“4321” Models: Neutrinos and Gravitational Wave Probes

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<u>Talk based on:</u>

Greljo and BAS: 1802.04274
Baumholzer, Greljo and BAS: 1912.xxxxx
Greljo, Opferkuch and BAS: 1910.02014

The Roadmap

- **Part 1:** [Greljo and BAS: 1802.04274]

  A. Overview of "4321" w/ family dependent gauge charges.

  B. Solution to neutrino mass catastrophe with ISS mechanism.

- **Part 2:** [Baumholzer, Greljo and BAS: 1912.xxxxx]

  A. Leptogenesis using the neutrino sector of "4321".

- **Part 3:** [Greljo, Opferkuch and BAS: 1910.02014]

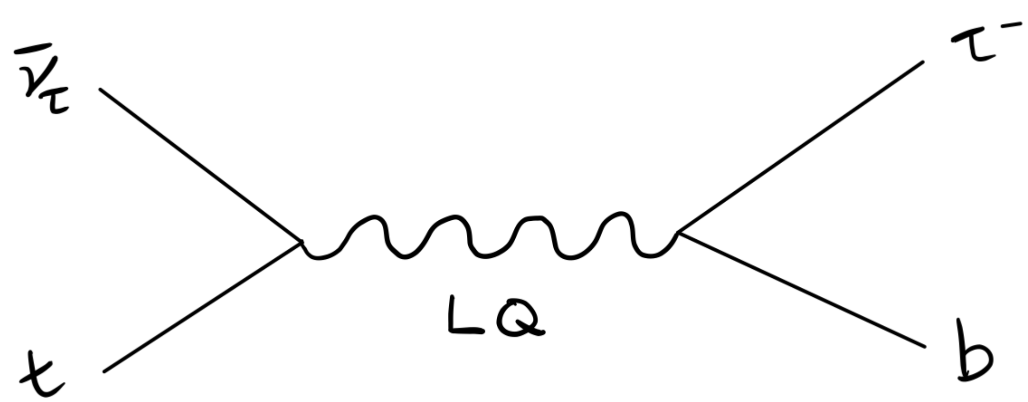
  A. Potential to probe PS^3-type models with gravitational waves.

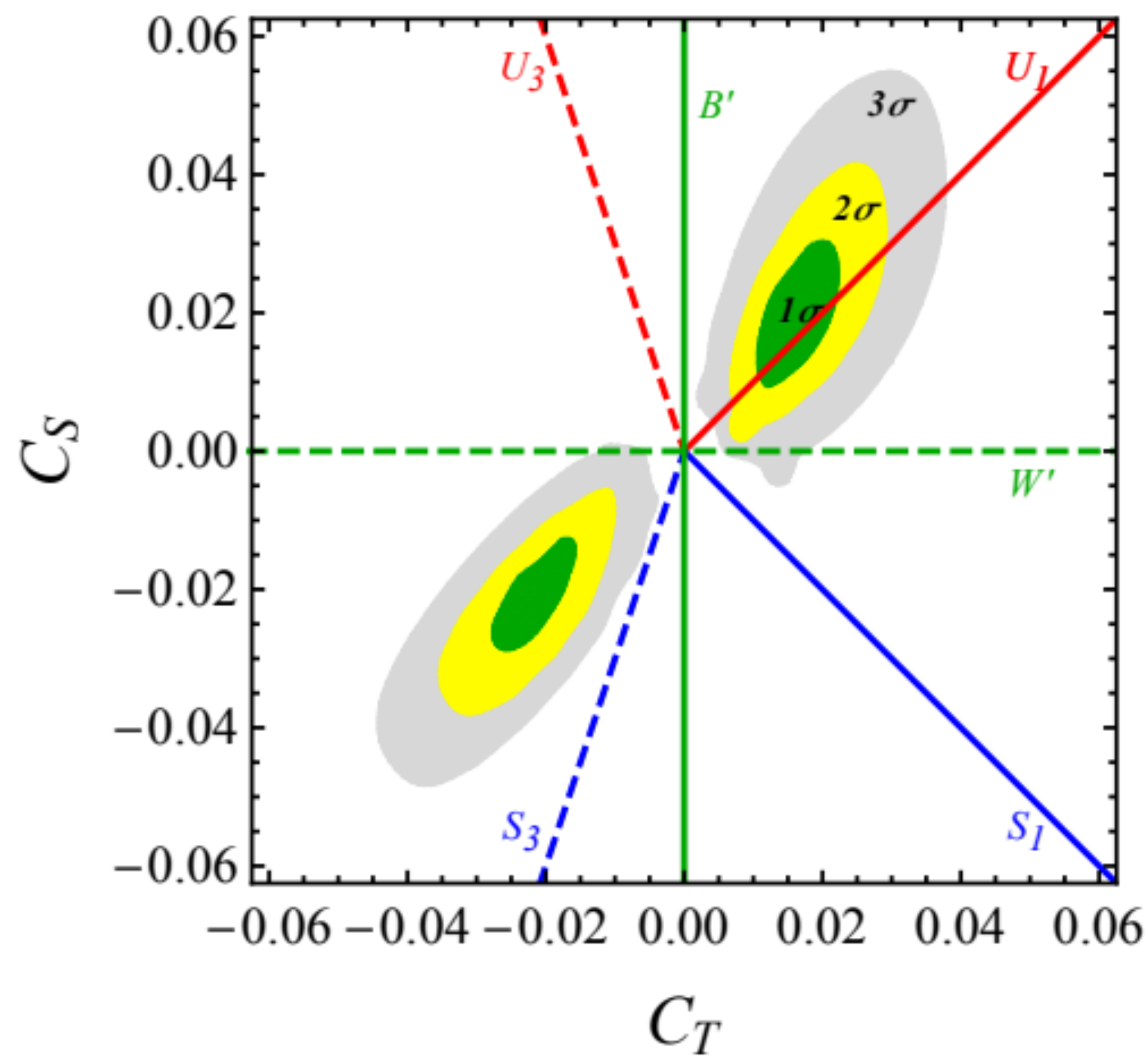
"Pati-Salam" Leptoquark

- Anomalies in low-energy flavor data can coherently be explained by a single TeV-scale massive vector boson mediator:

$$\boxed{U_1^\mu = (\mathbf{3}, \mathbf{1}, 2/3)}$$

- First leptoquark ever studied. Extremely interesting in the context of Pati-Salam quark-lepton unification.





$$C_S\,(\bar{Q}_L^i \gamma_\mu Q_L^j)(\bar{L}_L^\alpha \gamma^\mu L_L^\beta)$$
$$C_T\,(\bar{Q}_L^i \gamma_\mu \sigma^a Q_L^j)(\bar{L}_L^\alpha \gamma^\mu \sigma^a L_L^\beta)$$

<u>For an updated fit:</u> C. Cornella, J. Fuentes-Martin, G. Isidori, 1903.11517

[D. Buttazzo, A. Greljo, G. Isidori, D. Marzocca, 1706.07808]

Extended Gauge Group: The "4321" Model

$$G = SU(4) \times SU(3)' \times SU(2)_L \times U(1)'$$

$$\Big\downarrow \sim\text{TeV}$$

$$G_{\rm SM} = SU(3)_c \times SU(2)_L \times U(1)_Y$$

15 Broken Generators

$$G' = (\mathbf{8}, \mathbf{1}, 0)$$

$$Z' = (\mathbf{1}, \mathbf{1}, 0)$$

✓ $$U_1 = (\mathbf{3}, \mathbf{1}, 2/3)$$

New SM Fermion Embedding

- 3rd family SM fermions are charged under "421" and coupled directly to the LQ to address flavor anomalies.
- 1st and 2nd family SM fermions charged only under "321" and are not coupled directly to the LQ (avoids the FCNC problem of ordinary Pati-Salam).

"4321" w/ Family Dependent Gauge Charges

- 1st and 2nd family quarks and leptons charged under "321" but are SU(4) singlets. Here, i = 1,2.

Dominantly Light Family SM Fermions						
Gauge					Global	
Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)'$	$U(1)_{B'}$	$U(1)_{L'}$
$q_L'^i$	**1**	**3**	**2**	1/6	1/3	0
$u_R'^i$	**1**	**3**	**1**	2/3	1/3	0
$d_R'^i$	**1**	**3**	**1**	-1/3	1/3	0
$\ell_L'^i$	**1**	**1**	**2**	-1/2	0	1
$e_R'^i$	**1**	**1**	**1**	-1	0	1

- Third family quarks and leptons are embedded in fundamentals of SU(4).

Dominantly Third Family SM Fermions						
Gauge					Global	
Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)'$	$U(1)_{B'}$	$U(1)_{L'}$
ψ_L	**4**	**1**	**2**	0	1/4	1/4
ψ_R^u	**4**	**1**	**1**	1/2	1/4	1/4
ψ_R^d	**4**	**1**	**1**	-1/2	1/4	1/4

$$\psi_L = \begin{pmatrix} q_L'^3 \\ \ell_L'^3 \end{pmatrix} \qquad \psi_R^u = \begin{pmatrix} u_R'^3 \\ \nu_R'^3 \end{pmatrix} \qquad \psi_R^d = \begin{pmatrix} d_R'^3 \\ e_R'^3 \end{pmatrix}$$

Low Energy Limit of PS^3:

[M. Bordone, C. Cornella, J. Fuentes-Martin, G. Isidori, 1712.01368]

First Attempt at a Model

- The Lagrangian for the light families looks just like the SM.

$$\mathcal{L}_{12} = -\overline{q}'_L\, Y_u\, \widetilde{H}\, u'_R - \overline{q}'_L\, Y_d\, H\, d'_R - \overline{\ell}'_L\, Y_\nu\, \widetilde{H}\, \nu'_R - \overline{\ell}'_L\, Y_e\, H\, e'_R + \mathrm{h.c.}\ ,$$

→ In the absence of Yukawas: $U(2)^3_q \times U(2)^3_\ell$

*Small 1st and 2nd family Yukawas only softly break this symmetry.

- The 3rd family Lagrangian contains just the following terms

$$\mathcal{L}_3 = -y^u_H \overline{\psi}_L \widetilde{H} \psi^u_R - y^d_H \overline{\psi}_L H \psi^d_R + \mathrm{h.c.}$$

- Light family - 3rd family mixing not allowed without new fields.

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Predicts the same mass for the bottom quark and tau lepton. ✔

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$$\mathcal{L}_3 = -y^u_H \overline{\psi}_L \widetilde{H} \psi^u_R - y^d_H \overline{\psi}_L H \psi^d_R + \text{h.c.}$$

✗ Predicts the same mass for the top quark and tau neutrino.

Predicts the same mass for the bottom quark and tau lepton. ✓

- Light family - 3rd family mixing not allowed without new fields.

Third Family Quark and Lepton Masses

- Can add another Higgs to split the 3rd family quark and lepton masses.

$$\langle \Phi_0^{15} \rangle \equiv v_\Phi / \sqrt{2}$$

$$y_H^u,\, y_H^d,\, y_\Phi^u,\, y_\Phi^d$$

Scalar Fields						
Gauge					Global	
Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)'$	$U(1)_{B'}$	$U(1)_{L'}$
H	**1**	**1**	**2**	1/2	0	0
Φ	**15**	**1**	**2**	1/2	0	0
Ω_3	$\bar{\mathbf{4}}$	**3**	**1**	1/6	1/12	-1/4
Ω_1	$\bar{\mathbf{4}}$	**1**	**1**	-1/2	-1/4	3/4

$$v_{\rm EW}^2 = v_H^2 + v_\Phi^2$$

$$\tan\beta = v_\Phi / v_H$$

Up-type masses

$$m_t' = \frac{v_{\rm EW}}{\sqrt{2}} \left(y_H^u \cos\beta + \frac{1}{2\sqrt{6}} y_\Phi^u \sin\beta \right)$$

$$m_{\nu_\tau}' = \frac{v_{\rm EW}}{\sqrt{2}} \left(y_H^u \cos\beta - \frac{3}{2\sqrt{6}} y_\Phi^u \sin\beta \right)$$

Down-type masses

$$m_b' = \frac{v_{\rm EW}}{\sqrt{2}} \left(y_H^d \cos\beta + \frac{1}{2\sqrt{6}} y_\Phi^d \sin\beta \right)$$

$$m_\tau' = \frac{v_{\rm EW}}{\sqrt{2}} \left(y_H^d \cos\beta - \frac{3}{2\sqrt{6}} y_\Phi^d \sin\beta \right)$$

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Down-type masses

$$m_b' = \frac{v_{\rm EW}}{\sqrt{2}}\left(y_H^d \cos\beta + \frac{1}{2\sqrt{6}} y_\Phi^d \sin\beta \right) \checkmark$$

$$m_\tau' = \frac{v_{\rm EW}}{\sqrt{2}}\left(y_H^d \cos\beta - \frac{3}{2\sqrt{6}} y_\Phi^d \sin\beta \right) \checkmark$$

Bottom/Tau Splitting: $\dfrac{m_b}{m_\tau} \sim 2$

Third Family Quark and Lepton Masses

- Can add another Higgs to split the 3rd family quark and lepton masses.

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$$\tan\beta = v_\Phi / v_H$$

Up-type masses

$$m_t' = \frac{v_{\rm EW}}{\sqrt{2}} \left(y_H^u \cos\beta + \frac{1}{2\sqrt{6}} y_\Phi^u \sin\beta \right) ✓$$

$$m_{\nu_\tau}' = \frac{v_{\rm EW}}{\sqrt{2}} \left(y_H^u \cos\beta - \frac{3}{2\sqrt{6}} y_\Phi^u \sin\beta \right) ✗$$

Requires Tuning: $\dfrac{\rm meV}{v_{\rm EW}} \sim 10^{-14}$

**Generic problem with low-scale QL-unification. Resolved in our model- later in the talk.*

Down-type masses

$$m_b' = \frac{v_{\rm EW}}{\sqrt{2}} \left(y_H^d \cos\beta + \frac{1}{2\sqrt{6}} y_\Phi^d \sin\beta \right) ✓$$

$$m_\tau' = \frac{v_{\rm EW}}{\sqrt{2}} \left(y_H^d \cos\beta - \frac{3}{2\sqrt{6}} y_\Phi^d \sin\beta \right) ✓$$

Bottom/Tau Splitting: $\dfrac{m_b}{m_\tau} \sim 2$

Light-Third Family Mixing: EFT

- Light with 3rd family mixing is required, e.g. must generate the CKM.

- In the EFT picture, such operators are allowed at dimension-5, e.g. for quarks:

$$\mathcal{L}_{d5} = \frac{\lambda_q}{m_\chi} \left(\lambda_H^u \, \bar{q}_L' \Omega_3^T \widetilde{H} \, \psi_R^u + \lambda_H^d \, \bar{q}_L' \Omega_3^T H \, \psi_R^d \right)$$

[M. Bordone, C. Cornella, J. Fuentes-Martin, G. Isidori, 1712.01368]

- How to UV complete?

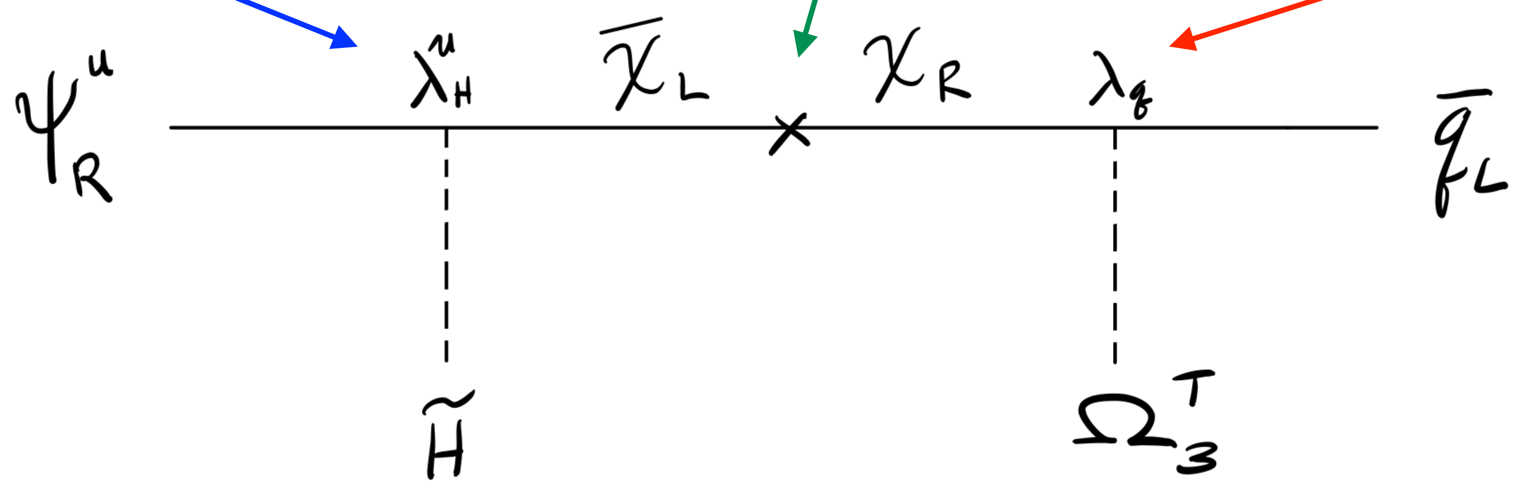
- A single new vector-like fermion with the same quantum numbers as ψ_L can do the job. Contains vector-like partners to SM doublets.

Light-Third Family Mixing: UV Completion

New Vector-like Fermions						
	Gauge				Global	
Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)'$	$U(1)_{B'}$	$U(1)_{L'}$
$\chi_{L,R}$	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	0	1/4	1/4

$$\chi_{L,R} = \begin{pmatrix} Q'_{L,R} \\ L'_{L,R} \end{pmatrix}, \qquad \Psi_L \equiv \begin{pmatrix} \psi_L \\ \chi_L \end{pmatrix}, \qquad \mathbf{y}_H^{u,d} \equiv \begin{pmatrix} y_H^{u,d} \\ \lambda_H^{u,d} \end{pmatrix}$$

$$\mathcal{L}_{3\chi} = -\,\underline{\overline{\Psi}_L\, \mathbf{y}_H^u \widetilde{H} \psi_R^u} - \overline{\Psi}_L\, \mathbf{y}_H^d H \psi_R^d - \underline{\bar{\Psi}_L \mathbf{m}\, \chi_R} - \bar{\ell}'_L \lambda_\ell\, \Omega_1^T \chi_R - \underline{\bar{q}'_L \lambda_q\, \Omega_3^T \chi_R} + \text{h.c.}$$



- Can get a better fit to the data with two copies of χ and also introducing an SU(4)-adjoint scalar Ω_{15} whose VEV gives another source of flavor and splits M_Q and M_L.

$$\mathcal{L} \supset -\lambda_{15} \overline{\psi}_L \Omega_{15} \chi_R - \lambda'_{15} \overline{\chi}_L \Omega_{15} \chi_R + \text{h.c.}$$

[C. Cornella, J. Fuentes-Martin, G. Isidori, 1903.11517]

Neutrino Mass Catastrophe

Up-type Dirac masses

$$m_t' = \frac{v_{\rm EW}}{\sqrt{2}}\left(y_H^u \cos\beta + \frac{1}{2\sqrt{6}} y_\Phi^u \sin\beta\right)$$

$$m_{\nu_\tau}' = \frac{v_{\rm EW}}{\sqrt{2}}\left(y_H^u \cos\beta - \frac{3}{2\sqrt{6}} y_\Phi^u \sin\beta\right)$$

Requires Tuning: $\frac{\rm meV}{v_{\rm EW}} \sim 10^{-14}$

Solution

- Accept a natural tau neutrino Dirac mass, i.e. $m_{\nu_\tau}' \sim v_{\rm EW}$
- Add singlet fermions such that the inverse seesaw mechanism (ISS) can be implemented to obtain the correct neutrino masses.

[P. Fileviez Perez and M. Wise, 1307.6213]

Complete Neutrino Sector of “4321”

Right Handed Singlet Fermions						
	Gauge				Global	
Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)'$	$U(1)_{B'}$	$U(1)_{L'}$
$\nu_R'^i$	**1**	**1**	**1**	0	0	1
S_R^a	**1**	**1**	**1**	0	0	-1

$$\mathcal{L}_\nu = -\,\Omega_1^T\,\overline{S_R^c}\,\lambda_R\psi_R^u - \overline{S_R^c}\,M_R\,\nu_R'$$

Lepton Number Conserving

Lepton Number Violating

$$-\,\frac{1}{2}\overline{S_R^c}\,\mu_S\,S_R - \frac{1}{2}\overline{\nu_R'^c}\,\mu_R\,\nu_R' - \overline{\ell}_L'\,Y_S\,\widetilde{H}\,S_R + \text{h.c.}$$

- Technically natural for lepton number violating parameters to be small, since $U(1)_{L'}$ is restored in the limit where they vanish.

- For simplicity, focus here on the first 3 terms to implement the ISS. No major change if other terms are included (if they are small).

Simplified Neutrino Sector of “4321”

Right Handed Singlet Fermions						
	Gauge				Global	
Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)'$	$U(1)_{B'}$	$U(1)_{L'}$
$\nu_R'^i$	**1**	**1**	**1**	0	0	1
S_R^a	**1**	**1**	**1**	0	0	-1

Lepton Number Conserving

Lepton Number Violating

$$\mathcal{L}_S = -\Omega_1^T \, \overline{S_R^c} \, \lambda_R \psi_R^u - \overline{S_R^c} \, M_R \, \nu_R' - \frac{1}{2} \overline{S_R^c} \, \mu_S \, S_R + \text{h.c.}$$

- The neutrino mass matrix takes the ISS form:

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & M_\nu^D & 0 \\ (M_\nu^D)^T & 0 & \widetilde{M}_R^T \\ 0 & \widetilde{M}_R & \mu_S \end{pmatrix}$$

$$\widetilde{M}_R = (M_R \;\; \tfrac{v_1}{\sqrt{2}} \lambda_R)$$

SU(4) breaking VEV $\langle \Omega_1 \rangle$: ~ TeV

Inverse Seesaw Mechanism

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & M_\nu^D & 0 \\ (M_\nu^D)^T & 0 & \widetilde{M}_R^T \\ 0 & \widetilde{M}_R & \mu_S \end{pmatrix}, \qquad M_\nu^D = \begin{pmatrix} \frac{v_H}{\sqrt{2}} U Y_\nu^{\rm diag} & -f_\nu \lambda_\ell \\ 0 & m'_{\nu_\tau} \end{pmatrix}$$

$$\widetilde{M}_R = (M_R \;\; \tfrac{v_1}{\sqrt{2}} \lambda_R)$$

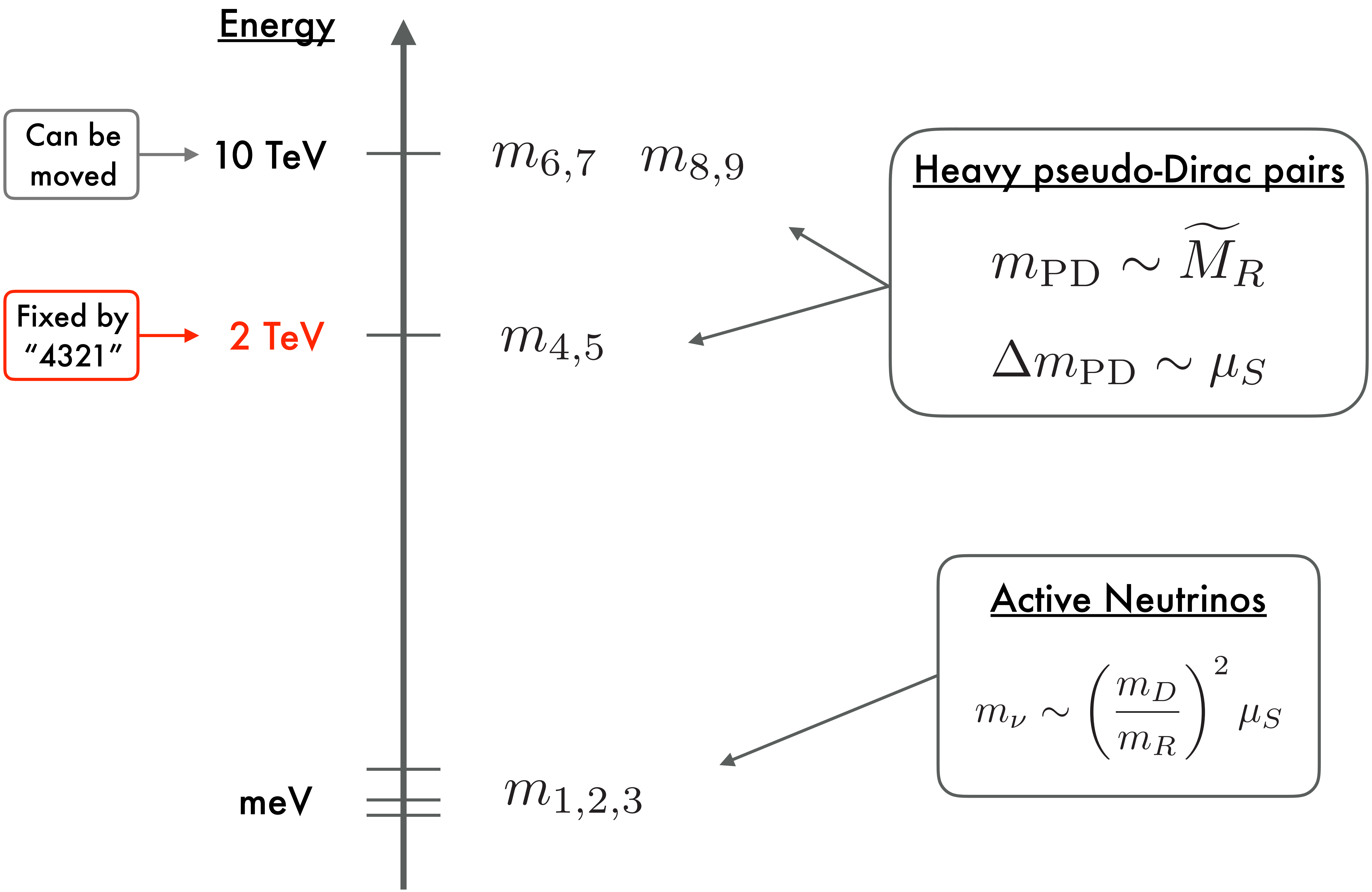
- ISS Hierarchy $\mu_S \ll M_\nu^D < \widetilde{M}_R$ which is naturally expected in the model gives 3 light Majorana neutrinos:

$$M_{\rm light} \approx M_\nu^D \widetilde{M}_R^{-1} \mu_S \, (\widetilde{M}_R^T)^{-1} (M_\nu^D)^T$$

- Parametrically, if $m_D \sim \mathrm{GeV}$, $m_R \sim \mathrm{TeV}$, works for $\mu_S \sim \mathrm{keV}$.

$$m_\nu \sim \left(\frac{m_D}{m_R} \right)^2 \mu_S$$

Example ISS Mass Spectrum



PMNS Non-Unitarity and B-Anomalies

- 3x3 light neutrino mixing matrix is now non-unitary:

$$N = \left[\mathbf{1} - \frac{1}{2}\Theta\,\Theta^\dagger\right] U_{\rm PMNS}\,, \qquad \Theta \approx M_\nu^D\,\widetilde{M}_R^{-1}$$

- PMNS Non-Unitary probed by $\epsilon = \mathbf{1} - NN^\dagger \approx \Theta\,\Theta^\dagger$, so parametrically there is a contribution at least as large as:

$$\epsilon \sim \frac{m_D^2}{m_R^2} \sim \frac{m_D^2}{v_1^2|\lambda_R|^2}$$

- Meanwhile,

$$\Delta R_D^{\tau\ell} \approx 2.2\,\Delta R_{D^*}^{\tau\ell} \approx \frac{5 v_{\rm EW}^2}{v_1^2 + v_3^2}\,.$$

LHC Direct Search Coloron Bound: $v_3 \gtrsim 1~\mathrm{TeV}$

$$\Longrightarrow \quad v_1 \lesssim 1~\mathrm{TeV}, \qquad \epsilon \sim 10^{-2}\left(\frac{m_D}{100~\mathrm{GeV}}\right)^2 \left(\frac{1~\mathrm{TeV}}{v_1|\lambda_R|}\right)^2$$

Sizable effect in B-physics implies sizable PMNS unitarity violation.

Neutrino Benchmark Point

$$\mathcal{M}_\nu = \left(\begin{array}{cc|cc|c} 0 & 0 & \frac{v_H}{\sqrt{2}} U Y_\nu^{\rm diag} & -f_\nu\,\lambda_\ell & 0 \\ 0 & 0 & 0 & m'_{\nu_\tau} & 0 \\ \hline \frac{v_H}{\sqrt{2}} Y_\nu^{\rm diag} U^T & 0 & \mu_R & 0 & M_R^T \\ -f_\nu\,\lambda_\ell^T & m'_{\nu_\tau} & 0 & 0 & \frac{v_1}{\sqrt{2}}\lambda_R^T \\ \hline 0 & 0 & M_R & \frac{v_1}{\sqrt{2}}\lambda_R & \mu_S \end{array}\right)$$

ISS Parameter	Value
m'_{ν_e}	1.67 GeV
m'_{ν_μ}	38.3 GeV
m'_{ν_τ}	10.0 GeV
$\sin\theta$	0.510
$f_\nu\lambda_\ell^{(1)}$	0.883 GeV
$f_\nu\lambda_\ell^{(2)}$	6.80 GeV
m_{QL}	2.00 TeV
m_R	10.0 TeV
μ_1	0.720 keV
μ_2	0.871 keV
μ_3	1.28 keV

Using Flavor Rotations: $\mu_S = \mathrm{diag}(\mu_1\,, \mu_2\,, \mu_3)$

$$\frac{v_H}{\sqrt{2}} U Y_\nu^{\rm diag} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} m'_{\nu_e} & 0 \\ 0 & m'_{\nu_\mu} \end{pmatrix}$$

Simplifying Ansatz: $\mu_R = \mathbf{0}$

$$M_R = \begin{pmatrix} m_R & 0 \\ 0 & m_R \\ 0 & 0 \end{pmatrix}\,, \qquad \frac{v_1}{\sqrt{2}}\lambda_R = \begin{pmatrix} 0 \\ 0 \\ m_{QL} \end{pmatrix}$$

Active Neutrino Parameters:

$$\sin^2\theta_{12} = 0.296\,, \qquad \Delta m^2_{32} = 2.56\times 10^{-3}\ \mathrm{eV}^2\,,$$
$$\sin^2\theta_{23} = 0.425\,, \qquad \Delta m^2_{21} = 7.36\times 10^{-5}\ \mathrm{eV}^2\,.$$
$$\sin^2\theta_{13} = 0.0214\,.$$

Neutrino Benchmark Point

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<u>PMNS Unitarity Violation:</u>

$$\epsilon = \mathbf{1} - NN^\dagger \approx \Theta\,\Theta^\dagger$$

<u>Our Benchmark Point:</u>

$$|\epsilon| = \begin{pmatrix} 4.04\times10^{-6} & 7.94\times10^{-6} & 2.21\times10^{-6} \\ 7.94\times10^{-6} & 2.24\times10^{-5} & 1.70\times10^{-5} \\ 2.21\times10^{-6} & 1.70\times10^{-5} & 2.50\times10^{-5} \end{pmatrix},$$

<u>Current Bounds:</u>

$$|\epsilon| < \begin{pmatrix} 2.1\times10^{-3} & 1.0\times10^{-5} & 2.1\times10^{-3} \\ 1.0\times10^{-5} & 4.0\times10^{-4} & 8.0\times10^{-4} \\ 2.1\times10^{-3} & 8.0\times10^{-4} & 5.3\times10^{-3} \end{pmatrix}$$

[S. Antusch, O. Fischer, 1407.6607]

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$$\mathcal{M}_\nu = \left(\begin{array}{cc|cc|c} 0 & 0 & \frac{v_H}{\sqrt{2}} U Y_\nu^{\rm diag} & -f_\nu\,\lambda_\ell & 0 \\ 0 & 0 & 0 & m'_{\nu_\tau} & 0 \\ \hline \frac{v_H}{\sqrt{2}} Y_\nu^{\rm diag} U^T & 0 & \mu_R & 0 & M_R^T \\ -f_\nu\,\lambda_\ell^T & m'_{\nu_\tau} & 0 & 0 & \frac{v_1}{\sqrt{2}}\lambda_R^T \\ \hline 0 & 0 & M_R & \frac{v_1}{\sqrt{2}}\lambda_R & \mu_S \end{array}\right)$$

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m_R	10.0 TeV
μ_1	0.720 keV
μ_2	0.871 keV
μ_3	1.28 keV

PMNS Unitarity Violation:

$$\epsilon = \mathbf{1} - N N^\dagger \approx \Theta\,\Theta^\dagger$$

$$\boxed{|\epsilon_{33}| \approx \left(\frac{m'_{\nu_\tau}}{m_{QL}}\right)^2}$$

Our Benchmark Point:

$$|\epsilon| = \begin{pmatrix} 4.04\times10^{-6} & 7.94\times10^{-6} & 2.21\times10^{-6} \\ 7.94\times10^{-6} & 2.24\times10^{-5} & 1.70\times10^{-5} \\ 2.21\times10^{-6} & 1.70\times10^{-5} & 2.50\times10^{-5} \end{pmatrix},$$

Current Bounds:

$$|\epsilon| < \begin{pmatrix} 2.1\times10^{-3} & 1.0\times10^{-5} & 2.1\times10^{-3} \\ 1.0\times10^{-5} & 4.0\times10^{-4} & 8.0\times10^{-4} \\ 2.1\times10^{-3} & 8.0\times10^{-4} & 5.3\times10^{-3} \end{pmatrix}$$

Probed by: $\mu \to e\gamma\,,\quad \mu \to 3e$

[S. Antusch, O. Fischer, 1407.6607]

Embedding the ISS Solution in PS³

- Consider a toy model of the neutrino sector of PS³

$$\mathcal{L}_\nu = -\Omega_1^T\,\overline{S_R^c}\,\lambda_R \psi_R^u - \overline{S_R^c}\,M_R\,\nu_R' - \frac{1}{2}\overline{S_R^c}\,\mu_S\,S_R - \frac{1}{2}\overline{\nu_R'^c}\,\mu_R\,\nu_R' - \overline{\ell}_L'\,Y_S\,\widetilde{H}\,S_R + \text{h.c.}$$

$$\Omega_{1,i}^T\,\overline{S_{R,a}^c}\lambda_{ai}\,\psi_{R,i}^u \xrightarrow{\text{Flavor Alignment}} \widetilde{M}_R = \frac{1}{\sqrt{2}}\begin{pmatrix} \lambda_1\,v_{1,1} & 0 & 0 \\ 0 & \lambda_2\,v_{1,2} & 0 \\ 0 & 0 & \lambda_3\,v_{1,3} \end{pmatrix}$$

(i = 1,2,3 for PS_i)

O(1) Couplings: $\widetilde{M}_R \approx \text{diag}(10^4, 10^3, 1)\ \text{TeV}$

- This hierarchy can perhaps be absorbed into the Majorana mass for S_R:

$$m_\nu \sim \left(\frac{m_D}{m_R}\right)^2 \mu_S\ , \qquad \mu_S \approx \text{diag}(10^6, 10^4, 1)\ \text{keV}$$

Embedding the ISS Solution in PS³

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$$\downarrow$$

$$\Omega_{1,i}^T\, \overline{S_{R,a}^c} \lambda_{ai}\, \psi_{R,i}^u \quad \xrightarrow[\text{Flavor Alignment}]{} \quad \widetilde{M}_R = \frac{1}{\sqrt{2}} \begin{pmatrix} \lambda_1\, v_{1,1} & 0 & 0 \\ 0 & \lambda_2\, v_{1,2} & 0 \\ 0 & 0 & \lambda_3\, v_{1,3} \end{pmatrix}$$

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Part II

Leptogenesis in "4321" Models

New

`[Baumholzer, Greljo, BAS]`
`work in progress`

Baryon Asymmetry of the Universe

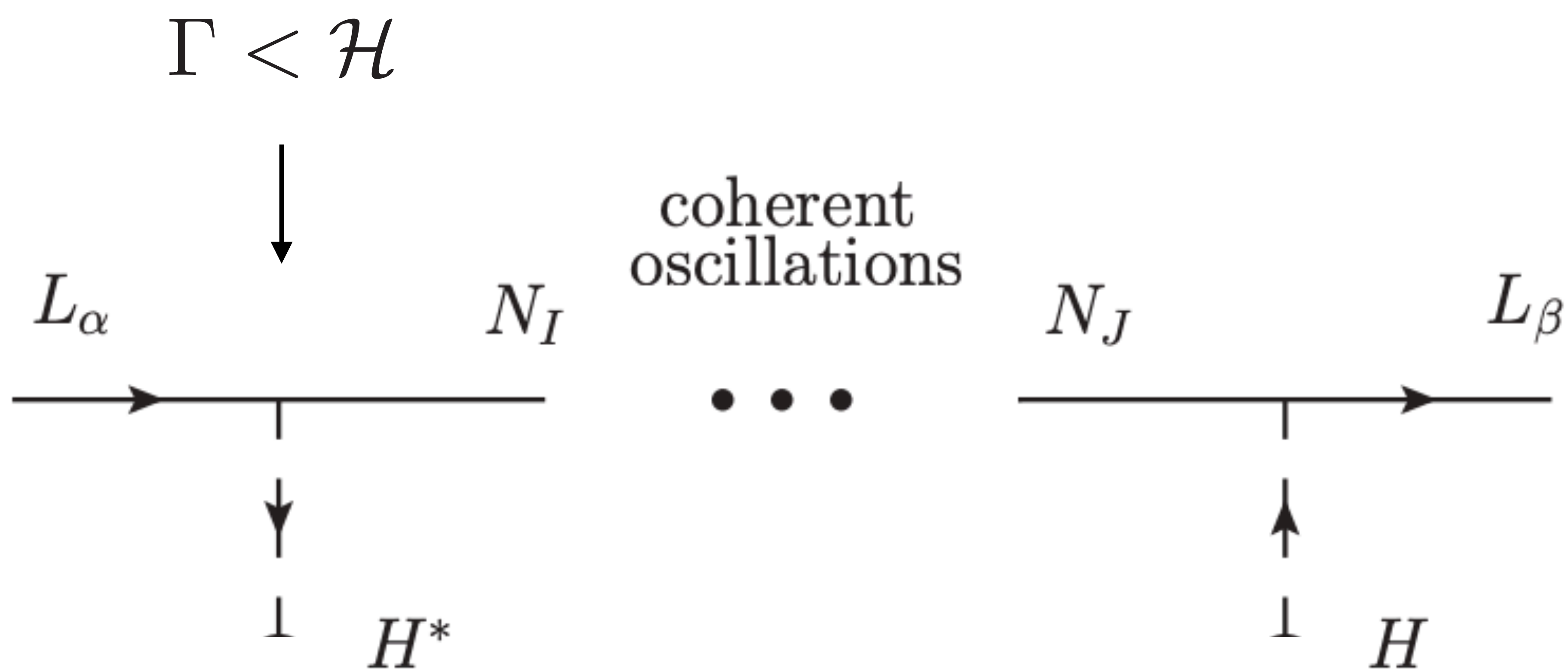
- Why is there more matter than anti-matter?

Quantified by: $$Y_B \equiv \frac{n_B - n_{\overline{B}}}{s_\gamma} \sim 10^{-10}$$

- Sakharov conditions:
    - Baryon number violation
    - C and CP Violation
    - Departure from thermal equilibrium

Requires new physics beyond the SM. What about "4321"?

ARS Leptogenesis



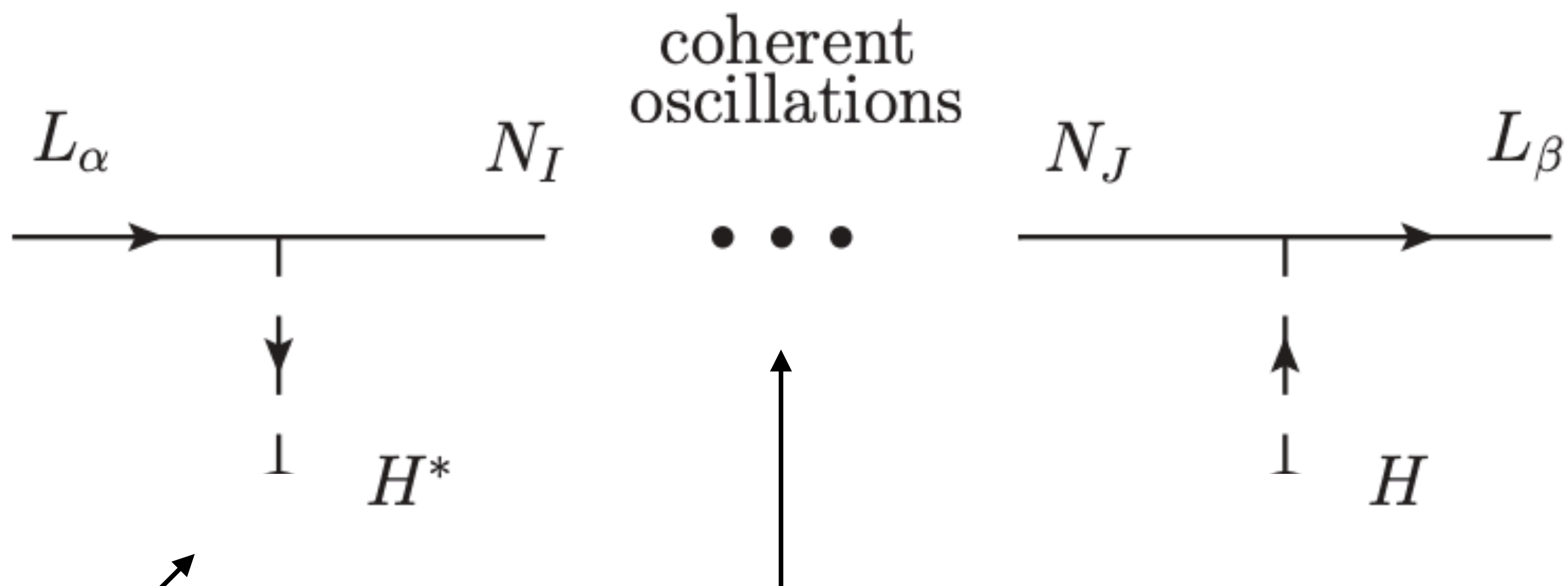
Out of equilibrium production of sterile neutrinos (at least one small Yukawa)

[Akhmedov, Rubakov, Smirnov, hep-ph/9803255]

[B. Shuve, I. Yavin, 1401.2459]

ARS Leptogenesis

Enhanced by small mass splitting between the pseudo-Dirac pairs of "4321"



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CP Violation

[Akhmedov, Rubakov, Smirnov, hep-ph/9803255]

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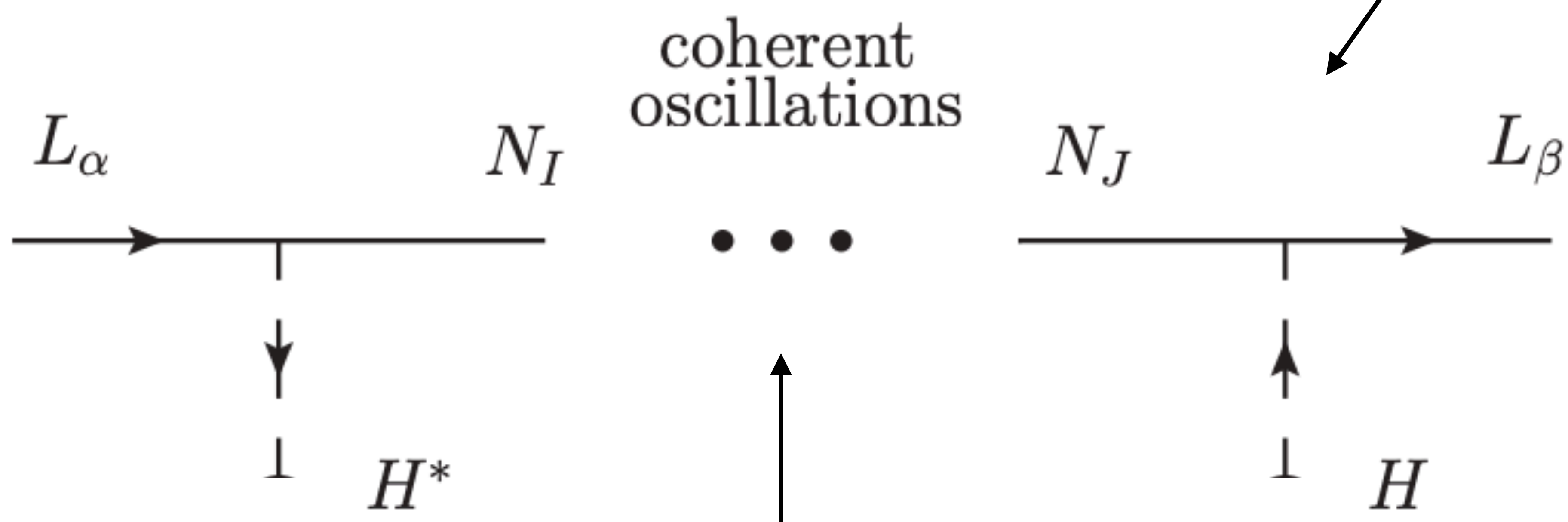
ARS Leptogenesis

Enhanced by small mass splitting between the pseudo-Dirac pairs of "4321"

$\Gamma_S(T_{\mathrm{EW}}) < \mathcal{H}(T_{\mathrm{EW}})$



Out of equilibrium production of sterile neutrinos (at least one small Yukawa)

CP Violation

Asymmetry communicated to SM at different rates. One sterile neutrino should stay out of equilibrium.

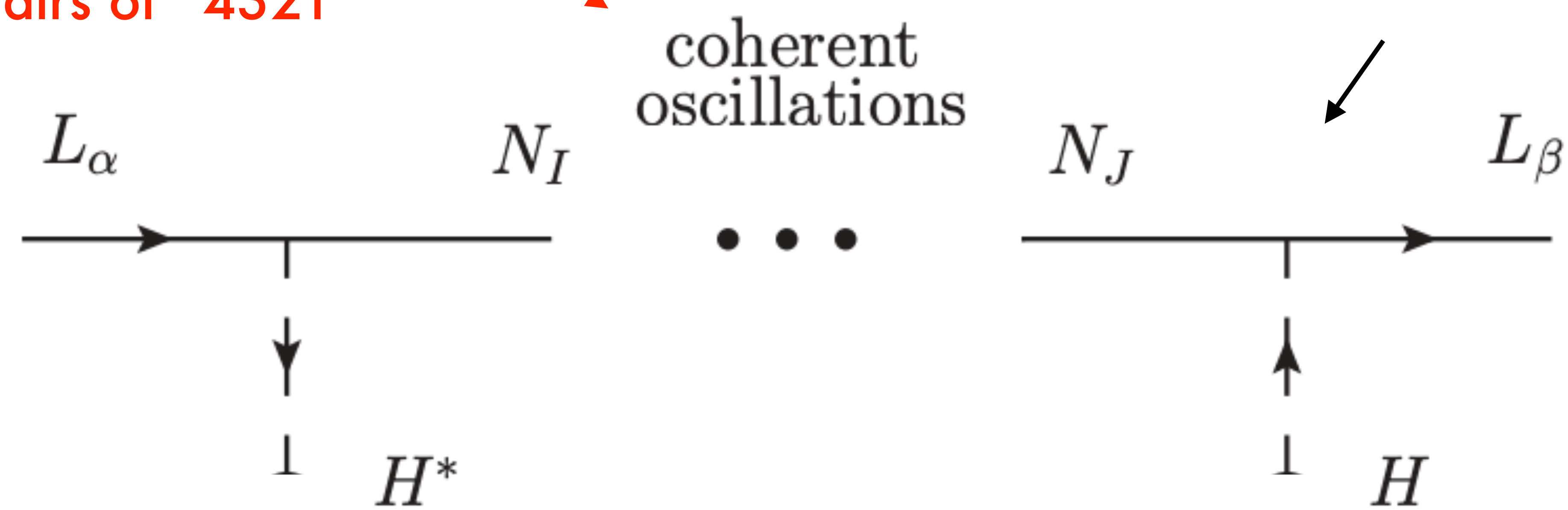
[Akhmedov, Rubakov, Smirnov, hep-ph/9803255]

[B. Shuve, I. Yavin, 1401.2459]

ARS Leptogenesis

Enhanced by small mass splitting between the pseudo-Dirac pairs of “4321”

$\Gamma_S(T_{\rm EW}) < \mathcal{H}(T_{\rm EW})$



- Because one sterile neutrino does not equilibrate before EW sphaleron freeze-out at $T_{\rm EW} \sim 140$ GeV :

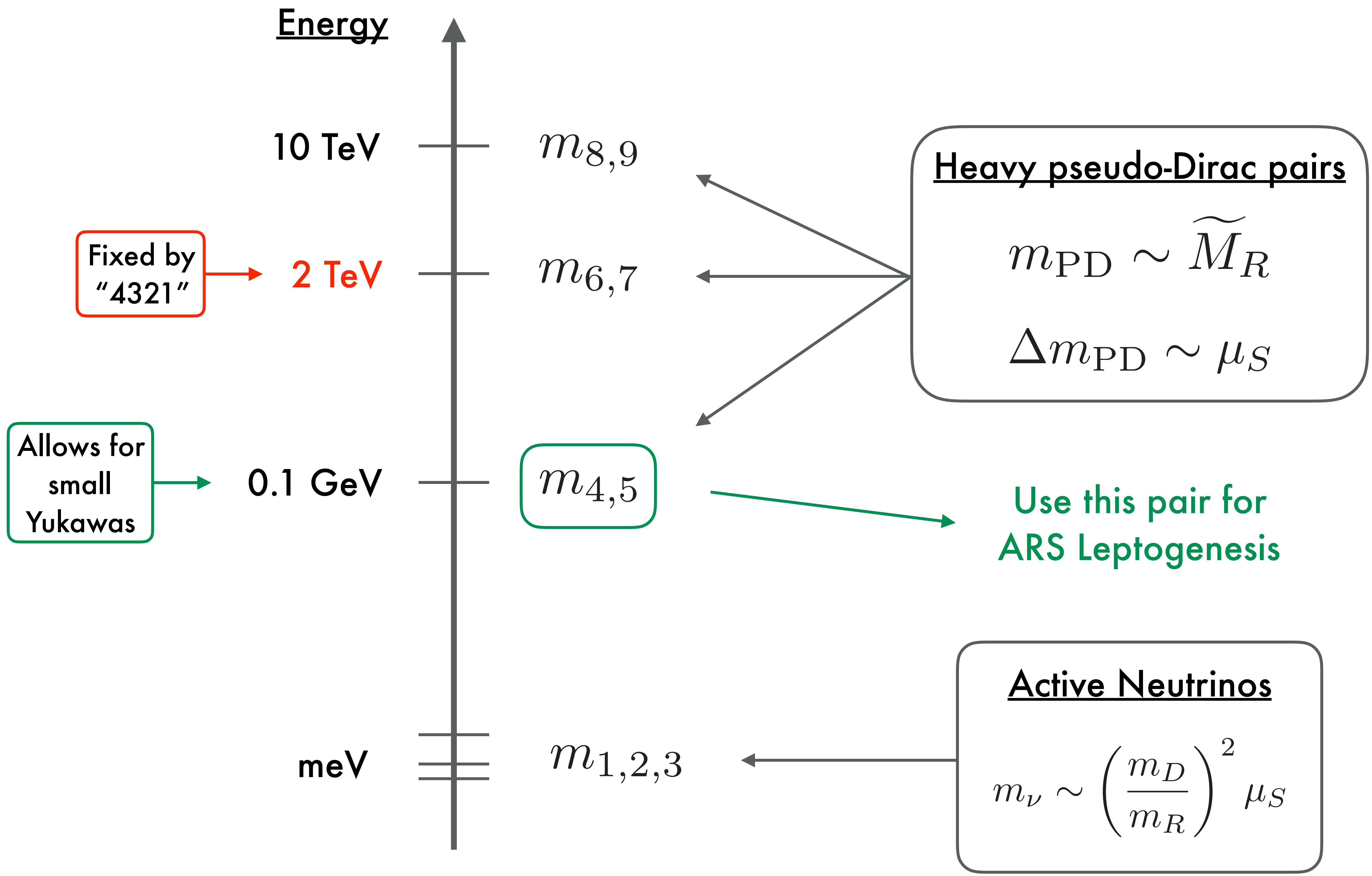
$$L_{\rm SM} = -L_S$$

Processed into non-vanishing B-asymmetry by sphalerons.

($L_{\rm tot}$ conserved)

[Akhmedov, Rubakov, Smirnov, hep-ph/9803255]

Mass Spectrum for Leptogenesis



CP Violation

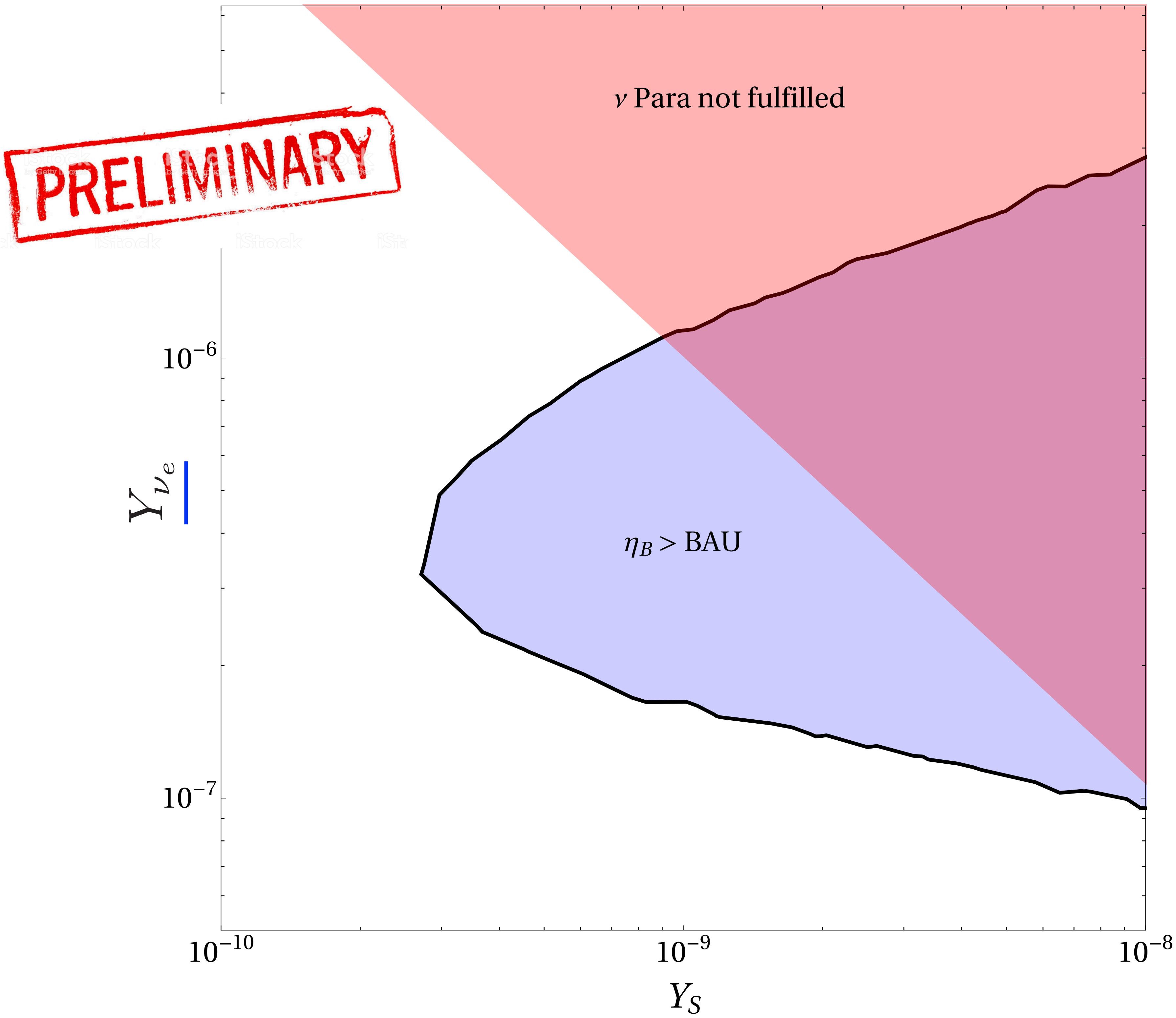
- A few options for complex phases:

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & M_\nu^D & M_S^D \\ (M_\nu^D)^T & \widetilde{\mu}_R & \widetilde{M}_R^T \\ (M_S^D)^T & \widetilde{M}_R & \mu_S \end{pmatrix} \longrightarrow \quad Y_S \, \overline{\ell}'_L \widetilde{H} S_R$$

- Asymmetry proportional to Im part of Yukawa in the mass basis:

$$\delta_\alpha = \sum_{i>j} \mathrm{Im}\left[F_{\alpha i}(F^\dagger F)_{ij} F^\dagger_{j\alpha}\right] \,, \qquad F_{\alpha I} = Y_{\alpha i}\,\mathcal{U}_{iI}$$

“4321” Leptogenesis



Couplings:

$$\frac{v_H}{\sqrt{2}} Y_\nu^{\text{diag}} = \begin{pmatrix} m'_{\nu_e} & 0 \\ 0 & m'_{\nu_\mu} \end{pmatrix}$$

$$\underline{Y_{\nu_e}} = \sqrt{2}\, m'_{\nu_e} / v_H$$

$$\underline{Y_S}\, \overline{\ell}'_L \widetilde{H} S_R$$

Part III

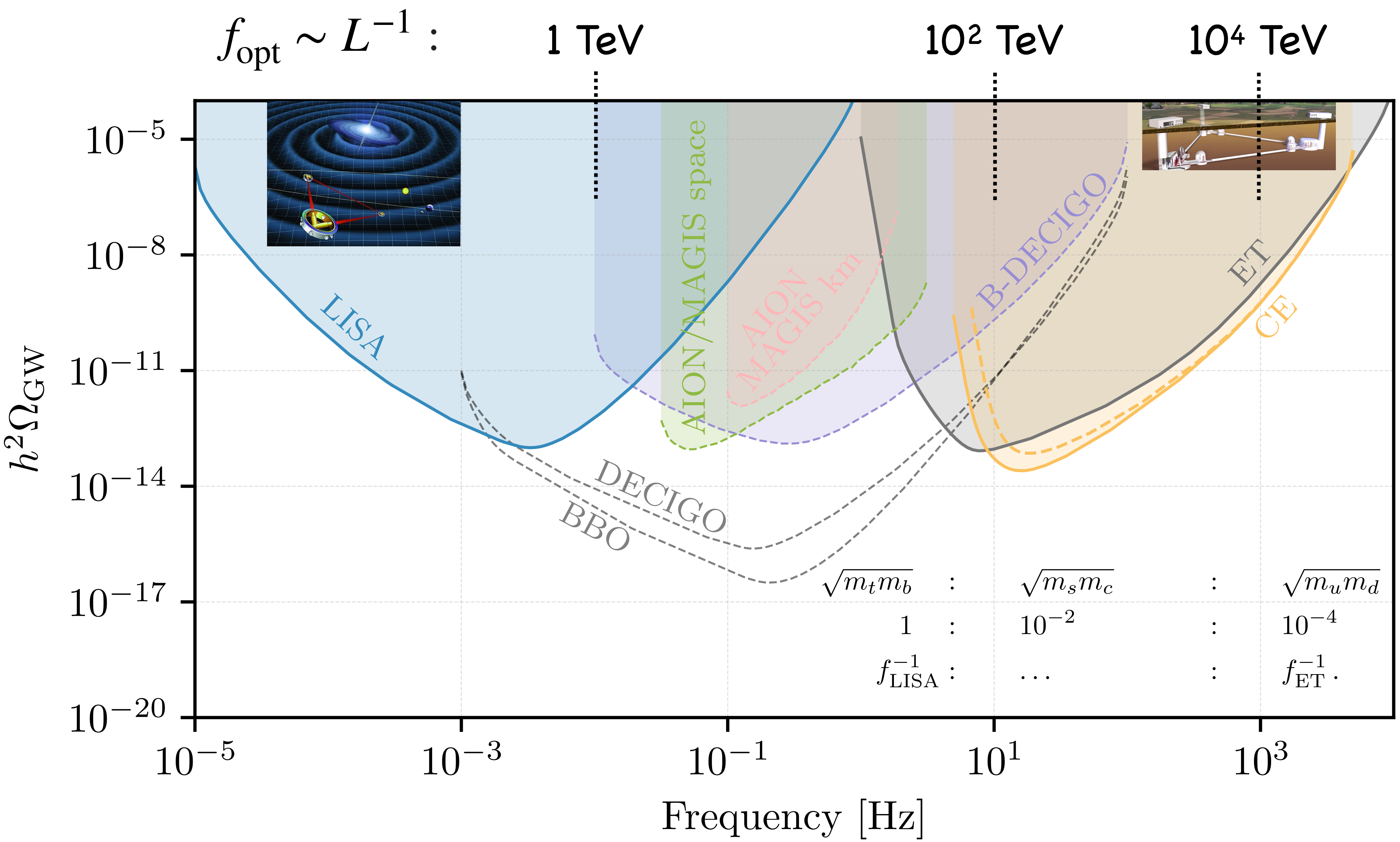
Gravitational Imprints of Flavor Hierarchies

New

`[Greljo, Opferkuch, BAS]`
`arXiv:1910.02014`

The Main Idea

- Upcoming gravitational wave experiments (2030's) can probe particle physics processes beyond the reach of colliders.

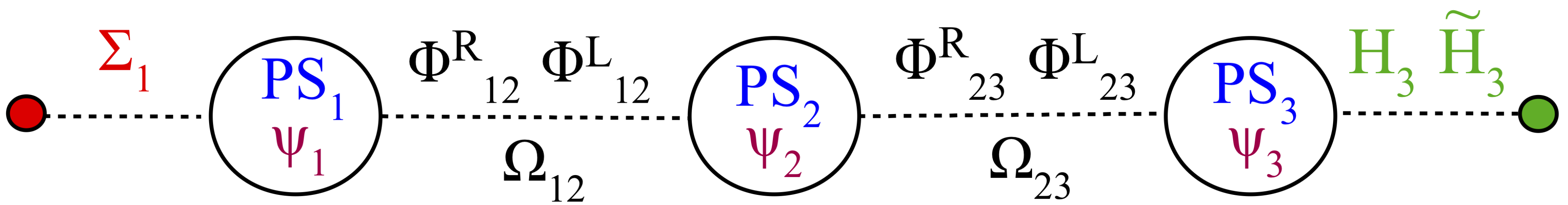


Model Example: Pati-Salam Cubed

- 5d Pati-Salam gauge symmetry deconstructed onto three 4d sites:

$$PS^3 \equiv PS_1 \times PS_2 \times PS_3$$

$$PS_i = [SU(4) \times SU(2)_L \times SU(2)_R]_i$$



<u>Fermions (one set per family)</u>

$$\Psi_L^{(i)} \equiv (\mathbf{4}, \mathbf{2}, \mathbf{1})_i$$
$$\Psi_R^{(i)} \equiv (\mathbf{4}, \mathbf{1}, \mathbf{2})_i$$

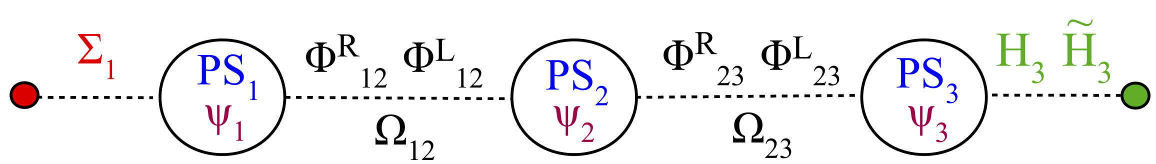
<u>Scalar and Link Fields</u>

$$\Sigma_1 \sim (\mathbf{4}, \mathbf{1}, \mathbf{2})_1 \ , \ H_3 \sim (\mathbf{1}, \mathbf{2}, \bar{\mathbf{2}})_3$$
$$\Phi^L_{ij} \sim (\mathbf{1}, \mathbf{2}, \mathbf{1})_i \times (\mathbf{1}, \bar{\mathbf{2}}, \mathbf{1})_j \ ,$$
$$\Phi^R_{ij} \sim (\mathbf{1}, \mathbf{1}, \mathbf{2})_i \times (\mathbf{1}, \mathbf{1}, \bar{\mathbf{2}})_j \ ,$$
$$\Omega_{ij} \sim (\mathbf{4}, \mathbf{2}, \mathbf{1})_i \times (\bar{\mathbf{4}}, \bar{\mathbf{2}}, \mathbf{1})_j \ ,$$

[M. Bordone, C. Cornella, J. Fuentes-Martin, G. Isidori, 1712.01368]

Model Example: Pati-Salam Cubed

- SM fermion masses and mixings are generated by breaking the PS3 gauge symmetry in a series of sequential steps.
- Flavor hierarchies <==> Series of hierarchical SSBs

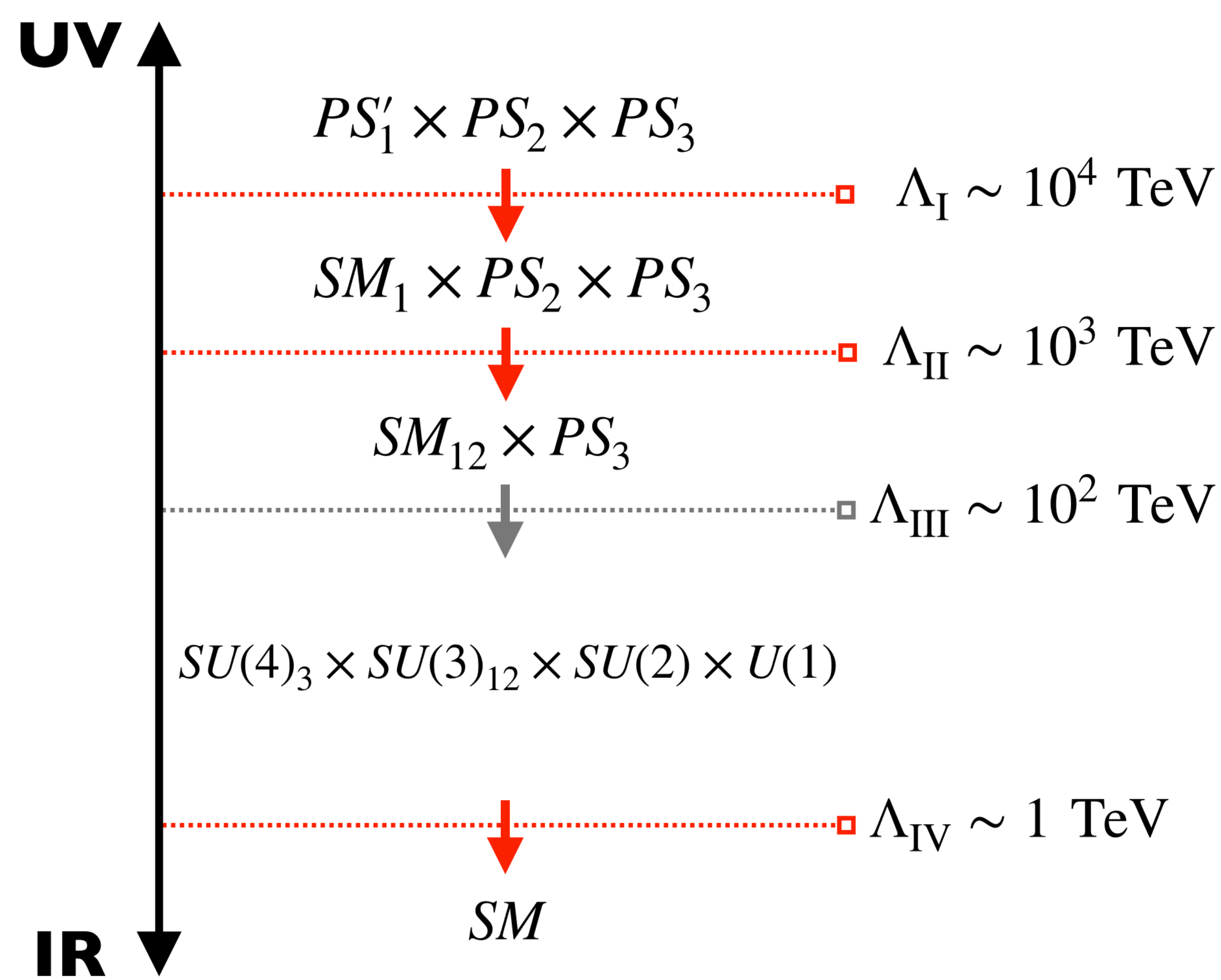


Yukawas

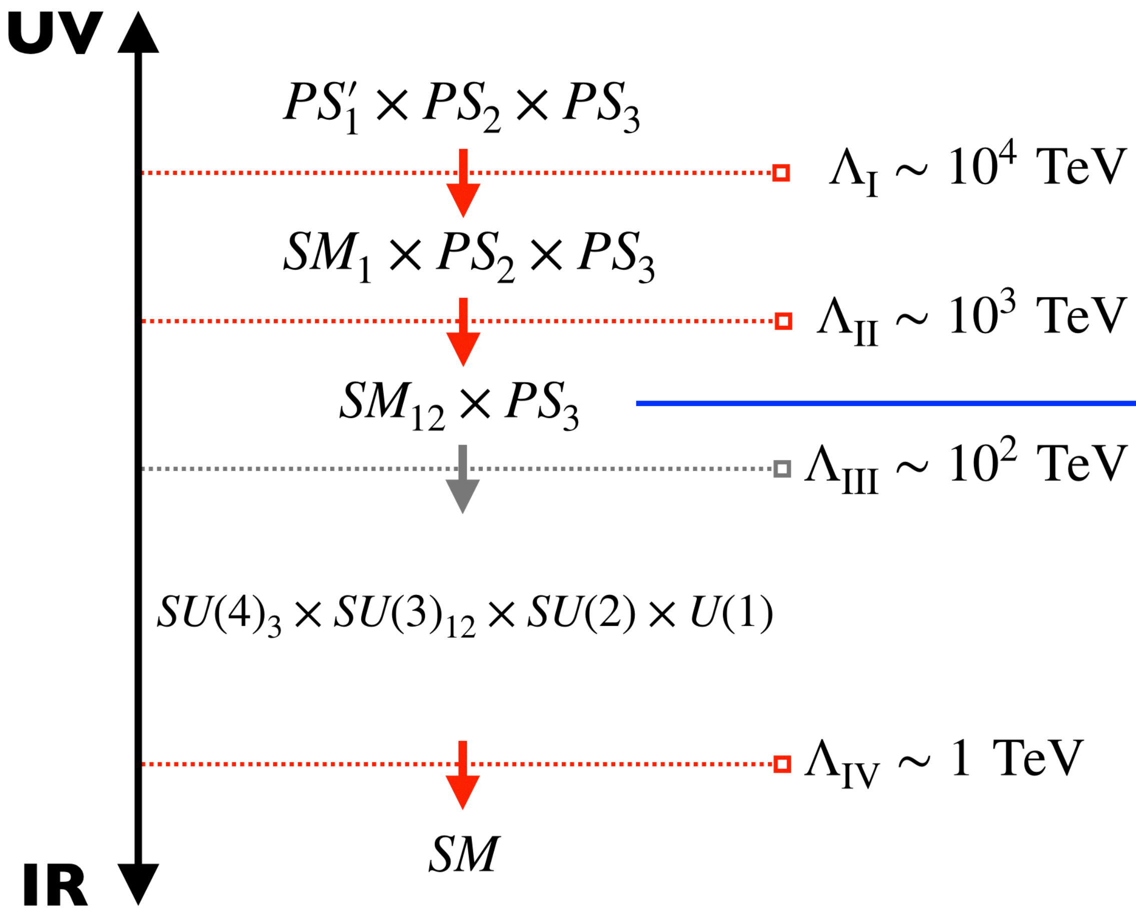
$$\mathcal{L} \supset \bar{\Psi}_L^{(3)} H_3 \Psi_R^{(3)}$$

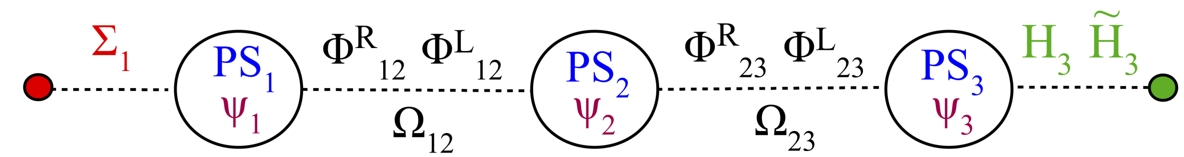
$$\mathcal{L}_{23} = \frac{1}{\Lambda_{\rm III}} \bar{\Psi}_L^{(2)} \Omega_{23} H_3 \Psi_R^{(3)} + \text{h.c.} \ ,$$

$$\mathcal{L}_{12} = \frac{1}{\Lambda_{\rm II}^2} \bar{\Psi}_L^{(k)} \Phi^L_{k3} H_3 \Phi^R_{3l} \Psi_R^{(l)} + \text{h.c.}$$



Model Example: Pati-Salam Cubed





$$SM_{12} \times PS_3$$

- U(2) Flavor symmetry
- CKM Matrix = Identity
- Yukawas allowed only for 3rd family

$$\mathcal{L} \supset \bar{\Psi}_L^{(3)} H_3 \Psi_R^{(3)} \longrightarrow Y_t \sim 1$$

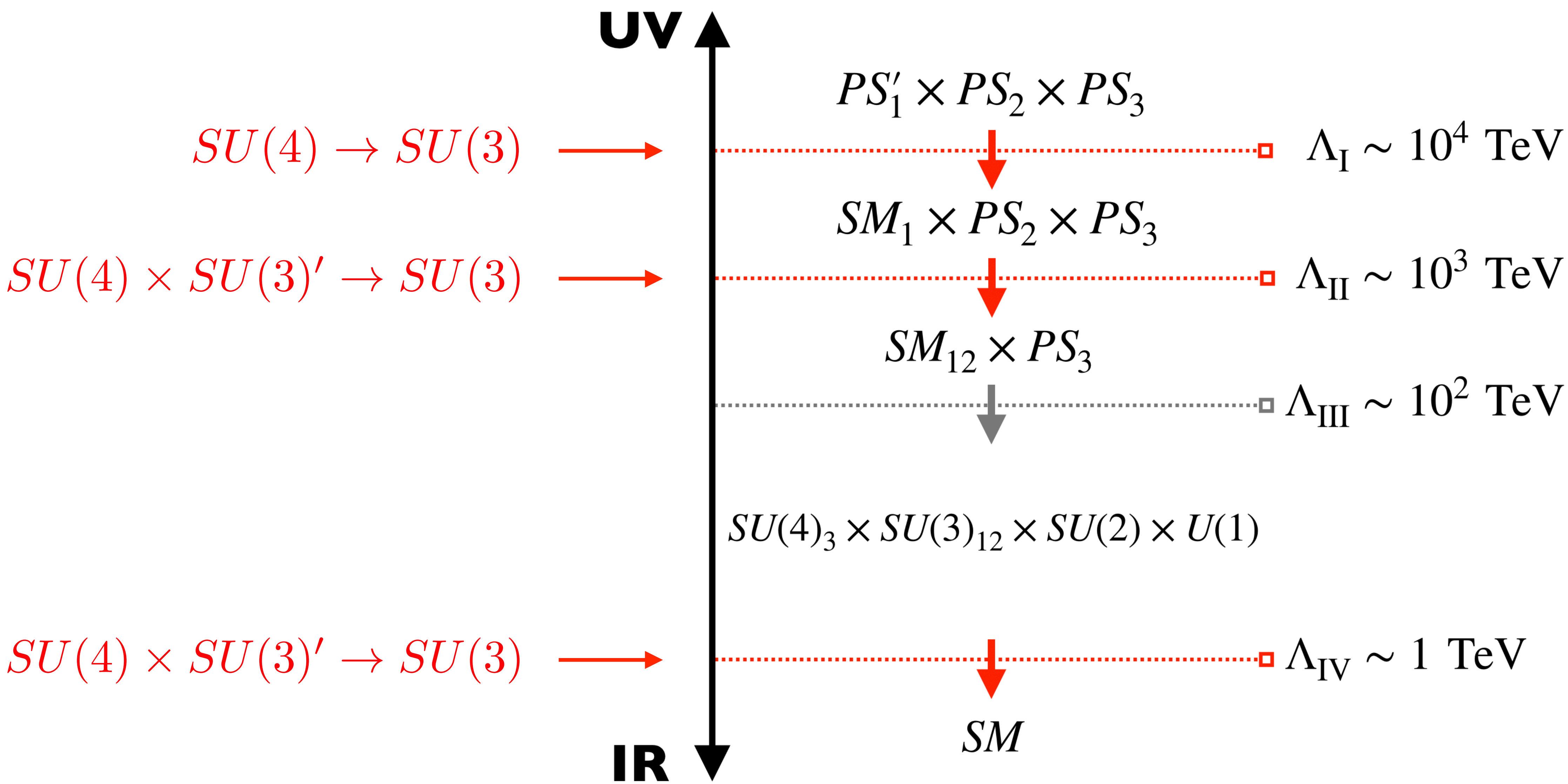
U(2)-breaking spurions perturb this picture

$$\mathcal{L}_{23} = \frac{1}{\Lambda_{\rm III}} \bar{\Psi}_L^{(2)} \Omega_{23} H_3 \Psi_R^{(3)} + \text{h.c.} \longrightarrow |V_{ts}| \sim \frac{\langle \Omega_{23} \rangle}{\Lambda_{\rm III}} \sim \frac{\Lambda_{\rm IV}}{\Lambda_{\rm III}}$$

$$\mathcal{L}_{12} = \frac{1}{\Lambda_{\rm II}^2} \bar{\Psi}_L^{(k)} \Phi^L_{k3} H_3 \Phi^R_{3l} \Psi_R^{(l)} + \text{h.c.} \longrightarrow Y_c \sim \frac{\langle \Phi^L_{23} \rangle \langle \Phi^R_{32} \rangle}{\Lambda_{\rm II}^2} \sim \frac{\Lambda_{\rm III}^2}{\Lambda_{\rm II}^2}$$

Phase Transitions of Pati-Salam Cubed

- Focus on the three PTs involving SU(4) breakings:



- These can very naturally be first-order phase transitions.

Cosmological Phase Transitions

- Nature of the PT controlled by the finite-temperature effective potential:

$$V_{\rm eff}(\underbrace{g, \lambda, v}_{\text{[fundamental parameters]}}, \phi, T) = V_0 + V_{\rm CW} + V_{T\neq 0}$$

[temperature]

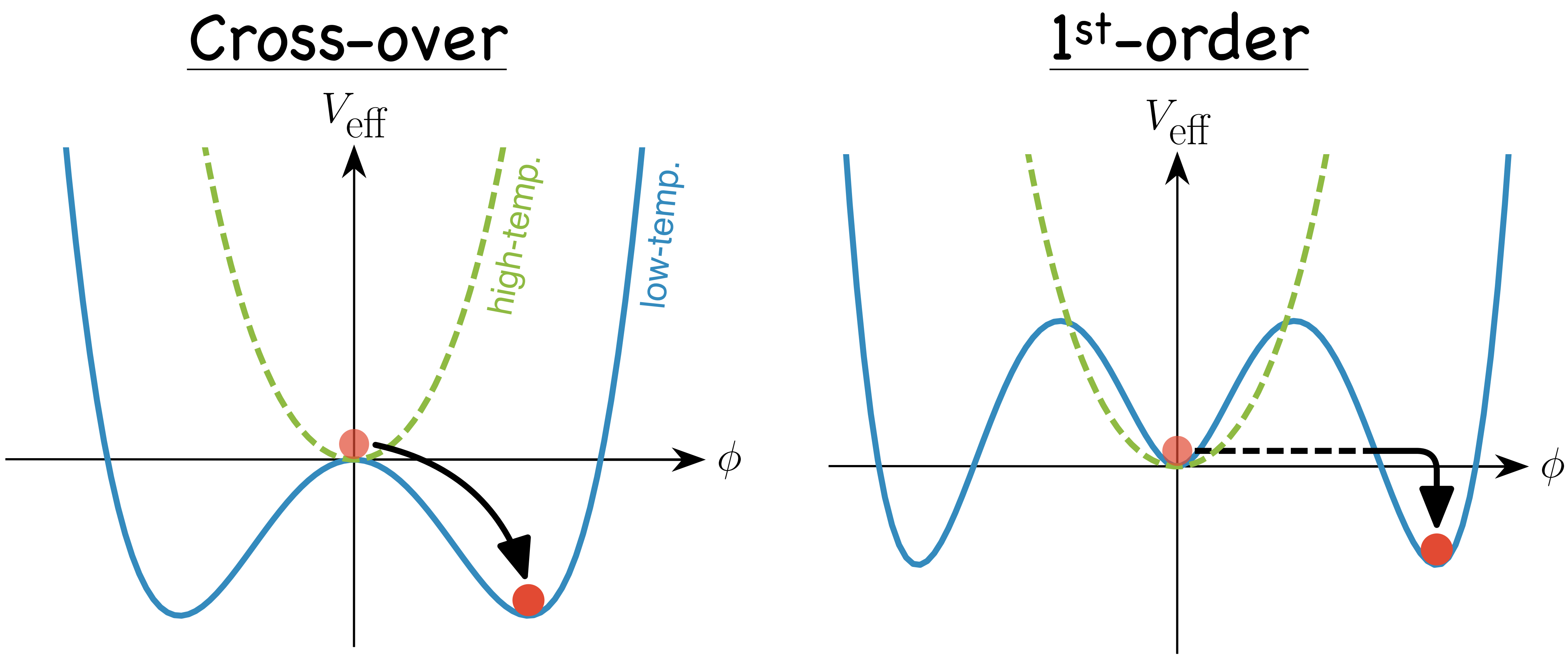


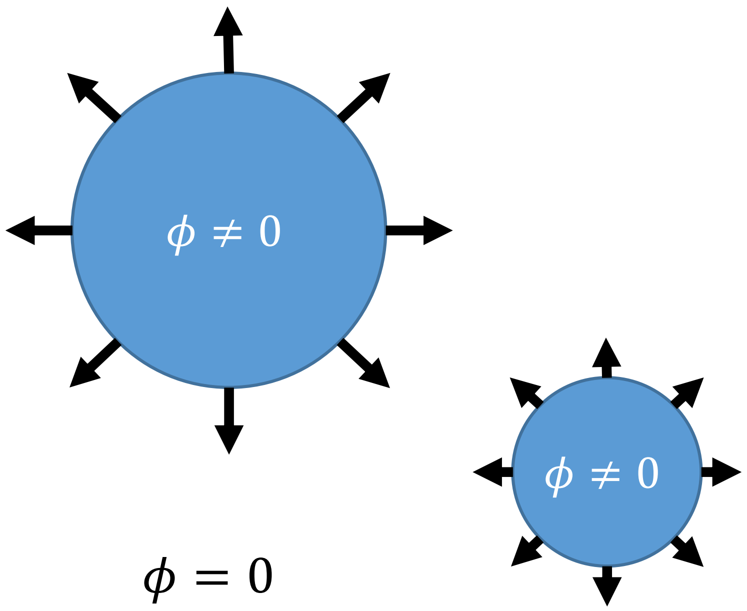
Figure from E. Madge

Cosmological First-Order Phase Transitions

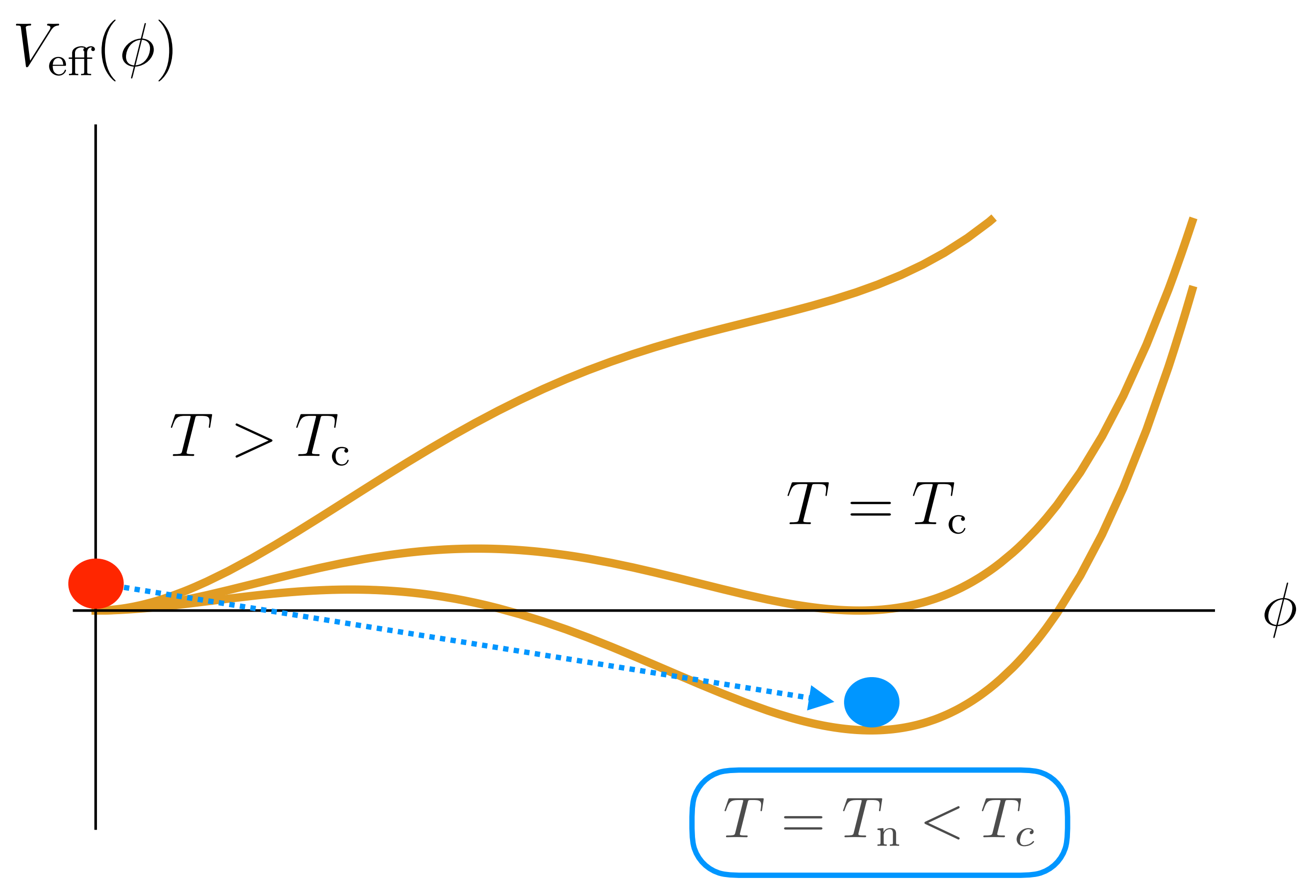
- Due to decreasing temperature, the scalar field will eventually tunnel from the false to the true vacuum.

- Tunneling occurs when: $\Gamma(T_\mathrm{n})H_\mathrm{n}^{-4} \sim 1$

- This defines the bubble nucleation temperature T_n .



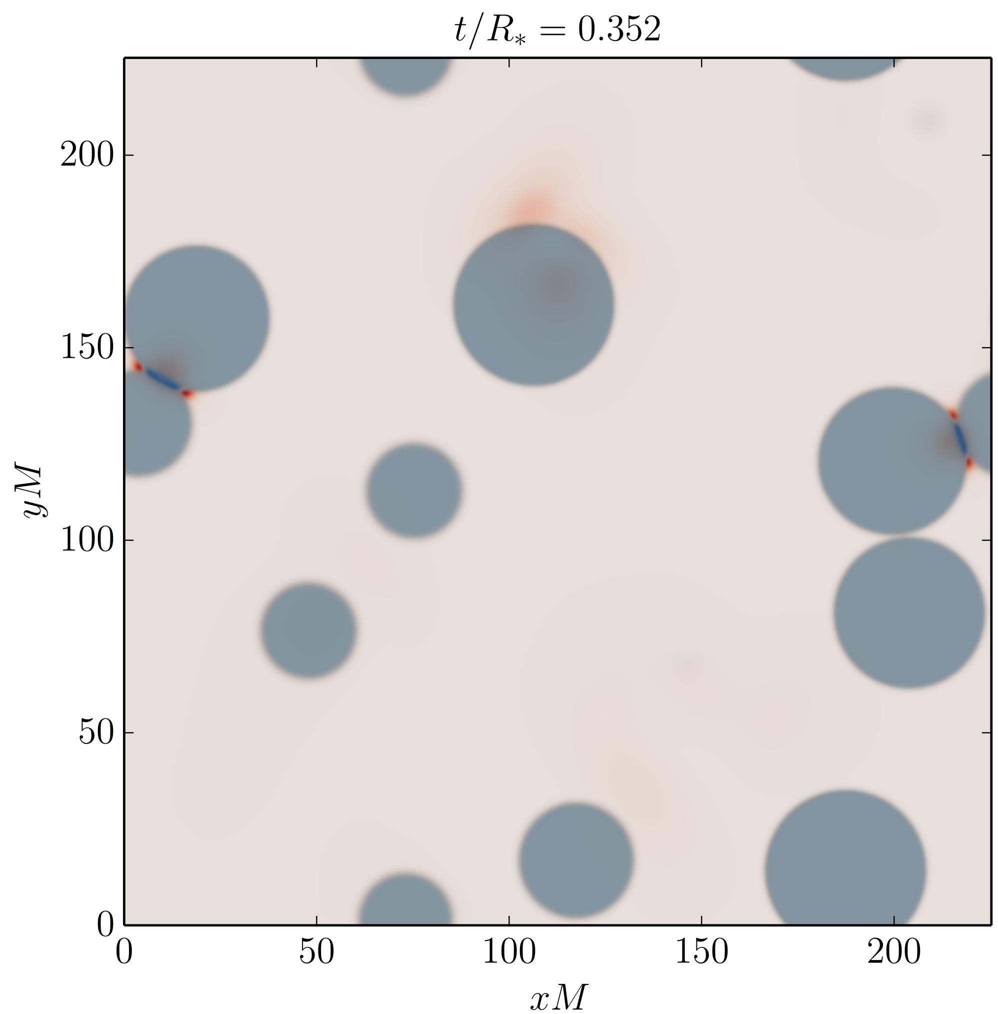
At T_n: Bubbles of broken phase nucleate and expand

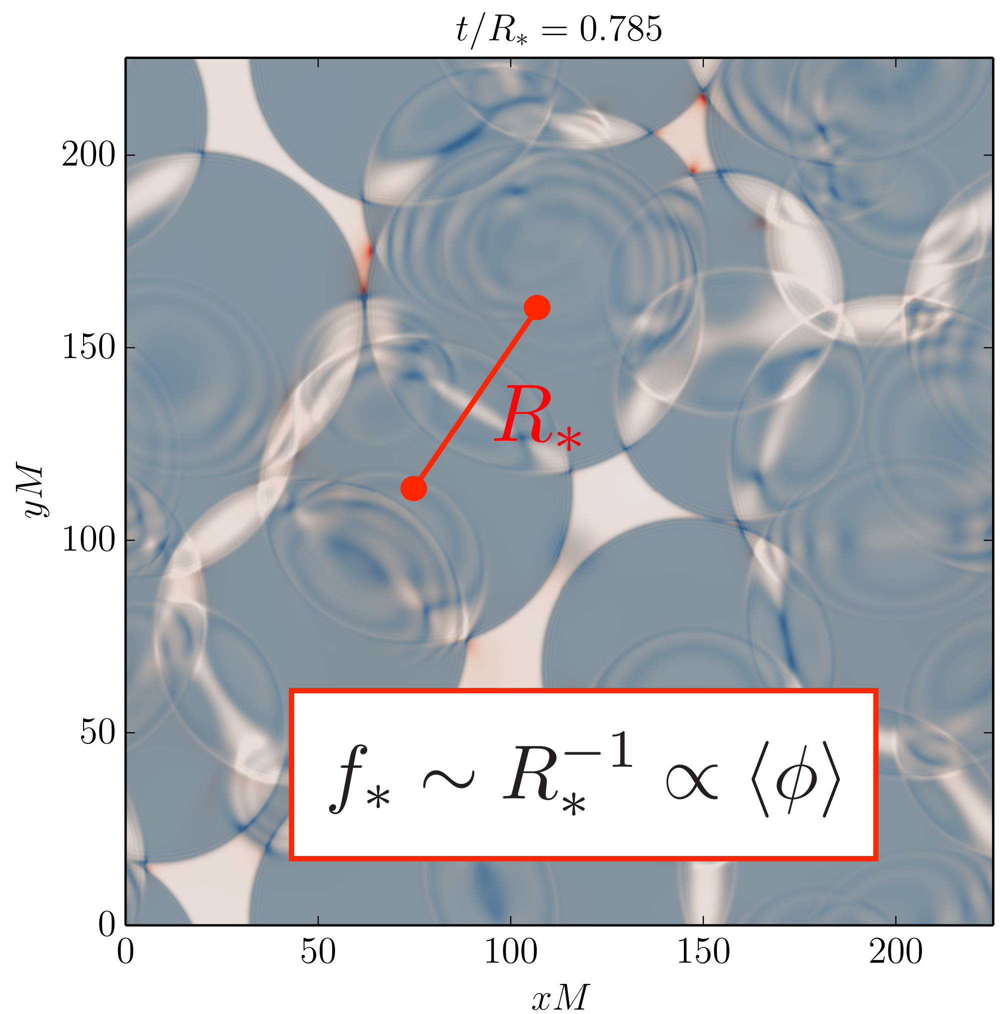


[see thesis by Moritz Breitbach]

GWs from Cosmological FOPTs

- Gravitational waves are relics of strong cosmological FOPTs!



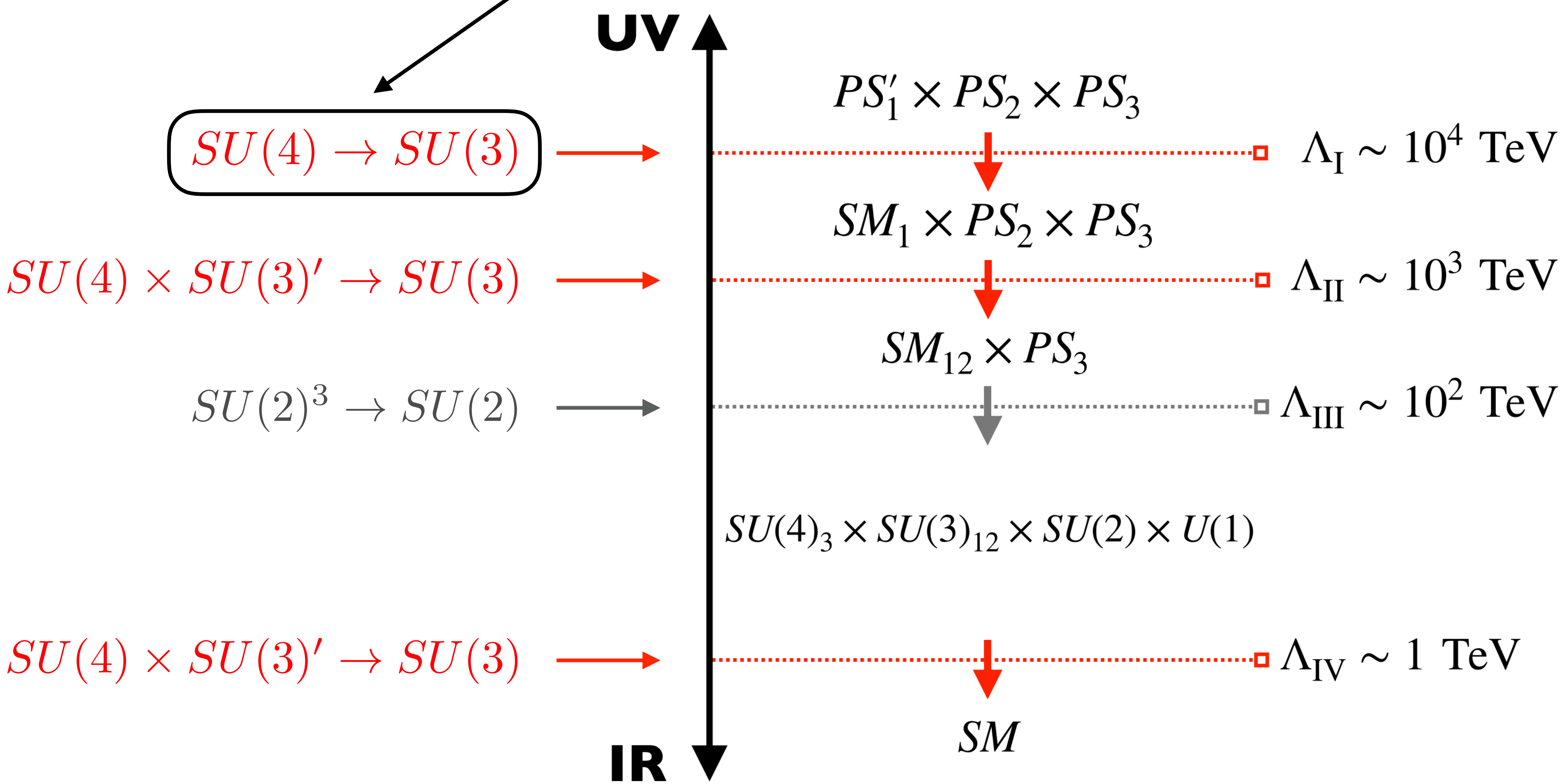


- Bubbles expand- spherical symmetry ==> No GW yet. (Birkhoff's Theorem)
- Bubbles collide, breaking spherical symmetry. Anisotropic energy distribution ==> GW

[D. Cutting, M. Hindmarsh, D.J. Weir 1802.05712]

Calculation: Simplified 4-to-3 Model

- Take the simplest “4-to-3” breaking at the scale Λ_{I} .



- Computed “4x3-to-3” breaking as well- qualitatively similar.

Calculation: Simplified 4-to-3 Model

- Consider the breaking pattern: $SU(4) \to SU(3)$

  Massive gauge bosons: **15 = 8 + 6 + 1**

  Leptoquark + Z′

- Matter content [all in **4** of SU(4)]

$$\langle \Sigma \rangle = (0,0,0,v/\sqrt{2})^T , \qquad \Psi_L , \quad \Psi_R .$$

  Scalars: **4 = 3 + 1**

  Goldstones + Massive radial mode: $\mathbf{Re}\,\Sigma_4 \equiv \phi/\sqrt{2}$

- No Yukawa interactions (gauge symmetry)

$$\mathcal{L} = \overline{\Psi} i \not{D} \Psi - \frac{1}{4}(F^a_{\mu\nu})^2 + |D_\mu \Sigma|^2 + \lambda v^2 |\Sigma|^2 - \lambda |\Sigma|^4$$

Model Parameters: g, λ, v

Calculation: Simplified 4-to-3 Model

- Finite temperature effective potential for $\mathbf{Re}\,\Sigma_4 \equiv \phi/\sqrt{2}$

$$V_{\rm eff}(\underbrace{g, \lambda, v, \phi}_{\text{[fundamental parameters]}}, T) = V_0 + V_{\rm CW} + V_{T\neq 0}$$

[temperature]

- Tree-level potential: $V_0(\lambda, v, \phi) = -\frac{1}{2}\lambda v^2 \phi^2 + \frac{\lambda}{4}\phi^4$

- Coleman-Weinberg:

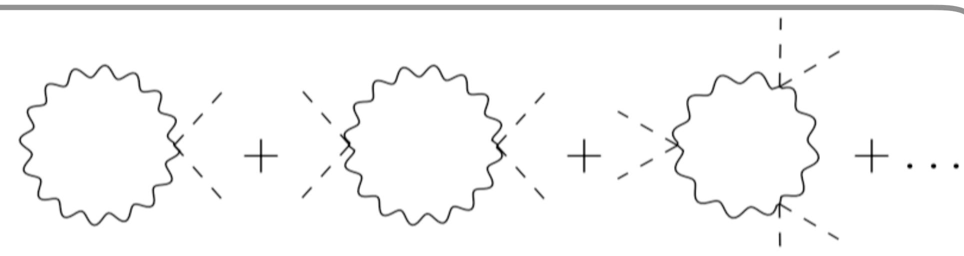
$$V_{CW}(g, \lambda, v, \phi) = \sum_b n_b \frac{m_b^4(\phi)}{64\pi^2}\left(\ln \frac{m_b^2(\phi)}{\mu_R^2} - C_a\right)$$

e.g.

$$m_{Z'}^2 = \frac{3g^2\phi^2}{8}$$

$$m_U^2 = \frac{g^2\phi^2}{4}$$

Zero temp part of:



(*) Small scalar quartics

Calculation: Simplified 4-to-3 Model

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$$V_{\text{eff}}(\underbrace{g, \lambda, v}_{\text{[fundamental parameters]}}, \phi, T) = V_0 + V_{\text{CW}} + V_{T\neq 0}$$

[temperature]

e.g.

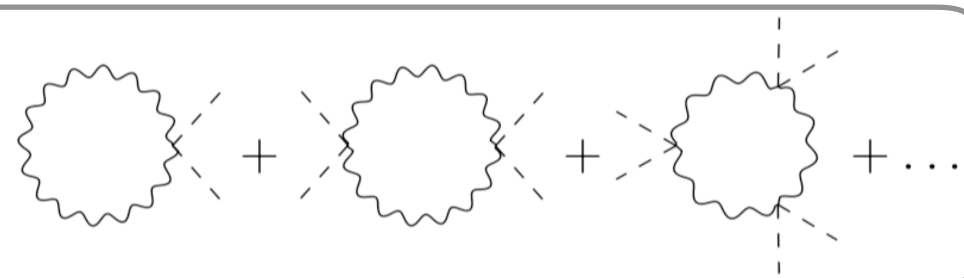
$$\Pi^L_{A^a_\mu}(T) = \frac{11}{6} g^2 T^2$$

$$\Pi^T_{A^a_\mu}(T) = 0$$

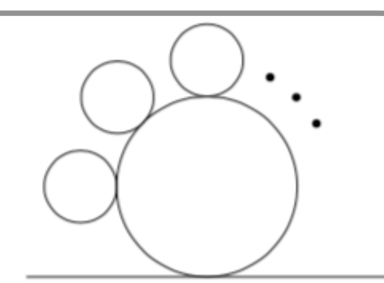
- 1-loop Thermal Potential:

$$V_{T\neq 0}(g, \lambda, v, \phi, T) = \frac{T^4}{2\pi^2} \sum_b n_b\, J_b \left(\frac{m_b^2(\phi) + \Pi_b(T)}{T^2} \right)$$

Finite temp part of:



Daisy Resummation:



(*) Small scalar quartics

Results: Simplified 4-to-3 Model

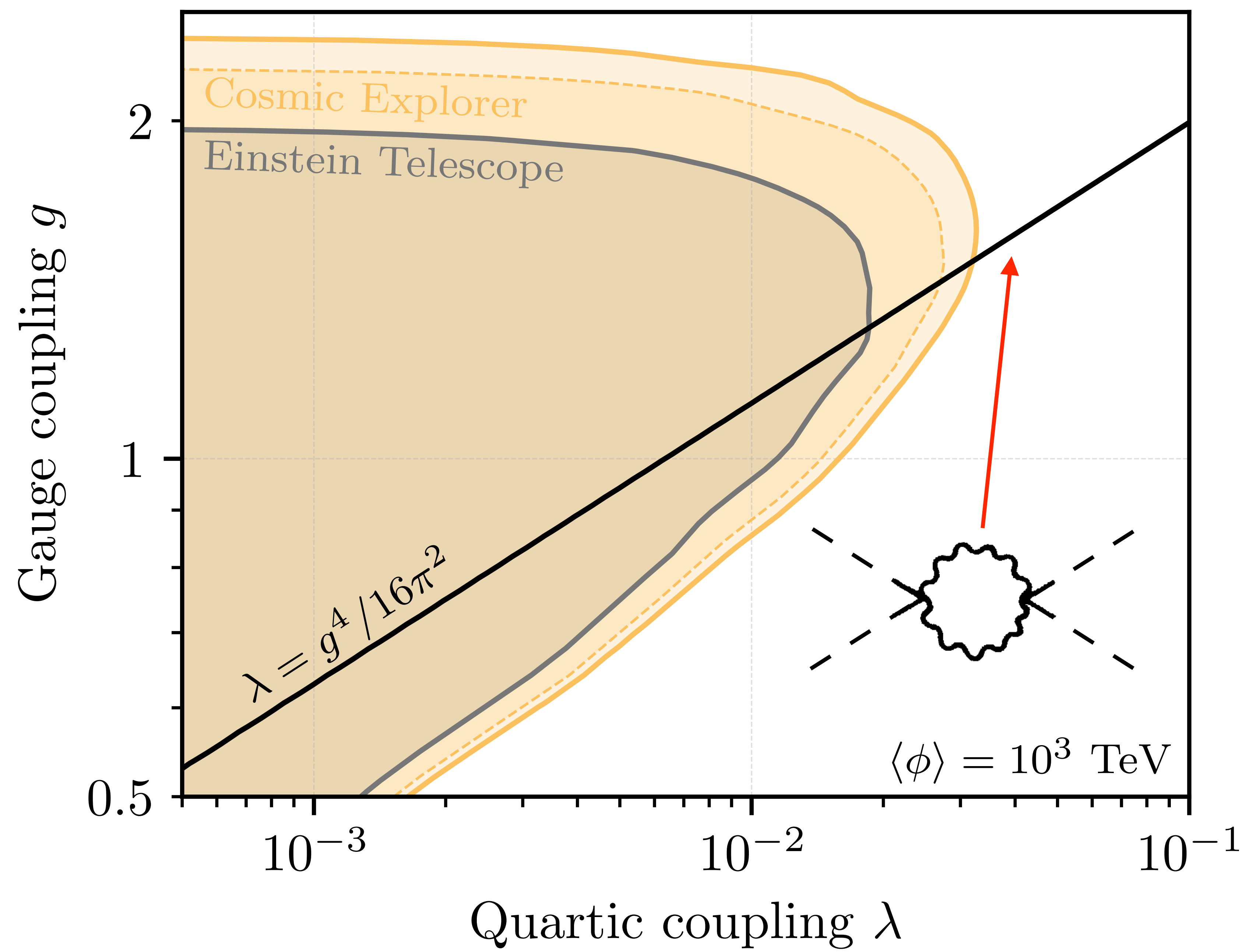
- Resulting gravitational wave signal is naturally detectable if:

$$\boxed{g \sim 1, \;\; \lambda \ll 1}$$

✓ PS³ embeds strong gauge group:

$$g_s \sim 1$$

✓ 5d gauge symmetry ==> suppressed scalar quartics.



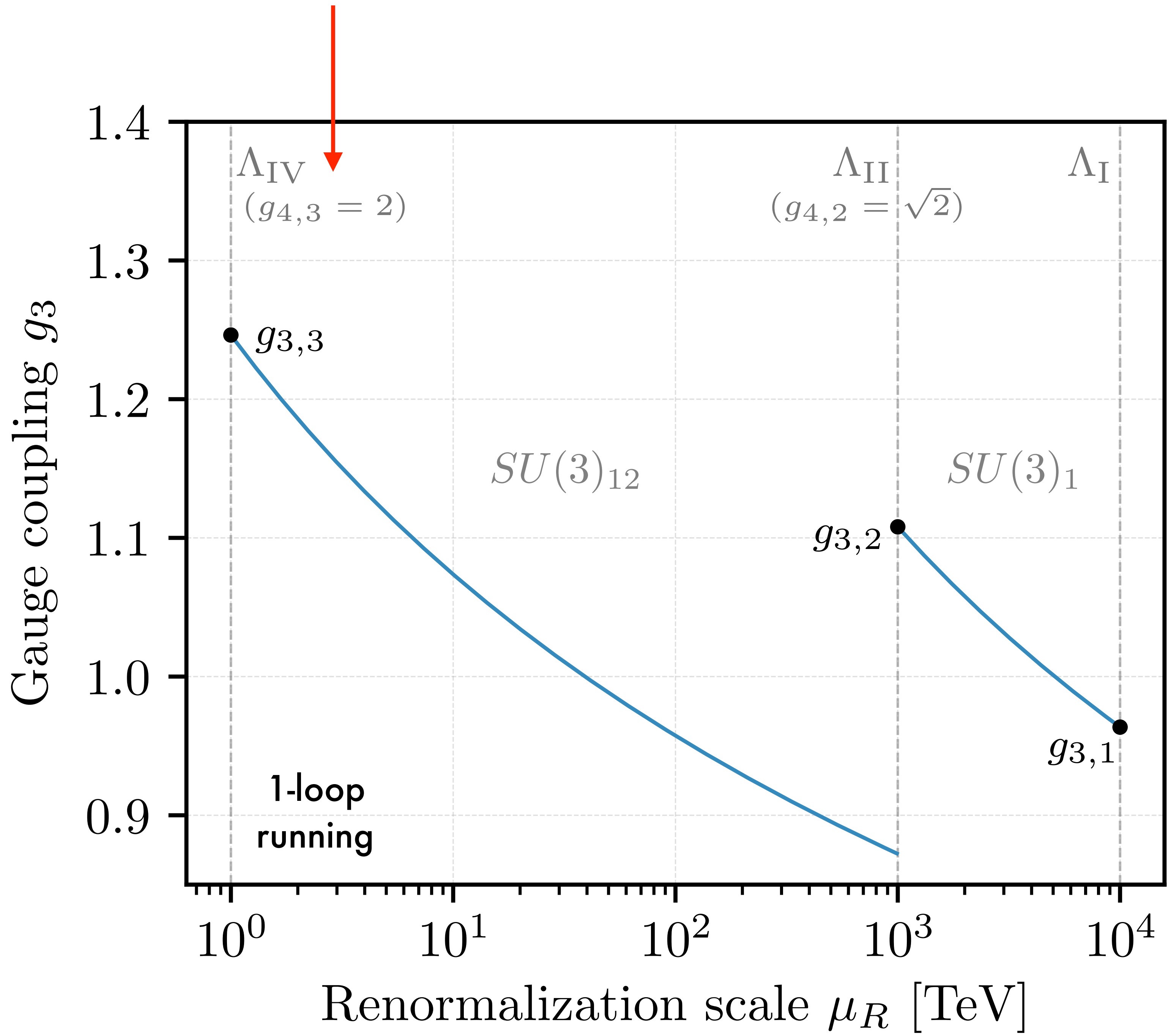
Gauge Couplings of Pati-Salam-Cubed

- Choose large SU(4) coupling at the TeV scale (flavor anomalies)

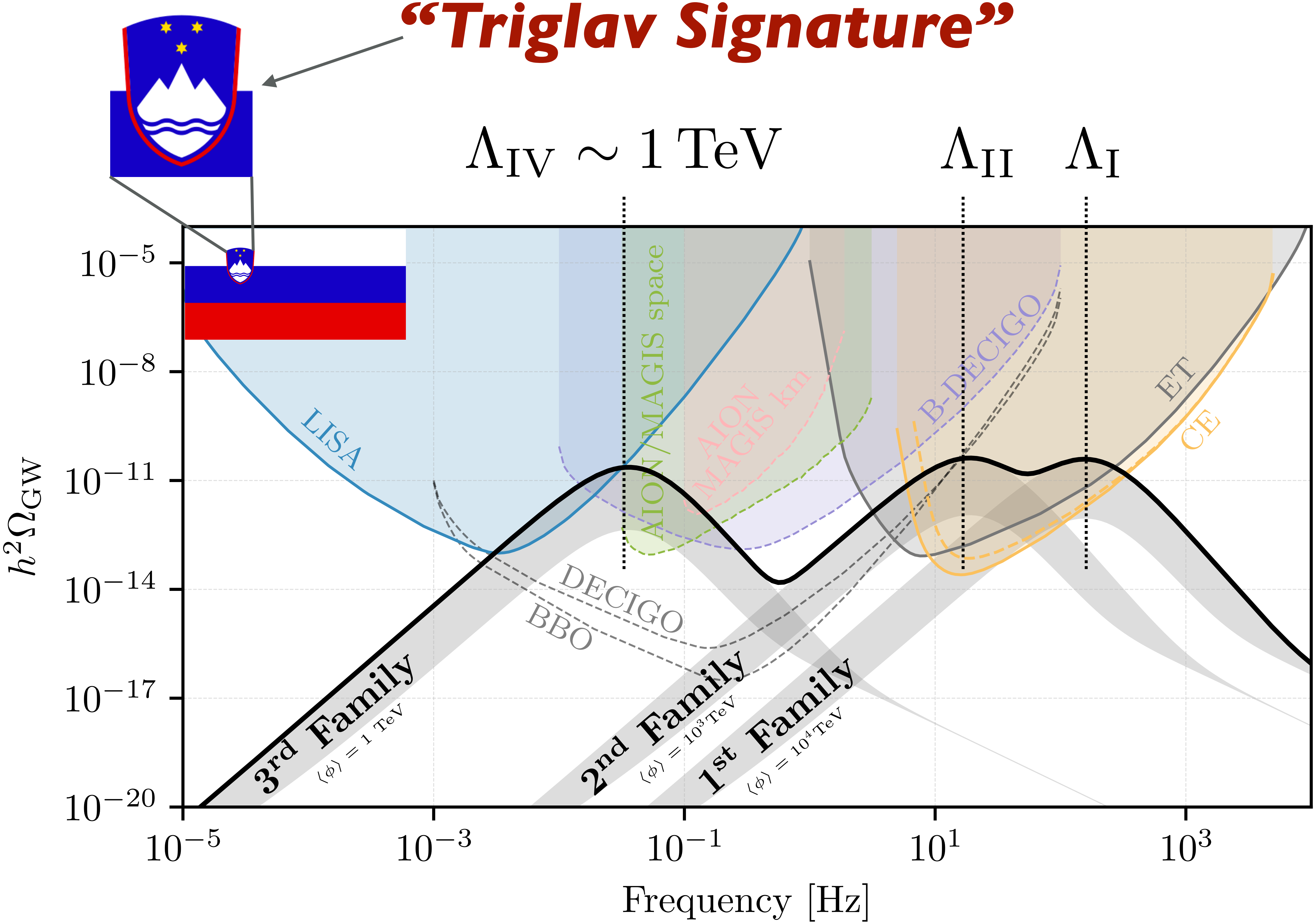
- Must match onto QCD when "4321" is broken at the TeV scale:

$$\frac{1}{g_s^2(\Lambda_{\rm IV})} = \frac{1}{g_{4,3}^2(\Lambda_{\rm IV})} + \frac{1}{g_{3,3}^2(\Lambda_{\rm IV})}$$

- Flavor anomalies + QCD dictate all gauge couplings are O(1)!



Gravitational Imprints of Pati-Salam Cubed: “Triglav Signature”



Conclusions

- "4321" models at the TeV scale offer the most coherent explanation for the current flavor anomalies.
- Our work addressed a major phenomenological issue of low-scale quark-lepton unification by achieving the correct neutrino masses and mixings via the ISS mechanism.
- The naturally small mass splittings of the heavy right-handed neutrinos may be used for low-scale leptogenesis.
- The parameters of Pati-Salam-Cubed (which offers a compelling UV embedding of "4321") naturally yield a series of first-order SSBs that produce observable GWs.