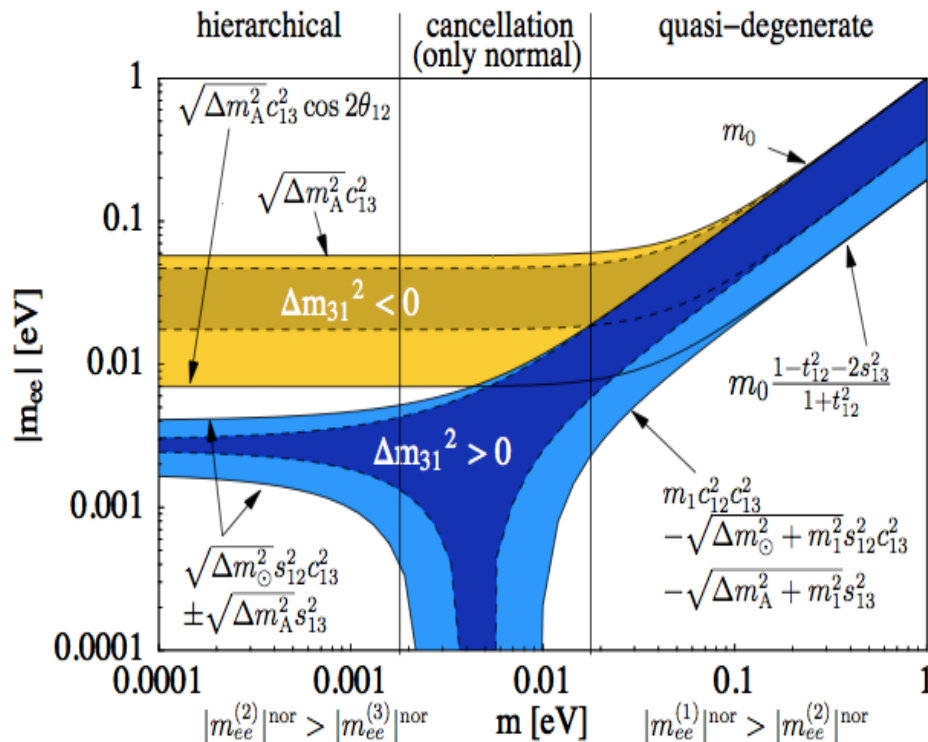
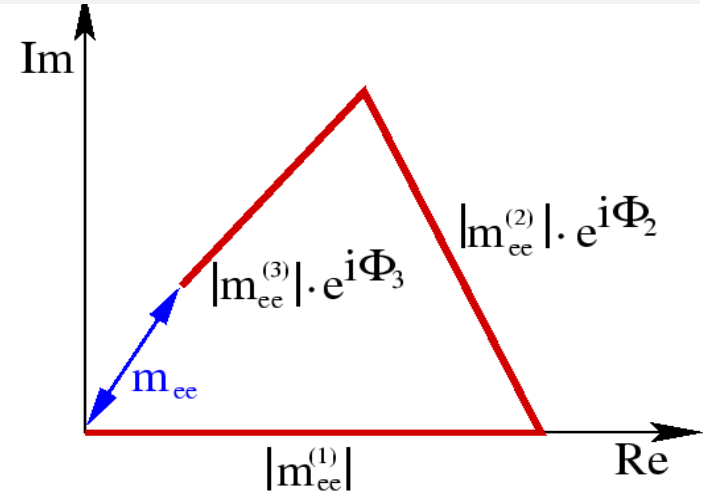
m_{ee} : The Effective Neutrino Mass

$$m_{ee} = |m_{ee}^{(1)}| + |m_{ee}^{(2)}| \cdot e^{i\Phi_2} + |m_{ee}^{(3)}| \cdot e^{i\Phi_3}$$

$$|m_{ee}^{(1)}| = |U_{e1}|^2 m_1$$

$$|m_{ee}^{(2)}| = |U_{e2}|^2 \sqrt{m_1^2 + \Delta m_{21}^2}$$

$$|m_{ee}^{(3)}| = |U_{e3}|^2 \sqrt{m_1^2 + \Delta m_{31}^2}$$



Comments:

- NMEs $\rightarrow$ unavoidable theory errors
- known Δm^2 from oscillations
TH + EX errors $\rightarrow$ bands
- ton-scale projects aim at covering IH
- global fits ...NH?
- cosmology... NH?
 $\rightarrow$ the case for $0\nu\beta\beta$ projects testing IH?
- $\rightarrow$ time to look at the wider picture...

The wider Motivation

Understanding the origin of fermion masses

- **Quark and lepton masses as well as their mixings show apparent regularities**
 - cries for an explanation → how can this be understood?
 - neutrinos are very valuable:
theoretically cleaner (no QCD coupling) + less hadronic effects in experiments

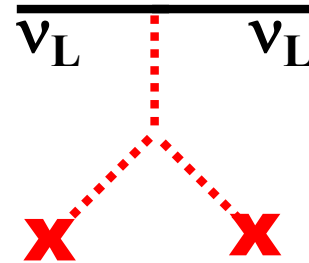
Role of neutrinos in cosmology

- **We would probably not exist without neutrino masses**
 - free streaming & $m_\nu \leftrightarrow$ small scale structure of the Universe ???
 - Baryon Asymmetry of the Universe may be a consequence of neutrino masses
- **Neutrinos are hot dark matter ($\sim 0.5\%$ of what is required)**
 - proof that particle dark matter can be a solution (contribution) of the DM problem
- **Unique role as cosmic messengers (Sun, Supernovae, UHE CR, ...)**
 - all directly or indirectly related to the question of neutrino masses and $0\nu\beta\beta$

Many other Neutrino Mass Options

2) new Higgs triplets Δ_L :

→ left-handed Majorana mass term:



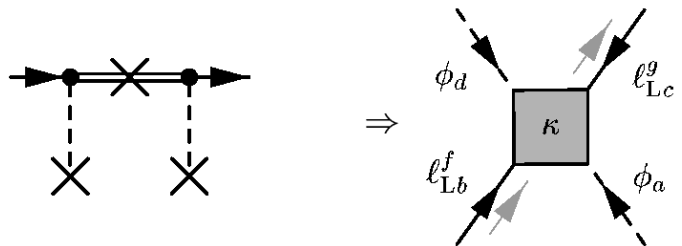
$$\Rightarrow M_L \bar{L} L^c$$

3) Both ν_R and new Higgs triplets Δ_L :

→ see-saw type II

$$m_\nu = M_L - m_D M_R^{-1} m_D^T$$

4) Higher dimensional operators: $d=5, \dots$

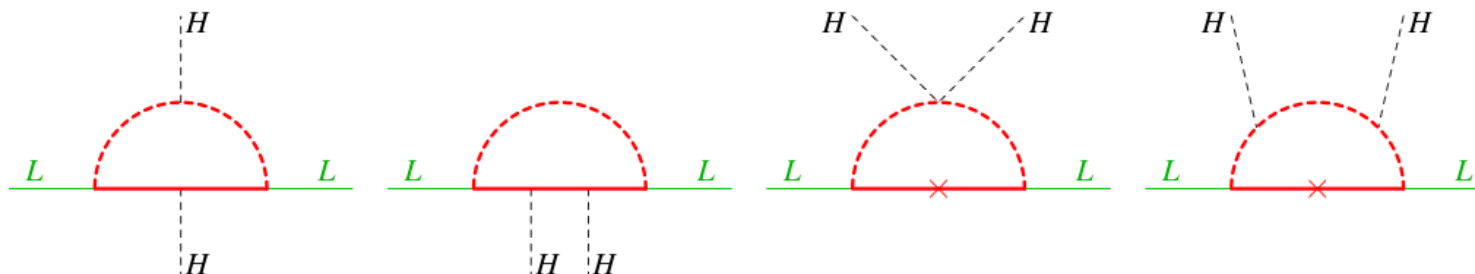


$\Leftrightarrow$

$$\mathcal{L}_{mass} = \kappa \cdot \bar{\nu}_L^C \nu_L \Phi^T \Phi$$

$$\Rightarrow M_L \bar{L} L^c$$

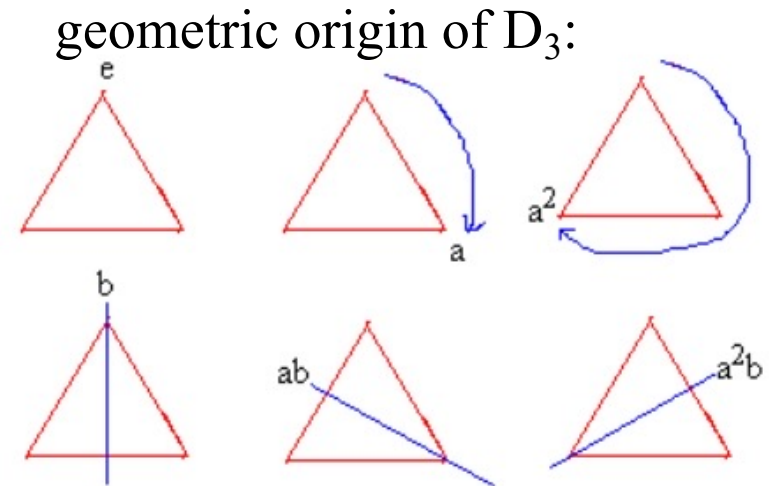
5) Radiative neutrino mass generation $\leftrightarrow$ BSM



Masses & Flavour Symmetries

- **the basic idea:**
horizontal symmetry (discrete, continuous)
- **broken at high scales**
- **by flavons**
→ **explain observed masses and mixings**

e.g. dihedral groups D_n



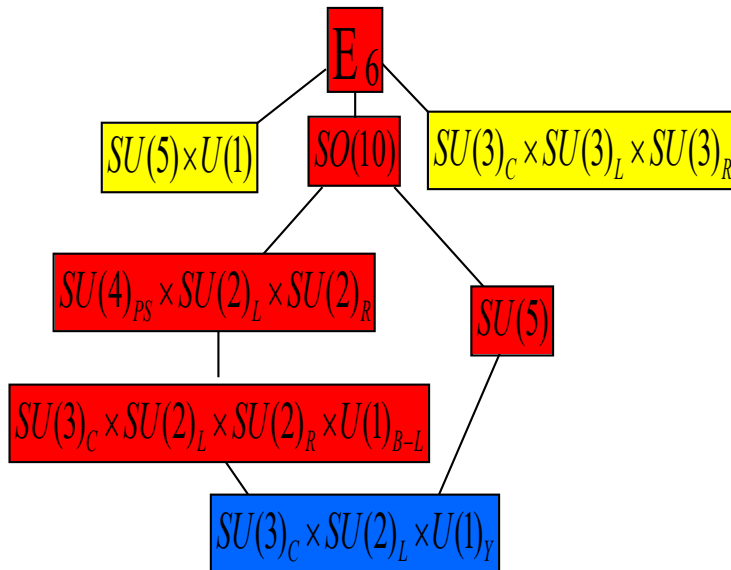
Many groups and breaking scenarios have been discussed
a phenomenologically promising example: D_5 [Hagedorn, ML, Plentinger](#)

task: search for mass terms which are for suitable Higgs singlets under D_5

- $$L = \{L_1, L_2, L_3\}$$
- 1) assign all fermions to representations
 - 2) write down any possible mass term using scalars $\leftrightarrow$ singlet under symmetry
 - 3) problem: many scalars (flavons), special VEVs, ...
→ many models ... new models $\leftrightarrow$ growing precision???

Even more Options / Requirments

6) Gauge unification, GUTs and Flavour symmetries



Generations are only copies

→ horizontal symmetries?

A4, S3, D5, T', ...

breaking...

→ explain regularities

more options ↔ more
constrains, precision

Quarks

Leptons

u	$\frac{2}{3}$ ~5	c	$\frac{2}{3}$ ~1350	t	$\frac{2}{3}$ 175000
d	$-\frac{1}{3}$ ~9	s	$-\frac{1}{3}$ ~175	b	$-\frac{1}{3}$ ~4500
ν_1	0?	ν_2	0?	ν_3	0?
e	0.511	μ	105.66	τ	1777.2
generation 1.		generation 2.		generation 3.	

7-N) More: further ν 's, SUSY, gauge groups, extra d, strings,...

- 'neutrino' is the most frequent name in titles of papers on INSPIRE...
- many ways to 'explain' neutrino masses
- mass mechanism & required extra fields are *NOT* known (ν_R , ϕ , Δ ,...)
- all BSM information is so far encoded into 3 masses and mixings

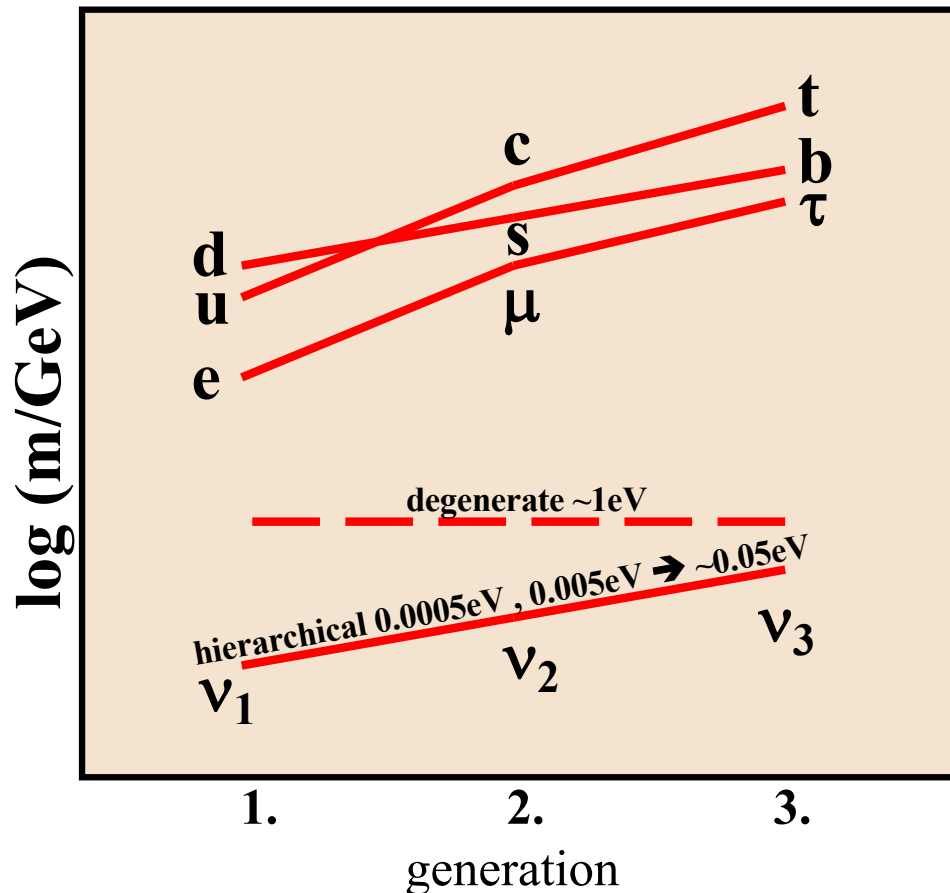
→ BSM physics affects oscillations, $0\nu\beta\beta$ and interactions (CEvNS)

The main Messages so far

- **Neutrinos have mass $\rightarrow$ 1st solid evidence for BSM physics**
- **There exist many options for mass generation**
 - $\rightarrow$ introducing only ν_R is a simple but strong assumption
 - $\rightarrow$ there exist many other well motivated scenarios for more
- **$0\nu\beta\beta$ is a consequence of L violation**
 - $\rightarrow$ there exist many ways to violate L
 - $\rightarrow$ introducing ν_R with Majorana mass M_R is only one option
 - $\rightarrow$ interpreting $0\nu\beta\beta$ results:
 - which fraction of L is from neutrino mass
 - how much does L-violation contribute to neutrino mass
 - $\rightarrow$ easily more complicated $\leftrightarrow$ unique potential for discovery of much more
- $\rightarrow$ Use and abuse of heuristic arguments for Majorana masses...**
 - usually: M_R is not forbidden so it must exist... $\rightarrow$ L-violation
 - global symmetries in quantum gravity... $\leftrightarrow$ L-violation: henn or egg

Interpreting empirical Regularities

Quarks & charged leptons → mass hierarchy pattern → neutrinos?



Quarks and charged leptons:

$$m_D \sim H^n ; n = 0, 1, 2 \rightarrow H \geq 20 \dots 200$$

Neutrinos: $m_\nu \sim H^n \rightarrow H \leq \sim 10$

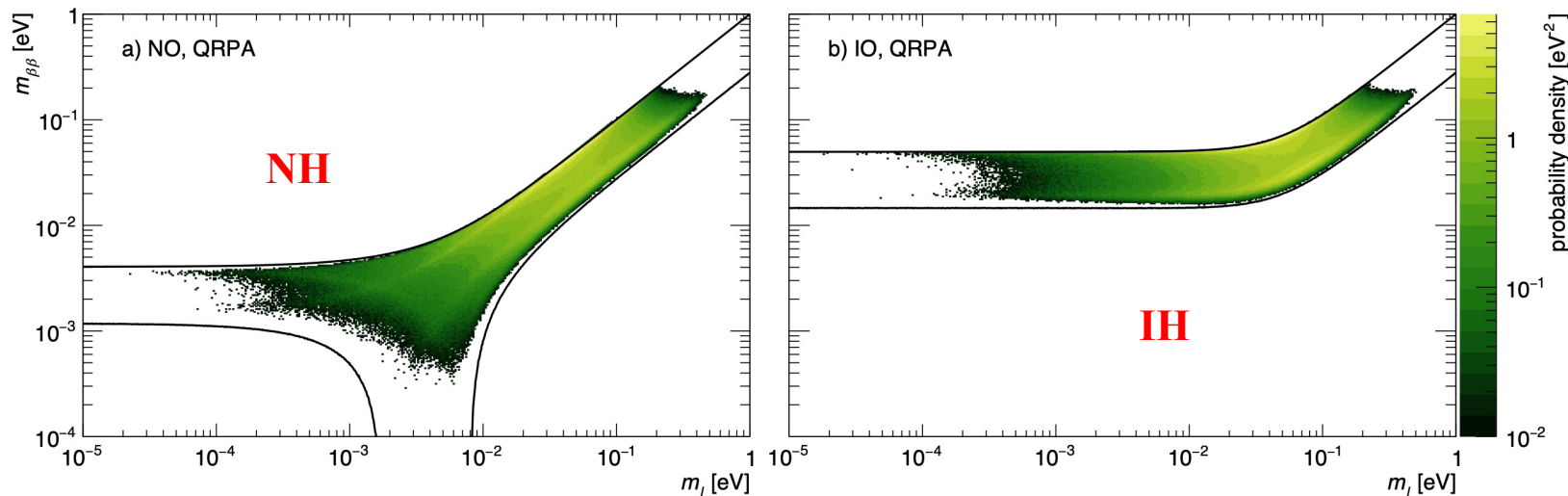
See-saw:

$$m_\nu = -m_D^T M_R^{-1} m_D$$

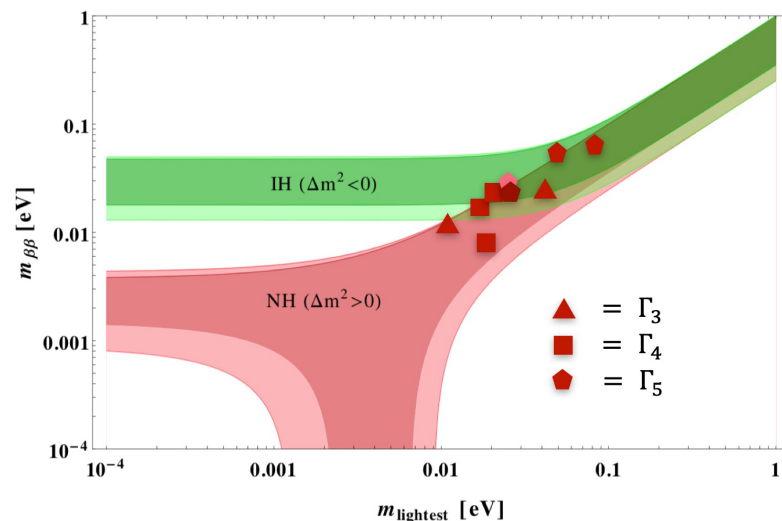
	↑↓	↑↓	↑↓	↑↓
H	$\lesssim 10$	≥ 20	?	≥ 20

- neutrinos are least hierarchical $\leftrightarrow$ See-saw suggests amplified hierarchy?
- less hierarchy in m_D or correlated hierarchy in M_R ? → theoretically connected?
- no problem if neutrinos are Dirac particles!

A lower or Limit from Numerology?



Agostini, Benato, Detwiler PRD 96 (2017) 053001 ; similar: Caldwell, Ettengruber, Merle, Schulz, Totzauer, PRD 96 (2017) 7, 073001

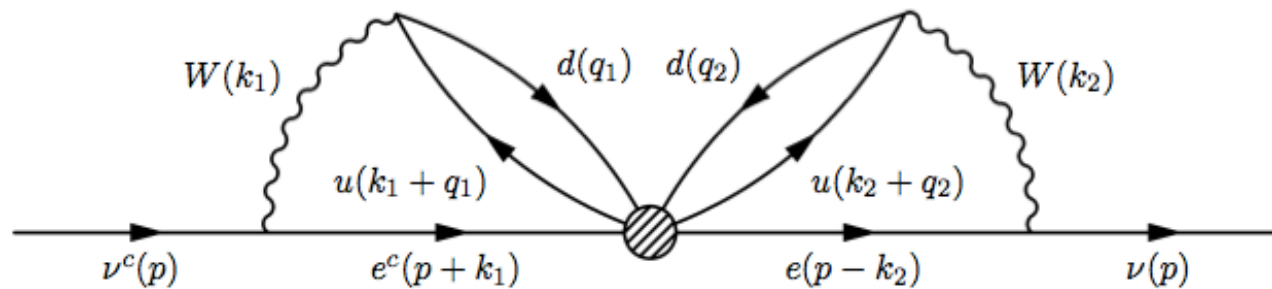


Feruglio, FLASY 2019, <http://indico.cern.ch/event/795851>

- **arguments that the signal is around the corner?**
- **theory: there is no parameter space probability**
 - ➔ SM+ m_ν : any number per se equally good
 - ➔ no theory measure & ν_R is an assumption
 - ...linear parameter scan + log scale plot predicts 1
- **many more assumptions**
 - ➔ discrete symmetries, no other BSM beyond ν_R
 - ➔ depends on symmetry
 - group algebra = $O(1)$ ➔ tends to predict upper end...
- **the same methods do not work for quarks, e, μ , τ**

The Schechter-Valle Theorem induced Mass

- SV: any $\Delta L=2$ operator which leads to $0\nu\beta\beta$ decay induces via loops Majorana masses: **observing $0\nu\beta\beta \rightarrow$ neutrinos have Majorana mass**
- assume $0\nu\beta\beta$ signal in today's experiments: **e.g. @IH $\rightarrow$ how much induced?**
 $\rightarrow$ calculate the relevant 4-loop diagram **Dürrr, ML, Merle**



- $\rightarrow \delta m_\nu = 10^{-25} \text{ eV} \rightarrow$ **extremely tiny** (only of academic interest)
- $\rightarrow$ cannot explain observed n masses and splitting's
- $\rightarrow$ Dirac neutrino mass term required to explain observed masses

Extreme (misleading) possibility:

- $0\nu\beta\beta = L$ violation induced by other BSM physics
- neutrino masses = Dirac (plus very tiny correction)

Beware of unjustified Assumptions

- 1) The magnitude of $0\nu\beta\beta$ and its relation to the physical mass
- 2) Majorana mass terms are the only $\Delta L=2$ operators

Ad 1):
$$\begin{pmatrix} \bar{\nu}_L & \bar{\nu}_R^c \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix} \rightarrow m_\nu = m_D^2/M_R \text{ plus: } M_R \gg M_D$$

→ saying that $0\nu\beta\beta$ implies Majorana masses is a consequence of assumptions

Example: Neutrino masses in conformal extensions of the SM

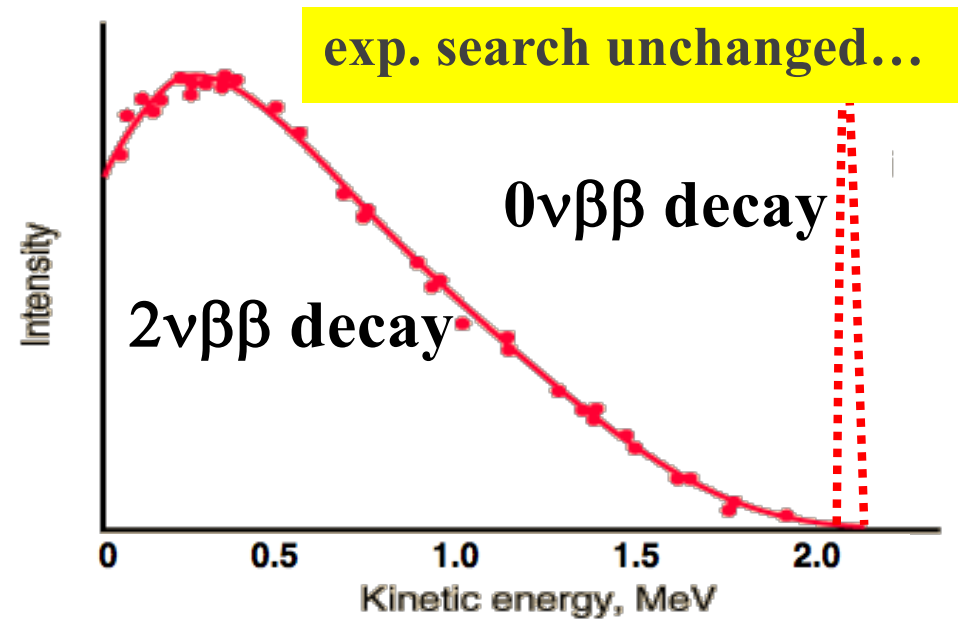
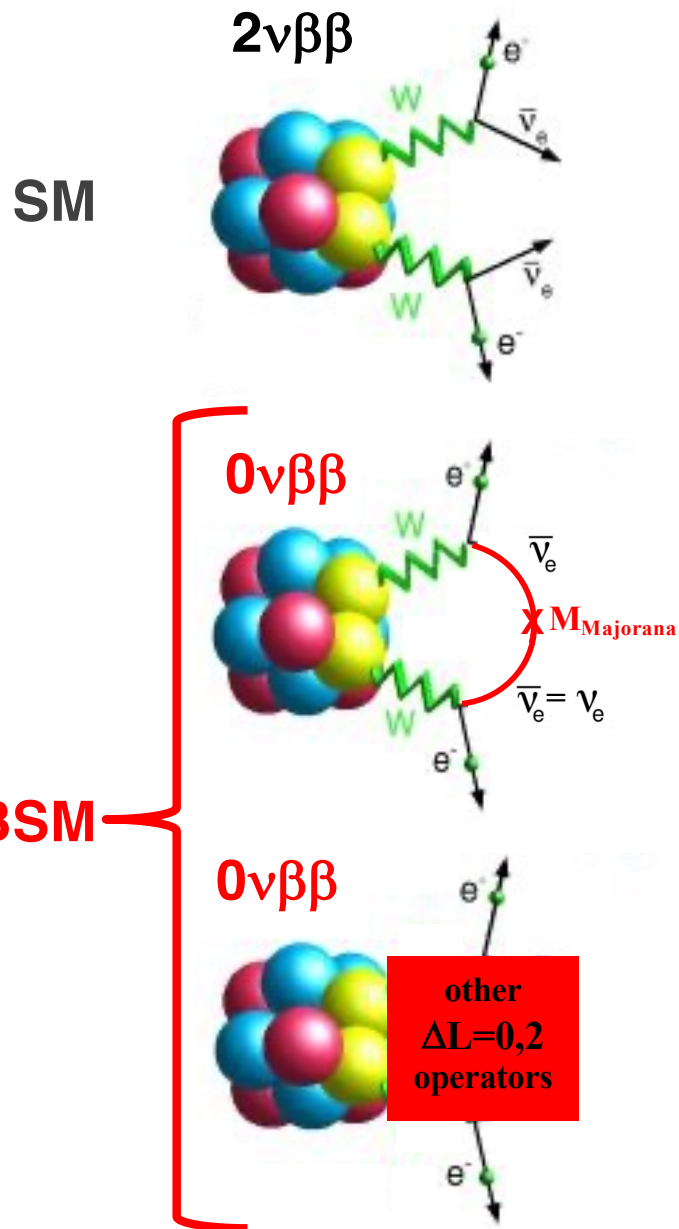
- Dirac mass terms as before: $m_D = y_D \langle H \rangle$ (Yukawa coupling * Higgs-VEV)
- Majorana masses $\leftrightarrow$ scales? $\rightarrow M_R = y_M \langle \Phi \rangle$ (Majorana Yukawa * new heavy VEV)

→ very interesting consequences:
$$\mathcal{M} = \begin{pmatrix} 0 & y_D \langle H \rangle \\ y_D^T \langle H \rangle & y_M \langle \phi \rangle \end{pmatrix}$$

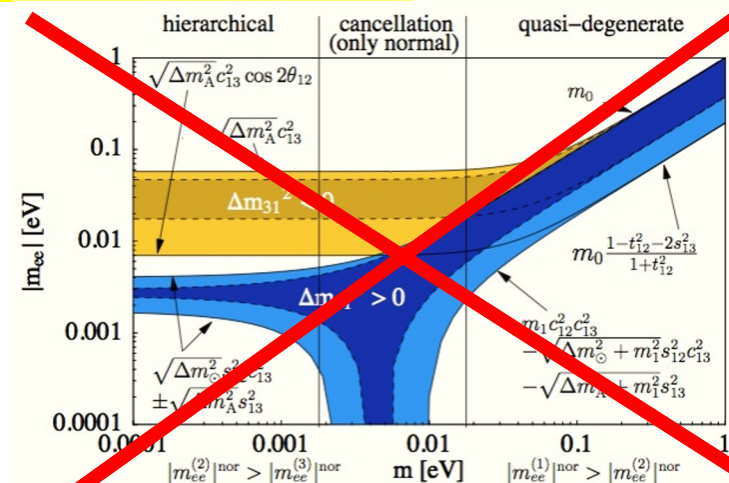
- Yukawa couplings can be (typically are) tiny: $y_M \ll 1 \rightarrow M_R \ll m_D$
 → pseudo Dirac neutrinos + Majorana component → see-saw relations are misleading!

NB: works for any neutrino mass model: $M \rightarrow y_x \cdot v_x \rightarrow$ very rich phenomenology

More general BSM L-Violating Processes

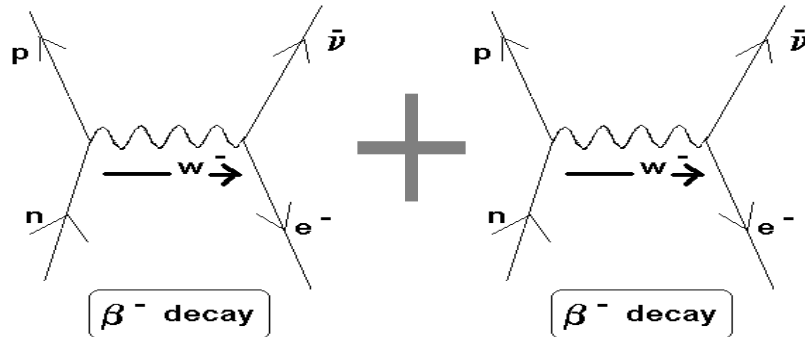


...interpretation changes:



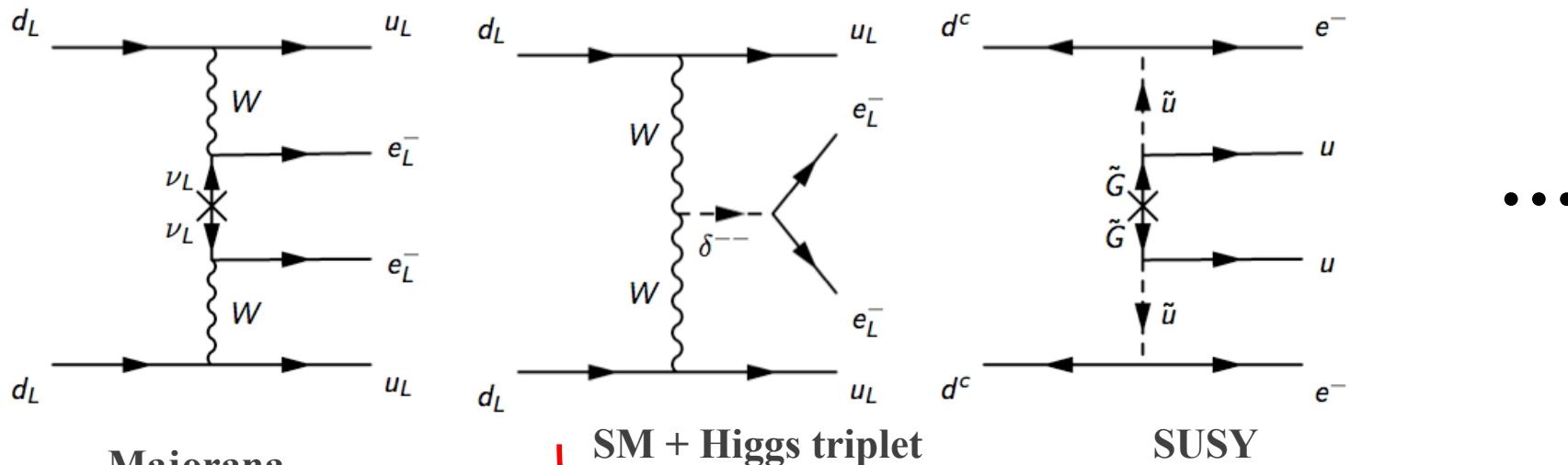
Other Double Beta Decay Processes

Standard Model:



→ 2 electrons + 2 neutrinos
 $2\nu\beta\beta$

Majorana ν -masses or other $\Delta L=2$ physics: → 2 electrons



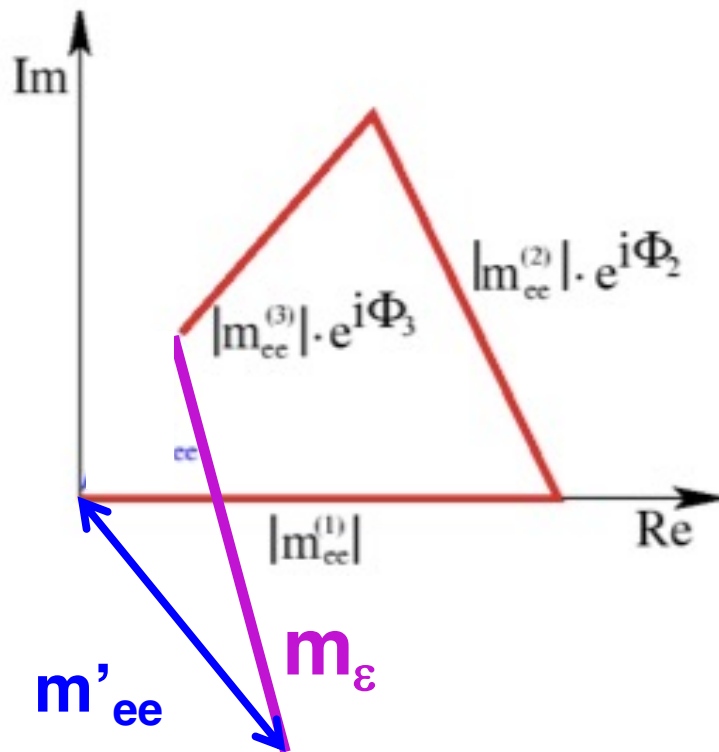
$0\nu\beta\beta$

Majorana
neutrino masses
 $\leftrightarrow$ Dirac?

SM + Higgs triplet

SUSY

important connections to LHC and LFV ...
sub eV Majorana mass $\leftrightarrow$ TeV scale physics



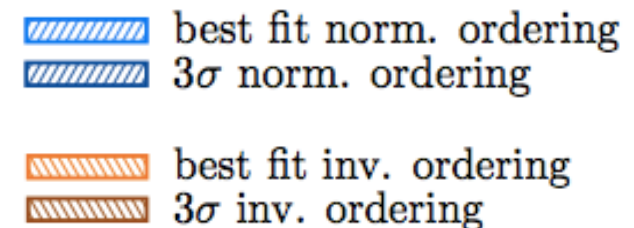
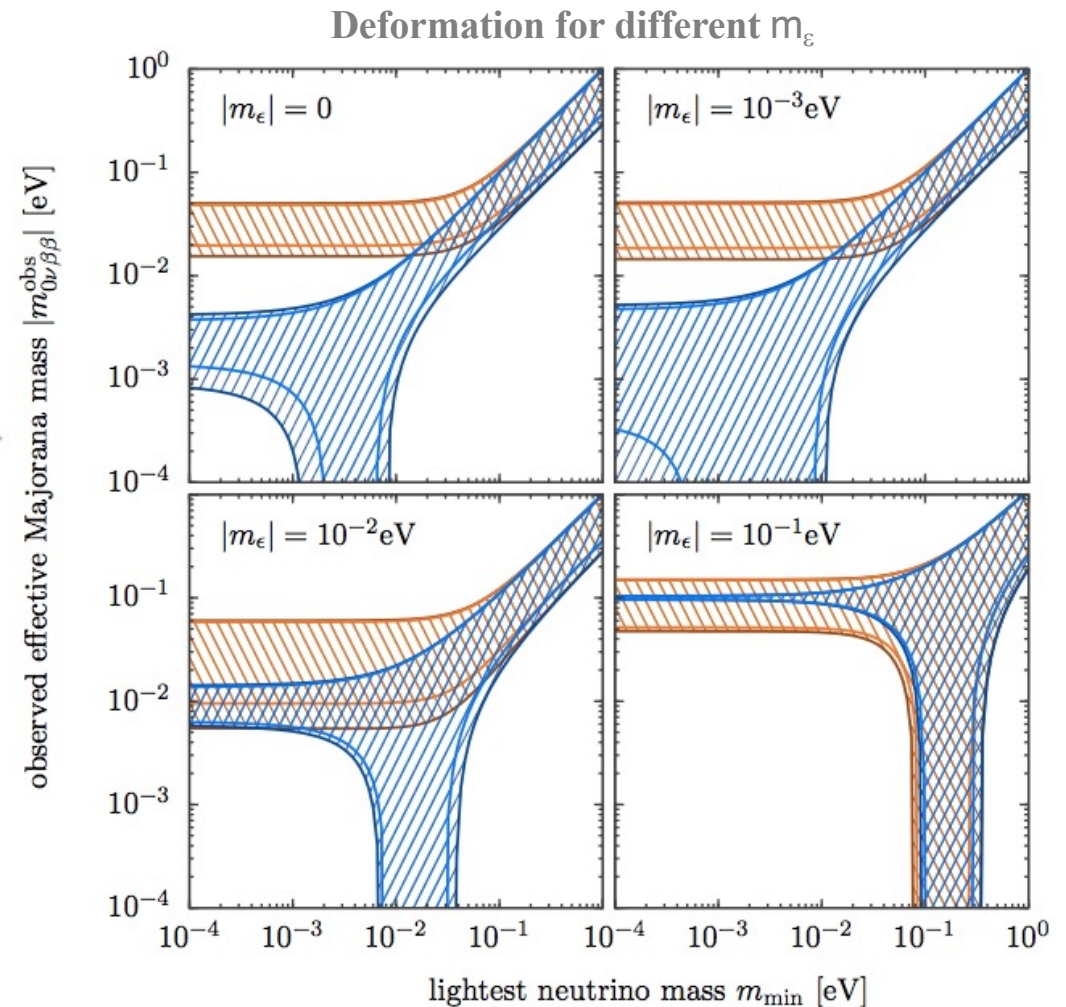
Interferences:

total $0\nu\beta\beta$

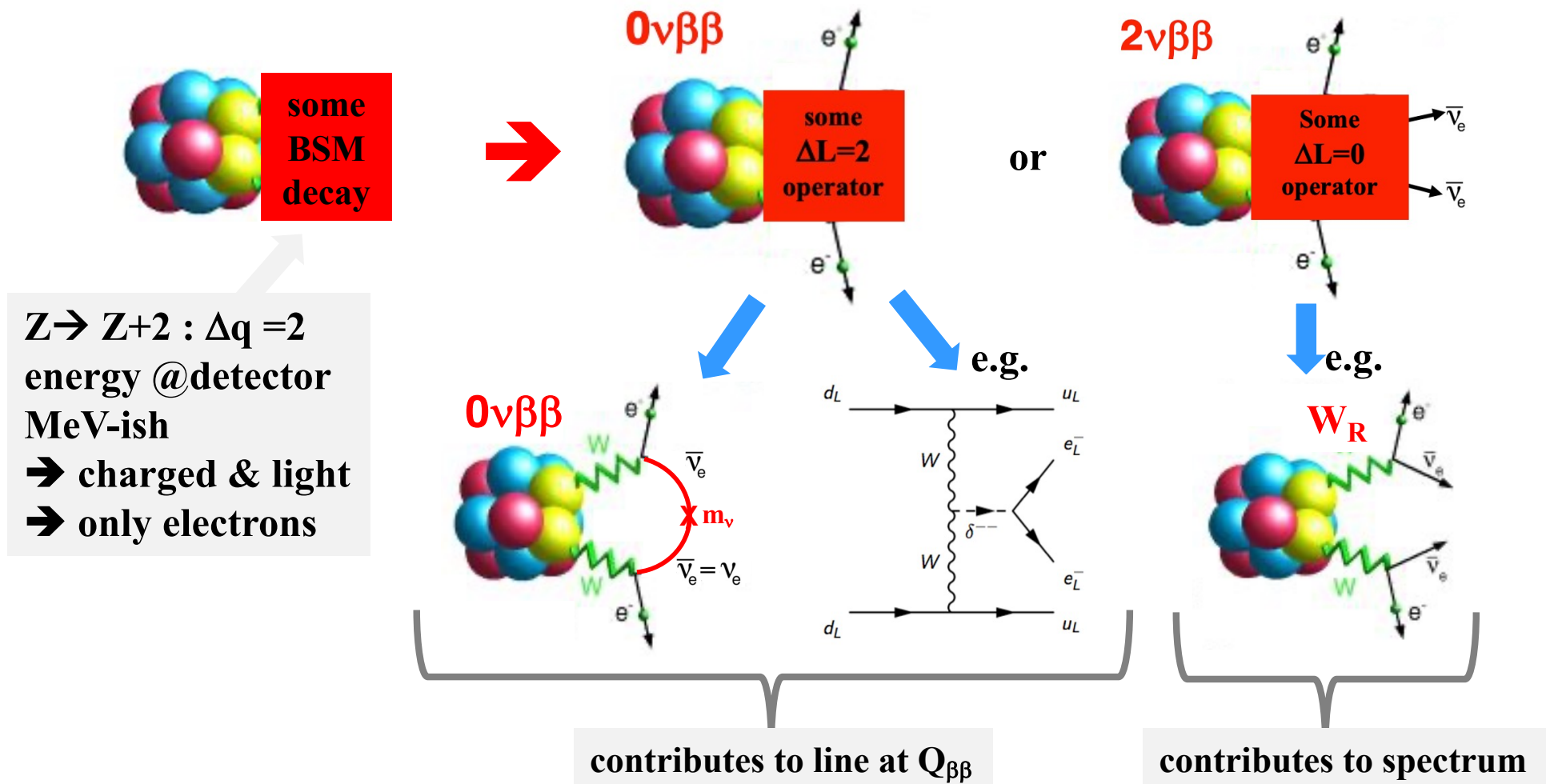
- neutrino contribution
- $m_{\epsilon} \leftrightarrow$ other $\Delta L=2$ physics
- shifts masses, mixings, CP phases
- deformation due to TeV physics

Extreme case:

- Dirac neutrino masses, signal in IH region
- all due to other $\Delta L=2$ physics



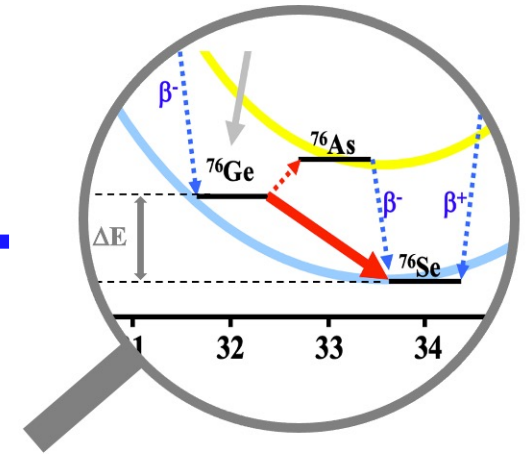
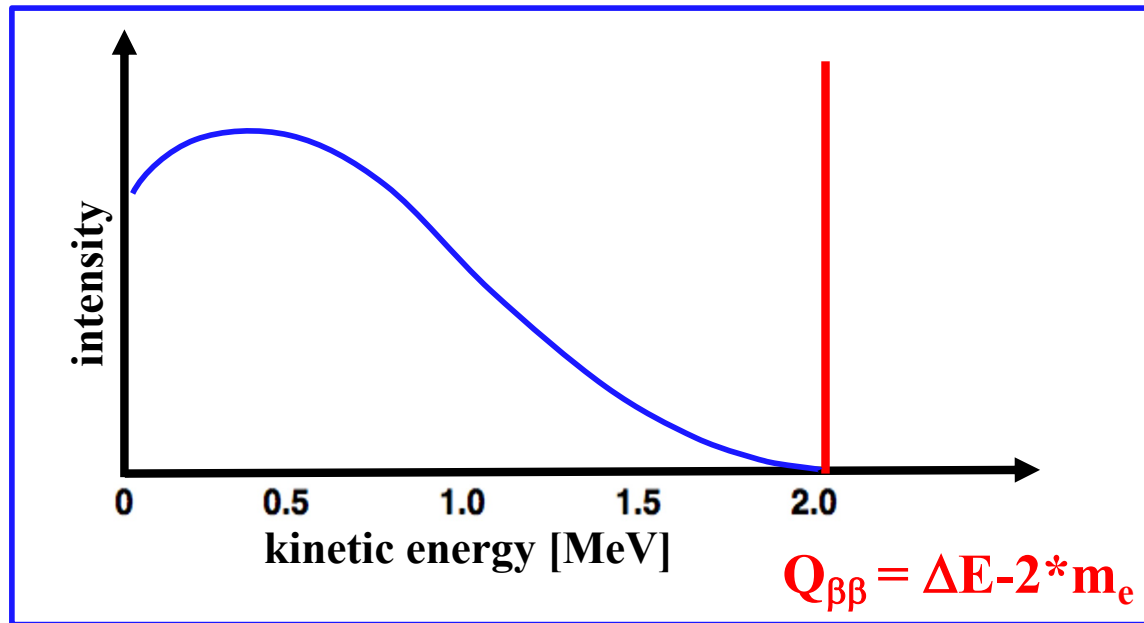
Double Beta Decay and BSM Physics



- many reasons for BSM physics with and w/o $\Delta L=2$
- if one ignores all other reasons → neutrino masses
- many BSM models affect both $0\nu\beta\beta$ and $2\nu\beta\beta$

→ why think only about neutrinos?

Modifications of the Energy Spectrum



BSM can affect:

- amplitudes of both $2\nu\beta\beta$ and $0\nu\beta\beta \leftrightarrow$ NME uncertainties
- shape
- line position

backgrounds in a real experiment $\leftrightarrow$ what can be detected

Examples:

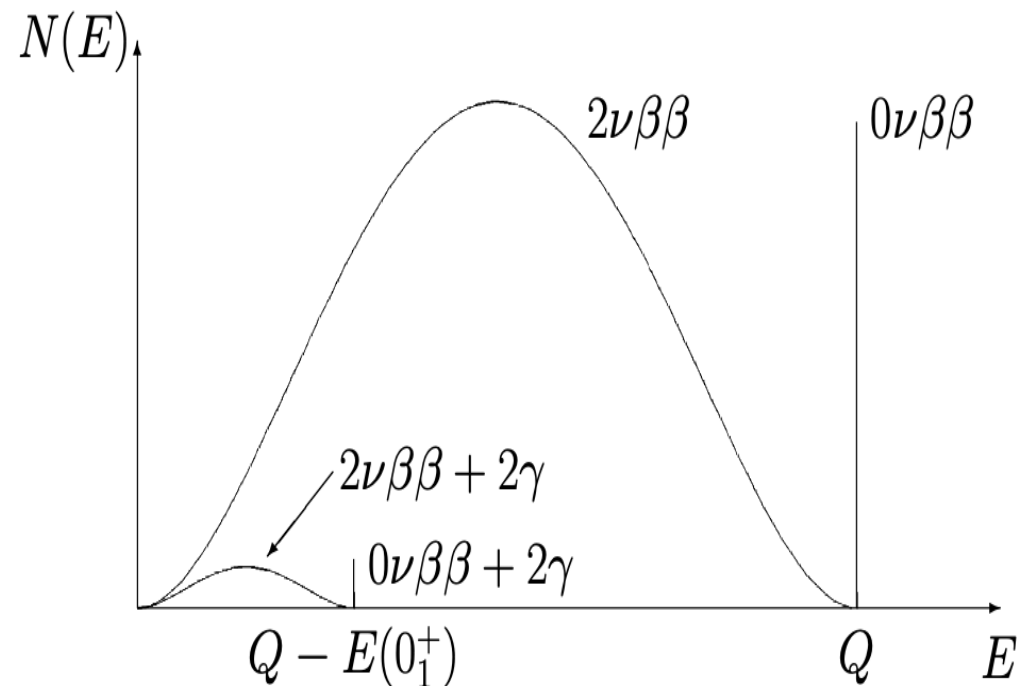
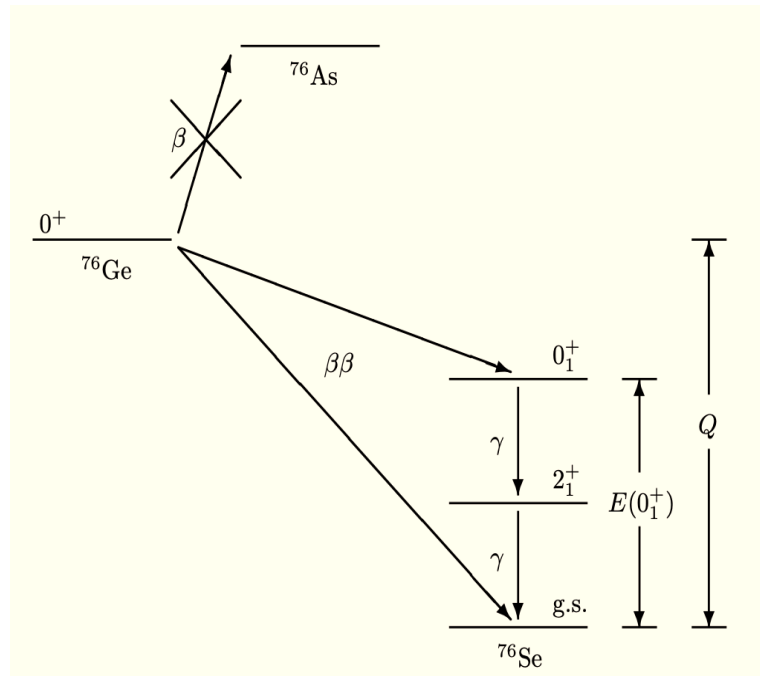
- sterile neutrinos with masses $\simeq$ MeV and $2\nu\beta\beta$
- right-handed currents $\rightarrow M_{\text{WR}}$
- ...

Consistency Test of $0\nu\beta\beta$ with one Isotope

If IH $\rightarrow$ experiments would see a significant number of events

$\rightarrow 0\nu\beta\beta$ can also go to excited states (subleading)

Duerr, ML, Zuber, PRD 84 (2011) 093004



$\rightarrow$ small corrections to the $0\nu\beta\beta$ spectrum
from sub-leading SM allowed transitions – not BSM

A nice consistency test with one isotope

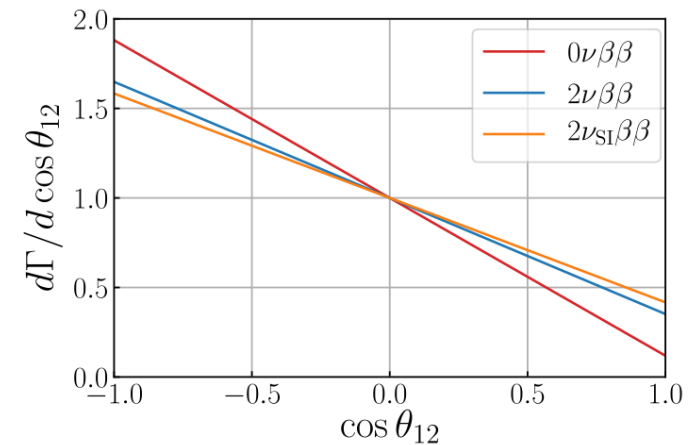
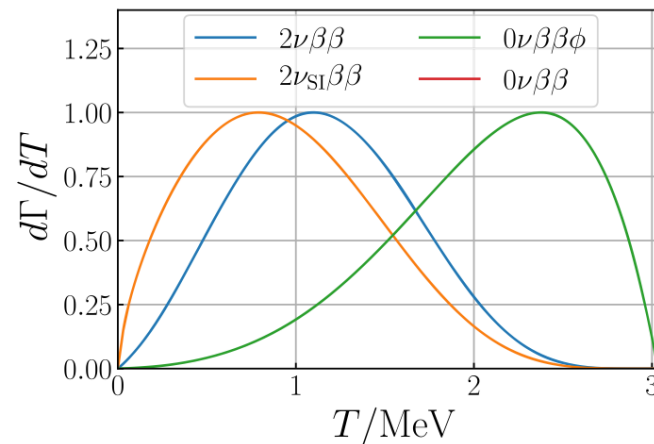
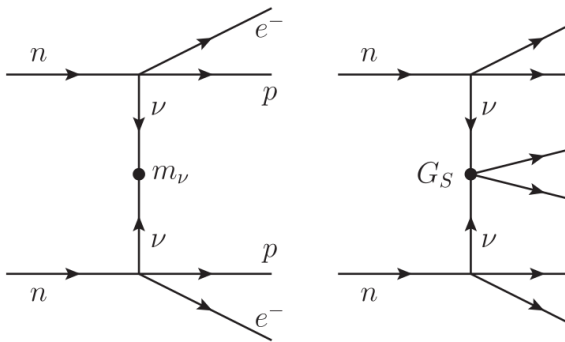
$\Delta E \leftrightarrow$ known energy levels $\rightarrow$ does not depend on NME uncertainties

Combine $0\nu\beta\beta$ and $2\nu\beta\beta$

Future experiments will measure $2\nu\beta\beta$ spectrum very precisely

→ combine $0\nu\beta\beta$ and $2\nu\beta\beta$ (effects on top of high statistics SM signal)

- **Lepton-number conserving right-handed currents**
Deppisch, Graf, Simkovic, PRL 125 (2020) 17, 171801
- **Sterile neutrino and light fermion searches through energy end point**
Bolton, Deppisch, Graf, Simkovic, PRD 103 (2021) 5, 055019, Agostini, et al., PLB 815 (2021) 136127)
- **Neutrino self-interactions**
Deppisch, Graf, Rodejohann, Xu, PRD 102 (2020) 5, 051701
- ...



Baryon Asymmetry of the Universe

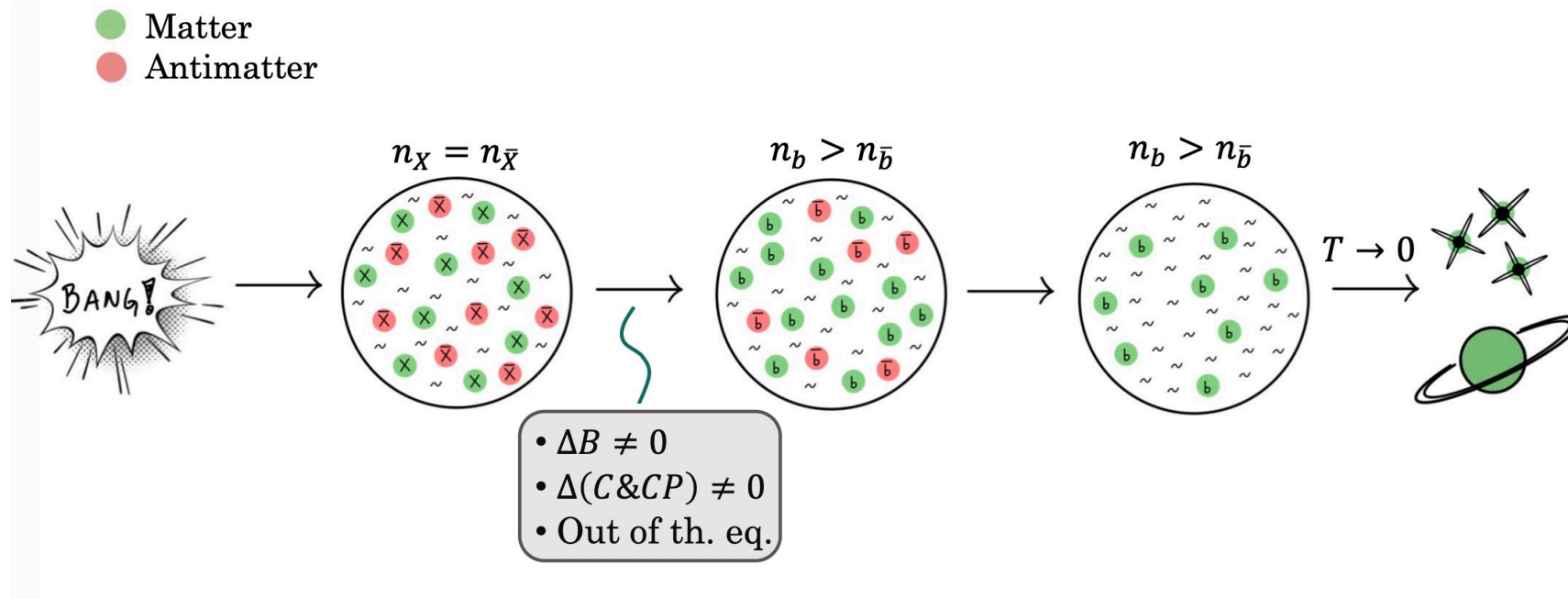
Baryon asymmetry of the Universe (BAU): observation

$$\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 6.1 \times 10^{-10}$$

Any explanation must fulfill the Sakharov conditions:

1. Baryon number violation
2. C & CP violation
3. Out of thermal equilibrium decays

fulfilled by SM



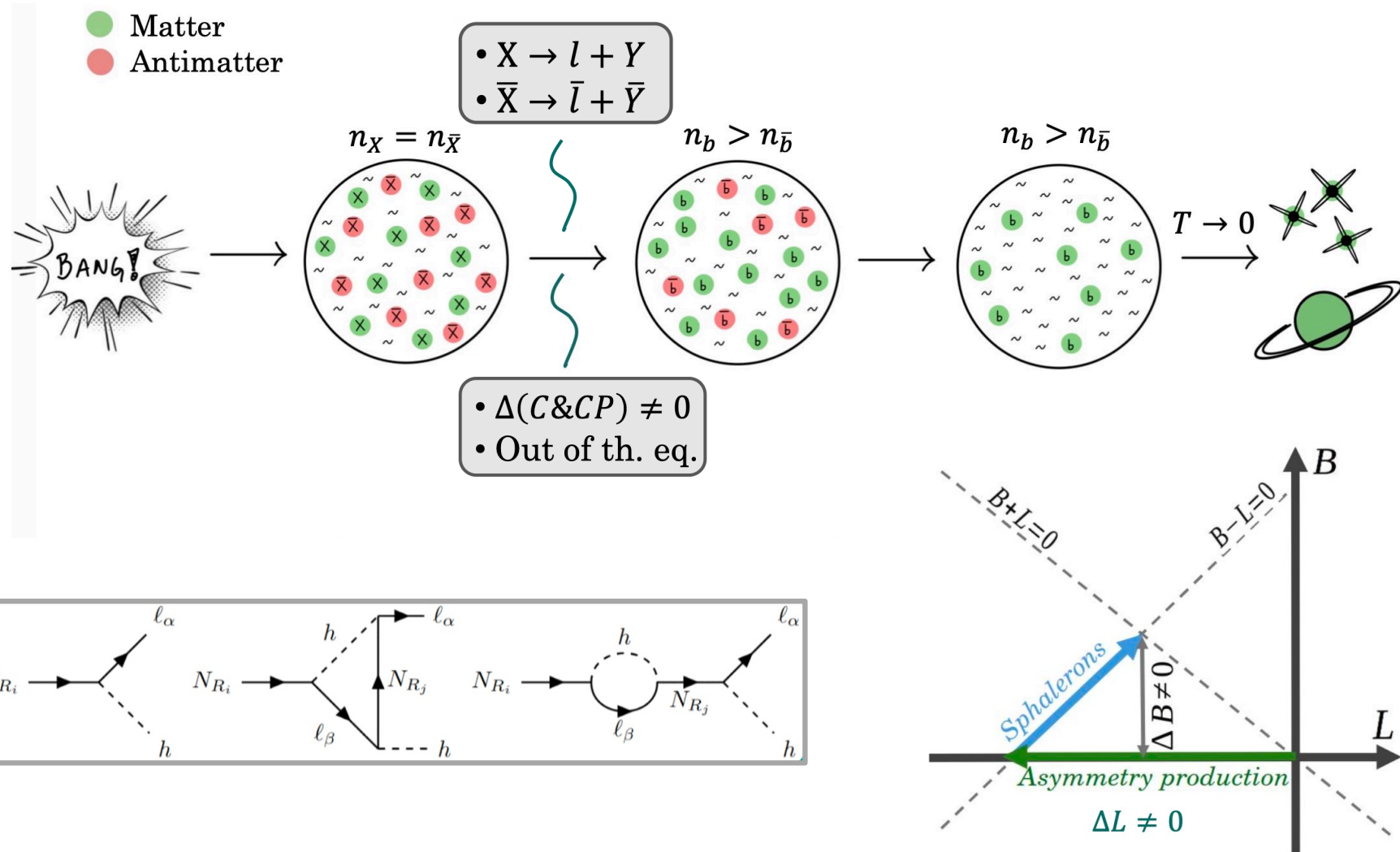
calculate in the SM

$$\eta_B^{SM} \sim 10^{-19}$$

➔ **BSM required!!!**

Leptogenesis

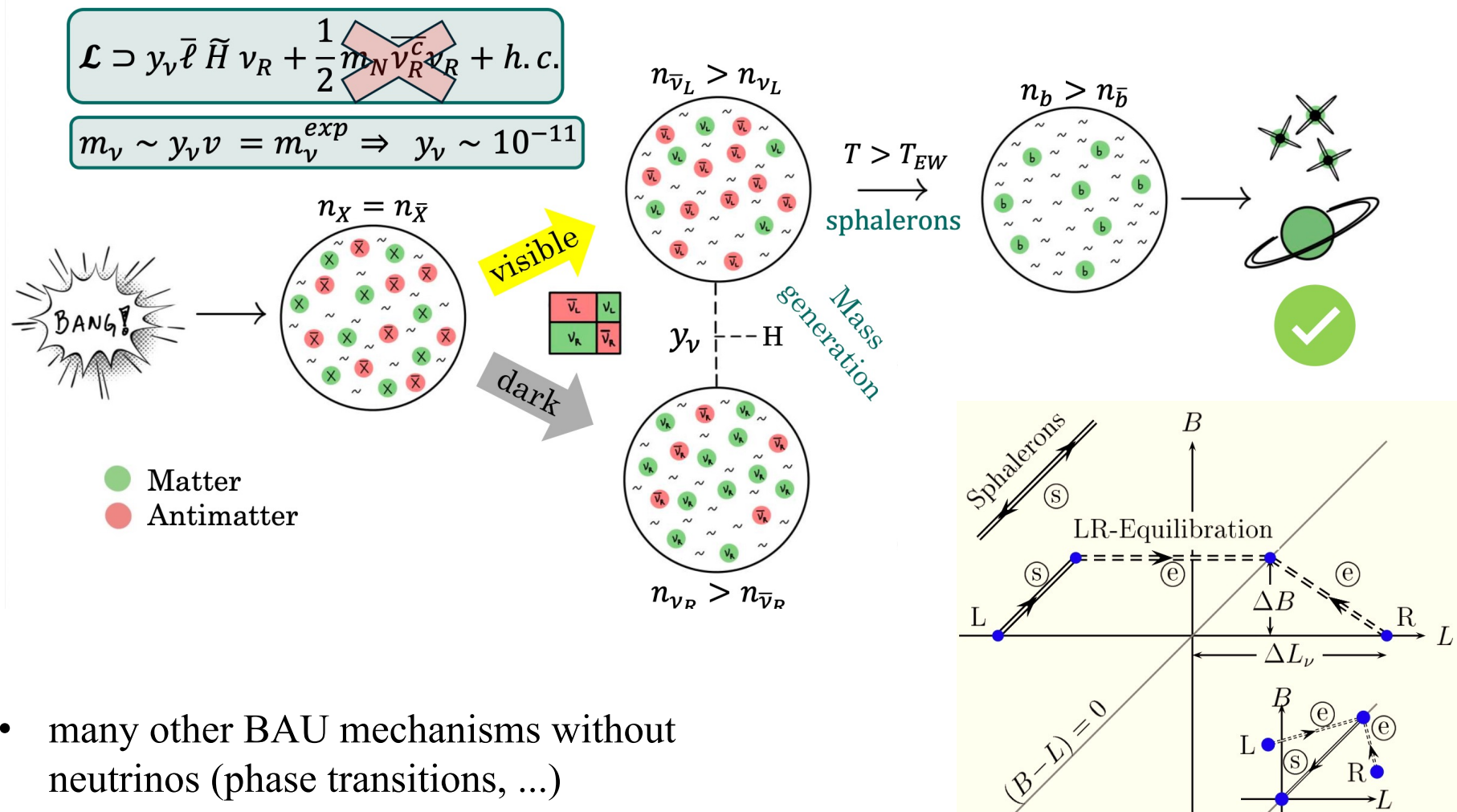
Heavy Majorana Neutrinos N_R with very large $M_R \rightarrow X$



B violation by combined L violation and B+L violation

Other BAU with and without Neutrinos

- ARS mechanism [Akhmedov, Rubakov, Smirnov](#)
BAU generated by CP-violating flavor oscillations of sterile (right-handed) neutrinos
- Dirac leptogenesis (with Dirac neutrino masses) [Dick, ML, Ratz, Wright](#)

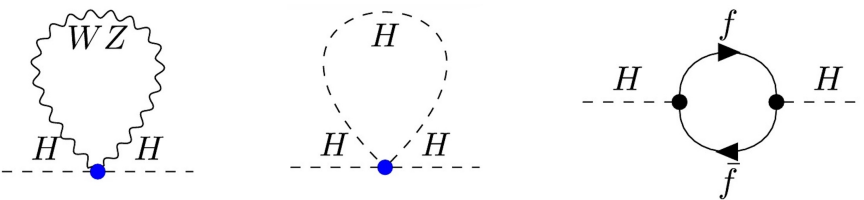


- many other BAU mechanisms without neutrinos (phase transitions, ...)

Hierarchy Problems (the usual Story)

Stability of vastly different scales under quantum corrections?

SM:

$$\delta M_H^2 =$$


$$\delta M_H^2 = \frac{\Lambda^2}{32\pi^2 V^2} (6M_W^2 + 3M_Z^2 + 3M_H^2 - 12M_t^2) \sim \Lambda^2 \gg M_H^2$$

- SM is renormalizable – no cutoff – no problem
 - ➔ **Veltman condition is meaningless**
- it becomes a problem if Λ stands for new physics = embedding
- embeddings require to talk about individual thresholds
 - ➔ quadratic sensitivity to some mean embedding scale Λ
 - ➔ **not RG invariant, no protective symmetry – at best partial**

The See-Saw and the Hierarchy Problem

SM+: massive neutrinos

- Dirac neutrino masses – no problem (Yukawa couplings like quarks)
- Majorana neutrino masses $\rightarrow$ more scales M_i
 $\rightarrow$ generates another HP problem for large M even if y_ν is tiny

from see-saw: $y_\nu^2 = M m_\nu / v^2$

$$\delta m_H^2 \simeq \frac{y_\nu^2}{16\pi^2} M^2$$

avoiding the problem:

$$M \lesssim 10^7 - 10^8 \text{ GeV}$$

- $\rightarrow$ **tension: leptogenesis want big M , while the hierarchy problem wants a lower M**
- $\rightarrow$ **low scale leptogenesis... $\leftrightarrow$ other BSM physics?**

And not to forget the 0th order hierarchy problem:

- why are (tree level) scales vastly different?
- why at all scales in the Lagrangian?

Conclusions

- neutrino physics is and will remain very interesting
 - unique potential to discover more BSM physics
 - neutrino mass limits from cosmology and lab will evolve within a few years:
 - ➔ a consistent trend towards NH ➔ may appear discouraging for $0\nu\beta\beta$
 - ➔ to be seen: NH or maybe IH or tensions from inconsistencies
 - IMPORTANT: $0\nu\beta\beta$ is a combined **consequence of all $\Delta L=2$ violations**
 - claiming that $0\nu\beta\beta$ comes entirely from Majorana masses depends on various assumptions in neutrino physics and BSM (Dirac, Majorana, other fields,...)
 - ➔ **$0\nu\beta\beta$ can show up anywhere between 0 and current limits**
 - ➔ **potential inconsistencies would be more exciting than consistent NH**
 - leptogenesis is interesting, but (in the context of $0\nu\beta\beta$) a bit over-sold
- ➔ how to move most effectively:
- different physics channels ➔ combination with other results / methods
 - time & cost ➔ make use of existing infrastructure (UG labs, equipment, ...)
 - ➔ develop and use technologies with favourable time/cost scaling
 - ➔ $0\nu\beta\beta$: good potential of metal loaded detectors