

A photograph of a large, paved square in Olomouc, Czech Republic. In the background, the historic town hall building with its green-roofed tower and clock face is visible. To the right stands the Baroque Holy Trinity Column, a tall stone pillar topped with a golden statue of the Virgin Mary. The sky is a warm, orange-tinted sunset. The foreground is a dark, paved surface.

IDPASC, Olomouc, September I 2022

Massive neutrinos

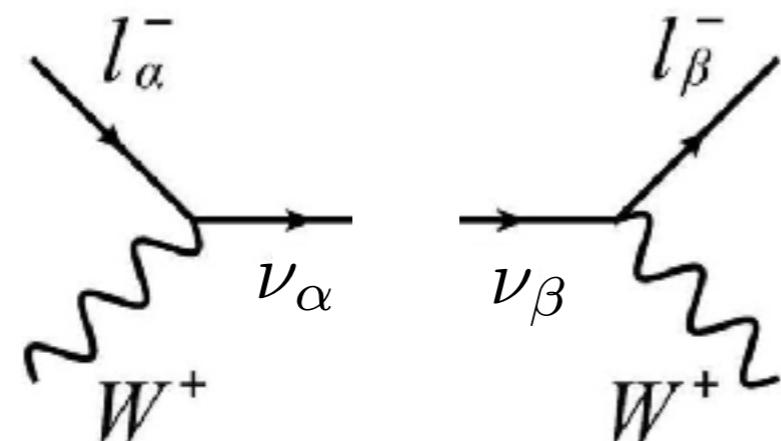
Michal Malinský

Institute of particle and nuclear physics, Charles University in Prague

Non-zero neutrino mass effects

Neutrino oscillations

Neutrinos produced in weak interactions \neq mass eigenstates (?)



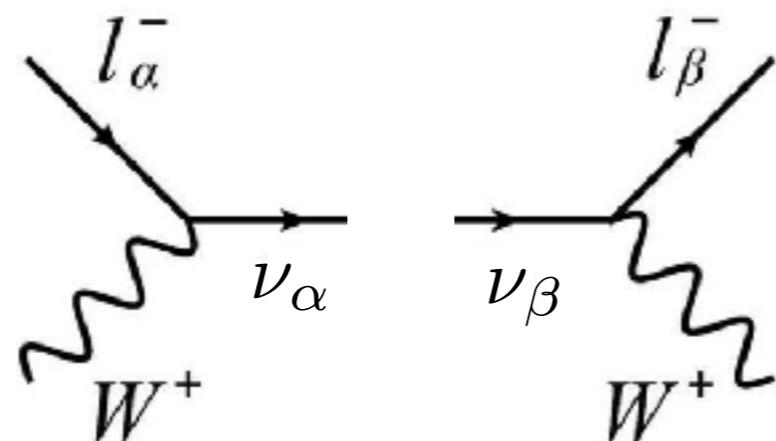
$$|\nu_\alpha\rangle = U_{\alpha 1}^* |\nu_1\rangle + U_{\alpha 2}^* |\nu_2\rangle$$

B. Pontecorvo, Sov.Phys.JETP 6 (1957) 429

Бруно Понтекорво

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NB Neutral kaon oscillations 1957

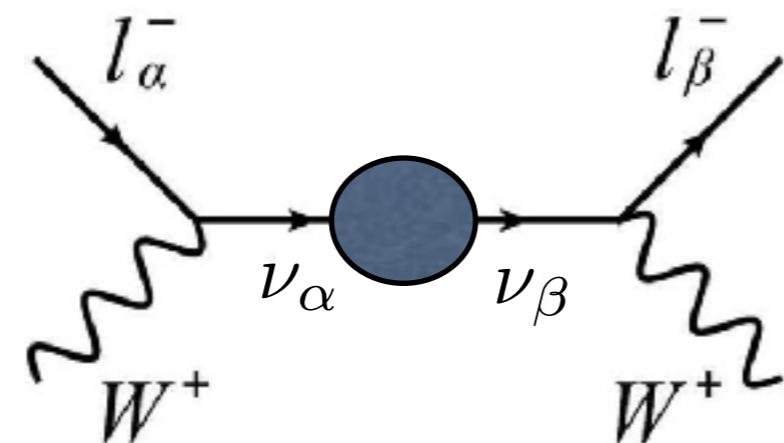
NB Muon neutrinos not before 1962!

M.L. Good, Phys. Rev. 106 (1957) 591

Lederman, Schwarz, Steinberger

Neutrino oscillations

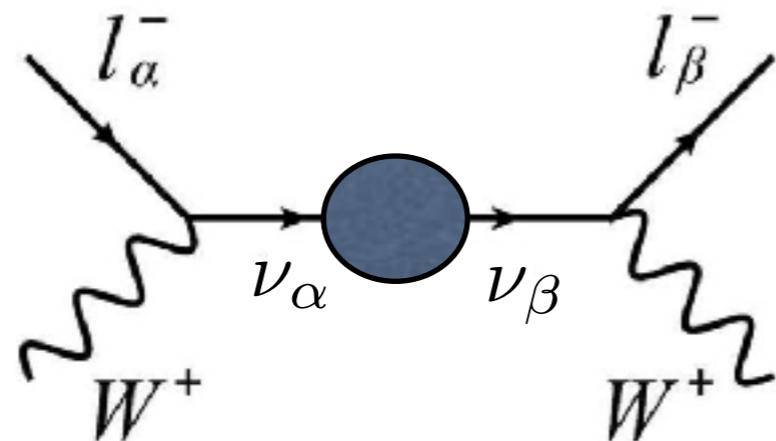
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$$|\psi, t\rangle = e^{-iHt} |\nu_e\rangle \quad \langle \nu_e | \psi, t \rangle = \langle \nu_e | e^{-iHt} |\nu_e\rangle = \sum_{i=1}^2 e^{-iE_i t} U_{ei} U_{ei}^*$$

Survival probability:

$$P(\nu_e \rightarrow \nu_e) = \dots = 1 - \sin^2 2\theta \times \text{oscillation factor}$$

mixing angle $\left(\frac{m_2^2 - m_1^2}{4E} L \right)$

Mixing in the lepton sector...

Direct analogy with quarks: $\mathcal{L} \ni \frac{g}{\sqrt{2}} \overline{u}_L^\alpha \gamma^\mu \textcolor{red}{V}_{\alpha i} d_L^i W_\mu^+ + h.c.$

$$\mathcal{L} \ni \frac{g}{\sqrt{2}} \overline{\ell}_L^\alpha \gamma^\mu \textcolor{red}{U}_{\alpha i} \nu_L^i W_\mu^- + h.c.$$

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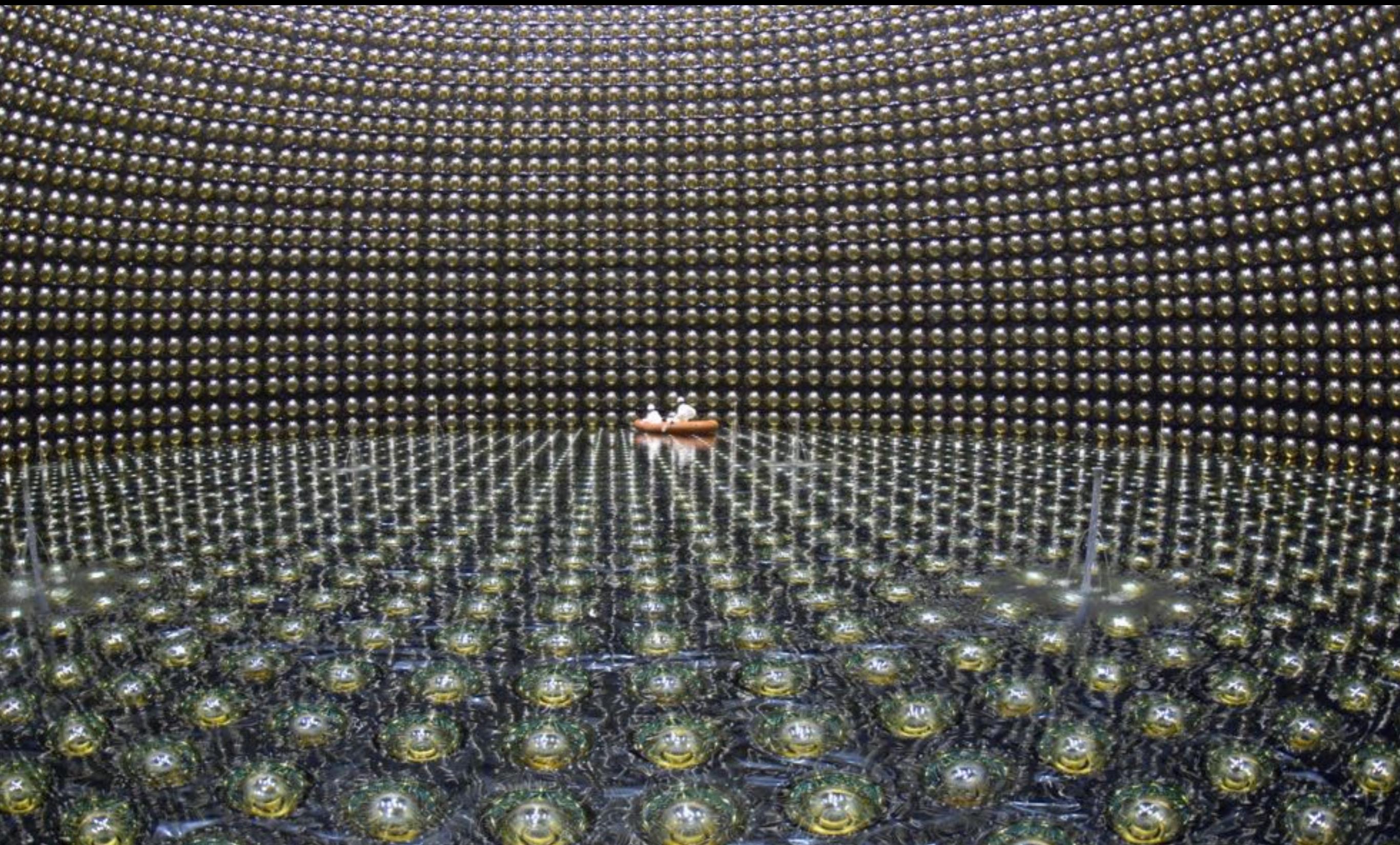
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$$\textcolor{red}{U} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{23}c_{12}s_{13}e^{i\delta} & c_{23}c_{12} - s_{23}s_{12}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}c_{12}s_{13}e^{i\delta} &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

Pontecorvo - Maki - Nakagawa - Sakata matrix

3 angles, 1 CP phase (visible in oscillations)

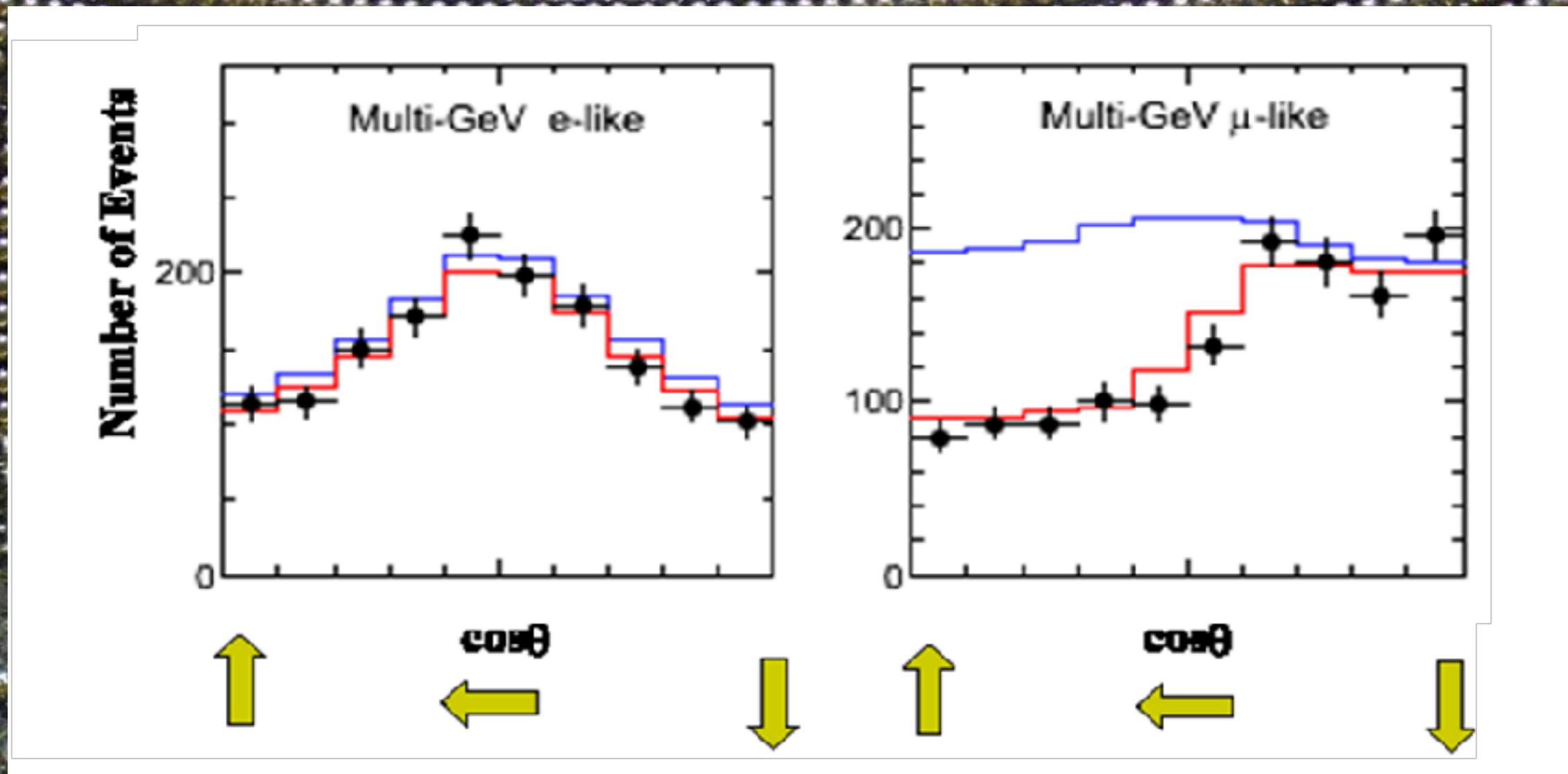
Atmospheric neutrino oscillations (1998)



Super-Kamiokande

50,000 tons of ultrapure water, about 11,000 PMTs

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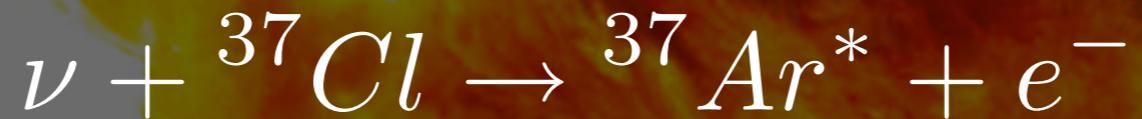


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Solar neutrino puzzle

late 1960's: Homestake mine, SD



Ray Davis jr.

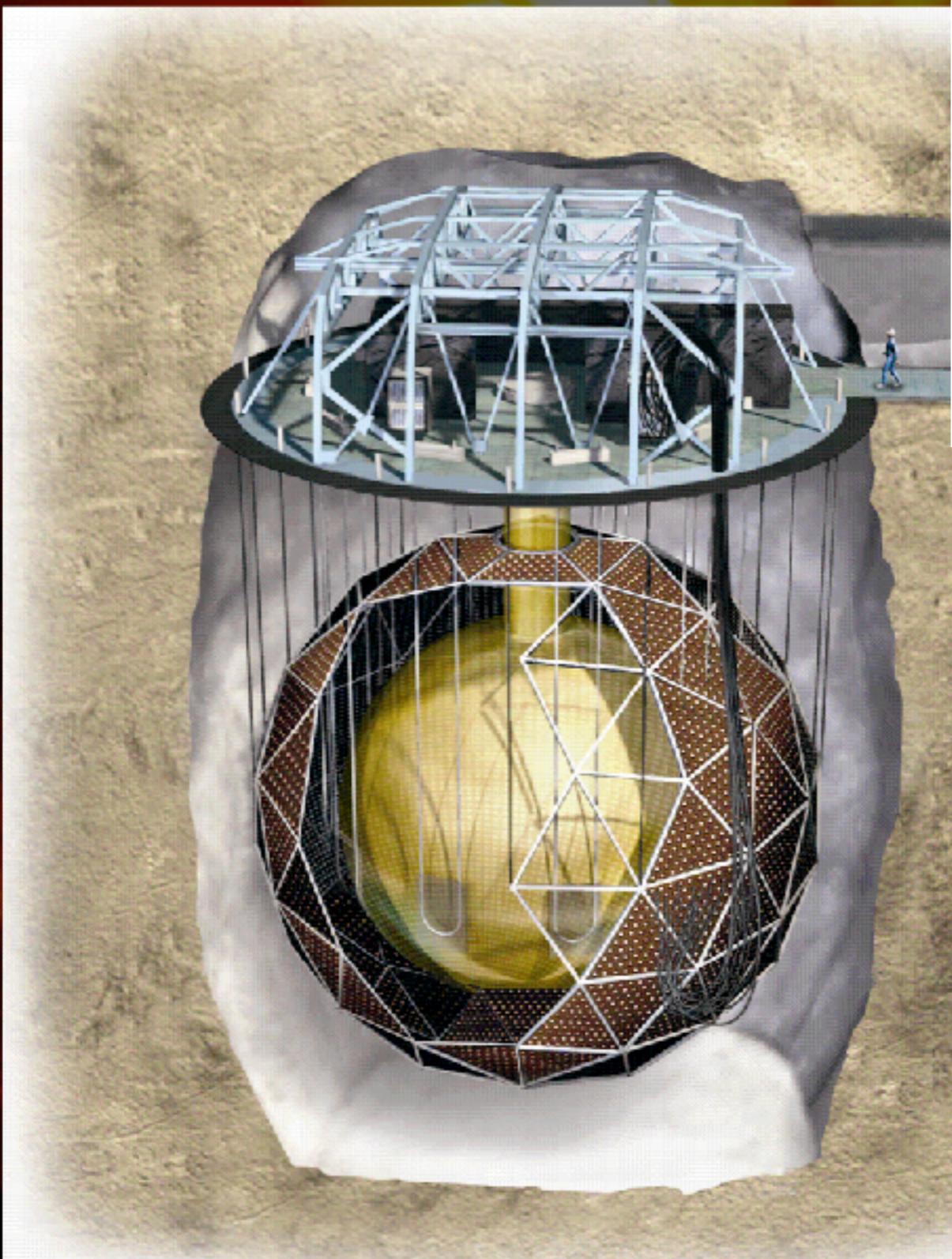


John Bahcall



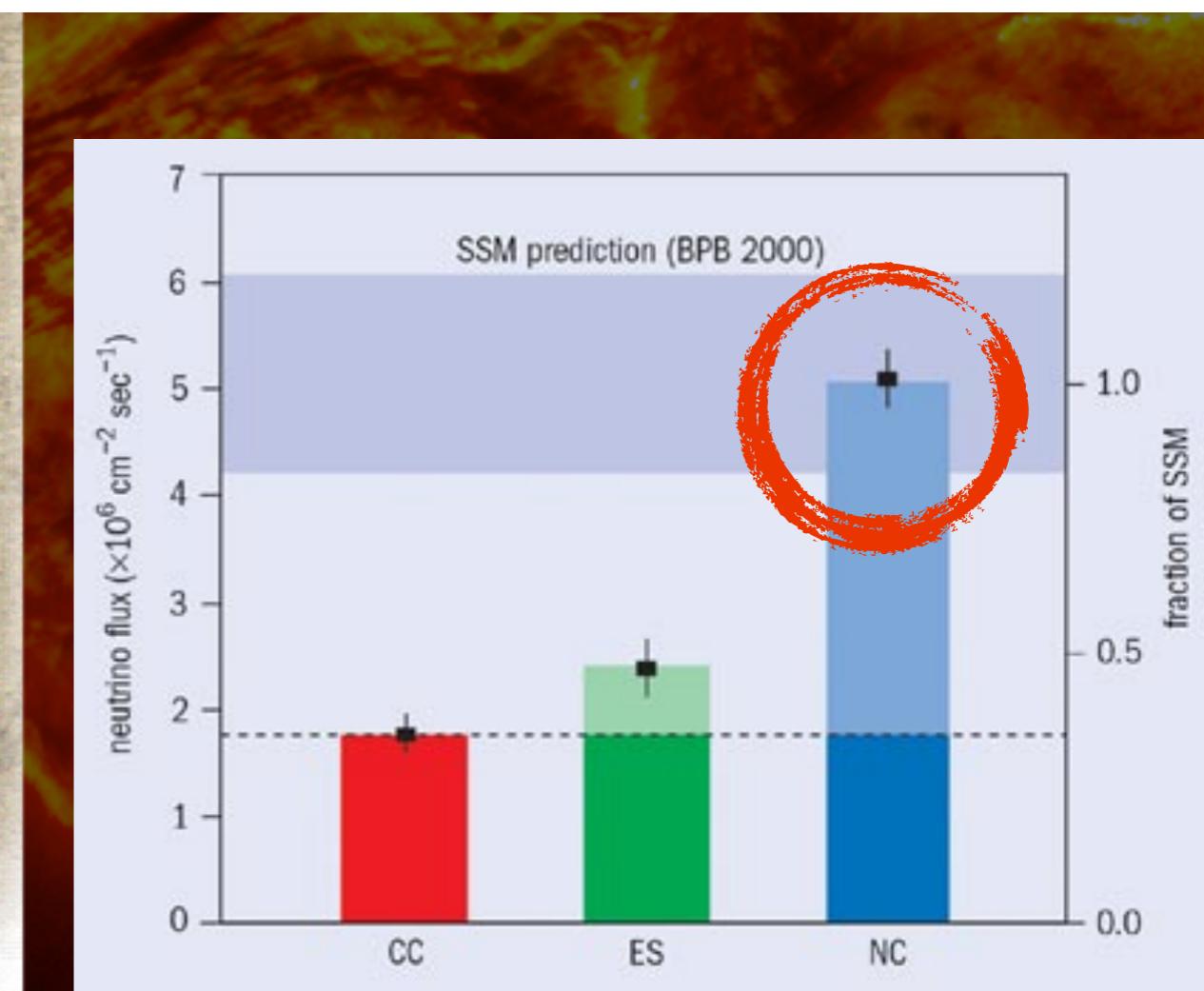
Only 1/3 of the predicted flux observed!

SNO (2000)



CC Charged Current Reaction	$v_e + d \rightarrow p + p + e^-$ only electron neutrinos in CC	$E_{threshold} = 1.4\text{MeV}$
NC Neutral Current Reaction	$v_x + d \rightarrow v_x + p + n$ all types in NC !!!	$E_{threshold} = 2.2\text{MeV}$
ES Elastic Scattering Reaction	$v_x + e^- \rightarrow v_x + e^-$ electron neutrinos preferred	$E_{threshold} \approx 0$

x denotes that this reaction will take place with any neutrino.



Neutrino oscillation parameters

Parameter	Best fit $\pm 1\sigma$	2σ range	3σ range
Δm_{21}^2 [10^{-5} eV 2]	$7.55^{+0.20}_{-0.16}$	7.20–7.94	7.05–8.14
$ \Delta m_{31}^2 $ [10^{-3} eV 2] (NO)	2.50 ± 0.03	2.44–2.57	2.41–2.60
$ \Delta m_{31}^2 $ [10^{-3} eV 2] (IO)	$2.42^{+0.03}_{-0.04}$	2.34–2.47	2.31–2.51
$\sin^2 \theta_{12}/10^{-1}$	$3.20^{+0.20}_{-0.16}$	2.89–3.59	2.73–3.79
$\theta_{12}/^\circ$	$34.5^{+1.2}_{-1.0}$	32.5–36.8	31.5–38.0
$\sin^2 \theta_{23}/10^{-1}$ (NO)	$5.47^{+0.20}_{-0.30}$	4.67–5.83	4.45–5.99
$\theta_{23}/^\circ$	$47.7^{+1.2}_{-1.7}$	43.1–49.8	41.8–50.7
$\sin^2 \theta_{23}/10^{-1}$ (IO)	$5.51^{+0.18}_{-0.30}$	4.91–5.84	4.53–5.98
$\theta_{23}/^\circ$	$47.9^{+1.0}_{-1.7}$	44.5–48.9	42.3–50.7
$\sin^2 \theta_{13}/10^{-2}$ (NO)	$2.160^{+0.083}_{-0.069}$	2.03–2.34	1.96–2.41
$\theta_{13}/^\circ$	$8.45^{+0.16}_{-0.14}$	8.2–8.8	8.0–8.9
$\sin^2 \theta_{13}/10^{-2}$ (IO)	$2.220^{+0.074}_{-0.076}$	2.07–2.36	1.99–2.44
$\theta_{13}/^\circ$	$8.53^{+0.14}_{-0.15}$	8.3–8.8	8.1–9.0

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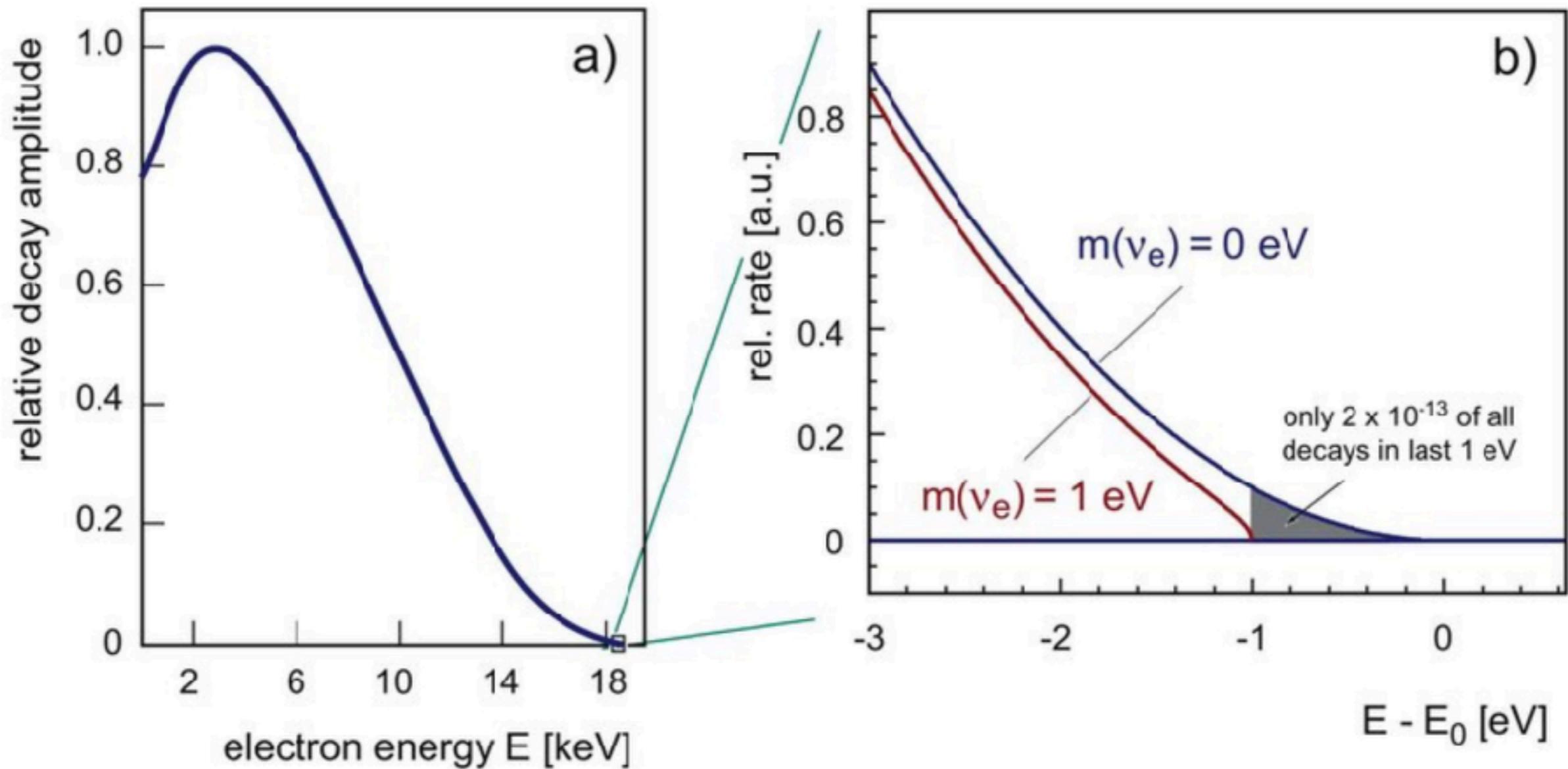
Parameter	Best fit $\pm 1\sigma$	2σ range	3σ range
δ/π (NO)	$1.32^{+0.21}_{-0.15}$	1.01–1.75	0.87–1.94
$\delta/^\circ$	238^{+38}_{-27}	182–315	157–349
δ/π (IO)	$1.56^{+0.13}_{-0.15}$	1.27–1.82	1.12–1.94
$\delta/^\circ$	281^{+23}_{-27}	229–328	202–349

A clear laboratory signal of physics beyond the SM!

**At least 2 neutrinos must be massive
(though presumably very light)**

Absolute neutrino mass scale (indirect indications)

Laboratory: beta decay spectrum



Laboratory: beta decay spectrum

KATRIN



$m_\nu < 1.1 \text{ eV}$ (90 % CL), goal: 0.2 eV (90 % CL) after 1000 days of data taking

Cosmology: neutrinos as a DM component

stable + neutral + abundant

Critical density fraction in neutrinos : $\Omega_\nu h_0^2 \sim 0.01 \times m_\nu$ [eV]

see cosmology lectures by Costas

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Cowsik - McClelland limit:

$$m_\nu \text{ [eV]} \lesssim 100 \times \Omega_\nu h_0^2$$

Gershtein, Zeldovic 1966

R. Cowsik, J. McClelland, Phys.Rev.Lett. 29 (1972) 669-670

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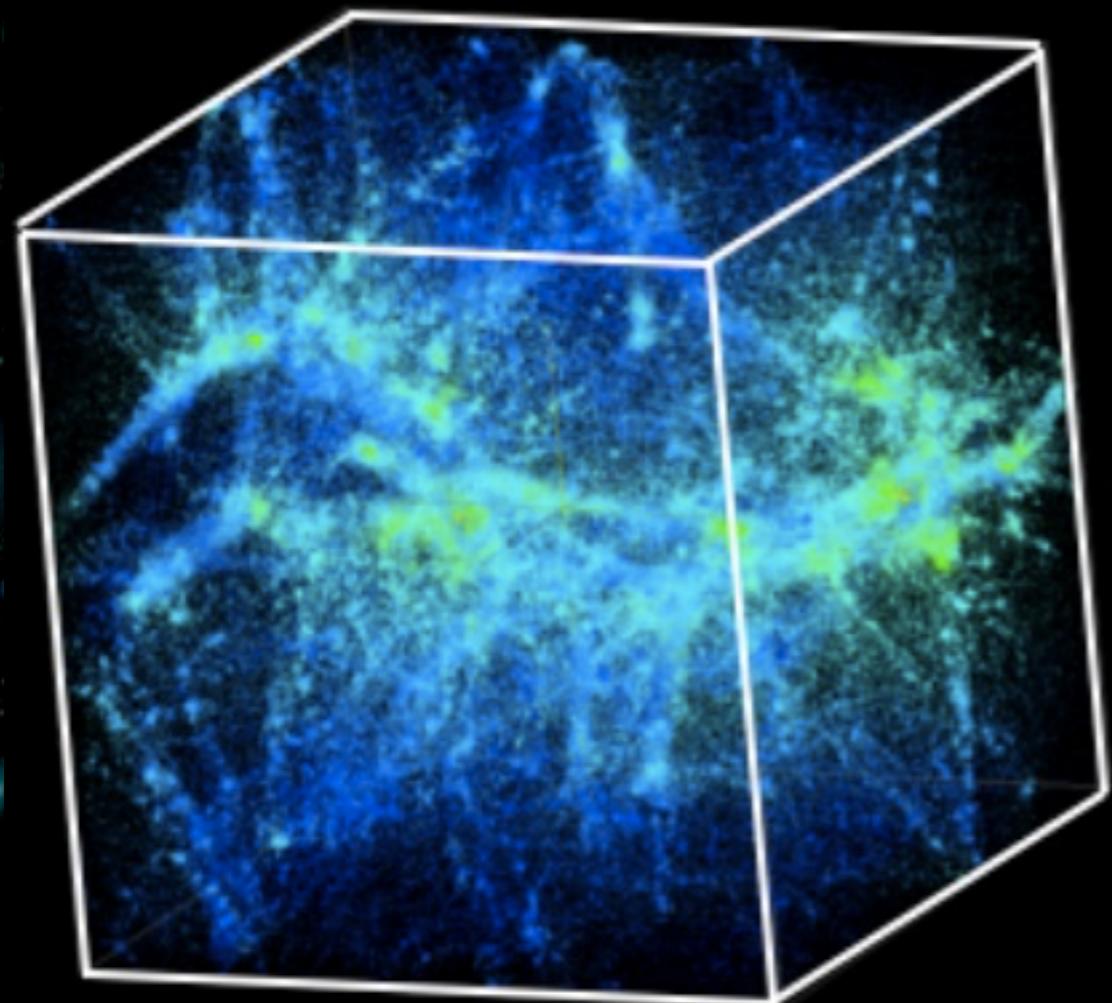
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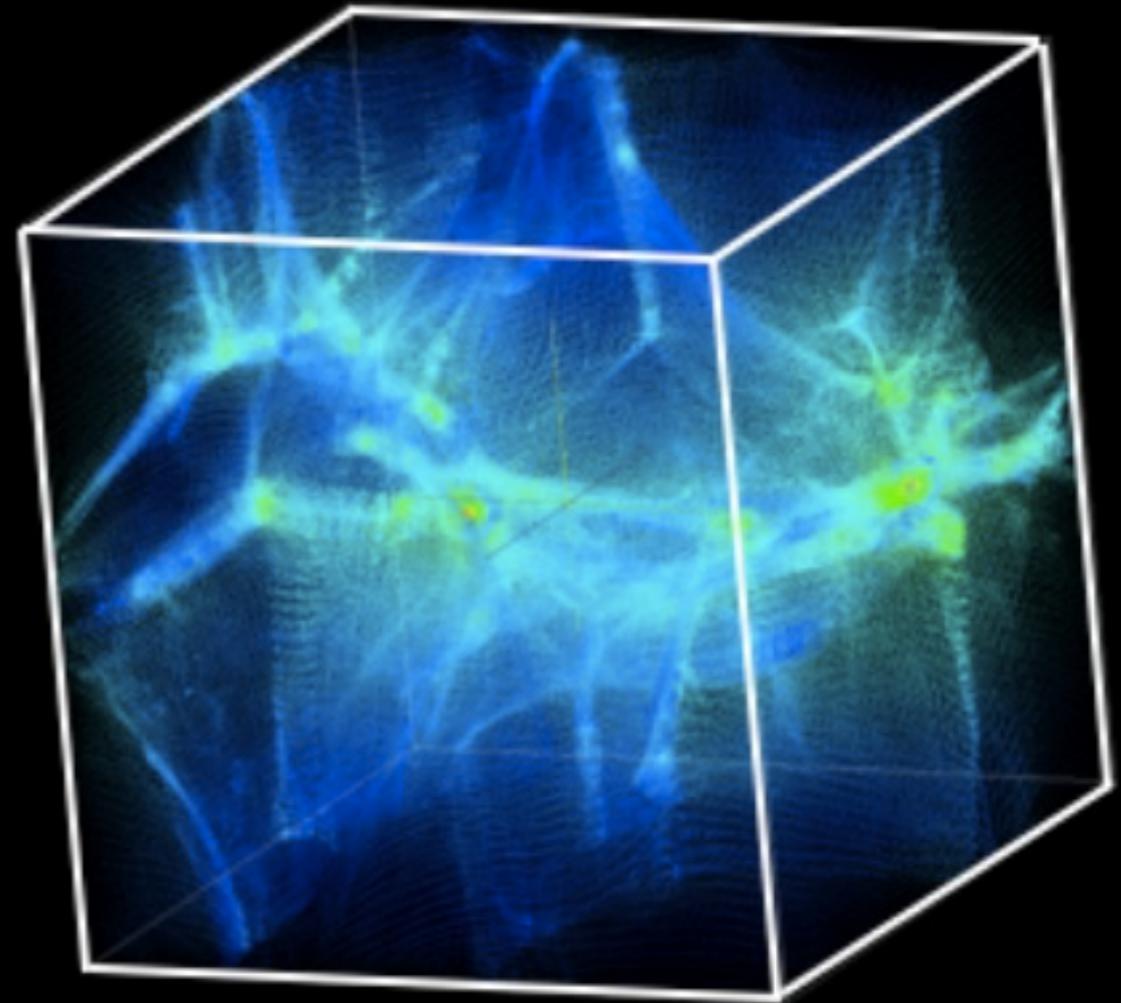
Structure formation tells us that this can not be saturated!

Structure formation with ν -dominated DM

Standard Model



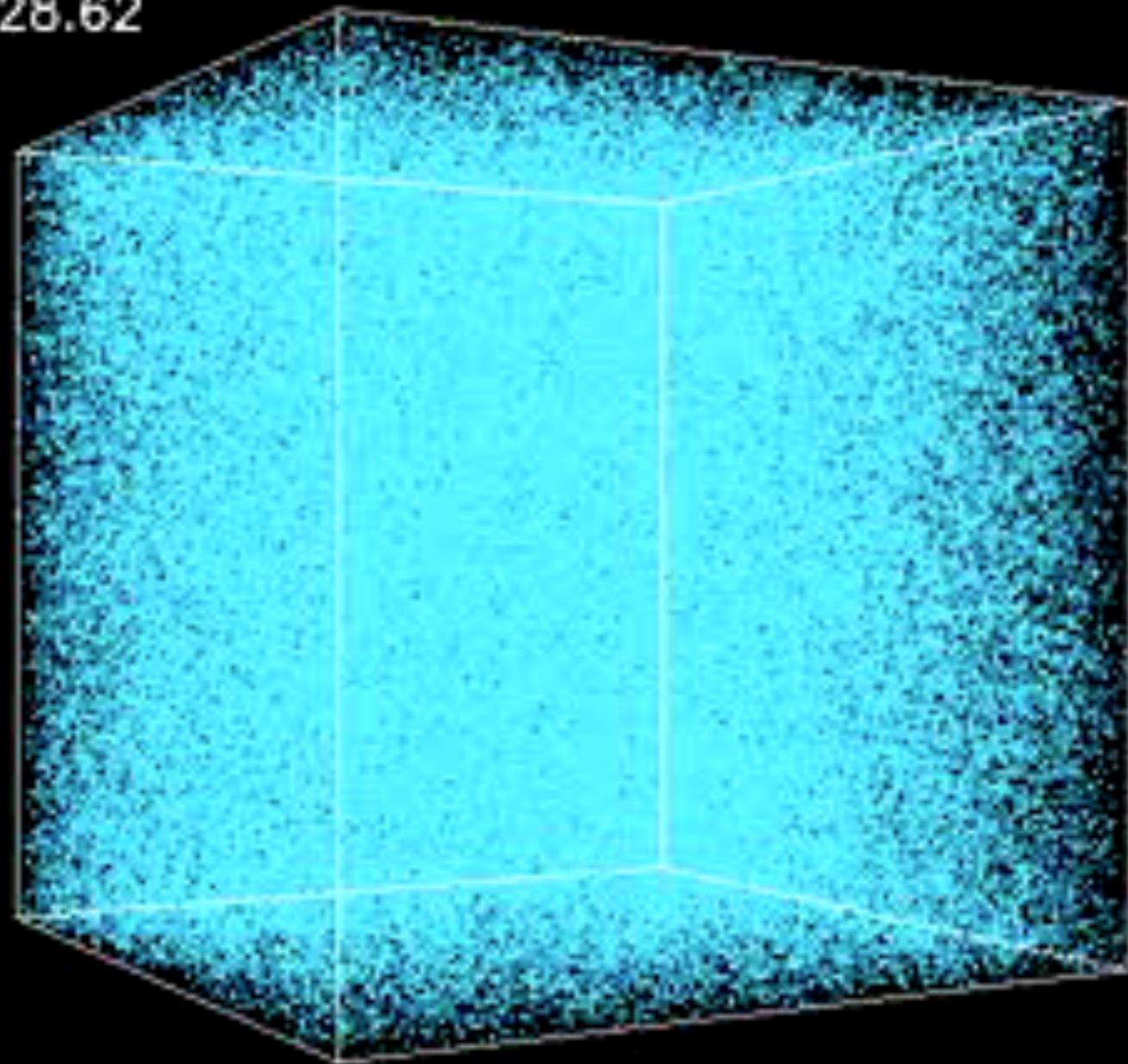
Warm dark matter



credit: K. Heitmann, Argonne NL

Structure formation in the Λ CDM cosmology

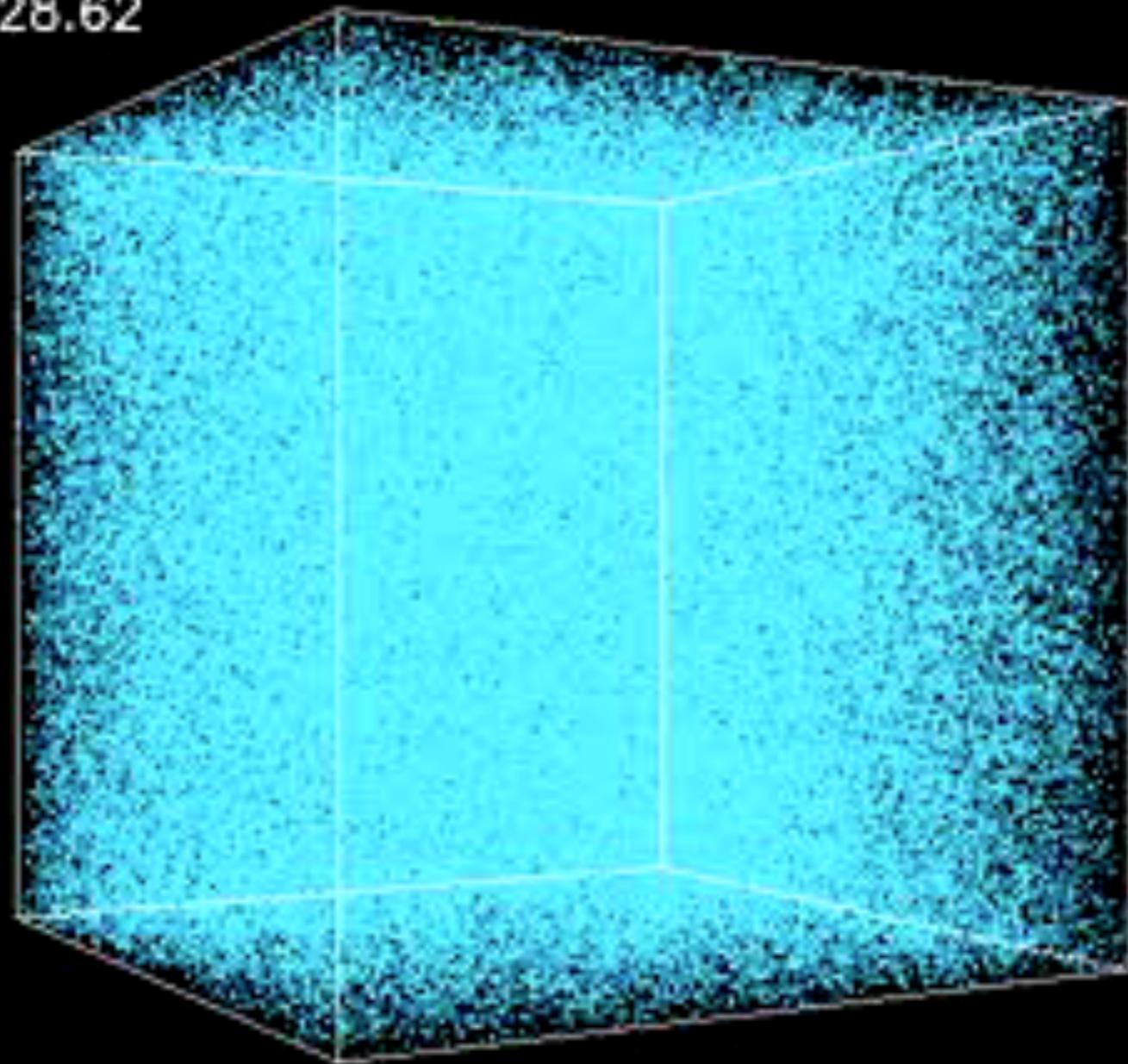
$Z=28.62$



credit: A. Kravtsov, A. Klypin, NCSA/CCP

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For details see Costas’ lecture

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Supercluster-size!

Devising massive neutrinos in simple extensions of the SM

Devising neutrino masses: the Dirac option

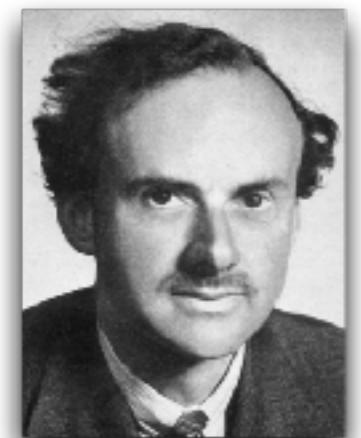
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Dirac mass terms (QED-like): $m \overline{\psi_L} \psi_R + h.c.$

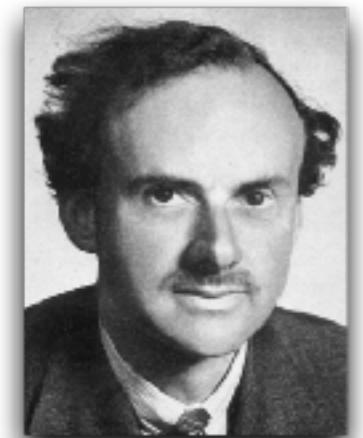


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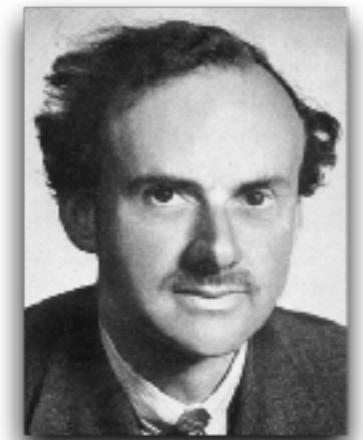
$$Y_{Dij} \overline{Q_L}_i \langle H \rangle D_{Rj} + Y_{Uij} \overline{Q_L}_i \langle \tilde{H} \rangle U_{Rj} + Y_{Eij} \overline{L_L}_i \langle H \rangle E_{Rj}$$

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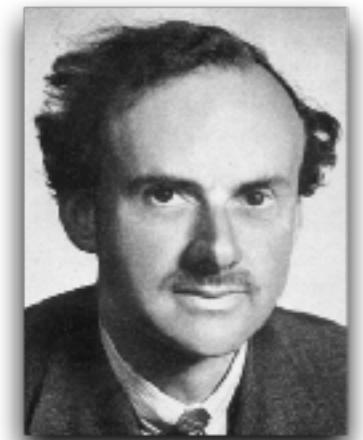
How about simply adding a RH neutrino component?

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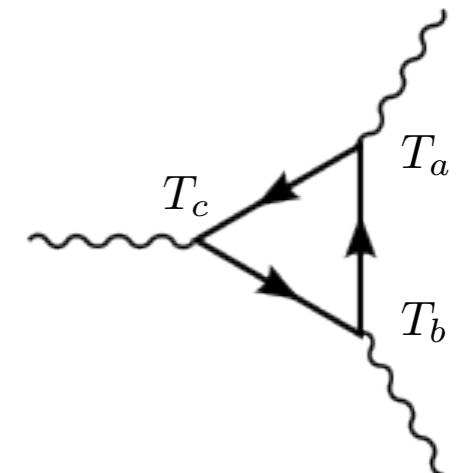
This is non as trivial as it may seem...

Charge dequantization in the SM with Dirac neutrinos

$SU(3) \times SU(2) \times U(1)$ gauge anomalies

$$\mathcal{A}_c \propto \frac{1}{32\pi^2} \text{Tr} (\{T_a, T_b\} T_c) \tilde{F}_{\mu\nu}^a F^{b\mu\nu}$$

$$\begin{aligned} Q_L &= (3, 2, Y_Q) \\ u_R &= (3, 1, Y_U) \\ d_R &= (3, 1, Y_D) \\ L_L &= (1, 2, Y_L) \\ e_R &= (1, 1, Y_E) \end{aligned}$$



R. Foot, H. Lew, and R. Volkas, J.Phys.G G19, 361 (1993)

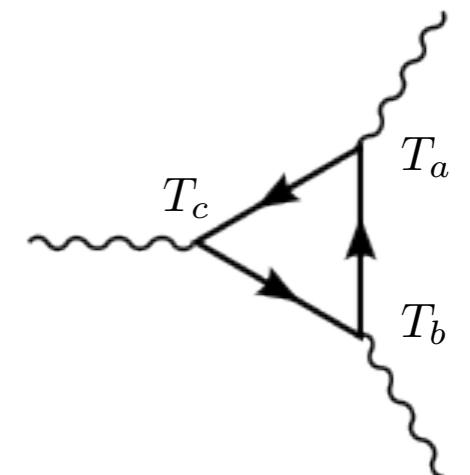
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$U(1)^3$:

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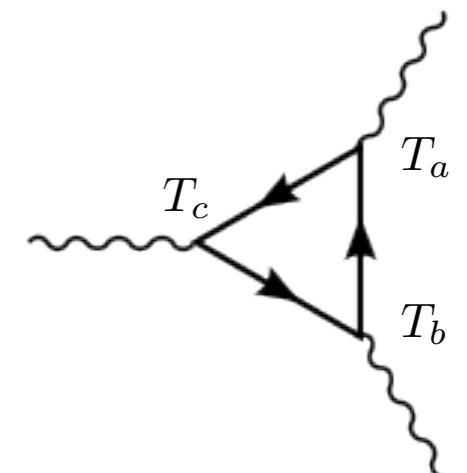
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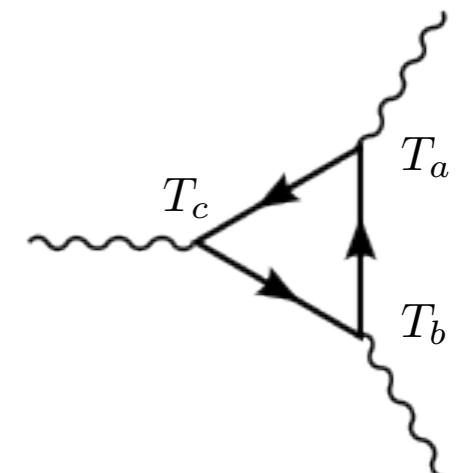
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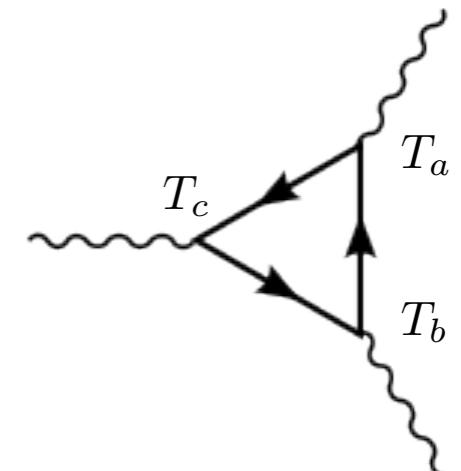
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$$-Y_Q + Y_D + Y_H = 0$$

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$$-Y_Q + Y_U - Y_H = 0$$

Solution:	$Y_Q = +\frac{1}{6}, \quad Y_U = +\frac{2}{3}, \quad Y_D = -\frac{1}{3},$
$Y_L = -\frac{1}{2}, \quad Y_E = -1$	

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With RH neutrinos one has one more variable:

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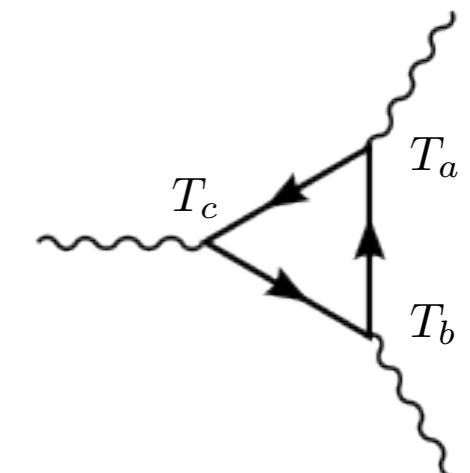
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Yukawas: $Y_{Dij} \overline{Q_L}_i \langle H \rangle D_{Rj} + Y_{Uij} \overline{Q_L}_i \langle \tilde{H} \rangle U_{Rj} + Y_{Eij} \overline{L_L}_i \langle H \rangle E_{Rj}$

$$-Y_Q + Y_D + Y_H = 0$$

$$-Y_L + Y_E + Y_H = 0$$

$$-Y_Q + Y_U - Y_H = 0$$

Solution:

$Y_Q = +\frac{1}{6}$, $Y_U = +\frac{2}{3}$, $Y_D = -\frac{1}{3}$,
$Y_L = -\frac{1}{2}$, $Y_E = -1$		

R. Foot, H. Lew, and R. Volkas, J.Phys.G G19, 361 (1993)

Charge dequantization in the SM with Dirac neutrinos

$SU(3) \times SU(2) \times U(1)$ gauge anomalies

$$\mathcal{A}_c \propto \frac{1}{32\pi^2} \text{Tr} (\{T_a, T_b\} T_c) \tilde{F}_{\mu\nu}^a F^{b\mu\nu}$$

With RH neutrinos one has one more variable:

Trick: just $SU(2) \times U(1)$ + Yukawas

$SU(2)^2 U(1)$:

$$6Y_Q + 2Y_L = 0$$

$U(1)^3$:

$$12Y_Q^3 + 4Y_L^3 - 6Y_U^3 - 6Y_D^3 - 2Y_E^3 - 2Y_N^3 = 0$$

$$N_R = (1, 1, Y_N)$$

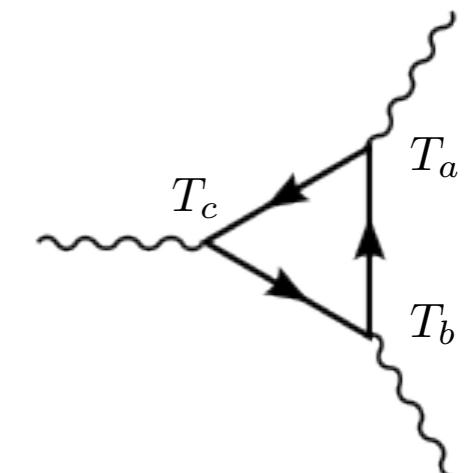
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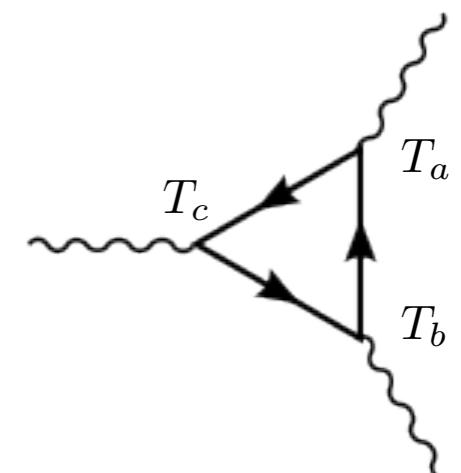
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$$-Y_L + Y_N - Y_H = 0$$

Solution:

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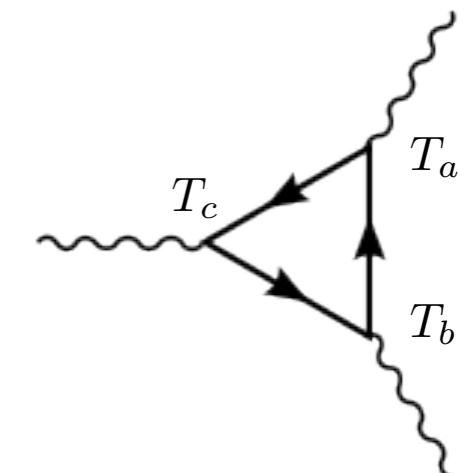
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$$-Y_L + Y_N - Y_H = 0$$

Solution:

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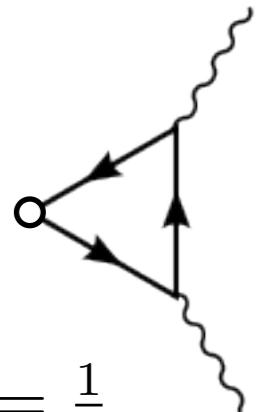
$$Y_L = -\frac{1}{2} + Y_N, \quad Y_E = -1 + Y_N$$

$$Y_N \in \mathbb{R}$$

R. Foot, H. Lew, and R. Volkas, J.Phys.G G19, 361 (1993)

Charge dequantization in the SM with Dirac neutrinos

Symmetry argument: B and L anomalies in the SM

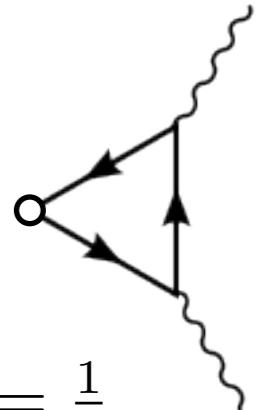


$$\mathrm{Tr}(\{Y, Y\}L) = \mathrm{Tr}(\{Y, Y\}B) = -\frac{1}{2} \quad \mathrm{Tr}(\{T_L^3, T_L^3\}L) = \mathrm{Tr}(\{T_L^3, T_L^3\}B) = \frac{1}{2}$$

$$\mathrm{Tr}(\{Y, Y\}(B - L)) = 0, \mathrm{Tr}(\{T_L^3, T_L^3\}(B - L)) = 0, \dots, \mathrm{Tr}(B - L)^3 \neq 0$$

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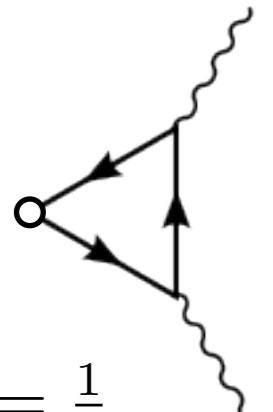
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B - L can be gauged !

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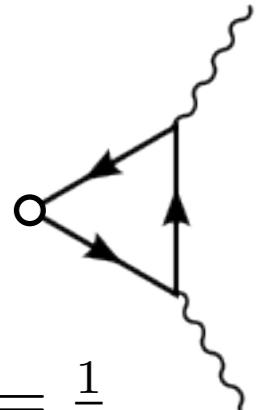
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Babu, Mohapatra, Phys.Rev. D41 (1990) 271

Foot, Lew, Volkas 1993

Experimentally (neutron neutrality): $|\varepsilon| < 10^{-21}$

Another interesting feature of B - L ...

	T_L^3	Y	Q
$\begin{pmatrix} u \\ d \end{pmatrix}_L$	$+\frac{1}{2}$ $-\frac{1}{2}$	$+\frac{1}{6}$	$+\frac{2}{3}$ $-\frac{1}{3}$
u_R	0	$+\frac{2}{3}$	$+\frac{2}{3}$
d_R	0	$-\frac{1}{3}$	$-\frac{1}{3}$
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$+\frac{1}{2}$ $-\frac{1}{2}$	$-\frac{1}{2}$	0 -1
ν_R	0	0	0
e_R	0	-1	-1

Another interesting feature of $B - L$...

	T_L^3	Y	Q	$(B - L)/2$
$\begin{pmatrix} u \\ d \end{pmatrix}_L$	$+\frac{1}{2}$ $-\frac{1}{2}$	$+\frac{1}{6}$	$+\frac{2}{3}$ $-\frac{1}{3}$	$+\frac{1}{6}$
u_R	0	$+\frac{2}{3}$	$+\frac{2}{3}$	
d_R	0	$-\frac{1}{3}$	$-\frac{1}{3}$	$+\frac{1}{6}$
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$+\frac{1}{2}$ $-\frac{1}{2}$	$-\frac{1}{2}$	0 -1	$-\frac{1}{2}$
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$\begin{pmatrix} u \\ d \end{pmatrix}_L$	$+\frac{1}{2}$ $-\frac{1}{2}$	$+\frac{1}{6}$	$+\frac{2}{3}$ $-\frac{1}{3}$	$+\frac{1}{6}$	0
u_R	0	$+\frac{2}{3}$	$+\frac{2}{3}$		
d_R	0	$-\frac{1}{3}$	$-\frac{1}{3}$	$+\frac{1}{6}$	
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$+\frac{1}{2}$ $-\frac{1}{2}$	$-\frac{1}{2}$	0 -1	$-\frac{1}{2}$	0
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u_R	0	$+\frac{2}{3}$	$+\frac{2}{3}$		$+\frac{1}{2}$
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ν_R	0	0	0		$+\frac{1}{2}$
e_R	0	-1	-1	$-\frac{1}{2}$	$-\frac{1}{2}$

Another interesting feature of $B - L$...

	T_L^3	Y	Q	$(B - L)/2$	$T^3\text{-like generator for RH fields!}$
$\begin{pmatrix} u \\ d \end{pmatrix}_L$	$+\frac{1}{2}$ $-\frac{1}{2}$	$+\frac{1}{6}$	$+\frac{2}{3}$ $-\frac{1}{3}$	$+\frac{1}{6}$	0
u_R	0	$+\frac{2}{3}$	$+\frac{2}{3}$		$+\frac{1}{2}$
d_R	0	$-\frac{1}{3}$	$-\frac{1}{3}$	$+\frac{1}{6}$	$-\frac{1}{2}$
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$+\frac{1}{2}$ $-\frac{1}{2}$	$-\frac{1}{2}$	0 -1	$-\frac{1}{2}$	0
ν_R	0	0	0		$+\frac{1}{2}$
e_R	0	-1	-1	$-\frac{1}{2}$	$-\frac{1}{2}$

Another interesting feature of $B - L$...

T³-like
generator
for RH fields!

	T_L^3	Y	Q	$(B - L)/2$	
(u) d	$+\frac{1}{2}$ $-\frac{1}{2}$	$+\frac{1}{6}$	$+\frac{2}{3}$ $-\frac{1}{3}$	$+\frac{1}{6}$	0
u_R	0	$+\frac{2}{3}$	$+\frac{2}{3}$		$+\frac{1}{2}$
d_R				$+\frac{1}{6}$	$-\frac{1}{2}$
	$Q = T_L^3 + T_R^3 + \frac{1}{2}(B - L)$				
(ν_e) e	$+\frac{1}{2}$ $-\frac{1}{2}$	$-\frac{1}{2}$	0 -1	$-\frac{1}{2}$	0
ν_R	0	0	0		$+\frac{1}{2}$
e_R	0	-1	-1	$-\frac{1}{2}$	$-\frac{1}{2}$

Majorana spinors

E. Majorana 1937:

Neutral spinor can be massive even with 2 components only!!!



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E. Majorana

RH neutrino is a full $SU(3) \times SU(2)$ singlet

$$\mathcal{L} \ni \bar{L}_L Y_\nu N_R \tilde{H} + \frac{1}{2} N_R^T C M_R N_R + h.c.$$

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If we engage this, the N_R hypercharge must be zero!

Charge quantization through anomalies restored!

Seesaw mechanism

P. Minkowski, Phys. Lett. B67, 421 (1977)

$$\mathcal{L} \ni \bar{\nu}_L m_D N_R + \frac{1}{2} M_R N_R^T C N_R + h.c. = \frac{1}{2} n_L^T C \mathcal{M} n_L + h.c.$$

$$\mathcal{M} = \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \quad n_L = \begin{pmatrix} \nu_L \\ (N_R)^C \end{pmatrix}$$

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Suppose $m_D \ll M_R$:

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$$m_2 = M_R$$

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$$n_2 \propto (N_R)^c + \mathcal{O}\left(\frac{m_D}{M_R}\right) \nu_L$$



Neutrino masses are naturally suppressed if M_R is large!

NB the argument is not water-tight (Yukawas self-renormalize)

$M_R \sim 10^{12-14} \text{ GeV}$

Lepton number violation (?)

L and B are not sacred in the SM anyway...

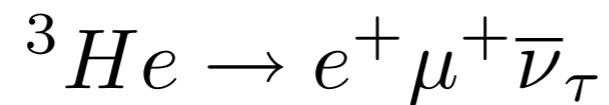
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$$^3He \rightarrow e^+ \mu^+ \bar{\nu}_\tau \quad \mathcal{A} \sim 10^{-\mathcal{O}(200)}$$

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Kuzmin, V. Rubakov, M. Shaposhnikov, PLB155, 1985

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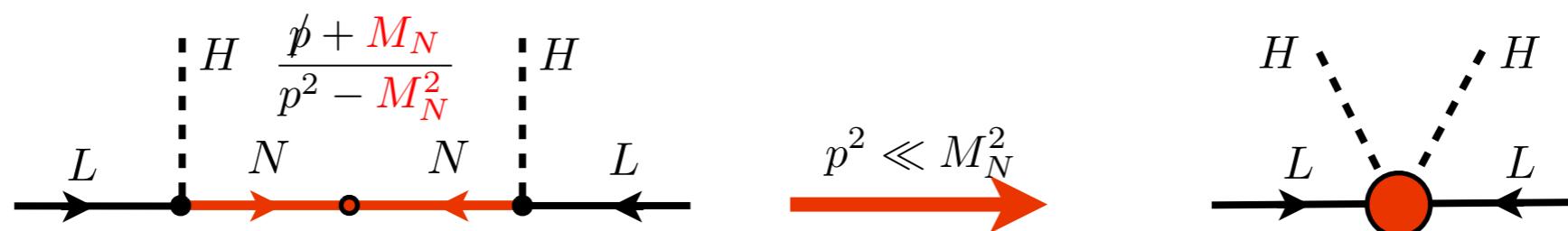
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Non-renormalizable (effective) case: **L broken explicitly at d=5**

$$\mathcal{L}_5 \sim \frac{c}{\Lambda} (L^T i\sigma_2 H) C (H^T i\sigma_2 L)$$

Weinberg's operator

S. Weinberg, PRL43, 1566 (1979)



PMNS mixing in the Majorana case

Majorana mass

$$\frac{1}{2}m\psi_L^T C \psi_L + h.c.$$

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Charged currents: $\mathcal{L} \ni \frac{g}{\sqrt{2}} \bar{\ell}_L^\alpha \gamma^\mu U_{\alpha i} \nu_L^i W_\mu^- + h.c.$

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

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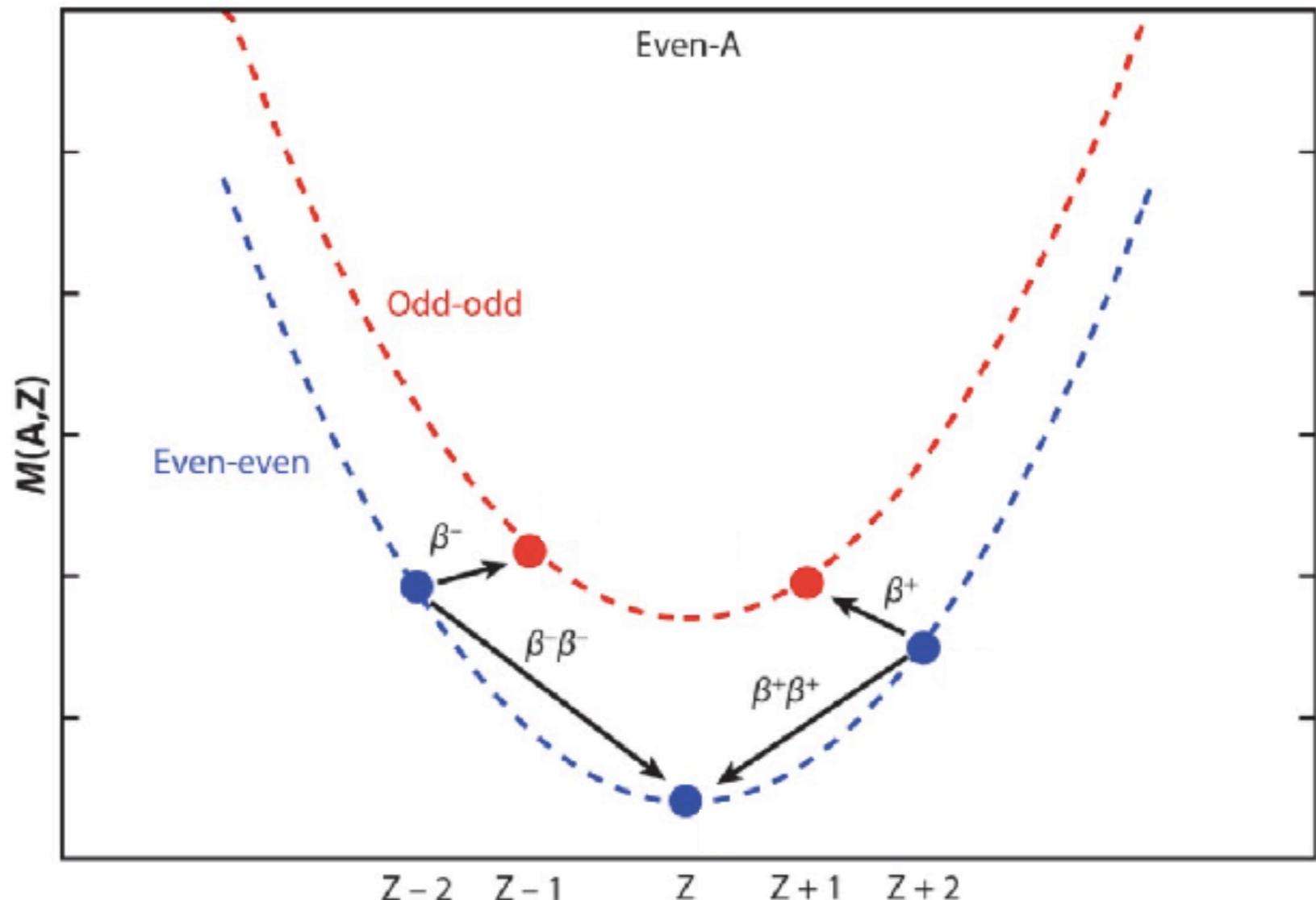
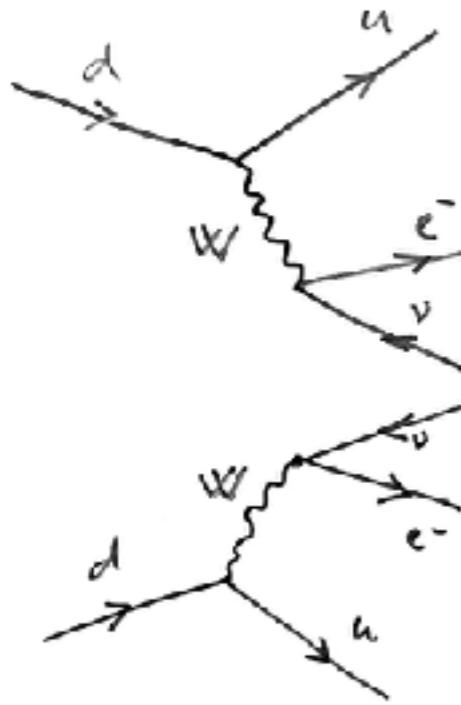
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3 physical CP phases (1 Dirac, 2 Majorana)!

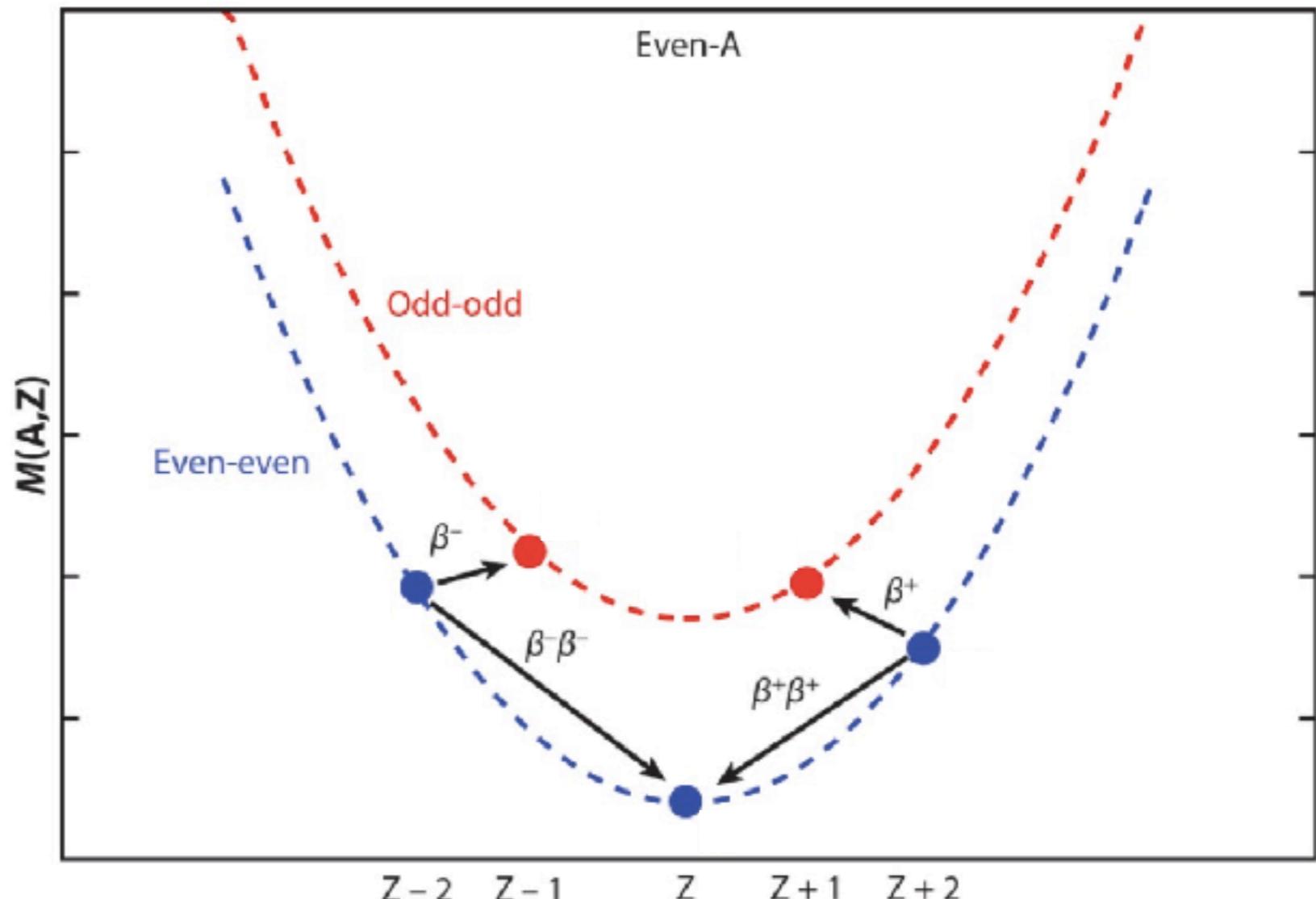
L violation in neutrinoless double beta decay

Double beta decay



“Standard” double beta decay: $2n \rightarrow 2p^+ + 2e^- + 2\bar{\nu}$

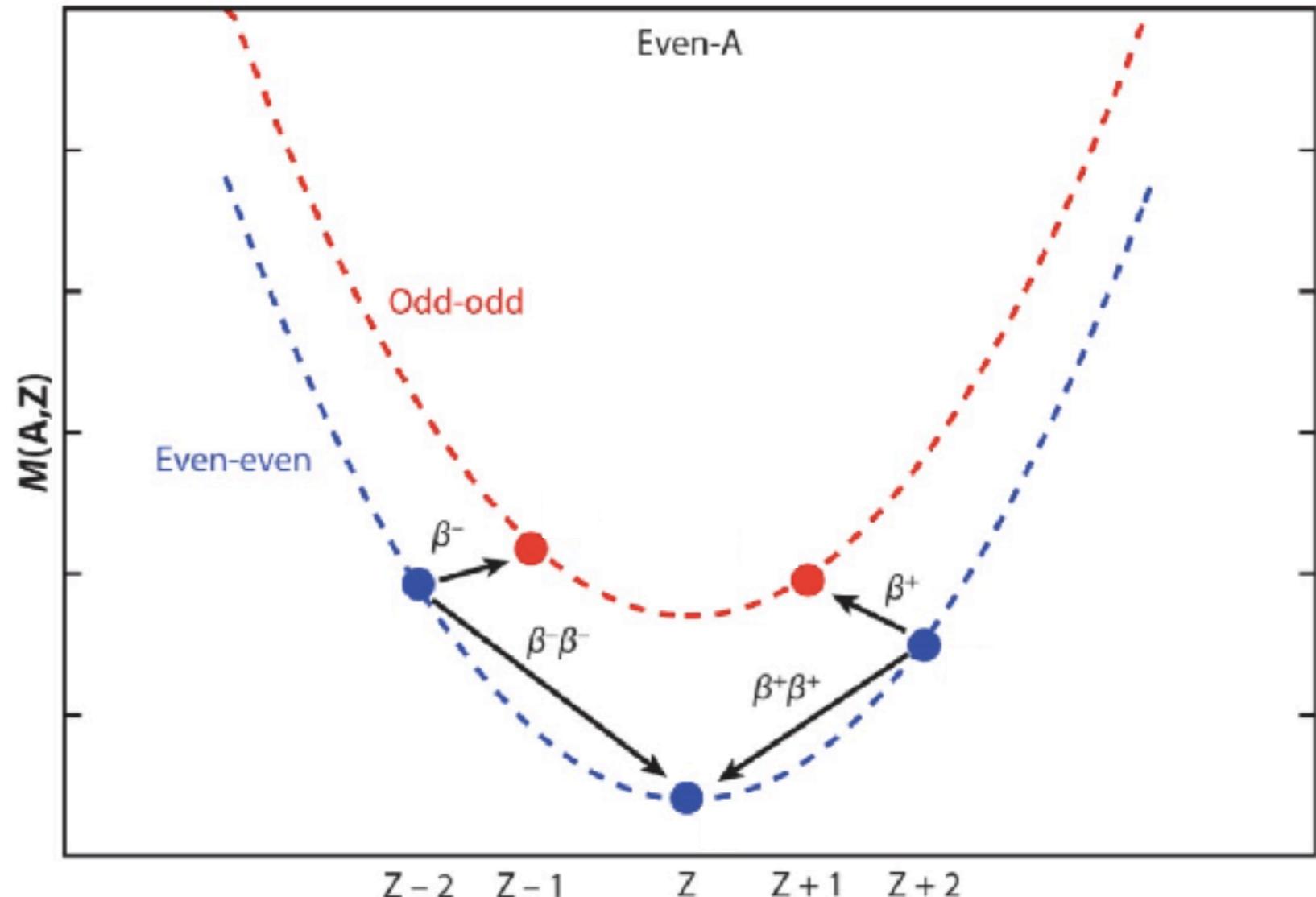
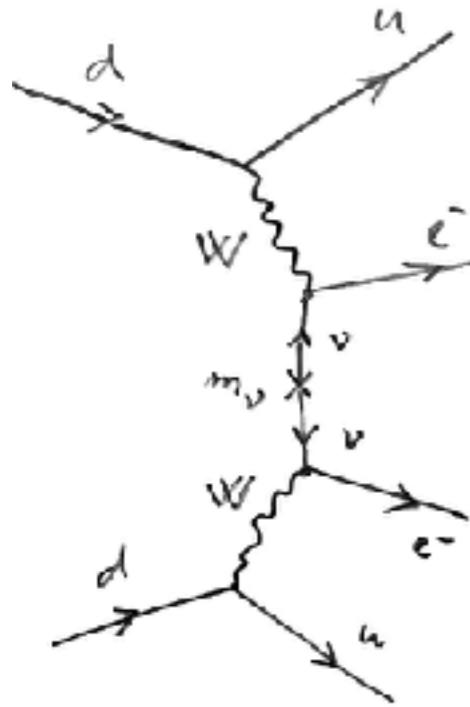
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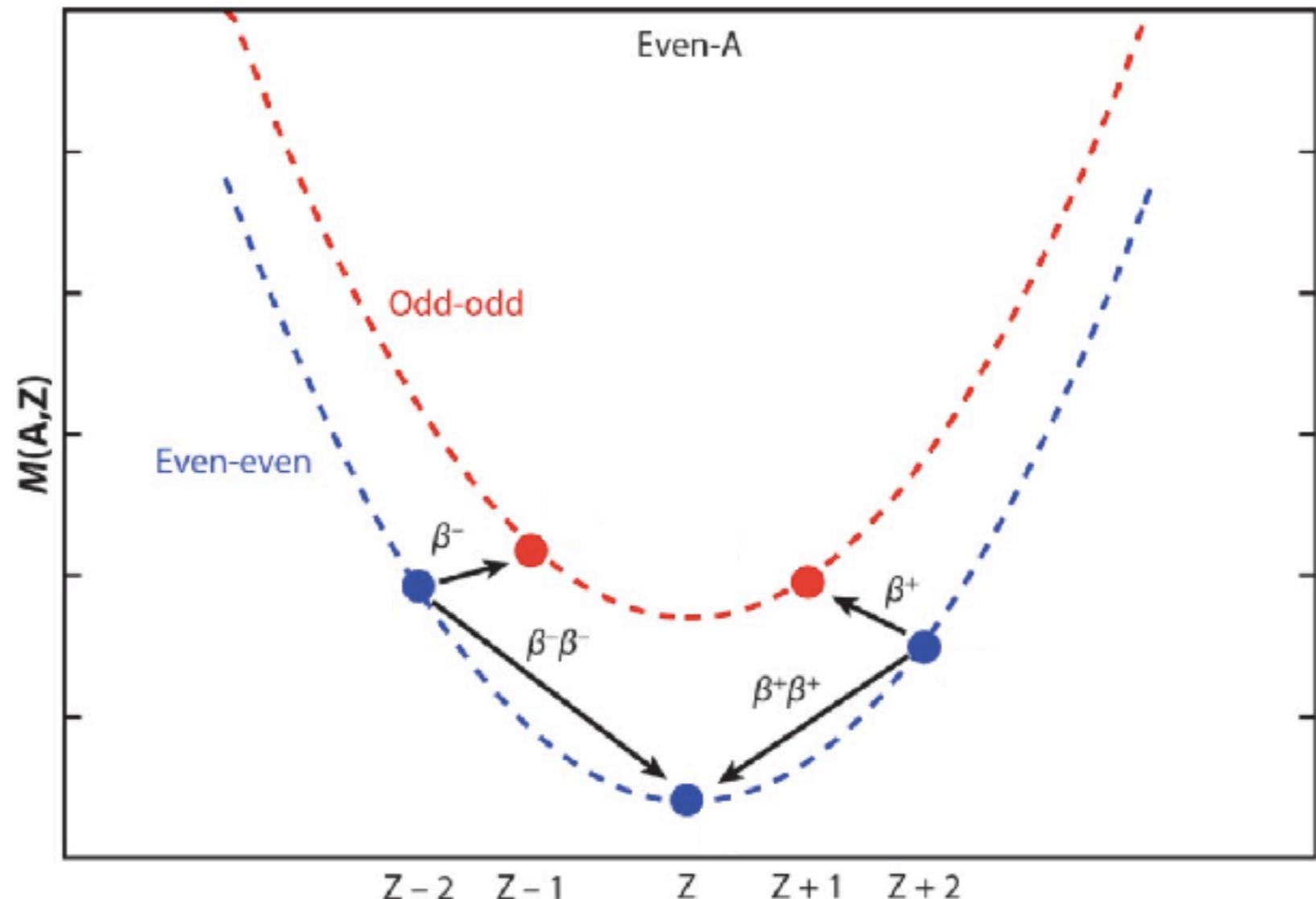
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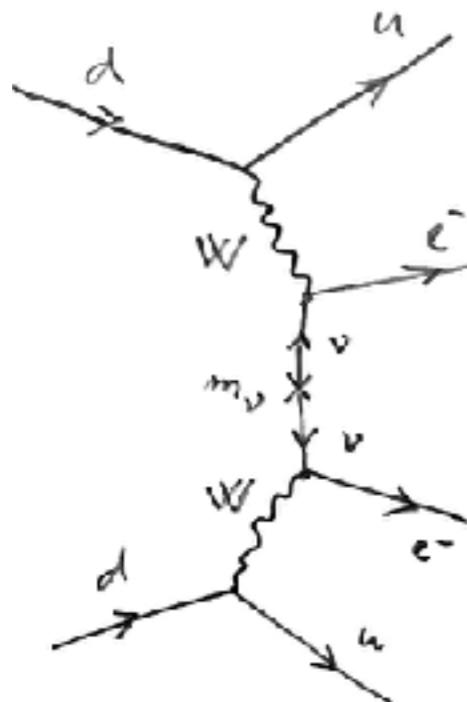
Neutrinoless double beta decay: $2n \rightarrow 2p^+ + 2e^- + 0\bar{\nu}$

Isotopes: ^{48}Ca , ^{76}Ge , ^{82}Se , ^{96}Zr , ^{100}Mo , ^{116}Cd , ^{130}Te , ^{136}Xe , ^{150}Nd



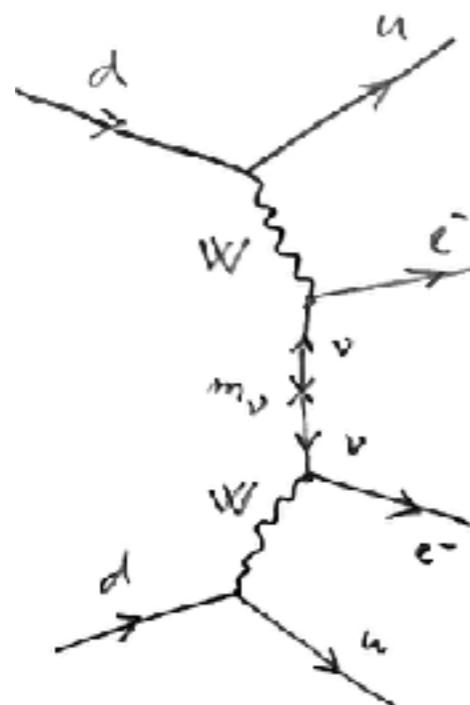
Neutrinoless double beta decay - lifetime estimates

Diagrammatics:



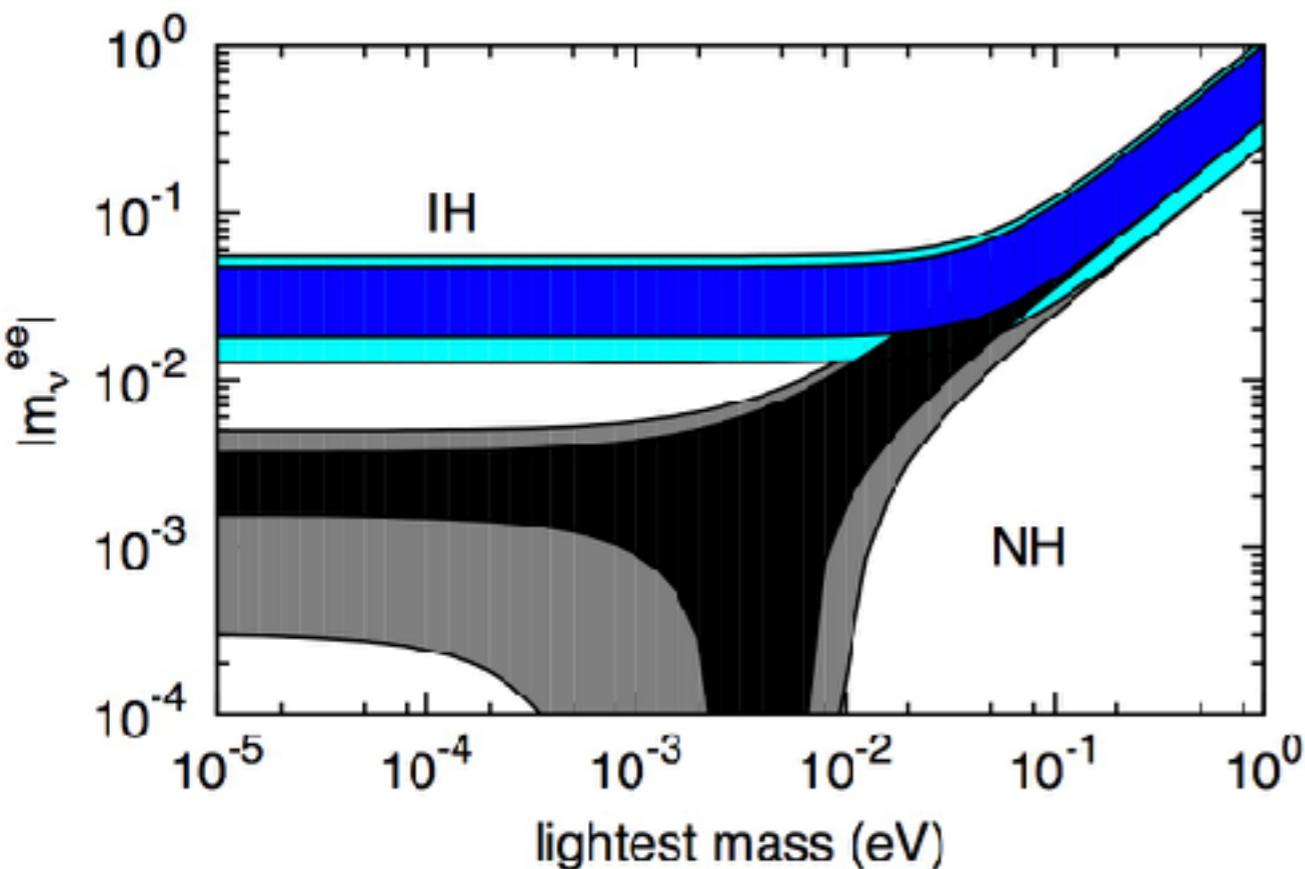
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$$\mathcal{A} \propto g^4 \frac{\langle m \rangle}{q^2}$$

Neutrinoless double beta decay - lifetime estimates

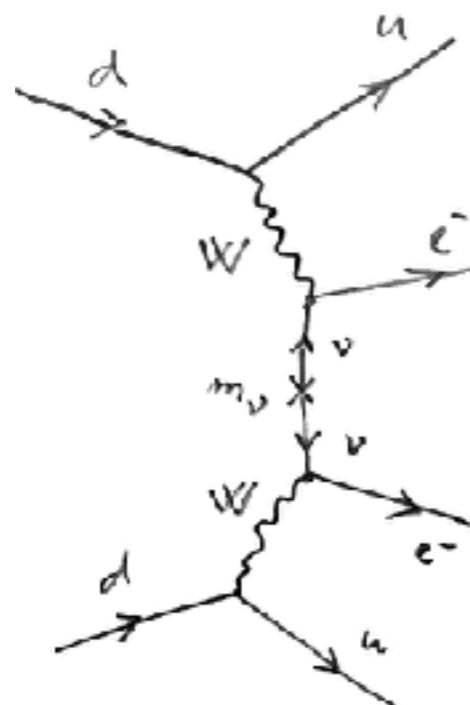


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Figures from Chakrabortty et al., 2012

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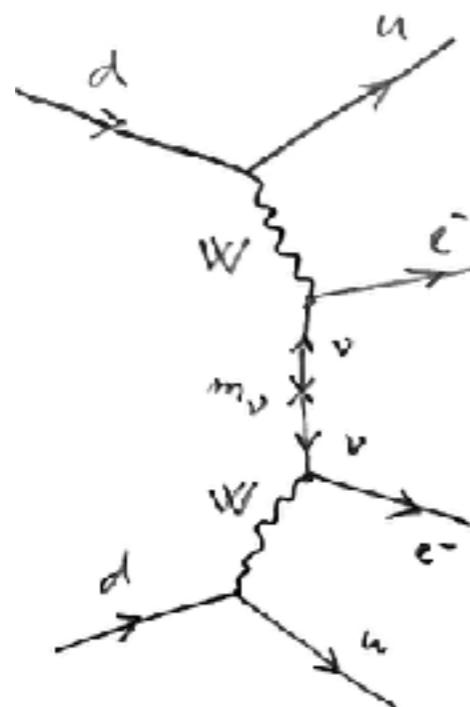


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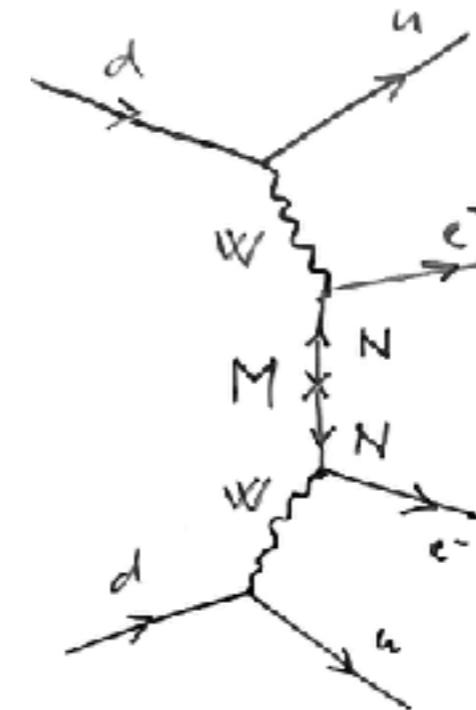
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Heavy neutrinos also feel gauge interactions!

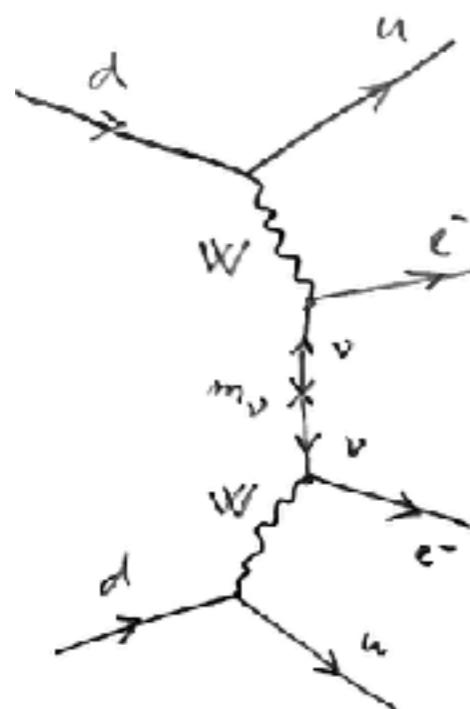


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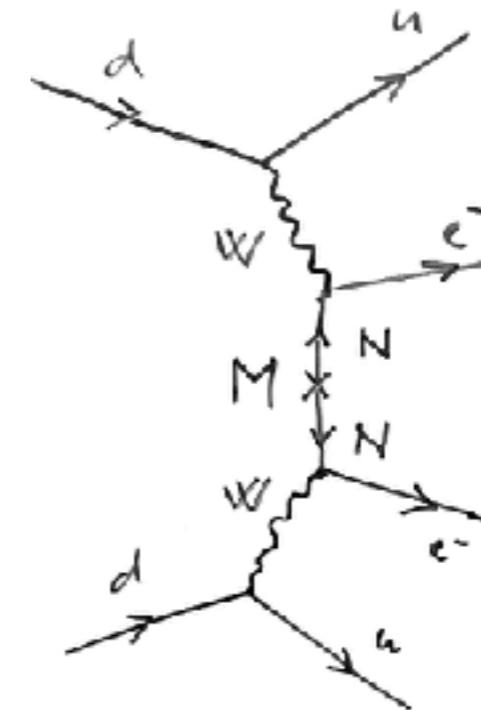
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Heavy neutrinos also feel gauge interactions!



$$F = \sqrt{m_\nu M^{-1}}$$

$$\mathcal{A} \propto g^4 \frac{\langle m \rangle}{q^2}$$

$$\mathcal{A} \propto g^4 \sum_i F^2 \frac{\kappa}{M_i}$$

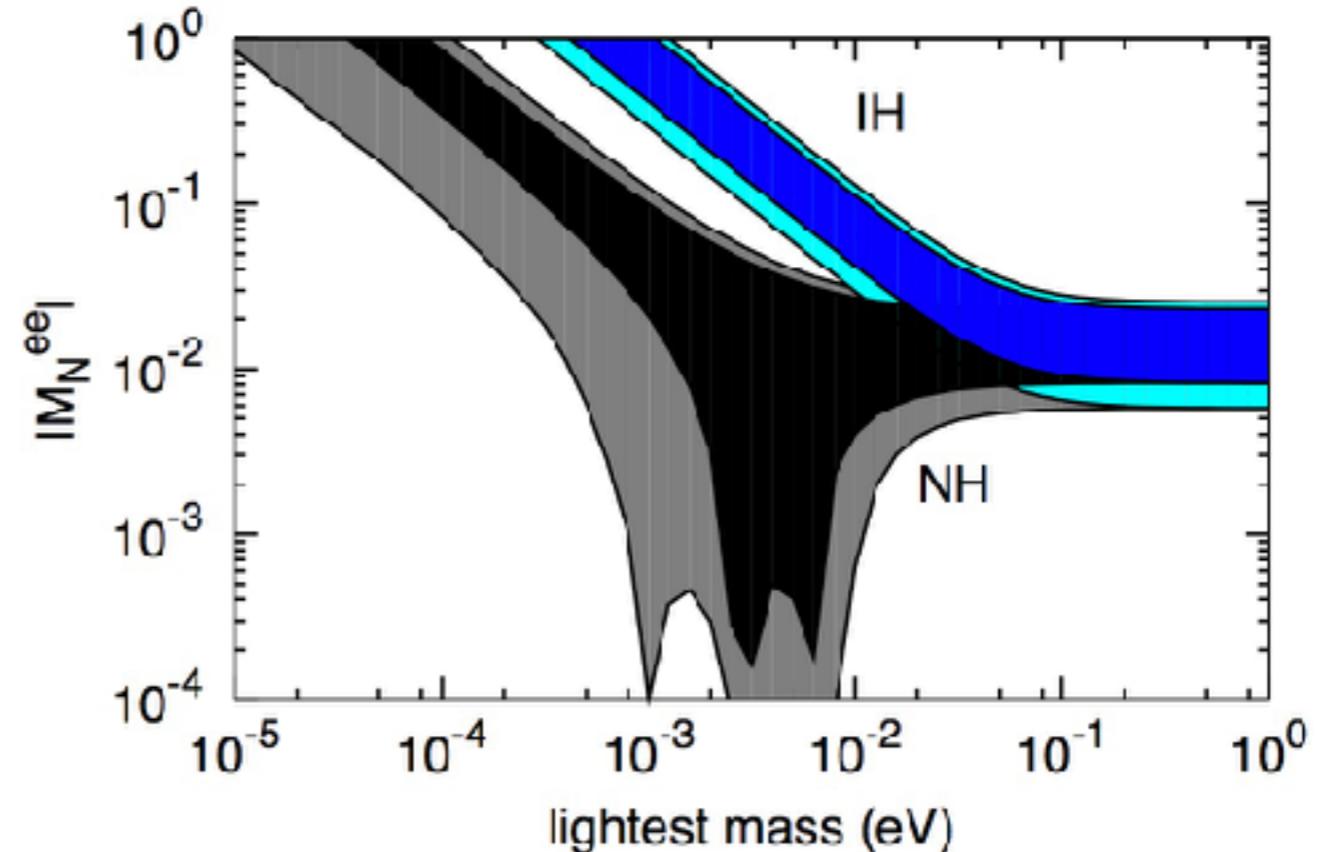
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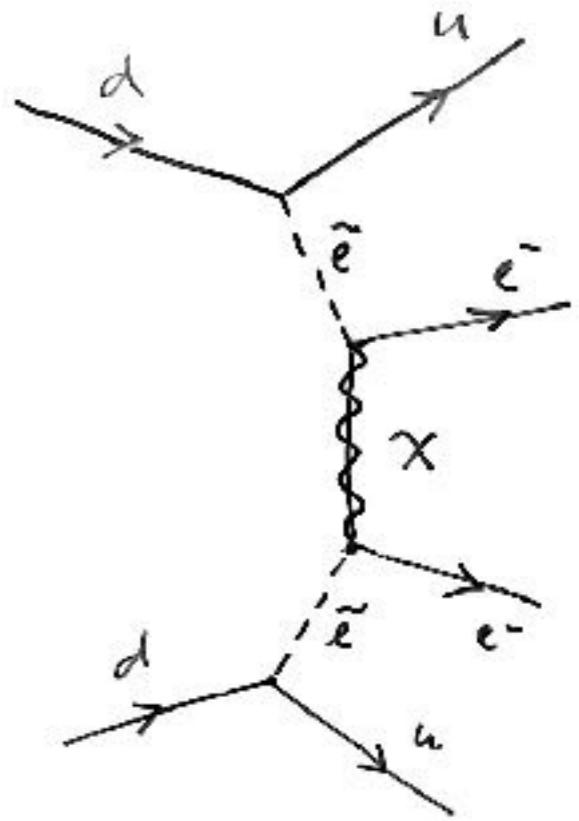
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What if there is something else?

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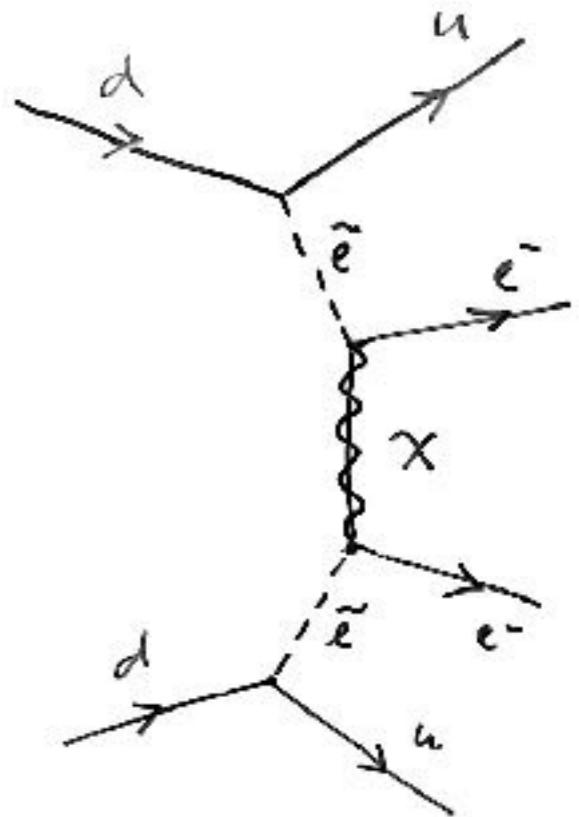
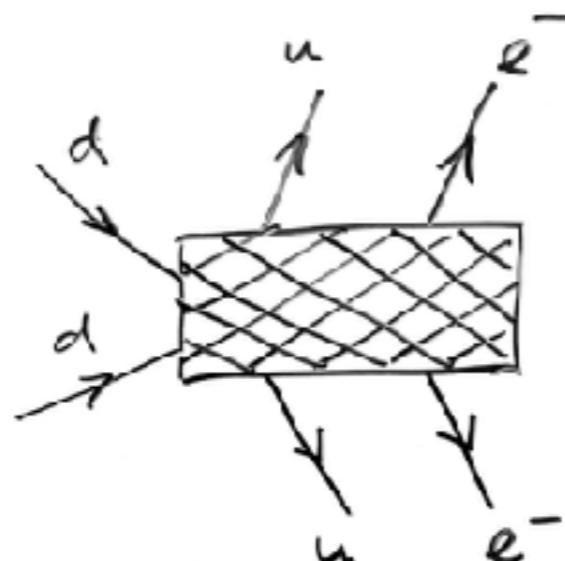
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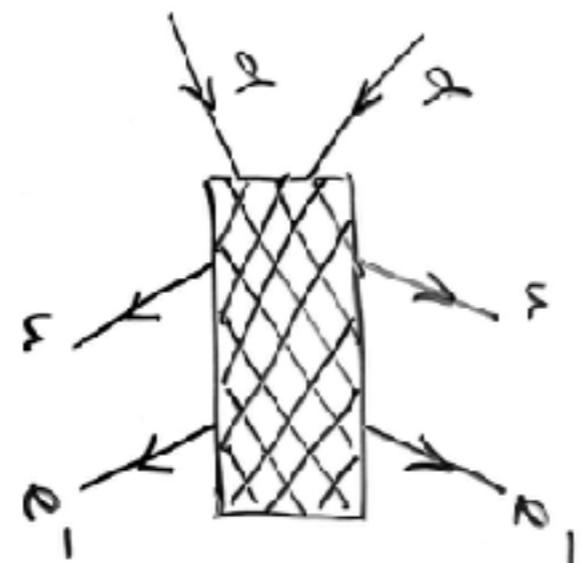


J. Schechter, J. F. W. Valle, PRD 1982
Takasugi, PLB 1984

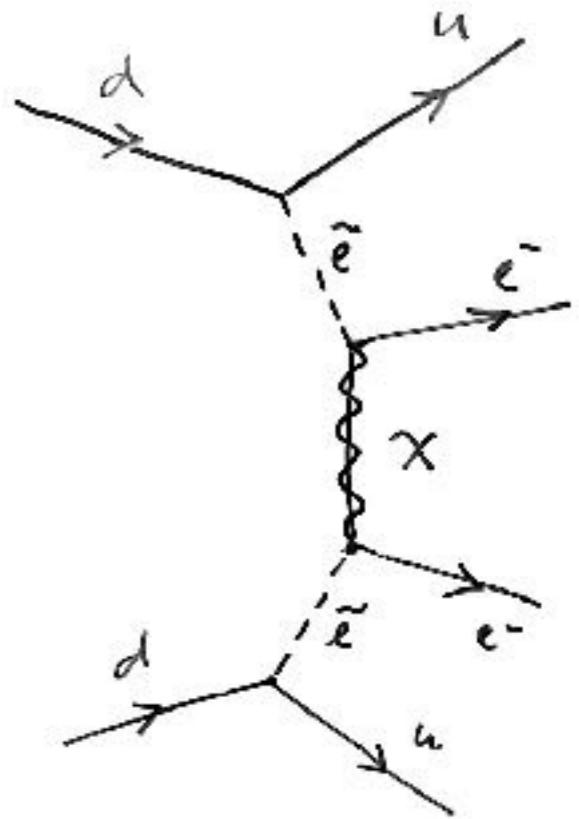
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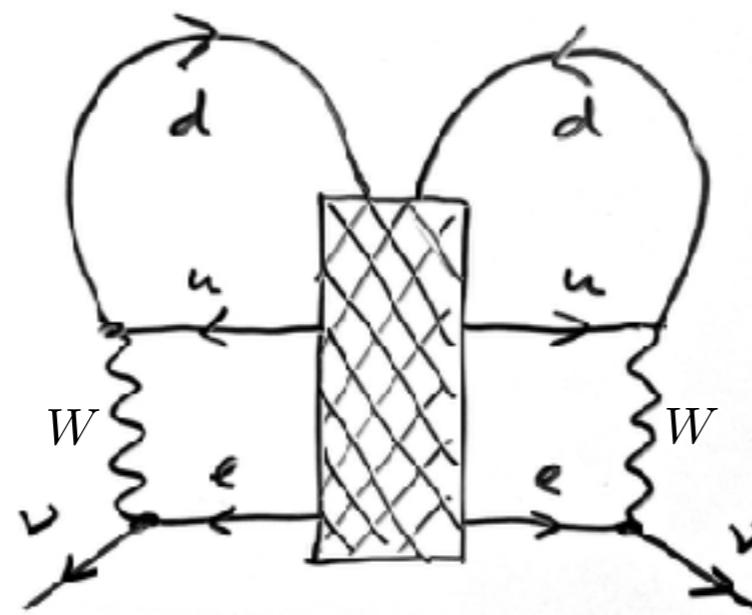
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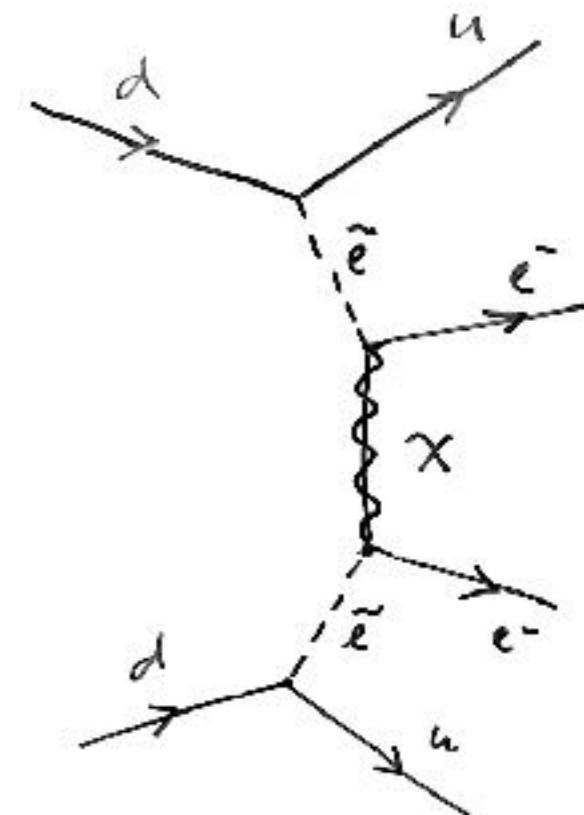
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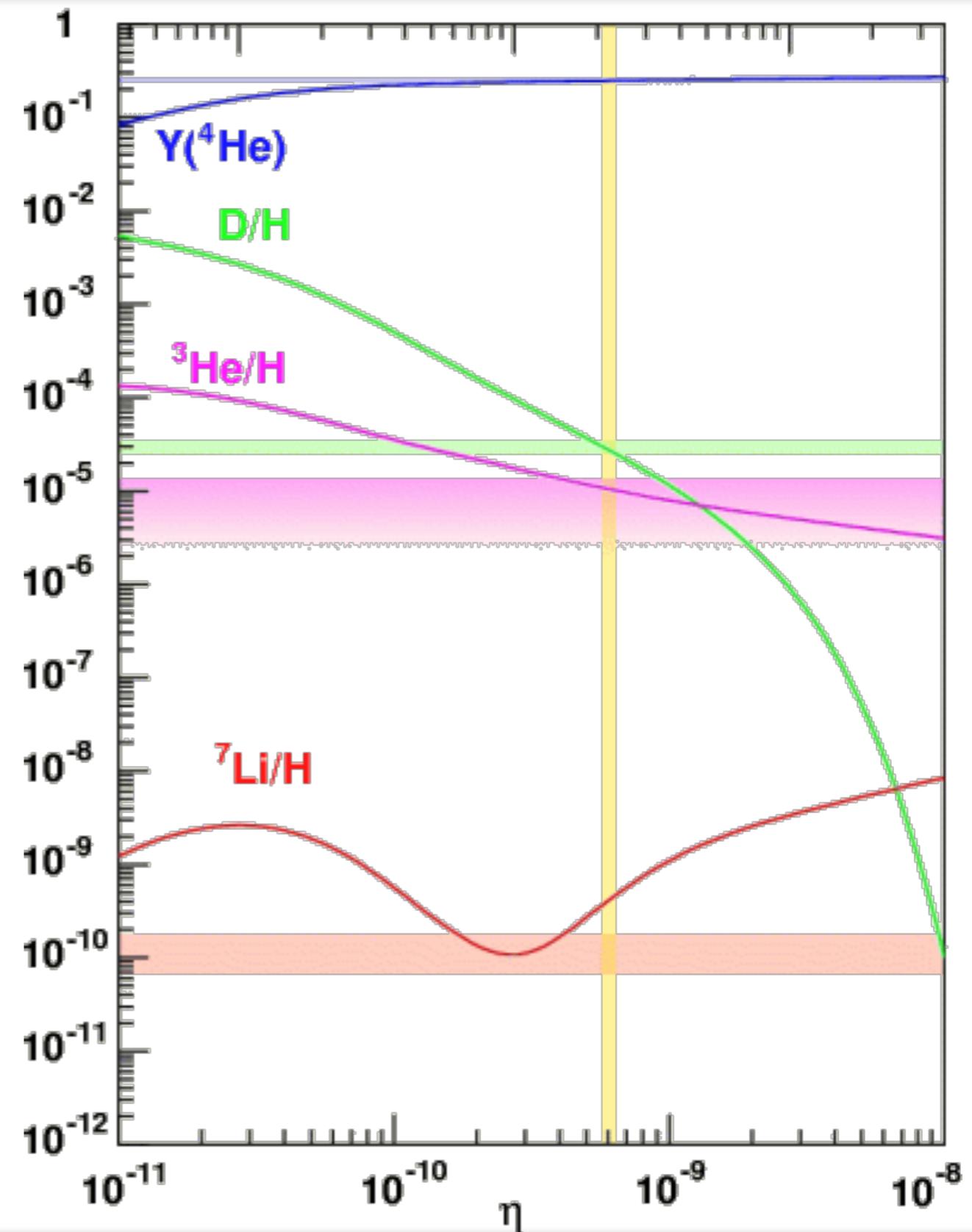
If neutrinoless double beta decay is seen, neutrinos are inevitably Majorana...

L violation in cosmology (?)

The η_B issue of the SM

Baryon to photon # density:

$$\frac{n_B}{n_\gamma} \equiv \eta_B = (6.1 \pm 0.3) \times 10^{-10}$$

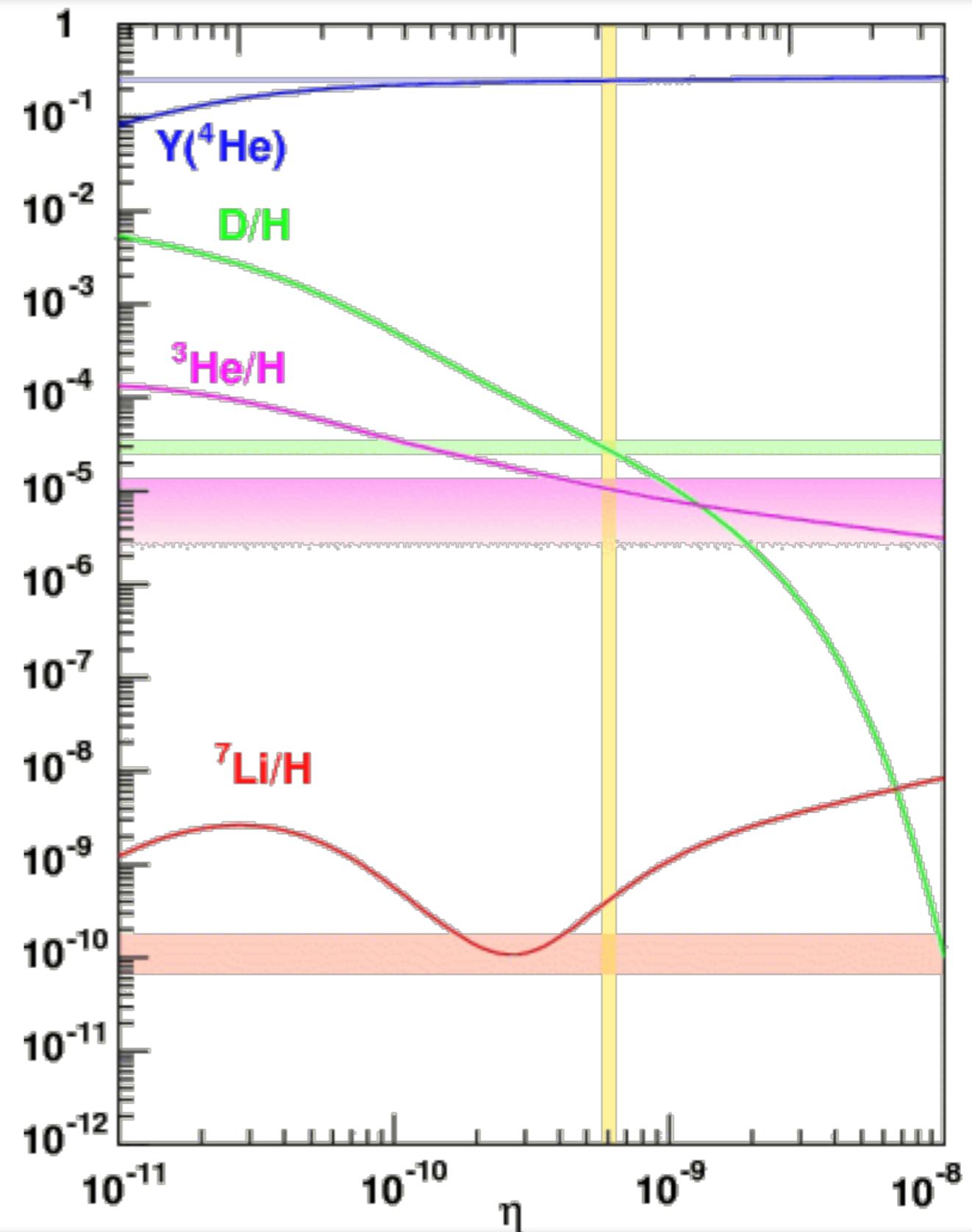


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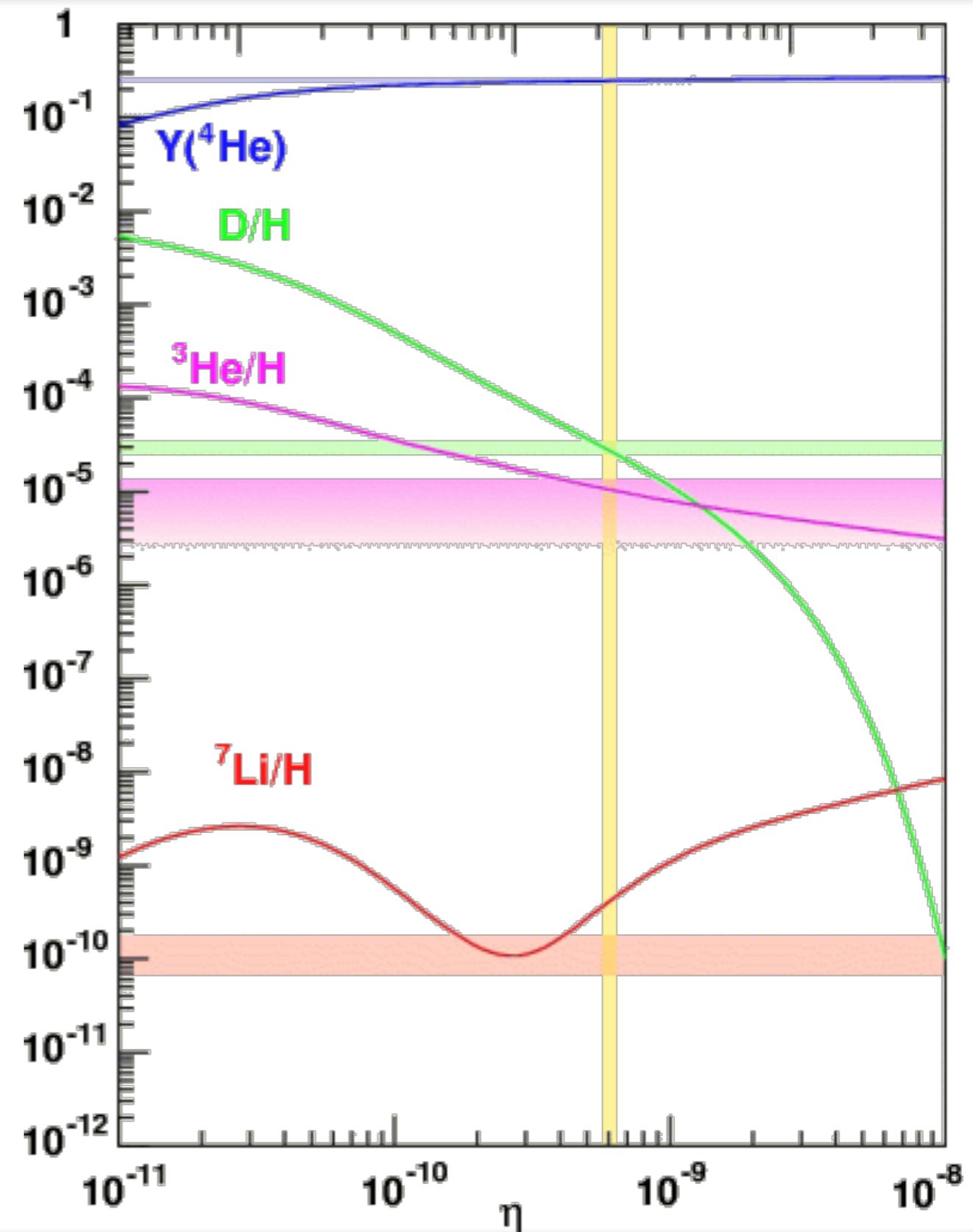
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**This is actually
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**Symmetric initial conditions:
(+ Standard model)**

$$\eta_{\text{SM}} \approx 10^{-18}$$



Cooking up a primordial baryon asymmetry

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1967: Sacharov's baryogenesis conditions



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- Baryon number violation
- C and CP violation
- Departure from thermal equilibrium



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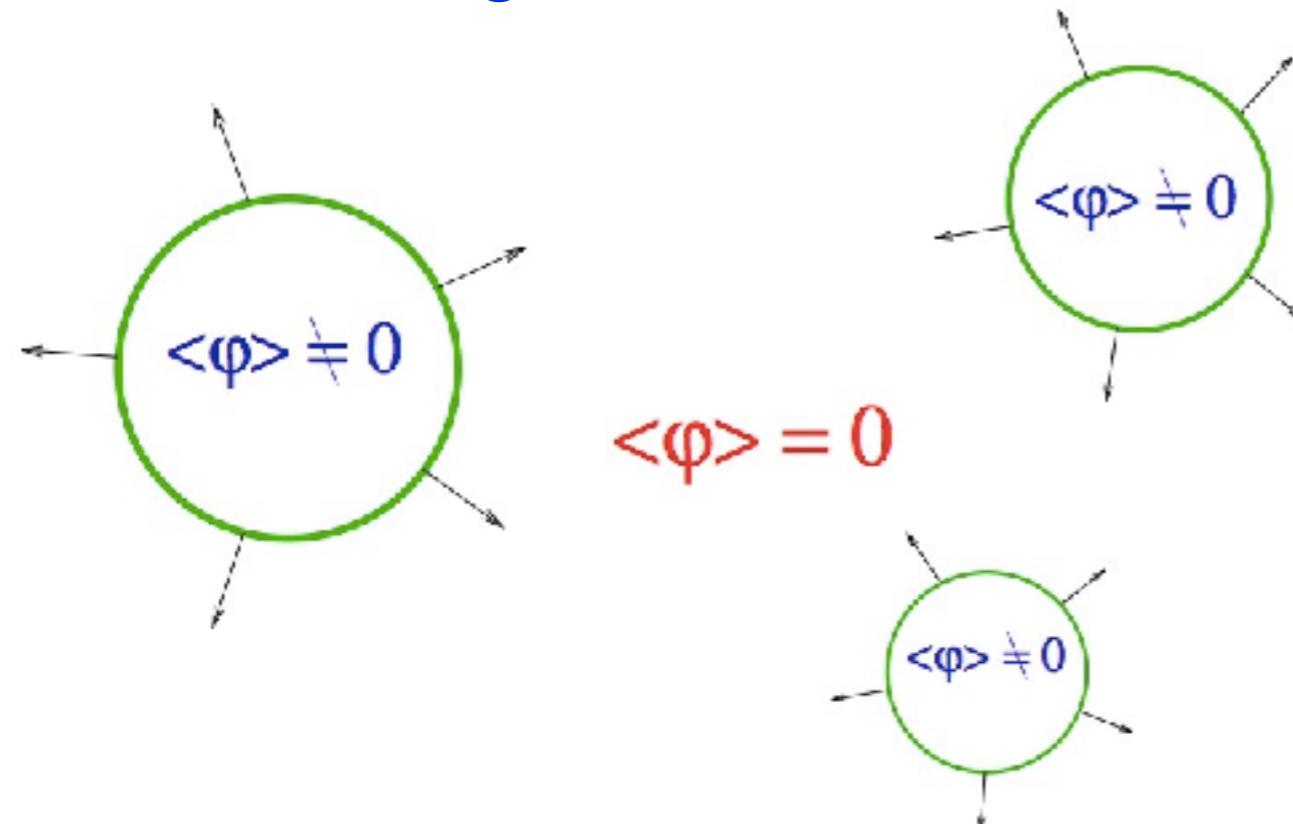
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All this is there in the Standard Model (!)

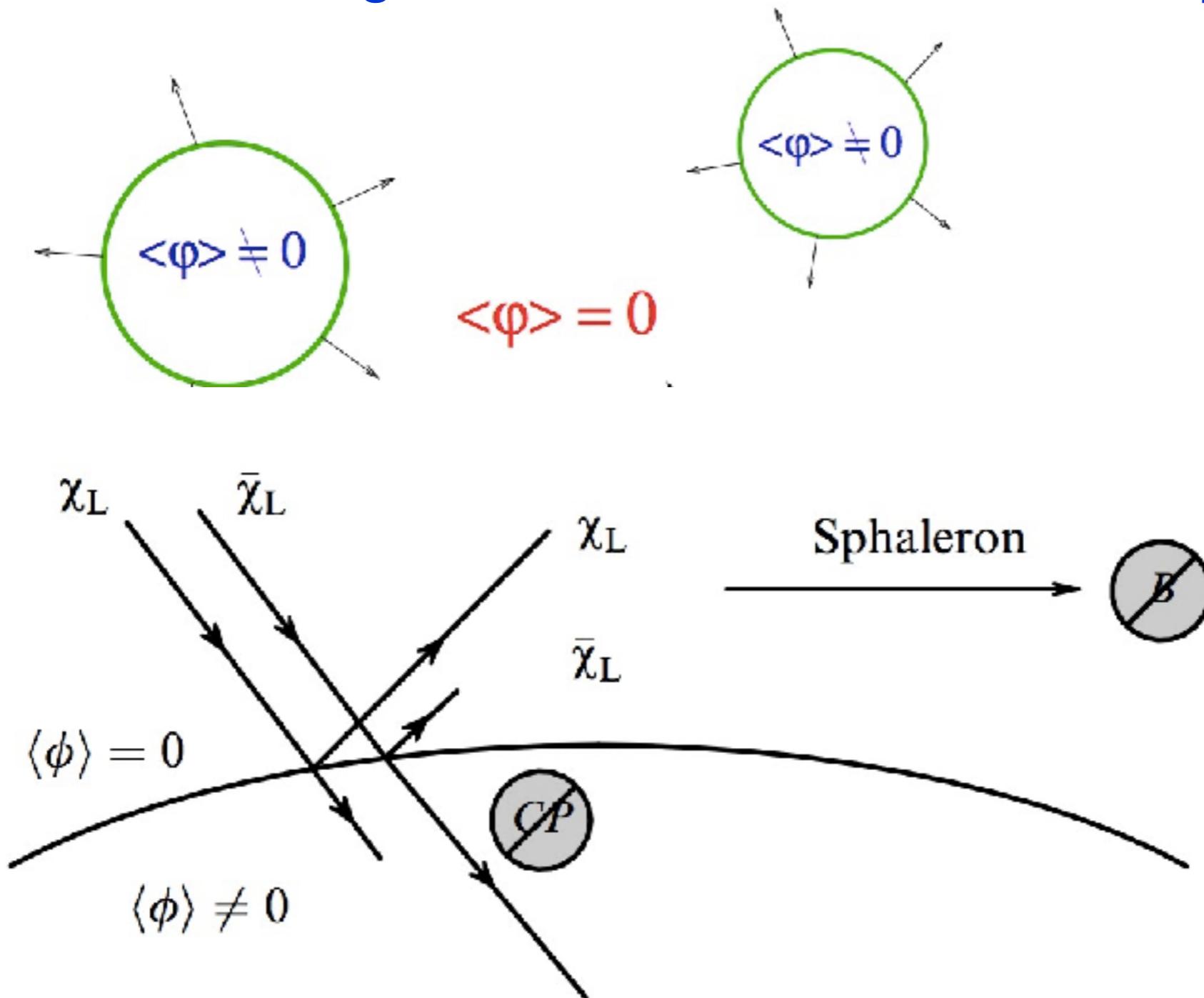
B+L generation during the EW phase transition?

Assume that “bubbles” grow below the EWPT critical temperature...



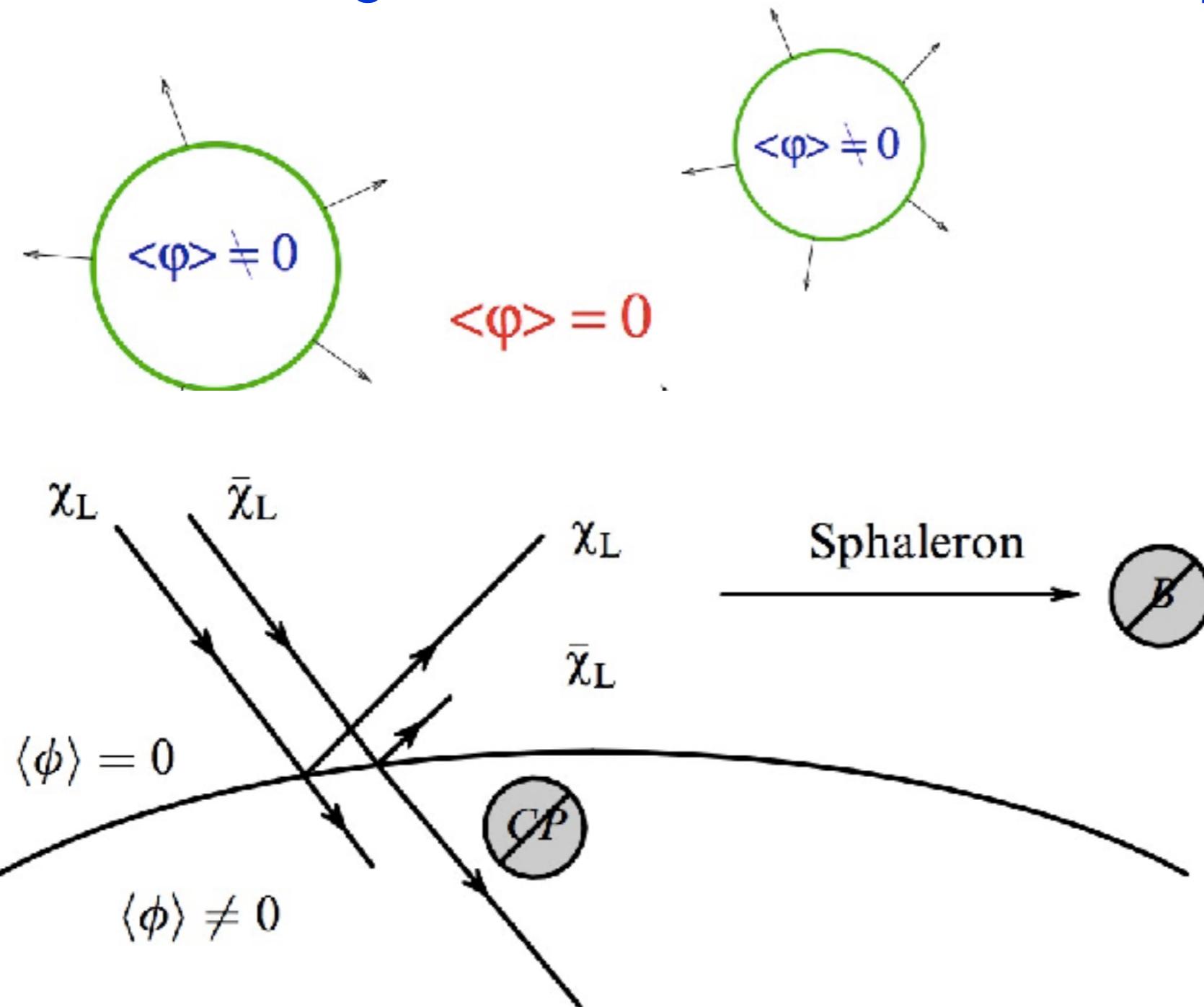
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B+L generation during the EW phase transition?

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Bubbles do not form for $m_H = 125$ GeV, not enough CPV in the SM !!!

Baryogenesis through leptogenesis (are we here thanks to Majorana neutrinos?)

Baryogenesis through leptogenesis

Perturbative LNV + nonperturbative BNV enough for baryogenesis

Fukugita, Yanagida, PLB174, 1986

$$\frac{n_B}{n_\gamma} \equiv \eta_B = (6.1 \pm 0.3) \times 10^{-10}$$

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I) Net L is generated in the (perturbative) super-heavy neutrino decays:

CP asymmetry: $\epsilon_1 = \frac{\sum_\alpha [\Gamma(N_1 \rightarrow \ell_\alpha H) - \Gamma(N_1 \rightarrow \bar{\ell}_\alpha \bar{H})]}{\sum_\alpha [\Gamma(N_1 \rightarrow \ell_\alpha H) + \Gamma(N_1 \rightarrow \bar{\ell}_\alpha \bar{H})]}$

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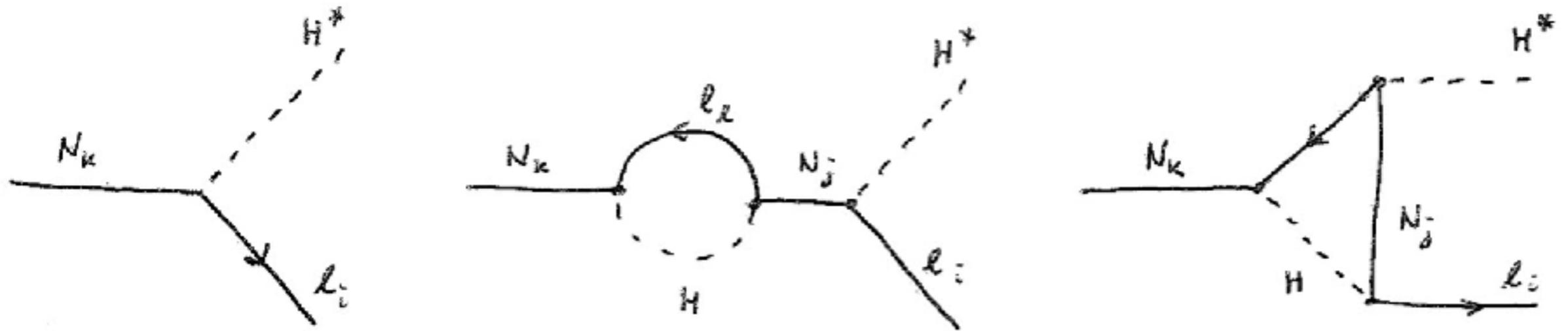
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2) Sphalerons provide L to B transitions before EWPT

Kuzmin, Rubakov, Shaposhnikov, PLB155, 1985

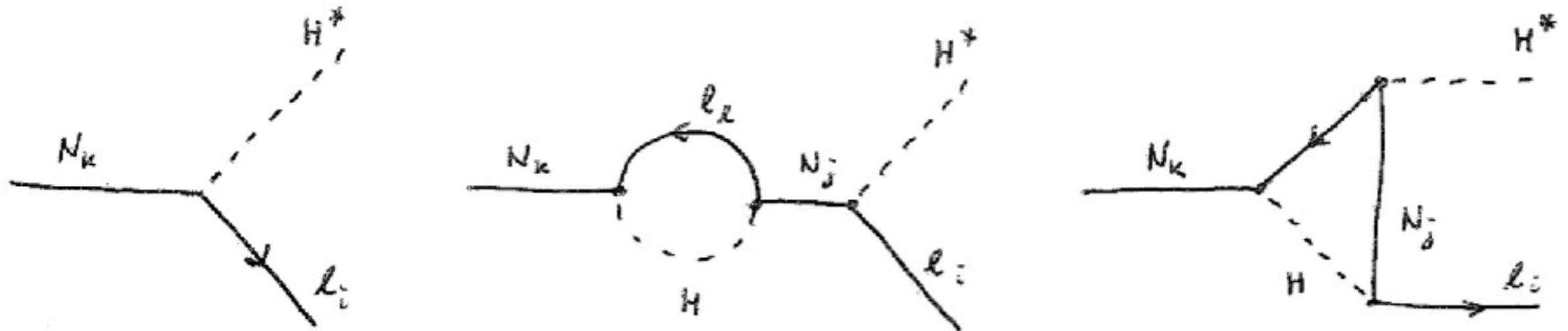
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CP asymmetry:

$$\epsilon_1 \approx -\frac{3}{8\pi} \frac{1}{(Y_N Y_N^\dagger)_{11}} \sum_{i=2,3} \text{Im} \left[(Y_N Y_N^\dagger)_{1i}^2 \right] \frac{M_1}{M_i}$$

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Davidson-Ibarra bound:

S. Davidson and A. Ibarra, Phys. Lett. B535, 25 (2002)

$$|\epsilon_1| \leq \frac{3}{16\pi} \frac{M_1(m_3 - m_2)}{v^2}$$

$$M_1 \gtrsim 10^9 \text{ GeV}$$



Thank you!