The Status of Flavor in Randall-Sundrum Models

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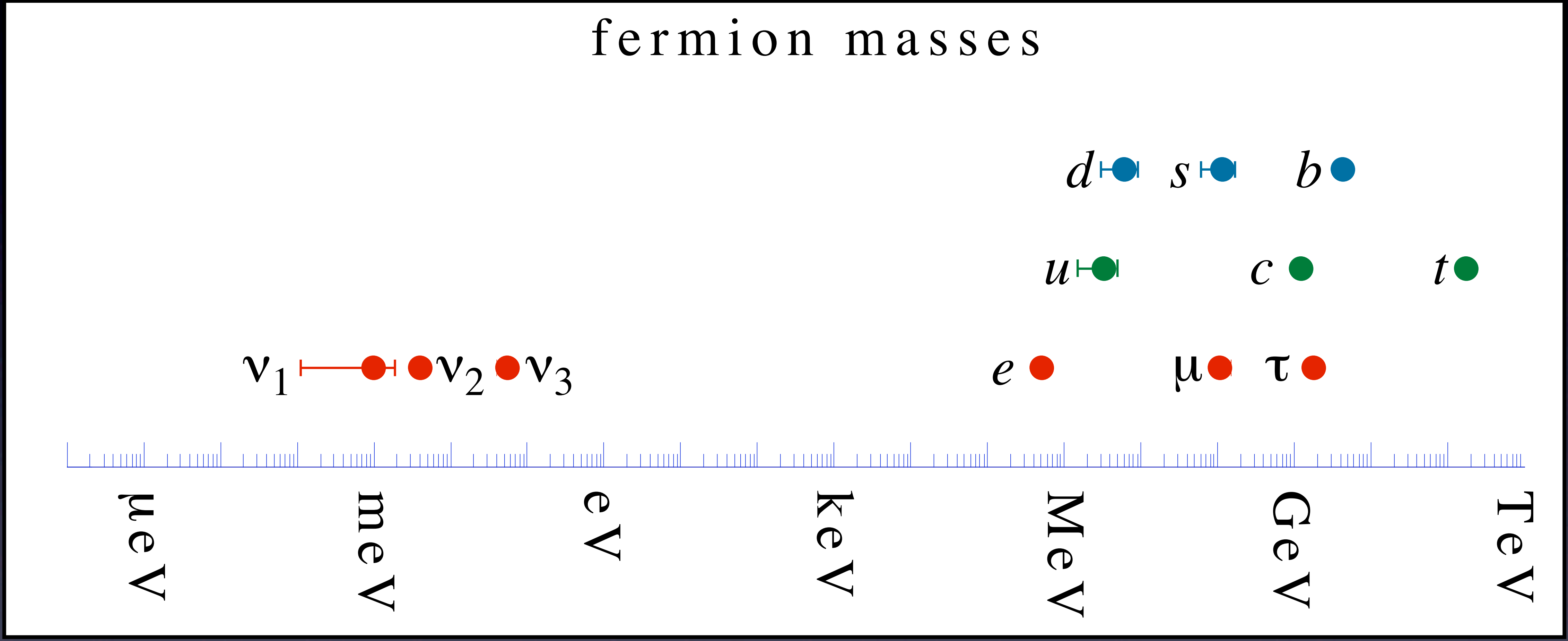
(CERN)

Ringberg Workshop on New Physics, Flavors and Jets

April 28th, 2009

Fermion masses & mixings



$$V_{CKM} \sim \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & \lambda^3 \\ \lambda & 1-\frac{\lambda^2}{2} & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

$$\lambda \approx 0.23$$

The SM flavor puzzle

$$Y_D = (m_d, m_s, m_b)/v$$

$$Y_U = V_{\rm CKM}^{\dagger}(m_u, m_c, m_t)/v$$

$$Y_D \approx (10^{-5}, 0.0005, 0.026)$$

$$Y_U \approx \begin{pmatrix} 10^{-5} & -0.002 & 0.007 + 0.004i \\ 10^{-6} & 0.007 & -0.04 + 0.0008i \\ 10^{-8} + 10^{-7}i & 0.0003 & 0.96 \end{pmatrix}$$

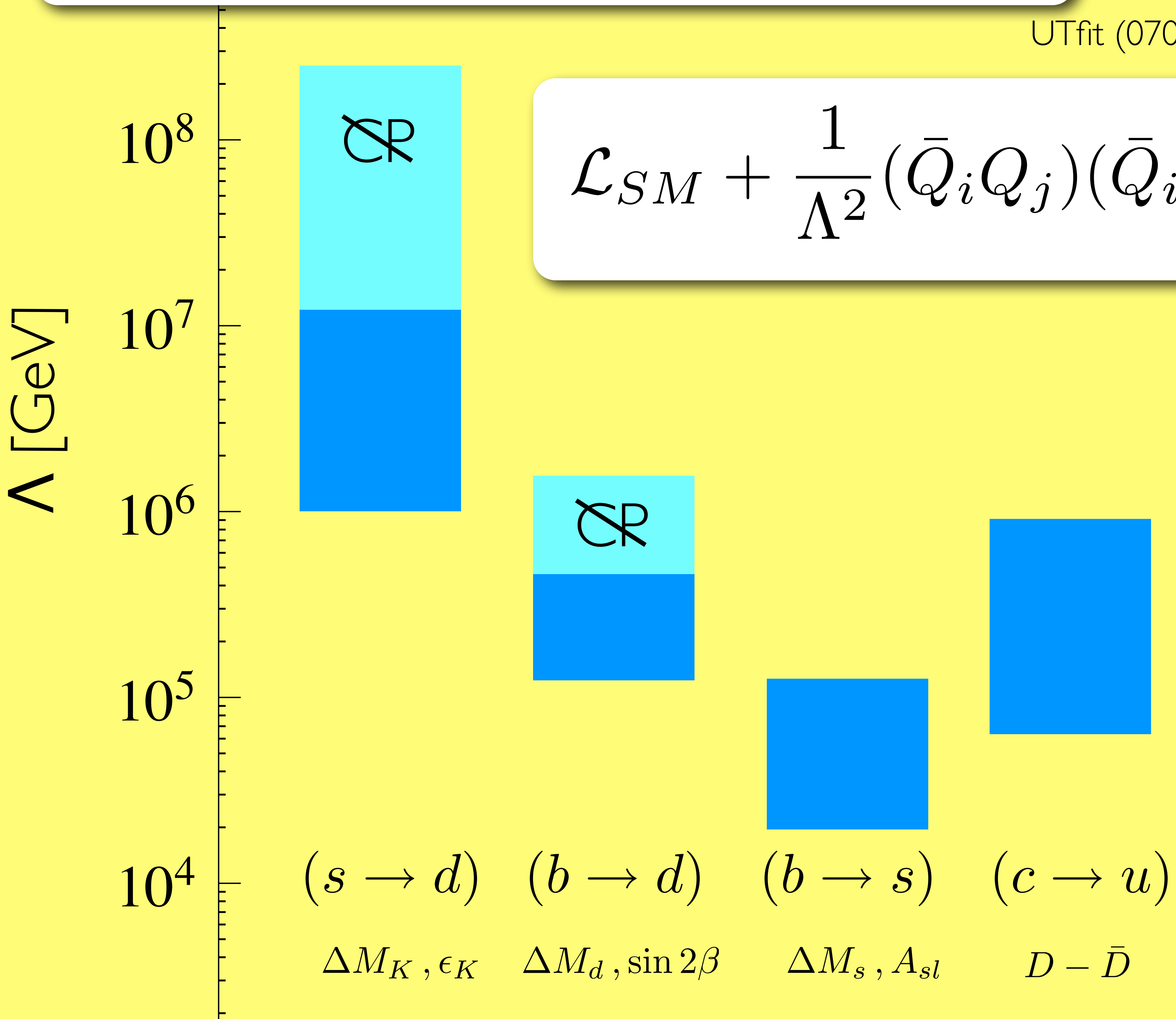
The SM quark flavor parameters have structure: small & hierarchical. Why?

Compare to: **$g_s \sim 1$, $g \sim 0.6$, $g \sim 0.3$, $\lambda_{\rm Higgs} \sim 1$**

Bounds on generic flavor violation

UTfit (0707.0636)

$$\mathcal{L}_{SM} + \frac{1}{\Lambda^2}(\bar{Q}_i Q_j)(\bar{Q}_i Q_j)$$



Origin of flavor

Dominating idea for a long time:

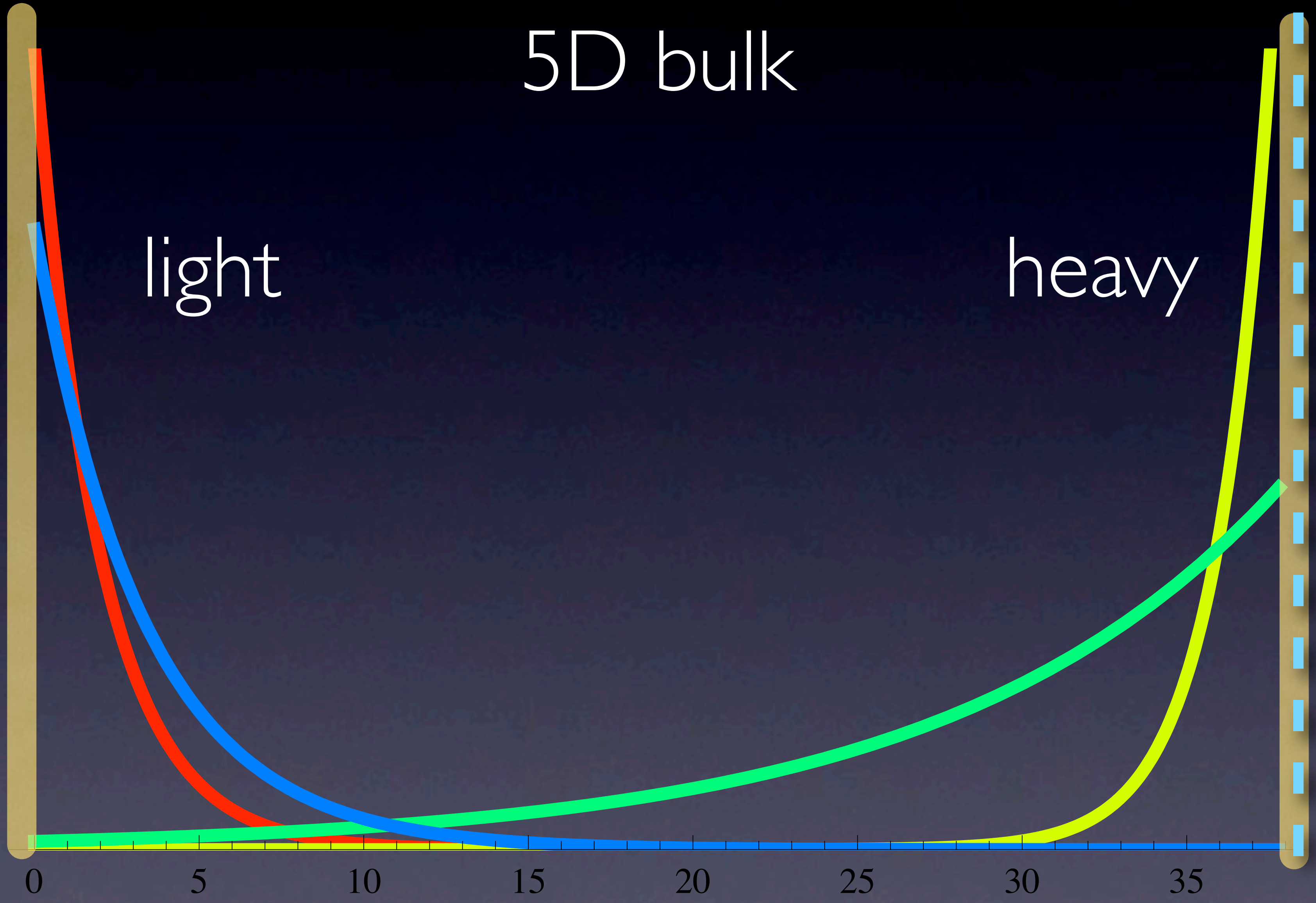
Hierarchies from symmetries (⇒ Graham Ross)

Alternative:

Hierarchies from geometrical sequestering
(⇒ this talk and Stefania Gori)

Geometrical sequestering

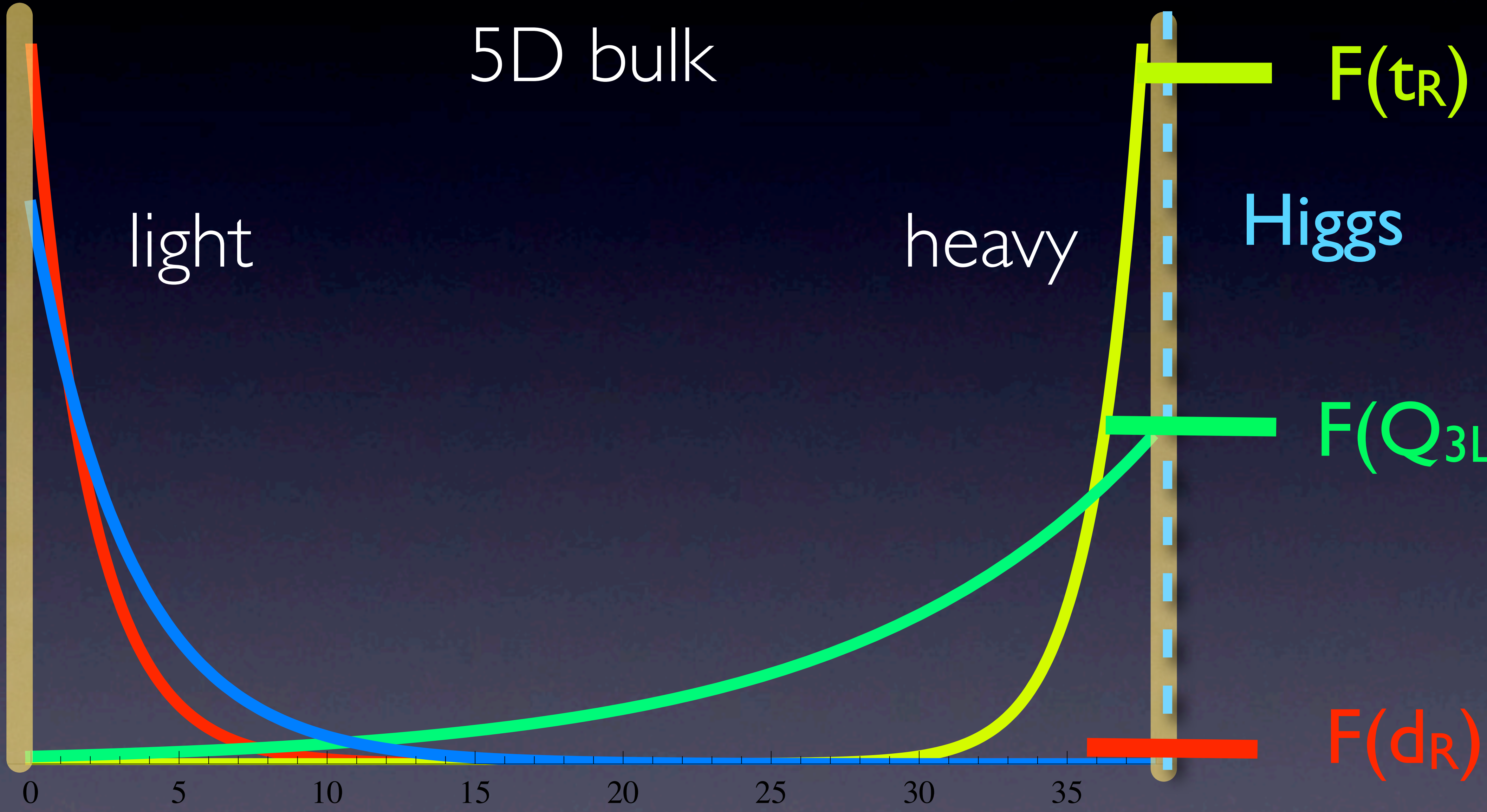
Arkani-Hamed, Schmaltz



Localization depends exponentially on O(1) parameter

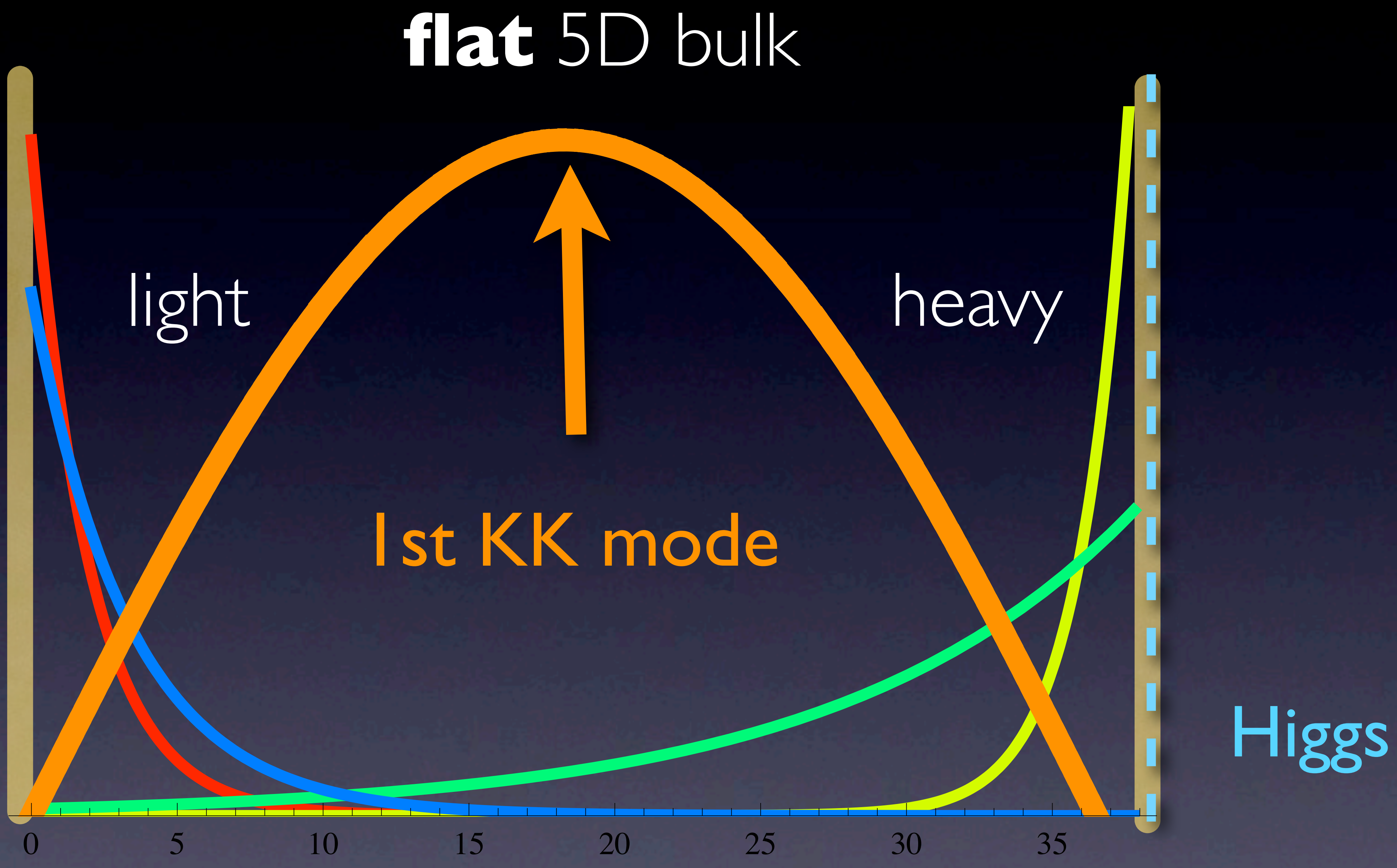
Geometrical sequestering

Arkani-Hamed, Schmaltz

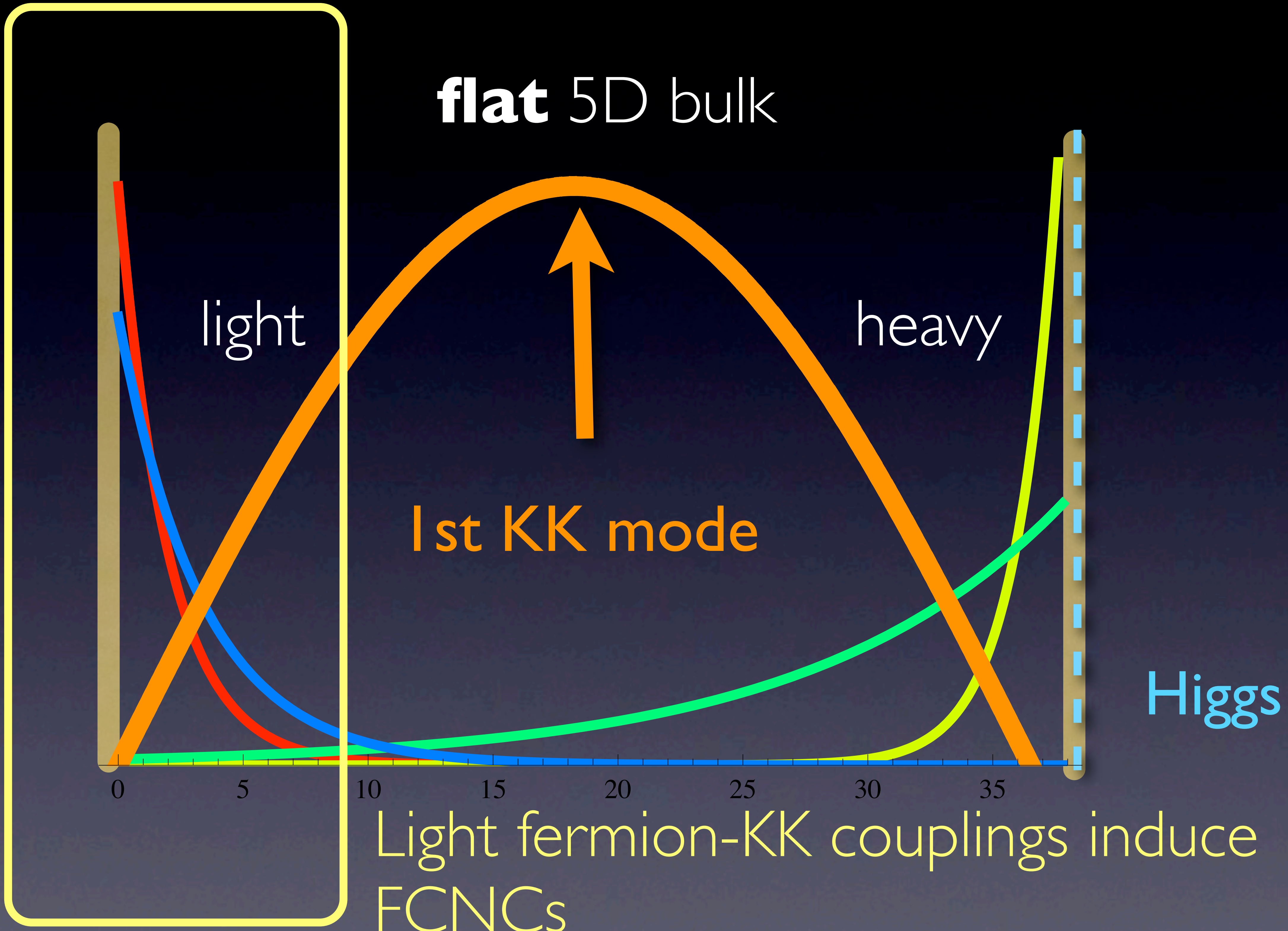


Localization depends exponentially on O(1) parameter

New sources for FCNCs



New sources for FCNCs



Light fermion-KK couplings induce FCNCs

Potential problems

Flat extra dimensions:

Delgado, Pomarol, Quiros ’99

o KK exchange induces unsuppressed FCNCs
$\Rightarrow M_{KK} \sim 1/R > 5000$ TeV

o Flat ED’s are EFT’s with $\Lambda \sim$ few x10/R

Even if KK mode coupling flavor universal/MFV
$\Rightarrow$ What explains 10^5 GeV suppression of

$$\mathcal{L}_{\rm eff} = \frac{1}{\Lambda^2}(\bar{s}d)(\bar{s}d) + \ldots \ ?$$

$$ds^2 = dx_\mu dx_\nu - dy^2$$

$$\Big\downarrow$$

Randall, Sundrum

$$ds^2 = \left(\frac{R}{z}\right)^2 \left(dx_\mu dx_\nu - dz^2\right) .$$

$$ds^2 = dx_\mu dx_\nu - dy^2$$

$$\Big\downarrow$$

Randall, Sundrum

$$ds^2 = \left(\frac{R}{z}\right)^2 \left(dx_\mu dx_\nu - dz^2\right) .$$

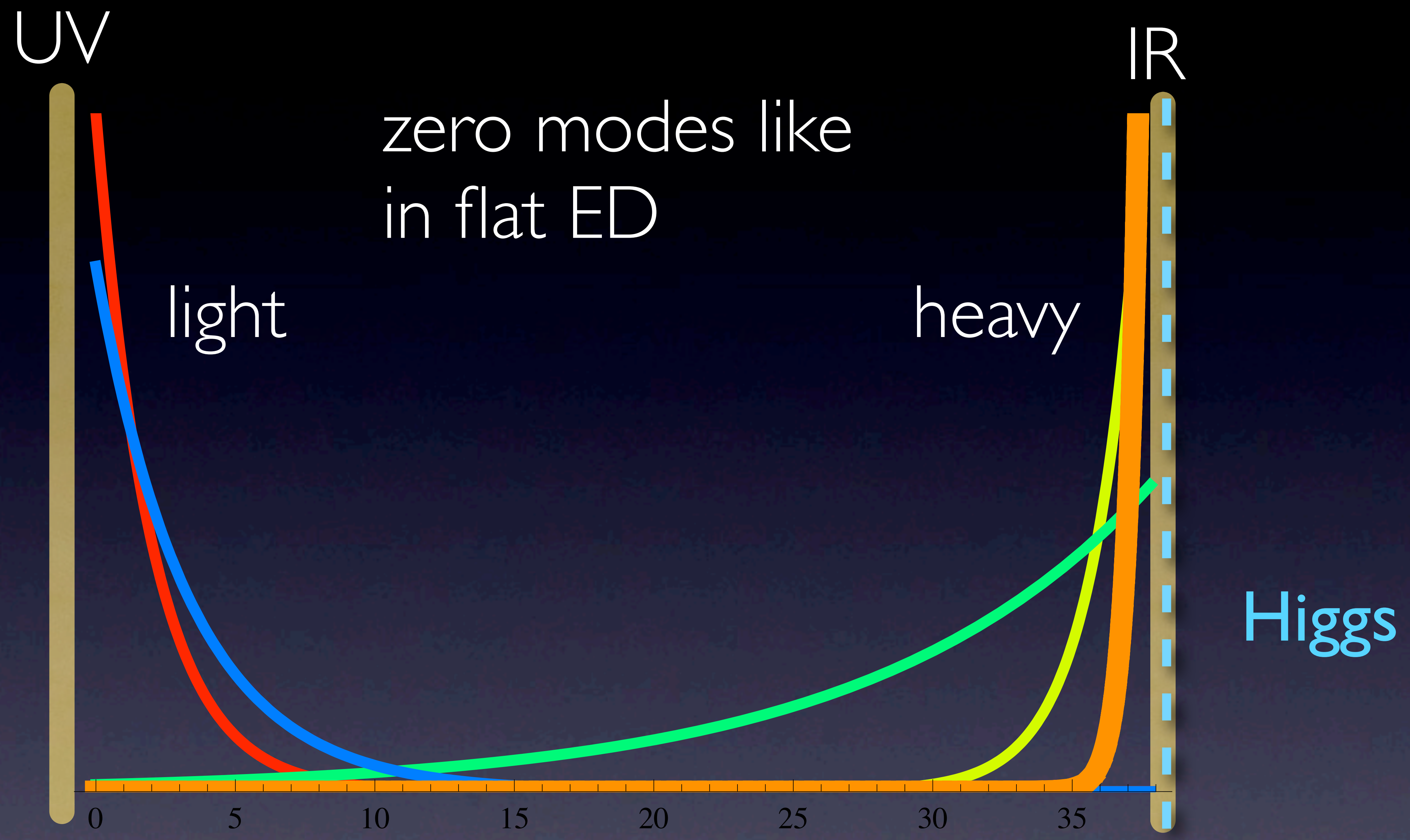
✓ solution to the hierarchy problem

✓ AdS/CFT description of holographic technicolor, composite Higgs, pGB composite Higgs

✓ high scale unification, log running of gauge couplings

Flavor in RS

Gherghetta, Pomarol



Flavor in RS

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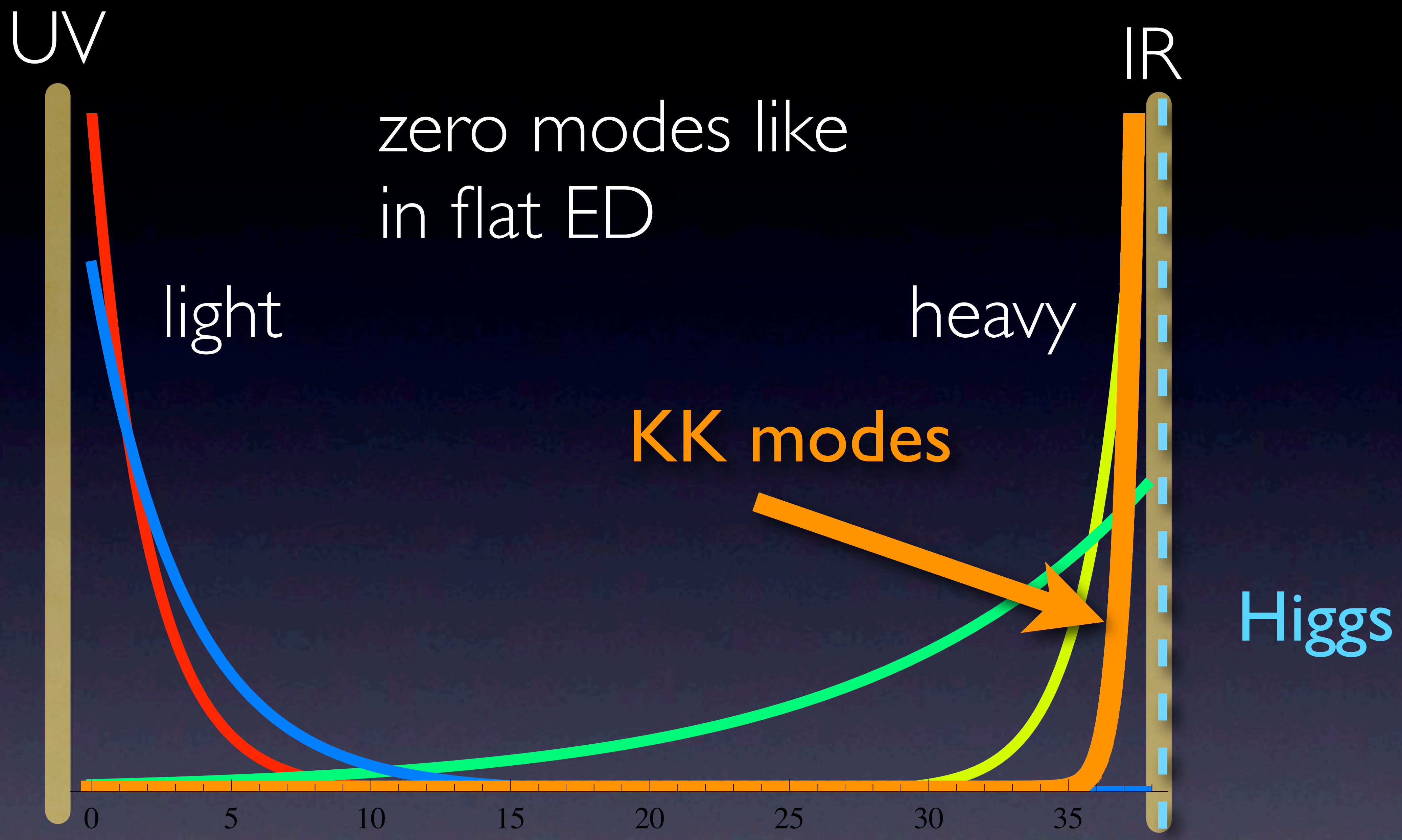

Flavor in RS

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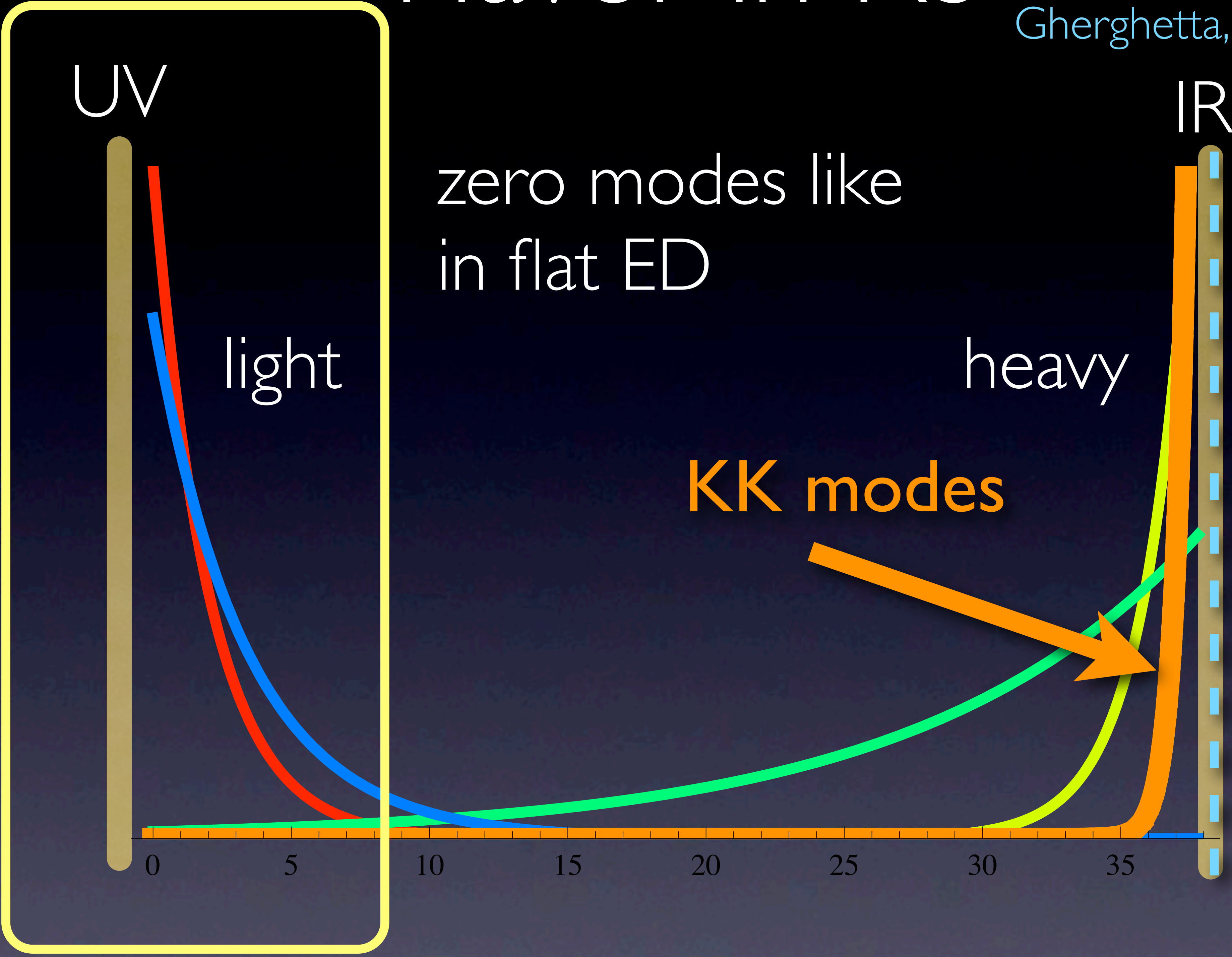


zero modes like
in flat ED

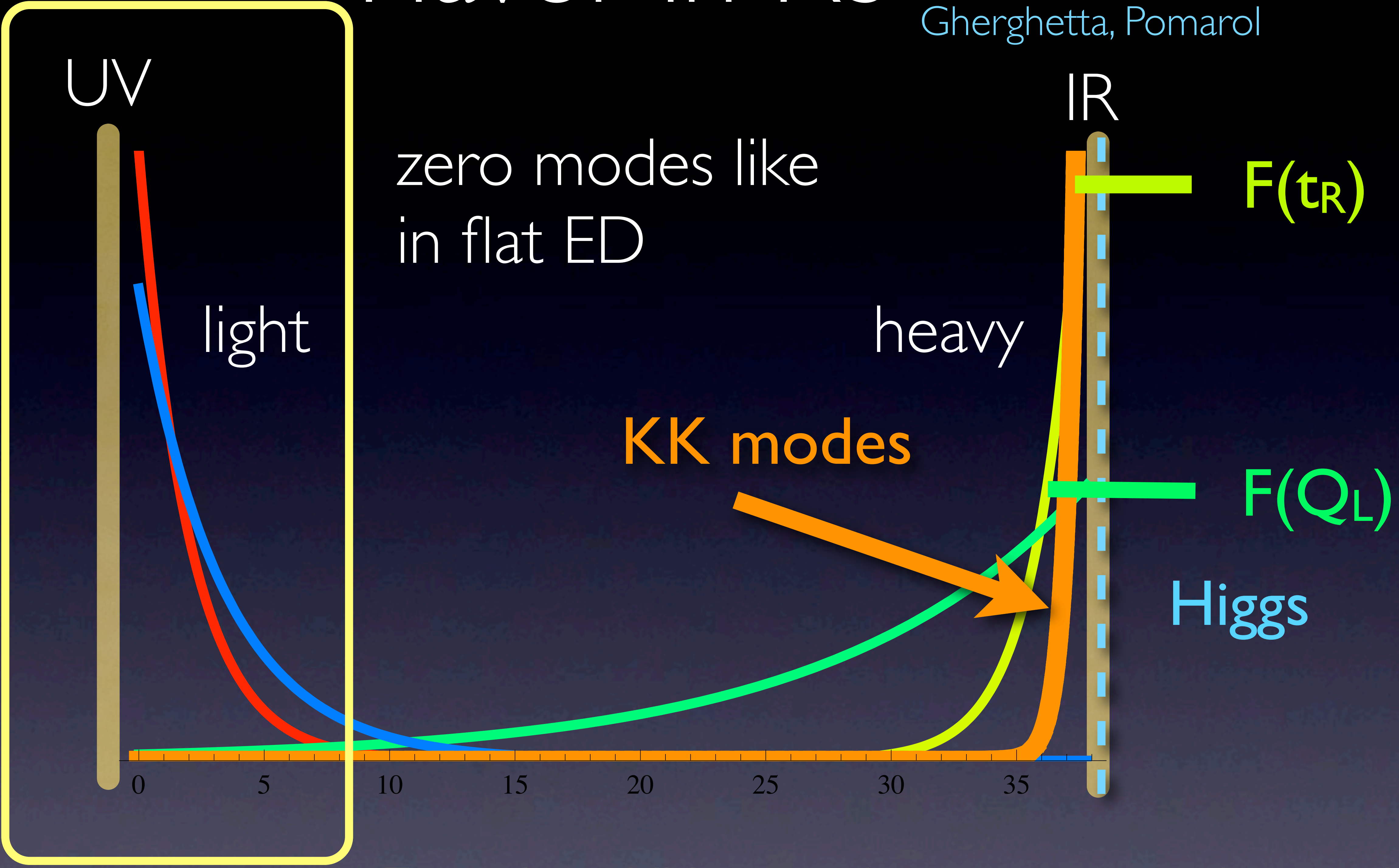
KK modes

Higgs

Fermion-KK coupling almost universal!

Flavor in RS

Gherghetta, Pomarol



zero modes like
in flat ED

Fermion-KK coupling almost universal!

Anarchy & Location, Location, Location

Zero mode wave function on IR brane

$F(c) \sim (\mathrm{TeV/Planck})^{c-1/2}$, $c_i \sim O(1)$

$$m^{(u)}_{ij} = \frac{v}{\sqrt{2}} F_{Q_i} (Y_u)_{ij} F_{u_j} \quad m^{(d)}_{ij} = \frac{v}{\sqrt{2}} F_{Q_i} (Y_d)_{ij} F_{d_j}$$

$\mathbf{Y_u}$ **,** $\mathbf{Y_d}$ ~ O(1): anarchic

Hierarchical mass spectrum for $\mathbf{F_1} \ll \mathbf{F_2} \ll \mathbf{F_3}$

$\Rightarrow$ $m_{ui} \sim F_{Qi} F_{ui} (v Y)$ $m_{di} \sim F_{Qi} F_{di} (v Y)$

Hierarchical mixing angles

Huber; Agashe, Perez, Soni

$$U_L^d m_{ij}^{(d)} U_R^d = \mathrm{diag}\,(\mathrm{m_d}, \mathrm{m_s}, \mathrm{m_b})$$

CKM matrix $V_{\mathrm{CKM}}^{ij} \sim (U_L^{u,d})^{ij} \sim F_{Q_i}/F_{Q_j}$

with i < j

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with i < j

$F_{Q1} / F_{Q3} \sim \theta_{13} \sim \lambda^3$

$F_{Q2} / F_{Q3} \sim \theta_{23} \sim \lambda^2$

Check:

$\Rightarrow \theta_{12} \sim F_{Q1} / F_{Q2} \sim F_{Q1} / F_{Q3} \cdot F_{Q3} / F_{Q2} \sim \lambda$

Non-trivial prediction.

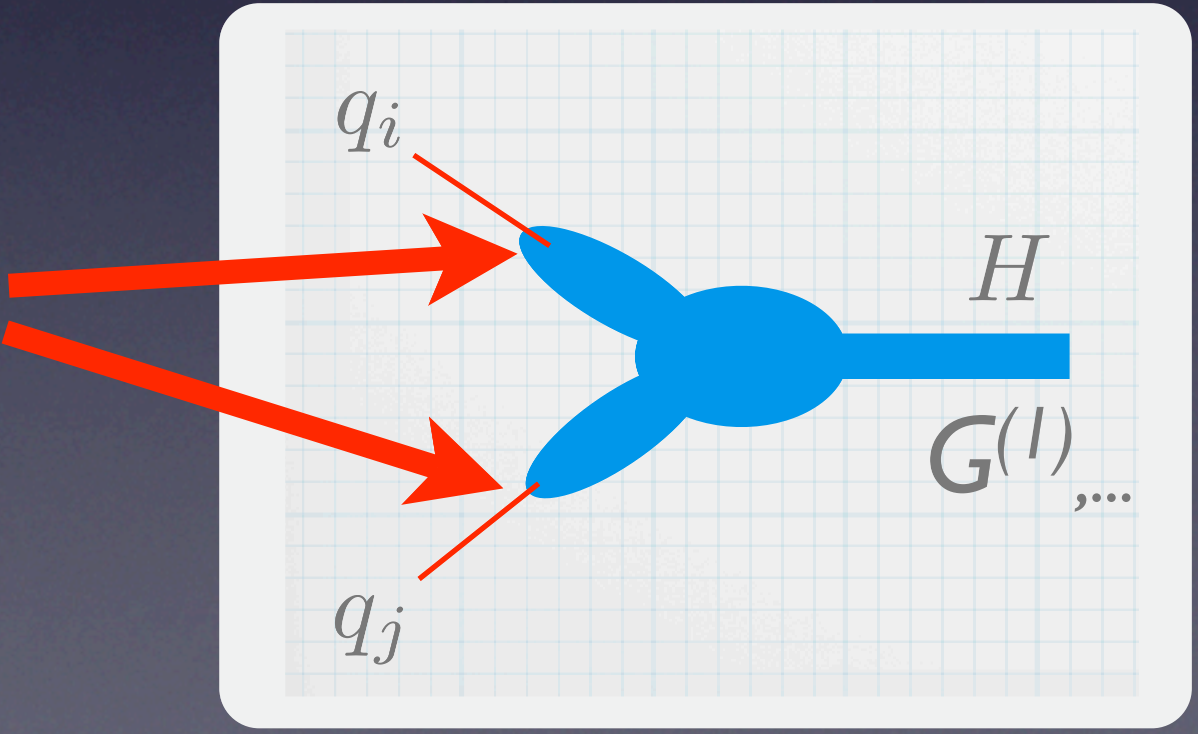
FCNC bounds satisfied?

F_Q, F_u, $F_d \neq 1_{3x3}$ will lead to FCNCs

$$g_5 \int dz \left(\frac{R}{z}\right)^4 G^{(1)}(z) f_L(z)^2 \approx g_4 \sqrt{\log\frac{R'}{R}}\left(-\frac{1}{\log\frac{R'}{R}} + F(c)^2\right)$$

c-dependent fermion KK-gauge coupling (same F_i as in Yukawa)

in **CFT** picture
mass ~ compositeness ~ F(c)
mixing with CFT excitation



4D CFT explanation

Contino, Pomarol

Quasi conformal sector between TeV … $M_{\rm pl}$

Linear coupling of SM fields to composites

$$\mathcal{L}_{\rm UV} \supset \lambda \bar{\mathcal{O}}_R \psi_L$$

$$\mu \frac{d\lambda}{d\mu} = \gamma\lambda \qquad \gamma = \dim[\mathcal{O}_{\mathcal{R}}] + 3/2 - 4$$

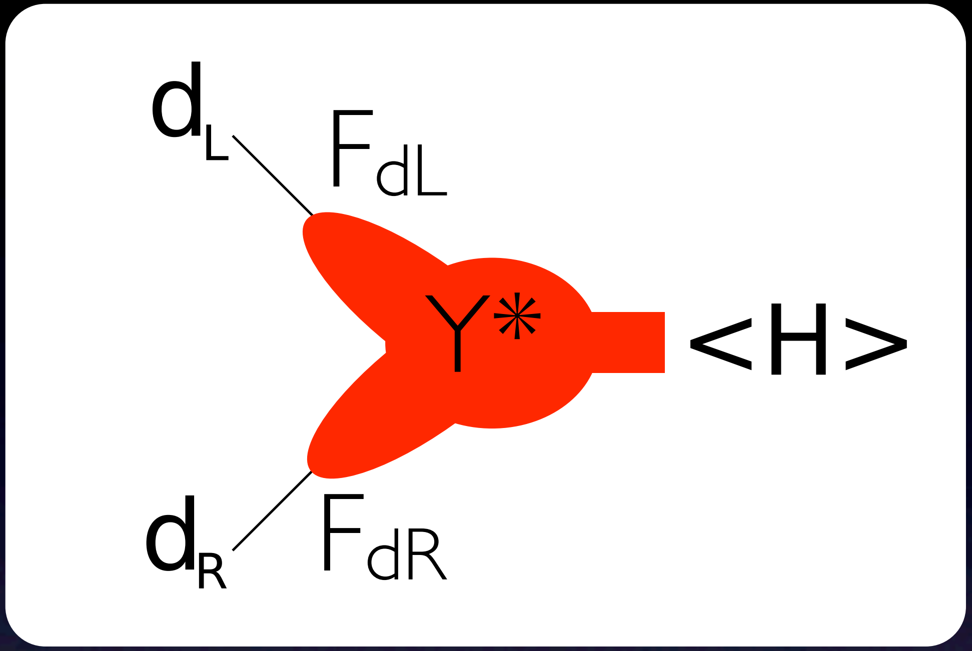
$$\lambda \sim \left(\frac{\rm TeV}{M_{Pl}}\right)^{\gamma}$$

AdS/CFT translation:

$$\gamma = c - \frac{1}{2}$$

Masses, mixings and FCNCs

Gherghetta, Pomarol; Huber;Agashe, Perez, Soni;



Masses and mixings from hierarchical overlaps

$$m_d \sim v\, F_{d_L} Y^* F_{d_R}$$

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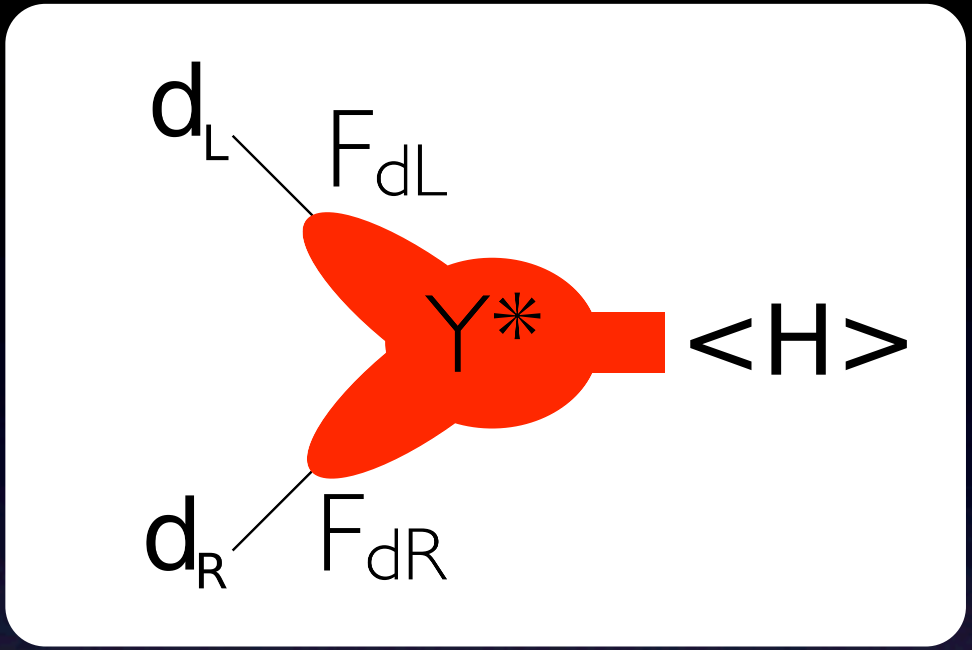
Gherghetta, Pomarol; Huber;Agashe, Perez, Soni;



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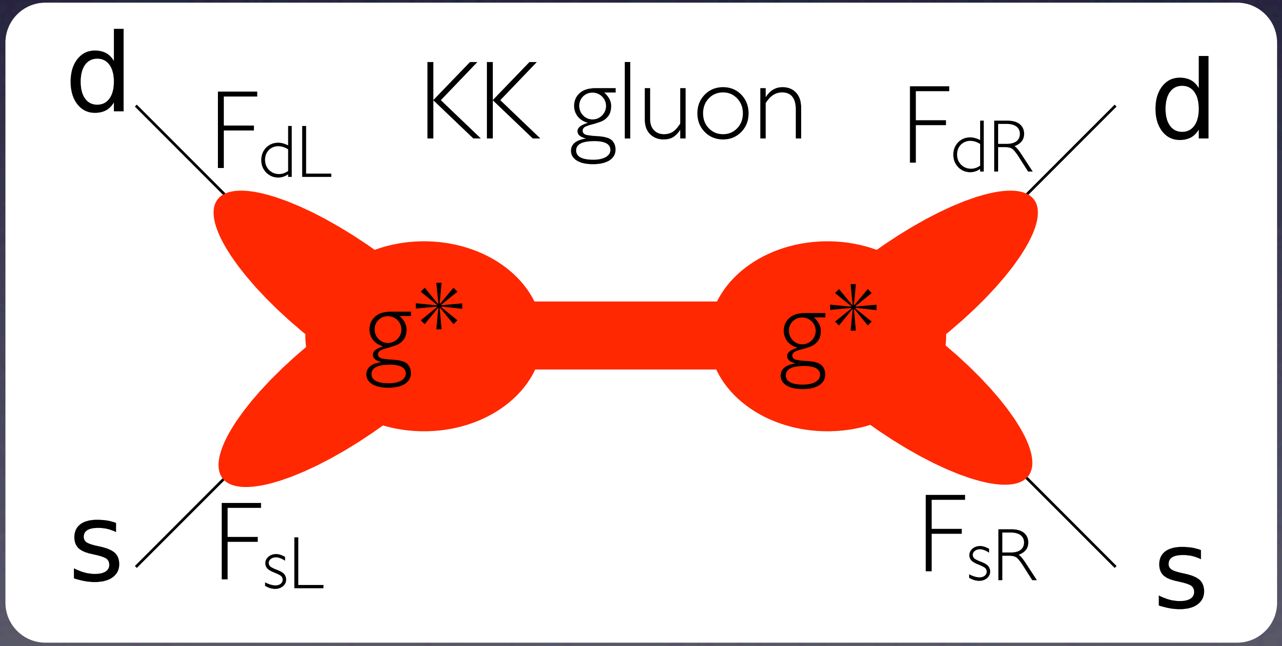


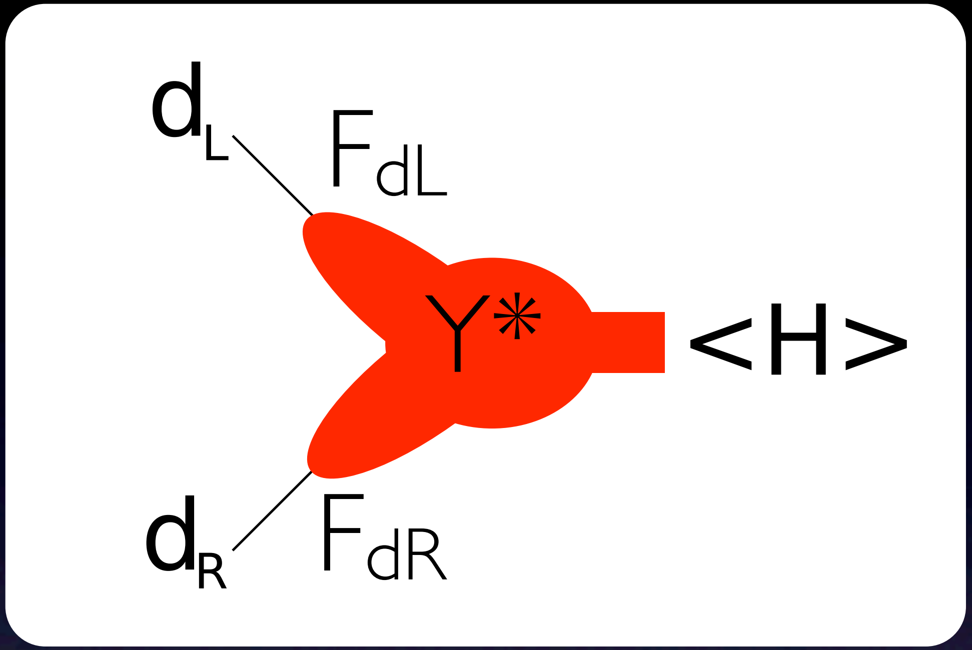
KK gluon FCNCs due to the same small overlaps F_i :

$$\sim \frac{(g^*)^2}{M_{KK}^2} F_{d_L} F_{d_R} F_{s_L} F_{s_R}$$

$$\sim \frac{(g^*)^2}{M_{KK}^2} \frac{m_d\, m_s}{(vY^*)^2}$$

Masses, mixings and FCNCs

Gherghetta, Pomarol; Huber;Agashe, Perez, Soni;



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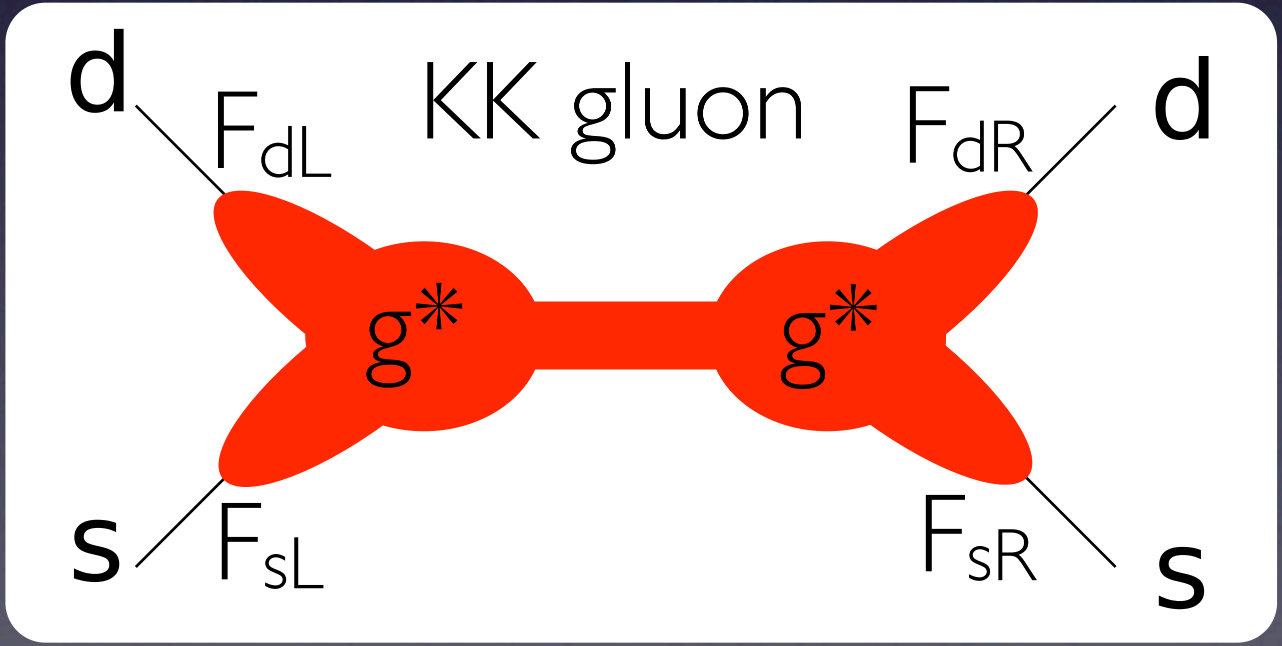
RS GIM



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Integrating out the KK gluon

Effective 4 fermi operators generated

$$\begin{aligned}\mathcal{H} &= \frac{1}{M_G^2}\left\lfloor \frac{1}{6} g_L^{ij} g_L^{kl} (\bar{q}_L^{i\alpha}\gamma_\mu q_{L\alpha}^j)\ (\bar{q}_L^{k\beta}\gamma^\mu q_{L\beta}^l) - g_R^{ij} g_L^{kl} \left((\bar{q}_R^{i\alpha} q_{L\alpha}^k)\ (\bar{q}_L^{l\beta} q_{R\beta}^j) - \frac{1}{3} (\bar{q}_R^{i\alpha} q_{L\beta}^l)\ (\bar{q}_L^{k\beta} q_{R\alpha}^j) \right) \right\rfloor \\ &= C^1(M_G)(\bar{q}_L^{i\alpha}\gamma_\mu q_{L\alpha}^j)\ (\bar{q}_L^{k\beta}\gamma^\mu q_{L\beta}^l) + C^4(M_G)(\bar{q}_R^{i\alpha} q_{L\alpha}^k)\ (\bar{q}_L^{l\beta} q_{R\beta}^j) + C^5(M_G)(\bar{q}_R^{i\alpha} q_{L\beta}^l)\ (\bar{q}_L^{k\beta} q_{R\alpha}^j)\end{aligned}$$

In particular

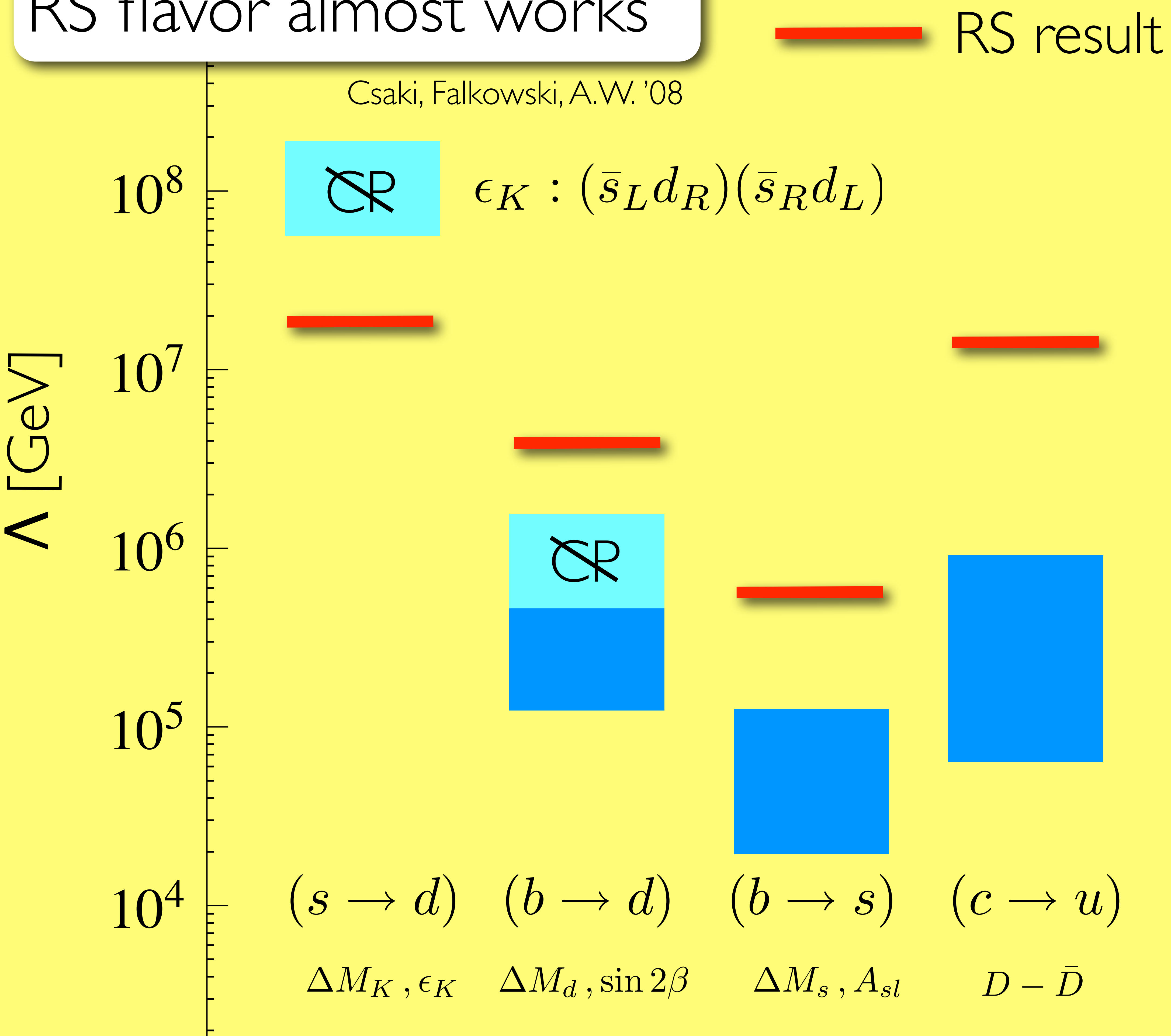
$$C_{4K}^{RS} \sim \frac{g_{s*}^2}{M_G^2} \frac{1}{Y_*^2} \frac{2 m_d m_s}{v^2}$$

Has both real and O(1) imaginary part.

3 TeV KK gluon mass

Parameter	Limit on Λ_F (TeV)	Suppression in RS (TeV)
$\mathrm{Re}C_K^1$	$1.0 \cdot 10^3$	$\sim r/(\sqrt{6}\,\lvert V_{td}V_{ts}\rvert f_{q3}^2) = 23 \cdot 10^3$
$\mathrm{Re}C_K^4$	$12 \cdot 10^3$	$\sim r(vY_*)/(\sqrt{2\,m_d m_s}) = 22 \cdot 10^3$
$\mathrm{Re}C_K^5$	$10 \cdot 10^3$	$\sim r(vY_*)/(\sqrt{6\,m_d m_s}) = 38 \cdot 10^3$
$\mathrm{Im}C_K^1$	$15 \cdot 10^3$	$\sim r/(\sqrt{6}\,\lvert V_{td}V_{ts}\rvert f_{q3}^2) = 23 \cdot 10^3$
$\mathrm{Im}C_K^4$	$160 \cdot 10^3$	$\sim r(vY_*)/(\sqrt{2\,m_d m_s}) = 22 \cdot 10^3$
$\mathrm{Im}C_K^5$	$140 \cdot 10^3$	$\sim r(vY_*)/(\sqrt{6\,m_d m_s}) = 38 \cdot 10^3$
$\lvert C_D^1\rvert$	$1.2 \cdot 10^3$	$\sim r/(\sqrt{6}\,\lvert V_{ub}V_{cb}\rvert f_{q3}^2) = 25 \cdot 10^3$
$\lvert C_D^4\rvert$	$3.5 \cdot 10^3$	$\sim r(vY_*)/(\sqrt{2\,m_u m_c}) = 12 \cdot 10^3$
$\lvert C_D^5\rvert$	$1.4 \cdot 10^3$	$\sim r(vY_*)/(\sqrt{6\,m_u m_c}) = 21 \cdot 10^3$
$\lvert C_{B_d}^1\rvert$	$0.21 \cdot 10^3$	$\sim r/(\sqrt{6}\,\lvert V_{tb}V_{td}\rvert f_{q3}^2) = 1.2 \cdot 10^3$
$\lvert C_{B_d}^4\rvert$	$1.7 \cdot 10^3$	$\sim r(vY_*)/(\sqrt{2\,m_b m_d}) = 3.1 \cdot 10^3$
$\lvert C_{B_d}^5\rvert$	$1.3 \cdot 10^3$	$\sim r(vY_*)/(\sqrt{6\,m_b m_d}) = 5.4 \cdot 10^3$
$\lvert C_{B_s}^1\rvert$	30	$\sim r/(\sqrt{6}\,\lvert V_{tb}V_{ts}\rvert f_{q3}^2) = 270$
$\lvert C_{B_s}^4\rvert$	230	$\sim r(vY_*)/(\sqrt{2\,m_b m_s}) = 780$
$\lvert C_{B_s}^5\rvert$	150	$\sim r(vY_*)/(\sqrt{6\,m_b m_s}) = 1400$

RS flavor almost works



Csaki, Falkowski, A.W. '08

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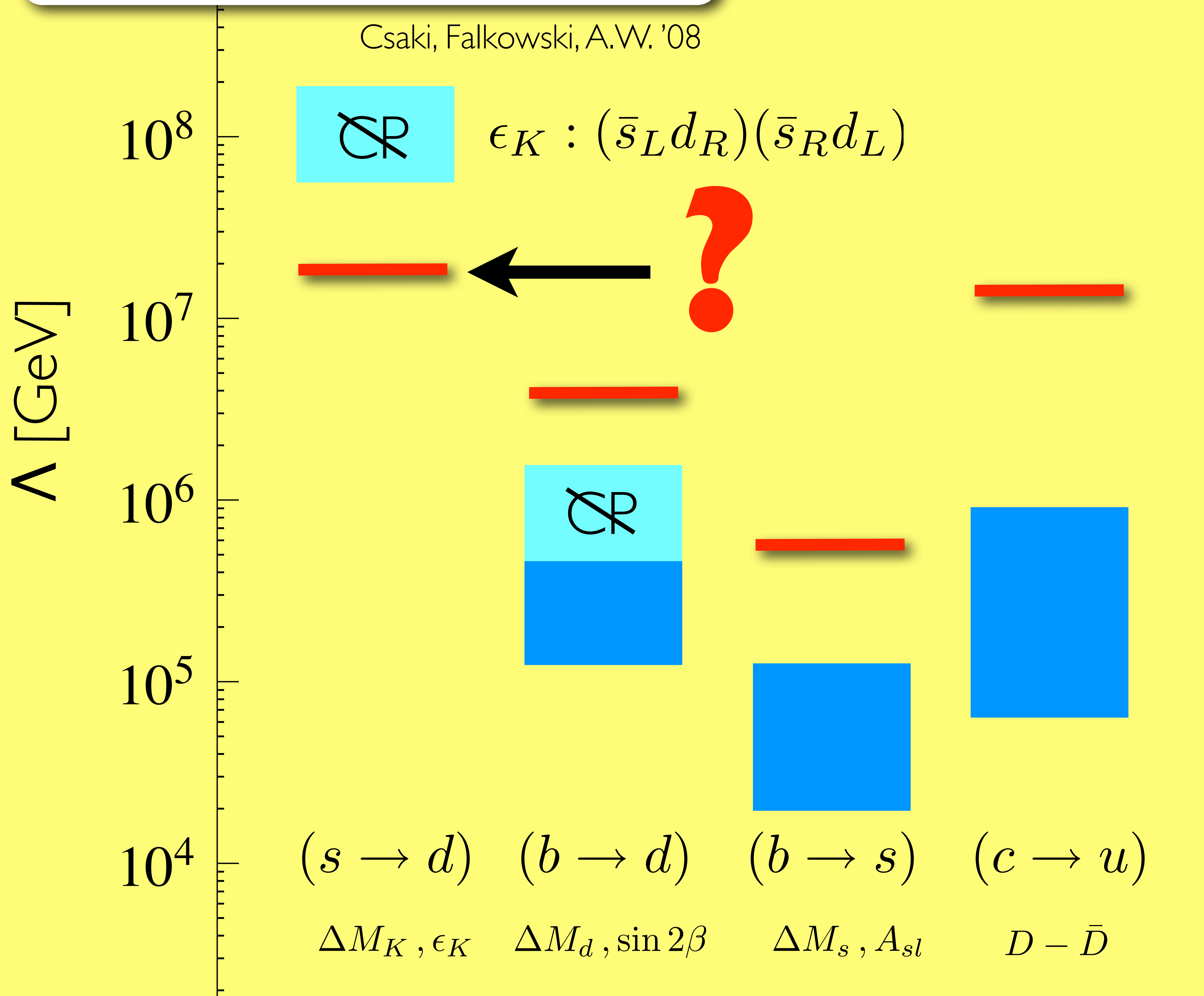
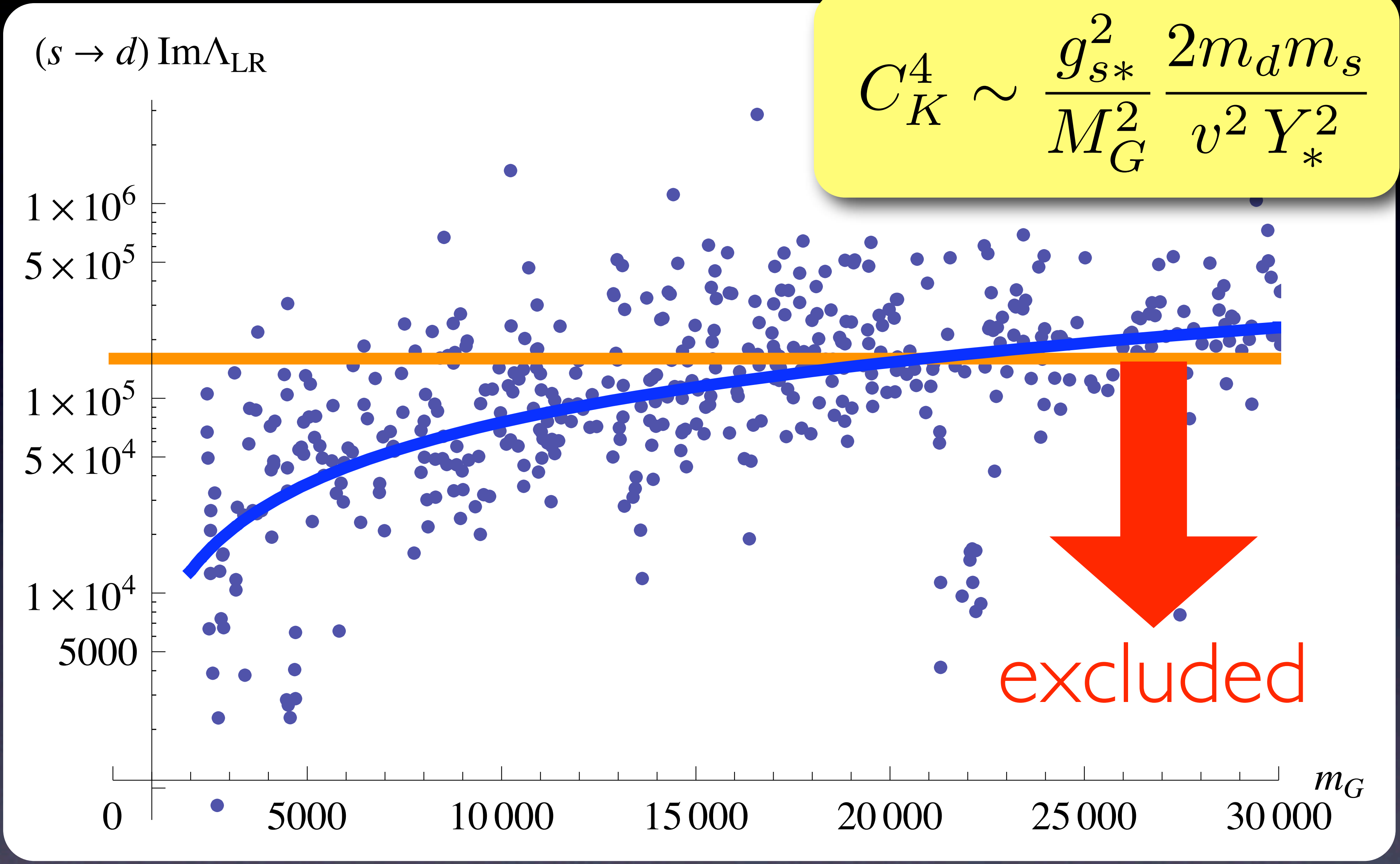


KK gluon mass bound in RS

Csaki, Falkowski, A.W.; Buras et. al.

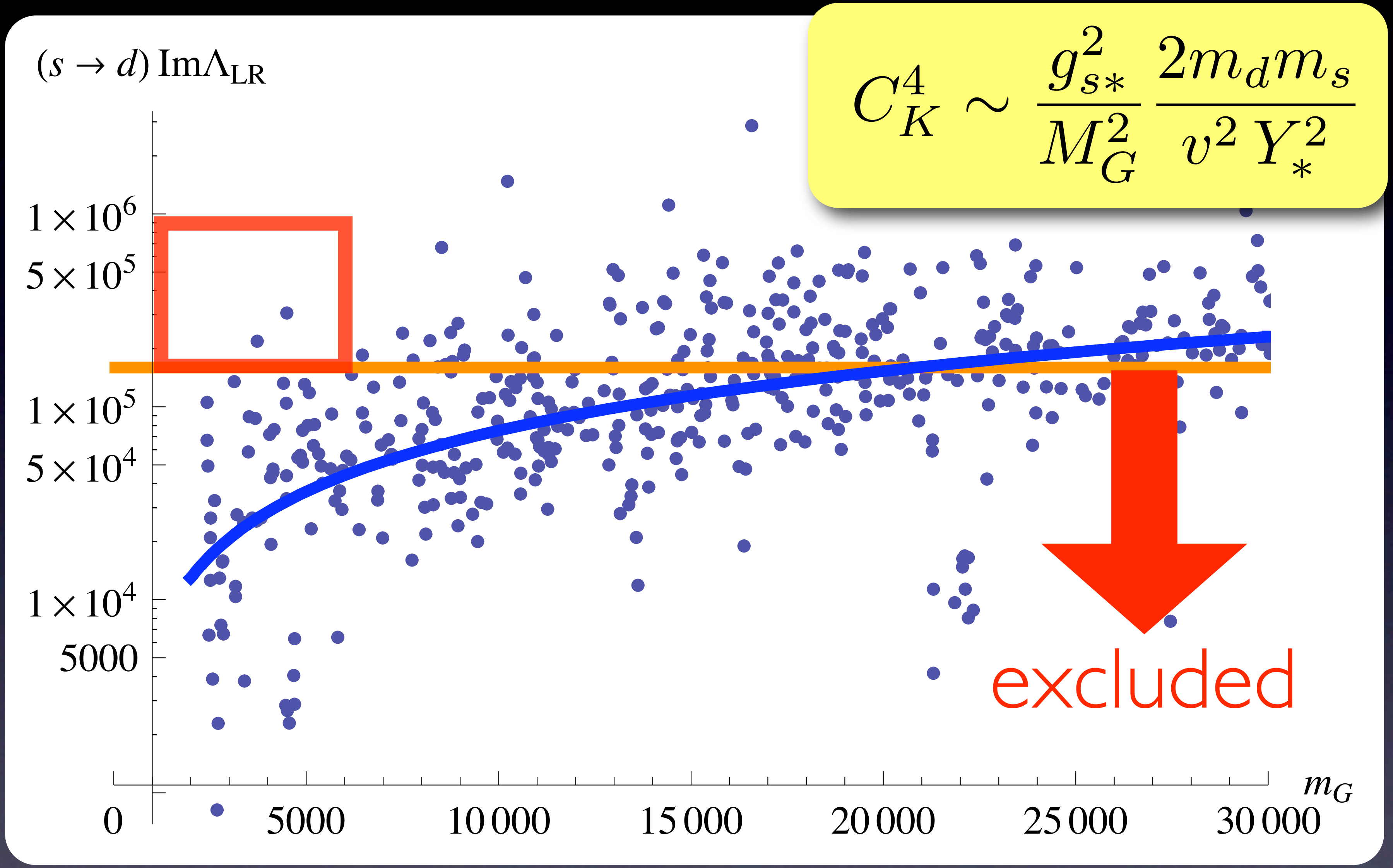


$$C_K^4 \sim \frac{g_{s*}^2}{M_G^2} \frac{2m_d m_s}{v^2\, Y_*^2}$$

excluded

KK gluon mass bound in RS

Csaki, Falkowski, A.W.; Buras et. al.



$$C_K^4 \sim \frac{g_{s*}^2}{M_G^2} \frac{2 m_d m_s}{v^2 Y_*^2}$$

Some points are ok: any rationale to live here?
Radiative stability?
Bound depends on bulk QCD coupling **g_{s*}** and **Y_***

Bounds with caveats

Main problem is CPV LR contribution to $\epsilon_K : (\bar{s}_L d_R)(\bar{s}_R d_L)$

$$C_{4K}^{RS} \sim \frac{g_{s*}^2}{M_G^2} \frac{1}{Y_*^2} \frac{2 m_d m_s}{v^2} \qquad C_{4K}^{pGB} \sim \frac{g_{s*}^2}{M_G^2} \frac{1}{g_*^2} \frac{8 m_d m_s}{v^2} \frac{1 + m^2}{\tilde{m}_d^2}$$

Csaki, Falkowski, A.W.

- o Reduce bulk QCD coupling g_{s*} by loop level matching and assume vanishing UV boundary kinetic terms × ½

Agashe, Azatov, Zhu

- o Larger Y_* allowed if Higgs in the bulk, more perturbative control **but** $Br(B \to X_s \gamma) \sim Y^{*6}$ × ½

m_G ~ 5-7 TeV ?

Uncomfortable corner of parameter space: Little hierarchy? Fine tuning? Perturbativity? Still no signal at LHC?

How can we evade the RS flavor problem?

Main message

Total anarchy does not seem to work

o Finetuned scales? Raise the scale to M_G ~ 20-30 TeV

o Finetuned Yukawas? Yukawas could miraculously give accidental cancellations

Buras et. al ⇒ Stefania's talk

o No tuning, we need to add more structure: Alignment and flavor symmetries

Fitzpatrick, Randall, Perez; Santiago; Csaki Falkowski, A.W;
Csaki, Grossman, Perez, Surujon,A.W. ; Agashe;

Spurion analysis

Without the Yukawas SM has

$$SU(3)_{Q_L} \times SU(3)_{u_R} \times SU(3)_{d_R}$$

global flavor symmetry.

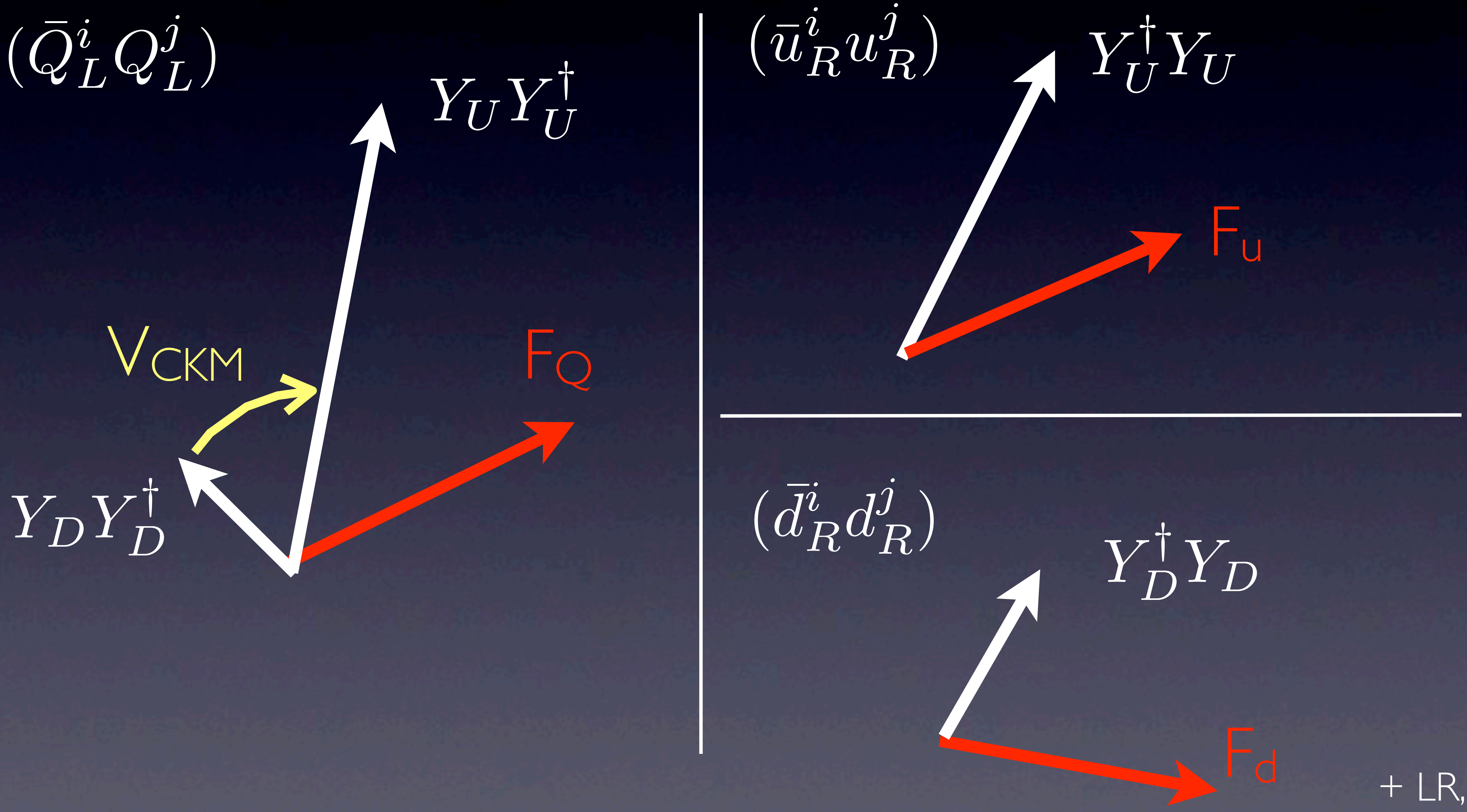
alternative picture: Davidson, Isidori, Uhlig

In RS broken by $Y_u^*, Y_d^* + F_Q, F_d, F_u$

No dangerous FCNCs in the down sector if

$Y_d^* + F_Q, F_d$ aligned (diagonal in the same basis)

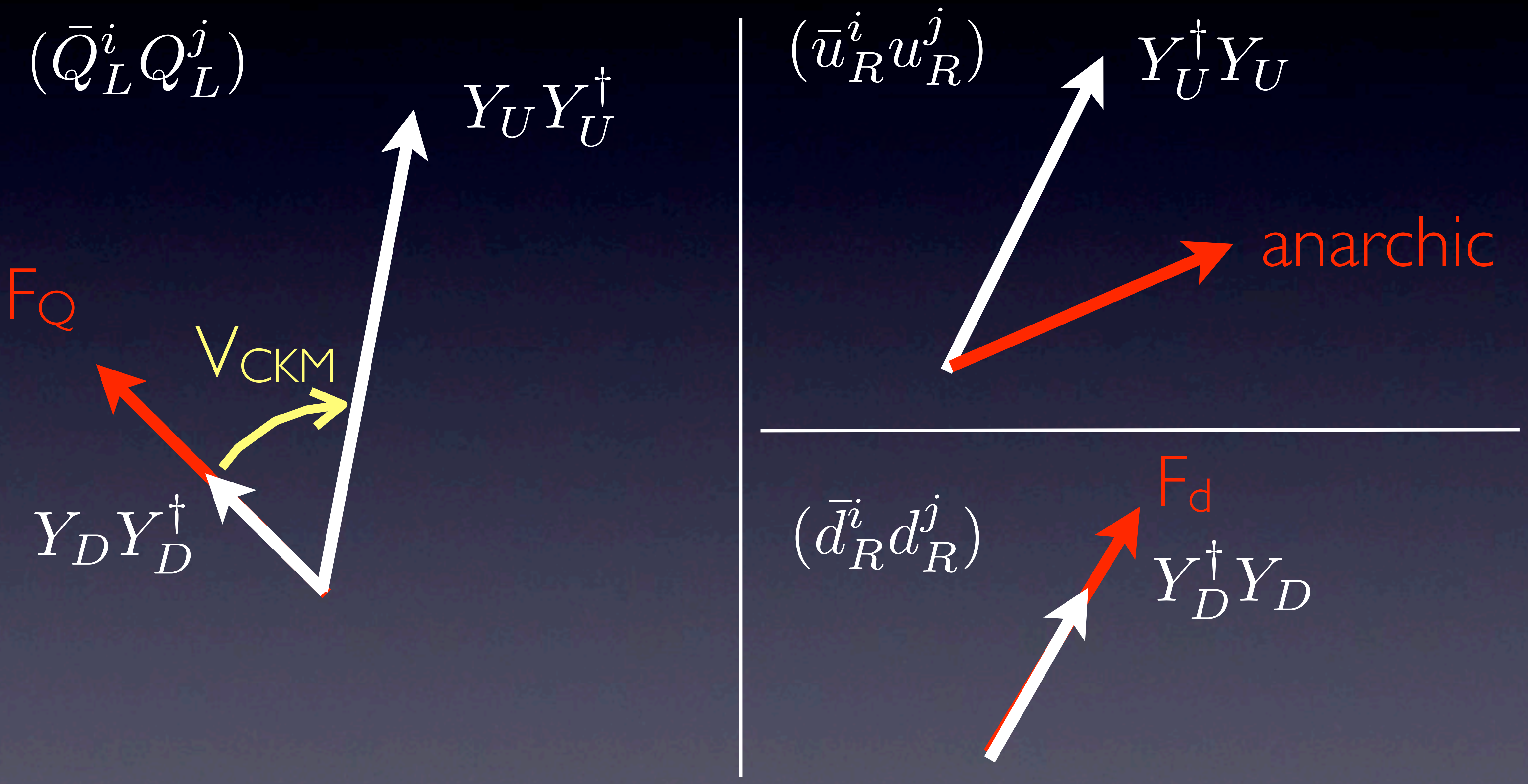
Anarchy



+ LR, RL

Align down sector

similar to Nir, Seiberg '93 for MSSM



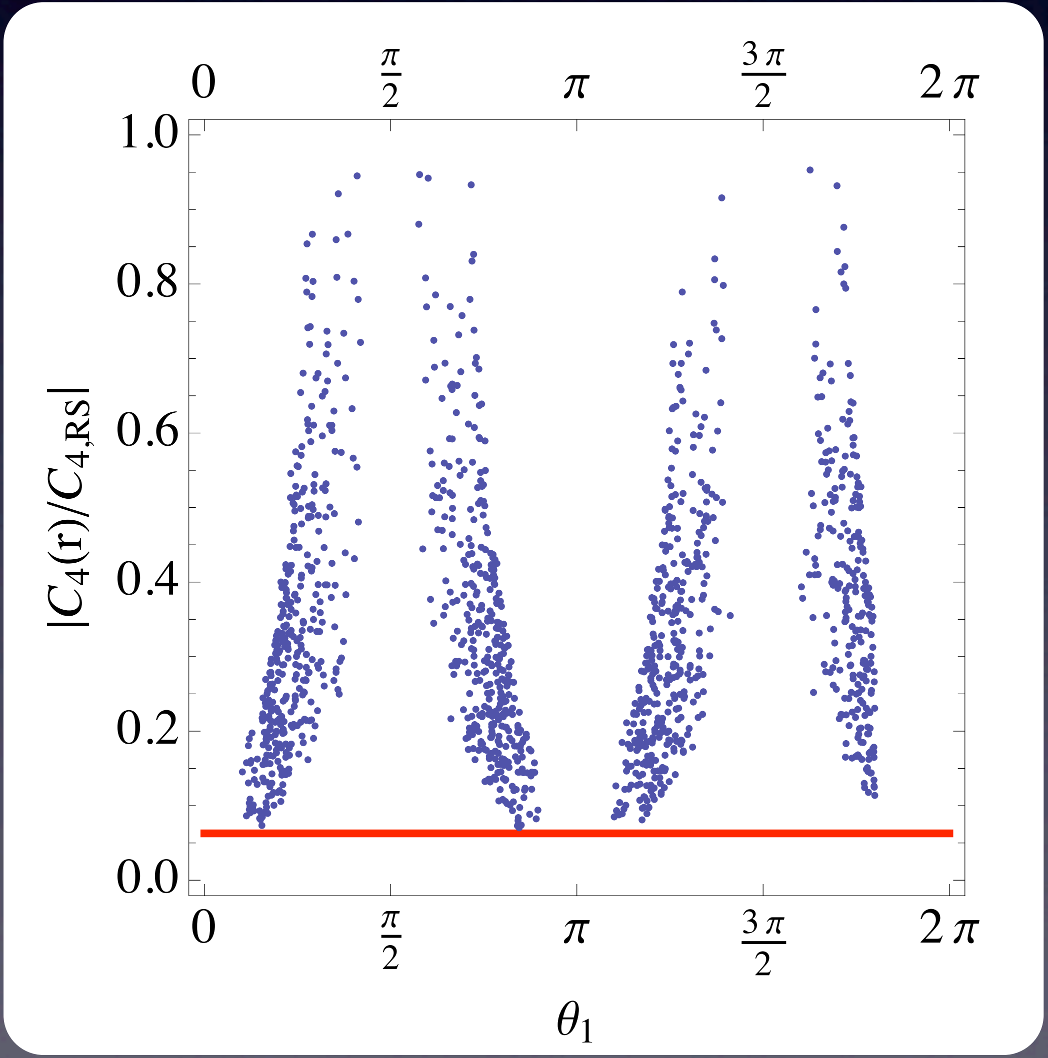
+ LR, RL

Aligning 5D MFV

Fitzpatrick, Randall, Perez; Csaki, Grossman, Perez, Surujon,A.W., in progress

$$c_Q \sim Y_d Y_d^\dagger + \epsilon Y_u Y_u^\dagger \qquad c_d \sim Y_d^\dagger Y_d \qquad c_u \sim Y_u^\dagger Y_u$$

for $\epsilon \to 0$ no FCNCs in the down sector.



Effective suppression, scan over 5D CKM keeping **ε** = 0.2 fixed.

Need $\epsilon \to 0$:
points to symmetry

Alignment due to shining

Csaki, Grossman, Perez, Surujon,A.W., in progress

In the bulk: gauged $SU(3)_Q \times SU(3)_d$ flavor symmetry.

$$F(c_Q) = F(Y_{*d} Y_{*d}{}^\dagger), \qquad F(c_d) = F(Y_{*d}{}^\dagger Y_{*d})$$

Rattazzi, Zafaroni

Breaking shines into the bulk by vev of dynamical Yukawa field Y_{*d} only (marginal operator)

Φ_d : (**3**,**1**,**<u>3</u>**), $<\Phi_d> = Y_{*d}\ (z/R)^{-\varepsilon}$

Large effects in up-FCNCs expected!

Alternative: horizontal U(1)'s

Csaki, Falkowski, A.W.

Alignment due to horizontal flavor symmetries

	Ψ_u	Ψ_{q_u}	Ψ_{q_d}	Ψ_d
$U(1)_q\,(+,-)$	$\cdot$	q_i	q_i	$\cdot$
$U(1)_d\,(-,+)$	0	0	d_i	d_i

split doublet natural candidate for pGB Higgs (Zb$\underline{\text{b}}$ protection)

U(1)$_q$ protects UV mixing $\theta q_{u,L}(0) - q_{d,L}(0) = 0$

U(1)$_d$ alignes Y$_{d*}$, c$_{qd}$, c$_d$

Predictions of U(1) solution

Gauged flavor symmetries : flavor bosons at the LHC?

Large (but controlled) flavor violation in the up-sector D-$\underline{\mathrm{D}}$ mixing

general discussion: Blum, Grossman, Nir, Perez

Parameter	Suppression	$f_{q_u^3} = 0.3$	$f_{q_u^3} = 1$	Bound (TeV)
$\lvert C_D^1 \rvert$	$\frac{\sqrt{6}}{g_{s*} \lambda^5 f_{q_u^3}^2} M_G$	$7.8 \cdot 10^3 M_G$	$0.7 \cdot 10^3 M_G$	$1.2 \cdot 10^3$
$\lvert C_D^1 \rvert$	$\frac{\sqrt{3} Y_*^2 v^2 \lambda^5 f_{q_u^3}^2}{\sqrt{2} g_{s*} m_u m_c} M_G$	$1.2 \cdot 10^3 M_G$	$1.3 \cdot 10^5 M_G$	$1.2 \cdot 10^3$
$\lvert C_D^4 \rvert$	$\frac{v Y_*}{g_{s*} \sqrt{2\, m_u m_c}} M_G$	$1.2 \cdot 10^3 M_G$	$1.2 \cdot 10^3 M_G$	$3.5 \cdot 10^3$
$\lvert C_K^1 \rvert$	$\frac{\sqrt{6}}{g_{s*} \lambda^5 f_{q_u^3}^2 \delta} M_G$	$3.0 \cdot 10^6 M_G$	$2.7 \cdot 10^5 M_G$	$1.5 \cdot 10^4$
$\lvert C_K^1 \rvert$	$\frac{\sqrt{3} Y_*^2 v^2}{\sqrt{2} g_{s*} m_d m_s \lambda \delta} M_G$	$1.5 \cdot 10^{10} M_G$	$1.5 \cdot 10^{10} M_G$	$1.5 \cdot 10^4$
$\lvert C_K^4 \rvert$	$\frac{Y_* v}{g_{s*} \sqrt{2 m_d m_s} \lambda^3 f_{q_u^3} \delta} M_G$	$2.8 \cdot 10^7 M_G$	$8.5 \cdot 10^6 M_G$	$1.6 \cdot 10^5$

Conclusions

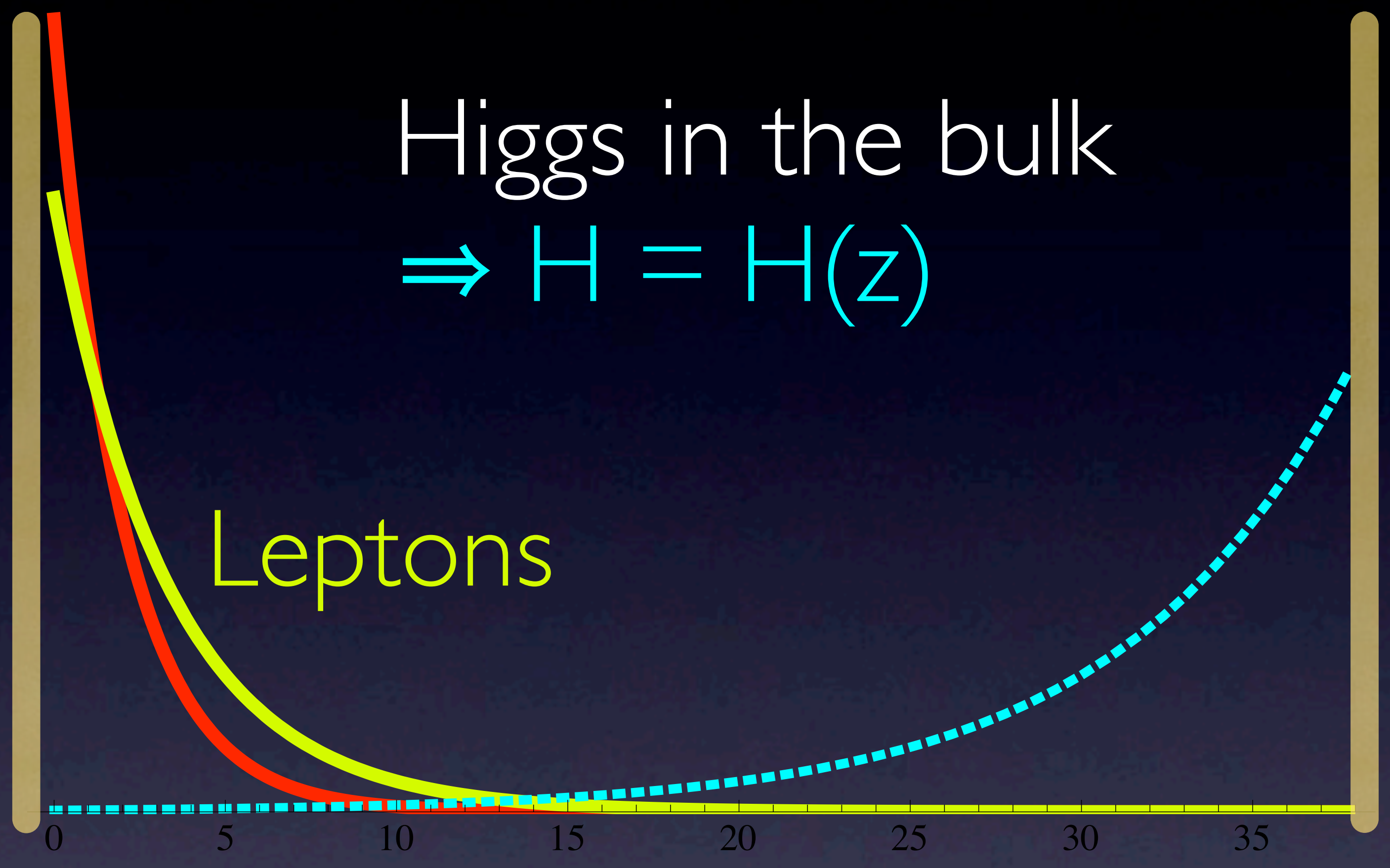
RS provides an interesting theory of flavor, dual to partial compositeness.

RS-GIM suppresses dangerous FCNCs, tension with CPV in Kaon sector

Anarchy alone needs fine-tuning to survive, additional structure in the flavor sector required
⇒ large FCNCs in the up-sector predicted

Back-up slides

Remark on lepton flavor


Higgs in the bulk

$\Rightarrow H = H(z)$

Neutrino wave function picks up UV tail of Higgs

Agashe, Sundrum, Okui

Exponential suppression of overall mass scale
but O(1) **ν** mixing angles.

Remark on lepton flavor

$$\begin{tikzcd}
 & Y_{4\mathrm{D},ij} \sim \int_0^a dy\, Y_{5\mathrm{D},ij}(y)\, e^{-(M_{L_i}+M_{R_j})y+M_H(y-a)} \arrow[dl, "(M_{L_i}+M_{R_j}>M_H)"'] \arrow[dr, "(M_{L_i}+M_{R_j}<M_H)"] & \\
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$M_i = c_i$

Neutrino wave function picks up UV tail of Higgs

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Mass terms from gauge interactions

Possible fermion embedding: **4** of SO(5)

$$\Psi_q = \begin{pmatrix} \boxed{q_q[+,+]} \\ u^c_q[-,+] \\ d^c_q[-,+] \end{pmatrix} \qquad \Psi_u = \begin{pmatrix} q_u[+,-] \\ \boxed{u^c_u[-,-]} \\ d^c_u[+,-] \end{pmatrix} \qquad \Psi_d = \begin{pmatrix} q_d[+,-] \\ u^c_d[+,-] \\ \boxed{d^c_d[-,-]} \end{pmatrix}$$

1) $\boxed{\qquad\quad}$ = chiral zero modes

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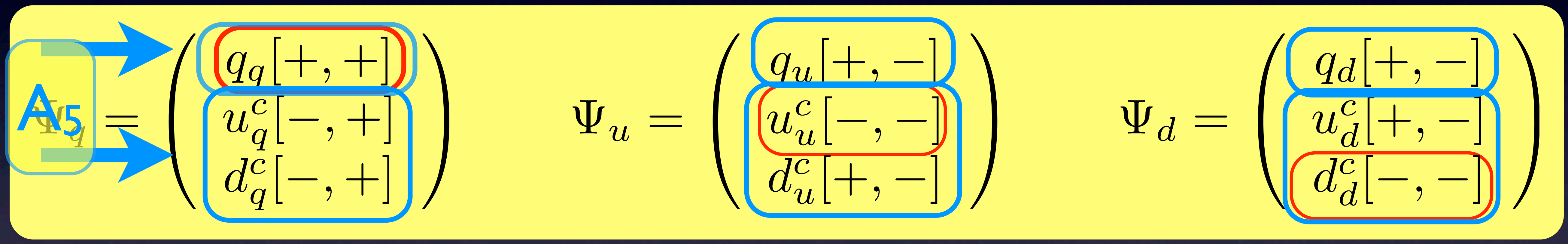

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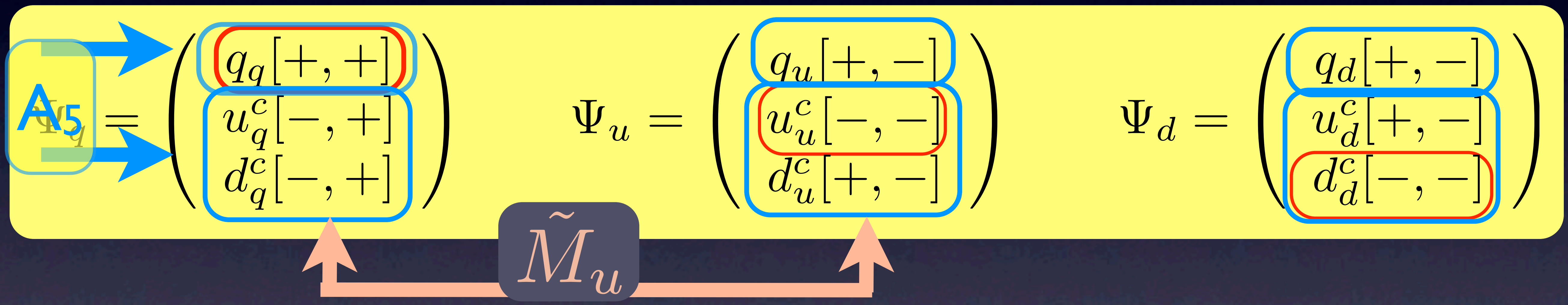

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3) SO(4) invariant brane masses mix multiplets

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Mass terms from gauge interactions

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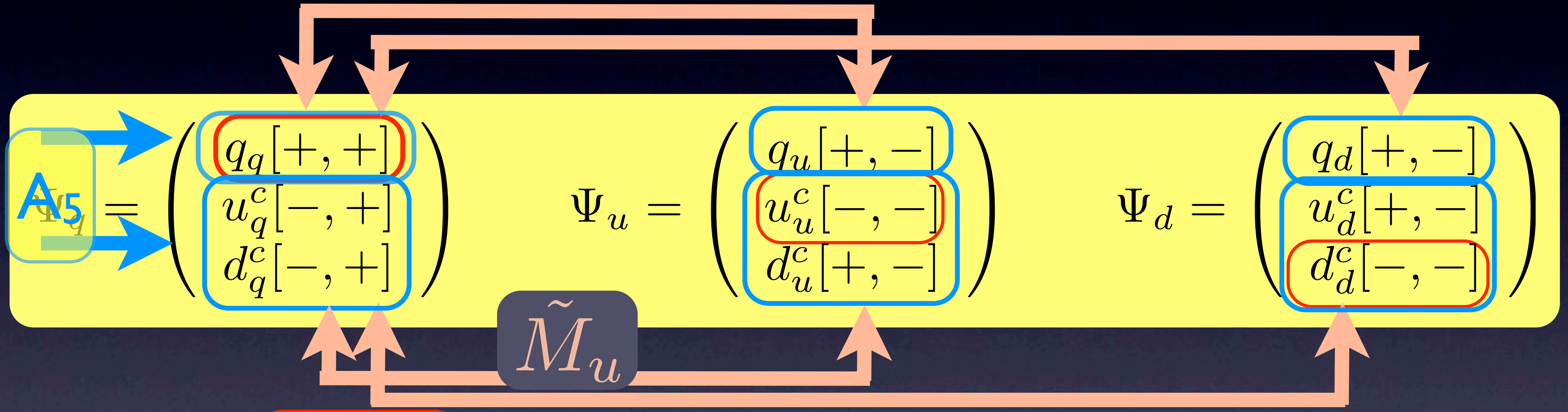

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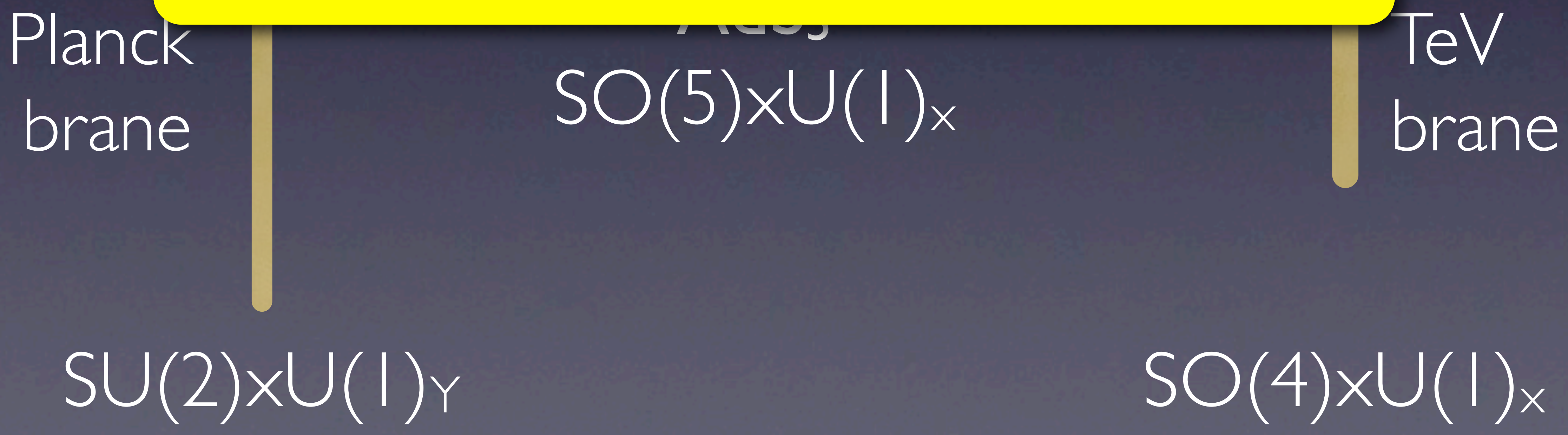
Holographic pGB Higgs model

Agashe, Contino, Pomarol

Simple model with

- A_5 zero mode $\in$ SO(5)/SO(4) = **Higgs**
- UV insensitive, dynamical EWSB
- s

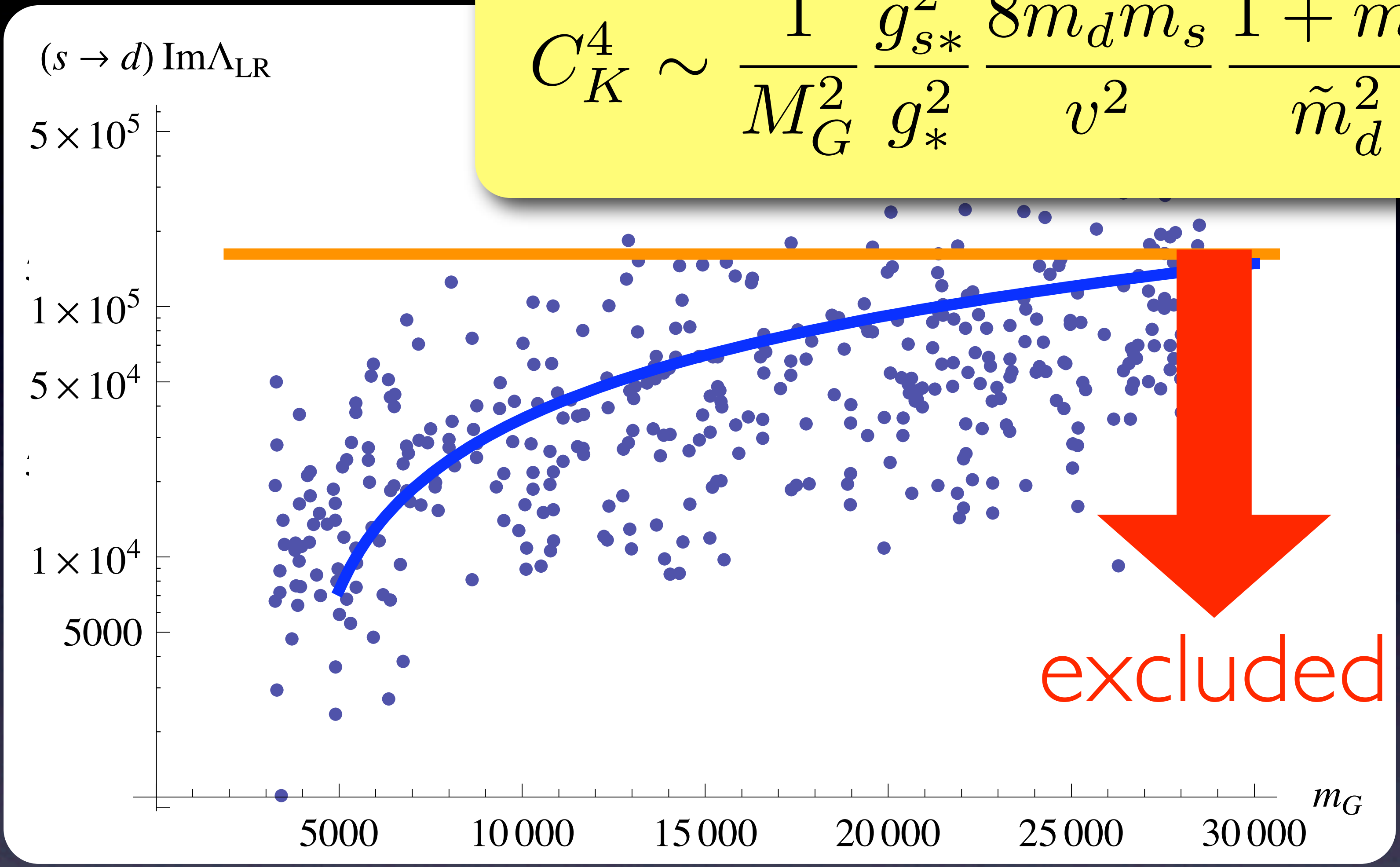
Dual to pGB composite Higgs (Georgi, Kaplan '83)



Bound for pGB Higgs

Csaki, Falkowski, A.W.;

$$C_K^4 \sim \frac{1}{M_G^2}\,\frac{g_{s*}^2}{g_*^2}\,\frac{8 m_d m_s}{v^2}\,\frac{1+m^2}{\tilde{m}_d^2}$$



$M_{KK} > 30$ TeV

FCNC constraint more severe in composite pGB!

Why? $Y^* \to g_* / 2$ & fermionic kinetic mixings

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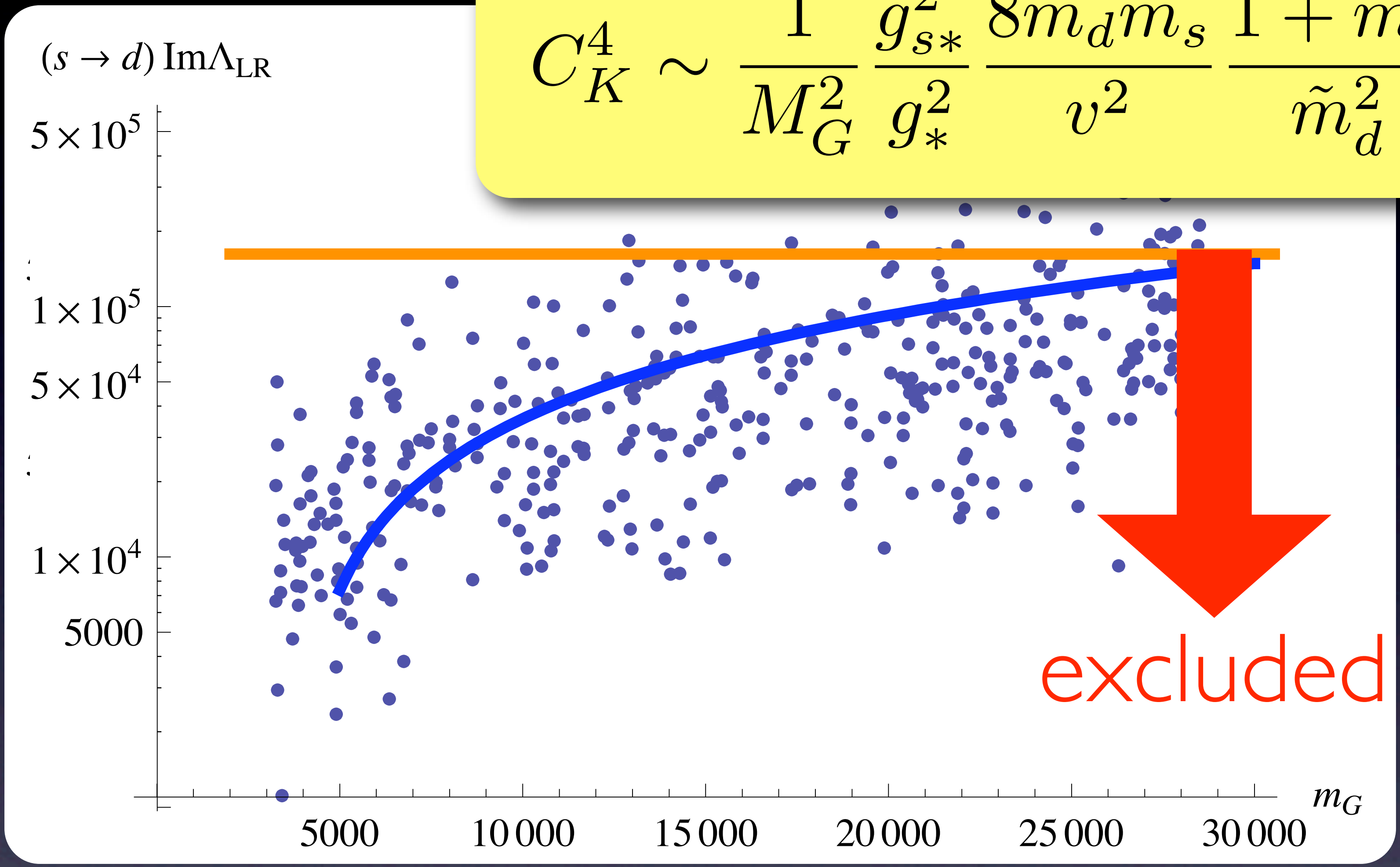

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