Neutrino Theory

Overview

- Heinrich Päs -

tu dortmund

3 years ago…

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.

3 years ago…

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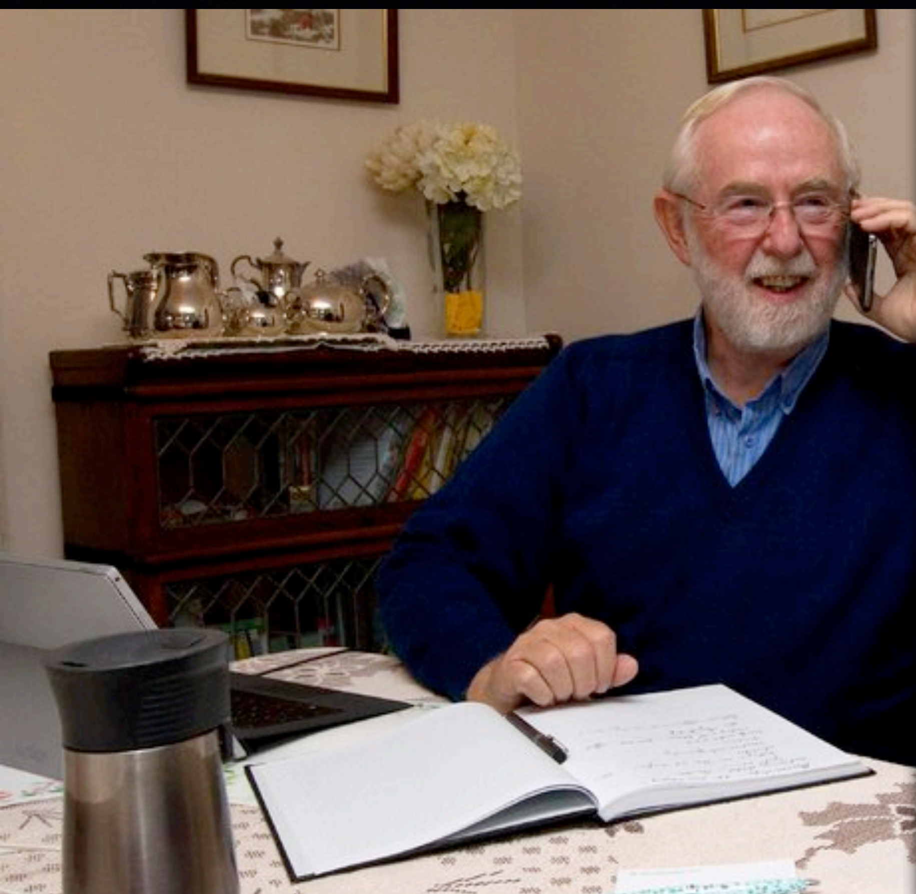

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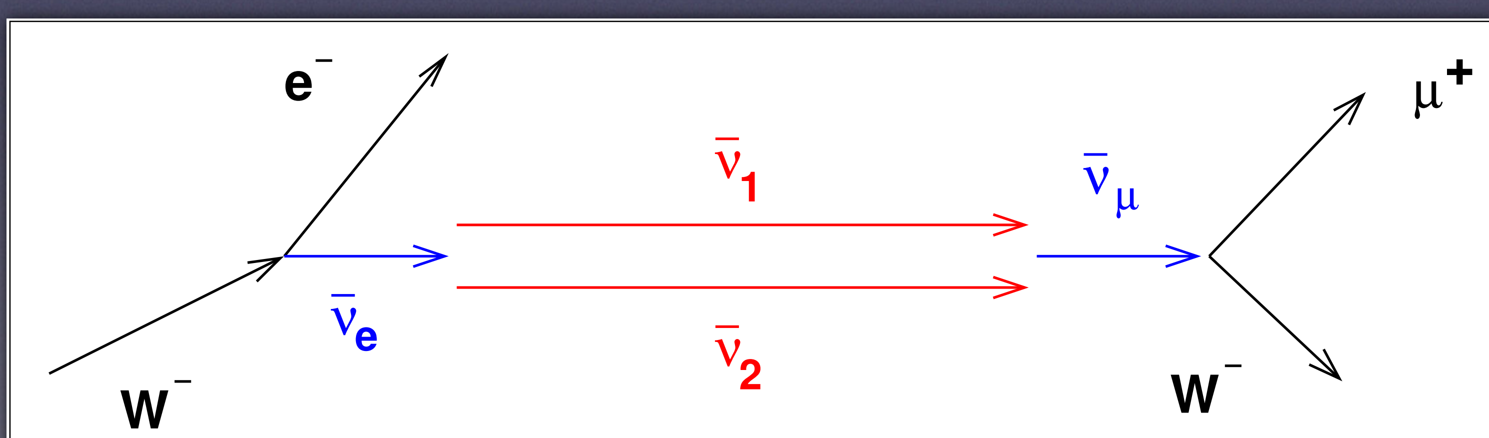


$$P = \sin^2 2\theta \, \sin^2 \frac{\Delta m^2 L}{4E_\nu}$$

...2018: Precision Science

$$U_{3\times3} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

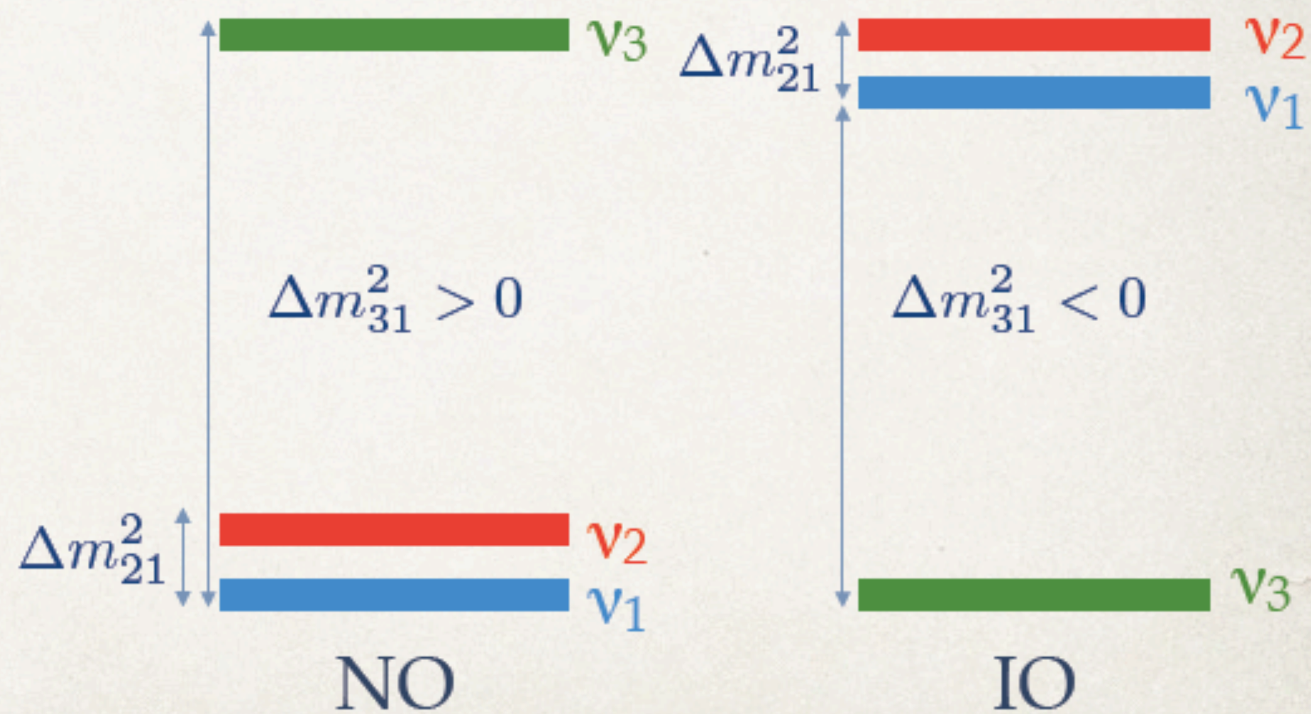
- three mixing angles: θ_{12}, θ_{23}, θ_{13}
- three CP phases: 1 Dirac + 2 Majorana
- three masses: m_1, m_2, m_3

⇒ absolute neutrino mass: m_0

⇒ two mass splittings:

$$\Delta m^2_{21}, \Delta m^2_{31}$$

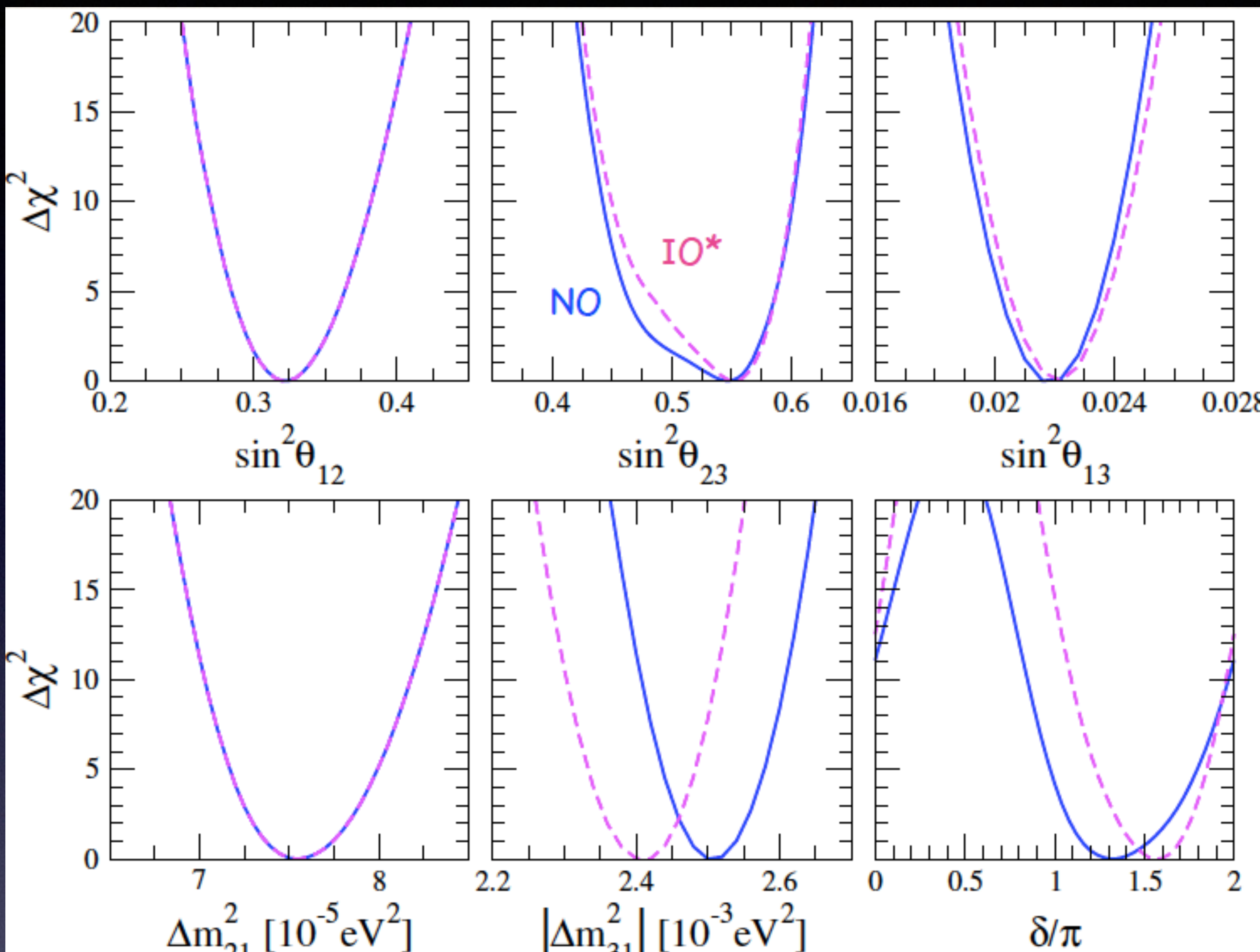
neutrino mass spectrum



$$|\Delta m^2_{31}|_{\rm NO} > |\Delta m^2_{31}|_{\rm IO}$$

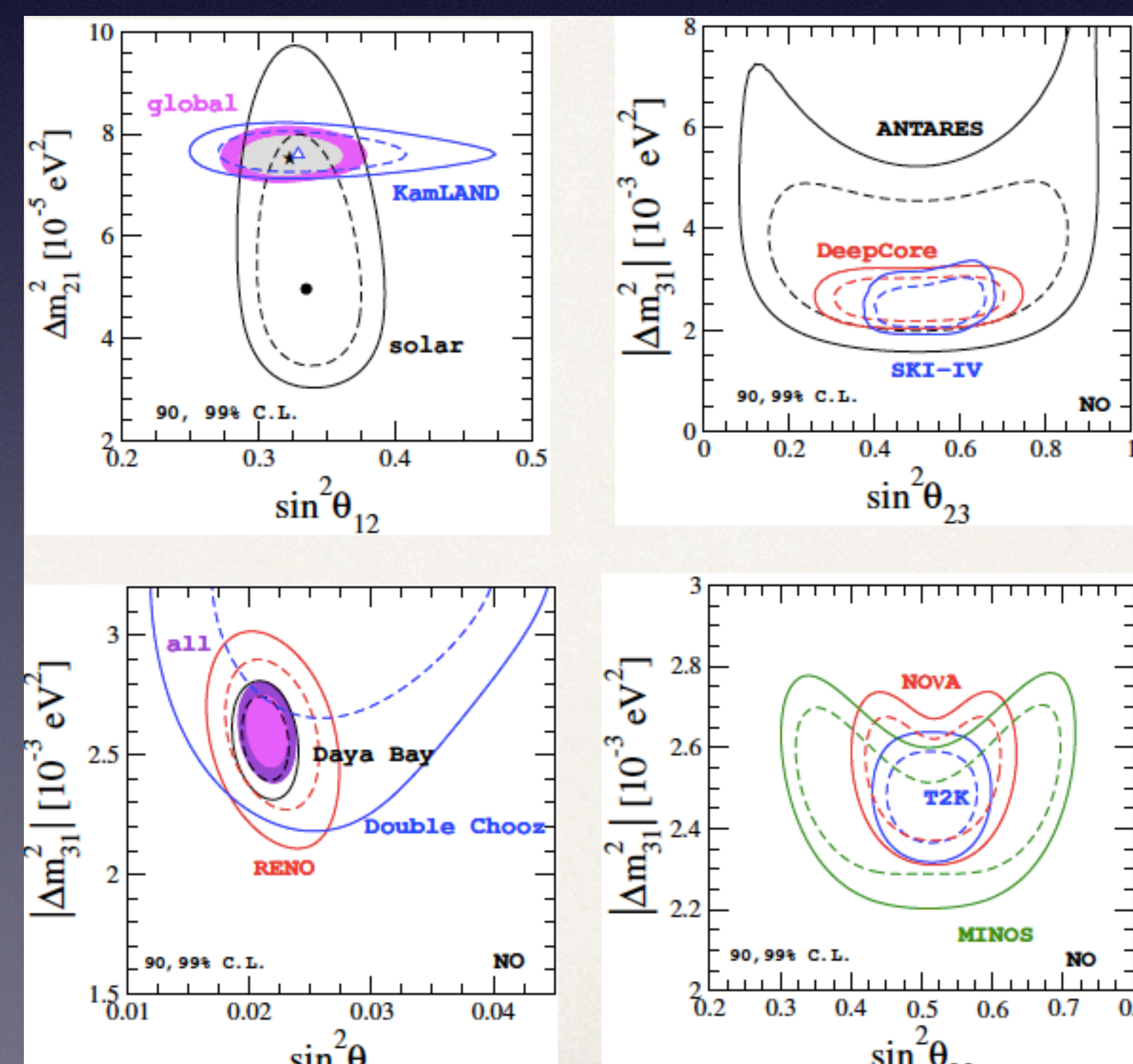
Mariam Tortola, Talk at Neutrino2018

Global data fits



Consistent picture of 3-neutrino mixing

Mariam Tortola, Talk at Netrino2018



Δm^2's and mixing angles determined at the few-% Level

Open Questions

- Absolute Mass Scale?
  →KATRIN, Cosmology
- Mass Hierarchy?
  →3σ preference for NO
- CP Violation?
  →2σ (NO)/3.8σ (IO) evidence for CPV
  →Best fit 3π/2
- Mechanism of Neutrino Mass Generation?
- Dirac or Majorana?
  →Lepton Number Violation?
- More than 3 Neutrinos?
  →Reactor, Gallium, LSND & MiniBooNE anomalies

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Why is this 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 ~~$m_M \overline{\nu_R^c} \nu_R$~~

Lepton Number Violation

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

New Symmetry, e.g. Lepton Number

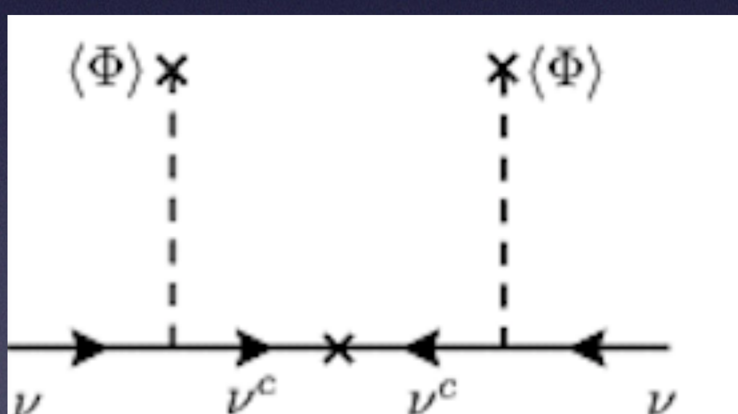
Lepton Number (Violation) is at the core of the link between ν mass & physics beyond SM!

Neutrino Mass Models

small m_ν ↔ neutral elementary fermion

↔ large scale unprotected by SM gauge symmetry

$$m_\nu \sim \frac{m_D^2}{M_R}$$

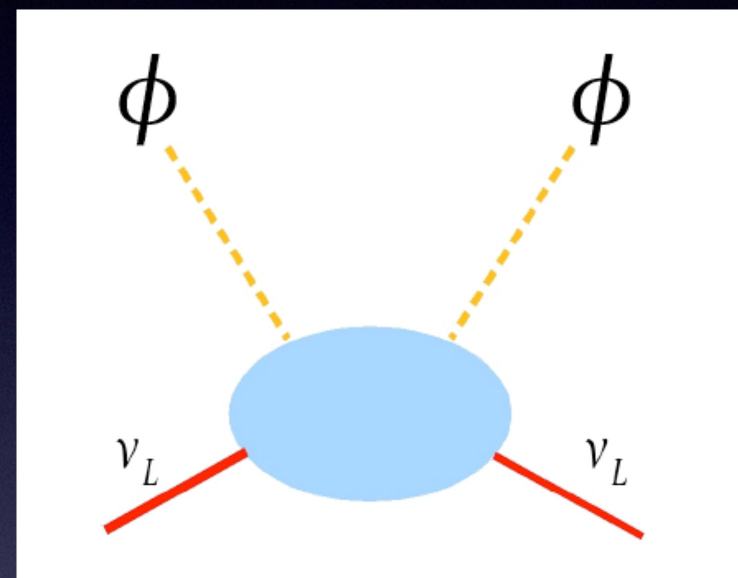


Seesaw-I: Fermion singlet

Minkowski '77

Seesaw-III: Fermion triplet

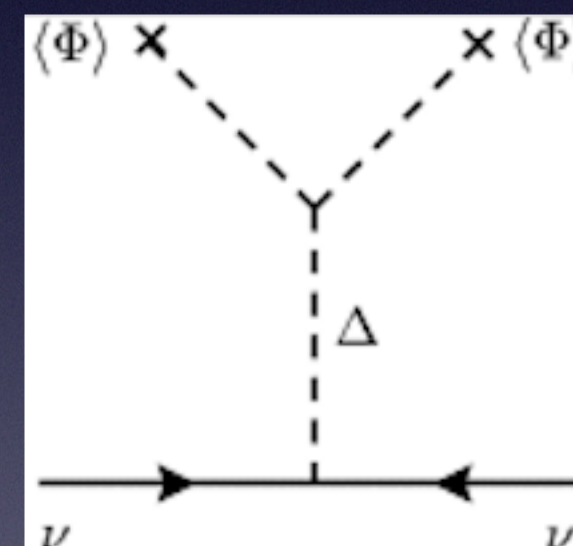
Foot, Lew, He, Joshi '89



Weinberg '77

→ *Talk by Oleg Antipin*

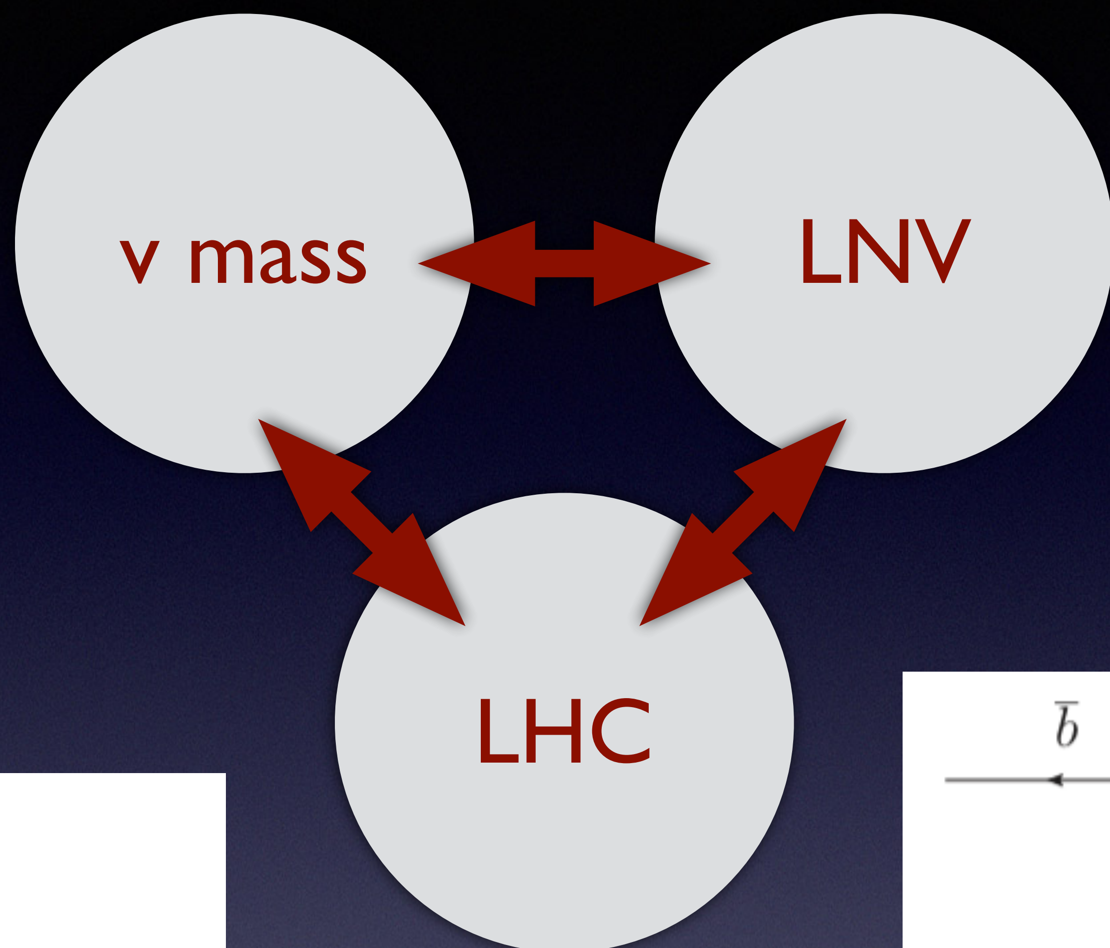
$$m_\nu \sim \frac{\langle\Phi\rangle^2}{\Lambda}$$

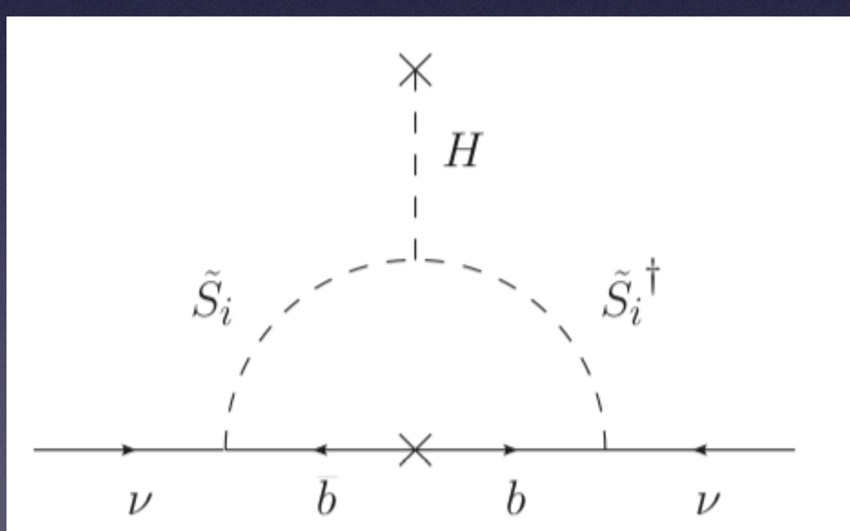


Seesaw-II: Scalar triplet

Magg & Wetterich '80;
Schechter & Valle '80;
Lazarides, Shafi, Wetterich '81;
Mohapatra & Senjanovic'81;...

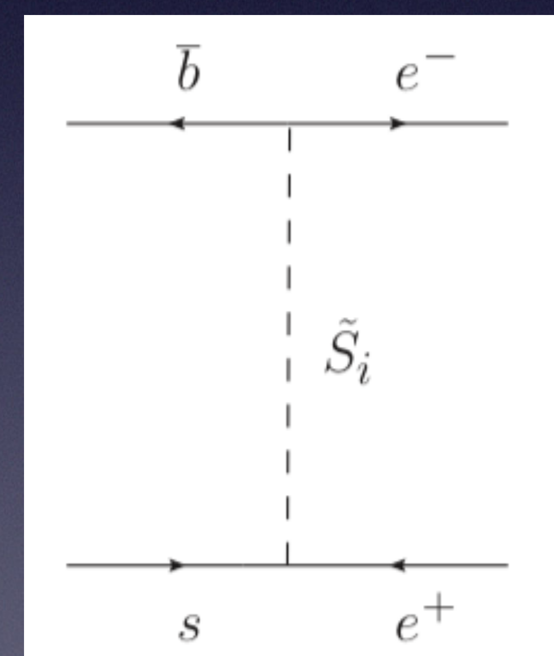
Neutrino Mass Models





Radiative Neutrino Masses from Leptoquark Loops

Hirsch, Klapdor-Kleingrothaus, Kovalenko '96

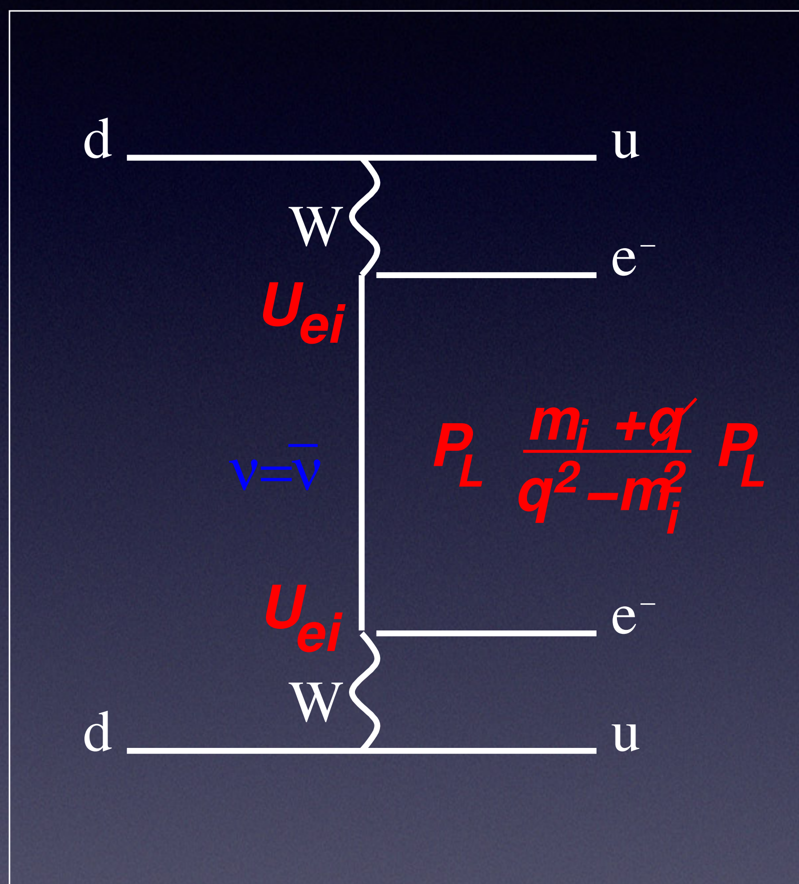


R_K & other Lepton-Flavor-Non-Universality Anomalies

HP & Schumacher '15

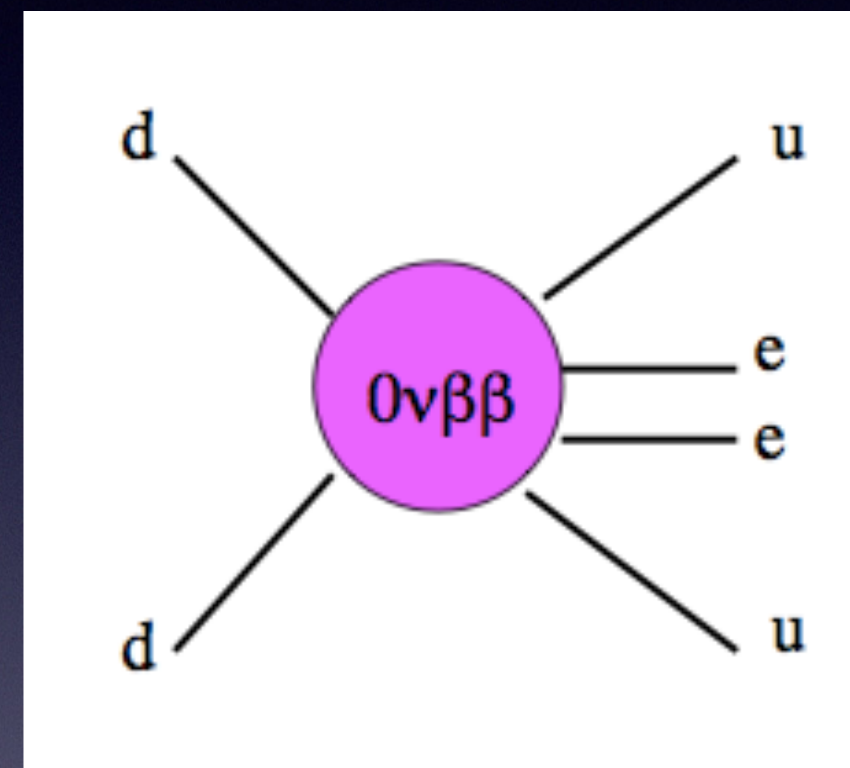
→ Talk by Lorenzo Capriotti

Most prominent: 0vBB decay



~ m_ν

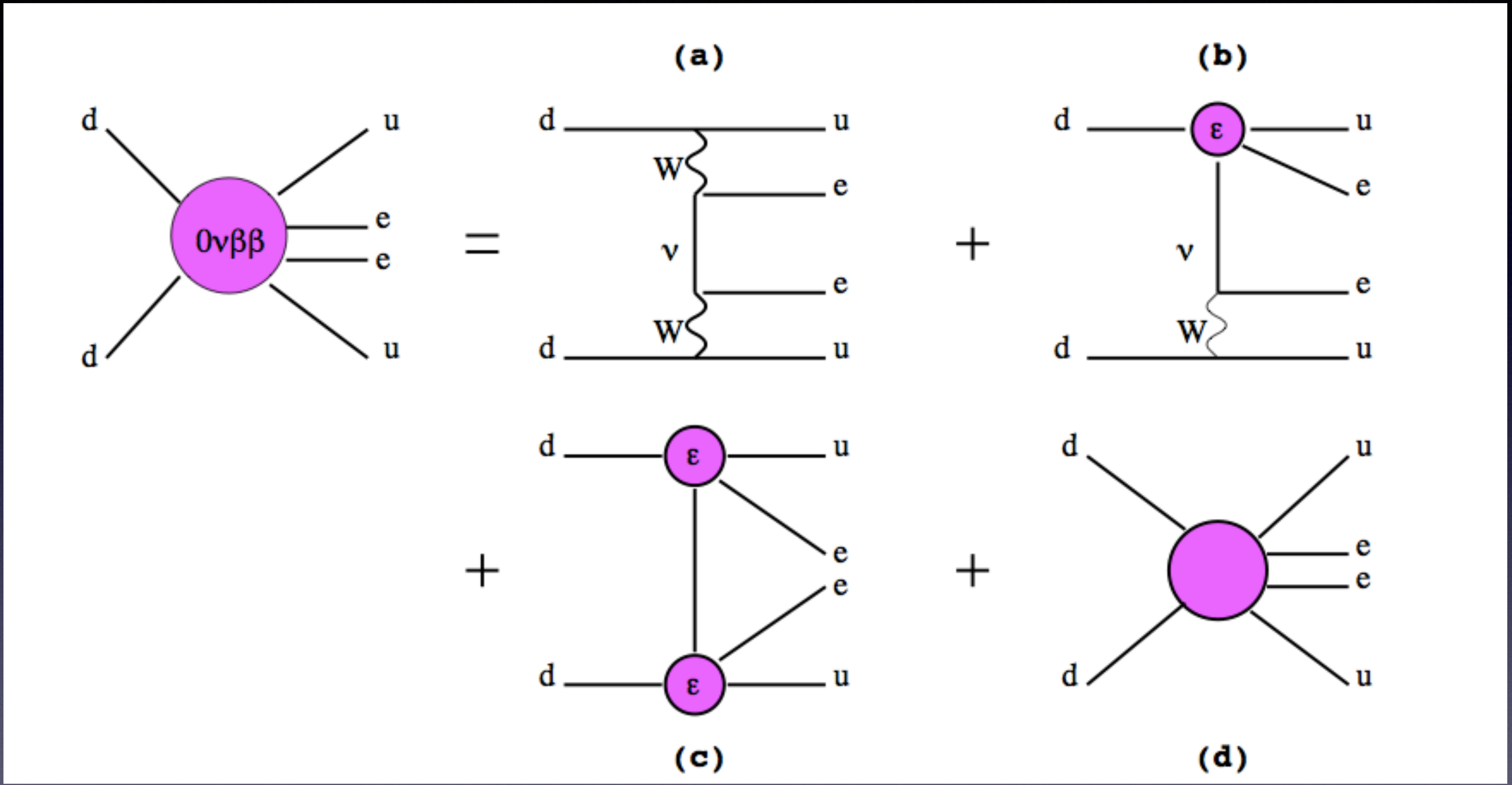
"Mass Mechanism"



General Case

HP, Rodejohann, 2015
Deppisch, Hirsch, HP, 2012

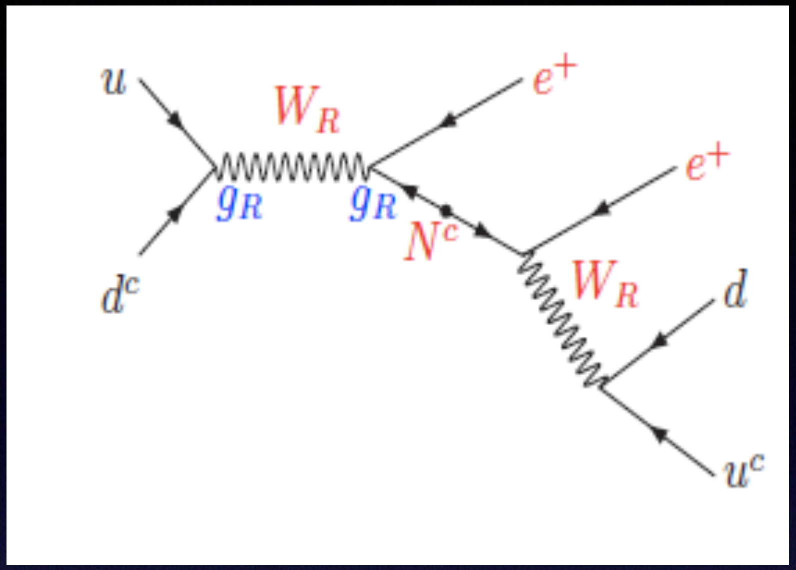
0vBB Decay



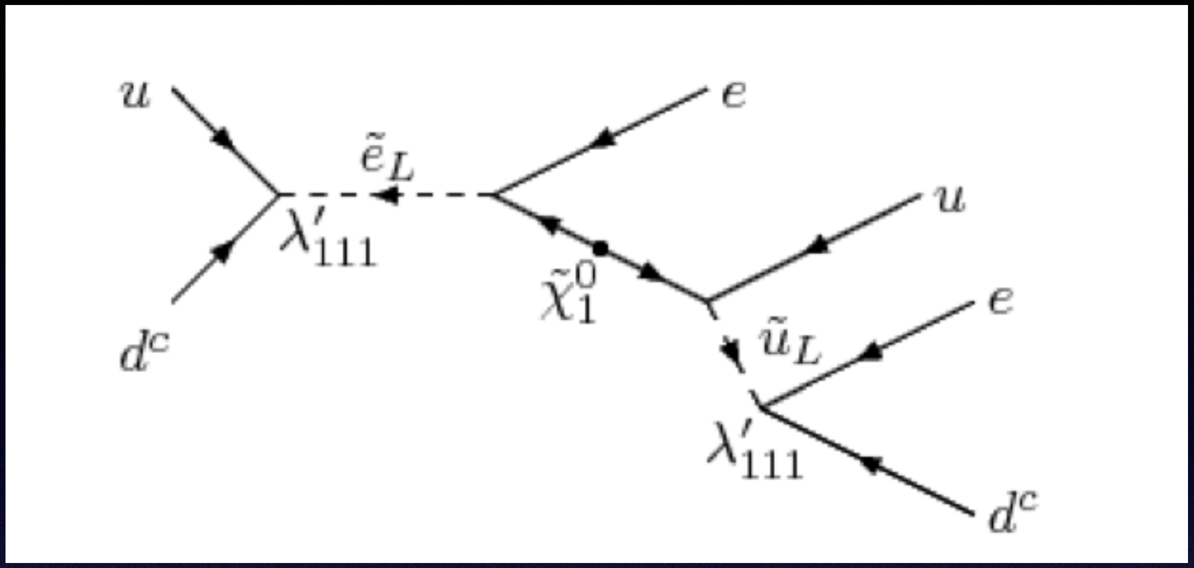
HP, Hirsch, Kovalenko, Klapdor-Kleingrothaus, 1999 & 2001

F. Deppisch, M. Hirsch, HP, 2012

0vBB @ LHC



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



Allanach, Kom, HP, PRL 2009

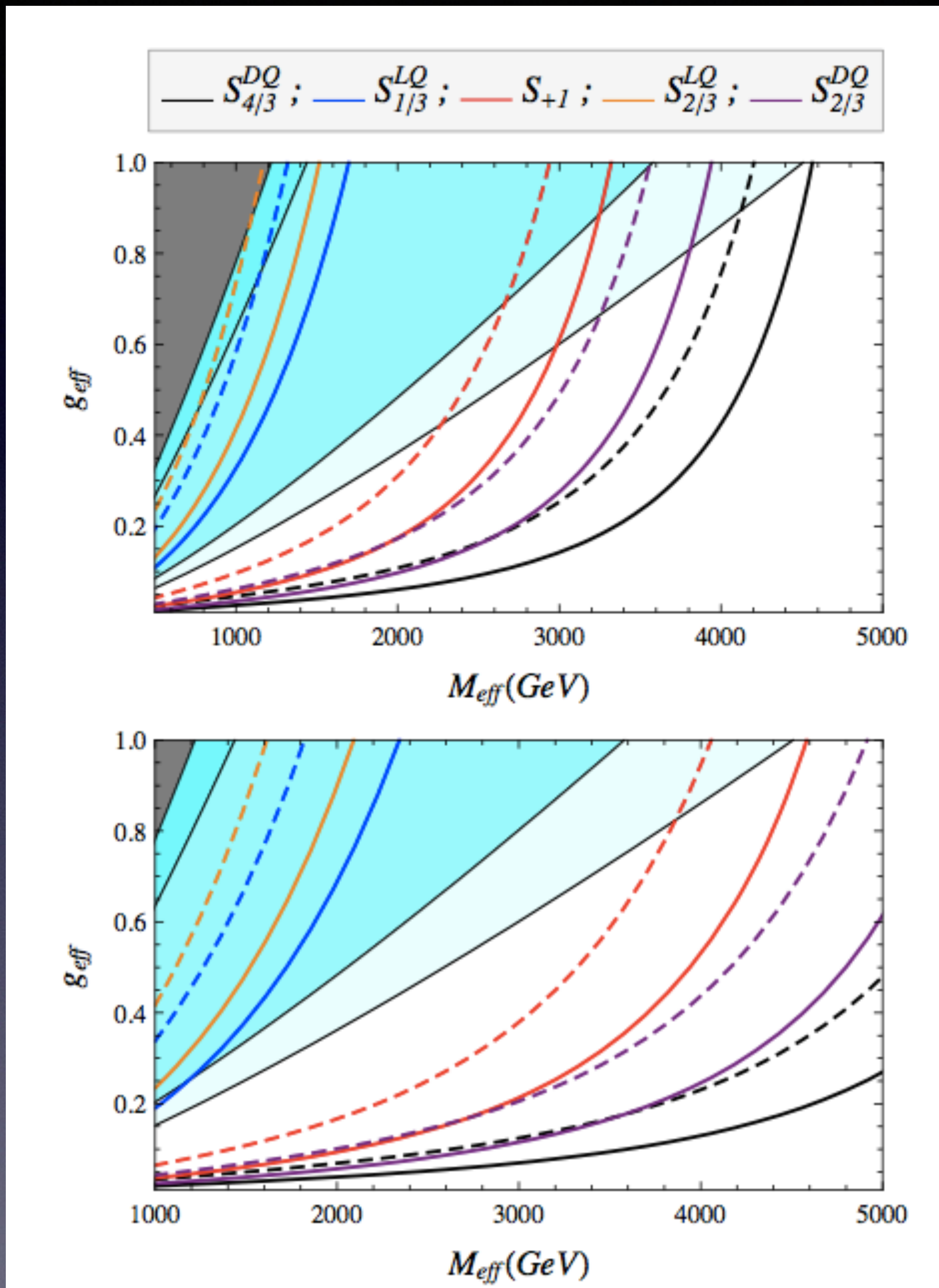
Model-independent approach also for LNV@LHC ?

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

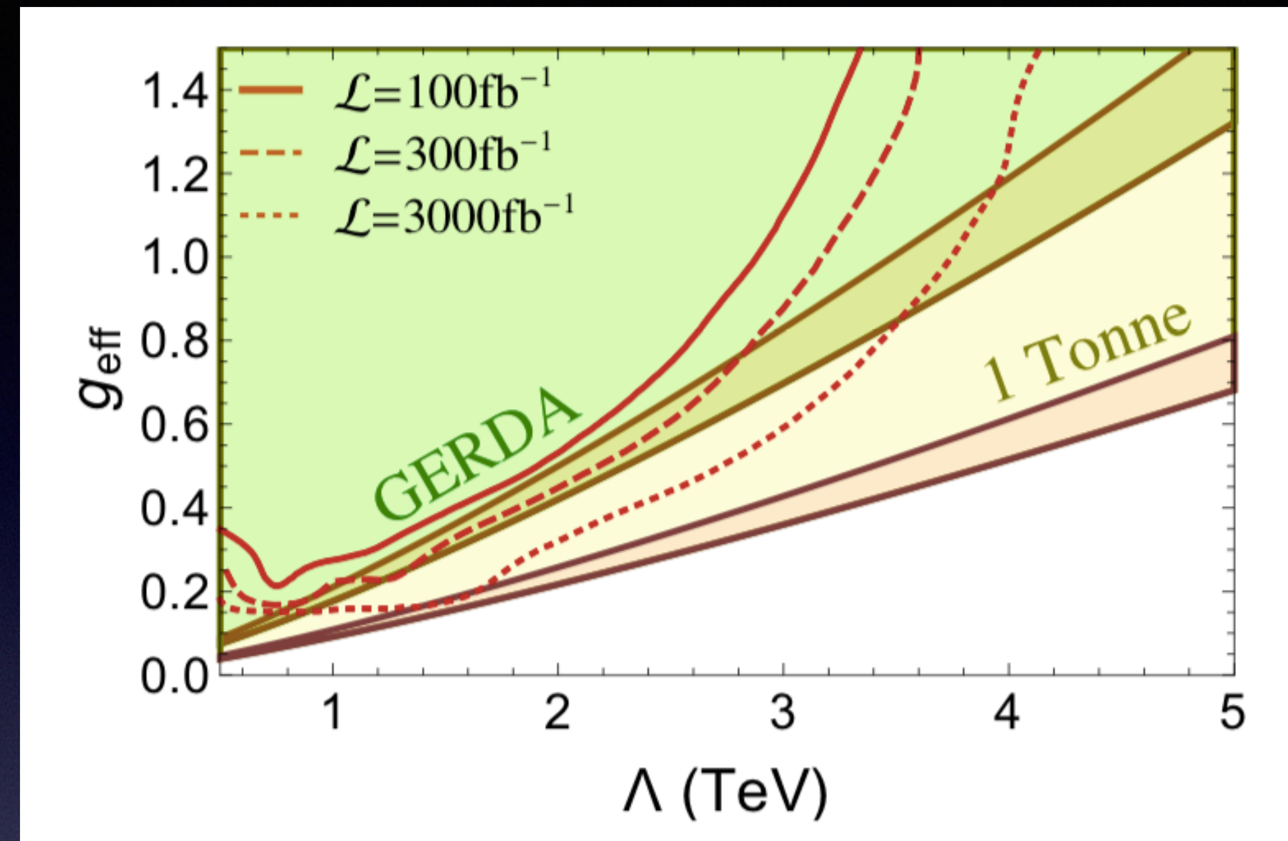
0νββ versus LHC SSD at $\sqrt{s}$ = 14 TeV

mψ= 200 GeV

mψ= 1 TeV



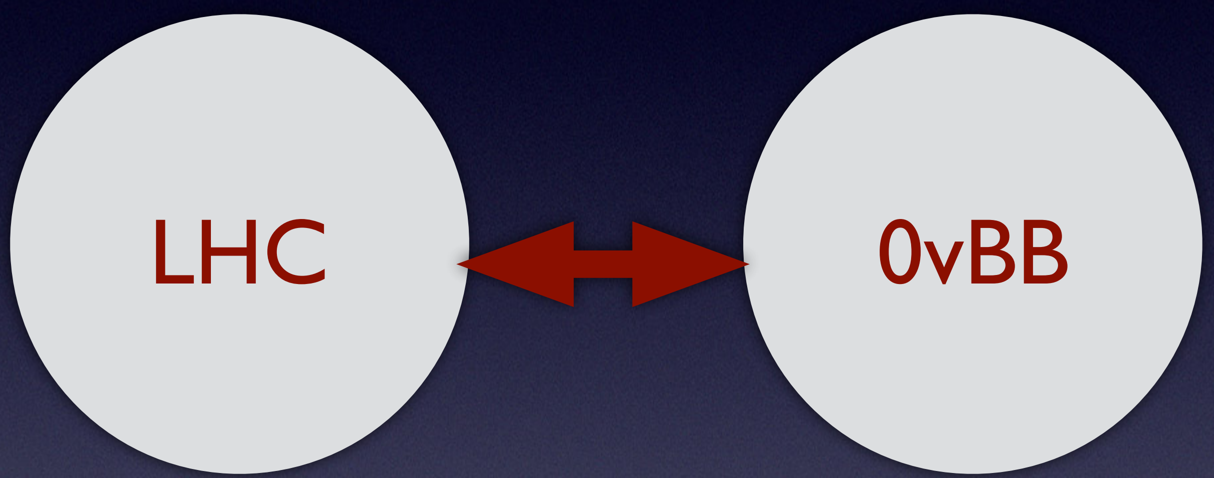
[Helo, Hirsch, Kovalenko, HP, 2013]



Taking into account previously unaccounted for physics and detector backgrounds at the LHC, renormalization group evolution, and long-range contributions to 0νββ nuclear matrix elements

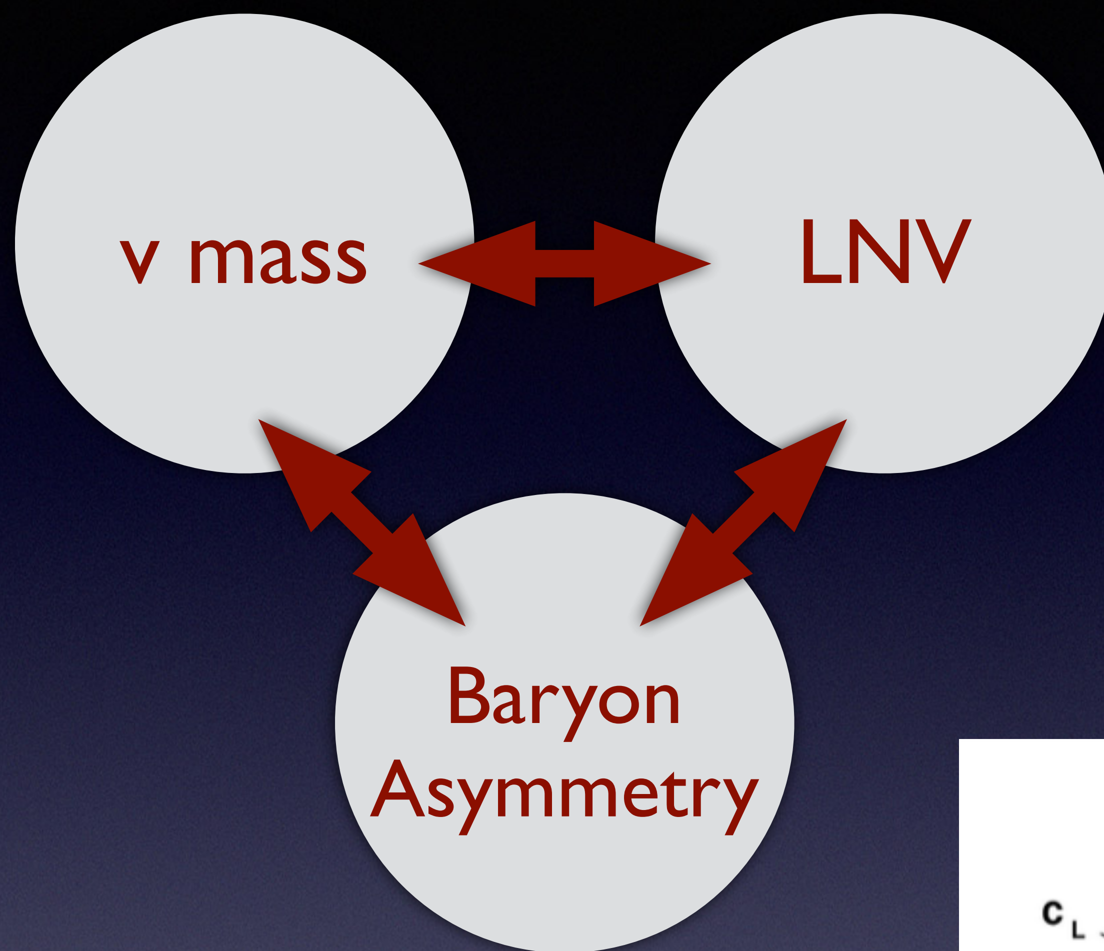
[Peng, Ramsey-Musolf, Winslow, 2015]

0νββ vs LHC sensitivities

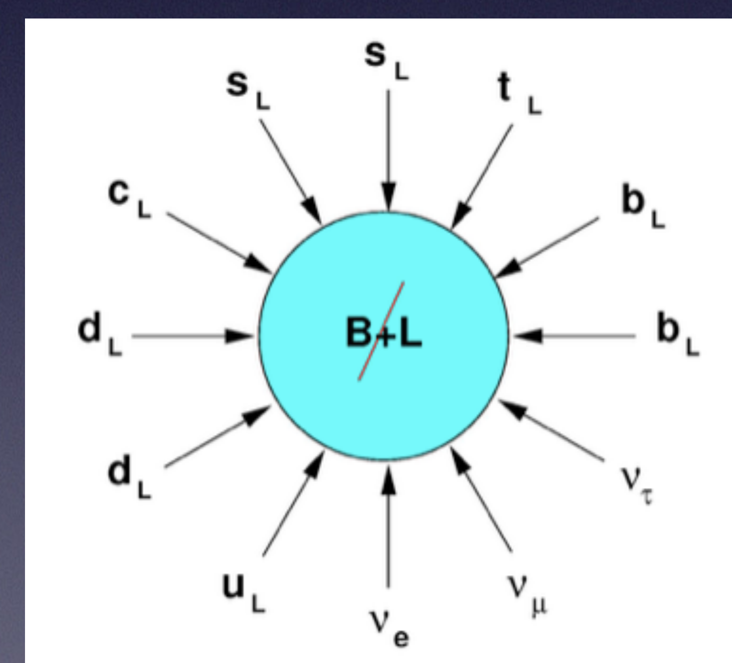


Complementarity

Neutrino Mass Models



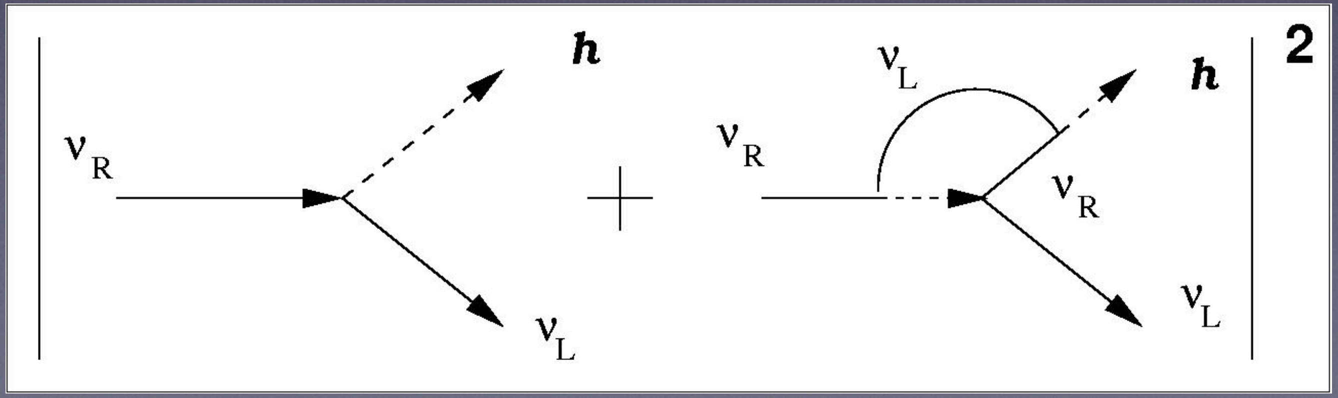
Lepton-Number-Violation:
→ anomaly-free combination
B-L



Sphalerons:
B+L-Violation within SM

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

Can Leptogenesis be falsified?

“Falsifying Leptogenesis at the LHC”

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

- 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

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"

Asymmetric dark matter models

Relation between the production mechanisms of the observed baryon asymmetry and the dark matter abundance

[S. Nussinov. Phys. Lett. B 165 (1985) 55-58]

[K.M. Zurek. Asymmetric Dark Matter, Phys. Rept., 537 (2014) 91-121]

[K. Petraki, R. Volkas, Int. J. Mod. Phys., A28 (2013) 1330028]

Asymmetric dark matter, baryon asymmetry and lepton number violation

Mads T. Frandsen,[1,*] Claudia Hagedorn,[1,†] Wei-Chih Huang,[1,2,‡] Emiliano Molinaro,[1,3,§] and Heinrich Päs[2,¶]

[1] *CP^3-Origins, University of Southern Denmark, Campusvej 55, DK-5230 Odense M, Denmark*

[2] *Fakultät für Physik, Technische Universität Dortmund, 44221 Dortmund, Germany*

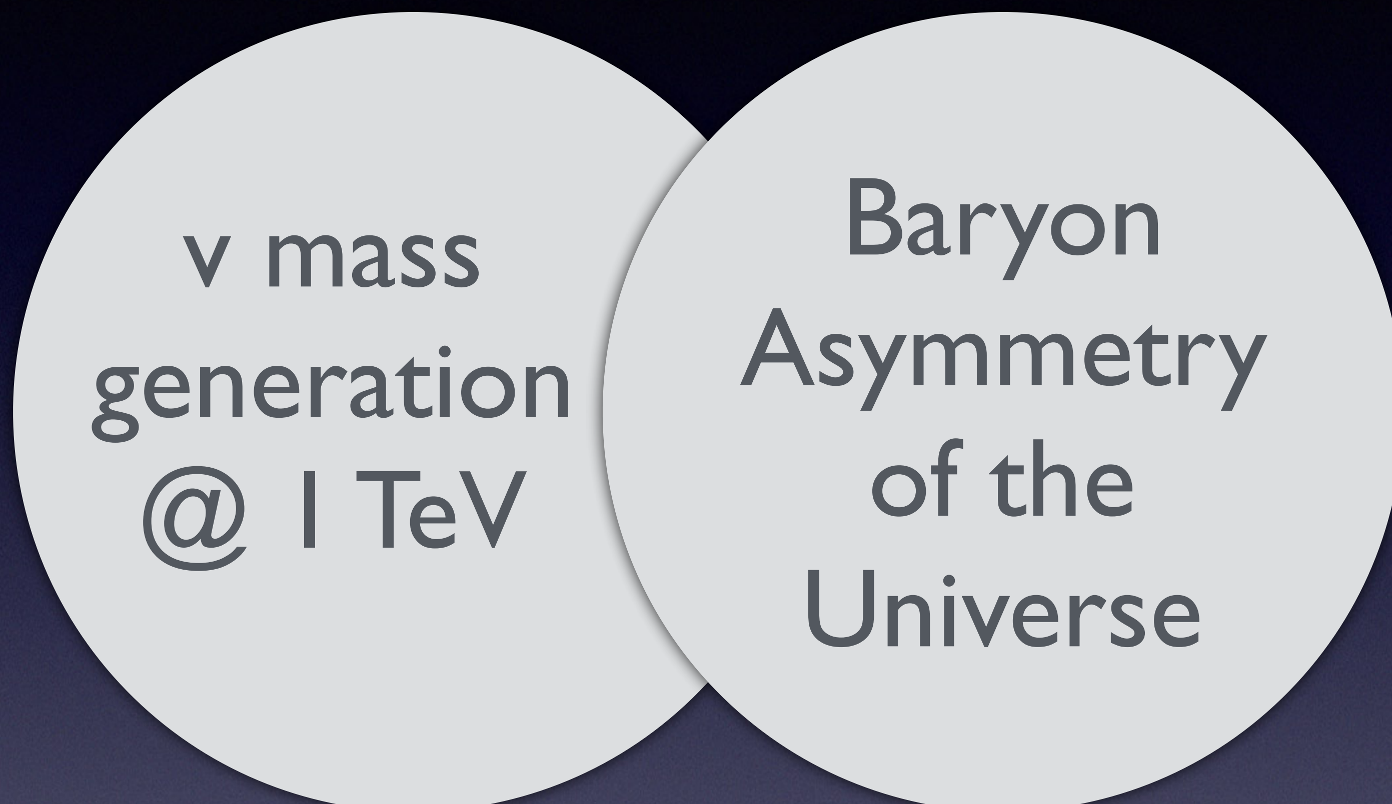
[3] *Department of Physics and Astronomy, University of Aarhus, Ny Munkegade 120, DK-8000 Aarhus C, Denmark*

We study the effect of lepton number violation (LNV) on baryon asymmetry, generated in the early Universe, in the presence of a dark sector with a global symmetry $U(1)_X$, featuring asymmetric dark matter (ADM). We show that in general LNV, observable at the LHC or in neutrinoless double beta decay experiments, cannot wash out a baryon asymmetry generated at higher scales, unlike in scenarios without such dark sector. An observation of LNV at the TeV scale may thus support ADM scenarios. Considering several models with different types of dark matter (DM), we find that the DM mass is of the order of a few GeV or below in our scenario.

[M.T. Frandsen, C. Hagedorn, W.C. Huang. E. Molinaro, H. Päs, arXiv: 1801.09314]

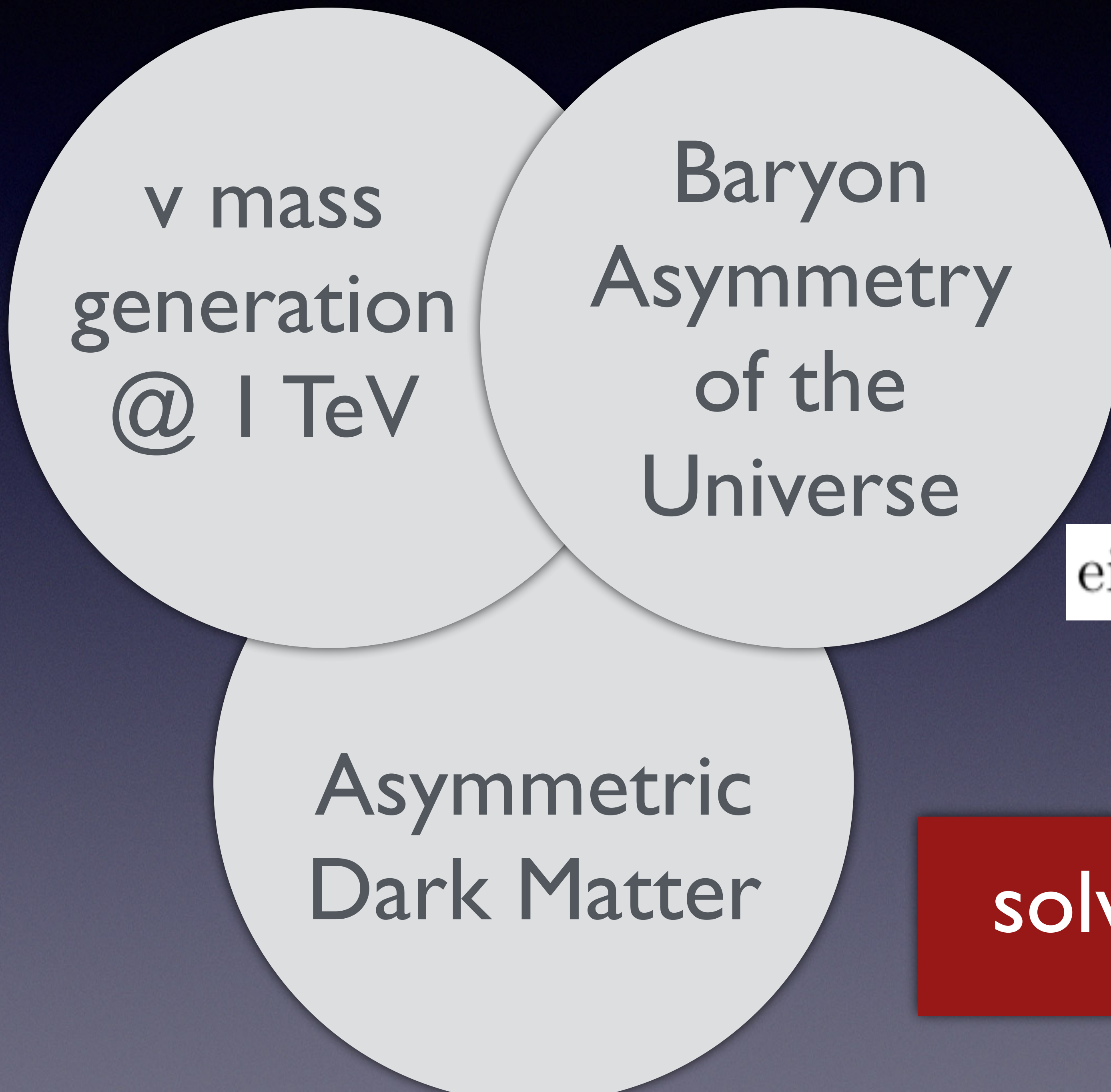
Baryons, Dark Matter & Lepton Number Violation

Problem



Baryons, Dark Matter & Lepton Number Violation

Problem



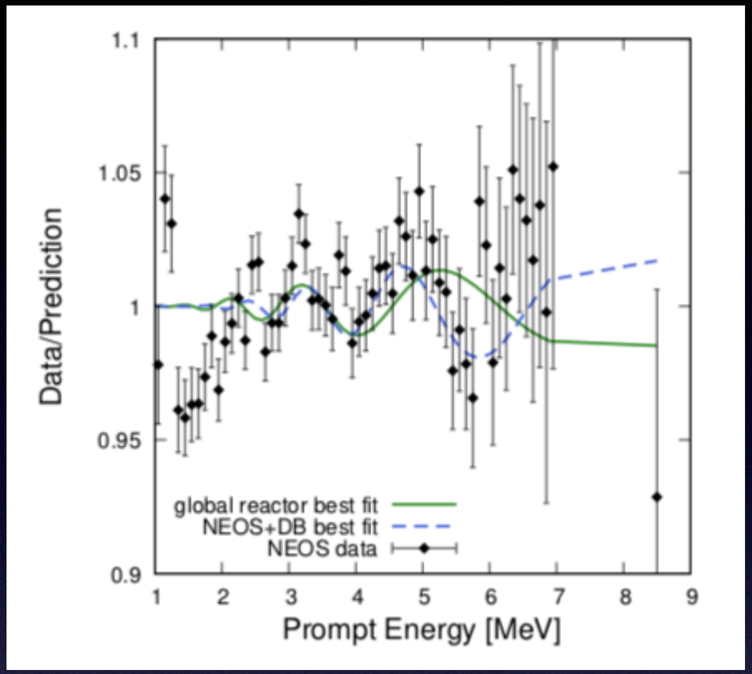
eight chemical potentials

free parameter

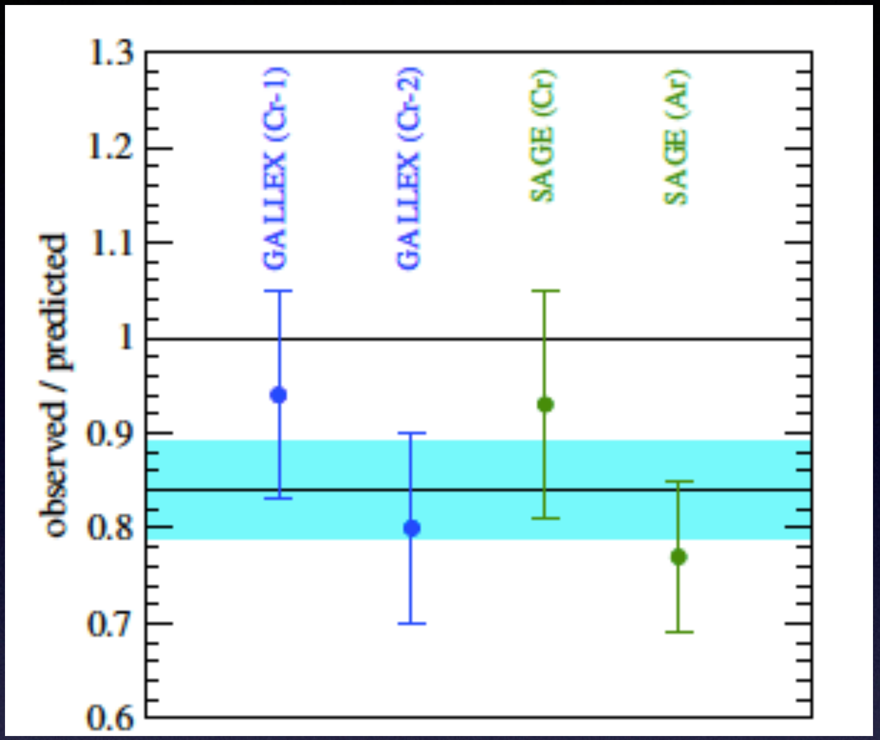
solved !!!

Sterile Neutrinos?

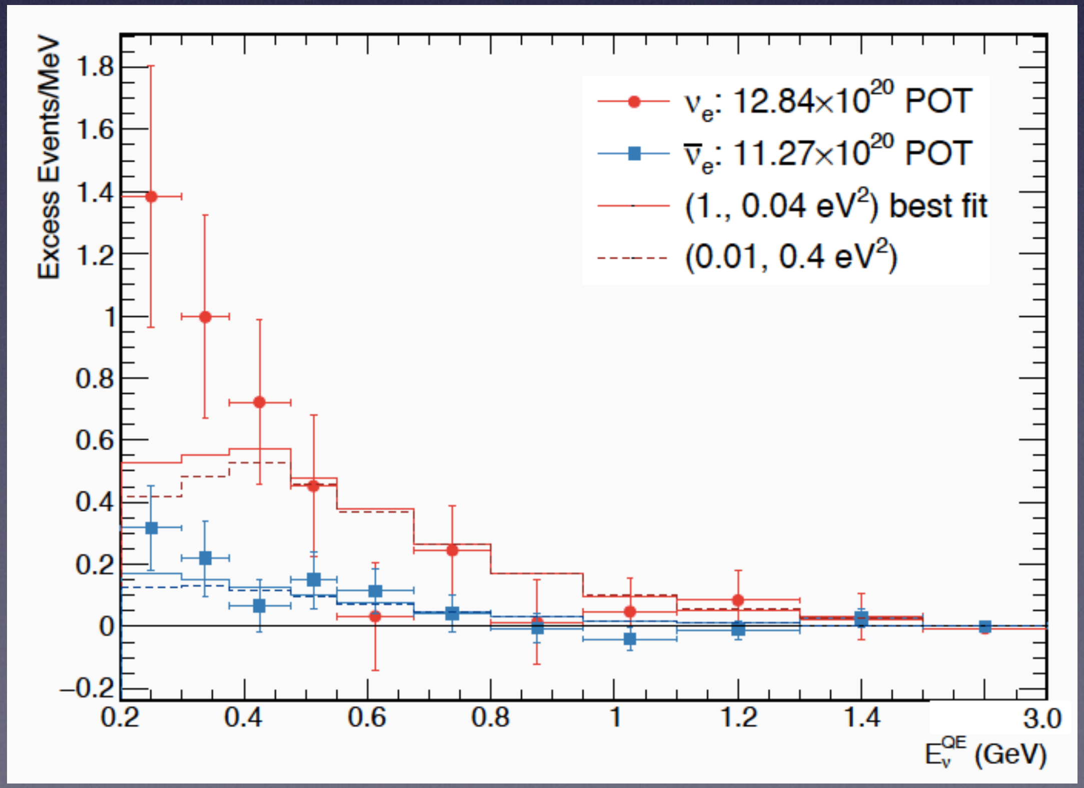
Reactor Anomaly



Gallium Anomaly



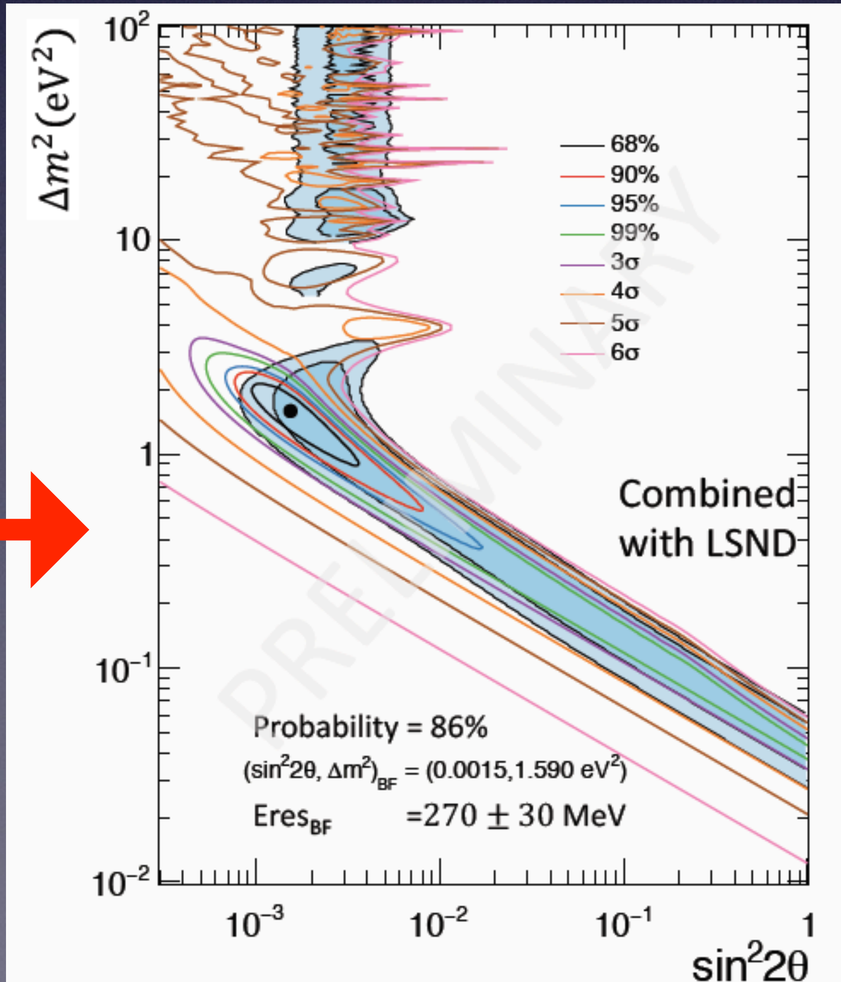
LSND/MiniBooNE Anomaly



4.8σ/6.1σ

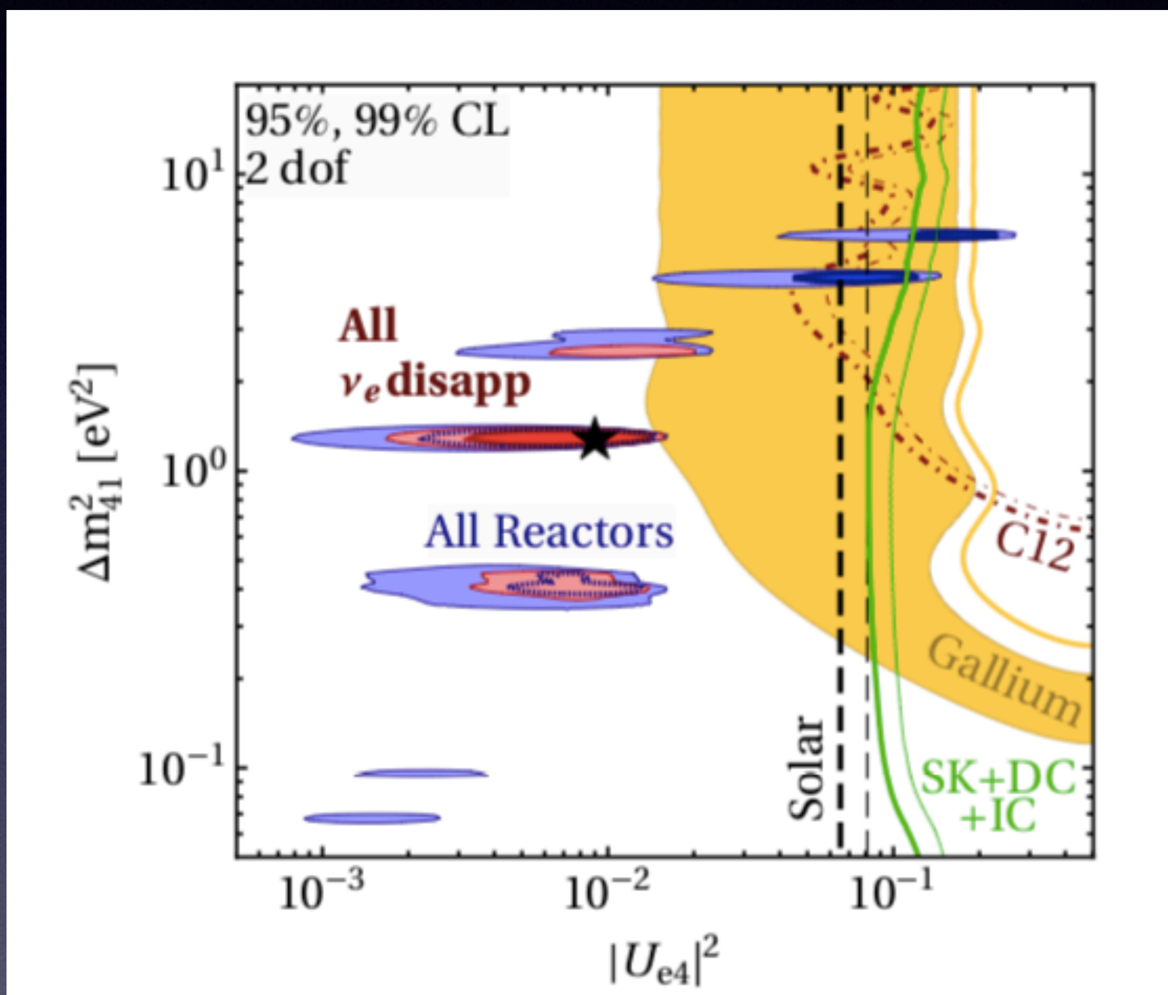
“MSW-like resonance model”

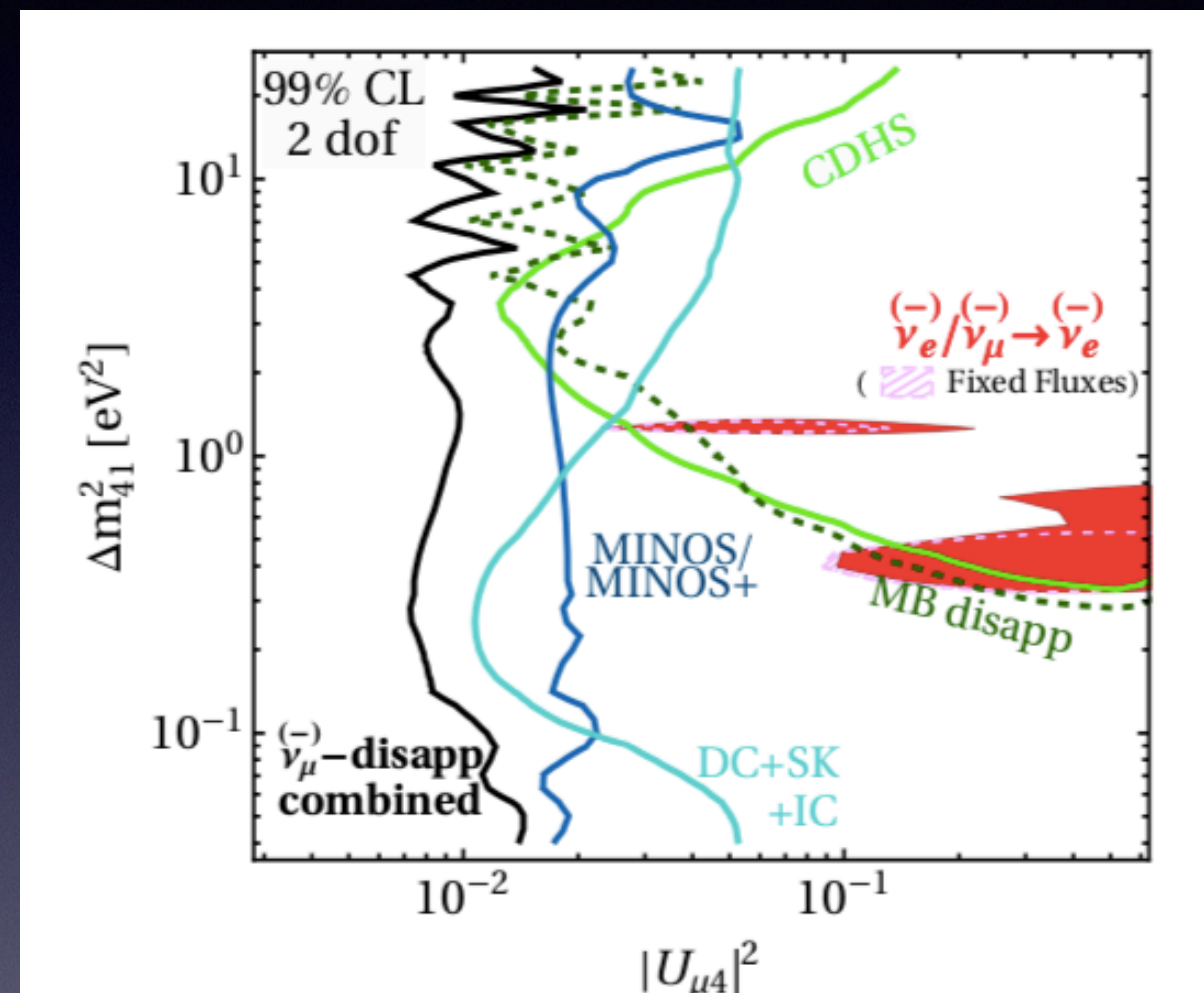
En-Chuan Huang, Talk at Netrino2018



Sterile Neutrinos?

Appearance versus Disappearance Experiments





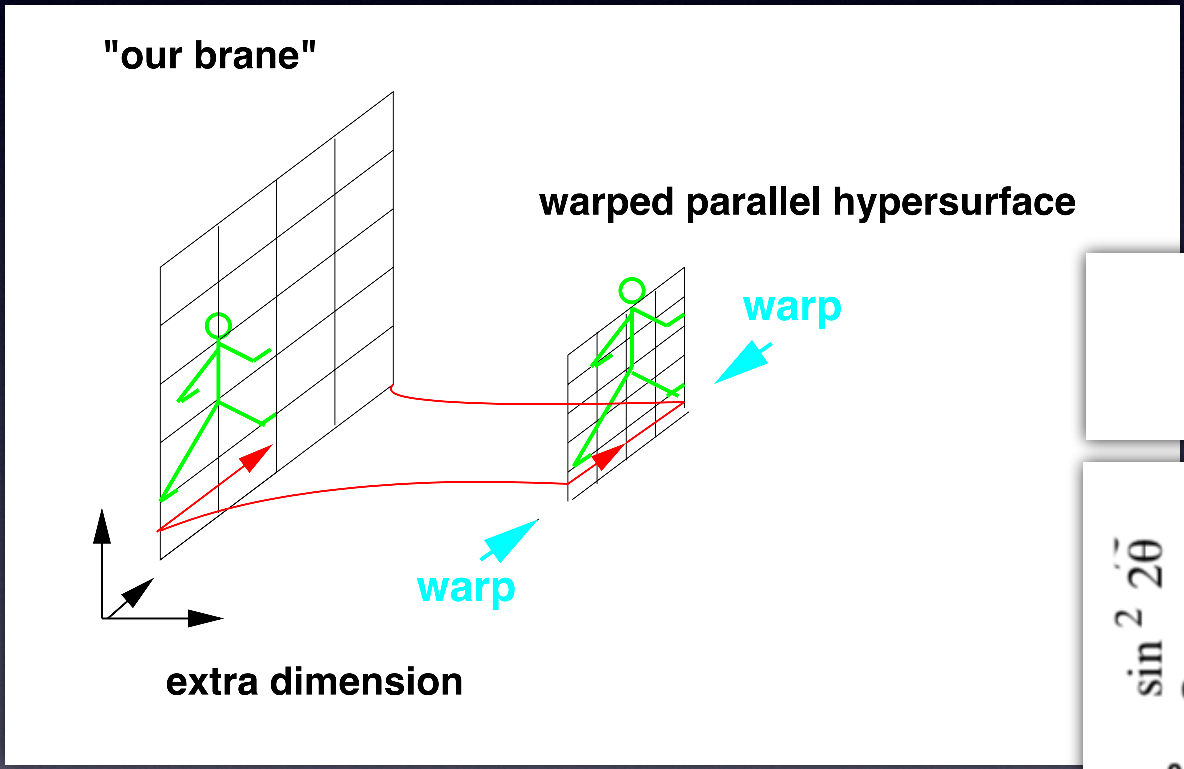
Dentler, Hernandez-Cabezudo, Kopp, Machado, Maltoni, Martinez-Soler, Schwetz, 2018

Sterile Neutrinos Shortcuts in Extra Dimensions?

Consider an asymmetrically warped extra dimension with a sterile neutrino in the bulk

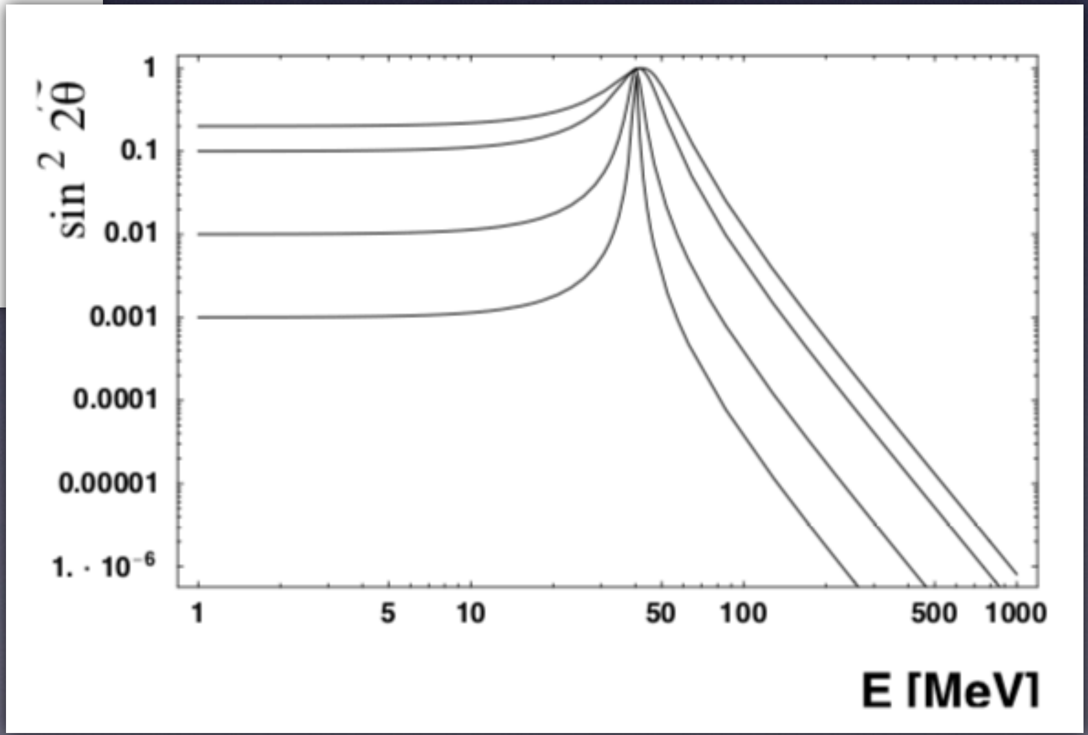
$$ds^2 = dt^2 - e^{-2k|u|}dx^2 - du^2$$

Chung, Freese, 1999, 2000
Csaki, Erlich, Grojean, 2001



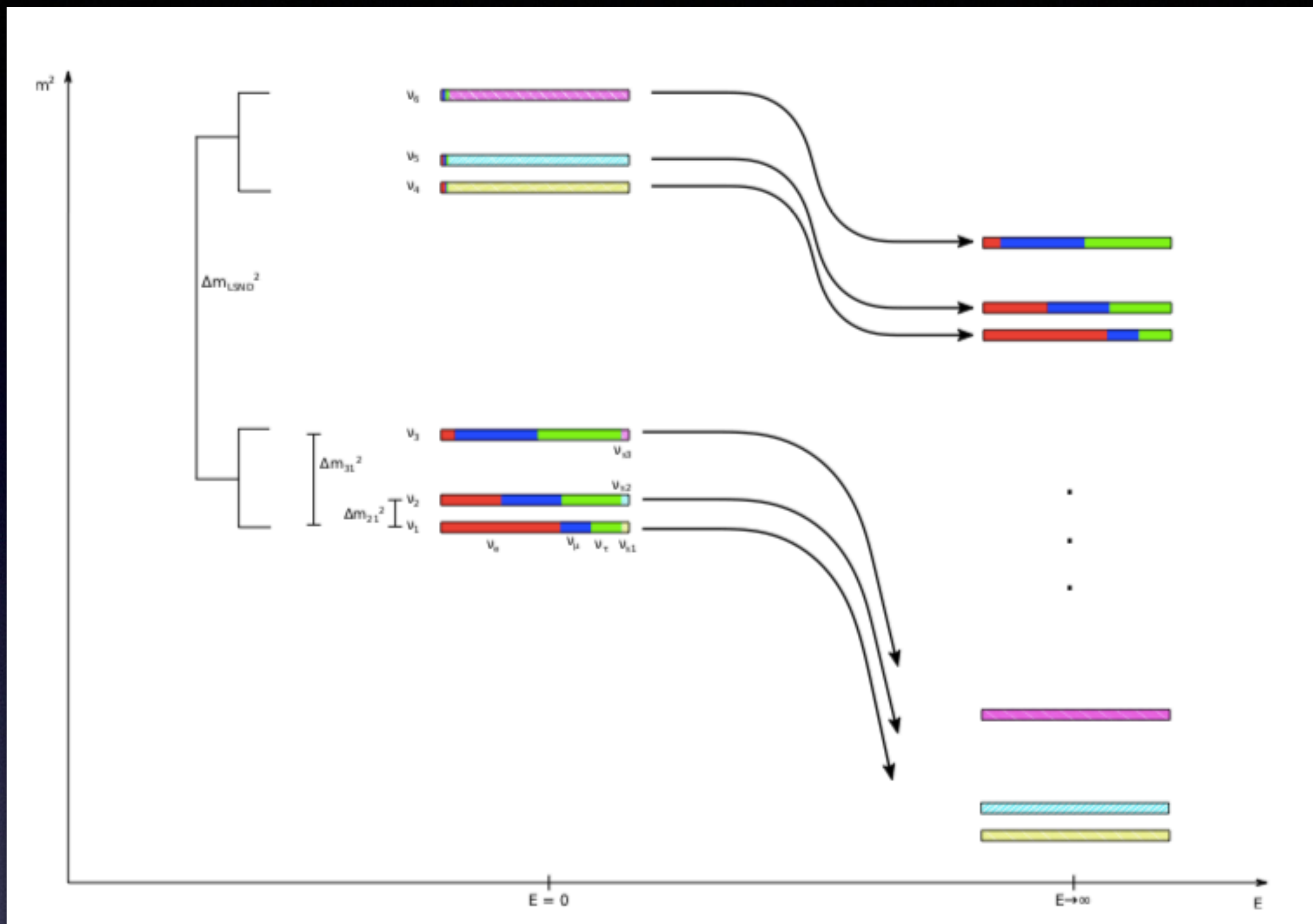
[Döring, HP, arXiv:1808.07734

$$E = p + m^2/2E + \textcolor{red}{\text{new terms}}$$



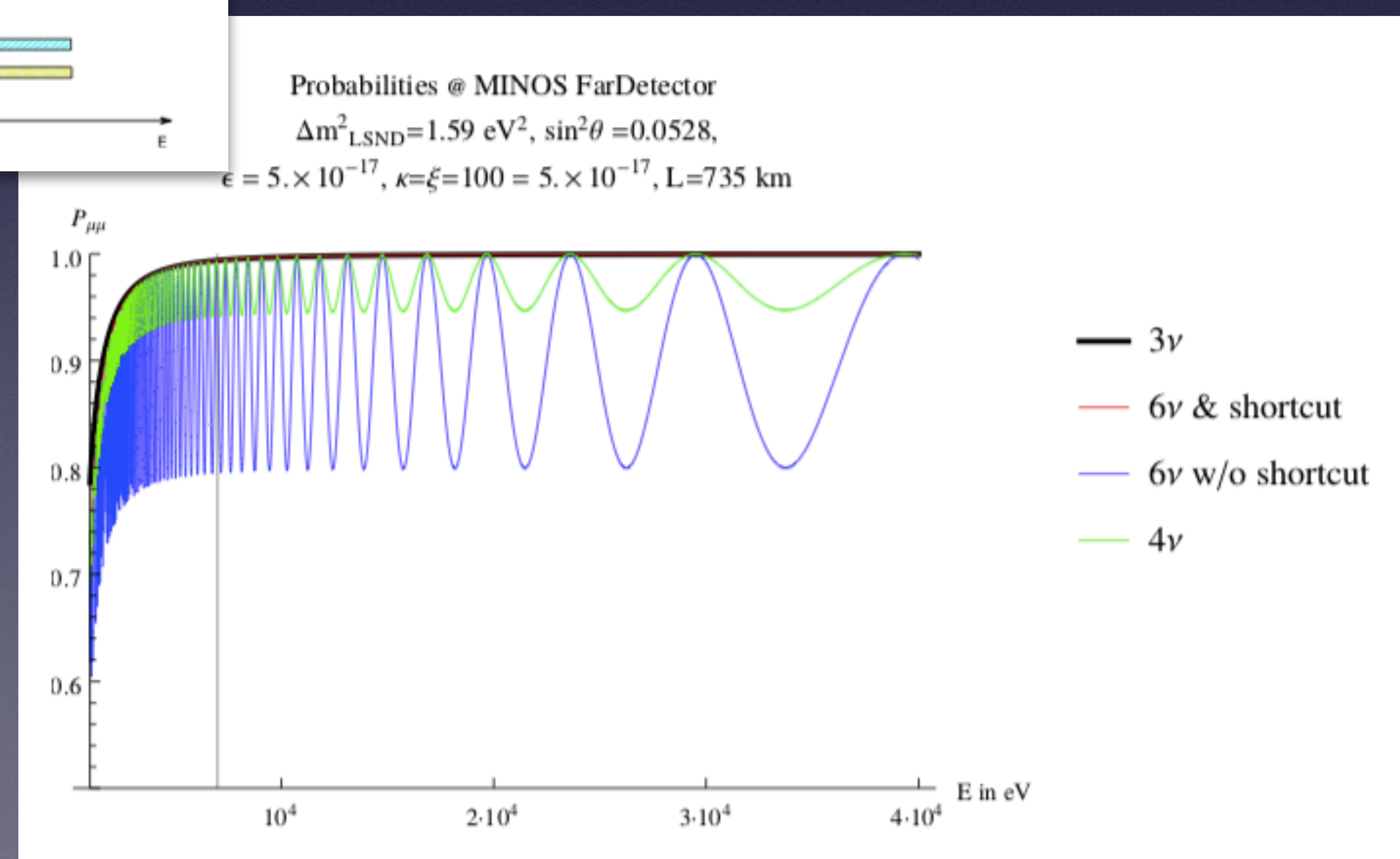
[HP, Pakvasa, Weiler, PRD72, 2005]

Sterile Neutrinos?



In a 3+3 model with democratic mixing the sterile neutrino decouples completely at high energies

Döring, HP, Sicking, Weiler, arXiv:1808.07460



Neutrinos as Messengers

IceCube neutrinos point to long-sought cosmic ray accelerator

IceCube Collaboration, 2018

→ *E.g.: Flavor Ratios: Feedback into fundamental Physics*

Summary

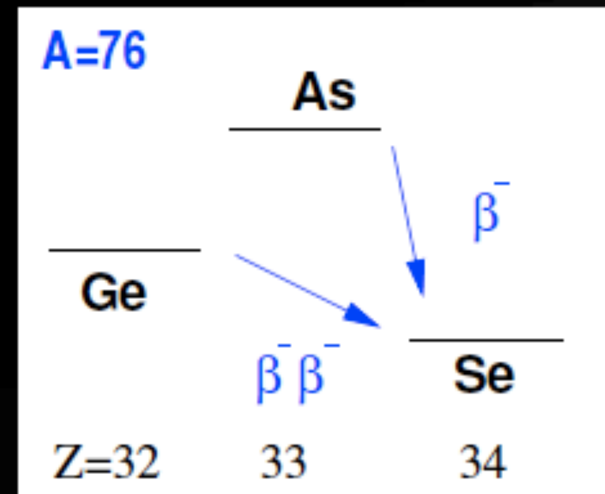
- Neutrinos: Consistent 3ν picture
- Open Questions: Origin? Dirac/Majorana?
- ν Mass ↔ LNV ↔ Physics BSM
- LNV ↔ Baryogenesis ↔ Dark Matter
- Various Anomalies: Sterile Neutrinos
- Neutrinos as Probes ↔ Multi-Messenger Astronomy

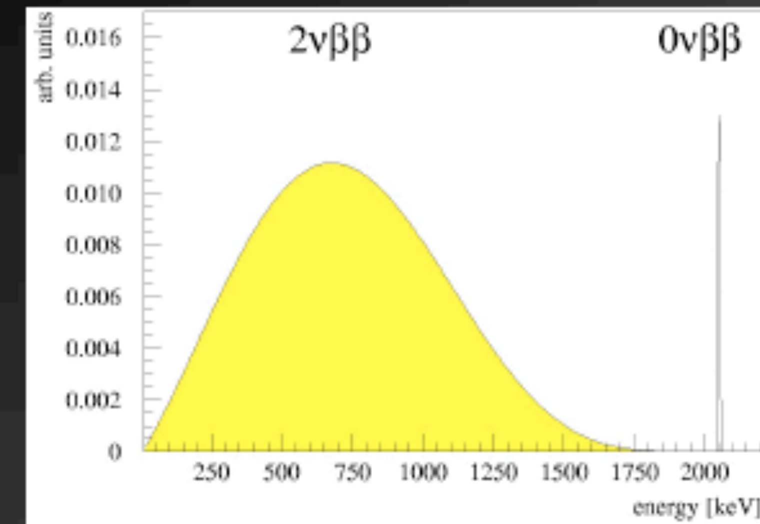
Outline

- Neutrinos 2018
- Open Questions
- Why is this interesting?
- Neutrino Mass Models
- Probing LNV: 0vBB & LHC
- Neutrinos & Baryogenesis
- Neutrinos as Messengers
- Sterile Neutrinos

What is 0vBB decay?

$$2n \rightarrow 2p + 2e^-$$





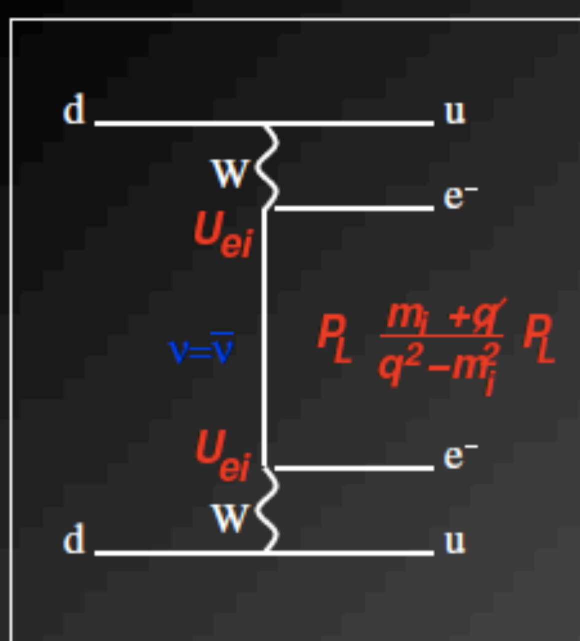
Mass mechanism:

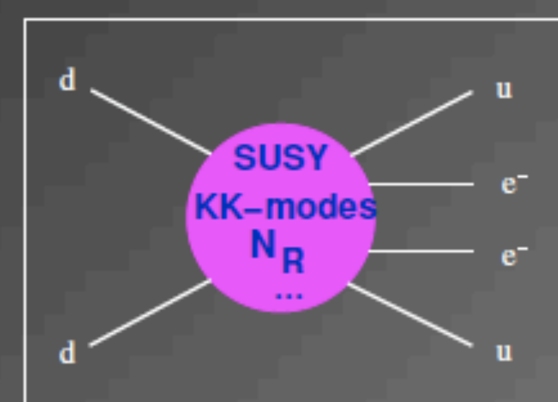
$$[T^{0\nu}_{1/2}]^{-1} \propto |\sum_i U^2_{ei} m_i|^2$$

In general: Every operator

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

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





[HP, W. Rodejohann, NJP 17 (2015) 115010]

[F. Deppisch, M. Hirsch, HP, JPG 39 (2012) 124007]

Apply the decomposition of to 0vBB @ LHC:

[Bonnet, Hirsch, Ota, Winter, 2013]

- 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]