Flavor hierarchies, flavor anomalies, and the Higgs mass from a warped extra dimension

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[Fuentes-Martin, Isidori, Lizana, Selimovic, BAS, 2203.01952]

Puzzles in the SM and Hints Toward New Physics

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\Psi} \not{D} \psi + |D_\mu \phi|^2 - V(\phi) + \bar{\Psi}_i y_{ij} \psi_j \phi + h.c.$$

Natural, Flavor Universal

Flavor Puzzle

- Has very hierarchical structure that does not seem accidental
- Violates LFU, quark number

Hints toward the structure of new physics?

Higgs Hierarchy Problem

- Instability of the Higgs mass under quantum corrections

TeV-scale new physics?

Flavor could have a Multi-scale Explanation

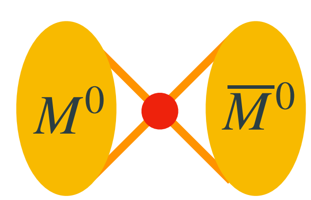
$$\mathscr{L}_{\rm SMEFT} = \mathscr{L}_{\rm Gauge} + \mathscr{L}_{\rm Higgs} + \mathscr{L}_{\rm Yukawa} + \sum_{i,d} \frac{1}{\Lambda_i^{d-4}} C_i \mathcal{O}_i^d$$

Non-trivial UV imprints

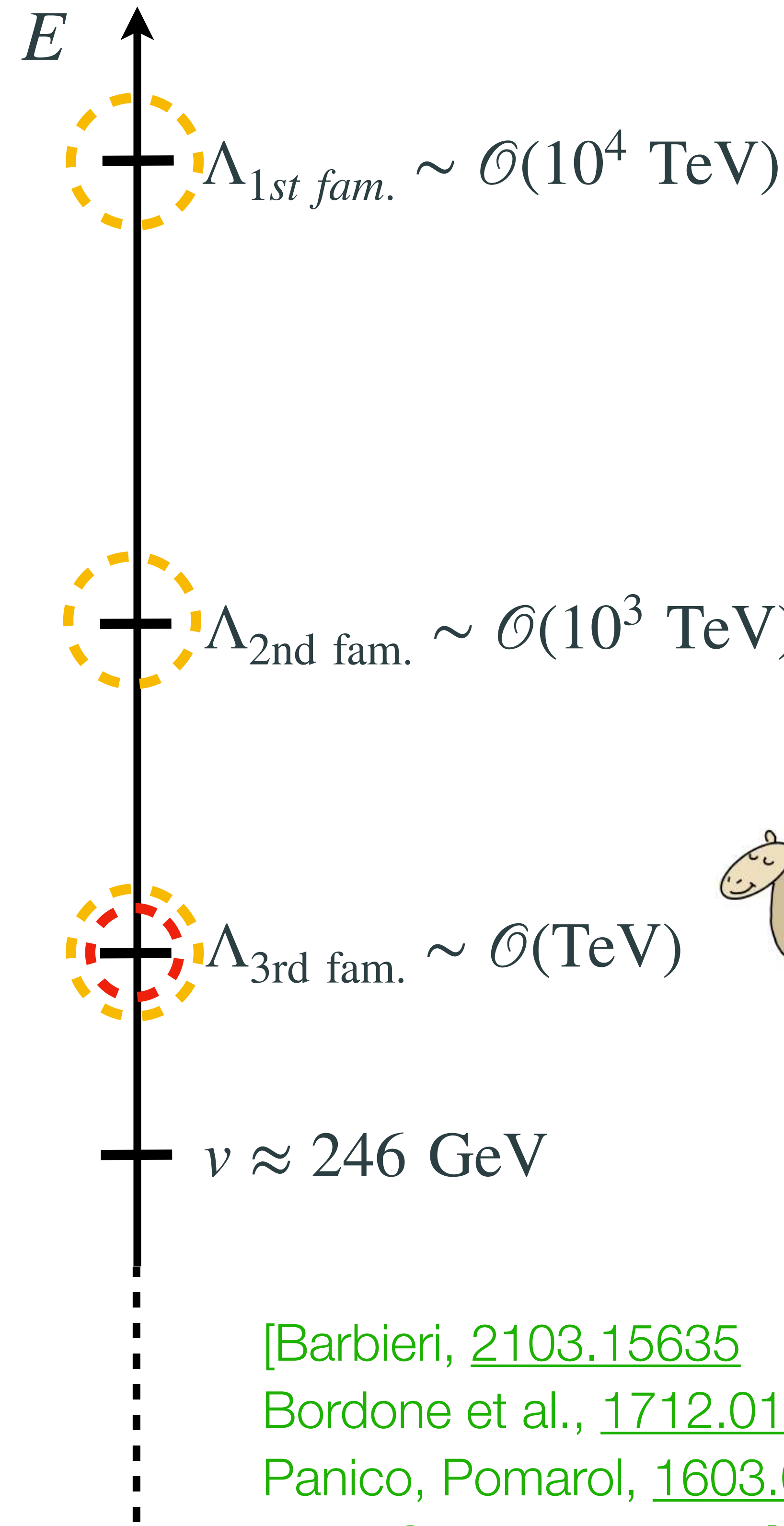
★ The SM Yukawas are very hierarchical because they originate from very different scales!

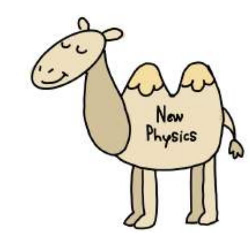
★ TeV-scale NP dominantly coupled to third and (to a lesser extent) second families [$\approx U(2)^5$ protection from flavor constraints]

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

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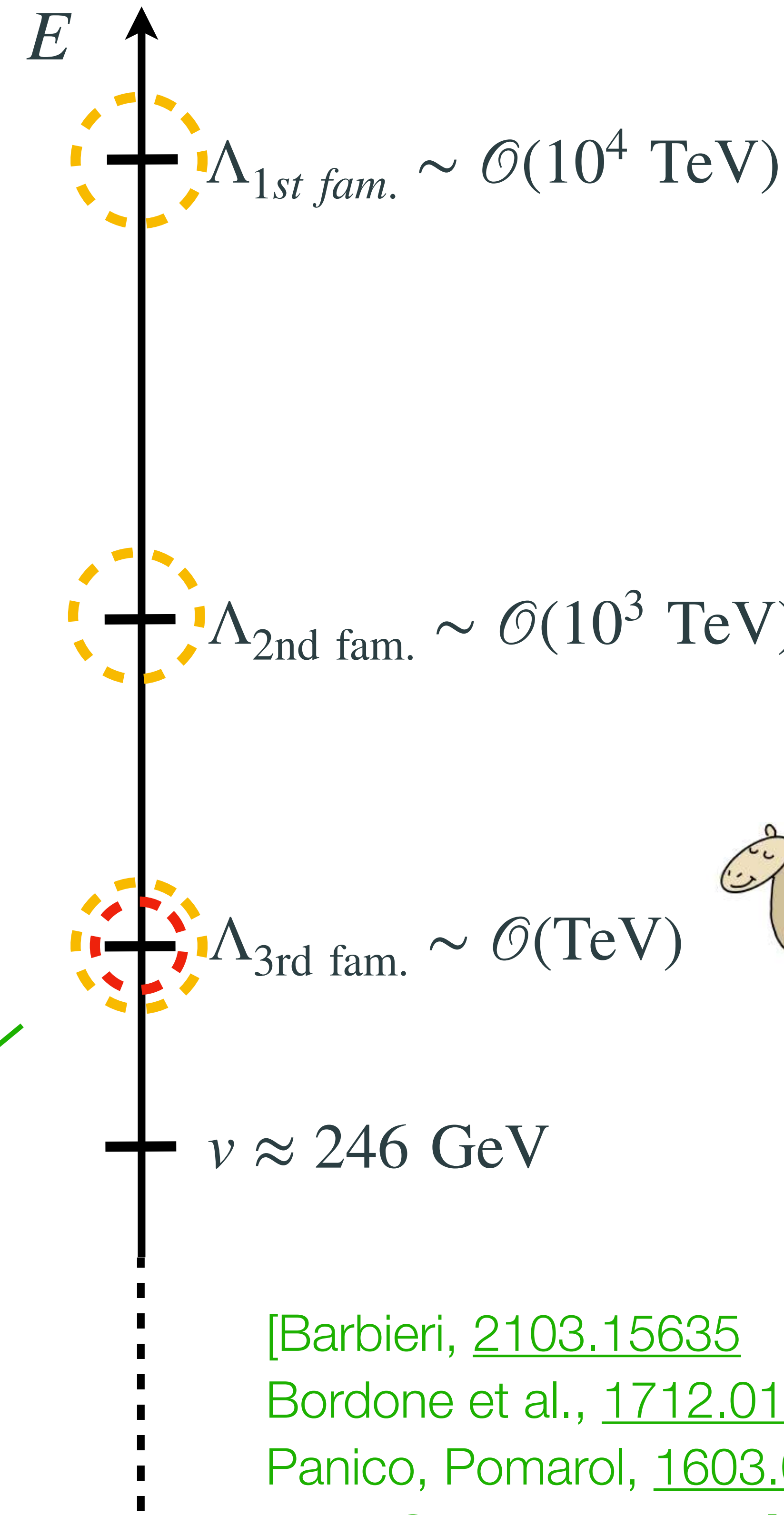

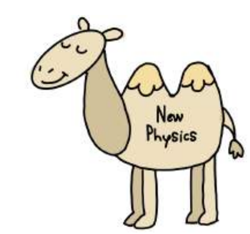

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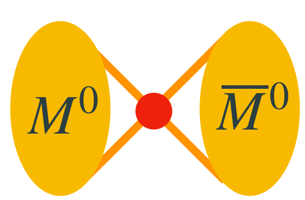


Perhaps we are already seeing hints in B-meson decays?

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

Combined Explanation of the B-anomalies

	Model	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
Scalars	$S_1 = (\mathbf{3}, \mathbf{1})_{-1/3}$	✗	✓	✗
	$R_2 = (\mathbf{3}, \mathbf{2})_{7/6}$	✗	✓	✗
	$\widetilde{R}_2 = (\mathbf{3}, \mathbf{2})_{1/6}$	✗	✗	✗
	$S_3 = (\mathbf{3}, \mathbf{3})_{-1/3}$	✓	✗	✗
Vector	$U_1 = (\mathbf{3}, \mathbf{1})_{2/3}$	✓	✓	✓
	$U_3 = (\mathbf{3}, \mathbf{3})_{2/3}$	✓	✗	✗

[Angelescu, Bečirević, Faroughy, Sumensari, 1808.08179]

★ $S_1 + S_3$

[Crivellin, Muller, Ota 1703.09226;
Buttazzo et al. 1706.07808;
Marzocca 1803.10972,…]

★ $S_3 + R_2$

[Bečirević et al., 1806.05689]

★ U_1 + UV completion

[di Luzio, Greljo, Nardecchia 1708.08450;
Calibbi, Crivellin, Li 1709.00692;
Bordone, Cornella, Fuentes-Martin, Isidori 1712.01368;
Barbieri, Tesi, 1712.06844; Greljo, BAS, 1802.04274]

The U_1 is (one of) the most promising mediators to explain the B anomalies:

✓ No tree-level $b \to s\nu_{(\tau)}\nu_{(\tau)}$

✓ Being a vector, possibility to realize a $U(2)^5$ from a flavor non-universal gauge symmetry (possible connection to the SM flavor puzzle)

✓ Third-family quark-lepton unification: Hint towards Pati-Salam-like unification

Gauge UV Completion for the U_1 Leptoquark

Based on "4321" gauge symmetry:

[di Luzio, Greljo, Nardecchia 1708.08450
Bordone, Cornella, Fuentes-Martin, Isidori
1712.01368, 1805.09328;
Greljo, BAS, 1802.04274]

$U(1)_Y$

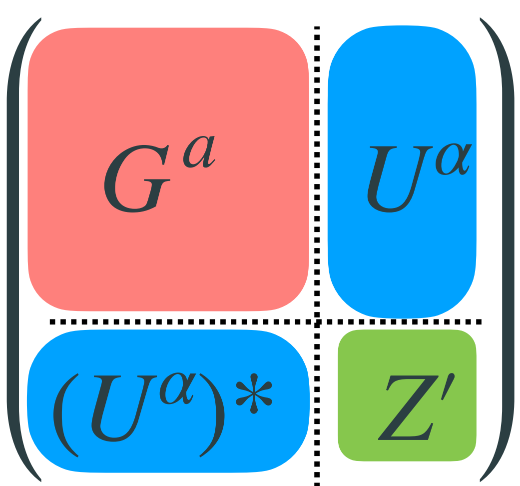
$$SU(4)_h \times SU(3)_l \times SU(2)_L \times U(1)_{l+R} \xrightarrow{\langle \Omega_{1,3,15} \rangle \sim \mathcal{O}(\mathrm{TeV})} SU(3)_c \times SU(2)_L \times U(1)_Y$$

$SU(3)_c$

Massive Gauge Bosons

$$U_1, G', Z'$$

$$SU(4) \sim$$



- Provides a UV completion for the U_1 vector LQ
- Necessarily comes with *G', Z'* [cannot have TeV-scale Pati-Salam unification: $SU(4) \supset SU(3)_c$]
- For $g_4 \gg g_{3,1}$, massive gauge bosons dominantly come from $SU(4)_h$

Third family quark-lepton unification at the TeV scale

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Bordone, Cornella, Fuentes-Martin, Isidori 1712.01368, 1805.09328;
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$SU(3)_c$

$$\psi_L \sim \begin{pmatrix} q_L^3 \\ \ell_L^3 \end{pmatrix} \qquad \psi_R^+ \sim \begin{pmatrix} u_R^3 \\ \nu_R^3 \end{pmatrix} \qquad \psi_R^- \sim \begin{pmatrix} d_R^3 \\ e_R^3 \end{pmatrix}$$

- 3rd family charged under $SU(4)_h$
  $\Longrightarrow$ Direct NP couplings (L+R)
- Light families under 321 (SM-like)
- Accidental approximate $U(2)^5$ flavor symmetry: $\psi = (\psi_1\ \psi_2\ \psi_3)$

Field	$SU(4)_h$	$SU(3)_l$	$SU(2)_L$	$U(1)_{l+R}$	
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**	$-1/3$	
ℓ_L^i	**1**	**1**	**2**	$-1/2$	
e_R^i	**1**	**1**	**1**	-1	
ψ_L	**4**	**1**	**2**	0	3rd family
$\psi_R^\pm$	**4**	**1**	**1**	$\pm 1/2$	
$\chi_{L,R}$	**4**	**1**	**2**	0	
H	**1**	**1**	**2**	$1/2$	
Ω_1	$\bar{\mathbf{4}}$	**1**	**1**	$-1/2$	
Ω_3	$\bar{\mathbf{4}}$	**3**	**1**	$1/6$	
Ω_{15}	**15**	**1**	**1**	0	

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

$SU(3)_c$

$$\chi = \begin{pmatrix} Q \\ L \end{pmatrix}$$

- CKM mixing and NP couplings to light families from the leading O(0.1) breaking of $U(2)_q \times U(2)_\ell$:

$$\mathcal{L} \supset -\bar{q}_L^i \lambda_q^i \Omega_3 \chi_R - \bar{\ell}_L^i \lambda_\ell^i \Omega_1 \chi_R$$
$$-y_+ \bar{\chi}_L \tilde{H} \psi_R^+ - y_- \bar{\chi}_L H \psi_R^-$$

Field	$SU(4)_h$	$SU(3)_l$	$SU(2)_L$	$U(1)_{l+R}$	
q_L^i	**1**	**3**	**2**	$1/6$	1st & 2nd families
u_R^i	**1**	**3**	**1**	$2/3$	
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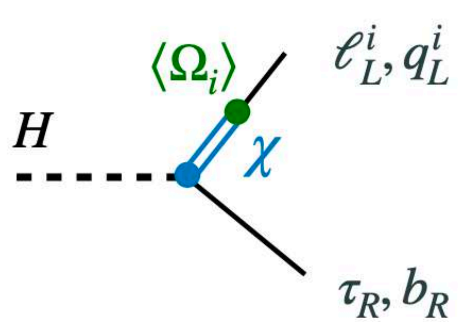
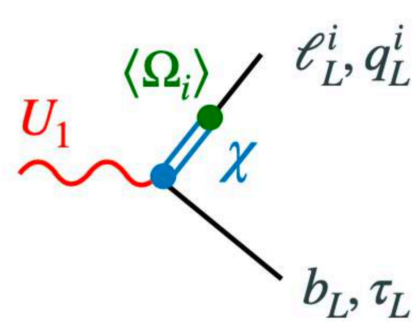
ψ_L	**4**	**1**	**2**	0	3rd family
$\psi_R^\pm$	**4**	**1**	**1**	$\pm 1/2$	
$\chi_{L,R}$	**4**	**1**	**2**	0	VL fermion
H	**1**	**1**	**2**	$1/2$	
Ω_1	$\bar{\mathbf{4}}$	**1**	**1**	$-1/2$	4321 SSB scalars
Ω_3	$\bar{\mathbf{4}}$	**3**	**1**	$1/6$	
Ω_{15}	**15**	**1**	**1**	0	



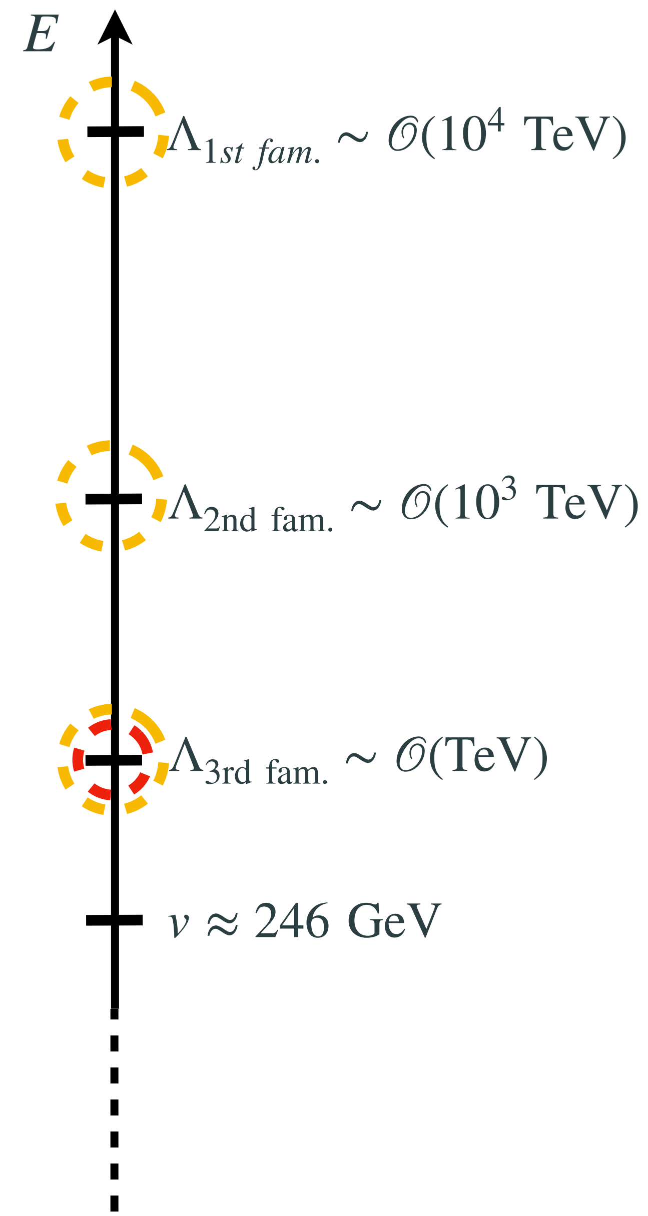


Why consider a 5D model?

✓ 4321 gauge models provide a nice combined explanation of the B-anomalies. Also fits well with the idea of 3rd family QL unification at the TeV scale: conceptually nice and allows us to realize a $U(2)^5$ flavor symmetry from the gauge symmetry.

But, 4321 doesn't say anything about:

1. EW hierarchy problem (IR problem)
2. Light Yukawa structure (UV problem)



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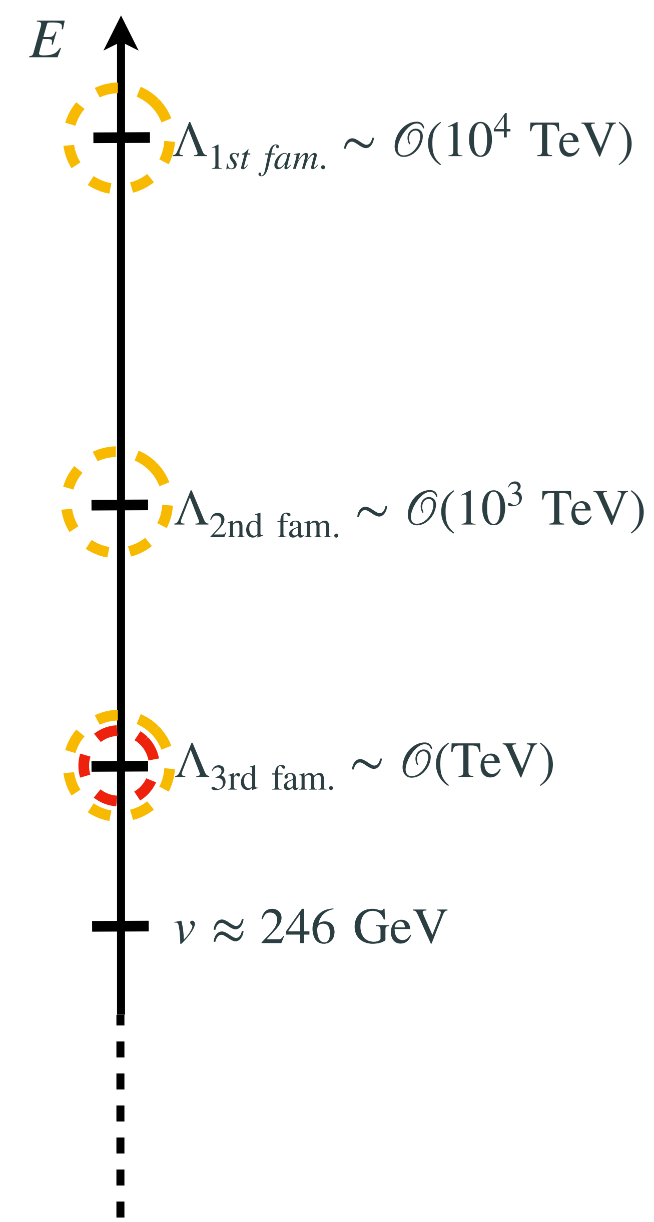
Naturally combined in a warped 5D setup!

1. Warped geometry stabilizes large scale hierarchies.
2. Light family masses/mixing explained by fermion localization "in the UV".



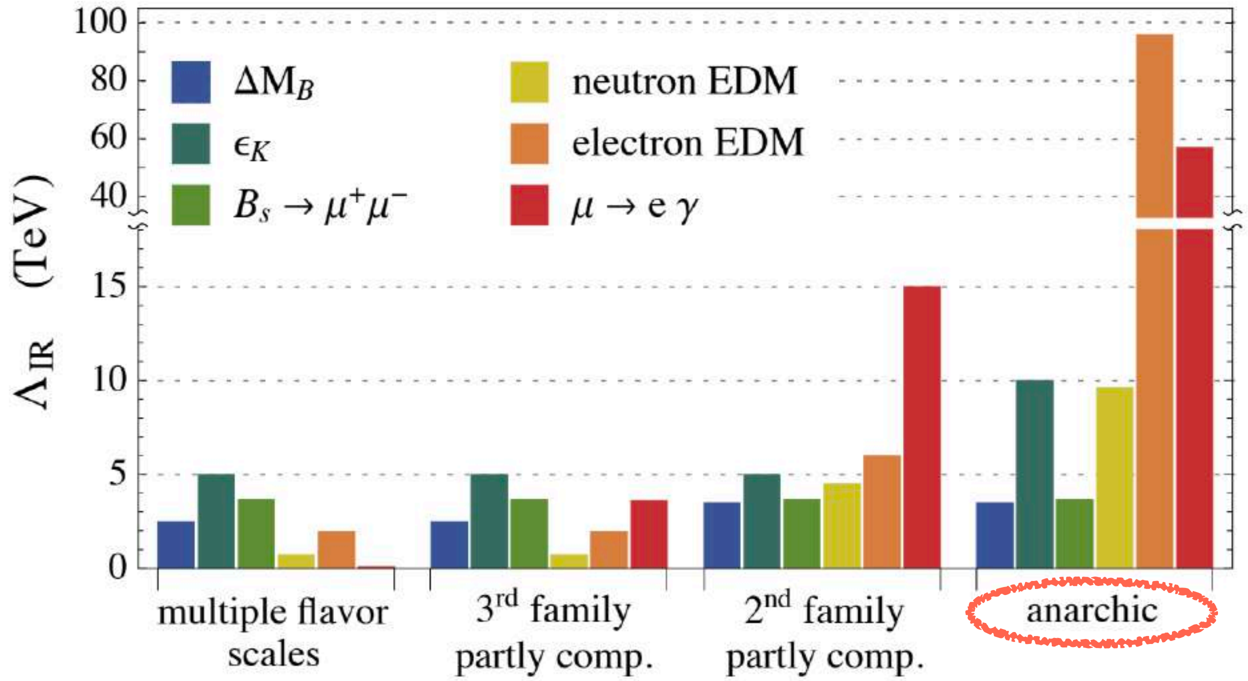
Flavor in Randall-Sundrum Models

- 5D Yukawa couplings are anarchical, Higgs in the IR
- Localize top in the IR, light families in the UV
- Light family Yukawas receive exponential suppression
- But, **RH** fields must reach the IR where **KK** modes peak

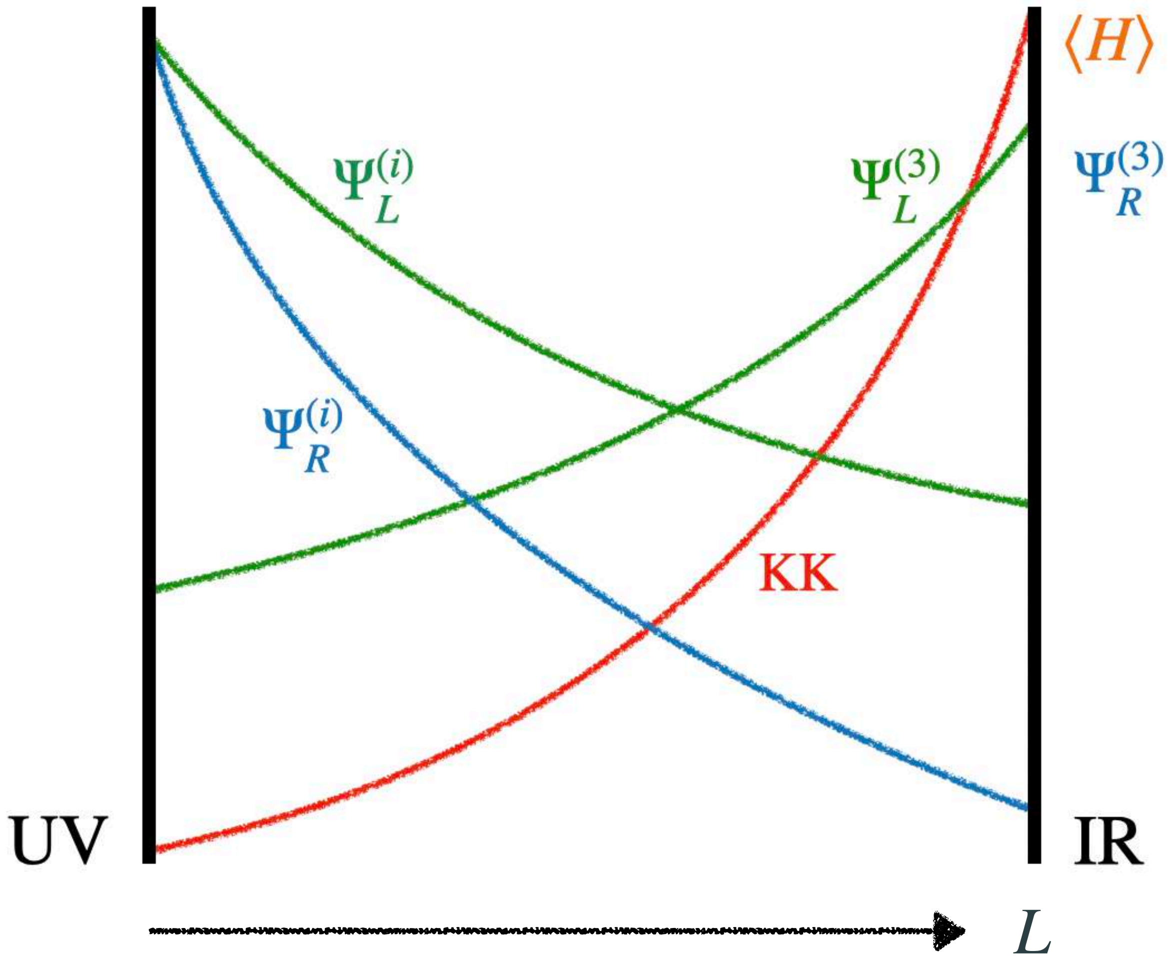
Dangerous dipoles (among others) generated at the IR scale

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

$$g_* \sim (0,0,1) \implies U(2) \text{ flavor sym}\,.$$



[Panico, Pomarol, 1603.06609]



$* \; \Lambda_{\rm IR}/\Lambda_{\rm UV} = e^{-kL}$ *Exponential hierarchies*

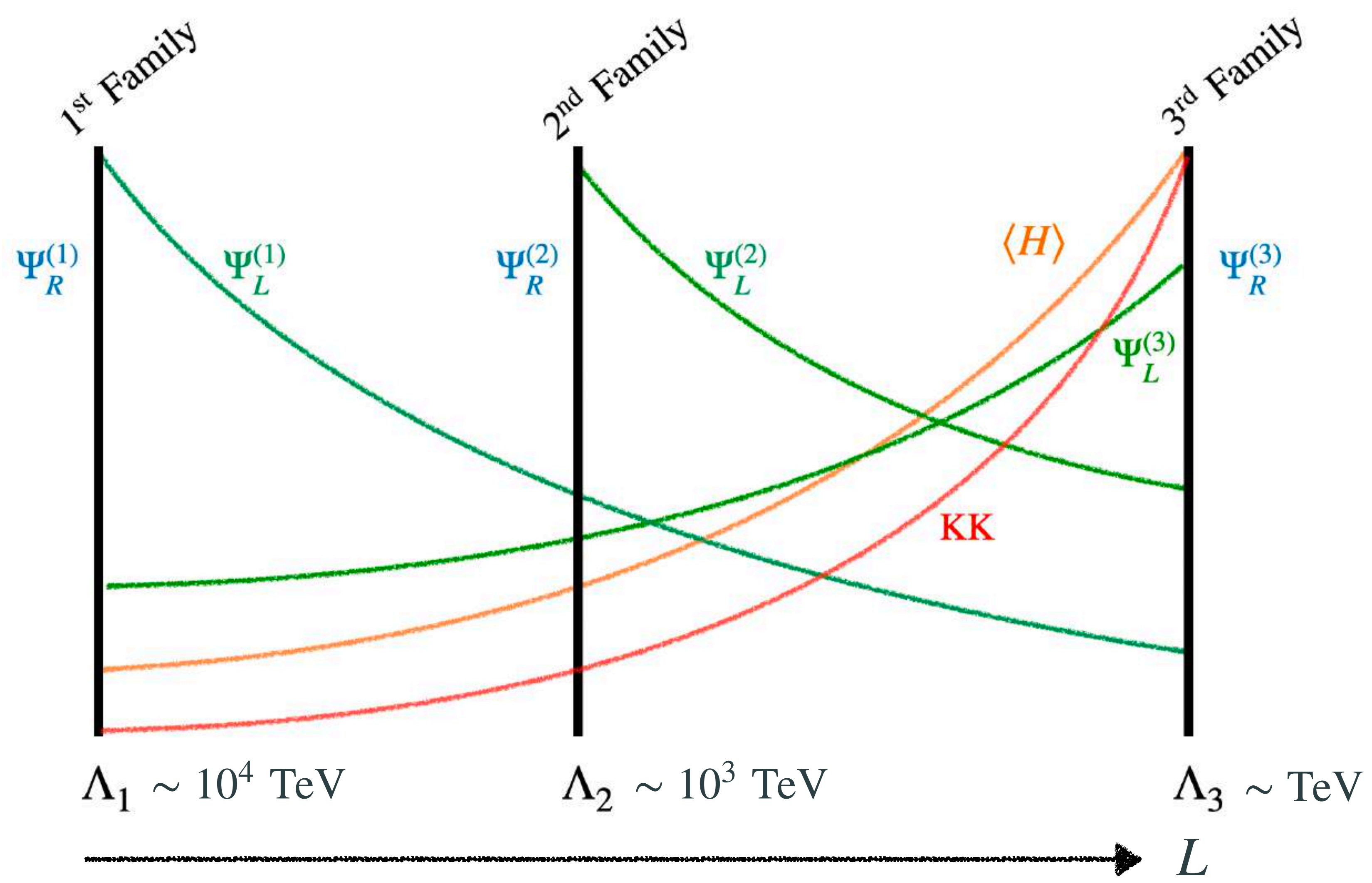
Benefits of a Multi-Scale Solution for Flavor

- Higgs profile extended into the bulk, **RH** fields localized in branes
- Light family Yukawas now done in the UV, smallness explained by the exponentially falling Higgs profile
- U(2) flavor symmetry with leading breaking in the **LH** sector.
- Dangerous operators involving **RH** fields naturally suppressed

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

Dangerous dipoles now suppressed by the UV scales

$$\sim \frac{g_*^2}{16\pi^2}\frac{m_e}{\Lambda_1^2}\,\bar{e}_L\sigma_{\mu\nu}e_R F^{\mu\nu}$$



Higgs VEV Profile

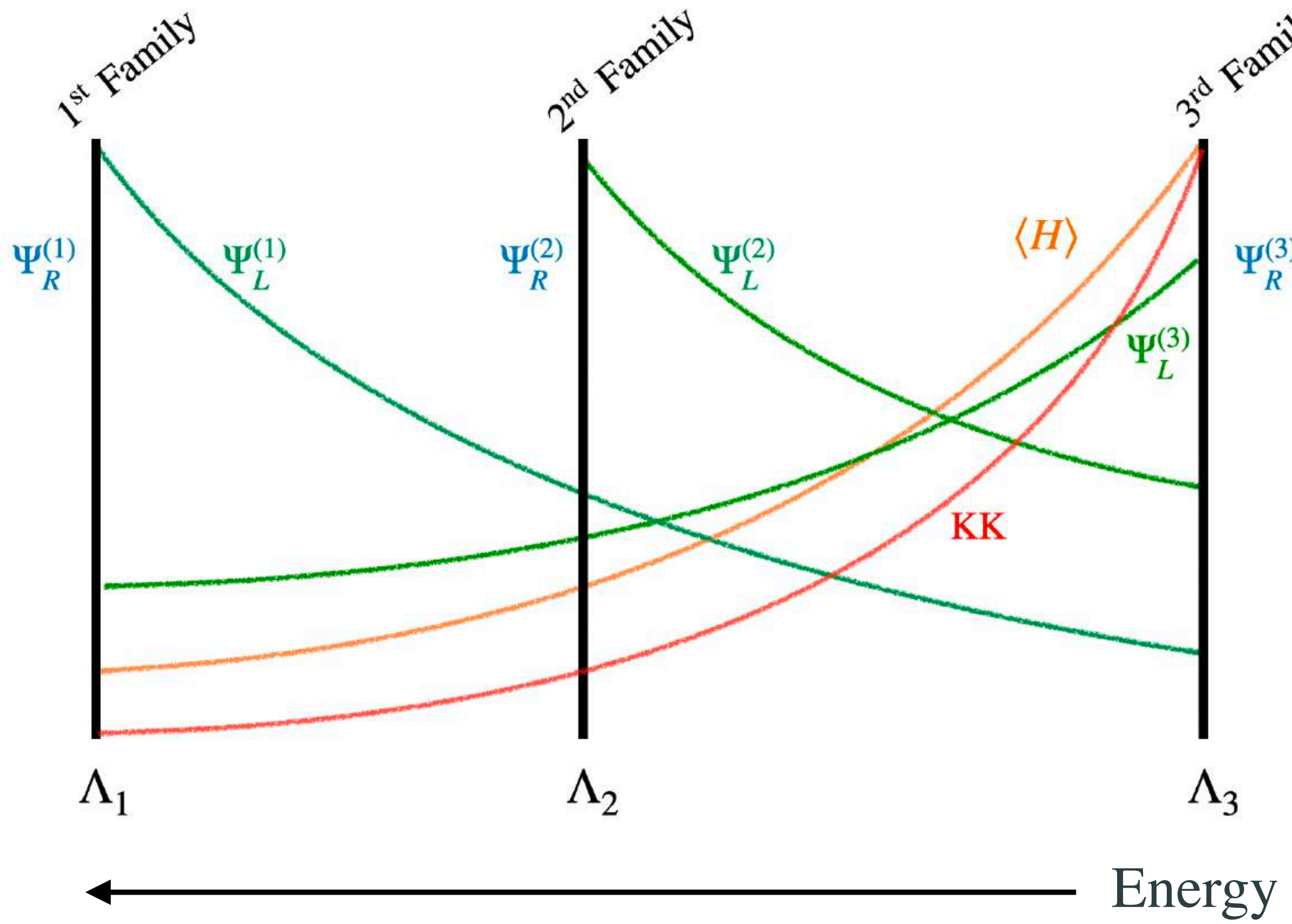
$$\langle H \rangle \sim v_{\rm EW}\, e^{-k(L-y)}$$

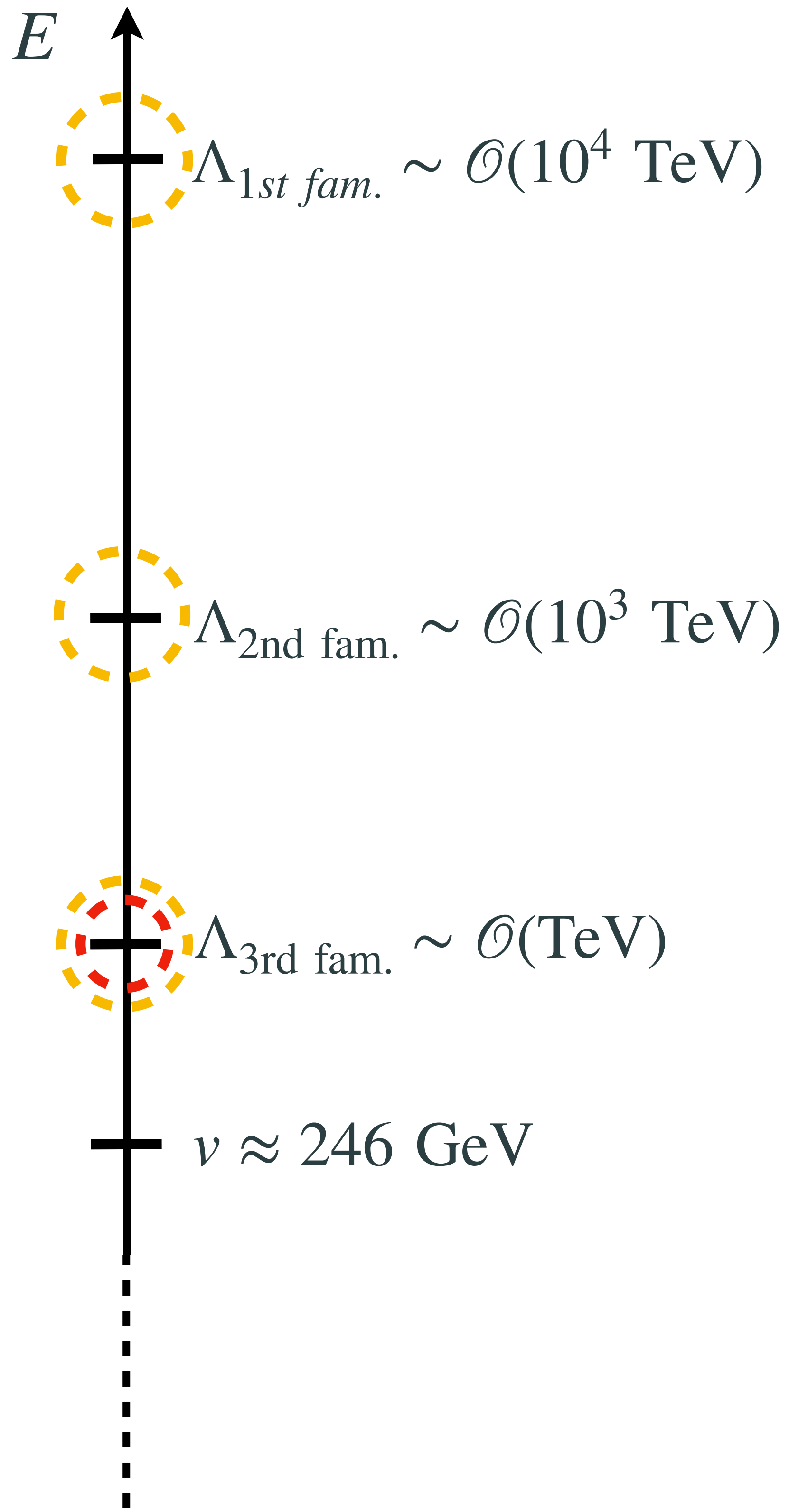
**Fermion mass hierarchy fixes the total volume:*

$$kL \approx \ln(m_t/m_u) \approx 10$$

[Fuentes-Martin, Isidori, Pagès, BAS, 2012.10492]

Roadmap to a Multi-scale Theory of Flavor





✔ 1. 4321 gauge symmetry at the TeV scale (3rd family QL unification, explanation of B-anomalies)

✔ 2. Flavor ↔ fermion (quasi)-localization in three branes

3. Higgs as a pNGB of the same dynamics responsible for breaking 4321 gauge symmetry

[Fuentes-Martin, Isidori, Pagès, BAS, 2012.10492
Fuentes-Martin, Isidori, Lizana, Selimovic, BAS, 2203.01952]

4321 + pNGB Higgs: The Composite Blueprint

Global symmetry	$\mathscr{G}_{\text{global}} = SU(4)_h \times SU(4)_l \times SO(5)$
Gauge symmetry	$\mathscr{G}_{\text{gauge}} = SU(4)_h \times SU(3)_l \times SU(2)_L \times U(1)_{l+R}$

(4321 gauged)

[Fuentes-Martin, Stangl, 2004.11376]

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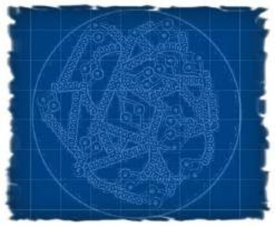

"Minimal Composite Higgs (MCHM)"

$$SO(5) \to SO(4) \equiv SU(2)_L \times SU(2)_R + 4\,\text{NGBs}$$

[Agashe, Contino, Pomarol, hep-ph/0412089]

★ $[\,4\,\text{NGBs} \sim \mathbf{4} \text{ or } (\mathbf{2}, \bar{\mathbf{2}}) \longleftrightarrow H\,]$

Global symmetry	$\mathcal{G}_{\text{global}} = SU(4)_h \times SU(4)_l \times SO(5)$	$(4_h \times 4_l \times \text{MCHM})$
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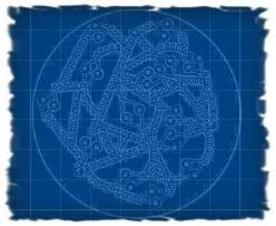

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Spontaneously broken by a condensate at some IR scale $f \sim$ few TeV

Global SBB	$\mathscr{G}_{\text{IR}} = SU(4)_D \times SO(4)$	(Custodial sym.)
Gauge SSB	$\mathscr{G}_0 = \mathscr{G}_{\text{gauge}} \cap \mathscr{G}_{\text{IR}} = SU(3)_c \times SU(2)_L \times U(1)_Y$	(Standard Model)
Goldstones	15 + 4 (15 eaten + NGB Higgs)	$(U_1, G', Z' + H)$

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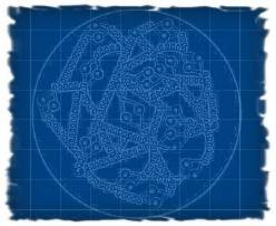

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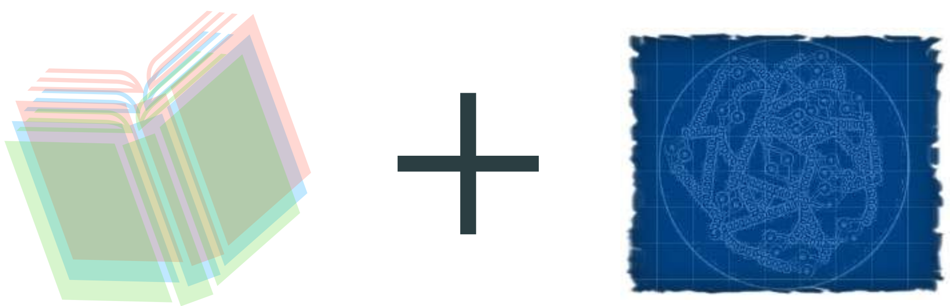
SM Higgs emerges as a Nambu-Goldstone boson of the same (strong) dynamics breaking 4321 gauge symmetry!

[Fuentes-Martin, Stangl, 2004.11376]

[Fuentes-Martin, Isidori, Lizana, Selimovic, BAS, 2203.01952]

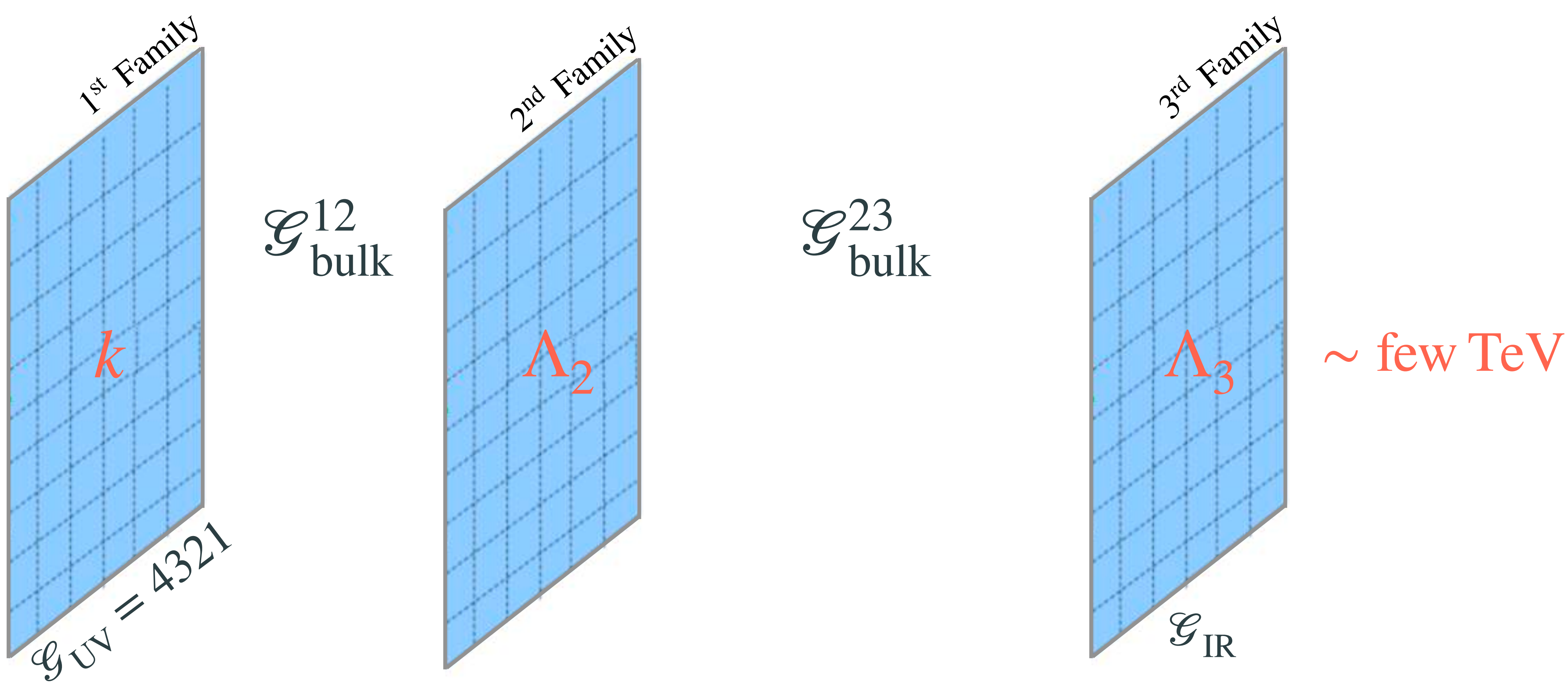
A Multi-Scale 5D Model

5D Model Builder's Toolbox



Spontaneous symmetry breakings

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



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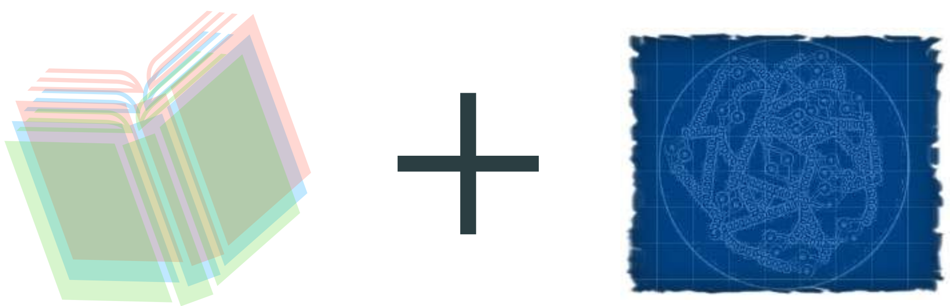

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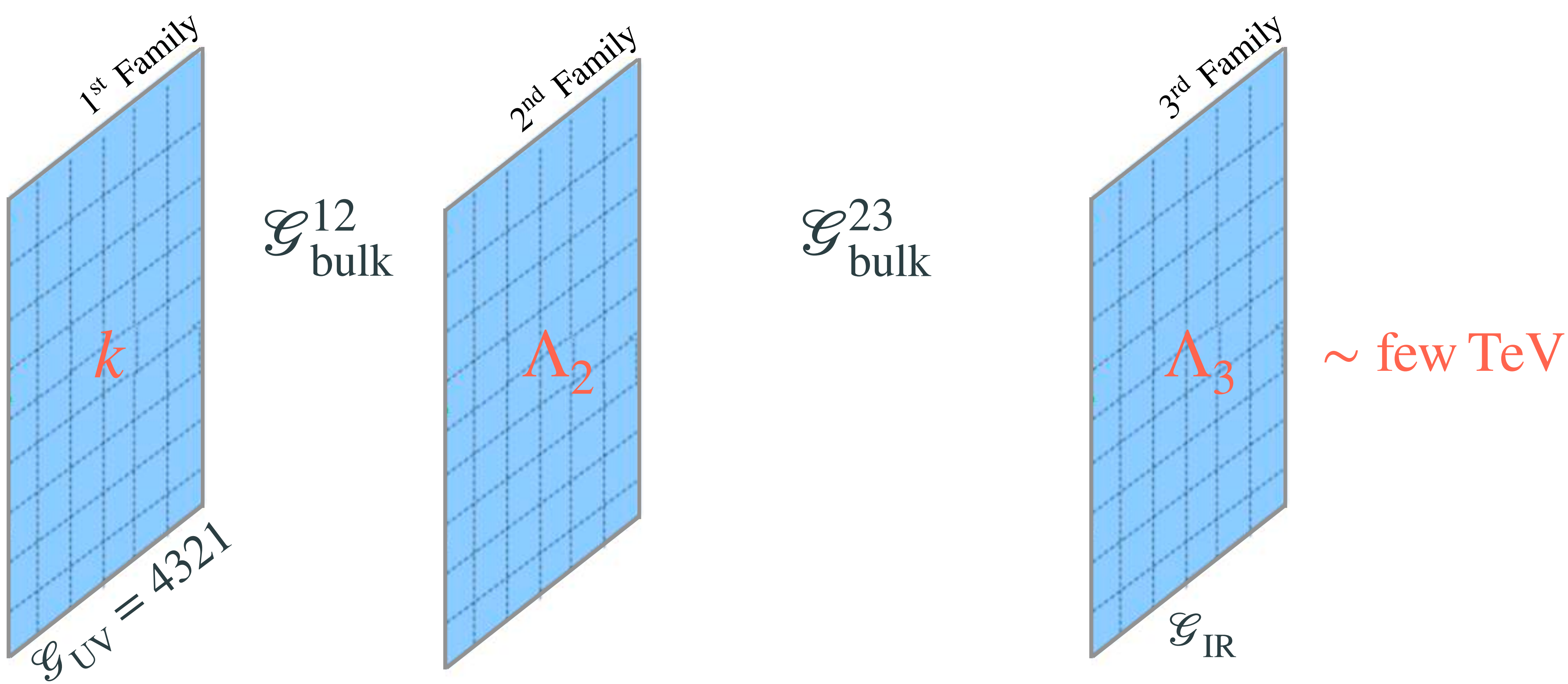
$$\mathscr{G}^{12}_{\text{bulk}} = SU(4)_h \times SU(4)_l \times SO(5)$$

Λ_2 (6 broken)

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



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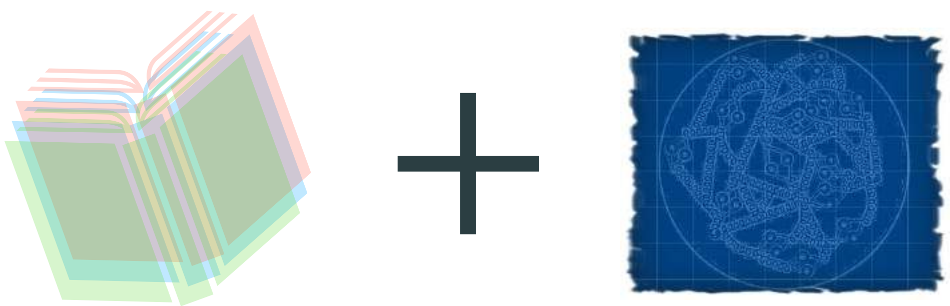

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Λ_2 (6 broken)

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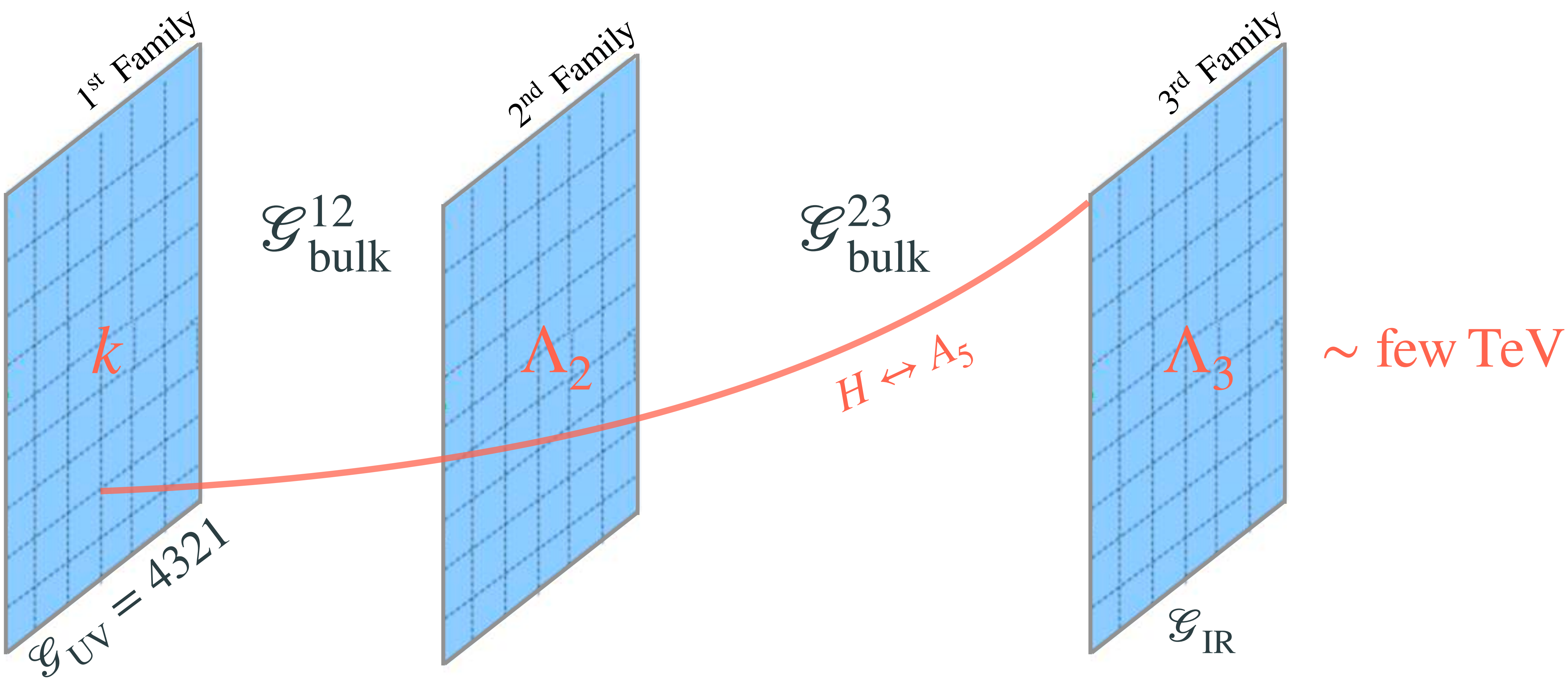
$\Lambda_3 = \Lambda_{\text{IR}}$ $(15 + 4 \text{ broken})$

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



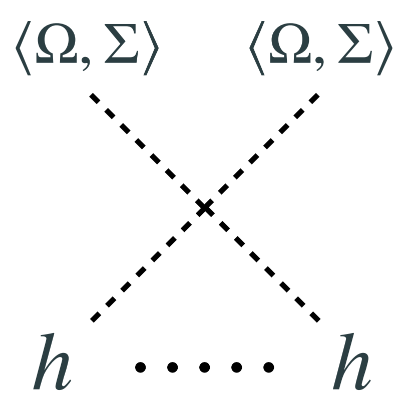
Fuentes-Martin, Isidori, Lizana, Selimovic, BAS, 2203.01952]

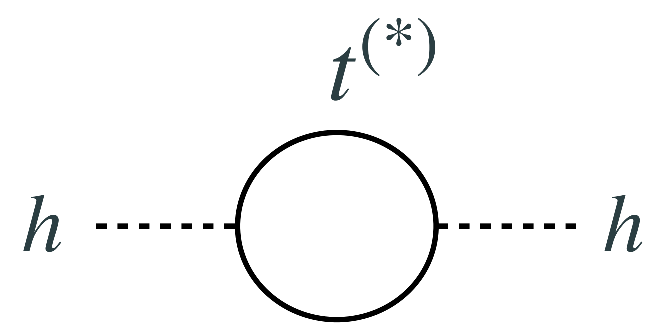
Higgs Potential

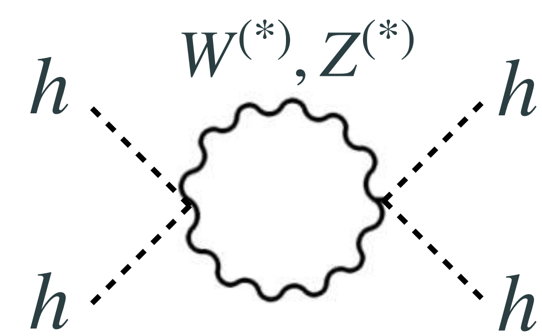
$$W(x) = e^{-i\theta(h(x)/f)}$$

- Potential is a function of the Wilson line.
- Tree-level contributions from the bulk scalars Σ, Ω that break $SO(5)$.
- 1-loop dominantly from the top and EW gauge bosons. Finite and fully calculable.

Field	$SU(4)_h$	$SU(4)_l$	$SO(5)$
Ψ^3	**4**	**1**	**4**
Σ	**1**	**1**	**5**
Ω	**1**	**4**	**4**







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

$\downarrow$ Ψ^3, Ω $\qquad$ $\downarrow$ Ψ^3, Σ, W, Z

Higgs decay constant :

$$f = \frac{2\Lambda_{\mathrm{IR}}}{g_*} \qquad (M_{\mathrm{KK}} = g_* f)$$

[Fuentes-Martin, Isidori, Lizana, Selimovic, BAS, 2203.01952]

Little hierarchy and the B-anomalies

Our model connects the mass of the 4321 gauge bosons to fine-tuning in the Higgs potential.

$$\underline{U_1\,, G'\,, Z' \text{ Masses :}} \qquad M_{15} = \frac{M_{\rm KK}}{\sqrt{2kL}} = \frac{g_* f}{\sqrt{2kL}} \qquad (g_* \approx 2.5,\ \ kL \approx 10)$$

$$\text{Fine tuning :} \quad \frac{v^2}{f^2}$$

[Fuentes-Martin, Isidori, Lizana, Selimovic, BAS, 2203.01952]

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Fine tuning : $\dfrac{v^2}{f^2}$

Light U_1 leptoquark preferred to minimize fine-tuning!

*But also a light coloron- direct searches require $M_{15} \gtrsim 3.5\,\mathrm{TeV}$ which translates to $f \gtrsim 6.4\,\mathrm{TeV}$.

[Fuentes-Martin, Isidori, Lizana, Selimovic, BAS, 2203.01952]

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Light U_1 leptoquark preferred to minimize fine-tuning!

*But also a light coloron- direct searches require $M_{15} \gtrsim 3.5\,\mathrm{TeV}$ which translates to $f \gtrsim 6.4\,\mathrm{TeV}$.

$$\text{Fine tuning :}\ \frac{v^2}{f^2} \approx 10^{-3}$$

(Could be improved slightly by splitting the 4321 gauge boson masses.)

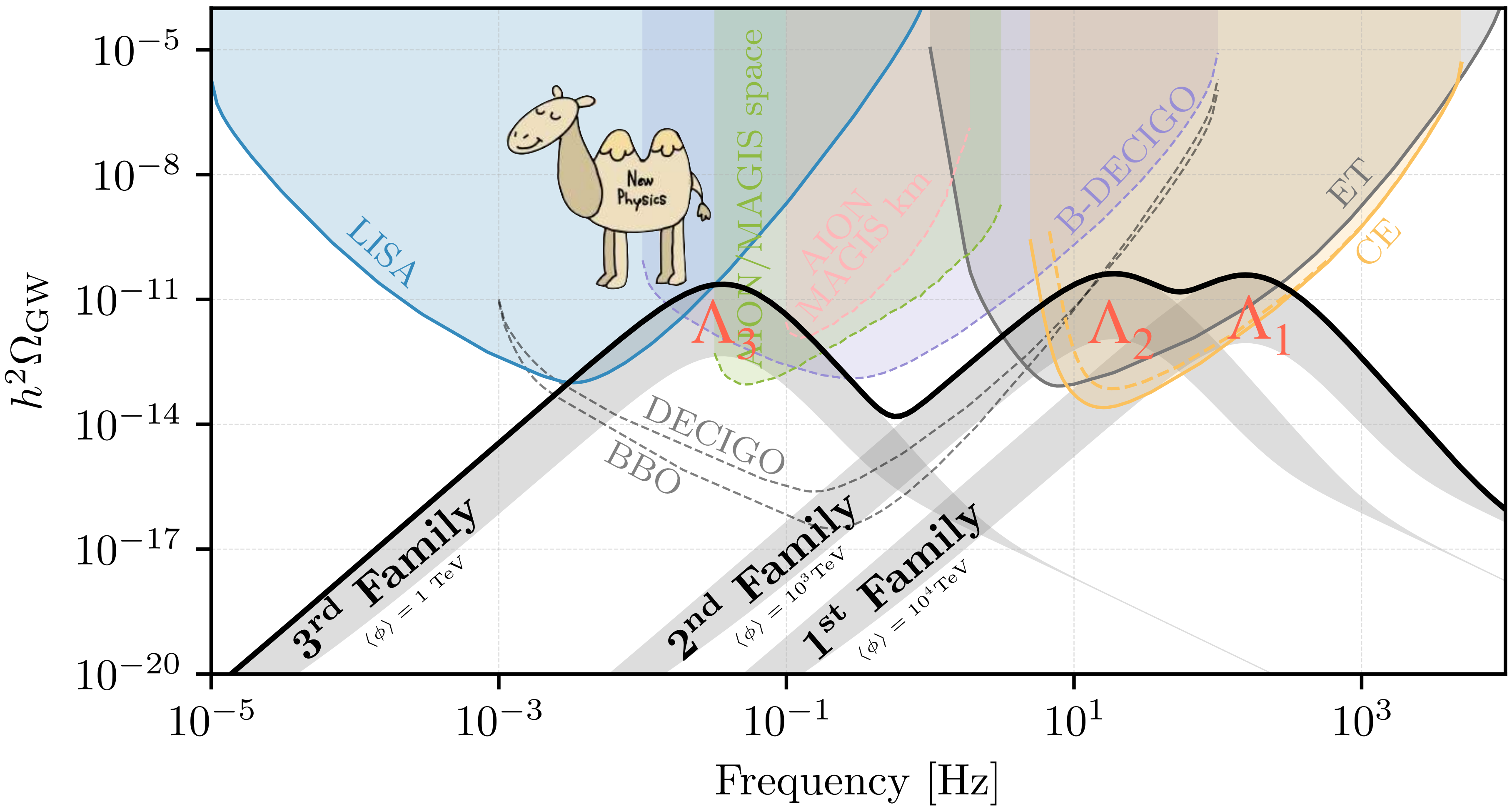
[Fuentes-Martin, Isidori, Lizana, Selimovic, BAS, 2203.01952]

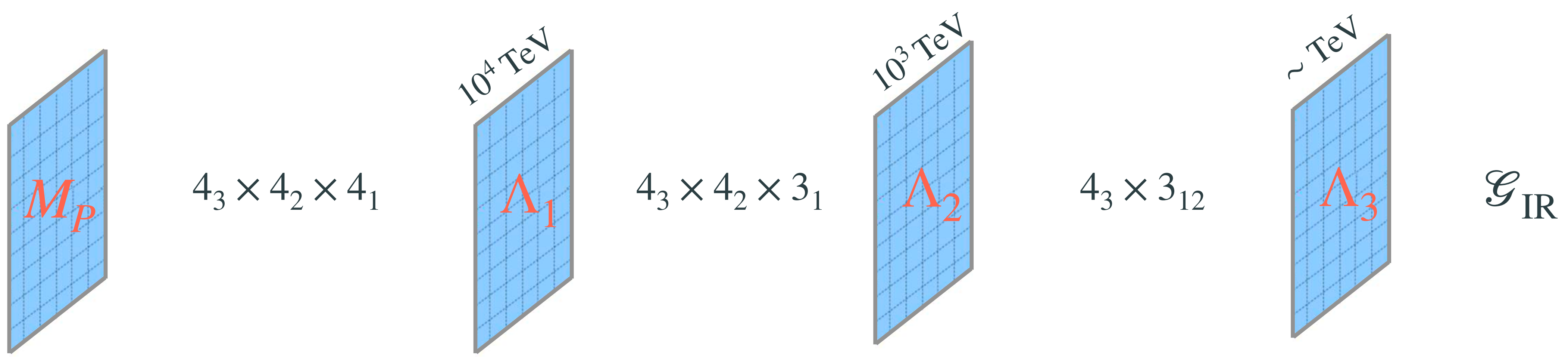
Conclusions

- We presented a model where flavor hierarchies naturally emerge from a 3-brane structure in a warped extra dimension, where each SM family is quasi-localized on a different brane.
- Our construction results in a $U(2)^n$ flavor symmetry with leading breaking in the left-handed sector.
- The Higgs emerges as a pseudo-Nambu-Goldstone boson from the same strong dynamics that breaks 4321 gauge symmetry.
- At low energies, the model reduces to the 4321 model, which is known to provide a good explanation of the *B*-meson anomalies.
- For more detail, ask me or see 2203.01952 and 2206.03096 .

Backup Slides

Extension to Planck and Cosmological Signatures





[Greljo, Opferkuch, BAS, 1910.02014]

[Bordone, Cornella, Fuentes-Martin, Isidori 1712.01368
Fuentes-Martin, Isidori, Lizana, Selimovic, BAS, 2203.01952]

Higgs Potential

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

$\alpha \downarrow$ Ψ^3, Ω

$\beta \downarrow$ Ψ^3, Σ, W, Z

Field	$SU(4)_h$	$SU(4)_l$	$SO(5)$
Ψ^3	**4**	**1**	**4**
Σ	**1**	**1**	**5**
Ω	**1**	**4**	**4**

Higgs Mass :

$$m_h^2 \equiv 2\lambda\langle h\rangle^2 \approx \frac{2\beta\langle h\rangle^2}{f^4}$$

Higgs VEV $(\alpha \approx -2\beta)$:

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

$$\lambda \approx \frac{1}{16\pi^2}\left[N_c\, y_t^4 \log\frac{\Lambda_{\rm IR}^2}{m_t^2} - \frac{9}{32}\zeta(3) g_*^2\left(3g_L^2 + g_Y^2\right) + \frac{\pi^2 g_*^4}{2(kL)^2}\frac{\langle\Sigma_{\rm IR}\rangle^2}{\Lambda_{\rm IR}^2}(\tilde{M}_{H'} - \tilde{M}_S)\right]$$

top loop | EW gauge loop | Σ tree

[Fuentes-Martin, Isidori, Lizana, Selimovic, BAS, 2203.01952]

Higgs Potential

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

$\alpha \downarrow \Psi^3, \Omega$ $\qquad$ $\beta \downarrow \Psi^3, \Sigma, W, Z$

Field	$SU(4)_h$	$SU(4)_l$	$SO(5)$
Ψ^3	**4**	**1**	**4**
Σ	**1**	**1**	**5**
Ω	**1**	**4**	**4**

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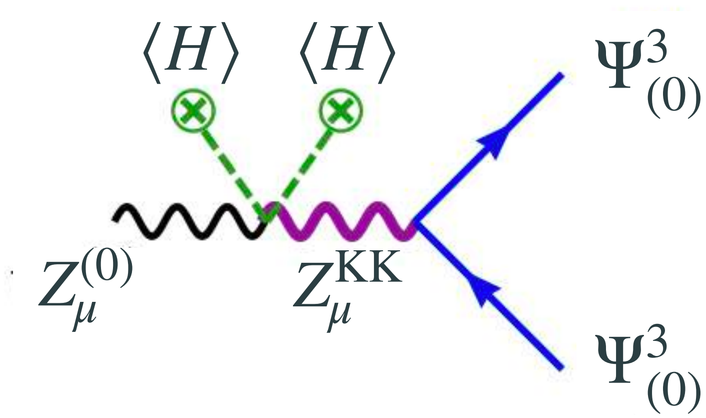
Quartic of the right size for $g_* \approx 2.5$, also compatible with the top Yukawa.

[Fuentes-Martin, Isidori, Lizana, Selimovic, BAS, 2203.01952]

Low-energy phenomenology, deviations from 4321

- Low energy pheno is the same as in the non-universal 4321 model.
- Strongest bound on the overall scale comes from coloron direct searches.
- Leading deviation in 3rd family EW vertex corrections from $\mathrm{KK} \leftrightarrow \mathrm{SM}$ mixing.



Benchmark Spectrum :

E

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

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

$$f \approx \frac{M_{\mathrm{KK}}}{g_*} \approx 6.4\,\mathrm{TeV}$$

$$M_{15} \approx \frac{g_* f}{\sqrt{2kL}} \approx 3.6\,\mathrm{TeV}$$

Leading effect in $Z \to \tau_L \tau_L$

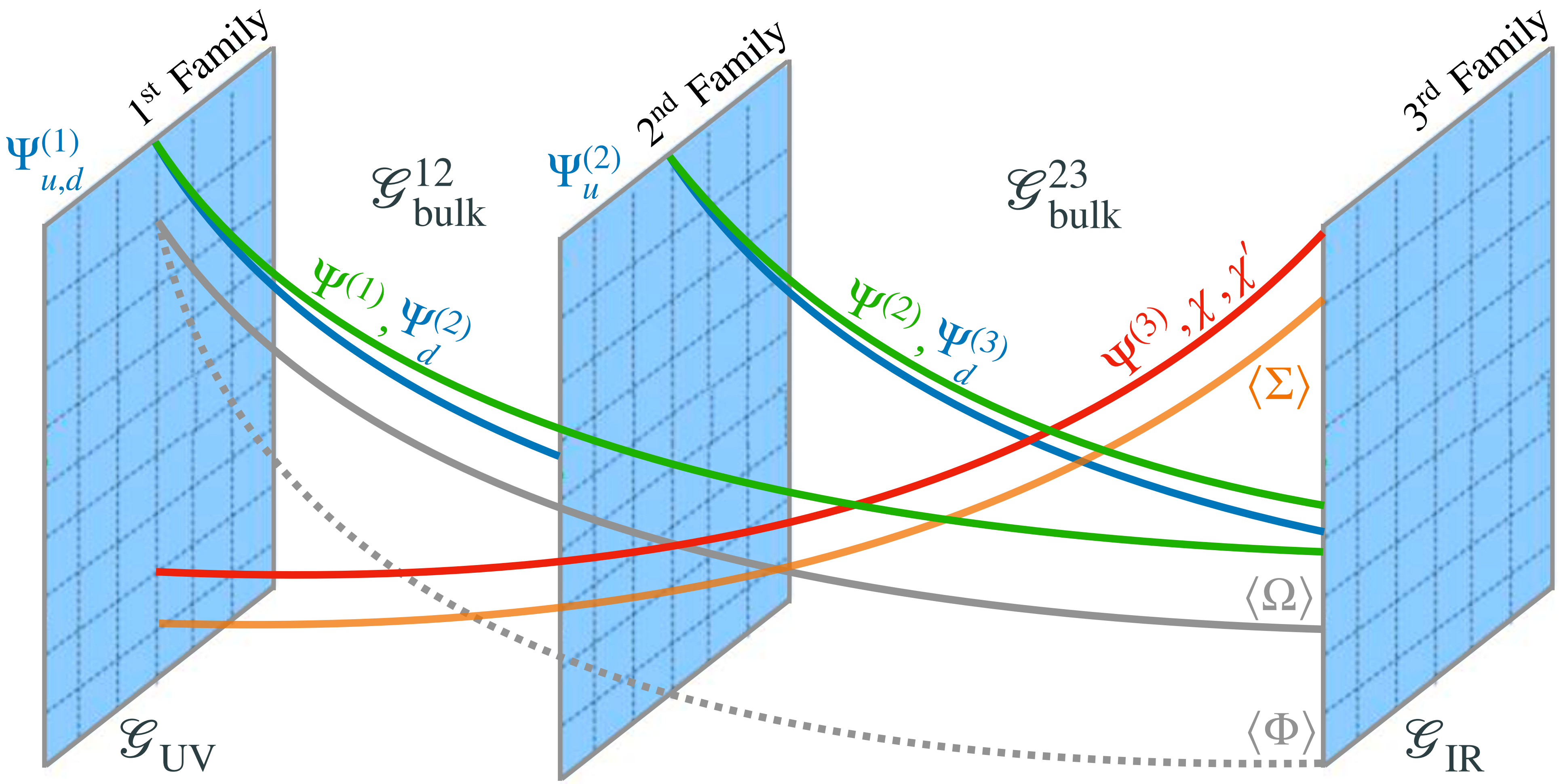
$$\frac{\delta g_{Z\Psi^3\Psi^3}}{g_{Z\Psi^3\Psi^3}} \approx -0.3\frac{m_Z^2}{M_{\mathrm{KK}}^2}\frac{g_*^2}{g_L^2} \approx -\frac{0.3}{4c_W^2}\frac{\langle h\rangle^2}{f^2} \lesssim 10^{-3} \qquad [f > 2.5\,\mathrm{TeV}\ \ (M_{\mathrm{KK}} > 6\,\mathrm{TeV})]$$

[Fuentes-Martin, Isidori, Lizana, Selimovic, BAS, 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**
Σ	**1**	**1**	**5**
Ω	**1**	**4**	**4**
Φ	**1**	**1**	**1**

$$\Psi^3 = \begin{bmatrix} \psi^3\,(+,+) \\ \psi^3_u\,(-,-) \\ \tilde\psi^3_d\,(+,-) \end{bmatrix}, \quad \Psi^3_d = \begin{bmatrix} \tilde\psi^3\,(+,-) \\ \tilde\psi^3_u\,(+,-) \\ \psi^3_d\,(-,-) \end{bmatrix}, \quad \mathcal{X}^{(\prime)} = \begin{bmatrix} \chi^{(\prime)}(\pm,\pm) \\ \chi^{(\prime)}_u\,(\mp,\pm) \\ \chi^{(\prime)}_d\,(\mp,\pm) \end{bmatrix},$$

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



IR Masses

$$\Psi^3 = \begin{bmatrix} \psi^3\,(+,+) \\ \psi_u^3\,(-,-) \\ \tilde{\psi}_d^3\,(+,-) \end{bmatrix}, \quad \Psi_d^3 = \begin{bmatrix} \tilde{\psi}^3\,(+,-) \\ \tilde{\psi}_u^3\,(+,-) \\ \psi_d^3\,(-,-) \end{bmatrix}, \quad \mathcal{X}^{(\prime)} = \begin{bmatrix} \chi^{(\prime)}(\pm,\pm) \\ \chi_u^{(\prime)}\,(\mp,\pm) \\ \chi_d^{(\prime)}\,(\mp,\pm) \end{bmatrix},$$

$$\Psi^j = \begin{bmatrix} \psi^j\,(+,+) \\ \tilde{\psi}_u^j\,(-,+) \\ \tilde{\psi}_d^j\,(-,+) \end{bmatrix}, \quad \Psi_u^j = \begin{bmatrix} \tilde{\psi}^j\,(+,-) \\ \psi_u^j\,(-,-) \\ \hat{\psi}_d^j\,(+,-) \end{bmatrix}, \quad \Psi_d^j = \begin{bmatrix} \hat{\psi}^j\,(+,-) \\ \hat{\psi}_u^j\,(+,-) \\ \psi_d^j\,(-,-) \end{bmatrix}.$$

$$\mathcal{L}_{\rm IR} \supset \left(\bar{\mathcal{X}}_L \tilde{M}_\chi + \bar{\Psi}_L^3 \tilde{M}_\Psi + \bar{\Psi}_L^j \tilde{m}_\psi^j\right) \mathcal{P}_L \mathcal{X}_R^\prime\,,$$

$$\begin{aligned}\mathcal{L}_{\rm IR} \supset\; & \bar{\Psi}_L^3 \tilde{M}_{\Psi d}^L \mathcal{P}_L \Psi_{dR}^3 + \bar{\Psi}_L^j \tilde{m}_{\Psi j}^R \mathcal{P}_R \Psi_R^3 + \bar{\mathcal{X}}_L \tilde{M}_{\chi u}^R \mathcal{P}_R \Psi_R^3 \\ & + \bar{\Psi}_L^j (\tilde{m}_{dj}^L \mathcal{P}_L + \tilde{m}_{dj}^R \mathcal{P}_R) \Psi_{dR}^3 + \bar{\mathcal{X}}_L (\tilde{M}_{\chi d}^L \mathcal{P}_L + \tilde{M}_{\chi d}^R \mathcal{P}_R) \Psi_{dR}^3\,.\end{aligned}$$

[Fuentes-Martin, Isidori, Lizana, Selimovic, BAS, 2203.01952]

Effective 4D "Holographic" Lagrangian

$$\mathcal{L}_{\rm IR} \supset \left(\bar{\mathcal{X}}_L \tilde{M}_\chi + \bar{\Psi}^3_L \tilde{M}_\Psi + \bar{\Psi}^j_L \tilde{m}^j_\psi\right) \mathcal{P}_L \mathcal{X}'_R \,,$$

$$\mathcal{L}_{\rm IR} \supset \bar{\Psi}^3_L \tilde{M}^L_{\Psi d} \mathcal{P}_L \Psi^3_{dR} + \bar{\Psi}^j_L \tilde{m}^R_{\Psi j} \mathcal{P}_R \Psi^3_R + \bar{\mathcal{X}}_L \tilde{M}^R_{\chi u} \mathcal{P}_R \Psi^3_R + \bar{\Psi}^j_L (\tilde{m}^L_{dj} \mathcal{P}_L + \tilde{m}^R_{dj} \mathcal{P}_R) \Psi^3_{dR} + \bar{\mathcal{X}}_L (\tilde{M}^L_{\chi d} \mathcal{P}_L + \tilde{M}^R_{\chi d} \mathcal{P}_R) \Psi^3_{dR} \,.$$

$$\Downarrow$$

$$-\mathcal{L}_{\rm 4D} \supset \frac{g_*}{2\sqrt{2}} \left[\bar{\psi}^3_L - \bar{\chi}_L \tilde{M}^R_{\chi u} - c_j\, e^{-\frac{k z_j}{2}}\, \bar{\psi}^j_L \tilde{m}^R_{\Psi j}\right] \tilde{H} \psi^3_{uR} + y^{ij}_u \bar{\psi}^i_L \tilde{H} \psi^j_{uR} + + y^{ij}_d \bar{\psi}^i_L H \psi^j_{dR}$$
$$+ \frac{g_*}{2\sqrt{2}}\, c_2\, e^{-\frac{k z_2}{2}} \left[\bar{\psi}^3_L \tilde{M}^L_{\Psi d} + \bar{\chi}_L (\tilde{M}^L_{\chi d} - \tilde{M}^R_{\chi d}) + c_j\, e^{-\frac{k z_j}{2}}\, \bar{\psi}^j_L (\tilde{m}^L_{dj} - \tilde{m}^R_{dj})\right] H \psi^3_{dR}$$
$$+ \frac{\Lambda_{\rm IR}}{\sqrt{kL}} \left[\bar{\psi}^3_L \tilde{M}_\Psi + \bar{\chi}_L \tilde{M}_\chi + c_j\, e^{-\frac{k z_j}{2}}\, \bar{\psi}^j_L \tilde{m}^j_\psi\right] \chi'_R + \text{h.c.}$$

Matching to 4321: $M_\chi = \tilde{M}_\chi \Lambda_{\rm IR}/\sqrt{kL} \approx 2 \text{ TeV}, \quad y_t = g_*/2\sqrt{2}, \quad y_+ = y_t \tilde{M}^R_{\chi u}, \quad \text{etc.}$

[Fuentes-Martin, Isidori, Lizana, Selimovic, BAS, 2203.01952]

Holographic Dictionary: A 5D Model Builder's Guide

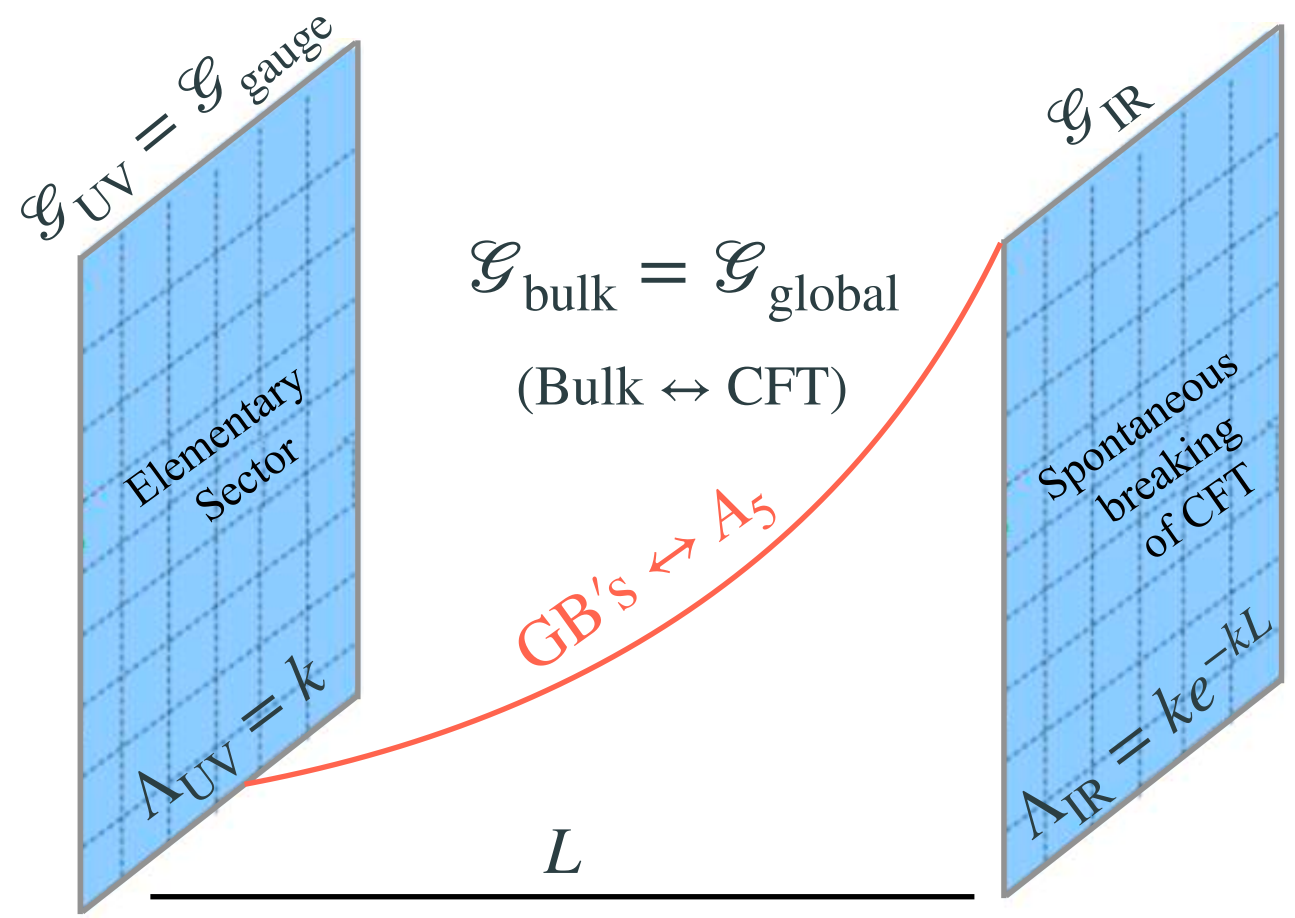
AdS/CFT correspondence relates a strongly coupled 4D CFT to a 5D theory with a warped fifth dimension.

Warped 5D (AdS_5)

$$ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2$$

Composite (4D CFT)

- Strongly coupled sector (CFT) with global symmetry $\mathscr{G}_{\rm global}$
- Elementary sector with gauge symmetry $\mathscr{G}_{\rm gauge} \subset \mathscr{G}_{\rm global}$
- CFT becomes strongly coupled at some IR scale and spontaneously breaks $\mathscr{G}_{\rm global} \to \mathscr{G}_{\rm IR}$
- NGBs in the coset $\mathscr{G}_{\rm global}/\mathscr{G}_{\rm IR}$



[Randall, Sundrum, hep-ph/9905221]

Gauge Sector

In breaking $\mathscr{G}^{23}_{\rm bulk} \to \mathscr{G}_{\rm IR}$, the 4321 gauge bosons acquire a mass of:

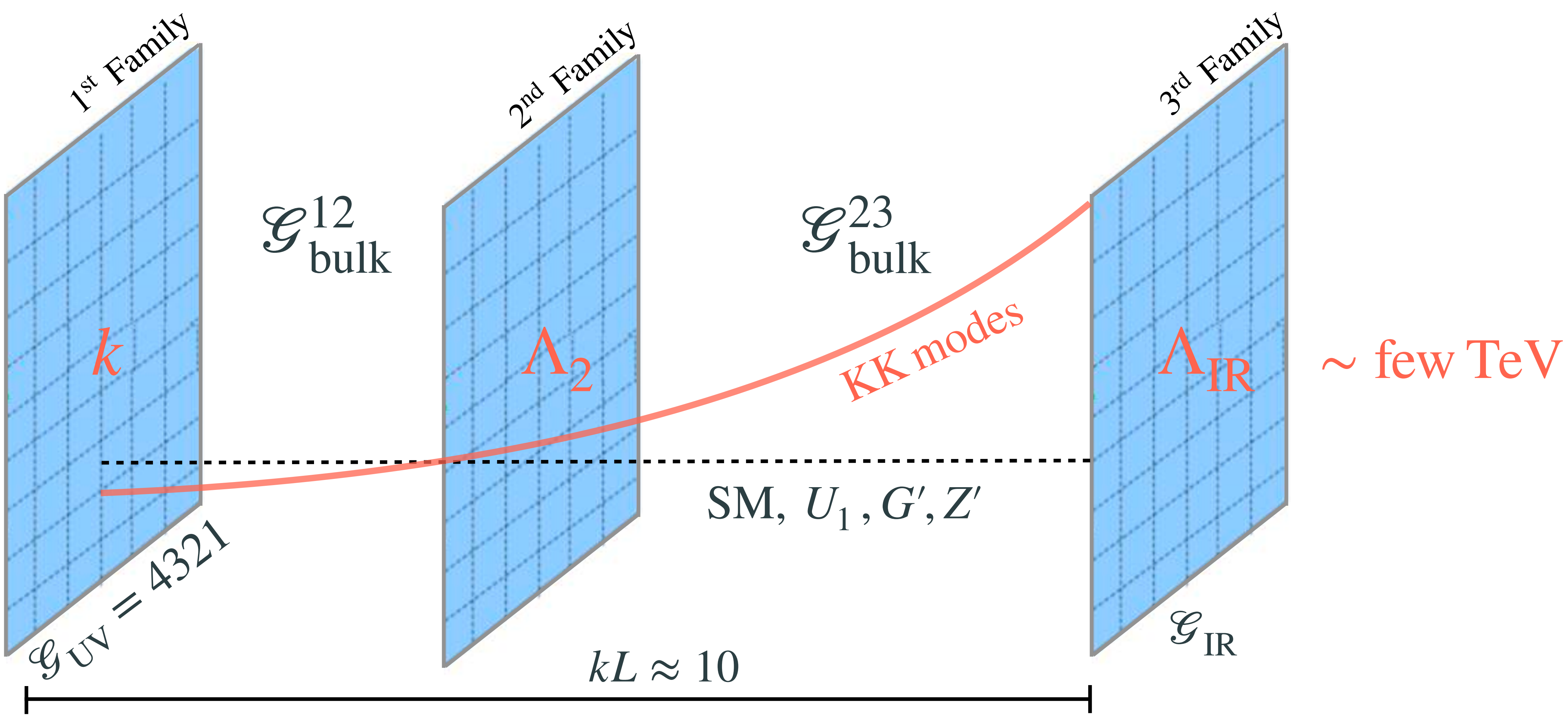
$$M_{15} = \sqrt{\frac{2}{kL}}\Lambda_{\rm IR} = \frac{M_{\rm KK}}{\sqrt{2kL}}$$

IR symmetry breaking

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

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

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



[Fuentes-Martin, Isidori, Lizana, Selimovic, BAS, 2203.01952]

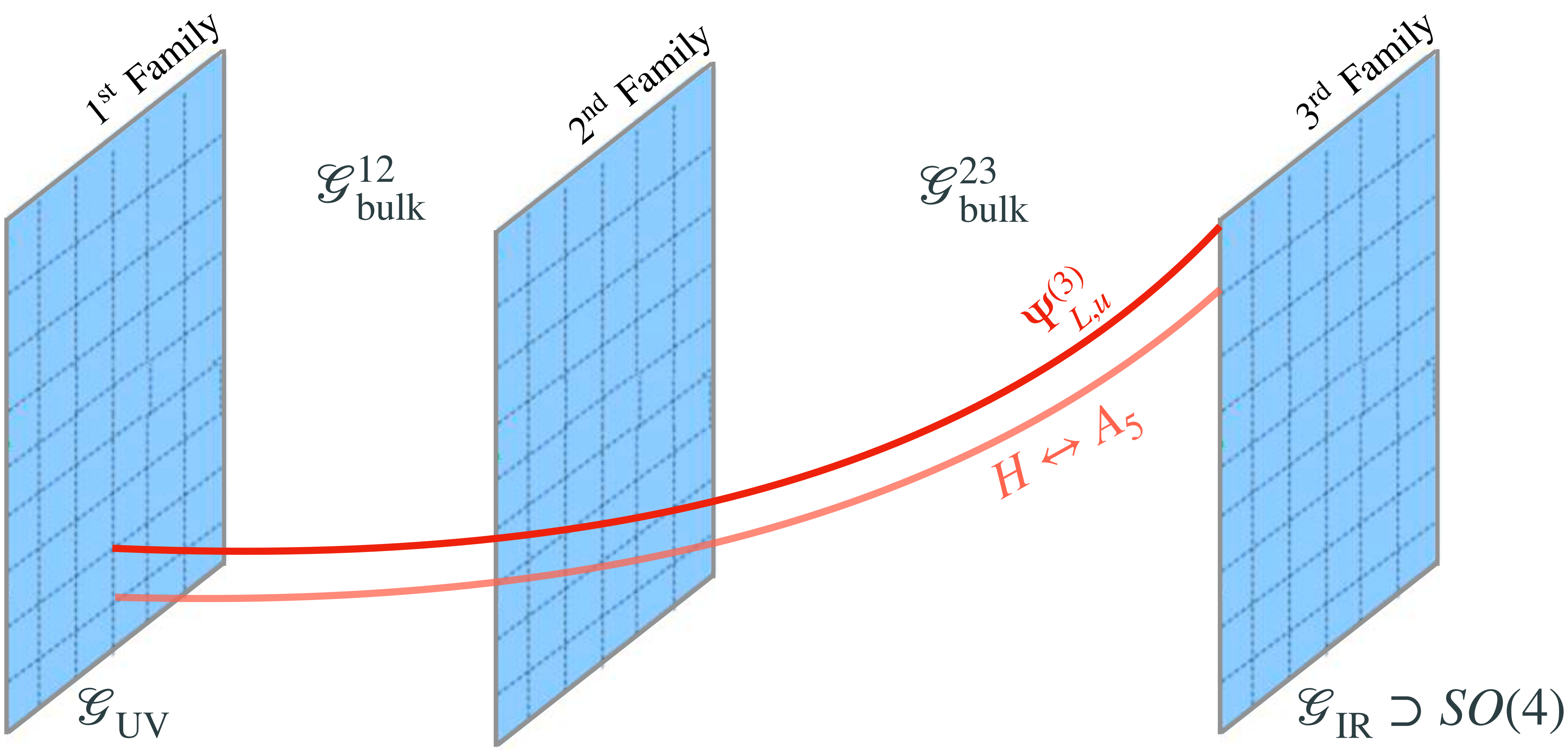
Gauge-Higgs Unification and the Top Yukawa

Field	$SU(4)_h$	$SU(4)_l$	$SO(5)$
Ψ^3	**4**	**1**	**4**

$$\Psi^3 = \begin{bmatrix} \psi^3\,(+,+) \\ \psi^3_u\,(-,-) \\ \tilde{\psi}^3_d\,(+,-) \end{bmatrix} \quad \begin{matrix} q_L \\ t_R \\ B_{L,R} \end{matrix} \quad \begin{matrix} SU(2)_L \\ \left.\begin{matrix} \\ \\ \end{matrix}\right\} SU(2)_R \end{matrix}$$

Can remove H from the bulk due to the $SO(5)$ invariance:

$$W(x) = e^{-i\theta(x)}\,, \qquad \theta(x) = g_5 \int_0^L dy\, A_5(x,y) = \frac{g_*}{\sqrt{2}} \frac{T^{\hat{a}} h^{\hat{a}}}{\Lambda_{\rm IR}}$$



[Fuentes-Martin, Isidori, Lizana, Selimovic, BAS, 2203.01952]

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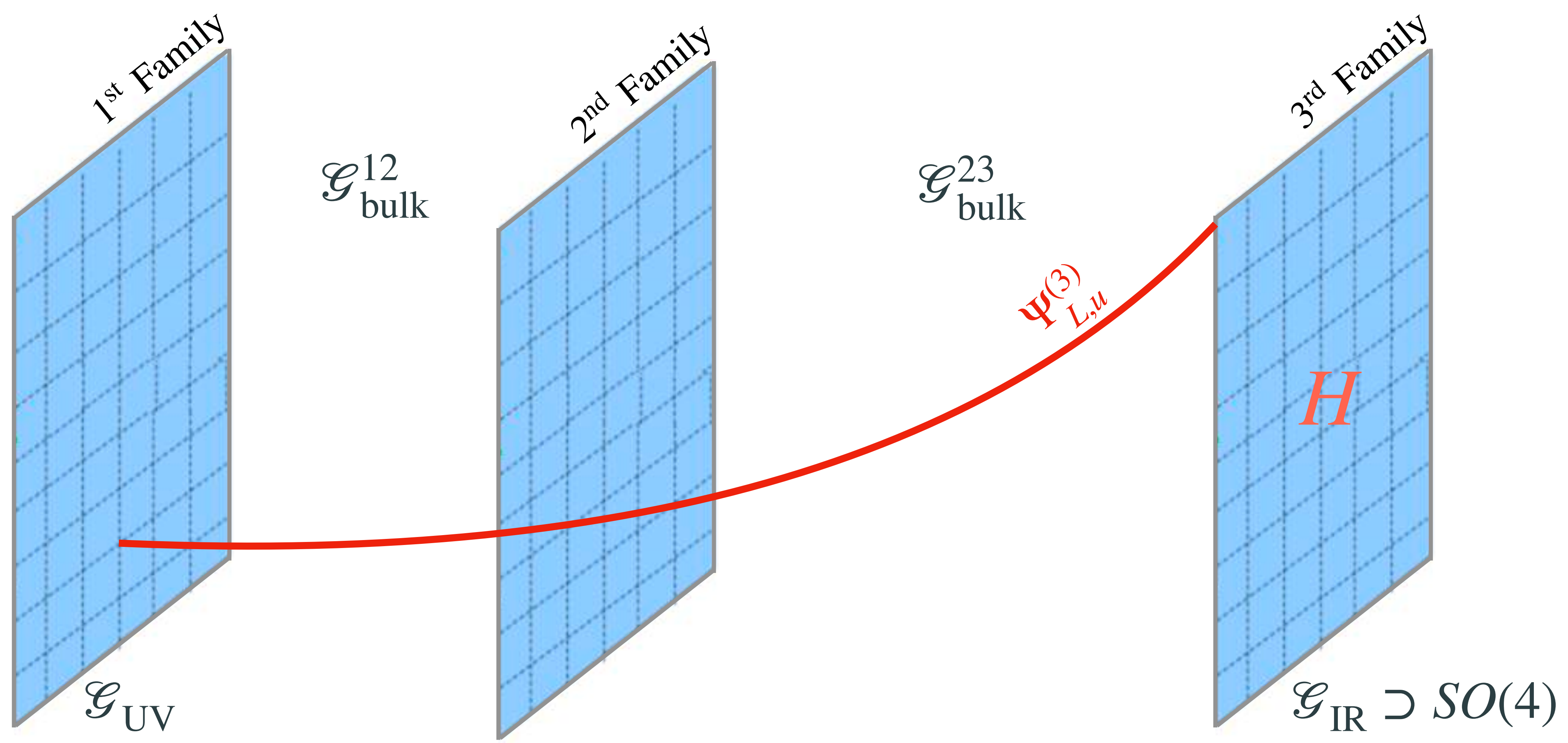
Field	$SU(4)_h$	$SU(4)_l$	$SO(5)$
Ψ^3	**4**	**1**	**4**

$$\Psi^3 = e^{-i\frac{g_*}{\sqrt{2}}\frac{T^{\hat{a}}h^{\hat{a}}}{\Lambda_{\rm IR}}} \begin{bmatrix} \psi^3\,(+,+) \\ \psi^3_u\,(-,-) \\ \tilde{\psi}^3_d\,(+,-) \end{bmatrix} \begin{matrix} q_L \\ t_R \\ B_{L,R} \end{matrix} \quad \begin{matrix} SU(2)_L \\ \left.\right\} SU(2)_R \end{matrix}$$

$$\mathcal{L}_{4\rm D} \supset -\frac{g_*}{2\sqrt{2}}\,\bar{\psi}^3_L H \psi^3_{uR}\, P(M_{\Psi^3}) \qquad (g_*^2 = g_5^2 k) \qquad \text{For } y_t : g_* \geq 2.2$$



[Fuentes-Martin, Isidori, Lizana, Selimovic, BAS, 2203.01952]

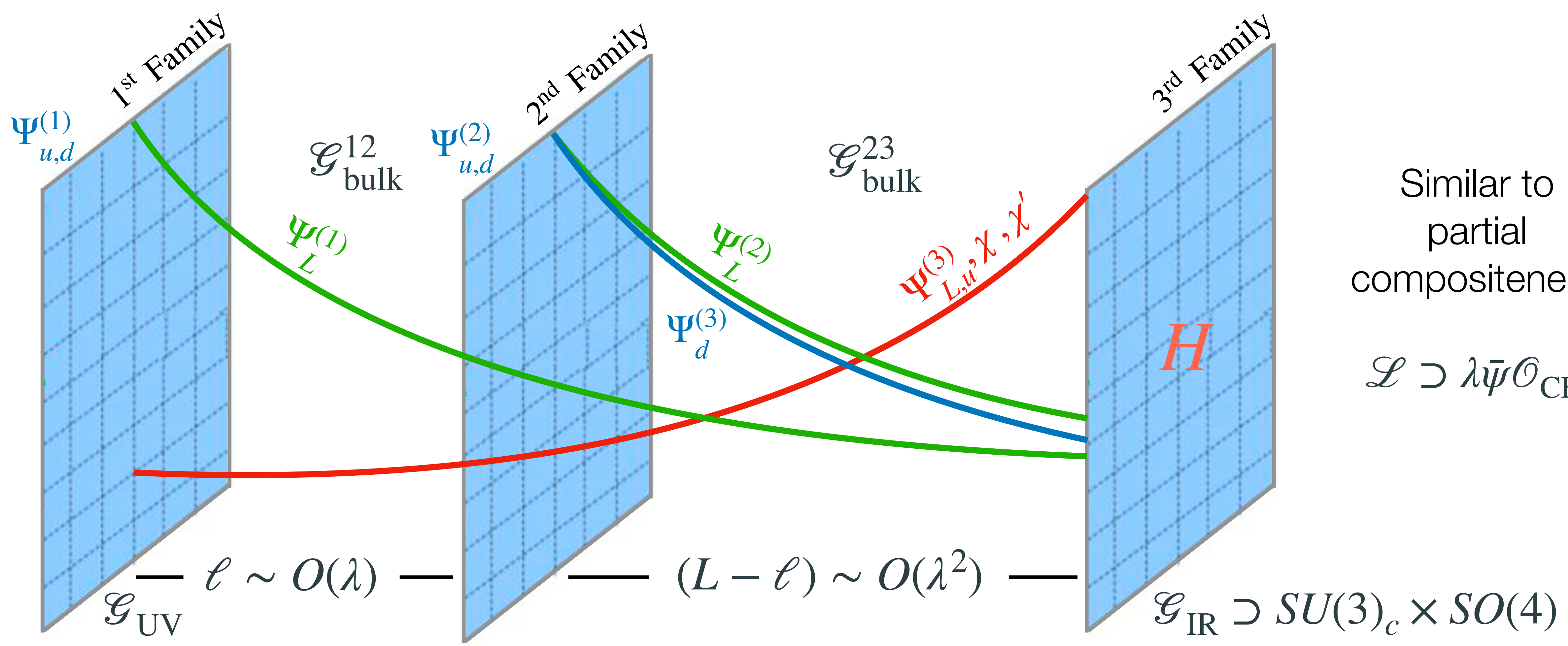
Light-Heavy Fermion Mixing in the IR

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**

- Mixing (Yukawa and VL) only occurs in the IR due to gauge symmetry (can be different for quarks and leptons).
- Results in a U(2) flavor symmetry with leading breaking in the **LH** sector.

$$y_{f1f2} = \frac{g_*}{2\sqrt{2}} \left(\tilde{M}^L_{12} - \tilde{M}^R_{12}\right) P(M_{f_1}, M_{f_2})$$

E.g. $P\big(M_{\Psi^j}, M_{\Psi^3}\big) \sim e^{-k(L-\ell_j)/2} \approx V_{j3}$



Similar to partial compositeness

$\mathscr{L} \supset \lambda \bar{\psi} \mathcal{O}_{\rm CFT}$

[Fuentes-Martin, Isidori, Lizana, Selimovic, BAS, 2203.01952]

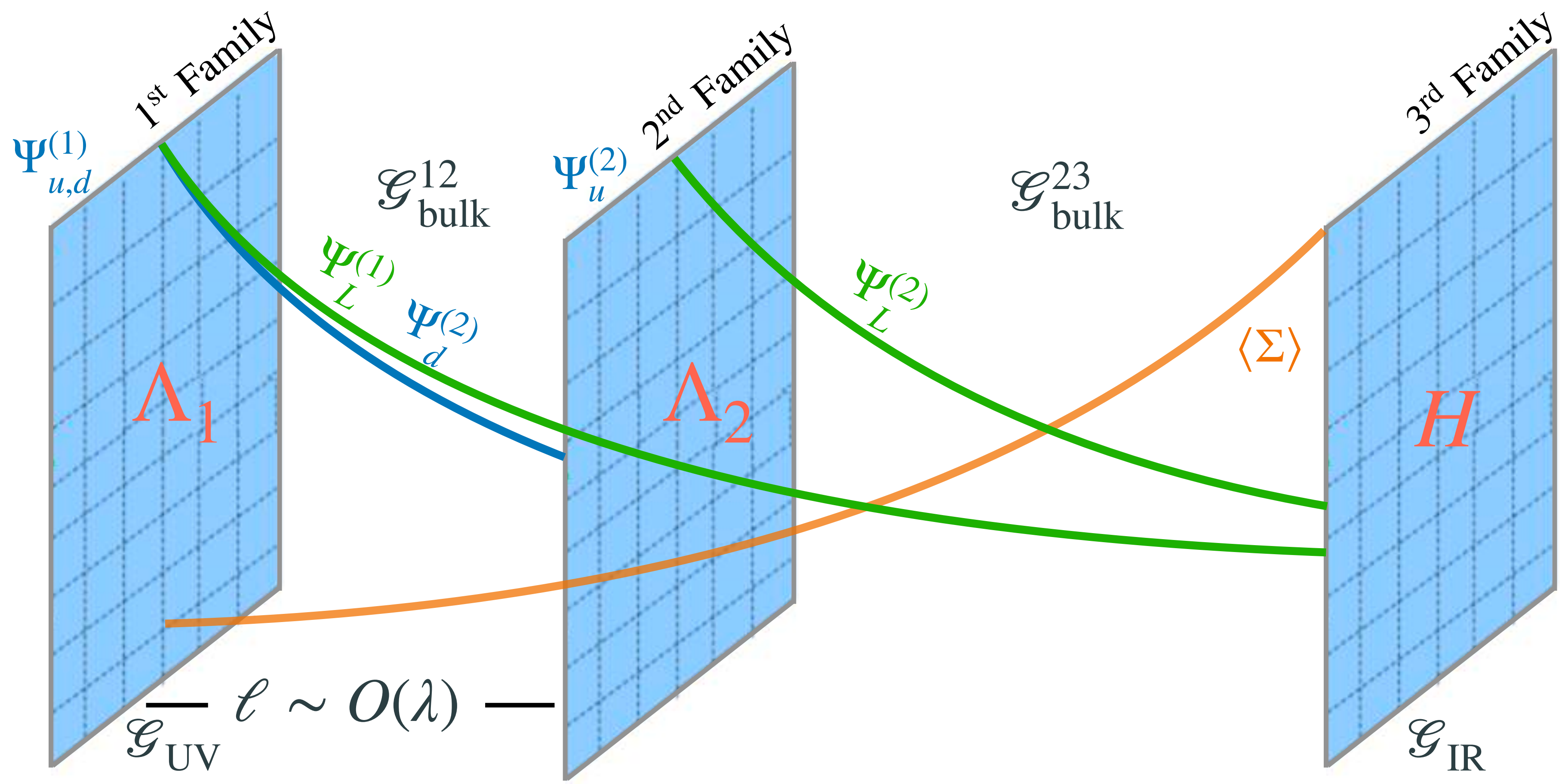
Light Family Yukawas in the UV

Field	$SU(4)_h$	$SU(4)_l$	$SO(5)$
$\Psi^j, \Psi^j_{u,d}$	**1**	**4**	**4**
Σ	**1**	**1**	**5**

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

$$\mathcal{L}_{5D} \supset -Y^{ij}_{u,d}\, \bar{\Psi}^i\, \Sigma^a\, \Gamma^a\, P_R \Psi^j_{u,d}$$

$$y^{ij}_{u,d} \approx \frac{g_*}{2\sqrt{2}}\, \tilde{Y}^{ij}_{u,d}\, \frac{\langle \Sigma_{\rm IR}\rangle}{\Lambda_{\rm IR}}\, e^{-k(L-\ell_j)}\, e^{-k(c_i^{(1)}-\frac{1}{2})|y_i-\ell_j|}\, e^{k(c_j^{(1)}+\frac{1}{2})|y_j-\ell_j|}$$



Direct (irrelevant) coupling to a composite operator containing the Higgs

$$\mathscr{L} \sim \frac{1}{\Lambda}\bar{\psi}_L \mathscr{O}_{\rm H} \psi_R$$

[Panico, Pomarol, 1603.06609]

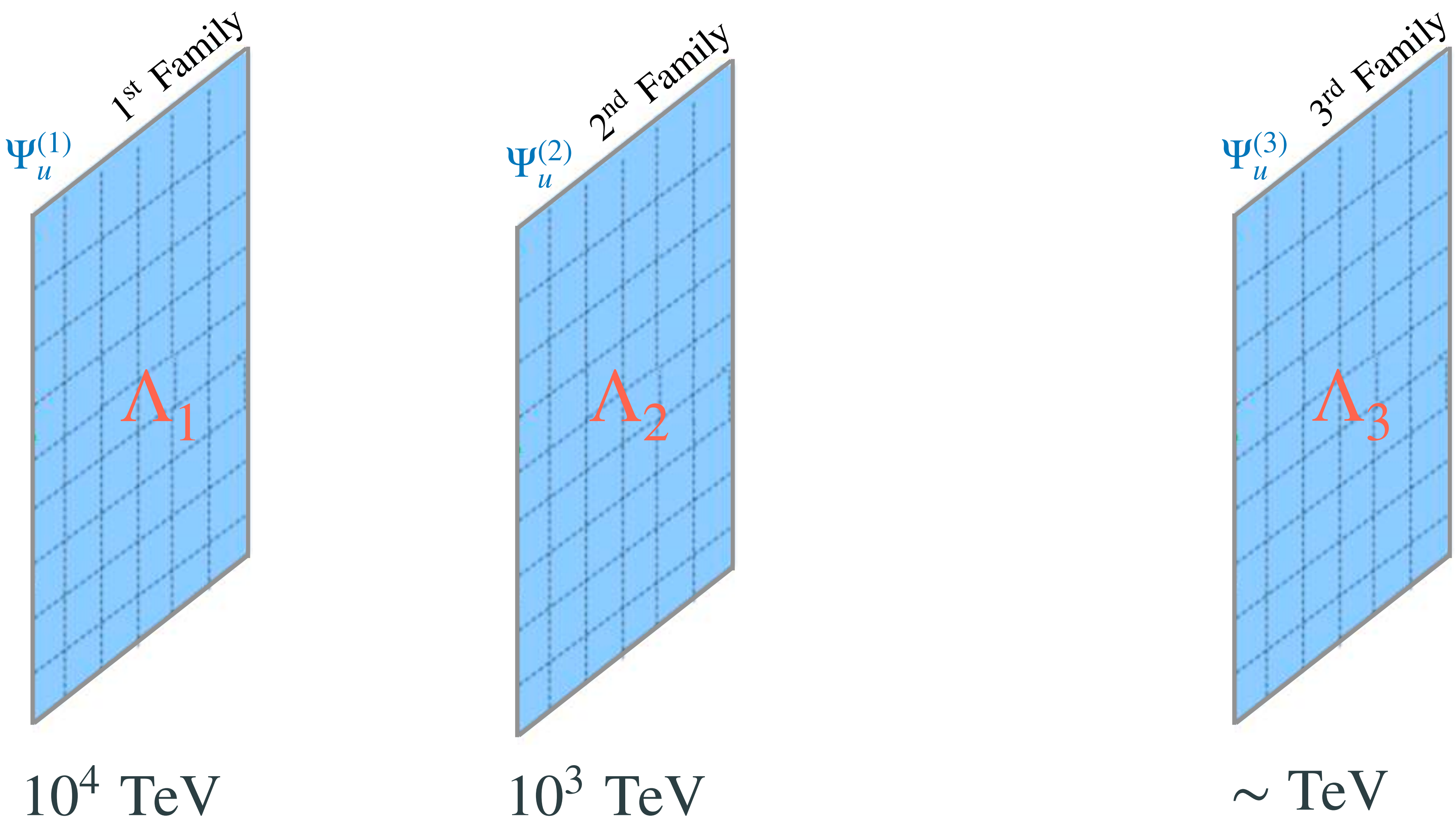
[Fuentes-Martin, Isidori, Lizana, Selimovic, BAS, 2203.01952]

A Comment on Neutrino Masses

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**

- Type 1 Seesaw would give:

$$\Psi_u \sim \begin{pmatrix} u_R \\ \nu_R \end{pmatrix}, \qquad m^i_\nu \sim \frac{(M^i_u)^2}{M^i_R} \rightarrow \frac{(M^i_u)^2}{\Lambda_i}$$



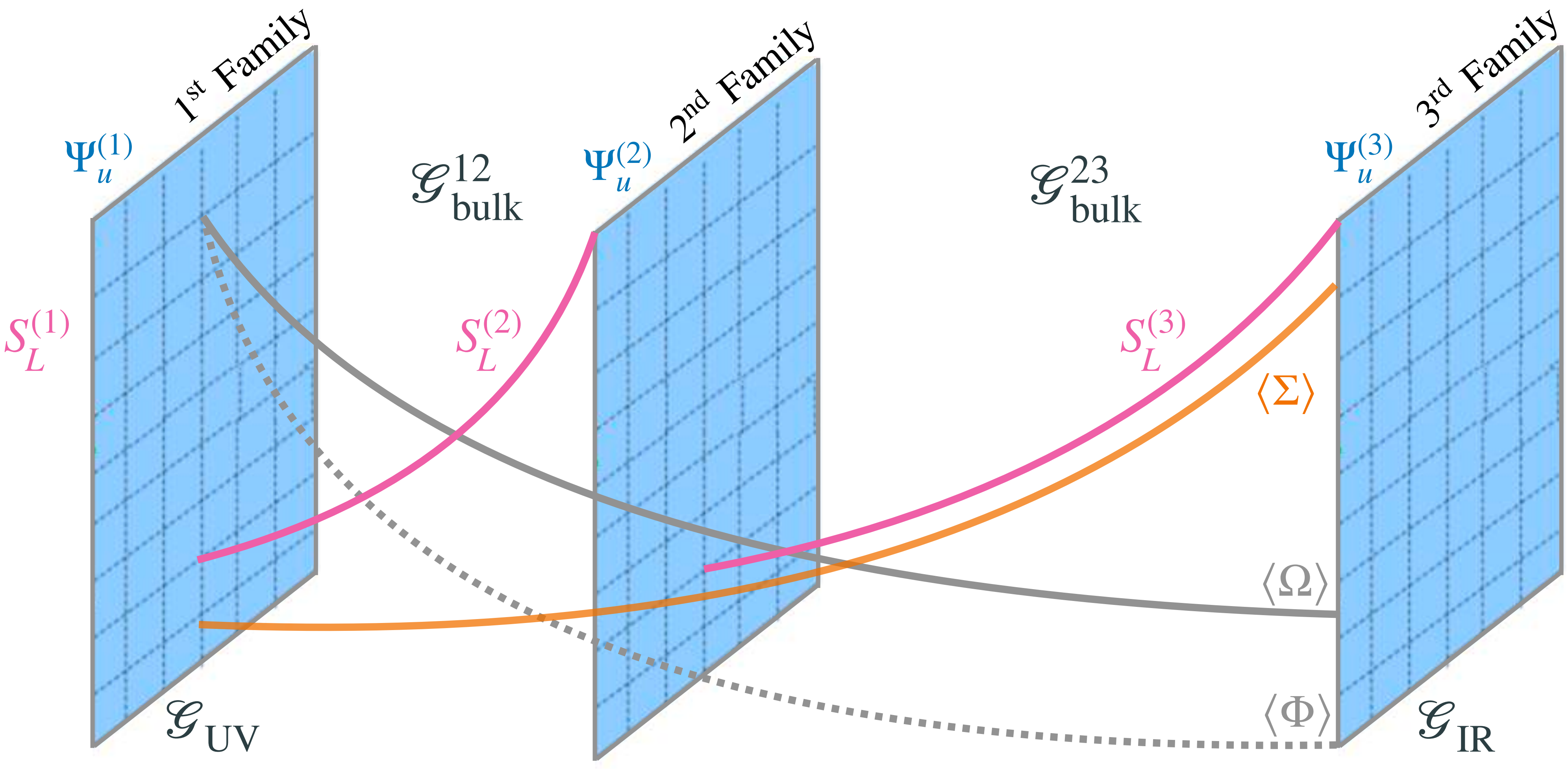
[Fuentes-Martin, Isidori, Pages, BAS, 2012.10492] [Fuentes-Martin, Isidori, Lizana, Selimovic, BAS, 2203.01952]

Neutrino Masses via an Inverse Seesaw Mechanism

	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**
ISS	Ω	**1**	**4**	**4**
	Φ	**1**	**1**	**1**

- Anarchic neutrino masses for:

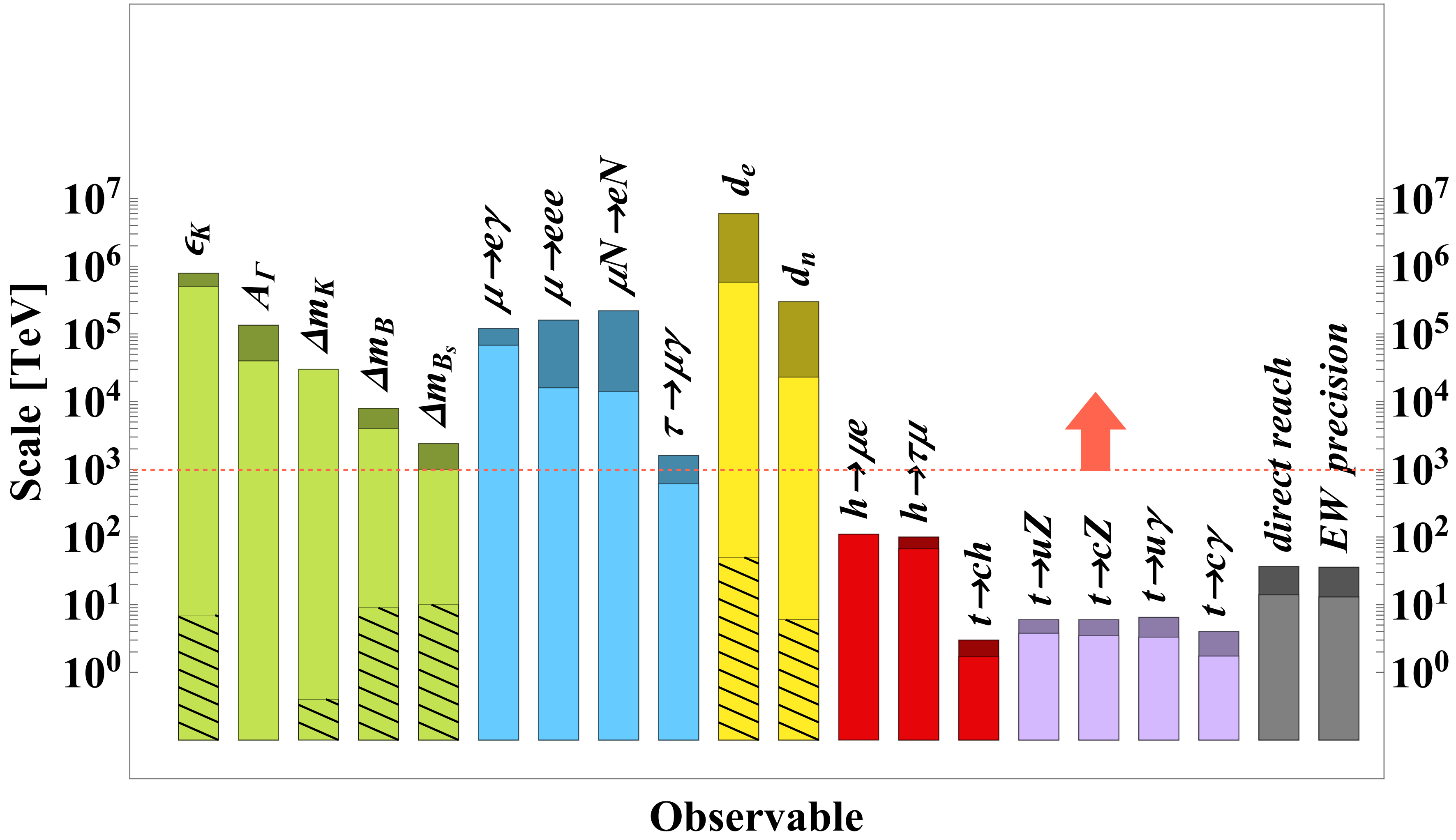
$$m^i_\nu = \left(\frac{M^i_u}{M^i_R}\right)^2 \mu_i \;\rightarrow\; \left(\frac{\langle\Sigma_i\rangle}{\langle\Omega_i\rangle}\right)^2 \langle\Phi_i\rangle \approx \text{const}\,.$$



[Fuentes-Martin, Isidori, Pages, BAS, 2012.10492]

[Fuentes-Martin, Isidori, Lizana, Selimovic, BAS, 2203.01952]

The Higgs Mass and the Flavor Puzzle



- Flavor bounds push the scale of flavor anarchic NP above 1000 TeV.
- NP that addresses the EW hierarchy problem should be light, but then it should have a very specific flavor structure to pass flavor bounds.
- Perhaps this same (flavored) NP sector is connected to the SM flavor puzzle…

[Physics Briefing Book 2020, 1910.11775]

4321 symmetry breaking and EWSB: Parallels

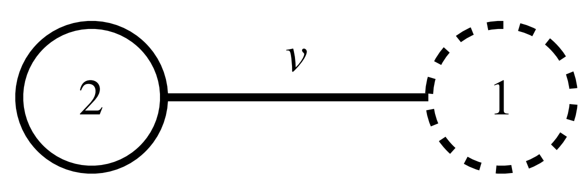
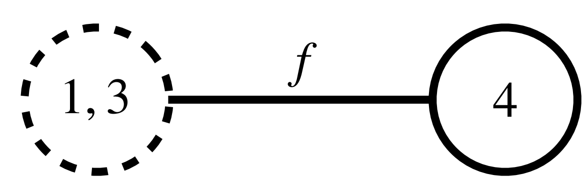
[Fuentes-Martin, Stangl 2004.11376]

$U(1)_Y$

$$SU(4)_h \times SU(3)_l \times SU(2)_L \times U(1)_{l+R} \xrightarrow{\langle \Omega_{1,3,15} \rangle \sim \mathcal{O}(\mathrm{TeV})} SU(3)_c \times SU(2)_L \times U(1)_Y$$

$SU(3)_c$

In the limit of vanishing gauge and Yukawa couplings:

	SM Higgs Sector	4321 Models
Global symmetry	$SU(2)_L \times SU(2)_R$	$SU(4)_l \times SU(4)_h$
Gauge symmetry	 $SU(2)_L \times U(1)_R$ Left-handed fermions × Right-handed fermions	 $U(1)_l \times SU(3)_l \times SU(4)_h$ Light fermions × Heavy fermions
Global SSB	$SU(2)_V$	$SU(4)_D$
Gauge SSB	$U(1)_V$	$U(1)_{B-L} \times SU(3)_c$
Goldstones	3 (3 eaten)	15 (15 eaten)

4321 symmetry breaking and EWSB: Parallels

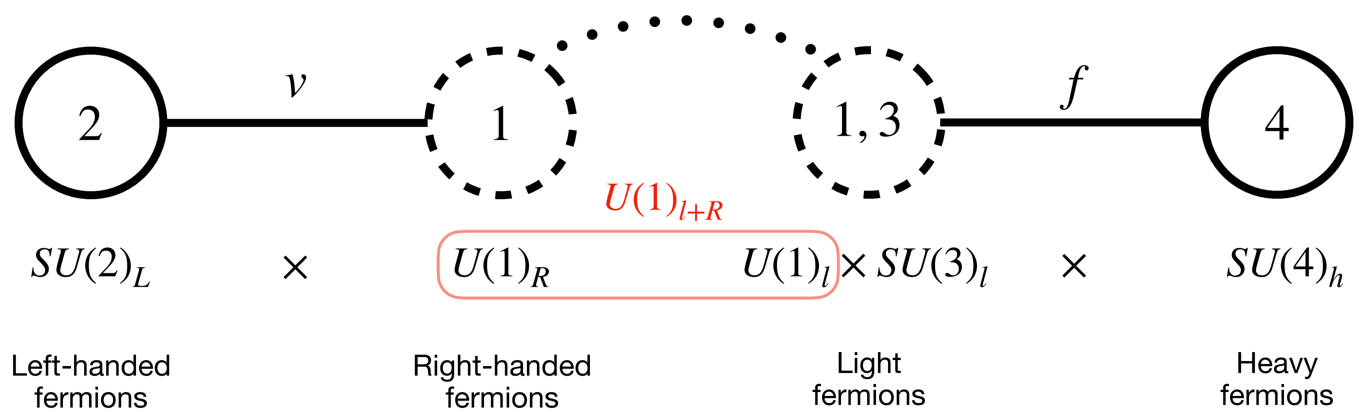
[Fuentes-Martin, Stangl 2004.11376]

$U(1)_Y$

$$SU(4)_h \times SU(3)_l \times SU(2)_L \times U(1)_{l+R} \xrightarrow{\langle \Omega_{1,3,15} \rangle \sim \mathcal{O}(\mathrm{TeV})} SU(3)_c \times SU(2)_L \times U(1)_Y$$

$SU(3)_c$

The two sites are connected by the gauging!!

<table>
<tr><th></th><th>SM Higgs Sector</th><th>4321 Models</th></tr>
<tr><td>Global symmetry</td><td>$SU(2)_L \times SU(2)_R$</td><td>$SU(4)_l \times SU(4)_h$</td></tr>
<tr><td>Gauge symmetry</td><td colspan="2">
</td></tr>
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<tr><td>Gauge SSB</td><td colspan="2">$U(1)_{\mathrm{em}} \times SU(3)_c$</td></tr>
<tr><td>Goldstones</td><td>$3\ (W, Z)$</td><td>$15\ (U_1, G', Z')$</td></tr>
</table>

Higgs Potential

Field	$SU(4)_h$	$SU(4)_l$	$SO(5)$
Ψ^3	**4**	**1**	**4**
Σ	**1**	**1**	**5**
Ω	**1**	**4**	**4**

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

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

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 :

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

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

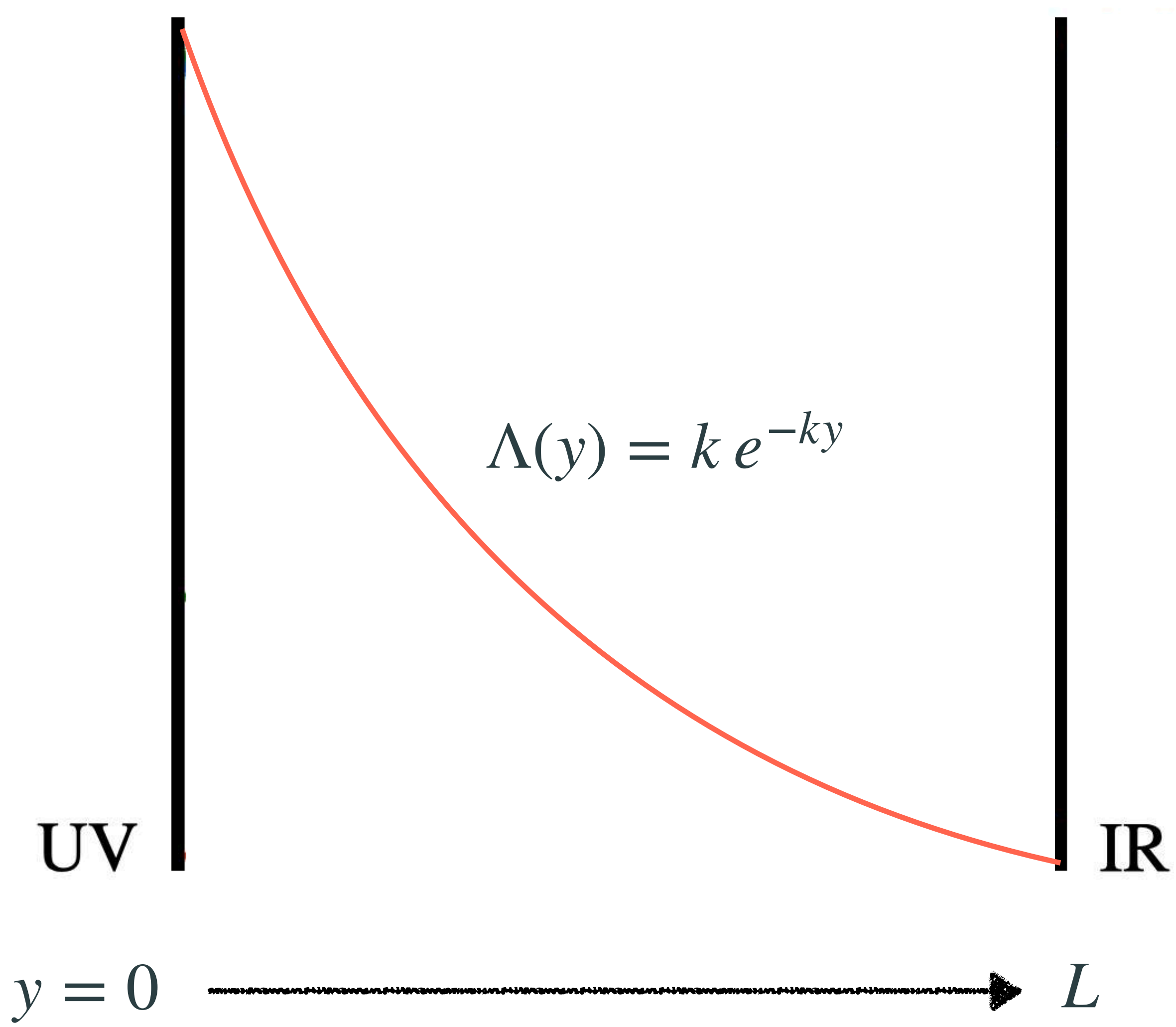
$$\beta_{\rm EW} \approx -\frac{9 f^4}{512\pi^2}\, g_*^2\, \zeta(3)\left(3g_L^2 + g_Y^2\right)$$

[Fuentes-Martin, Isidori, Lizana, Selimovic, BAS, 2203.01952]

5D Basics: Warping and Fermion Zero Modes

Warped Geometry (AdS_5)

$$ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2$$



* $\Lambda_{\mathrm{IR}}/\Lambda_{\mathrm{UV}} = e^{-kL}$

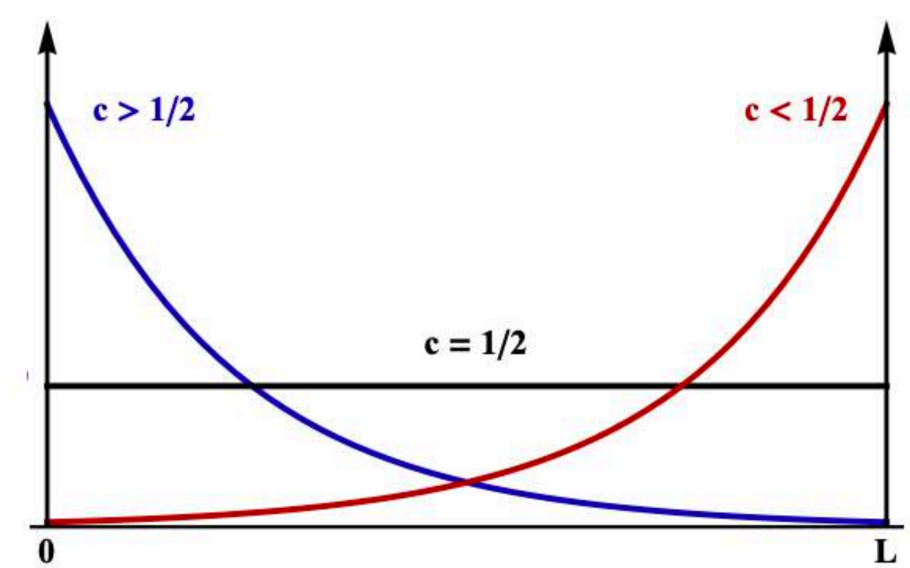
Planck hierarchy solved for $kL \approx 37$

KK Decomposition

$$X_{5\mathrm{D}}(x^\mu, y) = \frac{1}{\sqrt{L}}\sum_{n=0}^{\infty} f_n(y)\, X_n(x^\mu)$$

For fermion zero modes:

$$f_{(0)}^{\Psi_{L,R}}(y) = N_{L,R}\exp\left[\left(\frac{1}{2} \mp c_{L,R}\right)ky\right], \qquad c_{L,R} = \frac{M_{L,R}}{k}$$



*4D couplings determined by profile function overlap