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Theoretical motivations for precision measurements of oscillation parameters

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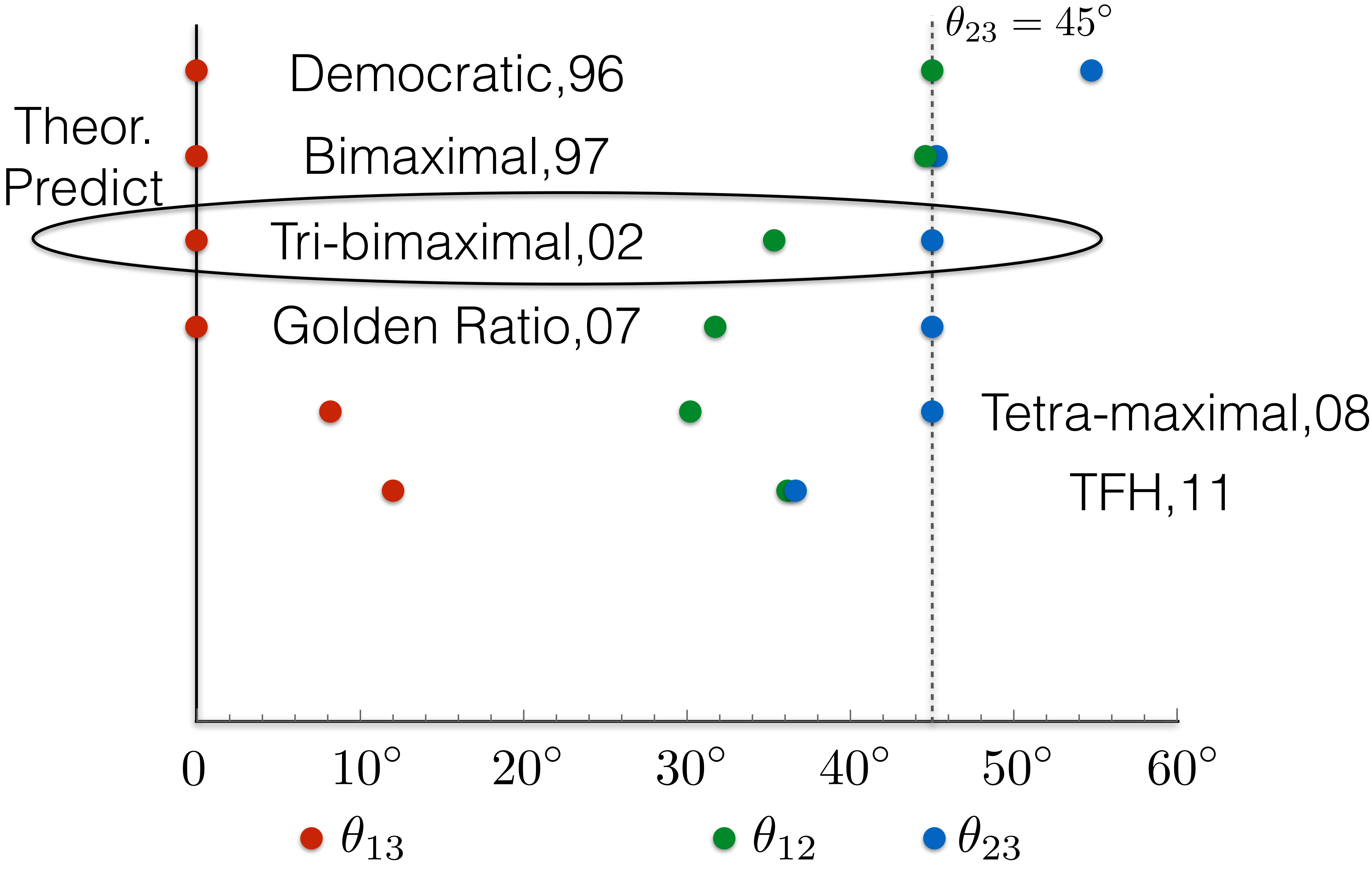
Mixing angles: theoretical predictions



Neutrino oscillation experiments

$$\Delta m^2_{ji} \equiv m_j^2 - m_i^2$$

$$\Delta_{ji} \equiv \Delta m^2_{ji} L/(4E)$$

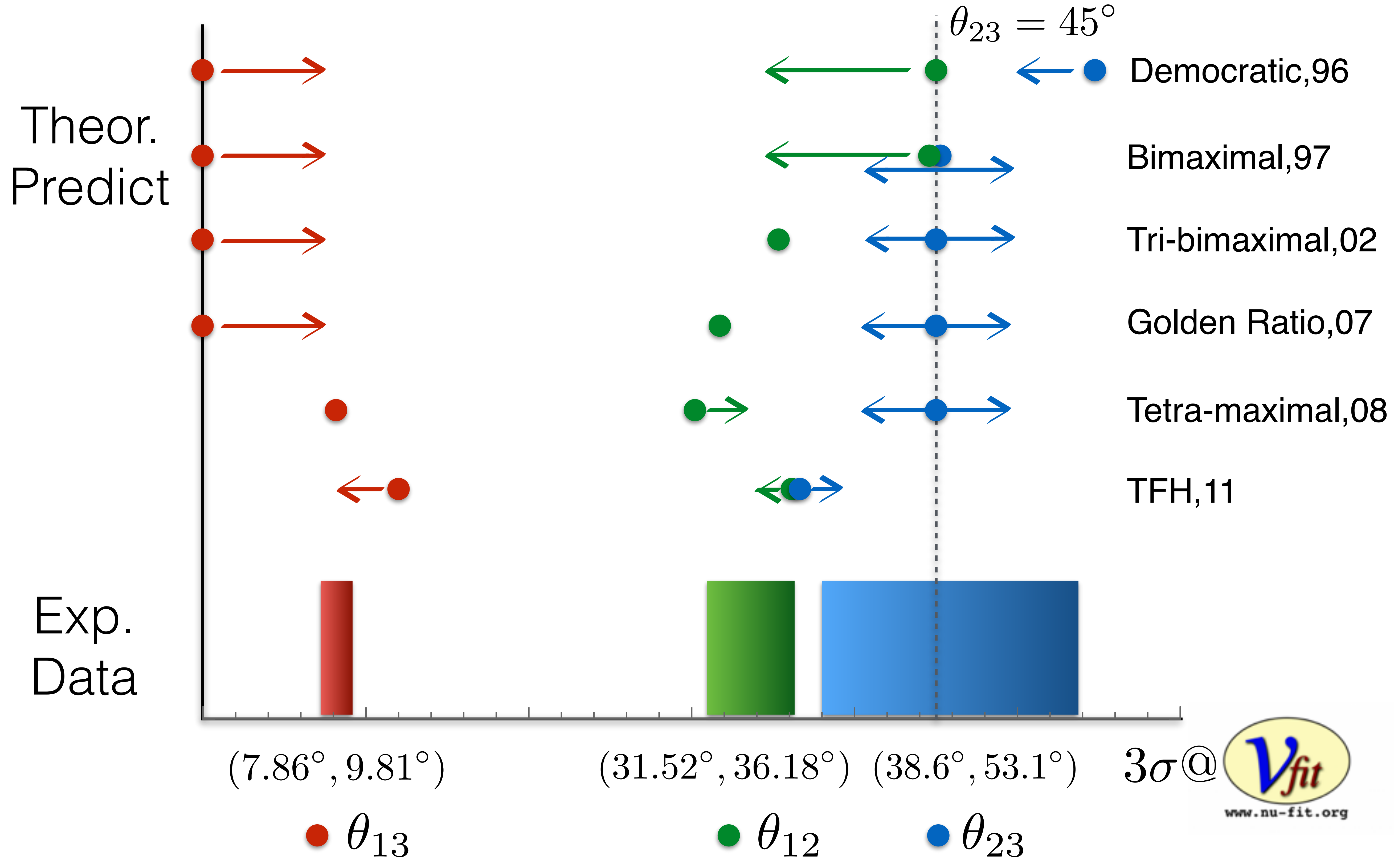
Type	Probability	Existing Experiments
Solar	P_{ee}	Super-K, SNO, Borexino, ...
	$P_{ee} \approx \sin^2\theta_{12}$	$P_{ee} \approx 1 - \frac{1}{2}\sin^2 2\theta_{12}$ (MSW effect)
Atmospheric	$P_{\mu\mu}, P_{\mu\tau}$	Super-K, ...
	$P_{\mu\tau} \approx 1 - P_{\mu\mu} \approx \sin^2 2\theta_{23}\sin^2\Delta_{31}$	
Reactor	$P_{\bar{e}\bar{e}}$	KamLAND, Daya Bay, Reno, Double Chooz, ...
	$P_{\bar{e}\bar{e}} \approx 1 - \sin^2 2\theta_{12}\sin^2\Delta_{21}$	$P_{\bar{e}\bar{e}} \approx 1 - \sin^2 2\theta_{13}\sin^2\Delta_{31}$
Accelerator	$P_{\mu\mu}, P_{\mu e}$	K2K, T2K, MINOS, NOvA, ...
	$P_{\mu\tau} \approx 1 - P_{\mu\mu} \approx \sin^2 2\theta_{23}\sin^2\Delta_{31}$	OPERA, $P_{\mu\tau}$

$$P_{\mu e} \approx \frac{s_{23}^2 \sin^2 2\theta_{13}}{(1-\hat{A})^2}\sin^2[(1-\hat{A})\Delta_{31}] + \frac{\alpha\tilde{J}\sin(\Delta_{31}+\delta)}{\hat{A}(1-\hat{A})}\sin(\hat{A}\Delta_{31})\sin[(1-\hat{A})\Delta_{31}],$$

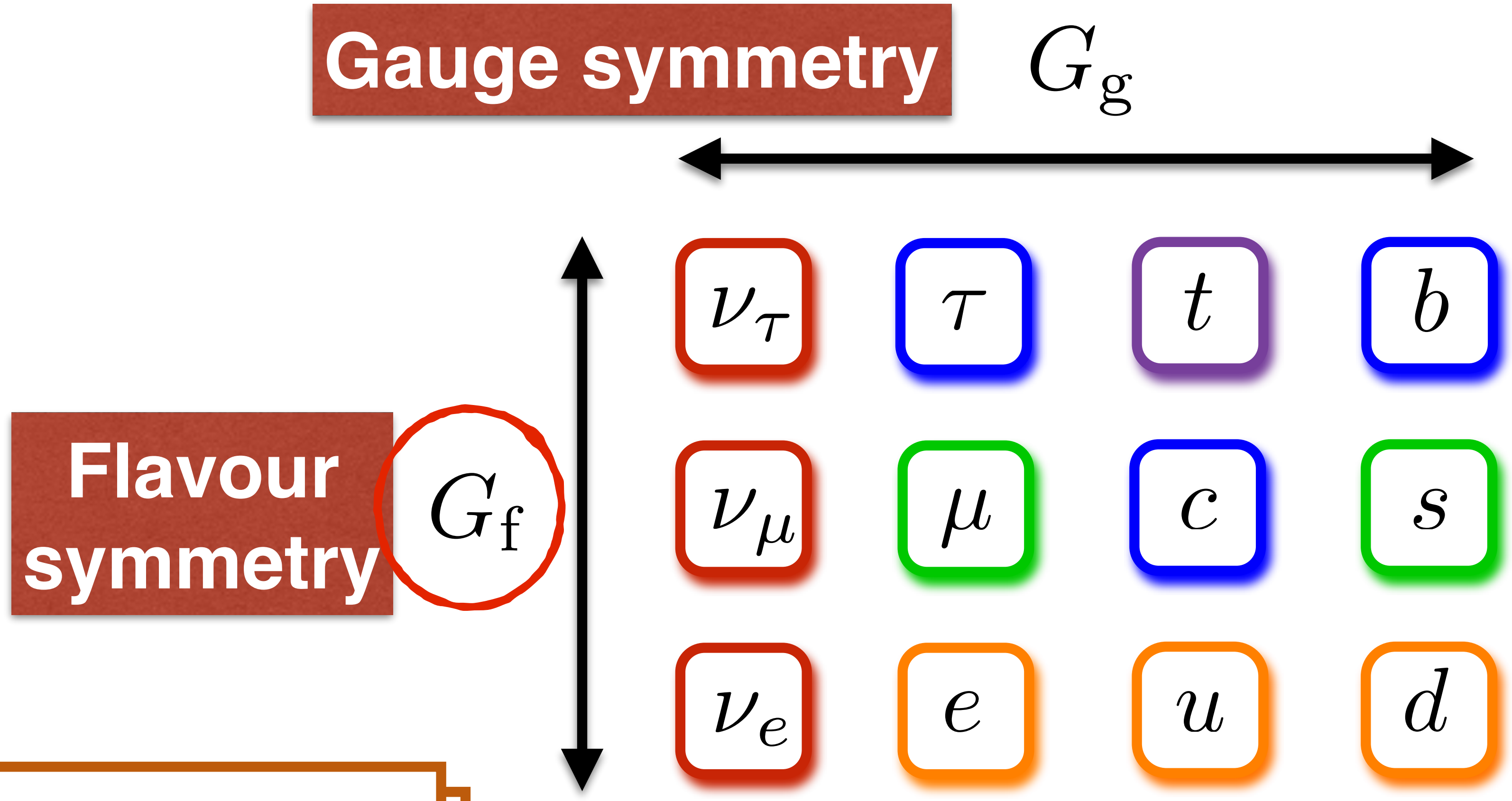
$$\tilde{J} = \cos\theta_{13}\sin 2\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23},\ \alpha = \Delta m^2_{21}/\Delta m^2_{31},\ \hat{A} = A_{\rm CC}/\Delta m^2_{31}$$

Next generation: DUNE, T2HK, JUNO, PINGU,……

Mixing angles: theories vs experiments



Flavour symmetry



Gauge symmetry G_{g}

Flavour symmetry G_{f}

Anarchy

	Continuous	Discrete
Abelian	U(1)	Z_n
Non-Abelian	SU(3), SO(3),…	A_4, S_4, A_5, $\Delta(48)$, …

Constant mixing patterns

- Before 2012, Tri-bimaximal (TBM)

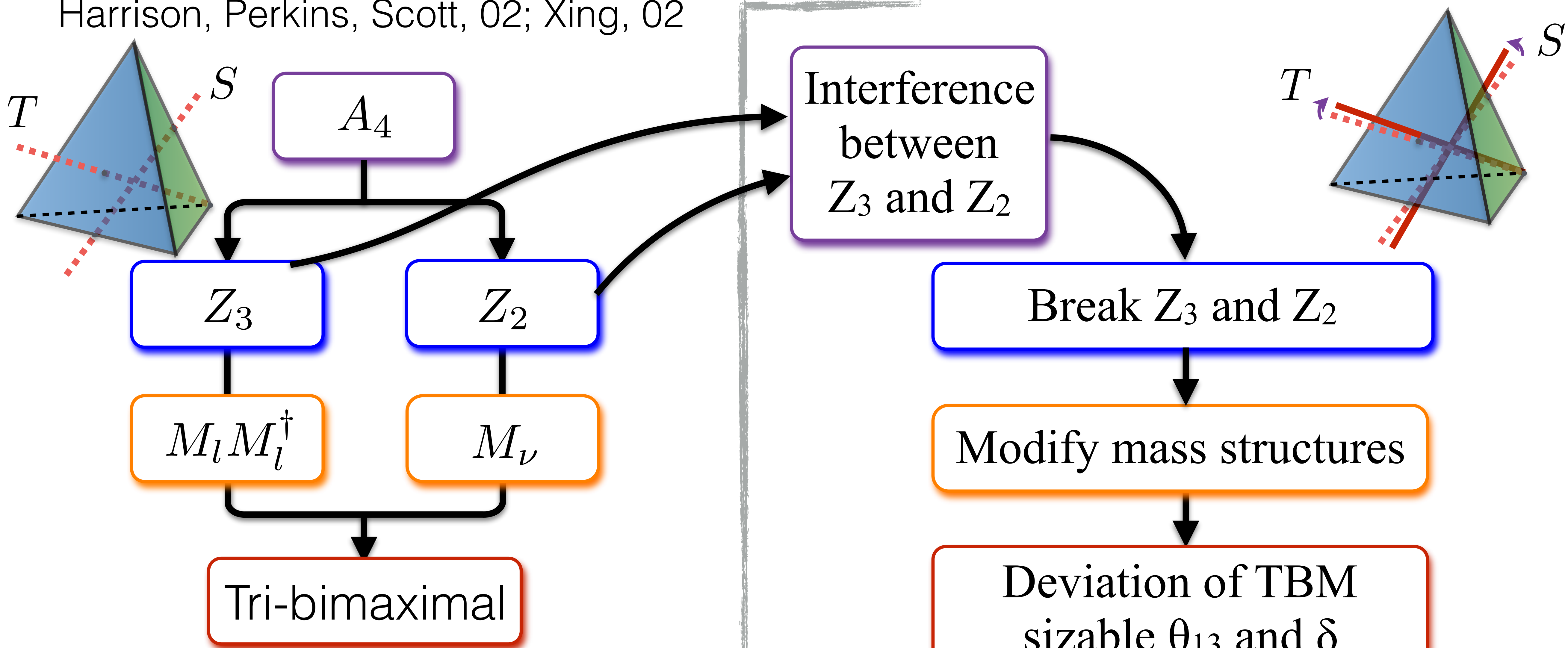
$$|U| = \begin{pmatrix} \frac{2}{\sqrt{6}} & \frac{1}{\sqrt{3}} & 0 \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

$$\sin^2\theta_{13} = 0$$
$$\sin^2\theta_{12} = 1/3$$
$$\sin^2\theta_{23} = 1/2$$

Harrison, Perkins, Scott, 02; Xing, 02

- After 2012, special corrections are needed:

$$U = U_{\text{TBM}} + \delta U$$



Altarelli, Feruglio, 05; 06.

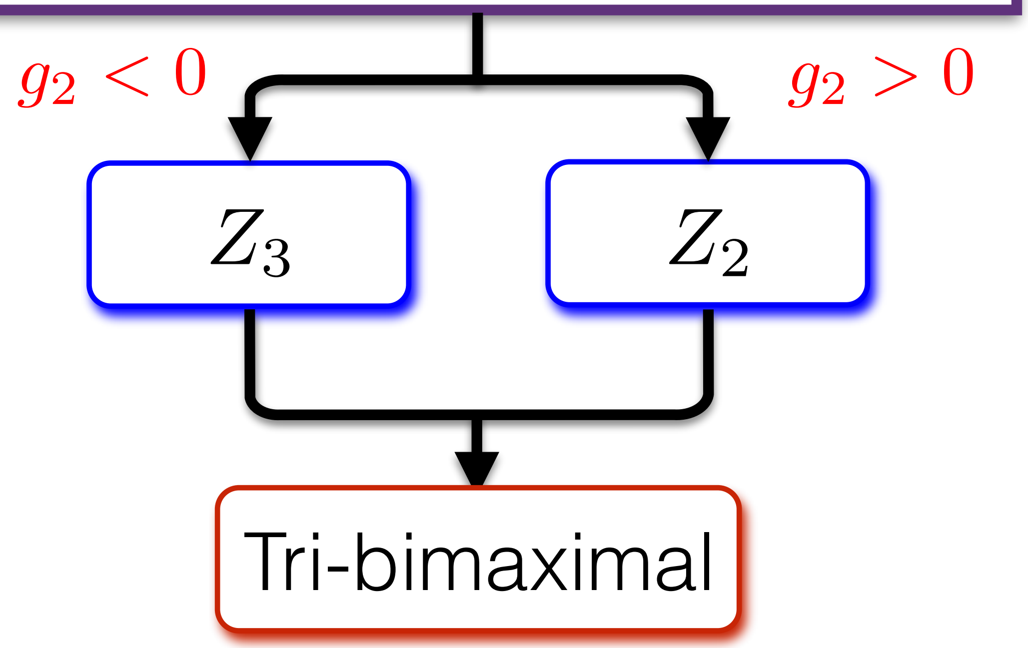
Mixing induced by flavon cross couplings

- An economical model   Pascoli, YLZ, JHEP 1606, 073 (2016)

$$V_{\text{flavon}} = V(\varphi) + V(\chi) + V(\varphi, \chi) + \cdots$$

Self Couplings   **Cross Couplings**

$$\boxed{\begin{gathered} V(\varphi) = \mu_\varphi^2 I_1 + g_1 I_1^2 + g_2 I_2 \\ I_1 = \varphi_1^2 + \varphi_2^2 + \varphi_3^2 \\ I_2 = \varphi_1^2\varphi_2^2 + \varphi_2^2\varphi_3^2 + \varphi_3^2\varphi_1^2 \end{gathered}}$$



$$\sin\theta_{12} = \frac{1}{\sqrt{3}}(1 - 2|\epsilon_\varphi|\cos\theta_\varphi + 2\epsilon_\chi)$$

$$\sin\theta_{23} = \frac{1}{\sqrt{2}}(1 + |\epsilon_\varphi|\cos\theta_\varphi)$$

$$\sin\theta_{13} = \sqrt{2}|\epsilon_\varphi \sin\theta_\varphi|$$

$$\delta = \begin{cases} 270^\circ - 2|\epsilon_\varphi|\sin\theta_\varphi\,, & \theta_\varphi > 0\,, \\ 90^\circ - 2|\epsilon_\varphi|\sin\theta_\varphi\,, & \theta_\varphi < 0\,, \end{cases}$$

$$\boxed{\epsilon_\varphi = |\epsilon_\varphi| e^{i\theta_\varphi}}$$

Sum rule

$$\delta \approx \begin{cases} 270^\circ - \sqrt{2}\theta_{13}\,, & \theta_\varphi > 0\,, \\ 90^\circ + \sqrt{2}\theta_{13}\,, & \theta_\varphi < 0\,. \end{cases}$$

Origin of CP violations

- Explicit CP violations

Complex coefficients

$$\mathcal{L} = |\lambda| e^{i\alpha} \phi^4 + |\lambda| e^{-i\alpha} \phi^{*4} + \cdots$$

$$\xrightarrow{CP} \mathcal{L}' = |\lambda| e^{i\alpha} \phi^{*4} + |\lambda| e^{-i\alpha} \phi^4 + \cdots \neq \mathcal{L}$$

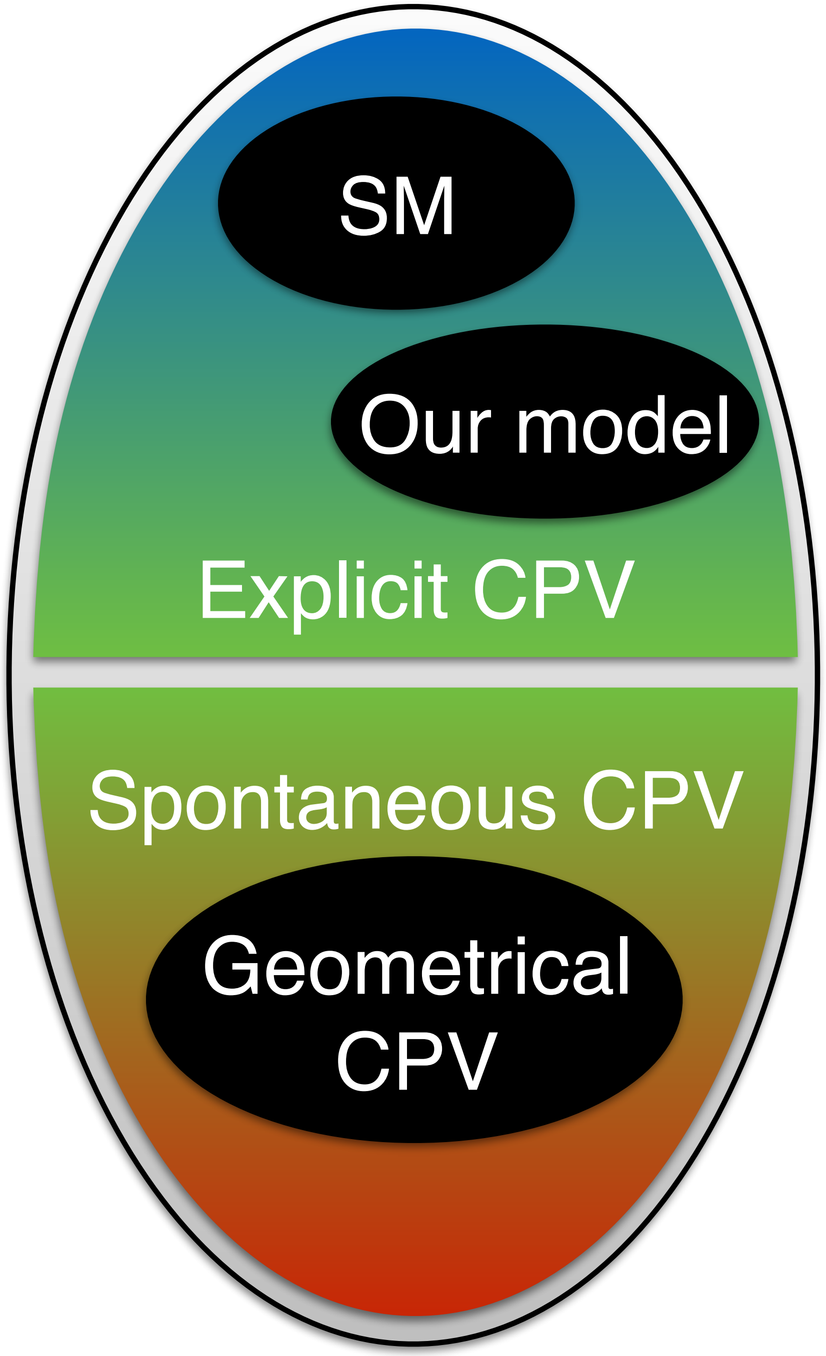
- Spontaneous CP violations

Real coefficients

No CP violations at some high scale.

CP violation arises from complex vacuum expectation values (VEV) of some scalars.

$$\langle \phi \rangle = (v_1 e^{i\alpha_1}, v_2 e^{i\alpha_2}, v_3 e^{i\alpha_3})^T$$



Geometrical CP Violation: analytical calculable CP-violating phases

Branco, Gerard, Grimus, 84; de Medeiros Varzielas, Emmanuel-Costa, 11

Generalised CP symmetry

- Generalised CP symmetry (GCP)

$$\begin{pmatrix}\phi_1\\ \phi_2\\ \phi_3\end{pmatrix} \to X \begin{pmatrix}\phi_1\\ \phi_2\\ \phi_3\end{pmatrix}^* \qquad \begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} \to X \begin{pmatrix}\nu_e^c\\ \nu_\mu^c\\ \nu_\tau^c\end{pmatrix} \qquad \text{with} \qquad (x^0, \vec{x}) \to (x^0, -\vec{x})$$

X is a unitary matrix (may not be an identity matrix).

- Consistency condition

Holthausen, Lindner, Schmidt, 1211.6953

$$\begin{tikzcd}
\Phi \arrow[r, "g' \in G_f"] \arrow[d, "CP"'] \arrow[r, bend right=60] & \rho(g')\Phi = X\rho(g)^* X^{-1}\Phi \\
X\Phi^* \arrow[r, "g \in G_f"'] & X\rho(g)^*\Phi^* \arrow[u, "CP^{-1}"']
\end{tikzcd}$$

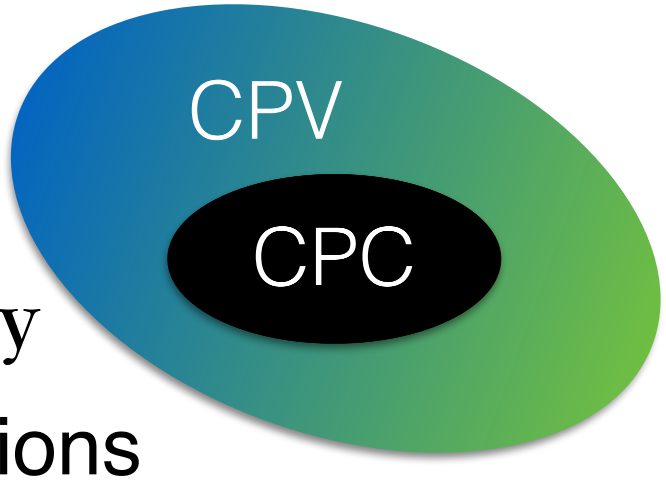
Once the flavour symmetry is fixed, all GCP candidates are determined.

- Powerful prediction

Feruglio, Hagedorn, Ziegler, 1211.5560

$$U_{\text{PMNS}} = \overbrace{P_{\alpha\beta\gamma}}^{\textbf{Row permutation}} \underbrace{V}_{\textbf{Constant matrix}} \overbrace{R(\theta)}^{\textbf{Rotation}} \underbrace{K_\nu}_{\text{diag}\{1,\pm1,\pm1\}} \overbrace{P_{ijk}}^{\textbf{Column permutation}}$$

Predictions of generalised CP symmetry



- CP conserving

$$X = \mathbf{1}_{3\times3} \qquad \delta = 0, 180^\circ.$$

- CP violations from generalised CP symmetry

μ-τ reflection symmetry => Maximal CP violations

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} \to \begin{pmatrix} \nu_e^c \\ \nu_\tau^c \\ \nu_\mu^c \end{pmatrix} \qquad M_\nu = \begin{pmatrix} A & B & B^* \\ B & C & D \\ B^* & D & C^* \end{pmatrix}$$

Babu, Ma, Valle, 02;
Harrison, Scott, 02.

$$\Longrightarrow \boxed{\theta_{23} = 45^\circ,\ \delta = 90^\circ, 270^\circ.}$$

μ-τ reflection symmetry is predicted by A_4, and any groups containing A_4, e.g. S_4, A_5, …

Feruglio, Hagedorn, Ziegler, 1211.5560; 1303.7178; Girardi, Meroni, Petcov, Spinrath, 1312.1966; Li, Ding, 1312.4401; Ballett, Pascoli, Turner, 1503.07543…… For a review, see Xing, Zhao,1512.04207.

Generalised CP symmetries also provide other possibilities that δ does not take specific values, e.g. Δ(48), Δ(96), and some other groups in the $\Delta(3n^2)$, $\Delta(6n^2)$ series.

Ding, YLZ, 1304.2645; 1312.5222;Ding, King, 1403.5846; Hagedorn, Meroni and Molinaro, 1408.7118; Ding, King and Neder, 1409.8005; Ding, King, 1510.03188.

Lepton asymmetry in the early Universe

- Baryon asymmetry in our observed Universe

$$\eta_B \equiv \frac{n_B - n_{\overline{B}}}{n_\gamma} \approx 6.2 \times 10^{-10}$$

- Baryogenesis via classical leptogenesis (in type I seesaw)

_N_ are Majorana fermions

Complex Yukawa couplings

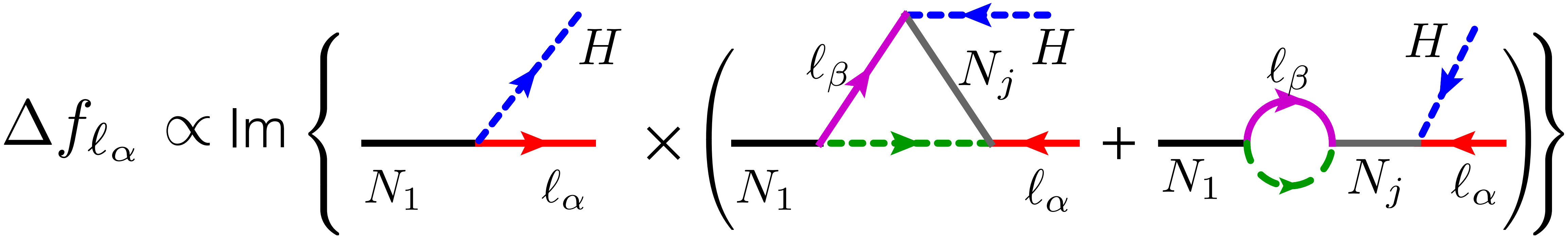
Decay of lightest _N_

Lepton asymmetry

Sphaleron $\Downarrow$ **(ΔB=ΔL)**

Baryon asymmetry

- Lepton asymmetry $\Delta f_{\ell_\alpha} \equiv f_{\ell_\alpha} - f_{\bar{\ell}_\alpha}$ in classical leptogenesis



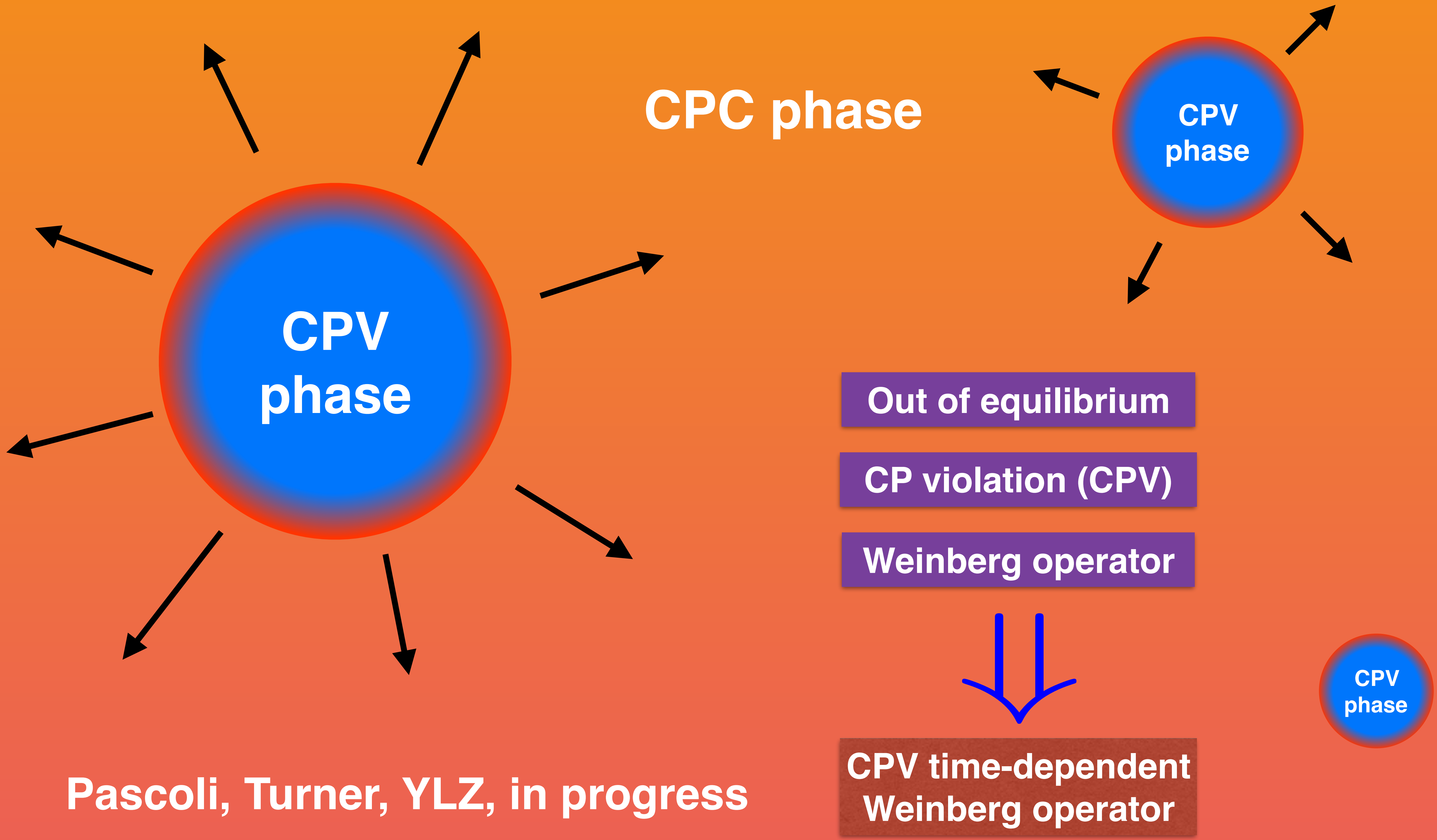
$$\propto \mathrm{Im}\{Y^*_{\nu\alpha1}(Y^\dagger_\nu Y_\nu)_{1j}Y_{\nu\alpha j}\}$$

[Fukugita, Yanagida, 1986]

Yukawa couplings between ℓ and N Y_ν cannot be real or proportional to a unitary matrix (ignoring flavour effect).

Alternative way for lepton asymmetry: CPPT

CP phase transition (CPPT) below the seesaw scale



CPC phase

Out of equilibrium

CP violation (CPV)

Weinberg operator

⇓

CPV time-dependent Weinberg operator

Pascoli, Turner, YLZ, in progress

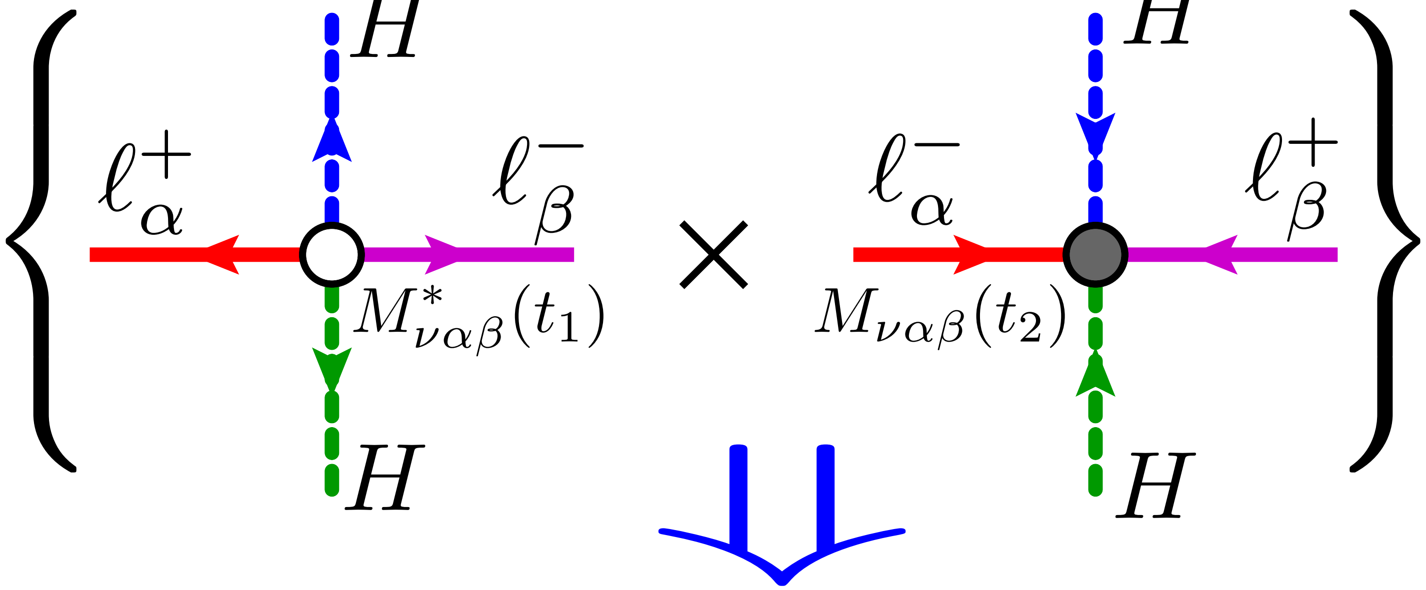
Alternative way for lepton asymmetry: CPPT

- Time-dependent coupling in the Weinberg operator

$$\mathcal{L}_{\rm d=5} = \frac{M^*_{\nu\alpha\beta}(t)}{v_H^2}\ell^c_{\alpha L}\ell^c_{\beta L}H^{*2} + \frac{M_{\nu\alpha\beta}(t)}{v_H^2}\ell_{\alpha L}\ell_{\beta L}H^2$$

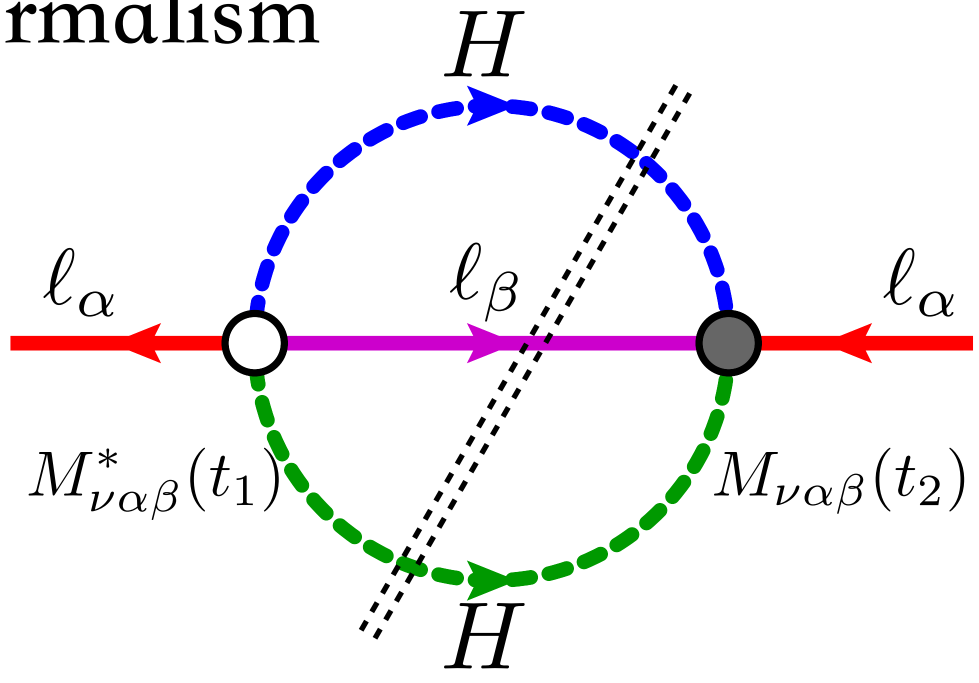
- Lepton asymmetry

$$\Delta f_{\ell_\alpha} \propto \ \mathrm{Im}$$



- Closed Time Path (CTP) formalism

$$\Delta f_{\ell_\alpha} \propto \int_{t_i}^{t_f} dt_1 \int_{t_i}^{t_f} dt_2$$



Alternative way for lepton asymmetry: CPPT

- Lepton asymmetry

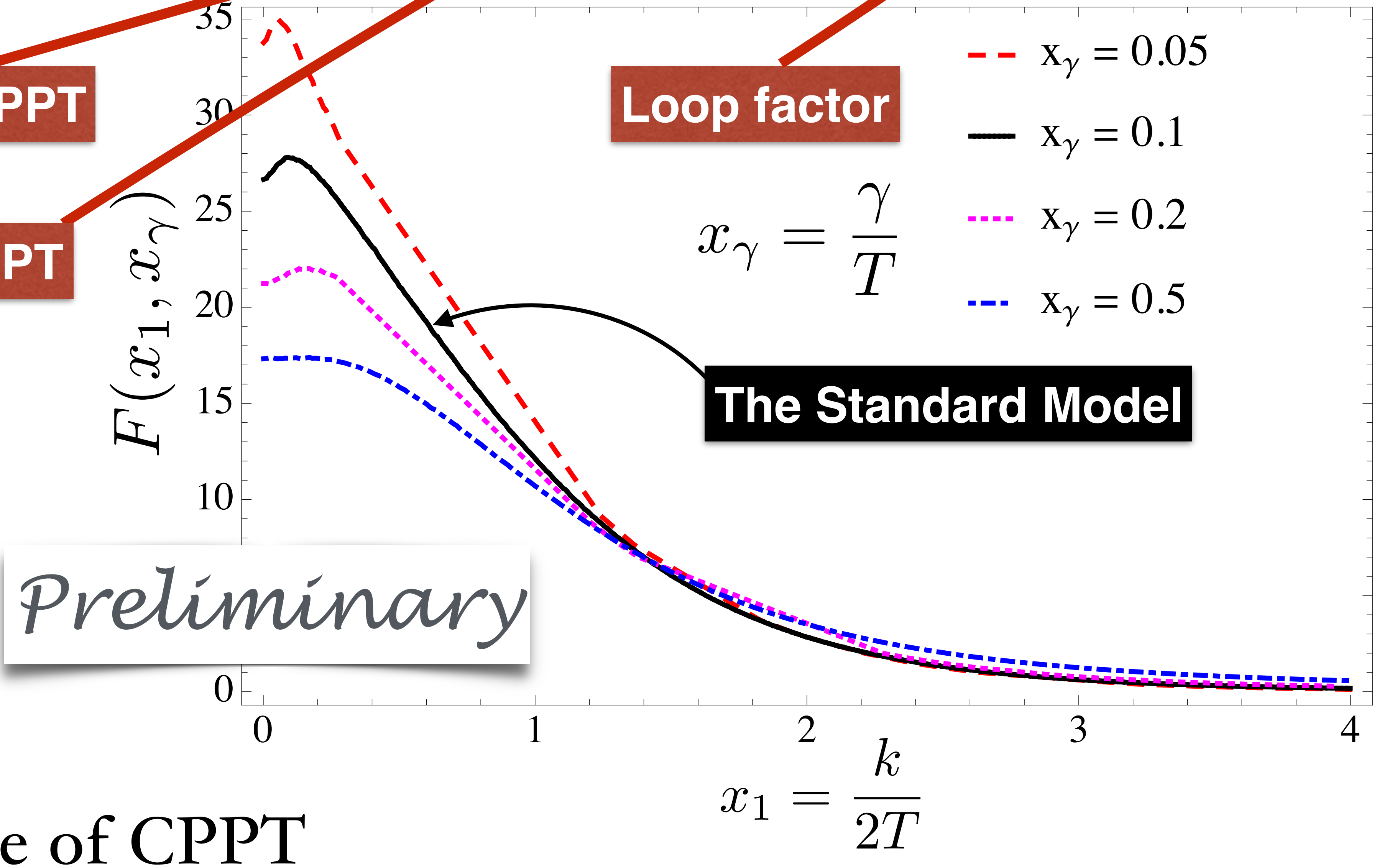
Pascoli, Turner, YLZ, in progress

$$\Delta f_\ell \equiv \sum_{\alpha=e,\mu,\tau} \Delta f_{\ell_\alpha}(k) = \mathrm{Im}\{\mathrm{tr}[M_\nu^0 M_\nu^*]\} \frac{3\,T^2}{(2\pi)^4 v_H^4} F\left(\frac{k}{2T}, \frac{\gamma}{T}\right)$$

v mass before CPPT

v mass after CPPT

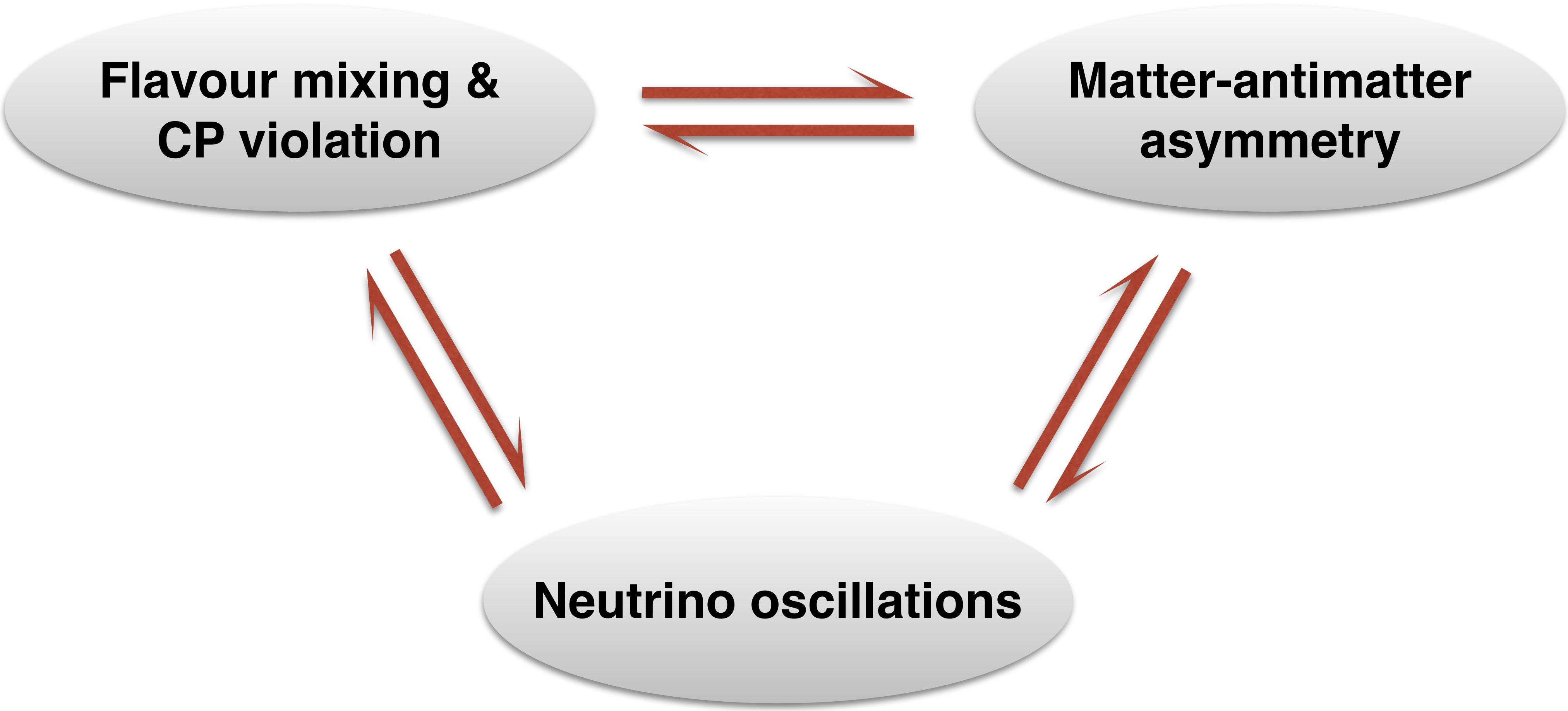
Loop factor



- Temperature of CPPT

$$T \sim 10 \sqrt{\Delta f_\ell}\, \frac{v_H^2}{m_\nu}$$

$$\begin{matrix} \Delta f_\ell > \eta_B \\ m_\nu = 0.1\mathrm{eV} \end{matrix} \Longrightarrow T > 10^{11}\ \mathrm{GeV}$$



Thank you very much