# Flavor hierarchies and anomalies from a 5D perspective

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University of Granada

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# A 5D model that…

- ★ Explains/Justifies the flavor hierarchies from a multi-scale origin
- ★ Reduces to 4321 ($U_1$ UV completion) at low energies
- ★ Stabilizes the Higgs hierarchy (Higgs as a pNGB)

[JFM, Isidori, Lizana,Selimović, Stefanek, 2203.01952]

# A 5D model that…

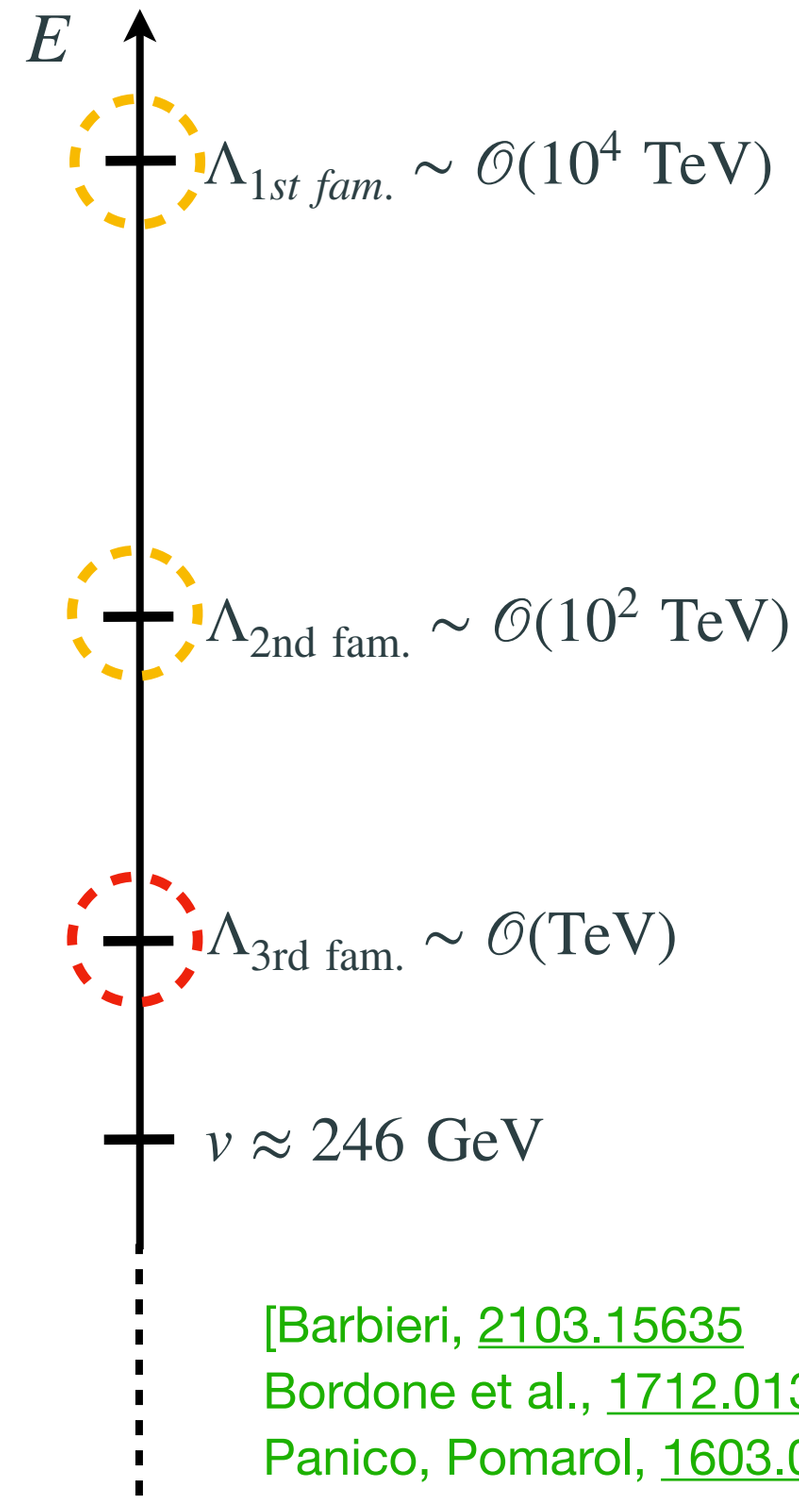
★ Explains/Justifies the flavor hierarchies from a multi-scale origin

[JFM, Isidori, Lizana,Selimović, Stefanek, 2203.01952]

# Multi-scale solution of the flavor problem/puzzle

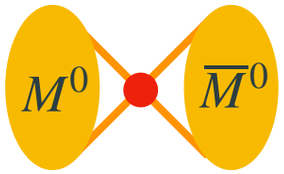
$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{Gauge}} + \mathscr{L}_{\text{Higgs}} + \mathscr{L}_{\text{Yukawa}} + \sum_{i,d} \frac{1}{\Lambda_i^{d-4}} C_i \mathcal{O}_i^d$$

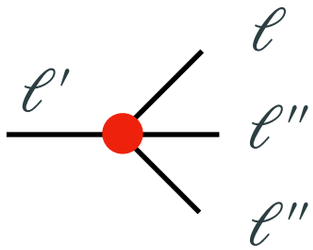
Non-trivial UV imprints




- ★ The SM Yukawas are very different because they originate at separate scales!
- ★ TeV-scale NP dominantly coupled to third and (to a lesser extent) second families [ protection from flavor constraints ]

e.g. from $\frac{1}{\Lambda^2}(\psi_i\psi_j)^2$




- ★ Direct production of new states at the LHC is naturally more suppressed [ NP scale can be lower ]

[Barbieri, 2103.15635
Bordone et al., 1712.01368
Panico, Pomarol, 1603.06609
Dvali, Shiftman, '00, …]

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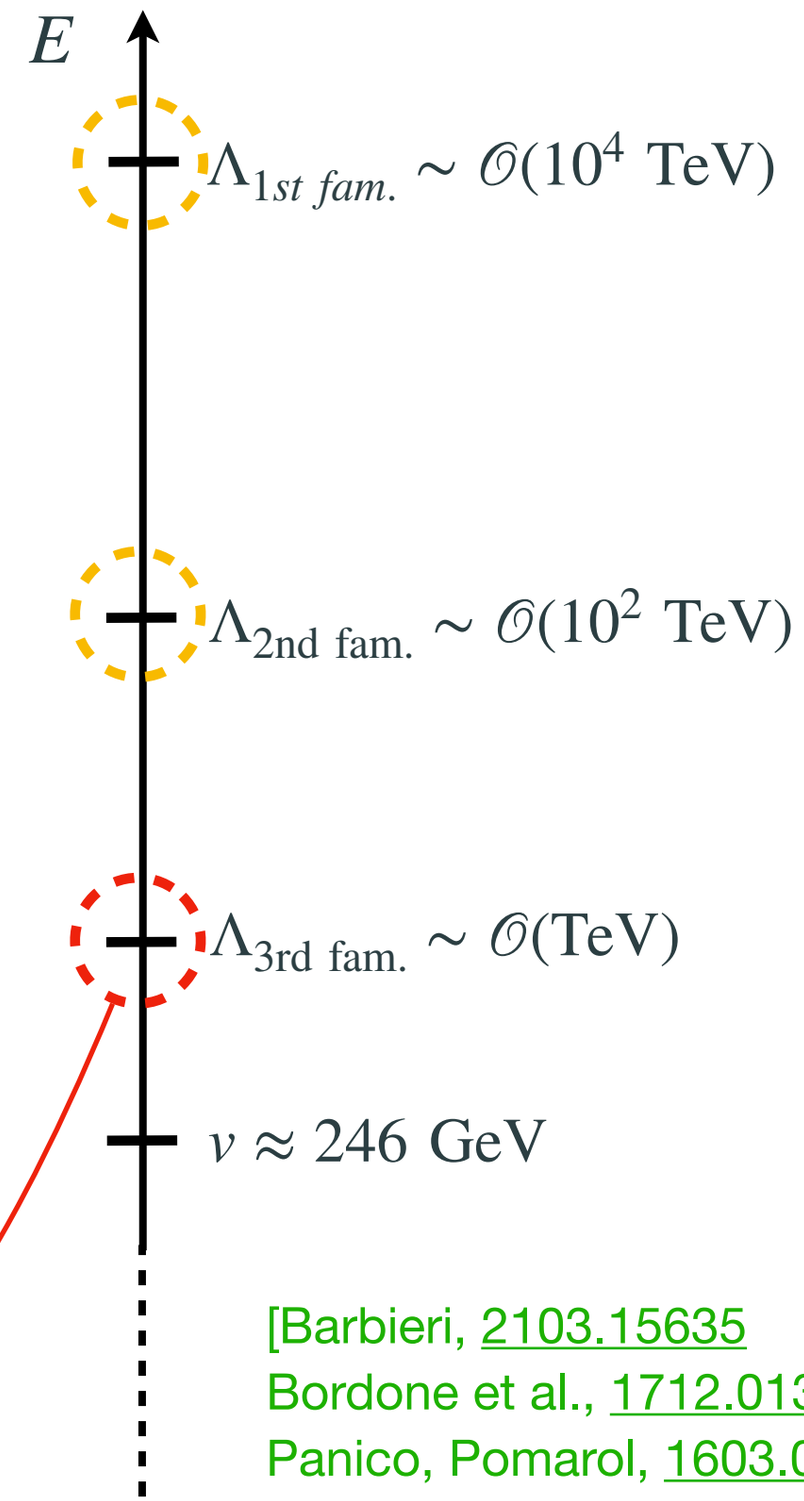


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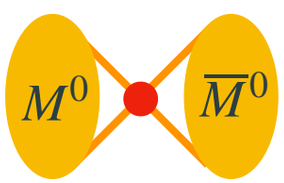
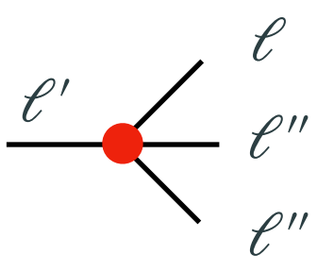
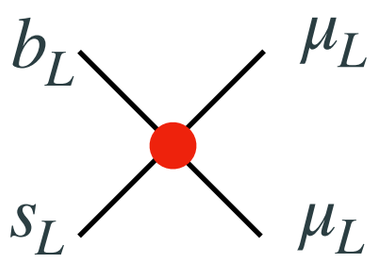


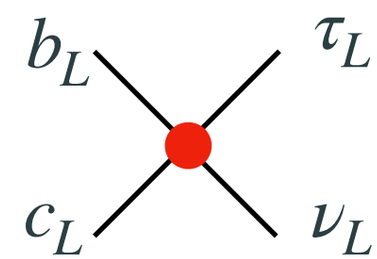

Perhaps we are already seeing hints in B-meson decays?

[Barbieri, 2103.15635
Bordone et al., 1712.01368
Panico, Pomarol, 1603.06609
Dvali, Shiftman, '00, …]

# Combined explanation of B anomalies




$\ll$




$$\sim \frac{1}{(40\ \text{TeV})^2}$$

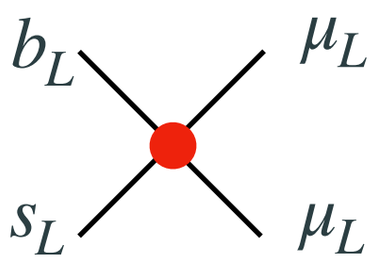
$$\sim \frac{1}{(3\ \text{TeV})^2}$$

$$3_q \to 2_q 2_\ell 2_\ell$$

$$3_q \to 2_q 3_\ell 3_\ell$$

The only source of **Lepton Flavor Universality Violation** in the SM (Yukawas) follows a very similar trend: $y_e \ll y_\mu \ll y_\tau$

# Combined explanation of B anomalies

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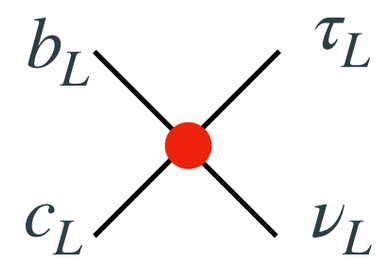


$$\sim \frac{1}{(1\ \text{TeV})^2} |V_q|\, |V_\ell|^2 \qquad\qquad \sim \frac{1}{(1\ \text{TeV})^2} |V_q|$$

$$3_q \to 2_q 2_\ell 2_\ell \qquad\qquad 3_q \to 2_q 3_\ell 3_\ell$$

The only source of **Lepton Flavor Universality Violation** in the SM (Yukawas) follows a very similar trend: $y_e \ll y_\mu \ll y_\tau$

Data consistent with TeV-scale NP with a Yukawa-like scaling with $|V_q|, |V_\ell| \sim 0.1$
[ roughly the size inferred from the SM Yukawa $|V_q| \sim V_{cb} \approx 0.04$ ]

[JF, Isidori, Pagès, Yamamoto, 1909.02519]

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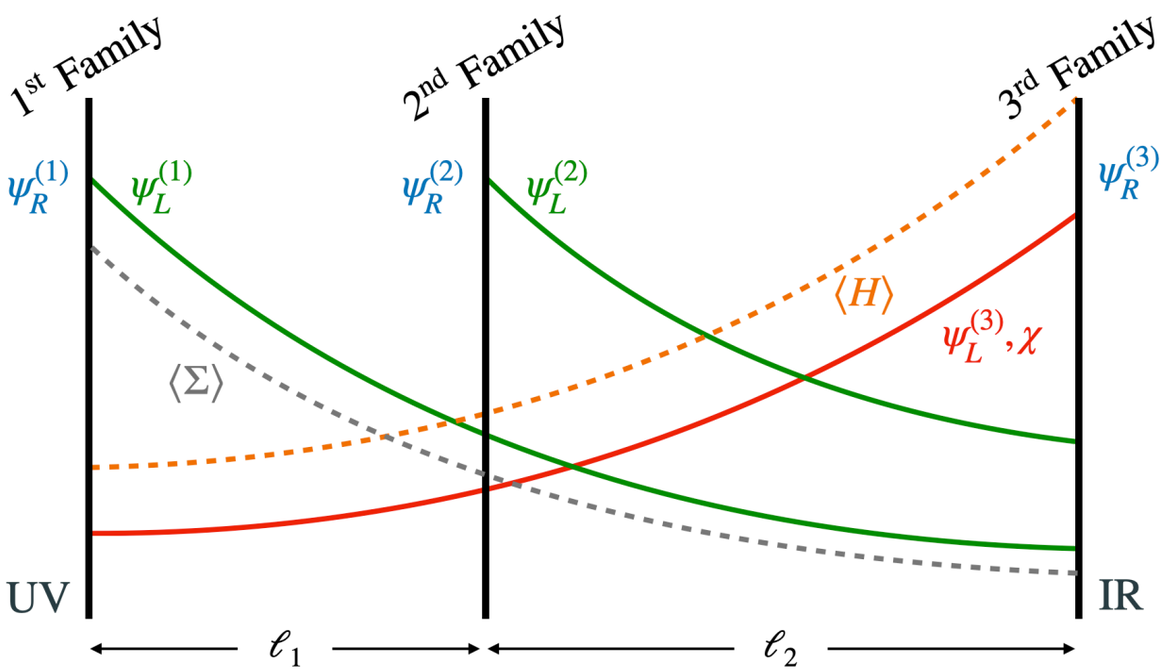
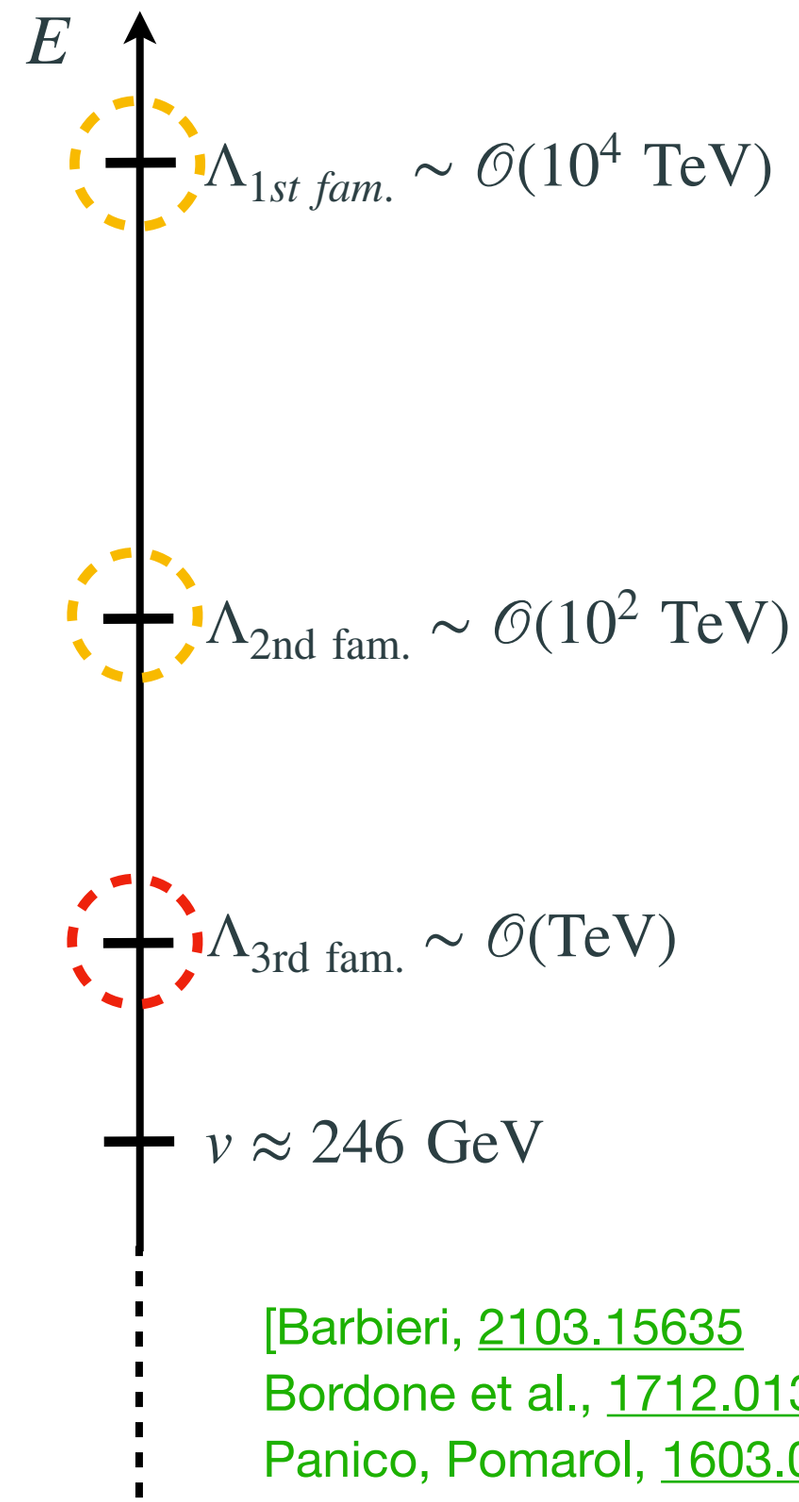



$\Longleftrightarrow$




Flavor $\longleftrightarrow$ fermion (quasi-)localization along an extra dimension

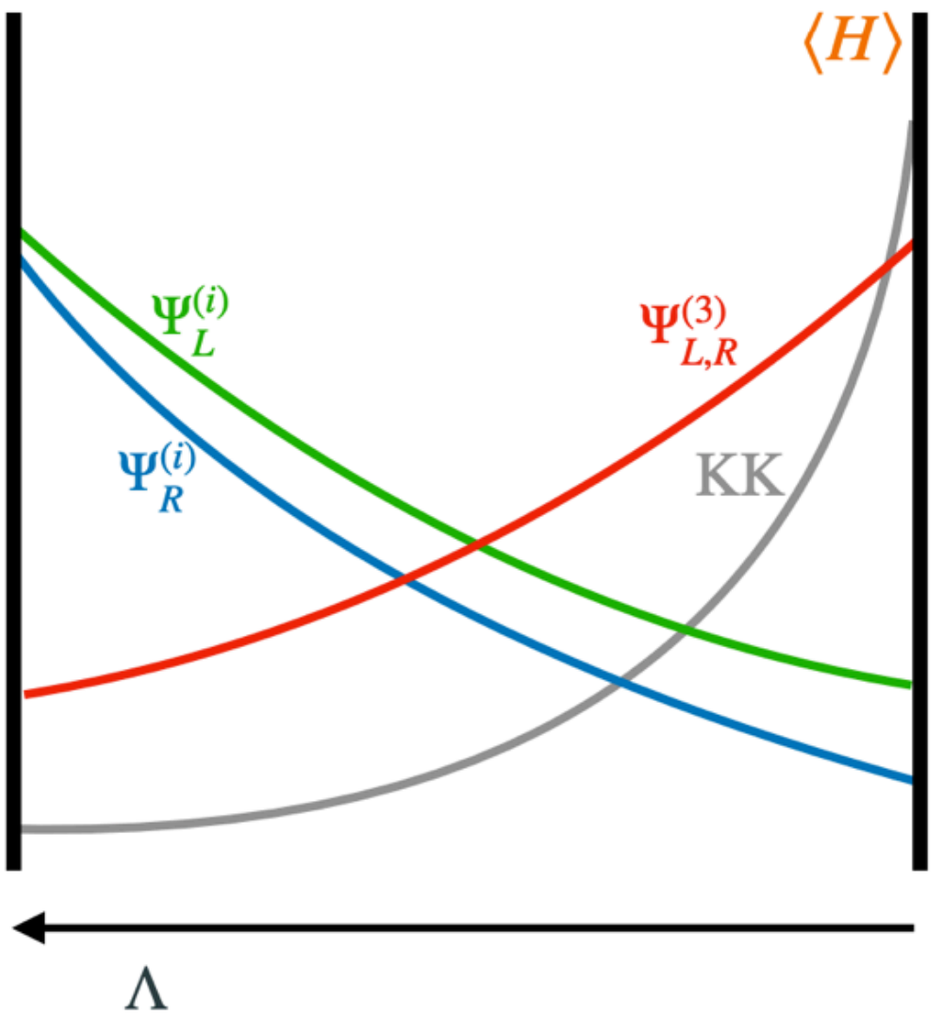
[Barbieri, 2103.15635
Bordone et al., 1712.01368
Panico, Pomarol, 1603.06609
Dvali, Shiftman, '00, …]

# Flavor in Randall-Sundrum

Curvature of the AdS slice

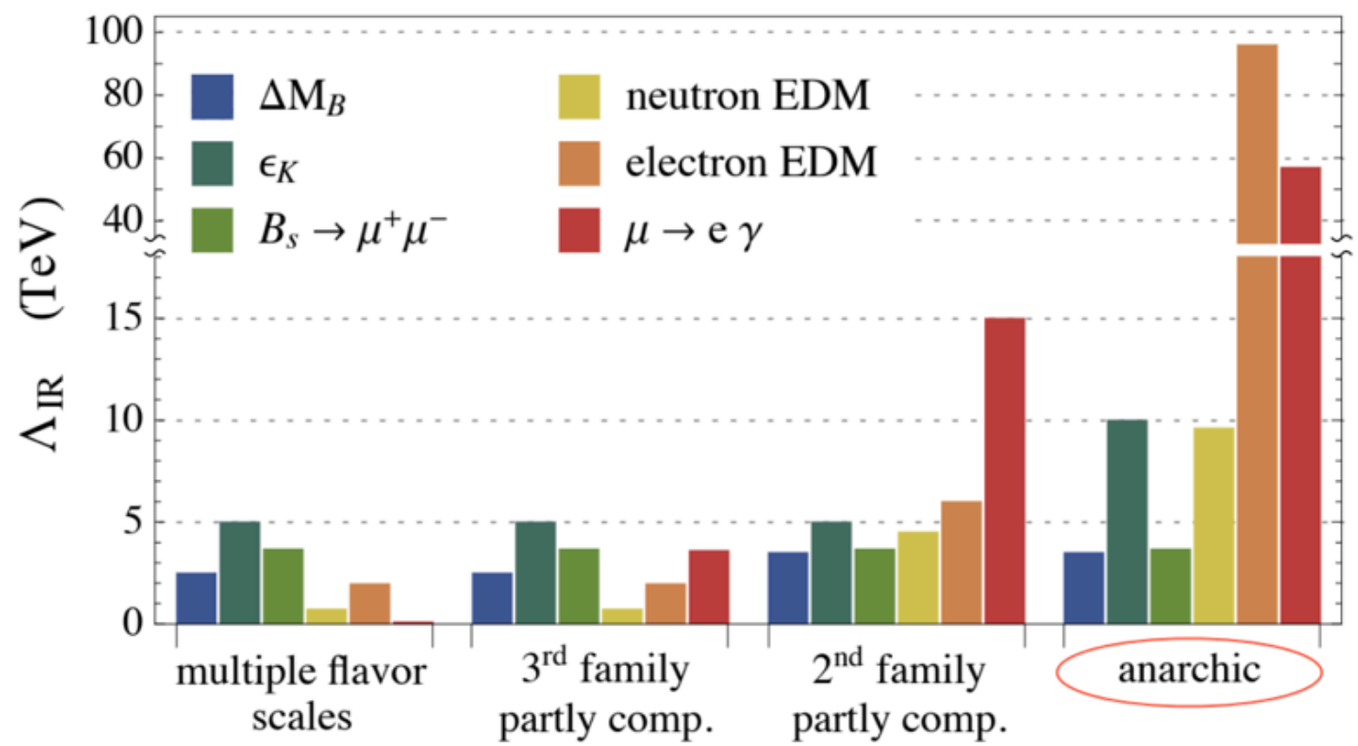
Warped 5D geometry (RS): $ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2$

- Justification of the Yukawa hierarchies through exponentiation + flavor anarchy
- Analogous to partial compositeness in composite models




Dangerous dipoles (among others) generated at the IR scale

$$\sim \frac{g_*^2}{16\pi^2}\frac{m_e}{\Lambda_{\rm IR}^2}\bar{e}_L\sigma_{\mu\nu}e_R F^{\mu\nu}$$




[Panico, Pomarol, 1603.06609]

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[JFM, Isidori, Lizana,Selimović, Stefanek, 2203.01952]

# Gauge UV completion for the $U_1$ leptoquark

$$U_1 \sim (3,1,2/3) \dashrightarrow SU(4) \dashrightarrow \mathrm{PS} = SU(4) \times SU(2)_L \times SU(2)_R$$

$$SU(4) \sim \begin{pmatrix} G^a & U^\alpha \\ (U^\alpha)^* & Z' \end{pmatrix} \qquad \psi_{L,R} = \begin{bmatrix} q^1_{L,R} \\ q^2_{L,R} \\ q^3_{L,R} \\ l_{L,R} \end{bmatrix}$$

Leptons as the fourth "color"

[Pati, Salam, Phys. Rev. D10 (1974) 275]
( only 7 years after the SM was proposed )

✓ $SU(4)$ is the smallest group containing the $U_1 \sim (\mathbf{3}, \mathbf{1}, 2/3)$

✓ No proton decay (protected by symmetry)

✘ Flavor-blind $U_1$ mediates $K_L \to \mu e \;\Rightarrow\; m_{U_1} \gtrsim 100\,\mathrm{TeV}$

✘ Extra fermions can make the $U_1$ non-universal, not the $Z'$

✘ Strongly coupled, universal $Z'$ would be excessively produced at the LHC

# 4321 model(s)

[Georgi and Y. Nakai, 1606.05865; Diaz, Schmaltz, Zhong, 1706.05033; Di Luzio, Greljo, Nardecchia, 1708.08450. See also Fornal, Gadam, Grinstein, 1812.01603]

We can "protect" the light families by de-correlating $SU(4)$ from the SM color group $(g_4 \gg g_3)$

**PS group:** $\mathcal{G}_{\rm PS} \supset SU(4) \times SU(2)_L \times U(1)_R$ [ Flavor universal ]

**4321 group:** $\mathcal{G}_{4321} \equiv SU(4)_h \times SU(3)_l \times SU(2)_L \times U(1)_{R+l}$ [ Flavor non-universal ]

$$\underbrace{\overbrace{SU(4) \times SU(3)' \times SU(2)_L \times U(1)_X}^{U(1)_Y}}_{SU(3)_c} \xrightarrow{SSB} SU(3)_c \times SU(2)_L \times U(1)_Y$$

$+U_1, Z', G'$

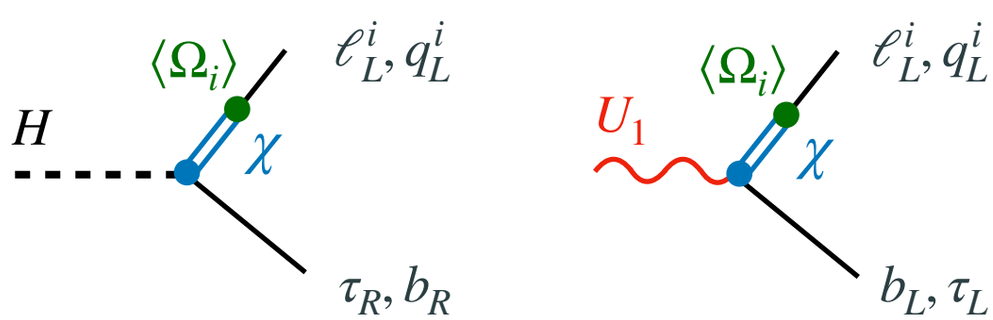
[ Flavor non-universal ]

# Third-family quark-lepton unification at the TeV scale

$$\underbrace{SU(4)_h \times SU(3)_l}_{SU(3)_c} \times SU(2)_L \times \overbrace{U(1)_{R+l}}^{U(1)_Y} \xrightarrow{\langle \Omega_{1,3,15} \rangle \sim \mathcal{O}(\text{TeV})} SU(3)_c \times SU(2)_L \times U(1)_Y + U_1, G', Z'$$

★ Direct new physics couplings to 3rd family only

★ CKM mixing and NP couplings to light families via (small) mixing with vectorlike fermions $\chi$




★ Fully calculable loop contributions

[JFM, Isidori, König, Selimovic, 1910.13474, 2006.16250, 2009.11296]

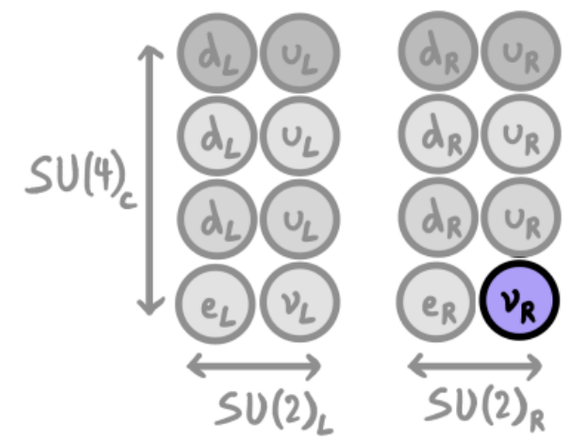
$i = 1,2$

| Field | $SU(4)$ | $SU(3)'$ | $SU(2)_L$ | $U(1)_X$ | |
|---|---|---|---|---|---|
| $q_L^i$ | **1** | **3** | **2** | $1/6$ | 1st & 2nd families |
| $u_R^i$ | **1** | **3** | **1** | $2/3$ | |
| $d_R^i$ | **1** | **3** | **1** | $-1/3$ | |
| $\ell_L^i$ | **1** | **1** | **2** | $-1/2$ | |
| $e_R^i$ | **1** | **1** | **1** | $-1$ | |
| $\psi_L$ | **4** | **1** | **2** | $0$ | 3rd family |
| $\psi_R^\pm$ | **4** | **1** | **1** | $\pm 1/2$ | |
| $\chi_L^i$ | **4** | **1** | **2** | $0$ | vectorlike fermions |
| $\chi_R^i$ | **4** | **1** | **2** | $0$ | |
| $H$ | **1** | **1** | **2** | $1/2$ | |
| $\Omega_1$ | $\bar{\mathbf{4}}$ | **1** | **1** | $-1/2$ | 4321 breaking scalars |
| $\Omega_3$ | $\bar{\mathbf{4}}$ | **3** | **1** | $1/6$ | |
| $\Omega_{15}$ | **15** | **1** | **1** | $0$ | |

[Bordone, Cornella, JFM, Isidori 1712.01368, 1805.09328; Greljo, Stefanek, 1802.04274; Cornella, JFM, Isidori 1903.11517]

# Third-family quark-lepton unification at the TeV scale

**PS multiplets**




In first approximation, third-family quark-lepton unification implies

$$y_\tau = y_b \quad ✓ \qquad\qquad y_{\nu_\tau} = y_t$$

[ $y_\tau = 0.8\, y_b$ at 2 TeV ]

TeV-scale unification limits Majorana mass for $\nu_R$ to $m_{\nu_R} \lesssim \text{TeV}$

Type-I see-saw: $m_\nu \approx \dfrac{m_D^2}{m_{\nu_R}} \sim 10 \text{ GeV}$ ✗ $\qquad m_D \equiv y_\nu v/\sqrt{2}$

**Solution:** Inverse seesaw via new fermion singlets $S_L^i$ with hierarchical Majorana masses $\mu^i$

[ Greljo, Stefanek, 1802.04274
Fileviez, Wise, 1307.6213 ]

$$m_\nu \approx m_D\, m_R^{-1}\, \mu\, (m_R^{-1})^\intercal m_D^\intercal$$

$$m_D^i \approx m_u^i \sim (10^{-2}, 1, 10^2) \text{ GeV}$$

$$\Longrightarrow \qquad \mu^i \sim (10^7, 10^{-1}, 10^{-9}) \text{ GeV}$$

# Third-family quark-lepton unification at the TeV scale

**Model prediction:** mixing between active neutrino and pseudo-Dirac heavy neutral leptons yields

PMNS unitarity violation

with the expected pattern: $$\eta \equiv |1 - NN^\dagger| \sim \left|\frac{m_D^3}{m_R^3}\right|^2 \begin{pmatrix} \epsilon_L^4 & \epsilon_L^3 & \epsilon_L^2 \\ \epsilon_L^3 & \epsilon_L^2 & \epsilon_L \\ \epsilon_L^2 & \epsilon_L & 1 \end{pmatrix} \qquad \epsilon_L \approx 0.1$$

First sign of violation in 33 entry: $$\eta_{33} \approx \left|\frac{m_D^3}{m_R^3}\right|^2 \sim \left|\frac{100\ \text{GeV}}{2\ \text{TeV}}\right|^2 = 2.5 \times 10^{-3}$$

$$\eta_{33}^{\text{exp}} < 5.3 \times 10^{-3} \quad (90\ \%\ \text{C.L.})$$

[Antusch, Fischer, 1407.6607]

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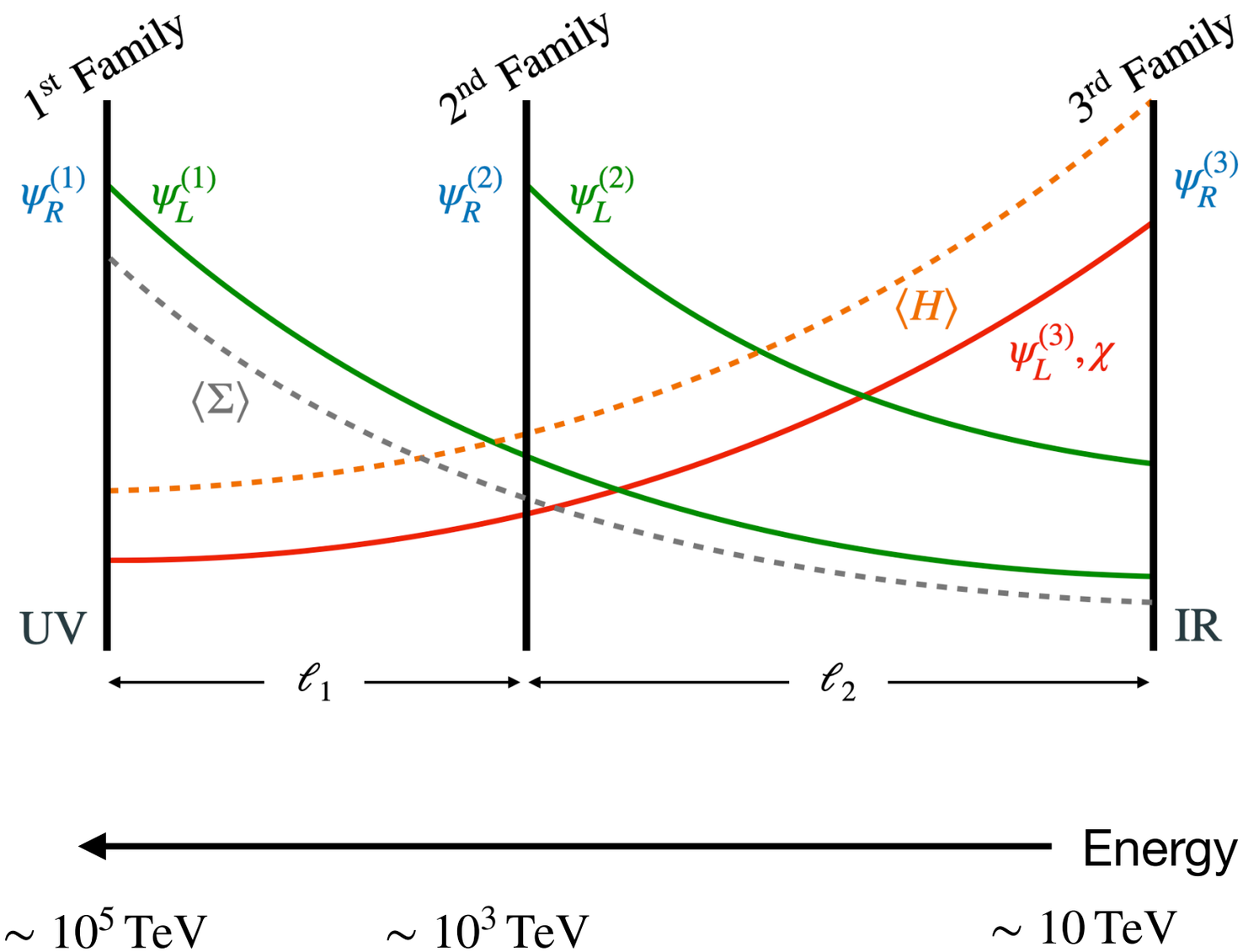
[JFM, Isidori, Lizana,Selimović, Stefanek, 2203.01952]

# A 5D UV completion of 4321

[JF, Isidori, Pagès, Stefanek, 2012.10492
JF, Isidori, Lizana, Selimovic, Stefanek, 2203.01952]

Attempt to construct a full theory of flavor by embedding the 4321 group in a compact warped extra dimension ( $\mathrm{AdS}_5$ ) with multiple four-dimensional branes




Flavor $\longleftrightarrow$ fermion (quasi-)localization in each of the branes

[Dvali, Shifman, '00; Panico, Pomarol, 1603.06609]

$$y_{ij} \approx y_t \, e^{-k(L-\ell_j)} \, e^{-k(c_i-1/2)(y_i-\ell_j)}$$

$k$ : Curvature of the AdS slice

Same dynamics that breaks 4321 also generates a pNGB Higgs $\longleftrightarrow$ stabilization of the EW hierarchy with an $\mathcal{O}(0.1\%)$ tuning (little hierarchy)

Anarchic neutrino masses via inverse see-saw mechanism

# Gauge sector

$$\mathcal{G}^{12}_{\text{bulk}} = SU(4)_h \times SU(4)_l \times SO(5)$$

$\Lambda_2$ (6 broken)

$$\mathcal{G}^{23}_{\text{bulk}} = SU(4)_h \times SU(3)_l \times U(1)_l \times SO(5)$$

$\Lambda_3 = \Lambda_{\text{IR}}$ (15 + 4 broken)

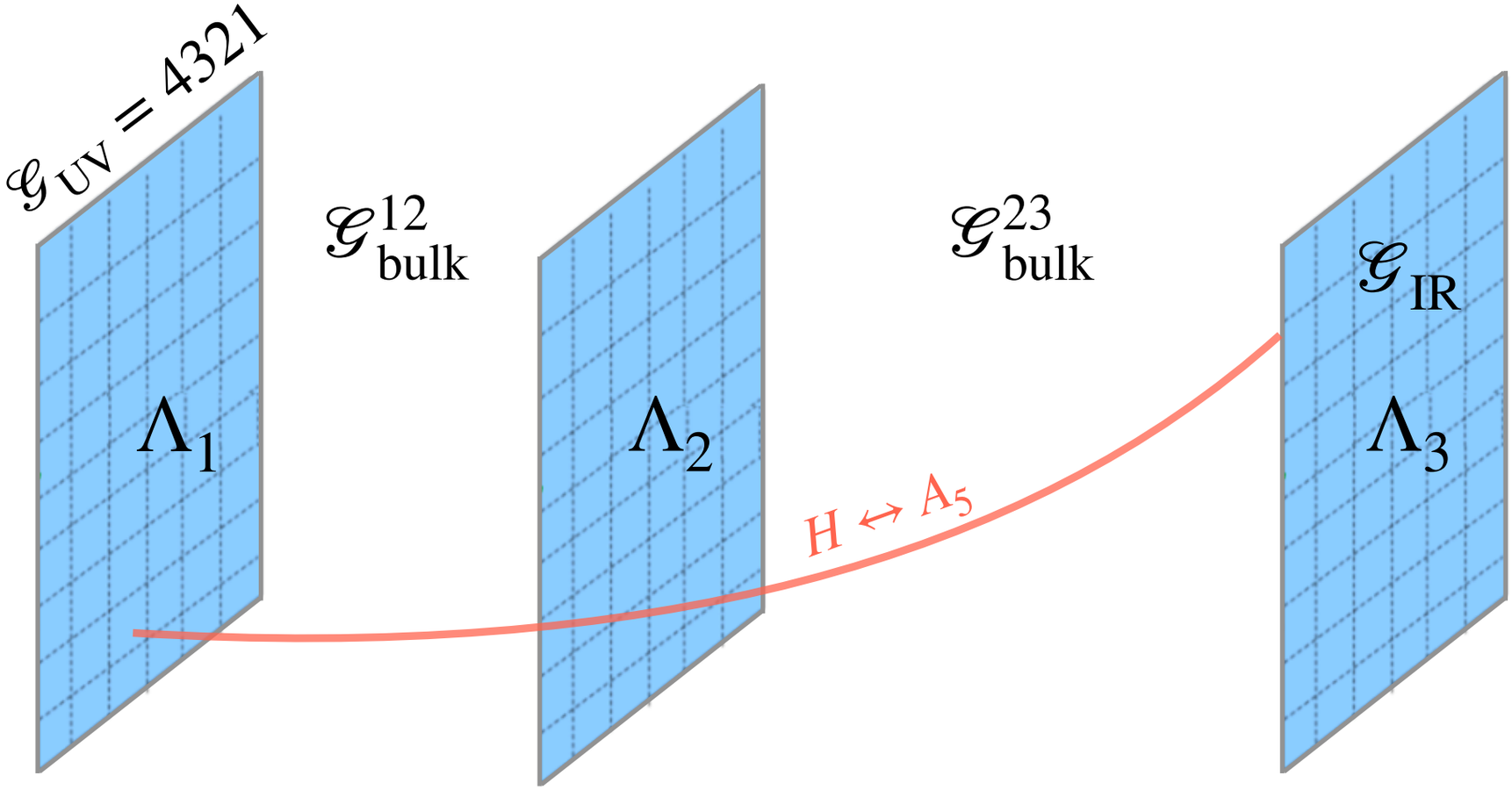
$$\mathcal{G}_{\text{IR}} = SU(3)_c \times U(1)_{B-L} \times SO(4)$$

Quark-lepton unification of light families

15 eaten by $U_1,\ G',\ Z',\ \ M_{4321} \sim \dfrac{M_{\text{KK}}}{\sqrt{2kL}}$

4 as pNGB Higgs

$$SO(5) \to SO(4) = SU(2)_L \times SU(2)_R$$




Minimal composite Higgs model

[Agashe, Contino, Pomarol, '04]

# Fermion and scalar sector

SM fermions and VLF

For neutrinos

For light Yukawas

| Field | $SU(4)_h$ | $SU(4)_l$ | $SO(5)$ |
|---|---|---|---|
| $\Psi^3 \quad \Psi^3_d \quad \chi^{(')}$ | **4** | **1** | **4** |
| $\Psi^j \quad \Psi^j_{u,d}$ | **1** | **4** | **4** |
| $\mathcal{S}^i$ | **1** | **1** | **1** |
| $\Phi$ | **1** | **1** | **1** |
| $\Omega$ | **1** | **4** | **4** |
| $\Sigma$ | **1** | **1** | **5** |

Fermions

Scalars

[JFM, Isidori, Pages, Stefanek, 2012.10492]

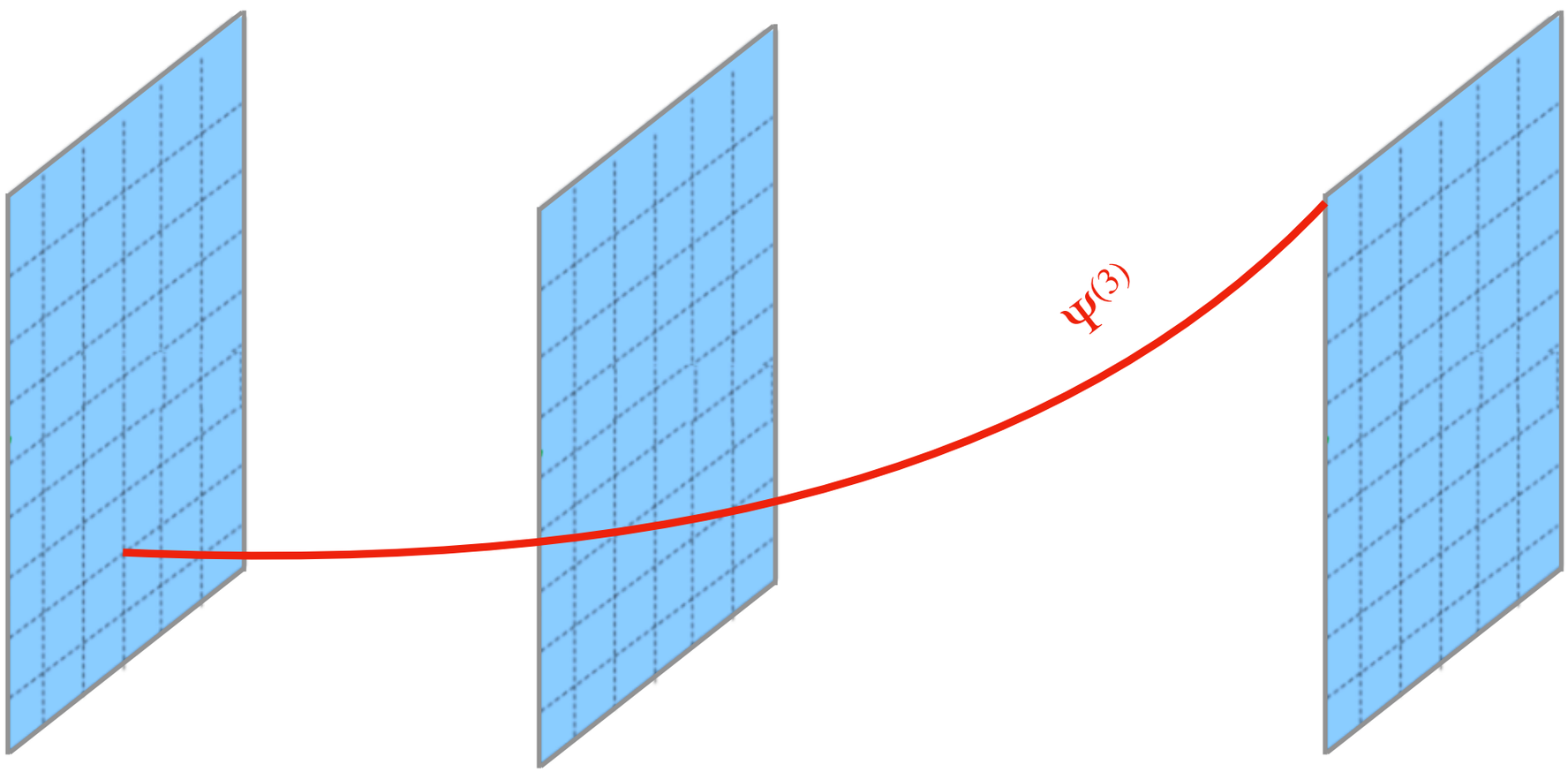
# Top Yukawa

| Field | $SU(4)_h$ | $SU(4)_l$ | $SO(5)$ |
|---|---|---|---|
| $\Psi^3$ | $\mathbf{4}$ | $\mathbf{1}$ | $\mathbf{4}$ |

$$\Psi^3 = \begin{bmatrix} q_L \\ t_R \\ \times \end{bmatrix} \begin{matrix} SU(2)_L \\ \left.\right\} SU(2)_R \\ \phantom{x} \end{matrix}$$

Top Yukawa from $\bar{\Psi}^3 A_5 \Psi^3$ coupling in the bulk

$$y_t = \frac{g_*}{2\sqrt{2}} P(M_{\Psi^3}) \qquad (g_*^2 = g_5^2 k) \qquad \text{For } y_t : g_* \geq 2.2$$

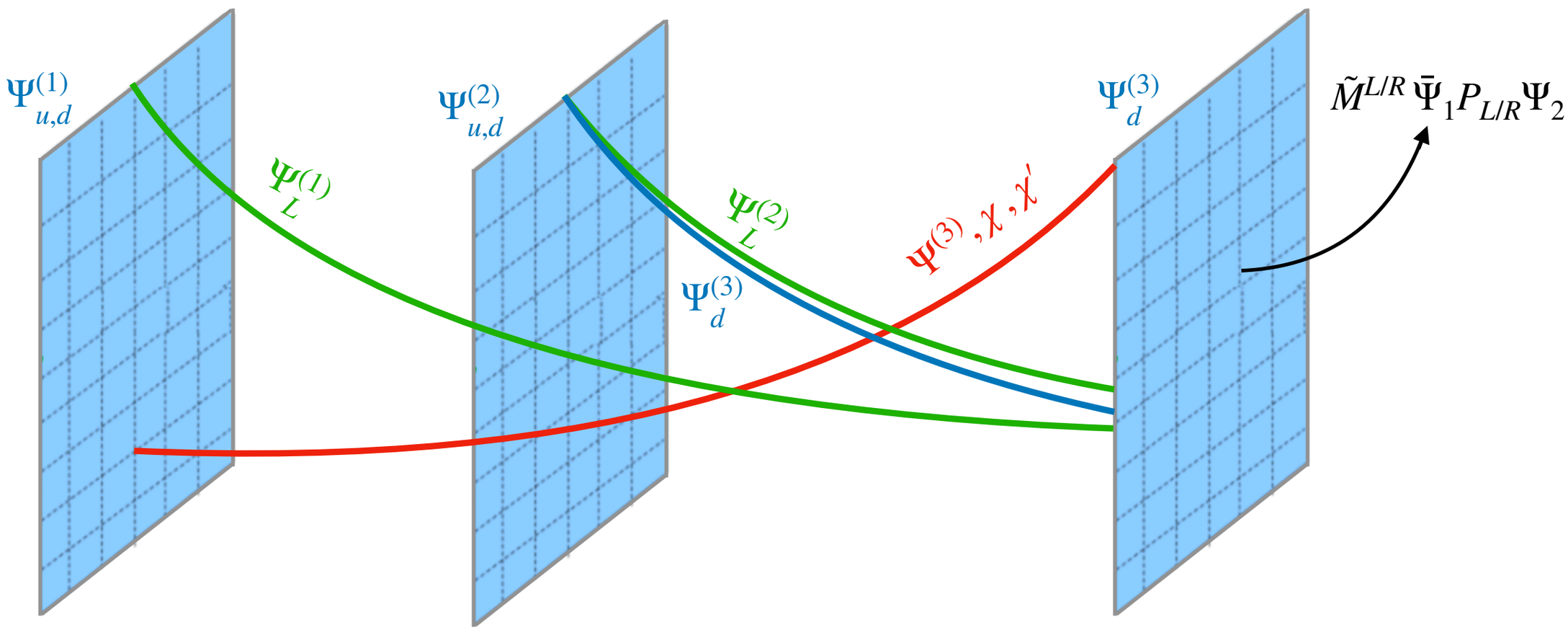


# Light-heavy mixing

| Field | $SU(4)_h$ | $SU(4)_l$ | $SO(5)$ |
|---|---|---|---|
| $\Psi^3, \Psi^3_d, \mathcal{X}^{(\prime)}$ | $\mathbf{4}$ | $\mathbf{1}$ | $\mathbf{4}$ |
| $\Psi^j, \Psi^j_{u,d}$ | $\mathbf{1}$ | $\mathbf{4}$ | $\mathbf{4}$ |

Mass mixing of light families with VLF and light-3rd family Yukawas from masses in the IR brane

$$y_{f_1 f_2} = \frac{g_*}{2\sqrt{2}}(\tilde{M}^L - \tilde{M}^R) \times \text{(profile suppression)}$$

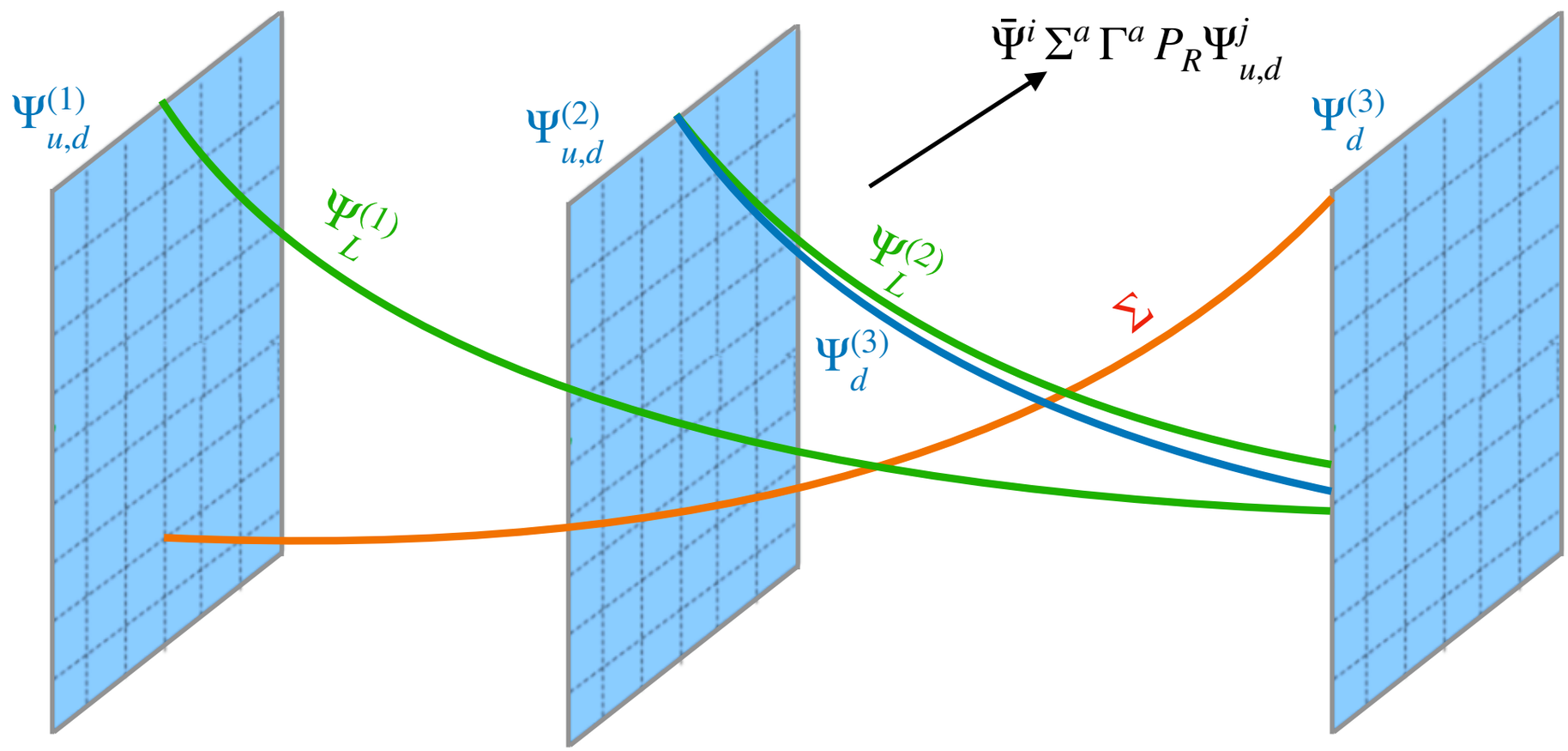


# Light Yukawas

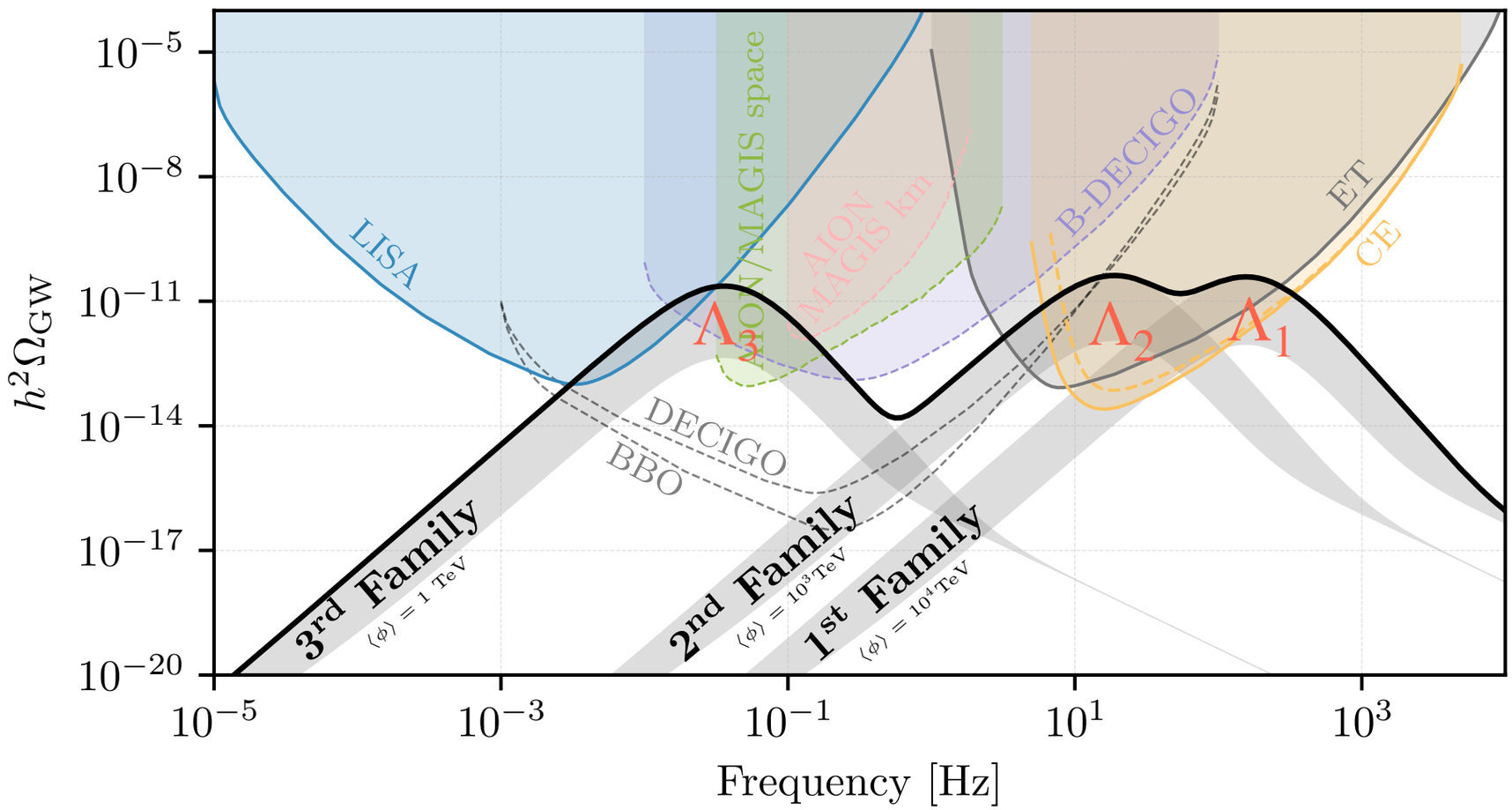
| Field | $SU(4)_h$ | $SU(4)_l$ | $SO(5)$ |
|---|---|---|---|
| $\Psi^j, \Psi^j_{u,d}$ | $\mathbf{1}$ | $\mathbf{4}$ | $\mathbf{4}$ |
| $\Sigma$ | $\mathbf{1}$ | $\mathbf{1}$ | $\mathbf{5}$ |

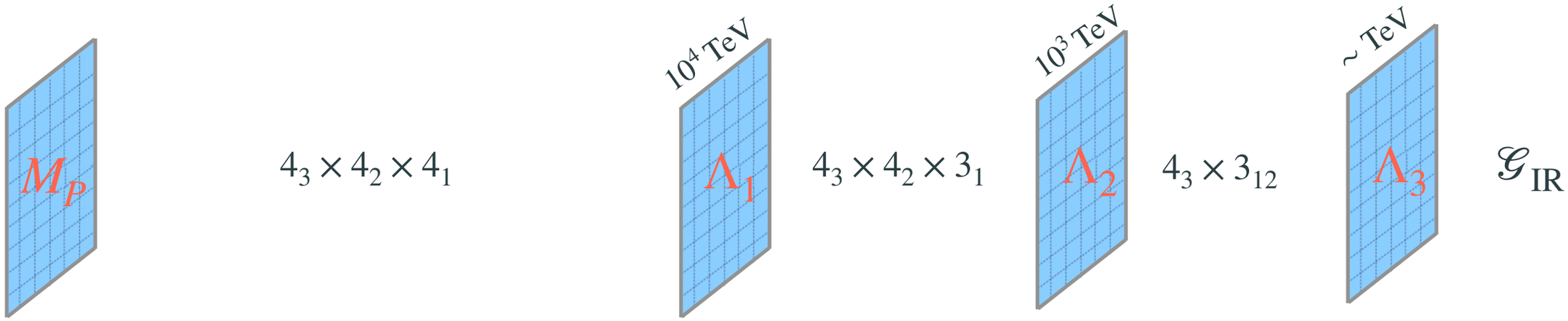
$\Sigma^T \sim (H' \; \phi)$ takes a VEV along the singlet direction and propagates the breaking of $SO(5)$ into the bulk

$$y^{ij}_{u,d} = \frac{g_*}{2\sqrt{2}} \tilde{Y}^{ij}_{u,d} \frac{\langle \Sigma_{\rm IR} \rangle}{\Lambda_{\rm IR}} \times \text{(profile suppression)}$$



# Extension to Planck and Cosmological Signatures




[Greljo, Opferkuch, Stefanek, 1910.02014;
JFM, Isidori, Lizana, Selimovic, Stefanek, 2203.01952]]

N.B.: $N_i \equiv SU(N)_i$

# Conclusions

The flavor puzzle and the hierarchy problem, when considered together, point to a multi-scale picture with the first NP threshold around the TeV

$\longrightarrow$ The $B$-physics anomalies nicely fit with this picture and might be its first manifestation

A flavor non-universal 4321 gauge theory provides a consistent framework for third-family quark-lepton unification at the TeV scale. This model can explain the B-anomalies, while retaining a flavor structure consistent with the Yukawas and the multi-scale picture

This UV solution can be justified from a multi-brane extra-dimensional construction where the Higgs emerges as a pNGB from the same strong dynamics that breaks 4321

**Thank you!**

# Backup

# Inverse see-saw and third-family PS unification

Inverse Seesaw setup

$$M_\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D^\intercal & 0 & m_R^\intercal \\ 0 & m_R & \mu \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \\ S_L^c \end{pmatrix}$$

Neutrino solution

$$m_\nu \approx m_D m_R^{-1} \mu (m_R^{-1})^\intercal m_D^\intercal$$

for $m_D^{(i)} \sim m_u^{(i)} \sim (10^{-2}, 1, 10^2)$ GeV

$m_R^{(i)} \sim (10^7, 10^5, 10^3)$ GeV

$\mu \sim (10^7, 10^{-1}, 10^{-9})$ GeV

$\Rightarrow 10^{-2}\ \text{eV} \lesssim m_\nu^{(i)} \lesssim 10^{-1}\ \text{eV}$

$\mu$ generated dynamically by singlet scalar $\Phi_i$ breaking spontaneously $U(1)_F \leftarrow$ fermion number

$$-\mathscr{L}_\nu \supset \underbrace{\bar{\Psi}_L^{(i)} H_i \Psi_R^{(i)}}_{\text{Dirac mass } m_D} + \underbrace{S_L^{(i)} \Sigma_i^\dagger \Psi_R^{(i)}}_{m_R \text{ matrix}} + \underbrace{(\epsilon_S \bar{S}_L^{(2)} \Sigma_1^\dagger \Psi_R^{(1)} + \cdots)}_{\text{Mixing}} + \underbrace{\bar{S}_L^{(i)} \Phi_i S_L^{(i)c}}_{\text{Majorana mass } \mu}$$

$\langle H_1 \rangle = \epsilon_H \langle H_2 \rangle = \epsilon_H^2 \langle H_3 \rangle$

$\langle \Sigma_3 \rangle = \epsilon_\Sigma \langle \Sigma_2 \rangle = \epsilon_\Sigma^2 \langle \Sigma_1 \rangle$

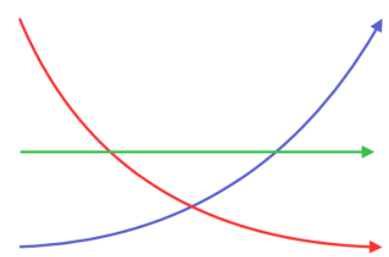
no link field needed as $U(1)_F$ global

$\langle \Phi_3 \rangle = \epsilon_\Phi \langle \Phi_2 \rangle = \epsilon_\Phi^2 \langle \Phi_1 \rangle$

Erase U(2)$^5$ in the neutrino sector:

very hierarchical $\mu^{(i)} \sim \langle \Phi_i \rangle$

hierarchical ratio $\dfrac{m_D^{(i)}}{m_R^{(i)}}$



$\Rightarrow$ anarchical $m_\nu^{(i)}$

(both masses and mixing angles)

Realised for:

$$\epsilon_\Phi \sim \epsilon_H^2\, \epsilon_\Sigma^2$$
$$\epsilon_S \sim \epsilon_H\, \epsilon_\Sigma$$

# The 5D model

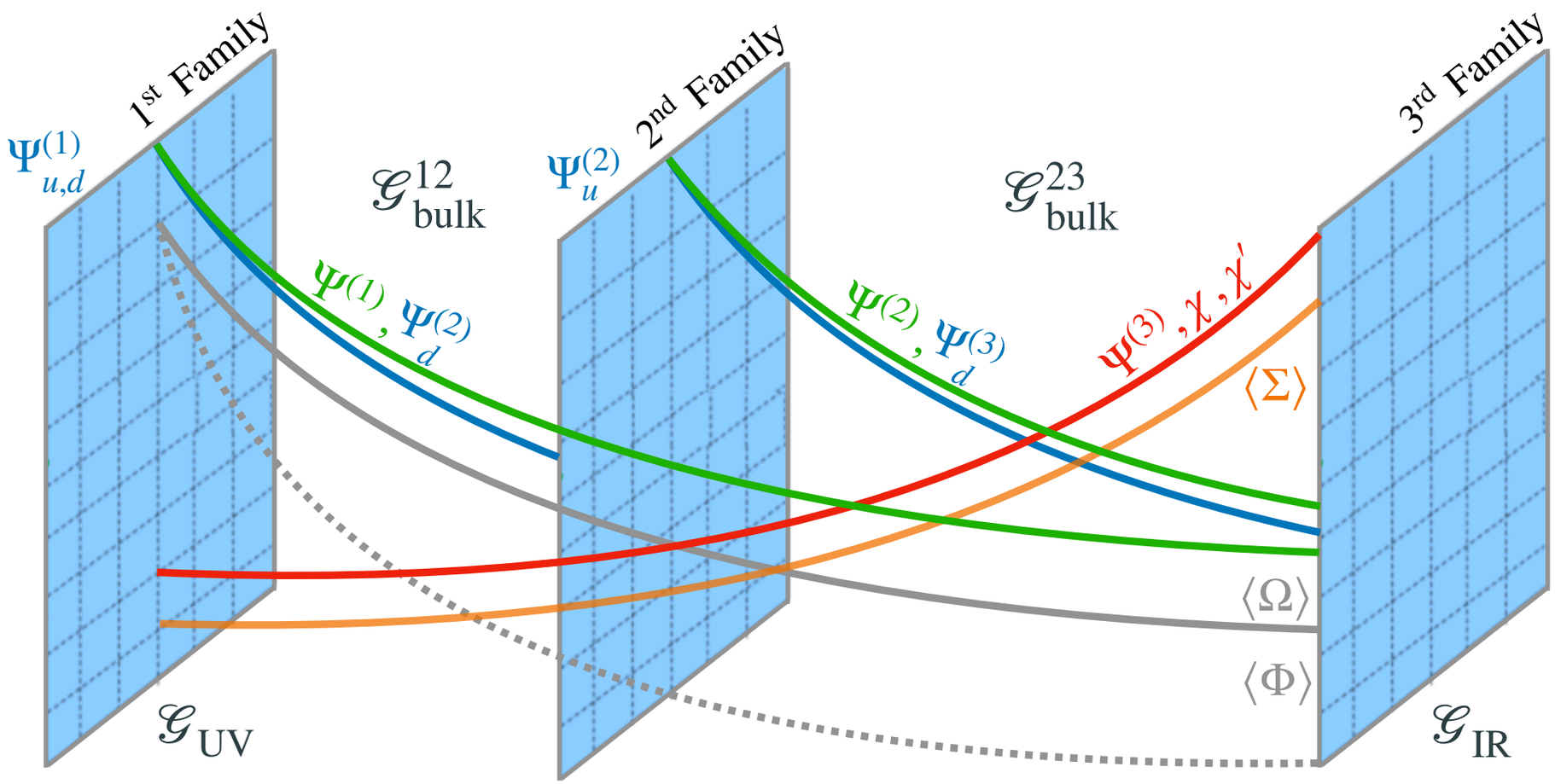
[JFM, Isidori, Lizana, Selimovic, Stefanek, 2203.01952]

| Field | $SU(4)_h$ | $SU(4)_l$ | $SO(5)$ |
|---|---|---|---|
| $\Psi^3, \Psi^3_d, \mathcal{X}^{(\prime)}$ | **4** | **1** | **4** |
| $\Psi^j, \Psi^j_{u,d}$ | **1** | **4** | **4** |
| $\mathcal{S}^i$ | **1** | **1** | **1** |
| $\Sigma$ | **1** | **1** | **5** |
| $\Omega$ | **1** | **4** | **4** |
| $\Phi$ | **1** | **1** | **1** |

$$\Psi^3 = \begin{bmatrix} \psi^3\,(+,+) \\ \psi^3_u\,(-,-) \\ \tilde{\psi}^3_d\,(+,-) \end{bmatrix}, \qquad \Psi^3_d = \begin{bmatrix} \tilde{\psi}^3\,(+,-) \\ \tilde{\psi}^3_u\,(+,-) \\ \psi^3_d\,(-,-) \end{bmatrix},$$

$$\mathcal{X}^{(\prime)} = \begin{bmatrix} \chi^{(\prime)}(\pm,\pm) \\ \chi^{(\prime)}_u\,(\mp,\pm) \\ \chi^{(\prime)}_d\,(\mp,\pm) \end{bmatrix}, \qquad \Psi^j = \begin{bmatrix} \psi^j\,(+,+) \\ \tilde{\psi}^j_u\,(-,+) \\ \tilde{\psi}^j_d\,(-,+) \end{bmatrix},$$

$$\Psi^j_u = \begin{bmatrix} \tilde{\psi}^j\,(+,-) \\ \psi^j_u\,(-,-) \\ \hat{\psi}^j_d\,(+,-) \end{bmatrix}, \qquad \Psi^j_d = \begin{bmatrix} \hat{\psi}^j\,(+,-) \\ \hat{\psi}^j_u\,(+,-) \\ \psi^j_d\,(-,-) \end{bmatrix},$$



# Higgs Potential

$$V(h) = \sum_r \frac{N_r}{16\pi^2} \int_0^\infty dp\, p^3 \log\left[\rho_r(-p^2)\right]$$

| Field | $SU(4)_h$ | $SU(4)_l$ | $SO(5)$ |
|---|---|---|---|
| $\Psi^3$ | **4** | **1** | **4** |
| $\Sigma$ | **1** | **1** | **5** |
| $\Omega$ | **1** | **4** | **4** |

$$V(h) \approx \alpha(h)\cos\left(\frac{h}{f}\right) - \beta(h)\sin^2\left(\frac{h}{f}\right)$$

VEV :

$$\alpha_\Omega \approx (\tilde{M}_\Omega^R - \tilde{M}_\Omega^L)\,\Lambda_{\rm IR}^2 \langle\Omega_{\rm IR}\rangle^2$$

$$\alpha_{\Psi^3}(h) \approx \frac{3N_c f^4}{32\pi^2}\zeta(3)\, y_t^2 g_*^2 - 2\beta_{\Psi^3}(h)$$

$$\cos(\langle h\rangle/f) = -\frac{\alpha}{2\beta}$$

Quartic :

$$\beta_\Sigma \approx \frac{1}{2}(\tilde{M}_{H'} - \tilde{M}_S)\frac{\Lambda_{\rm IR}^2}{(kL)^2}\langle\Sigma_{\rm IR}\rangle^2$$

$$\beta_{\Psi^3}(h) \approx \frac{N_c f^4}{16\pi^2}\, y_t^4 \left[\gamma + \log\frac{\Lambda_{\rm IR}^2}{m_t^2(h)}\right]$$

$$\beta_{\rm EW} \approx -\frac{9f^4}{512\pi^2}\, g_*^2\,\zeta(3)\left(3g_L^2 + g_Y^2\right)$$

[JF, Isidori, Lizana, Selimovic, Stefanek, 2203.01952]

# Low-energy phenomenology

- Below KK scale, same phenomenology as 4321 (B-anomalies)
- Main experimental limit coming from coloron direct searches:

$$M_{4321} \gtrsim 3.5\,\text{TeV}$$

[Cornella et al., 2103.16558]

Benchmark Spectrum :

$$M_{\text{KK}} \approx 2\Lambda_{\text{IR}} = 16\,\text{TeV}$$

$$\Lambda_{\text{IR}} = 8\,\text{TeV}$$

$$f_h \approx \frac{M_{\text{KK}}}{g_*} \approx 6.4\,\text{TeV}$$

$$M_{4321} \approx \frac{g_* f_h}{\sqrt{2kL}} \approx 3.6\,\text{TeV}$$

$E$

First deviations from 4321

So high that EWPD are ok

$[f > 2.5\,\text{TeV} \;\; (M_{\text{KK}} > 6\,\text{TeV})]$

[JF, Isidori, Lizana, Selimovic, Stefanek, 2203.01952]