Lepton Number Violation

and the

Baryon Asymmetry of the Universe

- HEINRICH PÄS -

tu
dortmund

MPI Seminar
Max-Planck-Institut für Kernphysik Heidelberg
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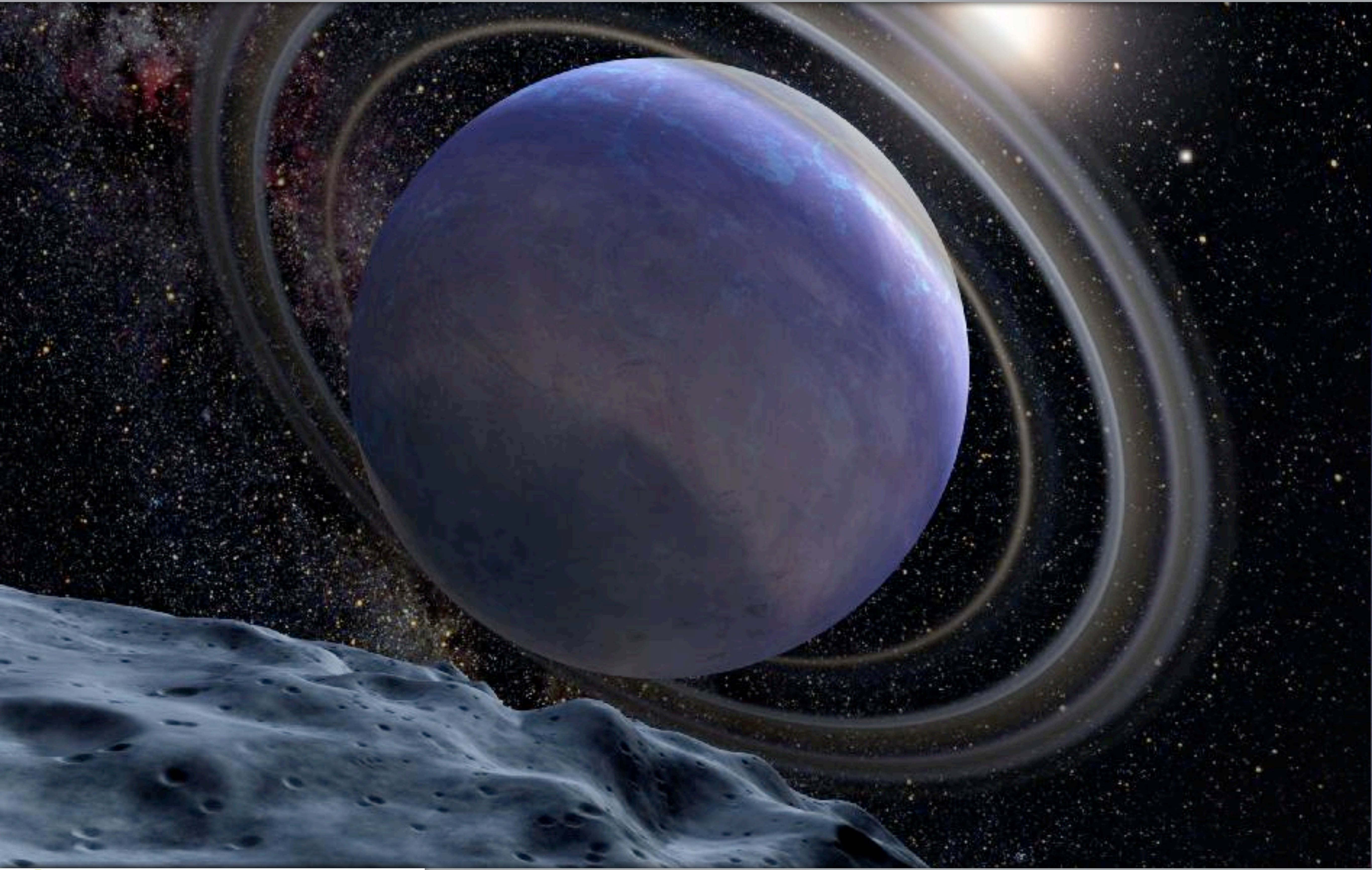
Outline

- The Baryon Asymmetry of the Universe
- Lepton Number Violation (LNV)
- Double Beta Decay
- LNV at the LHC
- Baryon Number Washout
- Conclusions

The Baryon Asymmetry of the Universe

Why is there something and not nothing?



The progress of cosmology in the last 30,000 years

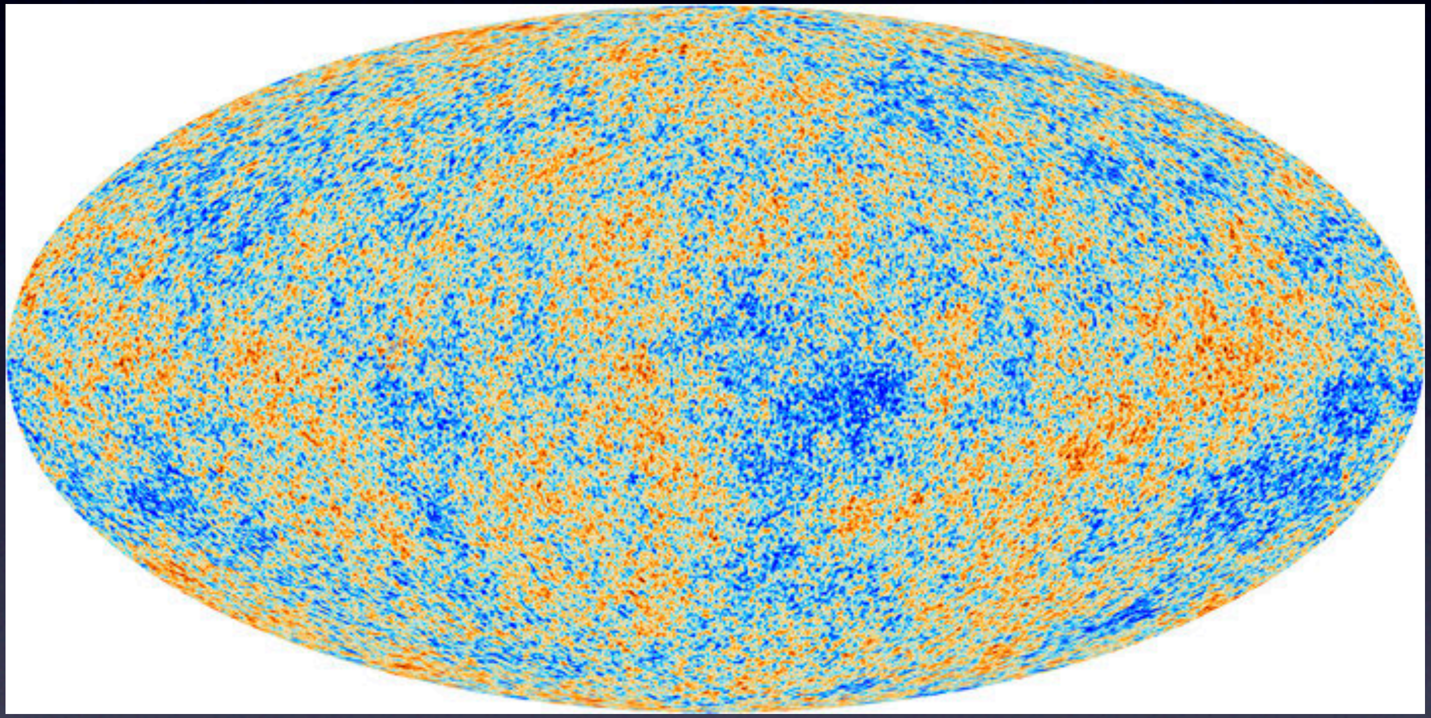
Evidence for a Baryon Asymmetry

- Spectrum of anti-protons in cosmic radiation (BESS/ balloon in 35 km height) consistent with production from cosmic primaries

- No anti-helium found (AMS spectrometers on space shuttle discovery and International Space Station ISS)

Evidence for a Baryon Asymmetry

- No traces of annihilation radiation in the local galaxy cluster



- No distortion of the cosmic microwave background

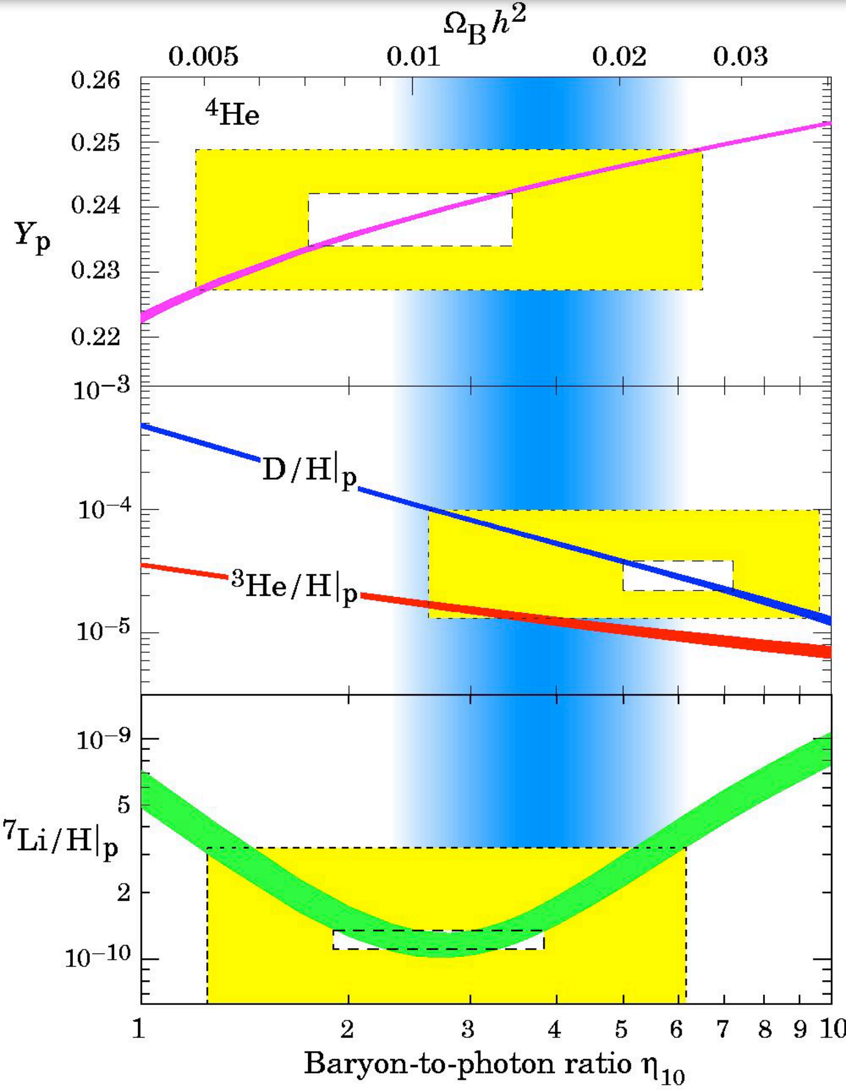
Size of the Baryon Asymmetry

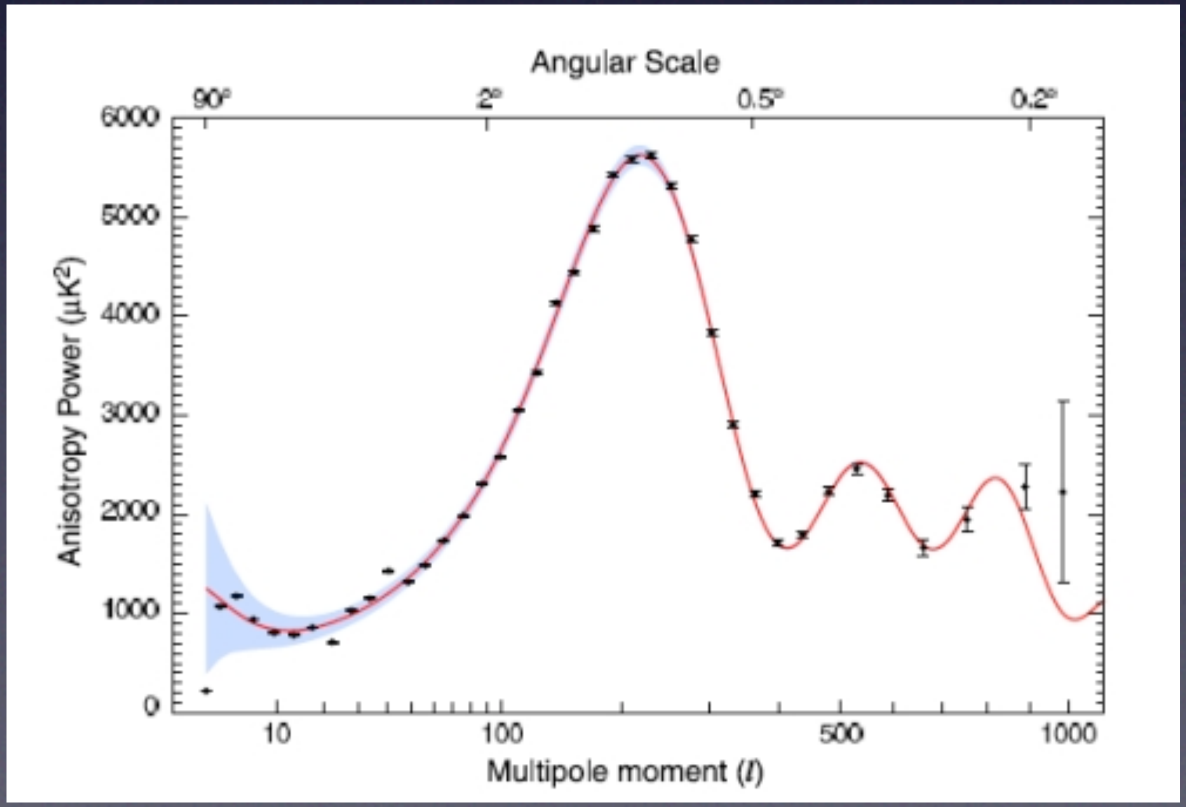
- Big Bang Nucleosynthesis: synthesis of

  $p,n \rightarrow D$, ^3He, ^4He, ^7Li

  depends on baryon and radiation density

$$\eta_B = \frac{n_B - n_{\overline{B}}}{n_\gamma}$$



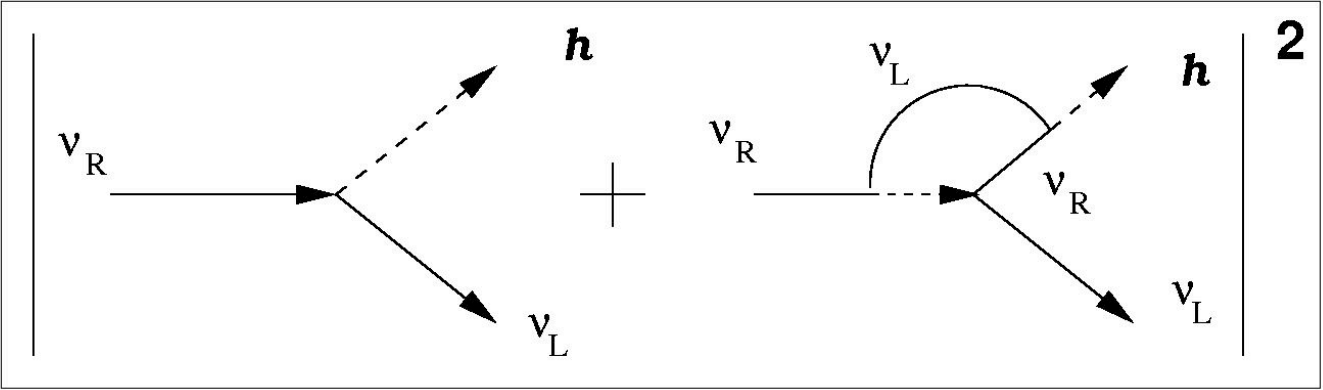


- CMB: comparing heights 1st peak (gravitation →→ gas) vs. 2nd peak (gravitation ↔ gas)

$$\eta_B^{\text{obs}} = (6.20 \pm 0.15) \times 10^{-10}$$

Baryogenesis

- Baryon Asymmetry as initial condition?
- Cosmic inflation: $a(t) \sim exp\,(\Lambda/3)\,t$
→ Universe flat, homogenous and empty
→ necessity of Baryogenesis after reheating
- 3 Sakharov conditions:
→ Non-Equilibrium
→ C and CP violation
→ Baryon Number Violation
- Prominent example – Leptogenesis:
right-handed neutrino decay in early Universe

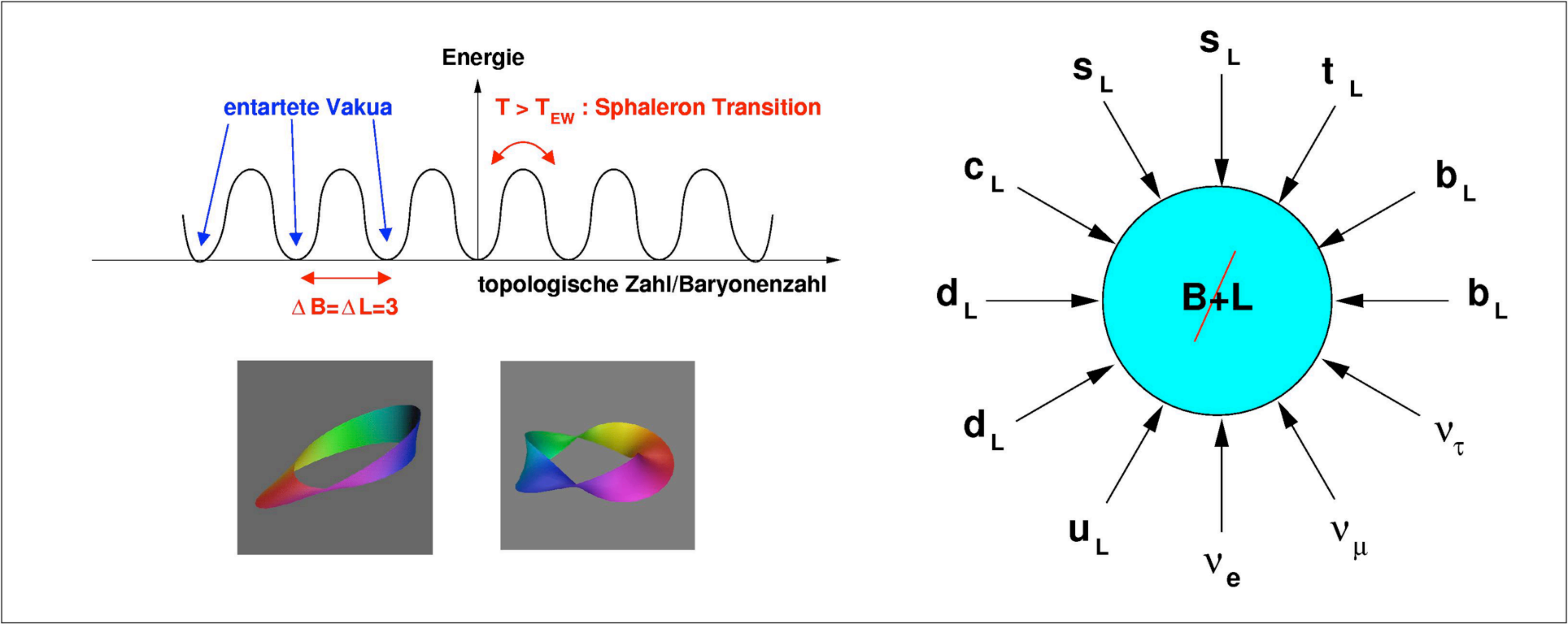


→ Lepton Asymmetry

[Fukugita, Yanagida, 1986]

Sphalerons

Sphalerons: B-Violation within the Standard Model



Topologically different field configurations ⇒
degenerate vacua with different baryon numbers [t'Hooft, 1976]

$T > T_{EW}$ ⇒ Transitions between vacua, B+L Violation

[Kuzmin, Rubakov, Shaposhnikov, 1985]

Baryogenesis

- Electroweak baryogenesis via Sphalerons?
  In the SM: EW phase transition not rapid enough (non-equilibrium), 2 competing vacua during phase transition necessary → depends on Higgs quartic coupling → only possible for Higgs masses < 70 GeV
- Physics beyond SM needed!
- Leptogenesis: B-L Asymmetry + B+L violating Sphalerons ⇒ B Asymmetry

Baryogenesis

Not simple:

“Das Nichts nichtet - the Nothing noths”

(Martin Heidegger)

BUT: This is NO talk on Baryogenesis !

So let’s assume we somehow created a Baryon Asymmetry and let’s go on with particle physics

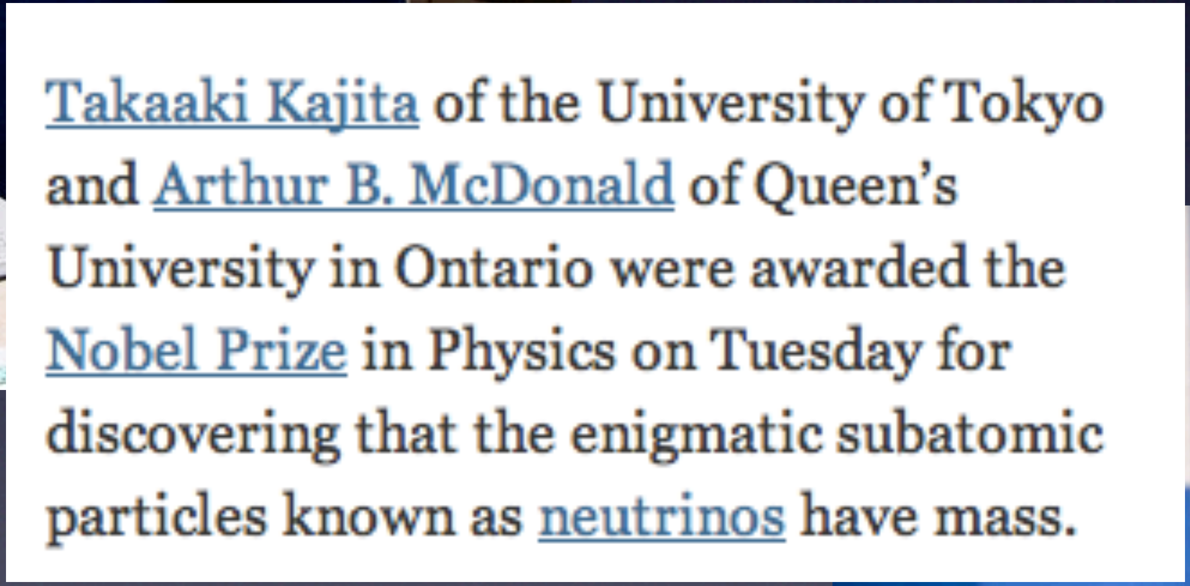
Lepton

Number

Violation

Why is
Lepton Number Violation
interesting
?

The New York Times



Takaaki Kajita of the University of Tokyo and Arthur B. McDonald of Queen's University in Ontario were awarded the Nobel Prize in Physics on Tuesday for discovering that the enigmatic subatomic particles known as neutrinos have mass.

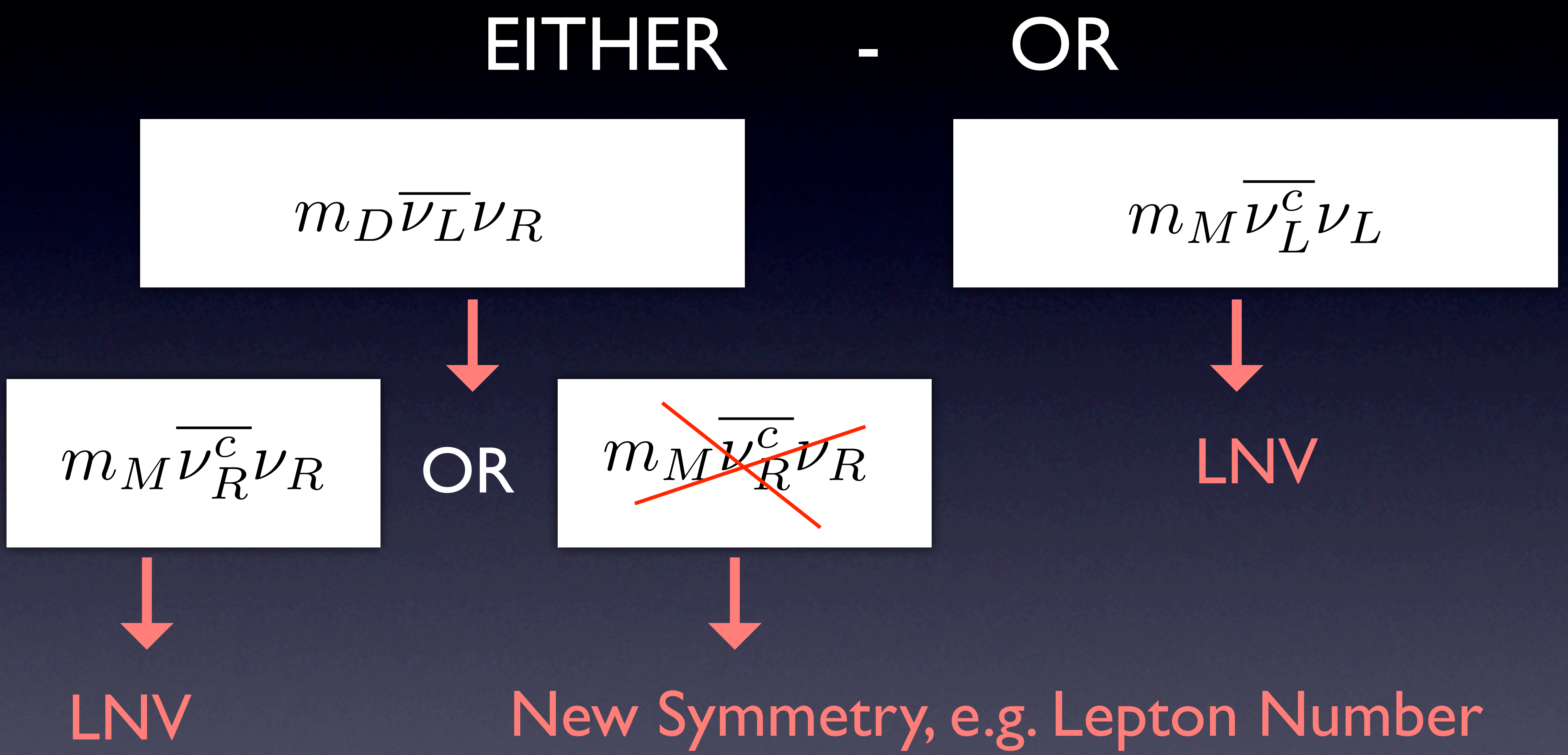
”Uncharacteristically for a physics conference people gave the speaker a standing ovation. I stood up too. Having survived every experimental challenge since the late 1970s the Standard Model had finally fallen. The results showed that at the very least the theory is incomplete.”

Hitoshi Murayama (UC Berkeley)
about the Neutrino-98-Konferenz

Bullshit ?

Why is LNV interesting ?

Why is a non-zero ν mass physics beyond SM ?



EITHER - OR

$m_D \overline{\nu_L} \nu_R$

$m_M \overline{\nu_L^c} \nu_L$

$m_M \overline{\nu_R^c} \nu_R$ OR $\cancel{m_M \overline{\nu_R^c} \nu_R}$

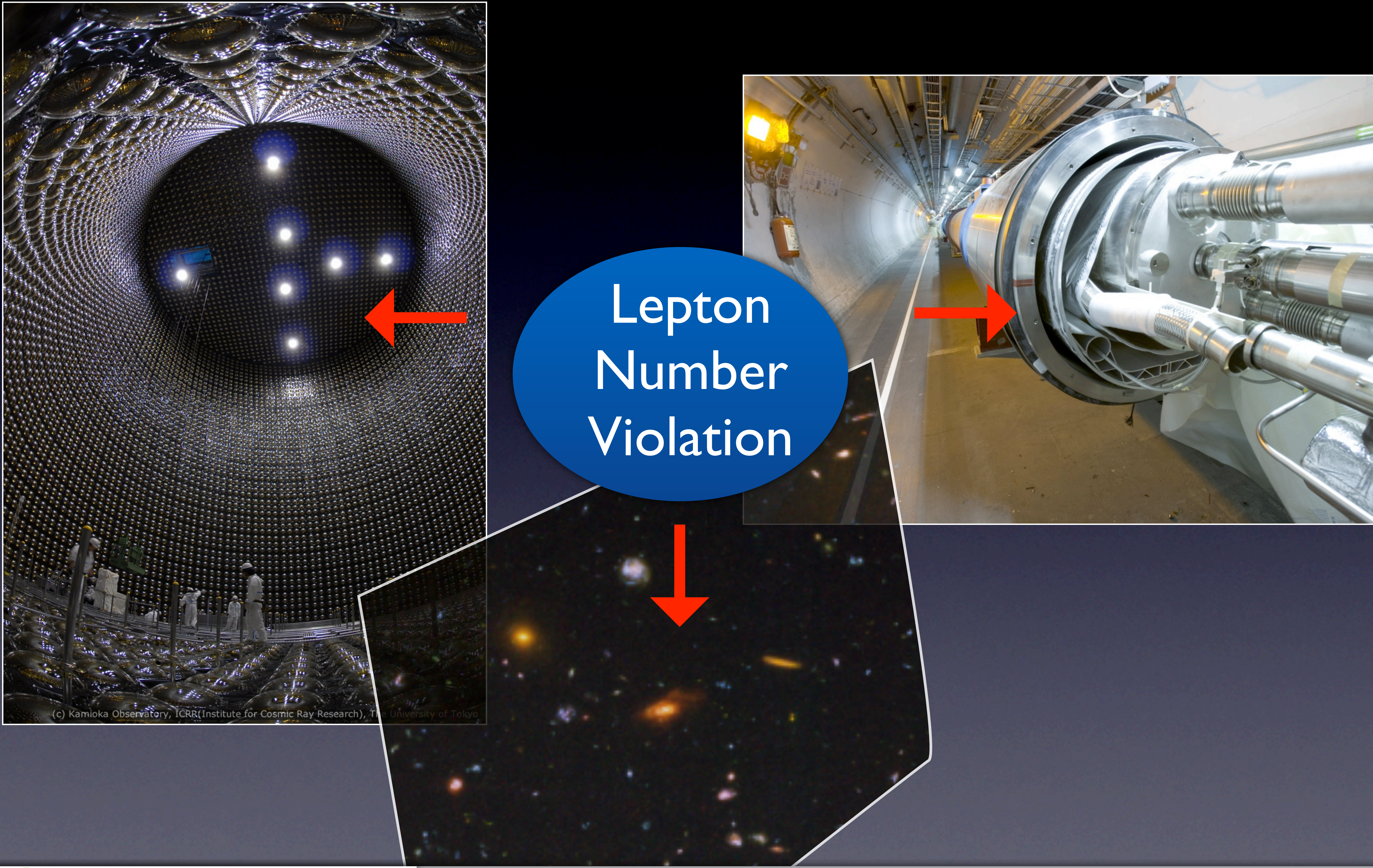
LNV

New Symmetry, e.g. Lepton Number

LNV
e.g.
Seesaw-I
[Minkowski'77]

Lepton Number (Violation) is at the core of the link between ν mass & physics beyond SM!

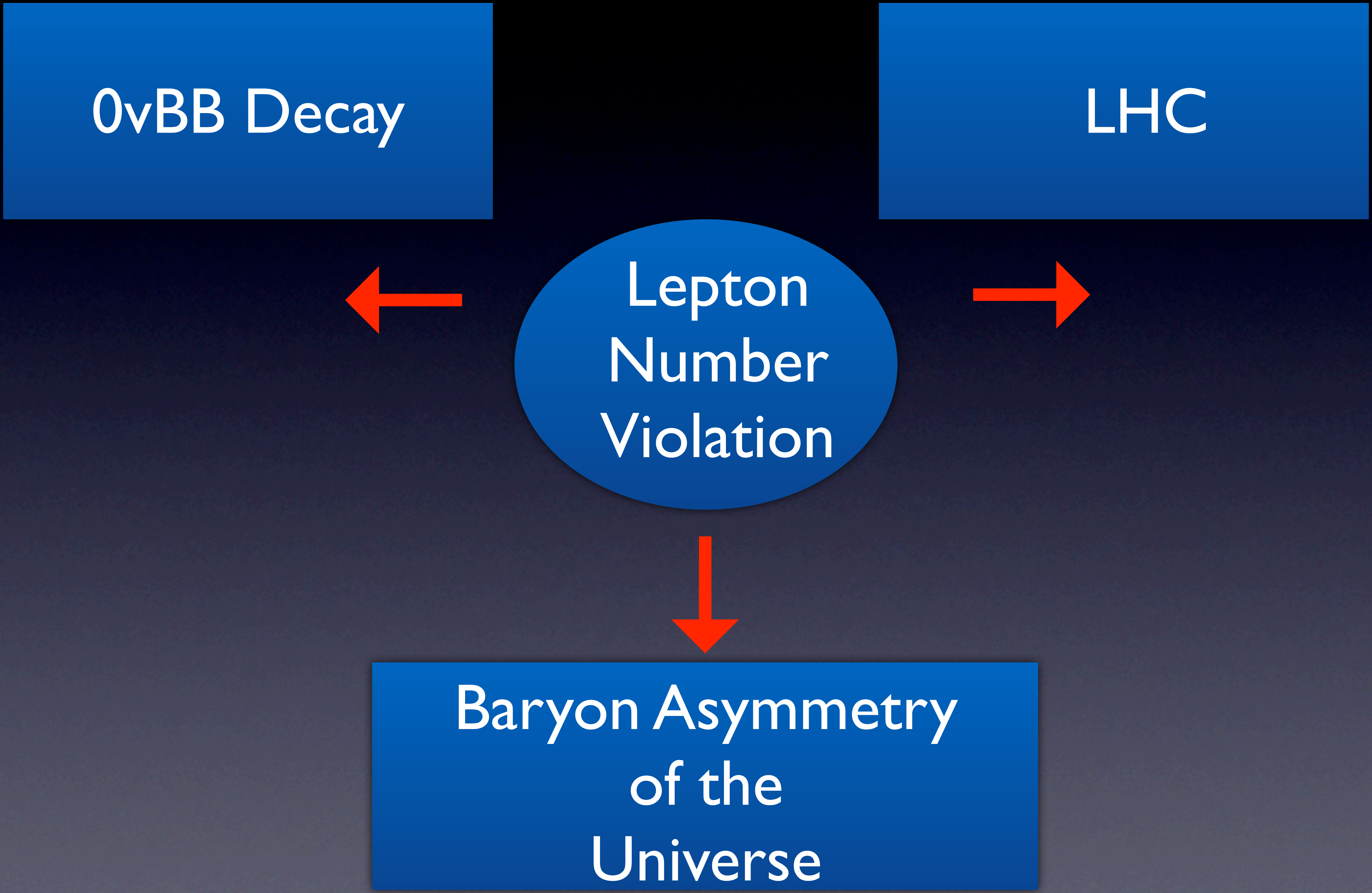
Key Message



Lepton Number Violation

(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Tokyo

Key Message



0vBB Decay

LHC

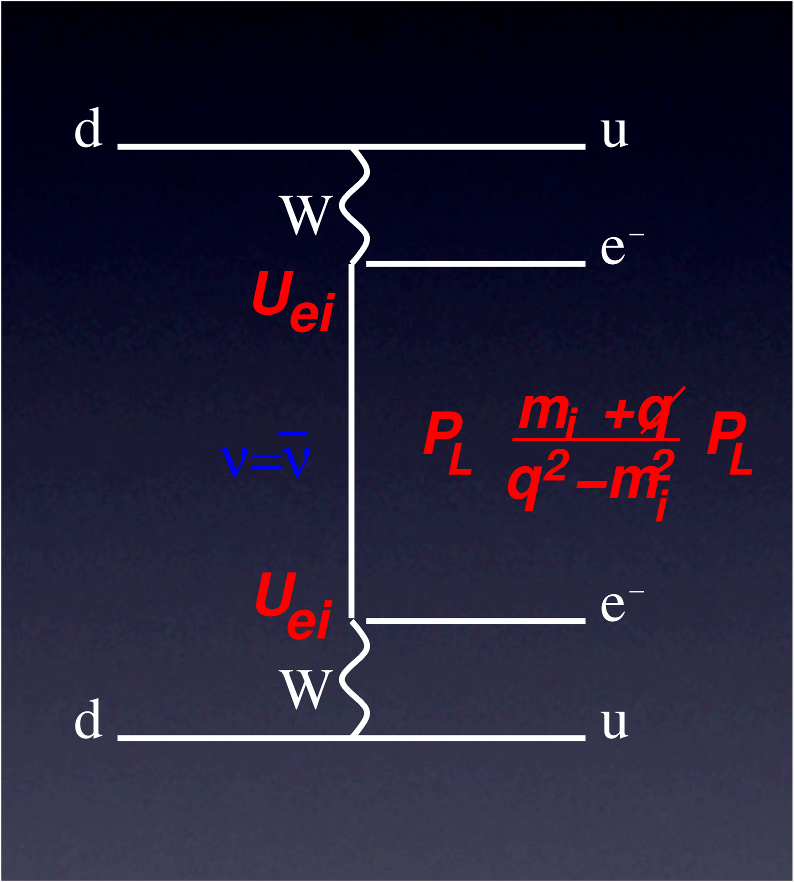
Lepton Number Violation

Baryon Asymmetry of the Universe

Double Beta Decay

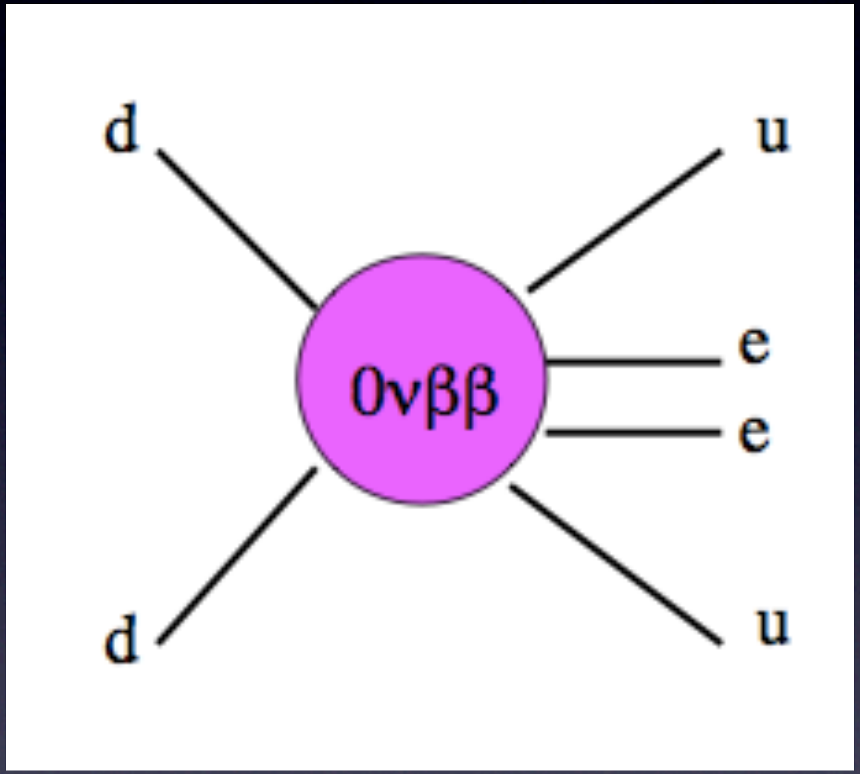
Probing LNV

Most prominent: 0vBB decay



$\sim m_\nu$

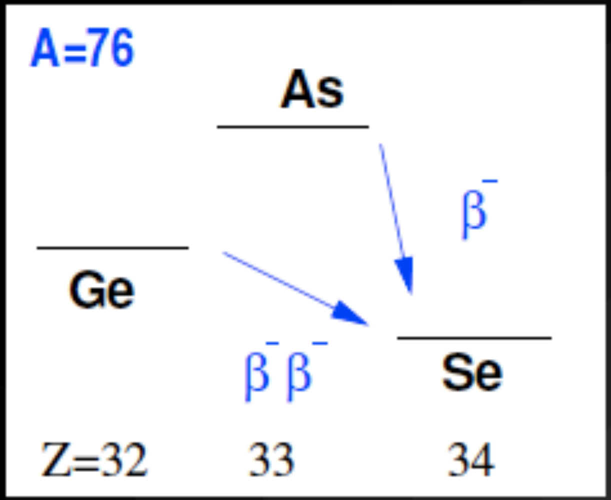
“Mass Mechanism”

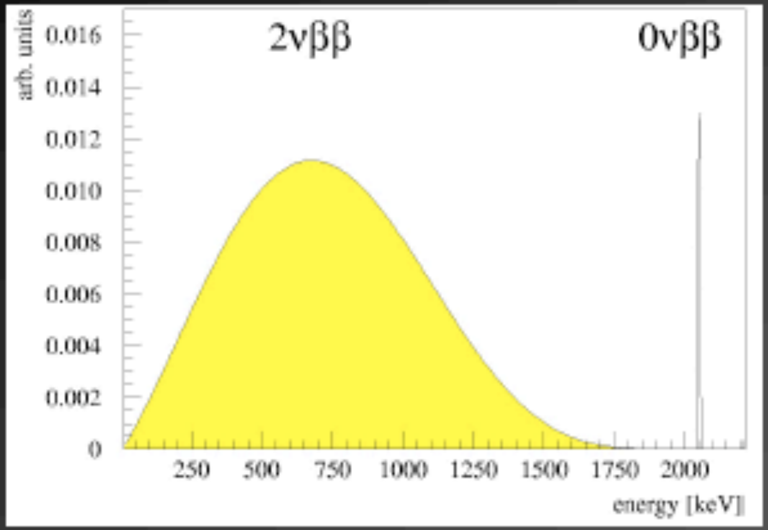


General Case

What is 0vBB decay?

$$\boxed{2n \rightarrow 2p + 2e^-}$$





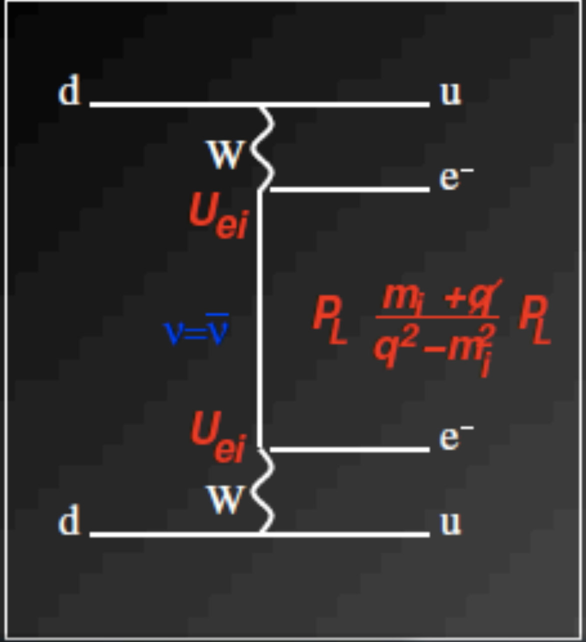
Mass mechanism:

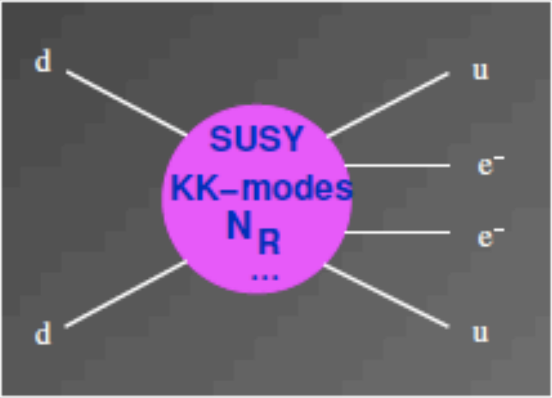
$$\boxed{[T^{0\nu}_{1/2}]^{-1} \propto |\sum_i U^2_{ei} m_i|^2}$$

In general: Every operator

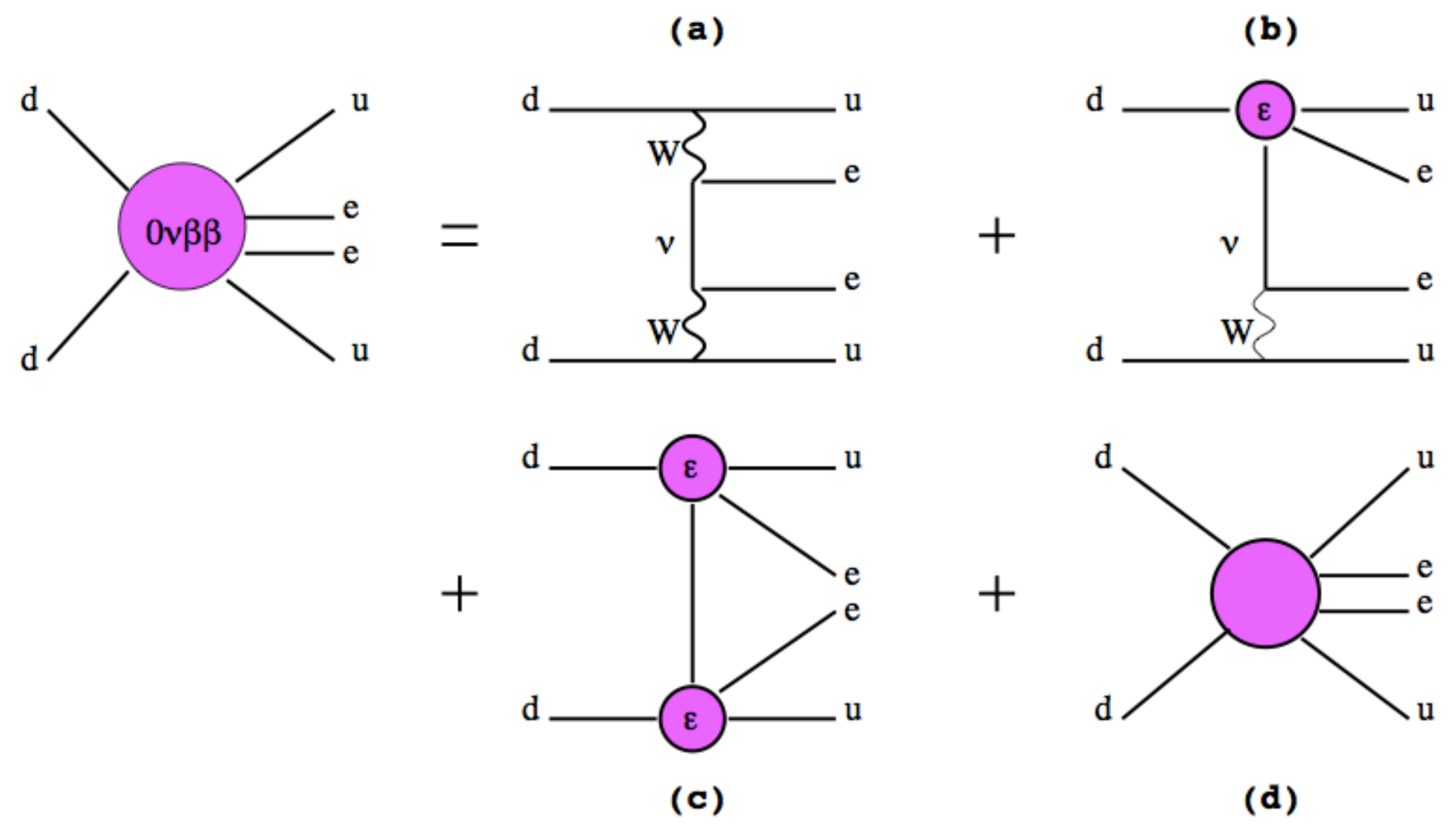
$$\boxed{\overline{p}\,\overline{p}\,\overline{e}\,\overline{e}\,nn/M^5}$$

will generate $0\nu\beta\beta$ decay



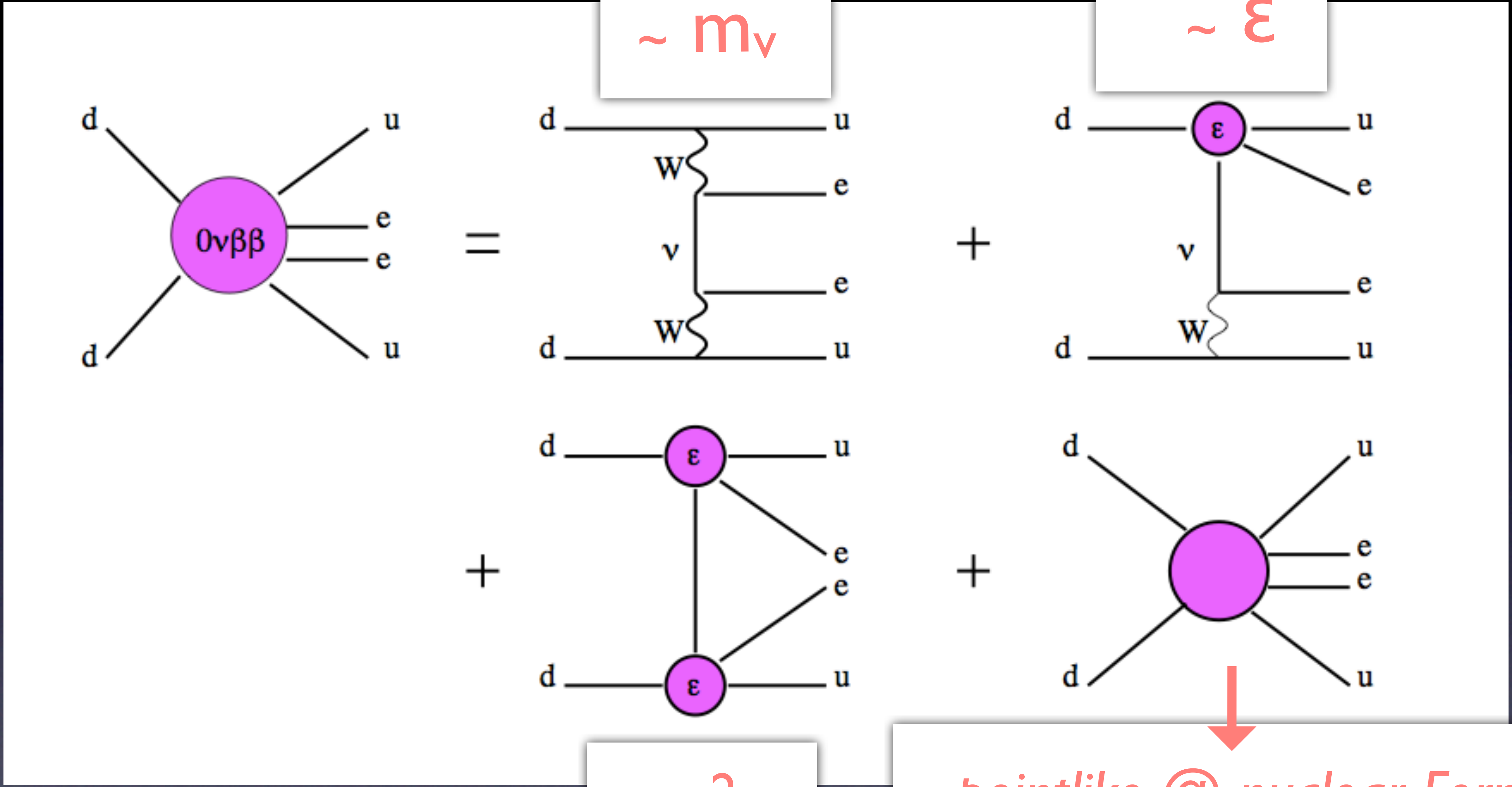


0vBB Decay



[HP, Hirsch, Kovalenko, Klapdor-Kleingrothaus, PLB 1999 & 2001]

0vBB Decay



~ m_ν

~ ε

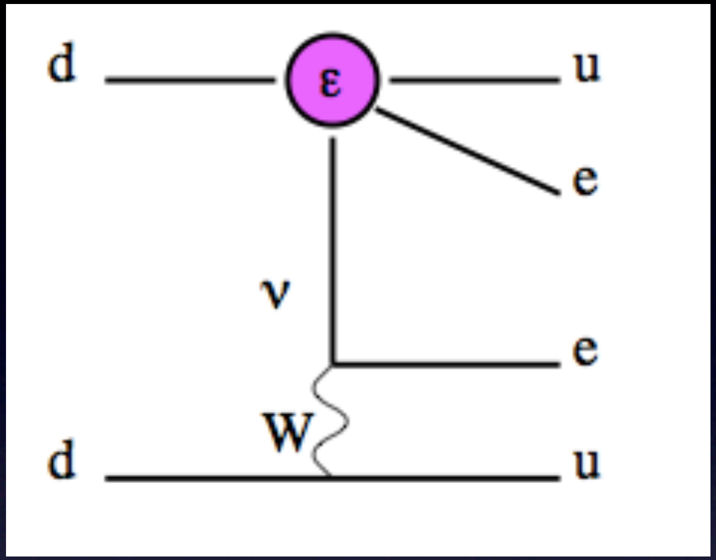
~ ε^2

pointlike @ nuclear Fermi momentum O(r_N^{-1})~100 MeV

[HP, Hirsch, Kovalenko, Klapdor-Kleingrothaus, PLB 1999 & 2001]

General parametrization for 0vBB Decay

Long-Range Part



$$\mathcal{L} = \frac{G_F}{\sqrt{2}}\{j^{\mu}_{V-A}J^{\dagger}_{V-A,\mu} + {\sum_{\alpha,\beta}}' \epsilon^{\beta}_{\alpha} j_{\beta} J^{\dagger}_{\alpha}\}$$

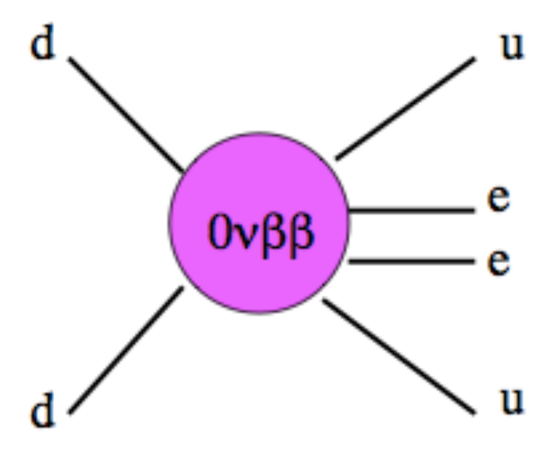
ϵ^{V+A}_{V-A}	$4.4 \cdot 10^{-9}$
ϵ^{V+A}_{V+A}	$7.0 \cdot 10^{-7}$
ϵ^{S+P}_{S-P}	$1.1 \cdot 10^{-8}$
ϵ^{S+P}_{S+P}	$1.1 \cdot 10^{-8}$
ϵ^{TR}_{TL}	$6.4 \cdot 10^{-10}$
ϵ^{TR}_{TR}	$1.7 \cdot 10^{-9}$

$$\begin{aligned}
\mathcal{O}_{V-A} &= \gamma^{\mu}(1-\gamma_5)\\
\mathcal{O}_{V+A} &= \gamma^{\mu}(1+\gamma_5)\\
\mathcal{O}_{S-P} &= (1-\gamma_5)\\
\mathcal{O}_{S+P} &= (1+\gamma_5)\\
\mathcal{O}_{T_L} &= \frac{i}{2}[\gamma_{\mu},\gamma_{\nu}](1-\gamma_5)\\
\mathcal{O}_{T_R} &= \frac{i}{2}[\gamma_{\mu},\gamma_{\nu}](1+\gamma_5).
\end{aligned}$$

[HP, Hirsch, Kovalenko, Klapdor–Kleingrothaus, PLB 1999]

General parametrization for 0vBB Decay

Short-Range Part



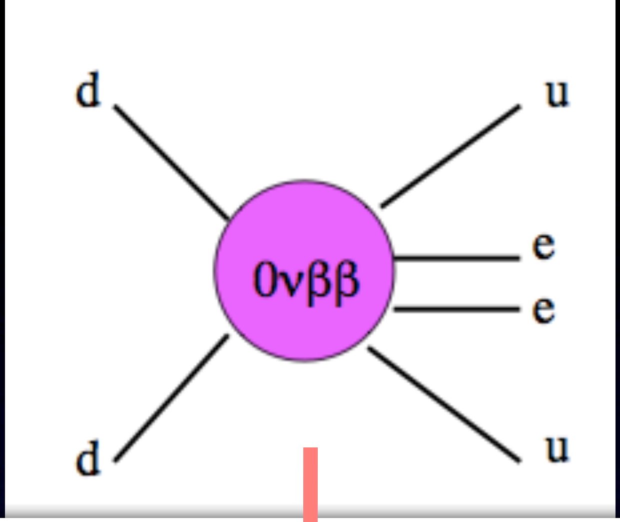
$$\mathcal{L} = \frac{G_F^2}{2} m_p^{-1} \{ \epsilon_1 J J j + \epsilon_2 J^{\mu\nu} J_{\mu\nu} j + \epsilon_3 J^{\mu} J_{\mu} j + \epsilon_4 J^{\mu} J_{\mu\nu} j^{\nu} + \epsilon_5 J^{\mu} J j_{\mu}$$
$$+ \epsilon_6 J^{\mu} J^{\nu} j_{\mu\nu} + \epsilon_7 J J^{\mu\nu} j_{\mu\nu} + \epsilon_8 J_{\mu\alpha} J^{\nu\alpha} j^{\mu}_{\nu} \},$$

$\lvert\epsilon_1\rvert$	$\lvert\epsilon_2\rvert$	$\lvert\epsilon_3^{LLz}\rvert, \lvert\epsilon_3^{RRz}\rvert$	$\lvert\epsilon_3^{LRz}\rvert, \lvert\epsilon_3^{RLz}\rvert$	$\lvert\epsilon_4\rvert$	$\lvert\epsilon_5\rvert$
$3 \cdot 10^{-7}$	$2 \cdot 10^{-9}$	$4 \cdot 10^{-8}$	$1 \cdot 10^{-8}$	$2 \cdot 10^{-8}$	$2 \cdot 10^{-7}$

[HP, Hirsch, Kovalenko, Klapdor-Kleingrothaus, PLB 2001]

LNV
at the
LHC

0vBB - LHC Complementarity



pointlike @ nuclear Fermi momentum $O(r_N^{-1}) \sim 100$ MeV

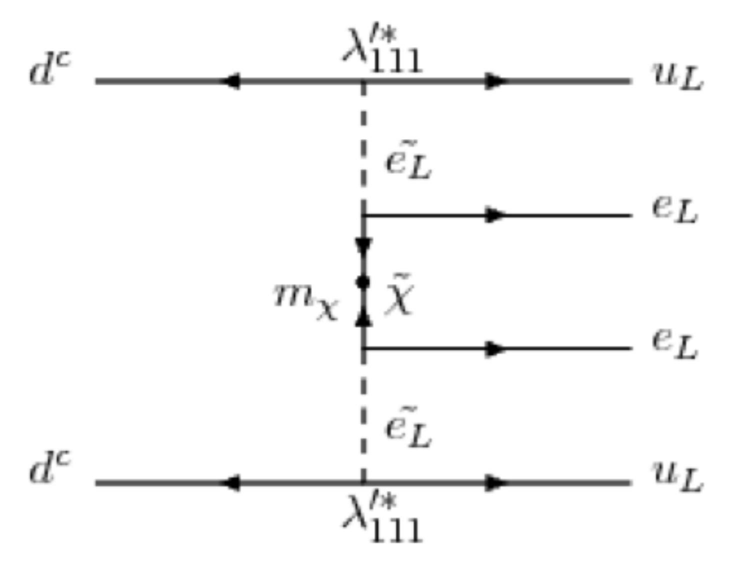
d = 9 operator

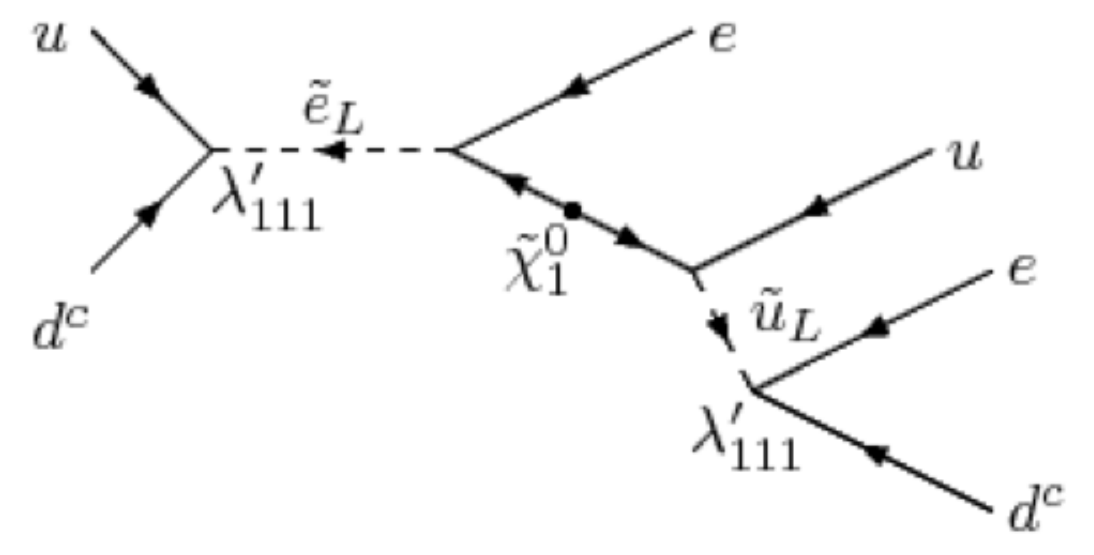
TeV scale particles

New Physics @ the LHC!

0vBB - LHC Complementarity!

0vBB @ LHC: Example RPV SUSY





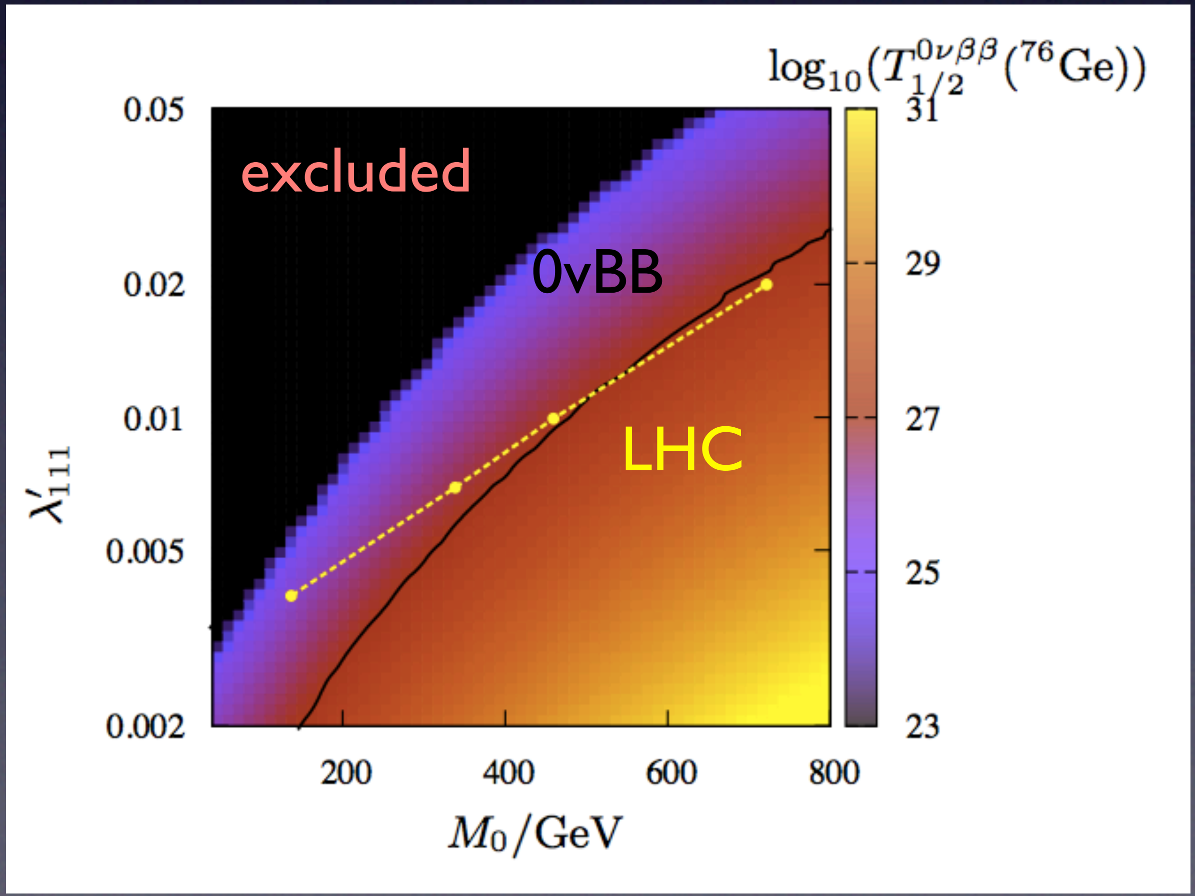
Like-Sign Di-Lepton Signal:

10 fb^{-1}, $\sqrt{s}$ = 14 TeV

SM + SUSY Background

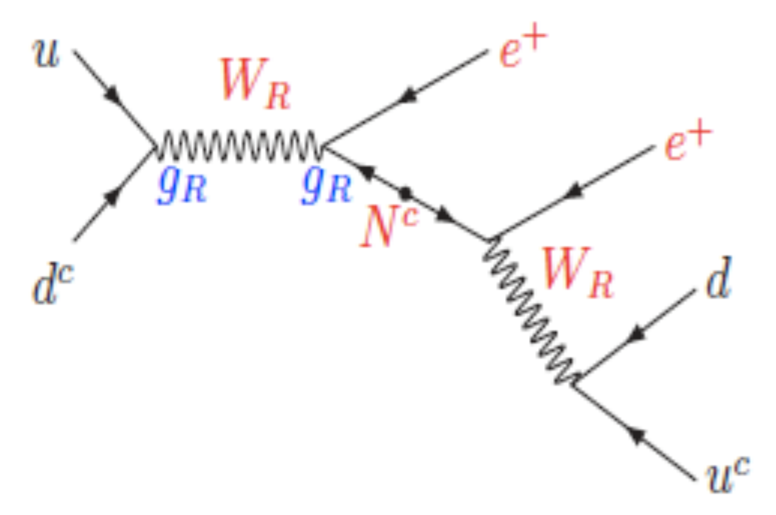
$$M_{1/2} = 300 \text{ GeV} + 0.6 M_0$$

[Allanach, Kom, HP, PRL 2009]



0vBB @ LHC

Also, e.g.
Left-Right
Symmetry:



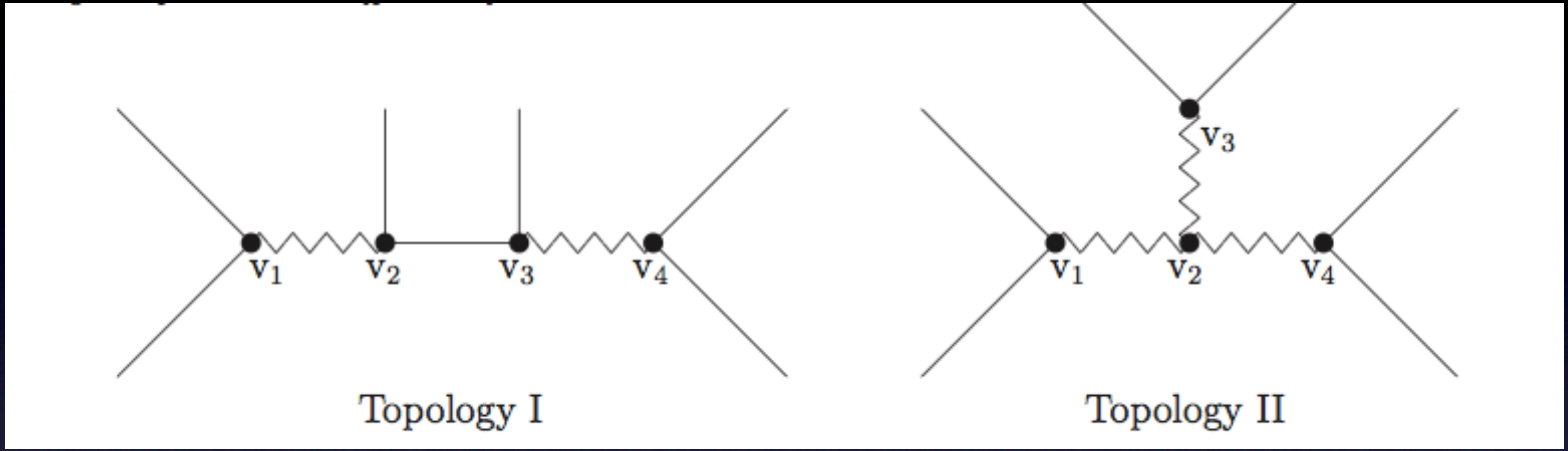
[Keung, Senjanovic 1983; Nemevsek, Nesti, Senjanovic, Tello 2001]

Model-independent approach also for LNV@LHC ?

- Necessary to go beyond effective field theory approach of [HP, Hirsch, Kovalenko, Klapdor-Kleingrothaus, PLB 1999]
- Open up vertices, systematic decomposition of the d=9 0vBB operator [Bonnet, Hirsch, Ota, Winter, 2013]

Systematic decomposition of 0vBB Decay

2 Topologies:



— Fermion

〰 Scalar or Vector

→ **VFV, SFS, SFV** **SSS, VVV, VVS, SSV**

⇒ Go through all gauge invariant possibilities giving rise to $\overline{u}\;\overline{u}\;\overline{e}\;\overline{e}\;d\;d\;\frac{1}{M^5}$ [Bonnet, Hirsch, Ota, Winter, 2013]

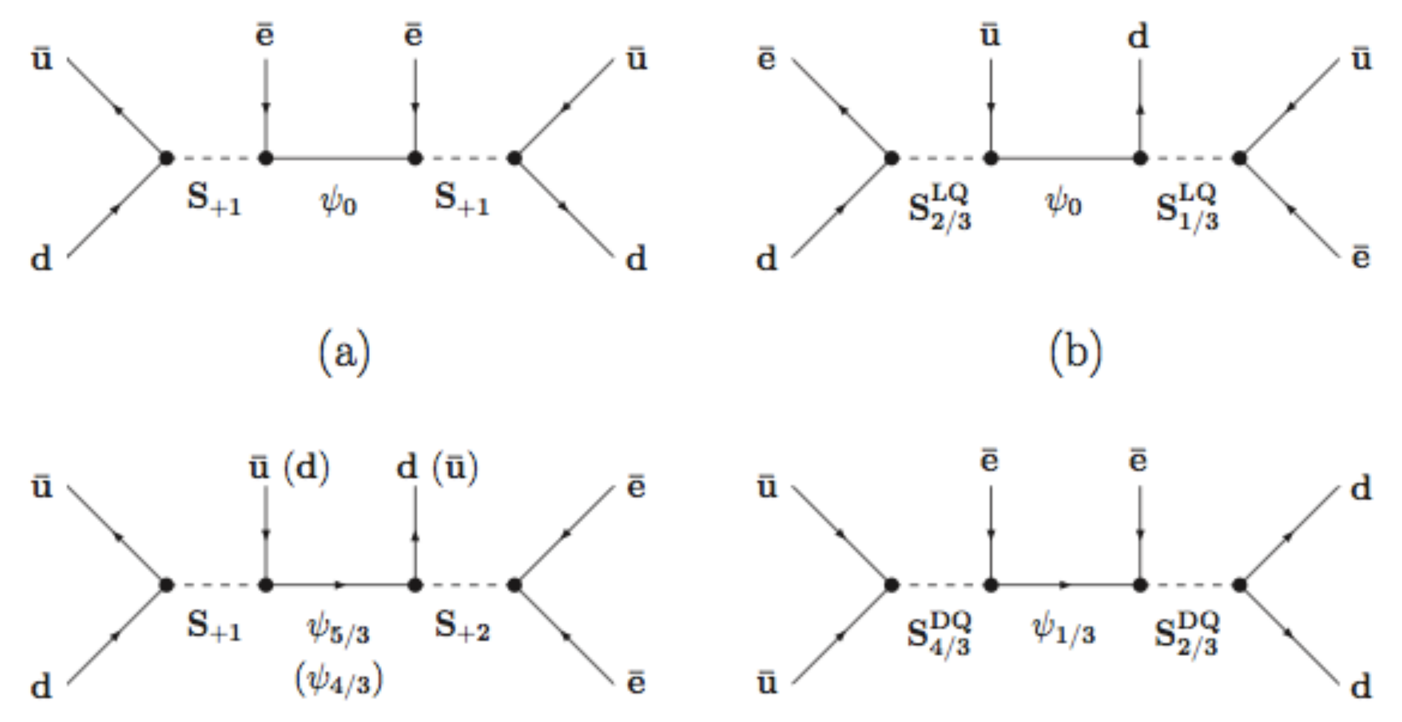
Model independent approach to 0νBB @LHC

Apply the decomposition of [Bonnet, Hirsch, Ota, Winter, 2013] to 0νBB @ LHC:

- Results for Scalars and Vectors very similar
- Concentrate on Scalars & Topology 1:

S_{charge},
S^{LQ}_{charge} $(L\neq 0, B\neq 0)$,
S^{DQ}_{charge} $(B=\pm 2/3)$

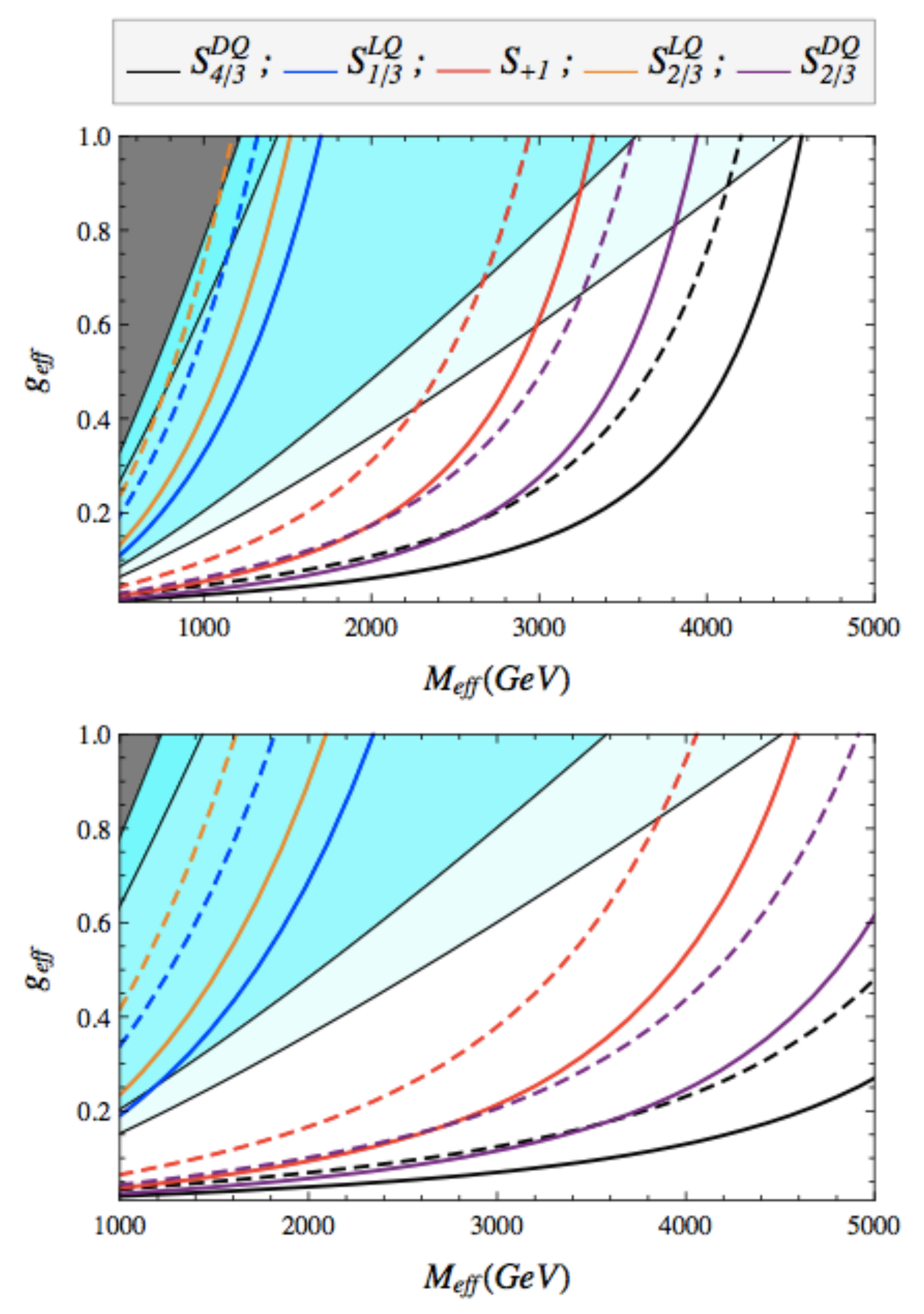
[Helo, Hirsch, Kovalenko, HP, 2013]



0νββ versus LHC SSD at √s = 14 TeV

mψ= 200 GeV

mψ= 1 TeV



0νββ - grey & blue areas: present bound, $T_{1/2}>10^{26}$y (smallest rate operator)

$T_{1/2}>10^{26}$y, $T_{1/2}>10^{27}$y (largest rate operator)

$$\mathcal{A}^{0\nu\beta\beta} \propto \frac{g_1 g_2 g_3 g_4}{m_{S_i}^2 m_{\psi_q} m_{S_j}^2} \equiv \frac{g_{eff}^4}{M_{eff}^5}.$$

LHC: curved lines

dashed: $Br^{eff}(S \rightarrow eejj)=10^{-2}$

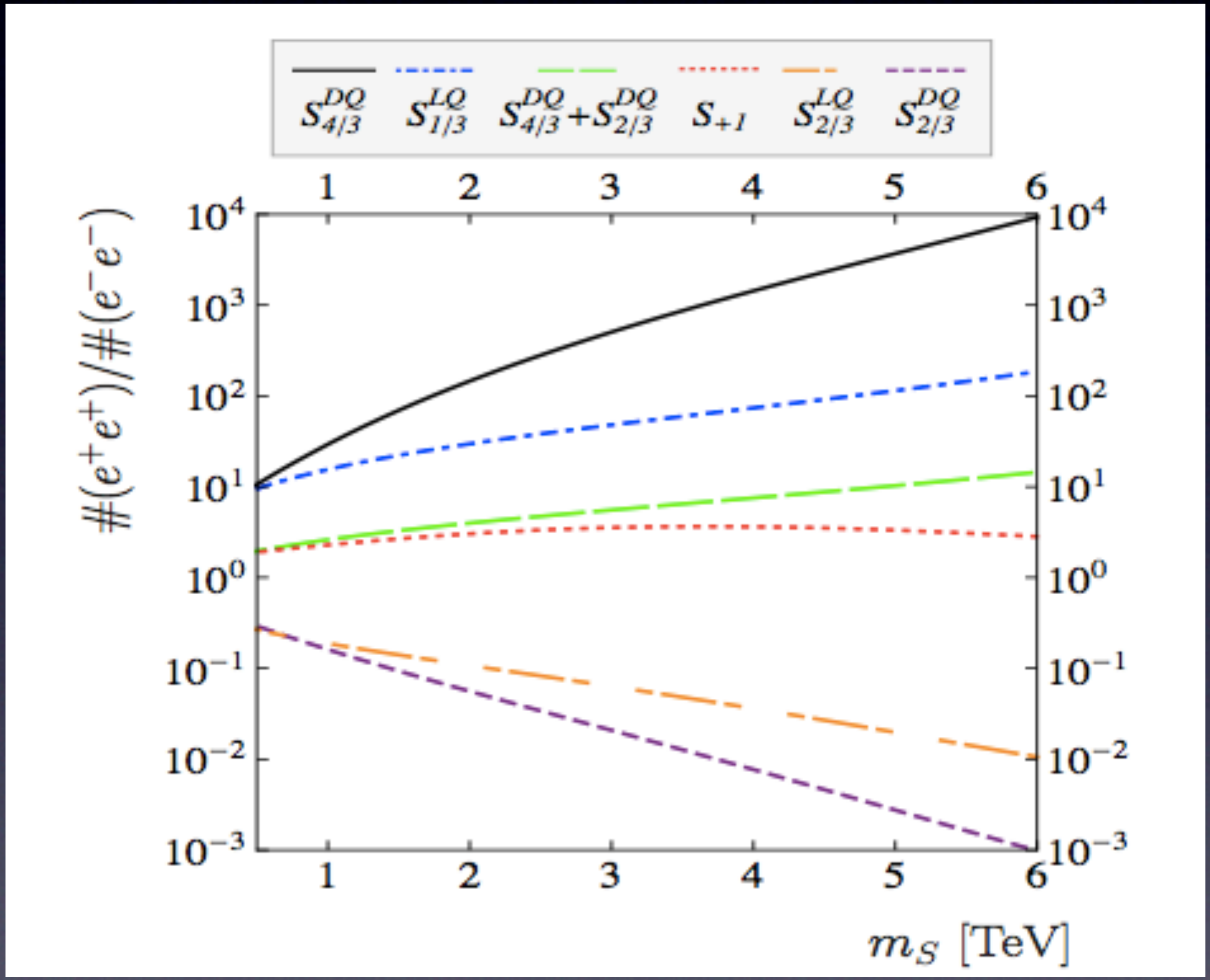
solid: $Br^{eff}(S \rightarrow eejj)=10^{-1}$

[Helo, Hirsch, Kovalenko, HP, 2013]

Discriminating 0νββ mechanisms: Charge Asymmetry

Moreover: LHC can discriminate contributions

- **Invariant mass peaks** (s–channel: $m^2_{eejj} \equiv m^2_S$)
- **Charge asymmetry** (due to different numbers of u,d,u^c,d^c in p and different diagrams



[J.C. Helo, M. Hirsch, S. Kovalenko, HP, PRD88 (2013) 1 011901]

0νββ vs LHC sensitivities

→ with the exception of Leptoquarks:

LHC more sensitive than 0vBB Decay !

0vBB signal → LHC signal

No LHC signal → no 0vBB signal

- OR-

0vBB is
Long Range
(e.g. mass-mechanism)

→ how to find out?

A major problem

Uncontroversial detection of $0\nu\beta\beta$ decay: uttermost importance!

- prove lepton number to be broken in Nature
- prove neutrinos to be Majorana particles Schechter and Valle, 1982

However: it will immediately generate another puzzle:

which mechanism that triggers the decay?

Without identification of the underlying mechanism:

- experimental evidence for $0\nu\beta\beta$ decay will only provide ambiguous information about the concrete physics underlying the decay!
- No information about m_ν can be obtained from a measurement of the neutrinoless double beta decay half life!

Big question:

what is it?

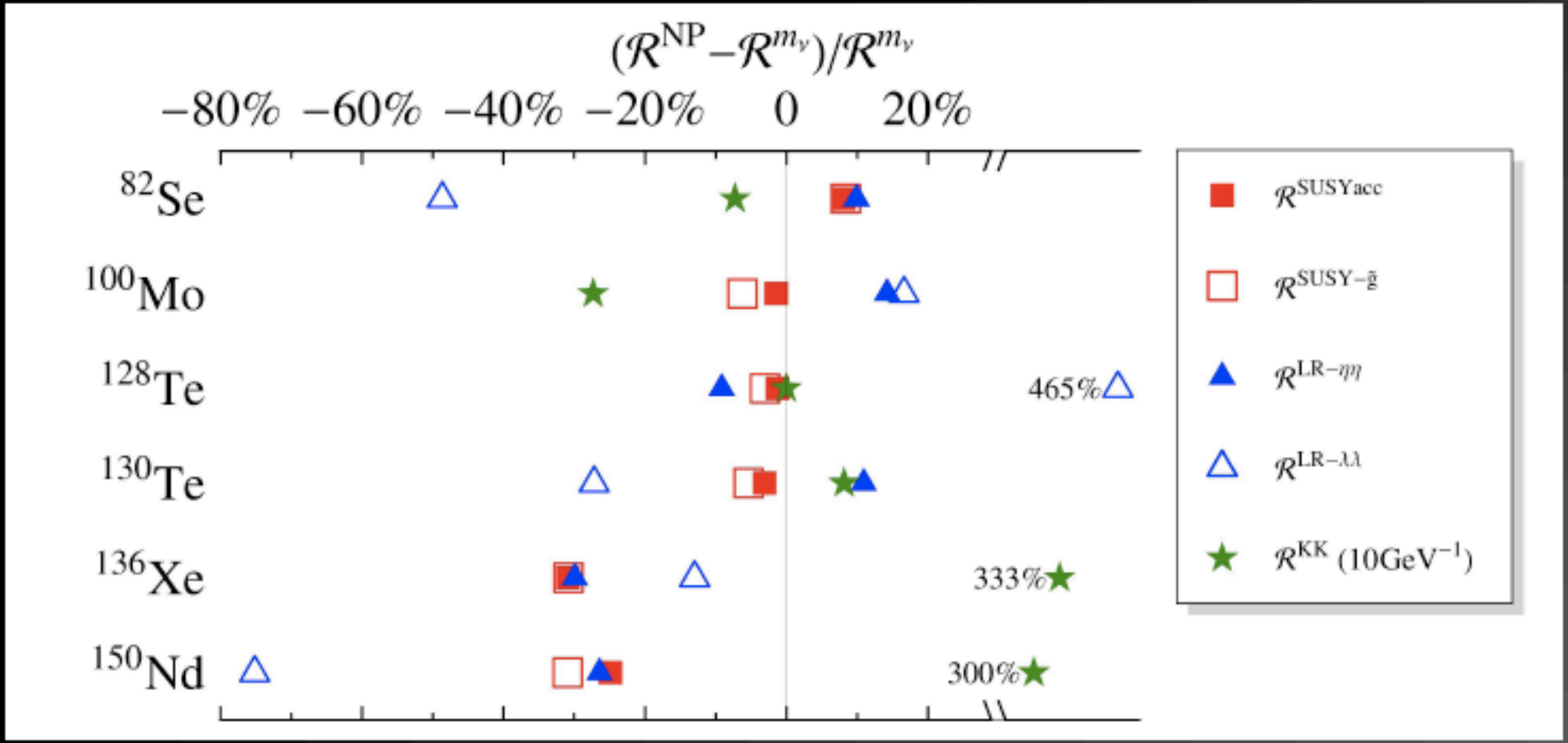
Half life ratios

- Concentrate on: different mechanisms result in different NMEs
- Problem: smaller NME for e.g. the mass mechanism as compared to any alternative new physics mechanism can be compensated by a larger value for the neutrino mass
- However: If one mechanism dominates → $\langle m_\nu \rangle$ or ϵ_{NP} drops out in the ratio of experimentally determined half lives for two different emitter isotopes

$$\boxed{\frac{T_{1/2}({}^{A}X)}{T_{1/2}({}^{76}\mathrm{Ge})} = \frac{|\mathcal{M}({}^{76}\mathrm{Ge})|^2 G({}^{76}\mathrm{Ge})}{|\mathcal{M}({}^{A}X)|^2 G({}^{A}X)}}$$

- ⇒ Half life ratios depend on the mechanism of double beta decay, but not on the new physics parameter!
- Compare with theoretical prediction for different mechanisms!
- Error in NME ratio can be reduced compared to theoretical error in one matrix element (cancellations of systematic effects)!

Half life ratios: Results



F. Deppisch, H. Päs, Phys. Rev. Lett. 98 (2007) 232501

Matrix elements calculated in the QRPA approach of A. Staudt, K. Muto and H. V. Klapdor- Kleingrothaus, Europhys. Lett. **13**, 31 (1990); M. Hirsch, K. Muto, T. Oda and H. V. Klapdor-Kleingrothaus, Z. Phys. A **347**, 151 (1994) or taken from literature using the same code

Half life ratios: results

- $\not{R}_P$ SUSY contributions:

  similar and rather small deviations

  Most effectively discriminated by comparing ^{82}Se and ^{136}Xe (60% variation)

- Left-right symmetric models:

  strong deviations for $\lambda\lambda$ combination, comparing ^{128}Te and ^{150}Nd:

  $$\boxed{T^{LR}_{1/2}/T^{m_\nu}_{1/2}[^{128}\mathrm{Te}] \gtrsim 20\times \; T^{LR}_{1/2}/T^{m_\nu}_{1/2}[^{150}\mathrm{Nd}]}$$

  small deviations for $\eta\eta$ combination comparison of ^{100}Mo and ^{136}Xe yields a variation of 70 %

- Extra-dimensional neutrino models with a large brane shift parameter:

  large deviations for ^{136}Xe and ^{150}Nd:

  $$\boxed{T^{KK}_{1/2}/T^{m_\nu}_{1/2}[^{150}\mathrm{Nd}] \gtrsim 5\times \; T^{KK}_{1/2}/T^{m_\nu}_{1/2}[^{100}\mathrm{Mo}]}$$

Caution: strong deformation of ^{150}Nd is ignored in most QRPA calculations

→ Simkovic, Pacearescu, Faessler, 2004

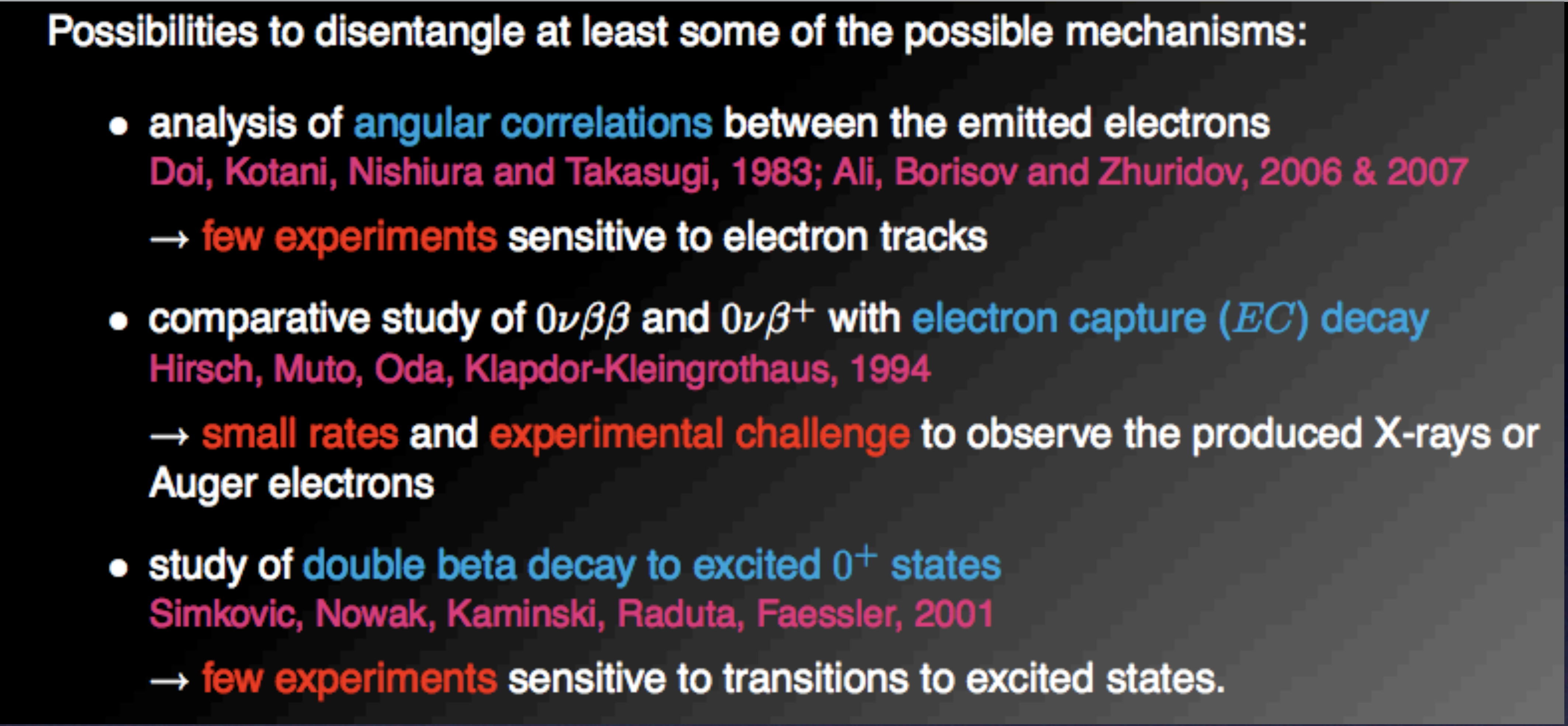
Nuclear matrix element uncertainties

- Theoretical errors of NME calculation dominate experimental errors ⇒ difficult to determine the confidence level with which either mechanism can be excluded to generate the observed double beta evidence!
- Assuming e.g. a statistical distribution of matrix element values ⇔ relative variation of 60% in $\mathcal{R}^{NP}({}^{A}X)$ w.r.t. $\mathcal{R}^{m_\nu}({}^{A}X)$ is significant only if NMEs would be known with an accuracy of 15%! → unrealistic!
- Estimates of uncertainties vary: factor 3-5 (spread of published values) to only 30% (uncertainties inherent in QRPA) Rodin, Faessler, Simkovic, Vogel, 2006

However:

- significance will increase if a whole set of measurements in different isotopes resembles the expected pattern
- systematical effects (like a too small g_{pp} in the pn-QRPA approach, a different g_A, higher-order terms, different model-space) will cancel out
- → check results with alternative codes!
- → include pion exchange which may be dominating in some of the models discussed!

$0\nu\beta\beta$: Pinning down the mechanism



Possibilities to disentangle at least some of the possible mechanisms:

- analysis of angular correlations between the emitted electrons
  Doi, Kotani, Nishiura and Takasugi, 1983; Ali, Borisov and Zhuridov, 2006 & 2007

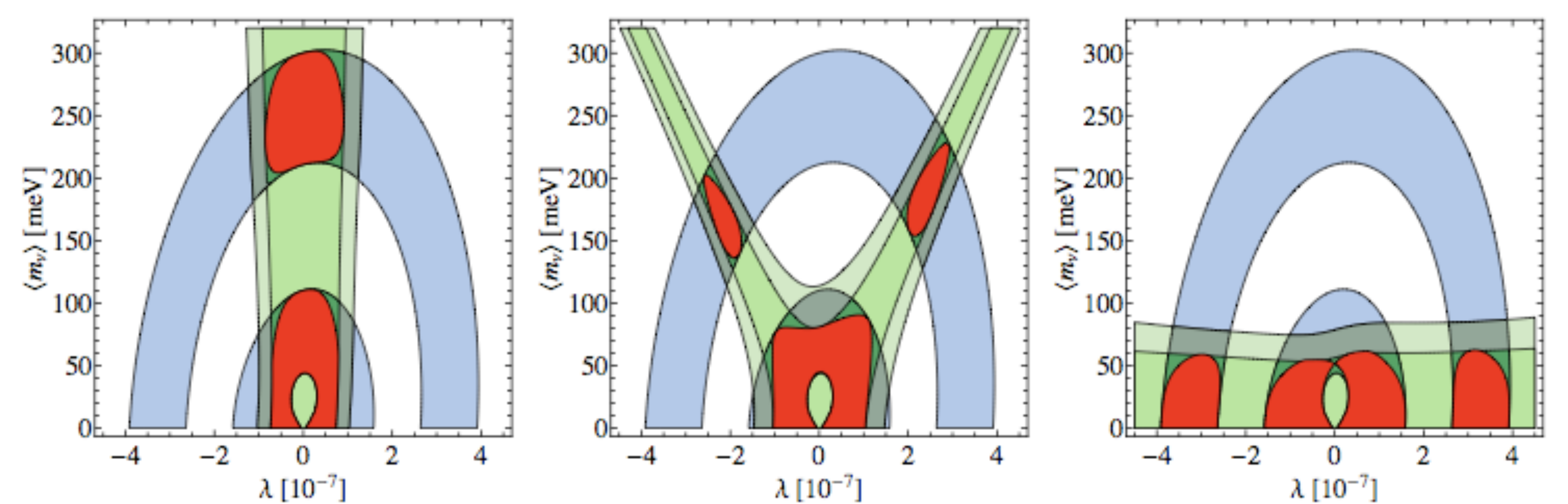
  → few experiments sensitive to electron tracks

- comparative study of $0\nu\beta\beta$ and $0\nu\beta^+$ with electron capture (EC) decay
  Hirsch, Muto, Oda, Klapdor-Kleingrothaus, 1994

  → small rates and experimental challenge to observe the produced X-rays or Auger electrons

- study of double beta decay to excited 0^+ states
  Simkovic, Nowak, Kaminski, Raduta, Faessler, 2001

  → few experiments sensitive to transitions to excited states.



[F. Deppisch +Super-NEMO, 2010]

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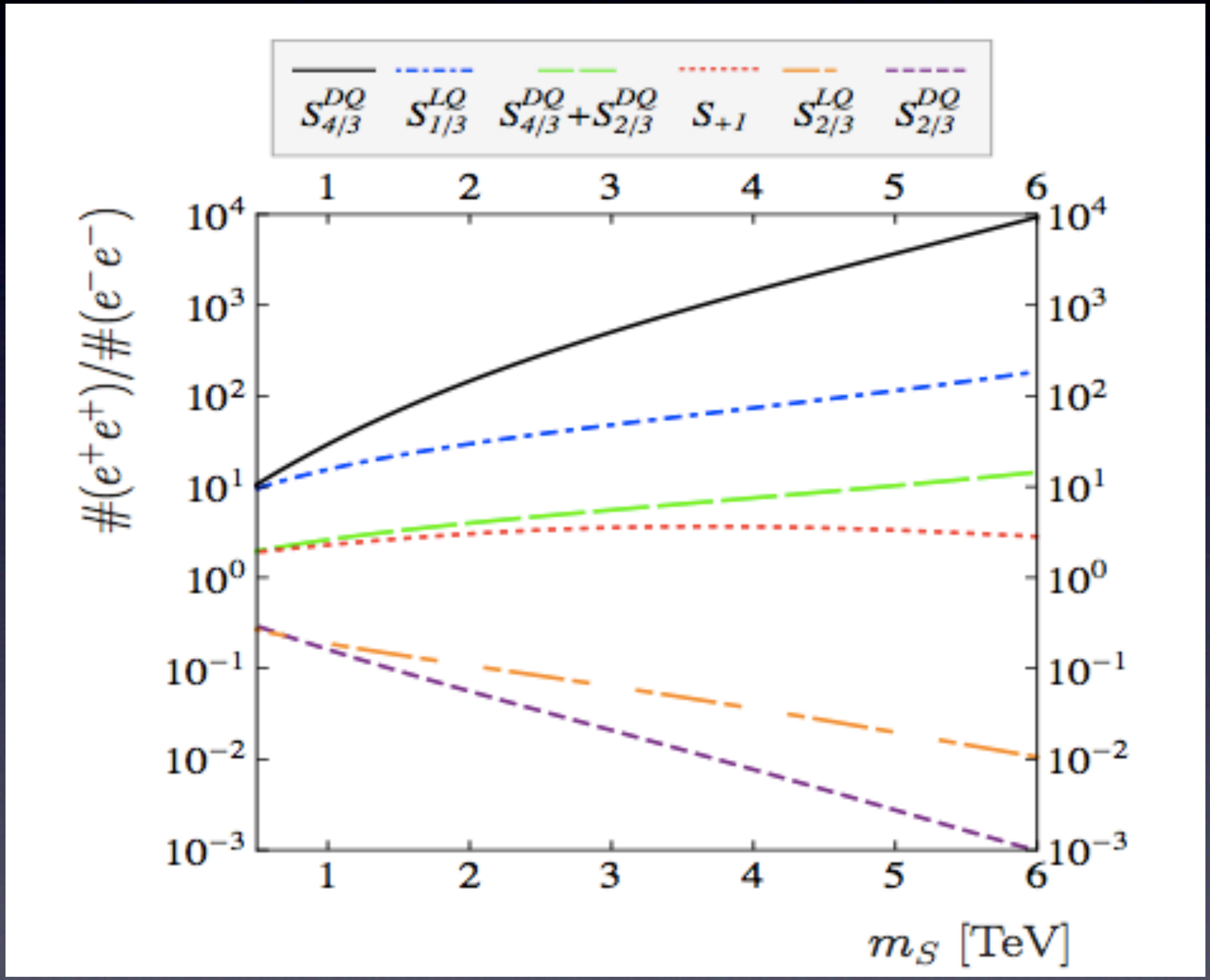


[J.C. Helo, M. Hirsch, S. Kovalenko, HP, PRD88 (2013) 1 011901]

What’s the connection with Baryogenesis ?

Baryon Number Washout

“Falsifying Leptogenesis at the LHC”

[F. Deppisch, J. Harz, M. Hirsch, PRL 112 (2014) 221601]

“Falsifying Leptogenesis at the LHC”

- LNV @ LHC
- Lower bound on washout of Lepton Number Asymmetry
- No out-of-equilibrium condition in early universe!

LNV and BAU

But **EVEN WORSE**: consider **Sphalerons**

Leptogenesis:

~~B-L~~ + ~~B+L~~

ν_R decay

Sphalerons

B Asymmetry

In Reverse:

~~B-L~~ + ~~B+L~~

e.g. LHC

Sphalerons

B washout

LNV and BAU

Large LNV @ LHC (or elsewhere) will washout ANY pre-existing Baryon Asymmetry, irrespective of the Baryogenesis mechanism (Leptogensis, etc...)

Original Paper: [Fukugita, Yanagida, 1990]

"Sphaleron induced Baryon Number Non-conservation and a constraint on Majorana neutrino masses"

Also:

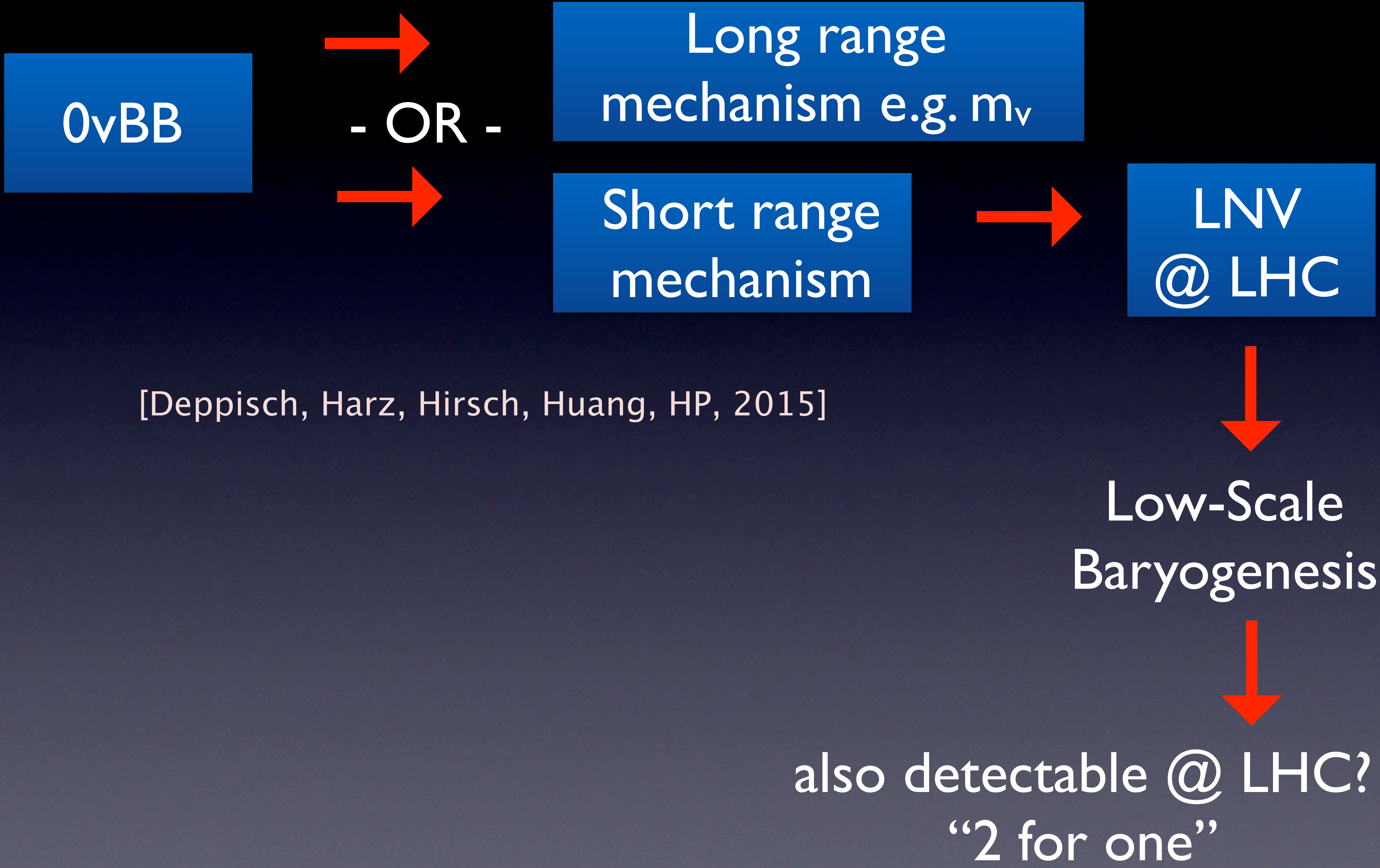
[Gelmini, Yanagida, 1992] keV-bound on ν mass

[Klapdor-Kleingrothaus, Kolb, Kuzmin, 1990] Bound on sneutrinos

[Hollenberg, HP, Schalla, 2011] Bound on 4th generation neutrinos

[...many others]

Conclusions I



0vBB

- OR -

Long range mechanism e.g. m_ν

Short range mechanism

LNV @ LHC

[Deppisch, Harz, Hirsch, Huang, HP, 2015]

Low-Scale Baryogenesis

also detectable @ LHC?

“2 for one”

Conclusions II

High scale baryogenesis → ~~LNV @ LHC~~ → If 0vBB

↓

Mass mechanism

m_ν

↓

Very probably high scale origin of m_ν

[Deppisch, Harz, Hirsch, Huang, HP, 2015]

But:
0vBB probes LNV only for the electron flavor!

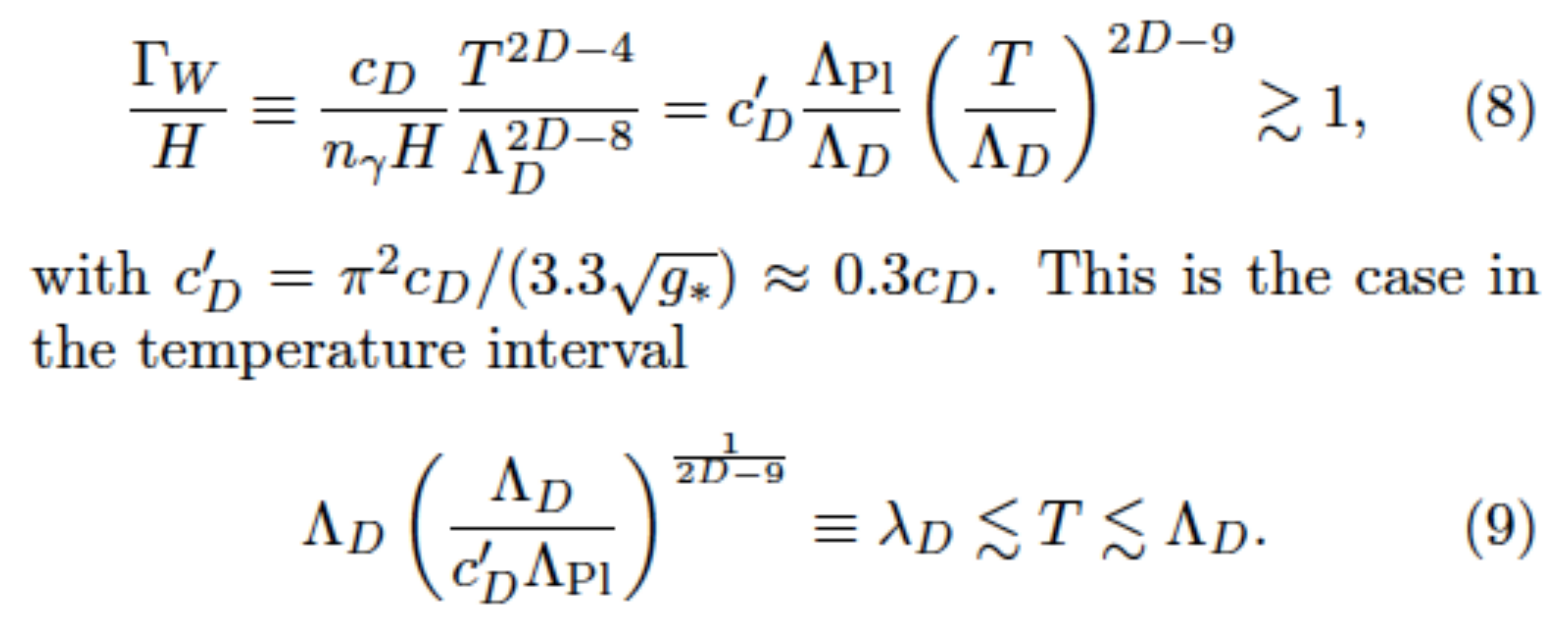
How to close this Flavor Loophole?

Outlook

Closing the flavor loophole:

combine 0vBB and LFV

Washout processes are in Thermal equilibrium for:



$$\frac{\Gamma_W}{H} \equiv \frac{c_D}{n_\gamma H}\frac{T^{2D-4}}{\Lambda_D^{2D-8}} = c'_D \frac{\Lambda_{\rm Pl}}{\Lambda_D}\left(\frac{T}{\Lambda_D}\right)^{2D-9} \gtrsim 1, \tag{8}$$

with $c'_D = \pi^2 c_D/(3.3\sqrt{g_*}) \approx 0.3c_D$. This is the case in the temperature interval

$$\Lambda_D\left(\frac{\Lambda_D}{c'_D\Lambda_{\rm Pl}}\right)^{\frac{1}{2D-9}} \equiv \lambda_D \lesssim T \lesssim \Lambda_D. \tag{9}$$

[Deppisch, Harz, Hirsch, Huang, HP, 2015]

Outlook

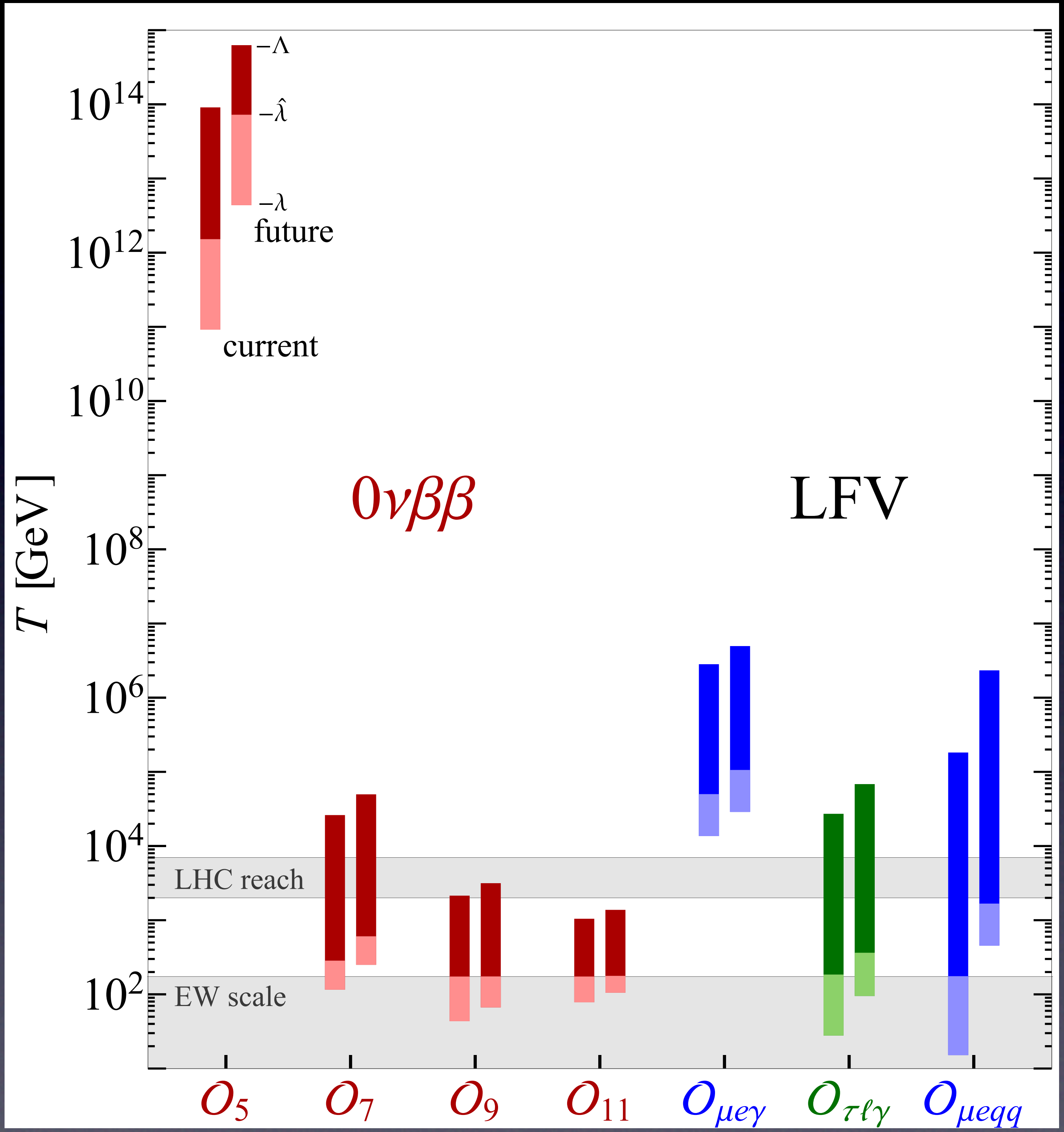
Outlook: closing the flavor loophole

combine 0vBB and LFV

Washout intervals:
lower bound: equilibrium
upper bound: EFT breakdown

$$T_{1/2} = 2.1 \times 10^{25}\ \mathrm{y}$$

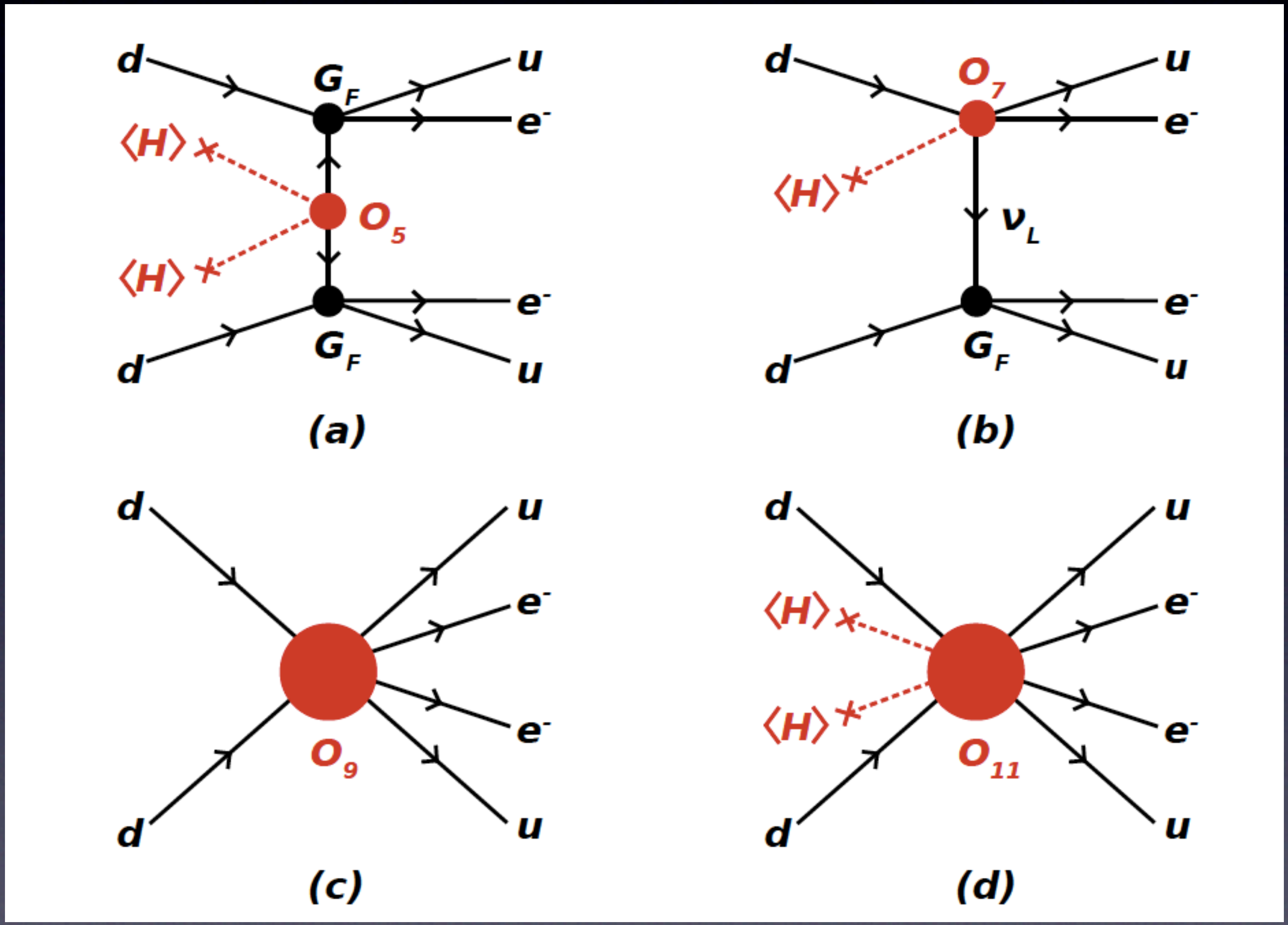
An asymmetry generated at scales above λ will be washed out if 0vBB is observed

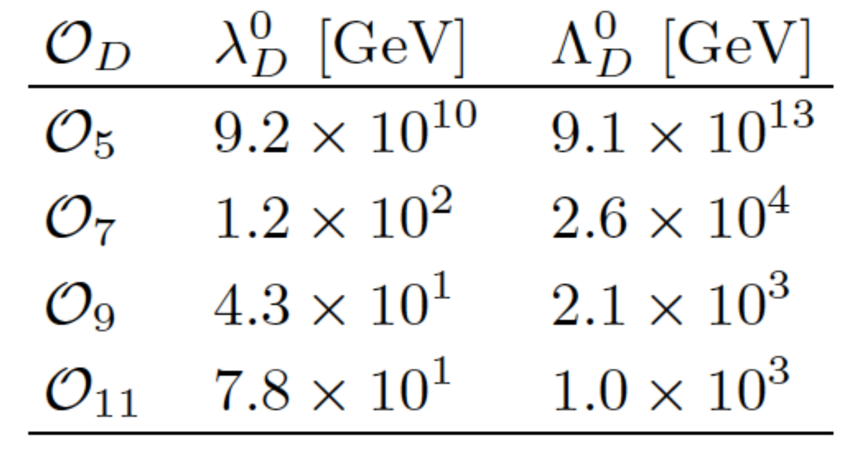


[Deppisch, Harz, Hirsch, Huang, HP, 2015]

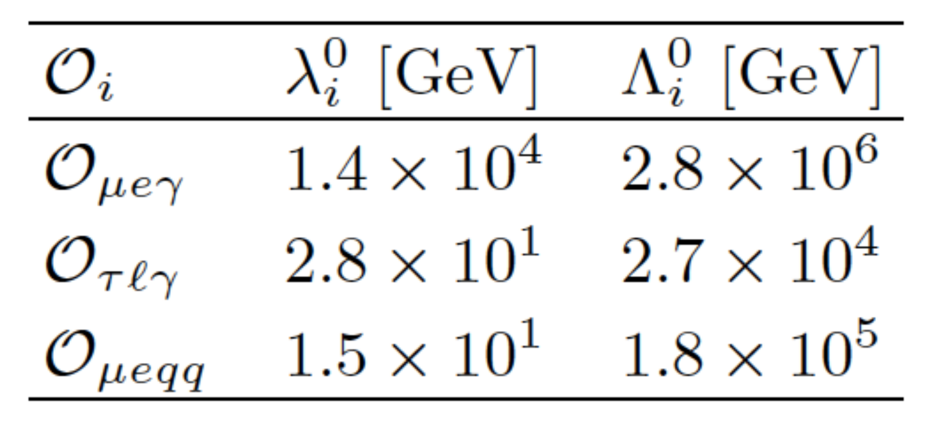
Outlook

Washout processes are in Thermal equilibrium for:





$\mathcal{O}_D$	λ_D^0 [GeV]	Λ_D^0 [GeV]
$\mathcal{O}_5$	9.2×10^{10}	9.1×10^{13}
$\mathcal{O}_7$	1.2×10^{2}	2.6×10^{4}
$\mathcal{O}_9$	4.3×10^{1}	2.1×10^{3}
$\mathcal{O}_{11}$	7.8×10^{1}	1.0×10^{3}



$\mathcal{O}_i$	λ_i^0 [GeV]	Λ_i^0 [GeV]
$\mathcal{O}_{\mu e\gamma}$	1.4×10^{4}	2.8×10^{6}
$\mathcal{O}_{\tau\ell\gamma}$	2.8×10^{1}	2.7×10^{4}
$\mathcal{O}_{\mu eqq}$	1.5×10^{1}	1.8×10^{5}

$$T_{1/2} = 2.1 \times 10^{25}\ \mathrm{y} \cdot (\Lambda_D/\Lambda_D^0)^{2d-8}$$

[Deppisch, Harz, Hirsch, Huang, HP, 2015]

Summary

0νββ →

\- EITHER -

LNV@LHC → Low scale Baryogenesis, "2 for 1"

\- OR -

very probably high-scale origin of m_ν

(like vanilla type-I seesaw + leptogenesis)

[Deppisch, Harz, Hirsch, Huang, HP, 2015]

Loopholes exist and should be checked!

(Flavor restriction, conserved charges, etc...)

[Deppisch, Harz, Hirsch, 2014; Antaramian, Hall, Rasin, 1994...]