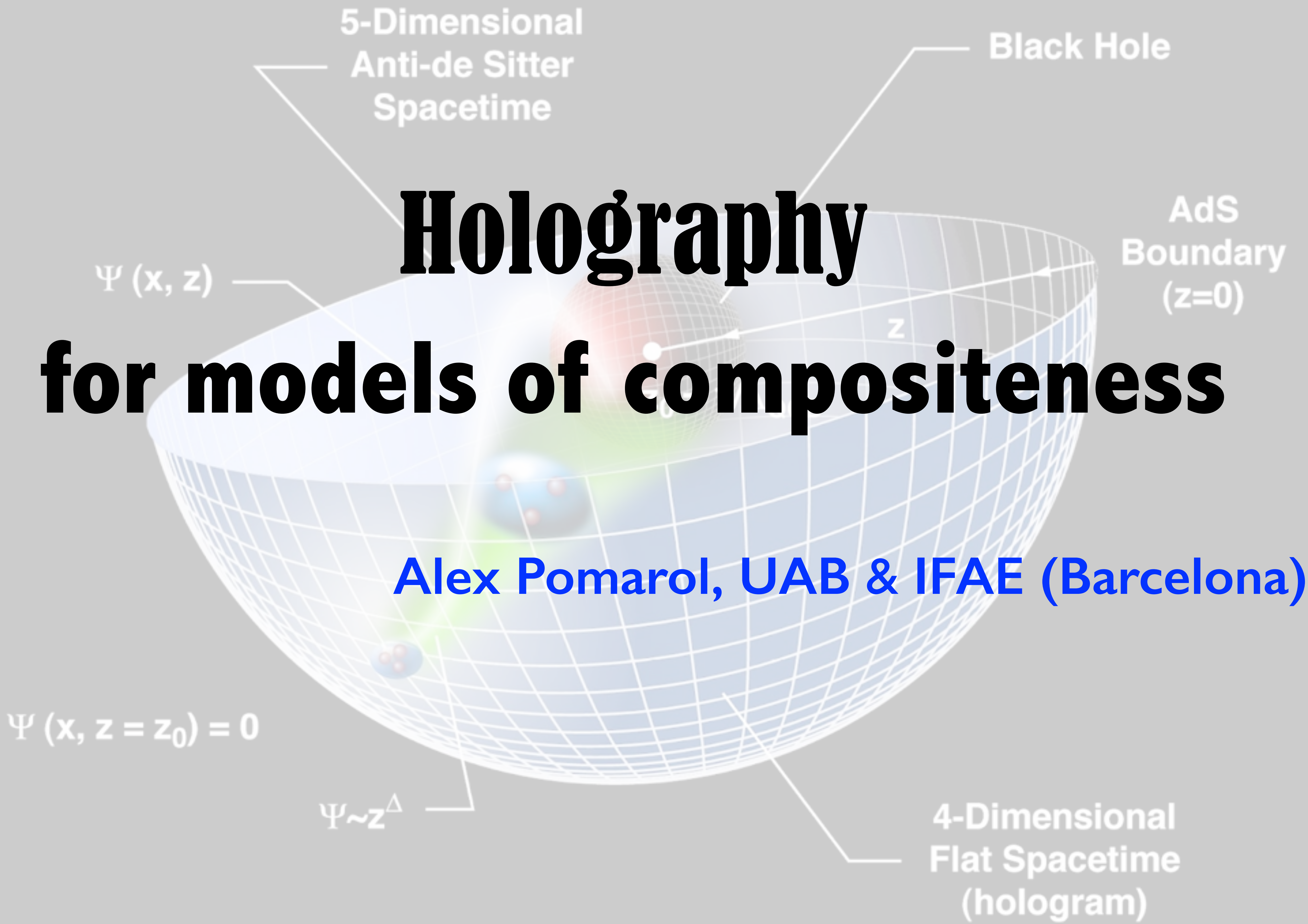
Holography
for models of compositeness

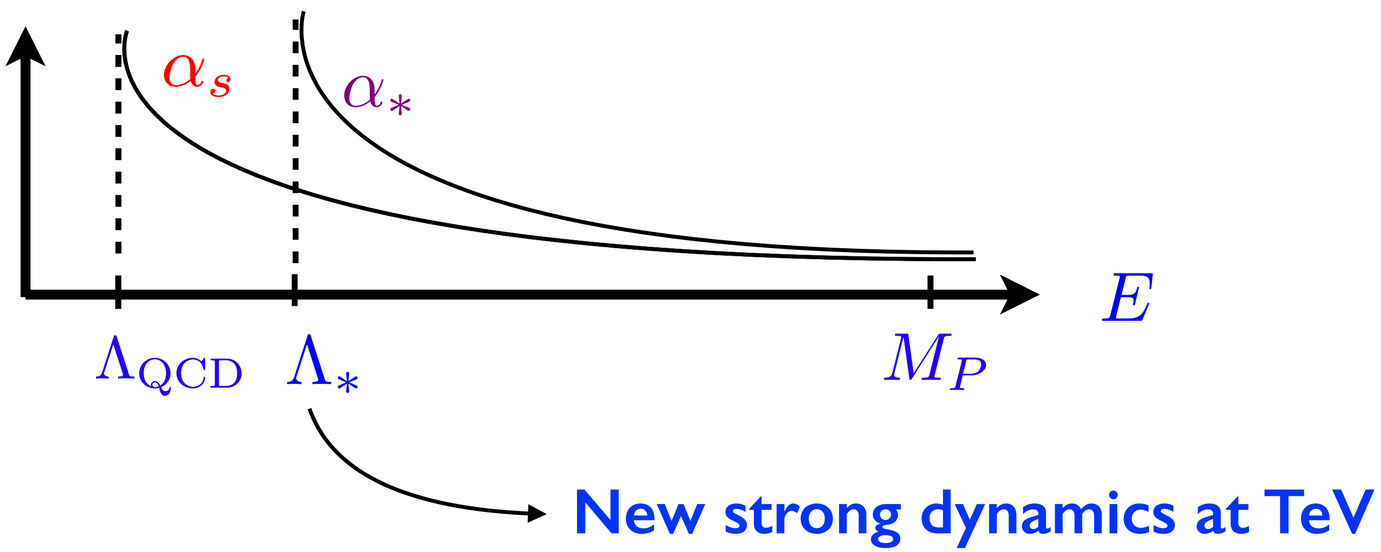
Alex Pomarol, UAB & IFAE (Barcelona)



Understanding the properties of **strongly-coupled theories** is of major interest:

- Understanding QCD

- Strong-dynamics can generate large hierarchies:



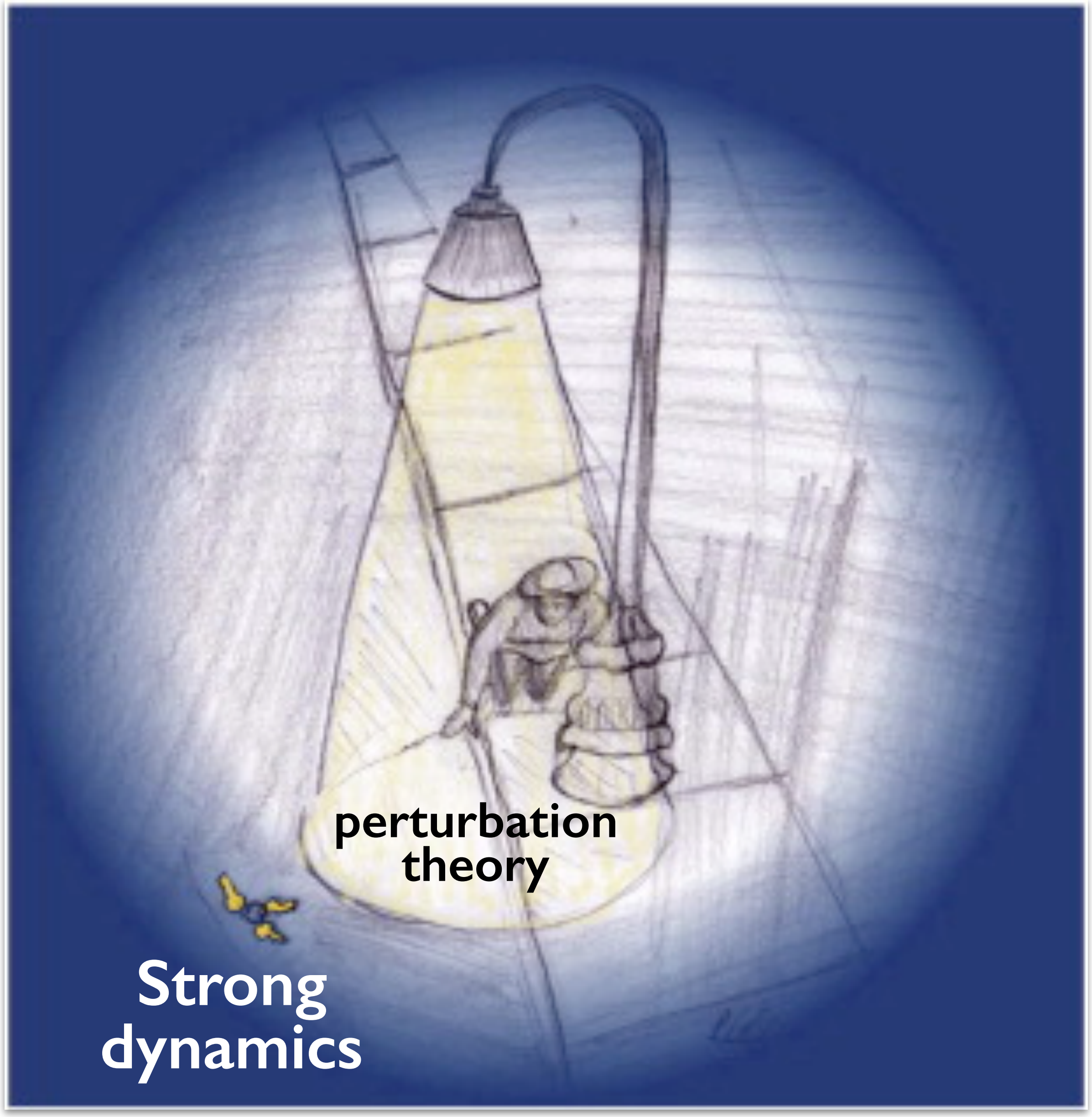
☛ explain $m_W \ll M_P$

could also be useful for fermion masses, axions, inflation,…

- Enlarge our charting on EFTs

Dealing with strong dynamics….

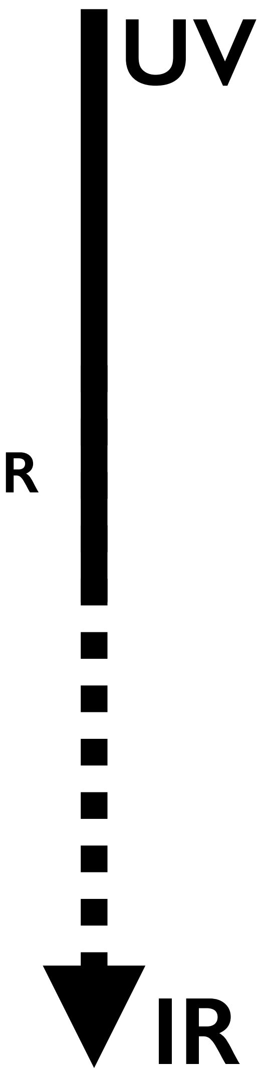
Beyond the lamp-post:



Dealing with strong dynamics….

We can well-define the UV theory:
gauge-symmetry
+ matter content

e.g. **SU(N_c) +** N_F **$q_{L,R}$**



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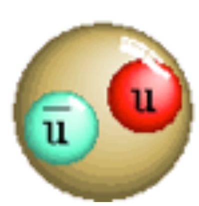

rich theory of
mesons and baryons

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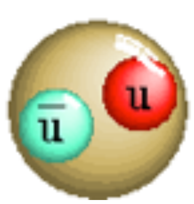

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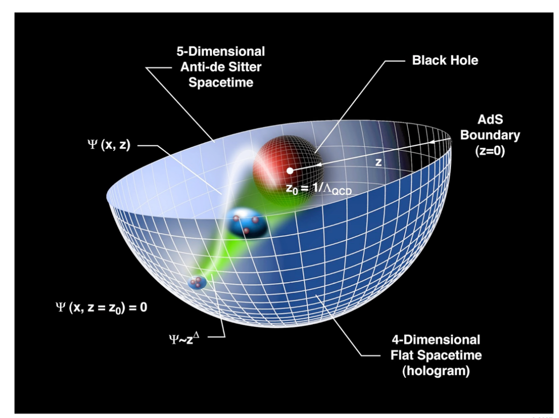

IR

Questions posed
to strong dynamics
can be addressed
by an **AdS_5**

predictive theories
of "mesons" and "baryons"!

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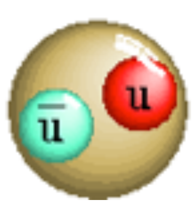

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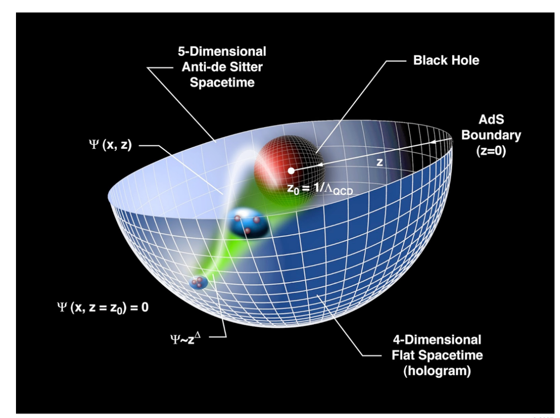

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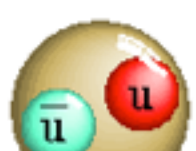

Lattice can help here

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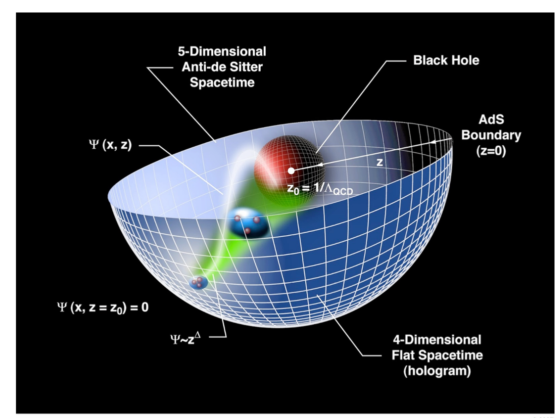

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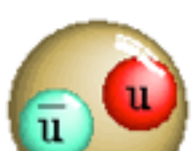

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string theory can help here

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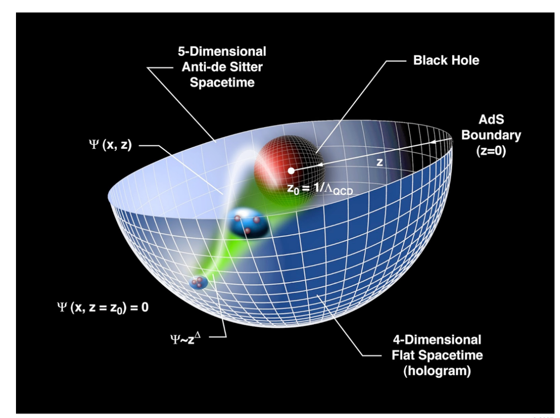

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The AdS/CFT correspondence

Strongly-coupled systems
i.e. Large N_c
Large $\lambda \equiv g^2 N_c$

⟷

Weakly-coupled Gravitational systems in higher-dimensions

explicit examples: **$\mathcal{N}$=4 SUSY ↔ $AdS_5 \times S_5$, …**

A more “low-energy” EFT approach:

Built a **5D EFT** with the “basic” ingredients needed to describe the **properties** of the strong-dynamics

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AdS/CFT dictionary

RG-scale **μ**	$\longrightarrow$	Extra coordinate ***z***
CFT_4	$\longrightarrow$	AdS_5
Operators	$\longrightarrow$	Fields
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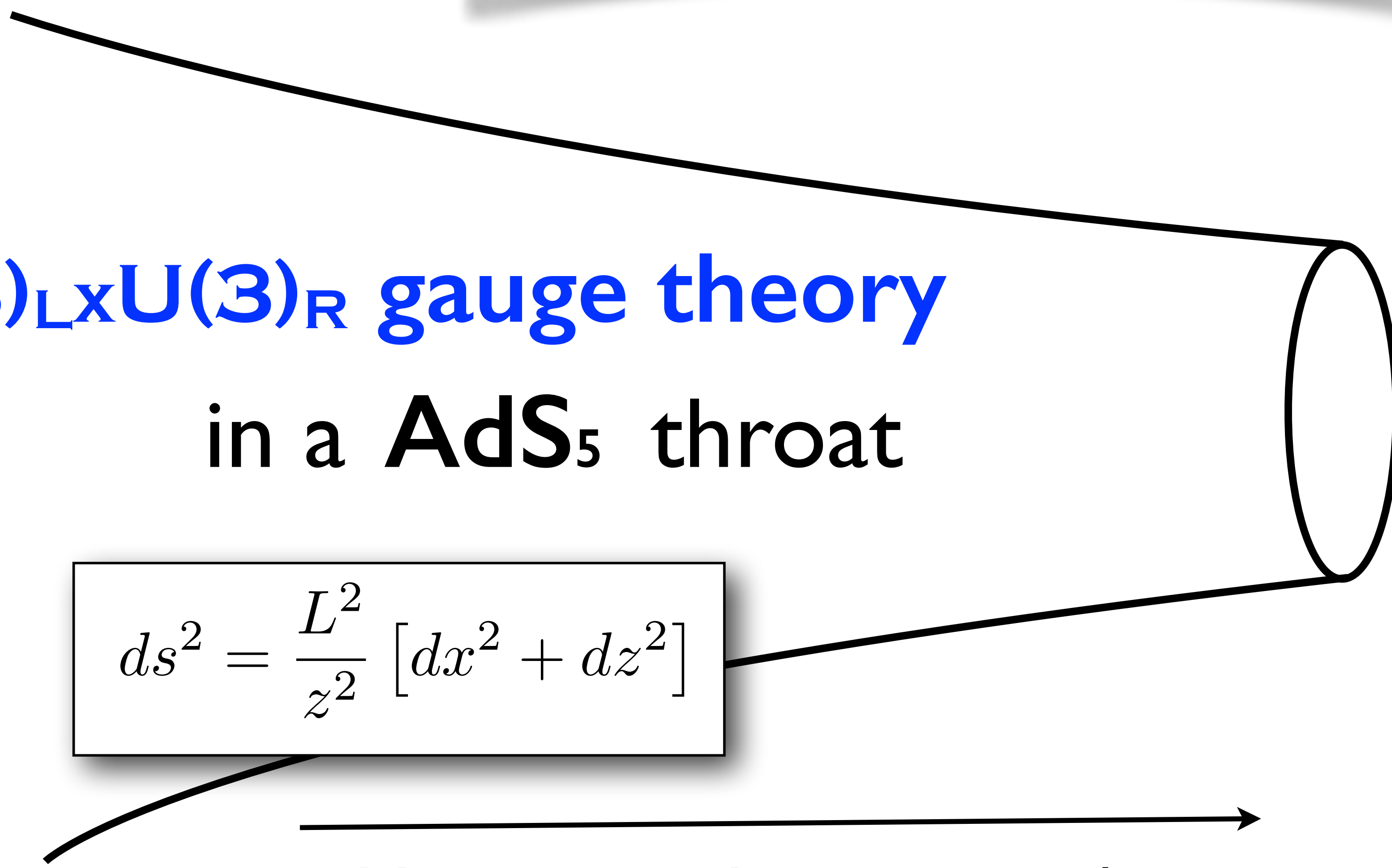
e.g. **QCD**-like theory (**N_F=3**) with chiral-symmetry breaking:

4D relevant operators:		5D fields:	$SU(3)_L \times SU(3)_R$
$\bar{q}_R q_L$	$\longrightarrow$	scalar Φ	$(\bar{3}, 3)$
$\bar{q}_L \gamma^\mu q_L$	$\longrightarrow$	vector L_M	(8,0)
$\bar{q}_R \gamma^\mu q_R$	$\longrightarrow$	vector R_M	(0,8)

Holographic QCD

Erlich, Katz, Son, Stephanov
Da Rold, A.P.



$U(3)_L x U(3)_R$ gauge theory

in a **AdS_5** throat

$$ds^2 = \frac{L^2}{z^2}\left[dx^2 + dz^2\right]$$

hard/soft wall

Mass gap ~ GeV

Holo. coordinate z ~ 1/μ

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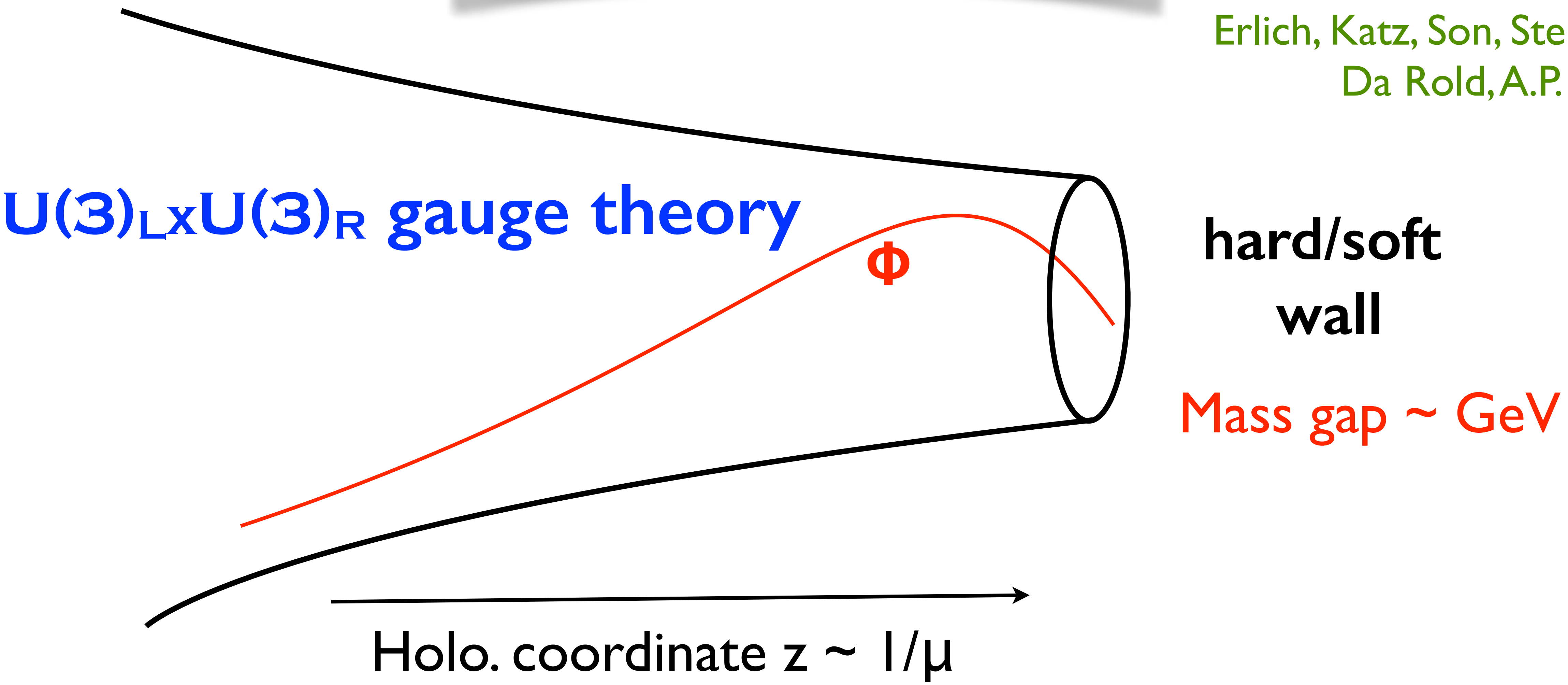
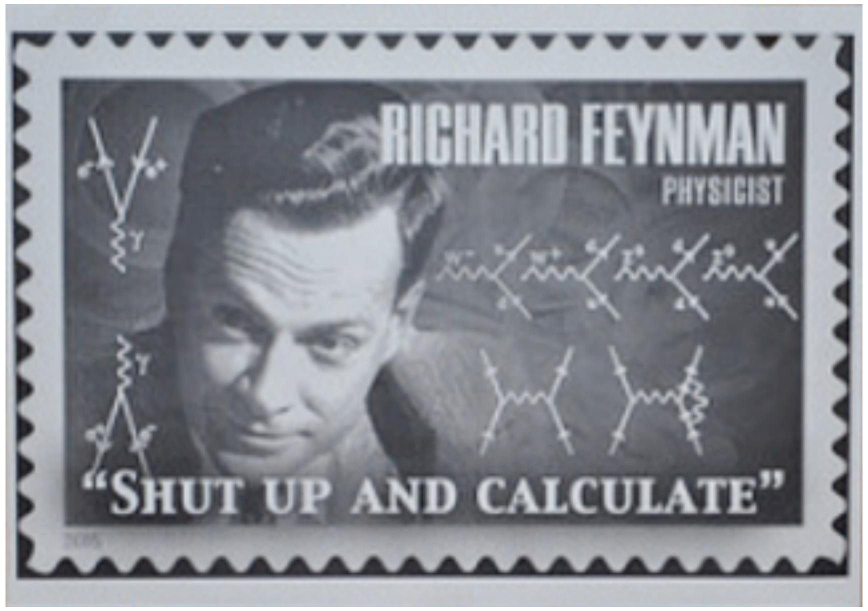
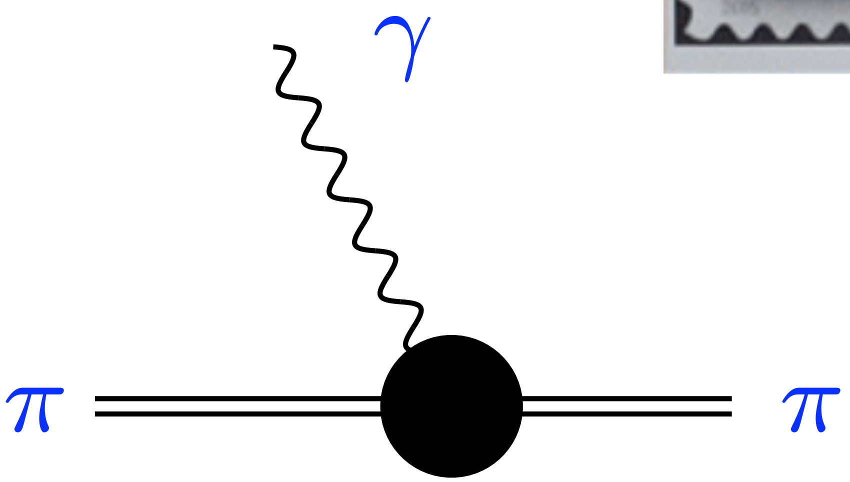


Symmetry breaking **$U(3)_L x U(3)_R \to U(3)_V$** *a la Higgs* in 5D: **$\langle\Phi\rangle \neq 0$**

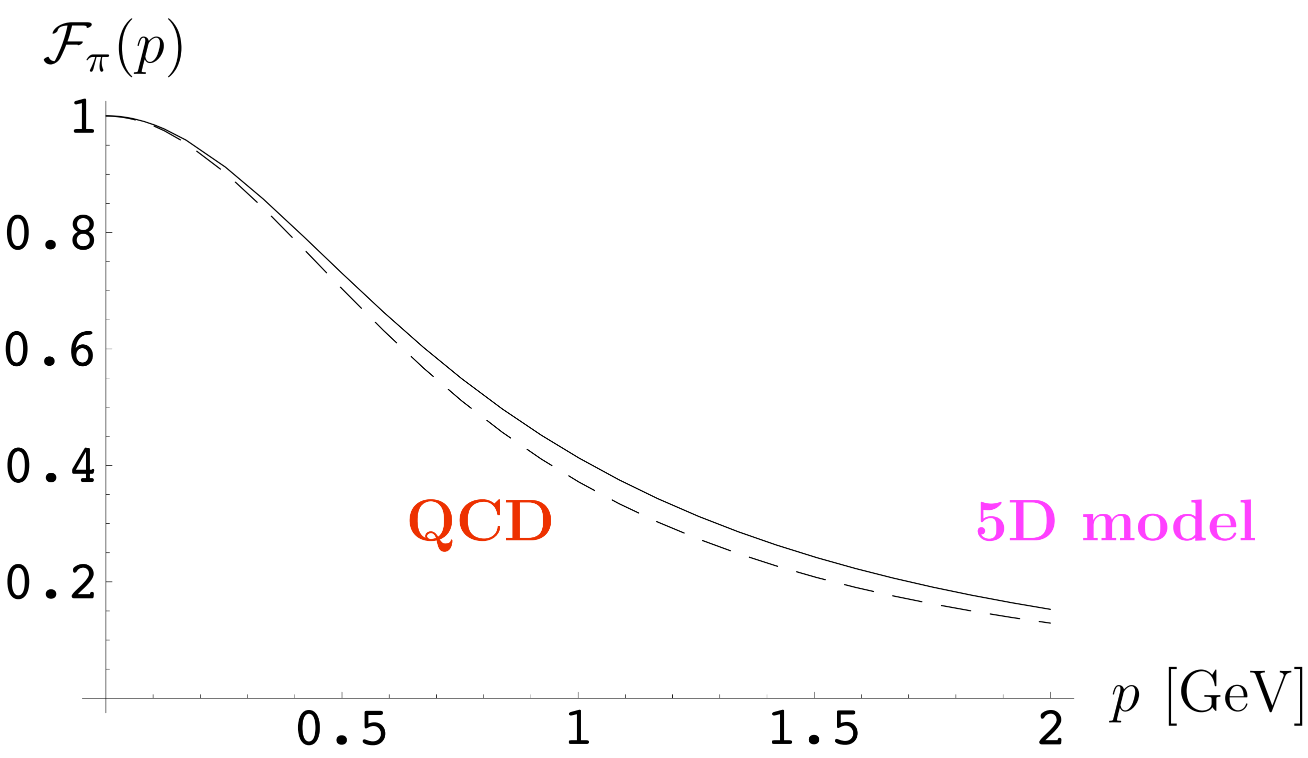
Kaluza-Klein states = QCD resonances (Weakly-coupled for large N_c)

Why extra-dimensional models are models of compositeness?





summing over
Kaluza-Klein



Impressive **similarity with QCD** even at the qualitative level (for lightest resonance physics)

	Experiment	AdS_5	Deviation
m_ρ	775	824	+6%
m_{a_1}	1230	1347	+10%
m_ω	782	824	+5%
F_ρ	153	169	+11%
F_ω/F_ρ	0.88	0.94	+7%
F_π	87	88	+1%
$g_{\rho\pi\pi}$	6.0	5.4	−10%
L_9	$6.9 \cdot 10^{-3}$	$6.2 \cdot 10^{-3}$	−10%
L_{10}	$-5.2 \cdot 10^{-3}$	$-6.2 \cdot 10^{-3}$	−12%
$\Gamma(\omega \to \pi\gamma)$	0.75	0.81	+8%
$\Gamma(\omega \to 3\pi)$	7.5	6.7	−11%
$\Gamma(\rho \to \pi\gamma)$	0.068	0.077	+13%
$\Gamma(\omega \to \pi\mu\mu)$	$8.2 \cdot 10^{-4}$	$7.3 \cdot 10^{-4}$	−10%
$\Gamma(\omega \to \pi ee)$	$6.5 \cdot 10^{-3}$	$7.3 \cdot 10^{-3}$	+12%

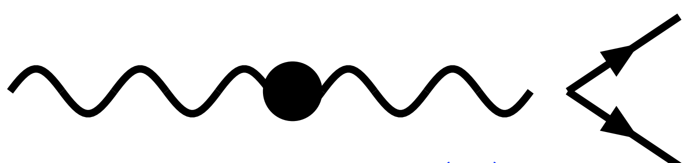
Average error ~ 10%

Why simple holographic models work so well for QCD?
(for the lightest resonance physics)

- Theory of weakly-coupled spin=0,1,2 resonances: **Incorporates the successes of large-N_c QCD**

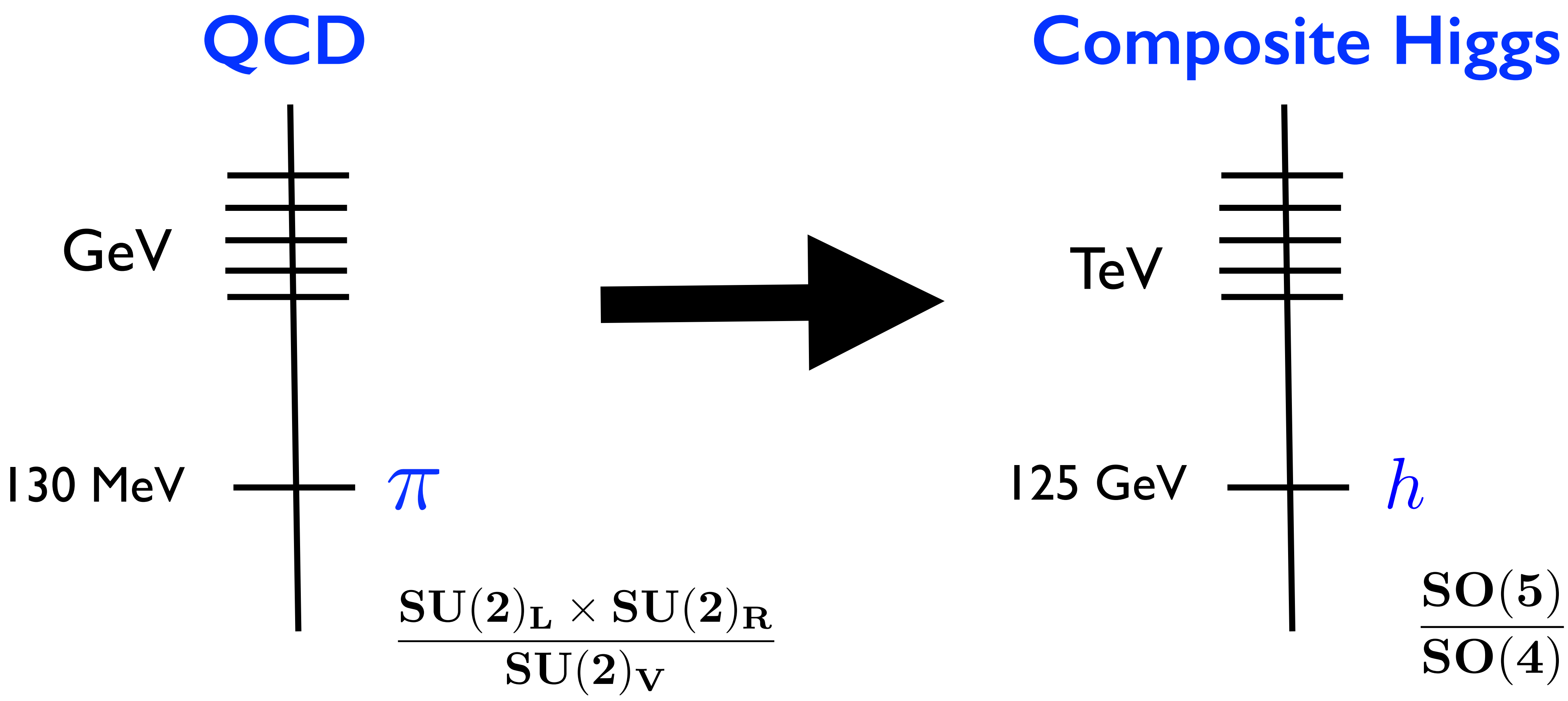
- Reproduces the **conformal** properties of QCD **at the UV**

- Predicts **Vector Meson Dominance** (VMD), incorporating its successes



γ $\rho^{(n)}$

Holography for composite Higgs



The **Higgs**, **the lightest** of the new strong resonances,

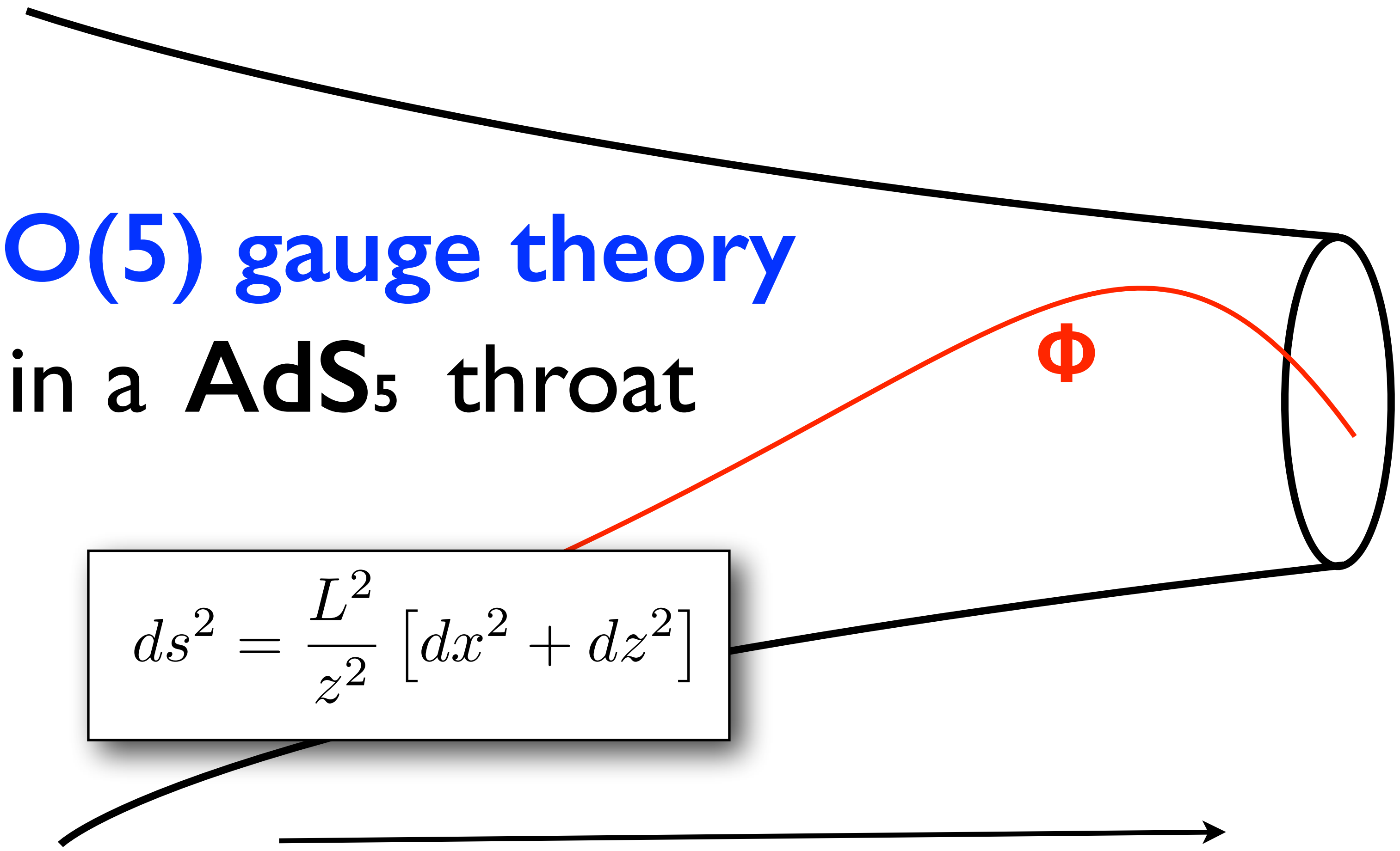
as pions in QCD: they are Pseudo-Goldstone Bosons (**PGB**)

Holographic Composite Higgs

Agashe, Contino, A.P.

SO(5) gauge theory

in a **AdS$_5$** throat



hard/soft wall

Mass gap ~ TeV

Holo. coordinate z ~ 1/μ

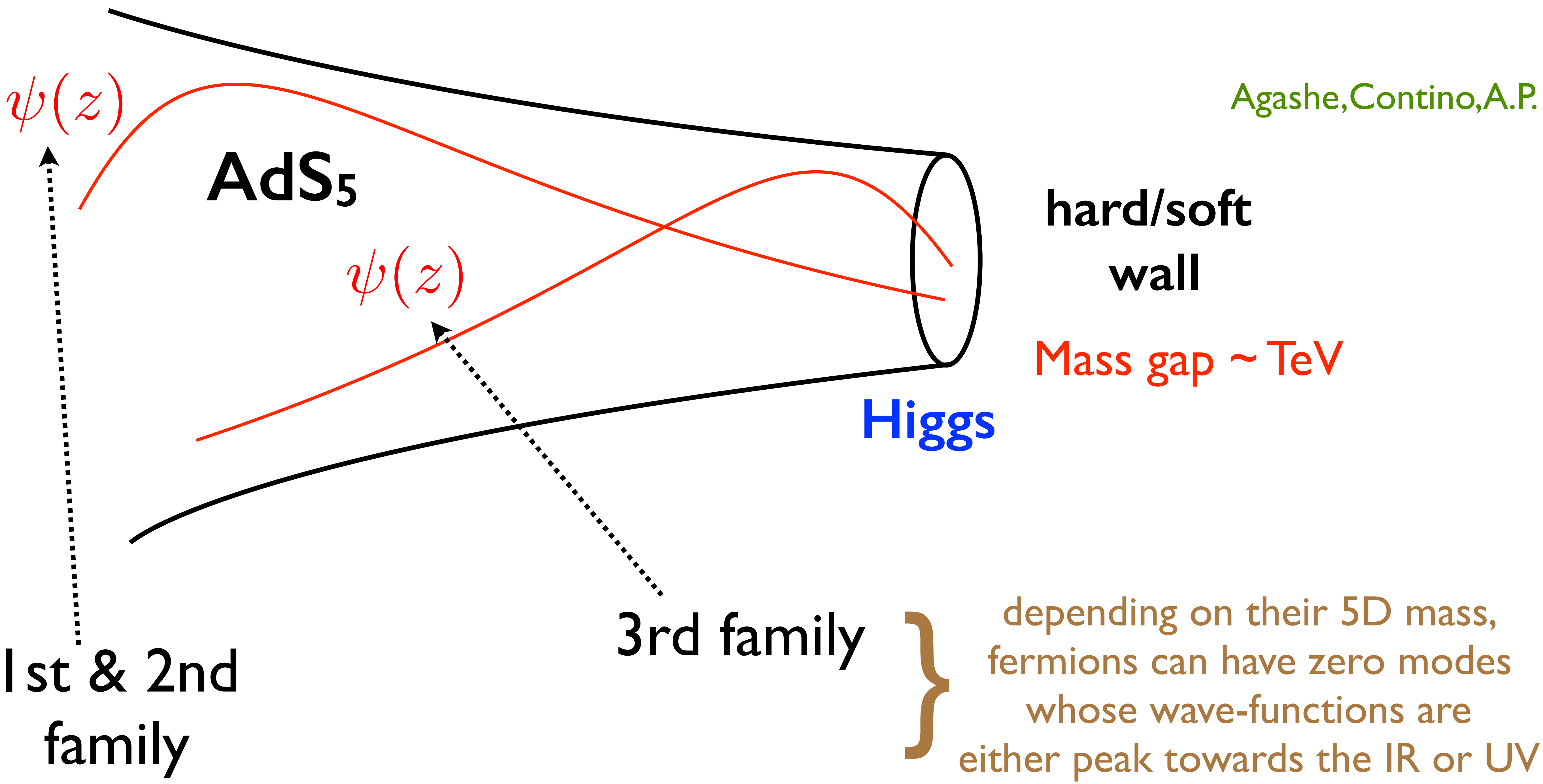
Symmetry breaking **SO(5)→SO(4)** *a la Higgs* in 5D: **⟨Φ⟩≠0**

☛ 4 PGBs = $\mathbf{2_1}$ of SU(2)xU(1) ∈ SO(4) ≡ **the Higgs**

Fermion masses

(the best lesson from holography)

Holographic Composite Higgs



Simple geometric approach to fermion masses

Using the AdS/CFT dictionary:

linear-mixing: $\mathcal{L}_{\rm lin} = \epsilon_{f_i}\, \bar{f}_i\, \mathcal{O}_{f_i}$

$\bar{f}_i$ → SM fermion

$\mathcal{O}_{f_i}$ → fermion operator of the strong sector

ϵ_f depend on the dim of the operator

$$\mathrm{Dim}[\mathcal{O}_{f_i}] = \mathbf{3/2} + |\mathbf{M_5 L} + \mathbf{1/2}|$$

For the top, we need large mixing:

$\mathrm{Dim}[\mathcal{O}_{top}] \lesssim 5/2$ needed!

e.g. $\mathcal{O}_{f_i} \sim \psi\psi\psi$

9/2(weak)→5/2(strong)

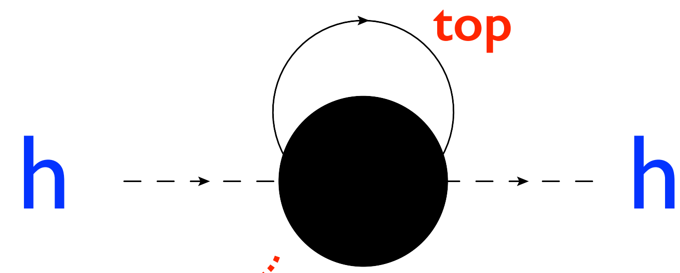
<u>AdS₅ prediction:</u>

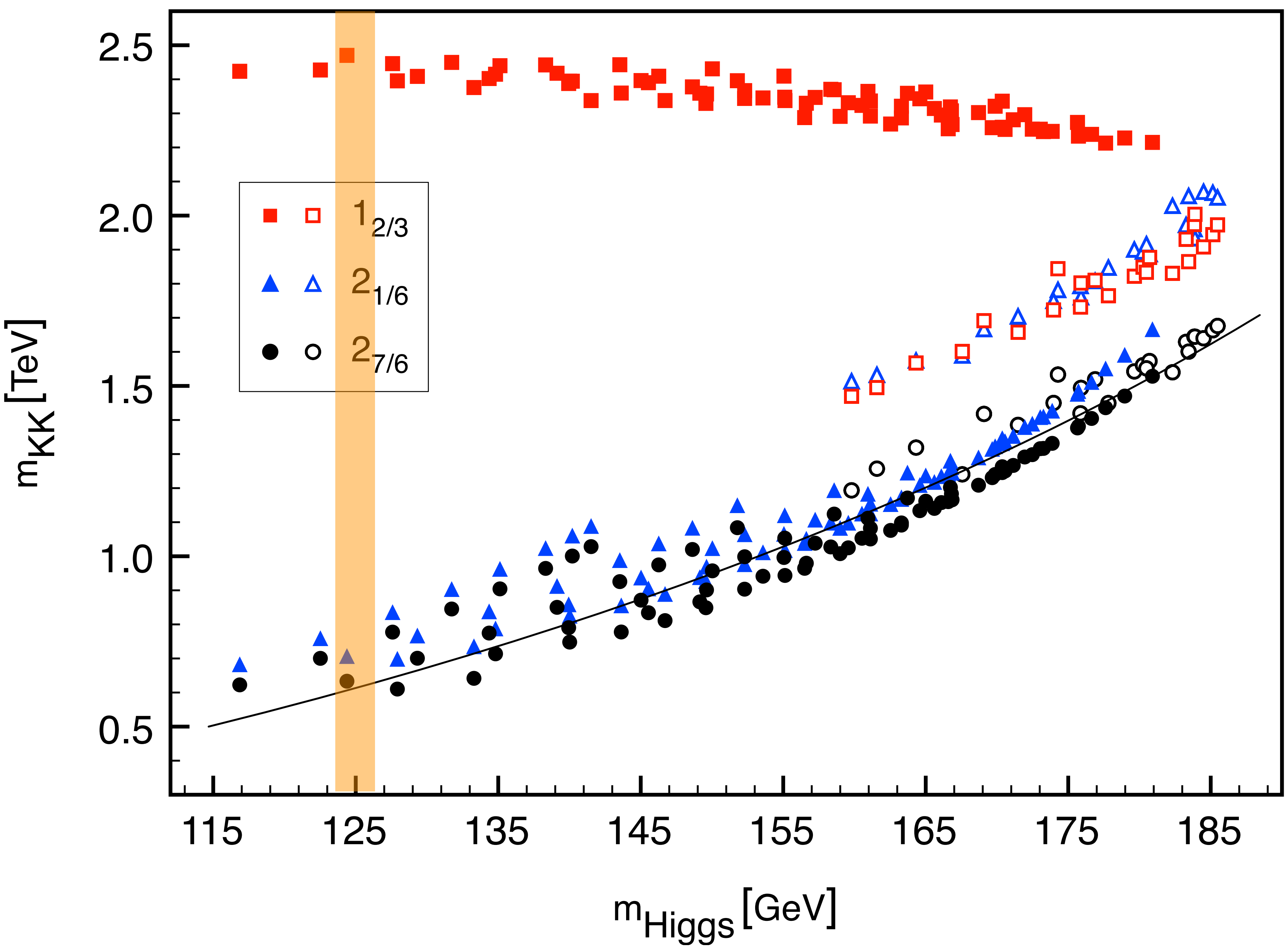
As $\dim[\mathcal{O}_{top}] \to 3/2$ ☛ $M_5L \to -1/2$ ☛ top-partners become light!

Higgs mass from AdS$_5$ models:

Contino, DaRold, AP 07

mass of the top-partner





$f = 500$ GeV

$m_\rho = 2.5$ TeV

Light Higgs - Light Resonance connection!

Exist QFTs with this property?

Light top partners also understood from the **CFT_4** perspective:

As dim[$\mathcal{O}_{top}$] → 3/2 ☛ Unitarity bound ☛ free fermion ☛ **massless!**

Flavor challenge II:

linear-mixing: $\mathcal{L}_{\rm lin} = \epsilon_{f_i}\, \bar{f}_i\, \mathcal{O}_{f_i}$

New sources of flavor breaking

Compatible with exp. bounds?

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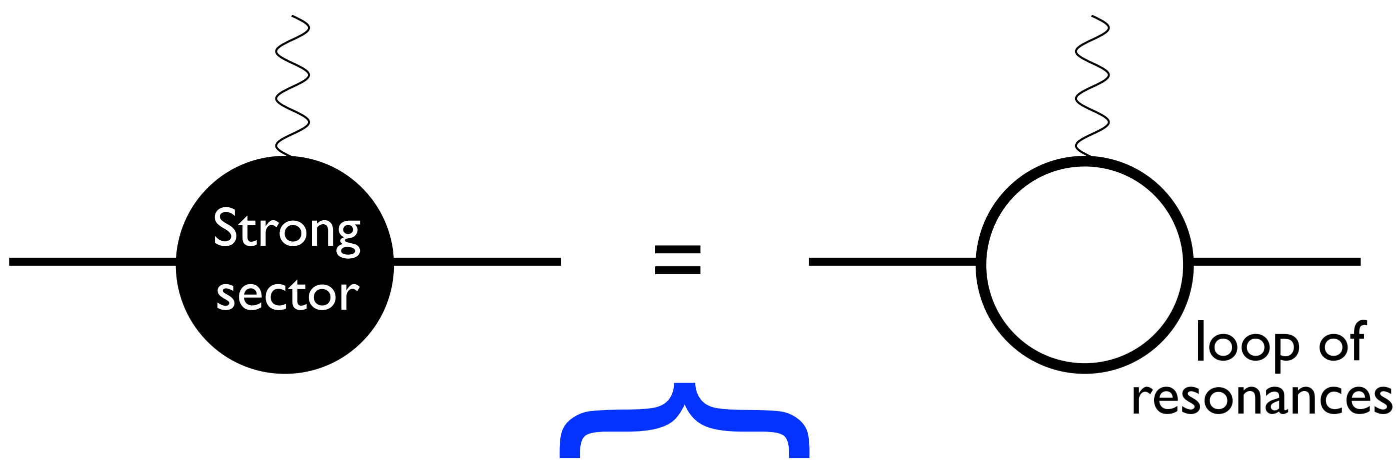
Potentially large dipoles (e.g. **EDMs, $\mu \to e\gamma$**):



EDM at most at one-loop!

crucial property of holographic models

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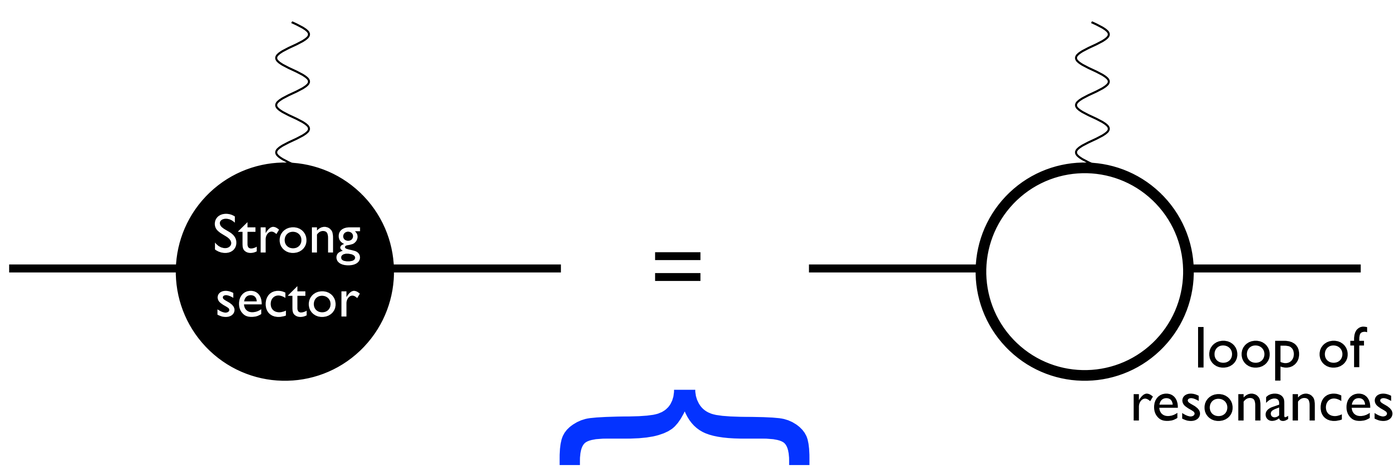


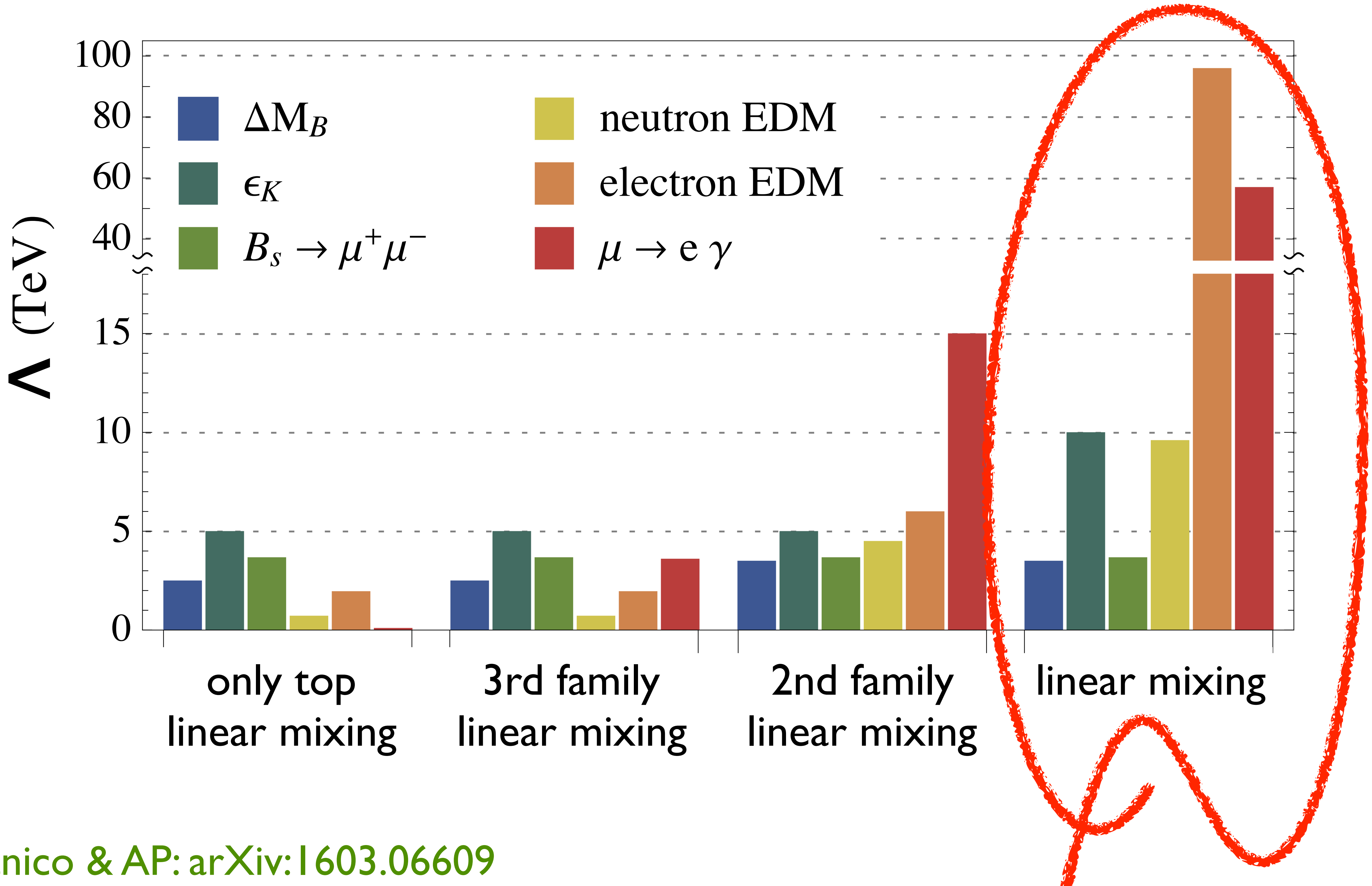
EDM at most at one-loop!

crucial property of holographic models

Also in QCD? some hints: $\frac{L_9+L_{10}}{L_9-L_{10}} \simeq \frac{6.9-5.5}{6.9+5.5} \sim 0.1$

New flavor-violating & CP-violating transitions

Lower bounds on the scale of the strong dynamics Λ

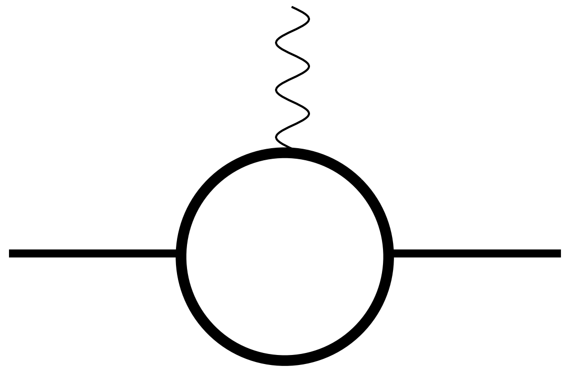


G.Panico & AP: arXiv:1603.06609

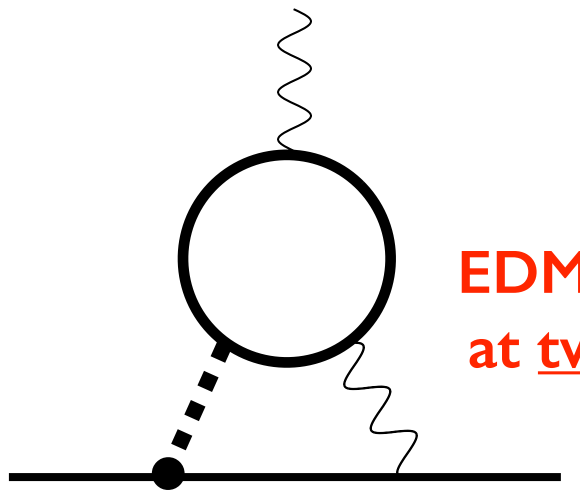
Towards suppressing dipoles

Avoid linear mixing of **light fermions** to BSM:

$$\mathcal{L}_{\rm lin} = \epsilon_{f_i}\, \bar{f}_i\, \mathcal{O}_{f_i}$$



Bilinear mixing: $\mathcal{L}_{\rm bil} \sim \bar{f}_i \mathcal{O}_H f_j$



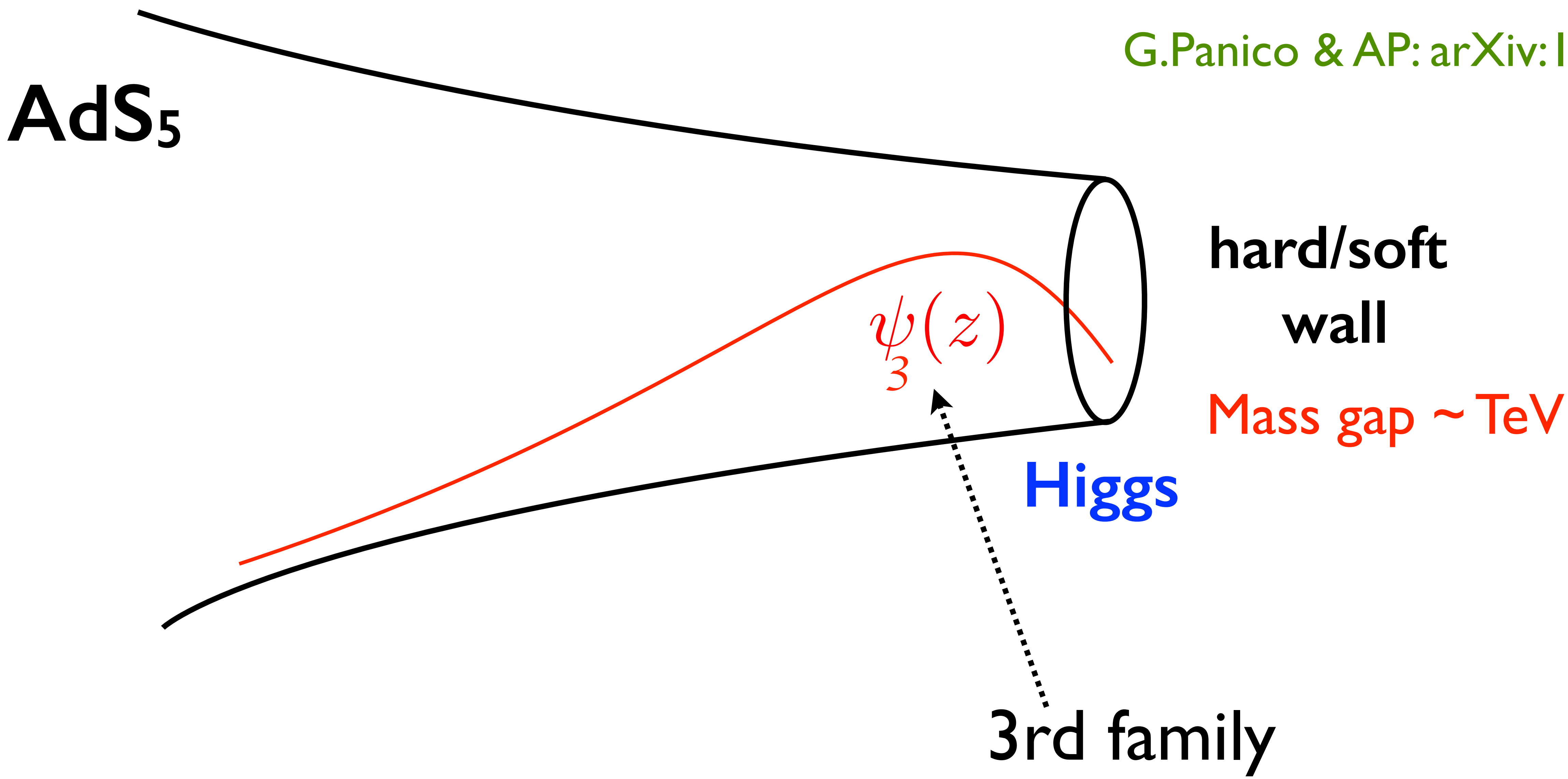
EDM at most at <u>two</u>-loop!

portal to the strong-sector: the Higgs

$$\langle 0|\mathcal{O}_H|H\rangle \neq 0 \;\; \textit{e.g.}\;\; \mathcal{O}_H \sim \bar{\psi}\psi$$

Holographic Model

G.Panico & AP: arXiv:1603.06609



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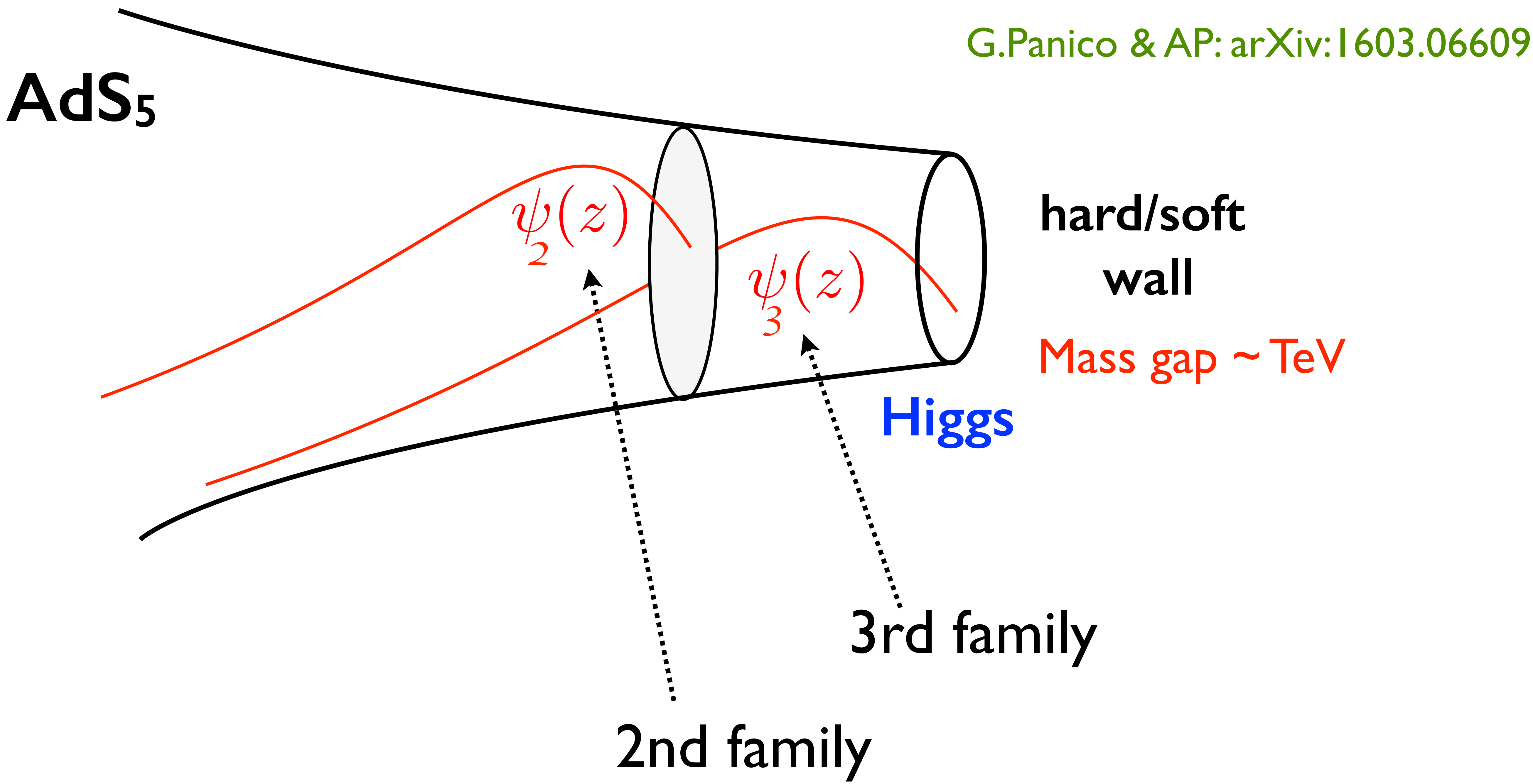

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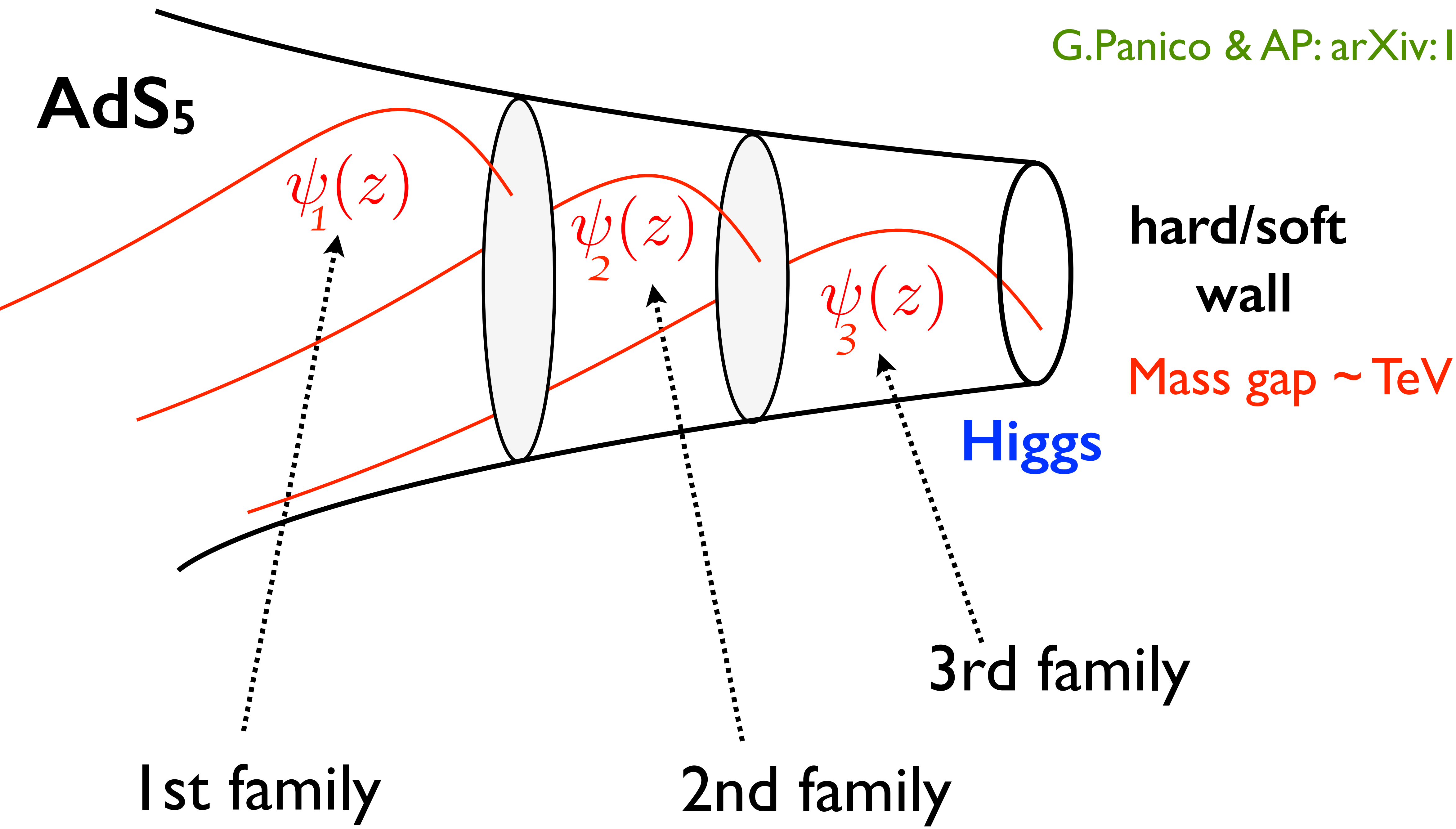

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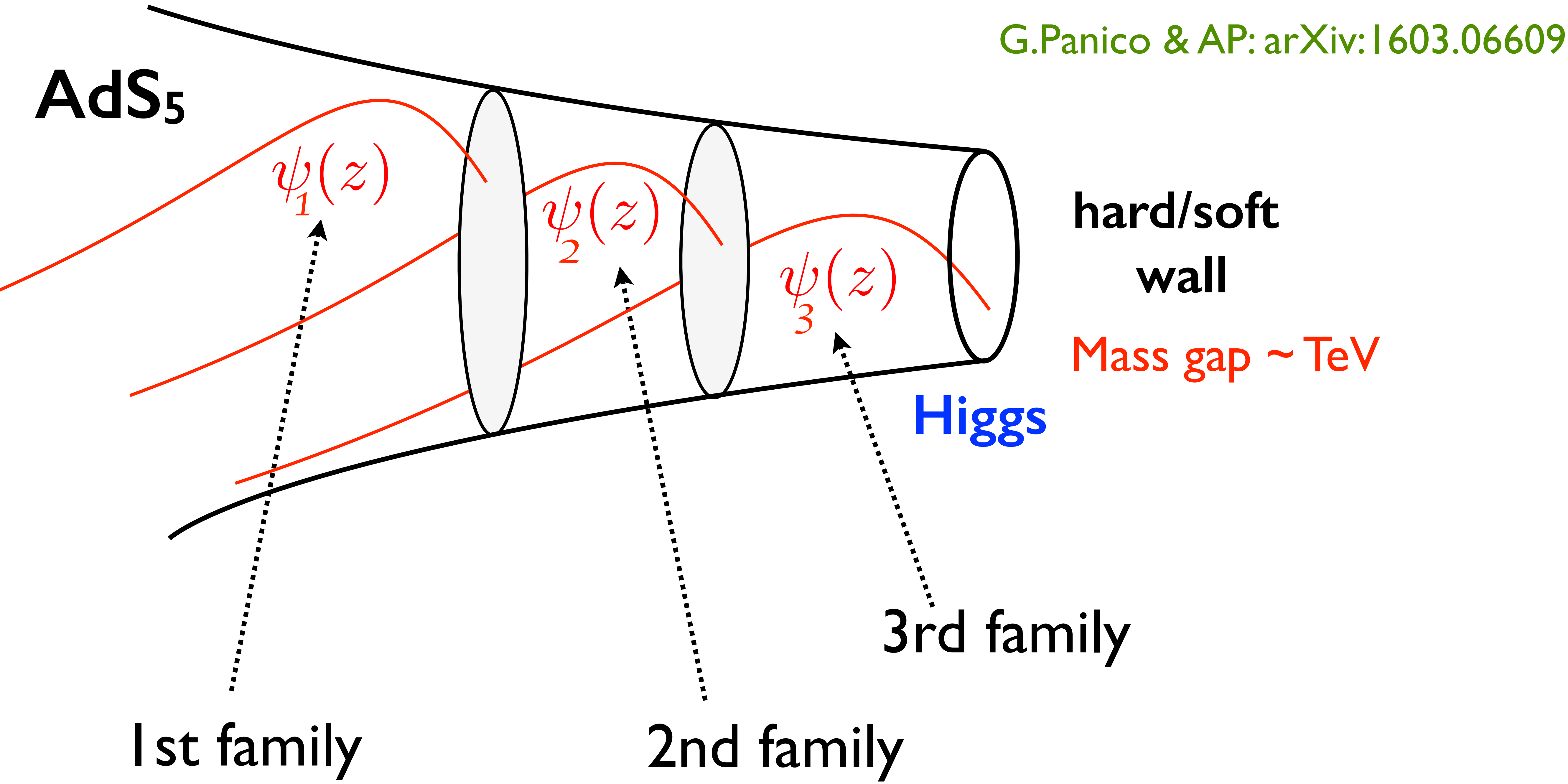
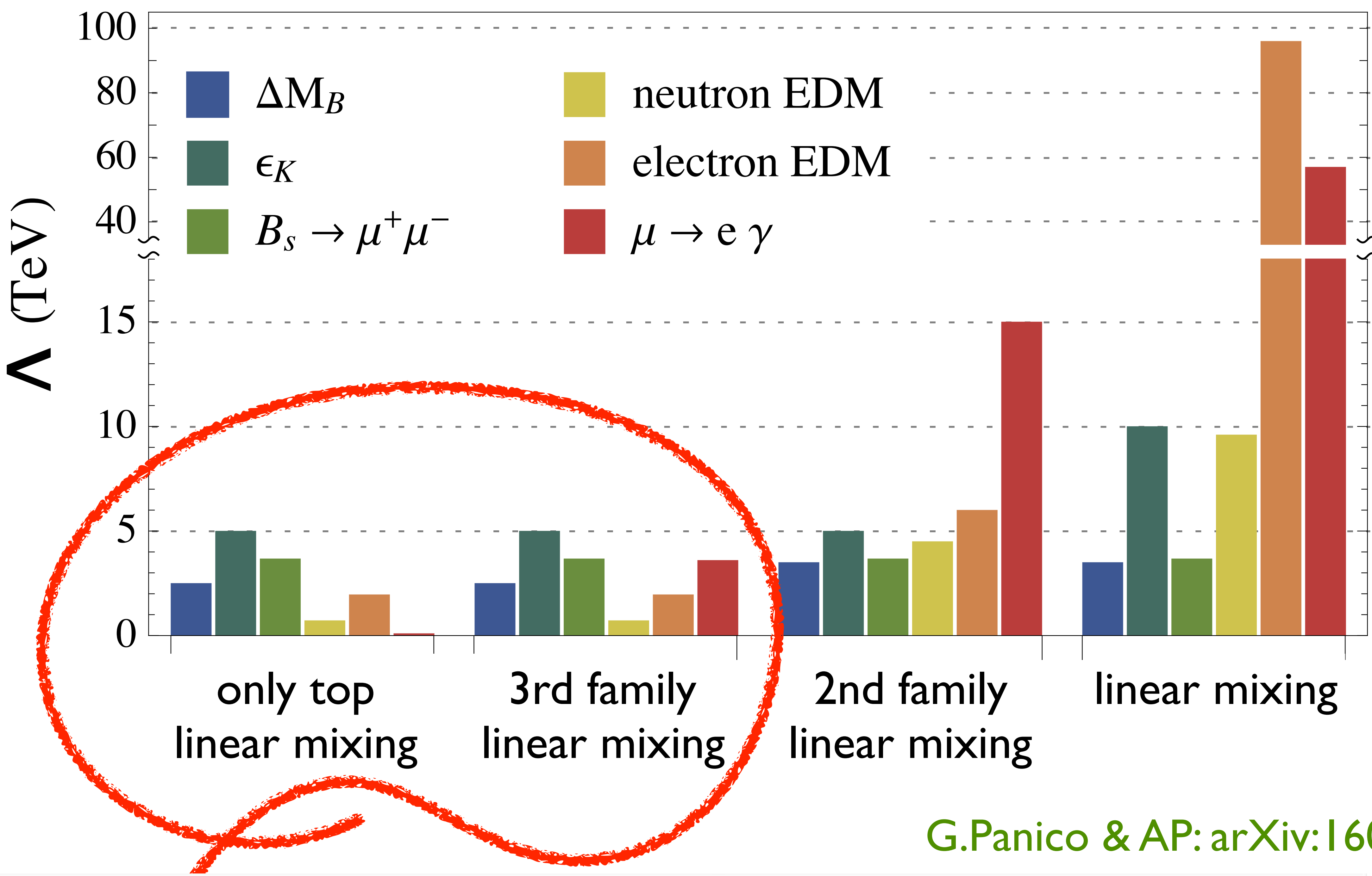


Flavor without symmetries!

New flavor-violating & CP-violating transitions

Lower bounds on the scale of the strong dynamics Λ



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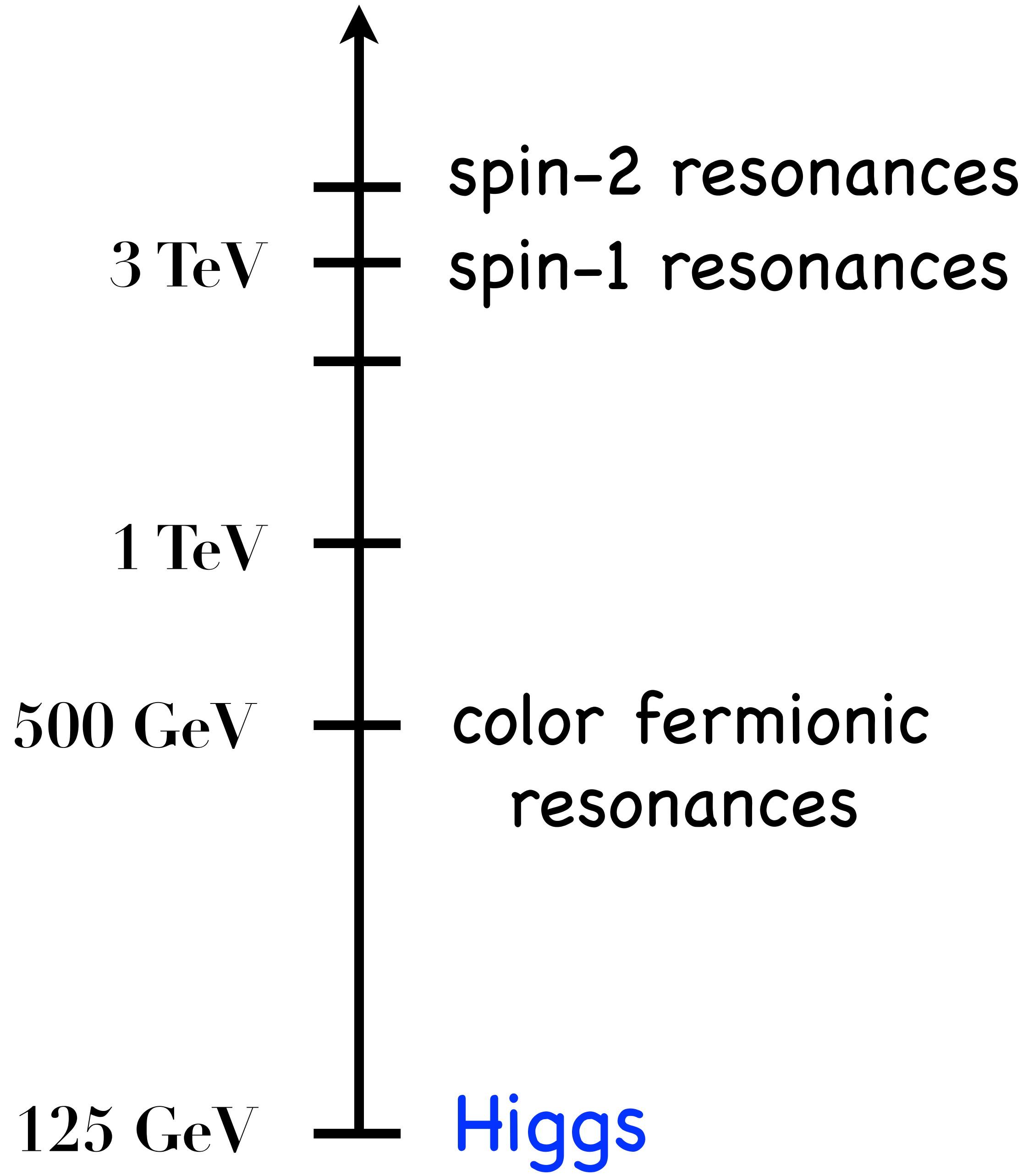
Passes all flavor & EDM tests: Bounds of $\mathcal{O}$(TeV)!

Expected spectrum in Composite Higgs Scenarios



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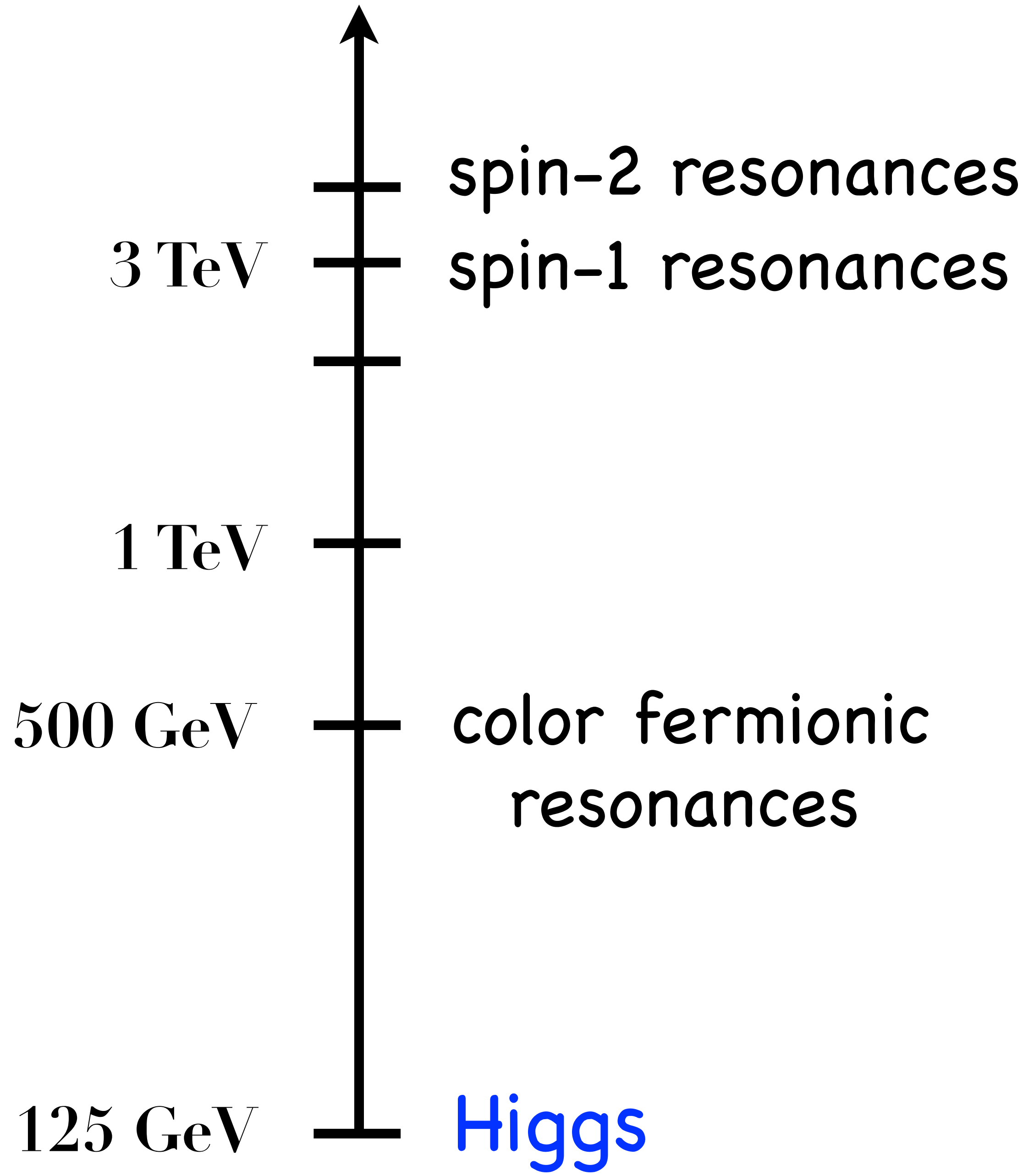


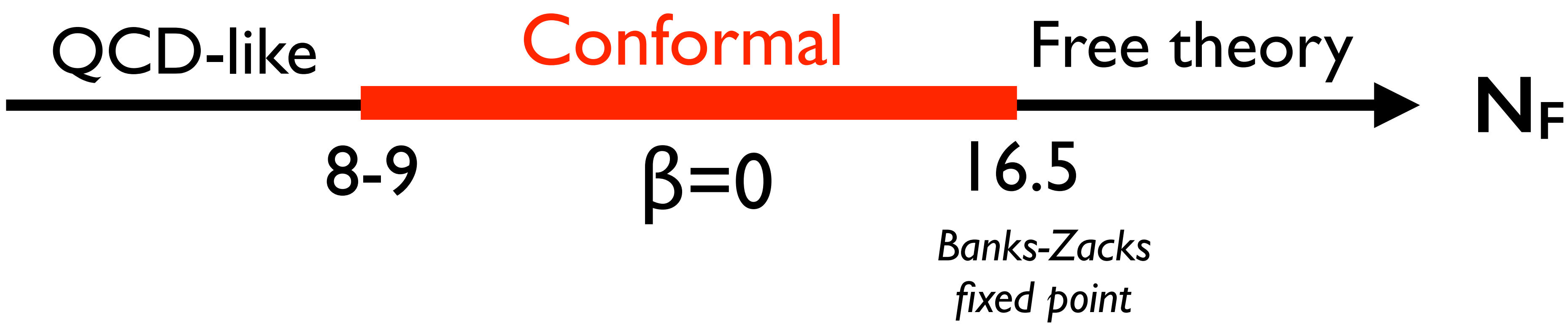
But **nothing yet seen** at the LHC:

The situation starts being **worrisome**, but not yet desperate

Are we missing something?

New inside from Lattice…

Conformal window in SU(3) with large number of fermions (N_F)



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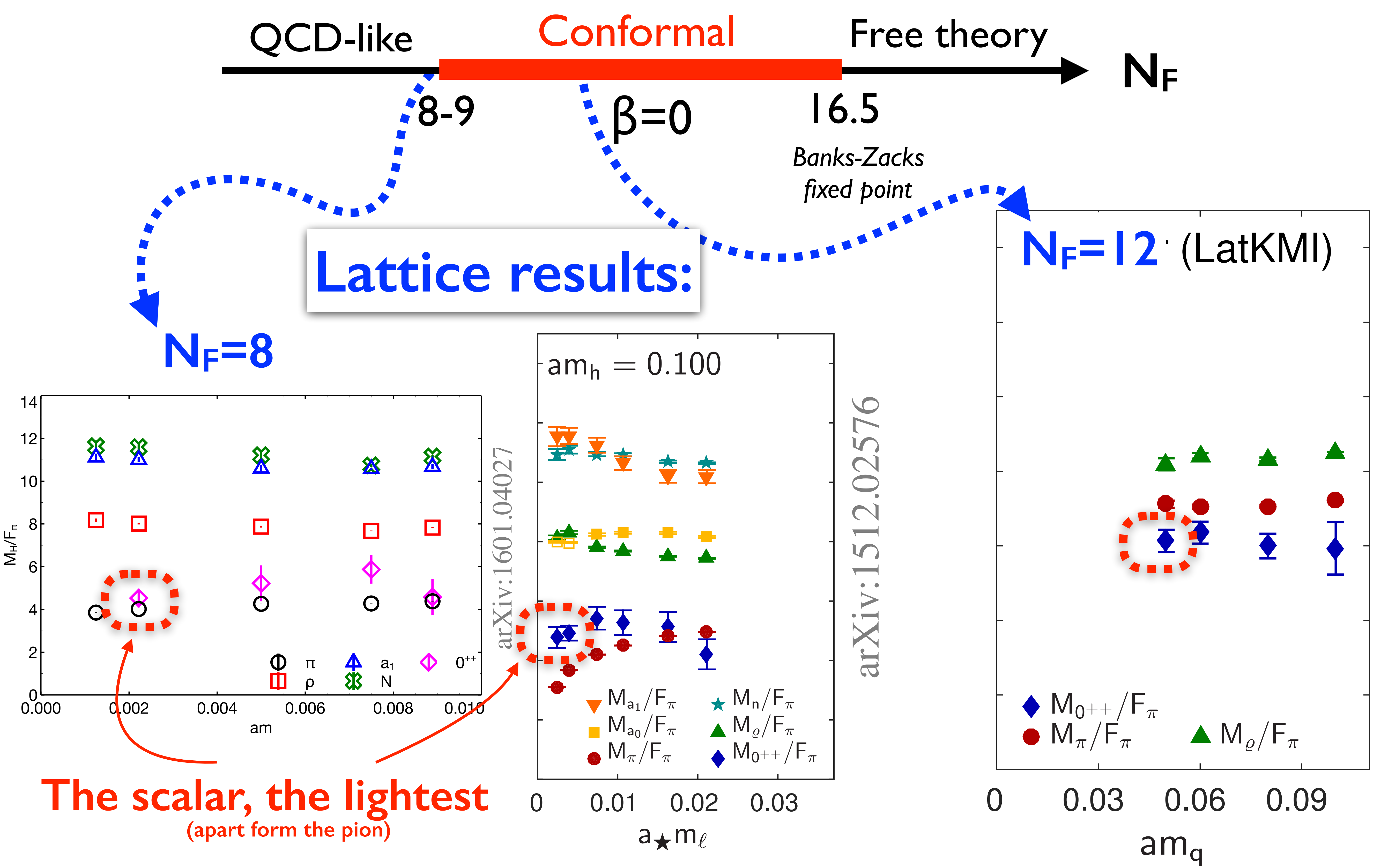

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