



University of
Zurich^{UZH}

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

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La Thuile 2022

Third family quark-lepton unification at the TeV scale

Based on “4321” gauge symmetry:

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

[Bordone, Cornella, Fuentes-Martin, Isidori
[1712.01368](#), [1805.09328](#);
Greljo, BAS, [1802.04274](#);
Cornella, Fuentes-Martin, Isidori [1903.11517](#)]



See talks by Claudia and Nudzeim

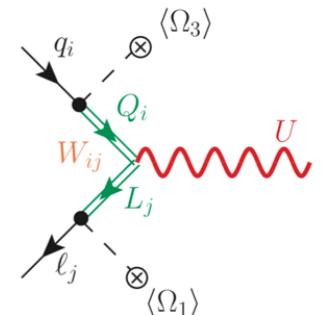
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- 3rd family charged under $SU(4)_h$
 \implies Direct NP couplings (L+R)
- Accidental approximate $U(2)^5$ flavor symmetry: $\psi = (\psi_1 \ \psi_2 \ \psi_3)$
- CKM mixing and NP couplings to light families from the leading O(0.1) breaking of $U(2)_q \times U(2)_\ell$:

Matter content

Field	$SU(4)_h$	$SU(3)_l$	$SU(2)_L$	$U(1)_{l+R}$
q_L^i	1	3	2	1/6
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
ψ_R^\pm	4	1	1	$\pm 1/2$
$\chi_{L,R}$	4	1	2	0
H	1	1	2	1/2
Ω_1	4	1	1	-1/2
Ω_3	4	3	1	1/6
Ω_{15}	15	1	1	0

1st & 2nd families

3rd family

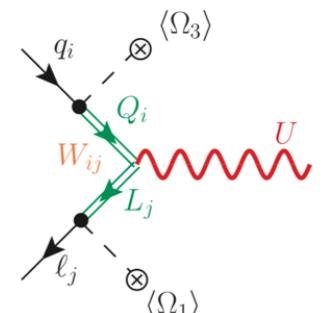
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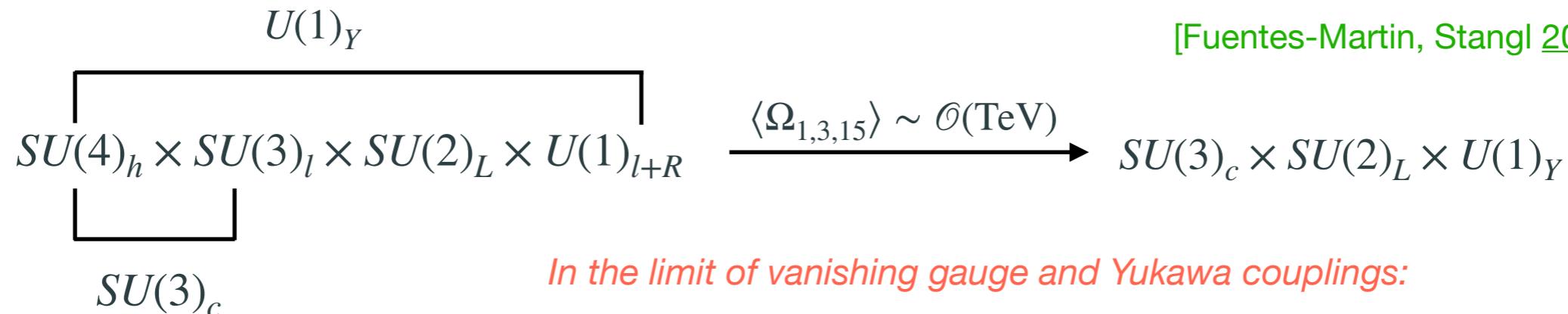
$$\begin{aligned} \mathcal{L} \supset & -\bar{q}_L^i \lambda_q^i \Omega_3 \chi_R - \bar{\ell}_L^i \lambda_\ell^i \Omega_1 \chi_R \\ & - y_+ \bar{\chi}_L \tilde{H} \psi_R^+ - y_- \bar{\chi}_L H \psi_R^- \end{aligned}$$

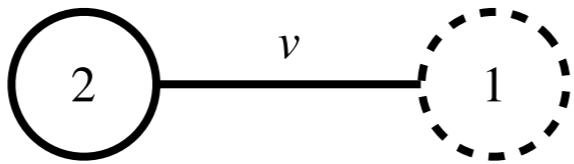
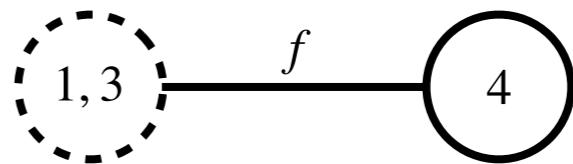
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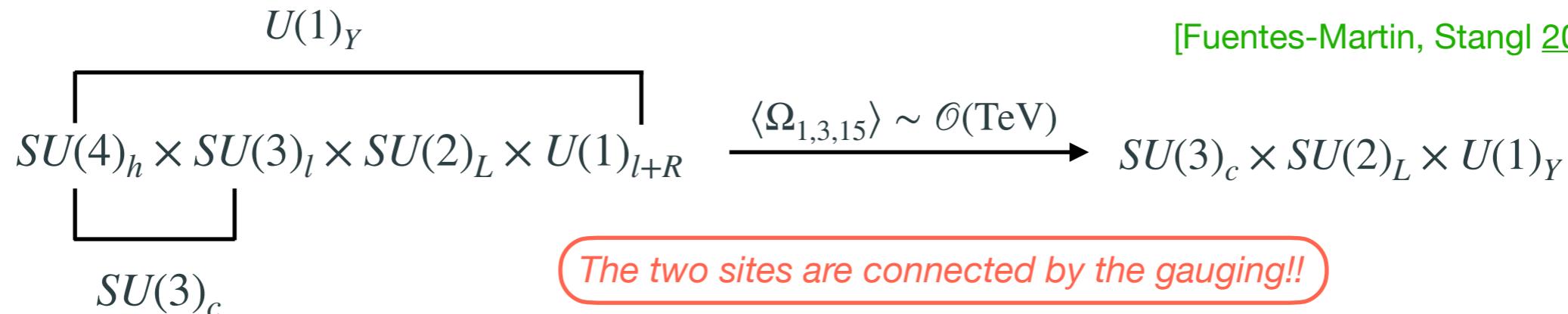
1st & 2nd families
3rd family
VL fermion
4321 SSB scalars

4321 symmetry breaking and EWSB: Parallels



	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



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Gauge symmetry	 $SU(2)_L \times U(1)_R \times U(1)_l \times SU(3)_l \times SU(4)_h$	$SU(4)_l \times SU(4)_h$
Global SSB	$SU(2)_V$	$SU(4)_D$
Gauge SSB		$U(1)_{\text{em}} \times SU(3)_c$
Goldstones	3 (W, Z)	15 (U_1, G', Z')

4321 + pNGB Higgs: The Composite Blueprint



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

(4321 gauged)

[Fuentes-Martin, Stangl, [2004.11376](#)]

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“Minimal Composite
Higgs (MCHM)”

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

[Agashe, Contino, Pomarol,
[hep-ph/0412089](#)]

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

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

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

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

[Fuentes-Martin, Stangl, [2004.11376](#)]

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Holographic Dictionary: A 5D Model Builder's Guide

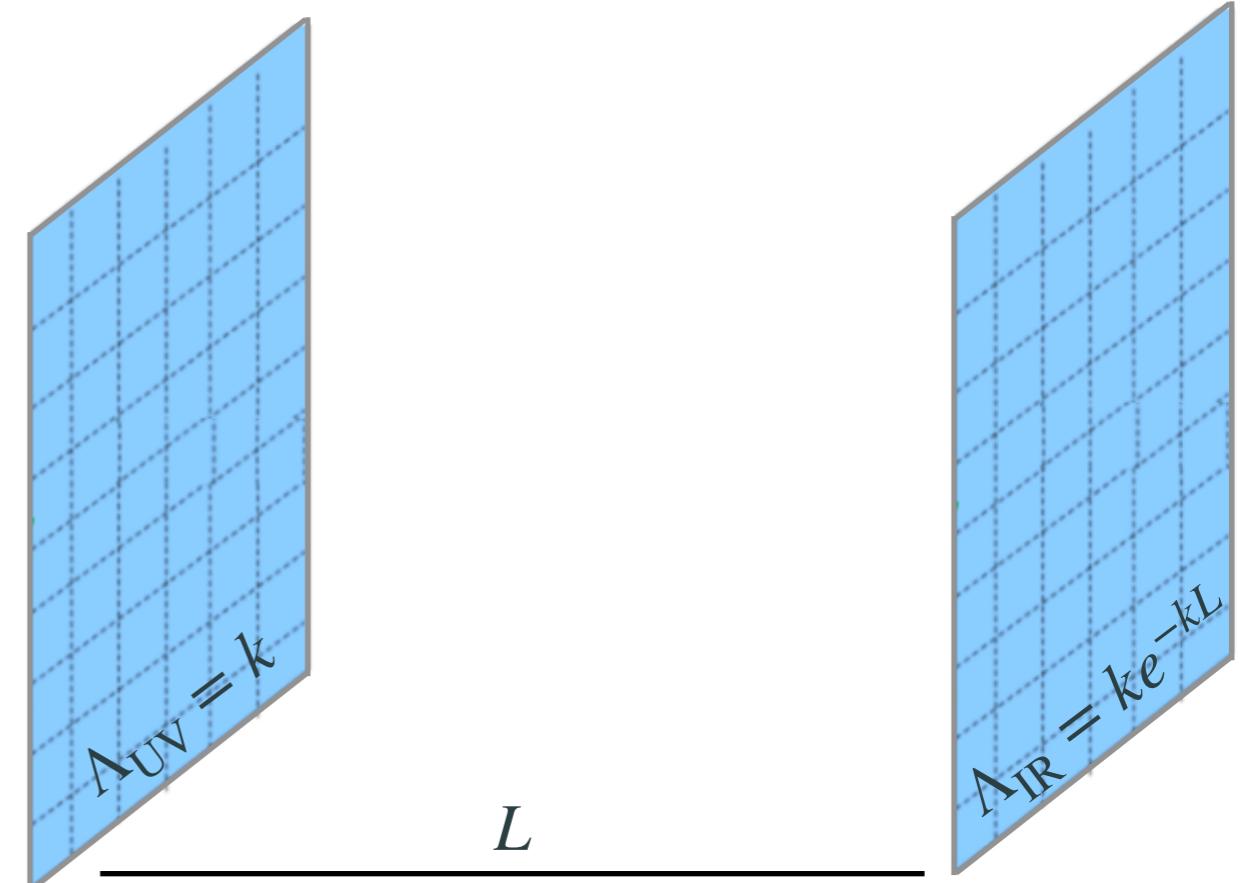


AdS/CFT correspondence relates a strongly coupled 4D CFT to a 5D theory with a warped fifth dimension.

Warped 5D (AdS_5)

Composite (4D CFT)

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



[Randall, Sundrum, [hep-ph/9905221](#)]

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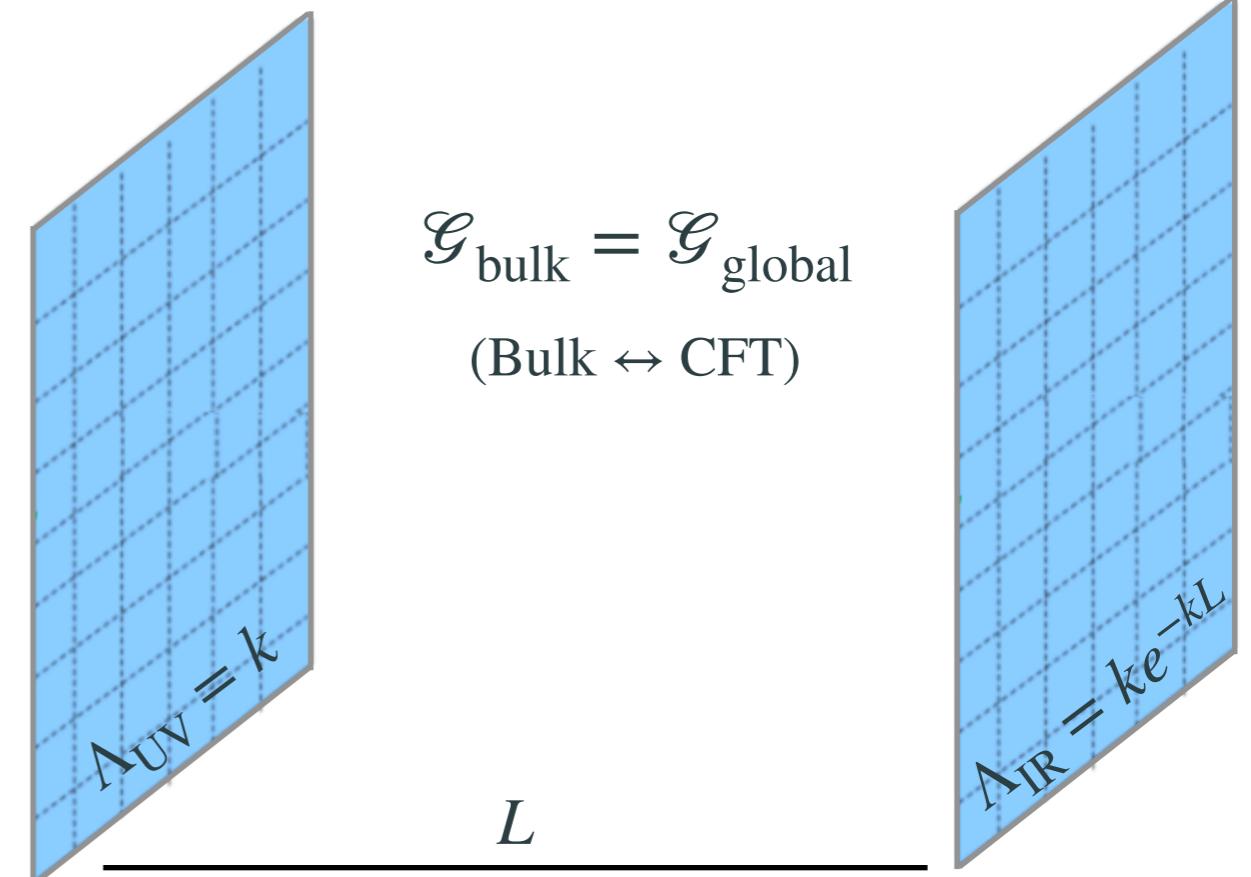
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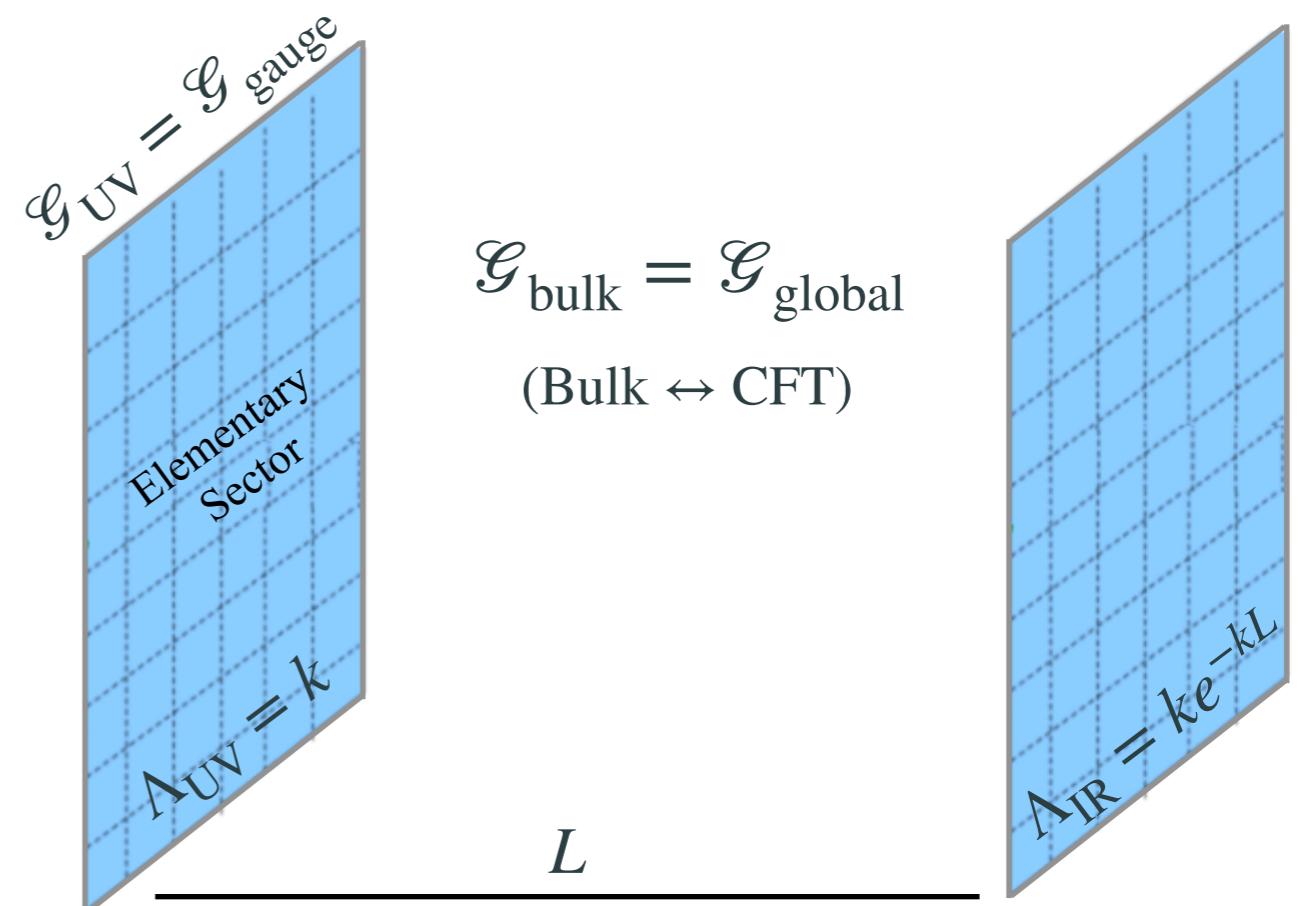
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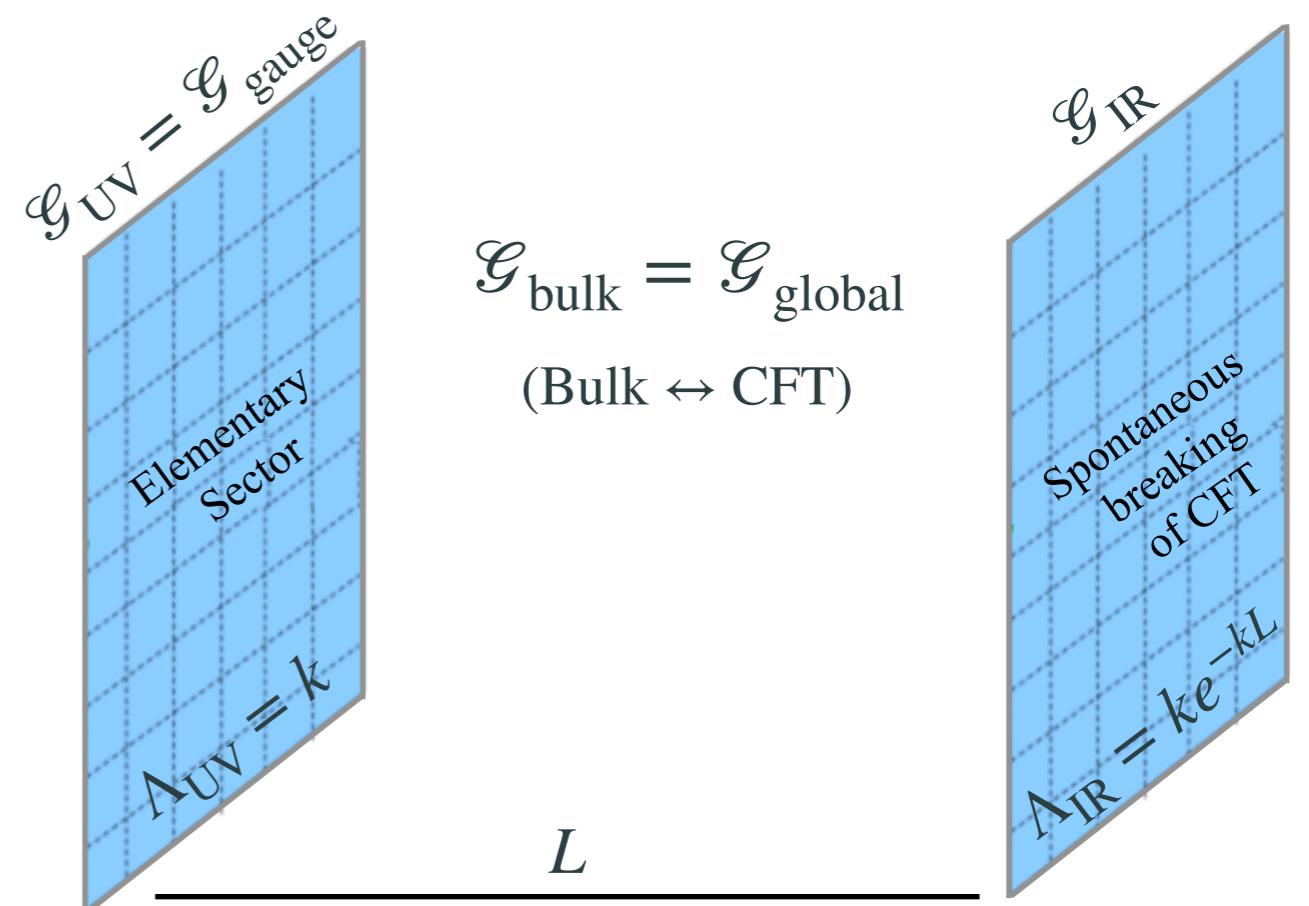
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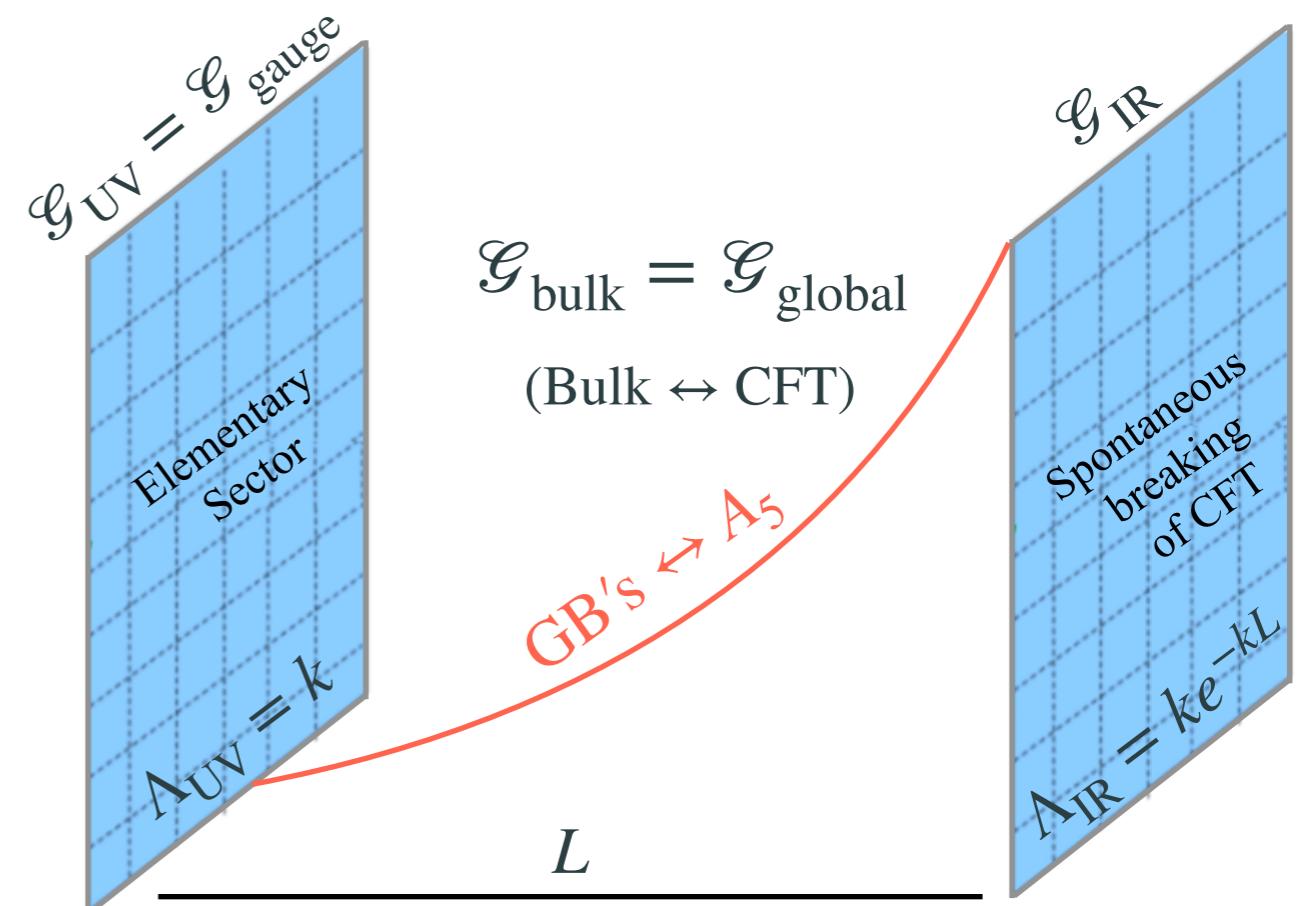
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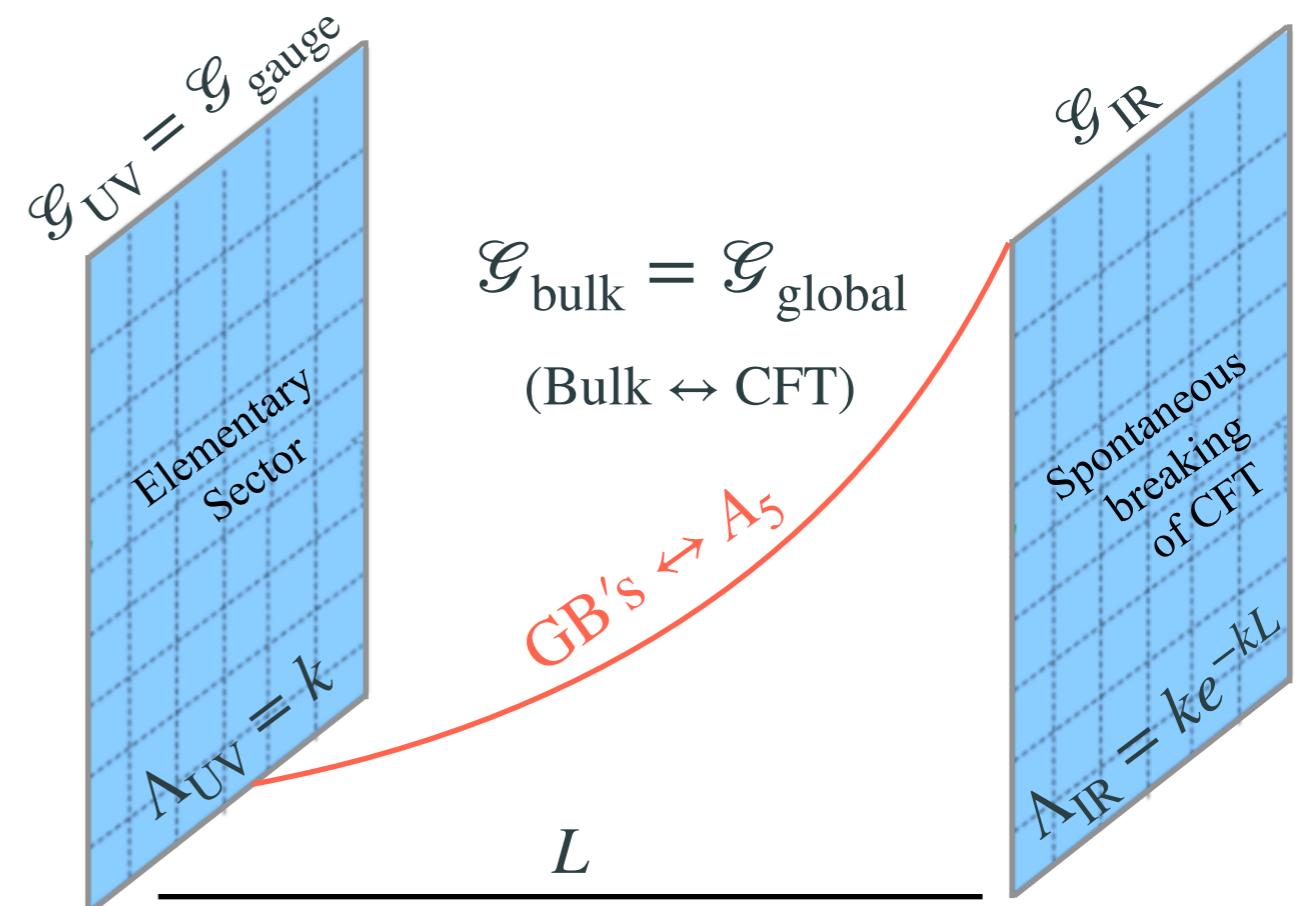
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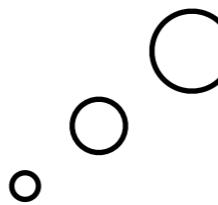


$$* \Lambda_{\text{IR}}/\Lambda_{\text{UV}} = e^{-kL} \quad \text{Large hierarchy solved à la RS}$$

[Randall, Sundrum, [hep-ph/9905221](#)]

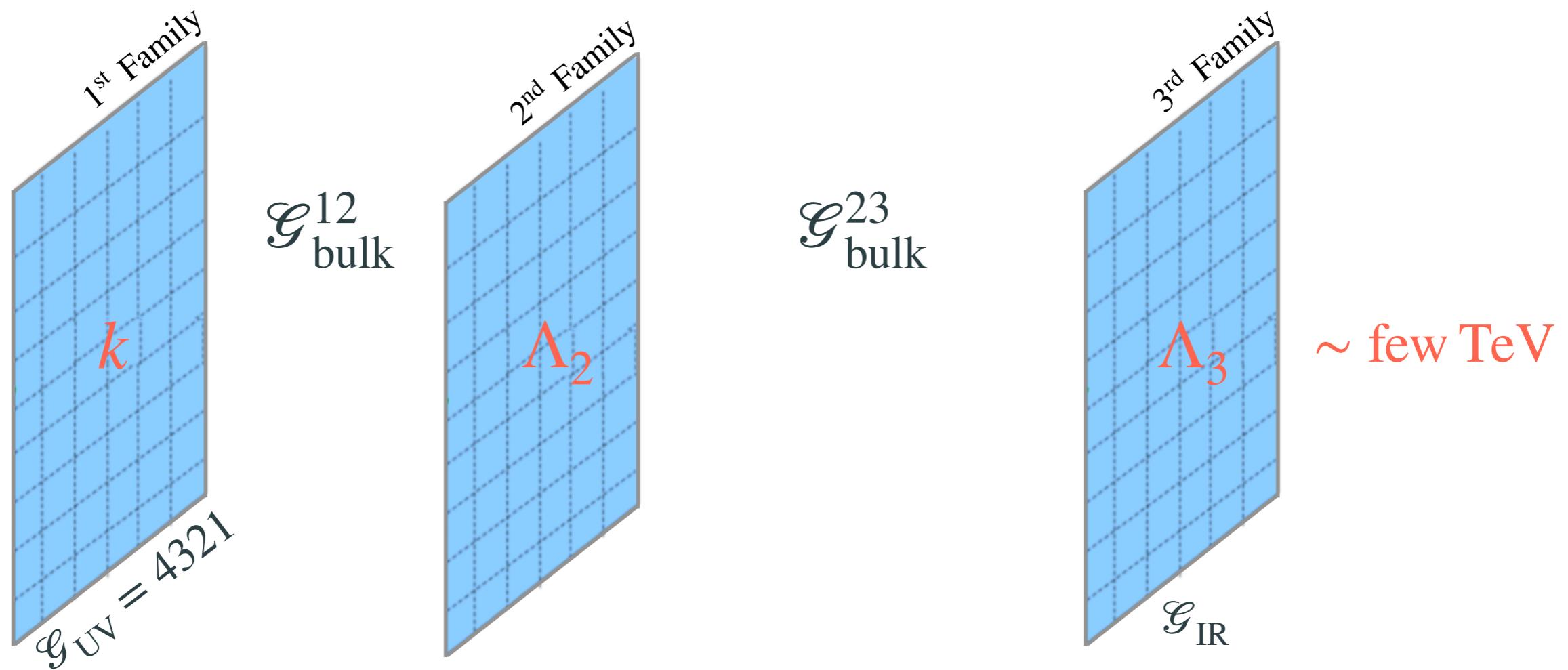
A Multi-Scale 5D Model

5D Model Builder's Toolbox



Spontaneous symmetry breakings

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

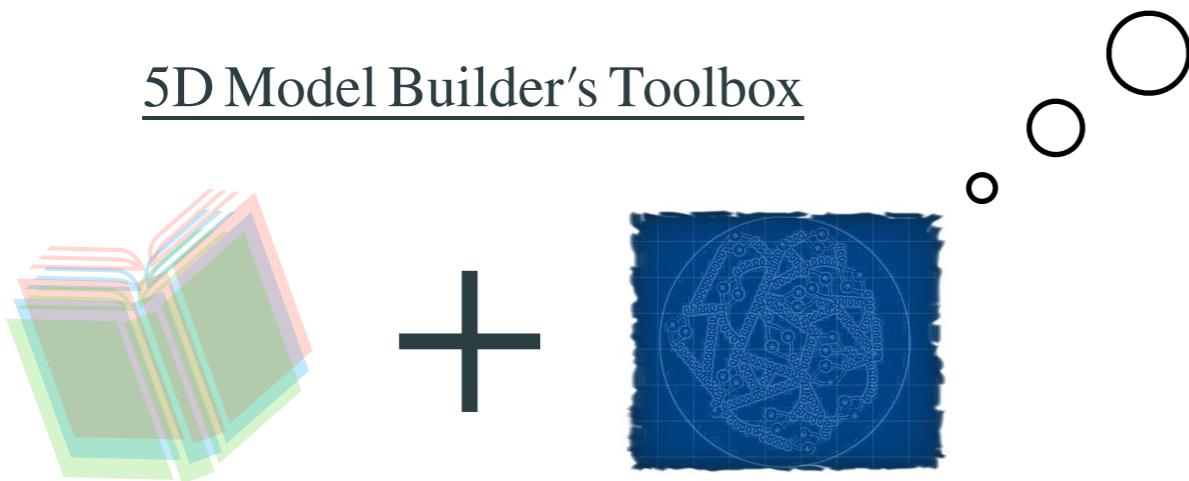


[Panico, Pomarol, [1603.06609](#)]

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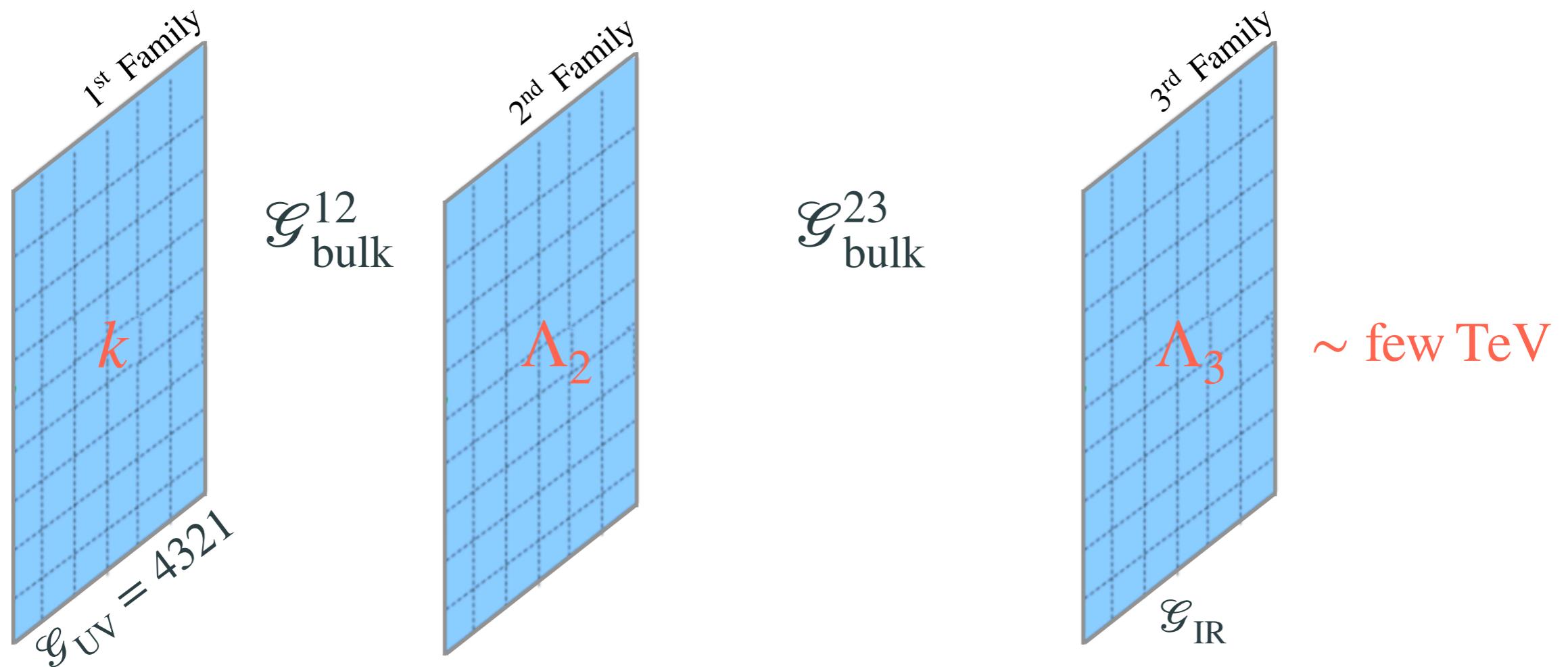


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↓ Λ_2 (6 broken)

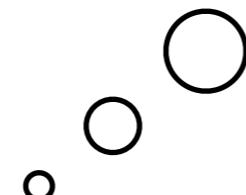
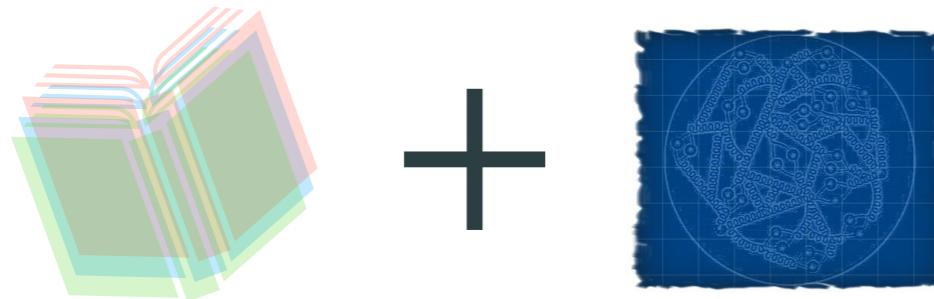
$$\mathcal{G}_{\text{bulk}}^{23} = SU(4)_h \times SU(3)_l \times U(1)_l \times SO(5)$$



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Spontaneous symmetry breakings

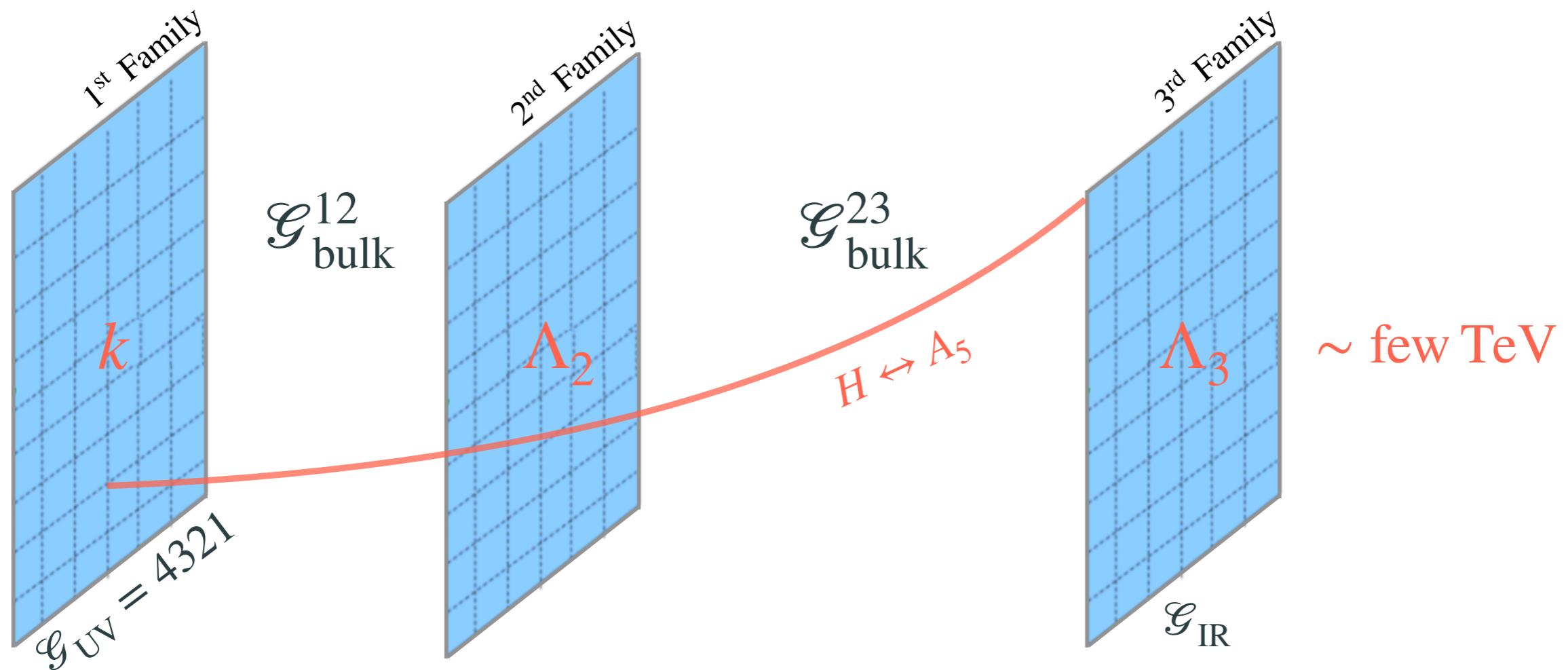
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$$\mathcal{G}_{\text{bulk}}^{23} = SU(4)_h \times SU(3)_l \times U(1)_l \times SO(5)$$

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

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



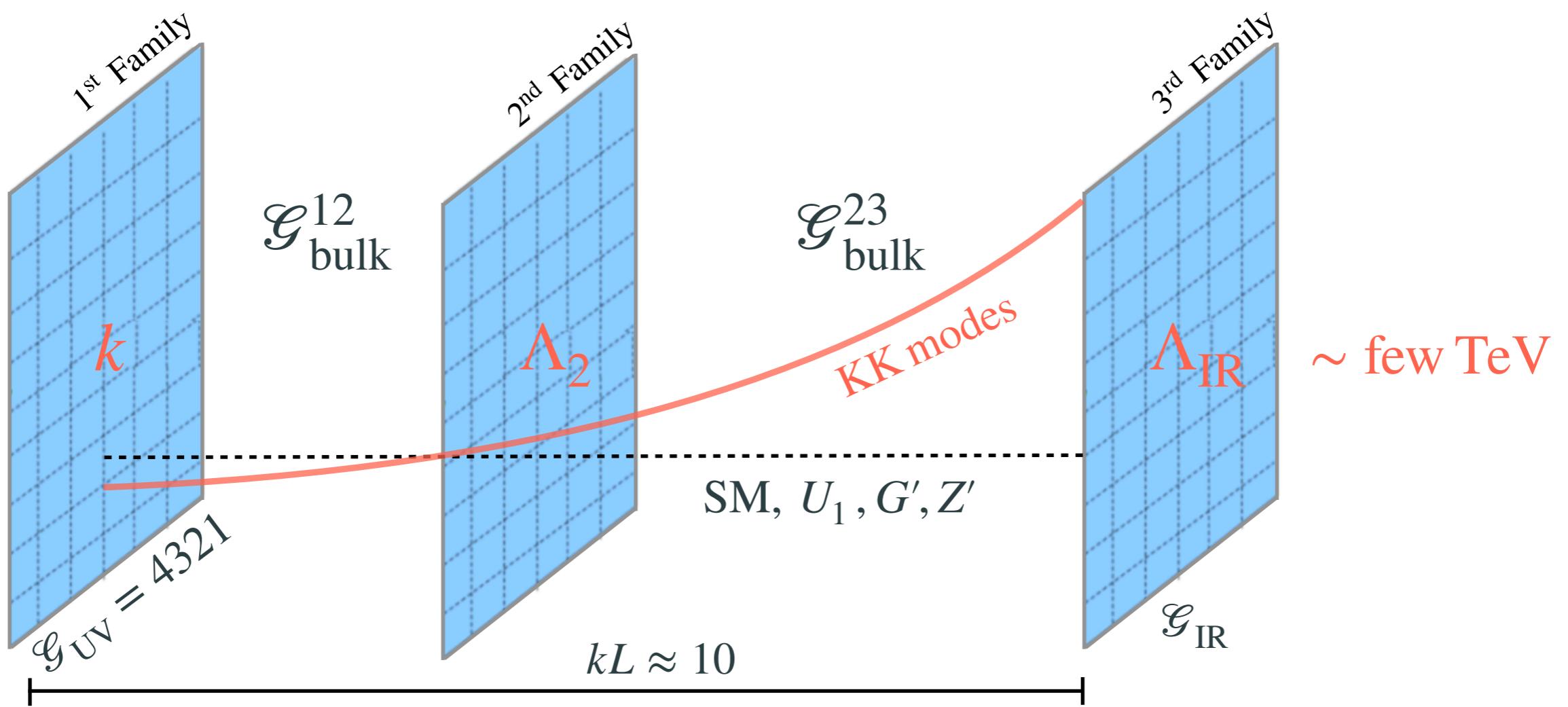
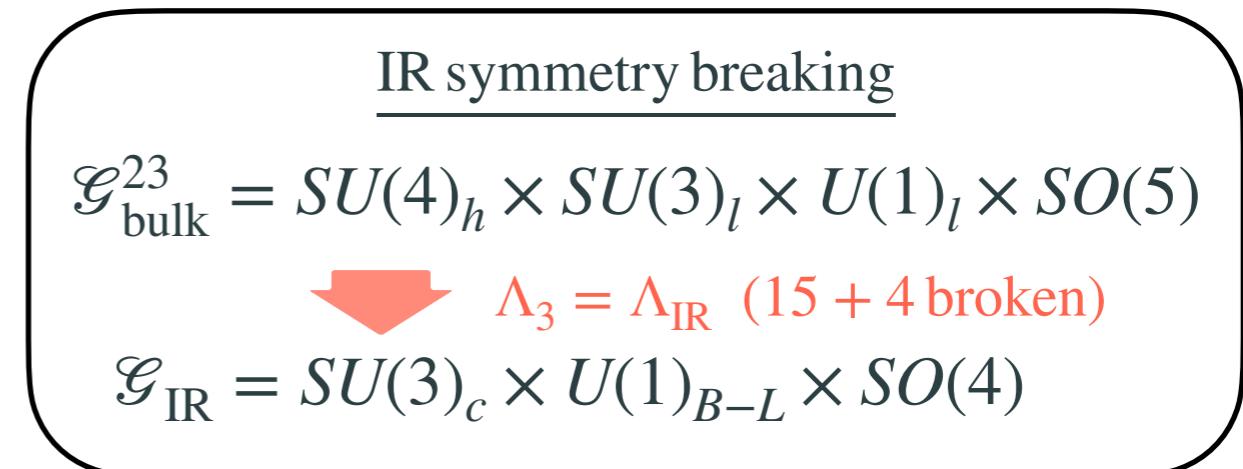
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Gauge Sector

In breaking $\mathcal{G}_{\text{bulk}}^{23} \rightarrow \mathcal{G}_{\text{IR}}$, the 4321 gauge bosons acquire a mass of:

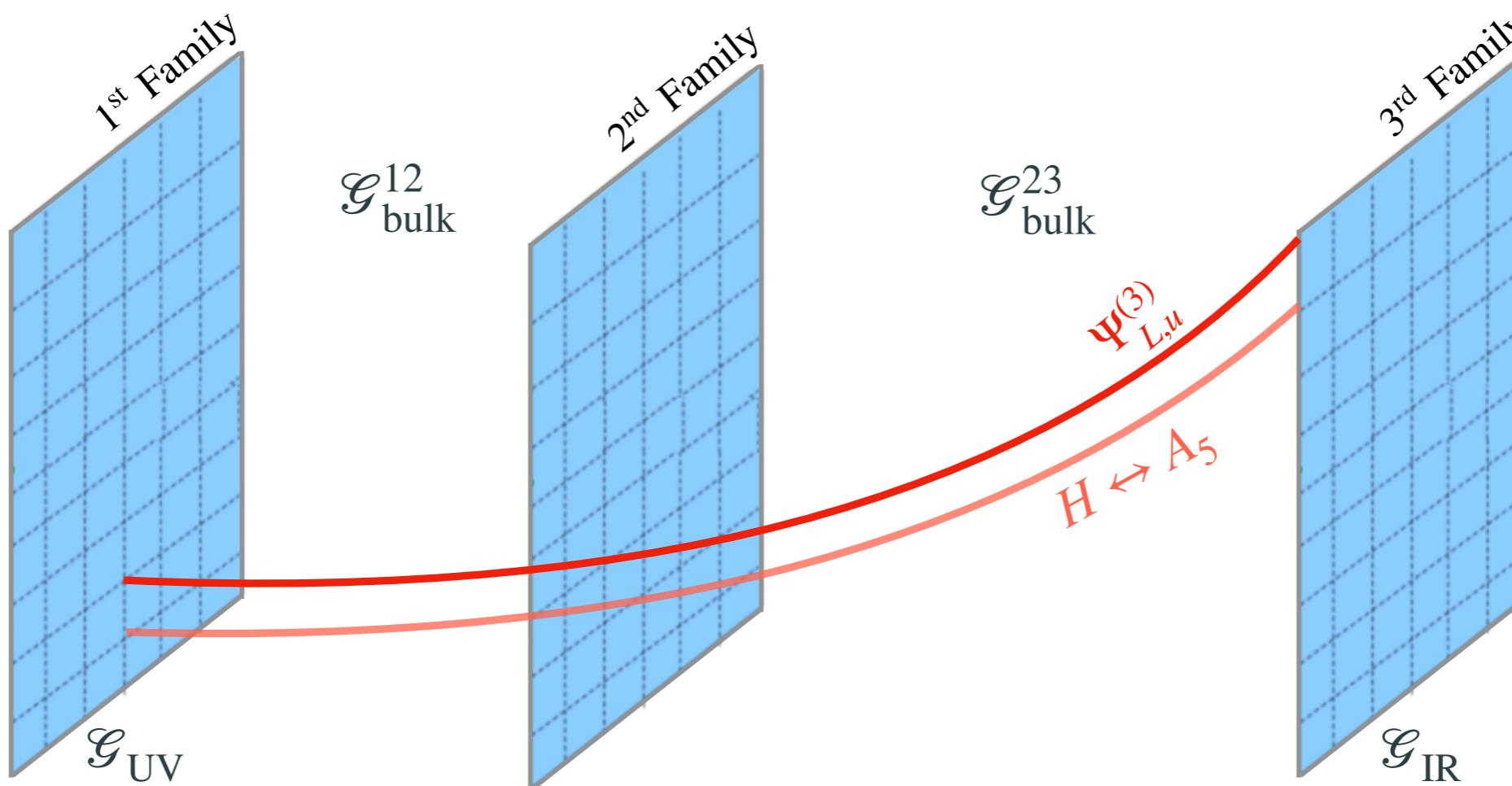
$$M_{15} = \sqrt{\frac{2}{kL}} \Lambda_{\text{IR}} = \frac{M_{\text{KK}}}{\sqrt{2kL}}$$



Gauge-Higgs Unification and the Top Yukawa

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

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



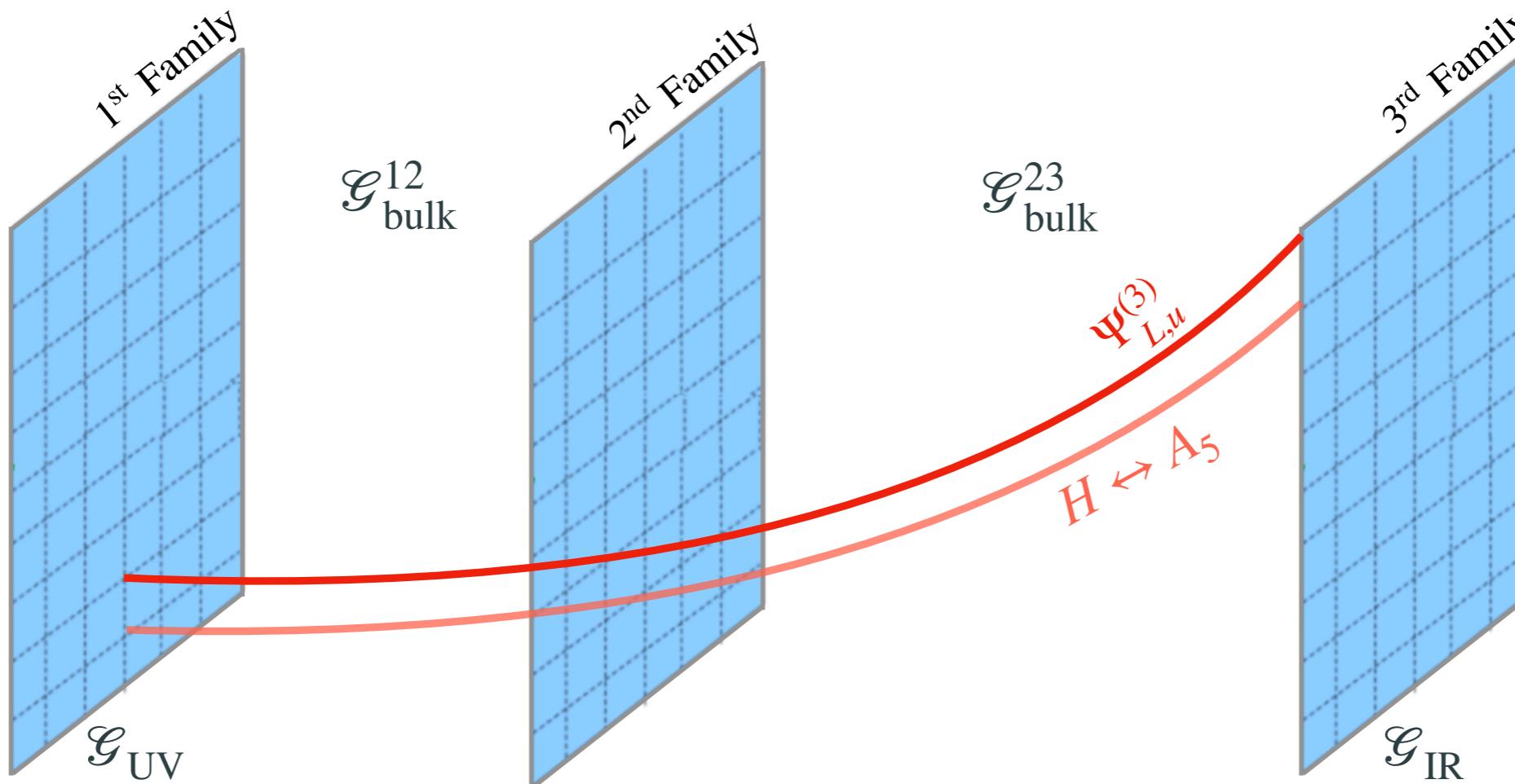
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Can remove H from the bulk due to the $SO(5)$ invariance:

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

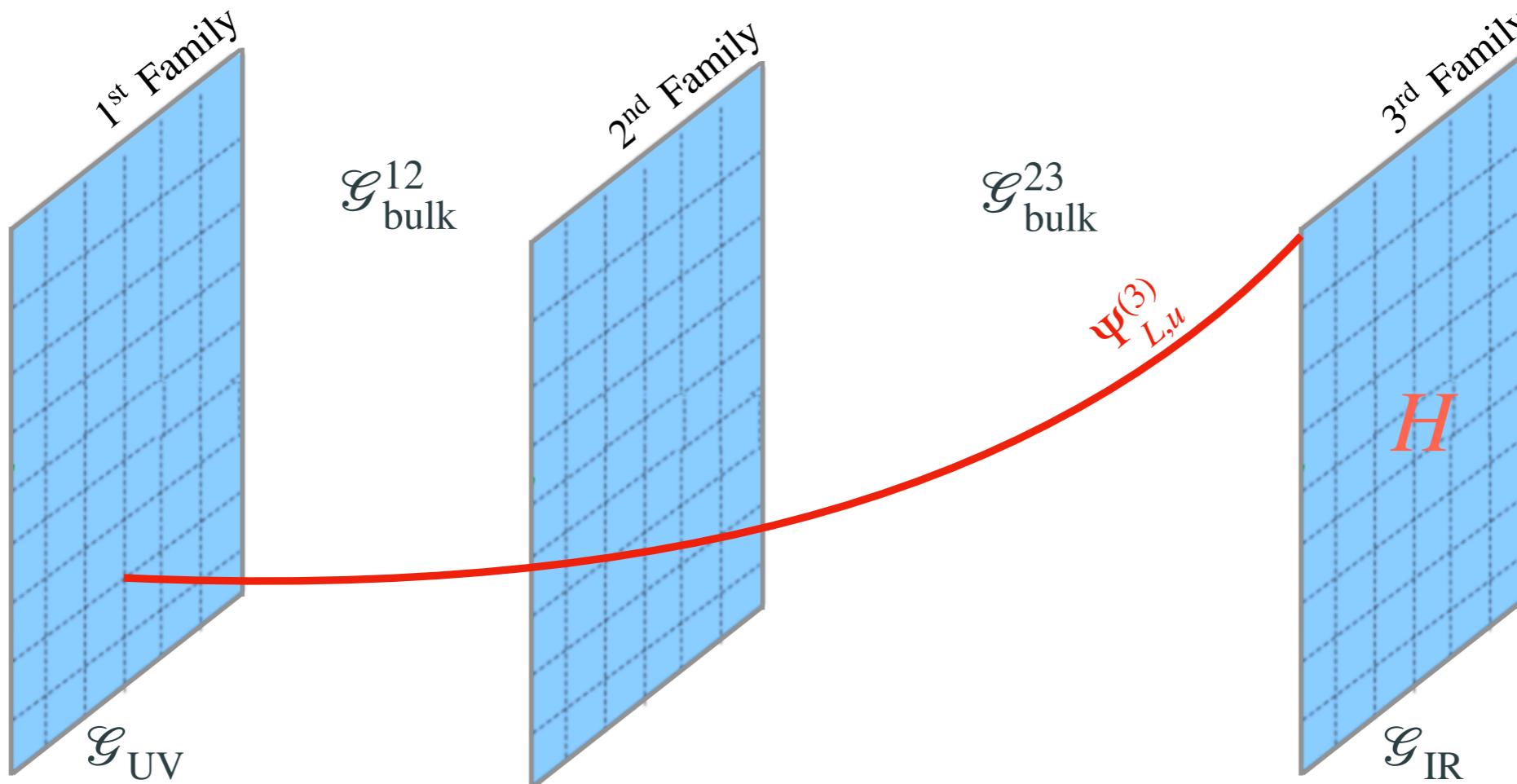


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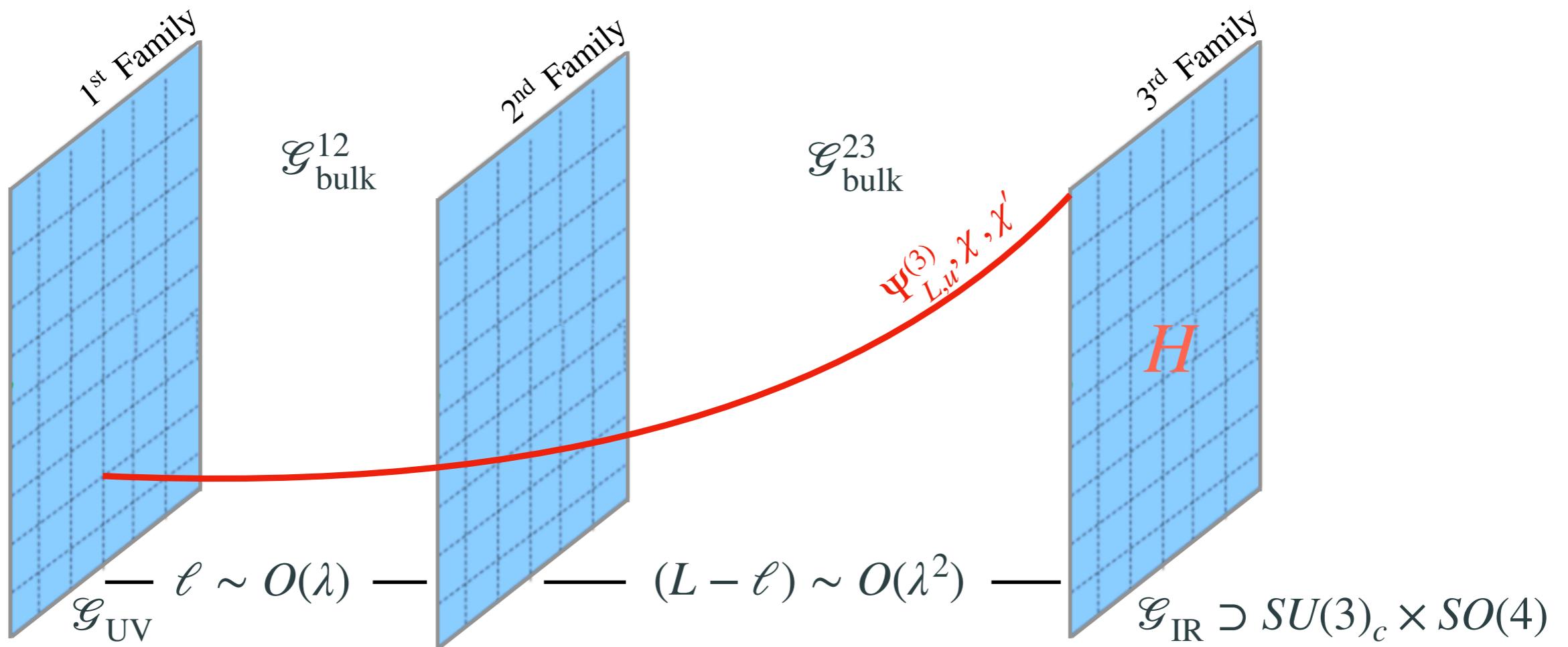
$$\Psi^3 = e^{-i \frac{g_*}{\sqrt{2}} \frac{T^{\hat{a}} h^{\hat{a}}}{\Lambda_{\text{IR}}}} \begin{bmatrix} \psi^3 (+, +) \\ \psi_u^3 (-, -) \\ \tilde{\psi}_d^3 (+, -) \end{bmatrix} \begin{array}{l} q_L \\ t_R \\ B_{L,R} \end{array} \} \begin{array}{l} SU(2)_L \\ SU(2)_R \end{array}$$

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



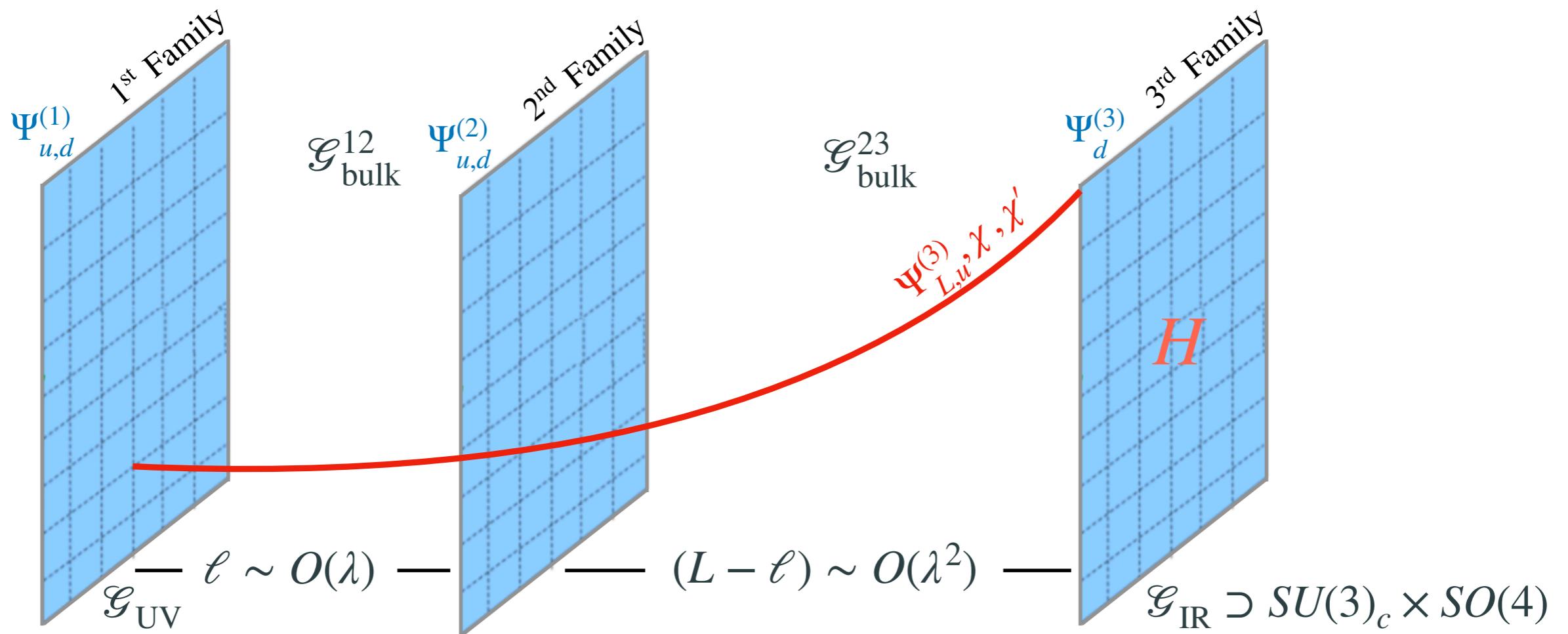
Light-Heavy Fermion Mixing in the IR

Field	$SU(4)_h$	$SU(4)_l$	$SO(5)$
Ψ^3, Ψ_d^3, χ'	4	1	4
$\Psi^j, \Psi_{u,d}^j$	1	4	4



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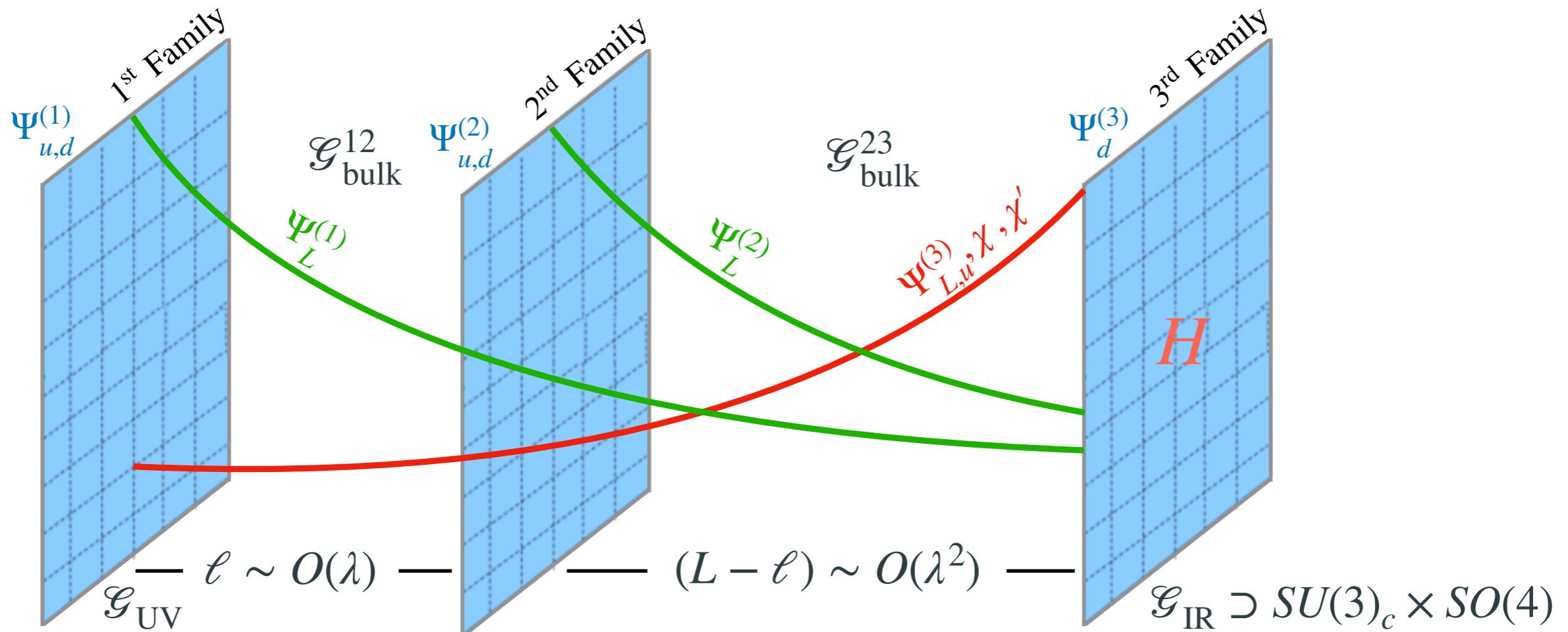
Light-Heavy Fermion Mixing in the IR

Field	$SU(4)_h$	$SU(4)_l$	$SO(5)$
Ψ^3, Ψ_d^3, χ'	4	1	4
$\Psi^j, \Psi_{u,d}^j$	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.

$$y_{f1f2} = \frac{g_*}{2\sqrt{2}} (\tilde{M}_{12}^L - \tilde{M}_{12}^R) P(M_{f_1}, M_{f_2})$$

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



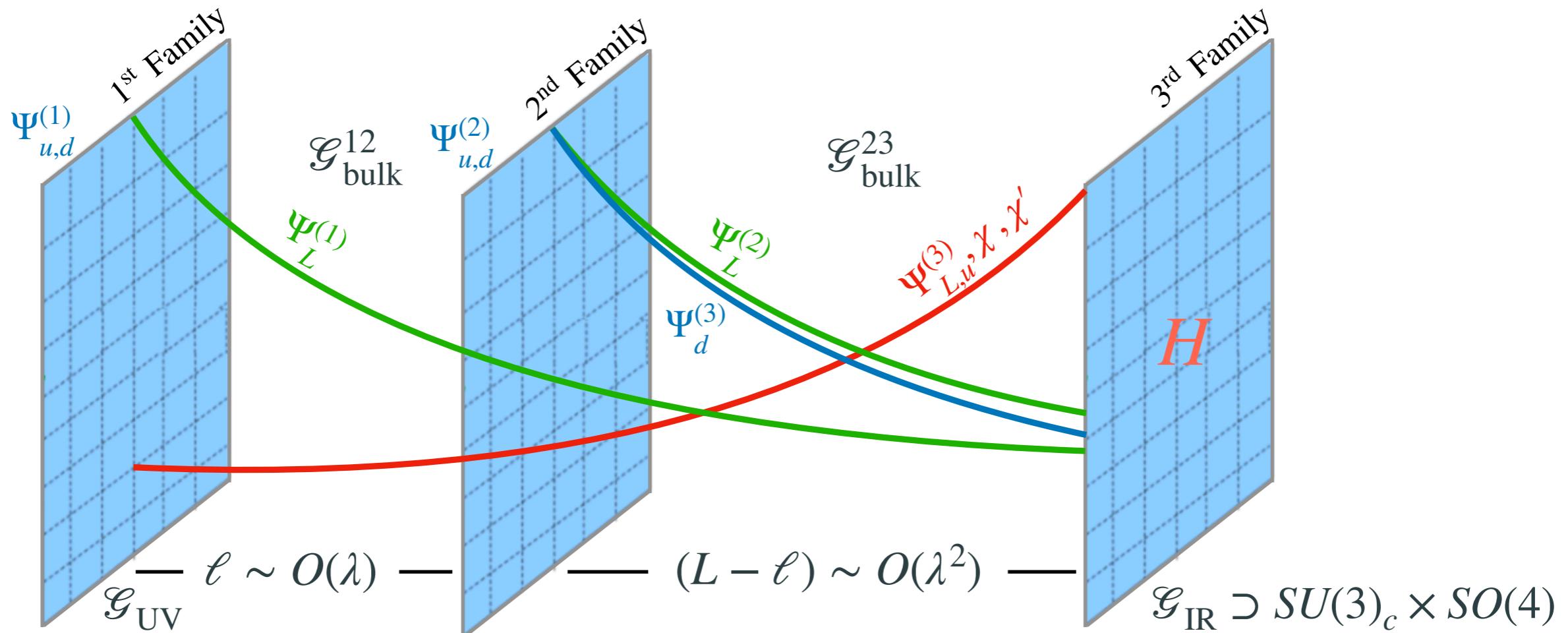
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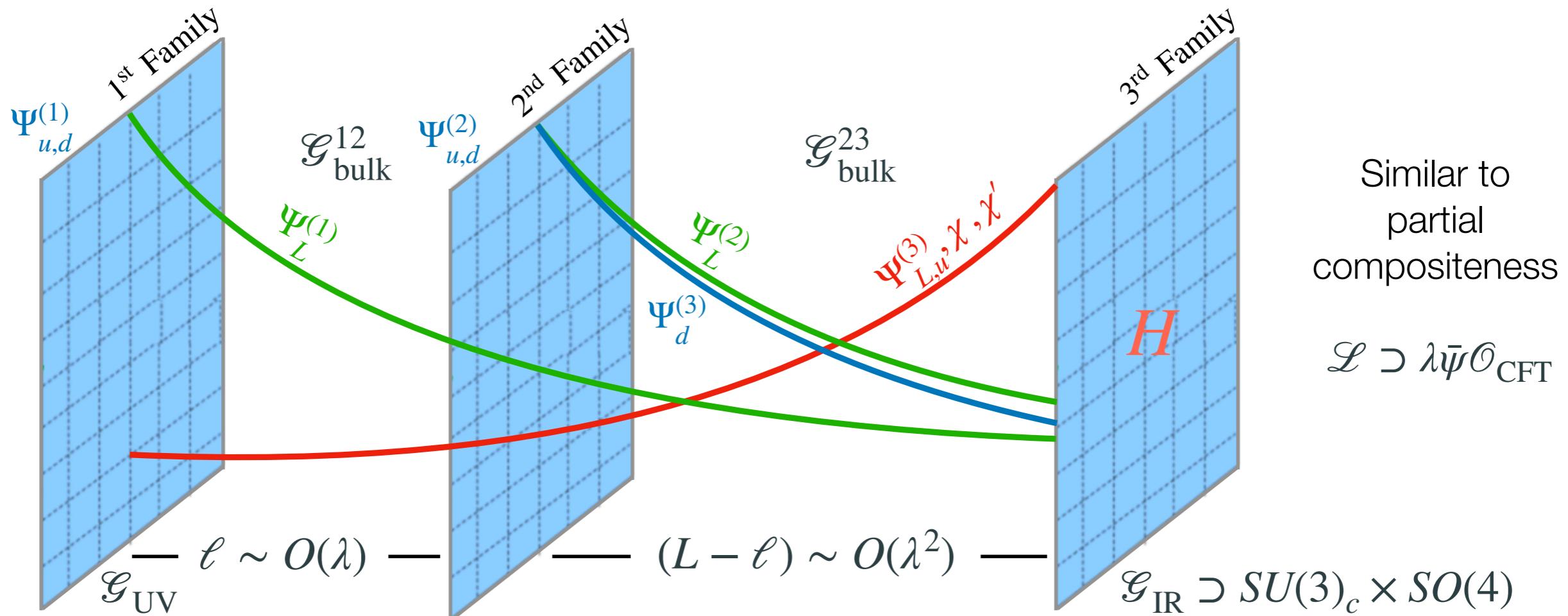
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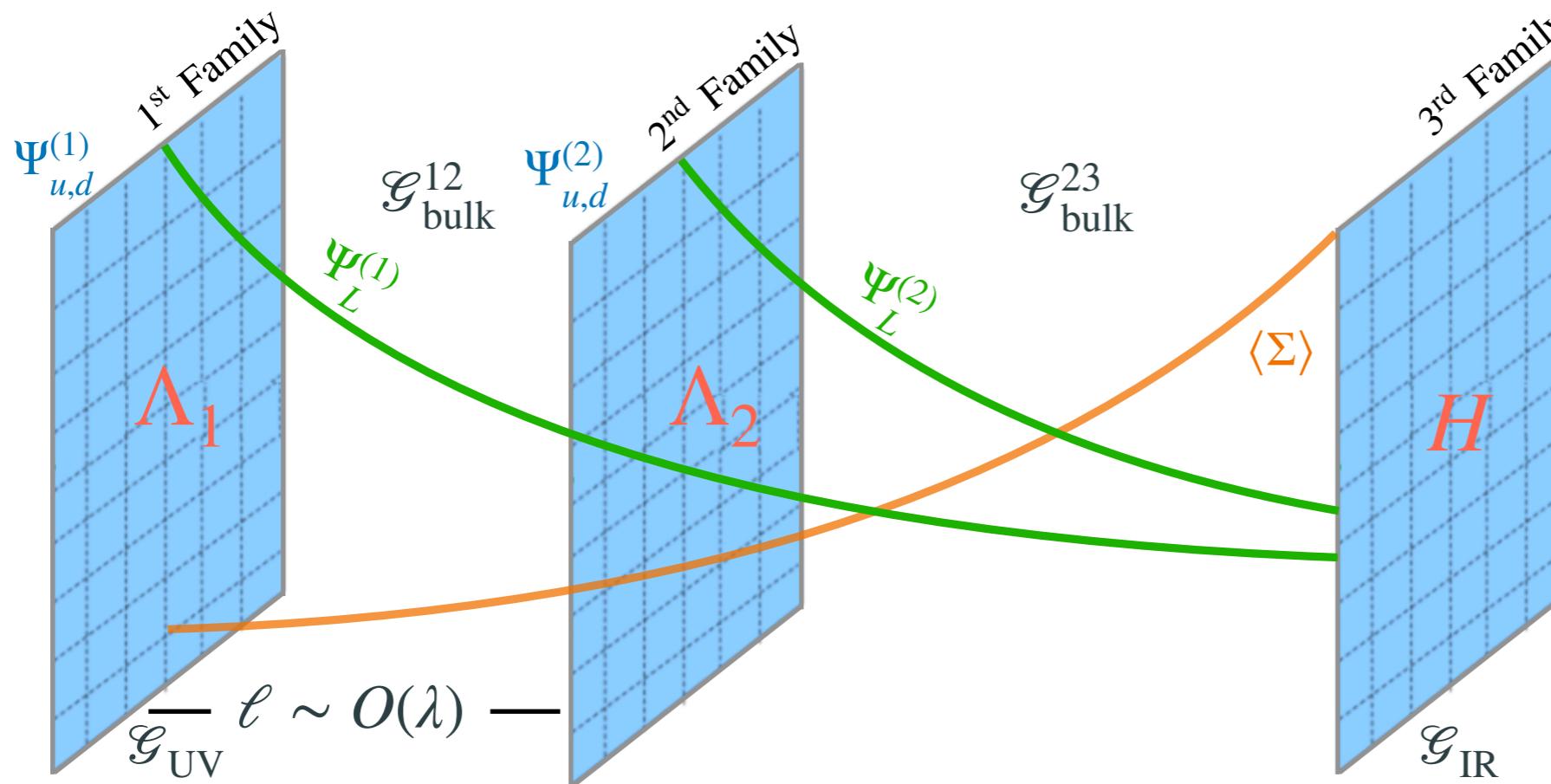
[Fuentes-Martin, Isidori, Lizana, Selimovic, BAS, [2203.01952](#)]

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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:

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



[Panico, Pomarol, [1603.06609](#)]

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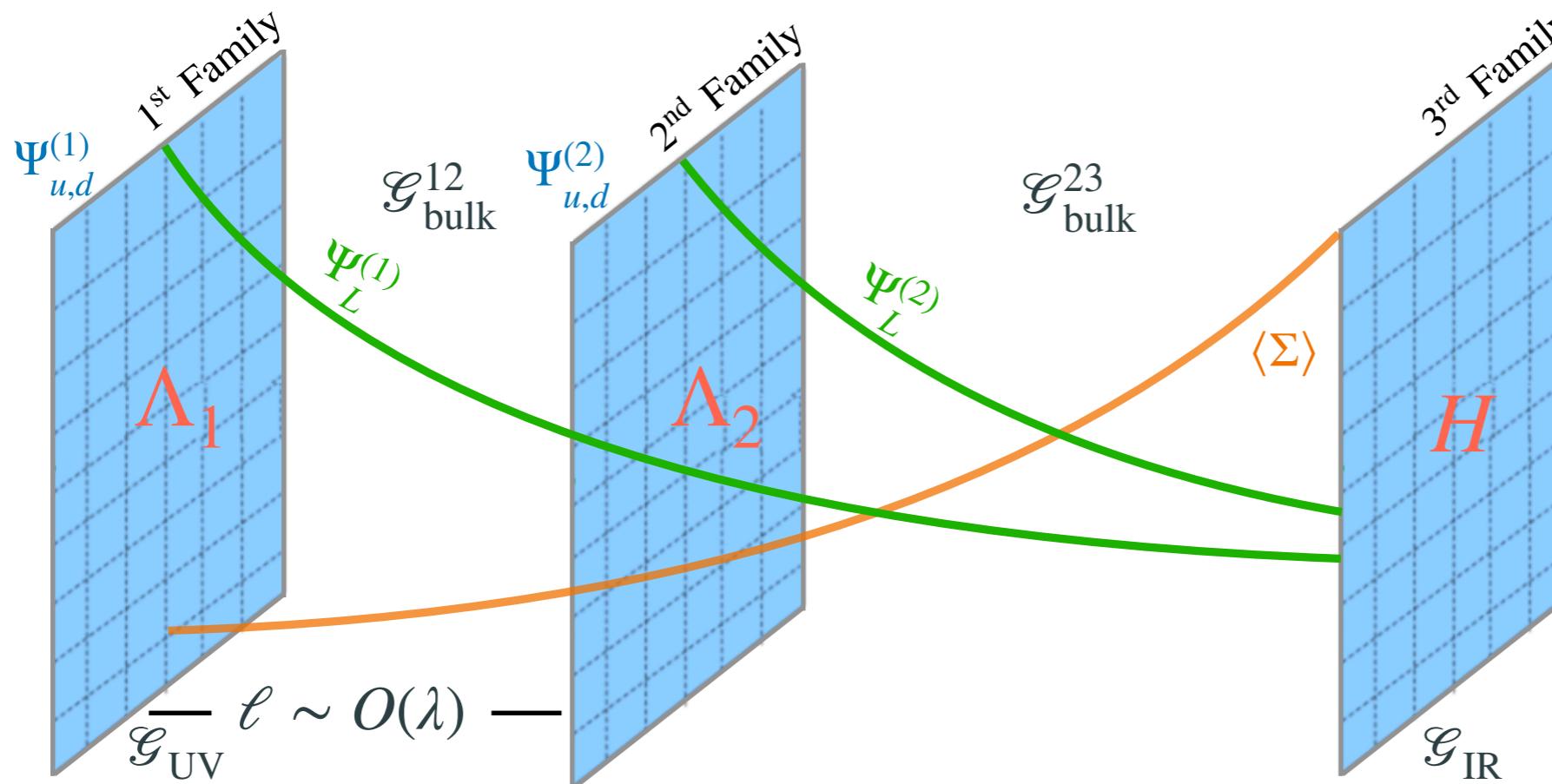
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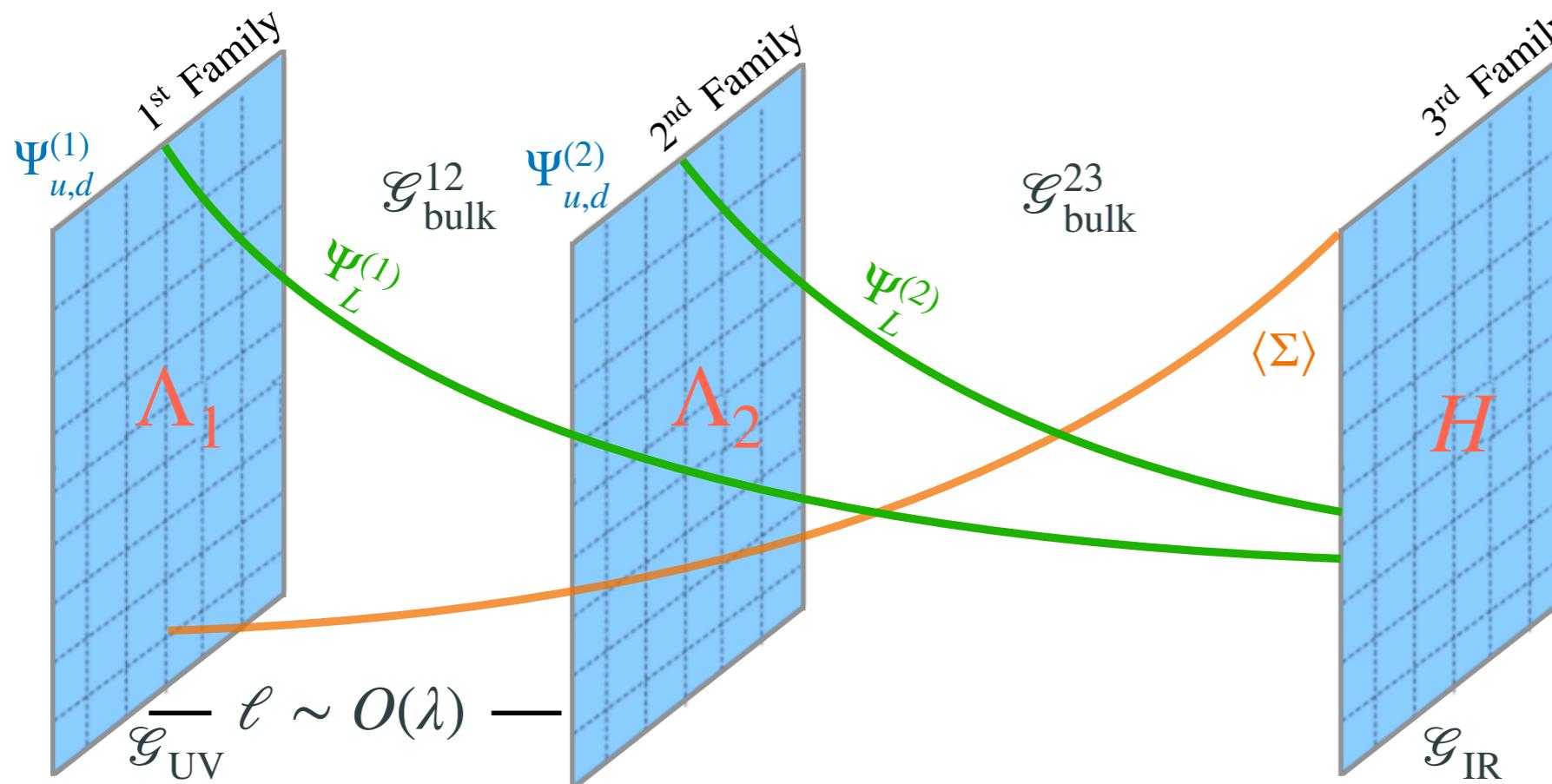
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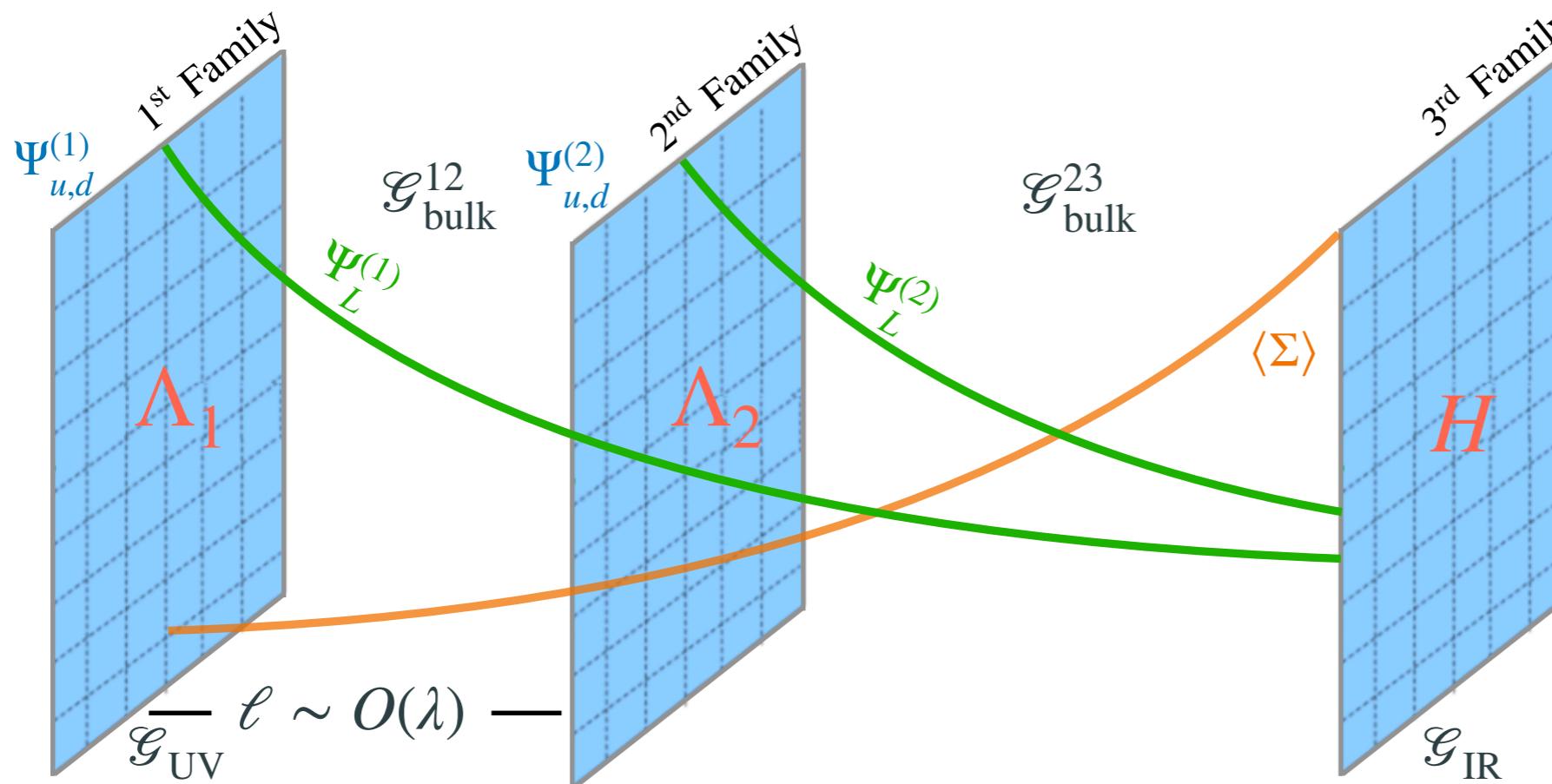
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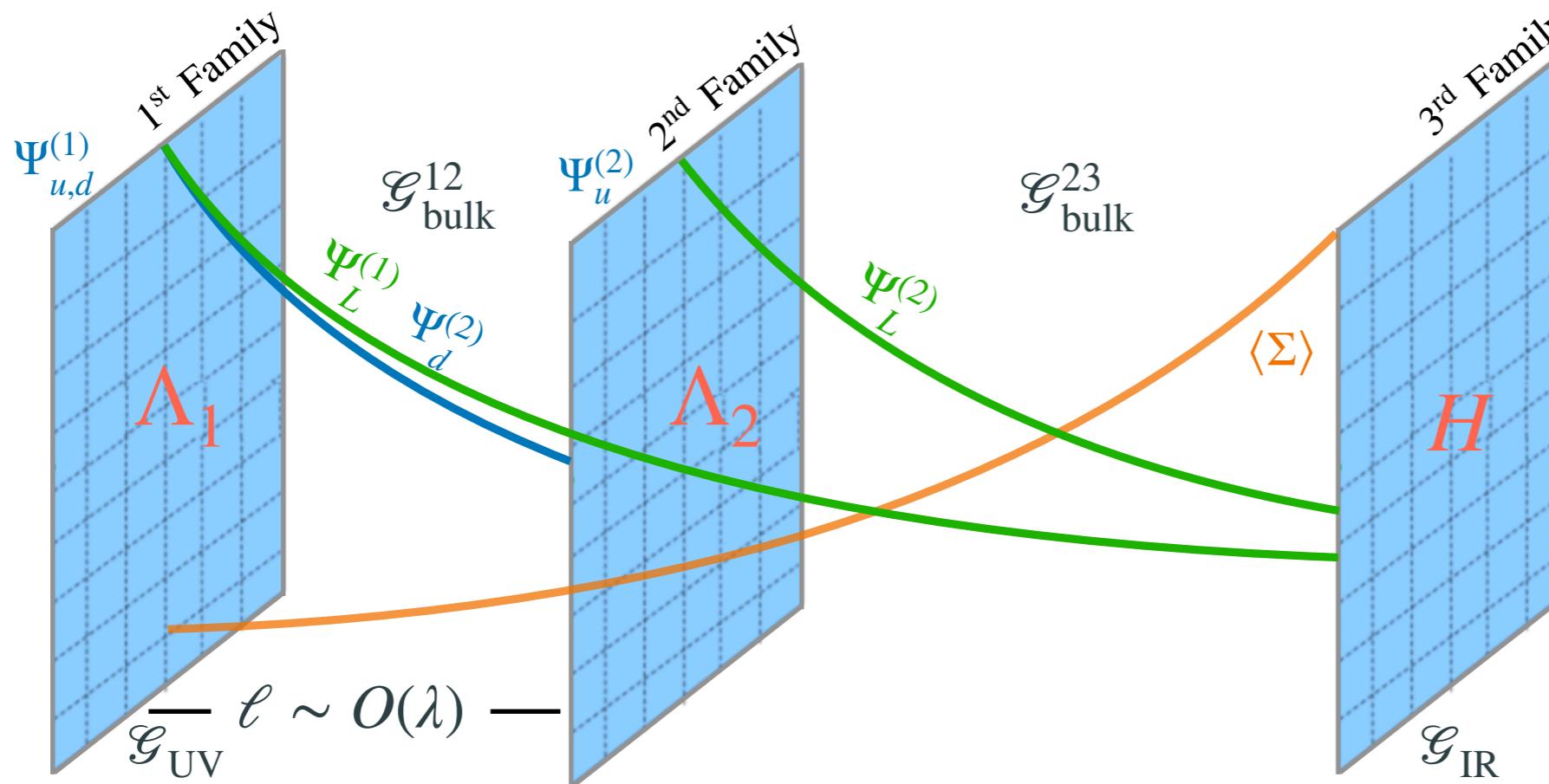
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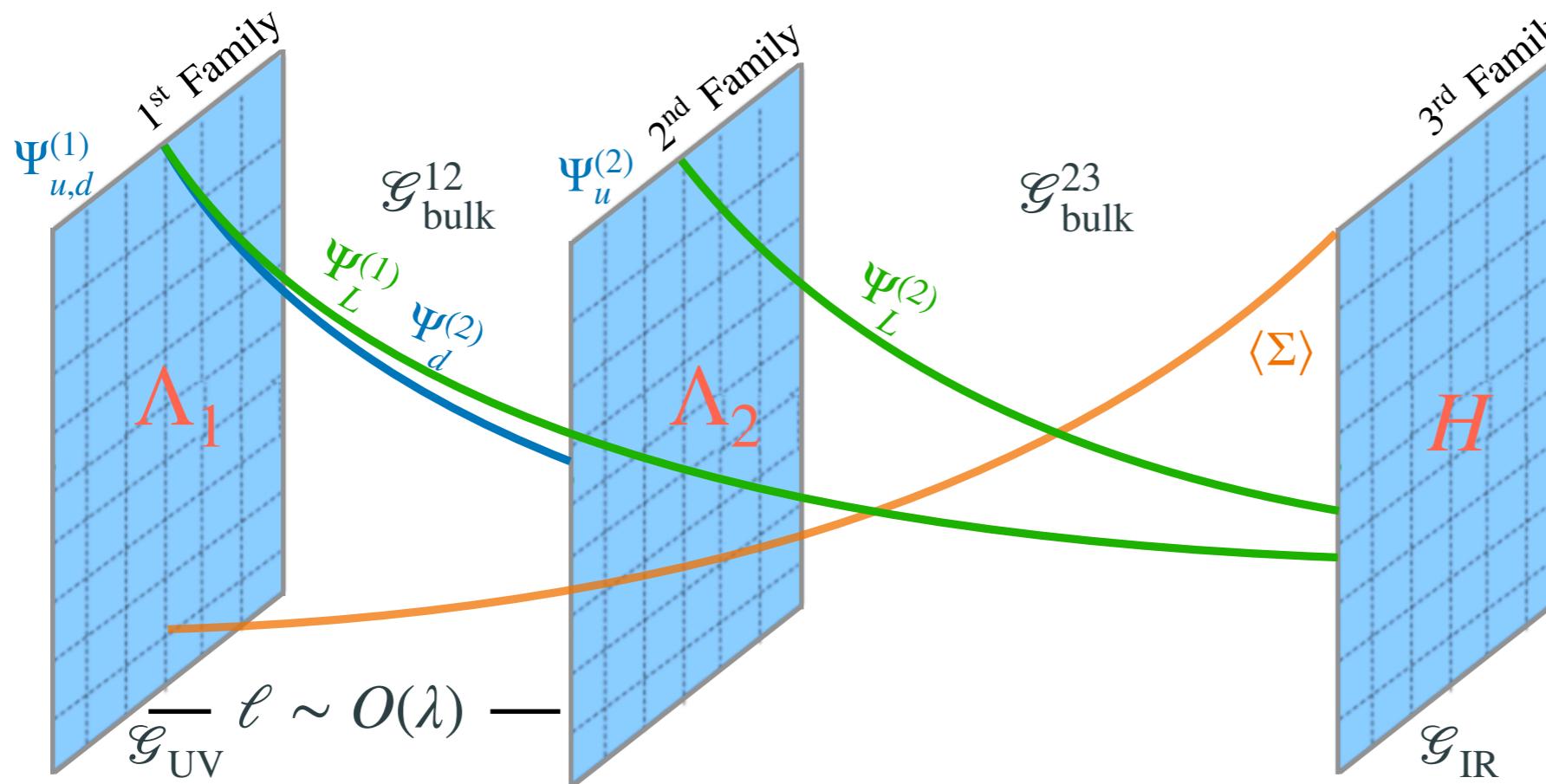
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Direct (irrelevant) coupling to a composite operator containing the Higgs

$$\mathcal{L} \sim \frac{1}{\Lambda} \bar{\psi}_L \mathcal{O}_H \psi_R$$

[Panico, Pomarol, [1603.06609](#)]

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Higgs Potential

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

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

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$$\lambda \approx \frac{1}{16\pi^2} \left[N_c y_t^4 \log \frac{\Lambda_{\text{IR}}^2}{m_t^2} - \frac{9}{32} \zeta(3) g_*^2 (3g_L^2 + g_Y^2) \right]$$

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

Little hierarchy and the B-anomalies

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

U_1, G', Z' Masses :

$$M_{15} = \frac{M_{\text{KK}}}{\sqrt{2kL}} = \frac{g_* f}{\sqrt{2kL}} \quad (g_* \approx 2.5, kL \approx 10)$$

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

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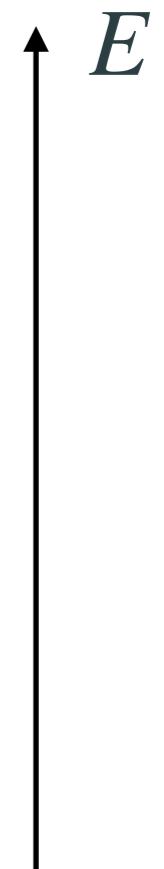
Benchmark Spectrum :

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

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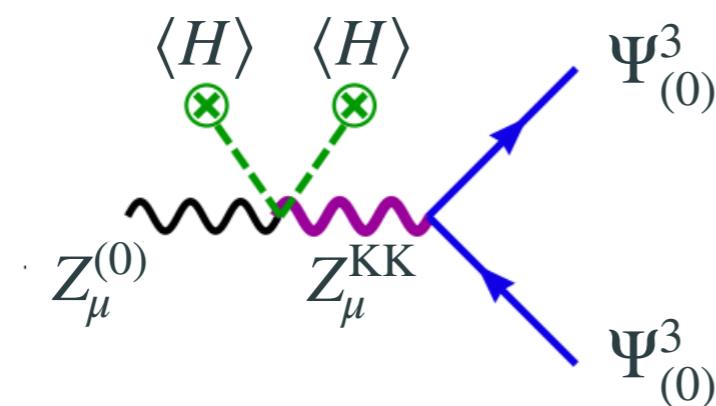
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Leading effect in $Z \rightarrow \tau_L \tau_L$

$$\frac{\delta g_{Z\Psi^3\Psi^3}}{g_{Z\Psi^3\Psi^3}} \approx -0.3 \frac{m_Z^2}{M_{\text{KK}}^2} \frac{g_*^2}{g_L^2} \approx -\frac{0.3}{4c_W^2} \frac{\langle h \rangle^2}{f^2} \lesssim 10^{-3}$$

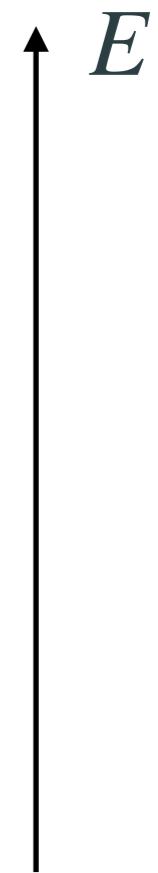
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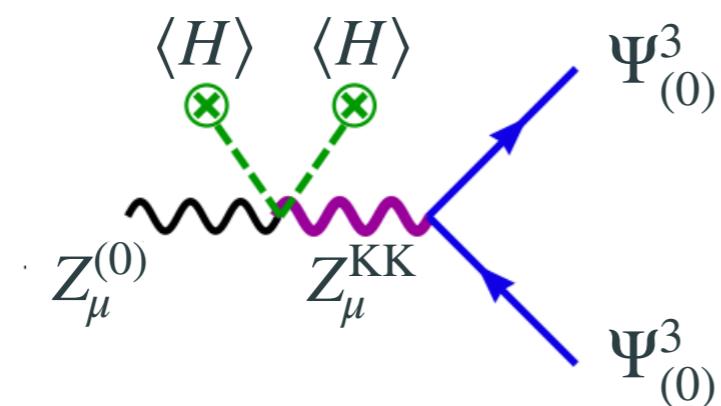
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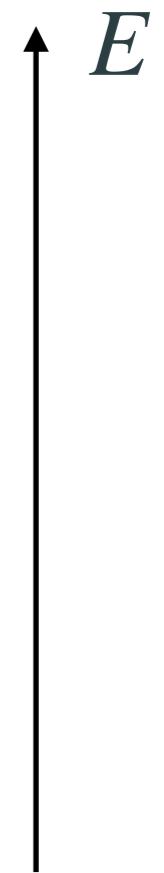
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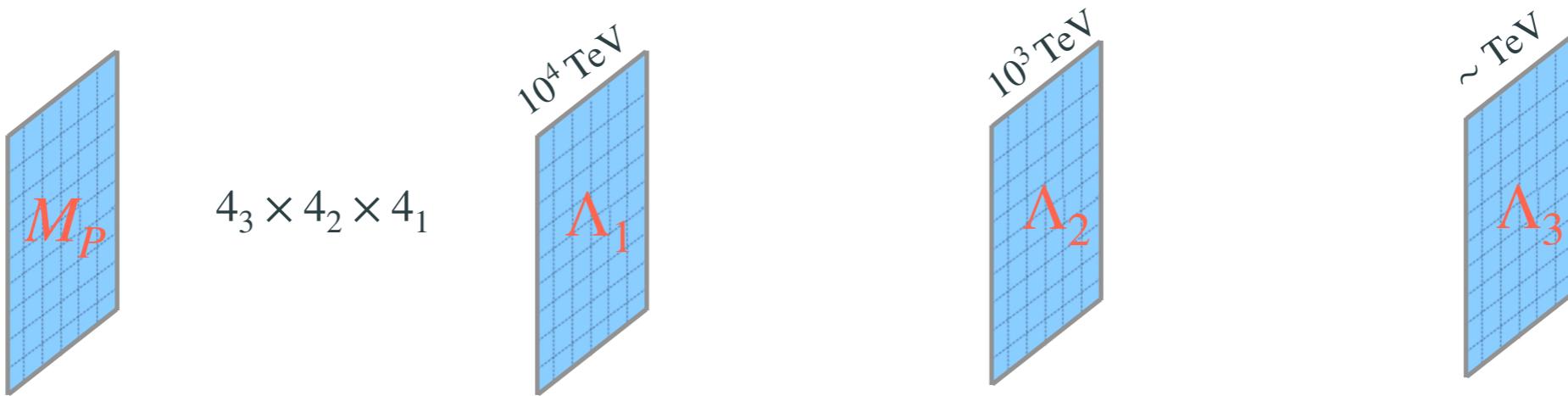
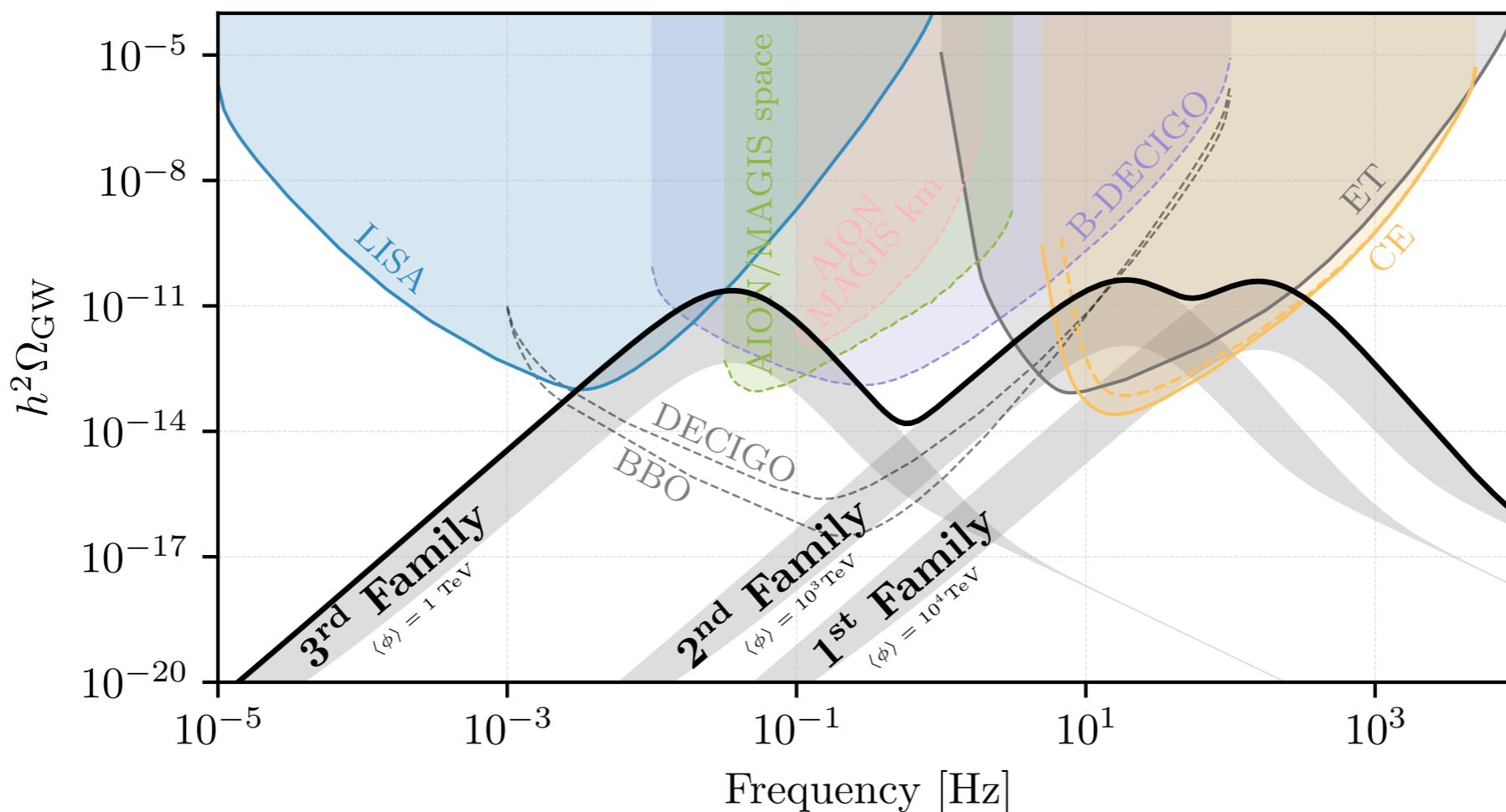
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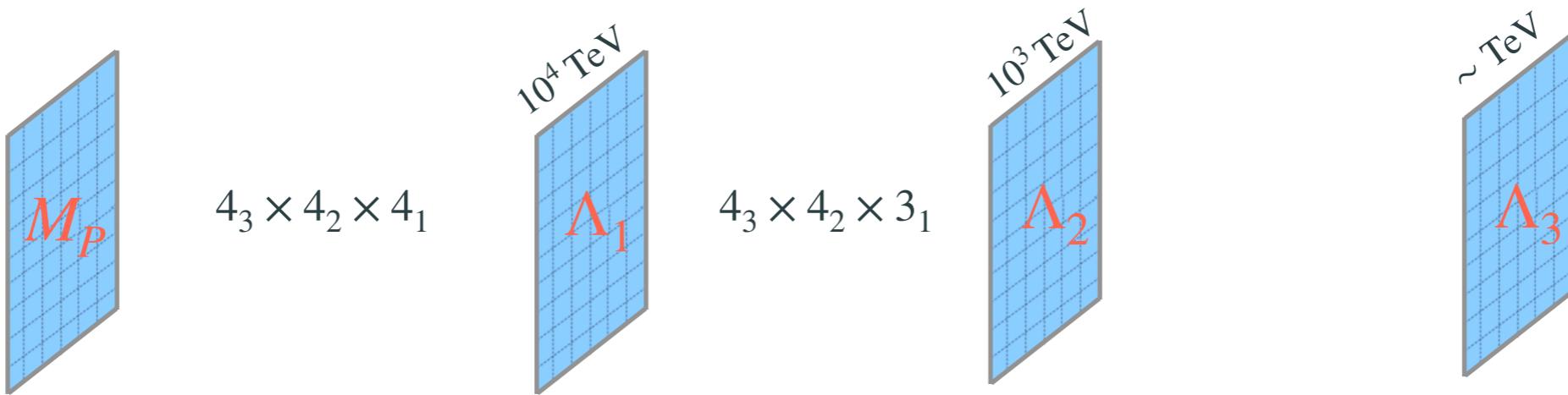
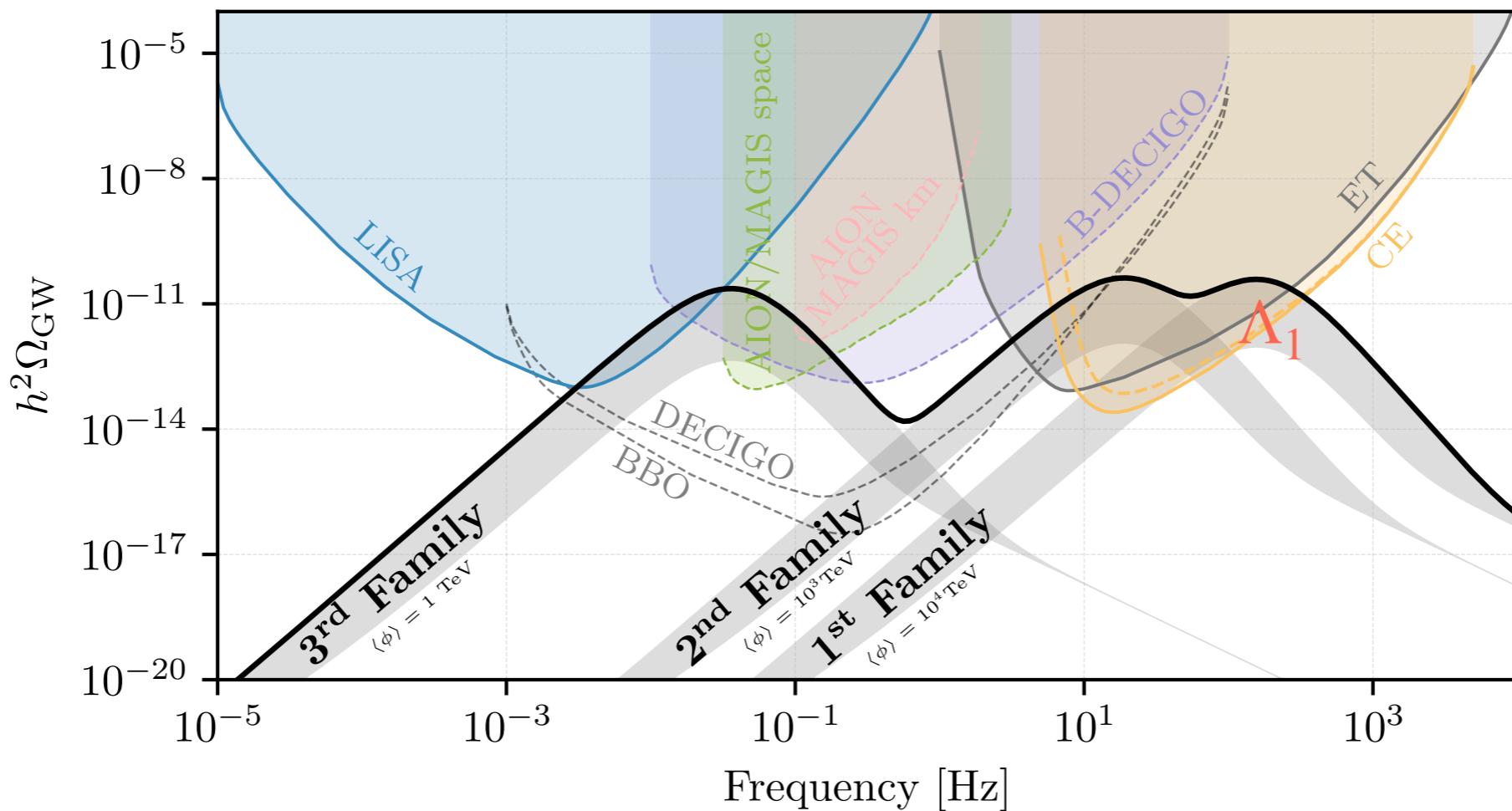
Extension to Planck and Cosmological Signatures



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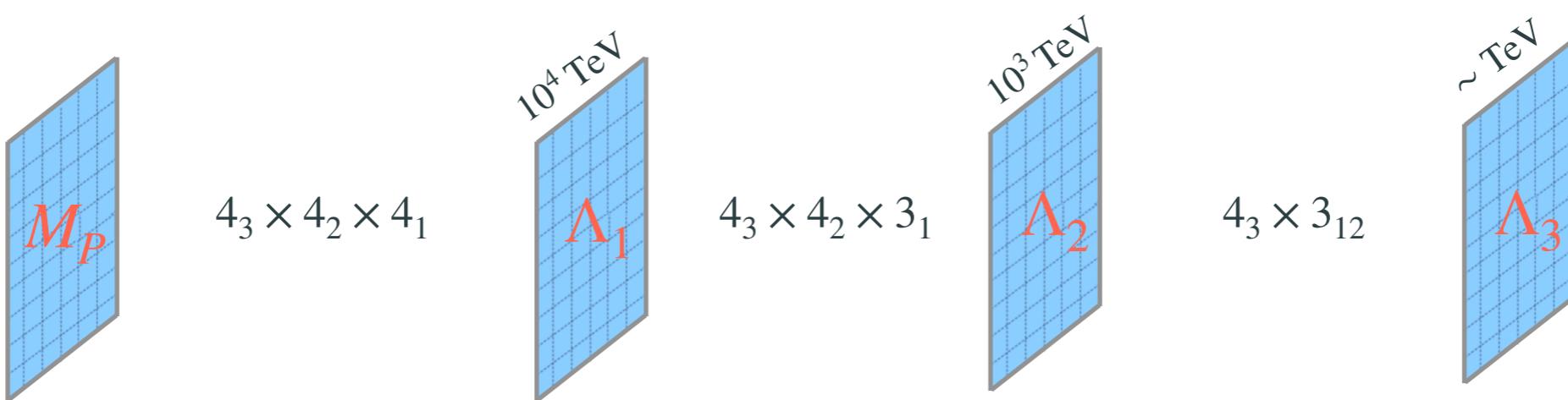
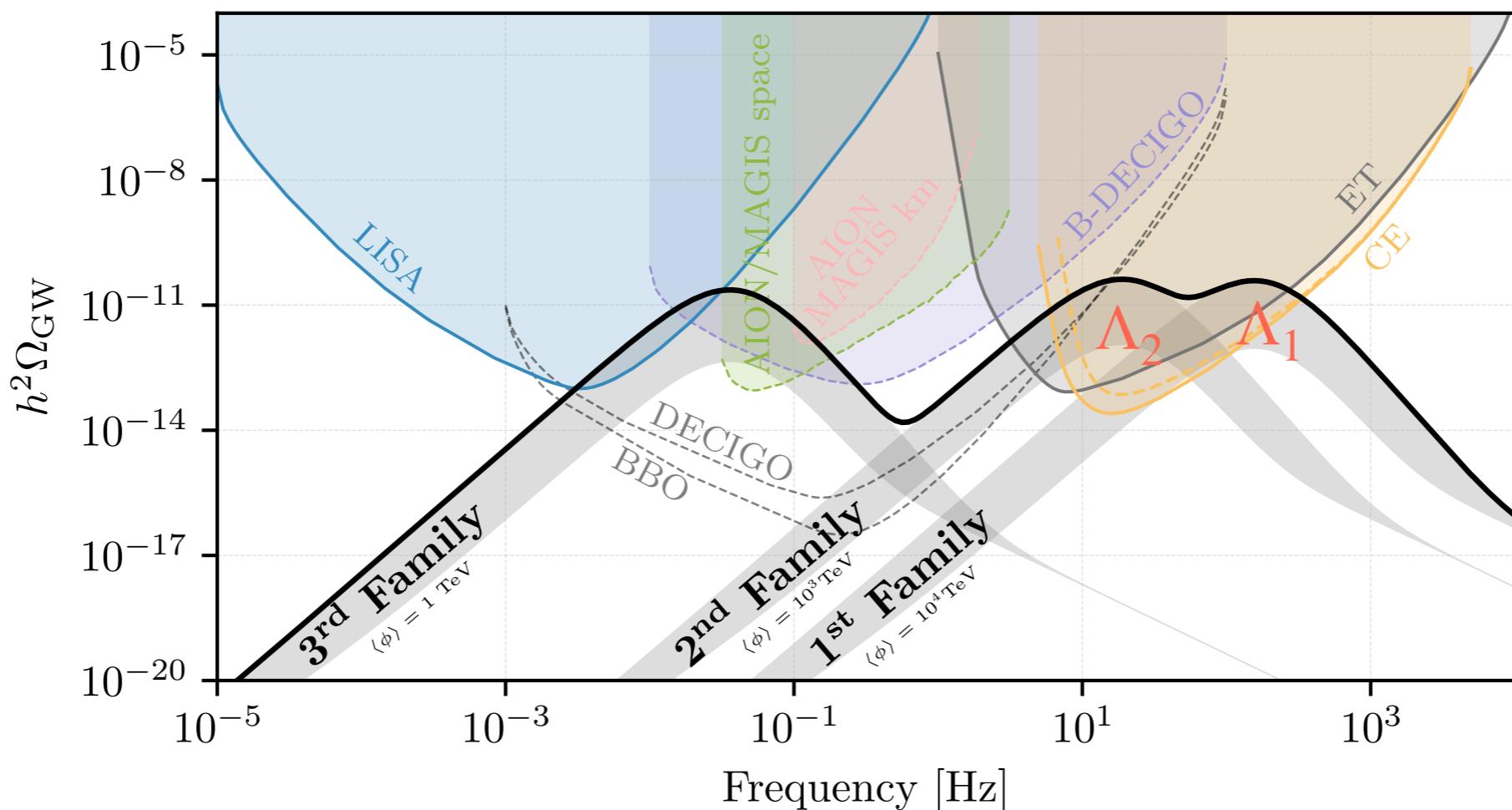
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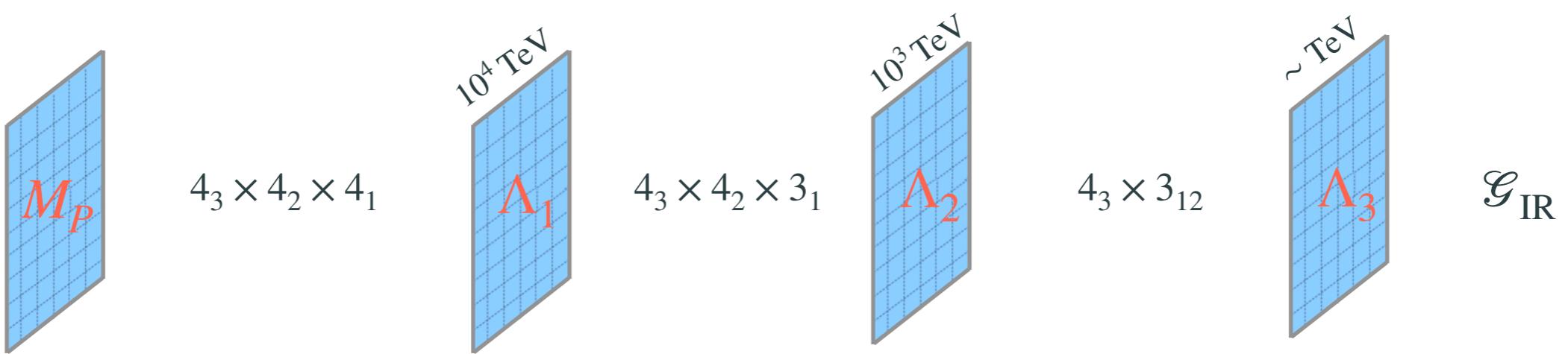
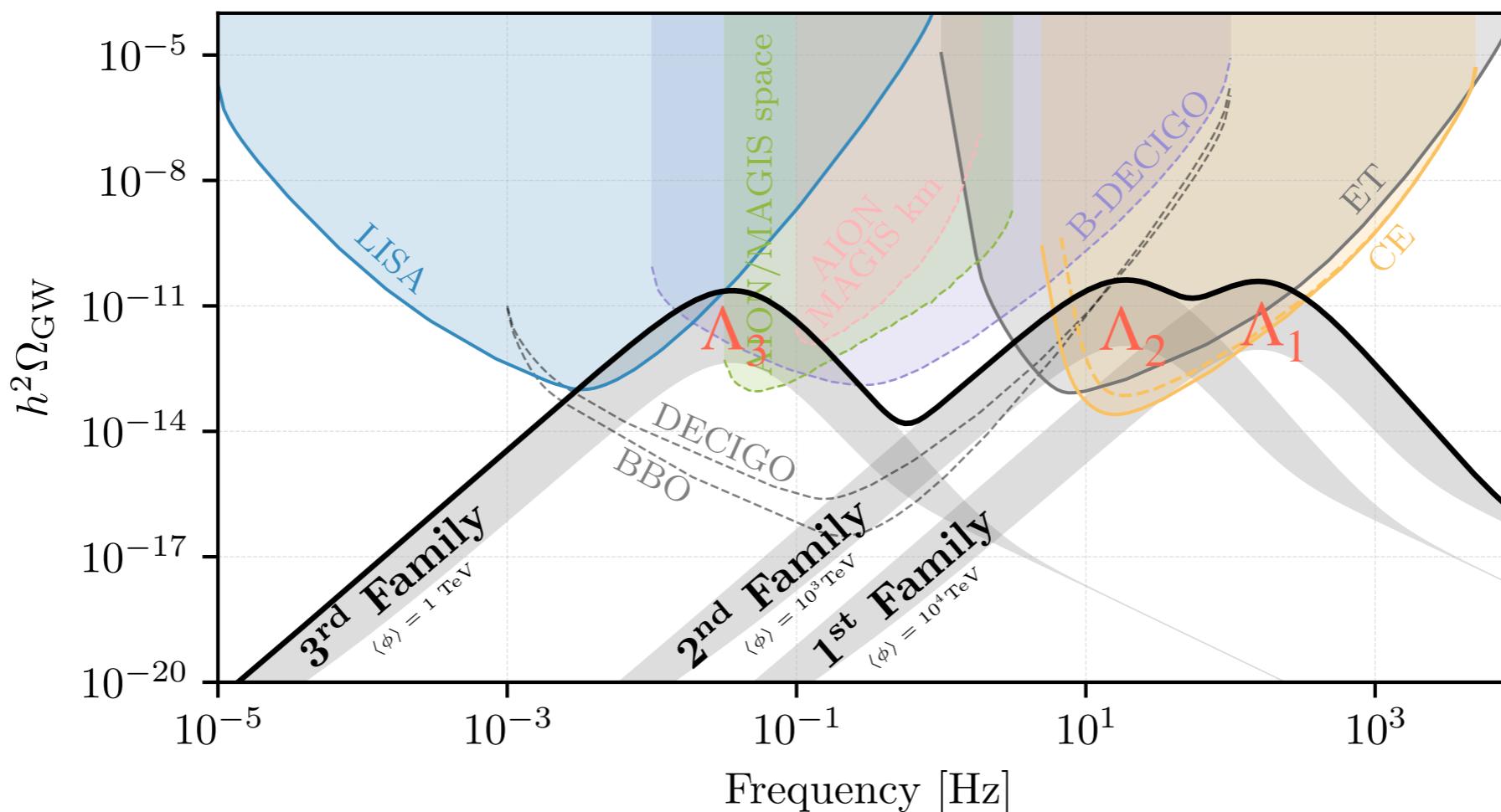
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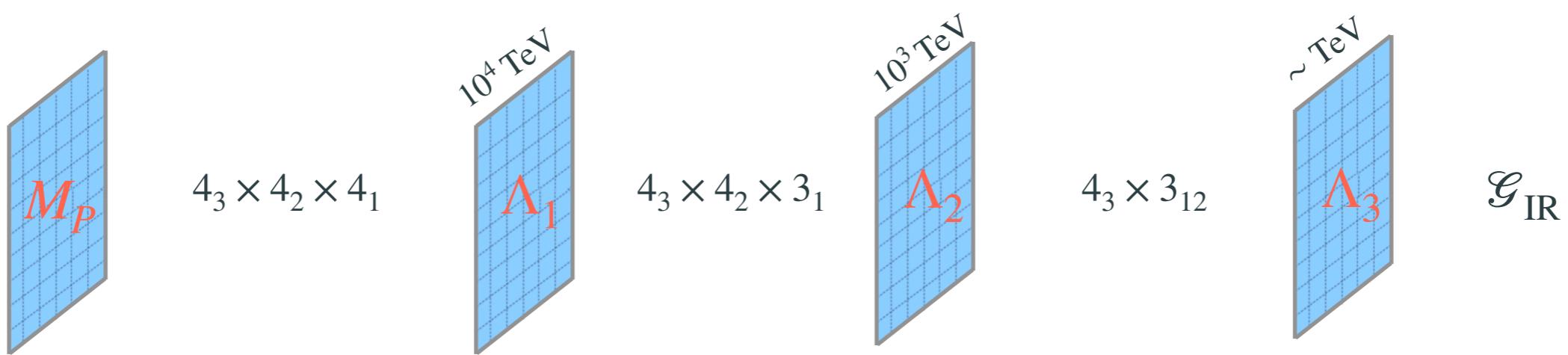
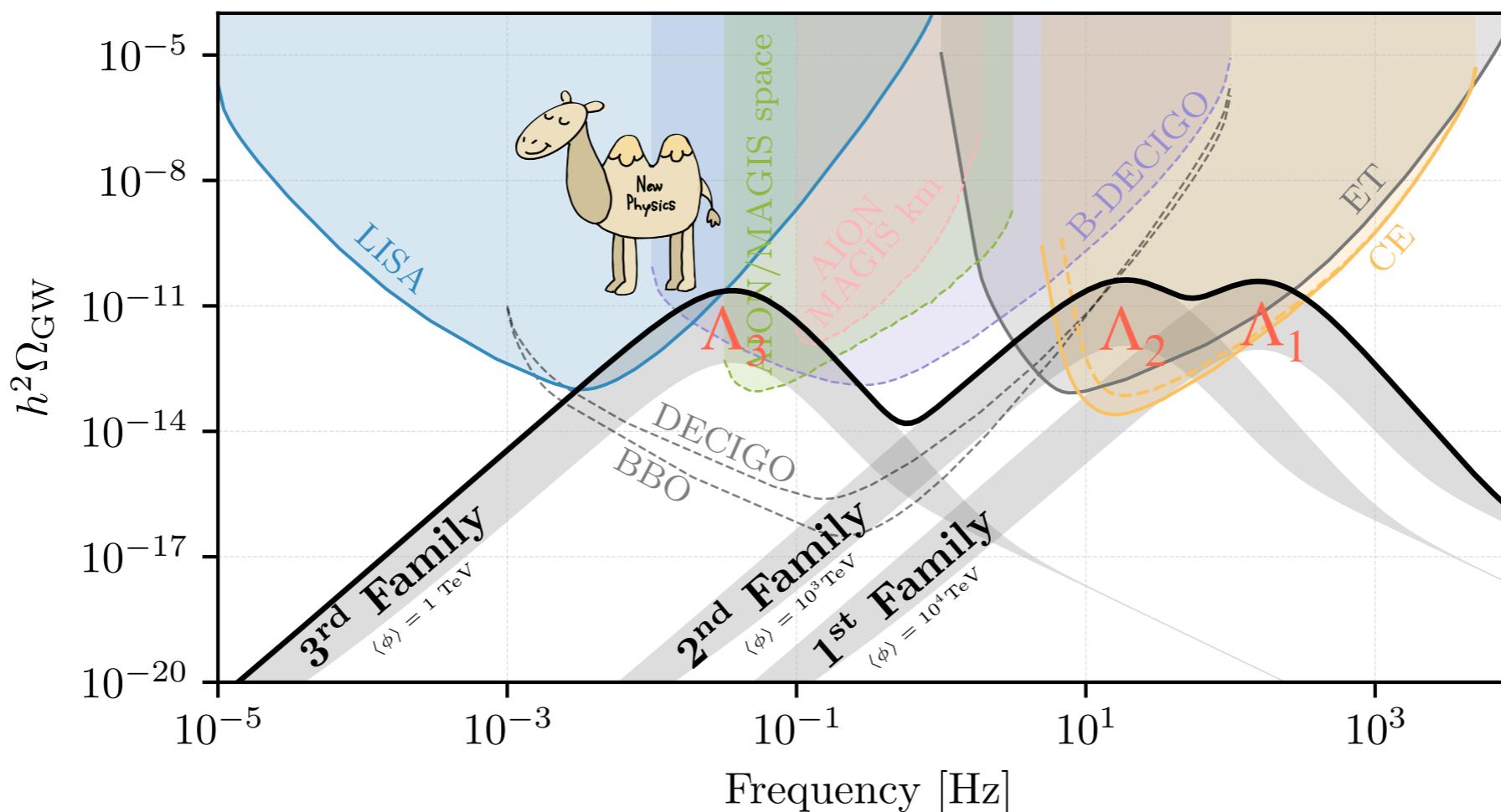
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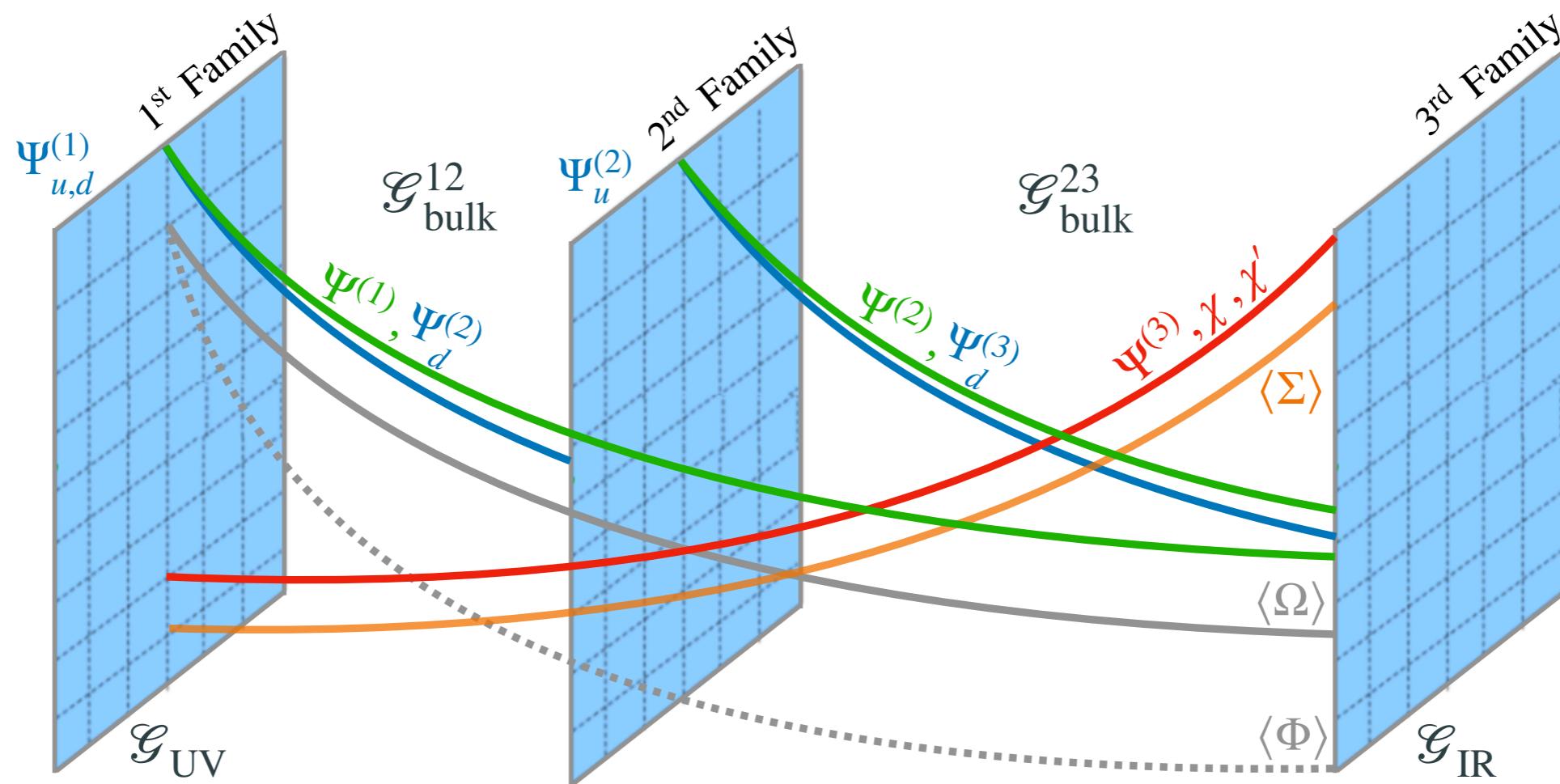
Backup Slides

Field	$SU(4)_h$	$SU(4)_l$	$SO(5)$
$\Psi^3, \Psi_d^3, \chi^{(\prime)}$	4	1	4
$\Psi^j, \Psi_{u,d}^j$	1	4	4
\mathcal{S}^i	1	1	1
Σ	1	1	5
Ω	1	4	4
Φ	1	1	1

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

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



Higgs Potential

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

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

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

VEV :

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

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

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

Quartic :

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

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

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

IR Masses

$$\begin{aligned}
\Psi^3 &= \begin{bmatrix} \psi^3 (+, +) \\ \psi_u^3 (-, -) \\ \tilde{\psi}_d^3 (+, -) \end{bmatrix}, & \Psi_d^3 &= \begin{bmatrix} \tilde{\psi}^3 (+, -) \\ \tilde{\psi}_u^3 (+, -) \\ \psi_d^3 (-, -) \end{bmatrix}, \\
\chi^{(\prime)} &= \begin{bmatrix} \chi^{(\prime)} (\pm, \pm) \\ \chi_u^{(\prime)} (\mp, \pm) \\ \chi_d^{(\prime)} (\mp, \pm) \end{bmatrix}, & \Psi^j &= \begin{bmatrix} \psi^j (+, +) \\ \tilde{\psi}_u^j (-, +) \\ \tilde{\psi}_d^j (-, +) \end{bmatrix}, \\
\Psi_u^j &= \begin{bmatrix} \tilde{\psi}^j (+, -) \\ \psi_u^j (-, -) \\ \hat{\psi}_d^j (+, -) \end{bmatrix}, & \Psi_d^j &= \begin{bmatrix} \hat{\psi}^j (+, -) \\ \hat{\psi}_u^j (+, -) \\ \psi_d^j (-, -) \end{bmatrix},
\end{aligned}$$

$$\mathcal{L}_{\text{IR}} \supset (\bar{\chi}_L \tilde{M}_\chi + \bar{\Psi}_L^3 \tilde{M}_\Psi + \bar{\Psi}_L^j \tilde{m}_\psi^j) \mathcal{P}_L \chi'_R,$$

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

Holographic Lagrangian

$$\begin{aligned}
-\mathcal{L} \supset & \frac{\Lambda_{\text{IR}}}{\sqrt{kL}} \left[(\bar{\psi}_L^3 \tilde{M}_\Psi + \bar{\chi}_L \tilde{M}_\chi + e^{-\frac{kz_j}{2}} \bar{\psi}_L^j \tilde{m}_\psi^j) \chi'_R \right] \\
& + \frac{g_*}{2\sqrt{2}} \left[\bar{\psi}_L^3 H \psi_{uR}^3 - e^{-\frac{kz_j}{2}} \bar{\psi}_L^j \tilde{m}_{\Psi j}^R H \psi_{uR}^3 \right. \\
& + e^{-\frac{kz_j}{2}} \left(\bar{\psi}_L^3 \tilde{M}_{\Psi d}^L H \psi_{dR}^3 + \bar{\chi}_L (\tilde{M}_{\chi d}^L - \tilde{M}_{\chi d}^R) H \psi_{dR}^3 \right) \\
& \left. + e^{-kz_j} \bar{\psi}_L^j (\tilde{m}_{dj}^L - \tilde{m}_{dj}^R) H \psi_{dR}^3 \right] + \text{h.c.} ,
\end{aligned}$$