Neutrino colloquium, Prague, October 24-25 2019

What is leptonic CP violation good for?

(Is it necessary or just optional?)

Michal Malinský

IPNP, Charles University in Prague

FACULTAS MATHEMATICA PHYSICAQUE

GAČR
CZECH SCIENCE FOUNDATION

Neutrino masses

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Dirac mass

$$m\,\overline{\psi_L}\psi_R + h.c.$$

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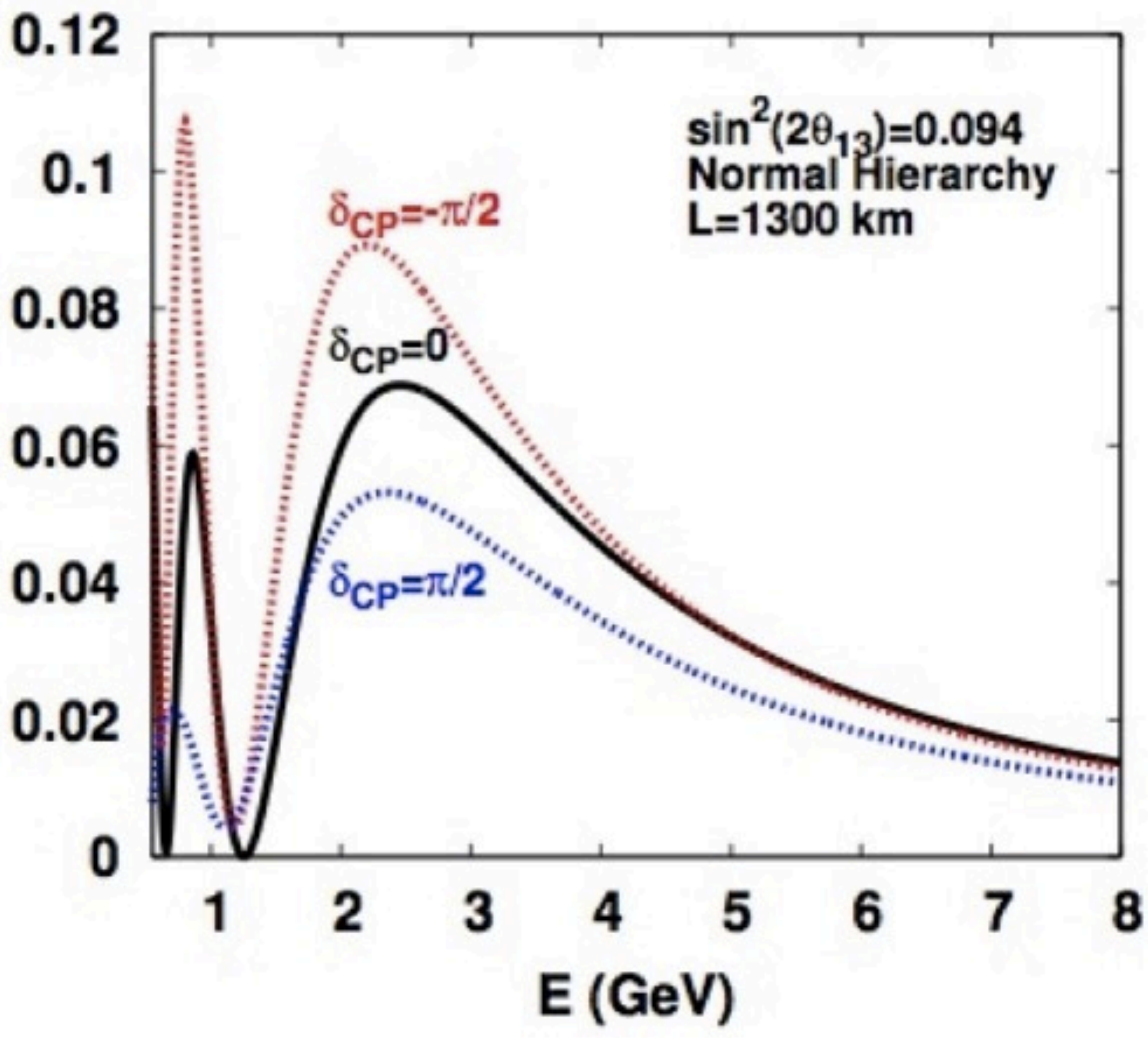
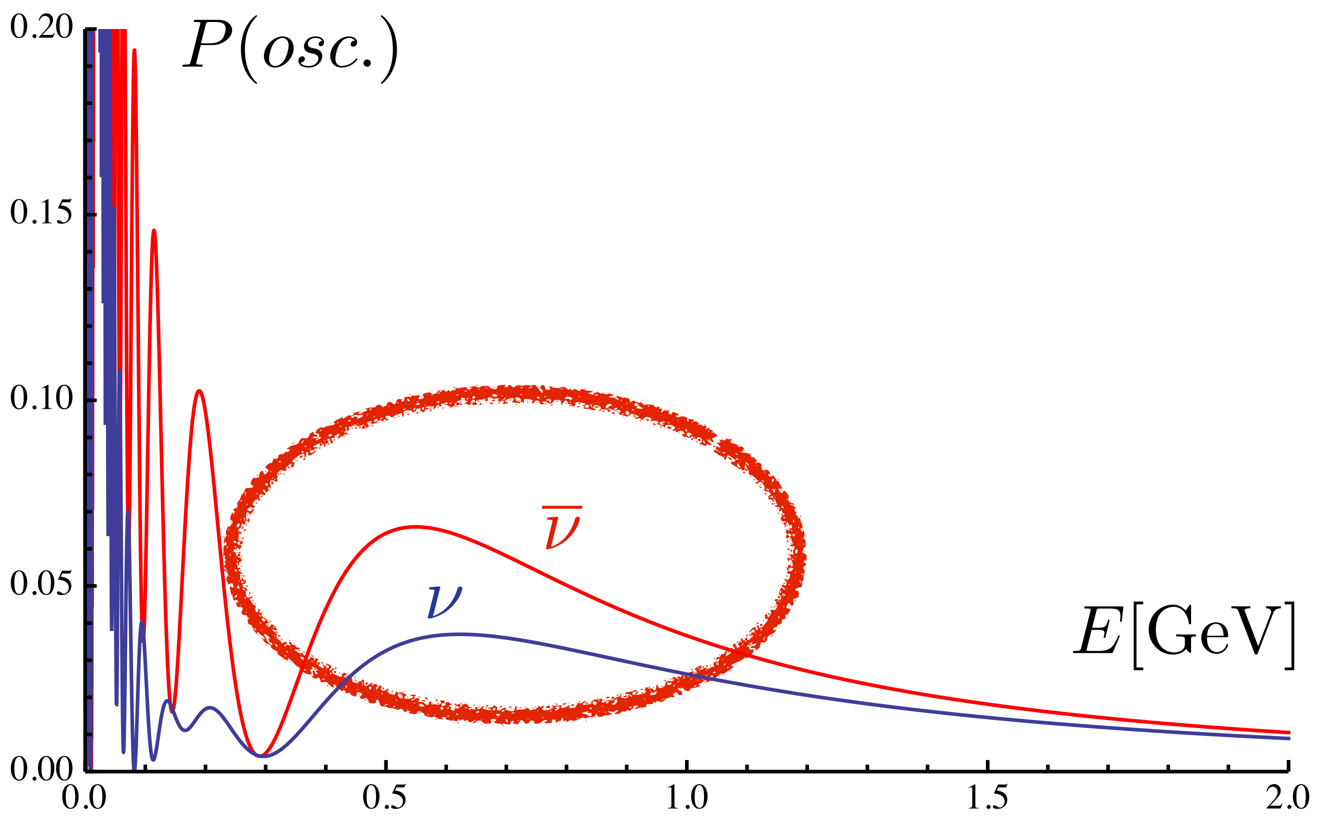
1 physical CP phase

CP violation in neutrino oscillations

Example: CP effects & NOvA, T2K etc. $(\nu_\mu \to \nu_e \, , \, \overline{\nu}_\mu \to \overline{\nu}_e)$





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- RHNs look very natural

Standard model matter fields + 3 RH neutrinos

	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
e_R	0	-1	-1

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	T_L^3	Y	Q	$(B-L)/2$
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Standard model matter fields + 3 RH neutrinos

	T_L^3	Y	Q	$(B-L)/2$	isotopic spin 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 d_R	0 0	$+\frac{2}{3}$ $-\frac{1}{3}$	$+\frac{2}{3}$ $-\frac{1}{3}$	$+\frac{1}{6}$	$+\frac{1}{2}$ $-\frac{1}{2}$
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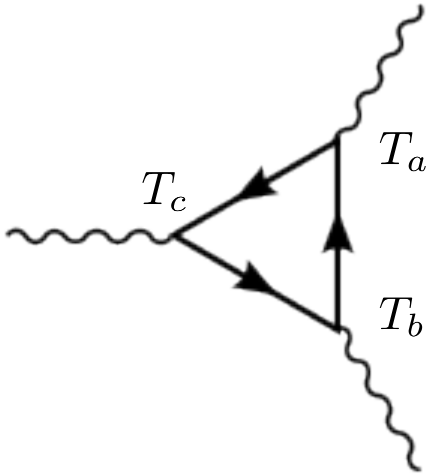
Charge dequantization in the SM with Dirac neutrinos

SU(3) x SU(2) x U(1) gauge anomalies

$$\mathcal{A}_c \propto \frac{1}{32\pi^2}\mathrm{Tr}\left(\{T_a,T_b\}T_c\right)\tilde{F}^a_{\mu\nu}F^{b\mu\nu}$$



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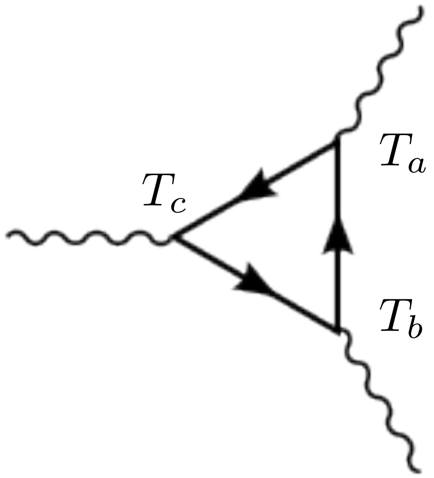

SU(2)² U(1): $6Y_Q + 2Y_L = 0$

U(1)³: $12Y_Q^3 + 4Y_L^3 - 6Y_U^3 - 6Y_D^3 - 2Y_E^3 = 0$

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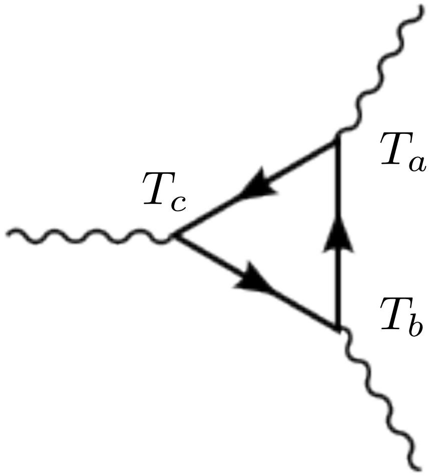

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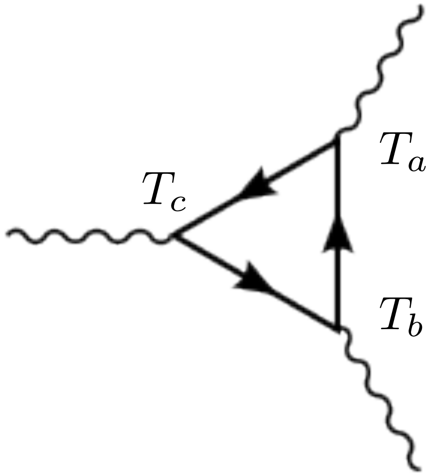

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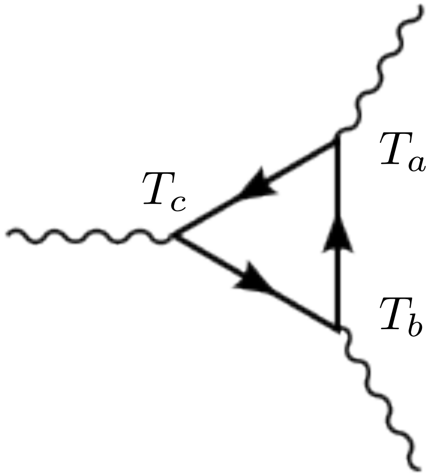

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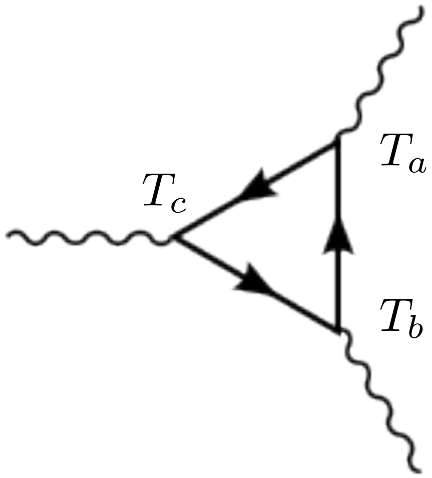

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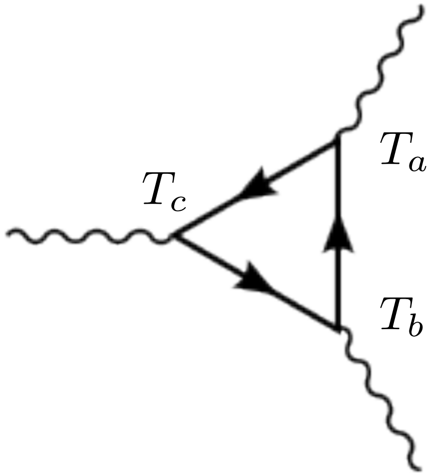

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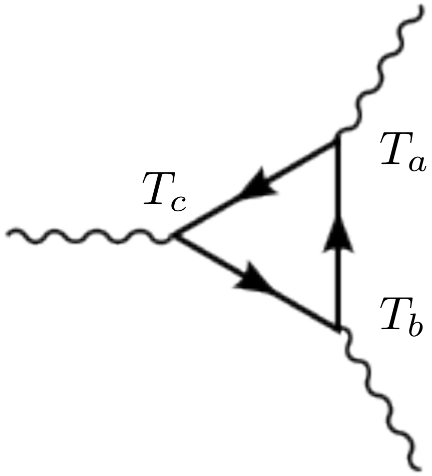

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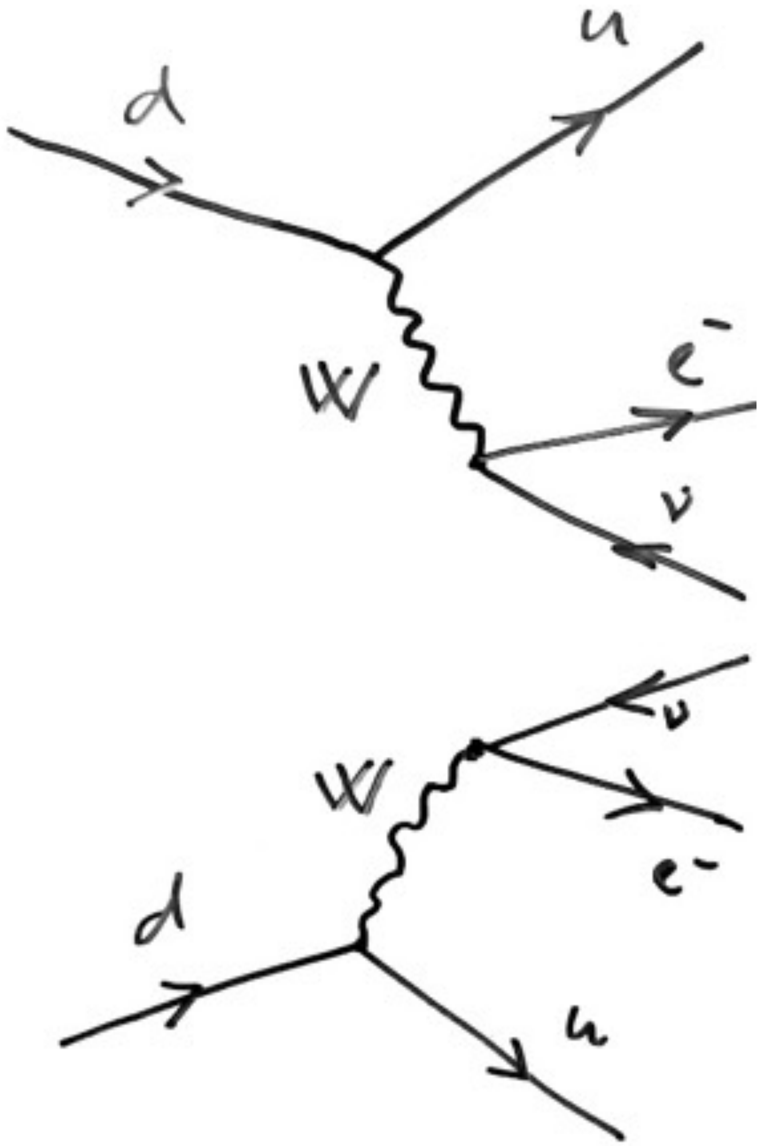
- Sphalerons (at high T) make the tunneling more efficient $\Rightarrow$ **early Universe**

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

Actually, we like LNV and Majorana neutrinos...

Neutrinoless double beta decay



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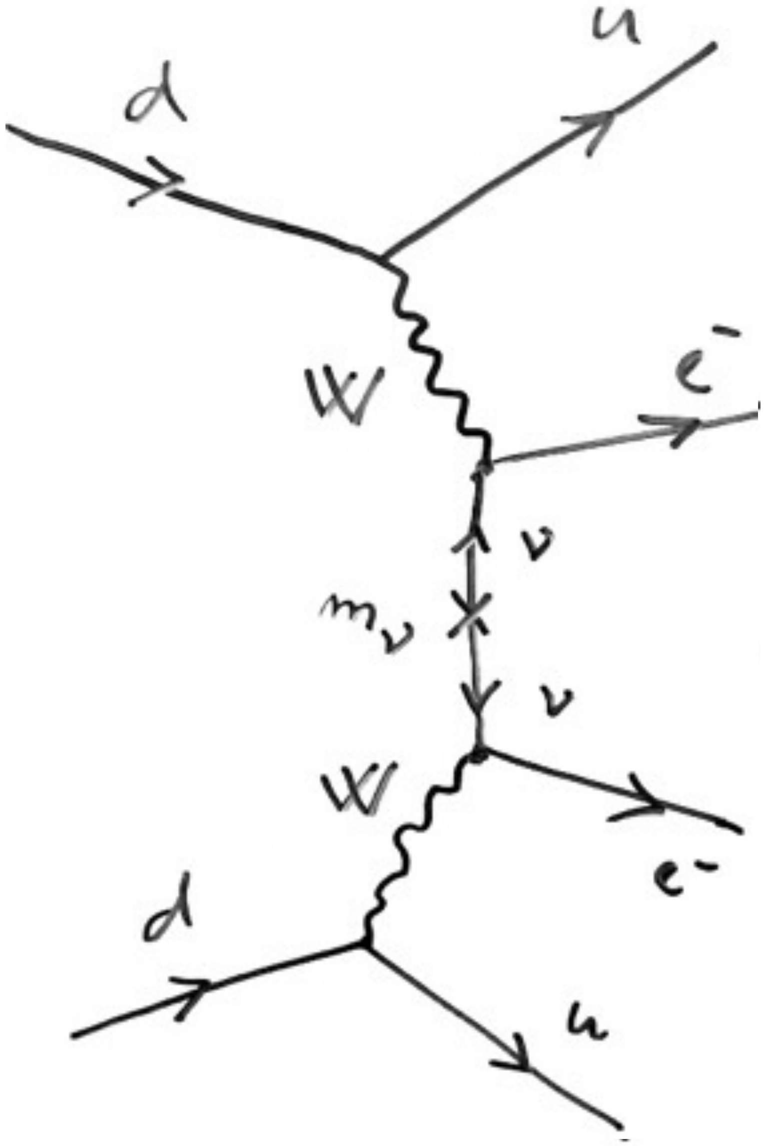

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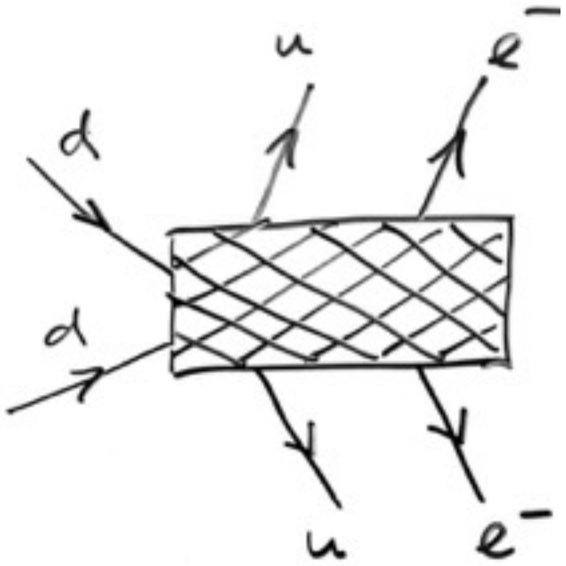

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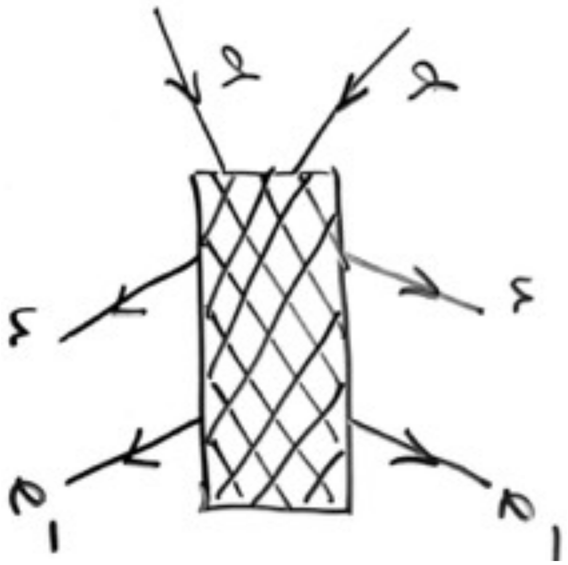

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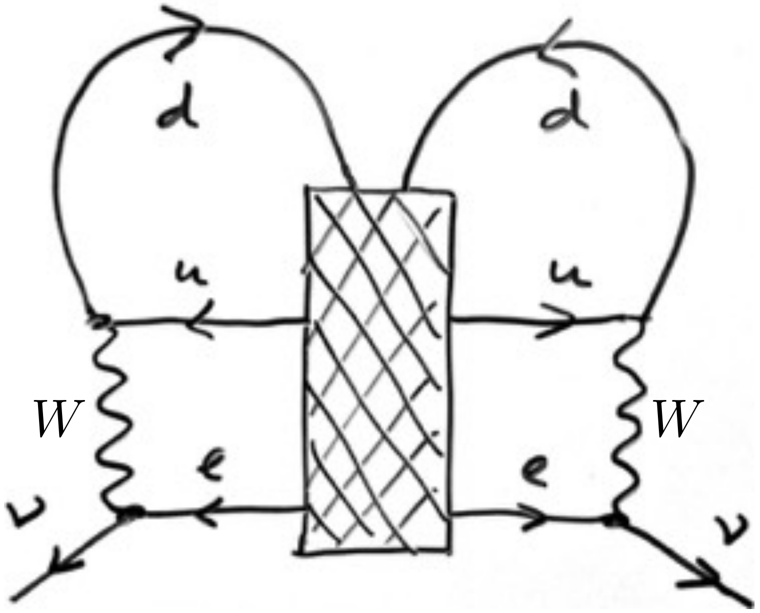

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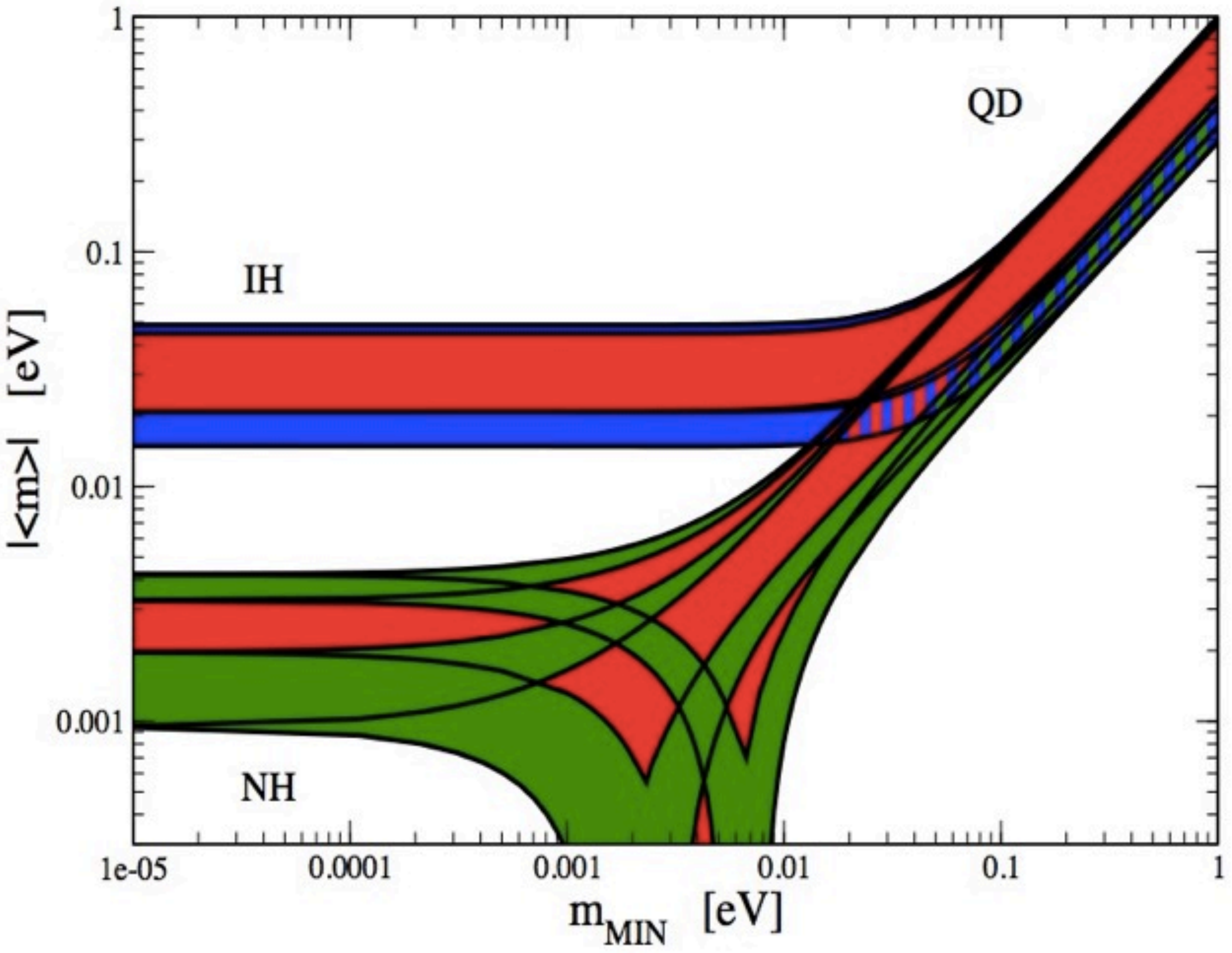
Difficult to decipher CP conservation from CPV in 0v2beta



S.T. Petcov, Int.J.Mod.Phys.A29 (2014) 1430028

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- **not gauge invariant !!!**

Seesaw type I - Majorana mass term for singlets

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

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

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Seesaw indicates a large new scale!

Why we like heavy Majorana neutrinos...

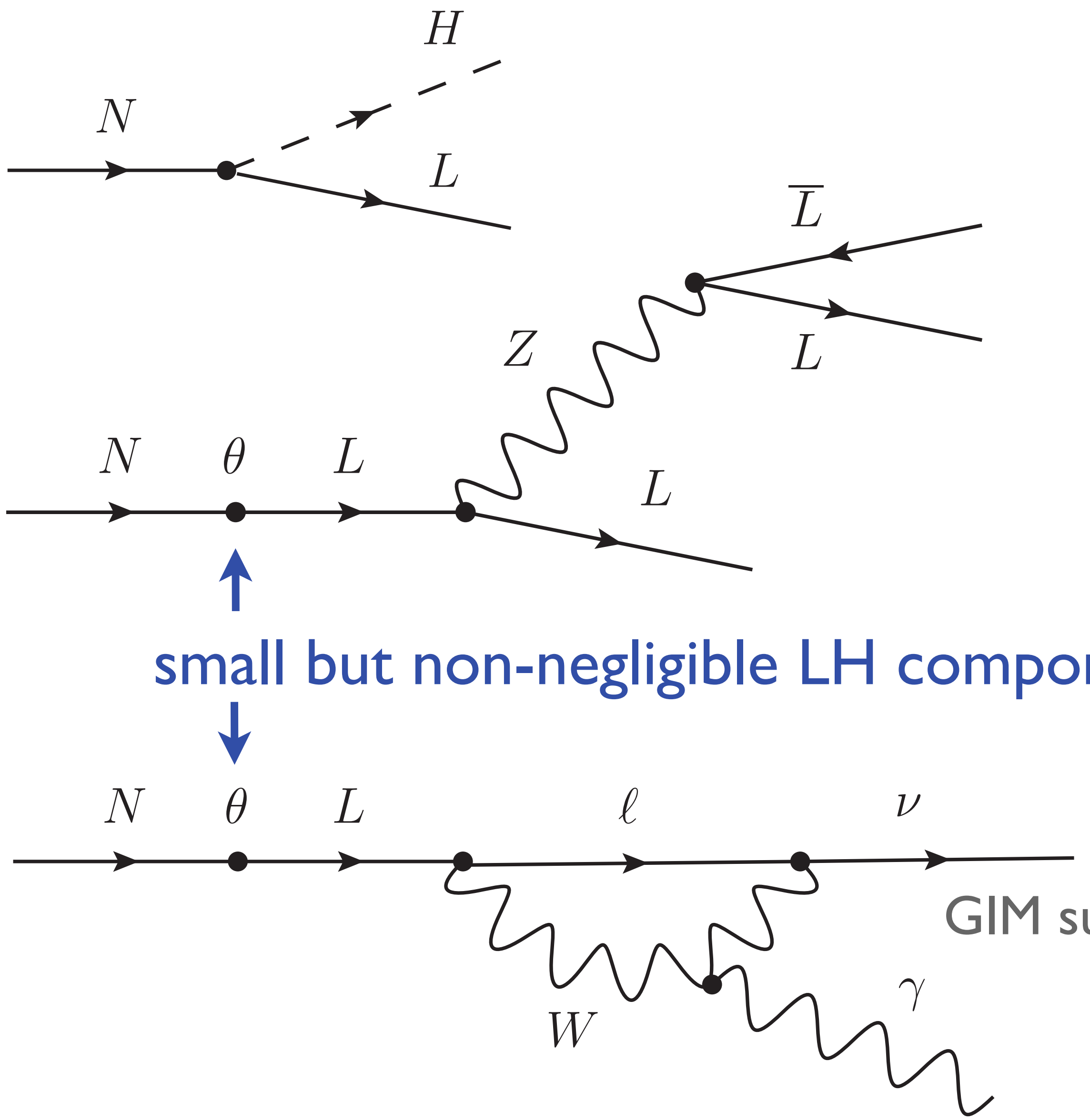
T. Asaka, S. Blanchet and M. Shaposhnikov, Phys. Lett. B631(2005) 151

RH neutrinos as DM: Stability is the main concern...

$m_N > m_H$: killed by

$m_N > m_e$: killed by

$m_N < m_e$: radiative decay

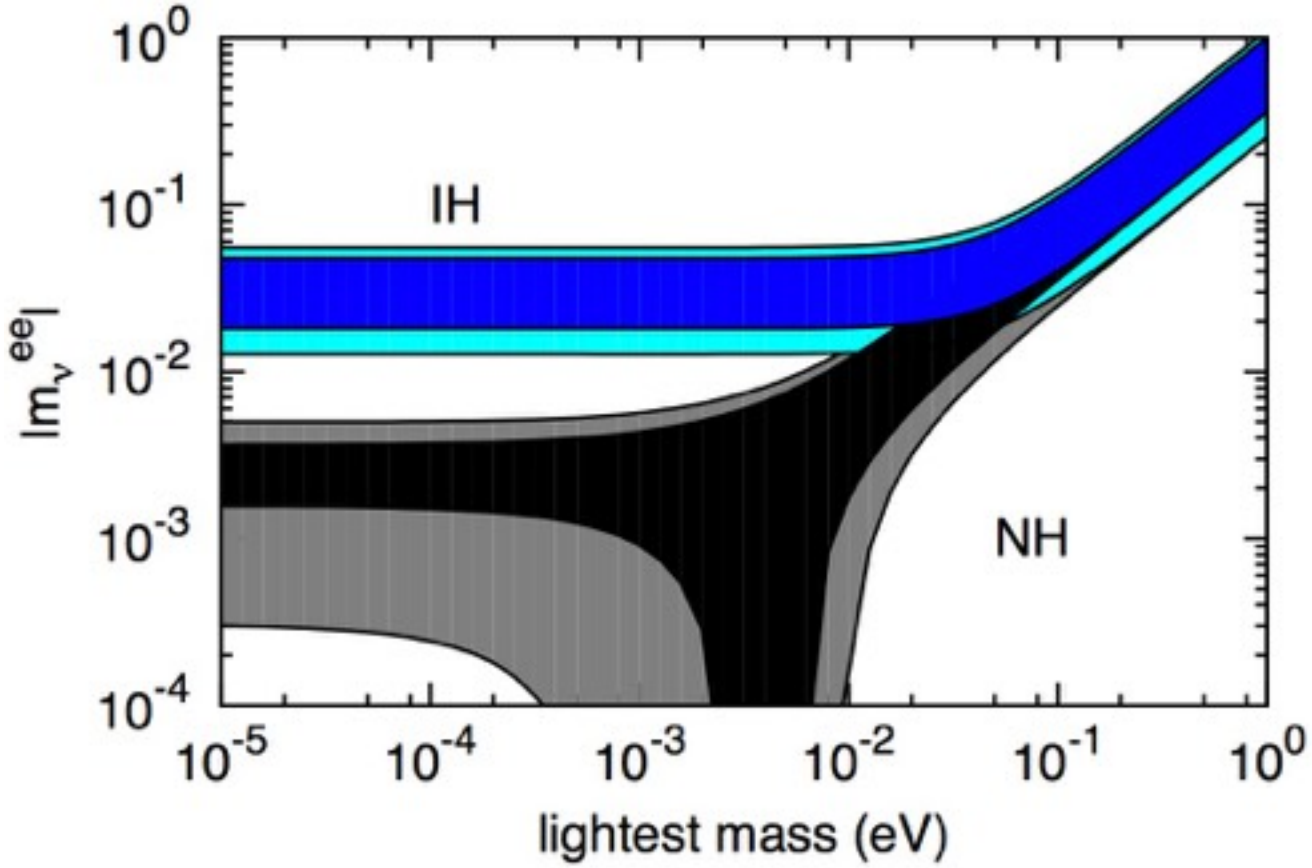


small but non-negligible LH component in N

GIM suppressed, OK

keV-ish RH neutrino acceptable, lighter would be "too hot".

Why we like heavy Majorana neutrinos...



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

Figures from Chakrabortty et al., 2012

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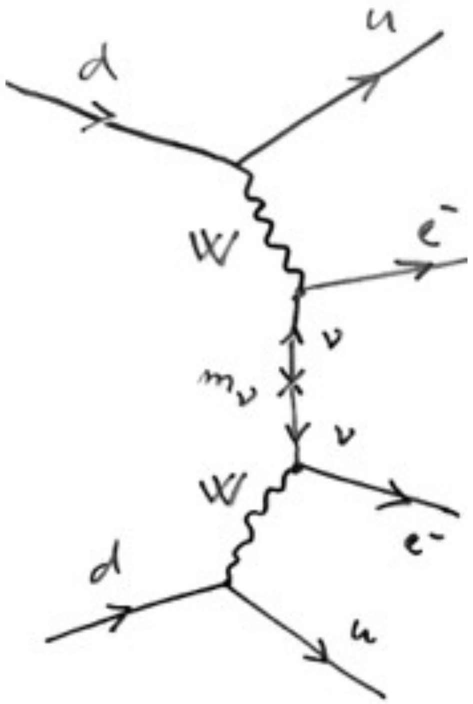
Diagrammatics:



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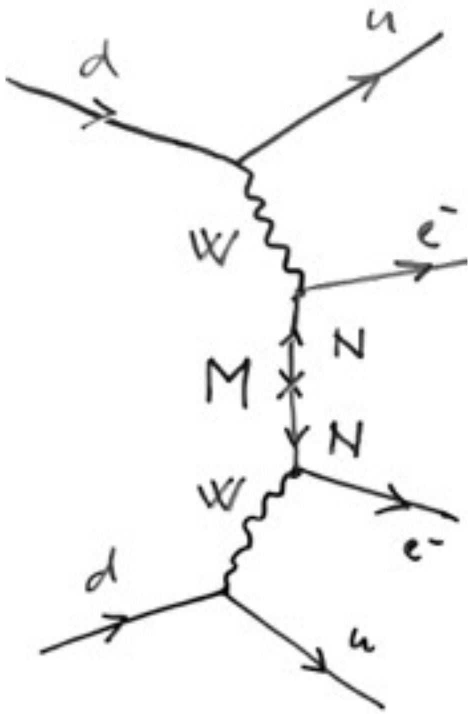
Heavy neutrinos also feel gauge interactions!



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

Figures from Chakrabortty et al., 2012

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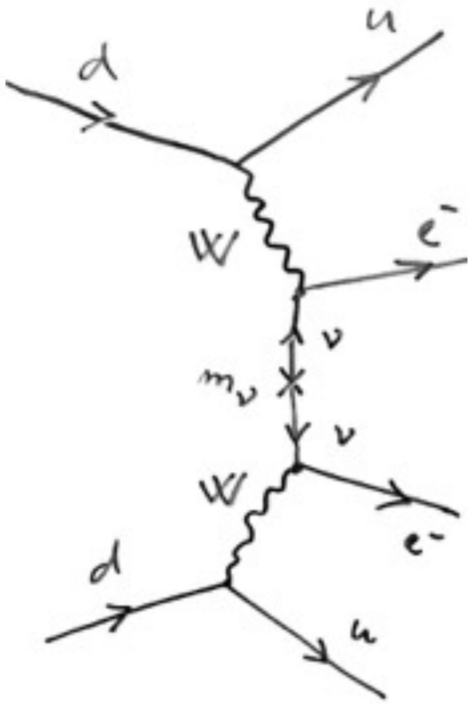

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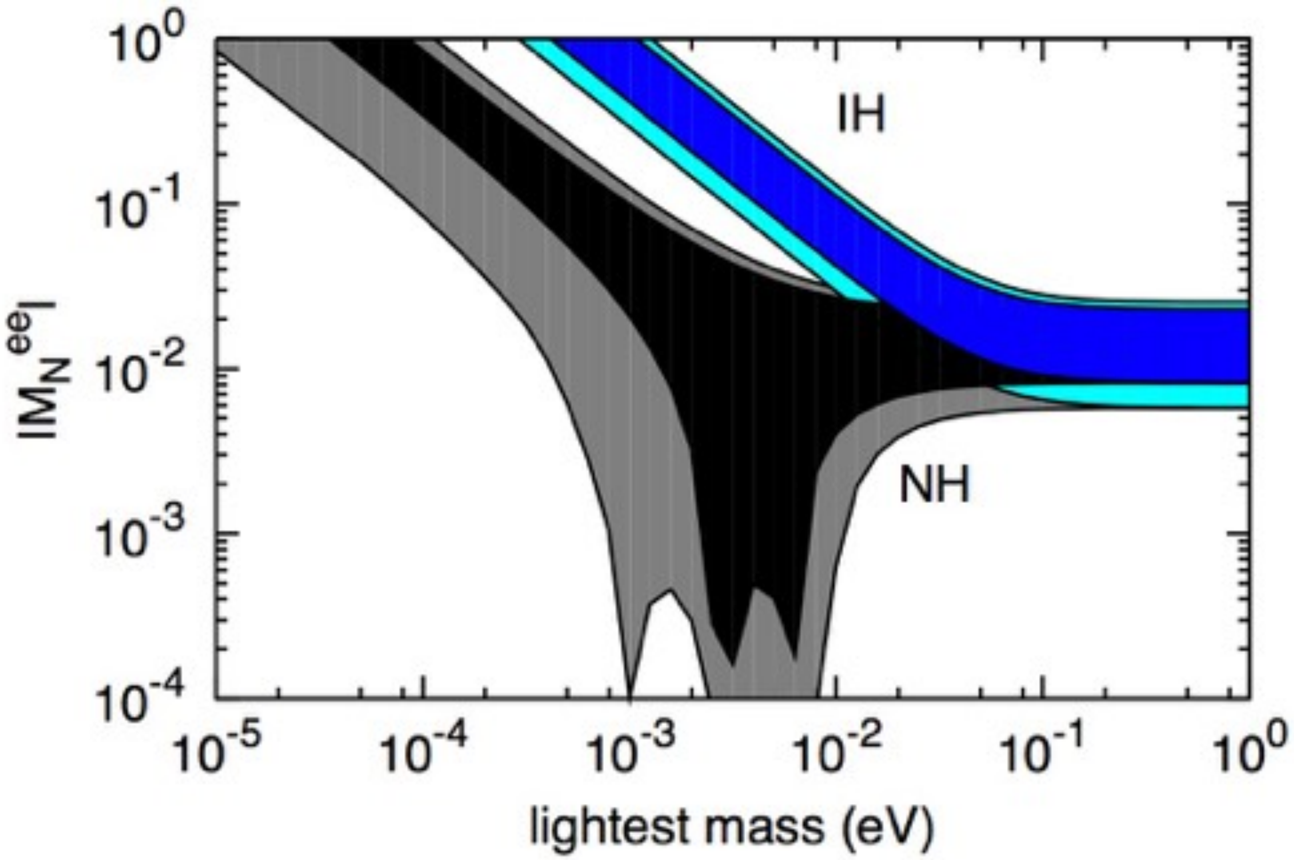


$$\mathcal{A} \propto g^4 \sum_i F^2 \frac{\kappa}{M_i}$$

Figures from Chakrabortty et al., 2012

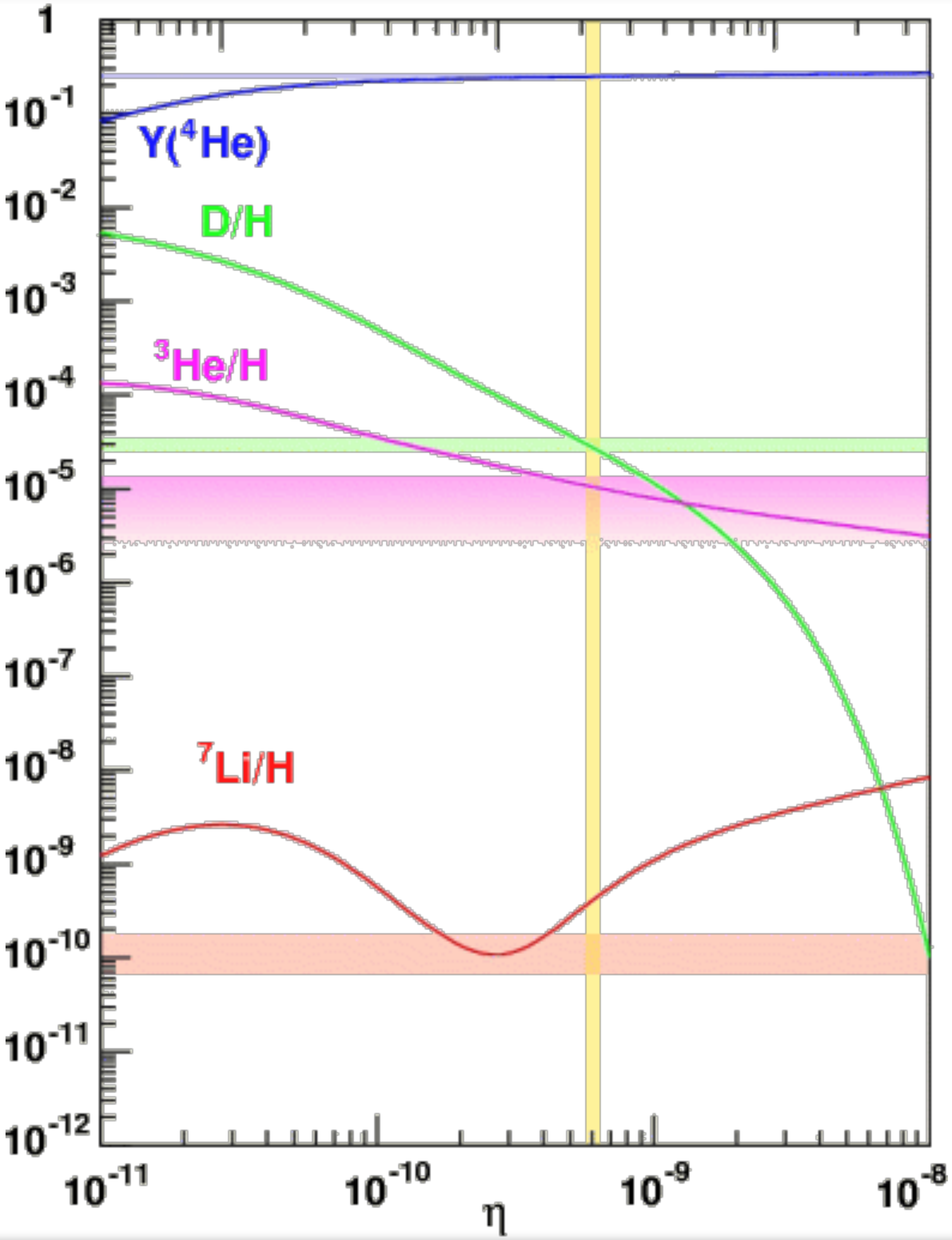
This may even dominate if M is in the TeV region or if there are RH currents around TeV

Is **CPV** in the PMNS matrix really needed?

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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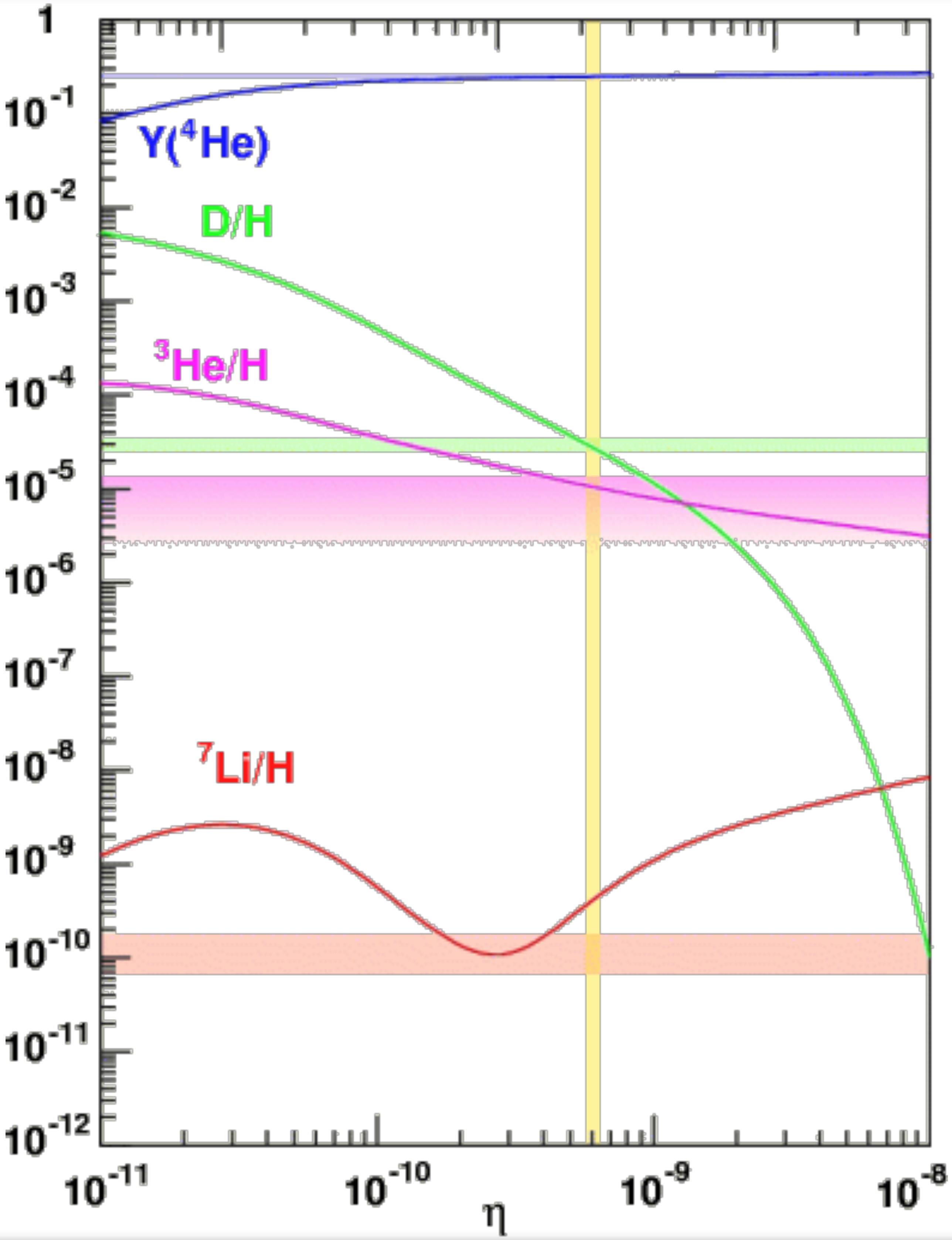

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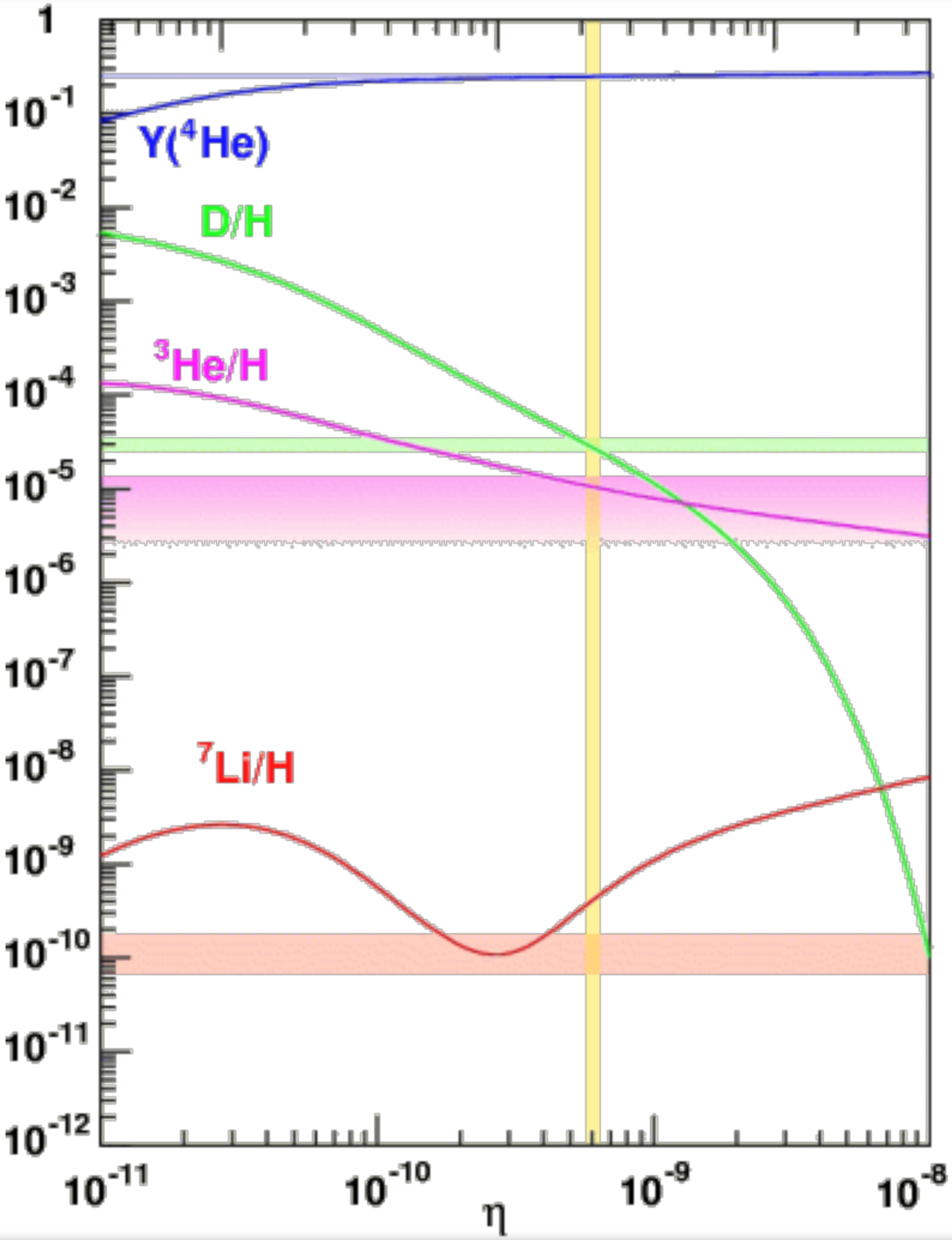
Symmetric initial conditions:

(Standard model)

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



Baryon assymmetry upper limit in a B-symmetric Universe

Baryon-antibaryon annihilation rate: $\sigma \propto \frac{1}{m_\pi^2}$

Hubble rate in a RD Universe: $H \sim \frac{T^2}{M_{Pl}}$

B-annihilation freeze-out: $T_{FO}^{B\bar{B}} \sim \frac{m_B}{\log(0.04 \times m_B M_{Pl} \sigma)} \sim 20\,\mathrm{MeV}$

Relic number density:

$$\boxed{\left.\frac{n_{EQ}}{n_\gamma}\right|_{T_{FO}} \sim 10^{-18}}$$

Cooking up a primordial baryon asymmetry

1967: Sacharov's baryogenesis conditions

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- C and CP violation
- Departure from thermal equilibrium

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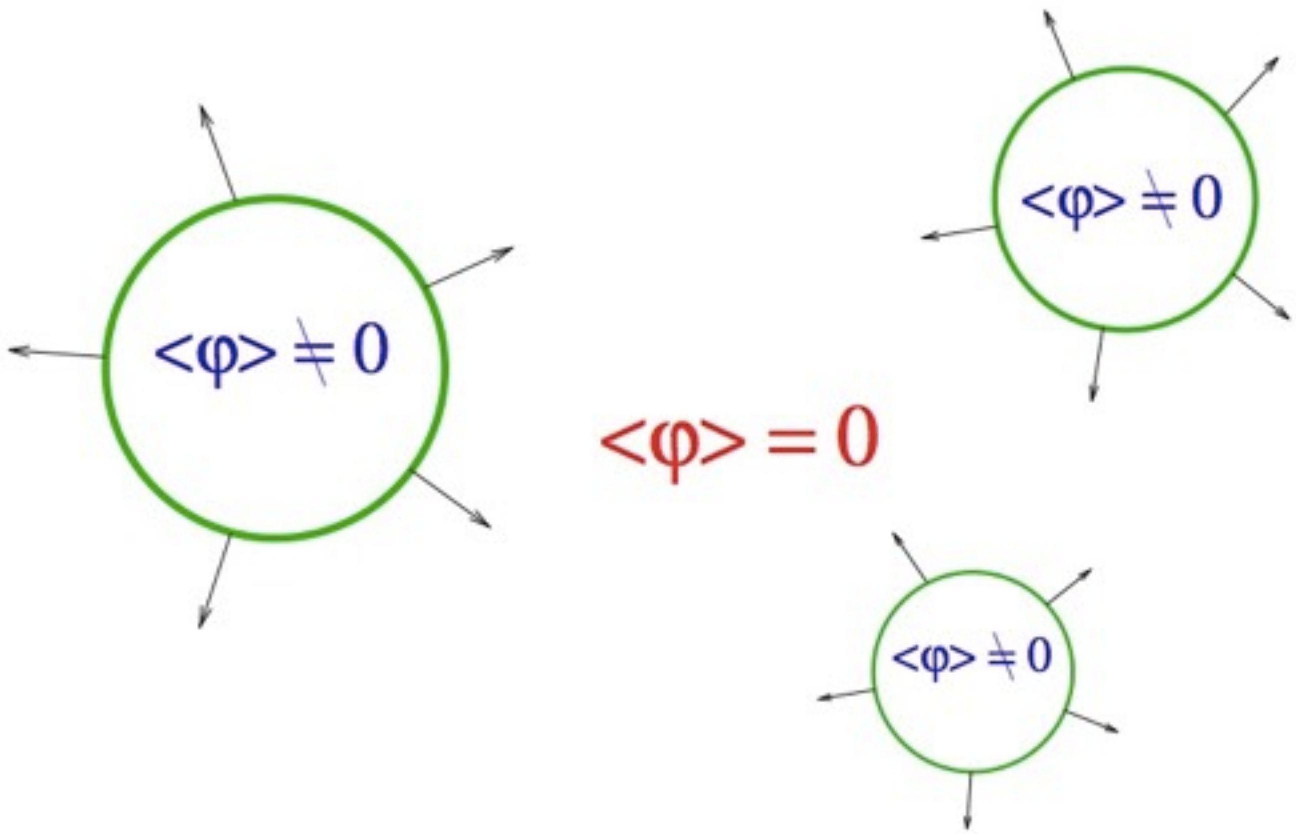
All this is there in the Standard Model (!)

B+L generation during the EW phase transition

Bubble growth below the EWPT critical temperature...



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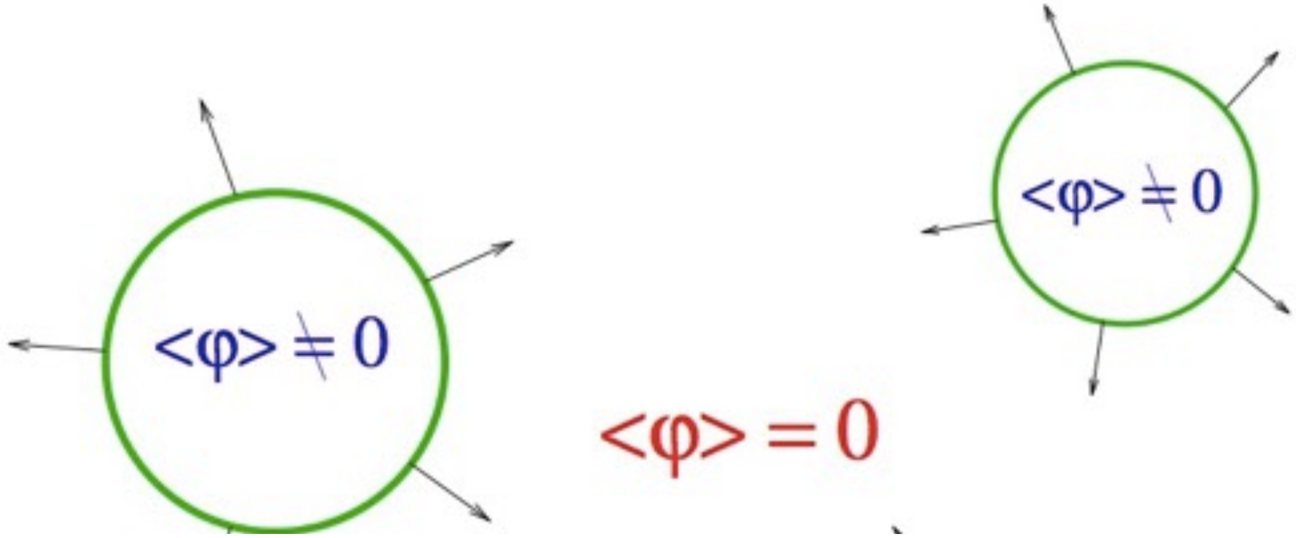

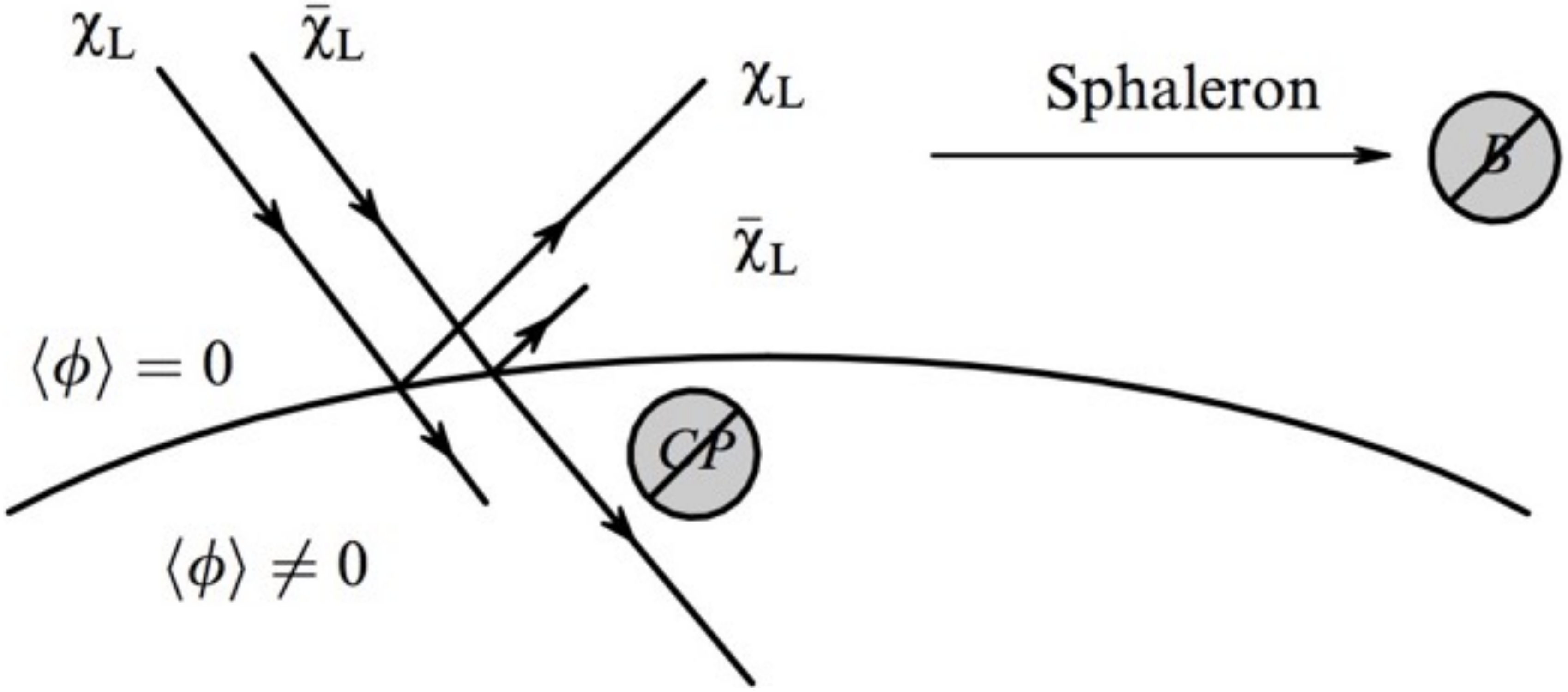

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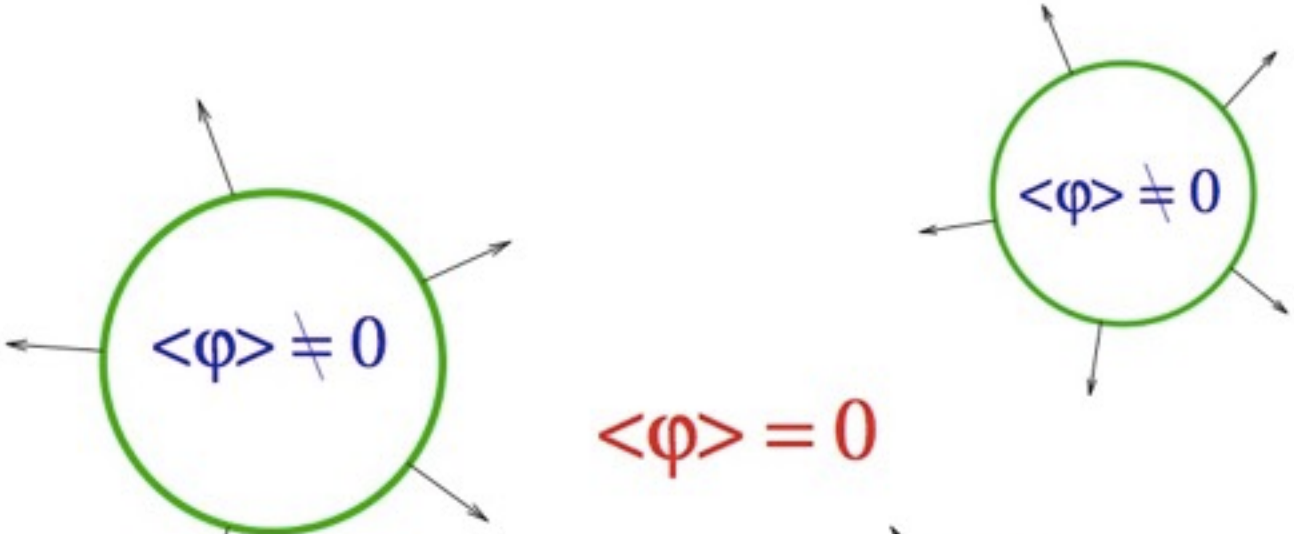

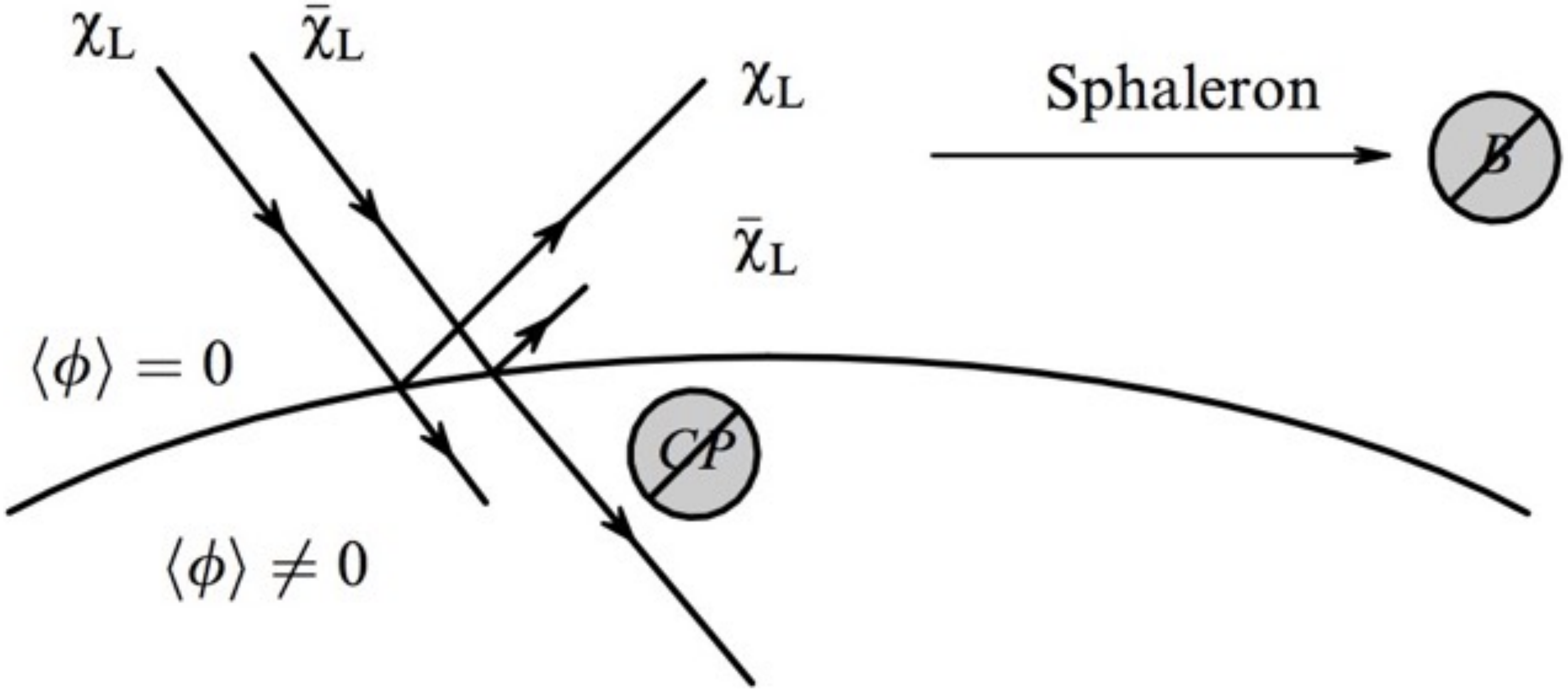

Bubbles do not form for m_H = 125 GeV, SM CPV too weak !!!

Baryogenesis through leptogenesis

Pert. LNV + nonpert. 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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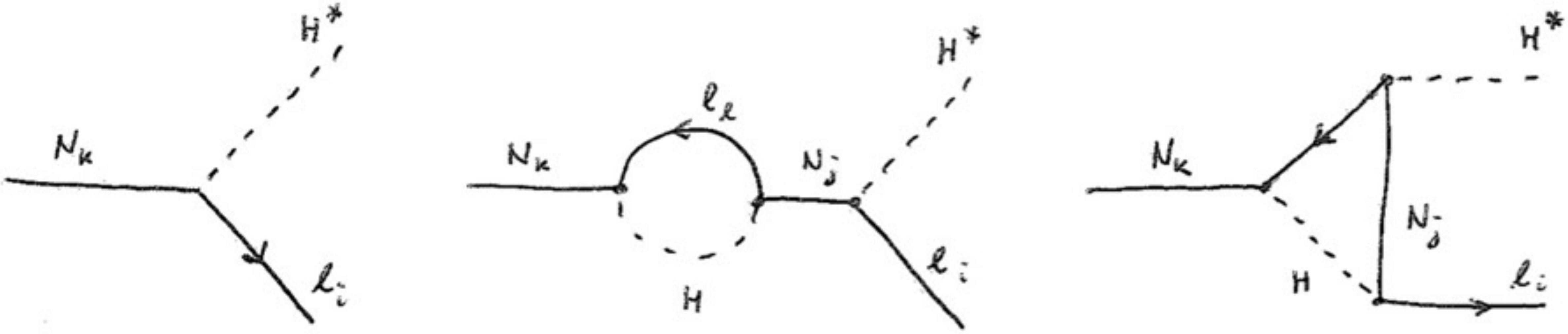
2) Sphalerons provide L to B transitions before EWPT

Kuzmin, Rubakov, Shaposhnikov, PLB155, 1985

Vanilla type-I seesaw leptogenesis



CP asymmetry (hierarchical limit, flavor-blind):

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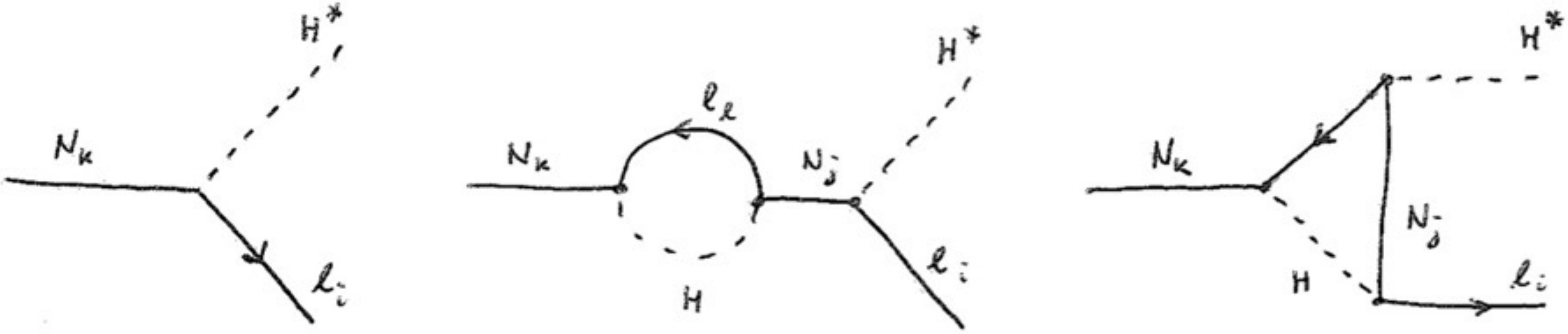

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Davidson-Ibarra bound: S. Davidson and A. Ibarra, Phys. Lett. B535, 25 (2002)

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

$$\boxed{M_1 \gtrsim 10^9\,\mathrm{GeV}}$$

CPV in type-I seesaw leptogenesis

2 sources of CPV effects in $\mathrm{Im}\left[(Y_N Y_N^\dagger)^2_{ij}\right]$

See tomorrow's talk by S.T. Petcov

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See tomorrow's talk by S.T. Petcov

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high-scale phases

PMNS

Flavor-blind case: $\varepsilon_1 \sim \frac{3M_1}{16\pi v^2}\mathrm{Im}\left[\sum_\alpha m_\alpha^2 R_{1\alpha}^2\right] \Big/ \sum_\alpha m_\alpha |R_{1\alpha}|^2$

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Flavor-blind case: $\varepsilon_1 \sim \frac{3M_1}{16\pi v^2}\mathrm{Im}\left[\sum_\alpha m_\alpha^2 R_{1\alpha}^2\right] \Big/ \sum_\alpha m_\alpha |R_{1\alpha}|^2$

Leptogenesis with flavour effects:

CPV in type-I seesaw leptogenesis

2 sources of CPV effects in $\mathrm{Im}\left[(Y_N Y_N^\dagger)_{ij}^2\right]$

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NH: $|s_{13}\sin\delta| \gtrsim 0.09$ sufficient for the effect to come from PMNS only

IH: For $-s_{13}\cos\delta \gtrsim 0.1$ leptogenesis **requires Majorana CPV in PMNS!**

Thank you for your kind attention!