

Continuum Naturalness

Seung J. Lee

Portorož 2019

Precision era in High Energy Physics

April 18

With B. Bellazzini, C. Csaki, J. Hubisz, J. Serra, J. Terning; PRX 2016

With C. Csaki, G. Lee, O. Telem; work in progress

With C. Csaki, S. Lombardo, G. Lee, O. Telem; 1811.06019 (JHEP)

With M. Park and Z. Qian; 1812.02679



Naturalness Paradigm Under Pressure

◆ **Naturalness** “typically” **implies new colored top partners**

~TeV scale to cut off the top contribution to the Higgs potential

not too many theoretical frameworks;

two major ones

AdS/CFT
warped extra dimension
(RS setup)

Supersymmetry:
stop

Composite Higgs:
Fermionic top partners
(partial compositeness)

Higgs is a fundamental scalar,
just like many other
SUSY partners

Higgs is a composite resonance,
just like many composite
resonances in the theory of
strong dynamics

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*Neutral Naturalness is not discussed in this talk

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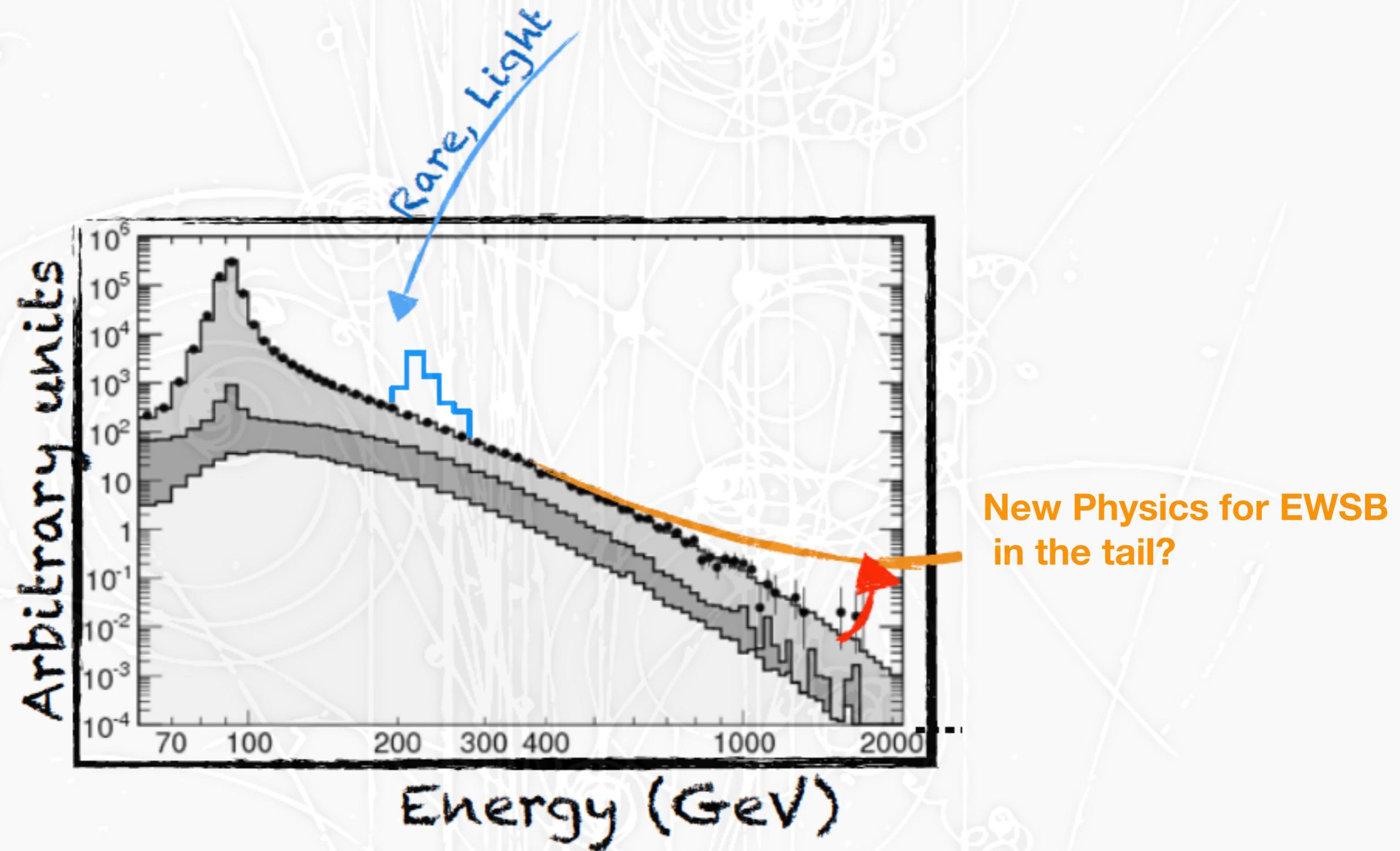
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No Resonance, No New Physics? Naturalness?



picture adapted from Francesco Riva

No Resonance, No New Physics? Naturalness?

- ◆ **New Physics may appear solely as a continuum**
 - approximately conformal sector (i.e. CFT broken by IR cutoff)
 - multi-particle states with strong dynamics (branch cut at $4m_\pi^2$ in $\pi\pi \rightarrow \pi\pi$ scattering)

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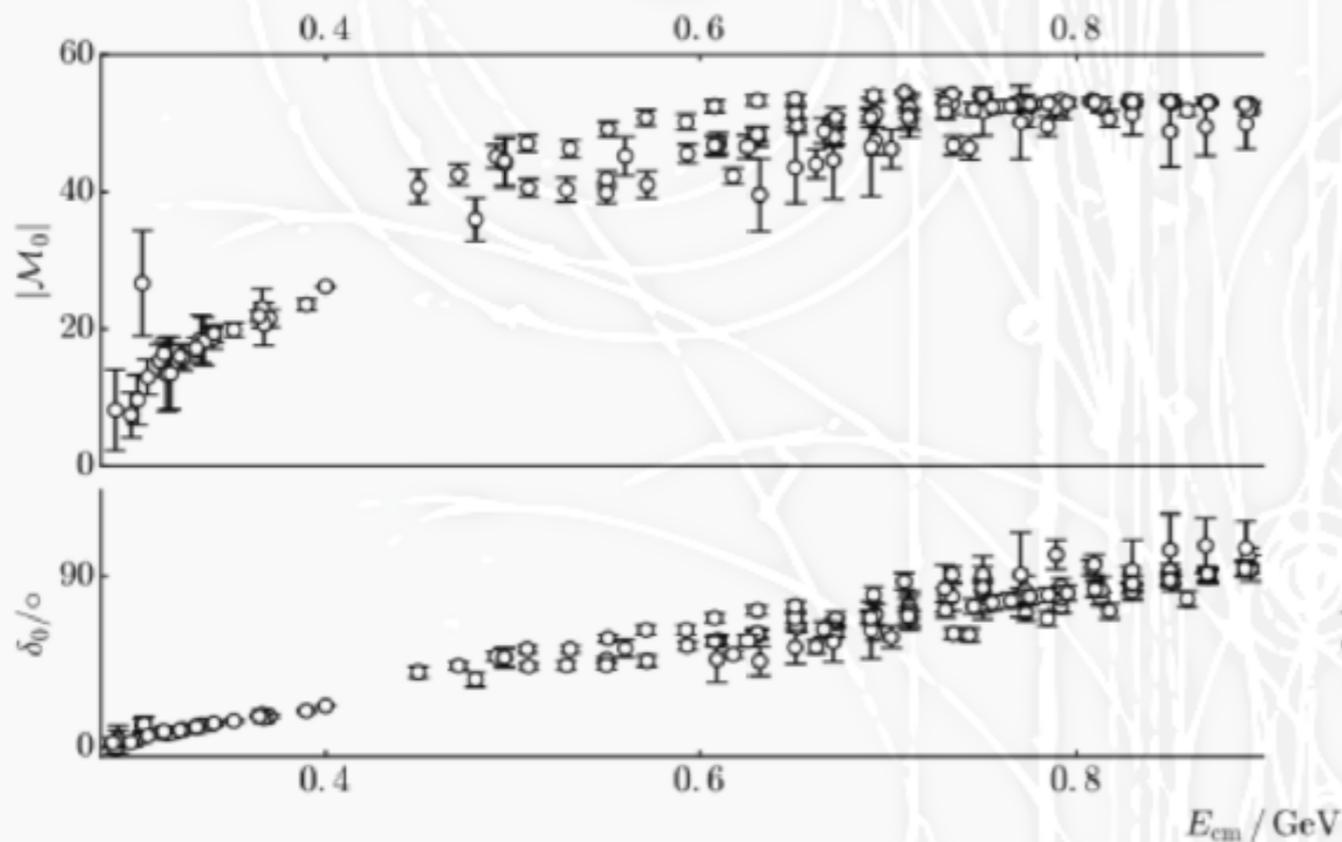
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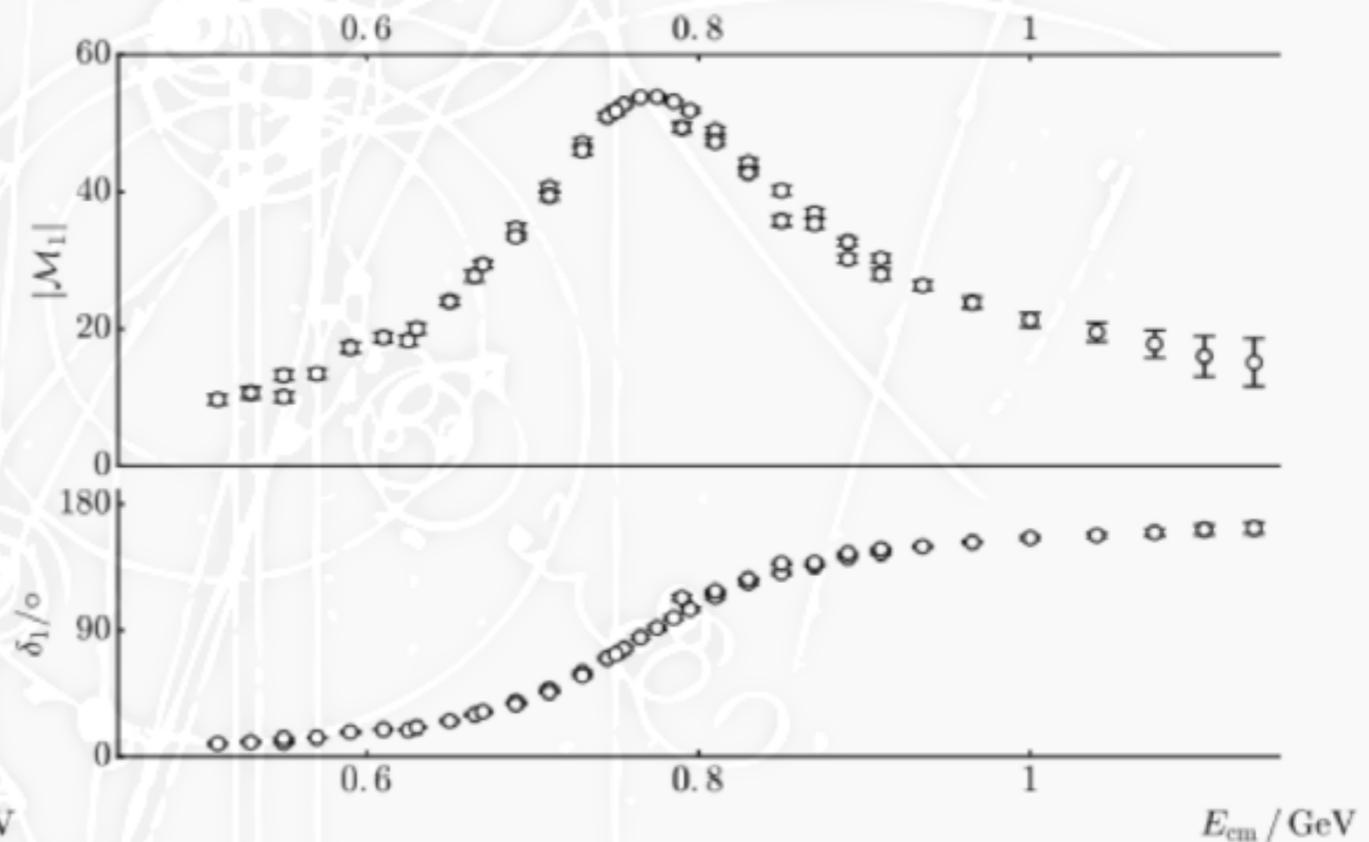
QCD

$\sigma / f_0(500)$

ρ



$M_\sigma = 450 \text{ MeV}$ $\Gamma_\sigma = 550 \text{ MeV}$



$M_\rho = 770 \text{ MeV}$ $\Gamma_\rho = 145 \text{ MeV}$

No Resonance, No New Physics? Naturalness?

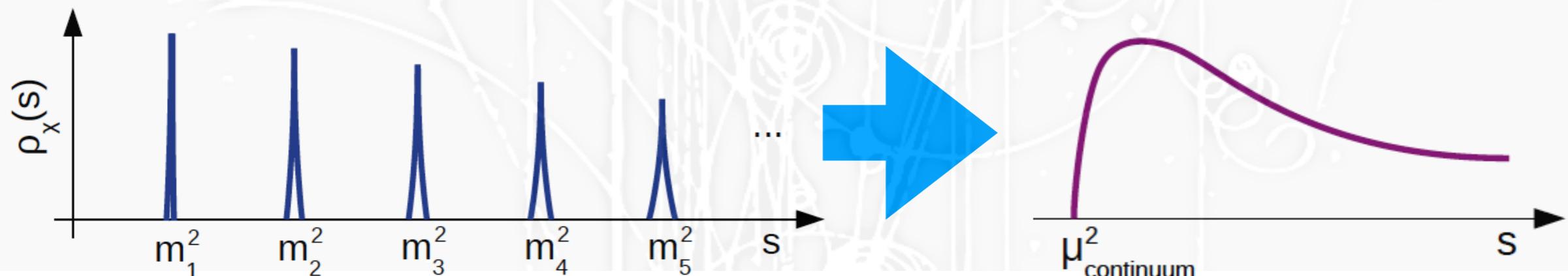
◆ New Physics may appear solely as a continuum

- If the new strong dynamics responsible for furnishing a composite Higgs is near a **quantum critical point**, the composite spectrum may effectively consist of a continuum with a mass gap.
- In this scenario, poles corresponding to the composite top partner (and vector meson) excitations have merged into a branch cut in the scattering amplitude.

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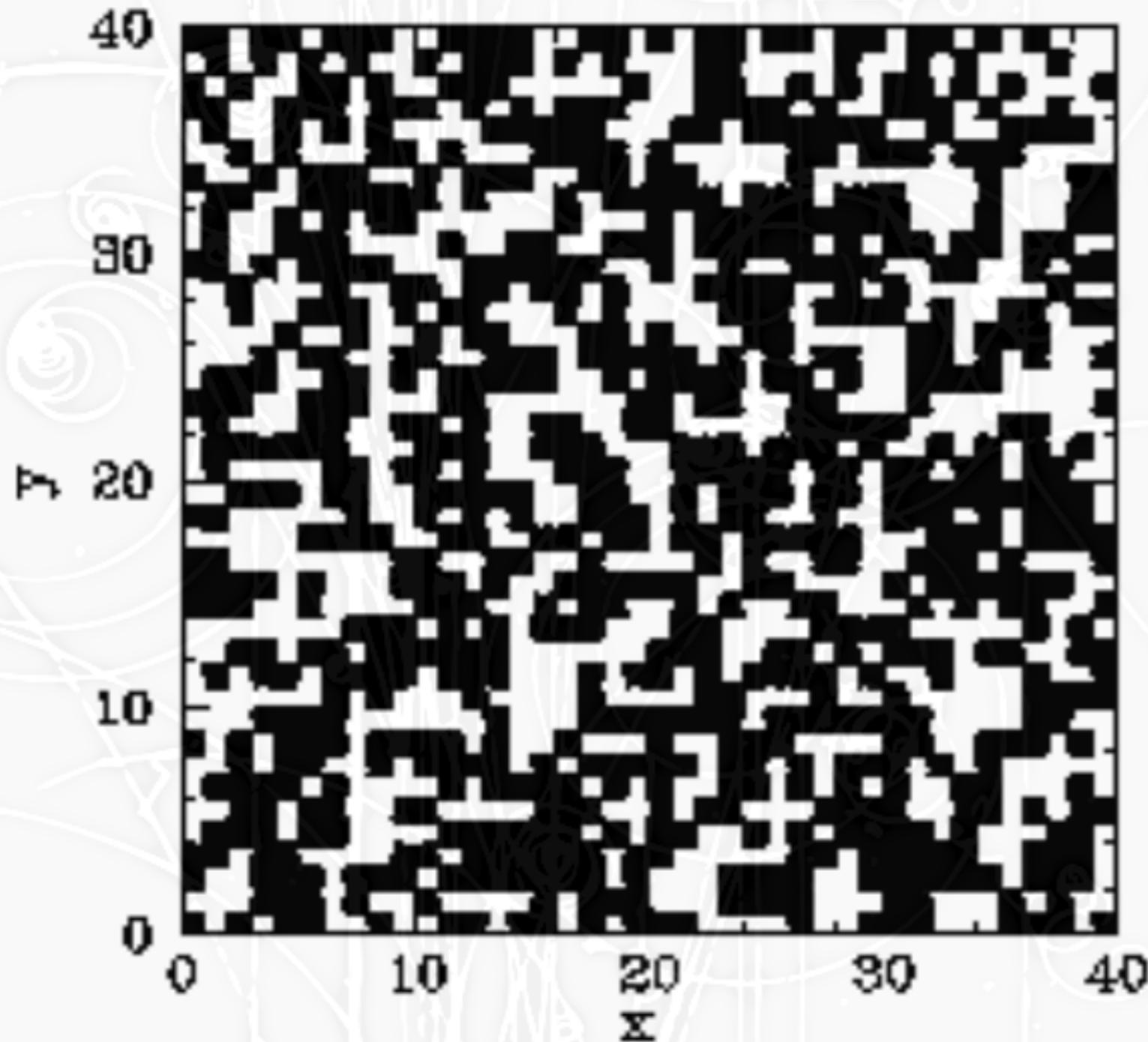
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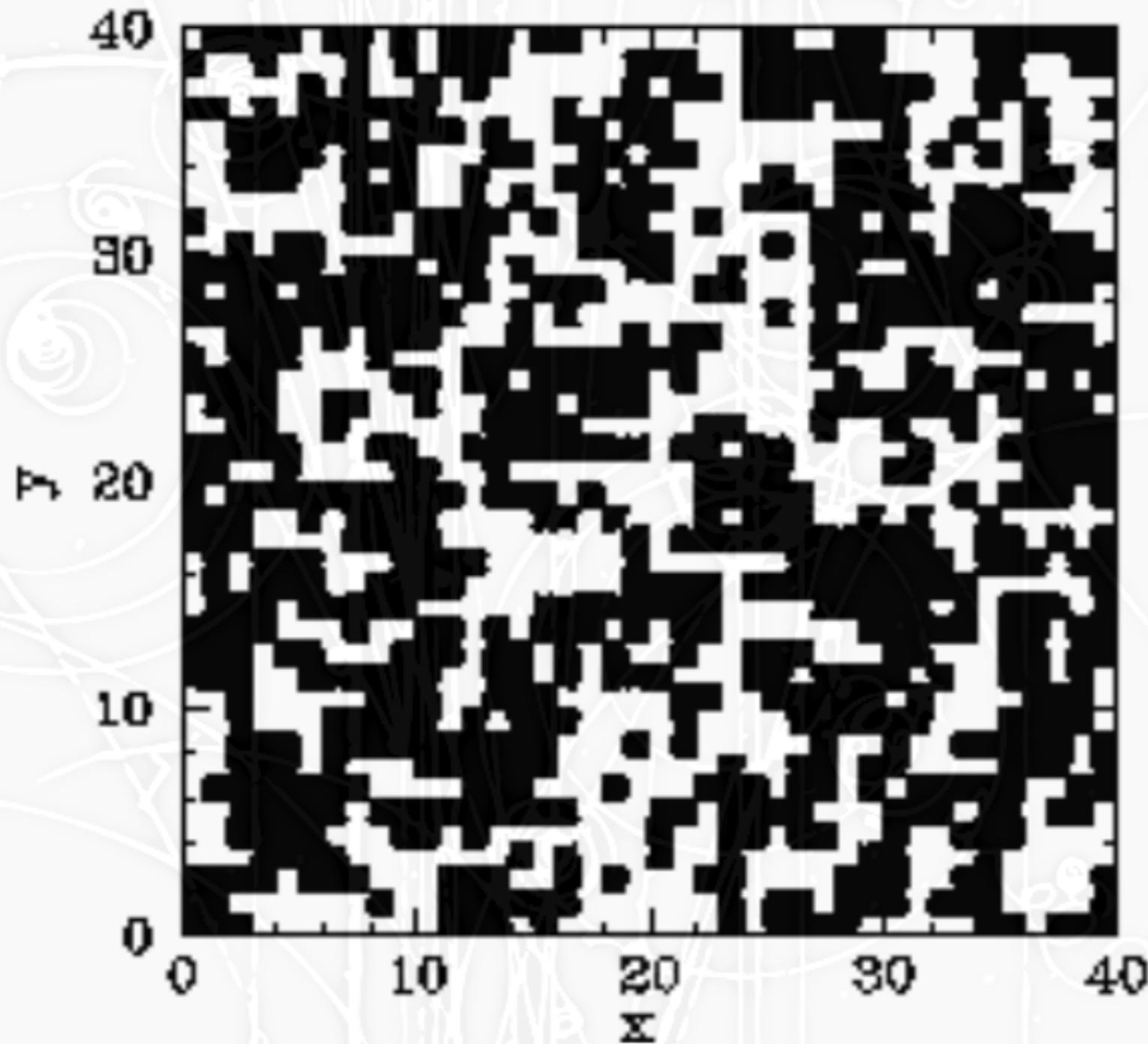
$$H = -J \sum s(x)s(x+n) - \mu\mathcal{H} \sum s(x)$$



$$s(x) = \pm 1$$

Ising Model

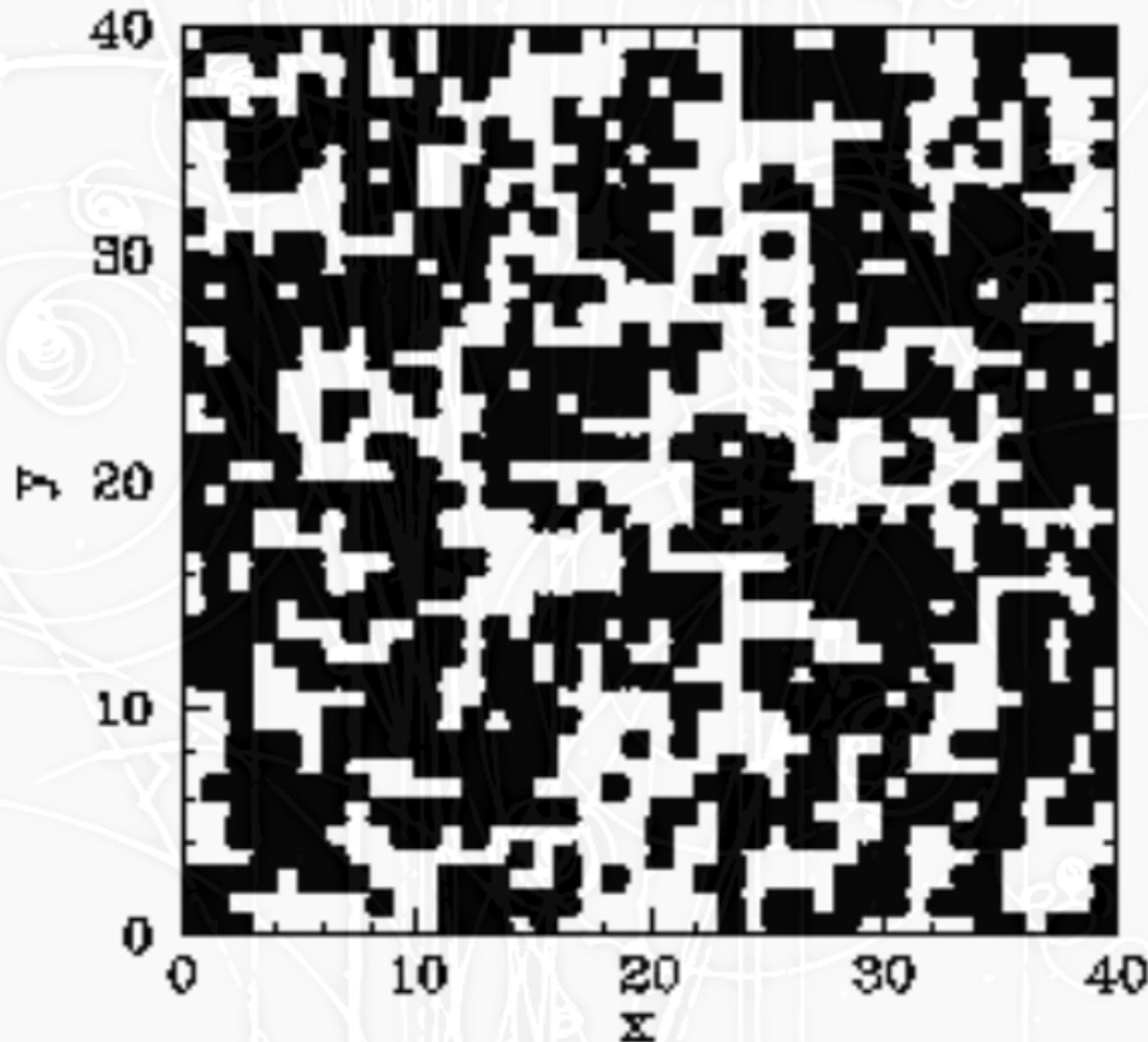
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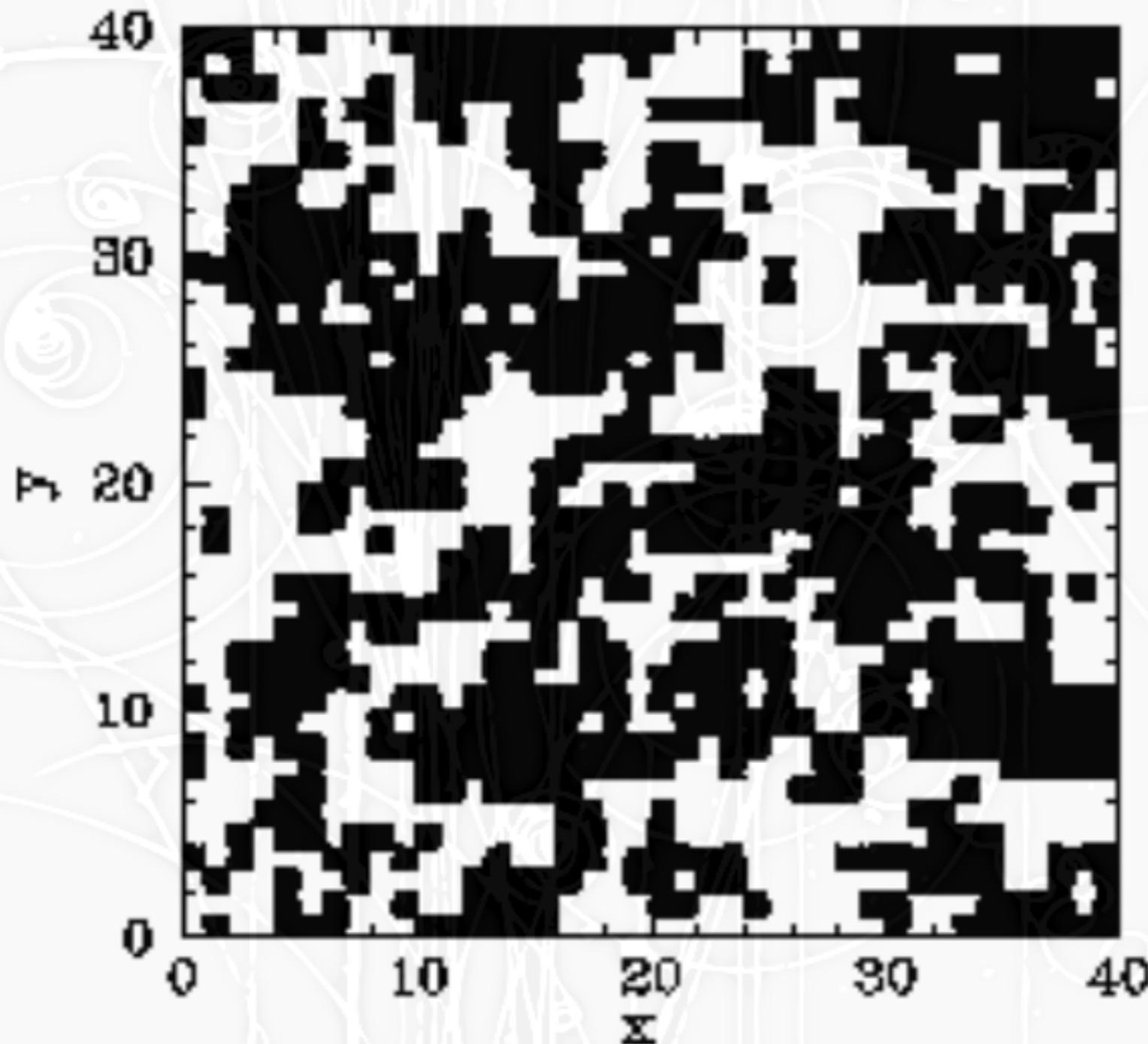
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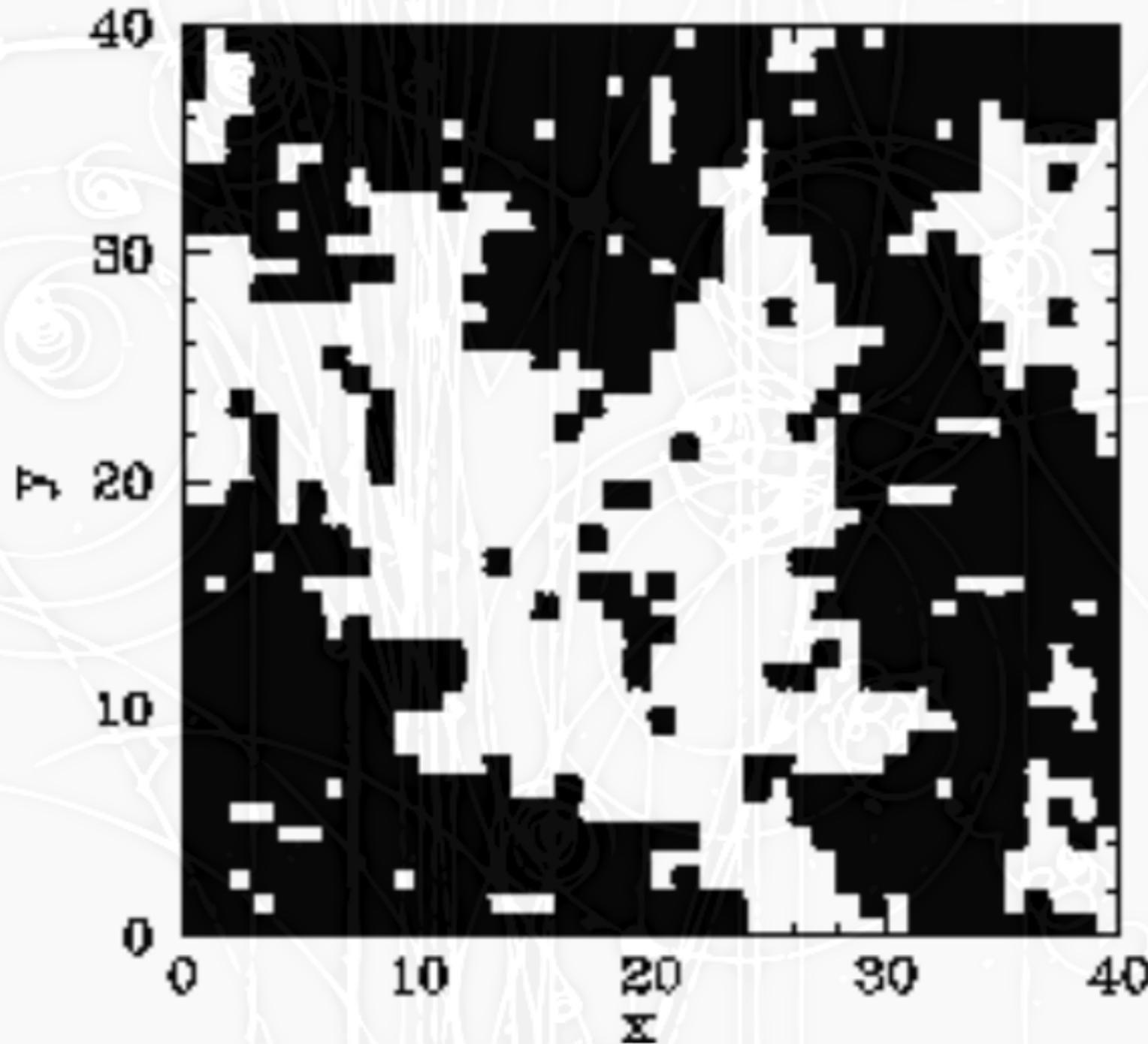
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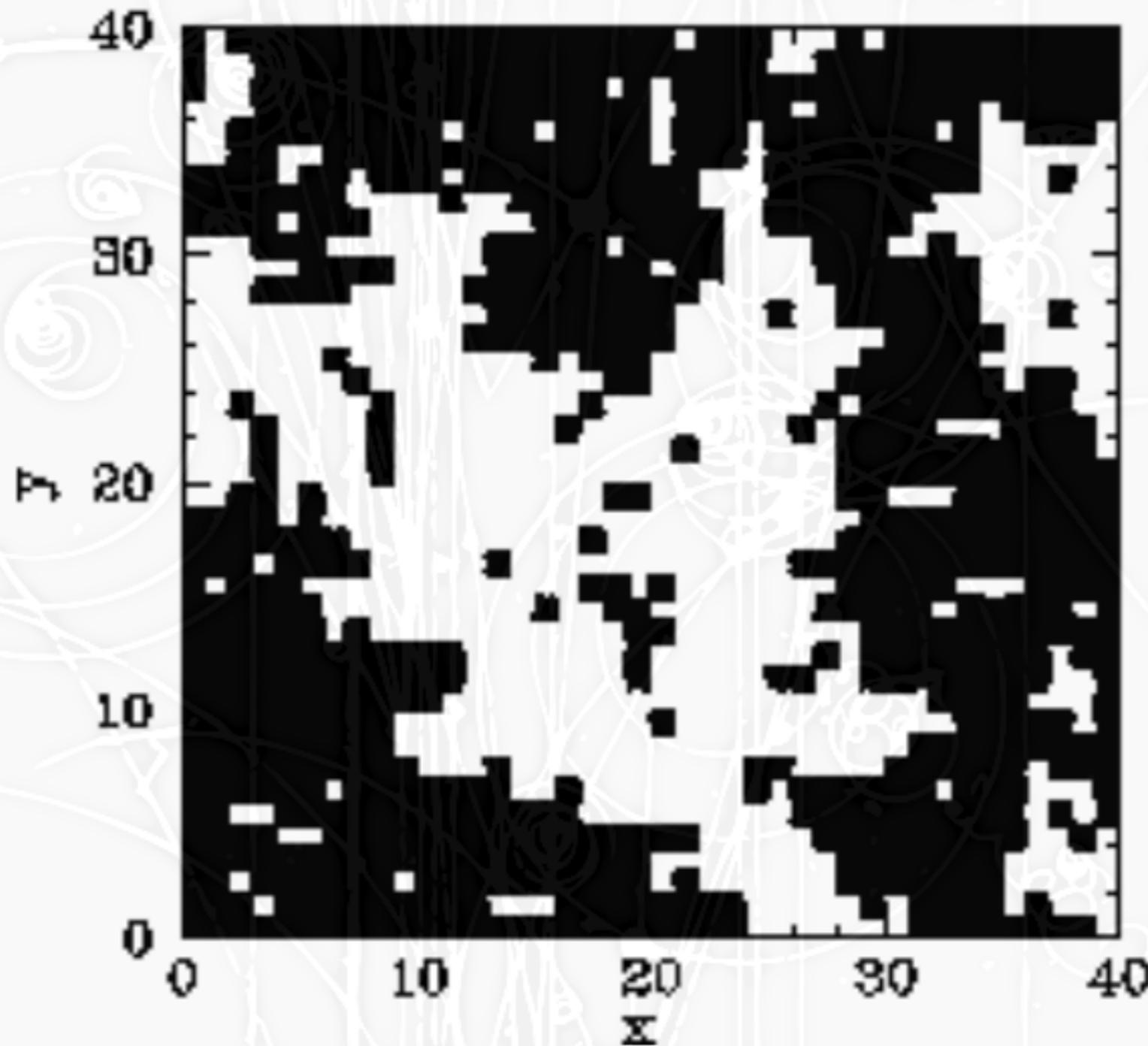
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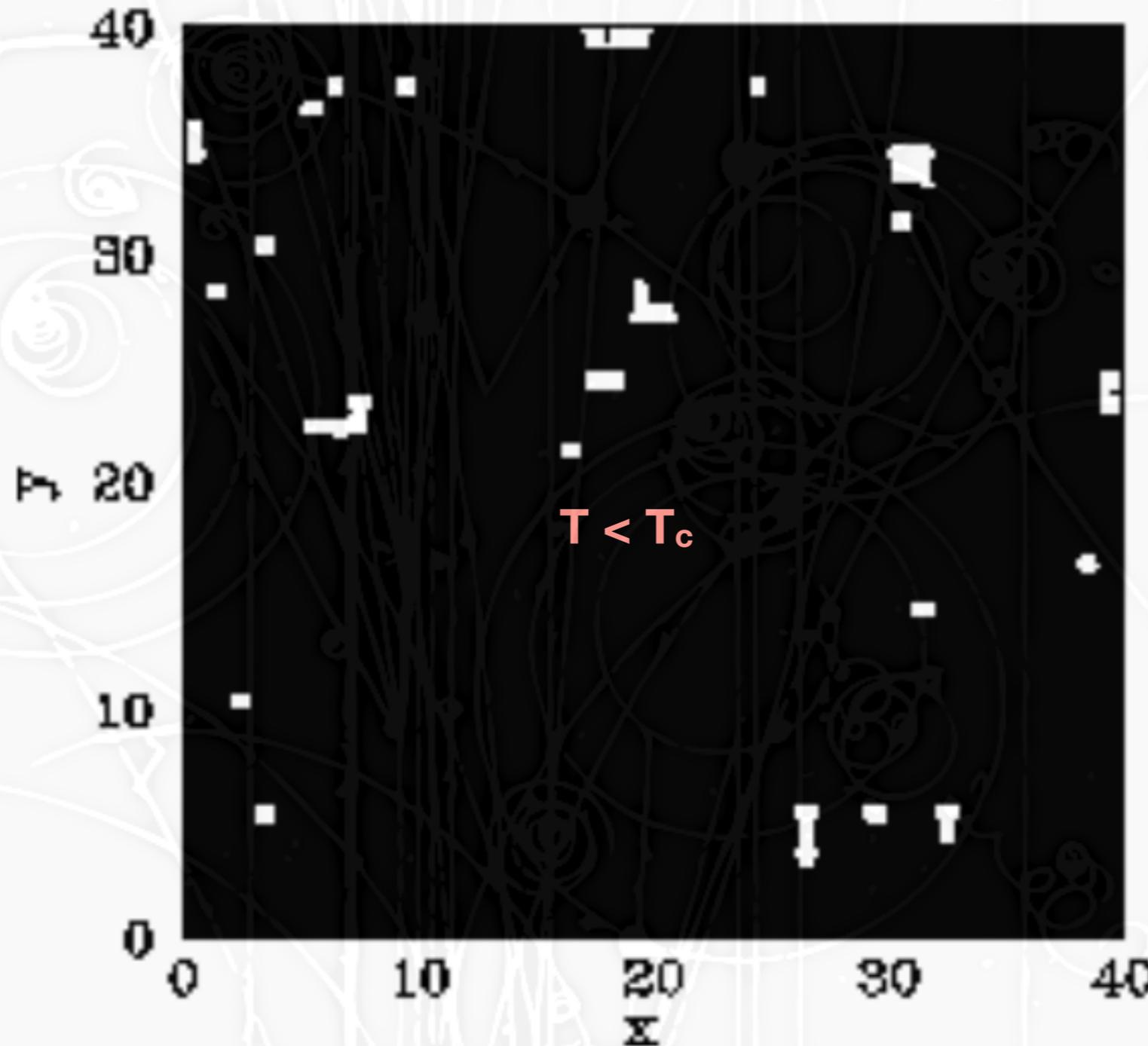
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$$e^{-|x|/\xi}$$

$$\lim_{T \rightarrow T_c} \xi = \infty$$

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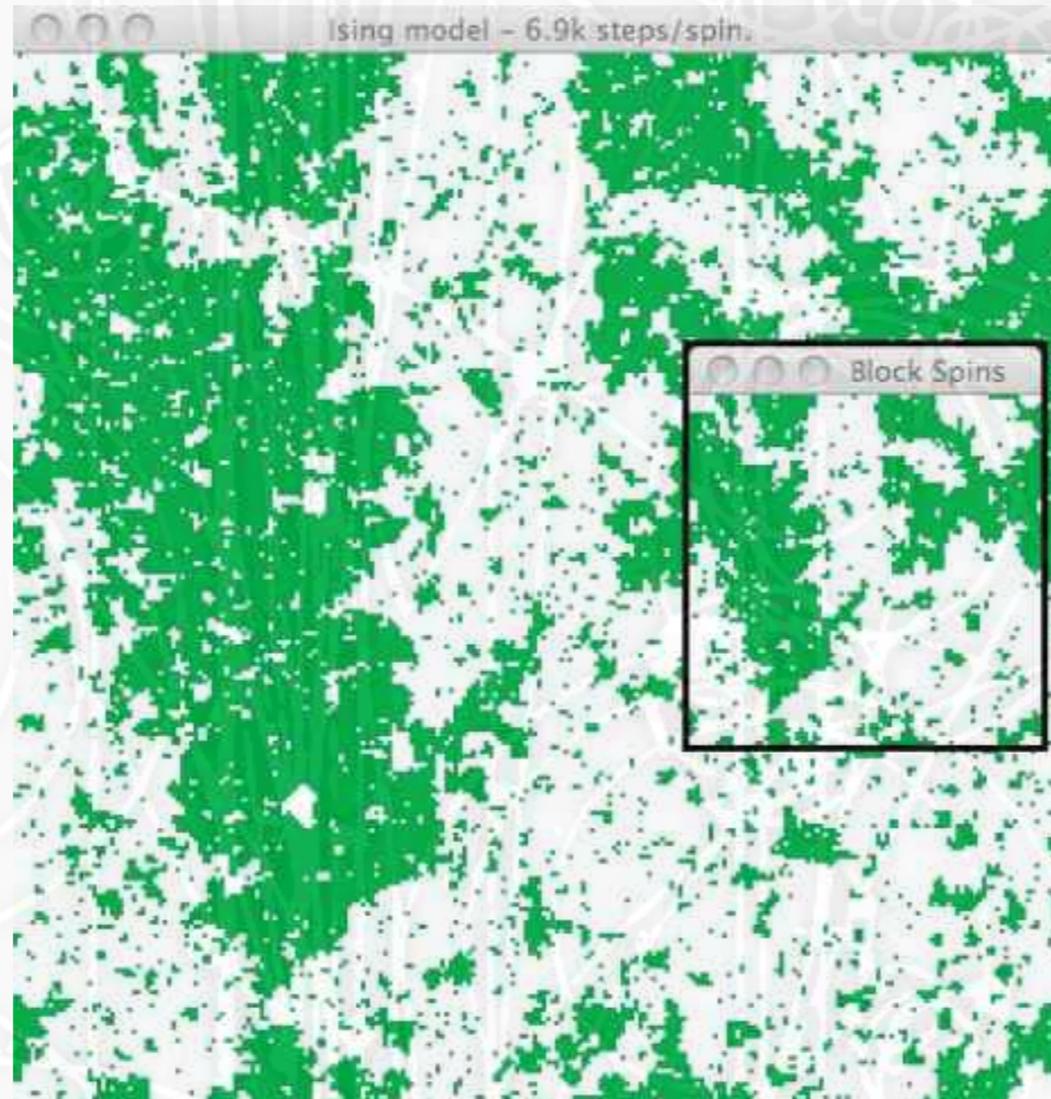
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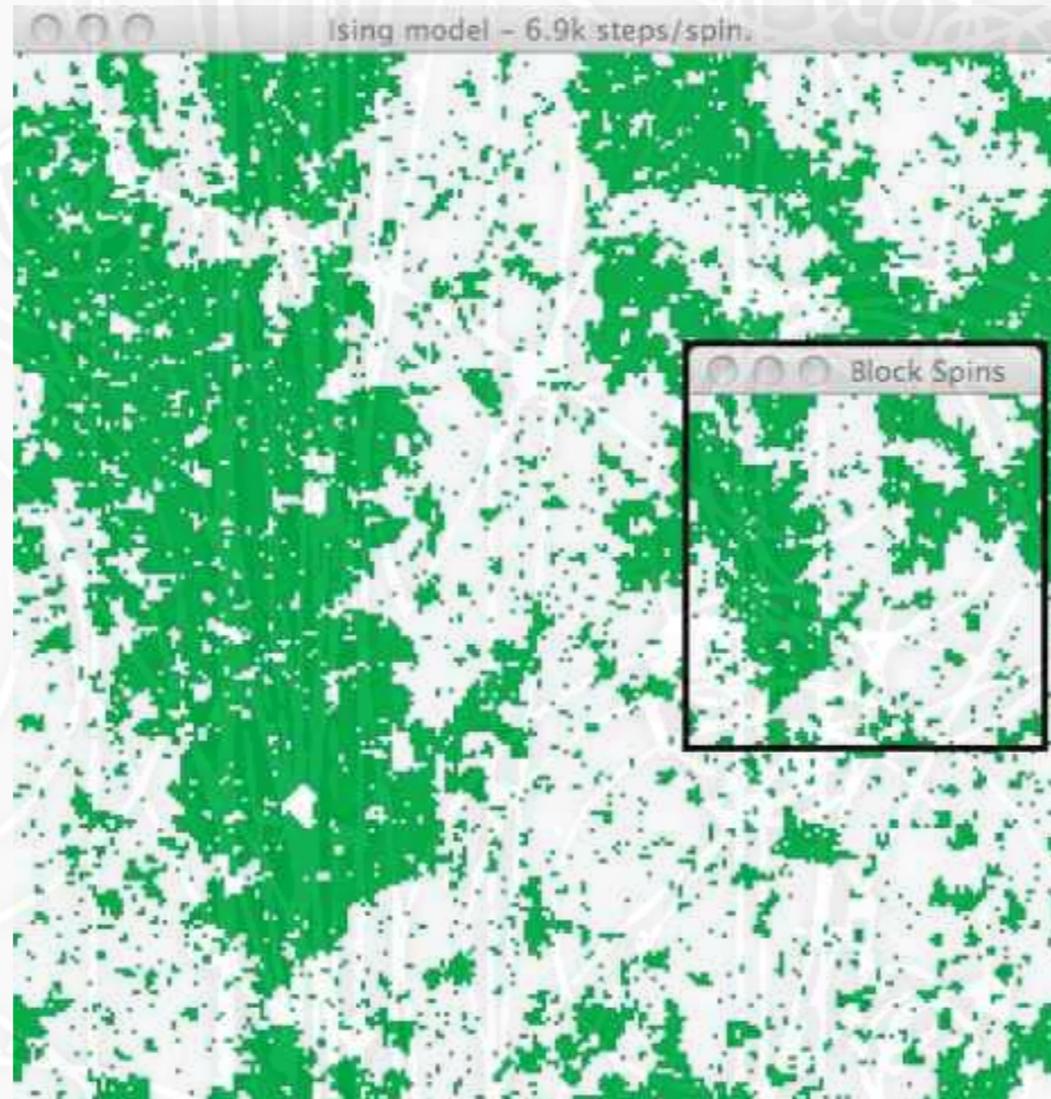
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Critical Ising Model is Scale Invariant



$$\text{at } T=T_c \quad \langle s(0)s(x) \rangle \propto \frac{1}{|x|^{2\Delta-1}}$$

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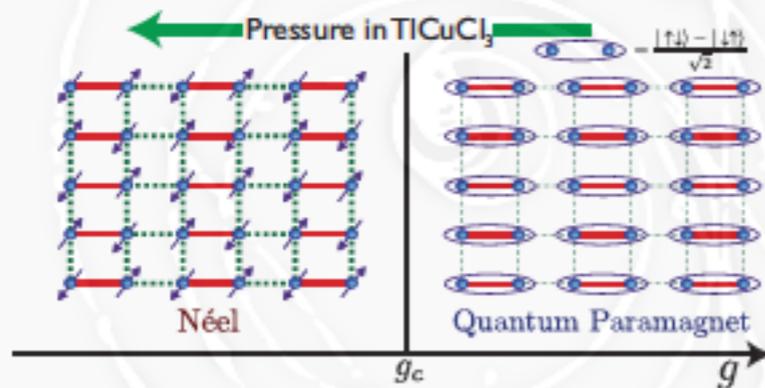
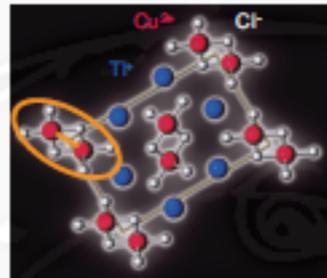


$$\text{at } T=T_c \quad \langle s(0)s(x) \rangle \propto \frac{1}{|x|^{2\Delta-1}} = \int d^3 p \frac{e^{ip \cdot x}}{|p|^{4-2\Delta}}$$

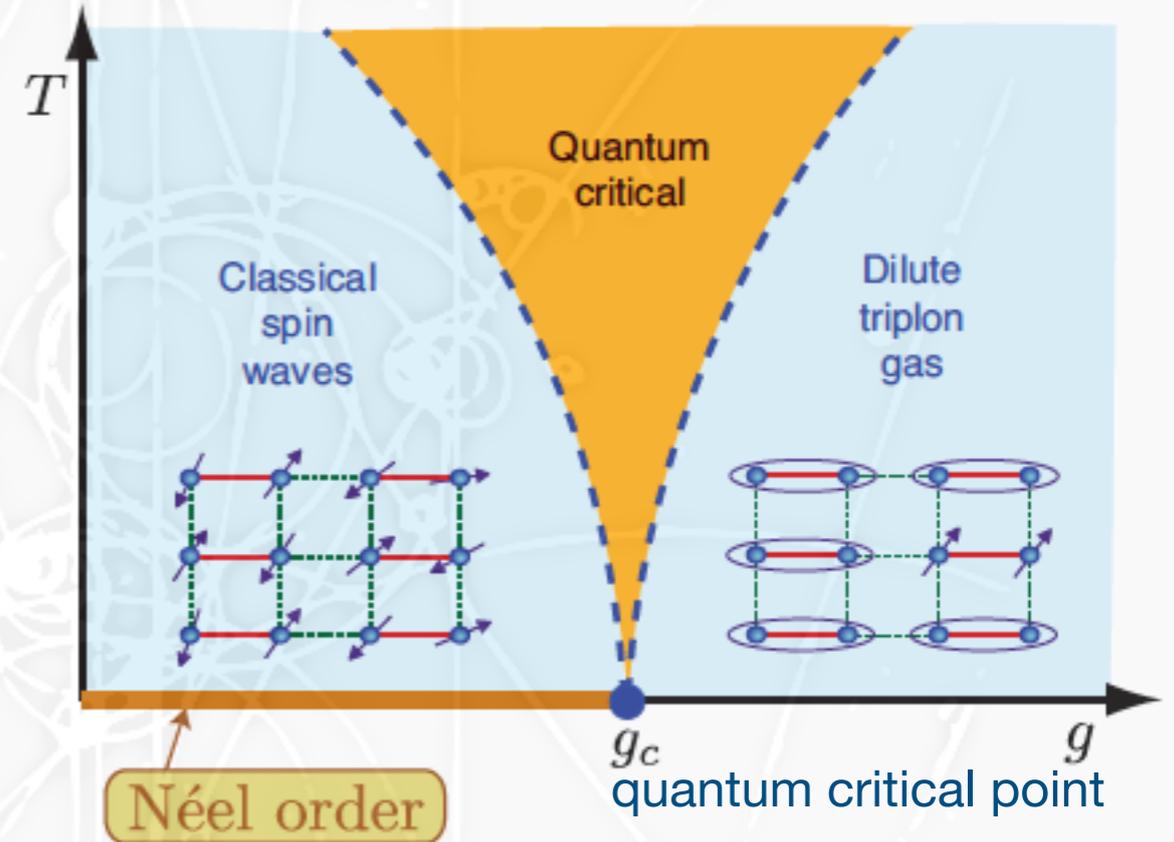
↑
critical exponent

Higgs & Quantum Phase Transition

Condensed matter systems can produce a light scalar by tuning the parameters close to a critical value where a continuous phase transition occurs.



Sachdev, arXiv:1102.4268

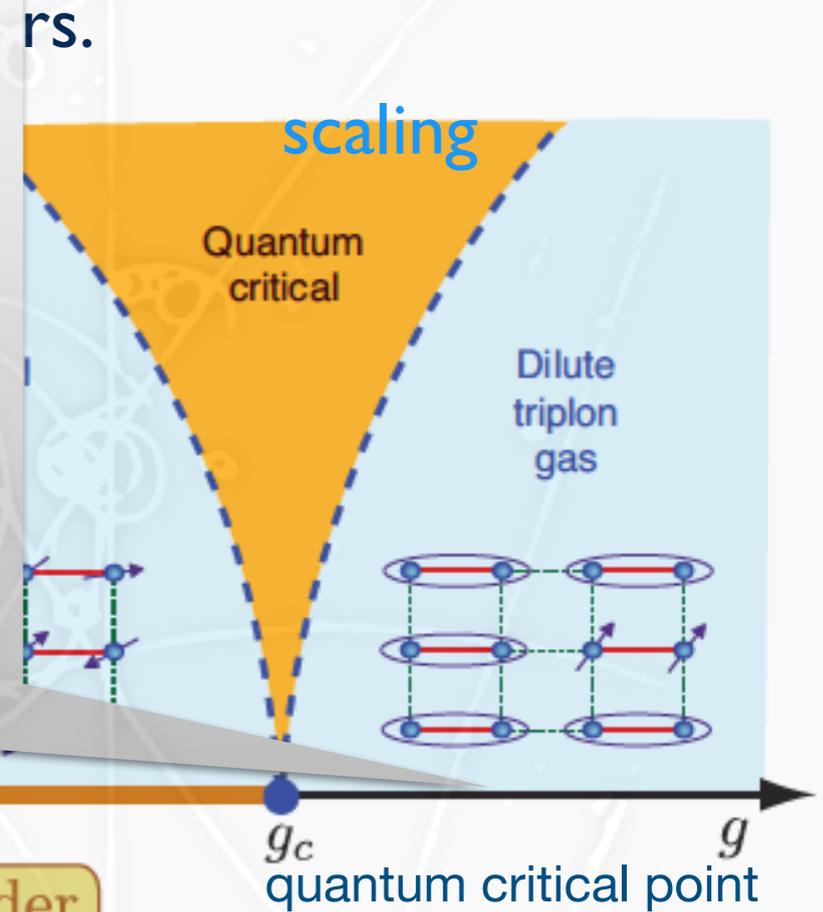


Higgs & Quantum Phase Transition

Condensed matter systems can produce a light scalar by tuning the parameters close

@2nd order QPT, @ critical point, all masses vanish & the theory is scale invariant, characterized by the dimensions of the field,

and at low energies we will see the universal behavior of some fixed point that constitutes the low-energy EFT.



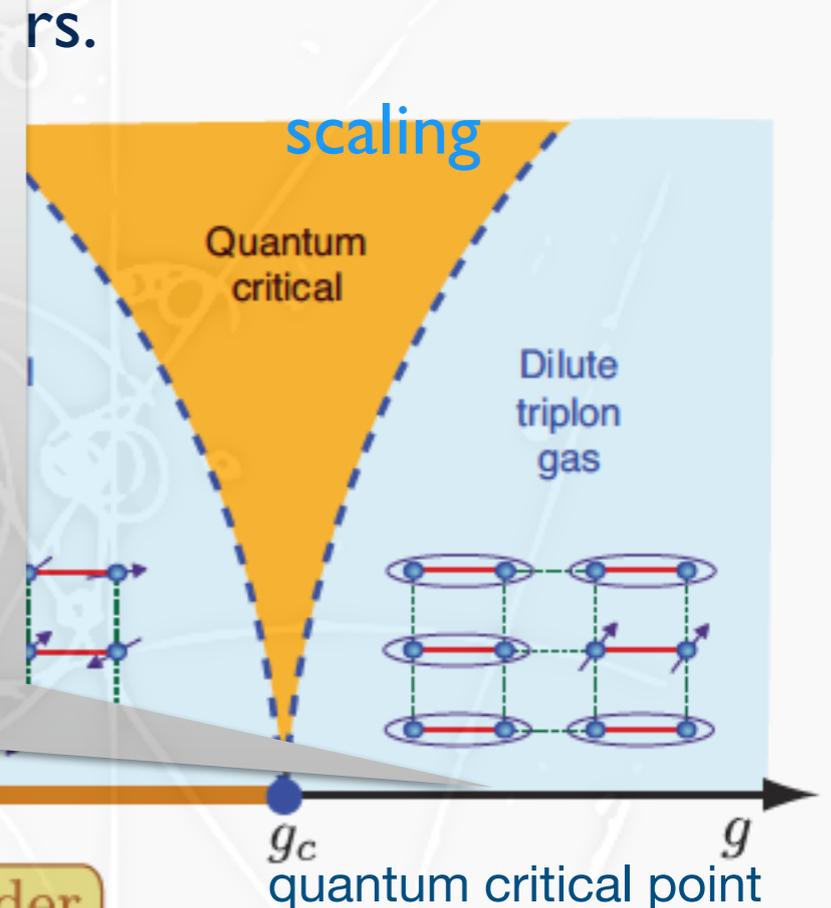
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What is the nature of electroweak phase transition?

Does the underlying theory also have a QPT?

If so, is it more interesting than mean-field theory?

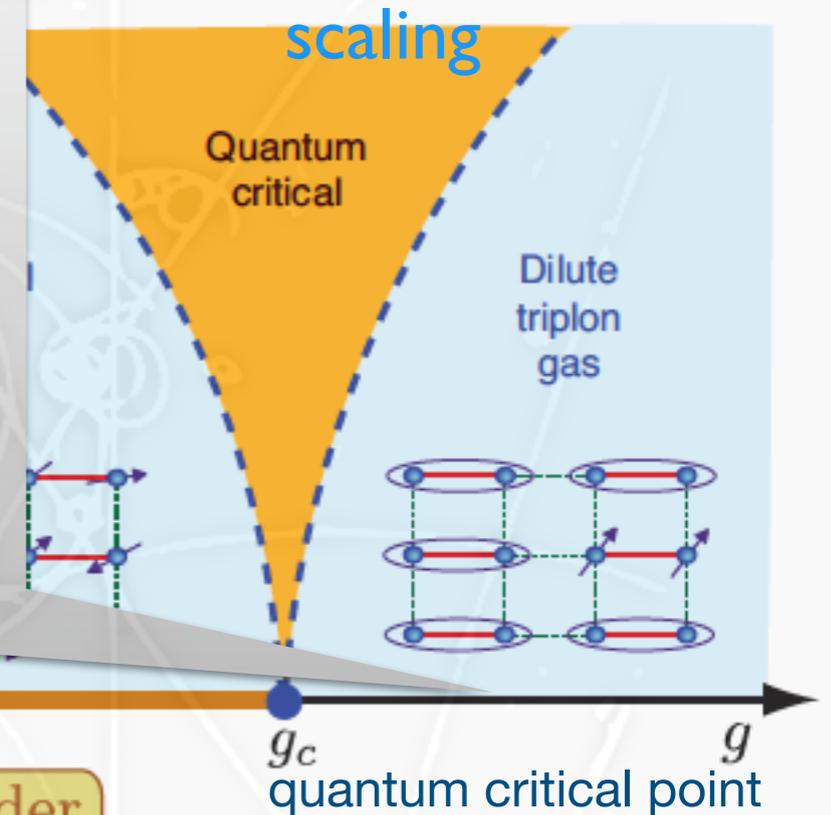
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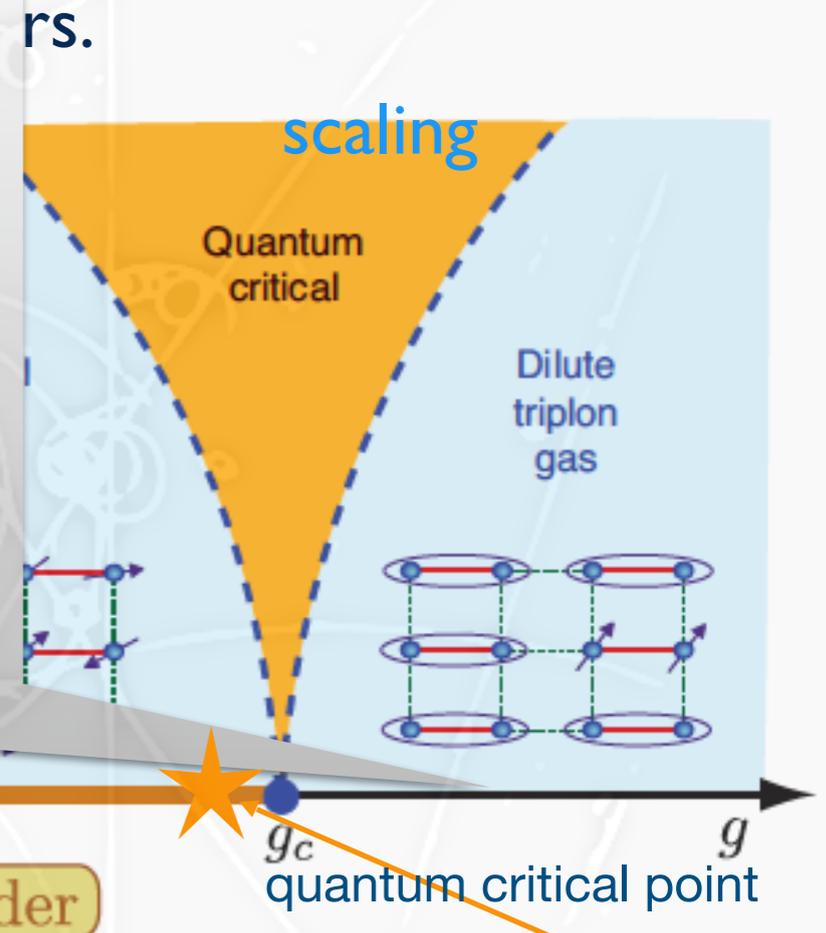
$$G(p) \sim \frac{i}{p^2} \quad \text{vs.} \quad G(p) \sim \frac{i}{(p^2)^{2-\Delta}} \quad \text{or} \quad G(p) \sim \frac{i}{(p^2 - \mu^2)^{2-\Delta}}$$

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AdS/CFT

$$\left\langle e^{\int d^4x \phi_0(x) \mathcal{O}(x)} \right\rangle_{\text{CFT}} \approx e^{S_{5\text{Dgravity}}[\phi(x,z)|_{z=0} = \phi_0(x)]}$$

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

$\mathcal{O} \subset \text{CFT} \leftrightarrow \phi$ AdS₅ field

AdS/CFT

$$ds^2 = \frac{R^2}{z^2} (dx_\mu^2 - dz^2)$$
$$z > \epsilon$$

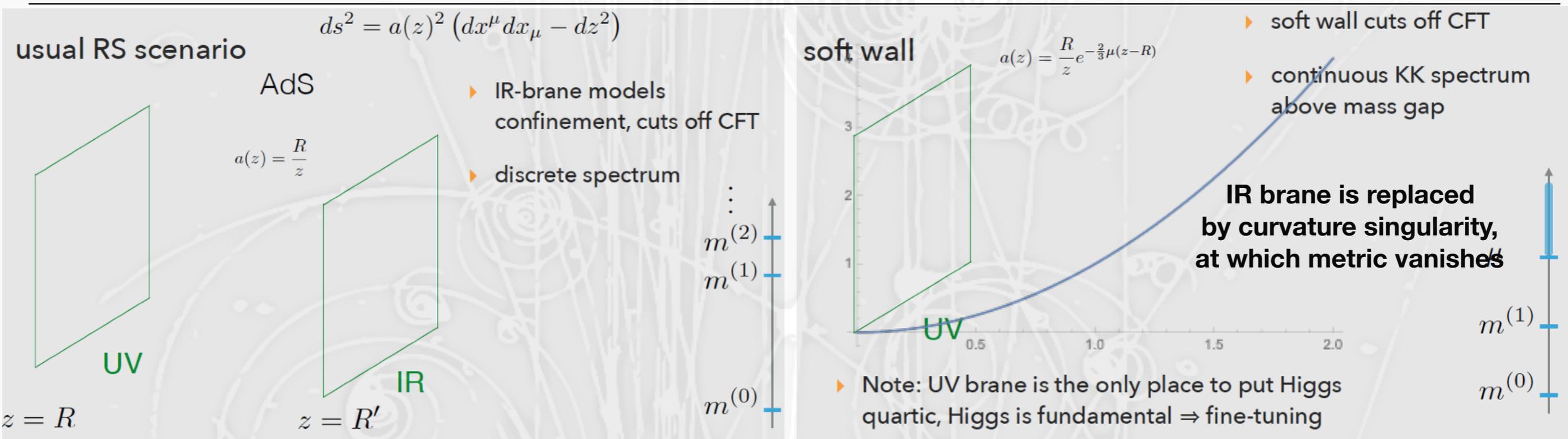
$$S_{bulk} = \frac{1}{2} \int d^4x dz \sqrt{g} (g^{\alpha\beta} \partial_\alpha \phi \partial_\beta \phi + m^2 \phi^2)$$

$$\phi(p, z) = az^2 J_\nu(pz) + bz^2 J_{-\nu}(pz)$$

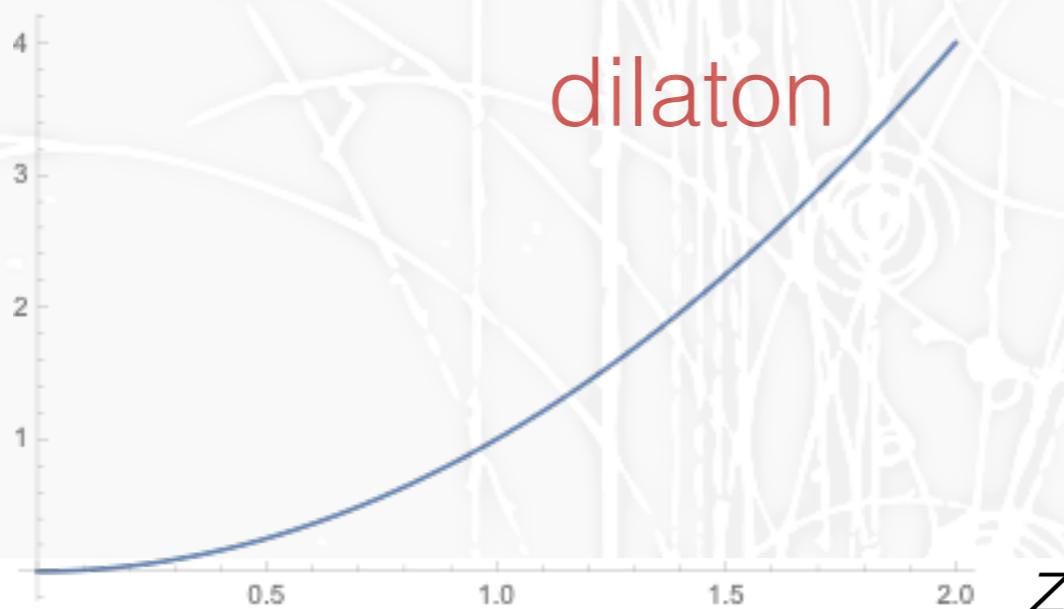
$$\Delta[\mathcal{O}] = 2 \pm \nu = 2 \pm \sqrt{4 + m^2 R^2}$$

$$\langle \mathcal{O}(p) \mathcal{O}(p) \rangle \propto \frac{\delta^{(4)}(p+p')}{(2\pi)^2} (p^2)^{\Delta-2}$$

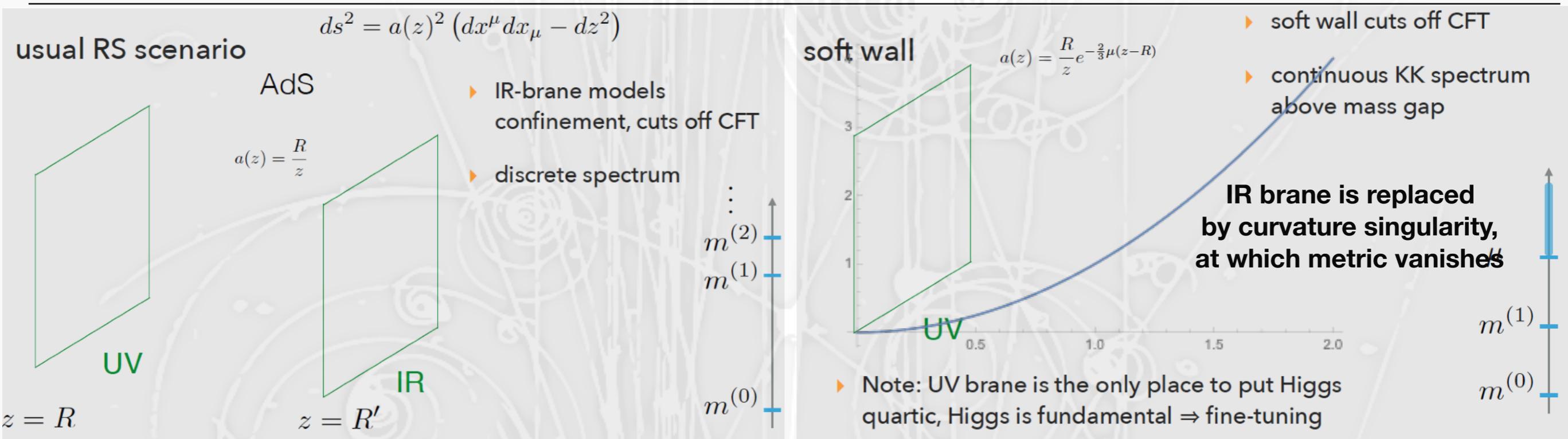
broken CFT



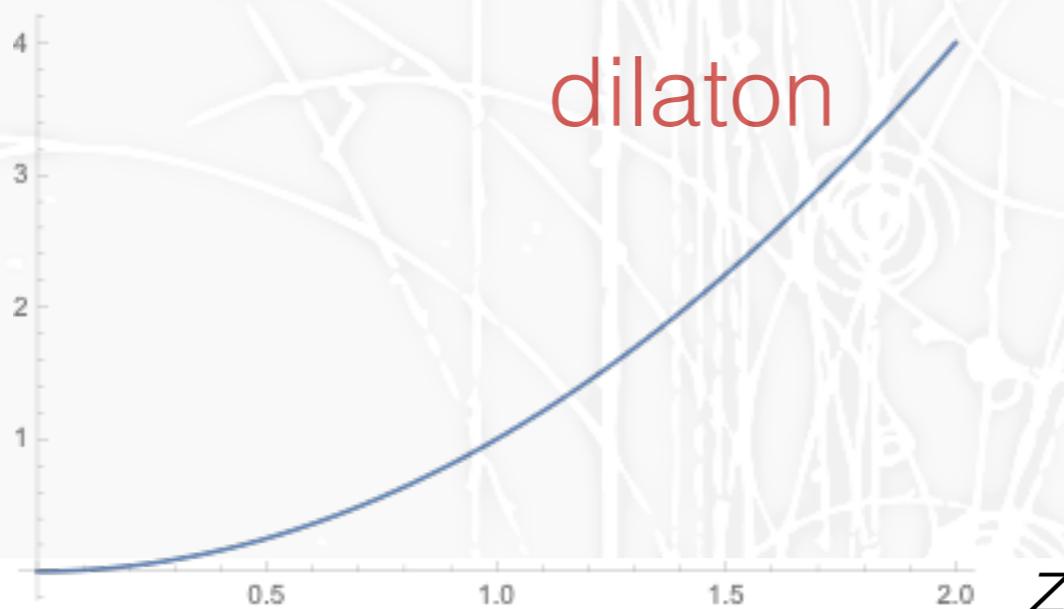
- ❖ Randall Sundrum 2 (only UV brane and bulk): cuts from 0 (CFT)
- ❖ RS1: putting IR cutoff at TeV
- ❖ New type of IR cutoff (soft wall) gives rise to a different phenomenology



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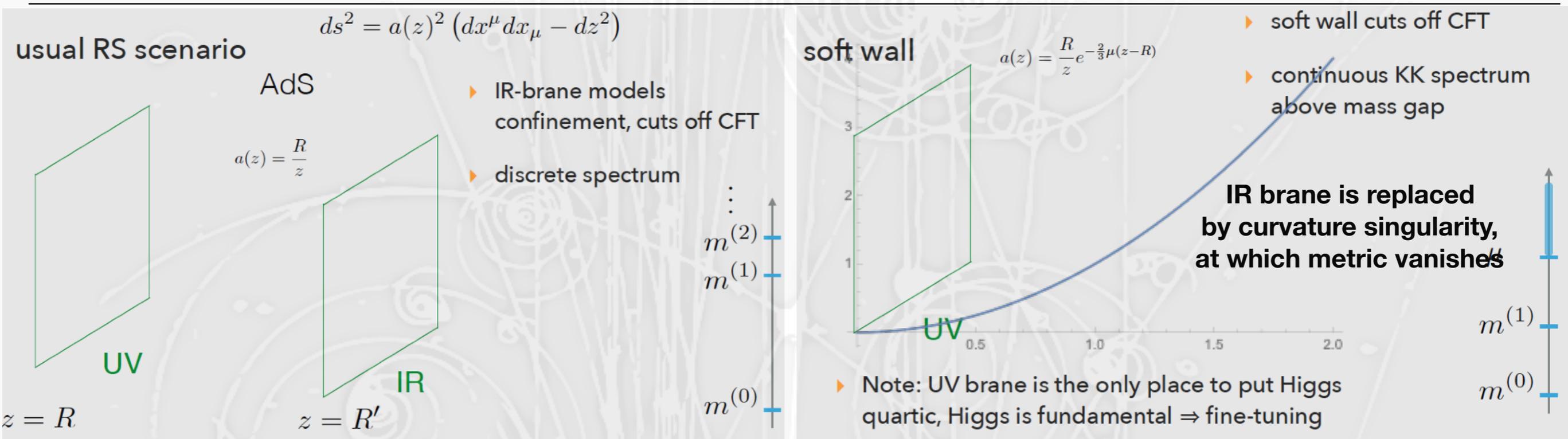


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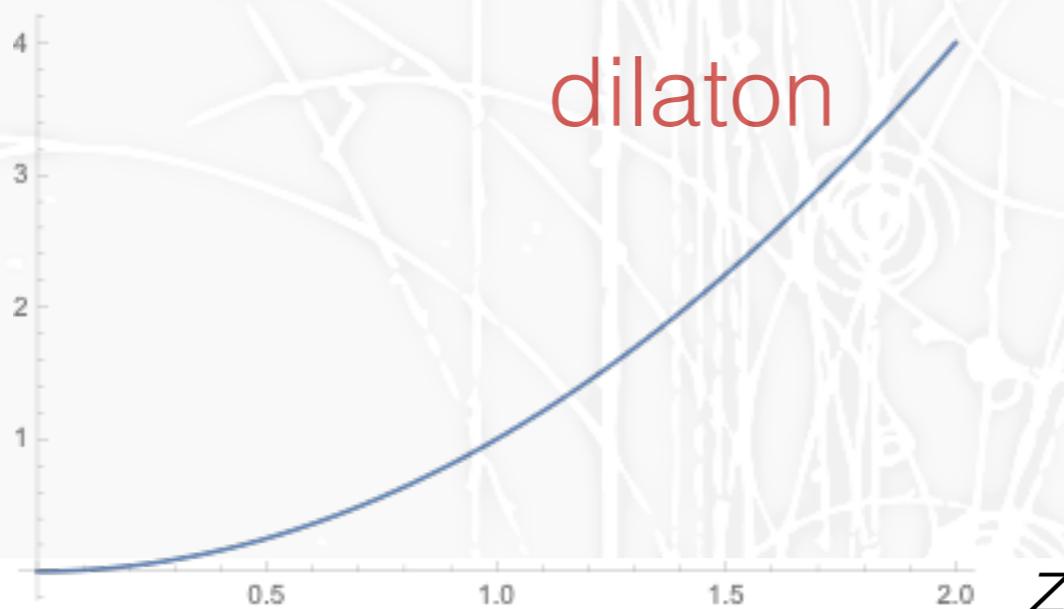


scalar getting VEV \Rightarrow marginal deformation of CFT

broken CFT



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broken CFT by IR cutoff

$$S_{\text{int}} = \frac{1}{2} \int d^4x dz \sqrt{g} \phi \mathcal{H}^\dagger \mathcal{H}$$

$$\phi = \left(\frac{\mu z}{R} \right)^2$$

$$z^5 \partial_z \left(\frac{1}{z^3} \partial_z \mathcal{H} \right) - z^2 (p^2 - \mu^2) \mathcal{H} - m^2 R^2 \mathcal{H} = 0$$

$$\langle \mathcal{O}(p) \mathcal{O}(p) \rangle \propto \frac{\delta^{(4)}(p+p')}{(2\pi)^2} (p^2 - \mu^2)^{\Delta-2}$$

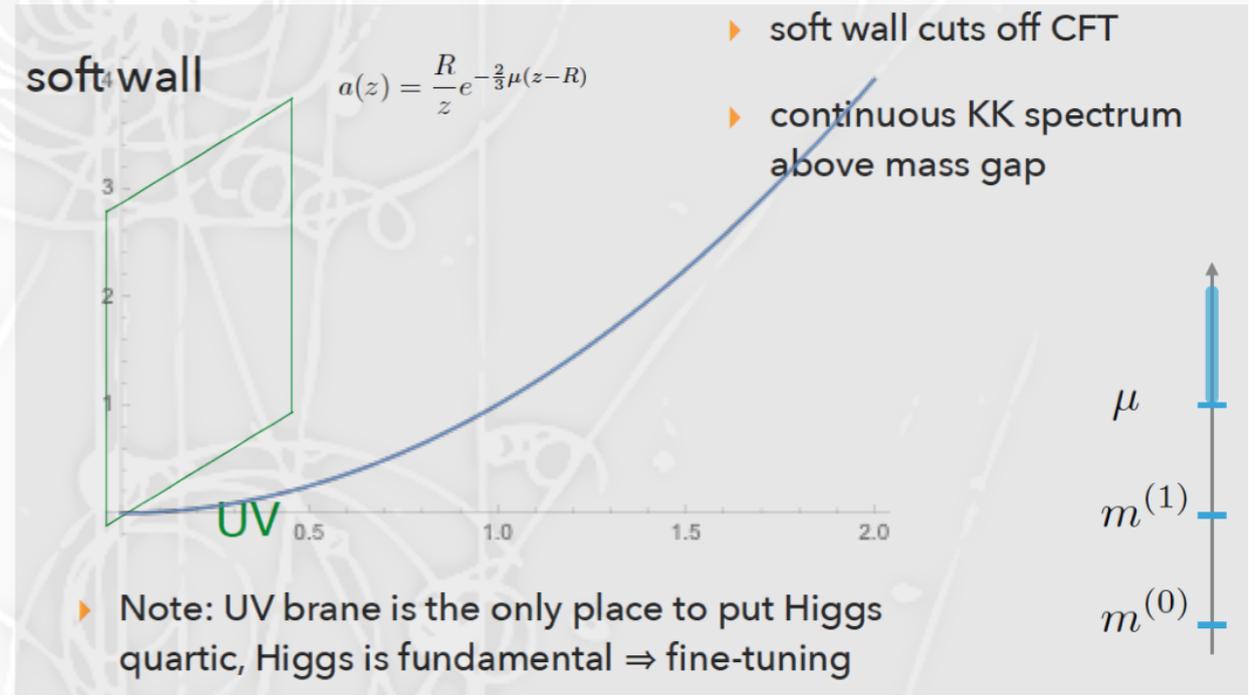
$$[\partial^2 - \mu^2]^{2-\Delta} \delta(x-y)$$

soft wall (AdS/QCD)

$$ds^2 = a(z) (dx^\mu dx_\mu - dz^2)$$

$$a(z) = \frac{R}{z} e^{-\frac{2}{3}\mu(z-R)^\nu}$$

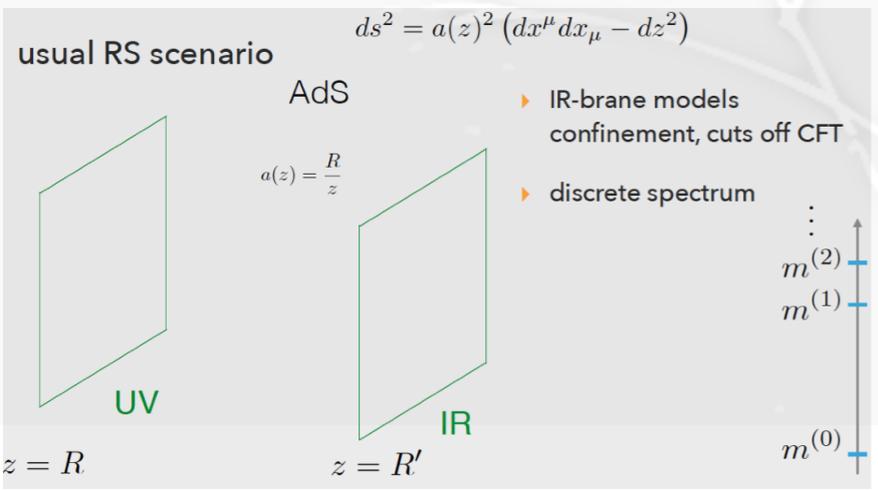
$$S_{\text{gauge}} = \int d^5x -\frac{1}{4} a(z) F_{MN}^2$$



EOM: $(a^{-1} \partial_z (a \partial_z) + p^2) f = 0$ $f = a^{-\frac{1}{2}} \Psi$

“Schrödinger Eqn”.: $(-\partial_z^2 + V(z)) \Psi = p^2 \Psi$, $V(z) = \frac{a''}{2a} - \frac{a'^2}{4a^2}$

$V(z) \Big|_{z \rightarrow \infty} \rightarrow \left(\frac{\mu}{3}\right)^2 \Rightarrow$ continuum begins at: $p^2 = (\mu/3)^2$



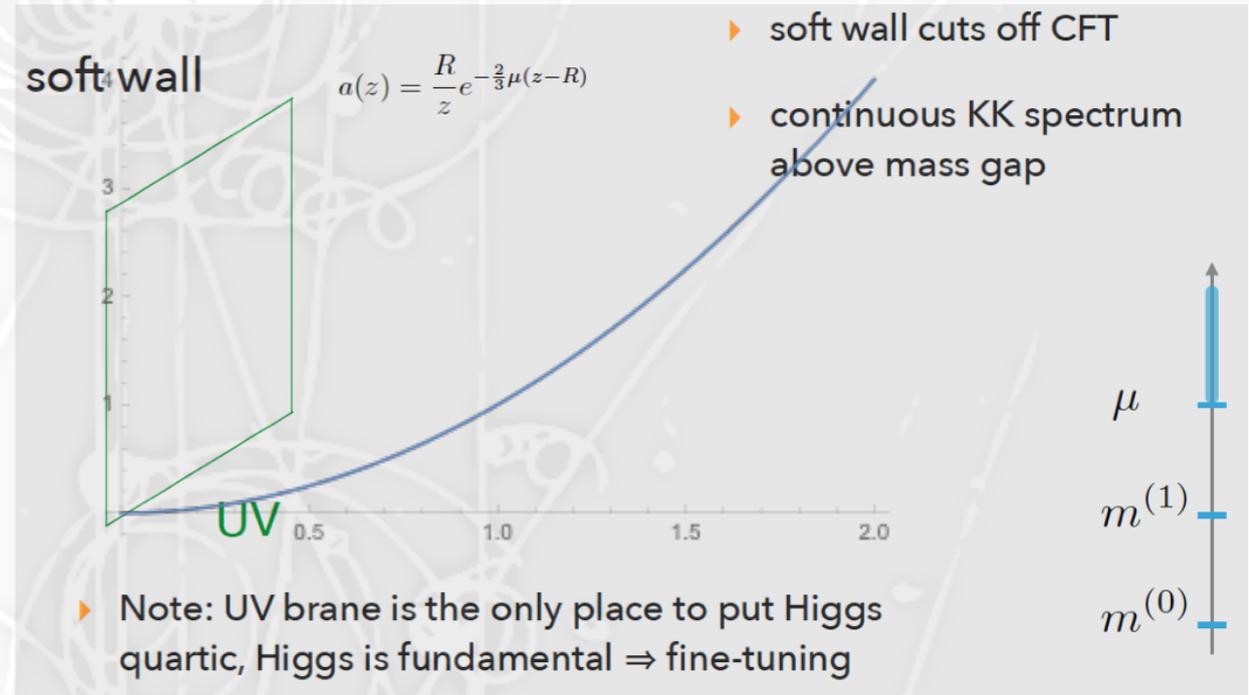
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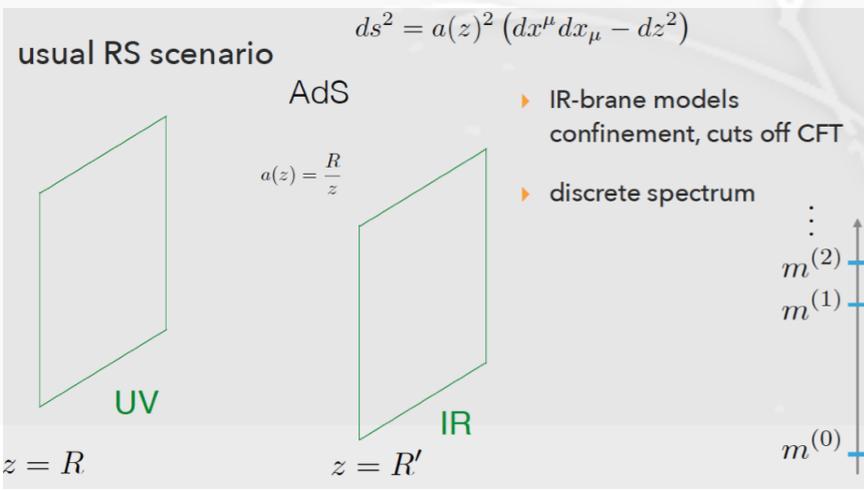
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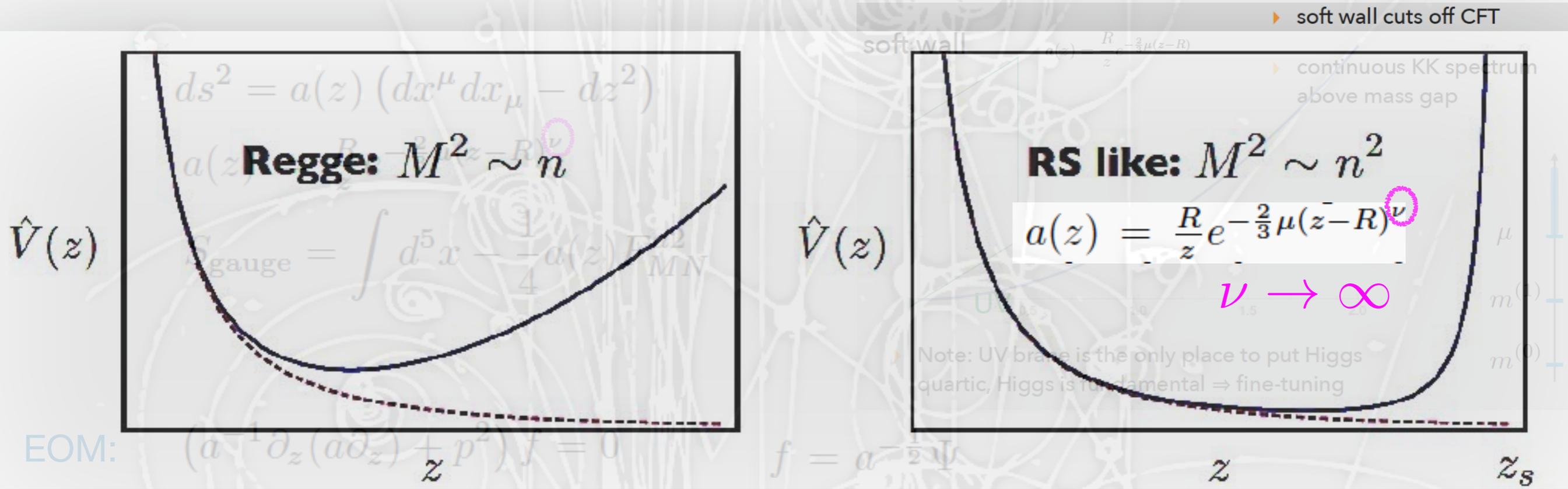
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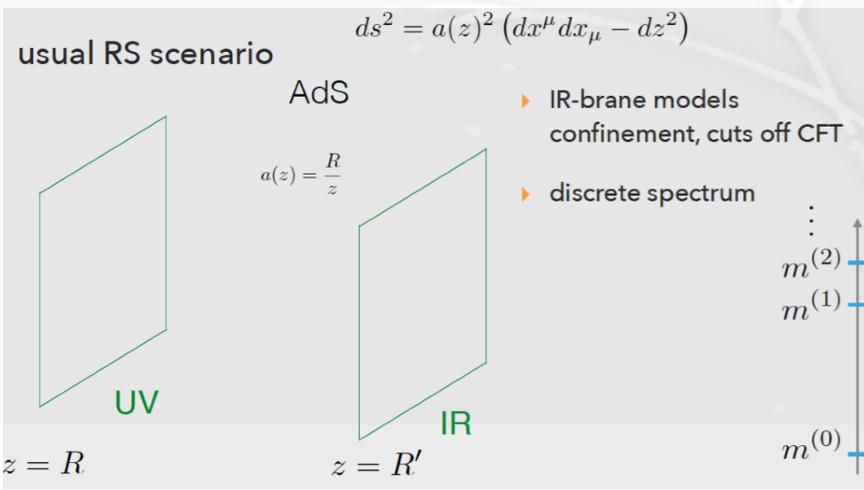
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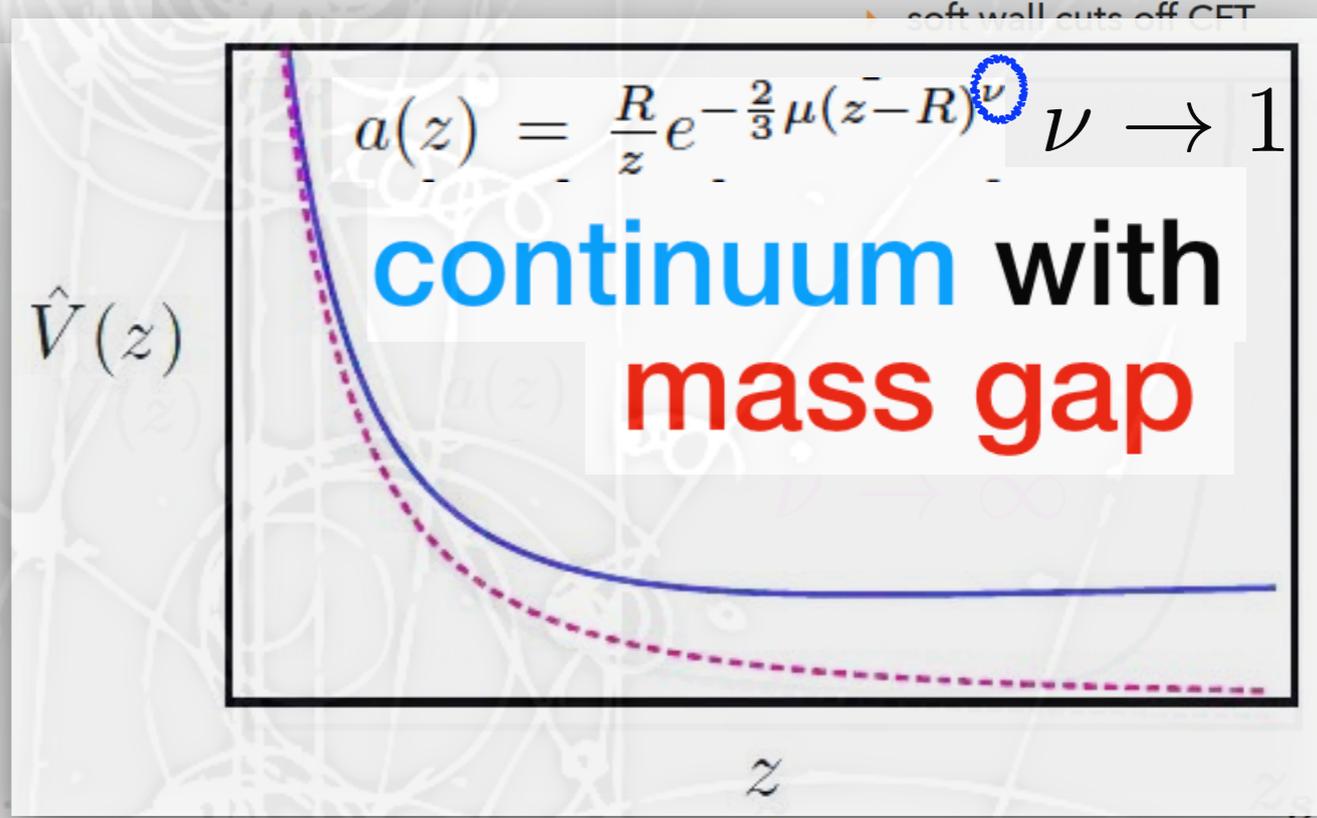
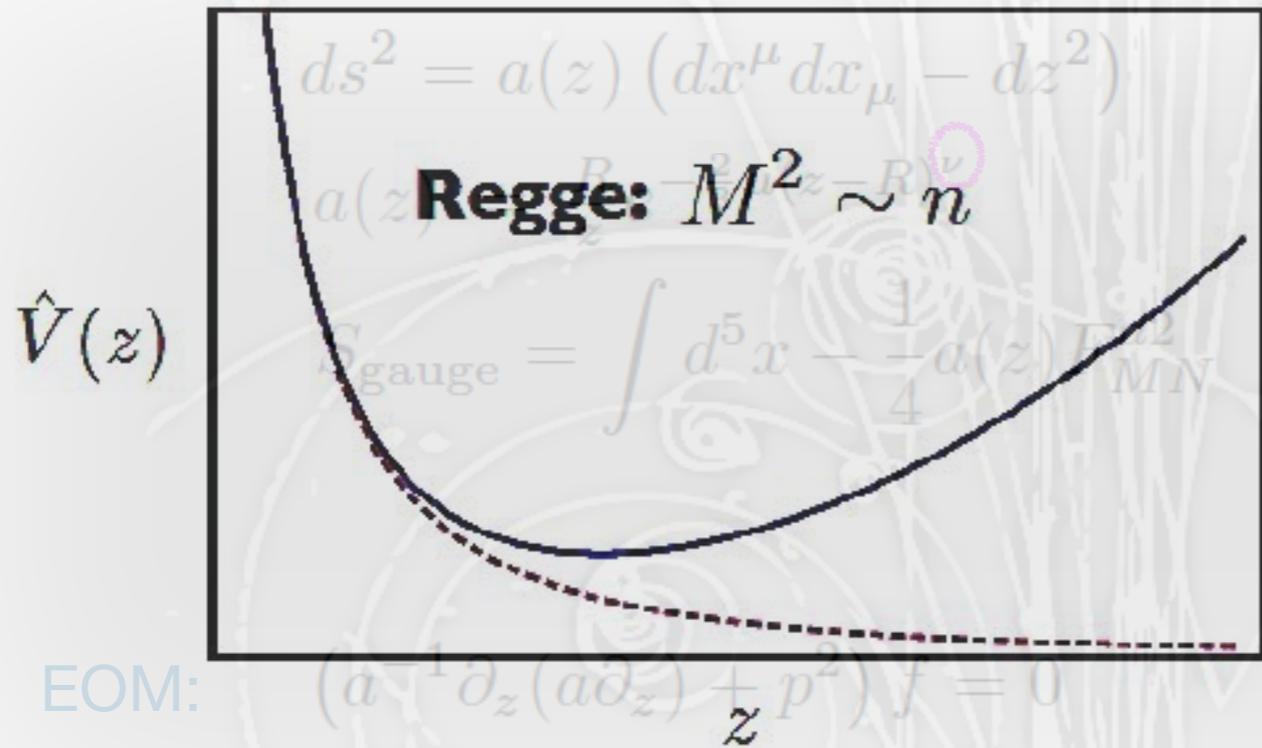
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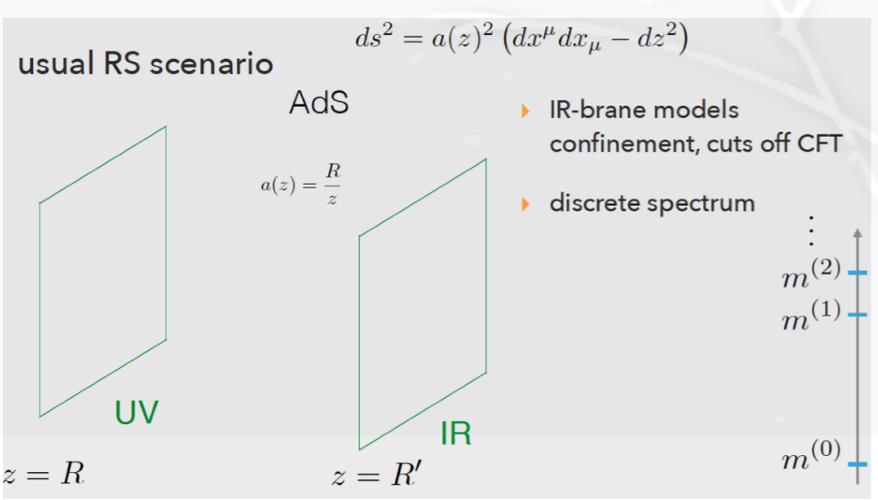


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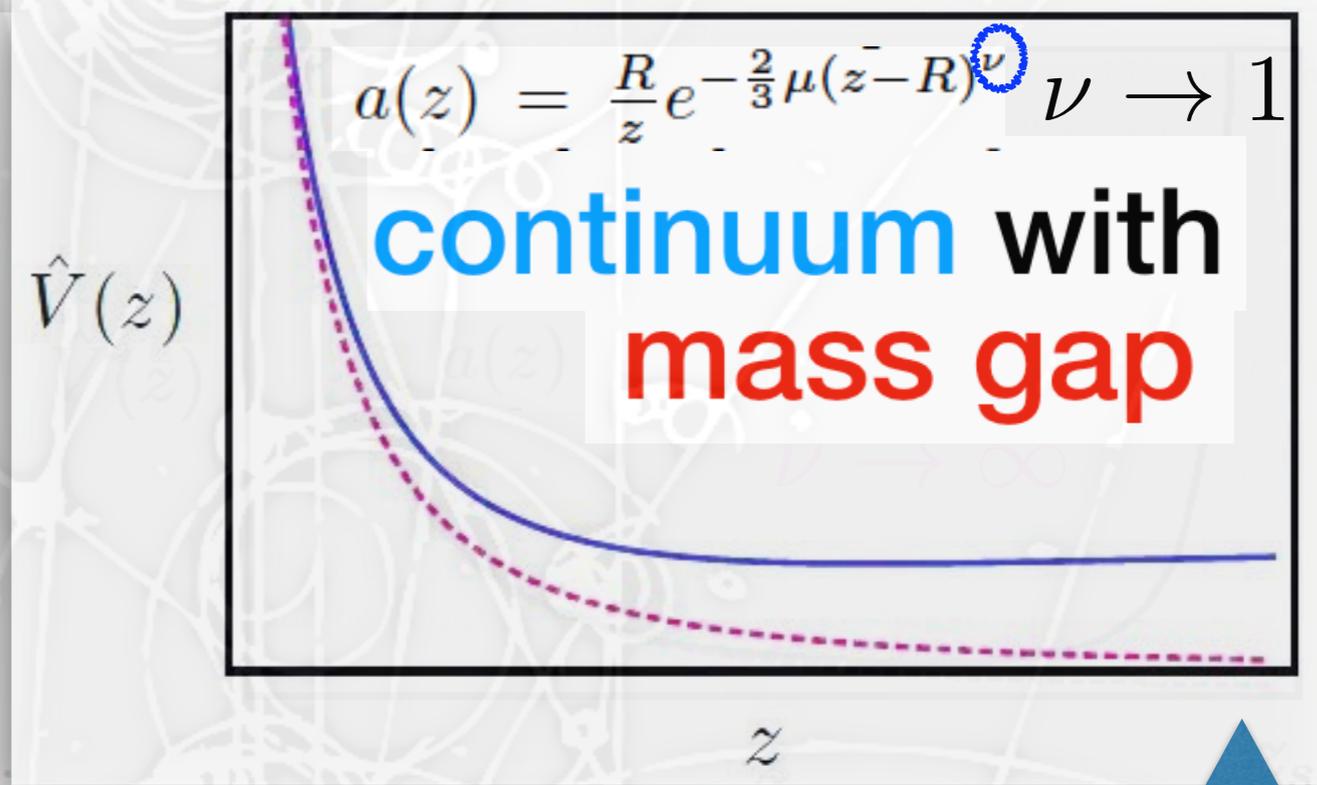
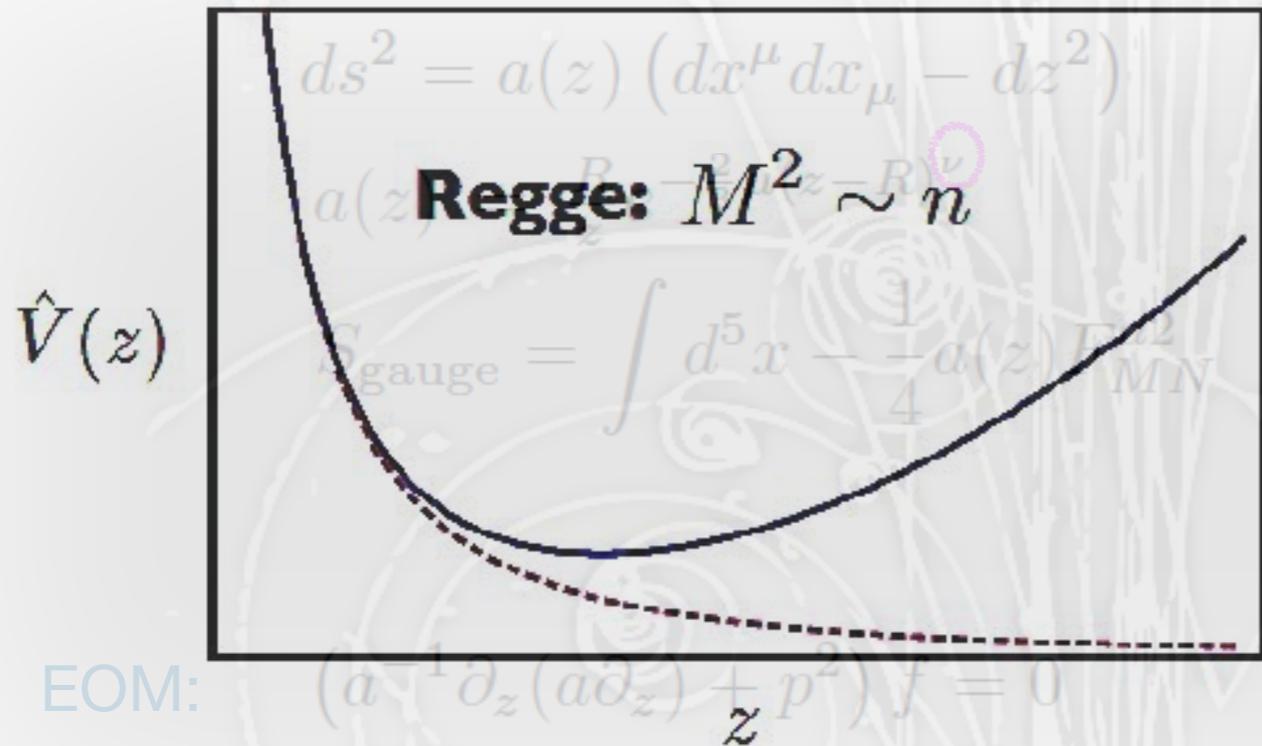
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$\rightarrow \infty$ (infinite well) \Rightarrow **KK towers**

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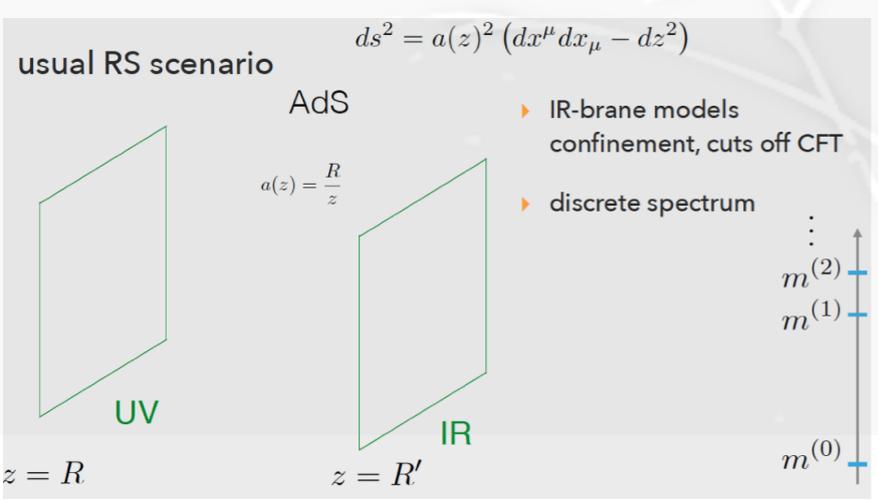


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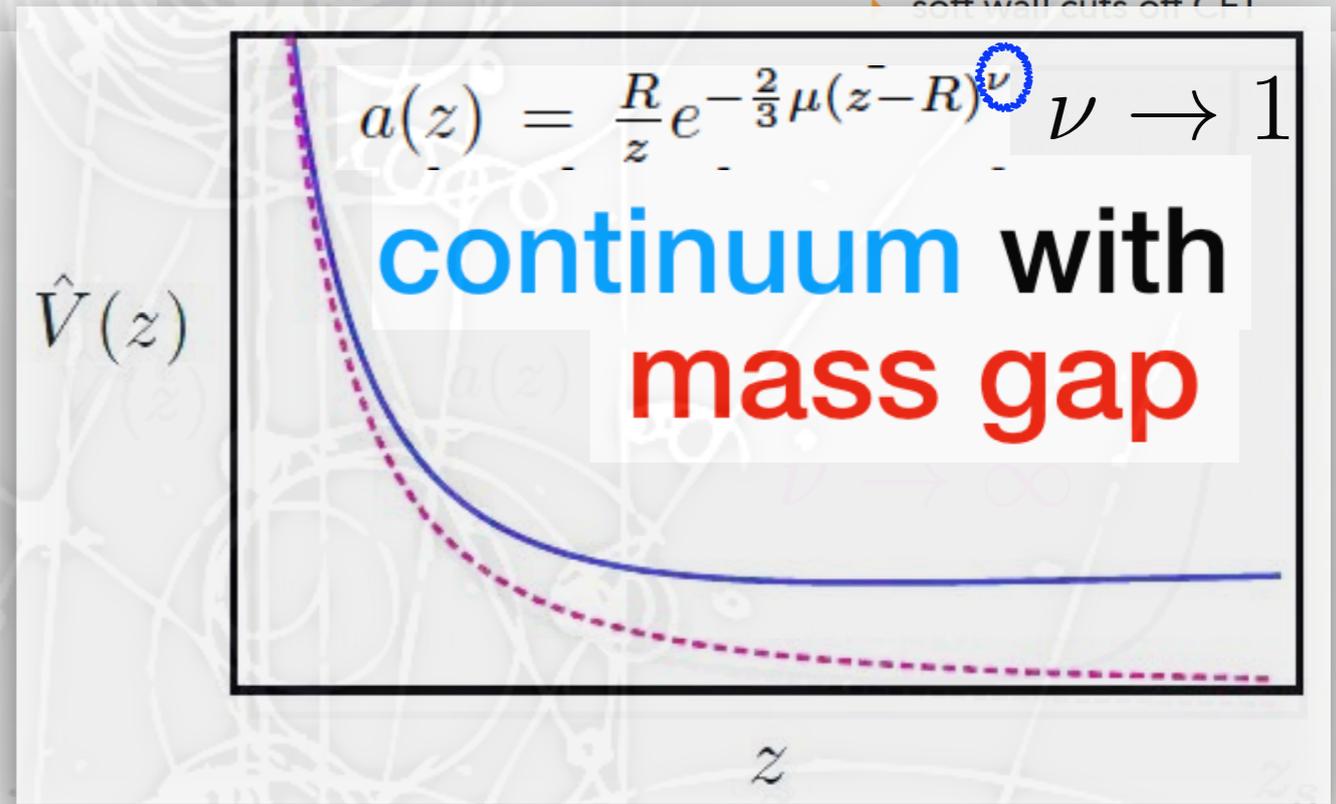
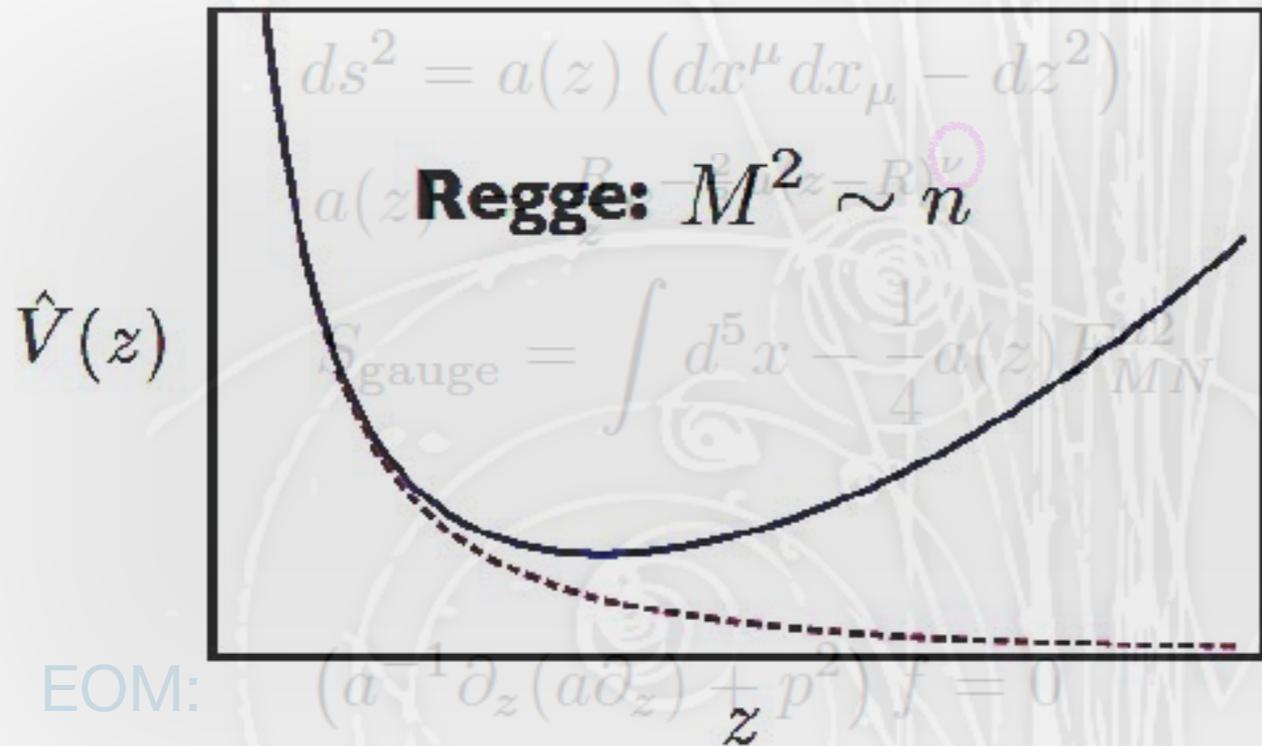
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Stabilization of this setting:
 Batell, Gherghetta, Sword '08
 Cabrer, Gersdorff, Quiros '09

$\rightarrow \infty$ (infinite well) \Rightarrow KK towers



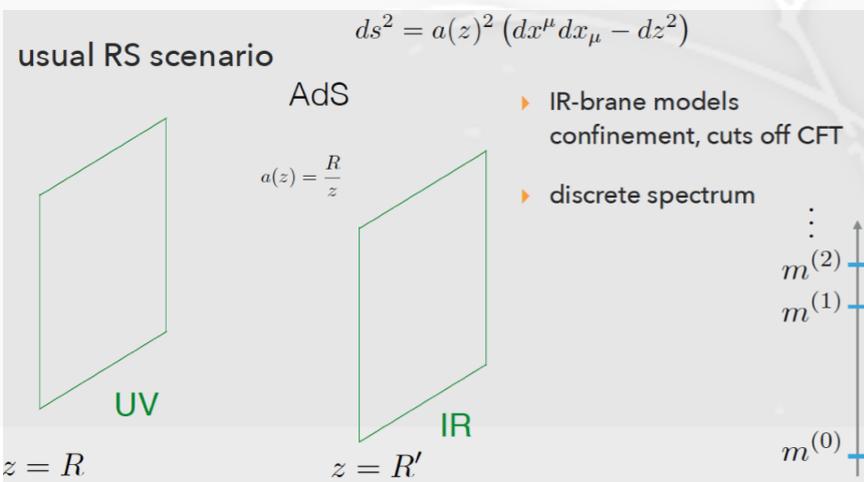
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soft wall (AdS/QCD)

$\hat{V}(z)$

$$ds^2 = a(z) (dx^\mu dx_\mu - dz^2)$$

$$a(z) \text{ Regge: } M^2 z \sim R^\nu n$$

$$S_{\text{gauge}} = \int d^5x \frac{1}{4} a(z) F_{MN}^2$$

$\hat{V}(z)$

$$a(z) = \frac{R}{z} e^{-\frac{2}{3}\mu(z-R)^\nu} \quad \nu \rightarrow 1$$
continuum with mass gap

UV

IR

linear dilaton:

around UV, vanishing,
only effect on IR and below

$$\Phi(z) = \mu(z - R)$$

$$z = R$$

$$z = R'$$

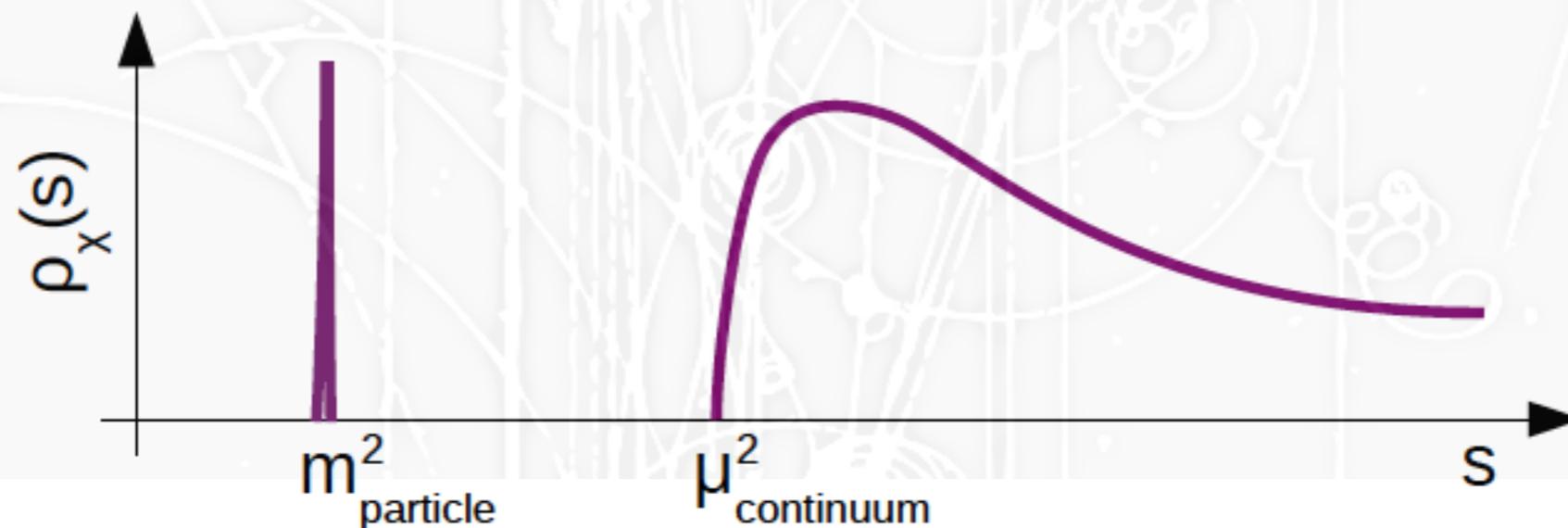
$$a_S(z) = \frac{R}{z}$$

z

The Quantum Critical higgs

- ❖ At a QPT the approximate scale invariant theory is characterized by [the scaling dimension \$\Delta\$](#) of the gauge invariant operators. SM: $\Delta = 1 + \mathcal{O}(\alpha/4\pi)$.
- ❖ We want to present a general class of theories describing a higgs field near a non-mean-field QPT.
- ❖ In such theories, in addition to the pole (Higgs), there can also be a higgs continuum, representing additional states associated with the dynamics underlying the QPT

$$G_h(p^2) = \frac{i}{p^2 - m_h^2} + \int_{\mu^2}^{\infty} dM^2 \frac{\rho(M^2)}{p^2 - M^2}$$



Quantum Critical Higgs (Generalized Free Fields)

Bellazzini, Csaki, Hubisz, SL, Serra, Terning

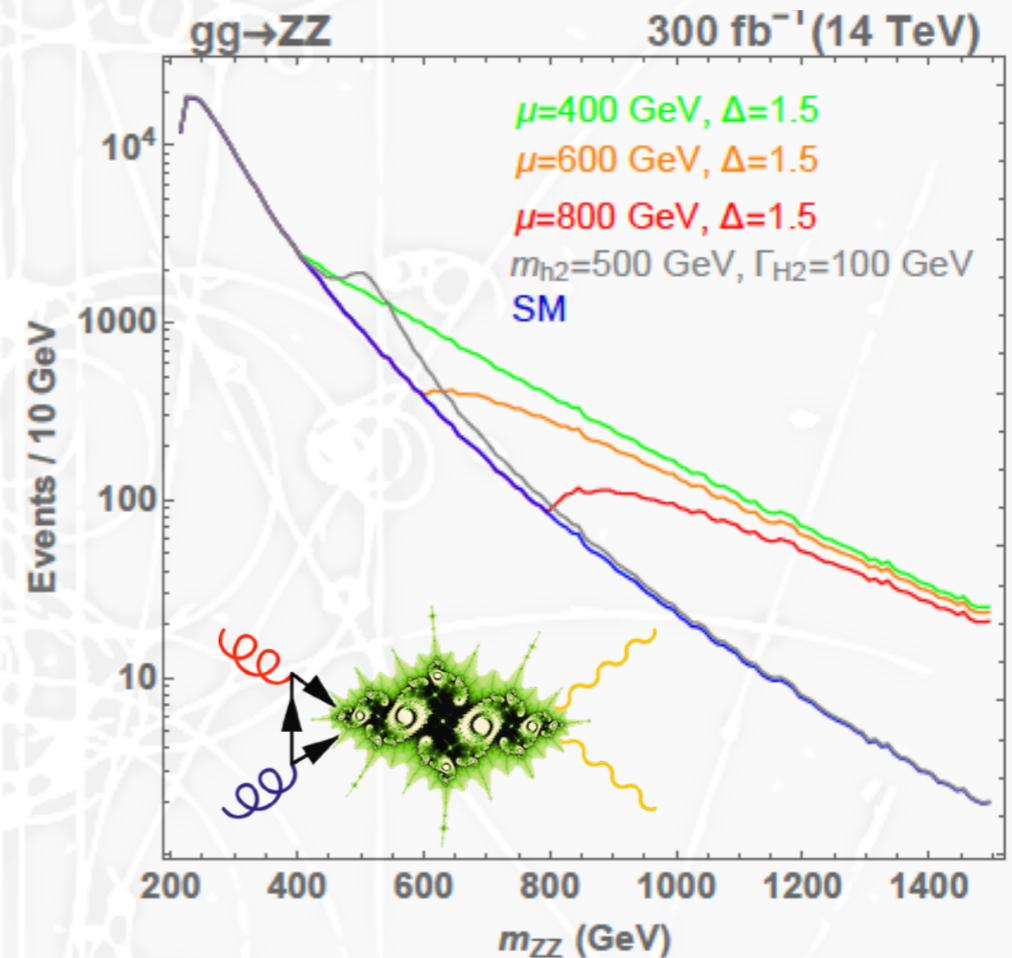
◆ 5D model:
$$S = \int d^4x dz \sqrt{g} \left[|D_M H|^2 - \frac{1}{4g_4^2} W_{MN}^a{}^2 - \phi(z) |H|^2 + \mathcal{L}_{\text{int}}(H) \right] + \int d^4x \mathcal{L}_{\text{perturbative}}$$

$$ds^2 = a(z)^2 (\eta_{\mu\nu} dx^\mu dx^\nu - dz^2)$$

$$a(z) = \frac{R}{z} e^{-\frac{2}{3}\mu(z-R)}$$

With the discovery of Higgs,
we need a pole (125 GeV)
and a gap to BSM continuum

Soft wall terminates CFT with continuum, not set of KK modes



Quantum Critical Higgs (Generalized Free Fields)

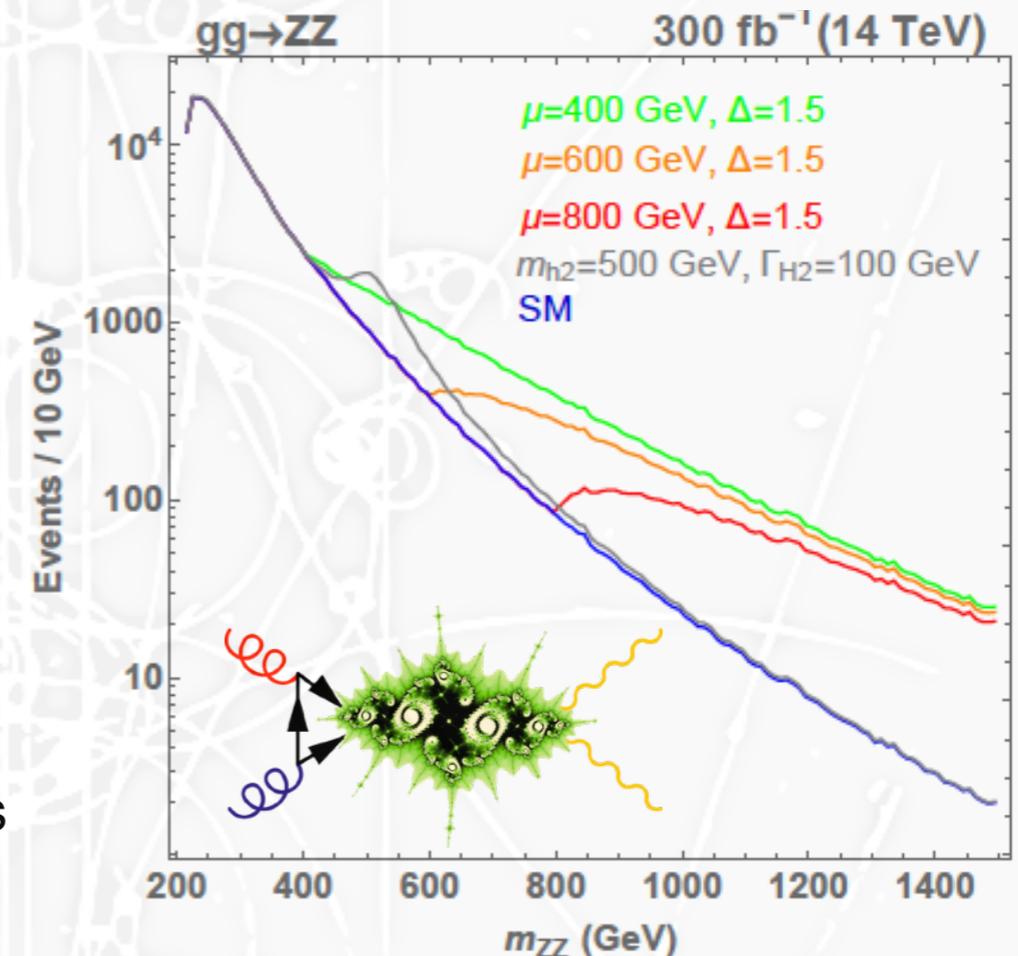
Bellazzini, Csaki, Hubisz, SL, Serra, Terning

◆ 5D model:
$$S = \int d^4x dz \sqrt{g} \left[|D_M H|^2 - \frac{1}{4g_4^2} W_{MN}^a{}^2 - \phi(z) |H|^2 + \mathcal{L}_{\text{int}}(H) \right] + \int d^4x \mathcal{L}_{\text{perturbative}}$$

$$ds^2 = a(z)^2 (\eta_{\mu\nu} dx^\mu dx^\nu - dz^2)$$

$$a(z) = \frac{R}{z} e^{-\frac{2}{3}\mu(z-R)}$$

With the discovery of Higgs, we need a pole (125 GeV) and a gap to BSM continuum



Soft wall terminates CFT with continuum, not set of KK modes

The momentum space propagator for the physical Higgs scalar can be written as

$$G_h(p) = -\frac{i Z_h}{(\mu^2 - p^2 + i\epsilon)^{2-\Delta} - (\mu^2 - m_h^2)^{2-\Delta}} ; \quad Z_h = \frac{(2 - \Delta)}{(\mu^2 - m_h^2)^{\Delta-1}}$$

c.f. unparticle propagator

Quantum Critical Higgs (Generalized Free Fields)

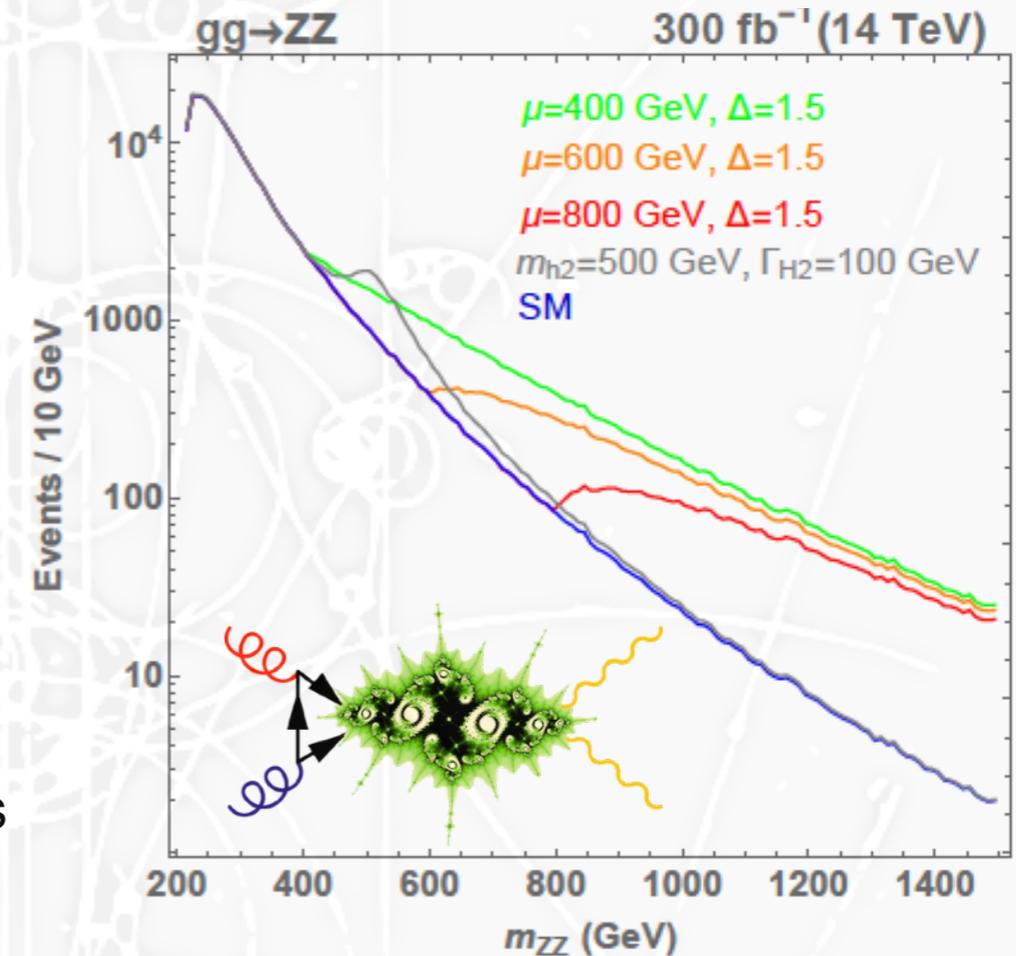
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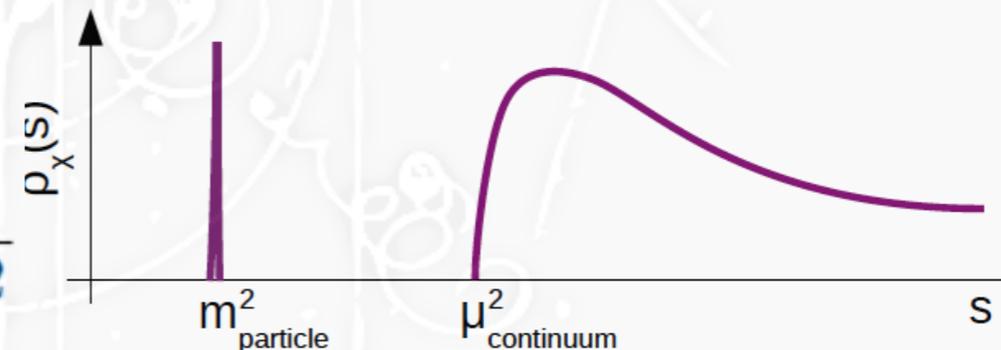
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Generally:

$$G_h(p^2) = \frac{i}{p^2 - m_h^2} + \int_{\mu^2}^{\infty} dM^2 \frac{\rho(M^2)}{p^2 - M^2}$$



SM recovered in limits $\mu \rightarrow \infty$ and/or $\Delta \rightarrow 1$

Generalized Free Fields via AdS/CFT

- SO(4) global symmetry is gauged in the 5D bulk

Cacciapaglia, Marandella and Terning 08'
 Falkowski and Perez-Victoria 08'
 Bellazzini, Csaki, Hubisz, SL, Serra, Terning 15'

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$$G_h(R, R, p^2) = i\tilde{Z}_h \left[\frac{\mu K_{1-\nu}(\mu R)}{R K_\nu(\mu R)} - \frac{\sqrt{\mu^2 - p^2} K_{1-\nu}(\sqrt{\mu^2 - p^2} R)}{R K_\nu(\sqrt{\mu^2 - p^2} R)} - M_0^2 \right]^{-1}$$

Soft wall terminates CFT with continuum, not set of KK modes

The bulk to brane propagator is then given by $G_h(R, z, p^2) = a^{-\frac{3}{2}}(z)(z/R)^{\frac{1}{2}} \frac{K_\nu(\sqrt{\mu^2 - p^2} z)}{K_\nu(\sqrt{\mu^2 - p^2} R)}$

=> reduce to the previous propagator in the limit $pR \ll 1$:

$$G_h(p) = -\frac{i Z_h}{(\mu^2 - p^2 + i\epsilon)^{2-\Delta} - (\mu^2 - m_h^2)^{2-\Delta}}$$

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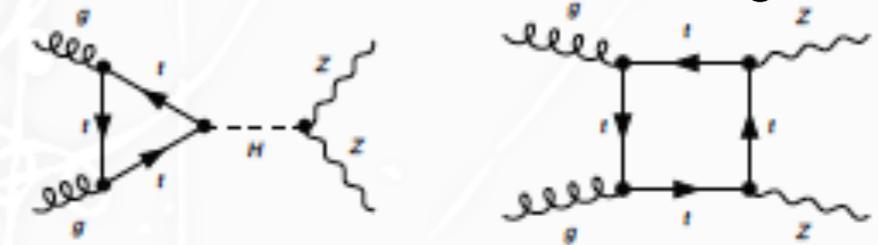
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obtain such propagator from a calculable model of this sort based on a Banks-Zaks fixed point in a supersymmetric QCD theory: Csaki, SL (work in progress)

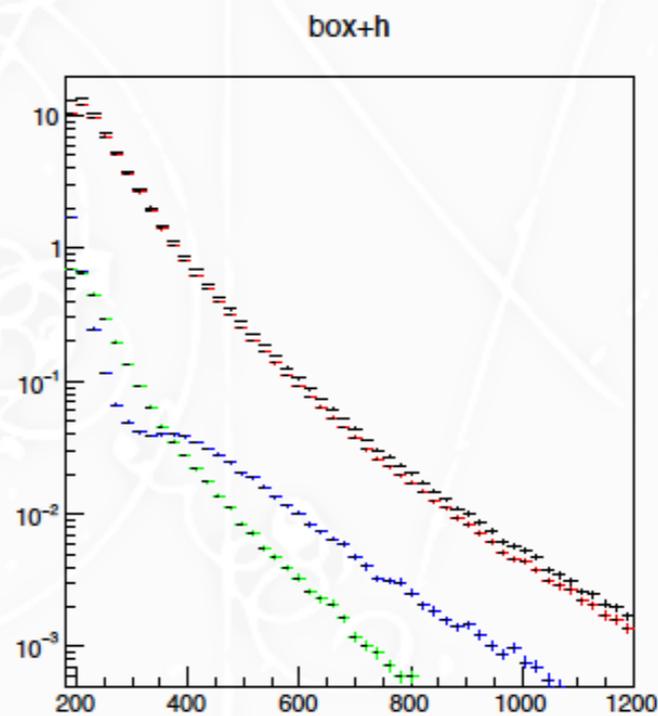
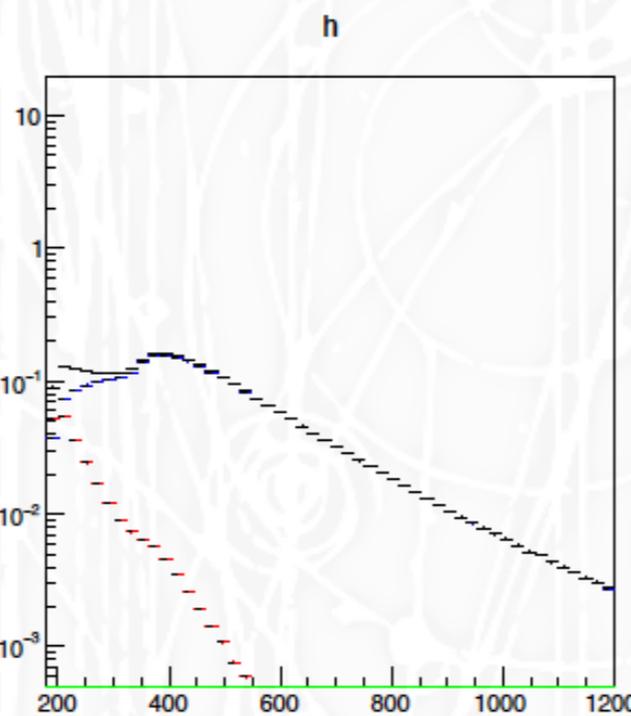
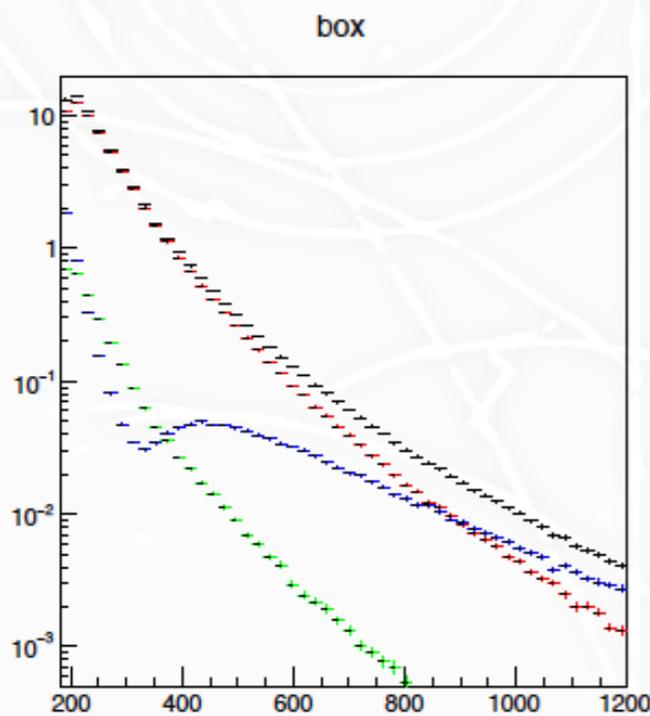
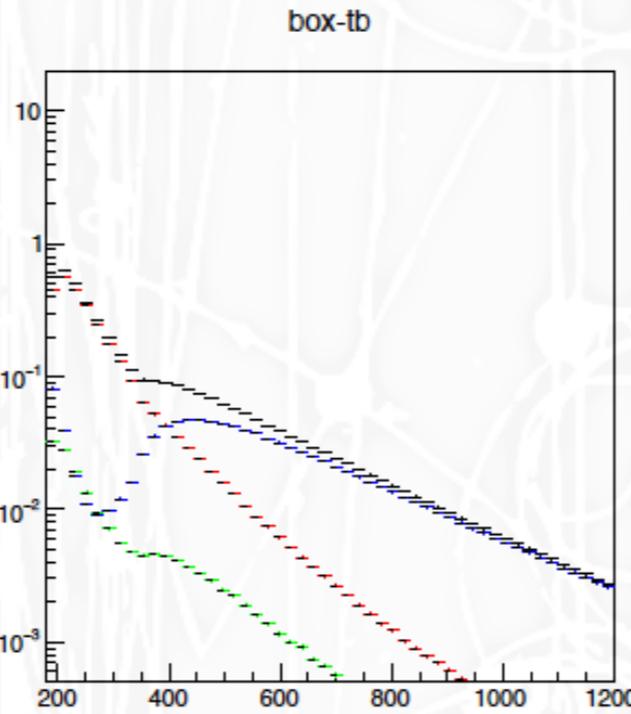
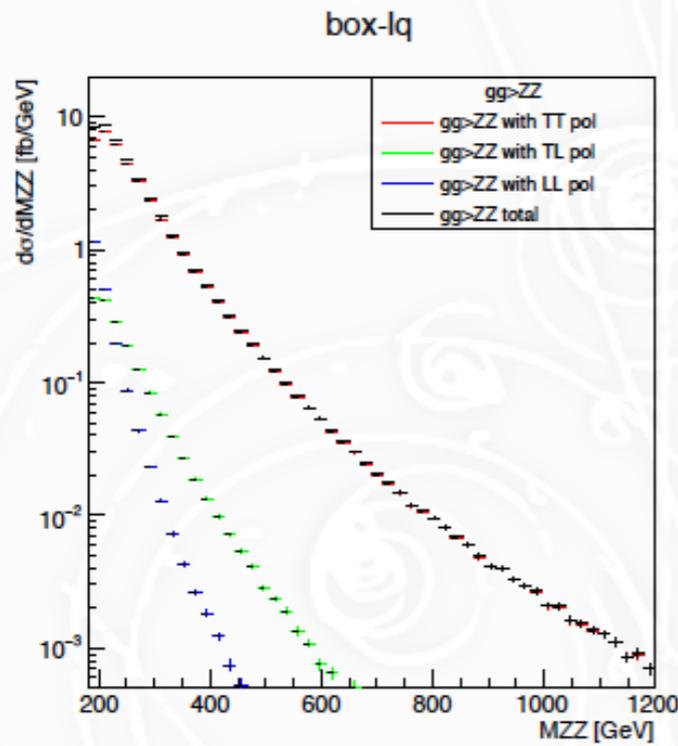
Probing Naturalness by the Tail of the Off-shell Higgs via $V_L V_L$ mode

SL, Park, Qian; to appear soon

unitarity: for the longitudinal mode, exact cancellation of the logarithmic divergence between

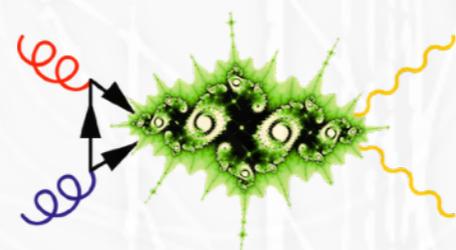
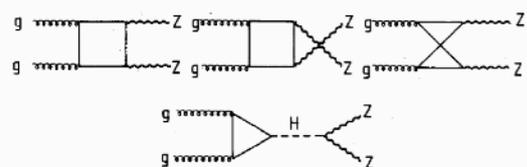
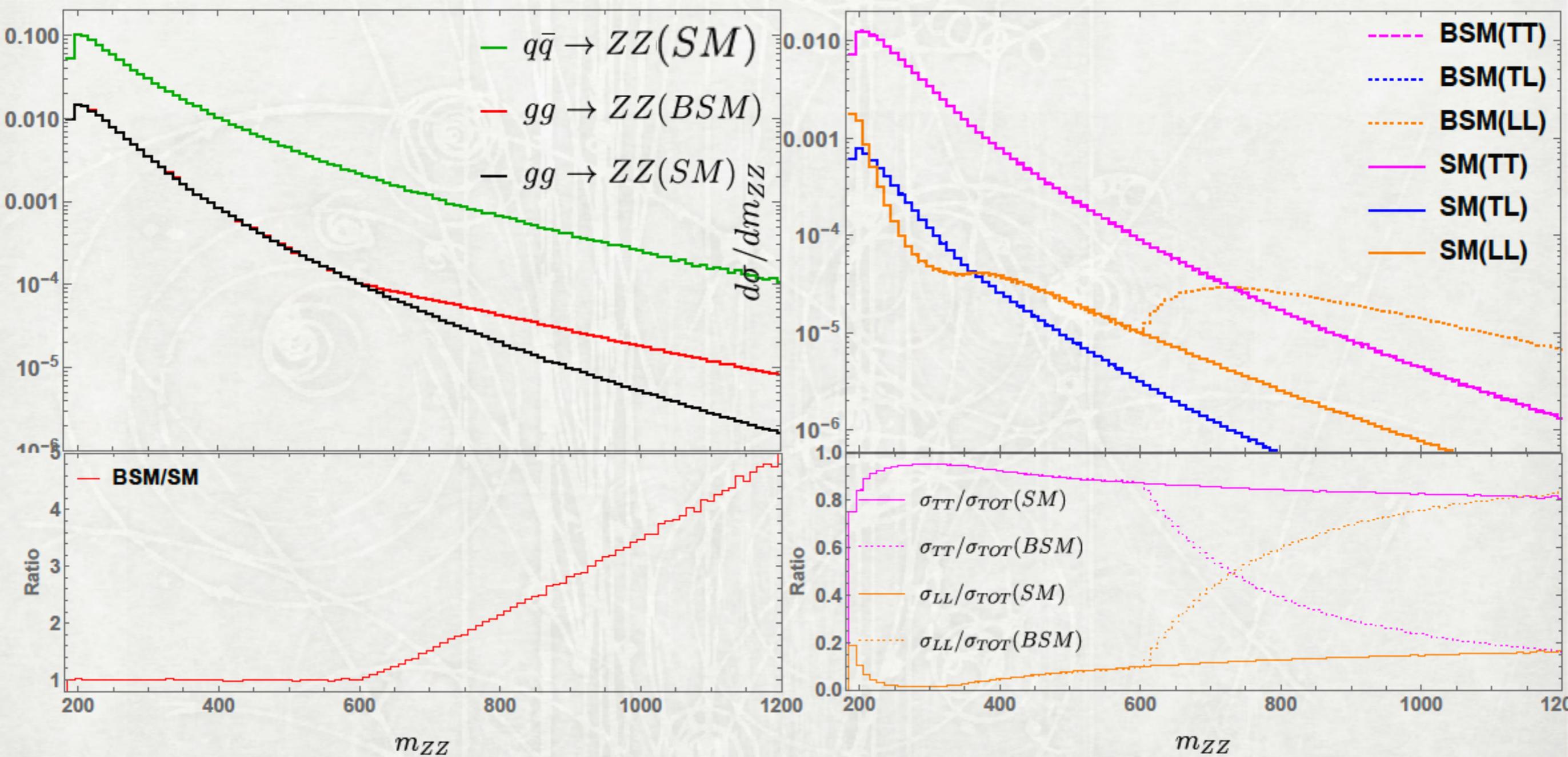


The individual polarization modes for $gg \rightarrow ZZ$ process in the high energy region.



Probing Naturalness by the Tail of the Off-shell Higgs via Tagging with angular observables

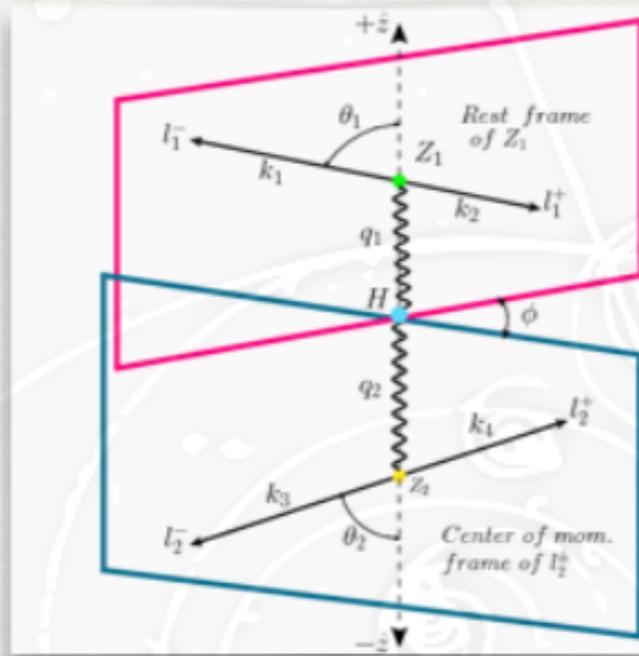
SL, Park, Qian



c.f.
$$\frac{1}{2\Lambda^4} \left(i\bar{\psi}\gamma^{\{\mu}\partial^{\nu\}}\psi + \text{h.c.} \right) D_\mu H^\dagger D_\nu H$$

Probing Naturalness by the Tail of the Off-shell Higgs via Polarization Tagging

SL, Park, Qian



Z Polarization \longleftrightarrow Angle $\cos \theta$ dist. from decay

$$\text{Transverse : } \frac{1}{\sigma} \frac{d\sigma}{d \cos \theta} \equiv \frac{3}{8} (1 + \cos^2 \theta)$$

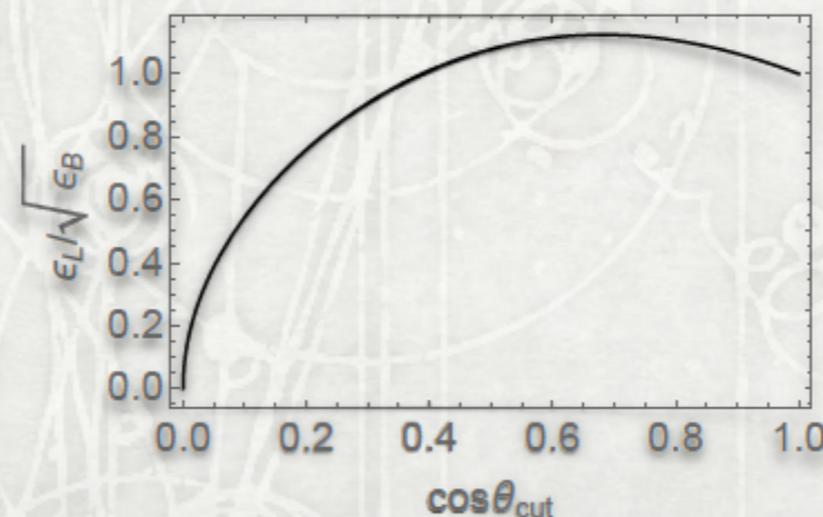
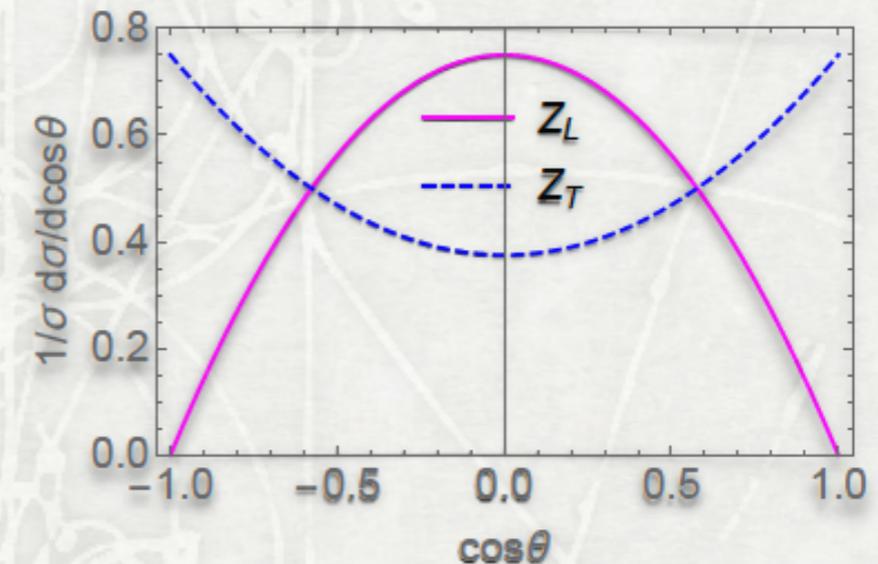
$$\text{Longitudinal : } \frac{1}{\sigma} \frac{d\sigma}{d \cos \theta} \equiv \frac{3}{4} (1 - \cos^2 \theta)$$

To optimize the longitudinal over transverse mode significance:

$$-0.68 < \cos \theta < 0.68$$

$$\cos \theta_C = 0.68$$

$$\{\epsilon_L, \epsilon_T\} = 86\%, 59\%$$



Direct Signals (double Higgs)

- ❖ Double Higgs production



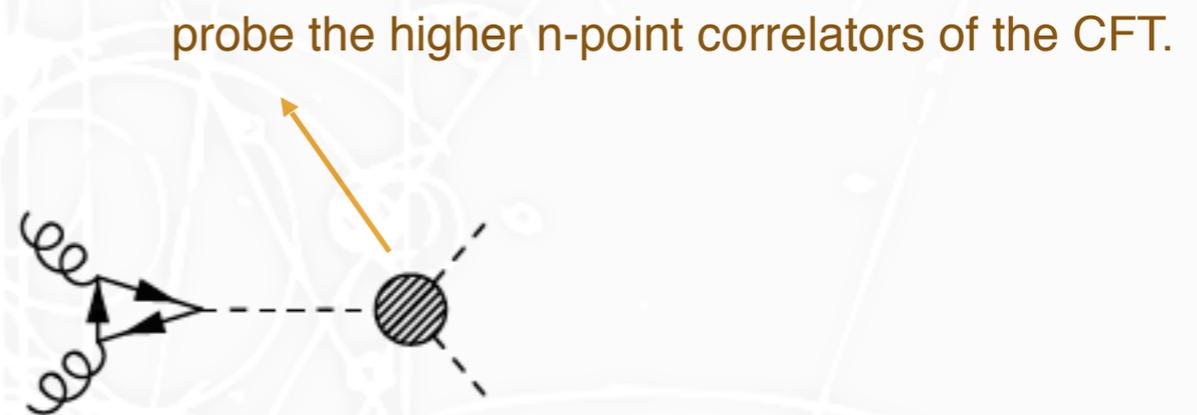
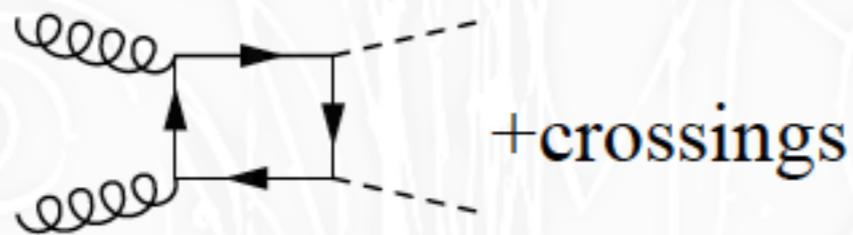
$$\frac{d\hat{\sigma}}{d\hat{t}} = \frac{\alpha_w^2 \alpha_s^2}{2^{15} \pi M_W^4 \hat{s}^2} (|\text{gauge1}|^2 + |\text{gauge2}|^2)$$

gauge1 = box + triangle (negative interference)

gauge2 = box (largest contribution)

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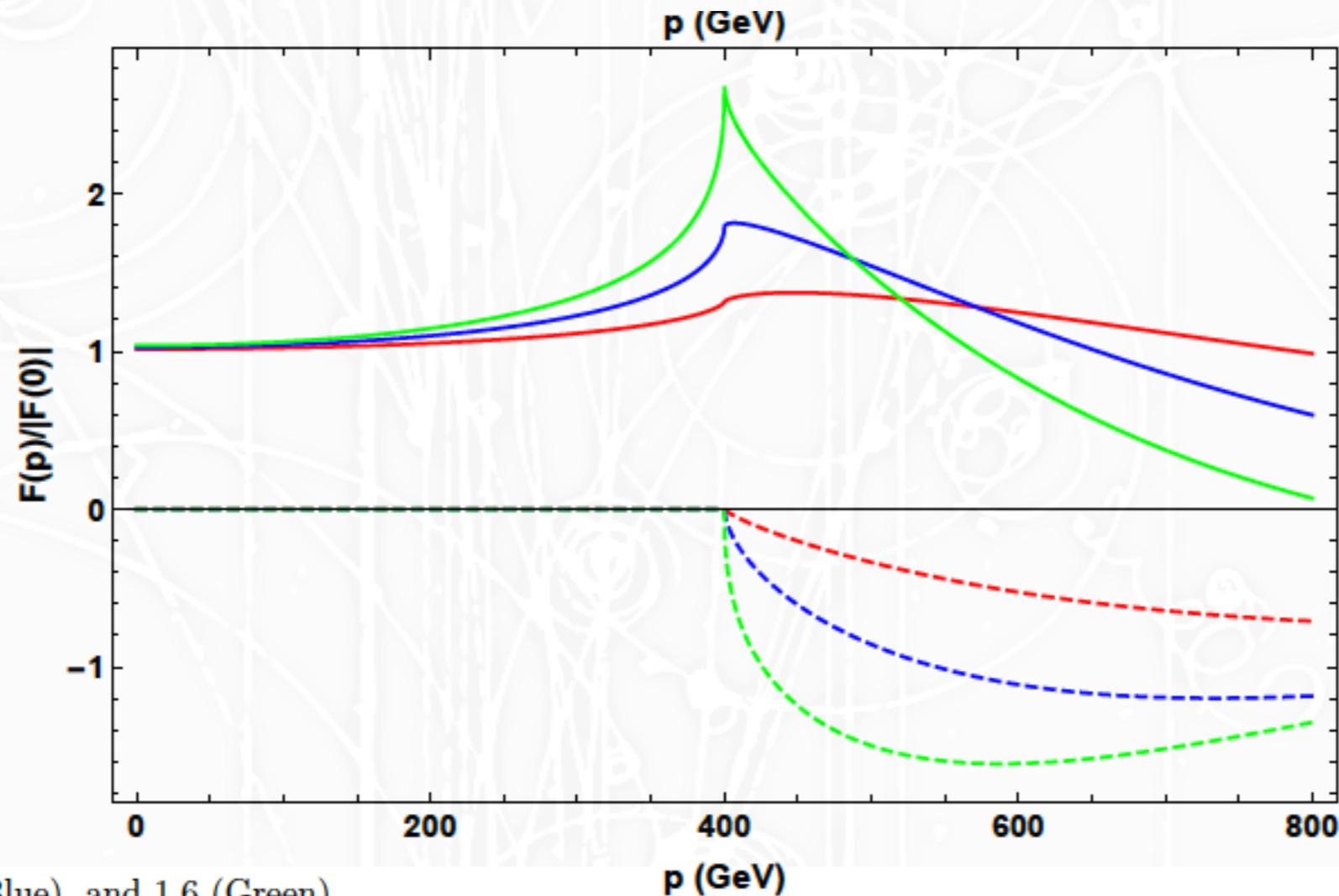
gauge2 = box (largest contribution)

Direct Signals (double Higgs)

- Form factors for trilinear Higgs self coupling

$$\lambda_5 (H^\dagger H)^2$$

$$F_{hhh} = \frac{\lambda_5}{L^2} \mathcal{V} \int_R^\infty dz \frac{1}{a} \left(\frac{z}{R}\right)^2 \frac{K_{2-\Delta}(\mu z)}{K_{2-\Delta}(\mu R)} \prod_{i=1}^3 \frac{K_{2-\Delta}(\sqrt{\mu^2 - p_i^2} z)}{K_{2-\Delta}(\sqrt{\mu^2 - p_i^2} R)}$$



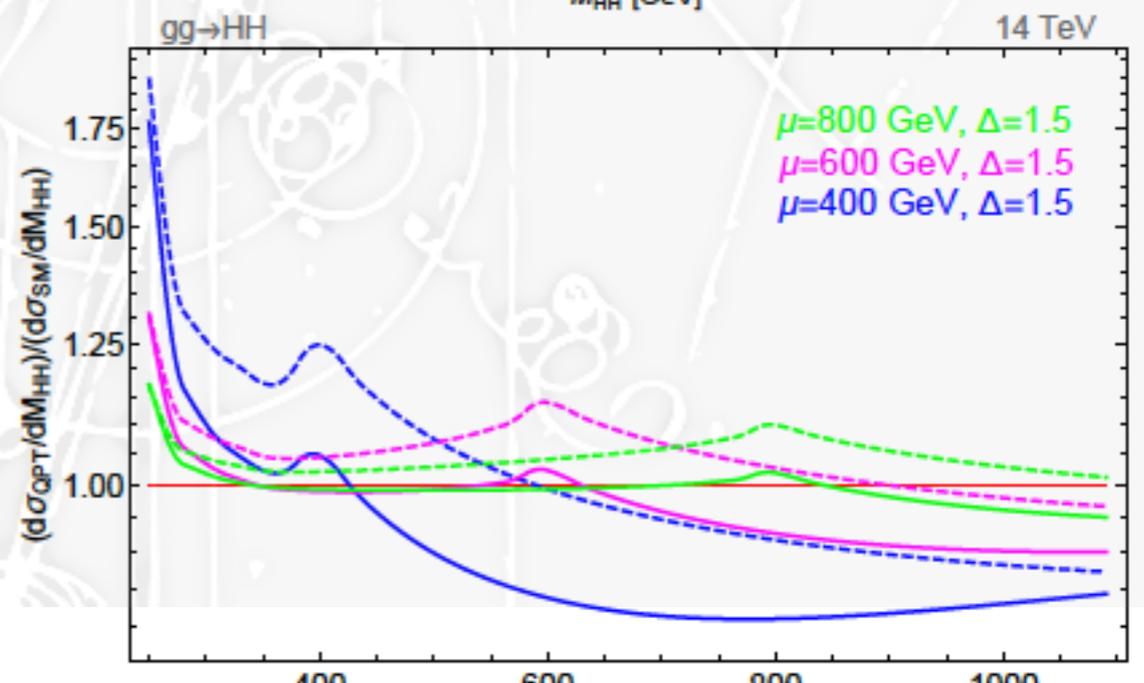
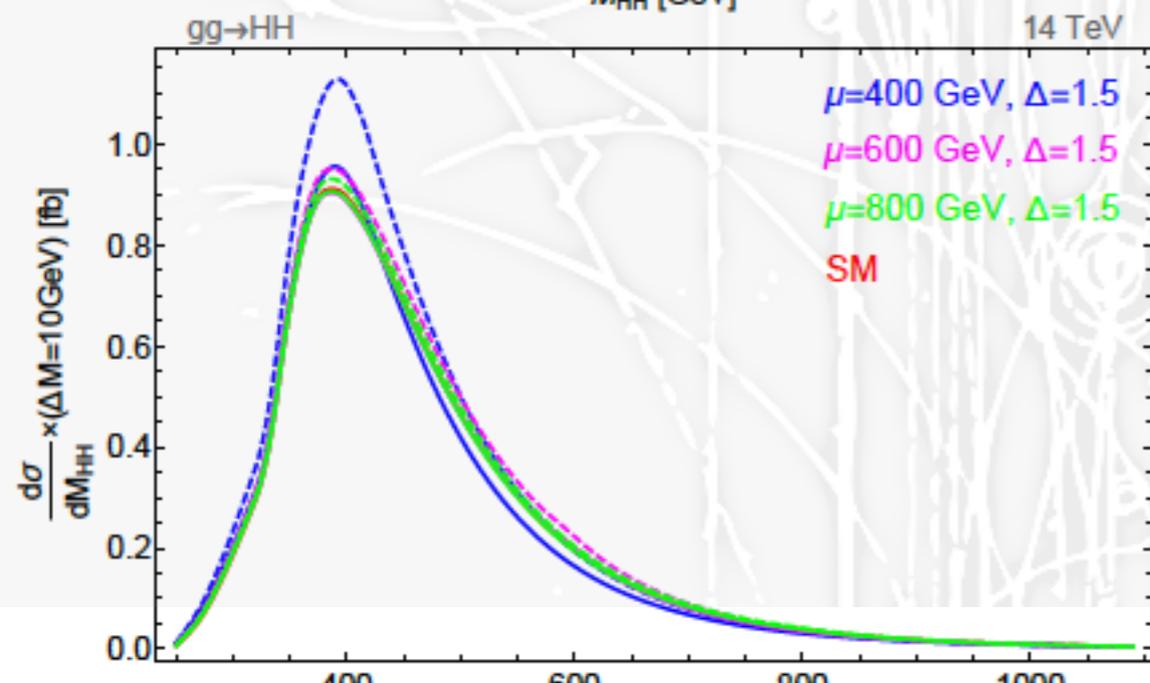
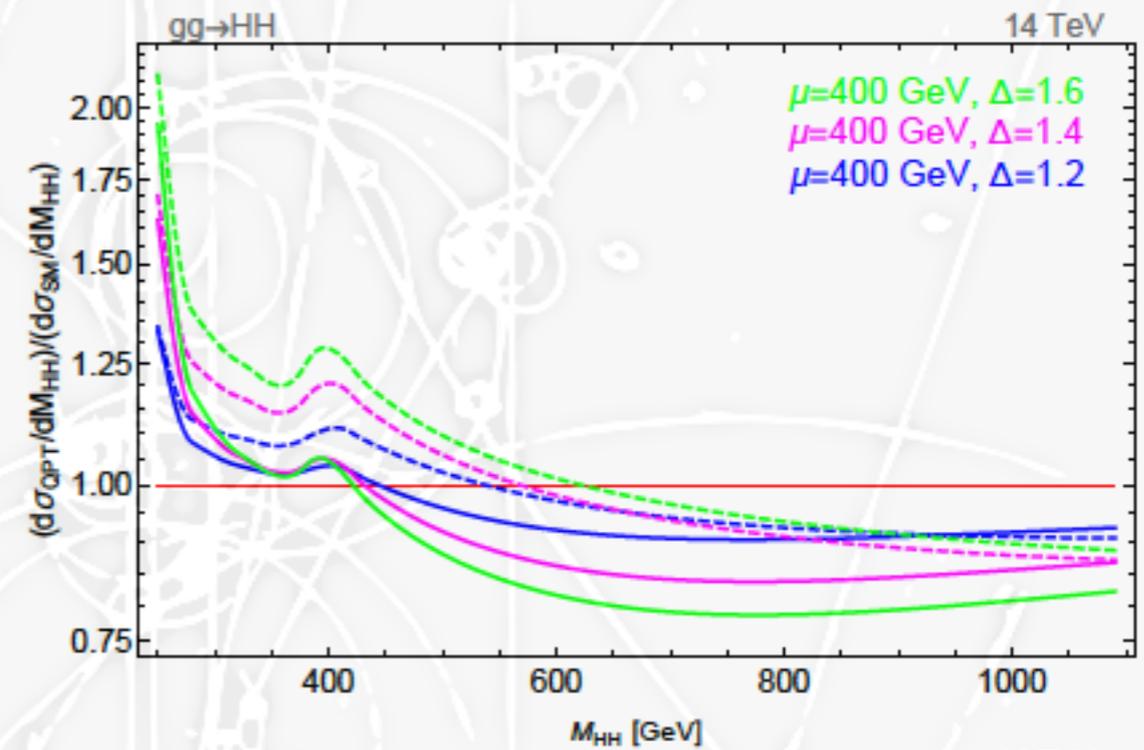
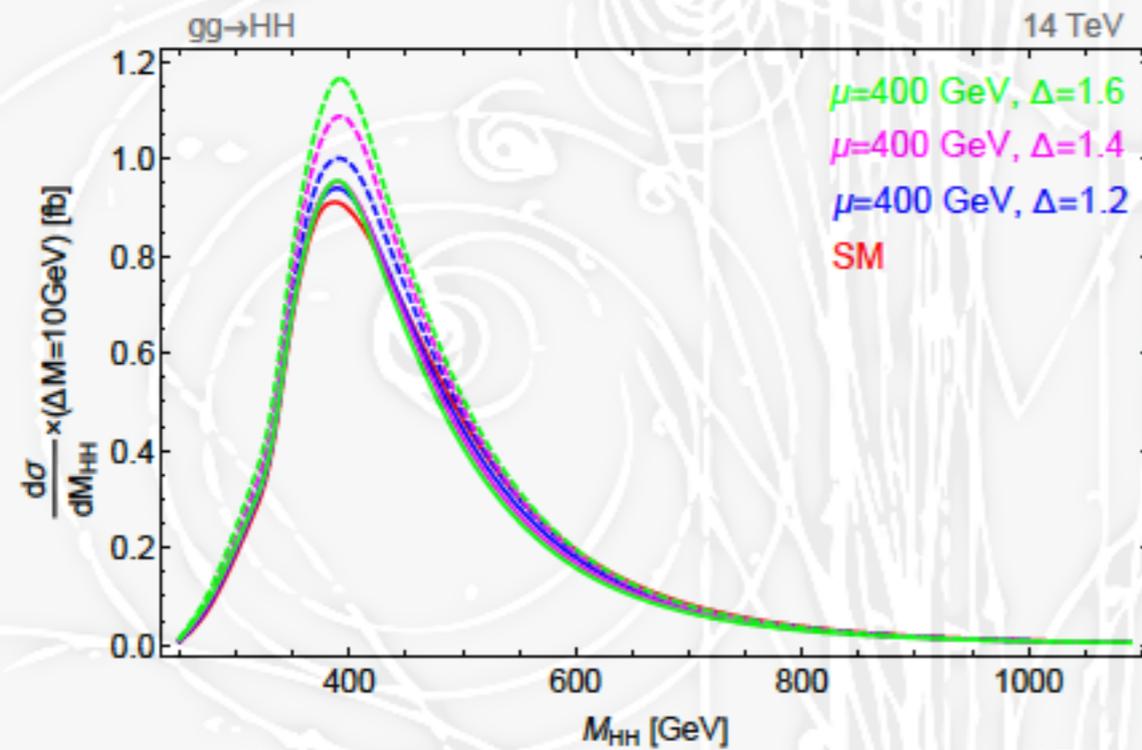
$$\mu = 400,$$

$\Delta = 1.2$ (Red) 1.4 (Blue), and 1.6 (Green).

Direct Signals (double Higgs)

❖ Double Higgs production

dashed lines correspond to the case where only the Higgs two-point function has non-trivial behavior inherited from a sector with strong dynamics.



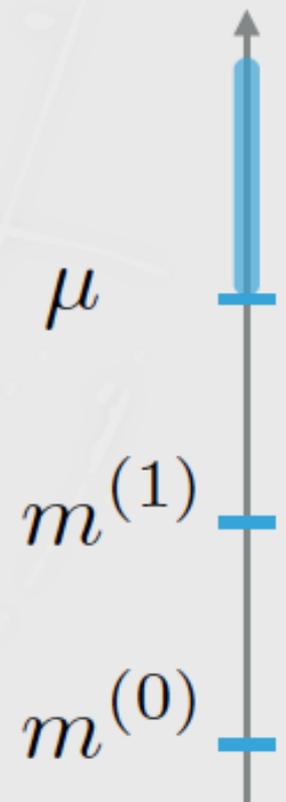
Quantum Critical Higgs

soft wall

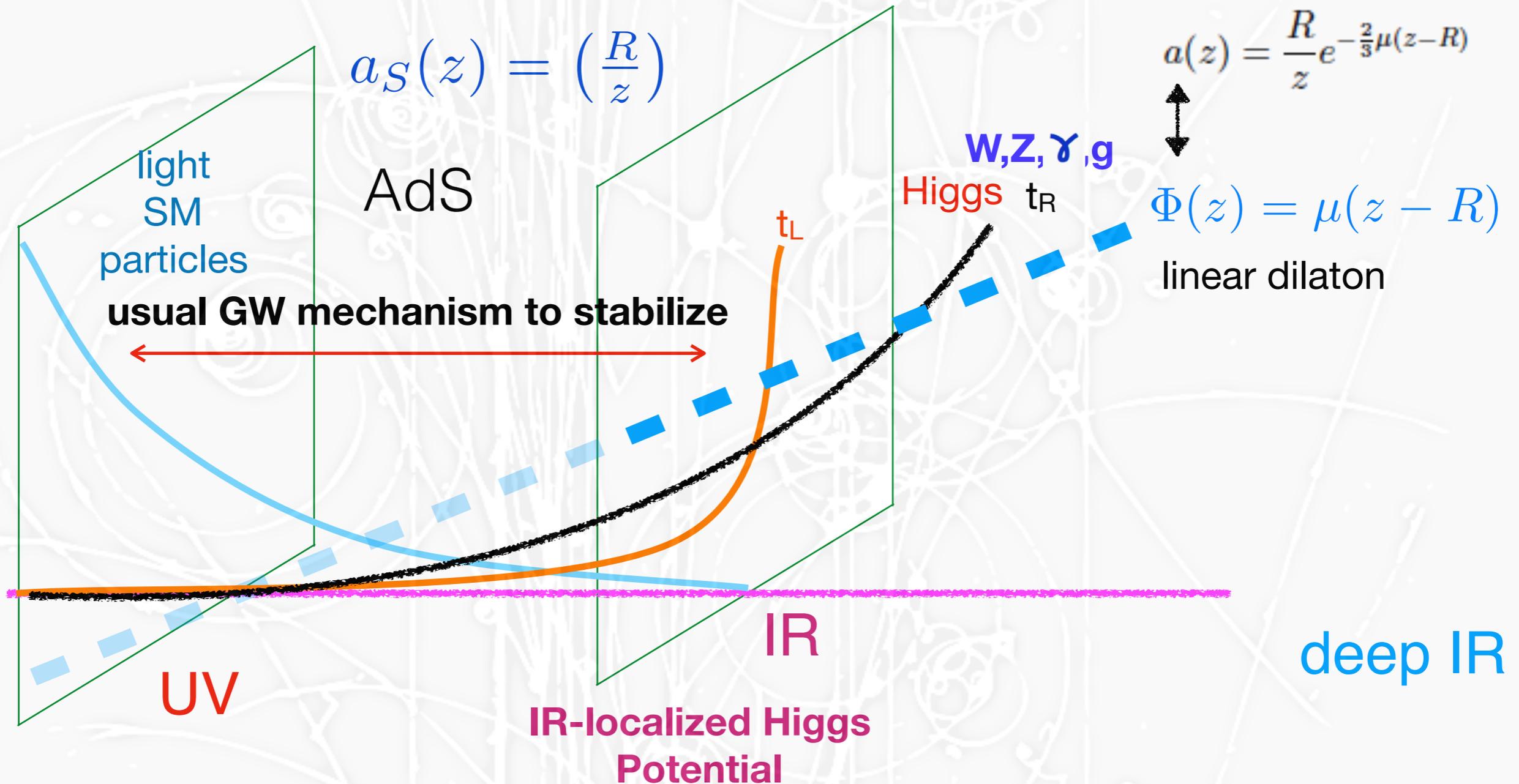


- ▶ soft wall cuts off CFT
- ▶ continuous KK spectrum above mass gap

- ▶ Note: UV brane is the only place to put Higgs quartic, Higgs is fundamental \Rightarrow fine-tuning

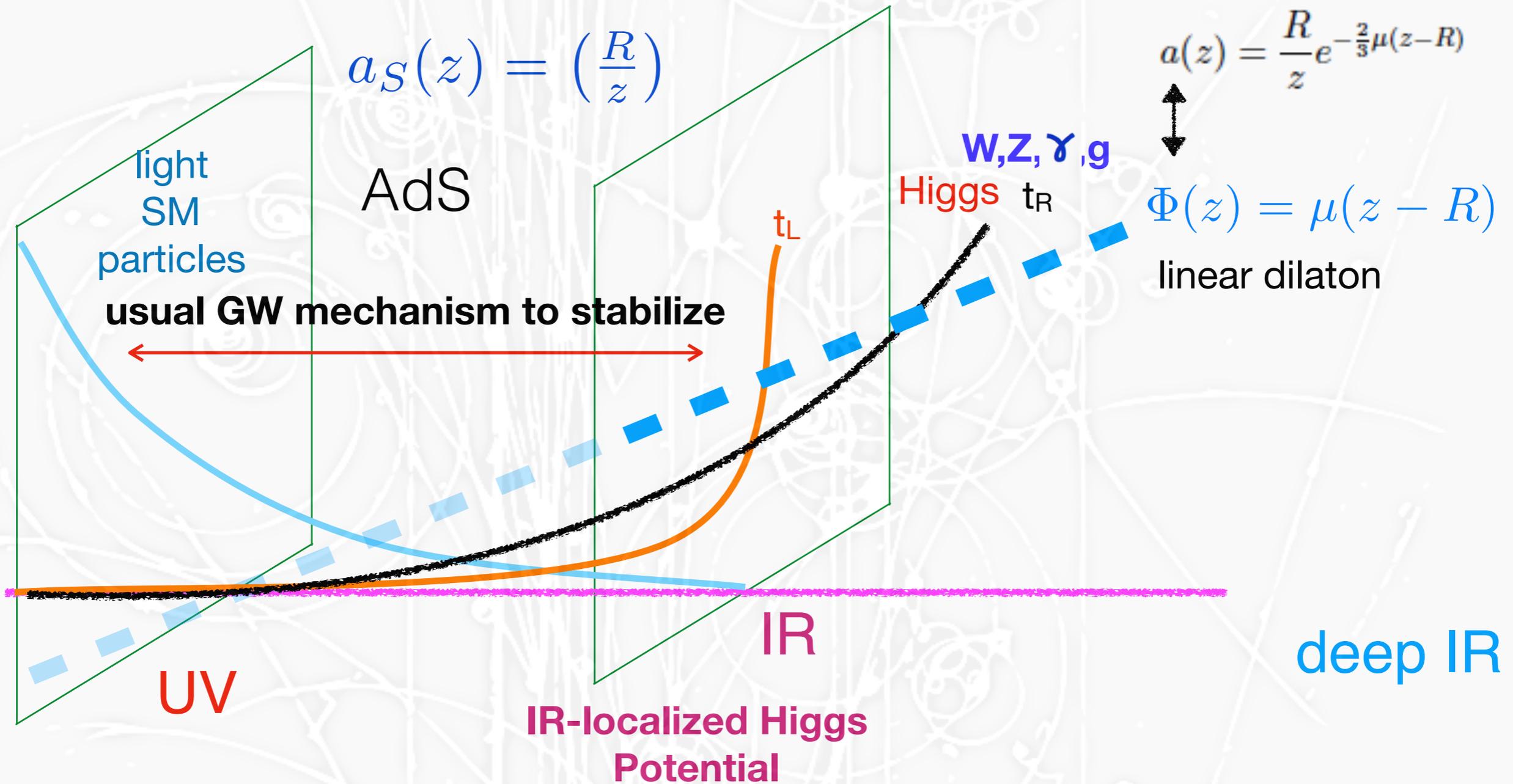


A Natural Quantum Critical Higgs: 5D linear dilaton



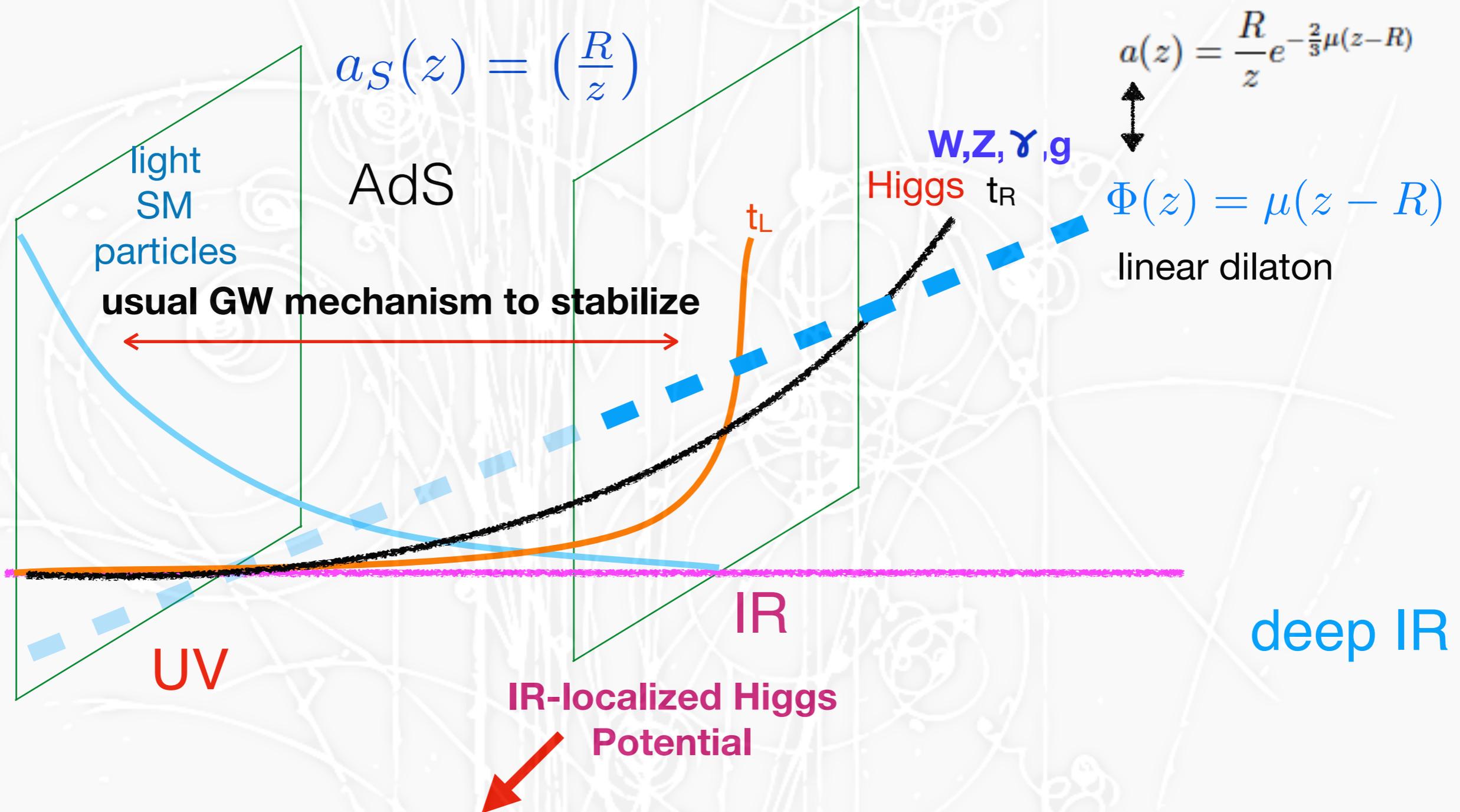
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Higgs arises from CFT with a domain wall (IR brane)



A Natural Quantum Critical Higgs: 5D linear dilaton

Higgs arises from CFT with a domain wall (IR brane)



taking a pole (physical Higgs) out of CFT
 => arises as a composite bound state of CFT

A “more” Natural model: Linear Dilaton

$$ig_5 \int_R^{R'} A_5 dz$$

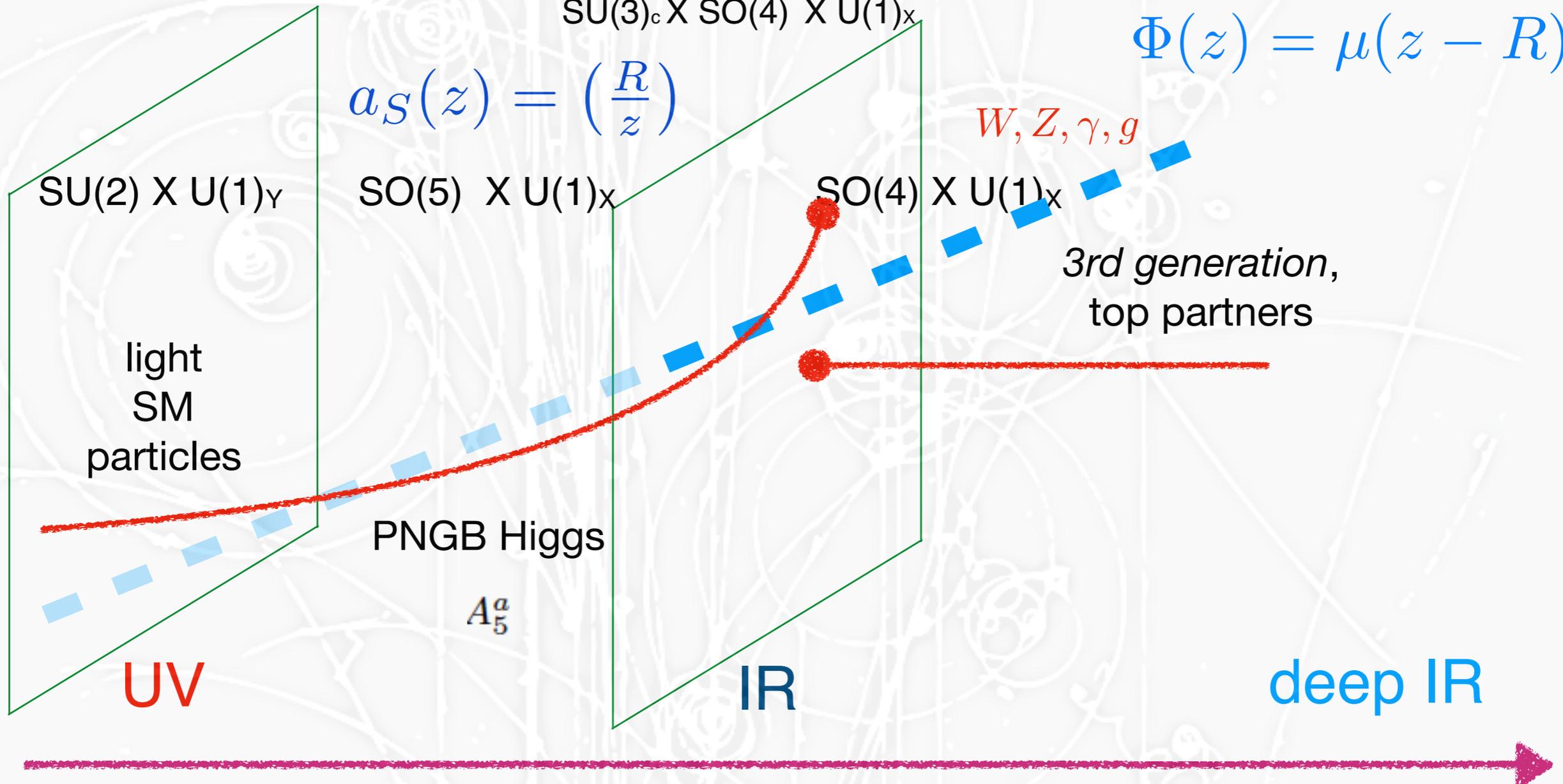
bulk gauge symmetry
broken down to

$$SU(3)_c \times SO(4) \times U(1)_x$$

linear dilaton:

$$\Phi(z) = \mu(z - R)$$

$$a_S(z) = \left(\frac{R}{z}\right)$$



theory gets closed to a fixed point, but then gets a mass gap

A “more” Natural model: Linear Dilaton

PNGB Higgs: Wilson line with A_5 (BC on IR brane)

$$ig_5 \int_R^{R'} A_5 dz$$

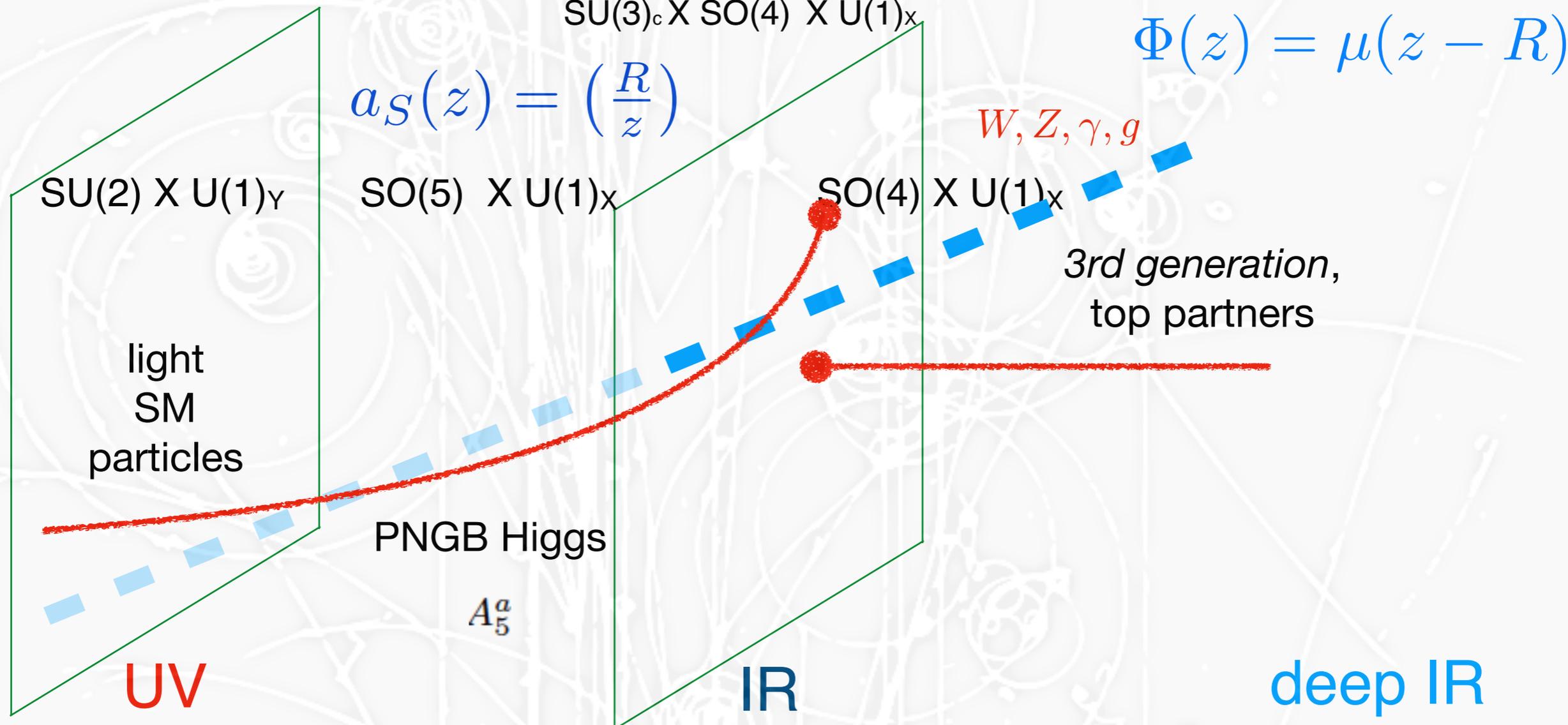
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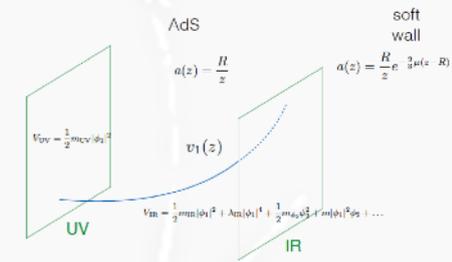
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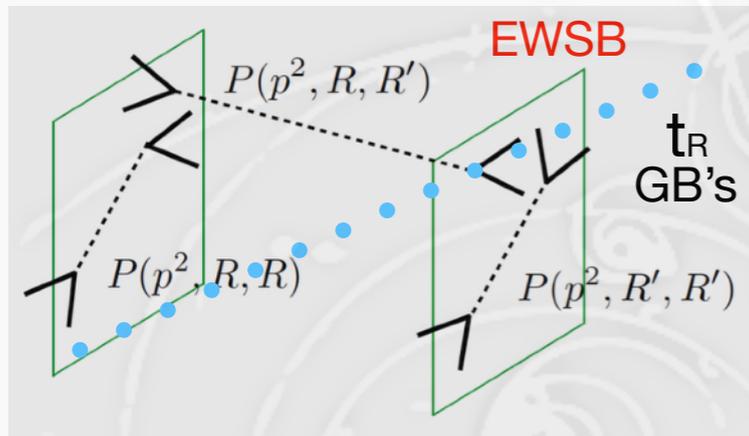
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Continuum Naturalness?

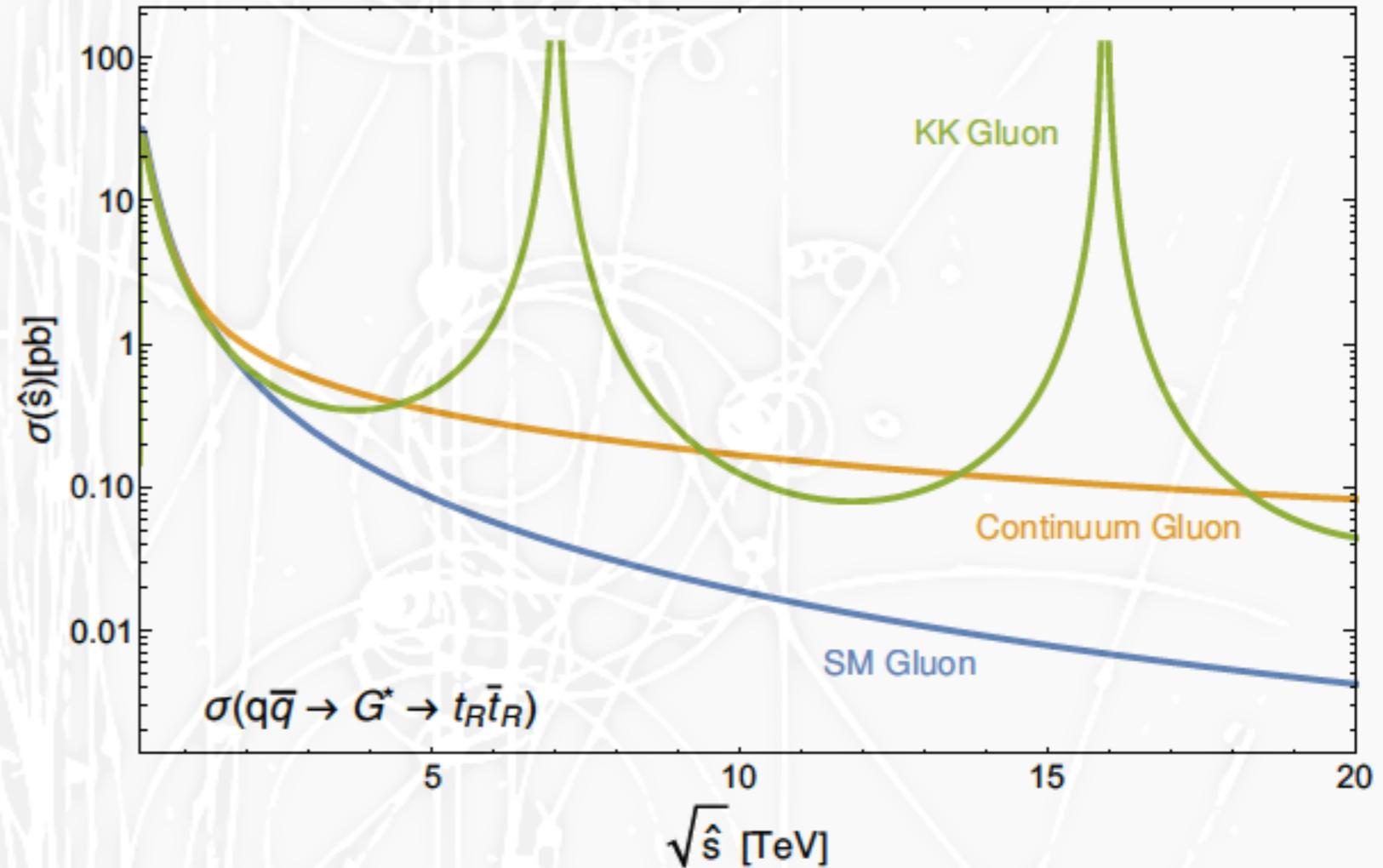
Csaki, Lombardo, Lee, SL, Telem



- ◆ New Physics (e.g. Top partner) appear solely as a continuum
 - KK gluon / colored ρ_c

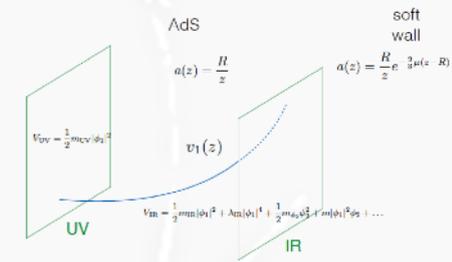


$$\mathcal{L}_E = a(z) e^{-\frac{4}{3}\mu(z-R)} \left[\frac{1}{4} F^{MN} F_{MN} \right]$$

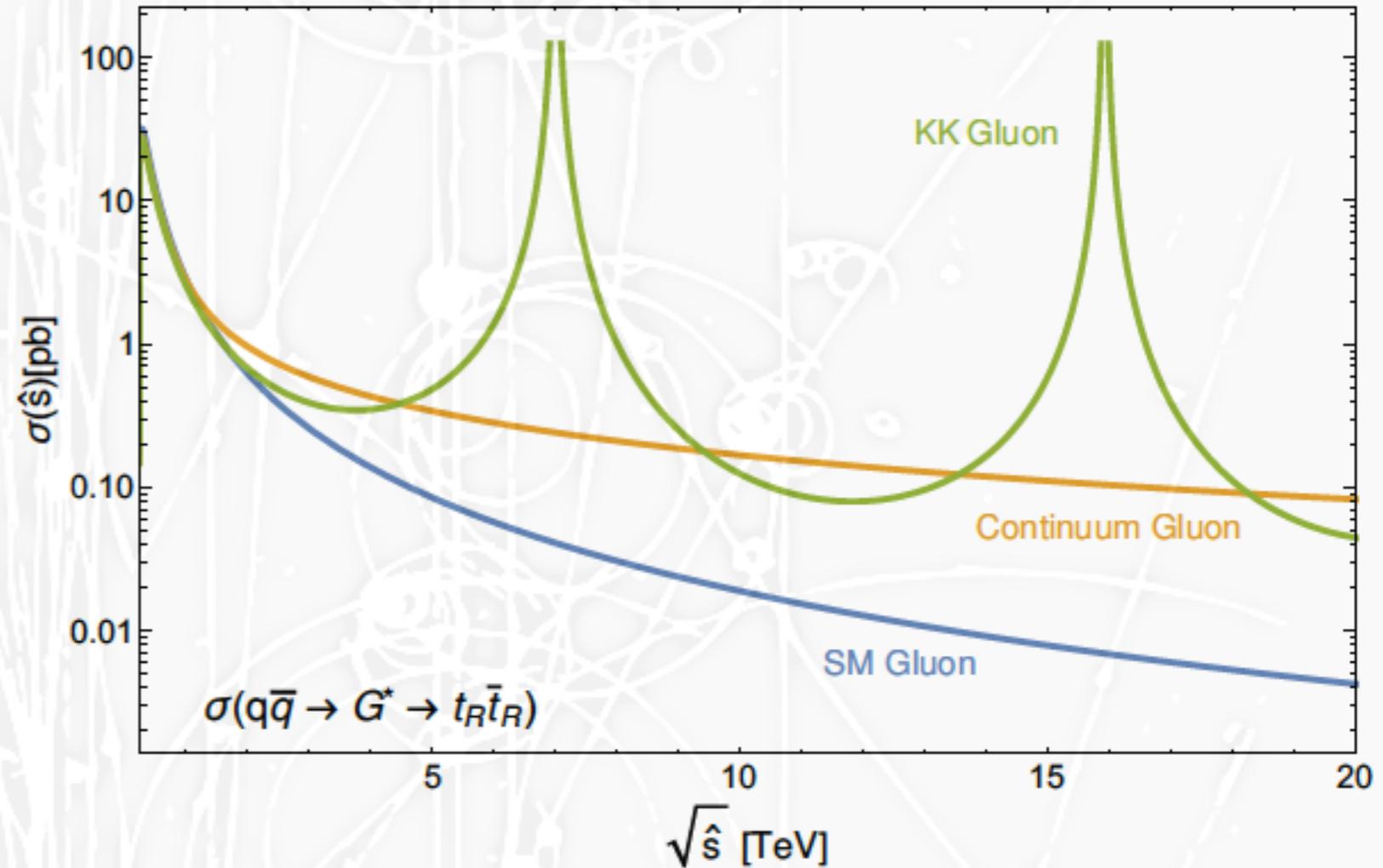
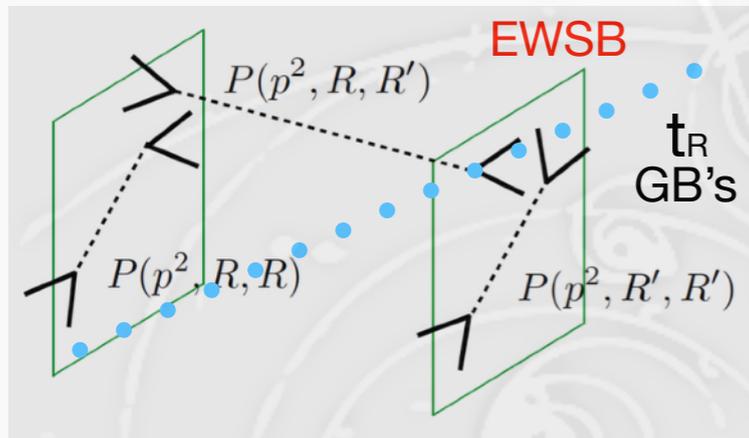


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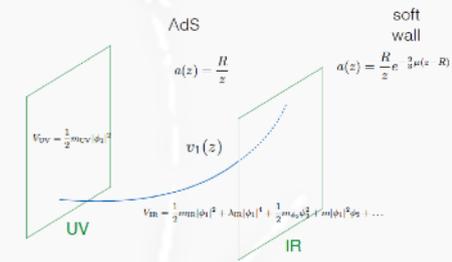
$$-\hat{A}''(z) + V_{\text{eff}}(z)\hat{A}(z) = p^2 \hat{A}(z)$$

$$\hat{A}(z) = \sqrt{\frac{R}{z}} e^{-\mu(z-R)} A(z)$$

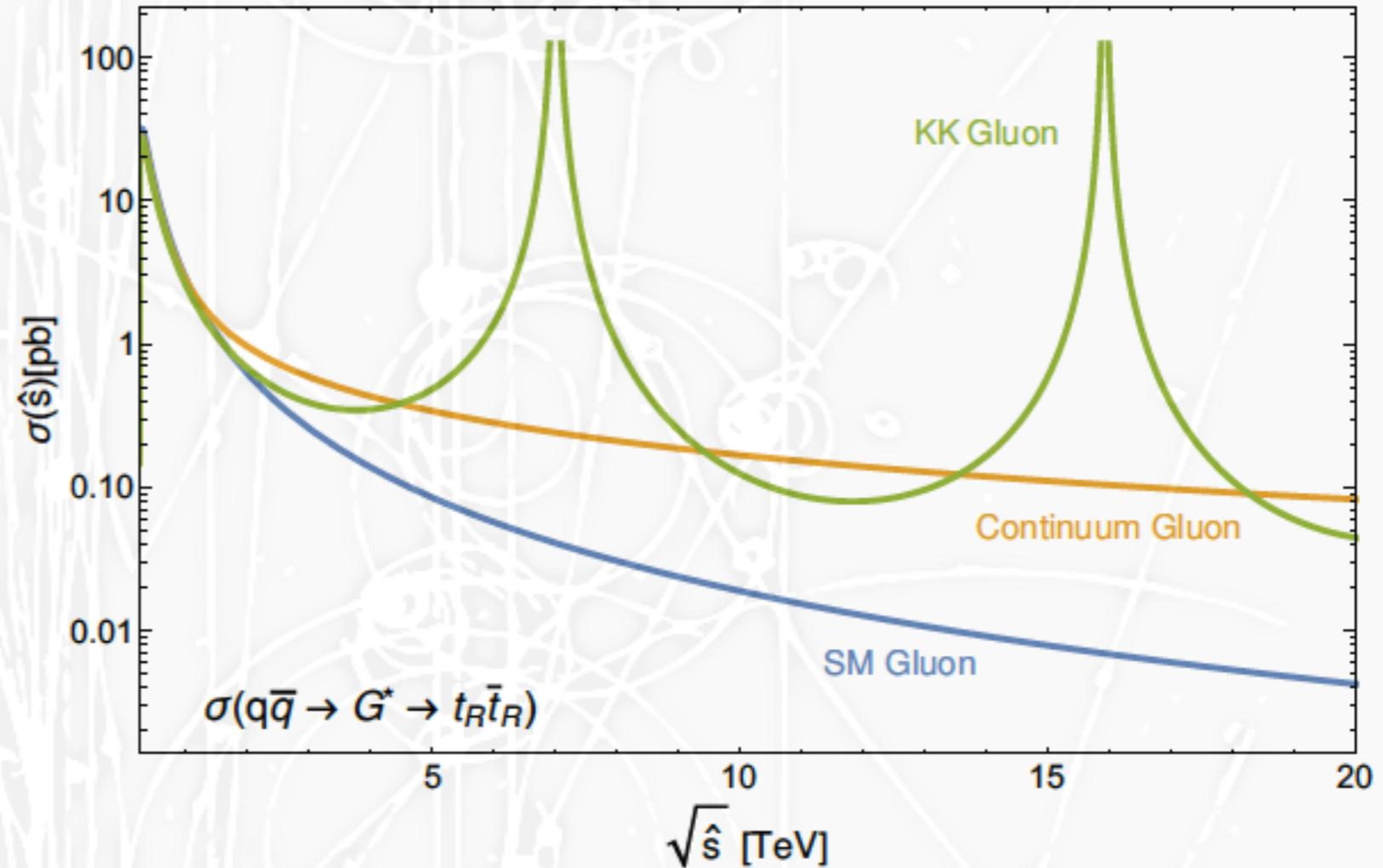
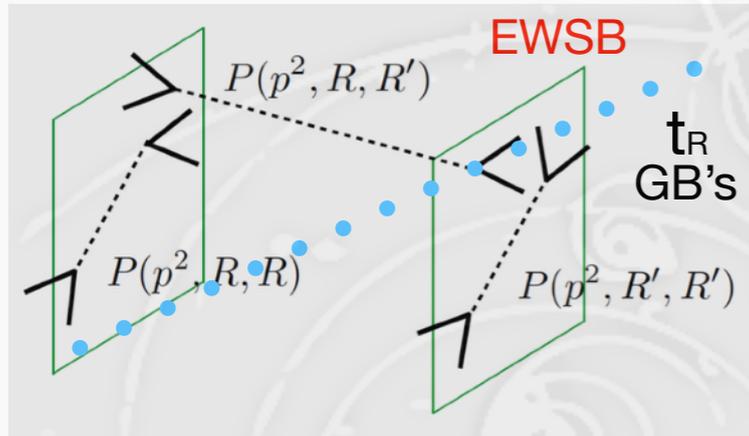
$$V_{\text{eff}}(z) = \mu^2 + \frac{\mu}{z} + \frac{3}{4z^2}$$

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Csaki, Lombardo, Lee, SL, Telem



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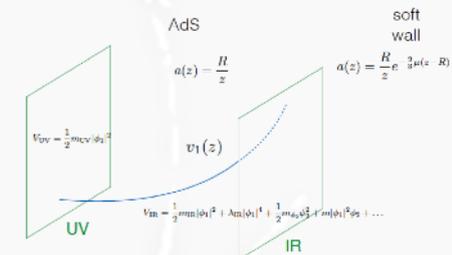
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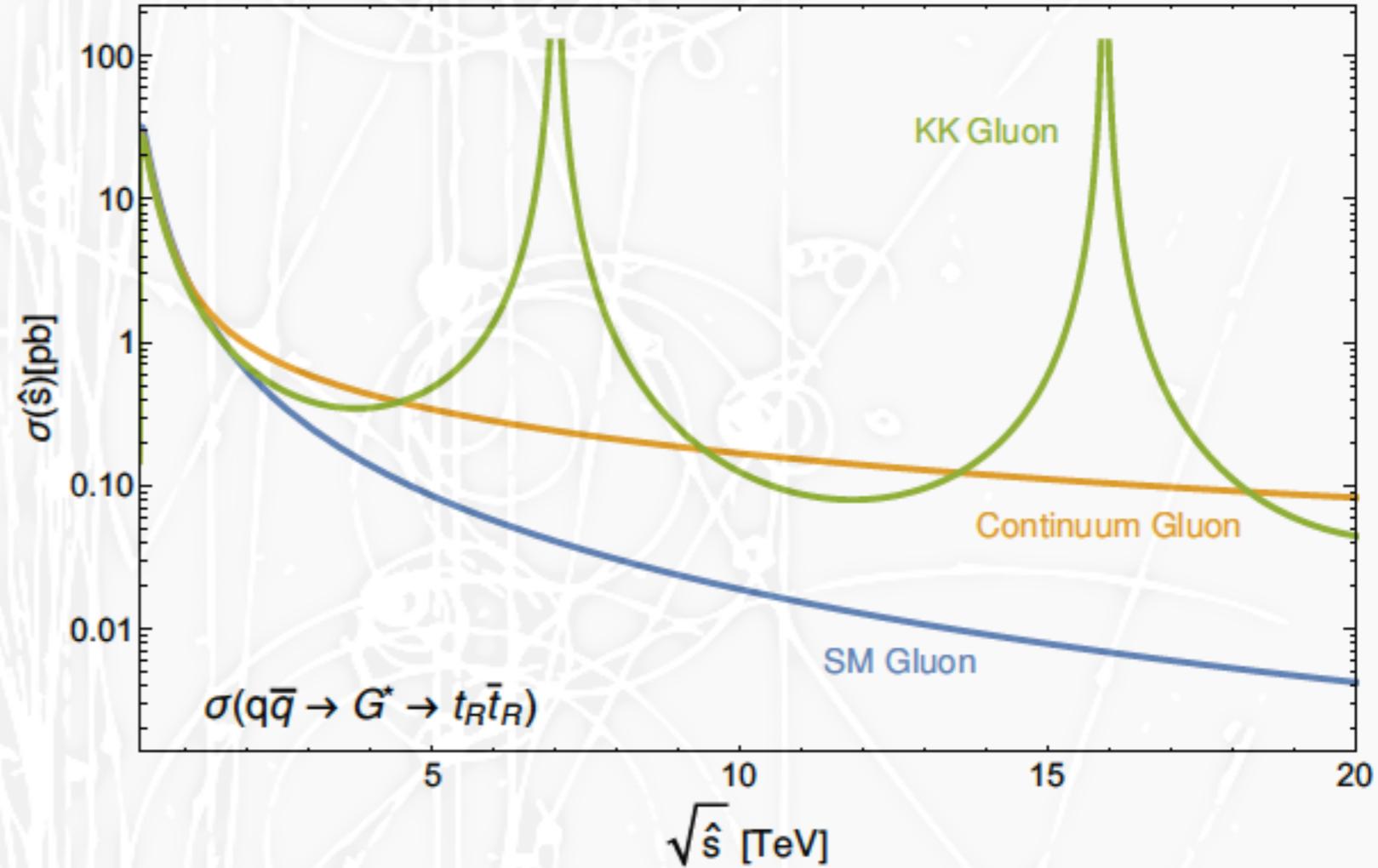
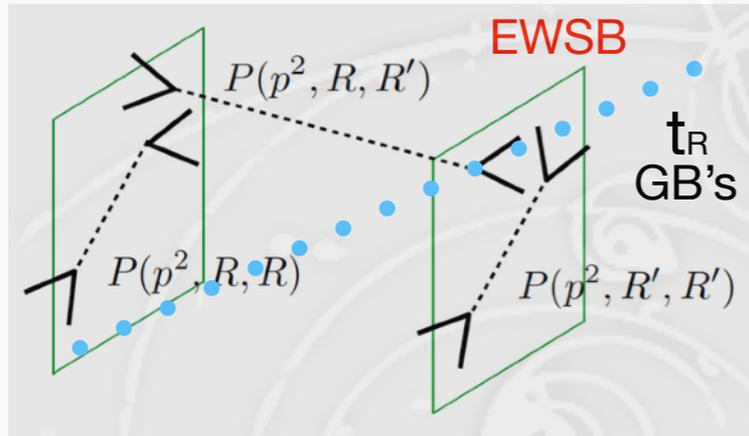
$$V_{\text{eff}}(z \rightarrow \infty) = \mu^2$$

Continuum Naturalness?

Csaki, Lombardo, Lee, SL, Telem



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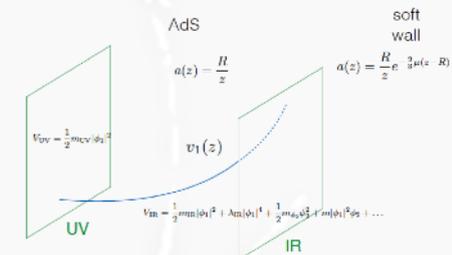
$$A(z) = A \sqrt{\frac{z}{R}} e^{\mu(z-R)} W\left(-\frac{\mu}{2\Delta}, 1; 2\Delta z\right) \quad \Delta = \sqrt{\mu^2 - p^2}$$

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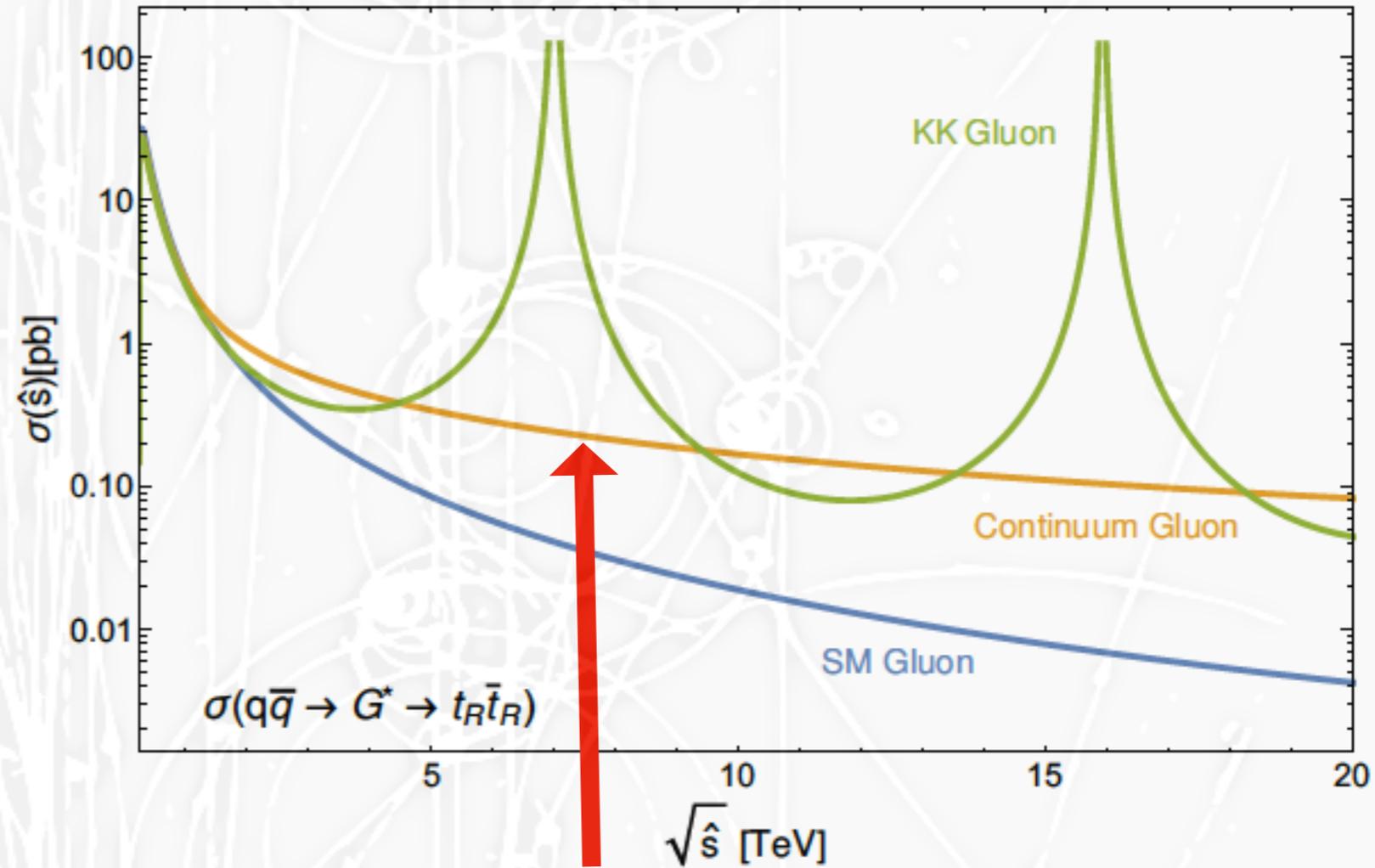
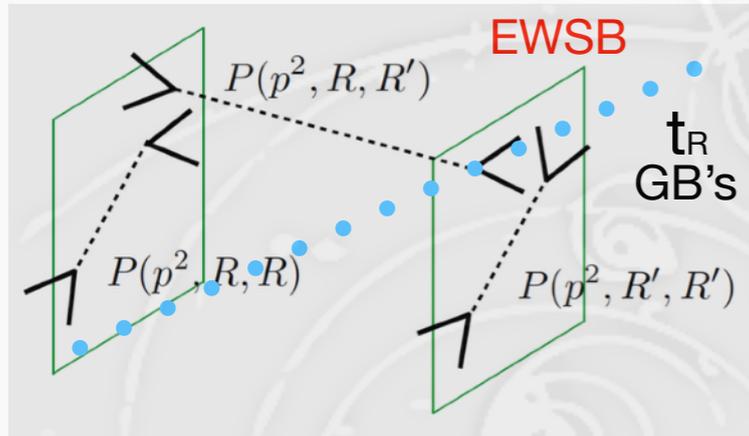
$$\rho(s) = \frac{1}{\pi} \lim_{z \rightarrow 0} \text{Im} \frac{A(z)}{A'(z)} = \frac{1}{2\pi s} \left[1 + i\psi \left(\frac{1}{2} + \frac{\mu}{2\Delta} \right) - i\psi \left(\frac{1}{2} - \frac{\mu}{2\Delta} \right) \right]$$

Continuum Naturalness?

Csaki, Lombardo, Lee, SL, Telem



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 - KK gluon / colored ρ_c



New Physics is hidden in the tail region!!

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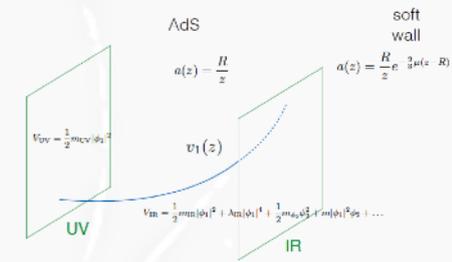
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Continuum Naturalness?

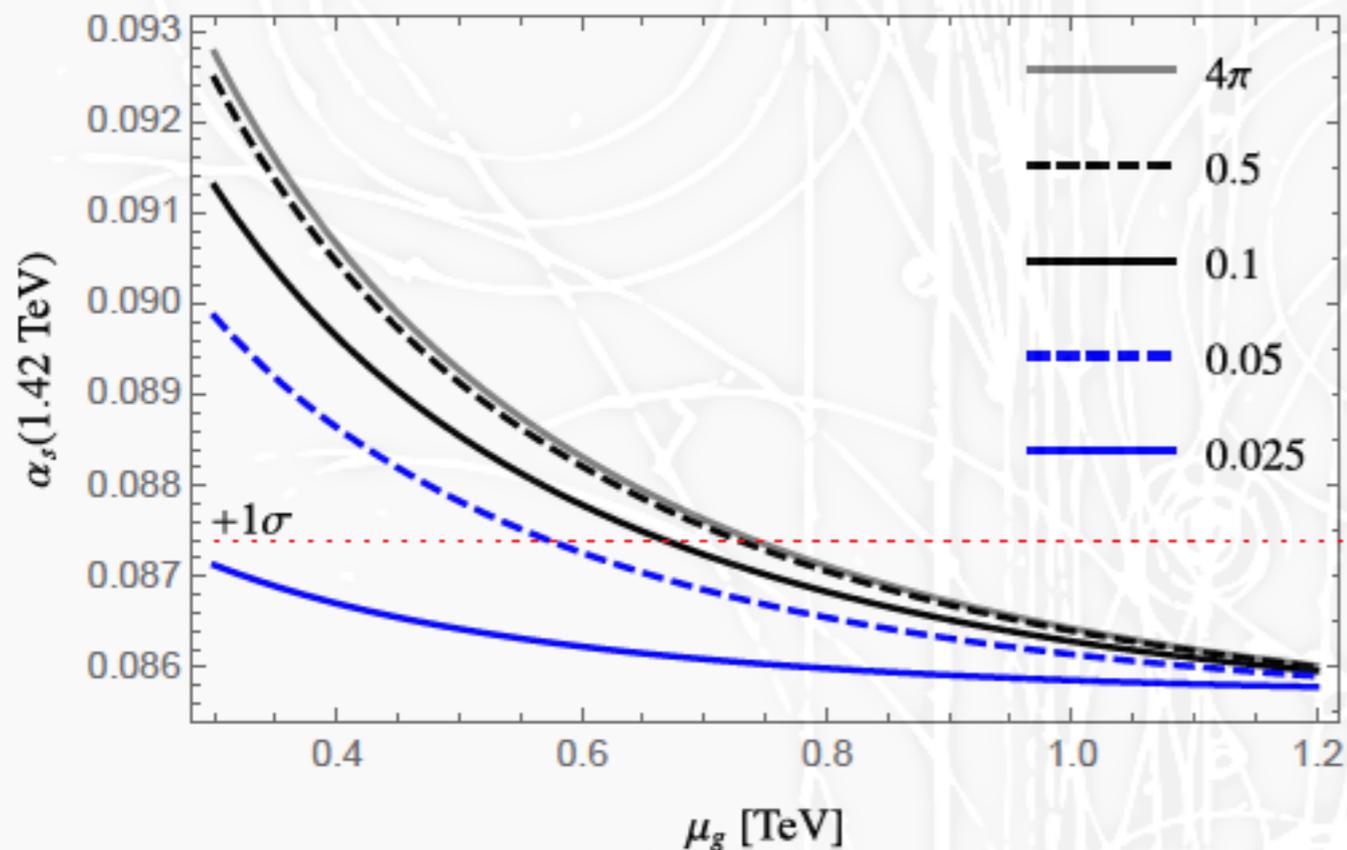
Csaki, Lombardo, Lee, SL, Telem



- ◆ New Physics (e.g. Top partner) appear solely as a continuum
 - **KK gluon / colored octet example: running of strong coupling**

e.g. CMS bound: α_s up to $Q \sim 1.42$ TeV

$$\frac{1}{g^2(Q)} = \frac{1}{g_5^2} \int_R^{1/Q} dz a(z) + \frac{1}{g_{UV}^2} - \frac{b_{UV}}{8\pi^2} \log\left(\frac{1}{RQ}\right)$$



$\mu_g > 600 - 700$ GeV

Continuum Top Partners (4D CFT picture)

Csaki, Lombardo, Lee, SL, Telem; to appear soon

◆ MCHM (Agashe, Contino, Pomarol) \Rightarrow continuum version

- elementary fields which mix with the composite operators and the

form factors: $\mathcal{L}_{\text{top}} = \bar{t}_L \not{p} \Pi_L(p) t_L + \bar{t}_R \not{p} \Pi_R(p) t_R + \bar{t}_L M(p) t_R + h.c.$

- 2-point function $\langle tt \rangle$ is given by

$$-i\Pi_t(p) = \frac{1}{\not{p} - \frac{M(p)}{\sqrt{\Pi_L(p)\Pi_R(p)}}} \stackrel{\text{Källén-Lehmann}}{=} \int dm^2 \frac{\not{p} + m}{p^2 - m^2} \rho_t(m^2)$$

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- non-local effective action:

$$S_{\text{eff}} = \int d^4x d^4y \bar{\psi}(x) (i\not{\partial}_y - m) \Sigma(x - y) \psi(y)$$

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- gauge invariant way:

$$S_{\text{eff}} = \int \frac{d^4p d^4k}{(2\pi)^8} \bar{\psi}(k) (\not{p} - m) \Sigma(p^2) F(k - p, p)$$

$$\rho_h = \frac{1}{\pi} \text{Im} \Sigma^{-1}$$

$$F(x, y) = \mathcal{P} \exp \left(-igT^a \int_x^y A^a \cdot dw \right) \psi(y)$$

Continuum States

Csaki, Lombardo, Lee, SL, Telem

- ◆ To describe the continuum (for example Weyl fermions)

$$\mathcal{L}_\chi = -i\bar{\chi}\bar{\sigma}^\mu p_\mu \chi \quad \longrightarrow \quad \mathcal{L}_\chi^{\text{cont.}} = -i\bar{\chi} \frac{\bar{\sigma}^\mu p_\mu}{p^2 G(p^2)} \chi$$

- ◆ G proportional to the 2-point function

$$\langle \bar{\chi} \chi \rangle^{\text{cont}} = i\sigma^\mu p_\mu G(p^2)$$

- ◆ Poles correspond to particles, branch cuts to continuum.

Characterized information written in terms of spectral density

$$G(p^2) = \int_0^\infty \frac{\rho(s)}{s - p^2 + i\epsilon} ds, \quad \rho(s) = \frac{1}{\pi} \text{Im}G(s)$$

Continuum with mass gap

Csaki, Lombardo, Lee, SL, Telem

- ◆ Fermion EOM's in this background can be solved exactly

- ◆ Fermion Lagrangian in “string frame” $a_S(z) = \frac{R}{z}$

$$\mathcal{L}_S = e^{-2\Phi(z)} a_S^5(z) \left[a_S^{-1}(z) \mathcal{L}_{\text{kin}} + \frac{1}{R} (c + y\Phi(z)) (\psi\chi + \bar{\chi}\bar{\psi}) \right]$$



bulk Yukawa coupling between the dilaton and the bulk fermion

- ◆ Kinetic term conventional

$$\mathcal{L}_{\text{kin}} = -i\bar{\chi}\bar{\sigma}^\mu p_\mu\chi - i\psi\sigma^\mu p_\mu\bar{\psi} + \frac{1}{2} \left(\psi \overleftrightarrow{\partial}_5 \chi - \bar{\chi} \overleftrightarrow{\partial}_5 \bar{\psi} \right)$$

- ◆ Go to Einstein frame to see physics best $a(z) = a_S(z) e^{-\frac{2}{3}\Phi(z)}$

$$\mathcal{L}_E = a^4(z) \mathcal{L}_{\text{kin}} + a^5(z) \frac{\hat{c}(z)}{R} (\psi\chi + \bar{\chi}\bar{\psi})$$

- ◆ Effective mass parameter $\hat{c}(z) \equiv (c + y\Phi(z)) e^{\frac{2}{3}\Phi(z)}$

Continuum Top Partners

Csaki, Lombardo, Lee, SL, Telem

◆ 5D holographic model with a linear dilaton

$$S_f = \int d^5x a(z)^4 \bar{\Psi} \left(i\gamma^M \partial_M + 2i \frac{a'(z)}{a(z)} \gamma^5 - \frac{a(z)c(z)}{R} \right)$$

$$c(z) = (c + \mu(z - R)) e^{\frac{2}{3}\mu(z-R)}$$
$$-i\bar{\sigma}^\mu \partial_\mu \chi - \partial_5 \bar{\psi} - 2 \frac{a'}{a} \bar{\psi} + \frac{ac}{R} \bar{\psi} = 0$$
$$-i\sigma^\mu \partial_\mu \bar{\psi} + \partial_5 \chi + 2 \frac{a'}{a} \chi + \frac{ac}{R} \chi = 0.$$

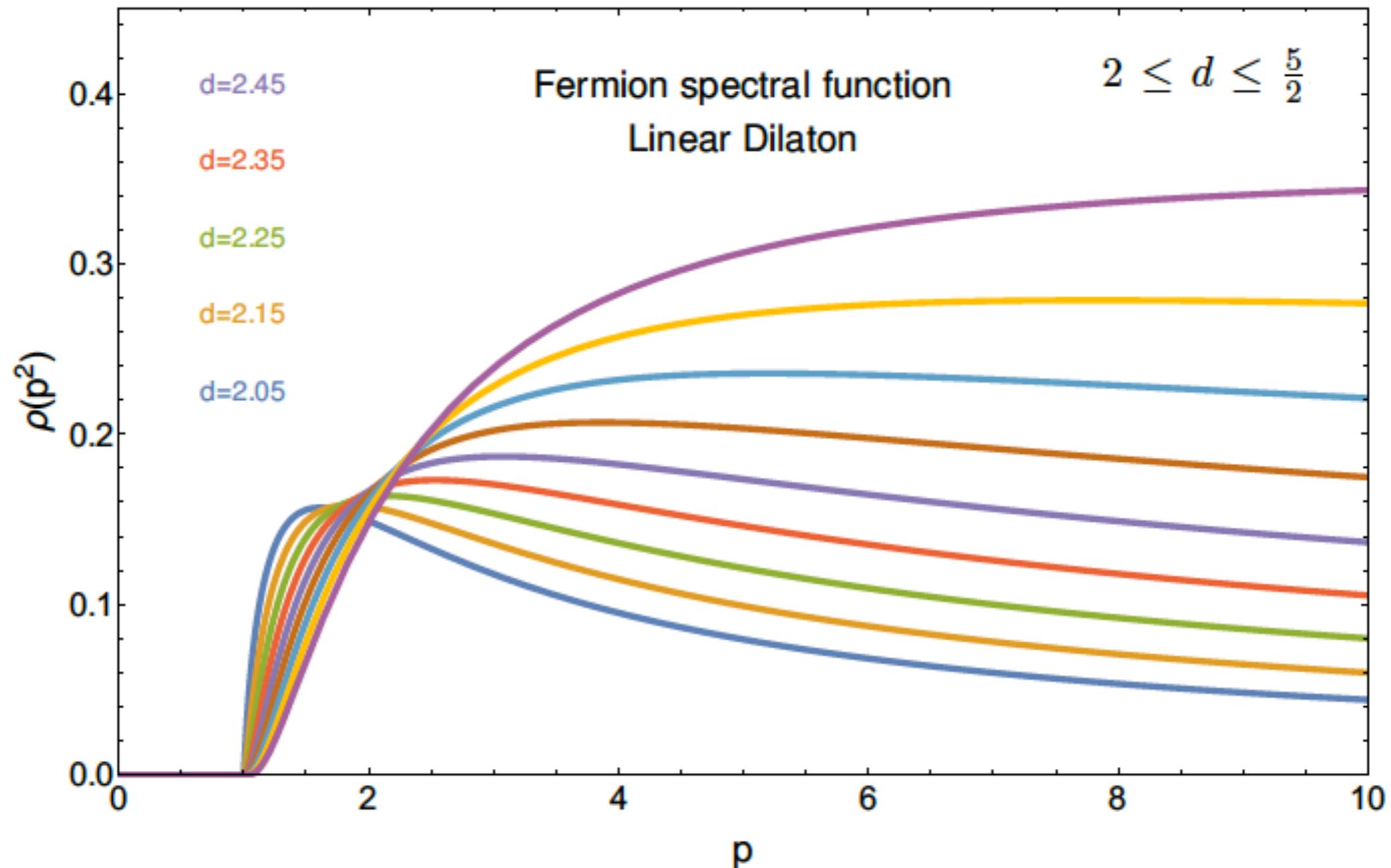
$$\chi = g(z)\chi(z)$$
$$\bar{\psi}(z) = f(z)\bar{\psi}(x)$$

$$g(z) = a^{-2} \left[A M \left(\kappa, 1/2 + c - R\mu, 2z\sqrt{\mu^2 - m^2} \right) \right. \\ \left. + B W \left(\kappa, 1/2 + c - R\mu, 2z\sqrt{\mu^2 - m^2} \right) \right],$$
$$f(z) = a^{-2} \left[C M \left(\kappa, 1/2 - c + R\mu, 2z\sqrt{\mu^2 - m^2} \right) \right. \\ \left. + D W \left(\kappa, 1/2 - c + R\mu, 2z\sqrt{\mu^2 - m^2} \right) \right],$$

Continuum Top Partners

Csaki, Lombardo, Lee, SL, Telem

- ◆ 5D holographic model with a linear dilaton



- profile of continuum depends on the scaling dimension of the fields

A Realistic Model

◆ Need the usual Composite Higgs setup in addition

◆ Bulk gauge group $G = SO(5) \times U(1)_X \rightarrow SO(4) \times U(1)_X$
 breaking on IR brane via BCs

◆ On UV brane, $G = SO(5) \times U(1)_X \rightarrow SU(2)_L \times U(1)_Y$
 $Y = T_R^3 + X$

◆ Wilson line for Higgs: $ig_5 \int_R^{R'} A_5 dz$
 (No other physical Wilson line beyond IR brane)

◆ Bulk fermions

$$Q_L(\mathbf{5})_{\frac{2}{3}} \rightarrow q_L(\mathbf{2})_{\frac{1}{6}} + \tilde{q}_L(\mathbf{2})_{\frac{7}{6}} + y_L(\mathbf{1})_{\frac{2}{3}},$$

$$T_R(\mathbf{5})_{\frac{2}{3}} \rightarrow q_R(\mathbf{2})_{\frac{1}{6}} + \tilde{q}_R(\mathbf{2})_{\frac{7}{6}} + t_R(\mathbf{1})_{\frac{2}{3}},$$

$$B_R(\mathbf{10})_{\frac{2}{3}} \rightarrow q'_R(\mathbf{2})_{\frac{1}{6}} + \tilde{q}'_R(\mathbf{2})_{\frac{7}{6}} + x_R(\mathbf{3})_{\frac{2}{3}} + y_R(\mathbf{1})_{\frac{7}{6}} + \tilde{y}_R(\mathbf{1})_{\frac{1}{6}} + b_R(\mathbf{1})_{-\frac{1}{3}}$$

A Realistic Model

- ◆ To generate Yukawa couplings, need localized mass terms

$$S_{\text{IR}} = \int d^4x \sqrt{g_{\text{ind}}} \left[M_1 \bar{z}_L t_R + M_4 (\bar{q}_L q_R + \bar{\tilde{q}}_L \tilde{q}_R) + M_b (\bar{q}_L q'_R + \bar{\tilde{q}}_L \tilde{q}'_R) \right]$$

- ◆ A realistic benchmark point

$$R/R' = 10^{-16}, \quad 1/R' = 2.81 \text{ TeV}, \quad \mu = 1 \text{ TeV}, \quad y = 1.75,$$

$$r = 0.975, \quad \sin \theta = 0.39,$$

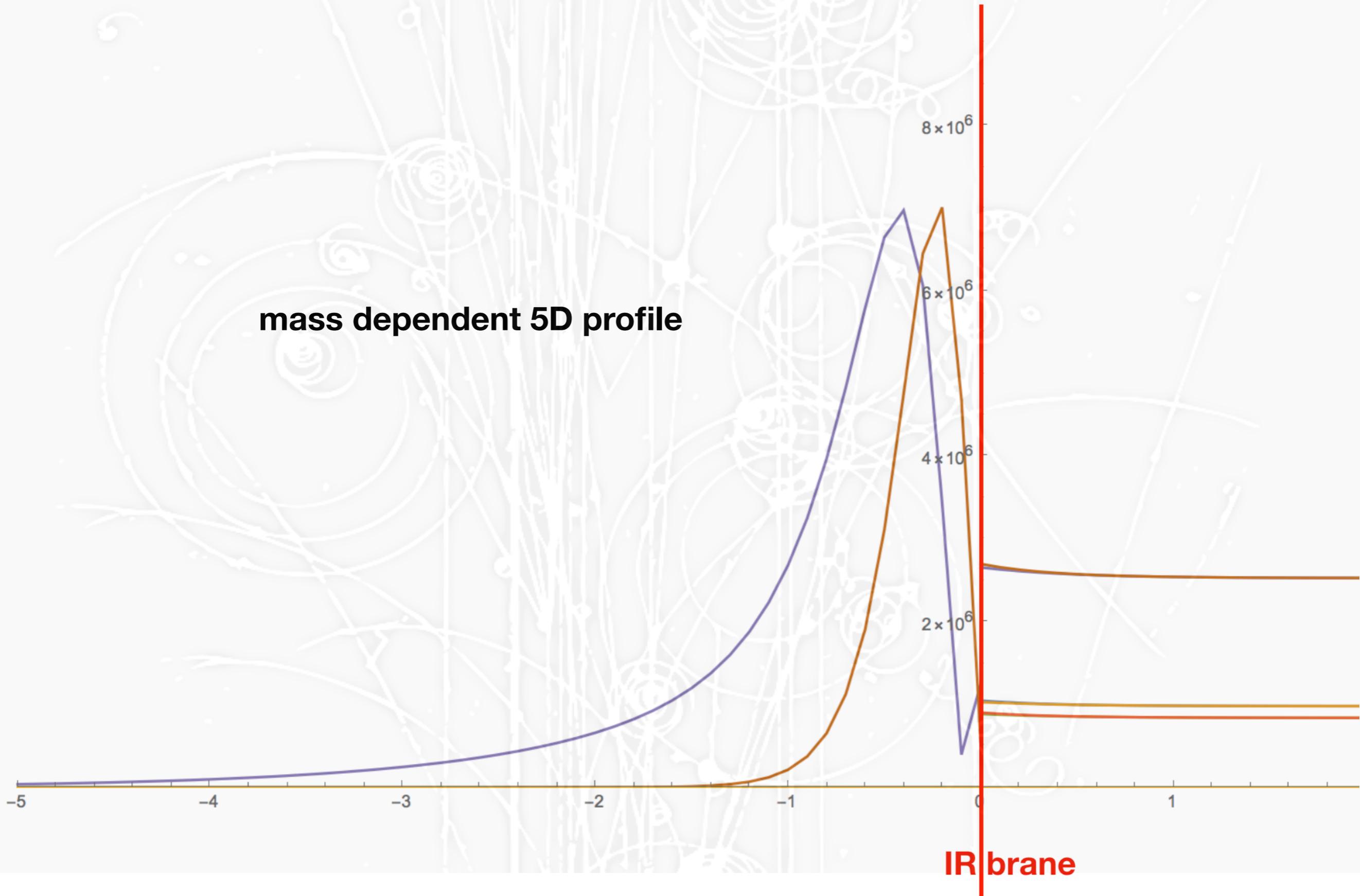
$$c_Q = 0.2, \quad c_T = -0.22, \quad c_B = -0.03,$$

$$M_1 = 1.2, \quad M_4 = 0, \quad M_b = 0.017.$$

- ◆ All SM parameters correctly reproduced with top slightly a bit light
- ◆ Choose safe point where gauge cont. at 1 TeV, fermion at 1.75 TeV

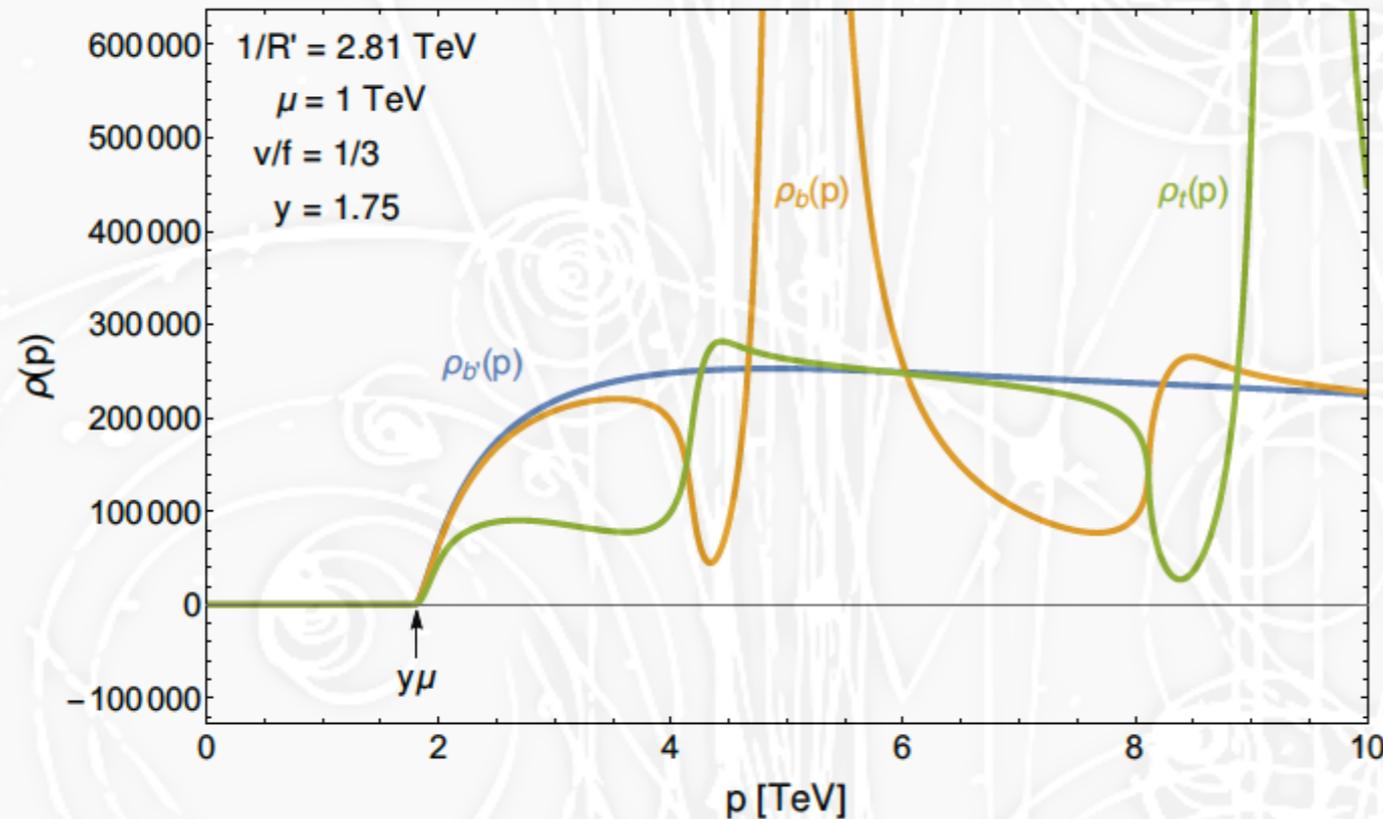
A Realistic Model

mass dependent 5D profile

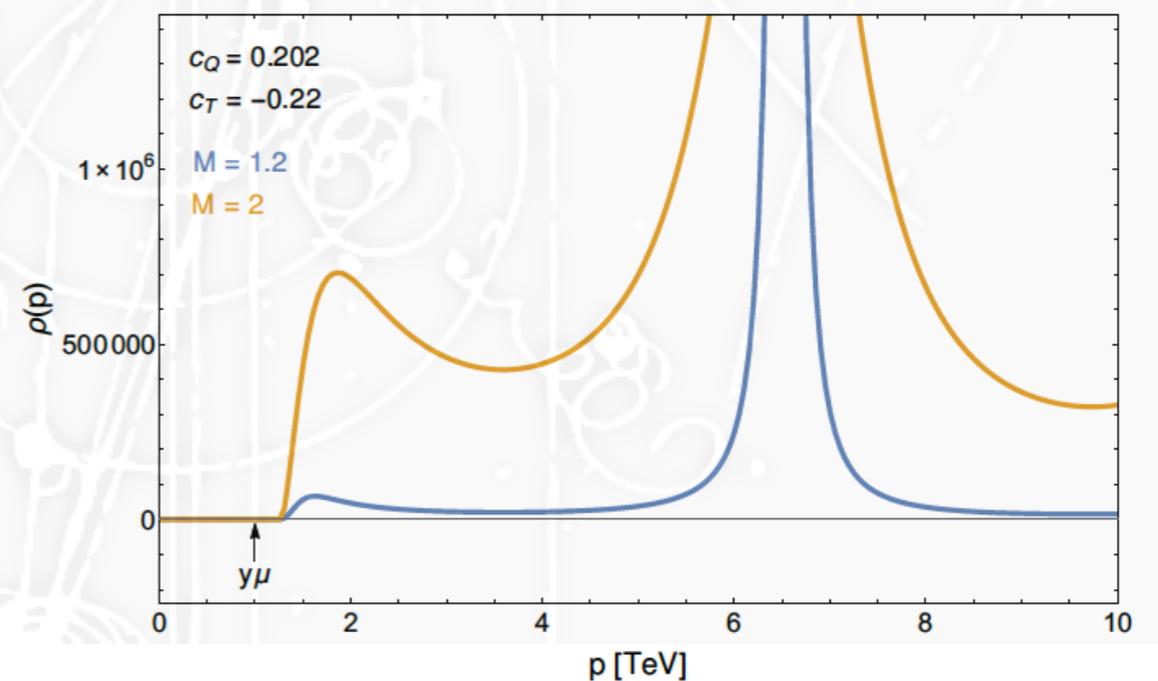
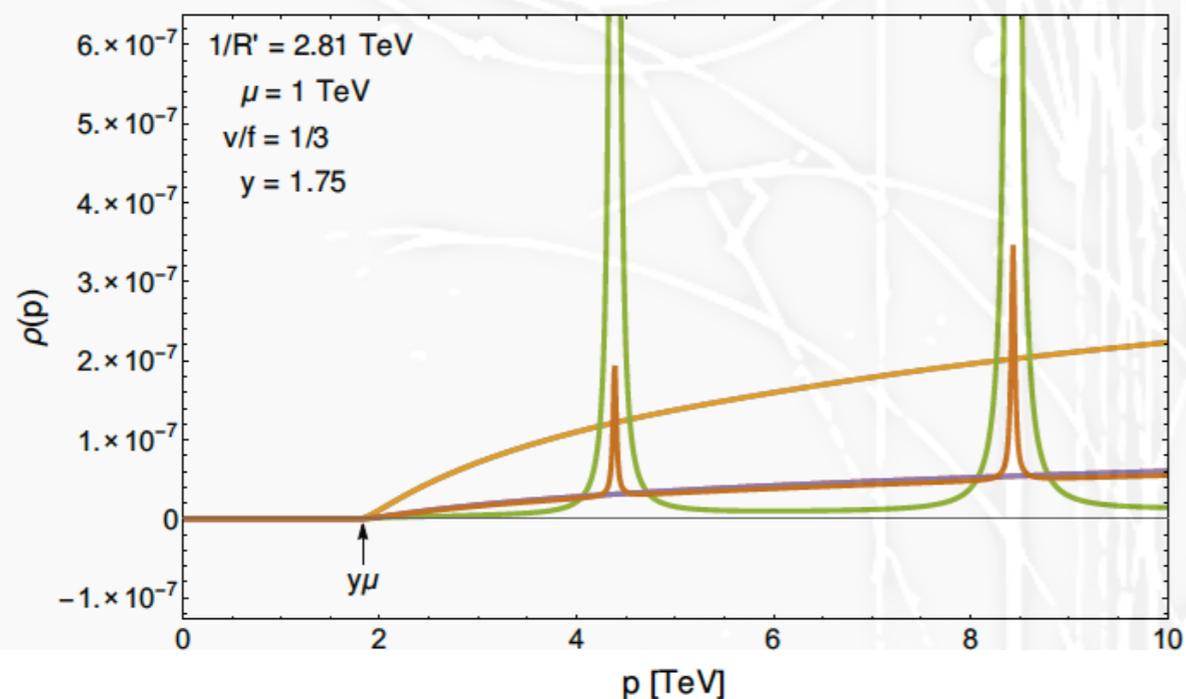


Fermionic Spectrum

- ◆ Fermion spectral densities. 3rd generation all very broad



- ◆ Exotic top partners- model dependent, could be probed as resonance at 100TeV collider

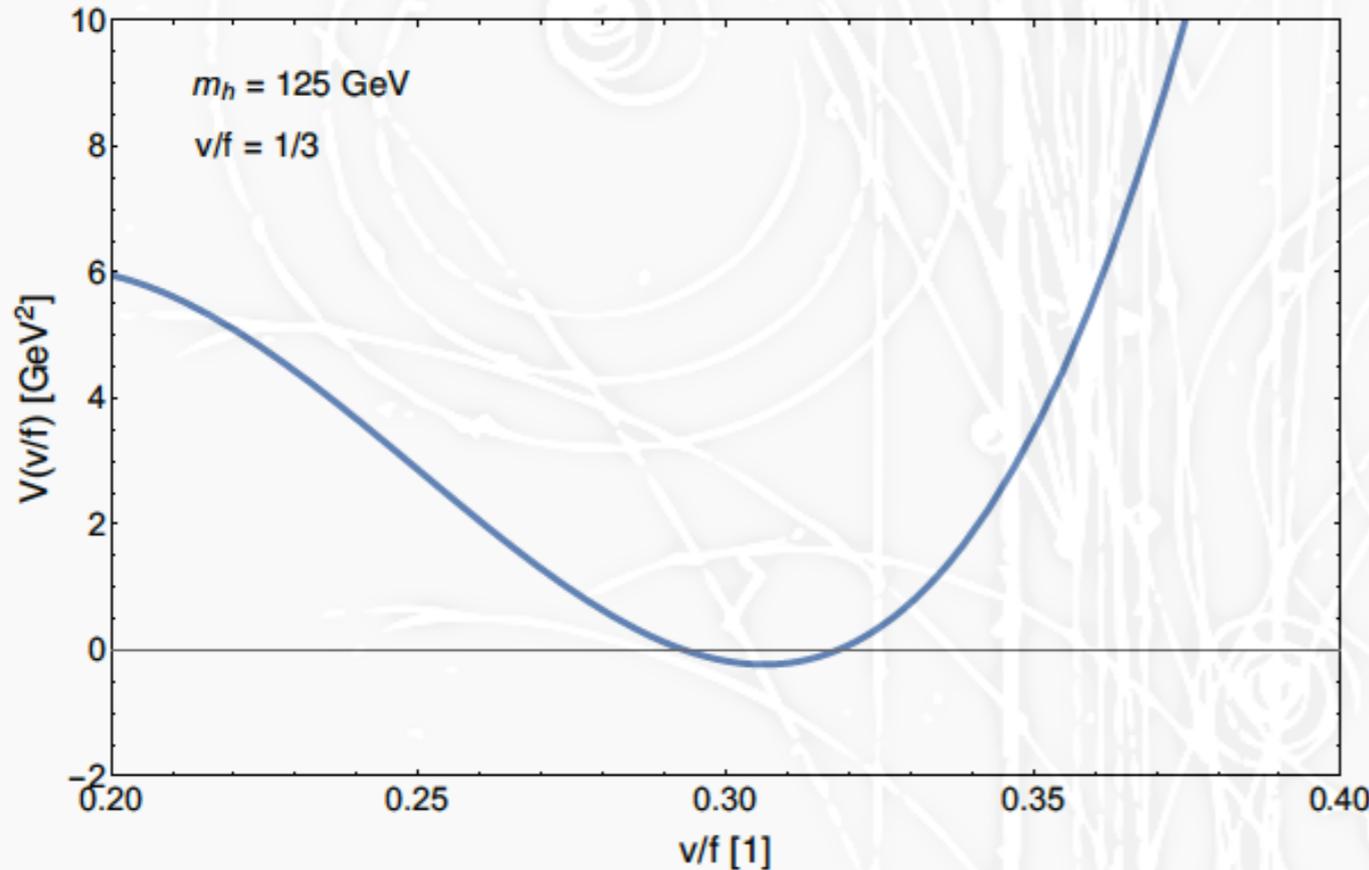


Continuum Top Partners

Csaki, Lombardo, Lee, SL, Telem; to appear soon

◆ Higgs Potential:
$$V(h) = \frac{3}{16\pi^2} \int dp p^3 \left[-4 \sum_{j=1}^{20} \log G_{f_j}(ip) + \sum_{k=1}^4 \log G_{g_k}(ip) \right]$$

tuning =
$$\left[\max_i \frac{d \log v}{d \log p_i} \right]^{-1} \quad p_i \in \{R, R', \mu, r, \theta, y, c_Q, c_T, c_B, M_1, m_4, M_d\}$$



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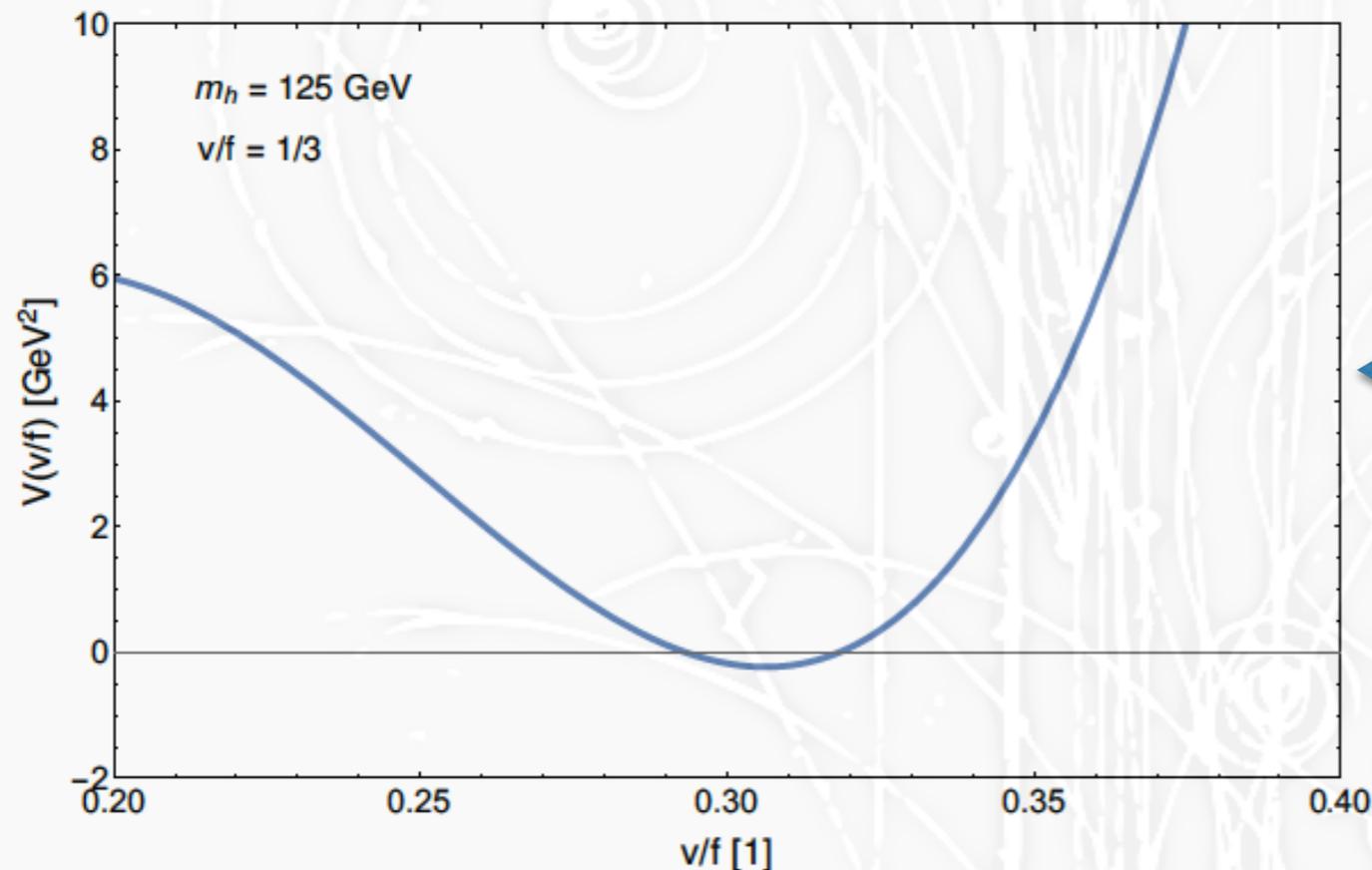
fermion continuum starts at $y\mu = 1.75 \text{ TeV}$

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→ 1% tuning

c.f.: with the same set up, usual composite Higgs model has 0.1% tuning

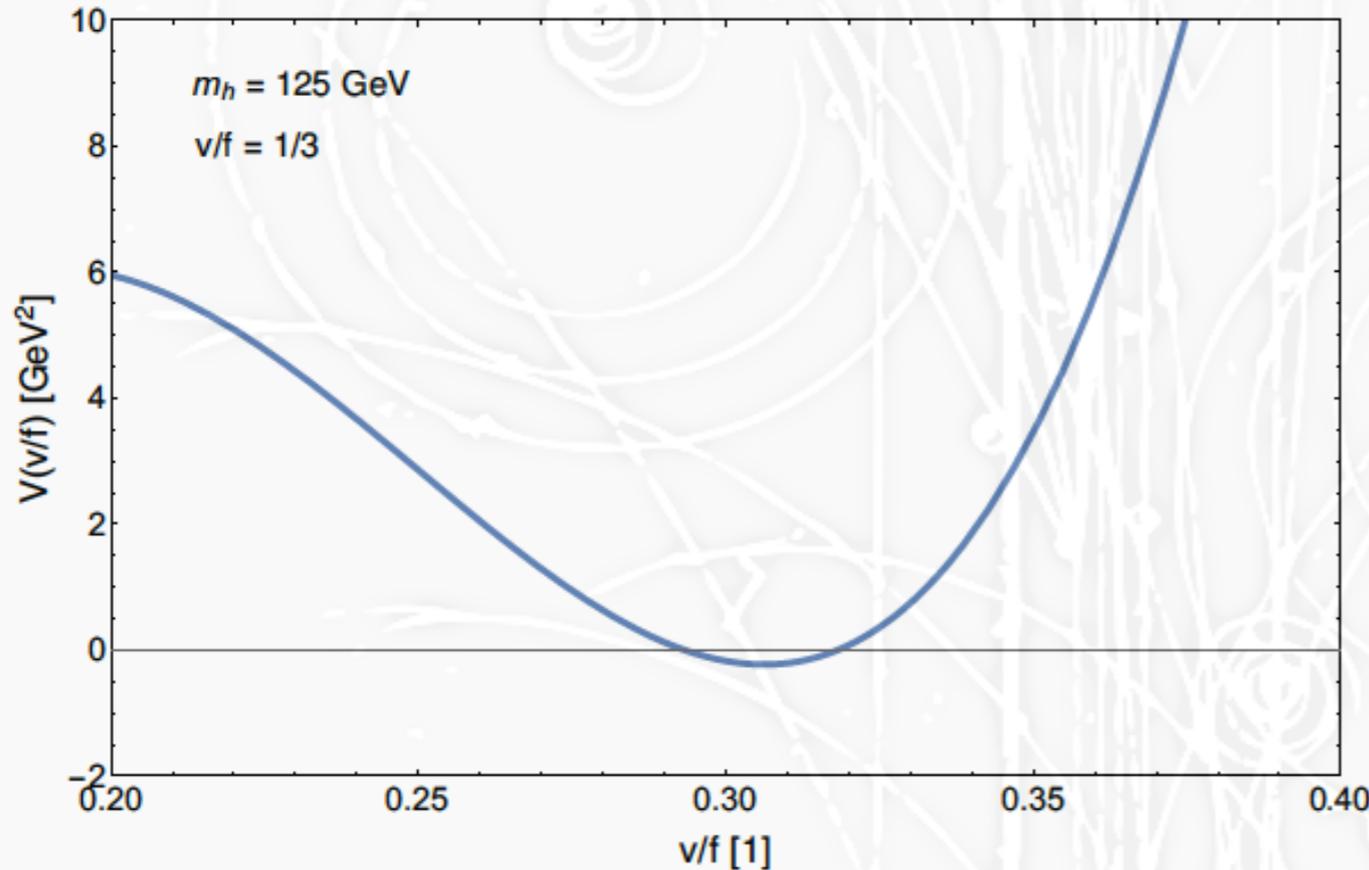
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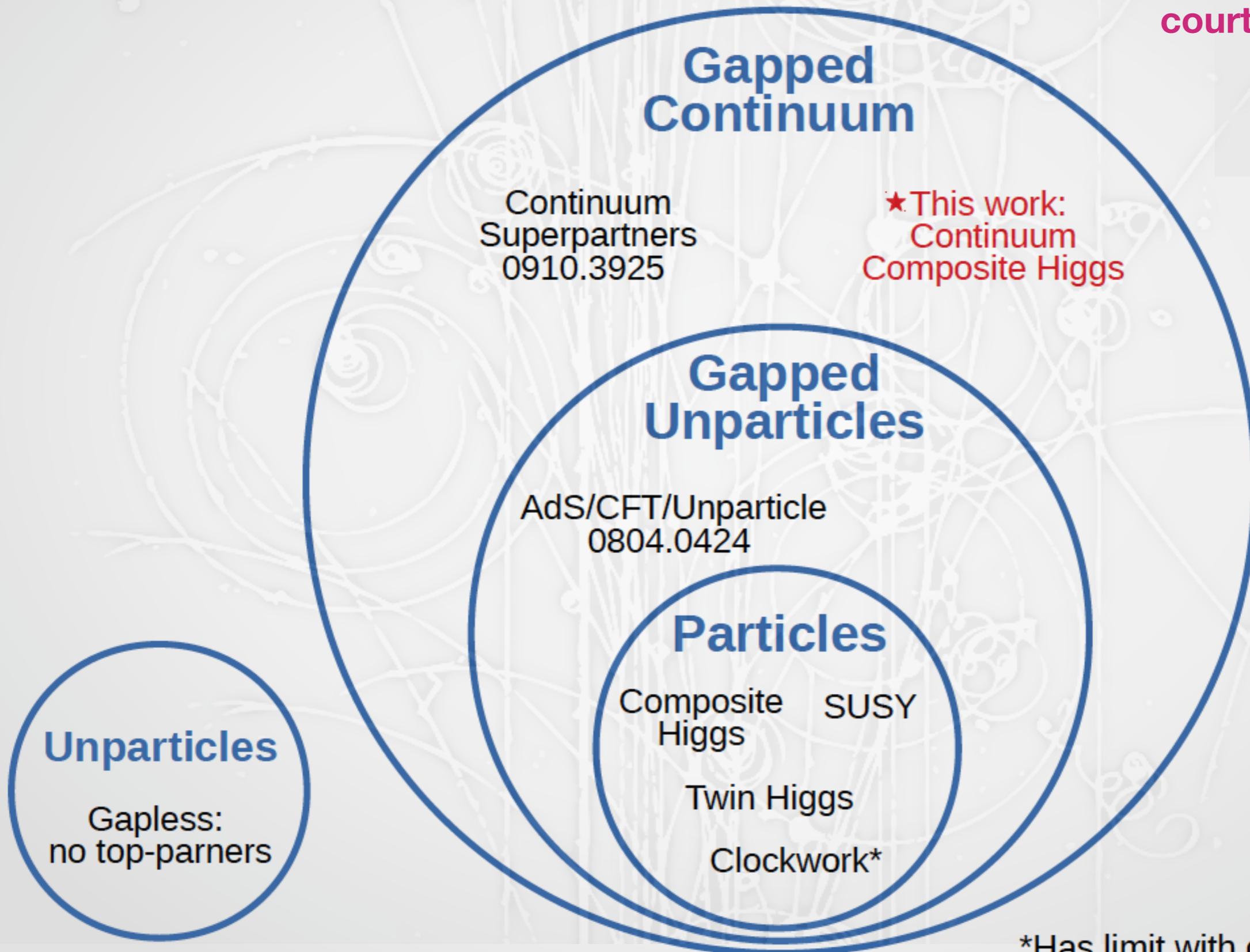
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Summary

- ◆ Searches at the LHC have placed the naturalness paradigm under pressure
- ◆ We provided a natural model (continuum composite Higgs model), where top and gauge partners could be continuum states from the strong dynamics of confinement
- ◆ The new continuum states in this scenario cannot be described as Breit-Wigner resonances, drastically changing their LHC pheno
- ◆ Naturalness is improved compared to the case with usual resonance type of top partners for the same confinement scale of strong dynamics

Summary

courtesy of C. Csaki



*Has limit with continuum partners

The background features a complex, abstract pattern of thin white lines. These lines form various shapes, including spirals, circles, and irregular, overlapping paths that create a sense of movement and depth. The overall effect is reminiscent of a hand-drawn or etched design on a light gray surface.

Thank you!