The Quest for Neutrino Mass

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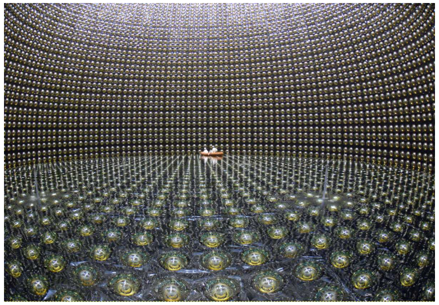
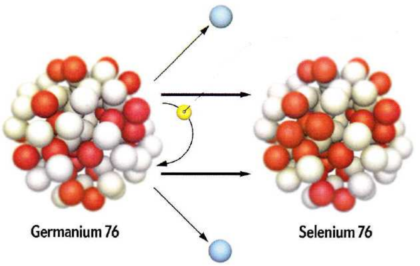




Noble Prize 2015

Nobel prize awarded:

"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

Content

$\mathcal{I}$. Introduction

Neutrinos and the SM - Where are neutrinos produced? - A bit of neutrino history

$\mathcal{II}$. Neutrino oscillations

What are neutrino oscillations? - - Solar, atmospheric and reactor neutrinos - status 2015

$\mathcal{III}$. Absolute mass scale of neutrinos

Single β decay - Supernova 1987A - Cosmology

$\mathcal{IV}$. Double beta decay

Majorana or Dirac? - Experiments - Mass mechanism - Exotics

$\mathcal{V}$. LNV @ LHC

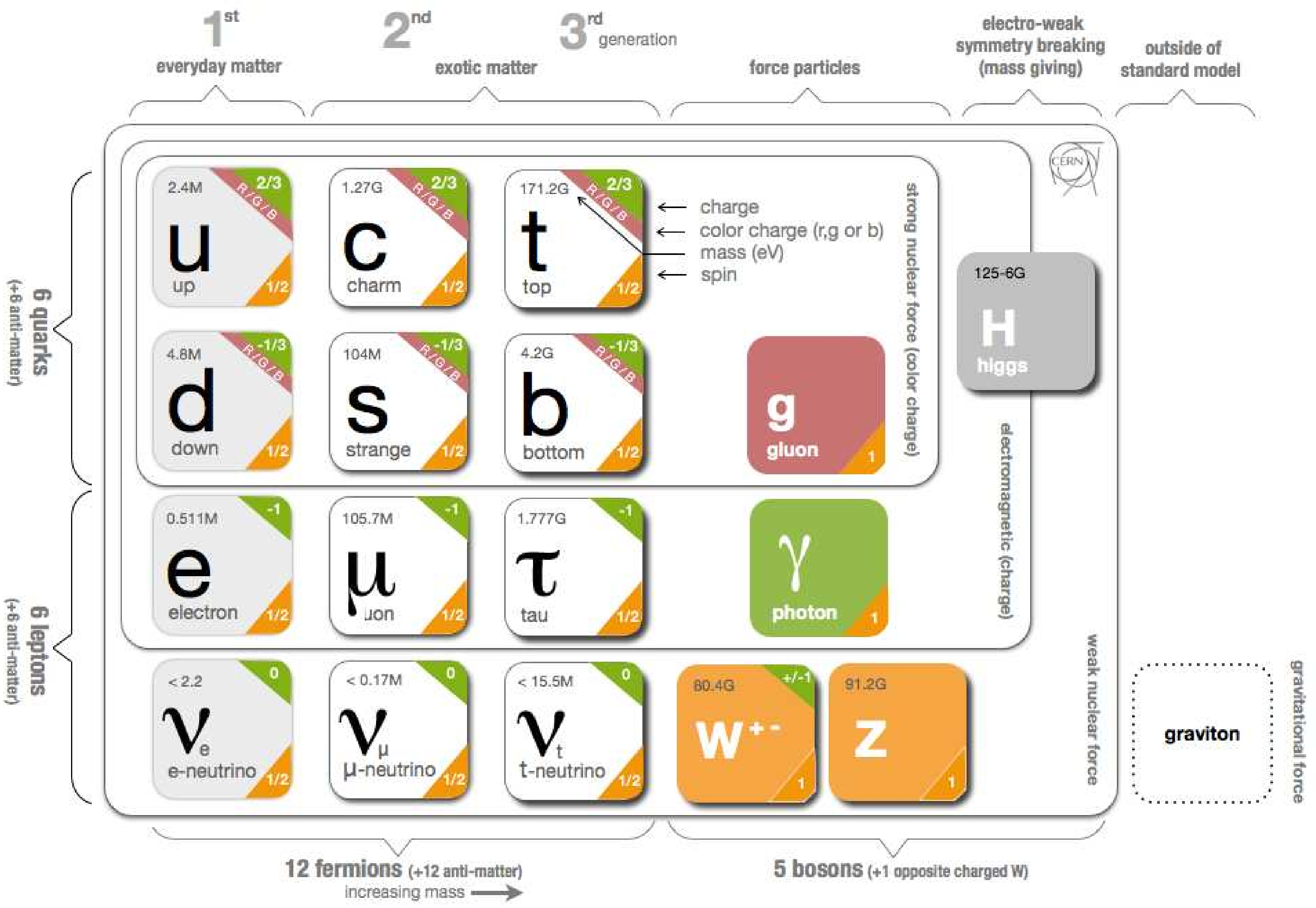
Left-right symmetry - Exotics - LNV and Leptogenesis

$\mathcal{VI}$. Summary

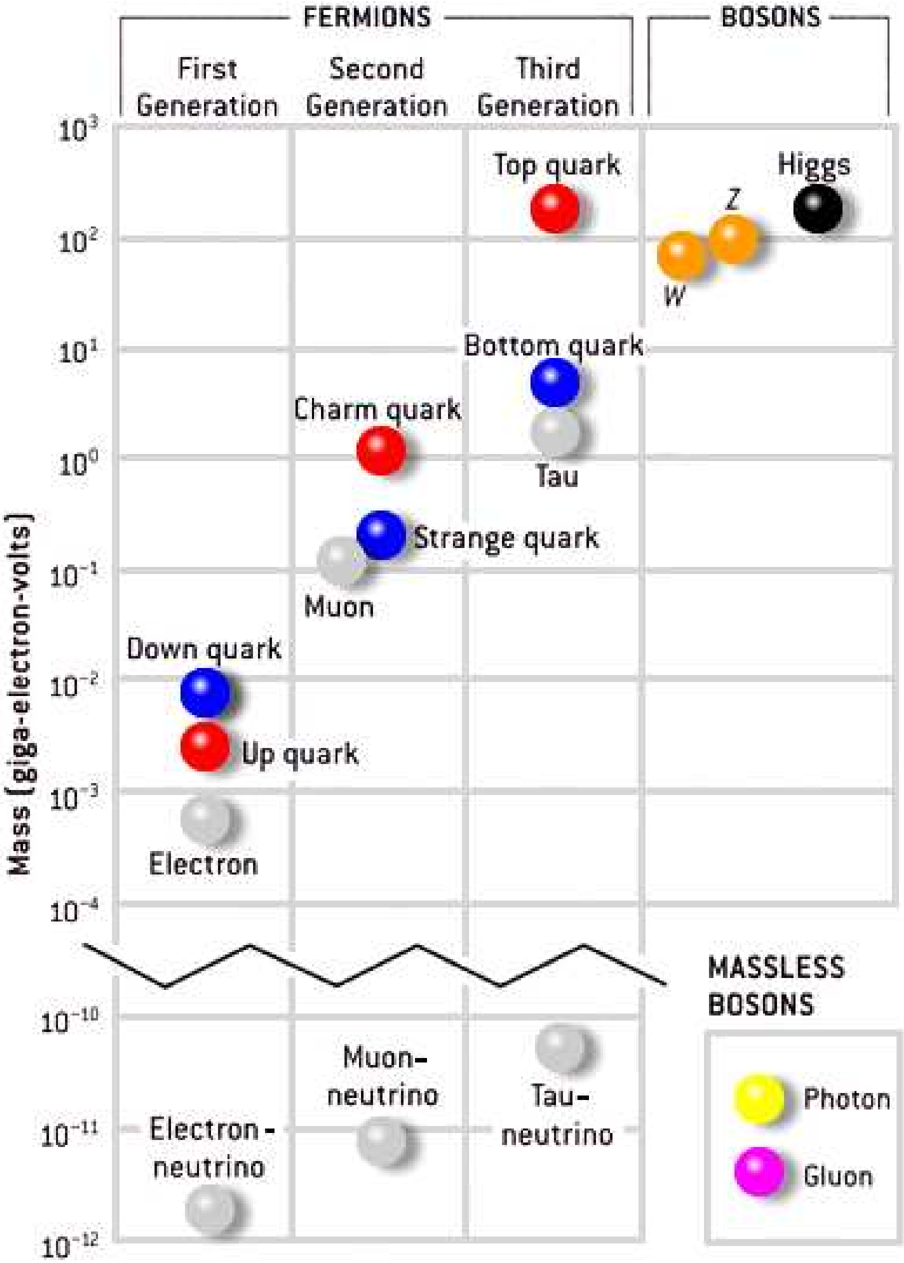
$\mathcal{I}.$

Introduction

The standard model



SM masses



Neutrinos lighter than all other fermions by (at least) factor: 10^6

Units:

1 GeV = $1.78 \cdot 10^{-27}$ kg

1 GeV = 10^3 MeV = 10^9 eV

Where are ν's produced?

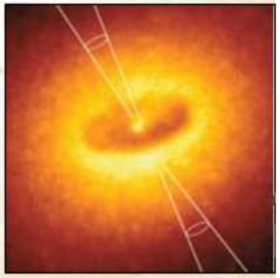
Reactors

Sun

Accelerators

Supernovae

Earth atmosphere

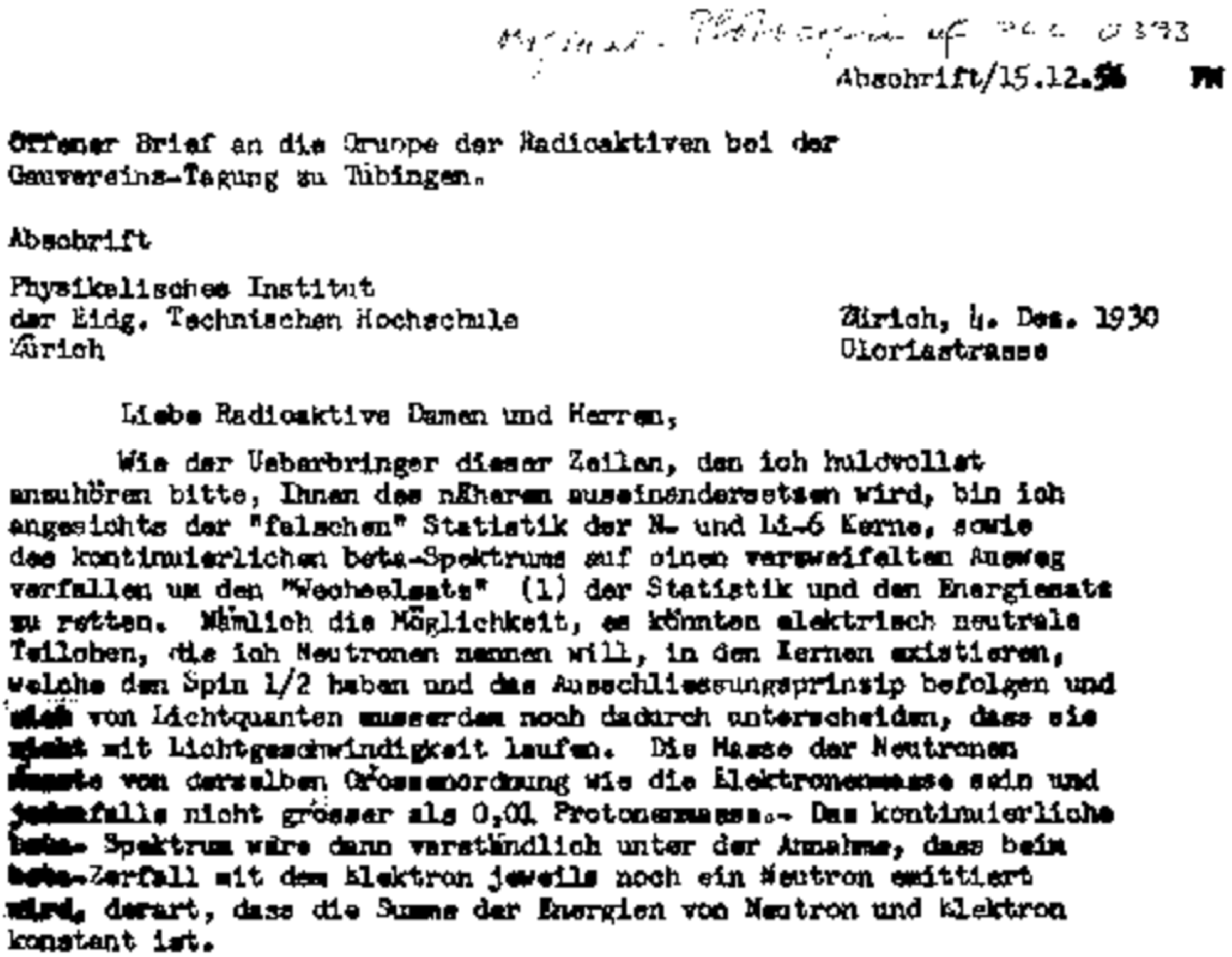


Active galaxies

Earth crust
radioactivity

Big Bang

The invention of the ν



Original - Photocopy of PLC 0393

Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

The invention of the ν

Zürich, 4. Dec. 1930

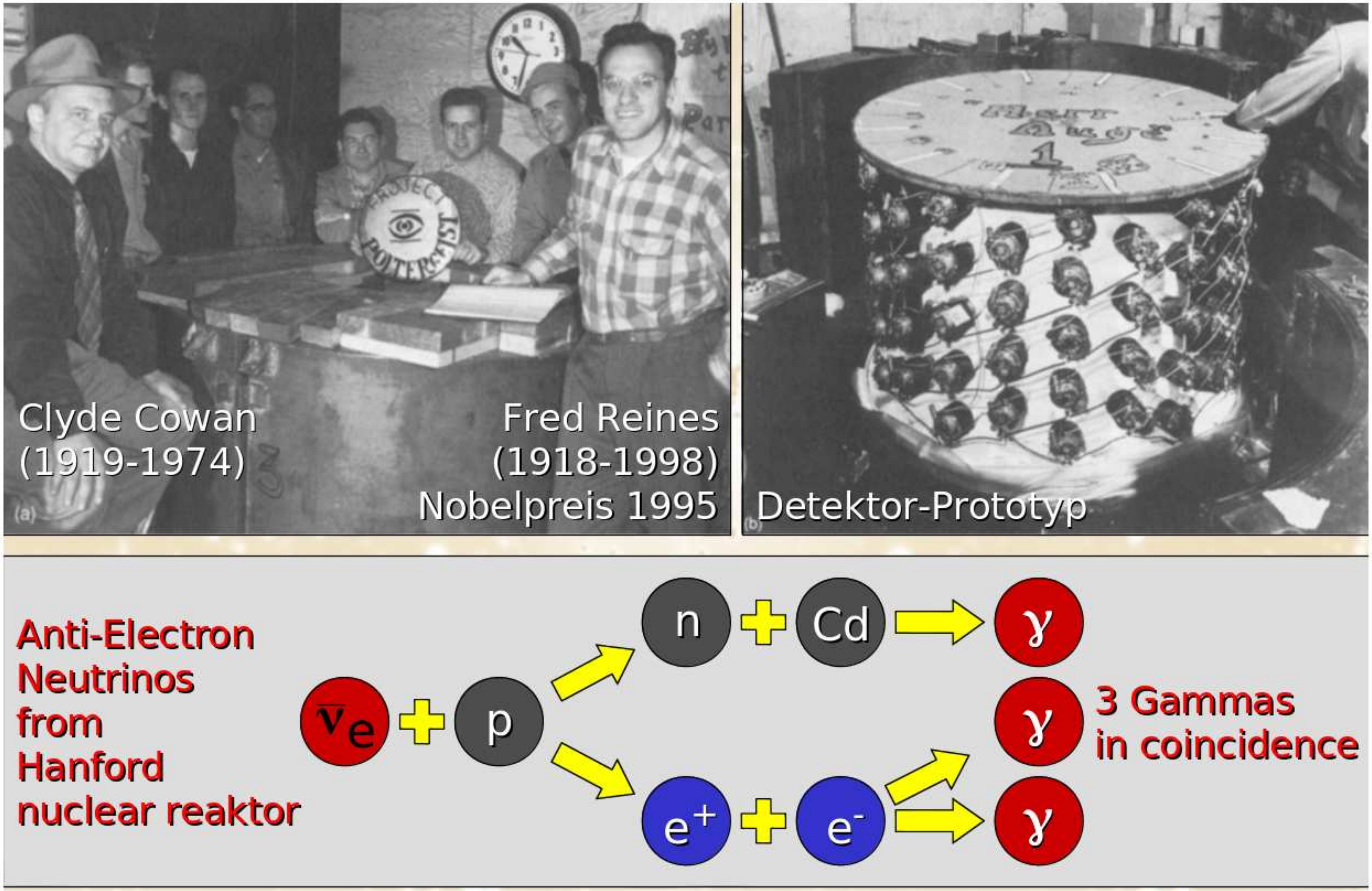
"Dear radio-active Ladies and Gentleman;

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, $\cdots$ I have hit upon a desperate remedy to save the $\cdots$ law of conservation of energy. Namely, the possibility that in the nuclei there could exist electrically neutral particles, which I will call neutrons*, that have spin 1/2 and obey the exclusion principle and that further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton mass. - The continuous beta spectrum would then make sense $\cdots$ so far I do not dare to publish anything about this idea, and trustfully turn first to you, dear radioactive people, with the question of how likely it is to find experimental evidence $\cdots$ Thus, dear radioactive people, scrutinize and judge. - Unfortunately, I cannot personally appear in Tübingen since I am indispensable here in Zürich because of a ball on the night from December 6 to 7. With my best regards to you, and also to Mr. Back, your humble servant

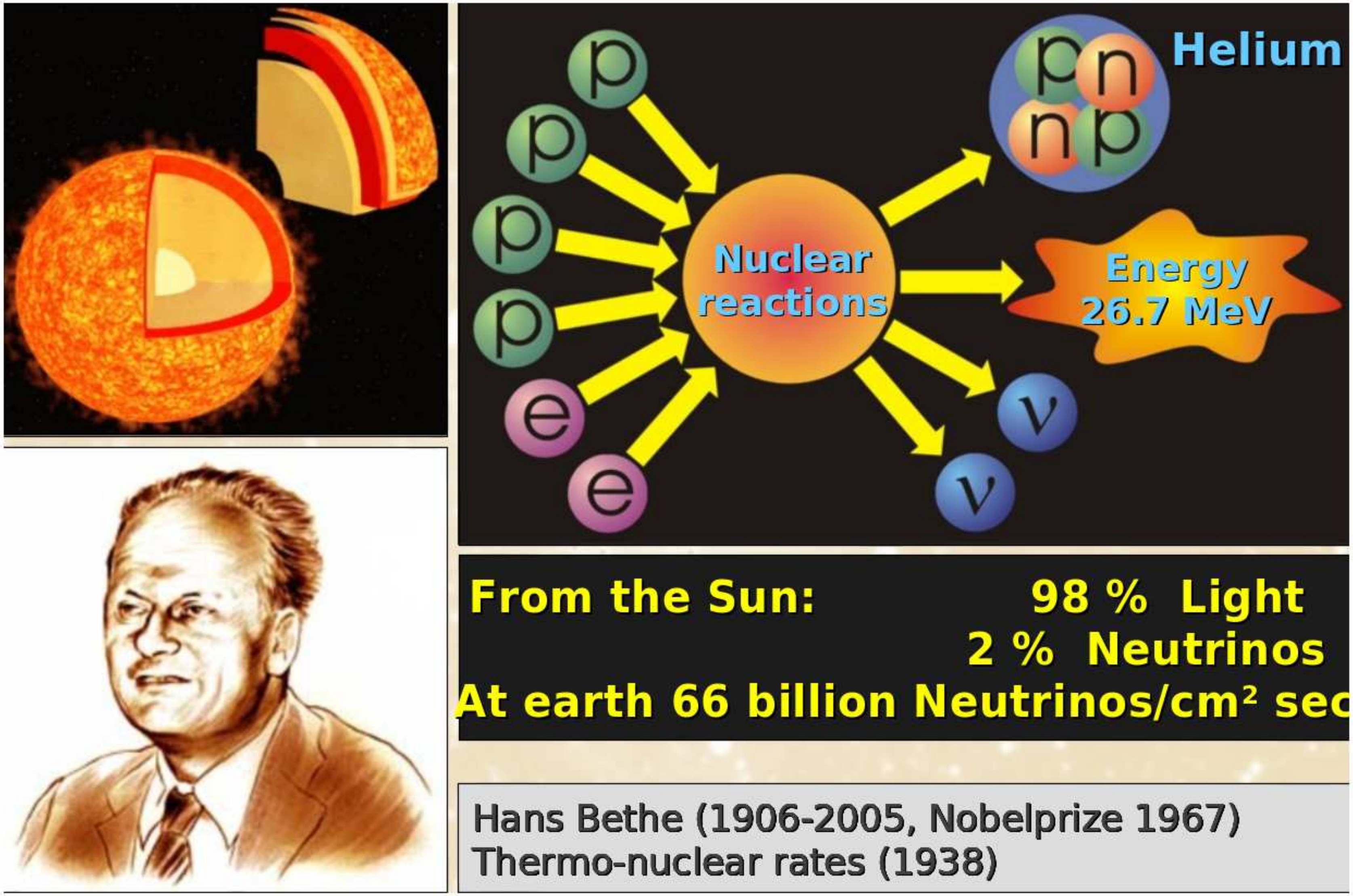
W. Pauli"

* - Neutrino

First detection (1956)



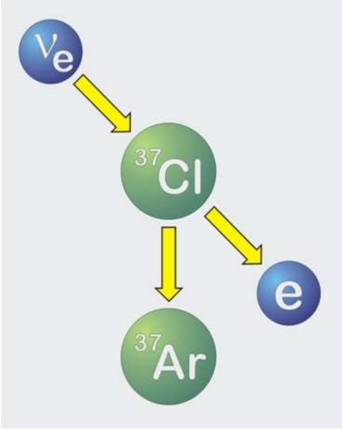
Solar neutrinos



From the Sun: 98 % Light
2 % Neutrinos
At earth 66 billion Neutrinos/cm² sec

Hans Bethe (1906-2005, Nobelprize 1967)
Thermo-nuclear rates (1938)

Solar neutrinos

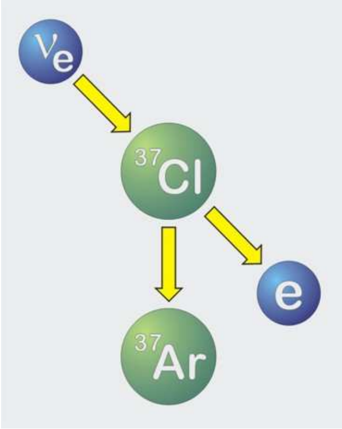


R. Davies Jr.
(starting 1967!)
Comparison between calculated
and measured neutrino events:

$R(exp/cal) \sim 1/2$

"Solar ν problem"

Solar neutrinos



R. Davies Jr.
(starting 1967!)
Comparison between calculated and measured neutrino events:

$R(exp/cal) \sim 1/2$

"Solar ν problem"

Solved in 2000/2002:
by experiments: SNO, KamLAND
NEUTRINOS CHANGE FLAVOUR!

$\mathcal{II}.$

Neutrino oscillations

Slides from:

Mariam Tortola

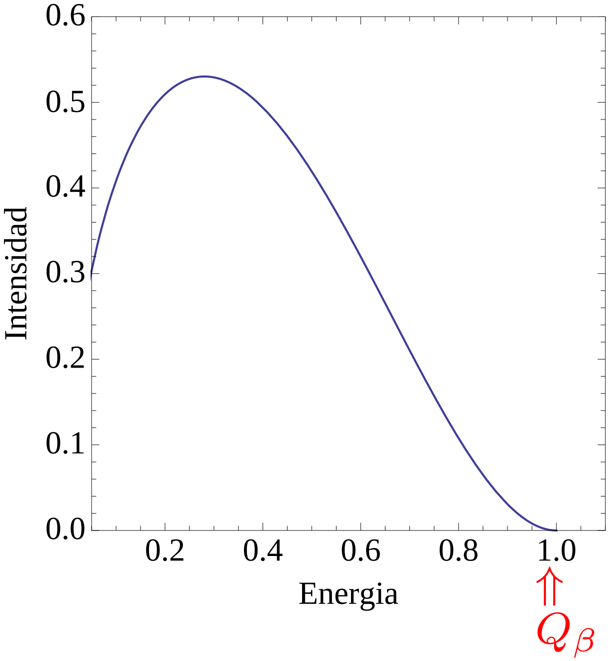
(IFIC, Valencia)

III.

Absolute neutrino mass scale

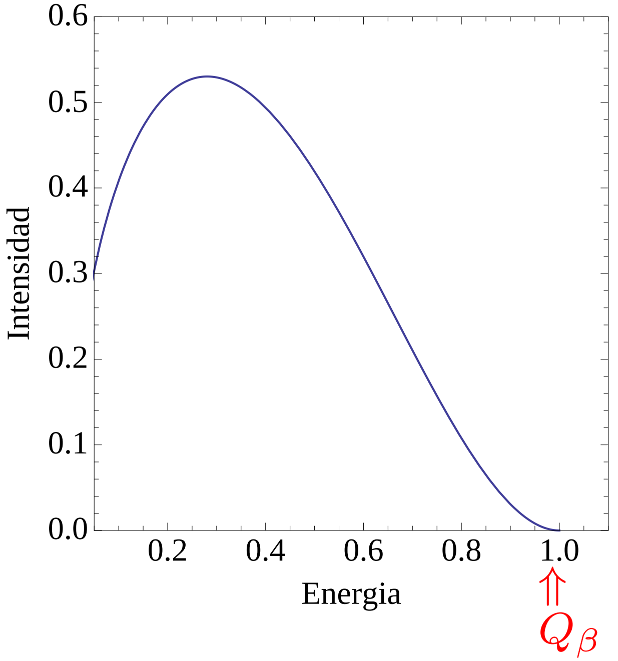
The β spectrum and m_ν

$$n \rightarrow p + e^- + \bar{\nu}_e$$

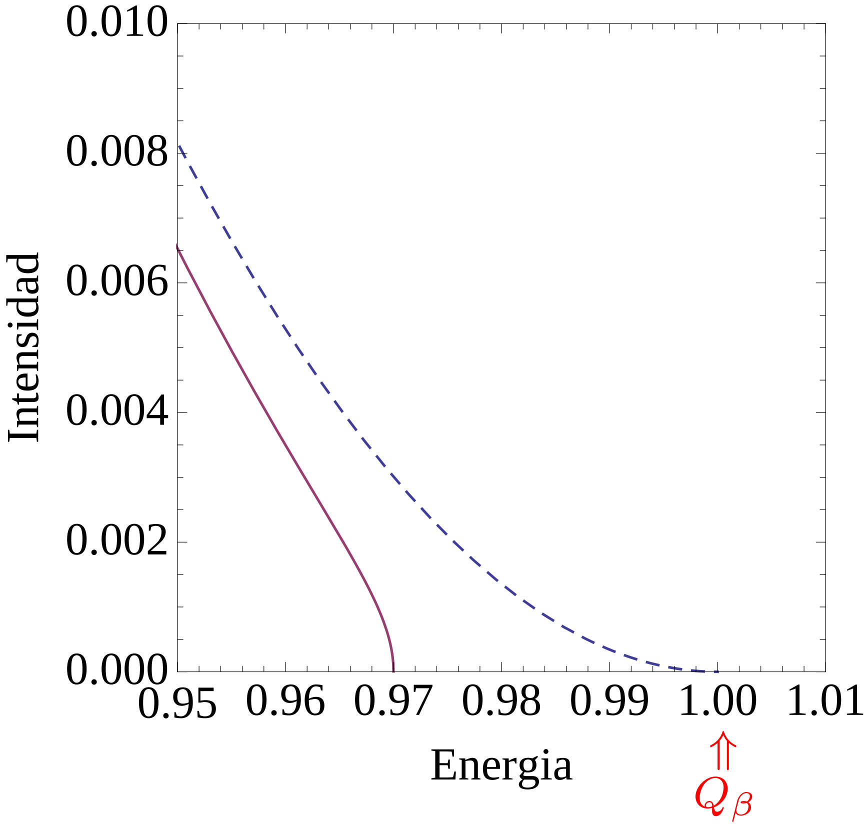


The β spectrum and m_ν

$$n \rightarrow p + e^- + \bar{\nu}_e$$



Zoom:



$| \Leftarrow Q_\beta - m_\nu \Rightarrow |$

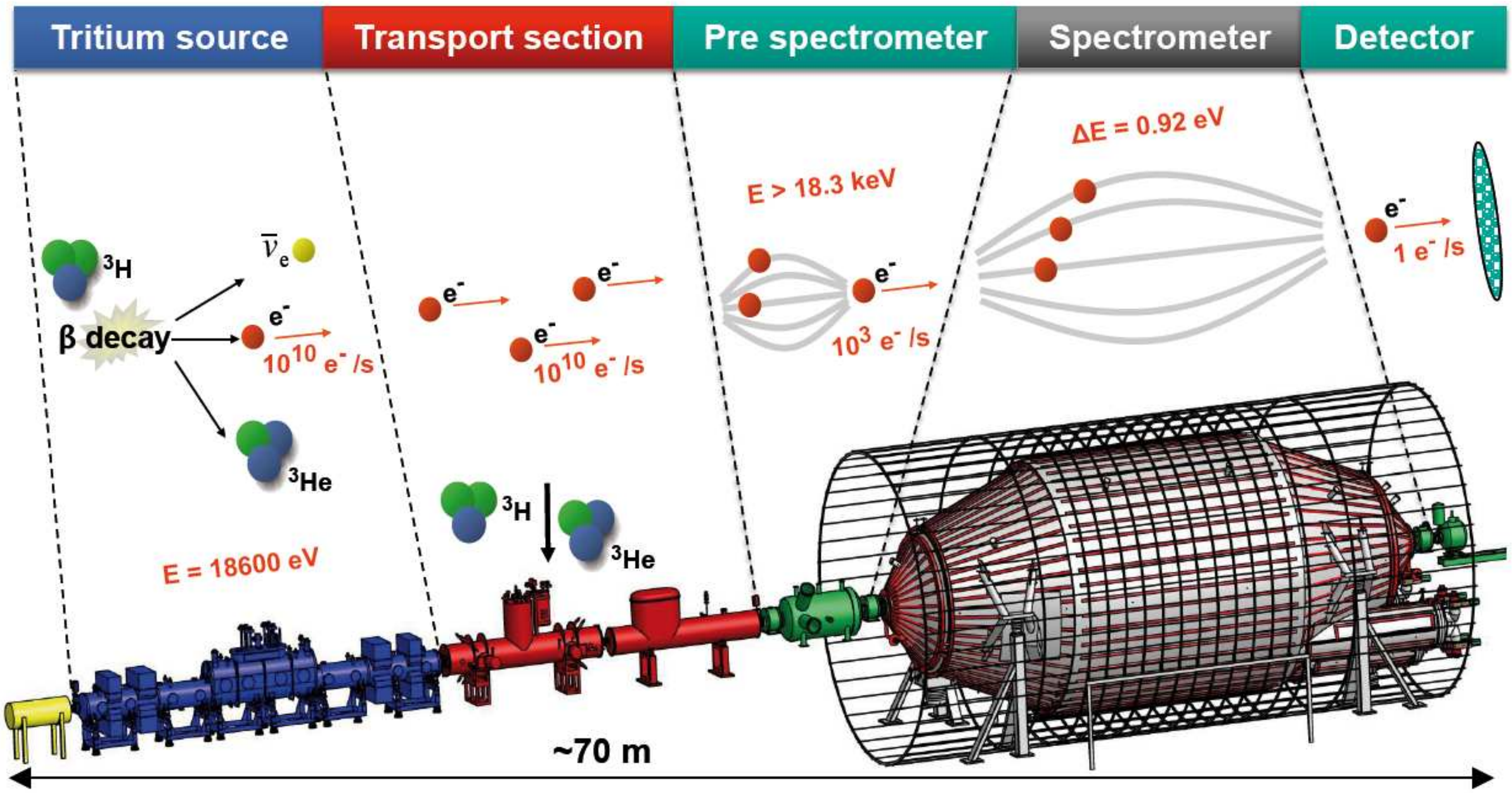
$\Rightarrow$ Classical method to search for neutrino mass

$\Rightarrow$ Important: Very few events near Q_β - $\simeq 10^{-13}$ in (Q_β- 1 eV, Q_β)

It ain't so easy ...

KATRIN = KArlsruhe TRitium Neutrino Experiment

· · · *to weigh a neutrino!*



Experiment: KATRIN

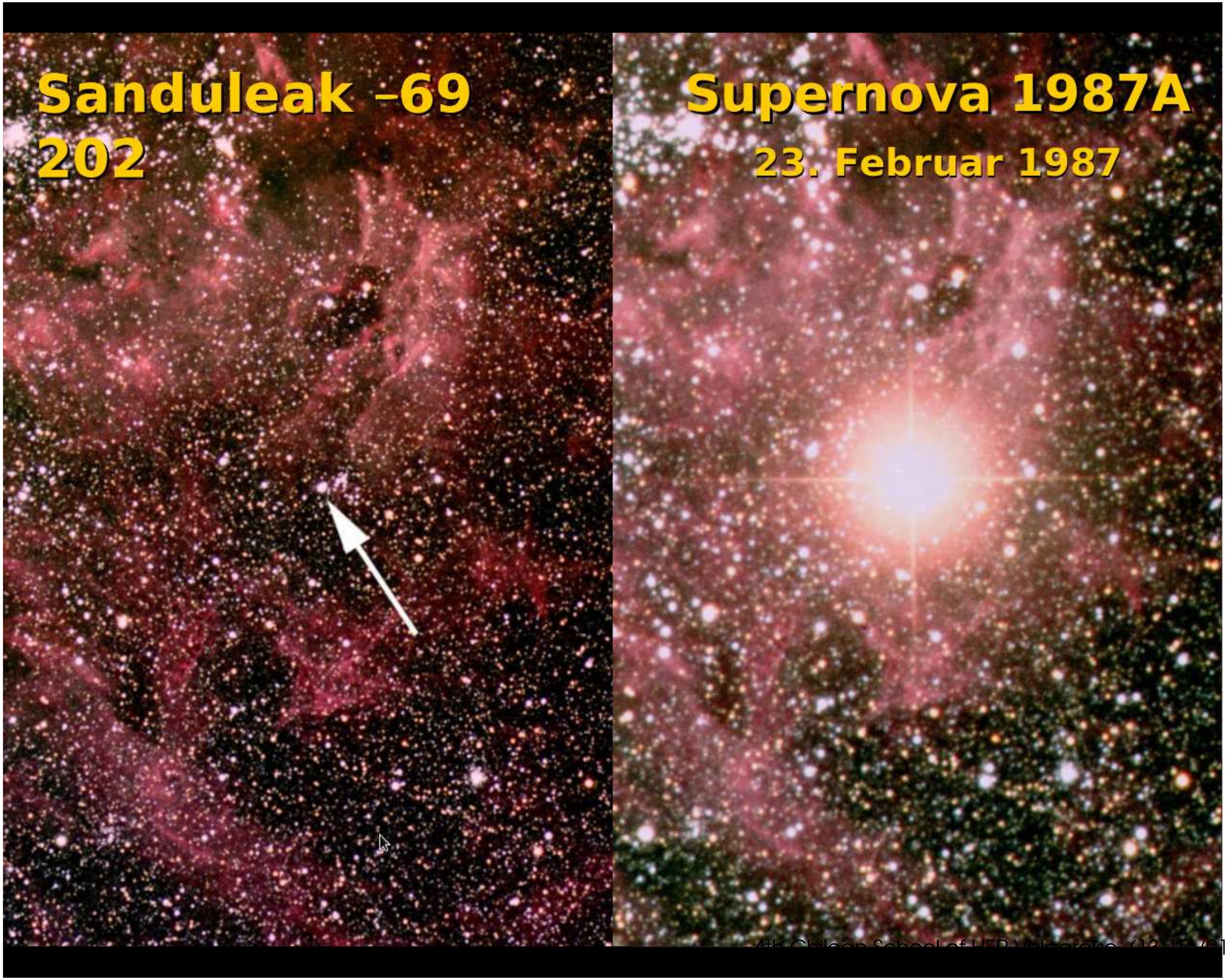
⇒ From source to detector $\simeq 70$ m

⇒ From 10^{10} electrons per sec to $1\ e/sec$

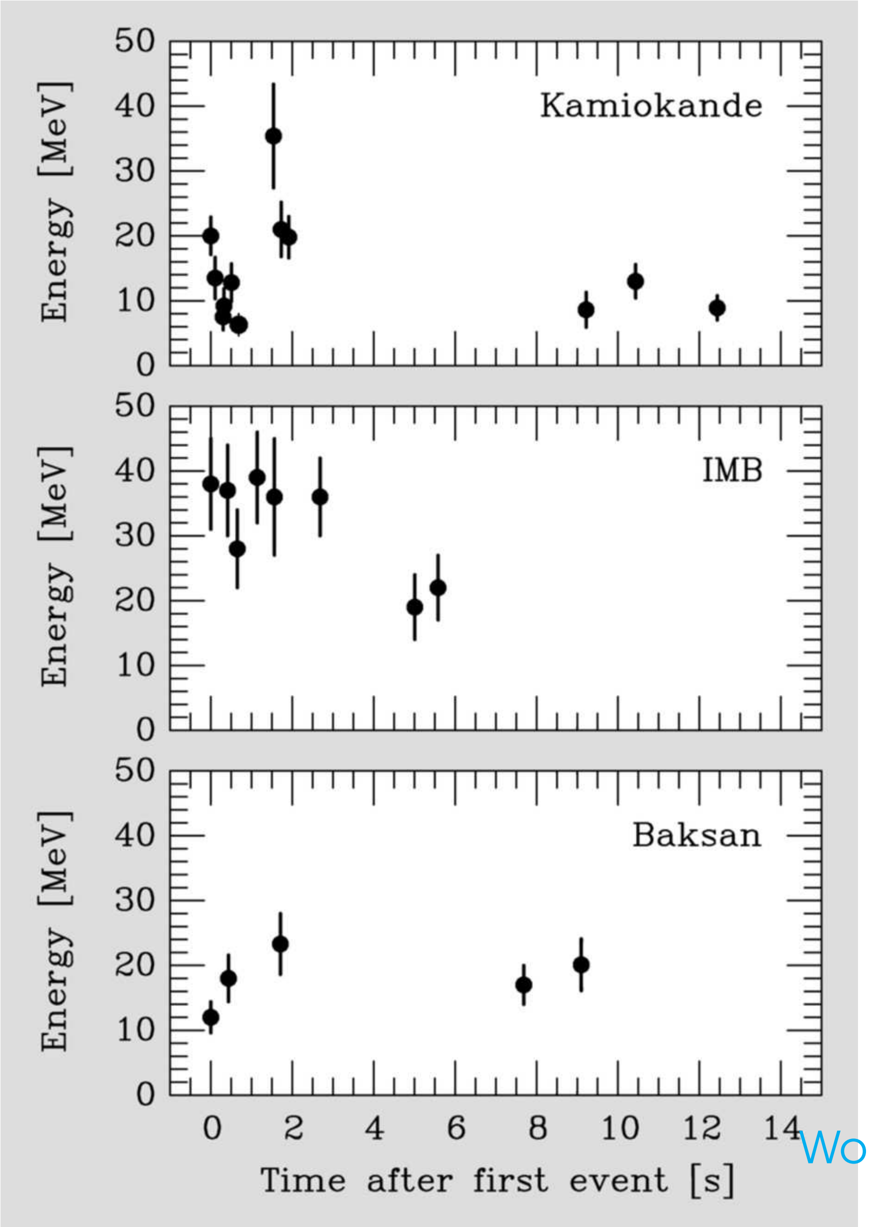
⇒ Will improve sensitivity from $m_\nu \lesssim 2.5$ eV to $m_\nu \lesssim 0.2$ eV

⇒ First data 2016 (?), final result in 5 years

Supernova neutrinos



Supernova neutrinos



About 20 neutrino events detected in Kamiokande and IMB

... from a total of 10^{58} (!!!) neutrinos emitted

Neutrinos arrive within $\sim$ 10 secs

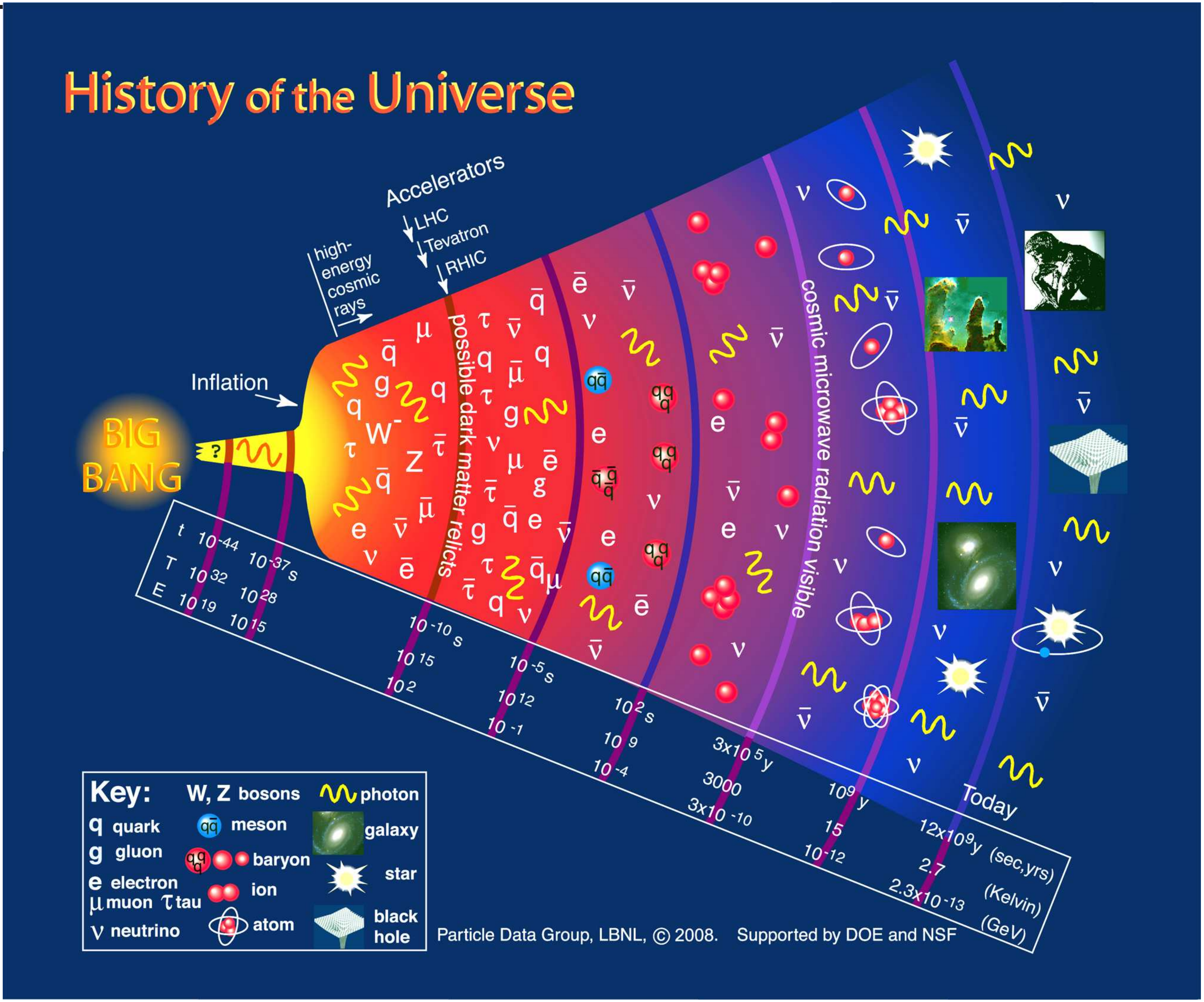
$m_\nu \lesssim 15$ eV

Both experiments:
Search for proton decay

... but found atmosperic and SN neutrinos!

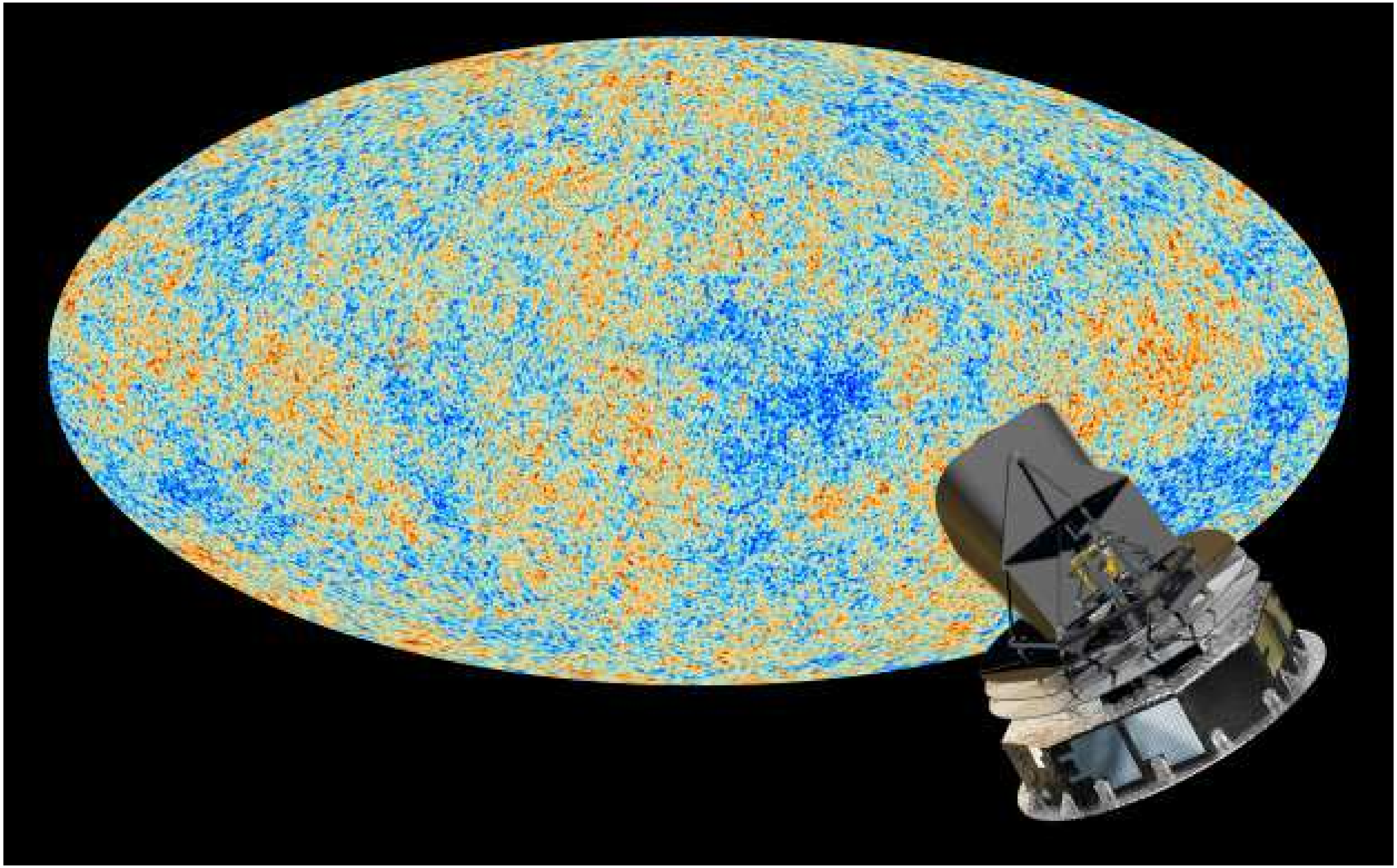
Future SN in the galaxy:
$10^4 - 10^5$ events!
Would allow a detailed check of SN physics

Cosmology and neutrinos

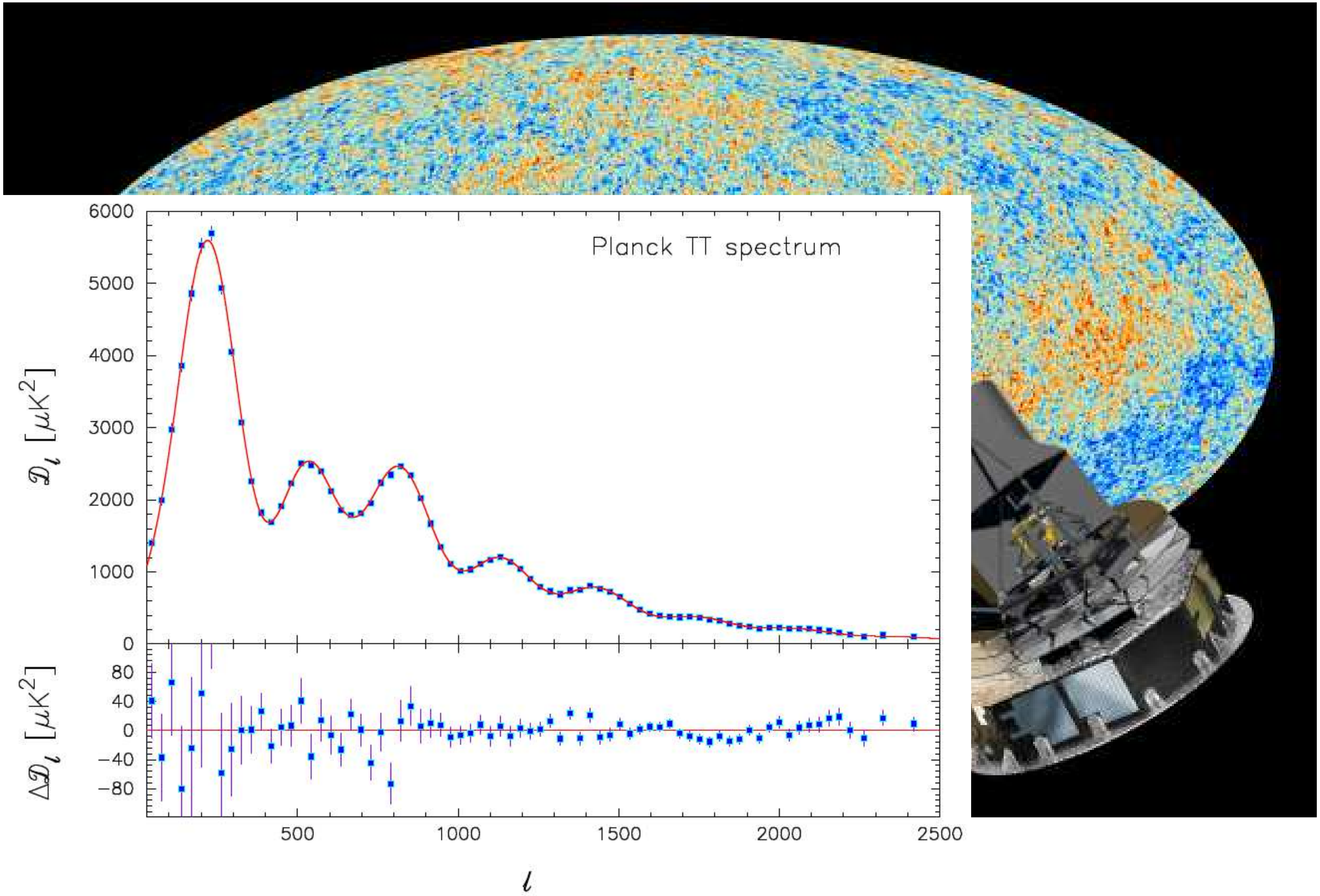


Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

CMB and PLANCK

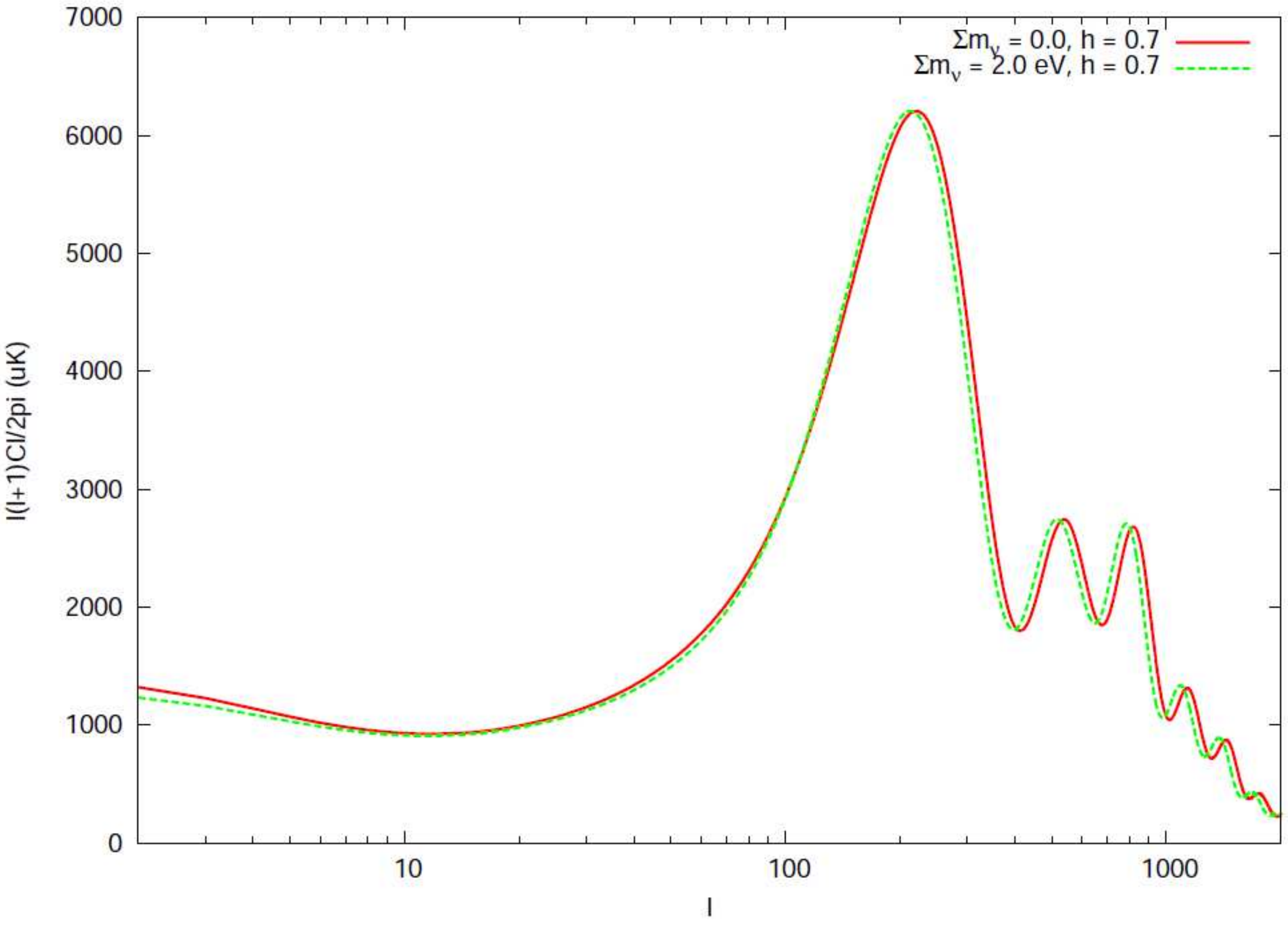


CMB and PLANCK

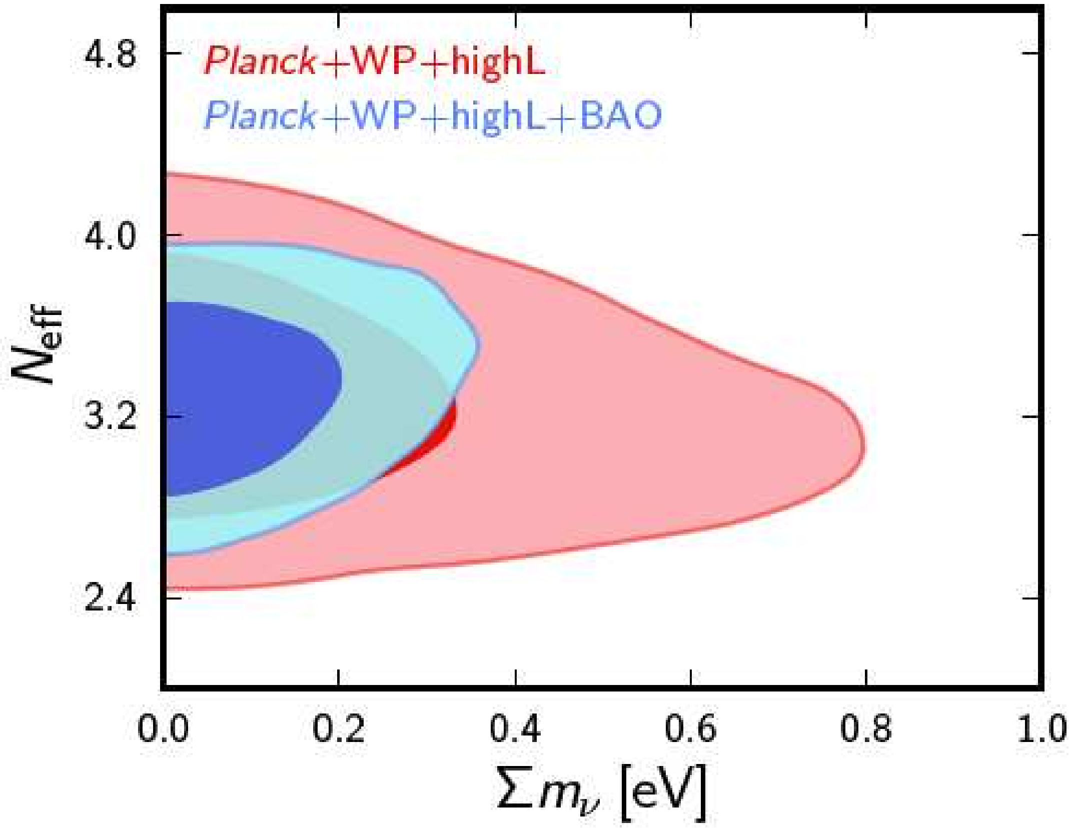


⇒ “Power spectrum” - Sensitive to: $\Omega_{Tot}, \Omega_B, \Lambda_C \cdots$

CMB and PLANCK



ν´s and Planck



⇒ Combination with WMAP, “high-L” and BAO:

$$\sum_i m_{\nu_i} \lesssim 0.28 \text{ eV and } N_{eff} = 3.32 \pm 0.54$$

⇒ Future data on gravitational lensing sensitive to ca 2025 (?): $\sum_i m_{\nu_i} \lesssim 0.05$ eV ?

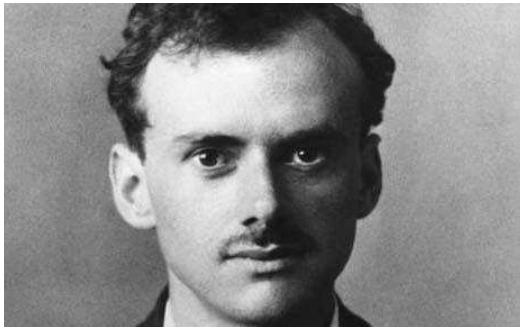
$\mathcal{IV}.$

Double beta decay

OR

Majorana or Dirac?

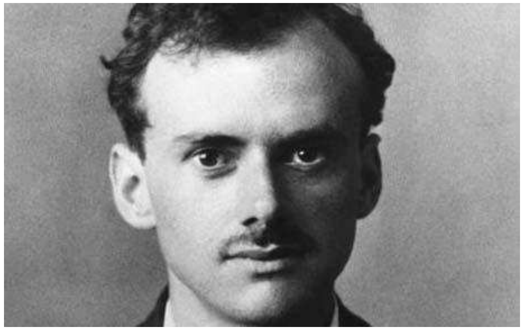
Particle = Antiparticle ?



P.A.M. Dirac:

"The electric charge of the electron is $Q(e) = -1$
$\Rightarrow$ anti-particle: positron $Q(e^c) = +1$"

Particle = Antiparticle ?



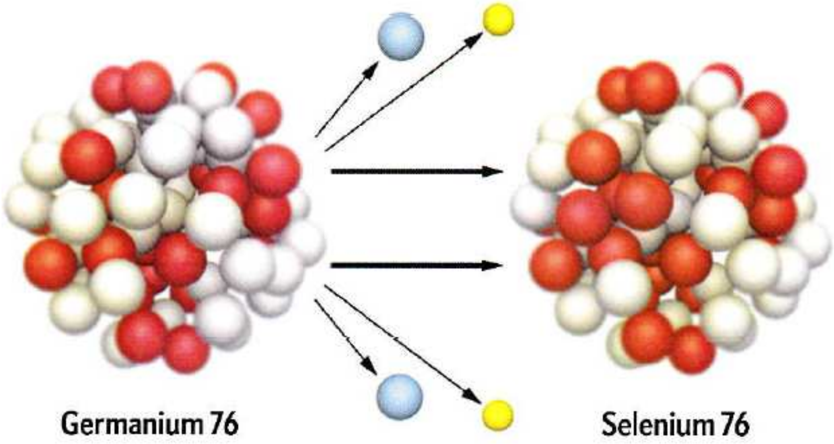
P.A.M. Dirac:

"The electric charge of the electron is $Q(e) = -1$
$\Rightarrow$ anti-particle: positron $Q(e^c) = +1$"

E. Majorana:

"No way to distinguish electrically neutral particles:
Anti-particle = Particle"

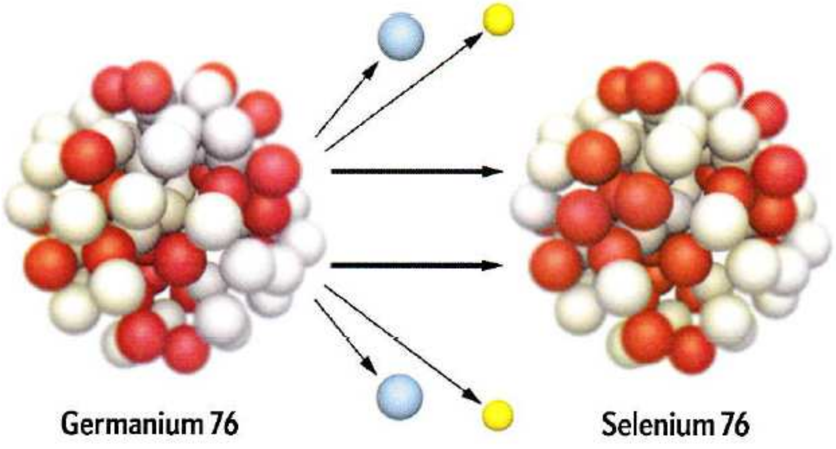
Double beta decay



$(Z, A) \Rightarrow (Z+2, A) + 2e^- + 2\bar{\nu}$

$\Rightarrow$ Two single β decays
in the same nucleus

Double beta decay



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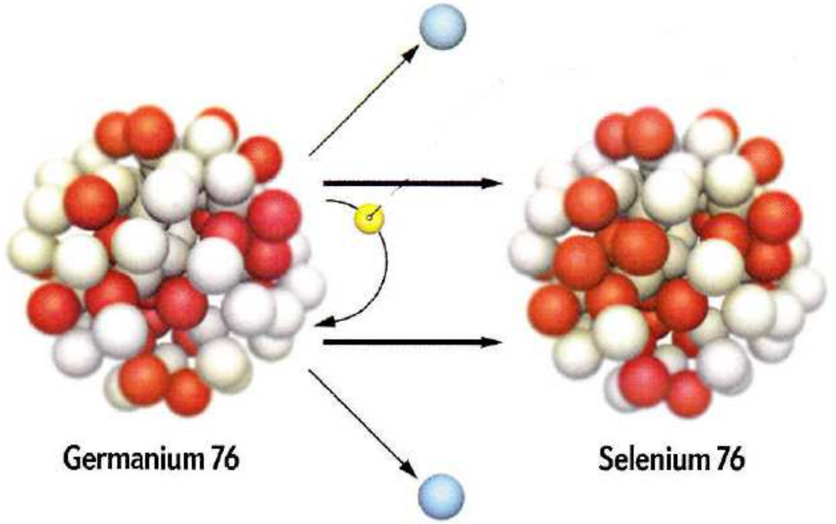


$(Z, A) \Rightarrow (Z+2, A) + 2e^-$

$\Rightarrow$ violates lepton number

$\Rightarrow$ only possible if $\nu \equiv \bar{\nu}$

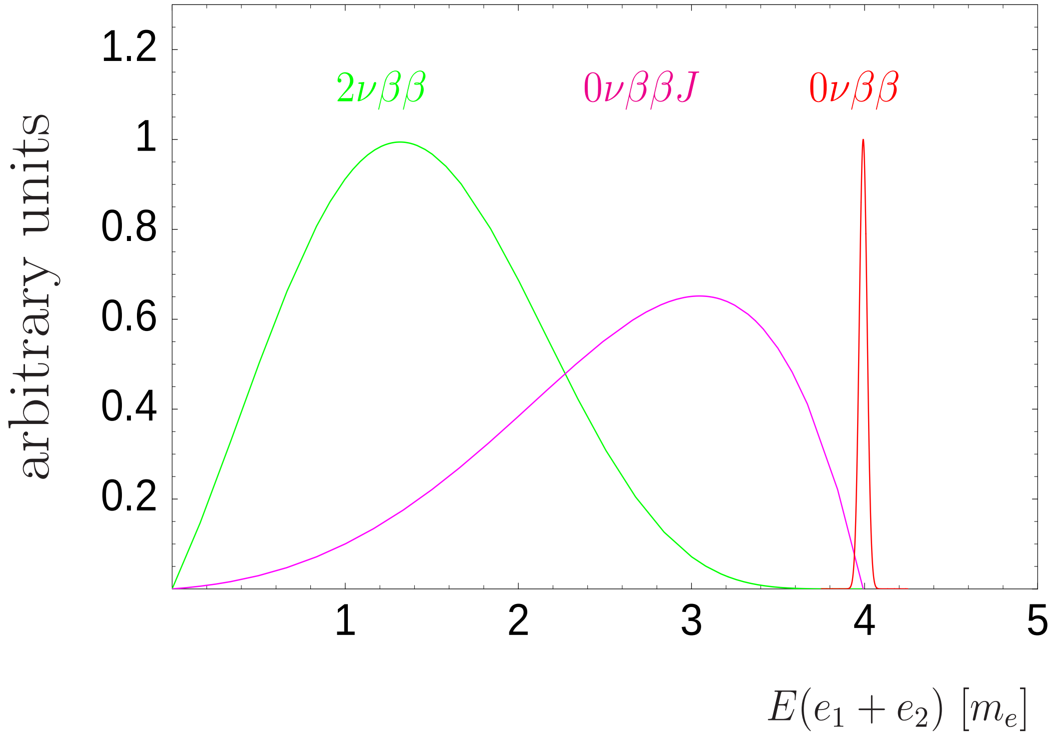
$\Rightarrow$ Half-life of decay:

$$T_{1/2} \propto (m_\nu)^{-2}$$

Distinguish $2\nu\beta\beta$ *from* $0\nu\beta\beta$*?*

⇒ The neutrinos are not detected: $2\nu\beta\beta$ continuous spectrum

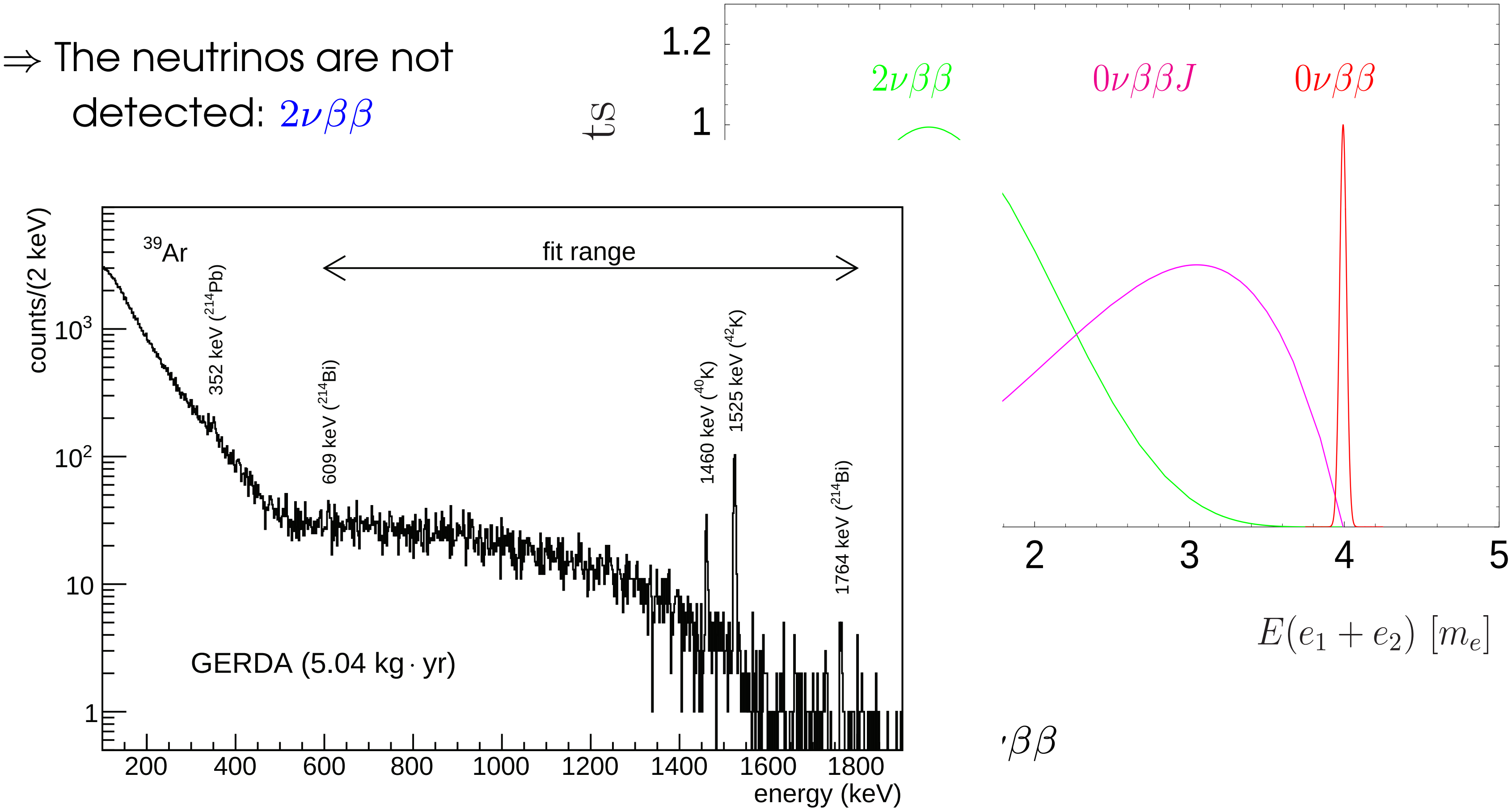
⇒ Only electrons: $0\nu\beta\beta$ peak at $Q_{\beta\beta}$



⇒ Energy resolution essential if the experiment wants to separate $2\nu\beta\beta$ from $0\nu\beta\beta$

Distinguish $2\nu\beta\beta$ from $0\nu\beta\beta$?

⇒ The neutrinos are not detected: $2\nu\beta\beta$



Real experimental spectrum: GERDA (Dic. 2012)

Half-life: $T_{1/2}^{2\nu\beta\beta} = (1.84 + 0.14 - 0.10) \times 10^{21}$ yr

Experimental sensitivity

Background-free experiment:

$$T_{1/2} \sim Mt$$

In the presence of background:

$$T_{1/2} \geq \; c \;\; a \; \sqrt{\frac{Mt}{B\Delta E}}$$

M : Source mass

t : Measuring time

B : Background

ΔE : Energy resolution

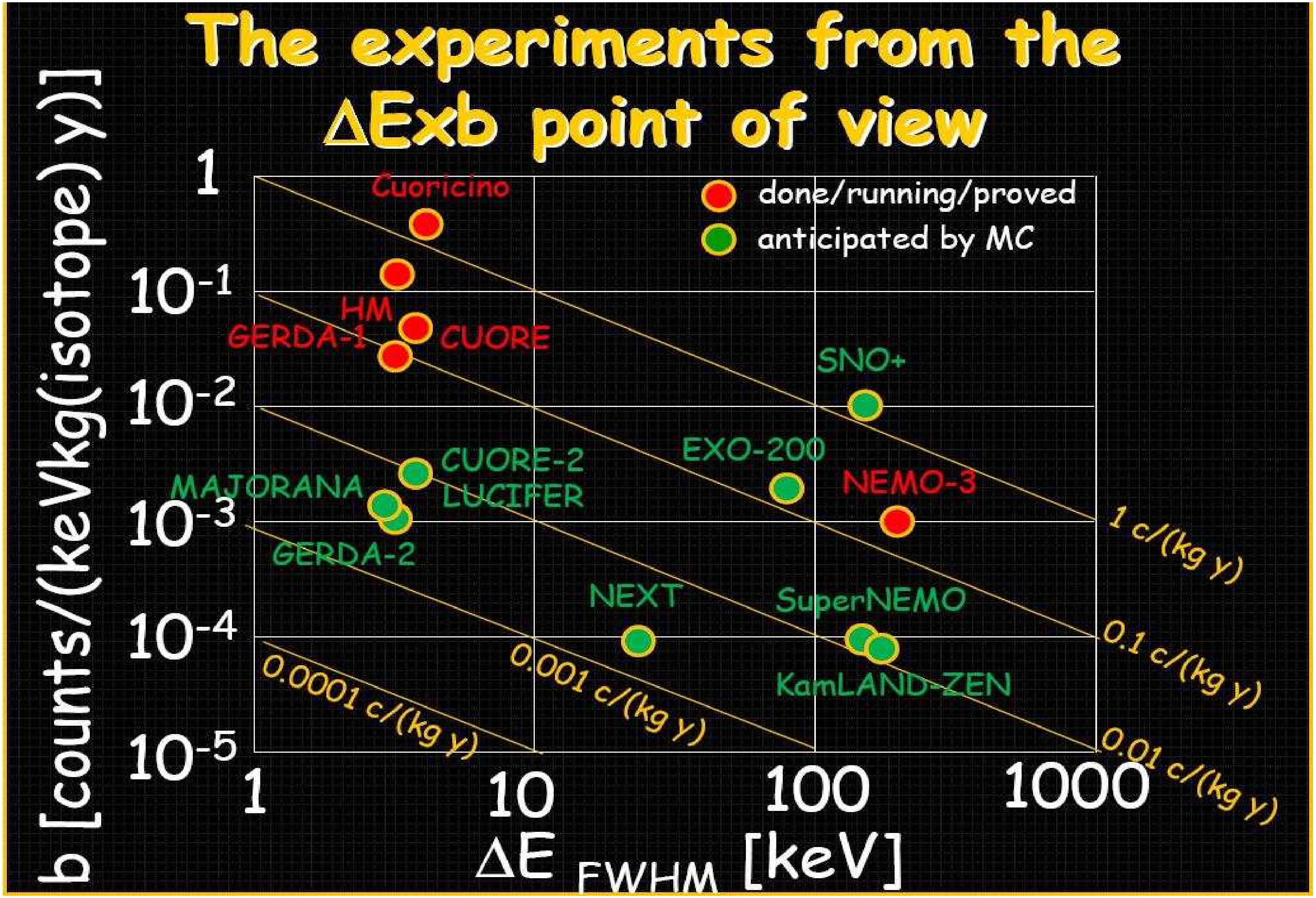
a : Enrichment

c : constants

1 ton of isotope
and $\Delta E \cdot B \leq \frac{1}{t \cdot y}$
for $\langle m_\nu \rangle \leq 10$ meV

Figure of Merit: ΔE versus b

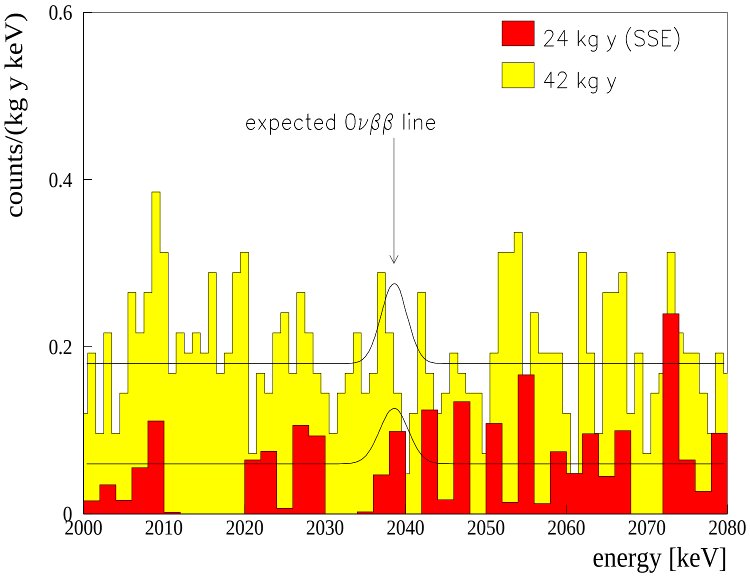
From: A. Giuliani



$0\nu\beta\beta$ decay with ^{76}Ge

	^{A}Z	Stat.:	Where:	$T_{1/2}^{0\nu\beta\beta}$ (y)	$\langle m_\nu \rangle$ (eV)	year:
Hd-Mo	^{76}Ge	35.5 kg y	LNGS	1.9 10^{25}	0.35	2003

Spectrum near peak of $0\nu\beta\beta$:

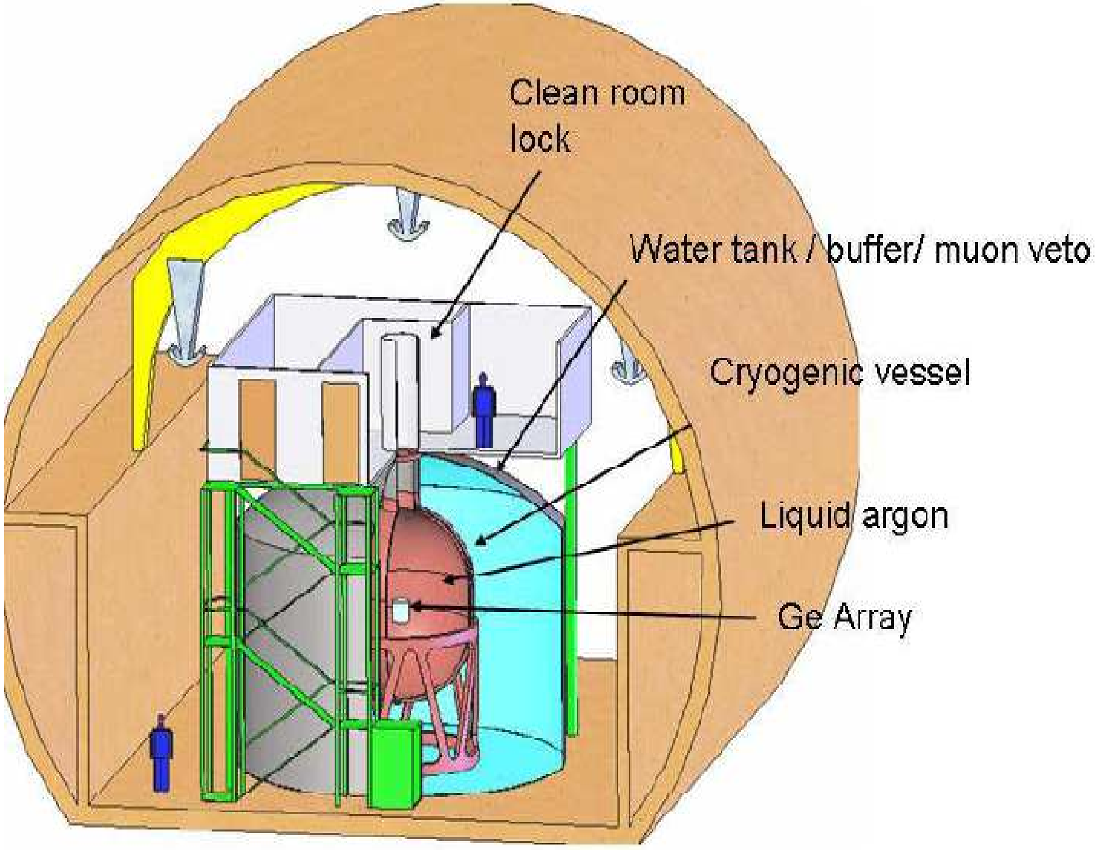


HD-Mo, setup ANG2-ANG4:

GERDA

Design of the GERDA experiment:

Concept:
Less radioactive background
by operation in liquid Ar



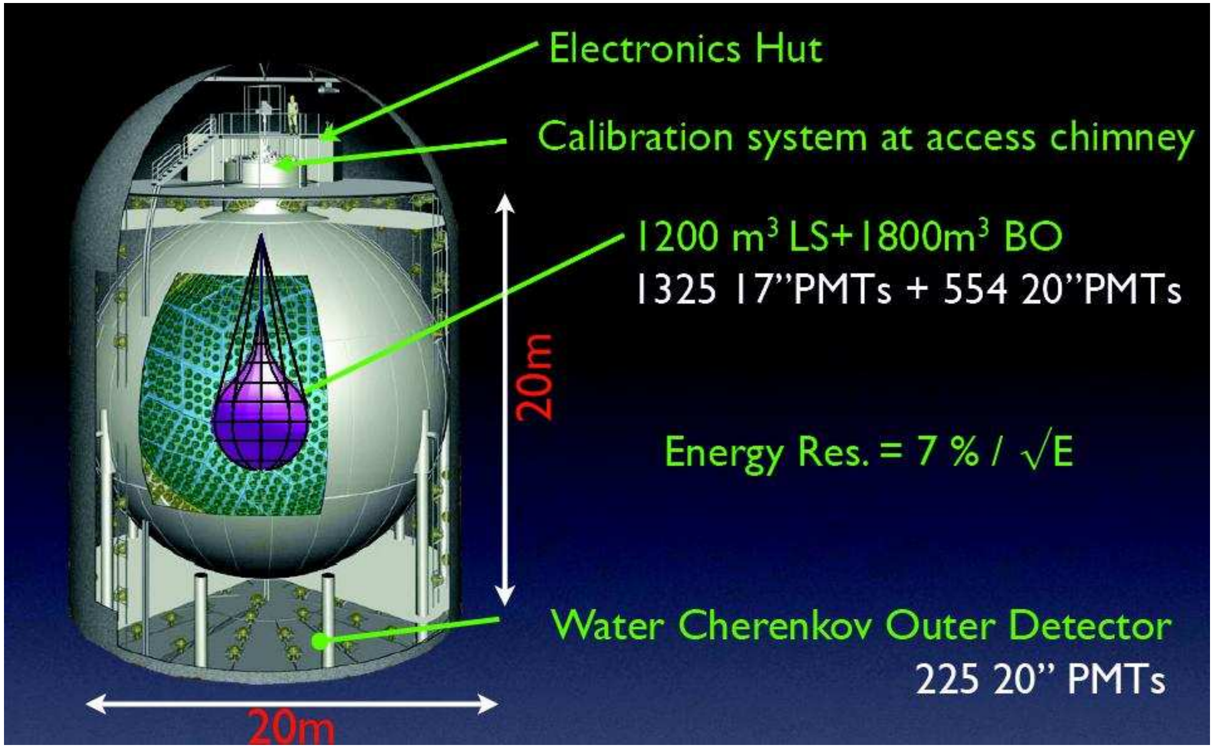
Phase-I:
$M \simeq 20$ kg ^{76}Ge

First results 2014/2015

Phase-II:
$M \simeq 35$ kg ^{76}Ge
$B \leq 10^{-3} \frac{1}{kg \cdot y \cdot keV}$

$\Rightarrow$ Improve limits to (or find $0\nu\beta\beta$ with) half-live up to 10^{26} ys

KamLAND-Zen



Put $\sim$ 400 kg ^{136}Xe into

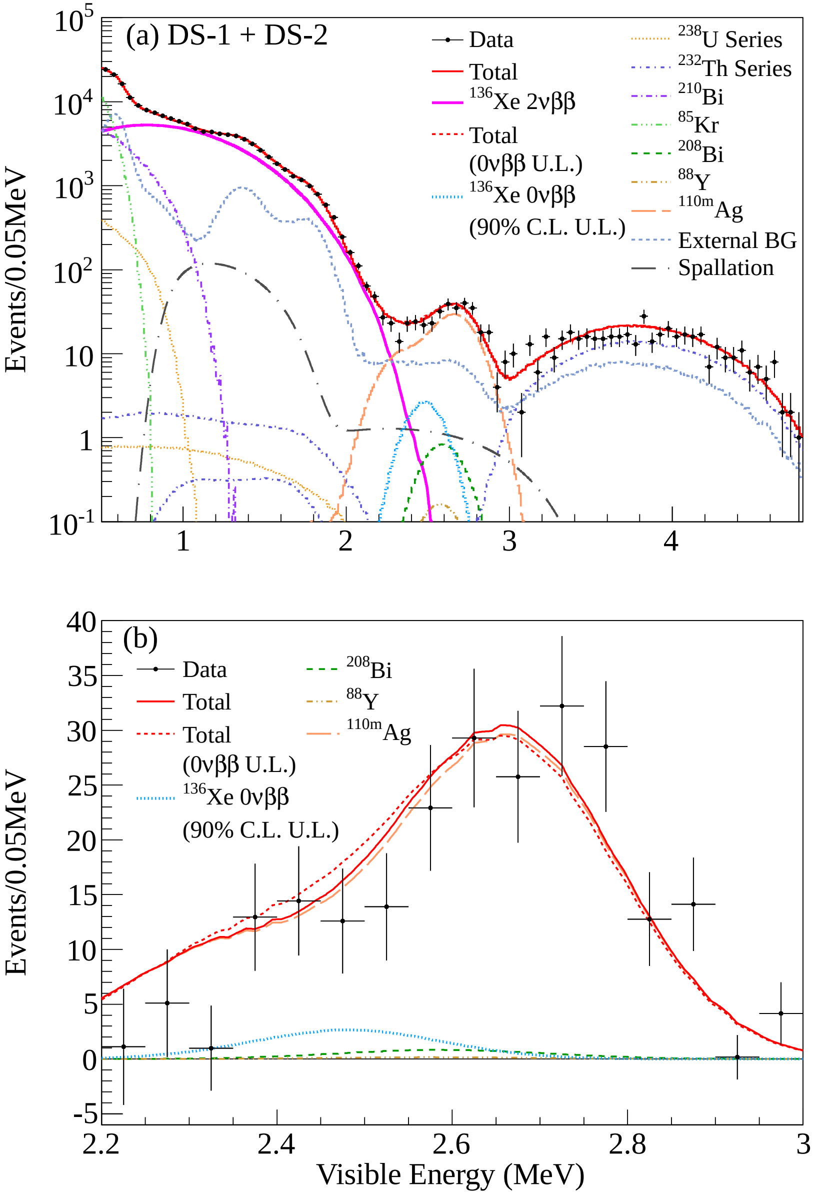
KamLAND $\Rightarrow$ KamLAND-Zen!

Monte-Carlo prediction:

$\langle m_\nu \rangle \lesssim 60$ meV in 2 ys!

Based on $b \lesssim 10^{-1}/(\mathrm{kg \cdot y \cdot keV})$

KamLAND-Zen



Background!

^{110m}Ag $\gtrsim 100$

larger than MC

Fukushima?

PRL 110 (2013) 062502:

Limit after subtraction:

Statistics: 89.5 kg · ys

$T_{1/2}^{0\nu\beta\beta}(^{136}Xe) \geq 1.9 \times 10^{25}$ ys

90 % c.l.

Neutrino 2014:

Purification in

progress, has reduced

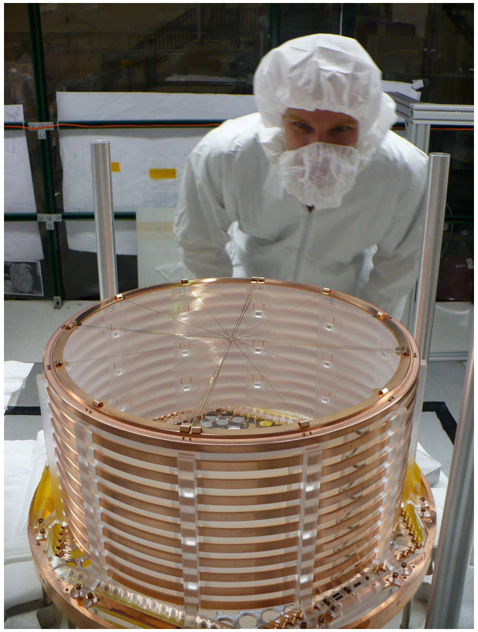
^{110m}Ag $\sim 1/10$

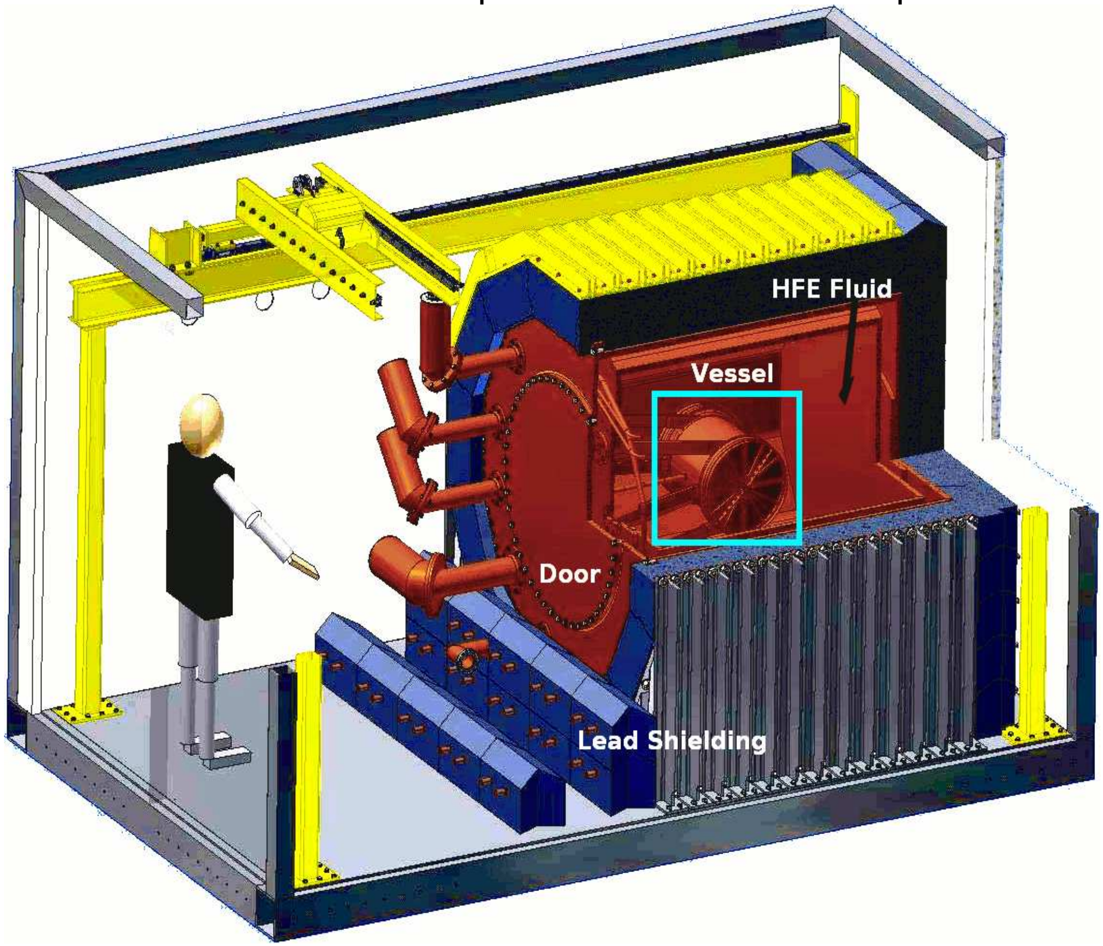
and continues ...

^{136}Xe: EXO-200

Setup of the EXO-200 experiment:

(Half a) TPC:



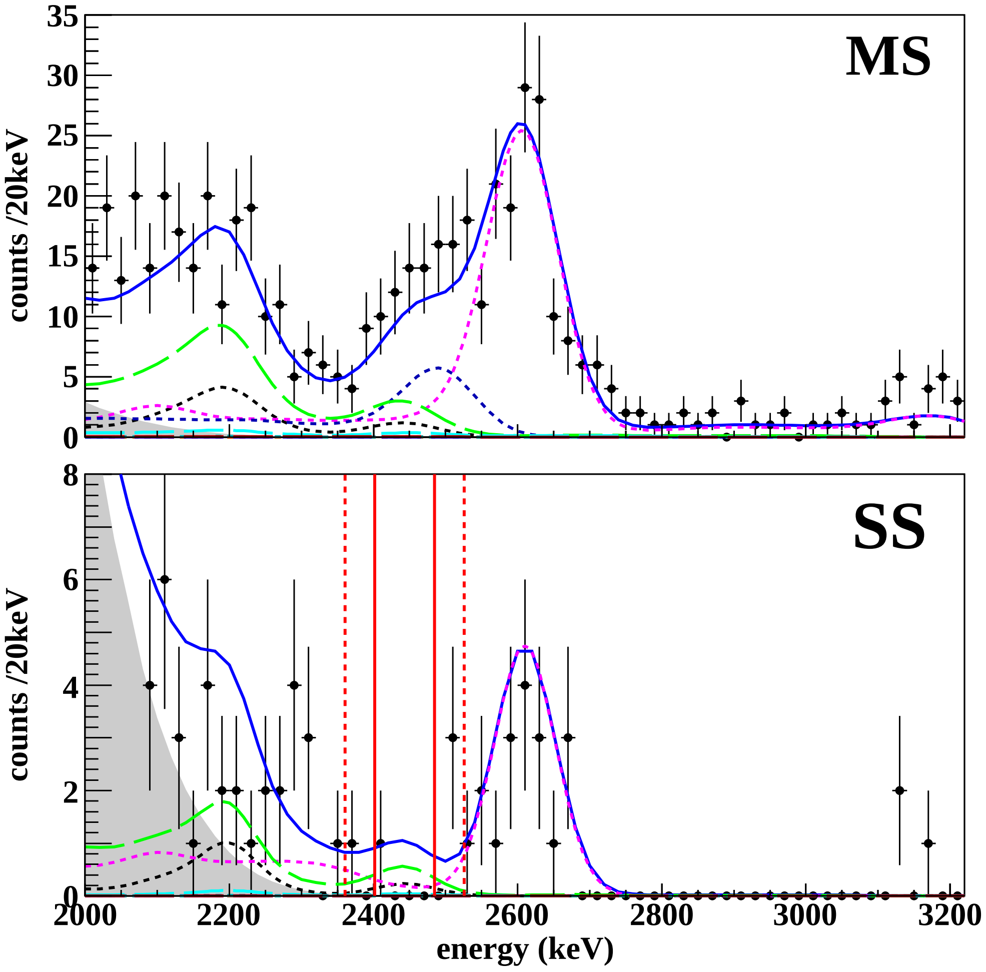


Nature 510 (2014) 229:
limit for $0\nu\beta\beta$-decay for ^{136}Xe:

$$T_{1/2} \geq 1.1 \times 10^{25} \text{ ys}$$

based on 100 kg·ys of data

^{136}Xe: EXO-200



Updated $0\nu\beta\beta$ result

Nature 510 (2014) 229

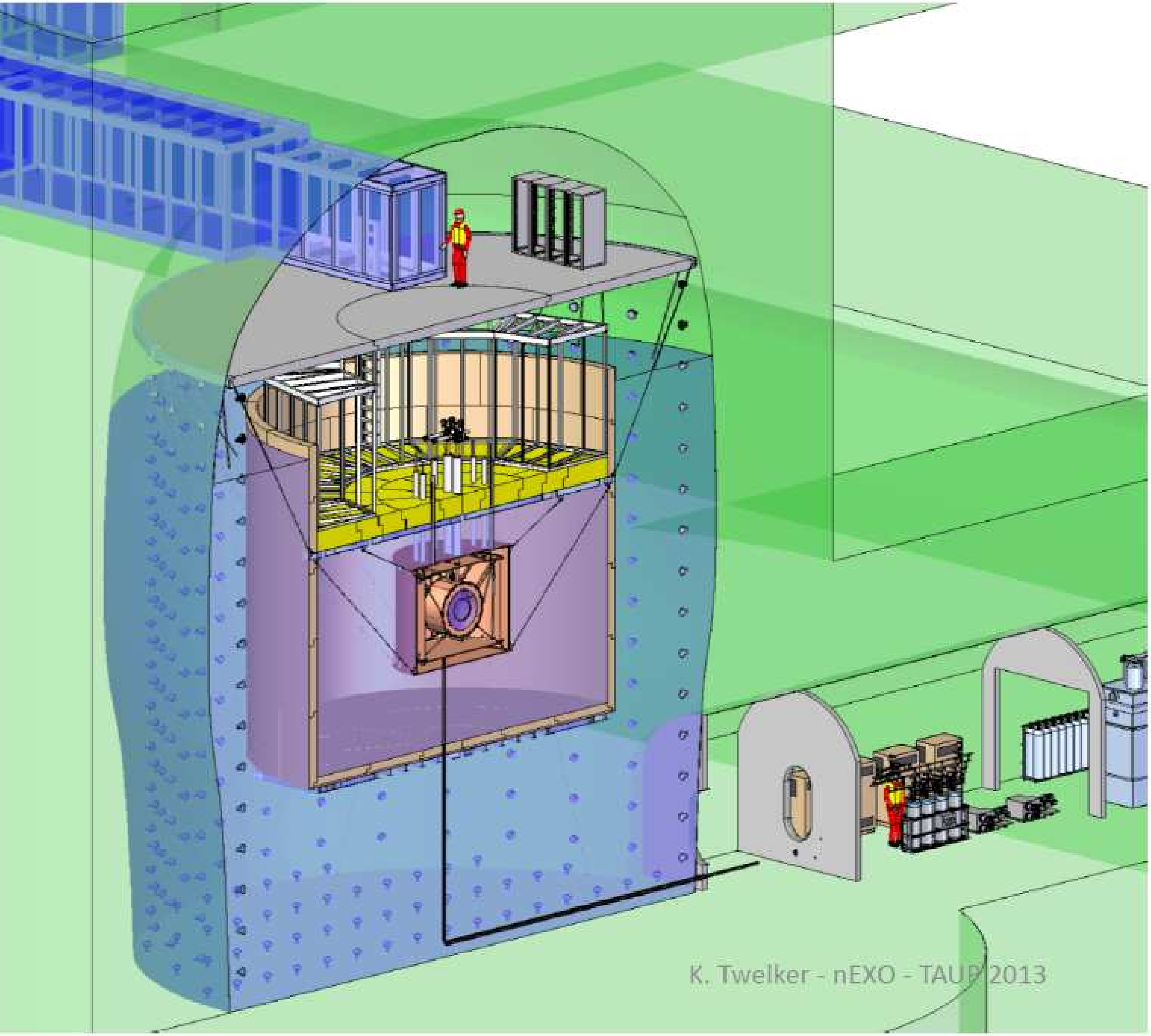
$b = 1.7 \times 10^{-3} / (\mathrm{kg} \cdot \mathrm{y} \cdot \mathrm{keV})$

Statistics: 100 kg · ys

$T_{1/2}^{0\nu\beta\beta}(^{136}Xe) \geq 1.1 \times 10^{25}$ ys

90 % c.l.

nEXO:



Proposal to

use 5 tons of ^{136}Xe

“Scale up EXO”

Install in SNOlab

Phase-I:

No Ba-tagging

$\langle m_\nu \rangle \lesssim 10$ meV in 5 ys

$T_{1/2}^{0\nu\beta\beta}(^{136}Xe) \geq$

7×10^{27} ys

Phase-II:

With Ba-tagging

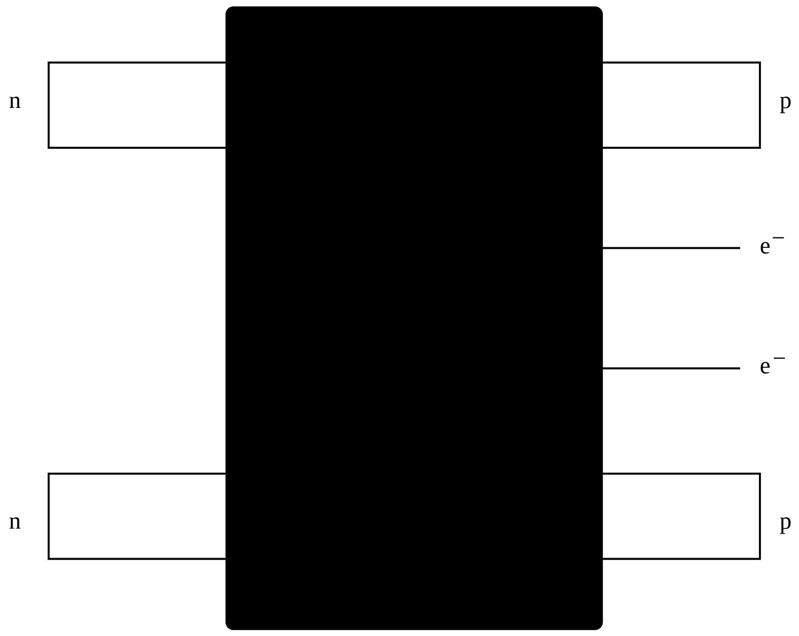
$\langle m_\nu \rangle \lesssim 4$ meV ??

$T_{1/2}^{0\nu\beta\beta}(^{136}Xe) \geq$

2×10^{28} ys??

Mass mechanism

Convert 2 neutrons to 2 protons + 2 electrons, simplest possibility for a $0\nu\beta\beta$ diagram:



Mass mechanism

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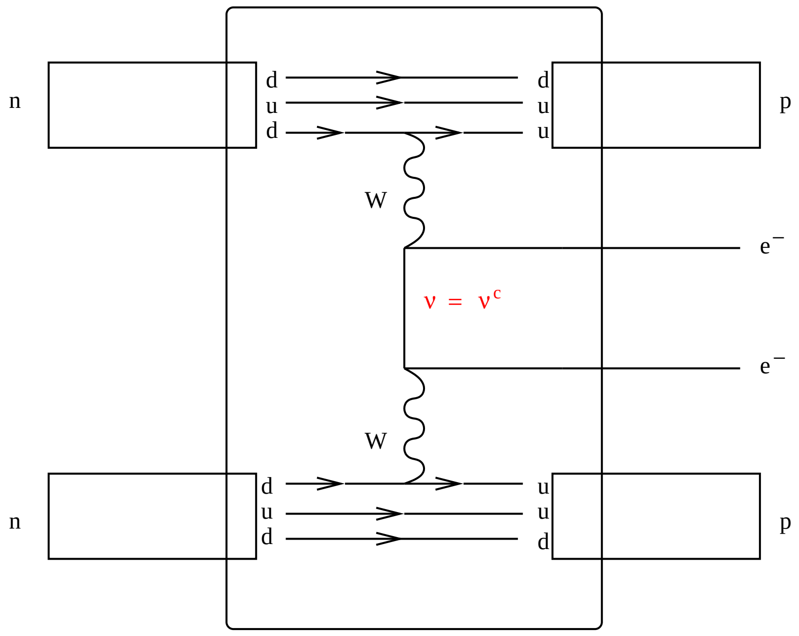


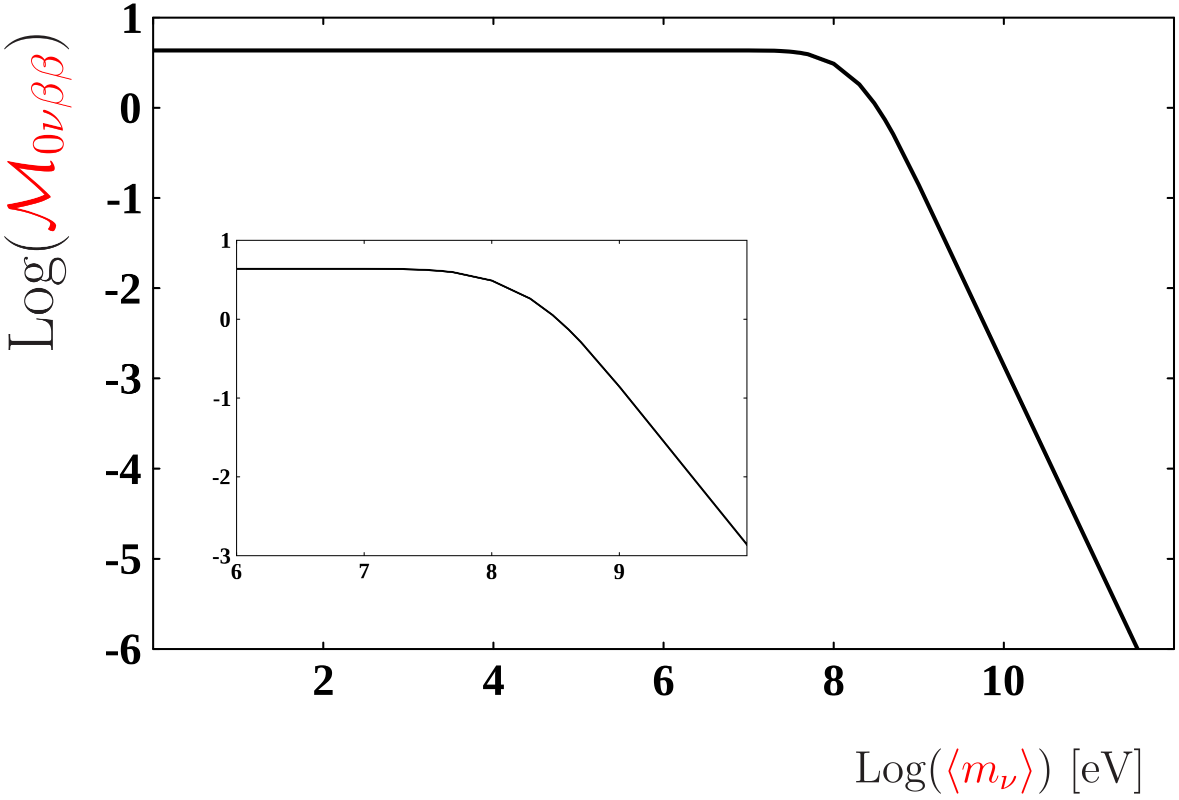
Neutrino propagator:

$$\int \frac{d^4p}{(2\pi)^4}\frac{m_\nu + \not p}{p^2 - m_\nu^2}$$

"Mass mechanism" because weak interaction is left-handed:

$$P_L(m_\nu + \not p\ )P_L = m_\nu P_L$$

$\mathcal{M}_{0\nu\beta\beta}$ as function of $\langle m_\nu \rangle$

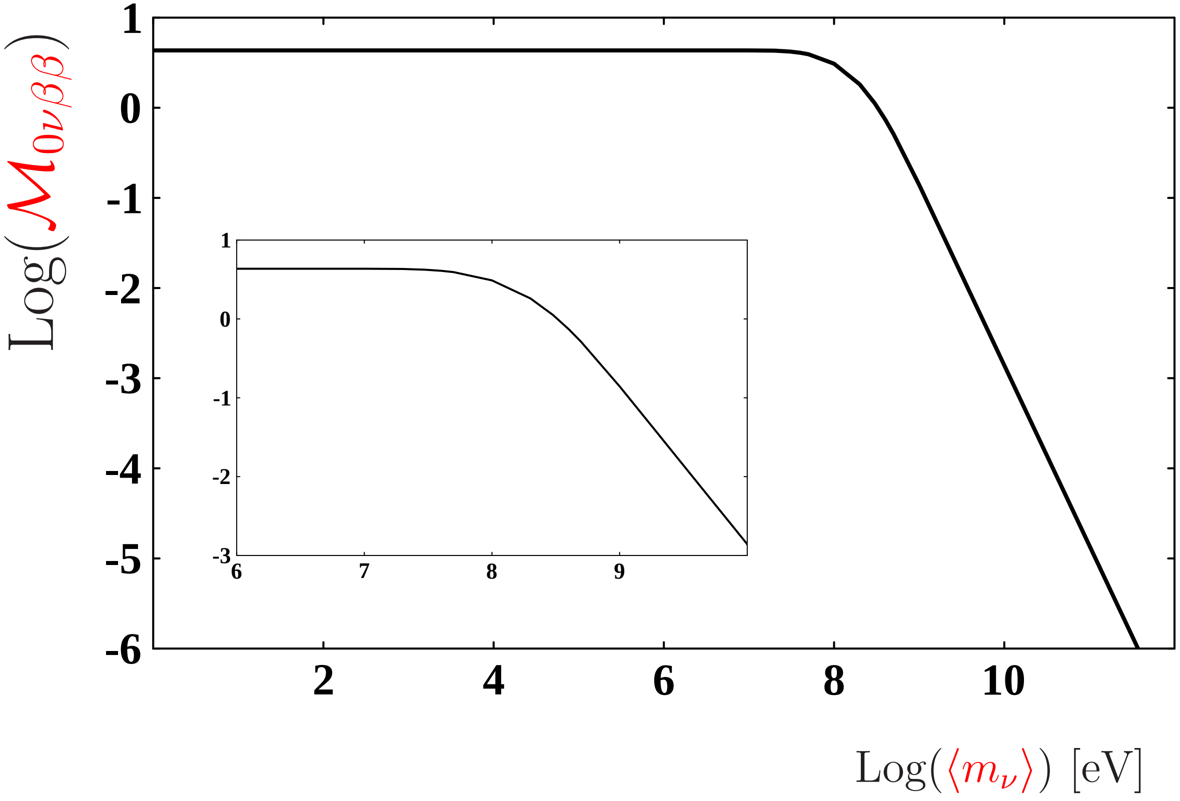


Take out m_ν from definition of $\mathcal{M}_{0\nu\beta\beta}$:

Constant for small m_ν $\Rightarrow$ $T_{1/2} \sim m_\nu^{-2} \mathcal{M}_L^{-2}$

$(\sim 1/m_\nu)^2$ for large m_ν $\Rightarrow$ $T_{1/2} \sim m_\nu^2 \mathcal{M}_H^{-2}$

$\mathcal{M}_{0\nu\beta\beta}$ as function of $\langle m_\nu \rangle$



"Transition region"

$m_\nu \simeq p_F$

$\simeq \mathcal{O}(100)$ MeV

Take out m_ν from definition of $\mathcal{M}_{0\nu\beta\beta}$:

Constant for small m_ν	$\Rightarrow$	$T_{1/2} \sim m_\nu^{-2} \mathcal{M}_L^{-2}$	"long-range" amplitude
$(\sim 1/m_\nu)^2$ for large m_ν	$\Rightarrow$	$T_{1/2} \sim m_\nu^2 \mathcal{M}_H^{-2}$	"short-range" amplitude

Three generations of ν

For 3 generation of neutrinos, 2 independent Δm^2_{ij}, and 3 independent angles θ_{ij}:

$$
\begin{aligned}
U &= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \cdot P \\
&= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot P
\end{aligned}
$$

Three generations of ν

For 3 generation of neutrinos, 2 independent Δm^2_{ij}, and 3 independent angles θ_{ij}:

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \cdot P$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot P$$

atmospheric	reactor	solar
Δm^2_{32}	Δm^2_{31}	Δm^2_{21}

Three generations of ν

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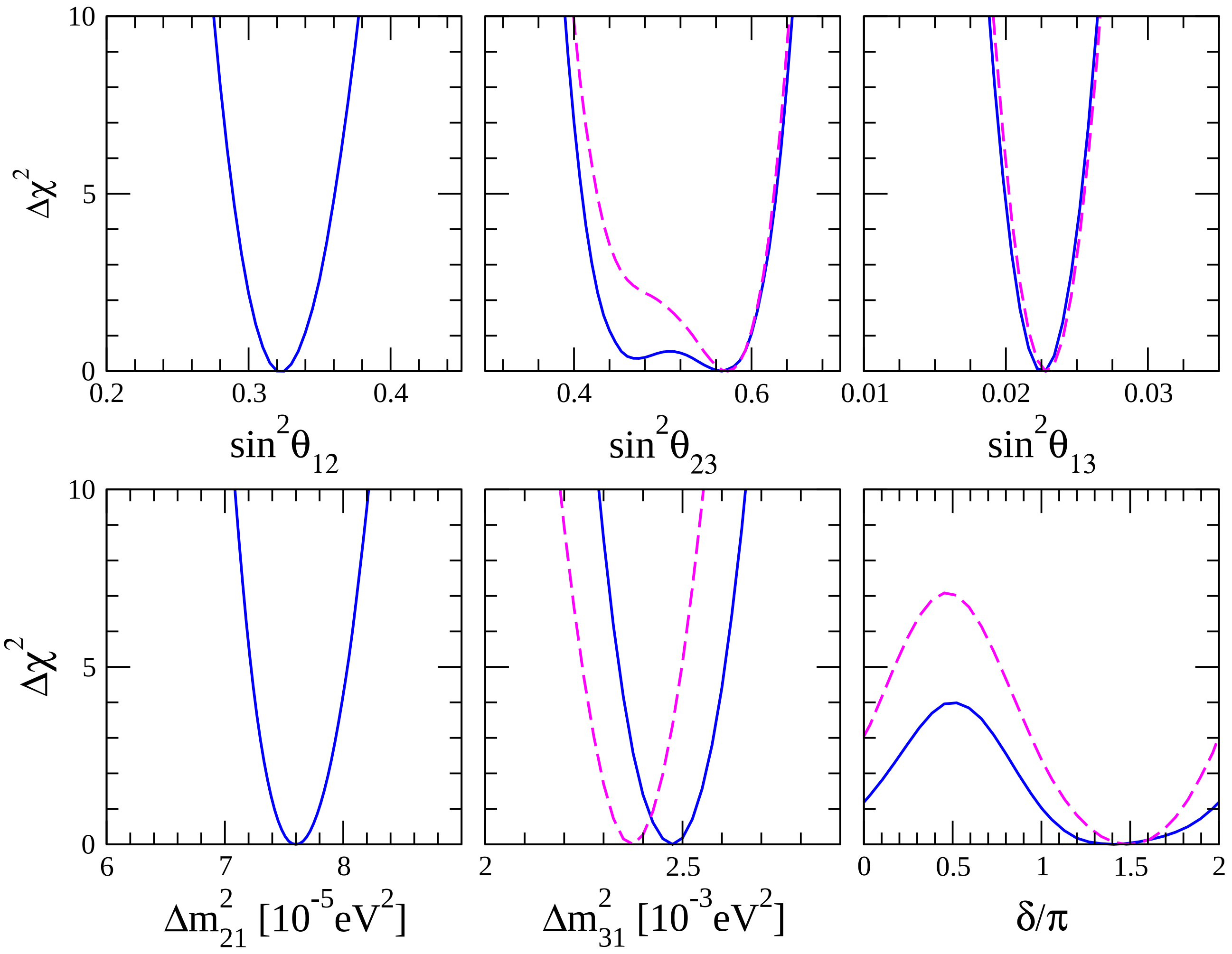
atmospheric	reactor	solar
Δm^2_{32}	Δm^2_{31}	Δm^2_{21}

$\Rightarrow$ P - diagonal matrix of Majorana phases

$\Rightarrow$ $\Delta m^2_{32} \equiv \Delta m^2_{31}$ - $\Delta m^2_{21} \simeq \Delta m^2_{31}$

Neutrino oscillation data



Forero, Tortola
& Valle, 2014

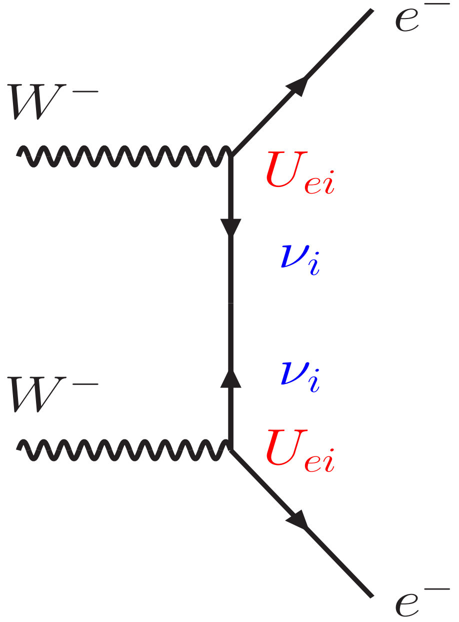
χ^2 distributions
for angles:

$\theta_\odot$, $\theta_{\rm Atm}$ and $\theta_{\rm R}$

χ^2 distributions
for Δm^2
and phase:

$\Delta m^2_\odot$, $\Delta m^2_{\rm Atm}$, δ

Neutrino mixing in $0\nu\beta\beta$



Each vertex:

$$W_\mu^- \bar{e}\gamma^\mu P_L U_{ei}\nu_i$$

Full propagator reads:

$$U_{ei}^2 \int \frac{d^4p}{(2\pi)^4} \frac{m_{\nu_i} + \not{p}}{p^2 - m_{\nu_i}^2}$$

Define in the limit of small neutrino masses:

$$\langle m_\nu \rangle = \sum_i U_{ei}^2 m_{\nu_i}$$

$\langle m_\nu \rangle$ and ν spectrum

Neutrinos mix, thus:

$$\begin{aligned}\langle m_\nu \rangle &= \sum_j U_{ej}^2 m_j \\ &= c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 e^{i\alpha} m_2 + s_{13}^2 e^{i\beta} m_3\end{aligned}$$

A priori seven unknown quantities:

⇒ 3 masses: m_i

⇒ 2 angles: θ_{12} and θ_{13}

⇒ 2 CP violating phases: α and β

$\langle m_\nu \rangle$ and ν spectrum

Neutrinos mix, thus:

$$\begin{aligned}\langle m_\nu \rangle &= \sum_j U_{ej}^2 m_j \\ &= c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 e^{i\alpha} m_2 + s_{13}^2 e^{i\beta} m_3\end{aligned}$$

+ Neutrino oscillation data:

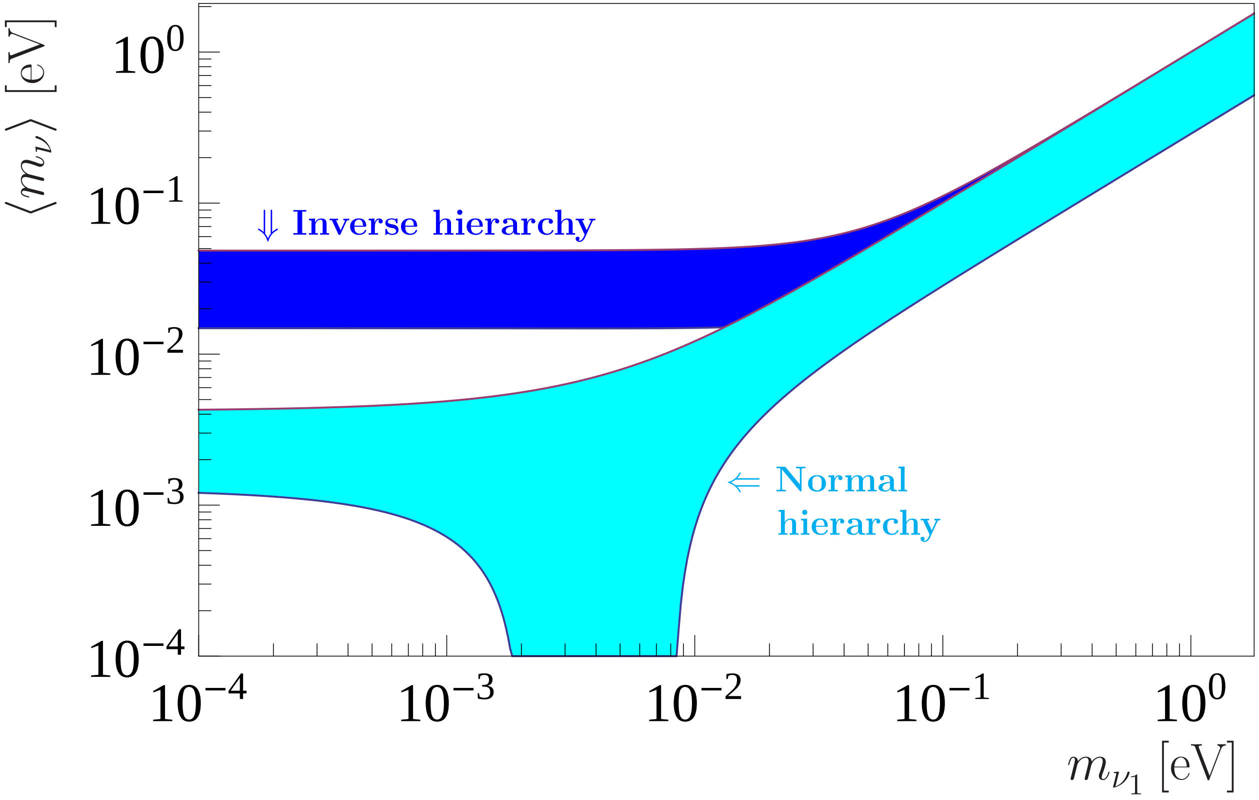
$\Rightarrow$ 1 mass: m_{ν_1} + $\Delta m^2_{\mathrm{Atm}}$, $\Delta m^2_{\odot}$

$\Rightarrow$ 2 angles: $\theta_\odot$ and θ_R

$\Rightarrow$ 2 CP violating phases: α and β

$\Rightarrow$ Two cases for hierarchy (NH and IH)

$\langle m_\nu \rangle$ *versus* m_{ν_1} *- status 2014*

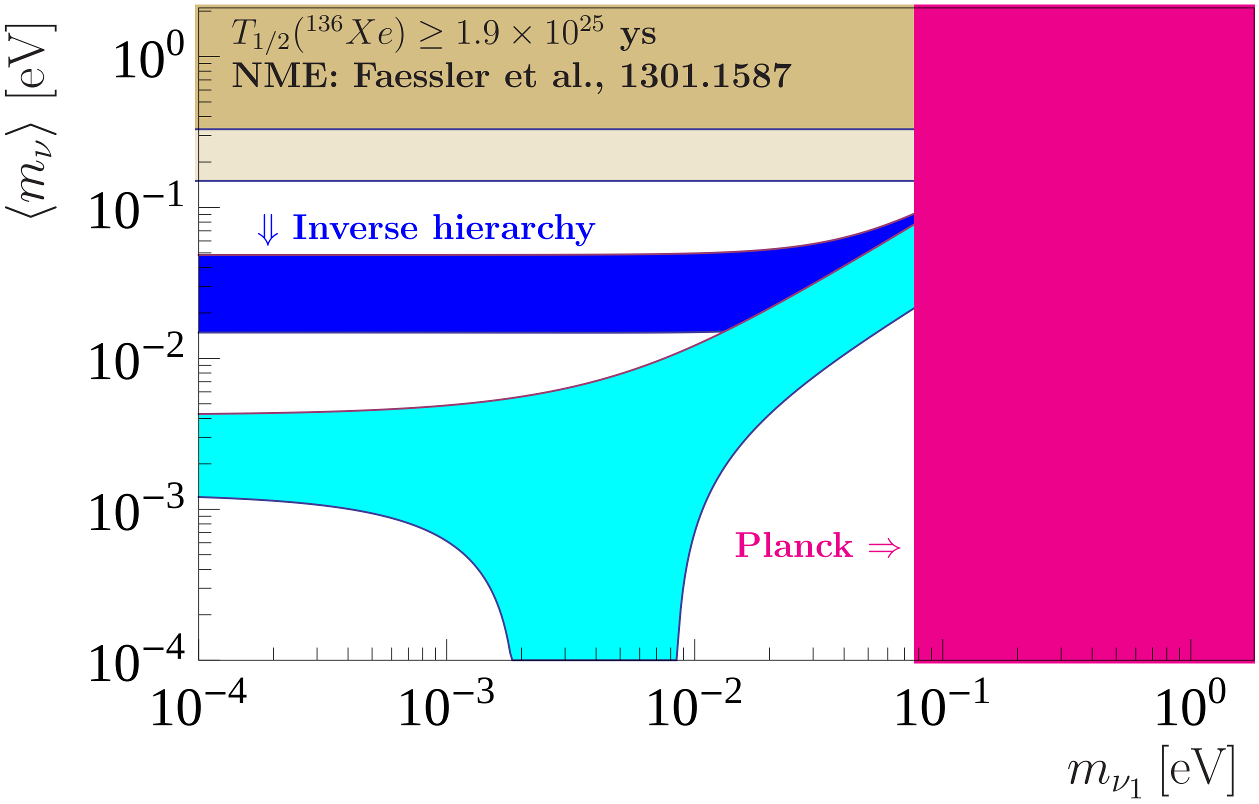


Global fit data from:

Forero, Tortola & Valle; arXiv:1405.7540

all ranges at 1 σ c.l.

$\langle m_\nu \rangle$ versus m_{ν_1} - status 2014



Global fit data from:

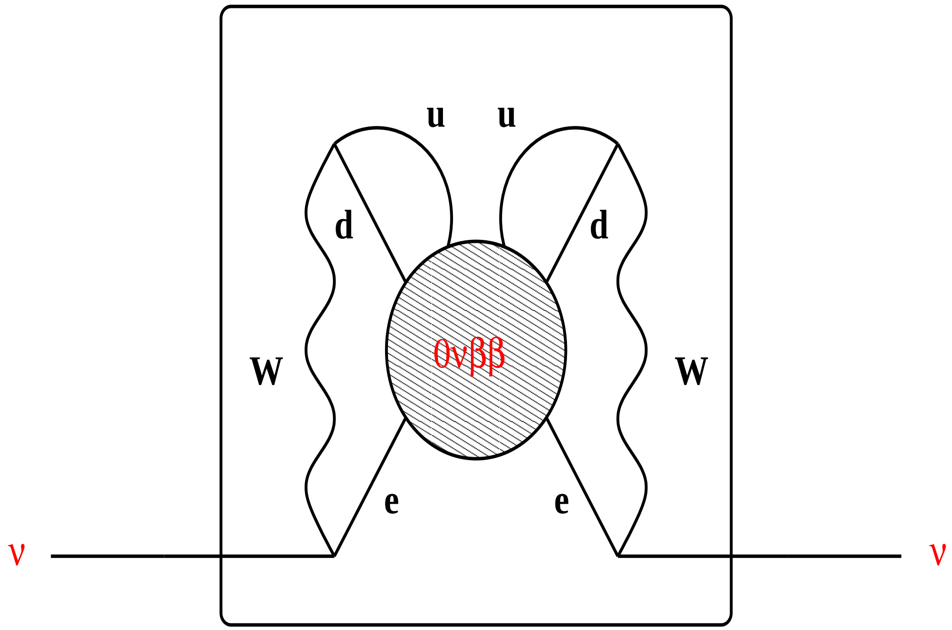
Forero, Tortola & Valle; arXiv:1405.7540

all ranges at 1 σ c.l.

⇒ Planck - limits from cosmological data

⇒ $T_{1/2}(^{136}Xe)$ - limit from KamLAND-Zen

Black Box Theorem



Schechter & Valle, PRD 1982

Takasugi, PLB 1984

If $0\nu\beta\beta$

is observed

the neutrino is a

Majorana particle!

⇒ 4-loop "butterfly" diagram: $m_\nu \sim 10^{-24}$ eV Duerr et al 2011

⇒ Tree-level, 1-loop, $\cdots$ 4-loop possible

⇒ Rule of thumb: Helo et al., 2015

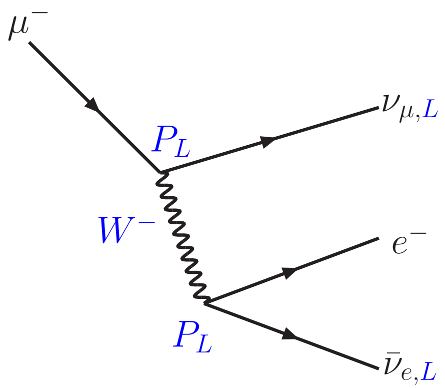
- → Models with tree-level, 1-loop m_ν - mass mechanism dominates
- → Models with 2-loop, 3-loop m_ν - mass mechanism $\sim$ SR
- → Models with 4-loop m_ν - SR dominates

$\mathcal{IV}.$

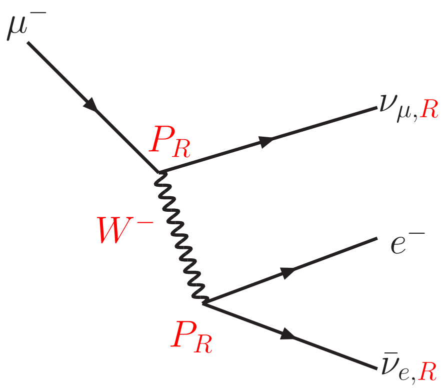
$0\nu\beta\beta$ decay, LNV and LHC

Left-right symmetry

Motivation:



$\sim 1/m^2_{W_L} \to G_F$



$\sim 1/m^2_{W_R}$

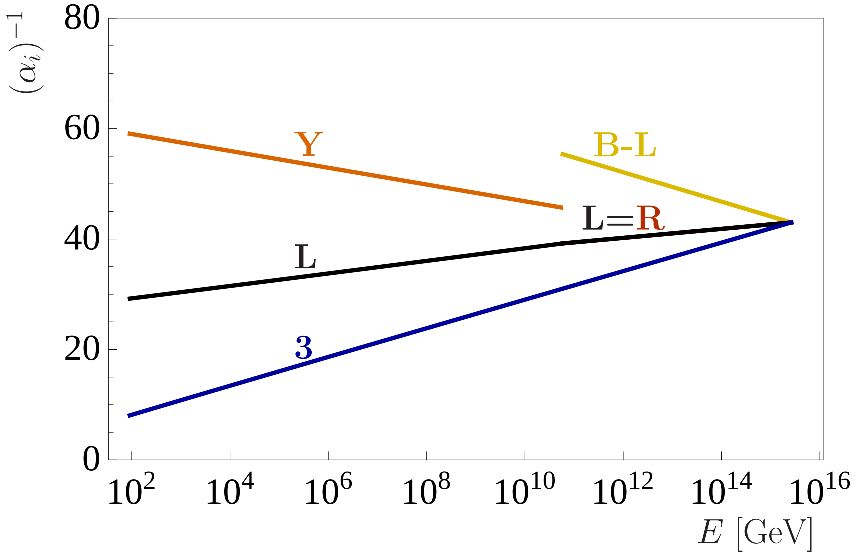
Extend standard model gauge group to:

$SU(3)_c \times SU(2)_L \times U(1)_Y \to SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

If $m_{W_R} \gg m_{W_L}$ - interactions mostly left-handed

$\Rightarrow$ LR symmetry implies: $L \leftrightarrow L^c$ - ν_R is part of theory!
$\Rightarrow$ Seesaw mechanism included in theory

GCU in LR?



Running of α_i^{-1} in the

minimal LR model

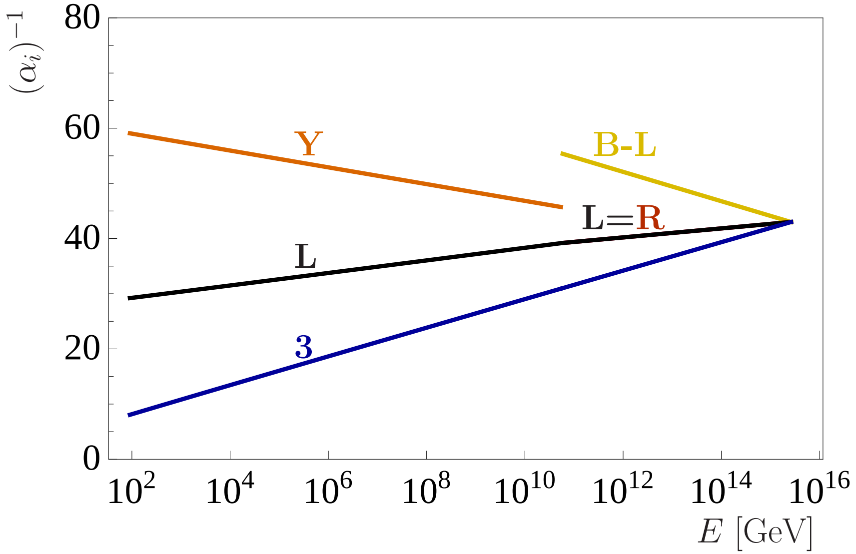
SM + $\Phi_{1,2,2,0}$ +$\Phi_{1,3,1,-2}$ + $\Phi_{1,1,3,-2}$

unifies at $E =$ (few) 10^{15} GeV

if $M_{LR} \simeq 10^{11}$ GeV

NOT TESTABLE EXPERIMENTALLY!

GCU in LR!



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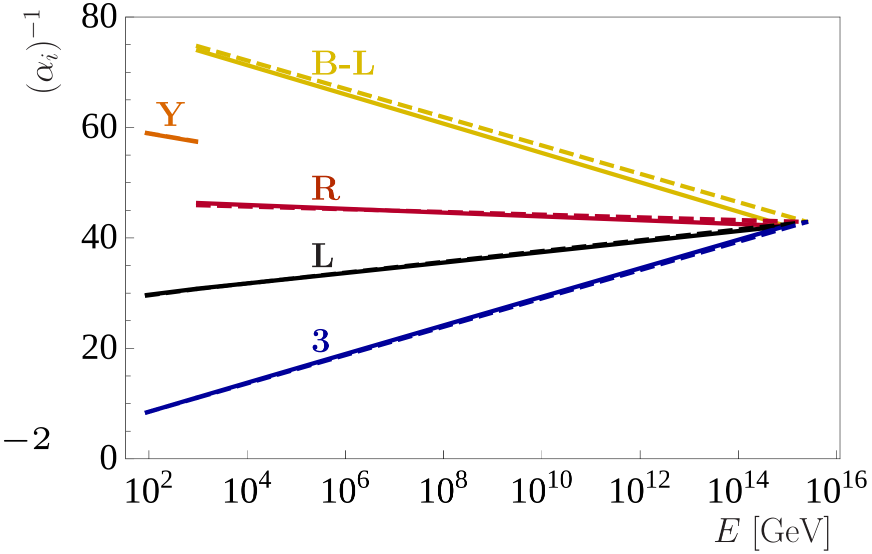
if $M_{LR} \simeq 10^{11}$ GeV

Arbeláez et al, PRD**D89**:

Many non-minimal LR models exist with perfect unification and $M_{LR} \simeq 1$ TeV!

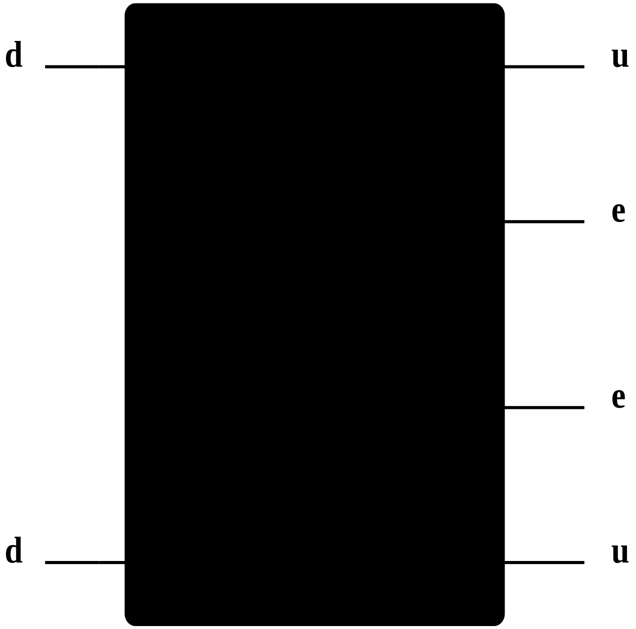
Example plot:

SM + $2\Phi_{1,2,2,0} + 3\Phi_{1,1,3,0} + 2\Phi_{1,1,3,-2}$



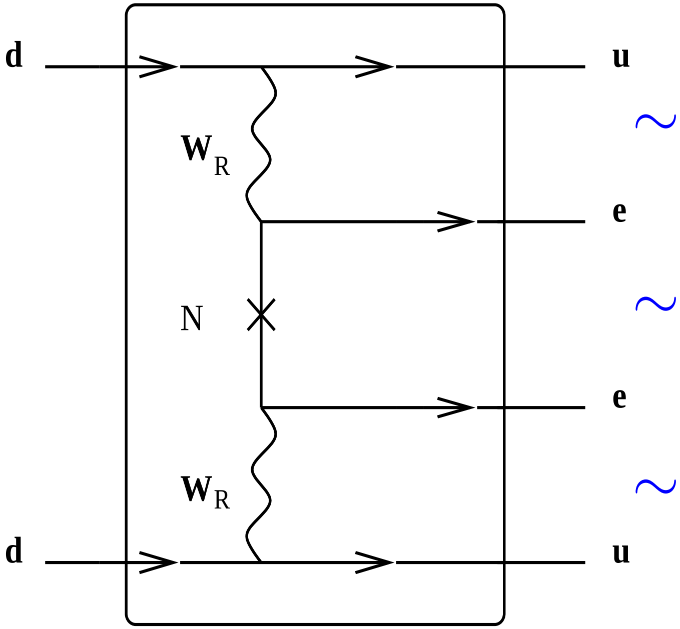
Black Box: Experiment

The experimentalist sees:



W_R and $0\nu\beta\beta$ decay

The experimentalist sees:



$\sim 1/m_{W_R}^2$

$\sim 1/m_N$

$\sim 1/m_{W_R}^2$

If $m_N \to \infty$

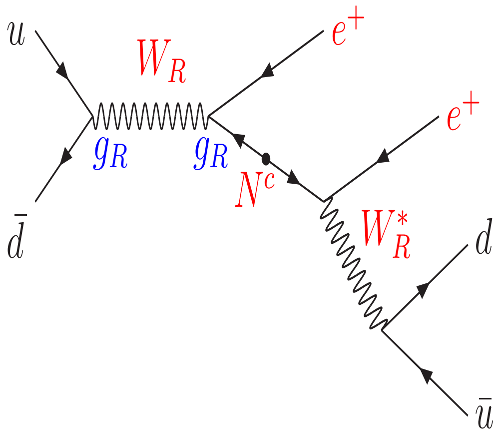
limit on

$m_{W_R} \to 0$

With $T_{1/2}^{0\nu\beta\beta}(^{136}Xe) \geq 1.6 \times 10^{25}$ ys:

$$m_{W_R} \gtrsim 1.3 \Big(\frac{\langle m_N \rangle}{[1\mathrm{TeV}]}\Big)^{-1/4} \ \mathrm{TeV}$$

Example: W_R @ LHC

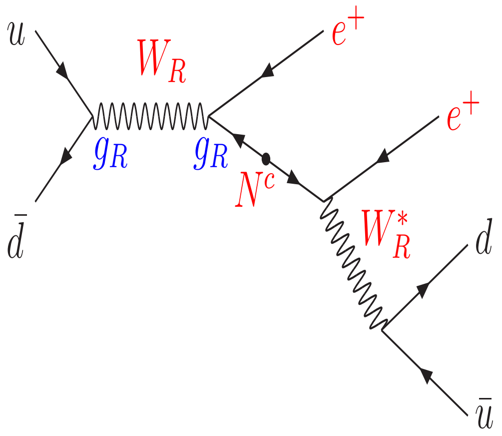


Keung & Senjanovic, 1983

Signal:

Same-sign and opposite-sign di-lepton + jets, **no** $\not{E}_T$

Example: W_R @ LHC



Keung & Senjanovic, 1983

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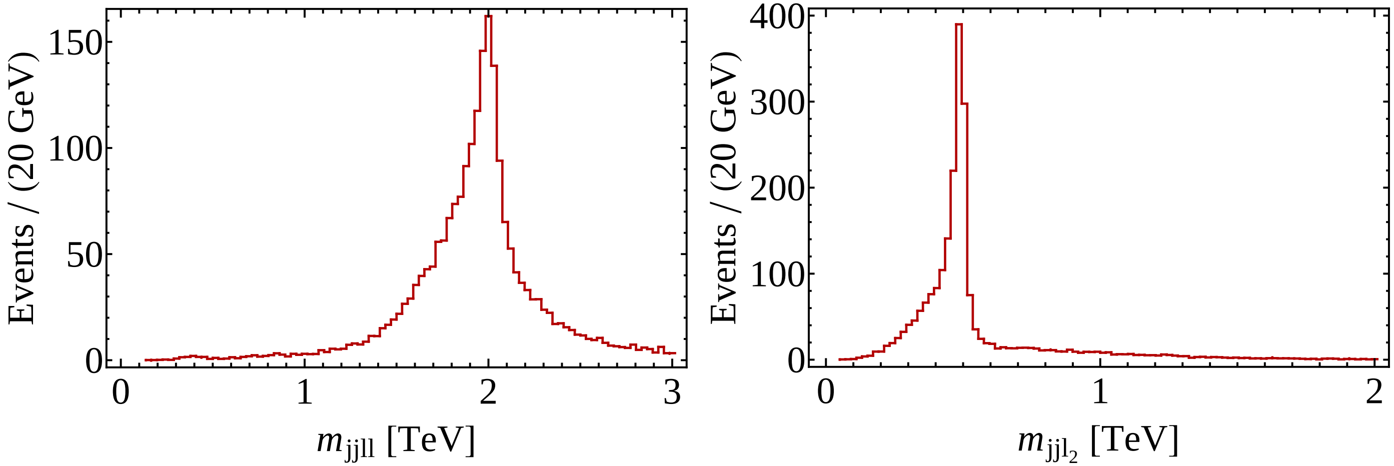
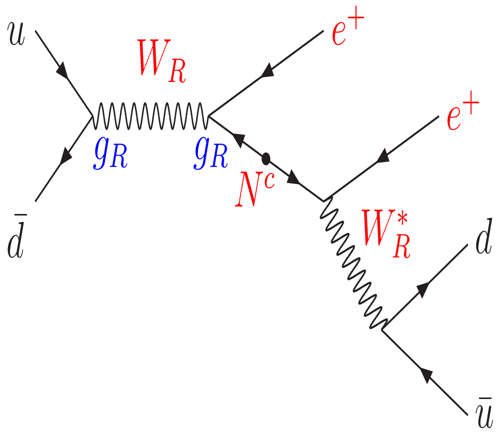
Plot from: S.P. Das et al., PRD **86**



$\Rightarrow$ Assumes $\mathcal{L} = 30$ fb^{-1} at $\sqrt{s} = 14$ TeV

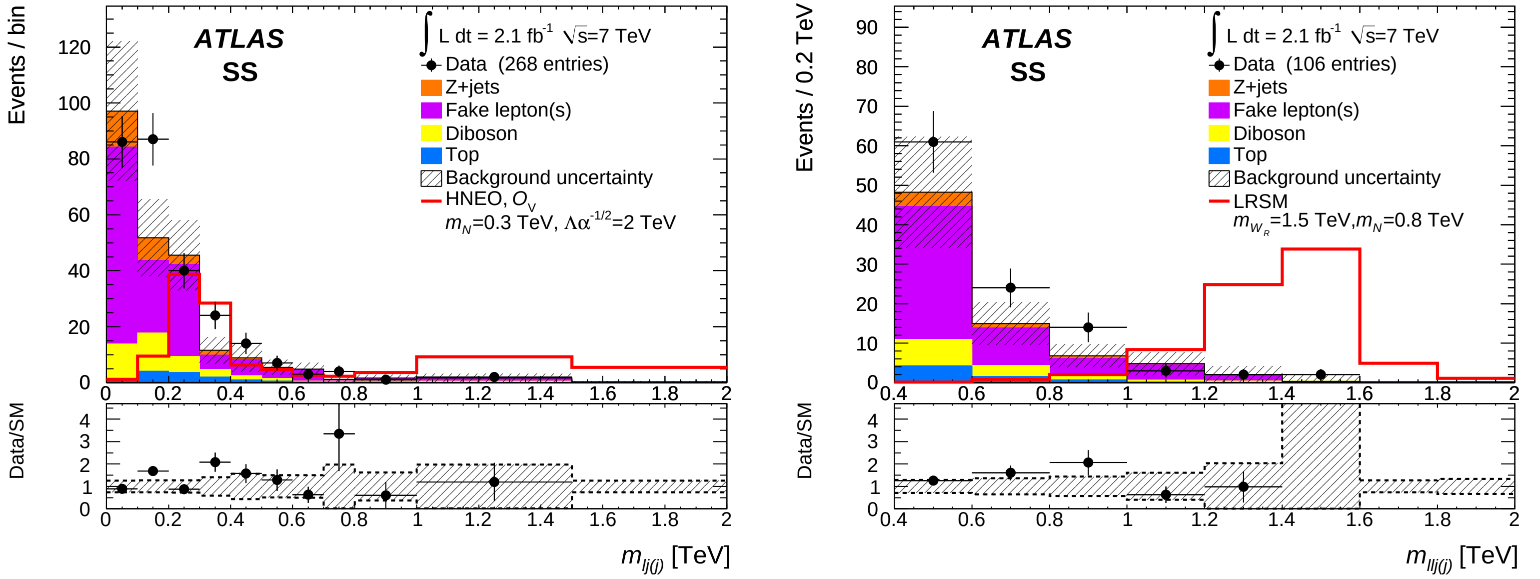
W_R @ LHC - 2012



Signal:

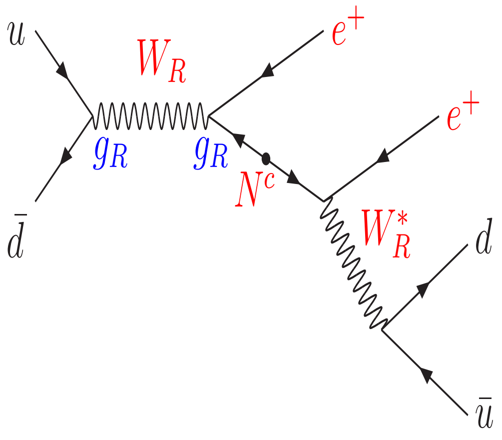
Same-sign and opposite-sign di-lepton + jets, **no** $\not{E}_T$

Plot from: ATLAS, Eur.Phys.J C72:



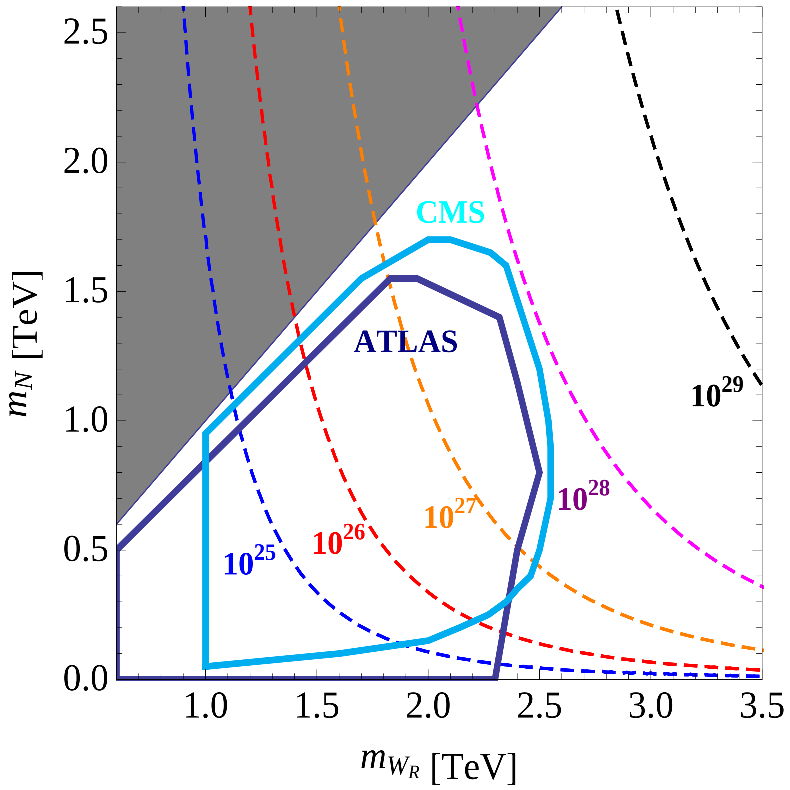
⇒ Assumes $\mathcal{L} = 2.1$ fb^{-1} at $\sqrt{s} = 7$ TeV

Status LHC, June 2014



Signal:

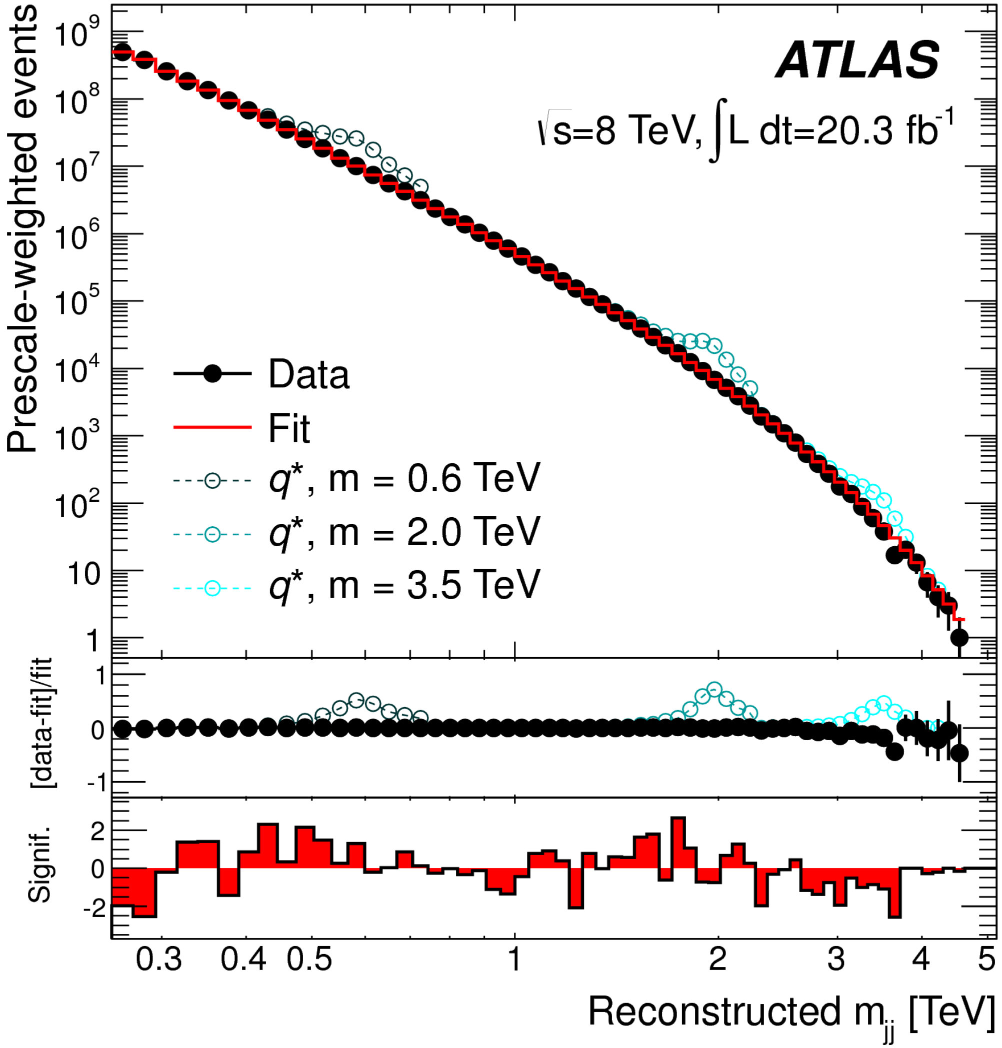
Same-sign and opposite-sign di-lepton + jets, **no** $\not{E}_T$



CMS (and ATLAS) with $\sqrt{s} = 8$ TeV:
Non-observation gives stringent limits on short-range W_R diagrams for $0\nu\beta\beta$ decay.

Assumes: $g_R = g_L$!

Dijet searches at LHC

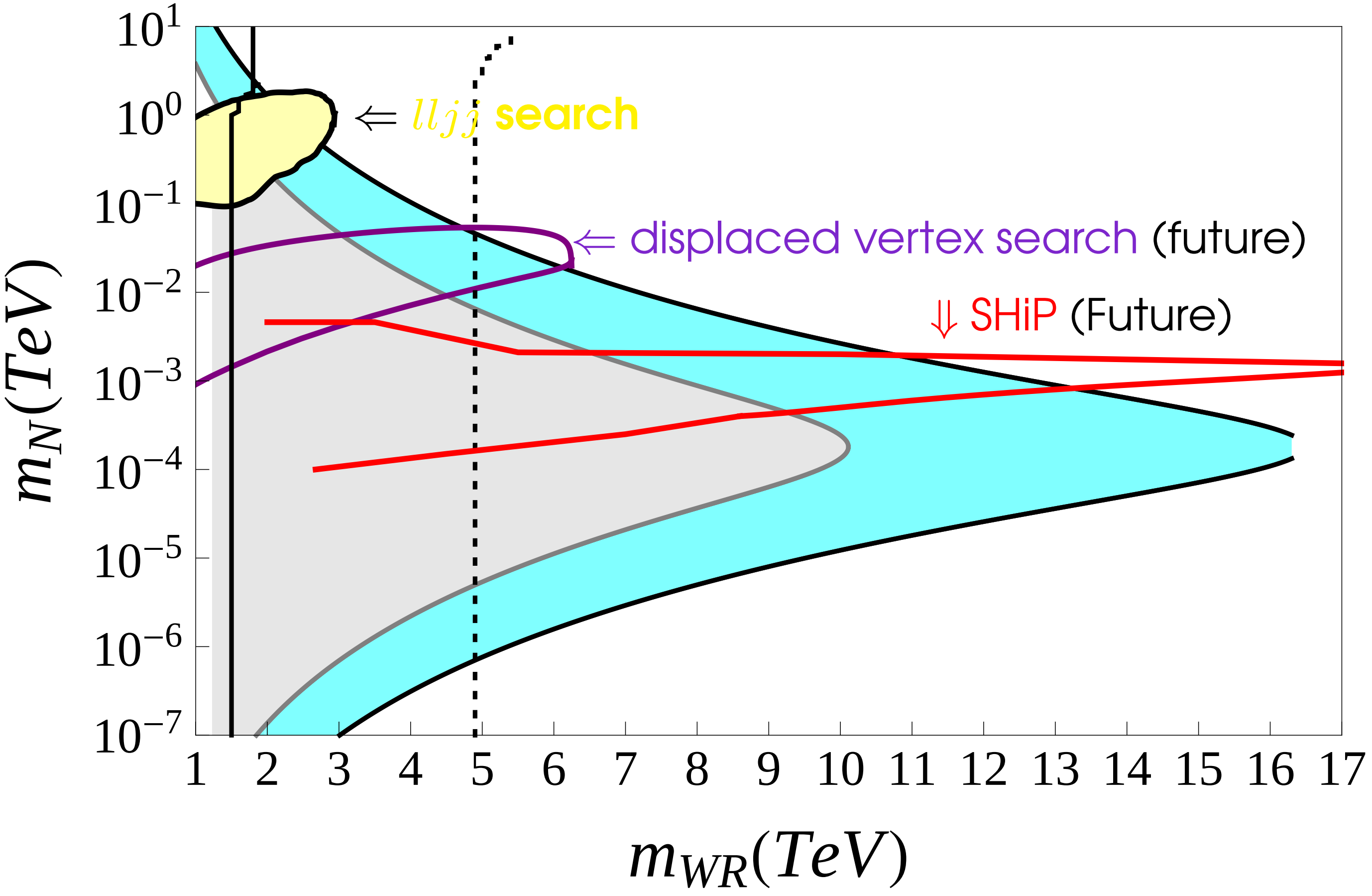


ATLAS collaboration
arXiv:1407.1376

Absence of resonance(s)
can be interpreted as
upper limits on couplings
as function of (hypothetical)
resonance mass

Dijet and $0\nu\beta\beta$ decay

Absence of $pp \to W_R \to jj$ gives limit on $0\nu\beta\beta$:



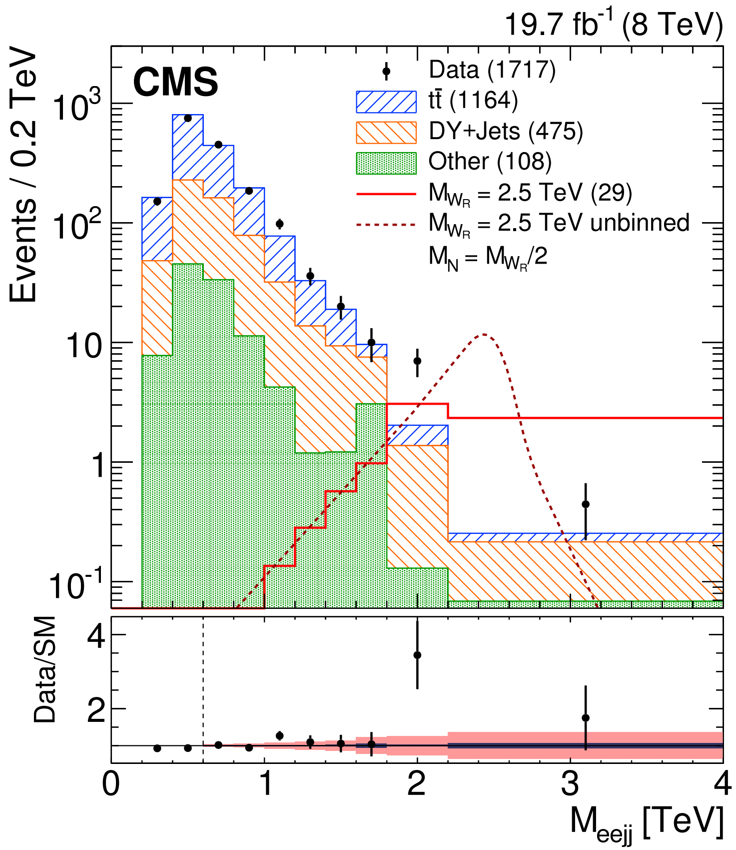
Helo & Hirsch
1509.00423

gray:
$T_{1/2}^{0\nu\beta\beta} \gtrsim 10^{25}$ **ys**

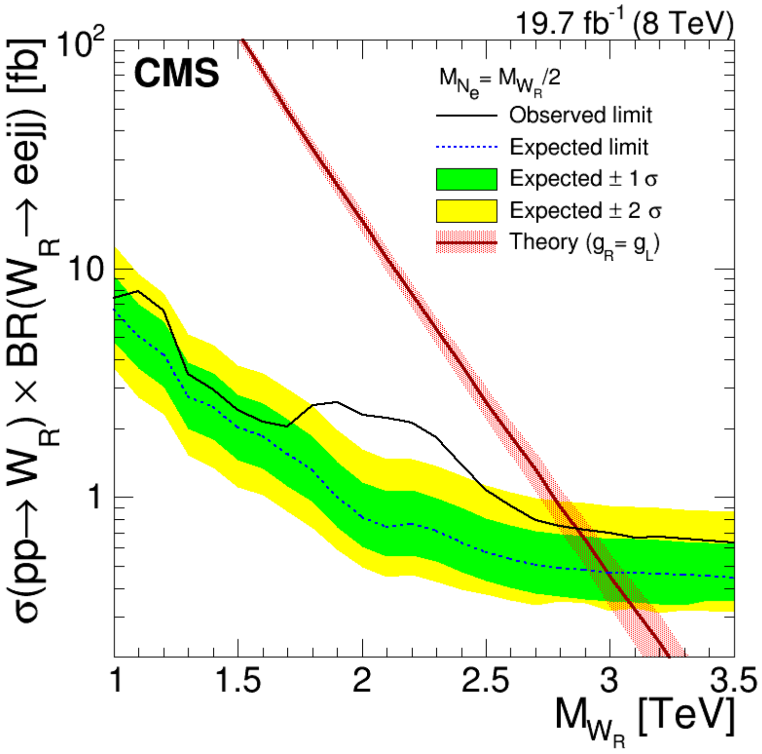
cyan:
$T_{1/2}^{0\nu\beta\beta} \gtrsim 10^{27}$ ys

$\Rightarrow$ **full (dashed) current limits (future sensitivity) for dijet data**

CMS excess: arXiv:1407.3683



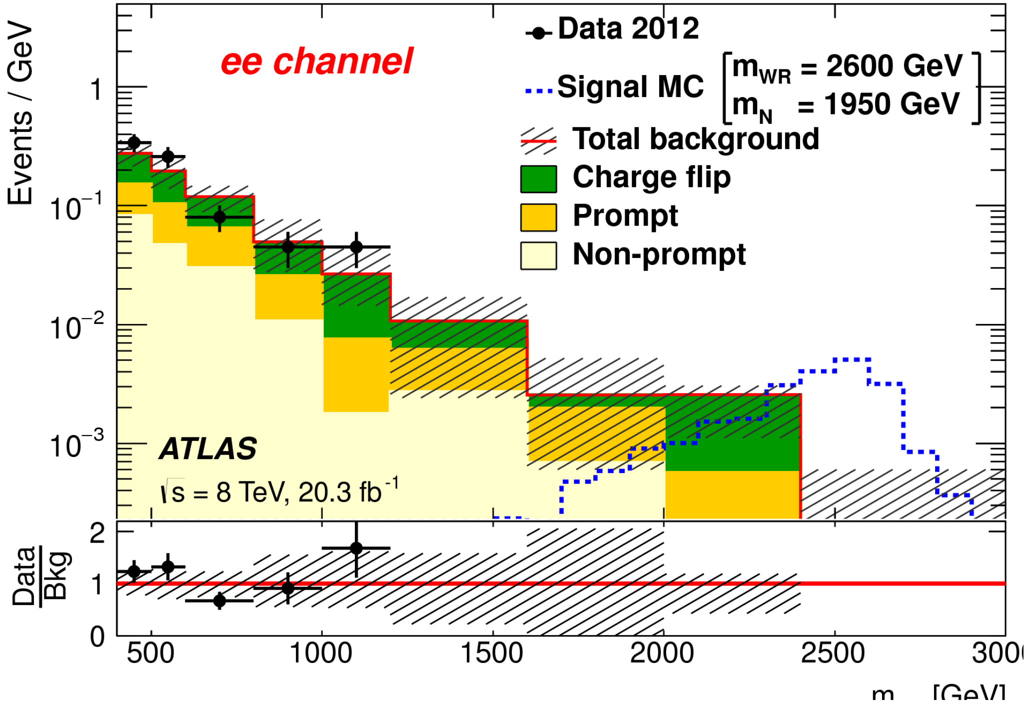
Local significance 2.8 σ



Note:

- ⇒ excess only in ee final state
- ⇒ only 1 out of 14 events is like-sign
- ⇒ no excess is seen in m_{e_2jj}

ATLAS like-sign lepton $+jj$



ATLAS; arXiv:1506.06020

does not confirm excess in $eejj$

... searches only for like-sign leptons

Note:

For $m_{eejj} \geq 1.5$ TeV

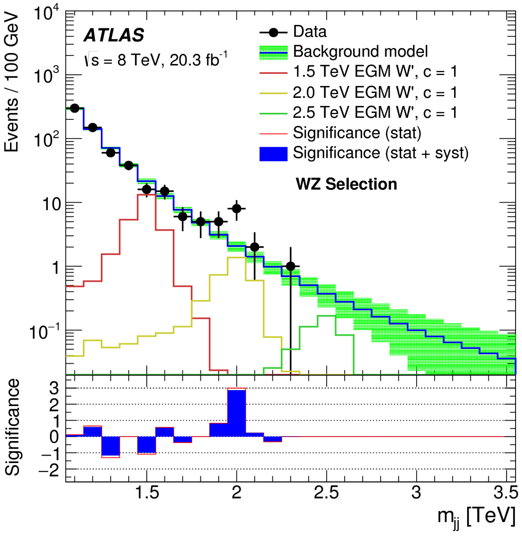
(5-6) events expected (BG)

Zero events observed!

ATLAS diboson searches

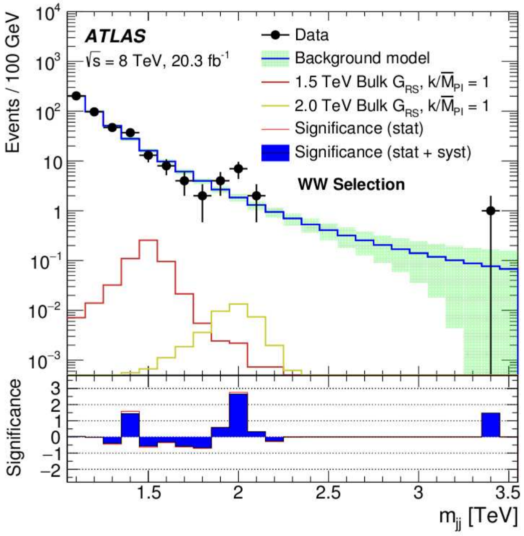
arXiv:1506.00962

Search for dijets compatible with a highly boosted W or Z boson decaying to quarks, using jet mass and substructure properties



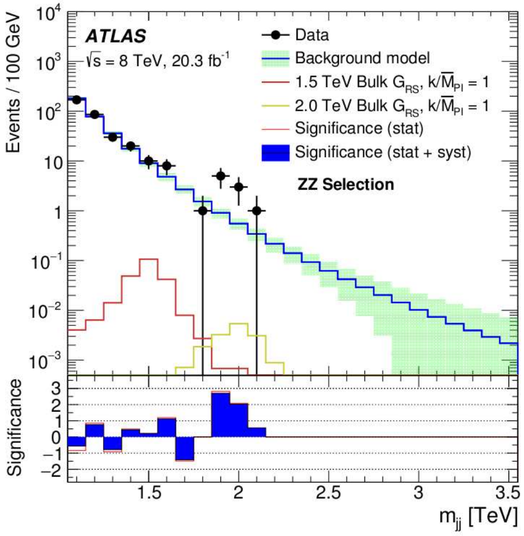
WZ like

$3.4\ \sigma$



WW like

$2.6\ \sigma$



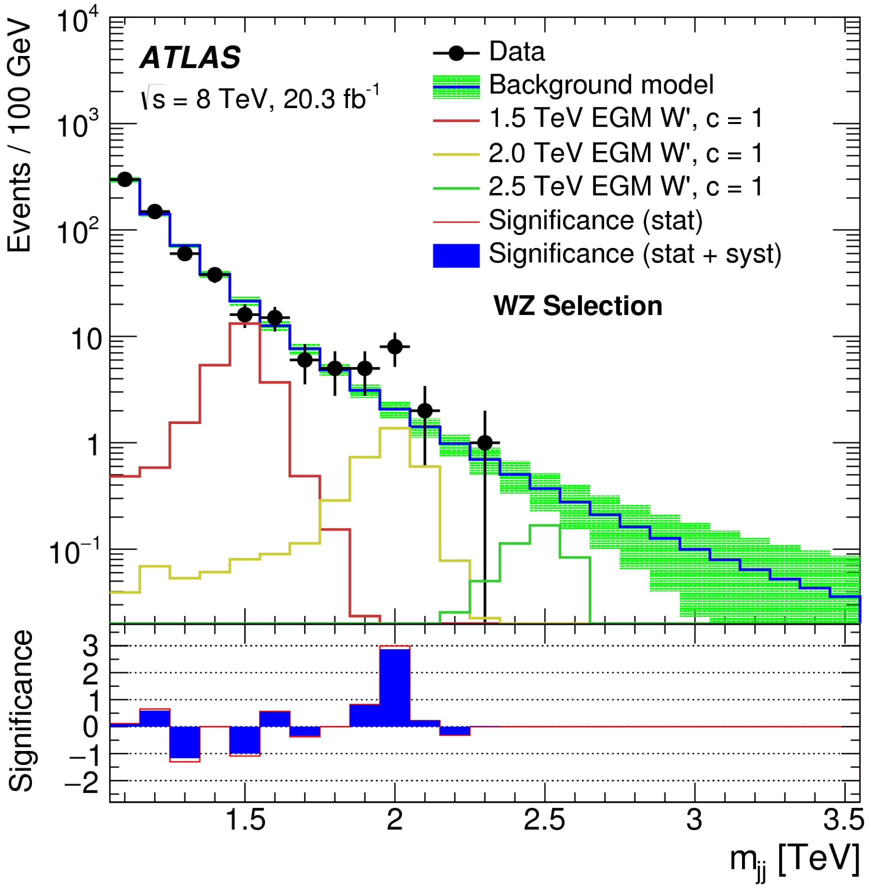
ZZ like

$2.9\ \sigma$

$\Rightarrow$ Note: Event samples are NOT independent, cuts “overlap”

$\Rightarrow$ More than 60 cites in 2 months!

ATLAS diboson searches



arXiv:1506.00962:

3.4 σ excess
around 2 TeV

In LR models:

$W_R^+ \to u\bar{d}$
- dijets

$W_R^+ \to llu\bar{d}$

$W_R^+ \to W^+ - Z^0$
- diboson search

$W_R^+ \to W^+ - h^0$
- ATLAS 1503.08089: $(ll,l\nu,\nu\nu)$+$\bar{b}b$

Conclusions

Neutrino mass models and $0\nu\beta\beta$ decay

Standard model fermions

Under the SM group, $SU(3)_c \times SU(2)_L \times U(1)_Y$, we have weak doublets:

$$L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \quad \propto \quad (\mathbf{1}, \mathbf{2}, -\frac{1}{2}) \qquad \text{and} \qquad Q = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \quad \propto \quad (\mathbf{3}, \mathbf{2}, \frac{1}{6})$$

and weak singlets:

$$e^c = e_R^* \quad \propto \quad (\mathbf{1}, \mathbf{1}, 1) \quad , \quad u^c = u_R^* \quad \propto \quad (\bar{\mathbf{3}}, \mathbf{1}, -\frac{2}{3})$$
$$d^c = d_R^* \quad \propto \quad (\bar{\mathbf{3}}, \mathbf{1}, \frac{1}{3})$$

For example SM Yukawa interactions:

$$\mathcal{L}^{\text{Yuk}} = Y_u Q \cdot H u^c + Y_d Q \cdot \tilde{H} d^c + Y_e L \cdot \tilde{H} e^c$$

where $H \propto (\mathbf{1}, \mathbf{2}, \frac{1}{2})$ and $\tilde{H} = (i\tau_2) H^*$

Theoretical expectation?

Majorana Neutrino mass

$$m_\nu \simeq \frac{(Yv)^2}{\Lambda}.$$

Weinberg, 1979

Smallness of neutrino mass
can be “explained” by:

Minkowski, 1977

$\Rightarrow$ High scale: Large Λ
“classical” seesaw

Yanagida, 1979
Gell-Mann, Ramond, Slansky, 1979
Mohapatra, Senjanovic, 1980
Schechter, Valle, 1980
$\ldots, \ldots, \ldots$
Foot et al., 1988

Theoretical expectation?

Majorana Neutrino mass generated from an n-loop dimension d diagram:

$$m_\nu \simeq \frac{(Yv)^2}{\Lambda} \cdot \epsilon \cdot \left(\frac{Y^2}{16\pi^2}\right)^n \cdot \left(\frac{Yv}{\Lambda}\right)^{d-5}$$

Smallness of neutrino mass can be "explained" by:

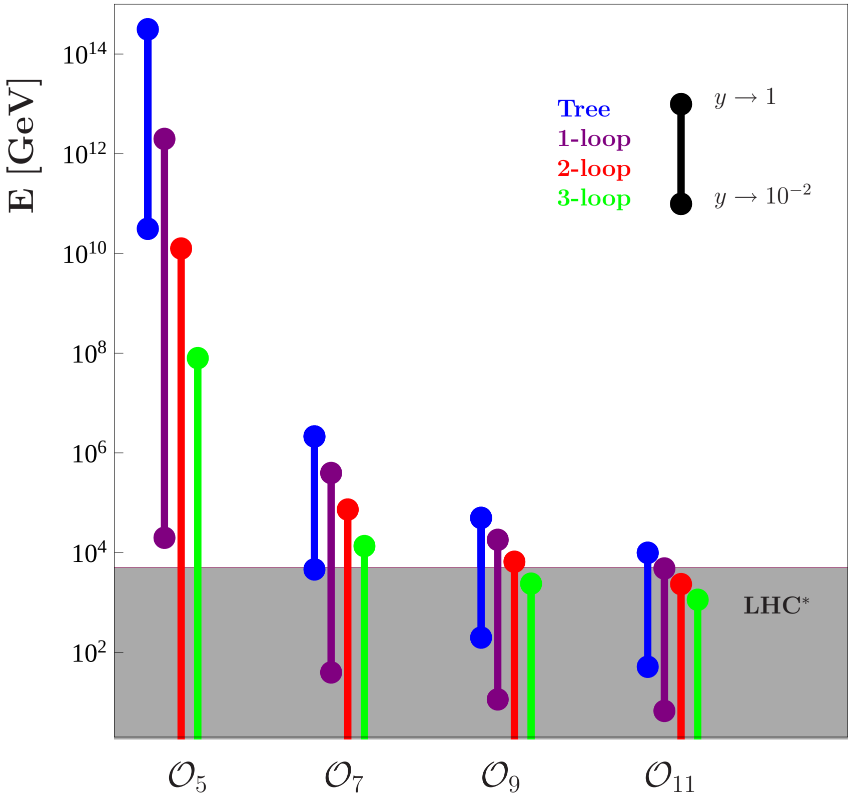
$\Rightarrow$ High scale: Large Λ
"classical" seesaw

$\Rightarrow$ Loop factor: $n \geq 1$
+ "smallish" $Y \sim \mathcal{O}(10^{-3} - 10^{-1})$

$\Rightarrow$ Higher order: $d = 7, 9, 11$

$\Rightarrow$ Nearly conserved L,
i.e. small ϵ ("inverse seesaw")

$\cdots$ or combination thereof



$\Delta L = 2$ operators

$d = 5$:

Weinberg, 1979

$$\mathcal{O}_W \propto \frac{c_{ij}}{\Lambda}(L_i H)(L_j H)$$

One d=5

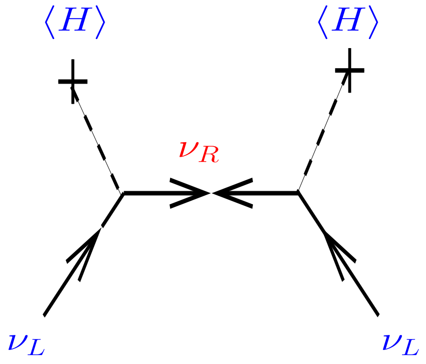
$\Delta L = 2$ operators

$d = 5$: Weinberg, 1979

$$\mathcal{O}_W \propto \frac{c_{ij}}{\Lambda}(L_i H)(L_j H)$$

One d=5

Example realization, seesaw type-I:



$\Lambda \simeq M_{\nu_{R_k}}$

$c_{ij} \propto Y^{\nu}_{ik} Y^{\nu}_{jk}$

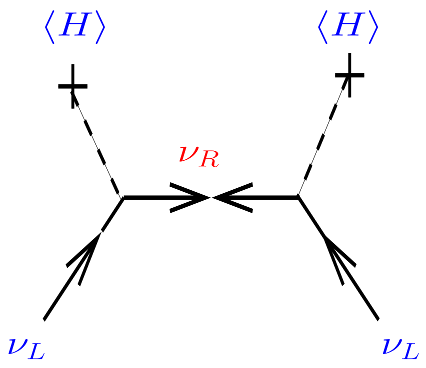
$\Delta L = 2$ *operators*

$d = 5$: Weinberg, 1979

$$\mathcal{O}_W \propto \frac{c_{ij}}{\Lambda}(L_i H)(L_j H)$$

One d=5

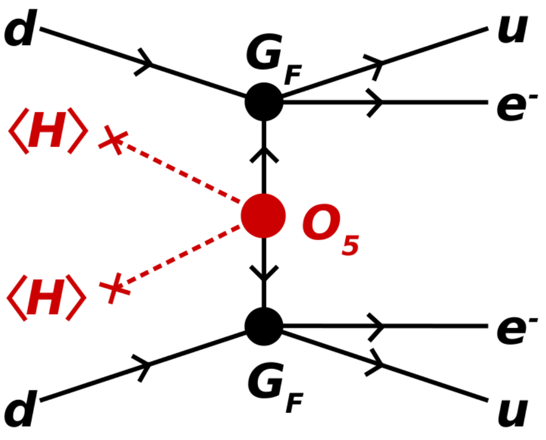
Example realization, seesaw type-I:



$\Lambda \simeq M_{\nu_{R_k}}$

$c_{ij} \propto Y^\nu_{ik} Y^\nu_{jk}$

$0\nu\beta\beta$ decay:

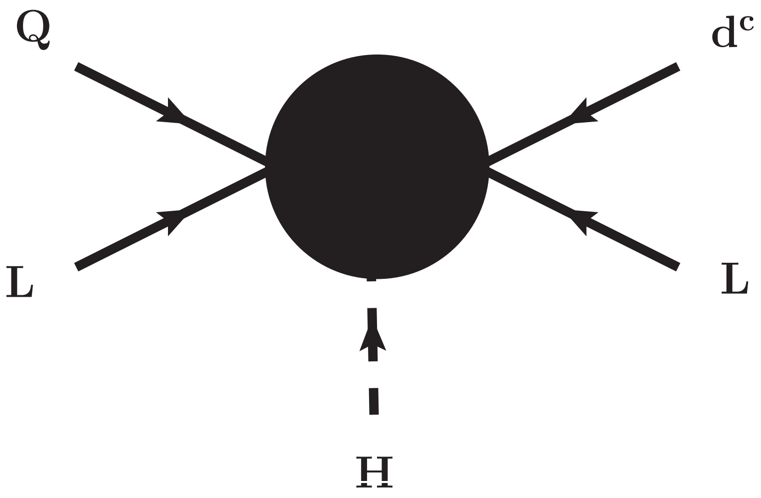


(a)

Mass mechanism!

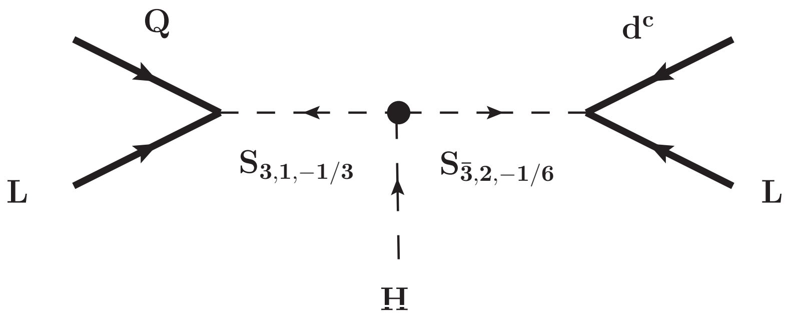
Example $d = 7$: $LLQd^cH$

Graphically:



Example $d = 7$: $LLQd^cH$

Again, more than one realization.
Example:

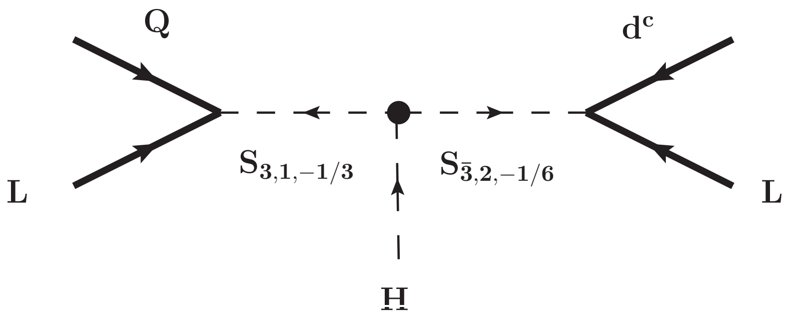


$S_{3,1,-1/3}$ - singlet leptoquark
$S_{3,2,1/6}$ - doublet leptoquark

$\Delta L = 2$, so ...

Example $d = 7$: $LLQd^cH$

Again, more than one realization.
Example:



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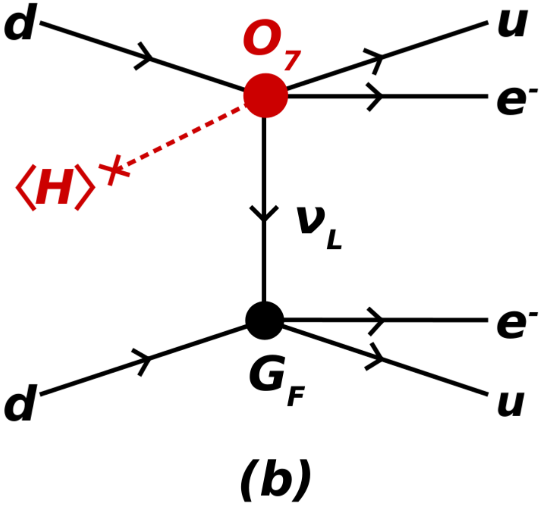
$0\nu\beta\beta$ decay:



Long range contribution!

$$\mathcal{A} \propto \frac{\mu \times \langle H^0 \rangle}{m^2_{3,1,1/3} m^2_{3,2,1/6}}$$

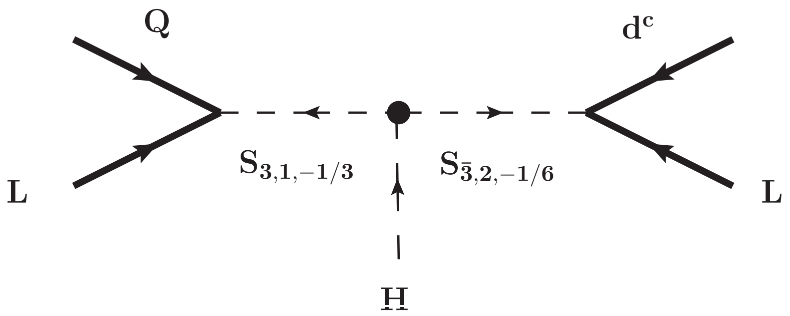
$$\propto \frac{v}{\Lambda^3}$$

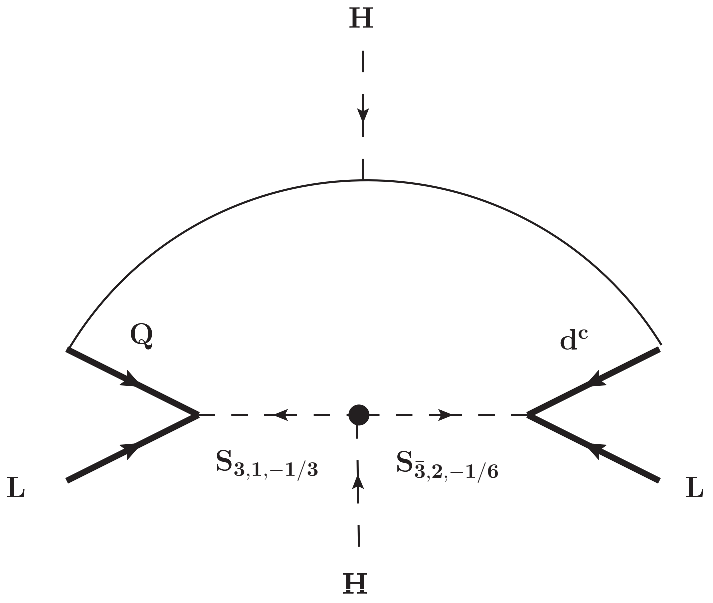
No helicity suppression!

Example $d = 7$: $LLQd^cH$

Again, more than one realization.
Example:

1-loop neutrino mass:



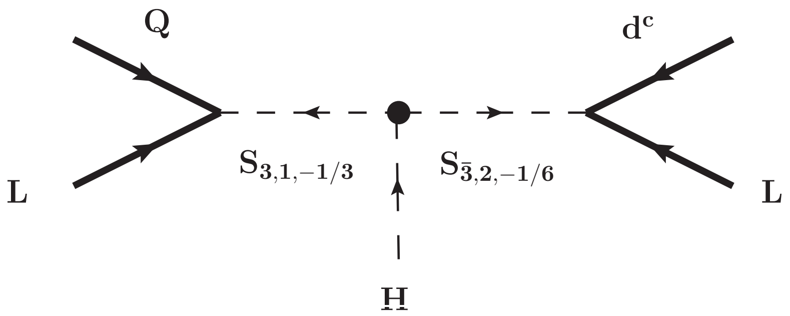


$S_{3,1,-1/3}$ - singlet leptoquark
$S_{3,2,1/6}$ - doublet leptoquark

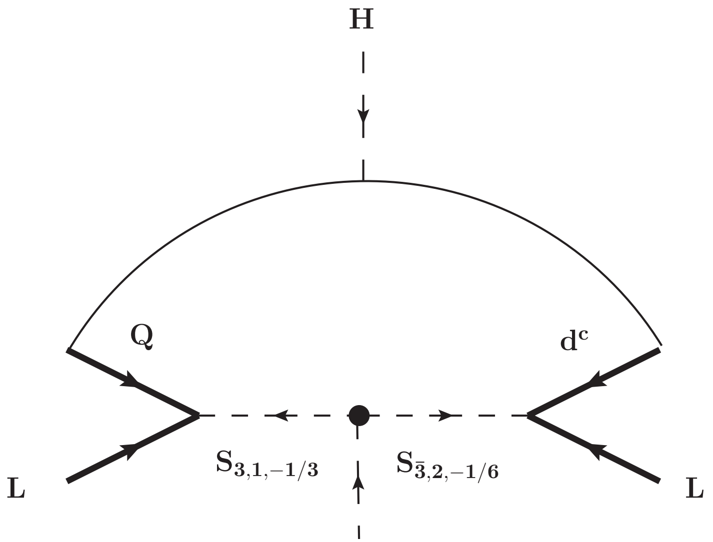
$\Delta L = 2$, so ...

Example $d = 7$: $LLQd^cH$

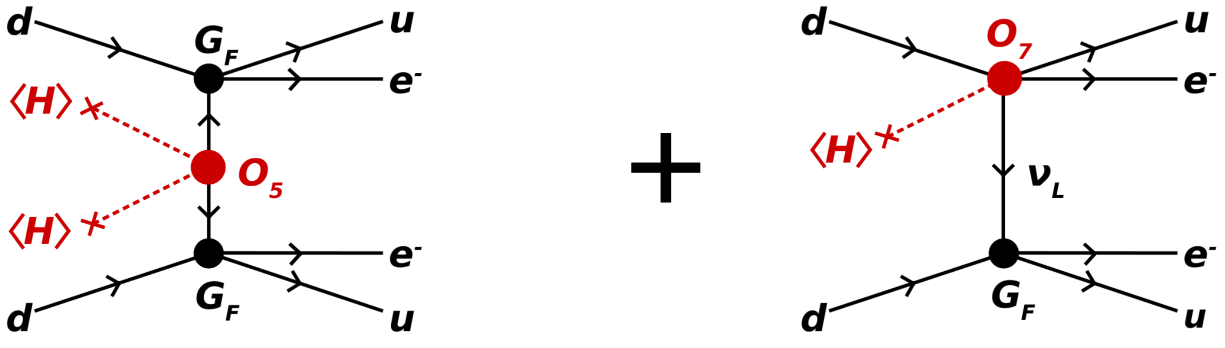
Again, more than one realization.
Example:



1-loop neutrino mass:



$0\nu\beta\beta$ decay has both contributions:



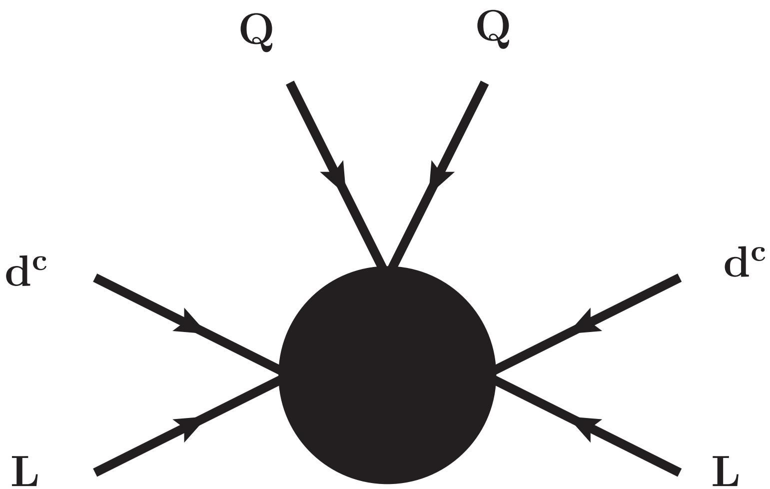
(a)

(b)

Example $d = 9$: $LLQd^cQd^c$

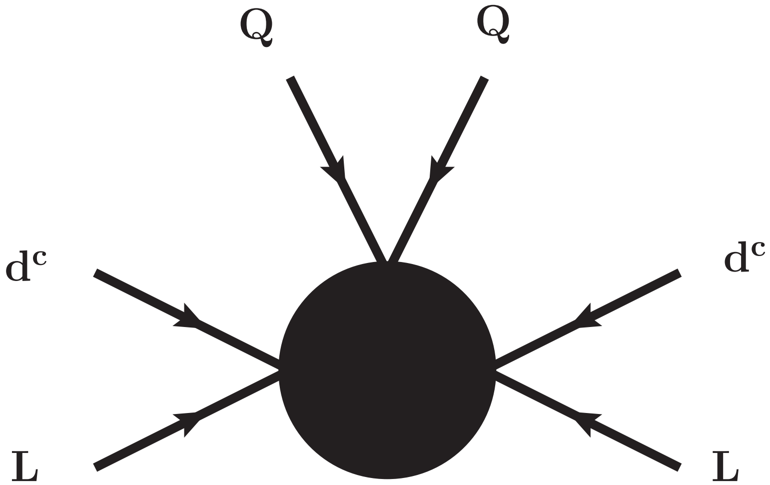
True $d = 9$ operator:

Many, many realizations ...



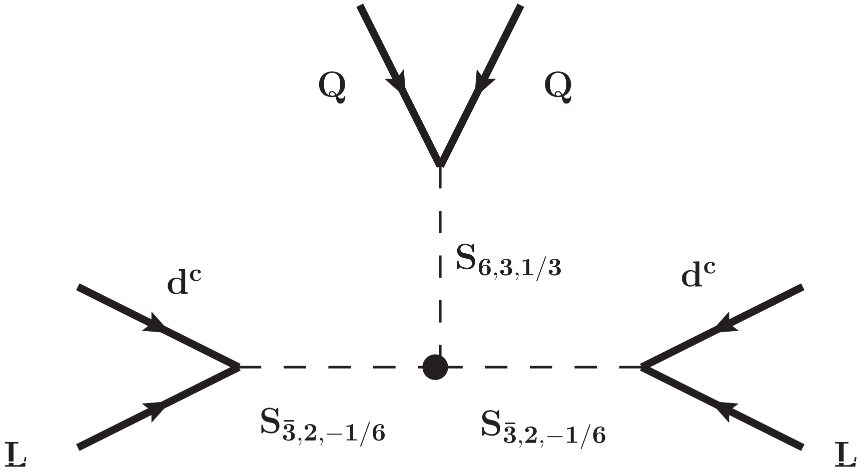
Example $d = 9$: $LLQd^cQd^c$

True $d = 9$ operator:



Many, many realizations ...

One example:

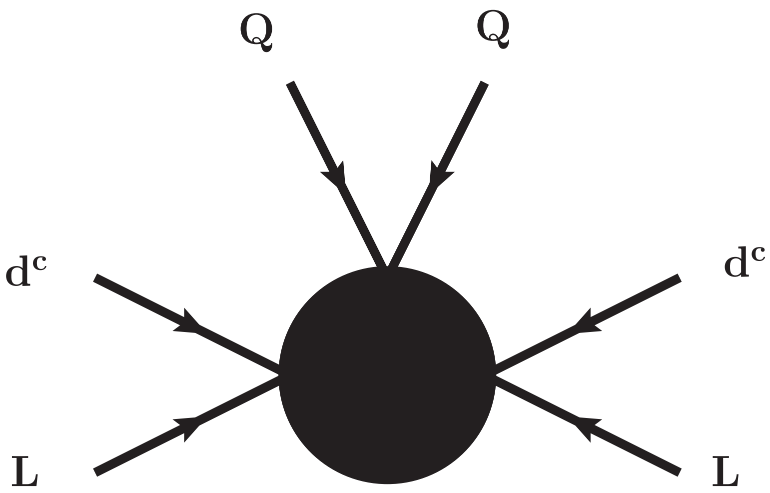


$S_{6,3,1/3}$ - triplet diquark

$S_{3,2,1/6}$ - doublet leptoquark

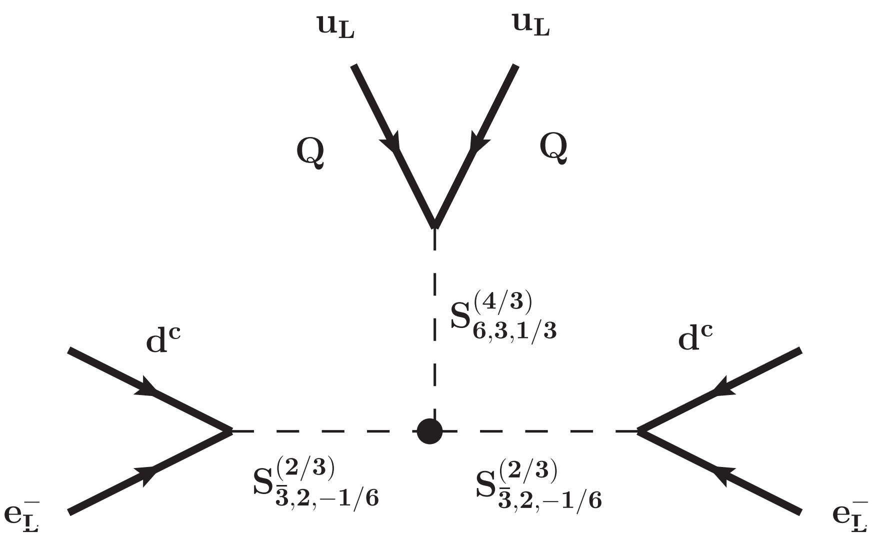
Example $d = 9$: $LLQd^cQd^c$

True $d = 9$ operator:



Many, many realizations ...

One example:



$S_{6,3,1/3}$ - triplet diquark

$S_{3,2,1/6}$ - doublet leptoquark

$0\nu\beta\beta$ decay without neutrino!

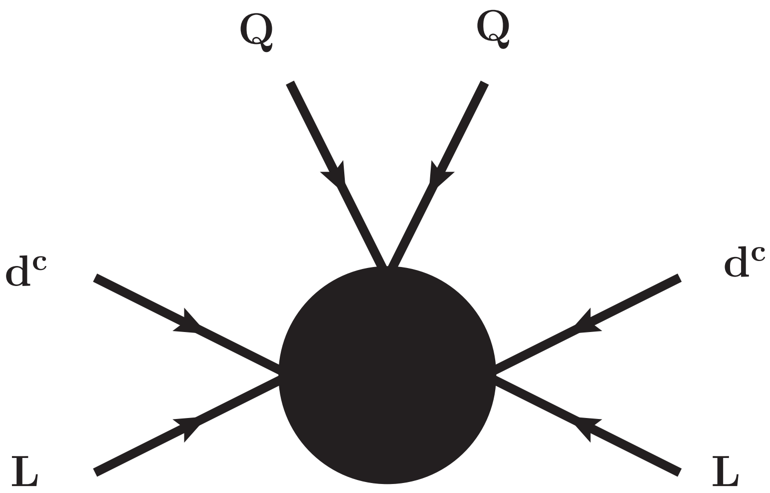
$\Delta L = 2$, so ...

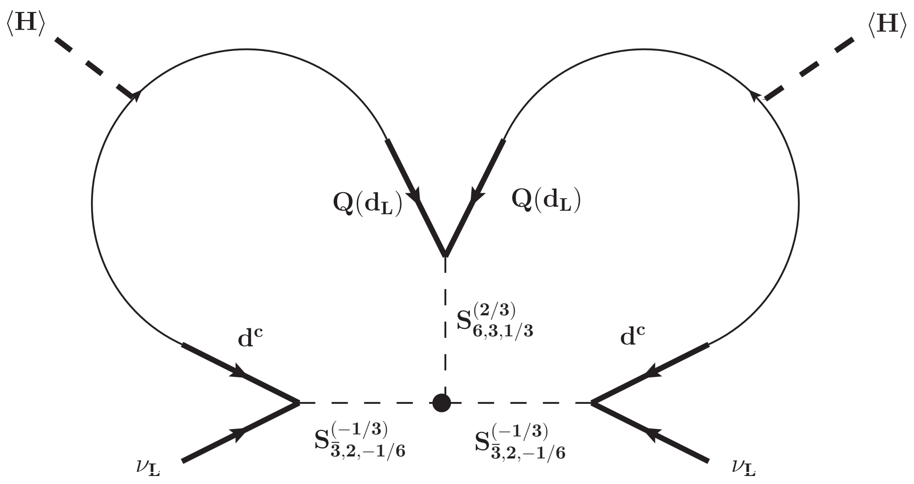
Example $d = 9$: $LLQd^cQd^c$

True $d = 9$ operator:

Many, many realizations ...

One example:





$S_{6,3,1/3}$ - triplet diquark

$S_{3,2,1/6}$ - doublet leptoquark

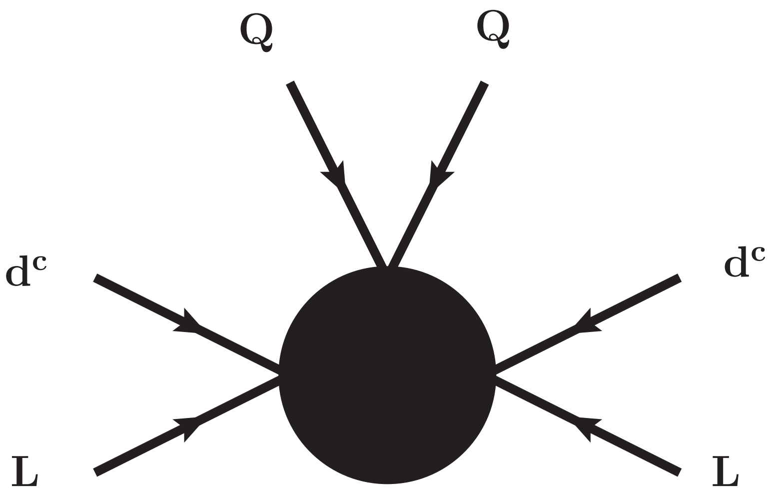
2-loop neutrino mass!

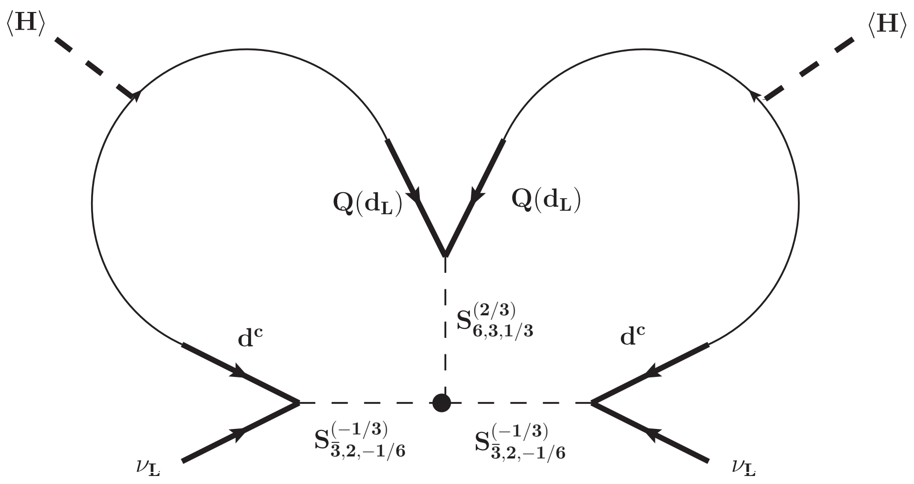
Example $d = 9$: $LLQd^cQd^c$

True $d = 9$ operator:

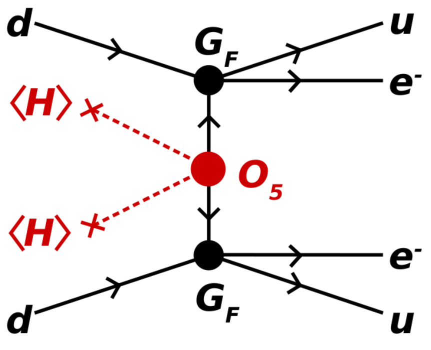
Many, many realizations ...

One example:



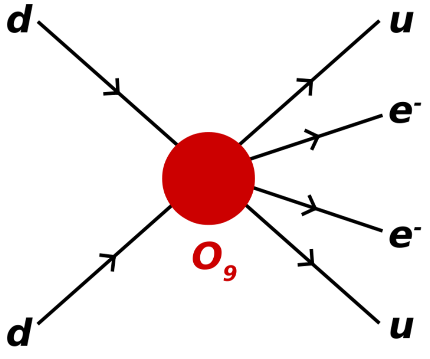


Again, $0\nu\beta\beta$ decay has two contributions:



(a)

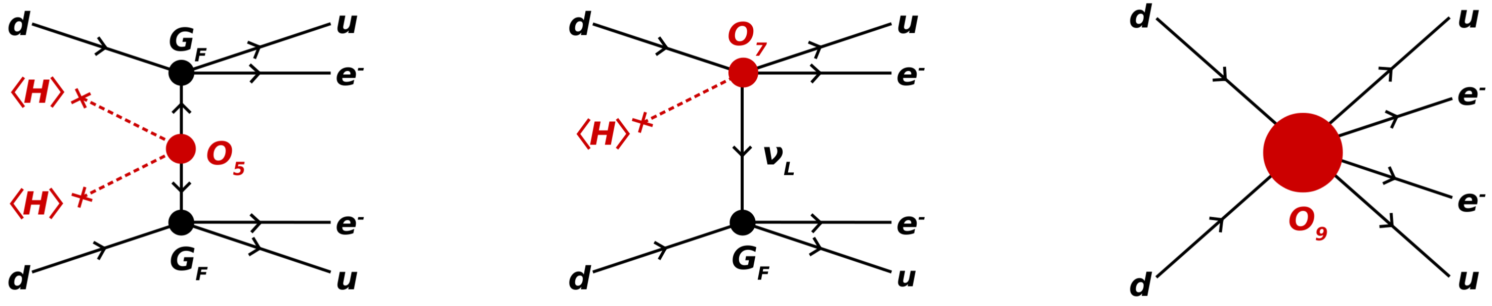
+



(c)

Distinguish mechanisms?

Amplitude for $(Z,A) \rightarrow (Z\pm 2, A) + e^{\mp}e^{\mp}$ can be divided into:

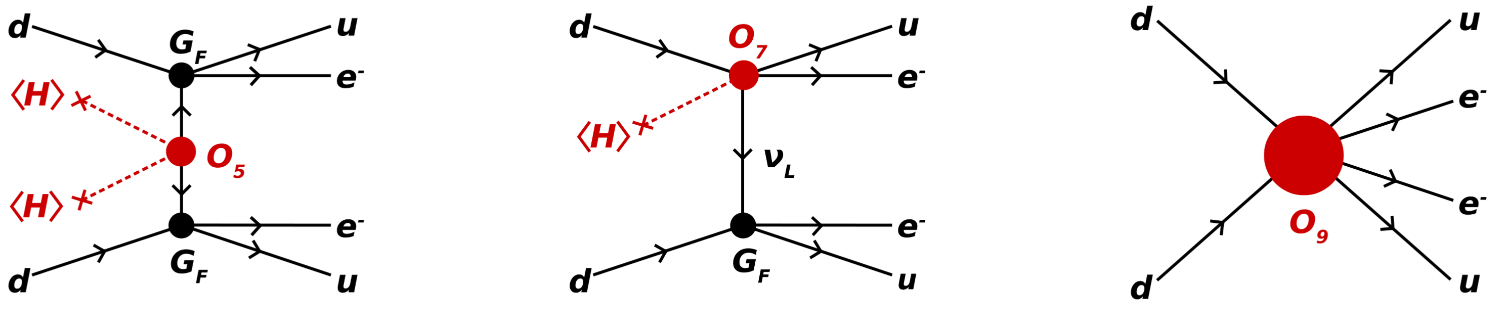


(a) (b) (c)

Mass mechanism "long-range" "short-range"

Distinguish mechanisms?

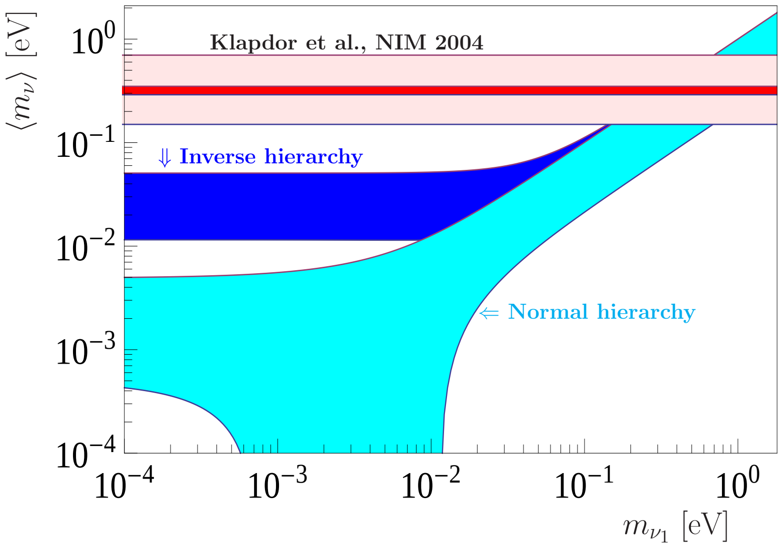
Amplitude for $(Z, A) \rightarrow (Z \pm 2, A) + e^{\mp}e^{\mp}$ can be divided into:



(a) **(b)** **(c)**

Mass mechanism "long-range" "short-range"

Compare with other experiments:
Cosmology
KATRIN?

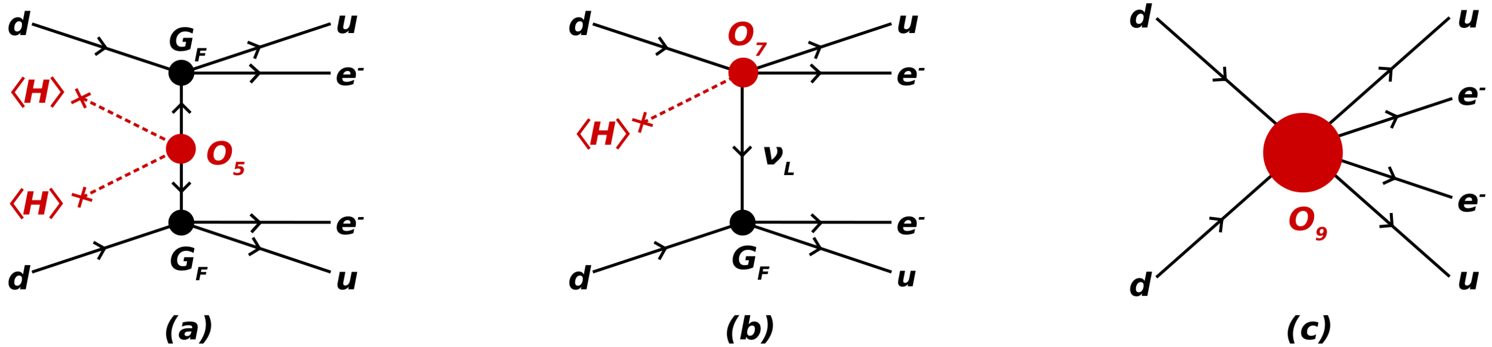


Red line:

Claim for $T^{0\nu\beta\beta}_{1/2}(^{76}Ge) = (1.19^{+0.37}_{-0.23}) \times 10^{25}$ ys

Distinguish mechanisms?

Amplitude for $(Z, A) \rightarrow (Z \pm 2, A) + e^{\mp} e^{\mp}$ can be divided into:



Mass mechanism

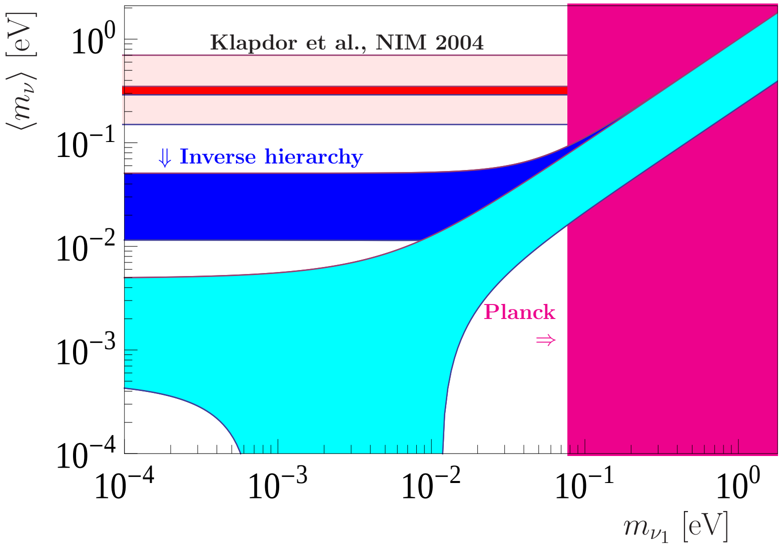
"long-range"

"short-range"

Compare with other experiments:

Cosmology

KATRIN?

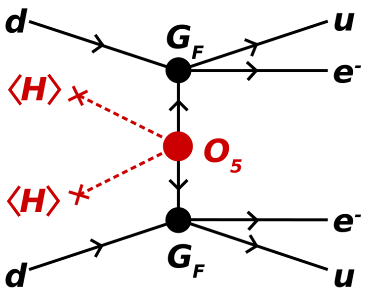


Planck + BAO:

NO overlap with allowed region of $\langle m_\nu \rangle$!

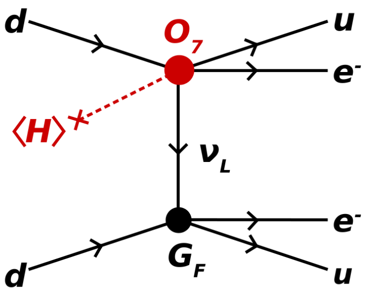
Distinguish mechanisms?

Amplitude for $(Z, A) \to (Z \pm 2, A) + e^{\mp} e^{\mp}$ can be divided into:



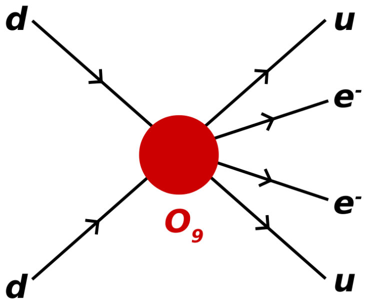
(a)

Mass mechanism



(b)

“long-range”



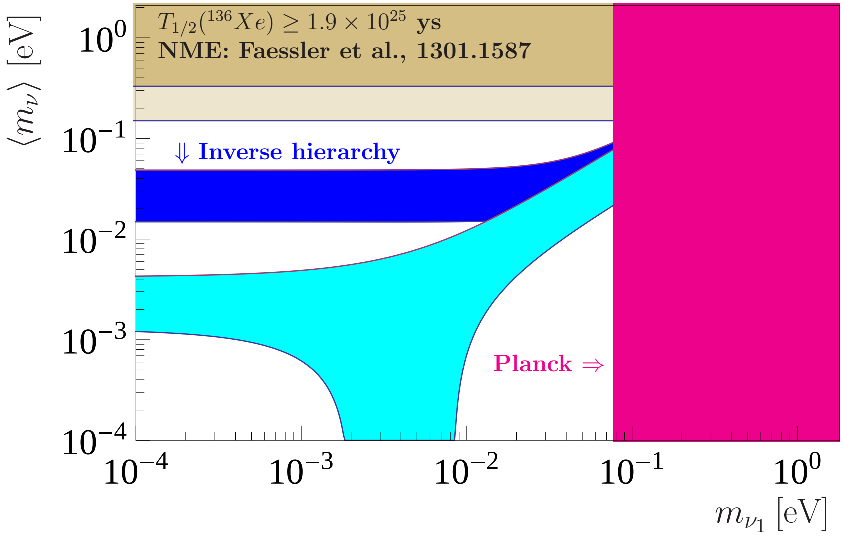
(c)

“short-range”

Compare with other experiments:

Cosmology

KATRIN?



Claim now ruled out by:

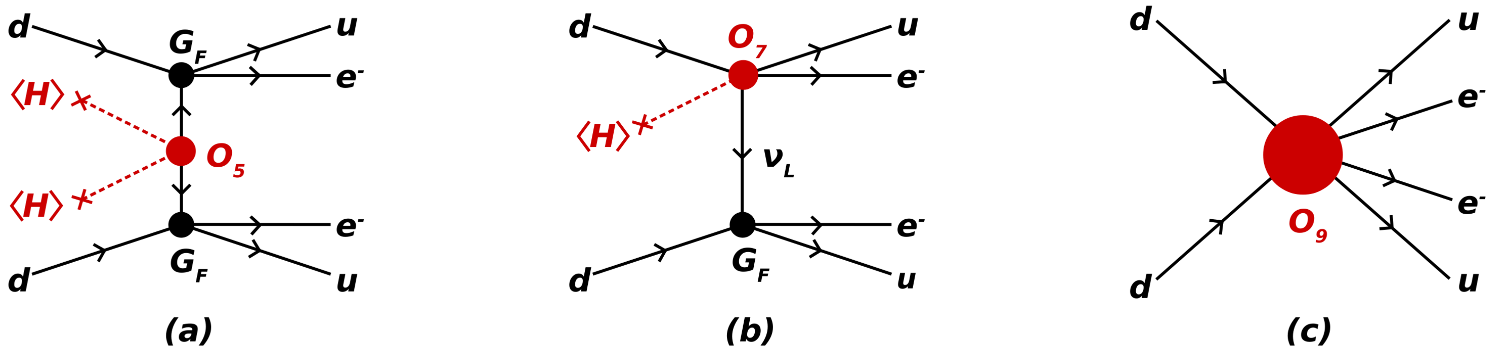
GERDA

EXO-200

KamLAND-Zen

Distinguish mechanisms?

Amplitude for $(Z, A) \to (Z \pm 2, A) + e^{\mp} e^{\mp}$ can be divided into:



(a) (b) (c)

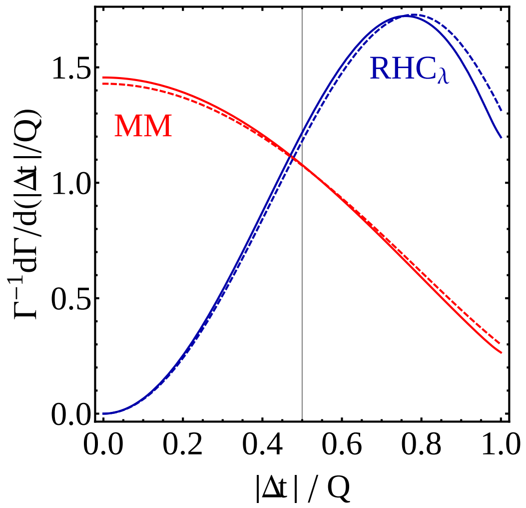
Mass mechanism

“long-range”

“short-range”

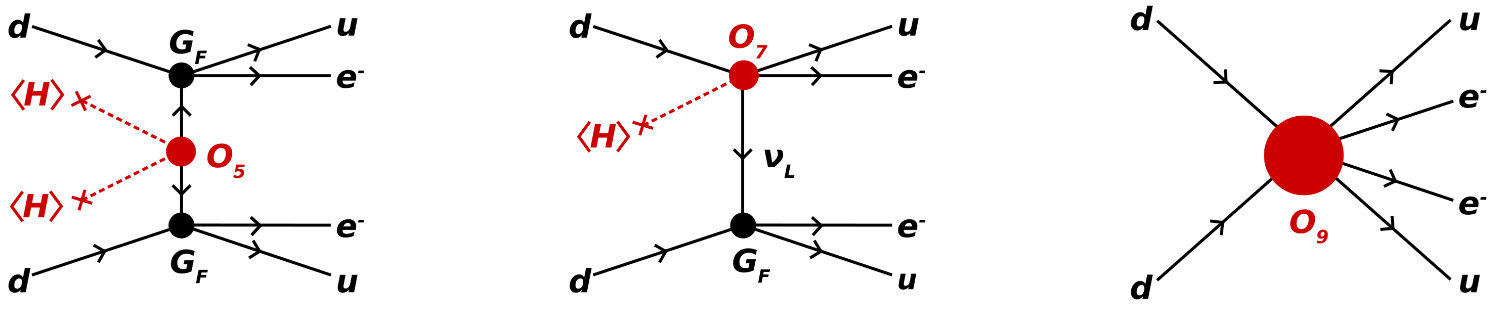
Angular correlations
$0\nu\beta^+/EC$ decays
LHC?

SuperNEMO
Arnold et al., 2010

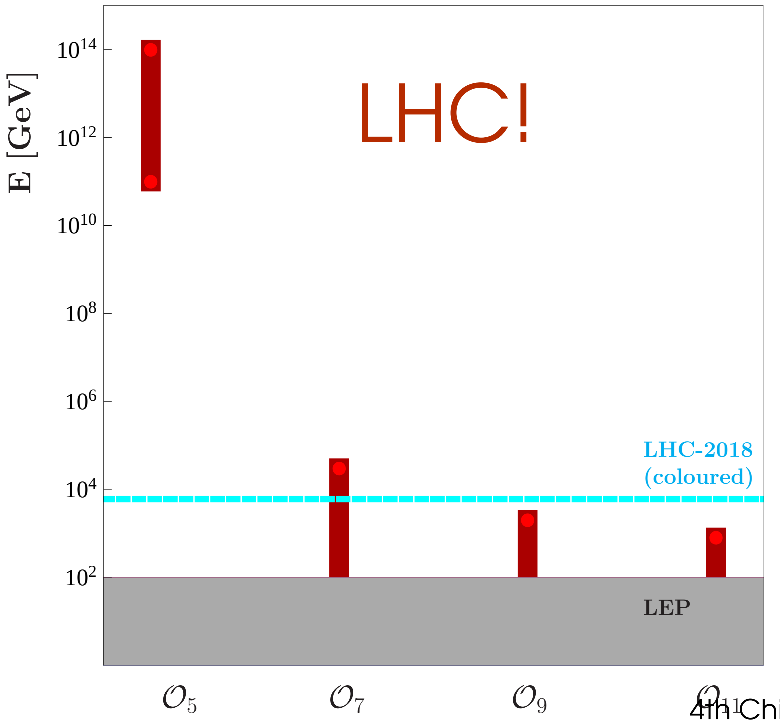


Distinguish mechanisms?

Amplitude for $(Z,A) \to (Z \pm 2, A) + e^{\mp}e^{\mp}$ can be divided into:



(a) (b) (c)



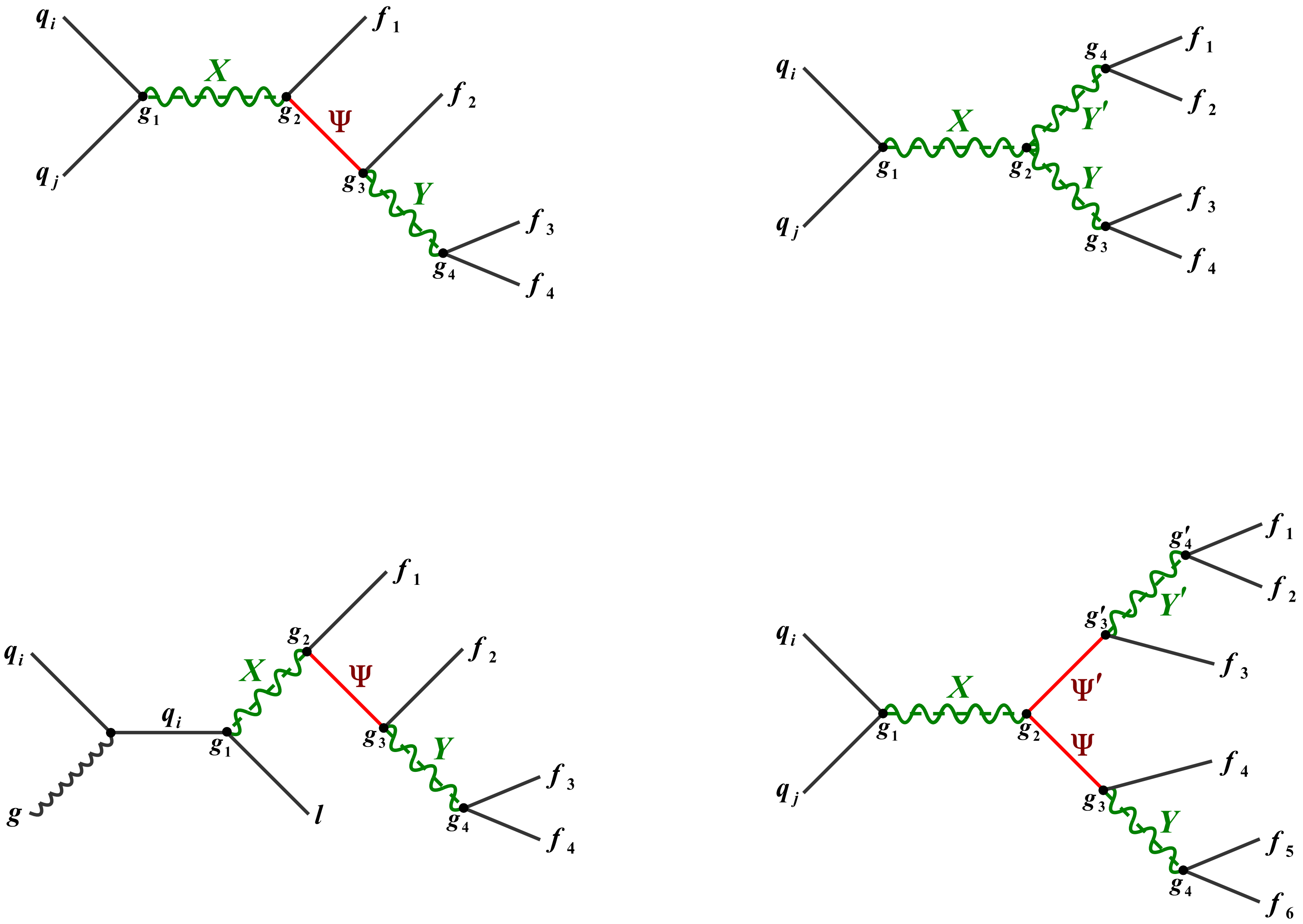
Estimate $0\nu\beta\beta$ sensitivity for different operators:

LHC tests $\mathcal{O}_9$ and $\mathcal{O}_{11}$

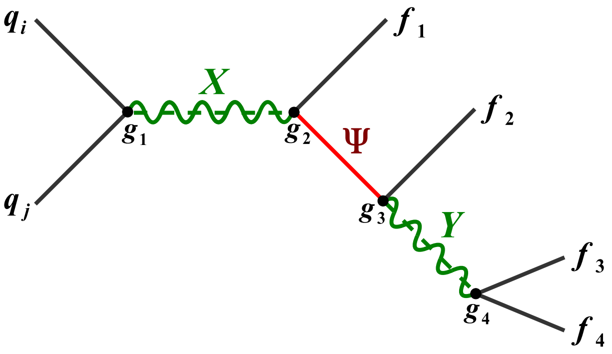
and partially $\mathcal{O}_7$

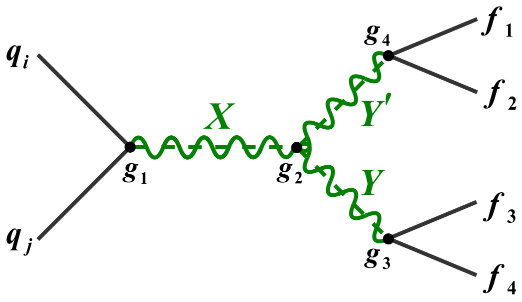
Leptogenesis and LHC

LNV @ LHC


q_i
q_j
X
Ψ
Y
g_1
g_2
g_3
g_4
f_1
f_2
f_3
f_4
q_i
q_j
X
Y'
Y
g_1
g_2
g_3
g_4
f_1
f_2
f_3
f_4
q_i
g
q_i
l
X
Ψ
Y
g_1
g_2
g_3
g_4
f_1
f_2
f_3
f_4
q_i
q_j
X
Ψ'
Ψ
Y'
Y
g_1
g_2
g'_3
g'_4
g_3
g_4
f_1
f_2
f_3
f_4
f_5
f_6

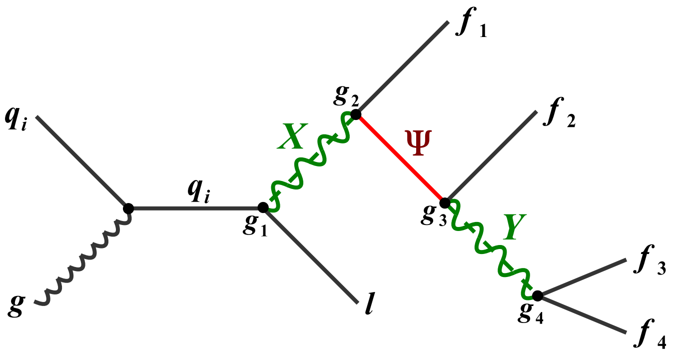
LNV @ LHC

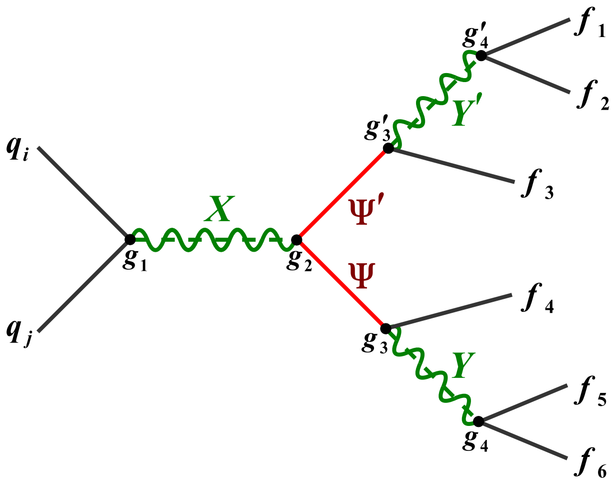




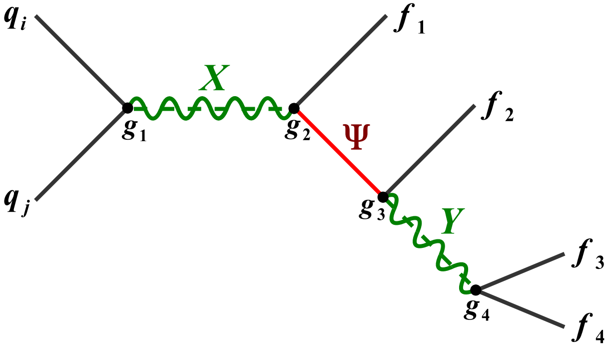
Example:

$u\bar{d} \to W_R^+ \to l^+ N \to l^+ l^+ jj$



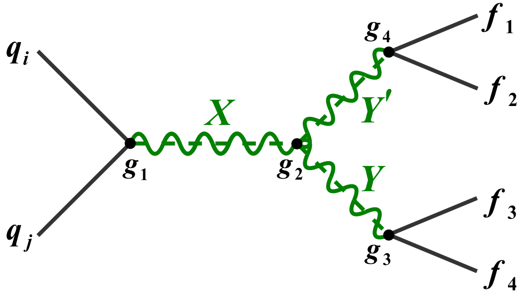


LNV @ LHC



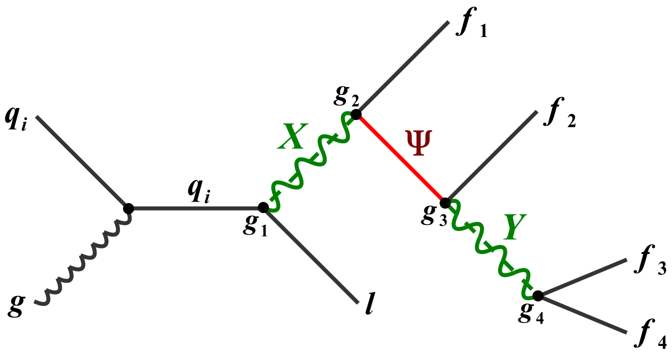
Example:

$u\bar{d} \to W_R^+ \to l^+ N \to l^+ l^+ jj$

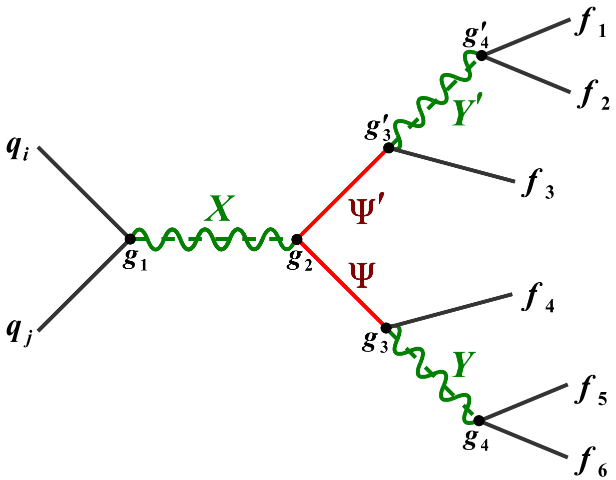


Example:

$uu \to S_{6,3,1/3} \to 2S_{3,2,1/6} \to l^+ l^+ jj$



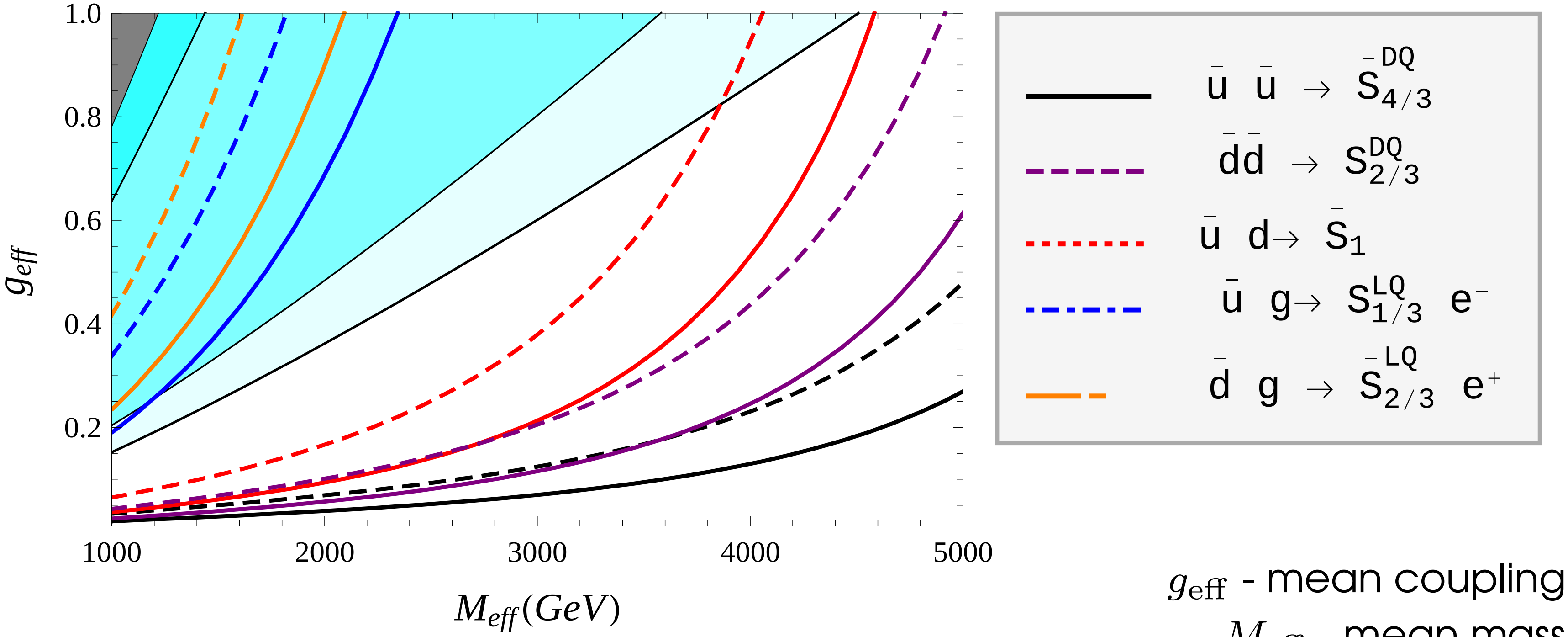
$ug \to S_{3,1,1/3} + l^+ \to l^+ l^+ jjj$



$q\bar{q} \to g \to \psi_{6,2,1/6} + \bar{\psi}_{6,2,1/6} \to l^+ l^+ jjjj$

$0\nu\beta\beta$ and LHC ($\sqrt{s} = 14$ TeV)

J.C. Helo et al,
PRD88 (2013)



g_{eff} - mean coupling
M_{eff} - mean mass

$\Rightarrow$ Assumed upper limit on $\sigma(pp \rightarrow X)$: 10^{-2} fb

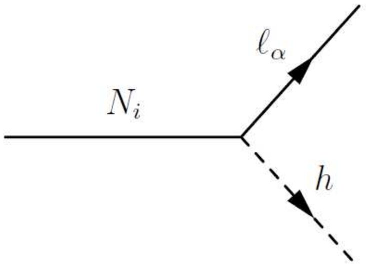
$\Rightarrow$ $m_F = 1000$ GeV (realistic (?) case)

$\Rightarrow$ Full lines: Br$= 10^{-1}$, dashed lines Br$= 10^{-2}$

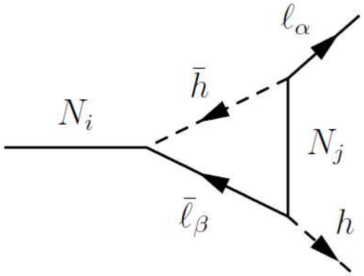
Leptogenesis

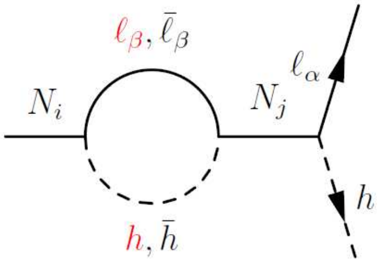
Sakharov's conditions:

(i) Baryon number violation
(ii) C and CP violation
(iii) departure from thermal equilibrium



(e) Tree



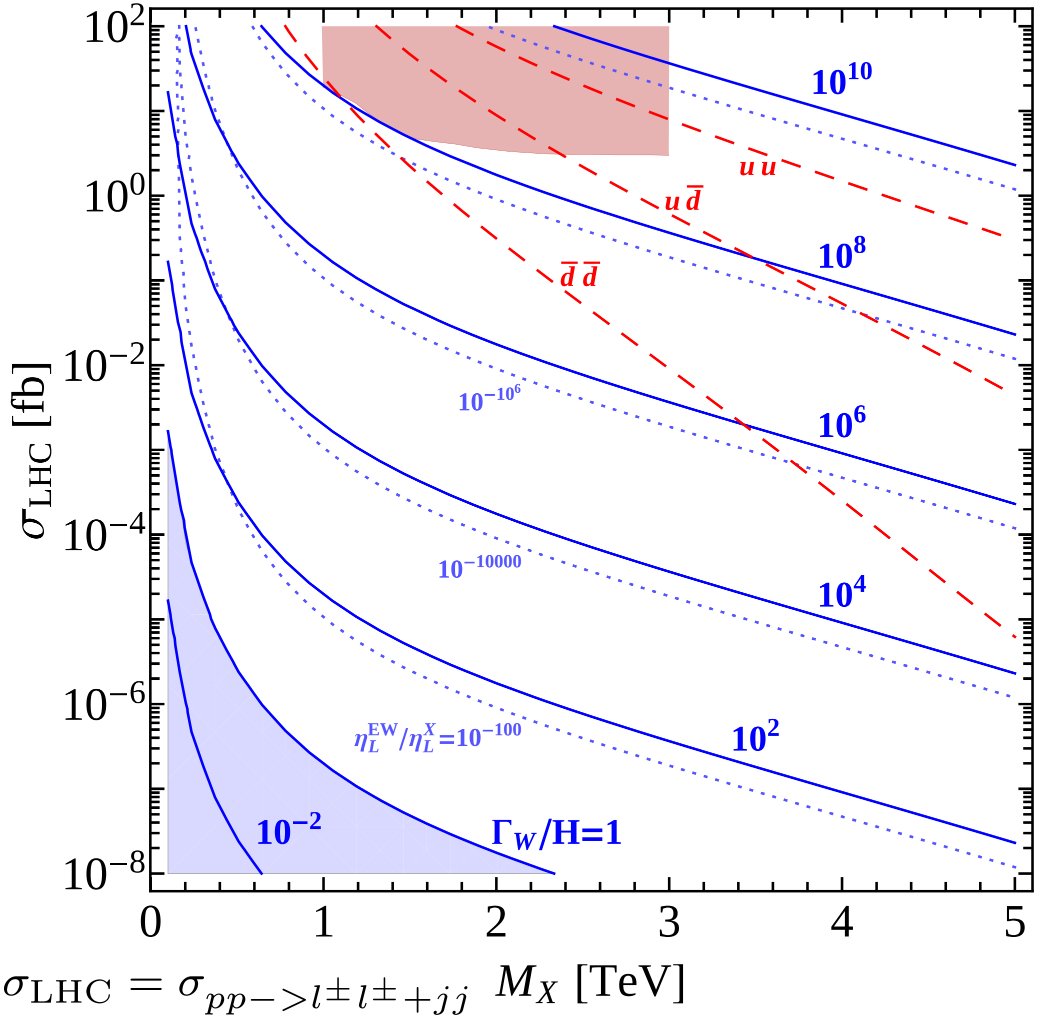


In Leptogenesis:

(i) Convert L to B through SM sphalerons
(ii) CP violation through interference tree $\leftrightarrow$ 1-loop
(iii) L out of equilibrium via right-handed neutrino decay

Leptogenesis and LHC

Deppisch, Hartz & Hirsch
PRL 112 (2014)



$\sigma_{\rm LHC} = \sigma_{pp->l^\pm l^\pm + jj}$

blue lines
washout factor Γ_W
- Suppression of L $\propto 10^{-\Gamma_W}$

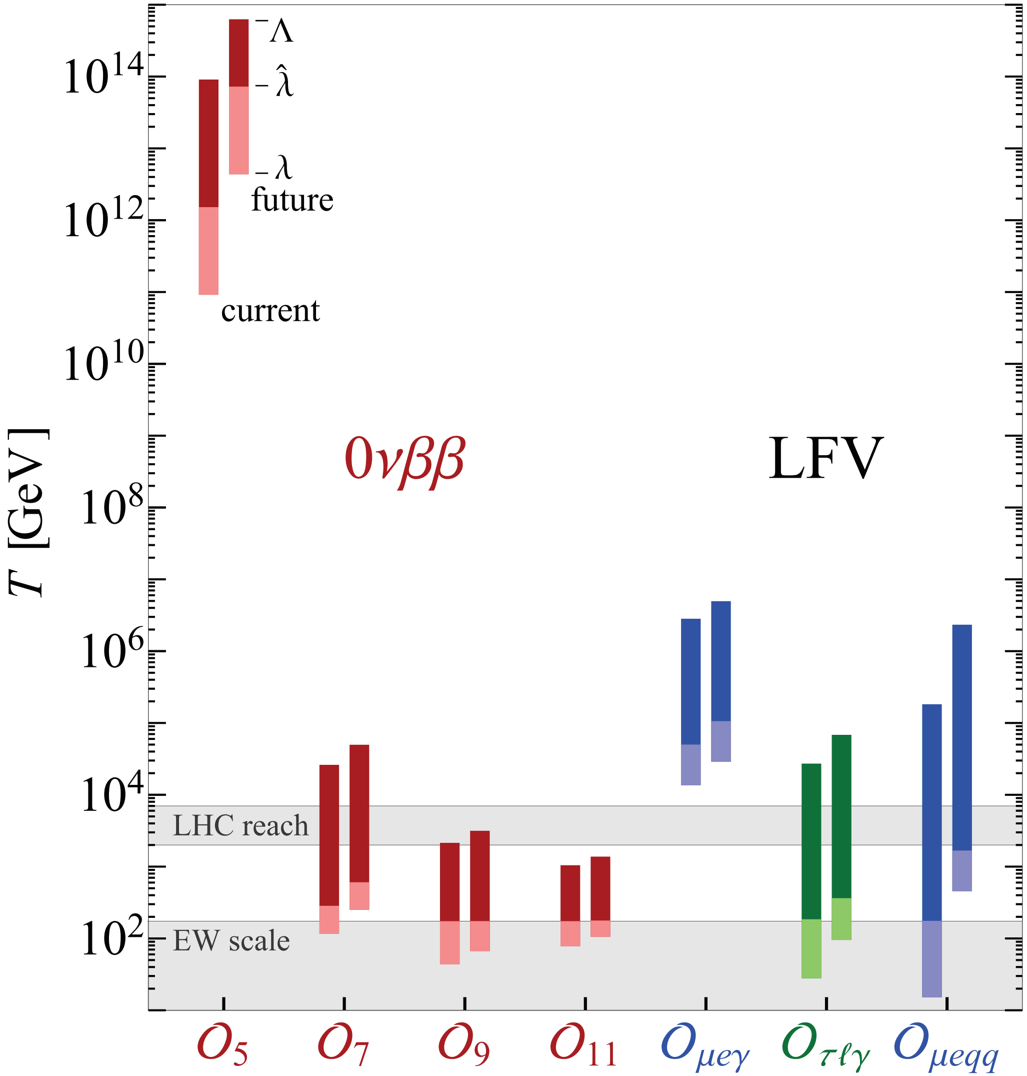
Observation of
LNV @ LHC implies:
(High-scale) Leptogenesis
is ruled out!

Loopholes???

(i) Resonant LG
with $m_N \ll m_X$?

(ii) Hide LG in τ's?

LG and $0\nu\beta\beta$ decay



Deppisch et al.,
2015

If $0\nu\beta\beta$ is found
and demonstrated to be
not due to $\langle m_\nu \rangle$

LG ruled out above
scale λ