The 1st Asian-European-Institutes (AEI) Workshop for BSM and the 9th KIAS Workshop on Particle Physics and Cosmology

Continuum Naturalness

- particle without particle

Seung J. Lee

Nov. 6, 2019

With C. Csaki, S. Lombardo, G. Lee, O. Telem; JHEP 2019(03)
With C. Csaki, G. Lee, O. Telem work in progress
With C. Csaki, W. Xue; work in progress

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

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

Composite Higgs:
Fermionic top partners
(partial compositeness)

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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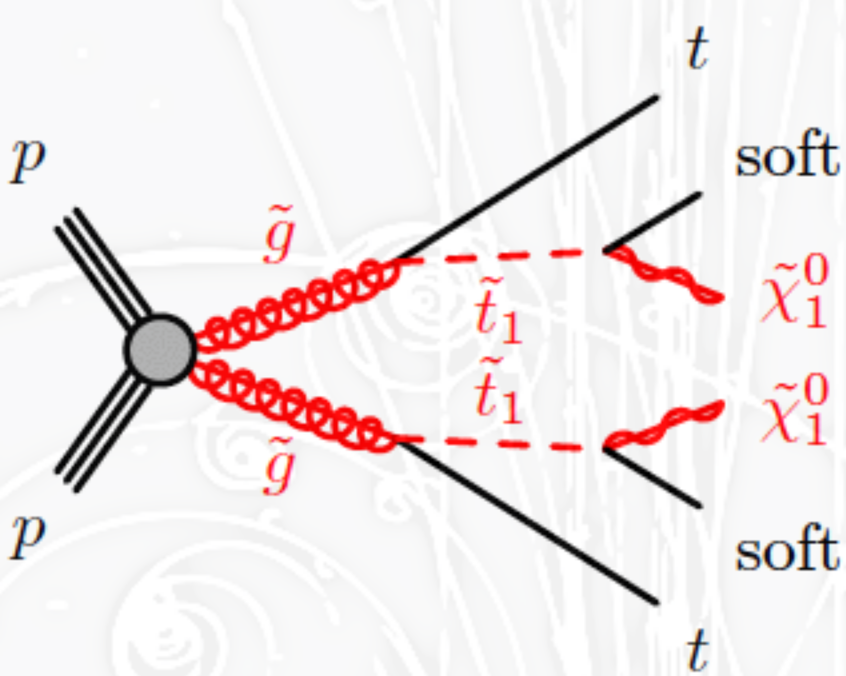
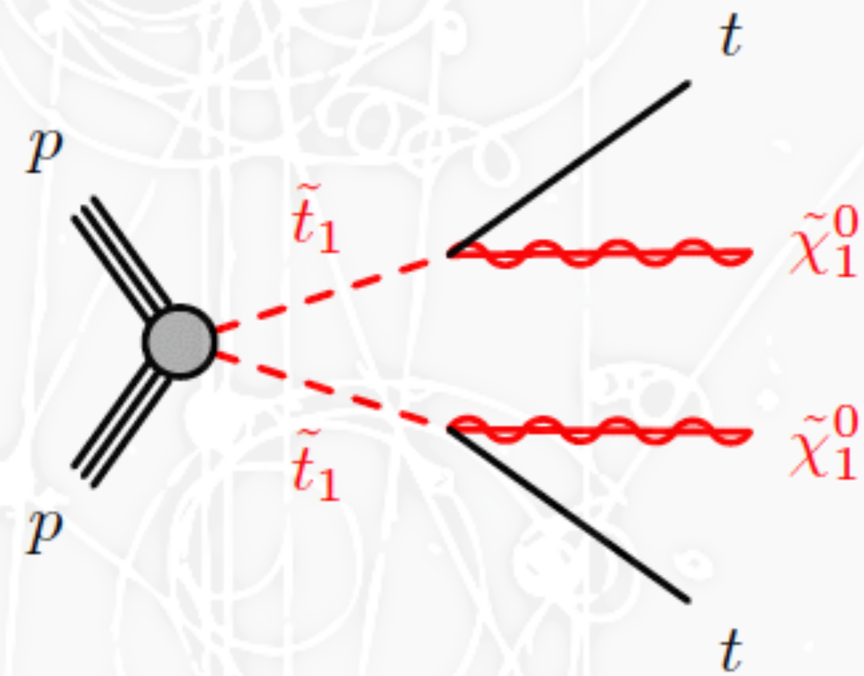
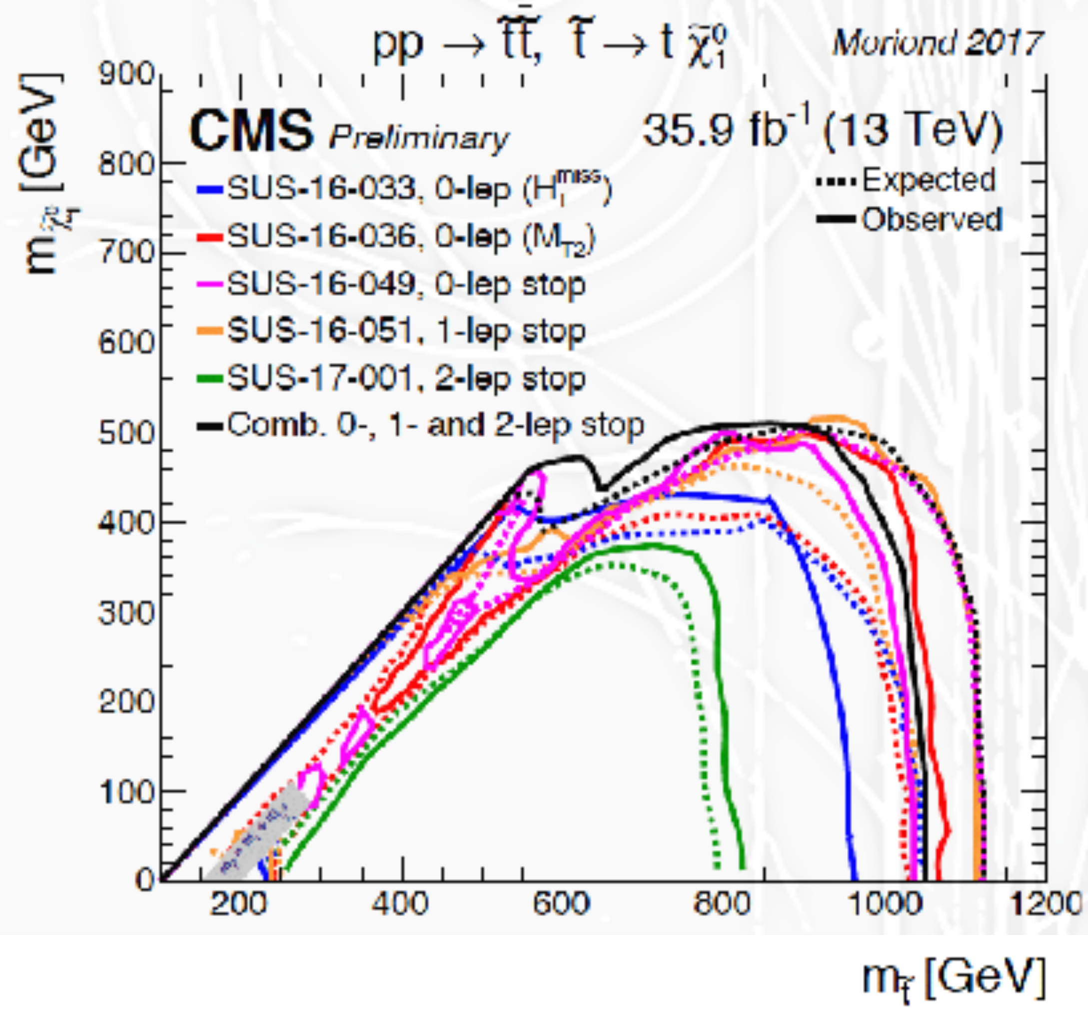
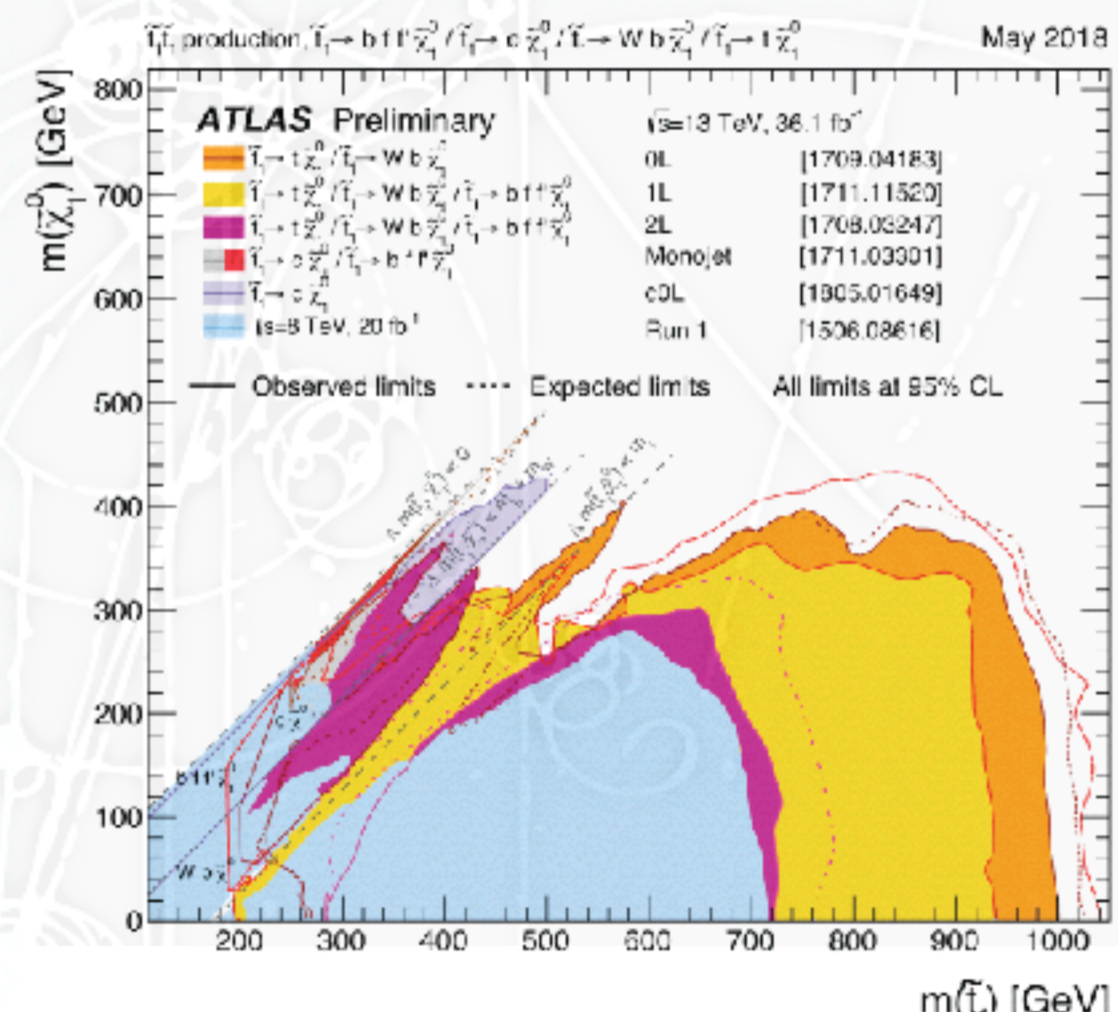
SUSY top partner searches





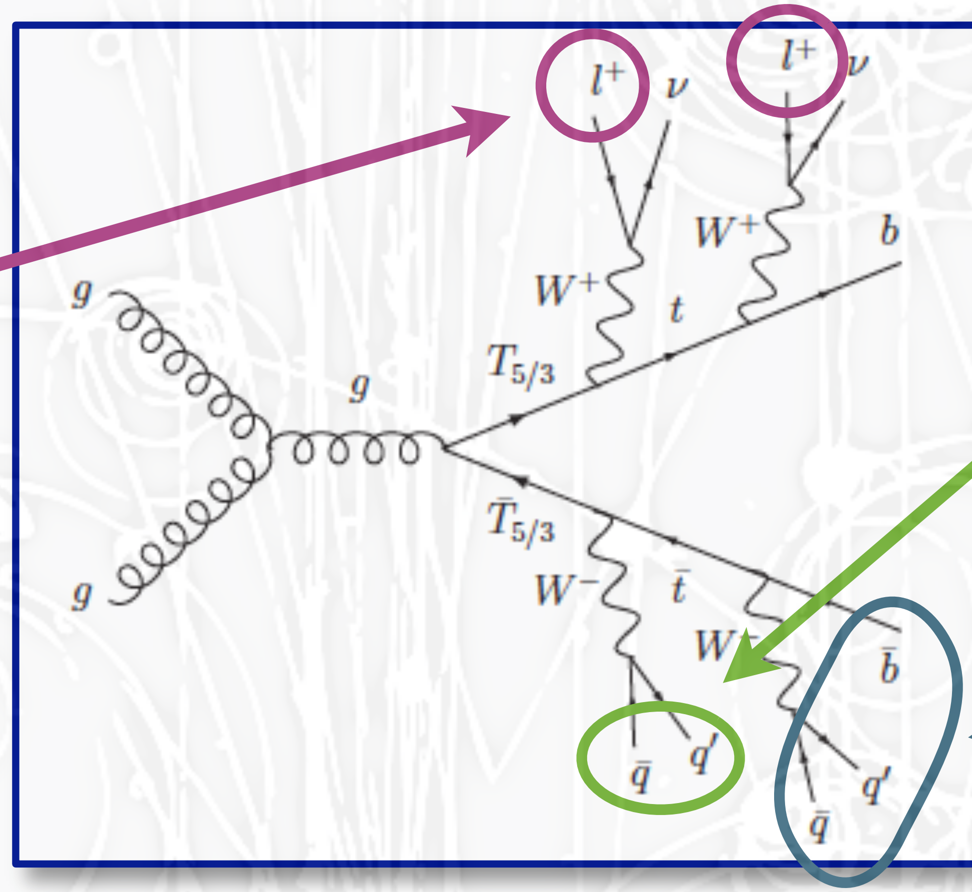




Composite Top Partner Searches

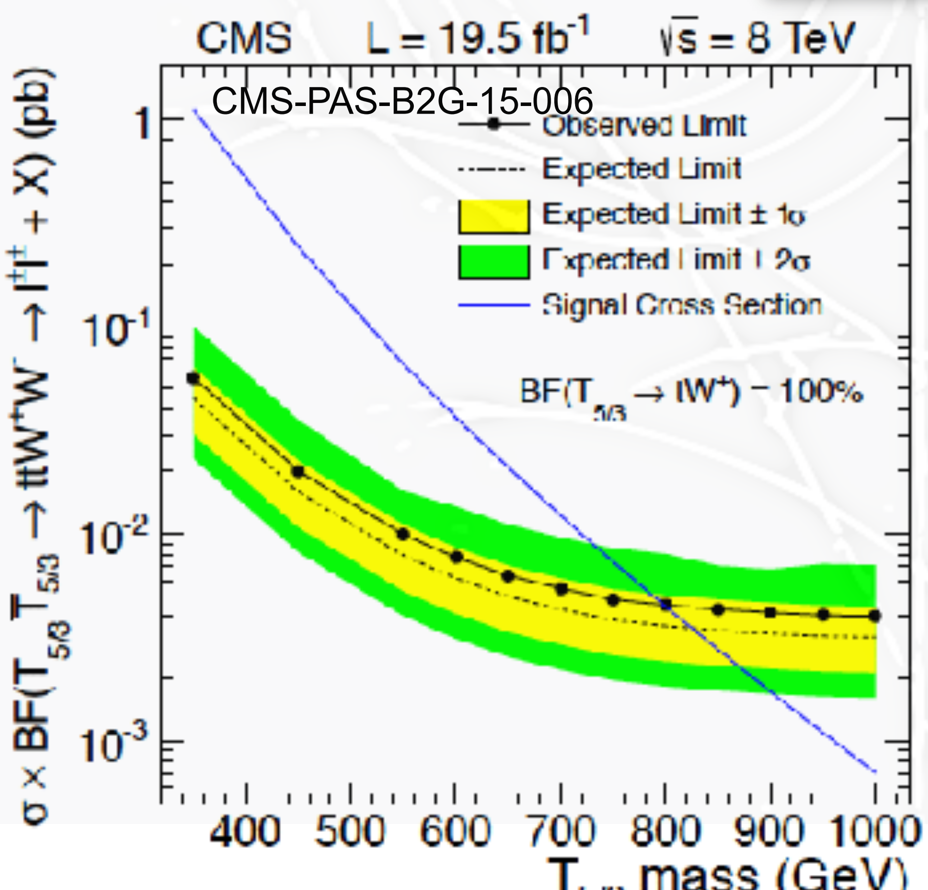
Simone, Matsedonski, Rattazzi, Wulzer `12
Azatov, Son, Spannowsky `13
Matsedonski, Panico, Wulzer `14

same-sign dileptons



W tag:
2 subjets,
M_j[60,130]

CMS top tag



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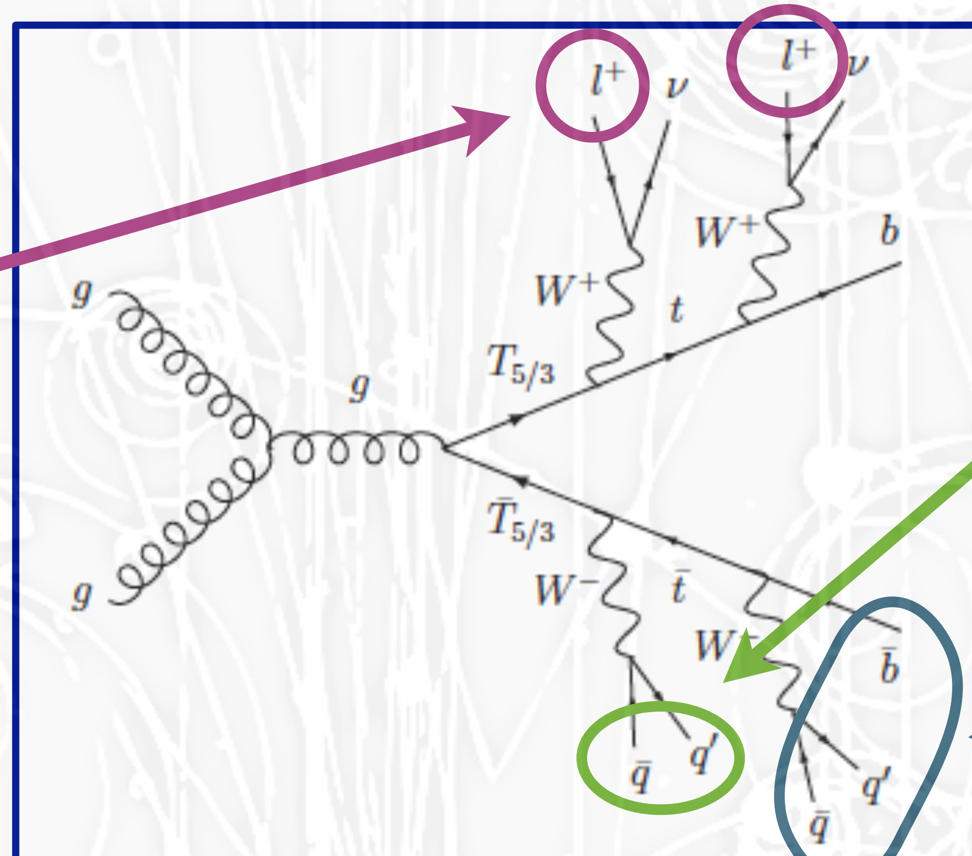

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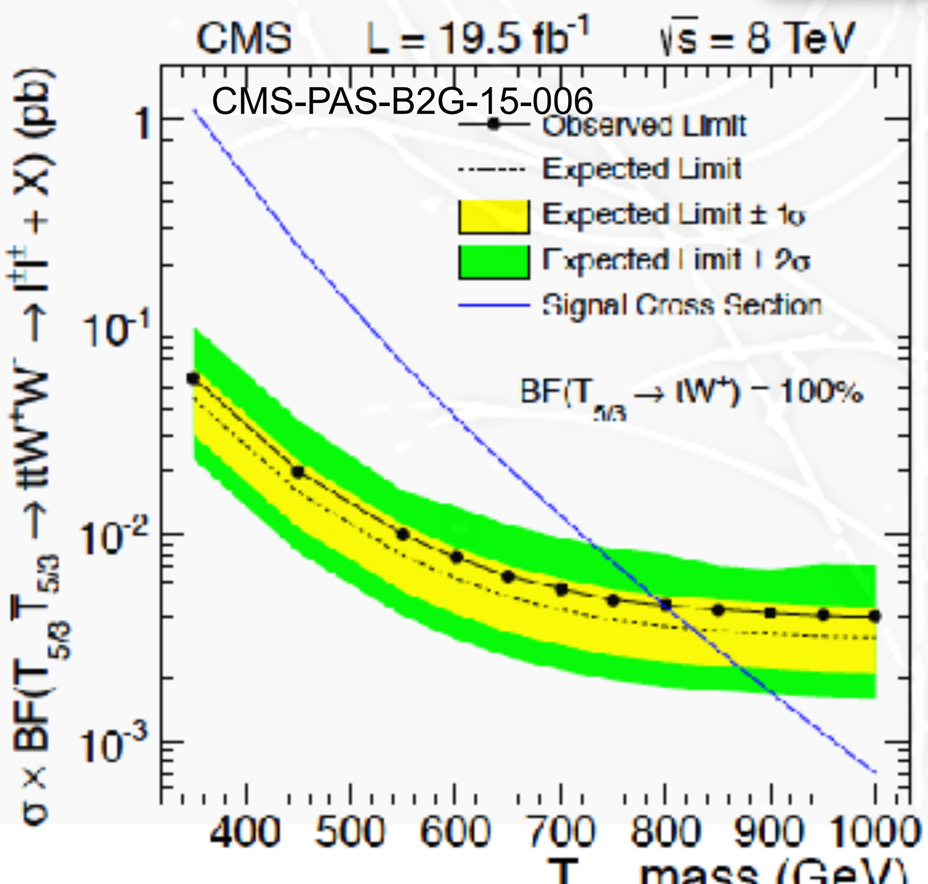

Oblique parameter fits of LEP & Tevatron data gave
f ≳ 800GeV

Grojean, Matsedonskyi, Panico `13

Ciuchini, Franco, Mishima, Silvestrini `13

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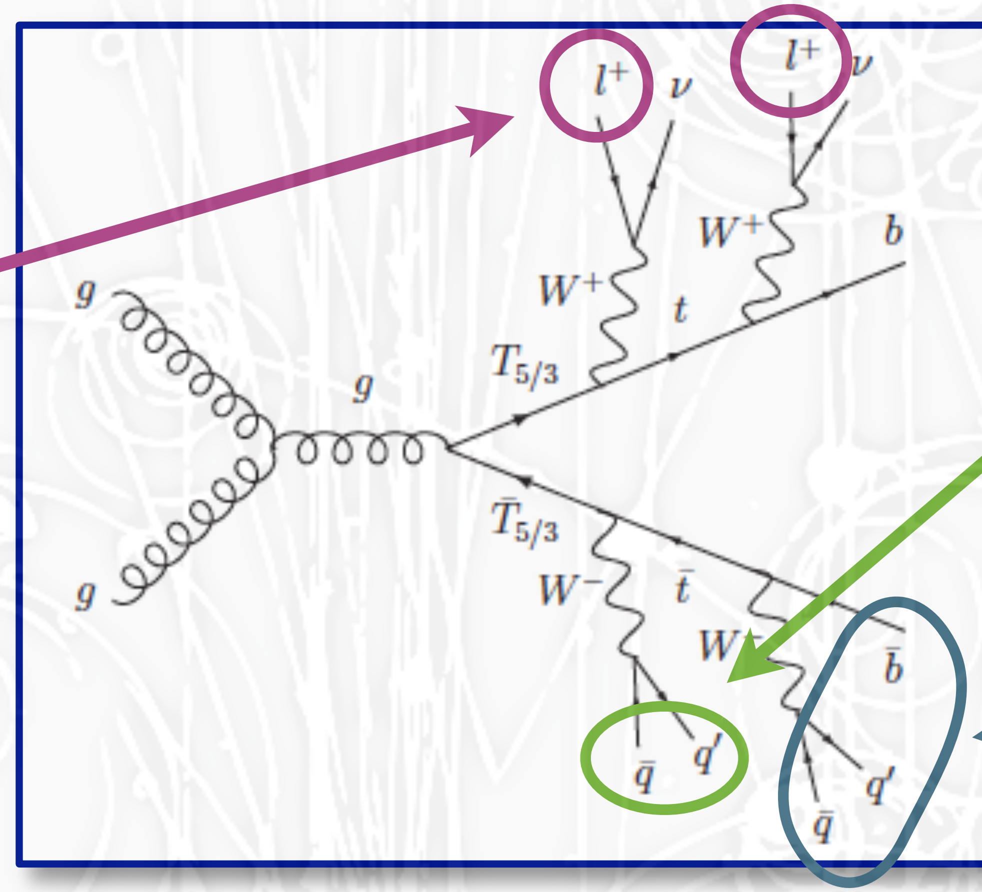

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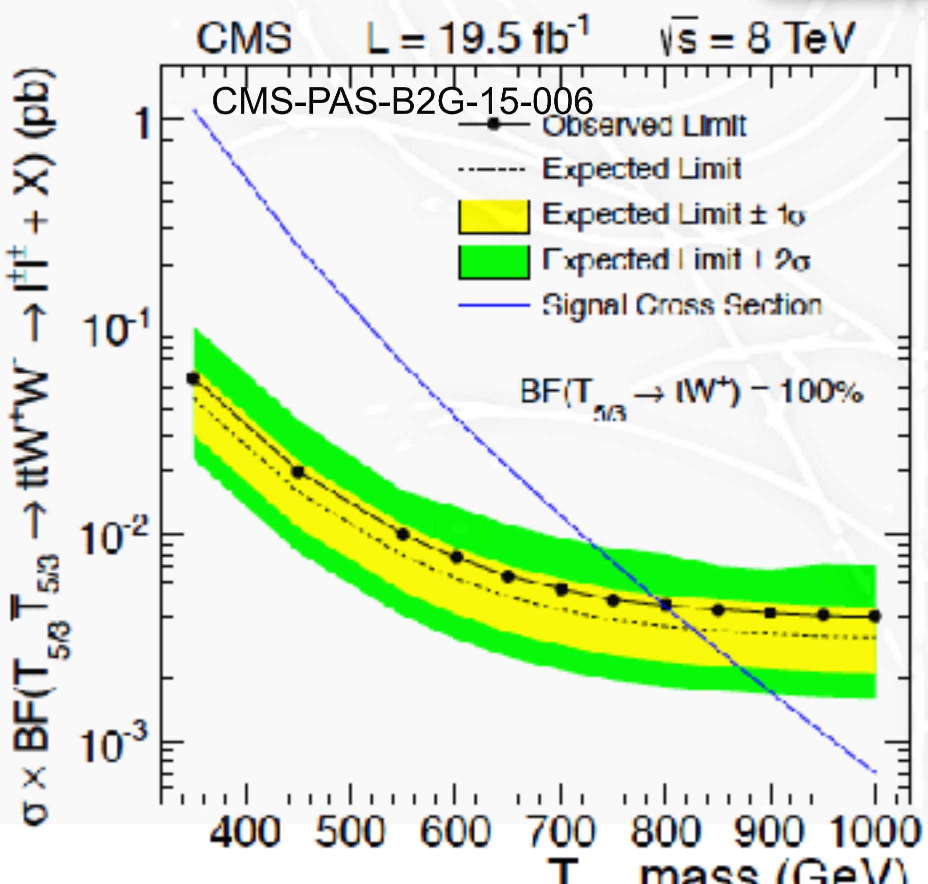

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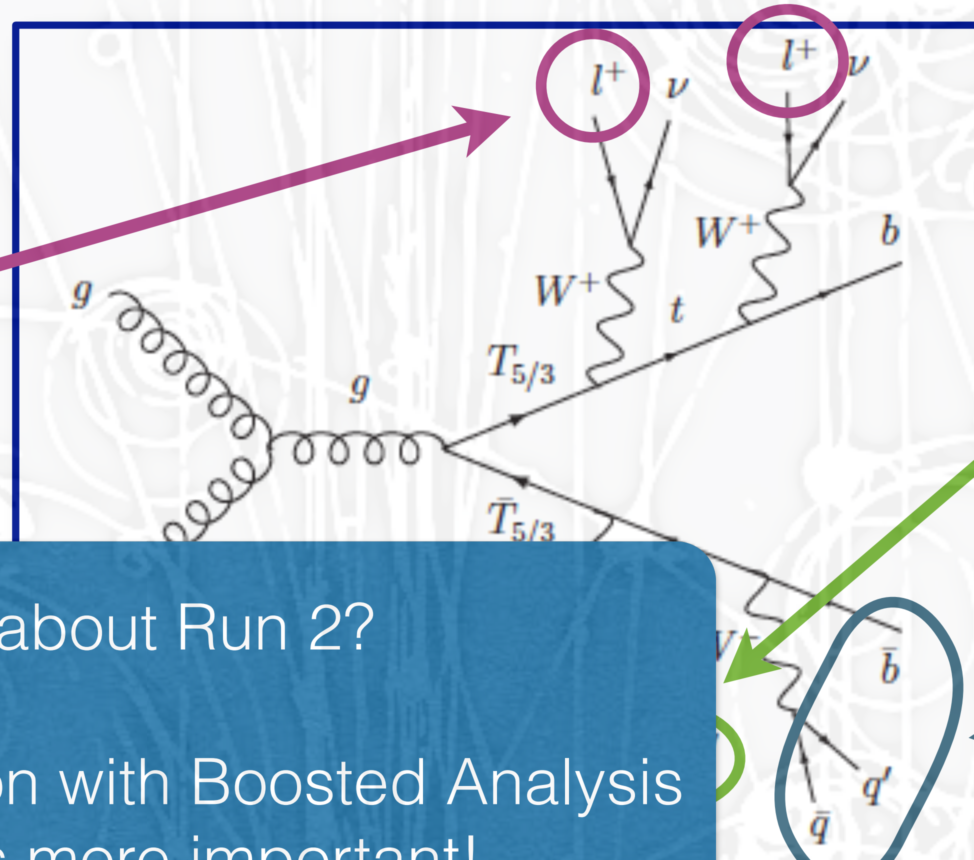

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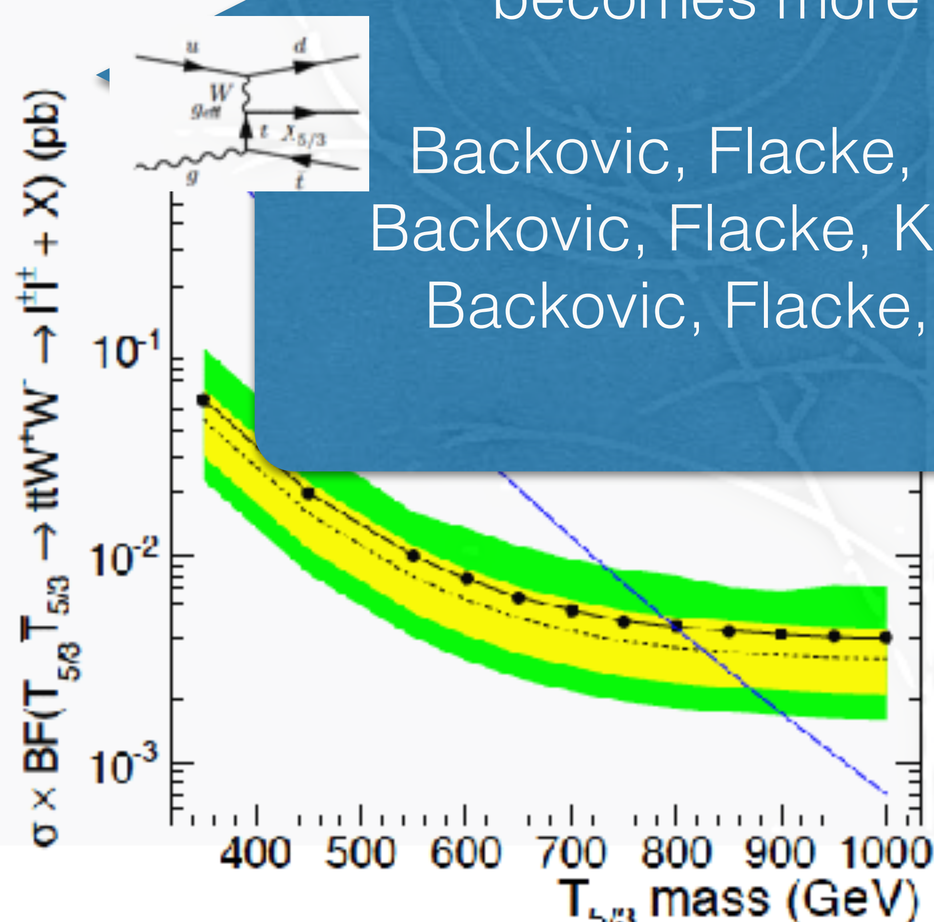
CMS top tag

How about Run 2?

Single production with Boosted Analysis becomes more important!

Backovic, Flacke, SL, Perez `14
Backovic, Flacke, Kim, SL (x2),`15
Backovic, Flacke, Kim, SL, `16



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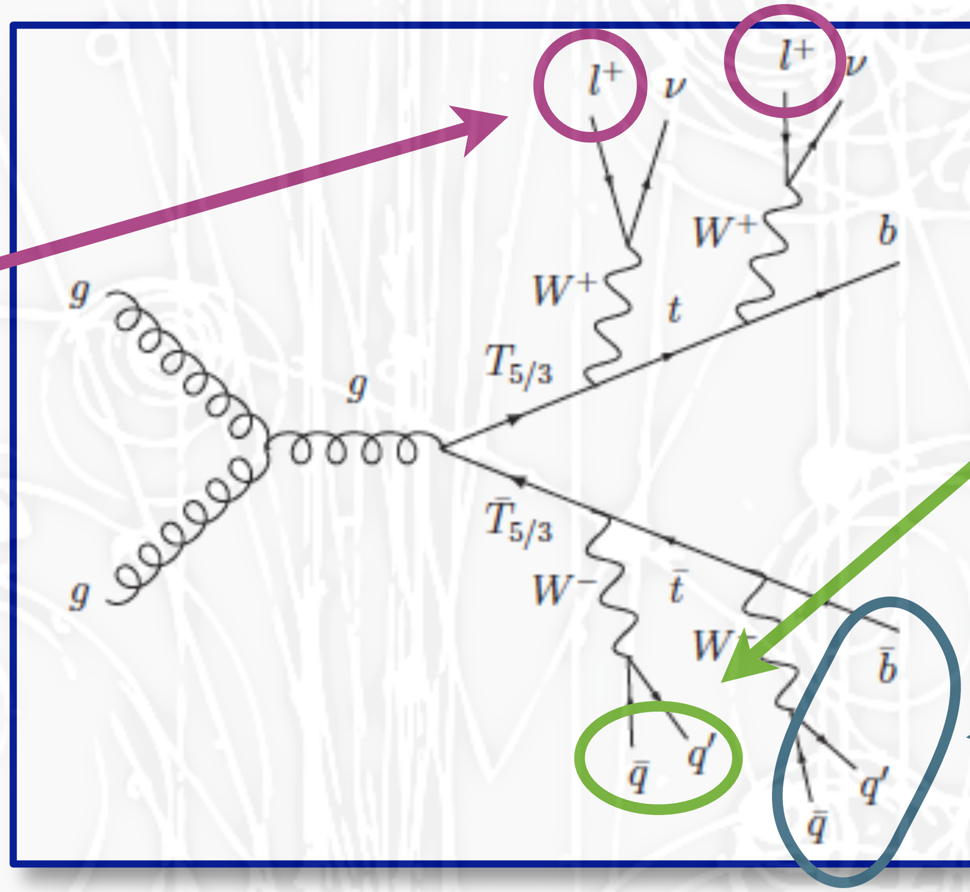

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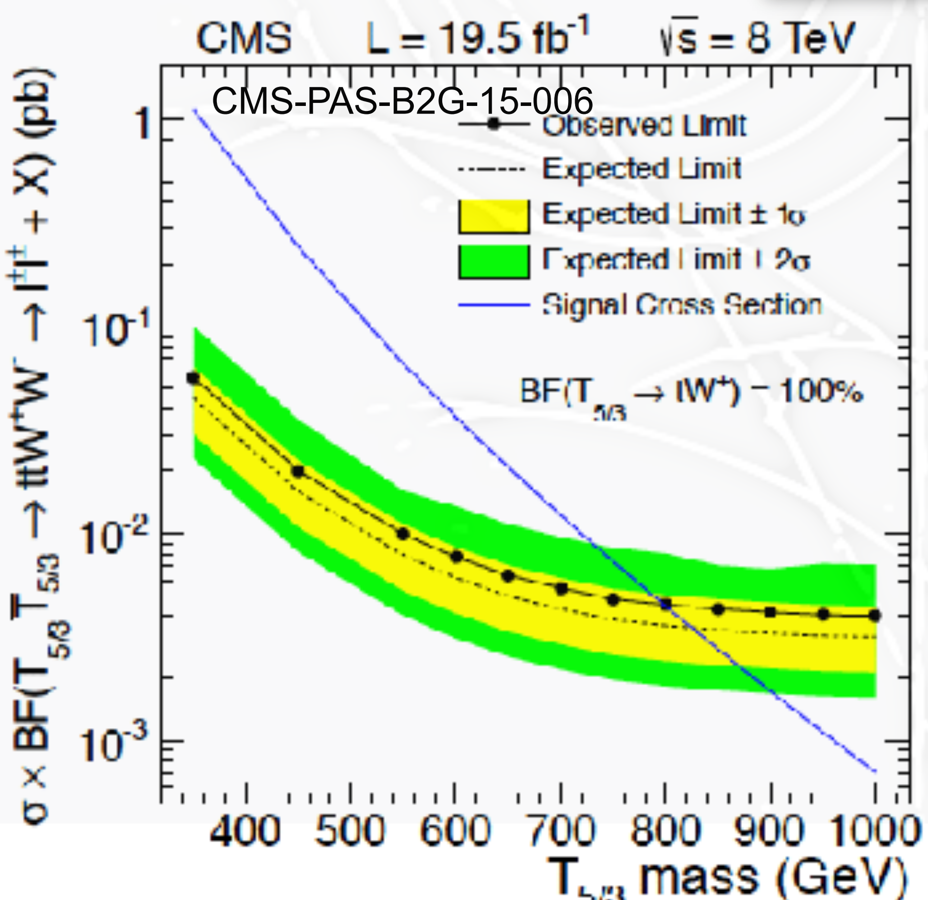

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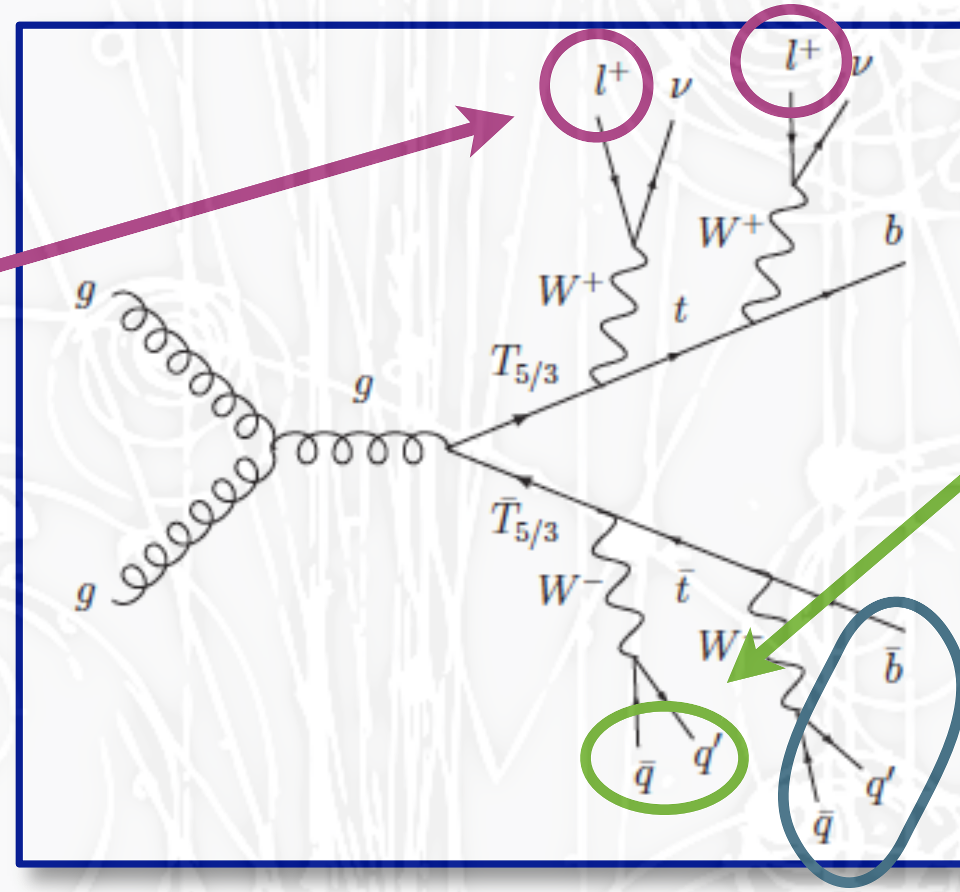

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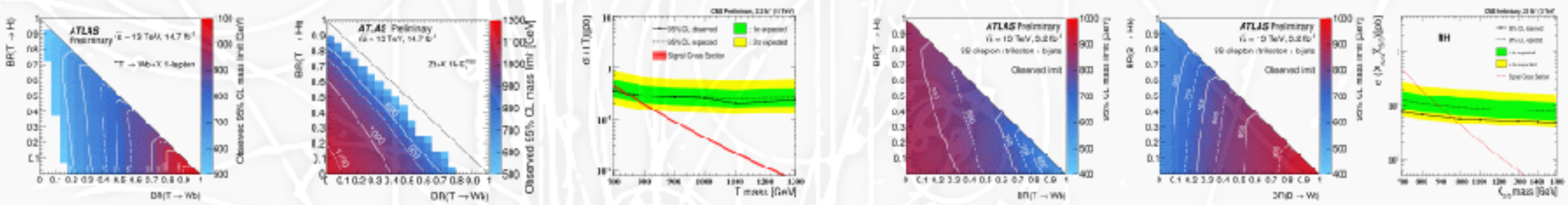
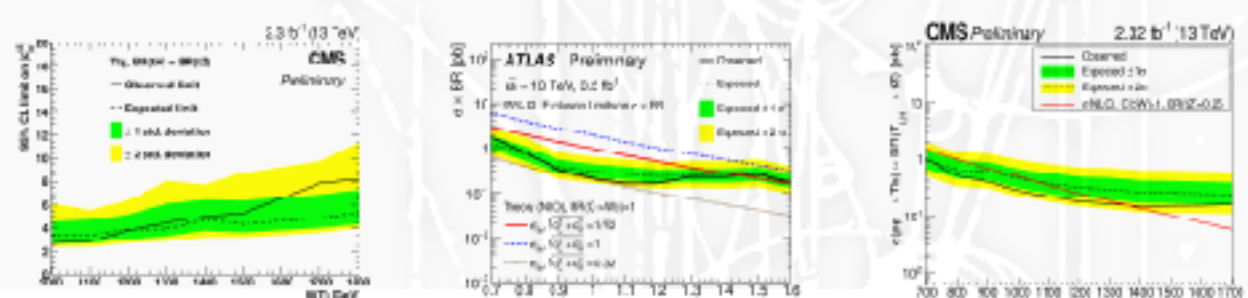
pair VLQ

TT→bW+x TT→tZ+x TT (T→tW,bZ,bH) TT→tH+x BB→tH+x XX→tWtW



single VLQ

T→tH T/Y→bW T→tZ, B→bZ

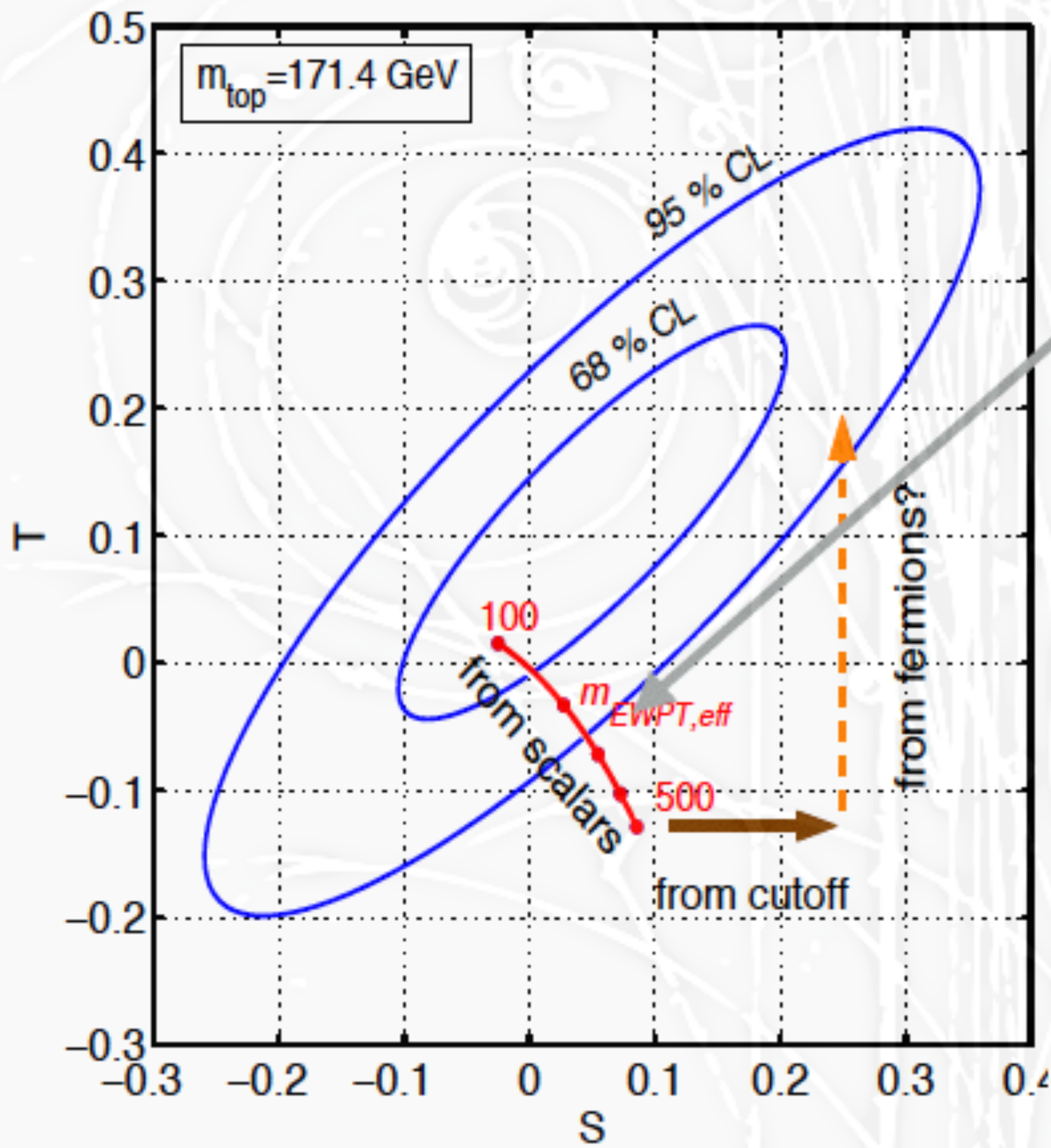


$T_{5/3}$ mass (GeV)

VLQ masses excluded up to:
- 1.4 TeV (100% BR T→Ht)
- 1.3 TeV (doublet)

$M(T_{5/3})$>1.2 TeV (95% CL)

EWPT and Top Partners



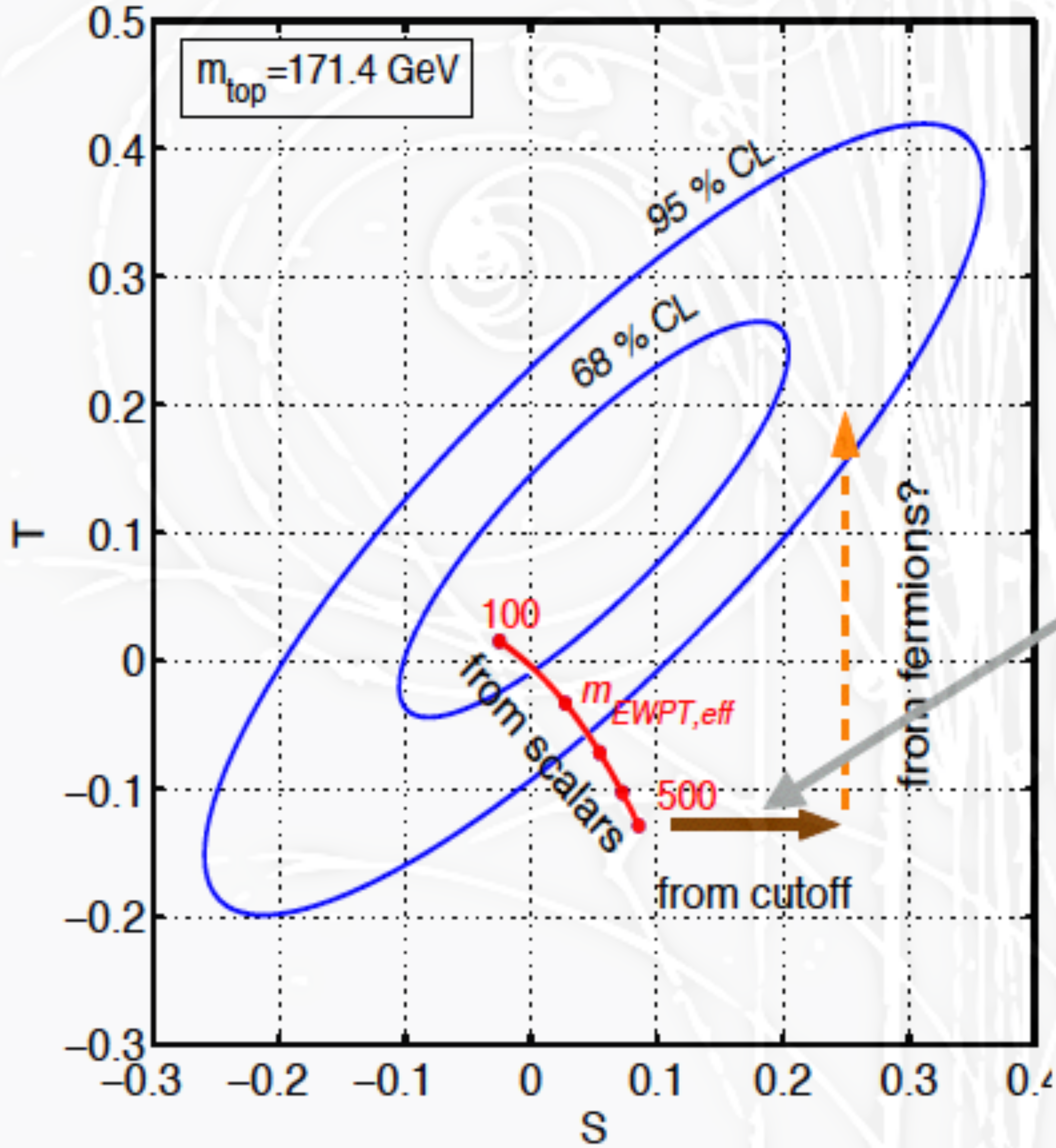
$$\Delta\hat{S} = \frac{g^2}{96\pi^2}\xi \log\left(\frac{8\pi m_W}{g m_h \sqrt{\xi}}\right)$$

$$\Delta\hat{T} = -\frac{3g'^2}{32\pi^2}\xi \log\left(\frac{8\pi m_W}{g m_h \sqrt{\xi}}\right)$$

Modified Higgs couplings go in bad direction.

Barbieri, Bellazzini, Rychkov, Varagnolo ,`07

EWPT and Top Partners



$$\Delta\hat{S} = \frac{g^2}{96\pi^2}\xi \log\left(\frac{8\pi m_W}{g m_h \sqrt{\xi}}\right) + \frac{m_W^2}{m_\rho^2}$$

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Resonance exchange as well

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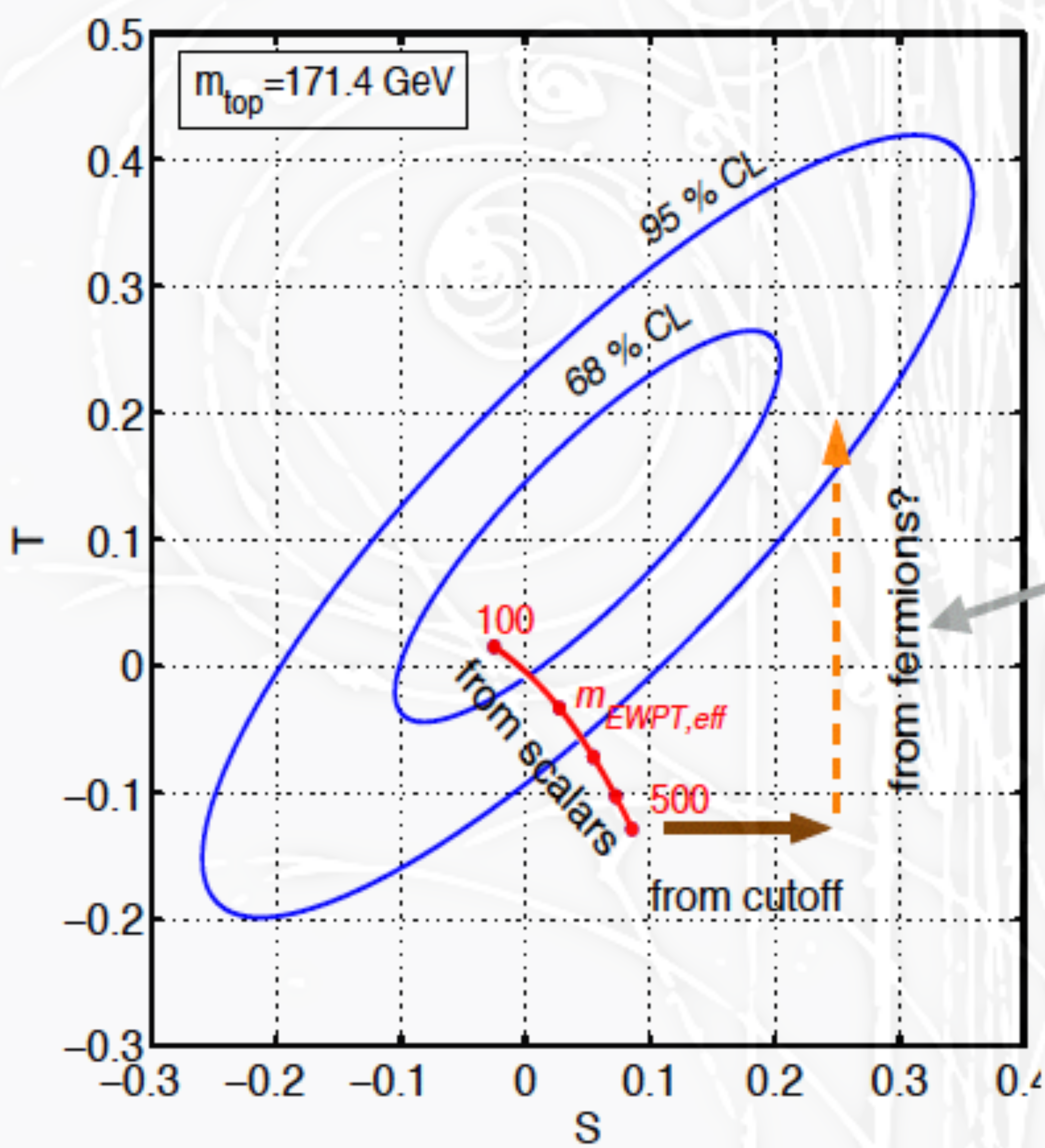


$$\Delta\hat{S} = \frac{g^2}{96\pi^2}\xi \log\left(\frac{8\pi m_W}{g m_h \sqrt{\xi}}\right) + \frac{m_W^2}{m_\rho^2} + \alpha\frac{g^2}{16\pi^2}\xi\,,$$

$$\Delta\hat{T} = -\frac{3g'^2}{32\pi^2}\xi \log\left(\frac{8\pi m_W}{g m_h \sqrt{\xi}}\right) + \beta\frac{3y_t}{16\pi^2}\xi\,,$$

Modified Higgs couplings go in bad direction.

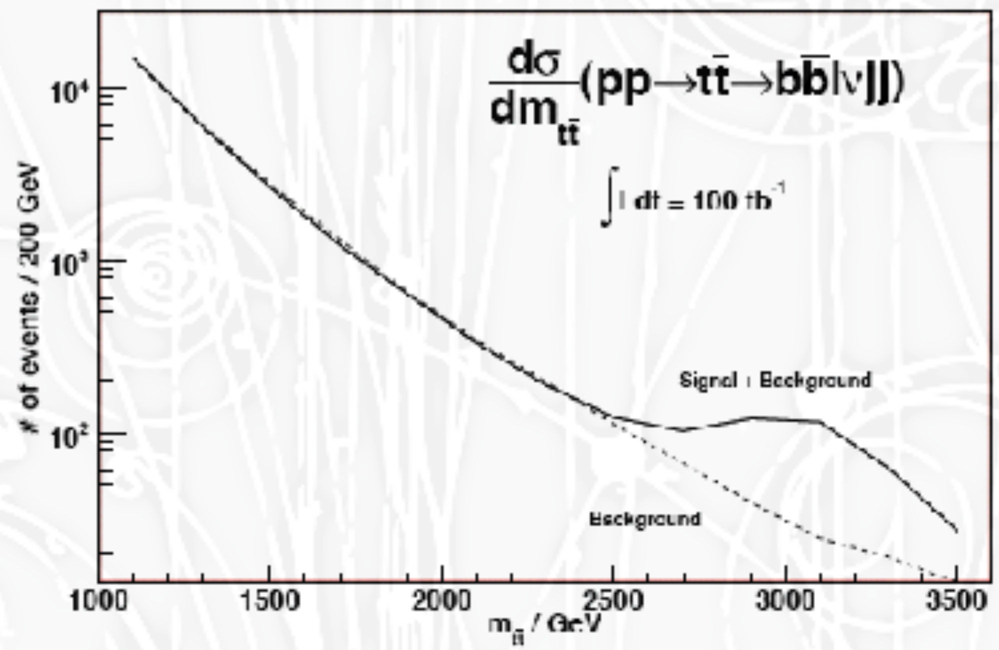
Resonance exchange as well

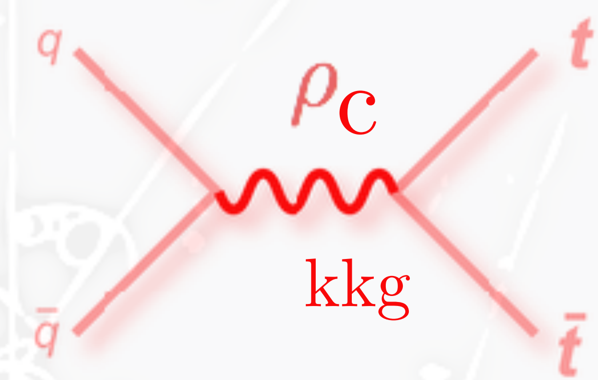
Light Top Partners come to rescue.

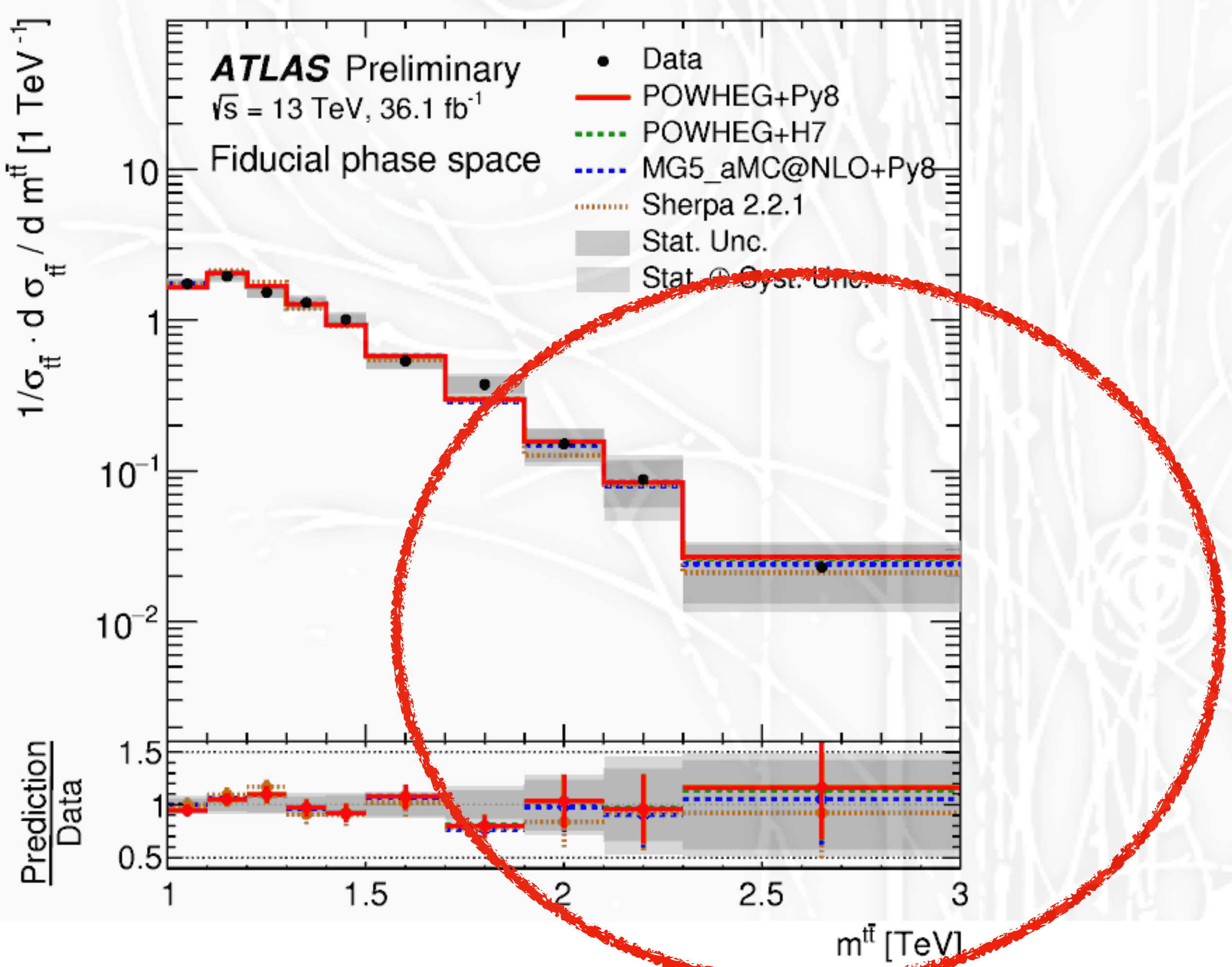
Barbieri, Bellazzini, Rychkov, Varagnolo ,`07

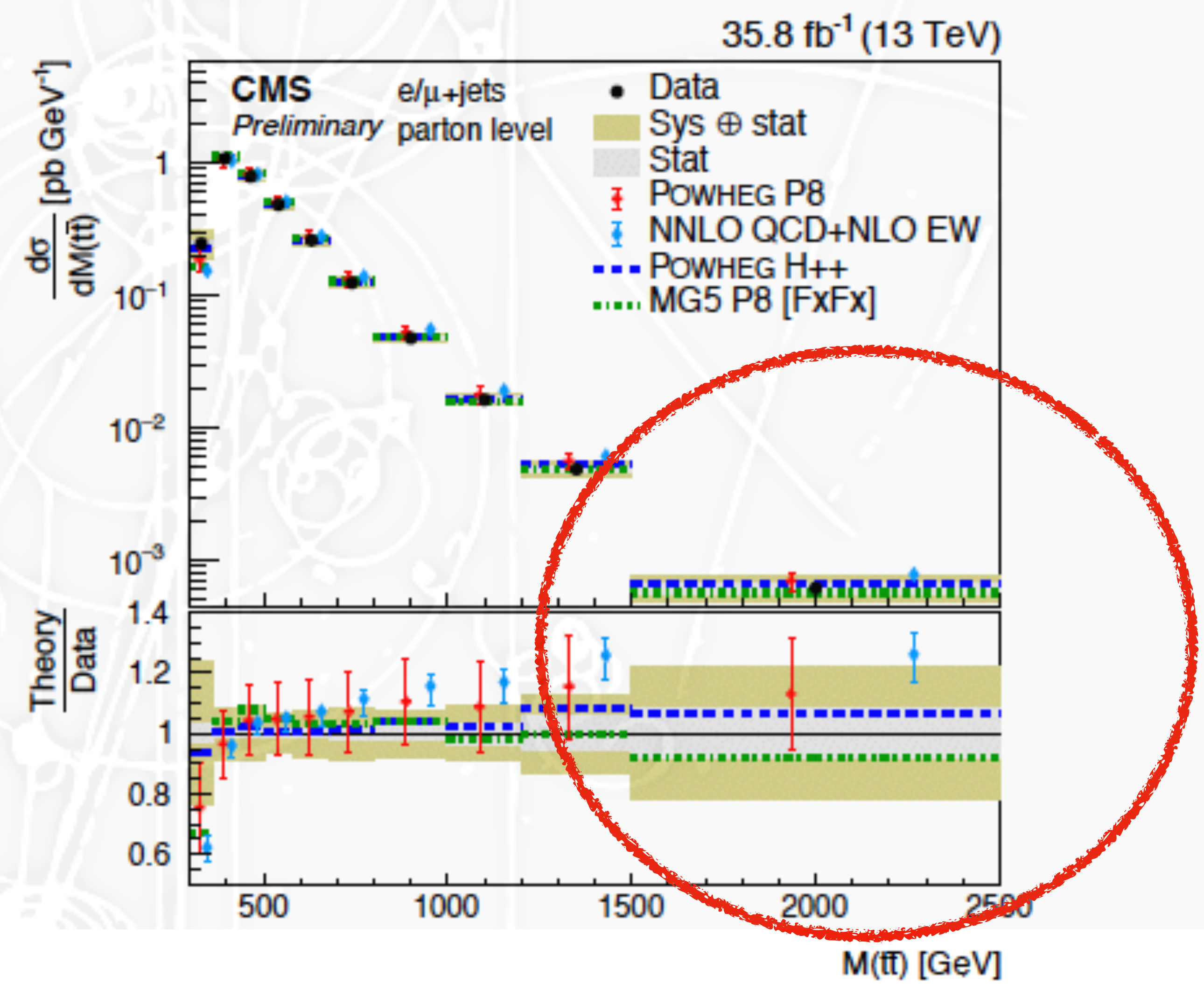
No Resonance, No New Physics? Naturalness?

$M_{KKG} = 3$ TeV









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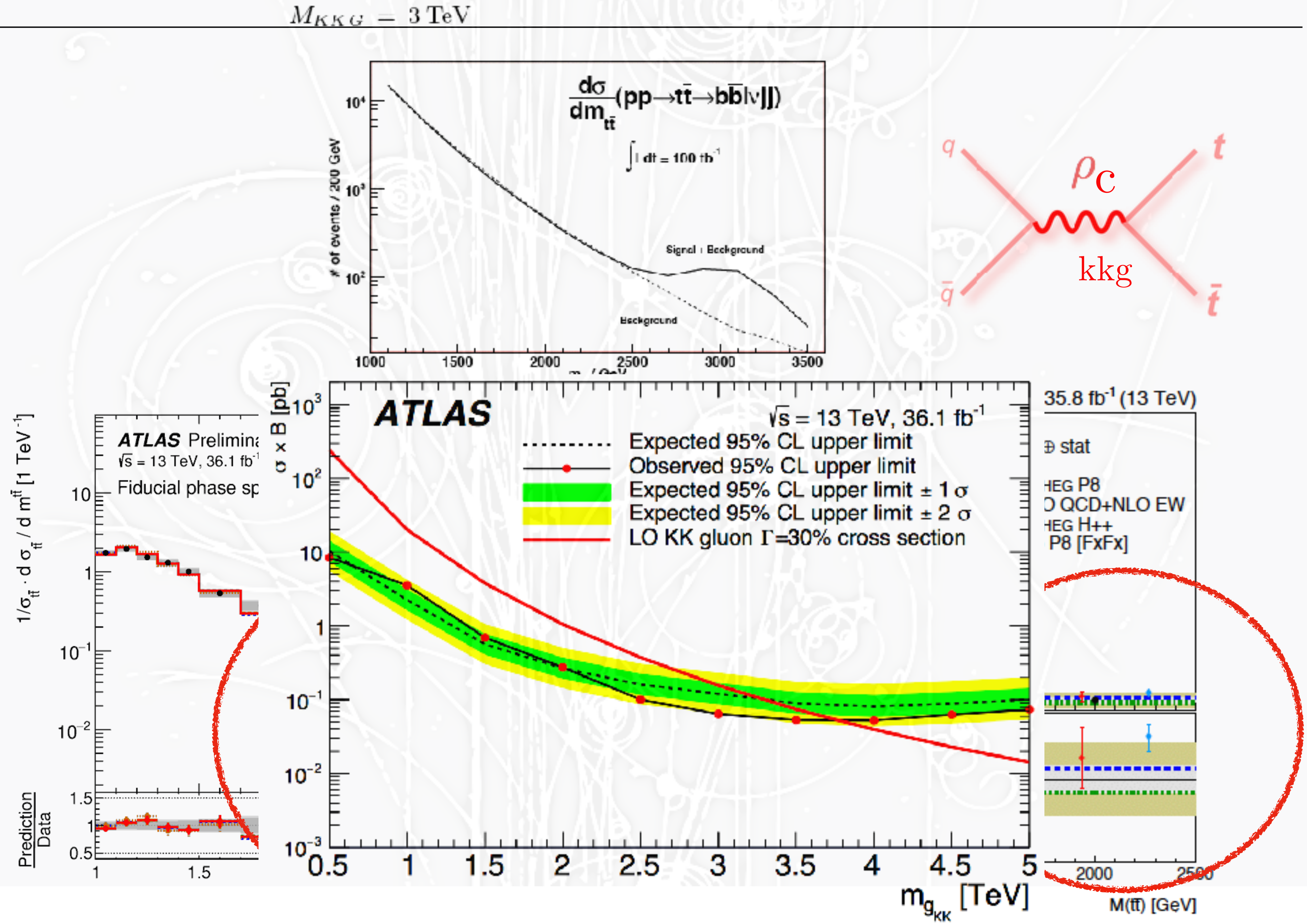

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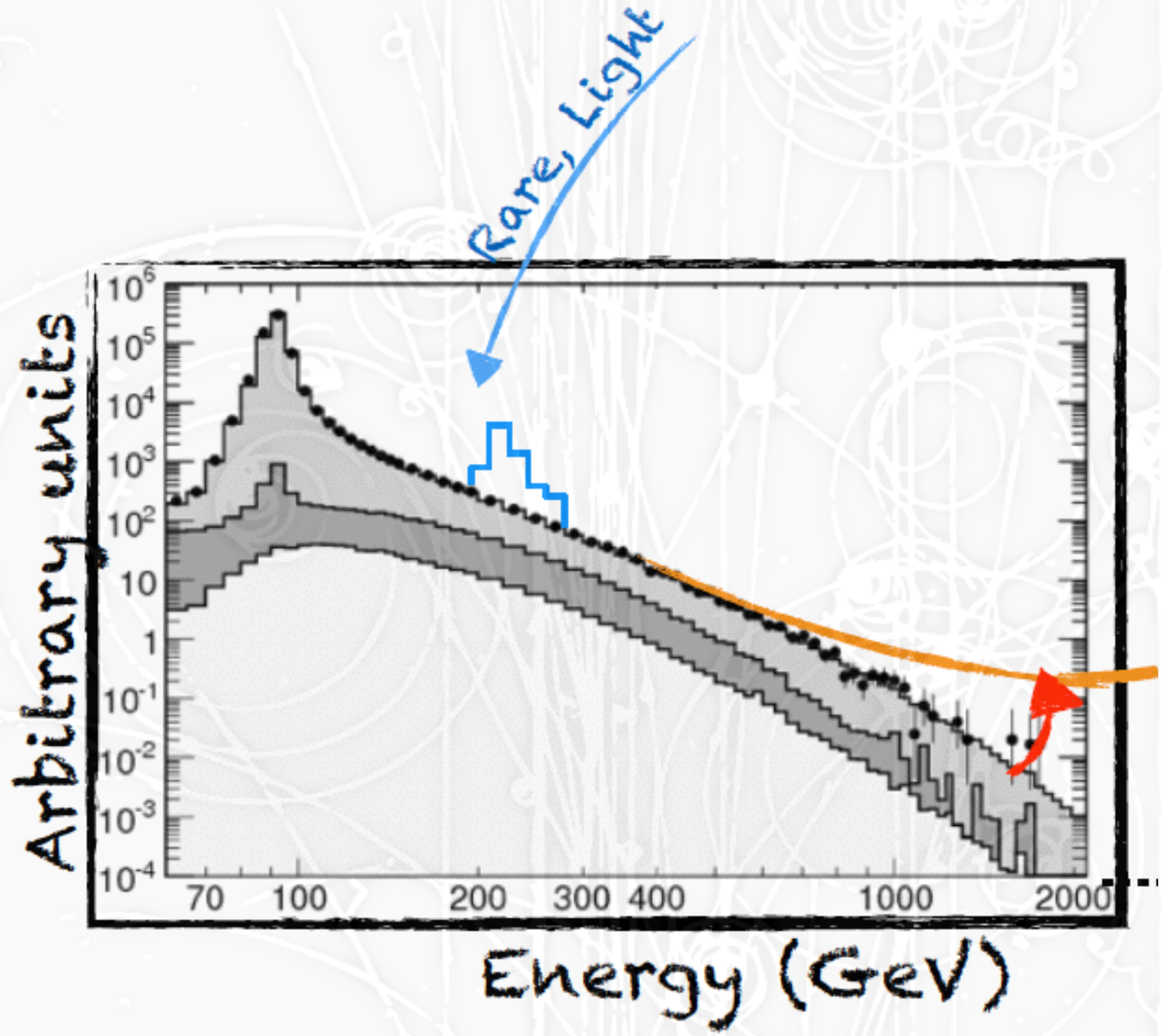

picture adapted from Francesco Riva

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

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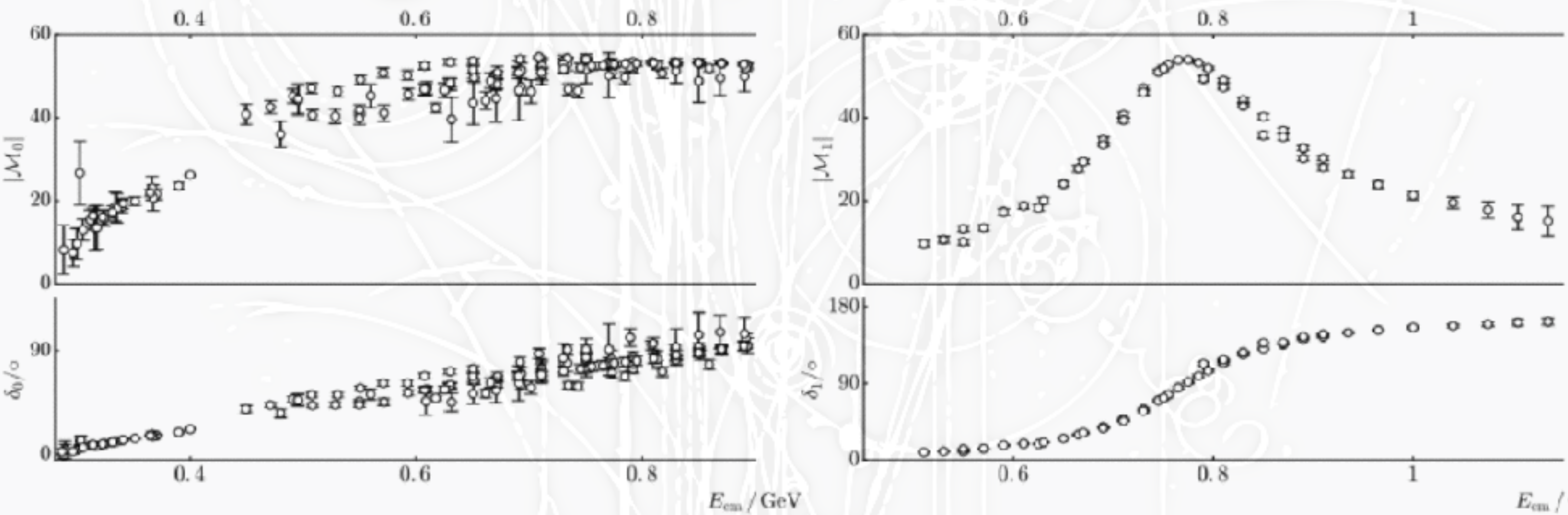
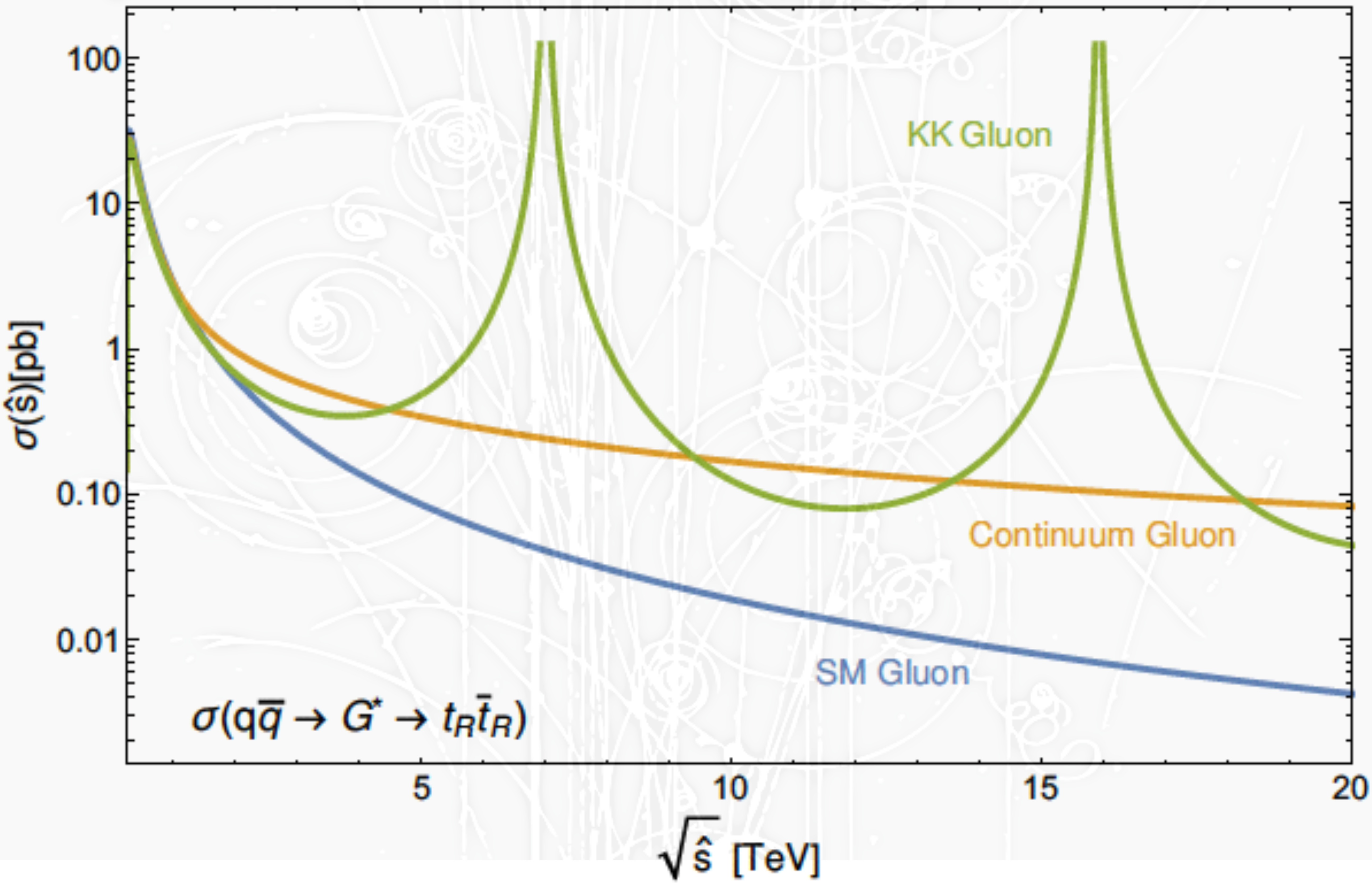
QCD

σ / $f_0(500)$ ρ

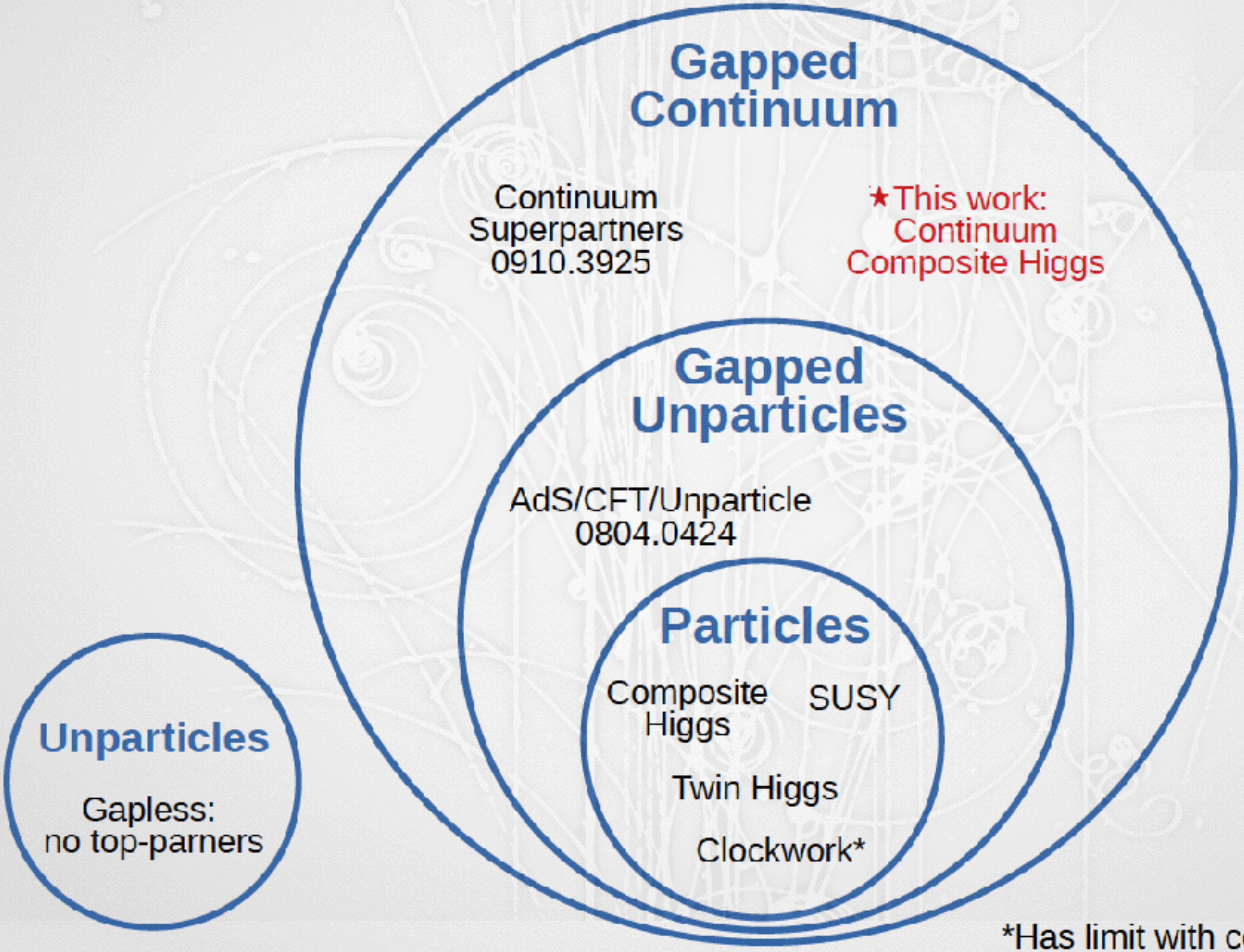


M_σ=450 MeV Γ_σ=550 MeV M_ρ=770 MeV Γ_ρ=145 MeV

No Resonance, No New Physics? Naturalness?



Short Outline



*Has limit with continuum partners

Continuum Top Partners

Csaki, Lombardo, Lee, SL, Telem

- ♦ MCHM (Agashe, Contino, Pomarol) => 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 <tt> is given by

Källén-Lehmann

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

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  - non-local effective action: $S_{\rm eff} = \int d^4x\, d^4y\, \bar{\psi}(x)(i\not{\partial}_y - m)\Sigma(x-y)\psi(y)$

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

$$\rho_h = \frac{1}{\pi}{\rm Im}\Sigma^{-1} \qquad F(x,y) = \mathcal{P}\exp\left(-igT^a\int_x^y A^a\cdot dw\right)\psi(y)$$

Particle Without Particle

- 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.

  - Idea: they may not be ordinary particles but form a continuum with a mass gap (similar to gapless unparticles like Terning et al. - also used gapped for SUSY)

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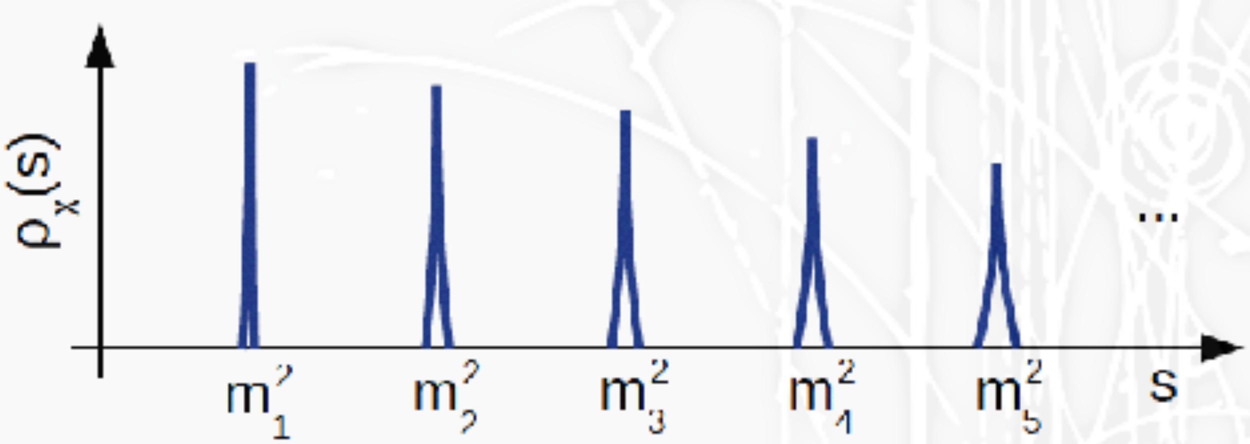
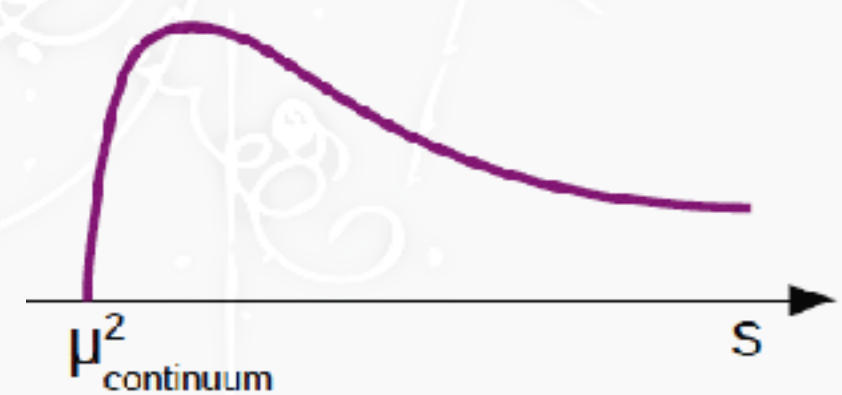
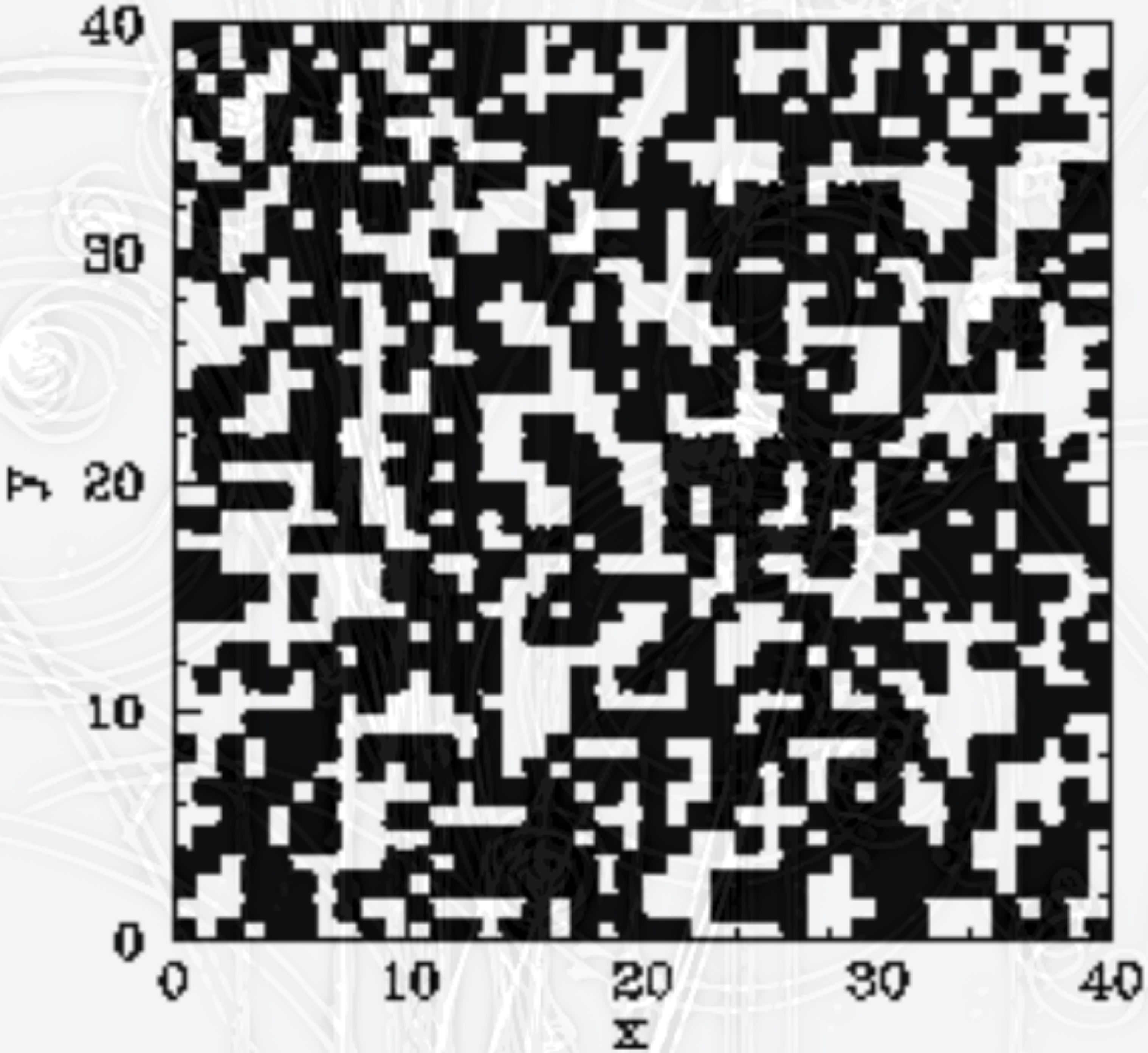




Ordinary composites vs Continuum partners

Ising Model

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



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

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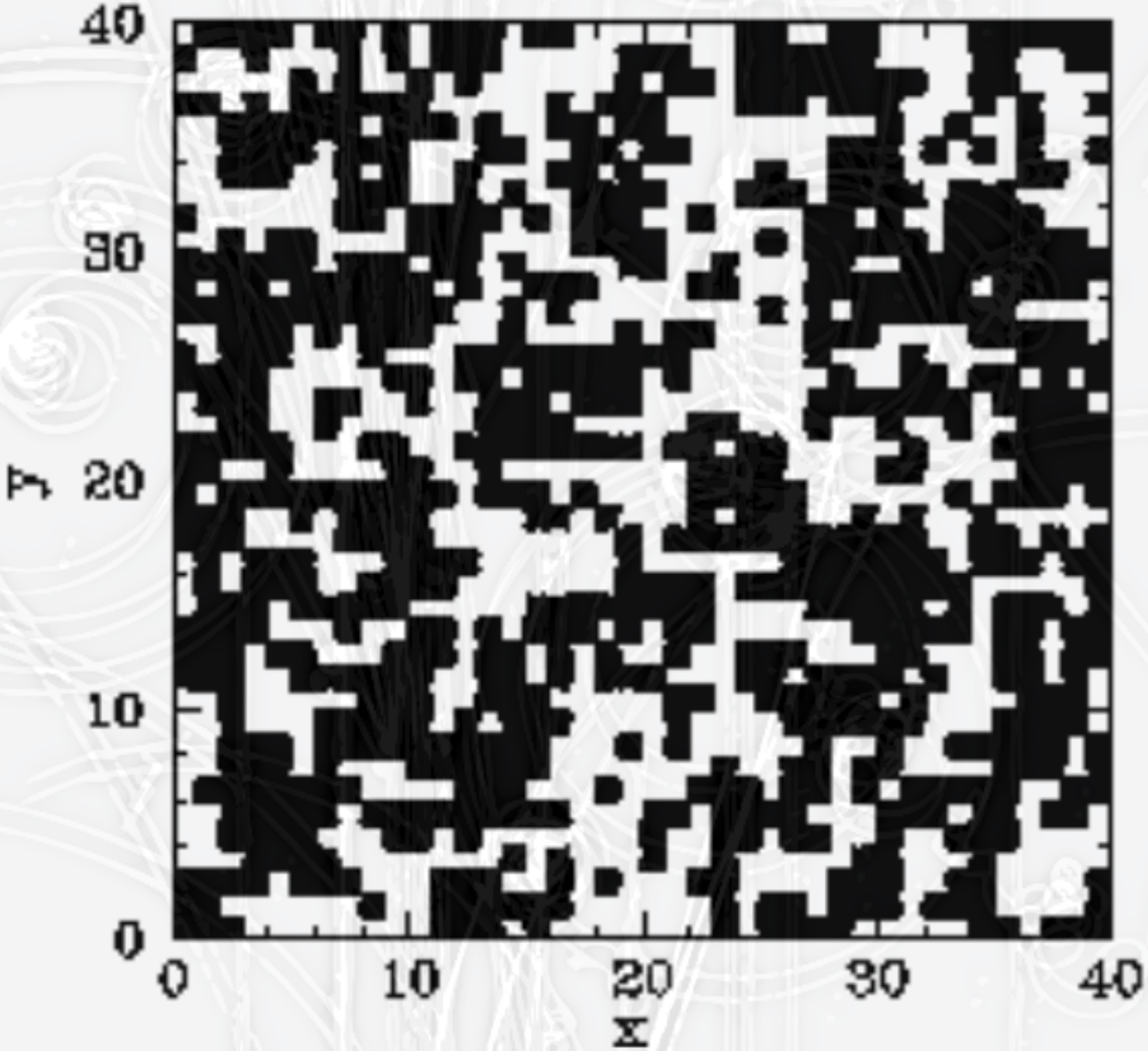

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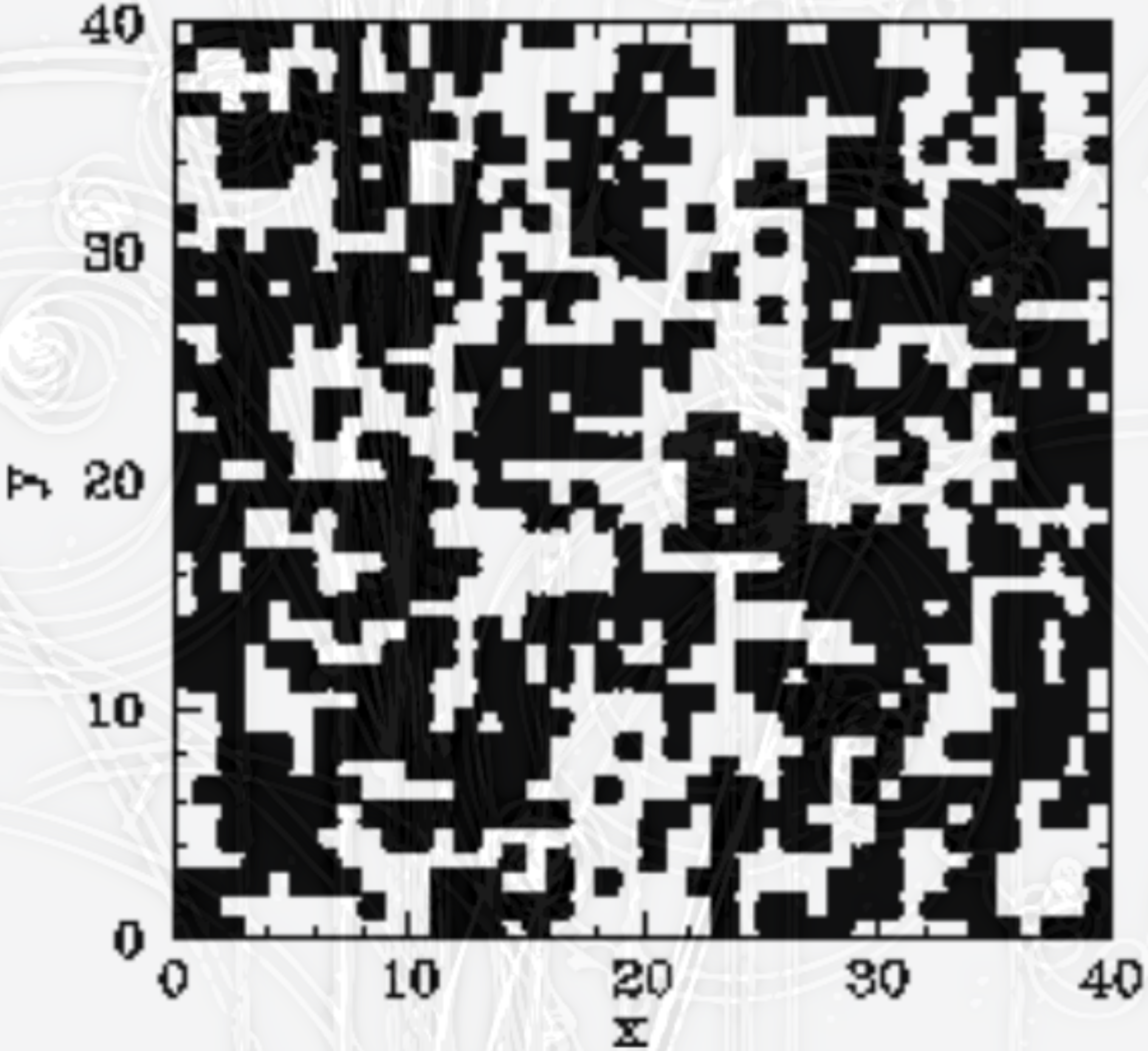

$$s(x) = \pm 1$$

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

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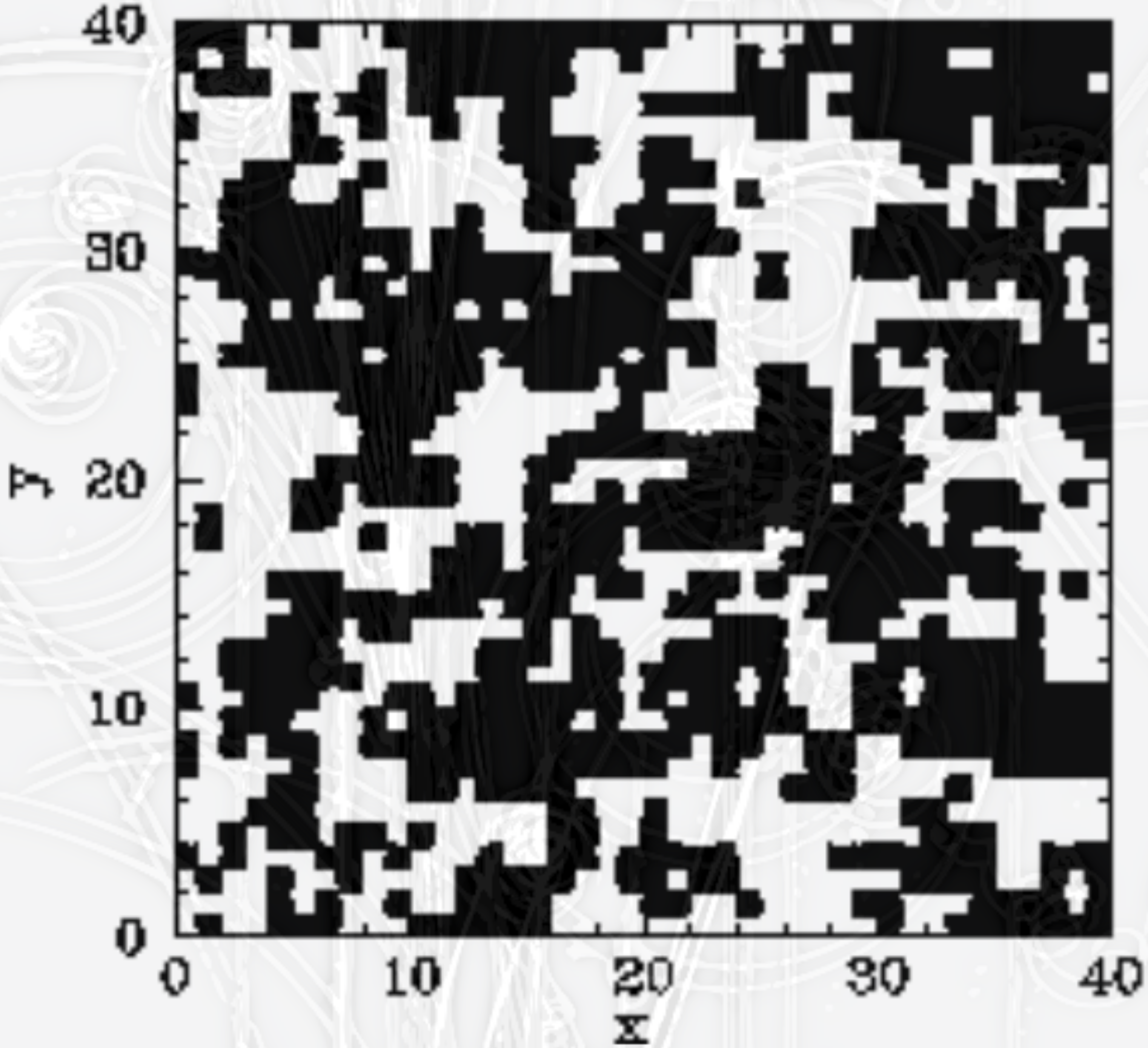

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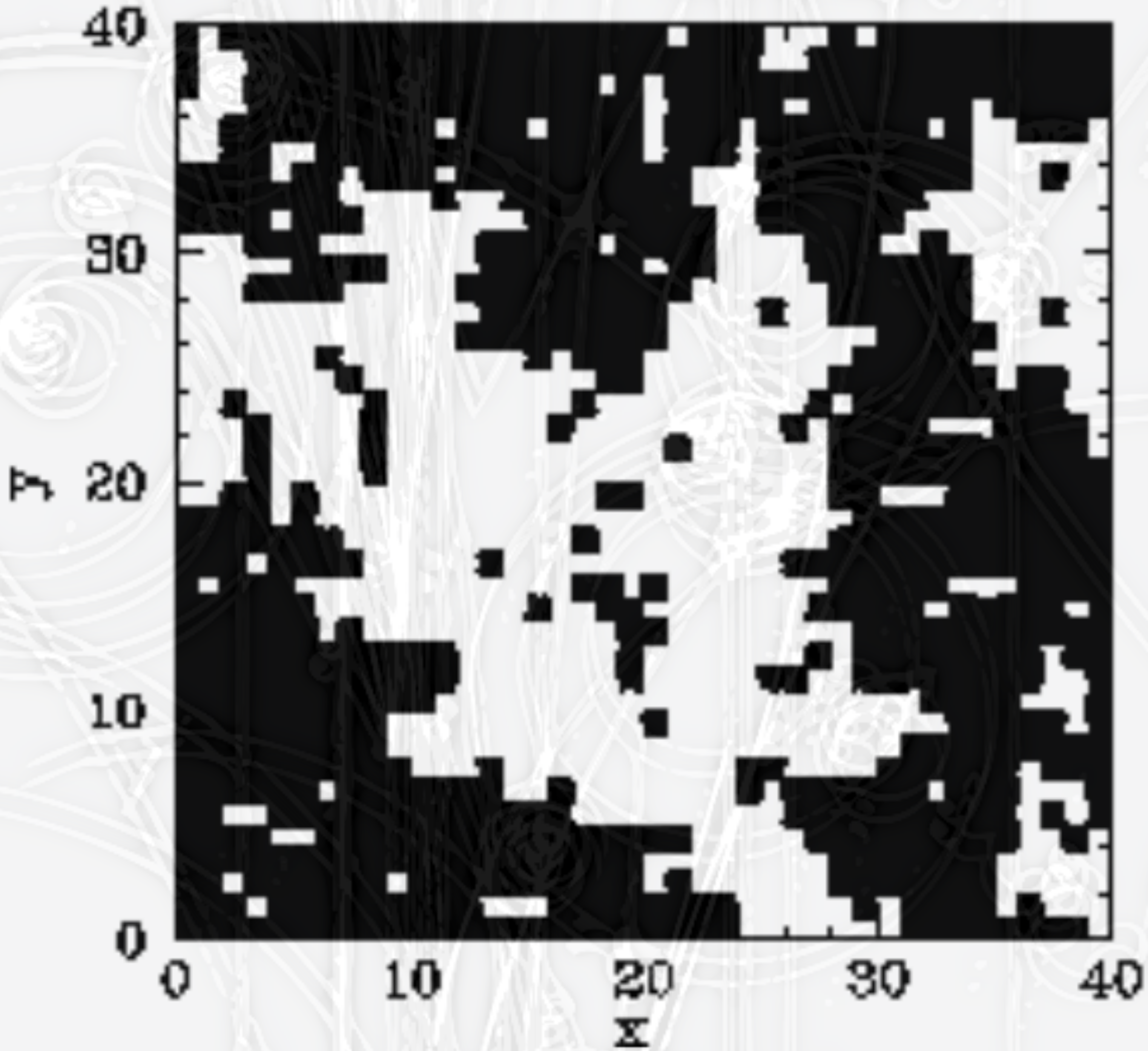

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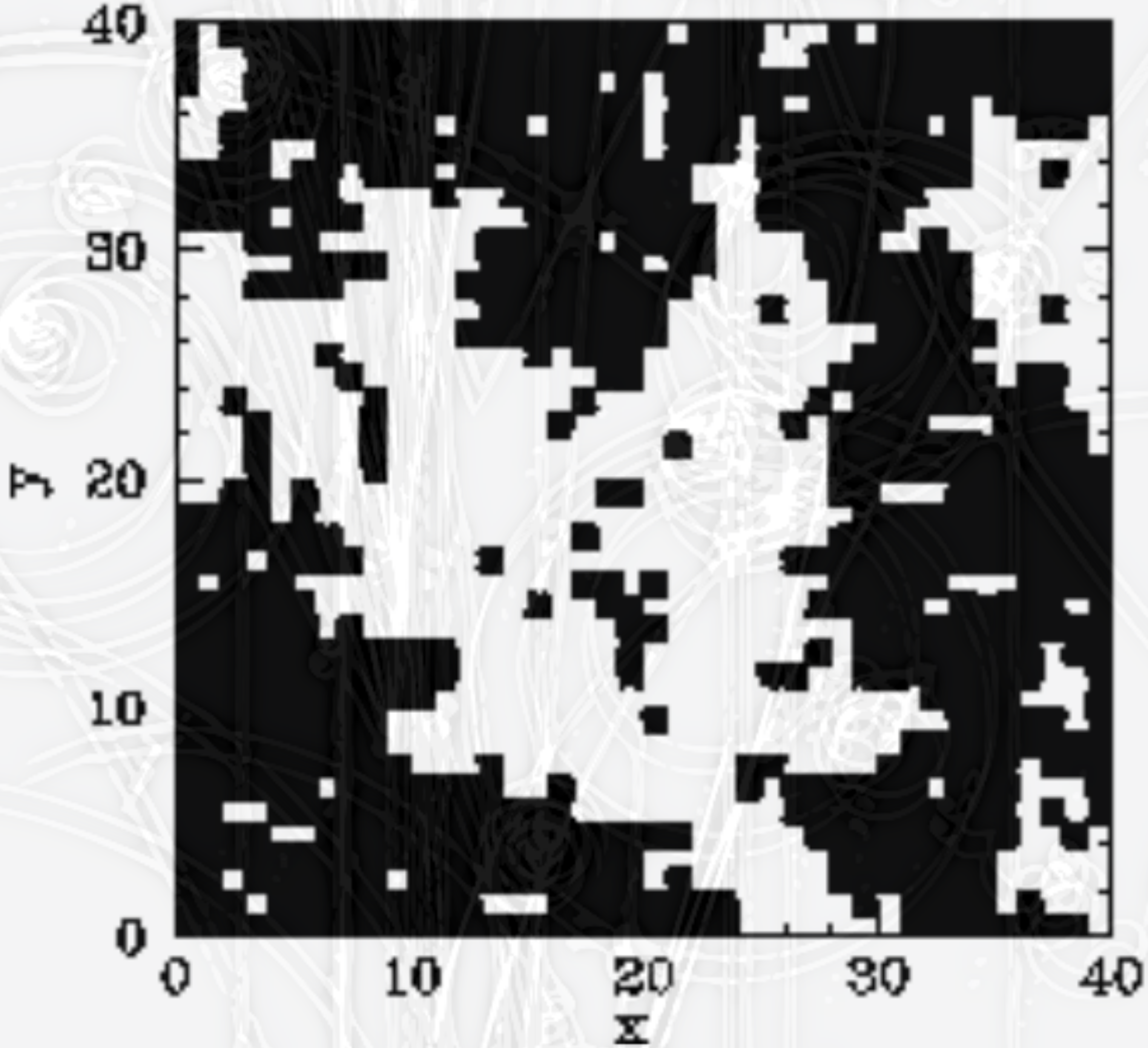

Richard Fitzpatrick

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

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

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

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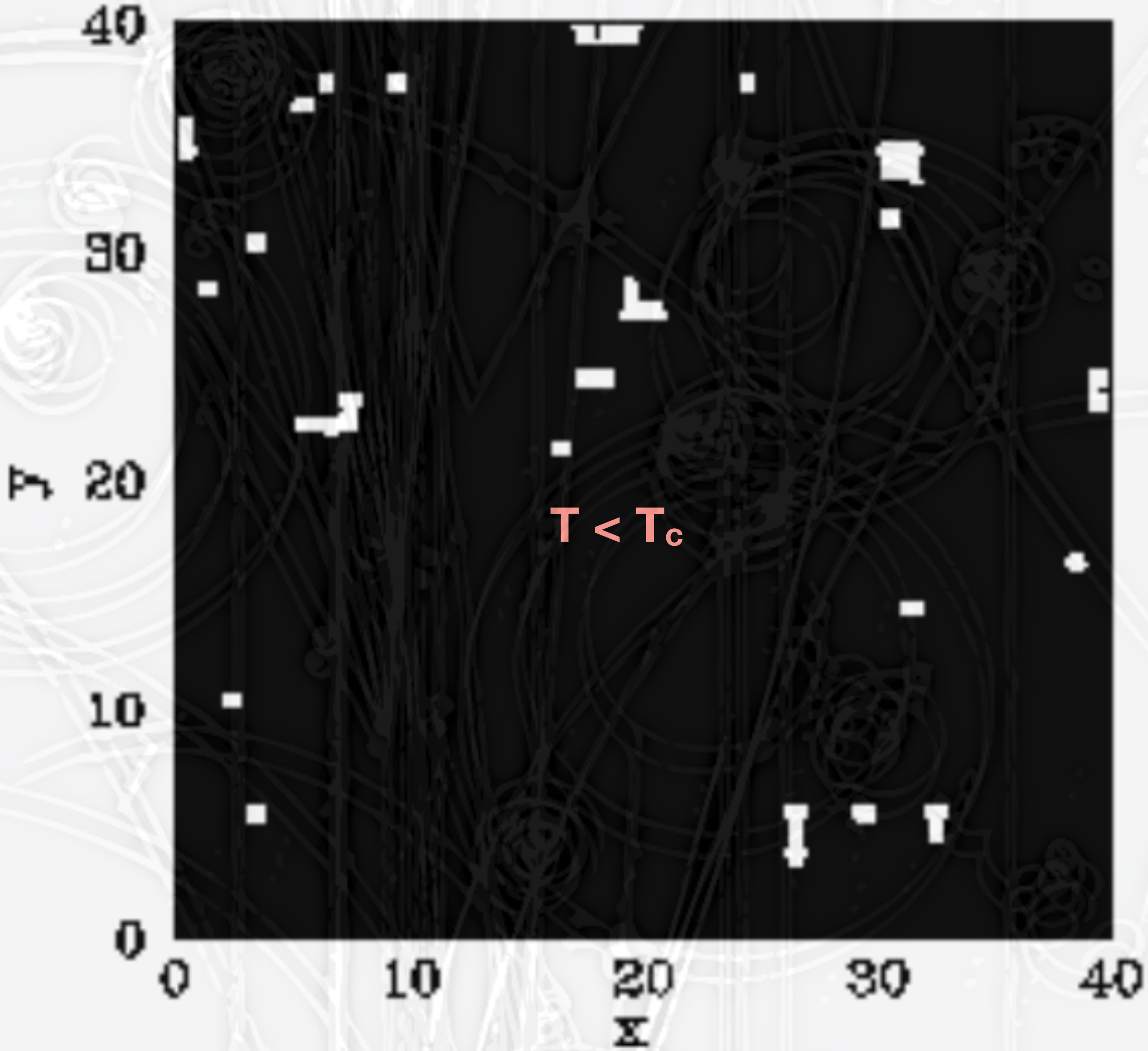

$$s(x) = \pm 1$$

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

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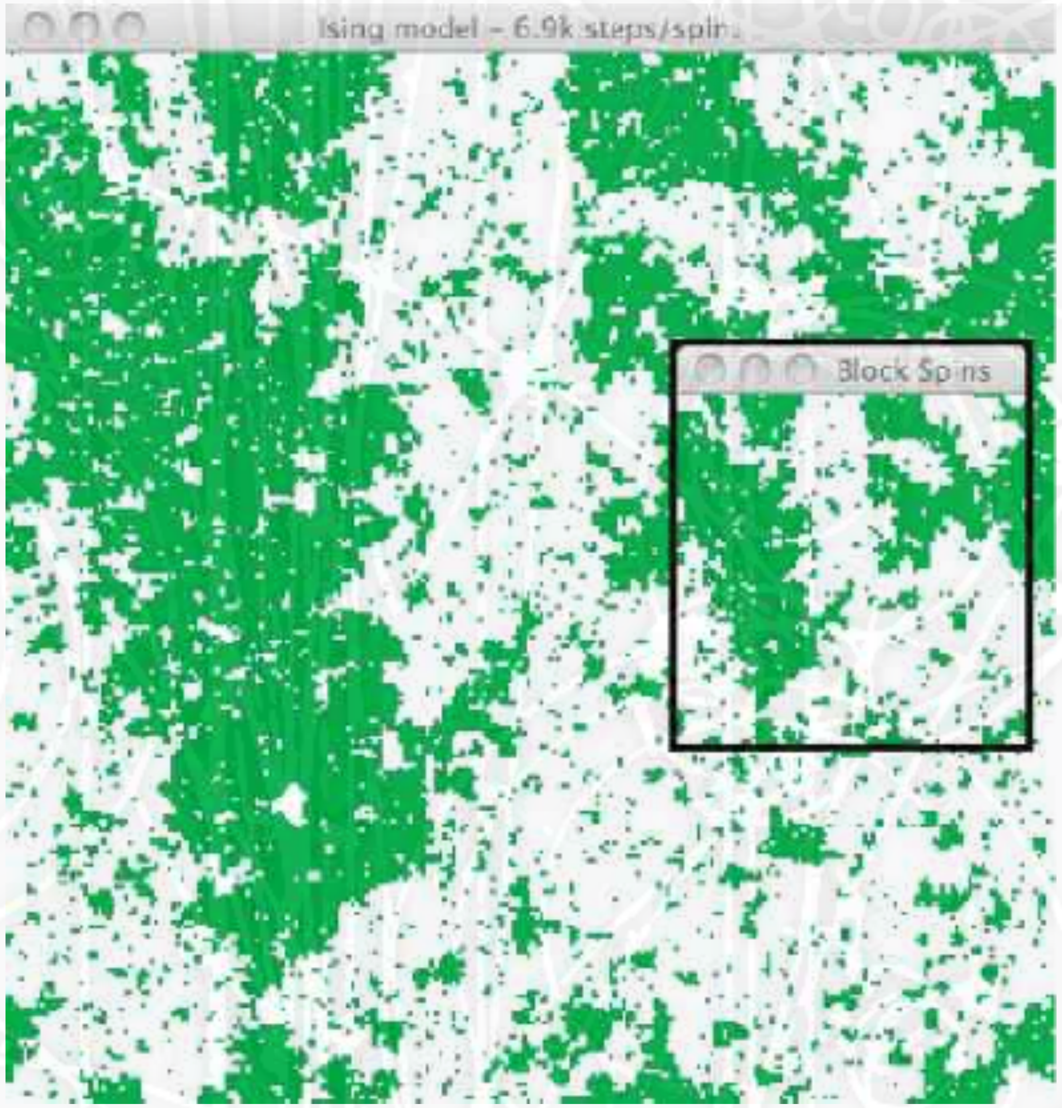
Critical Ising Model is Scale Invariant



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

Courtesy of J. Terning

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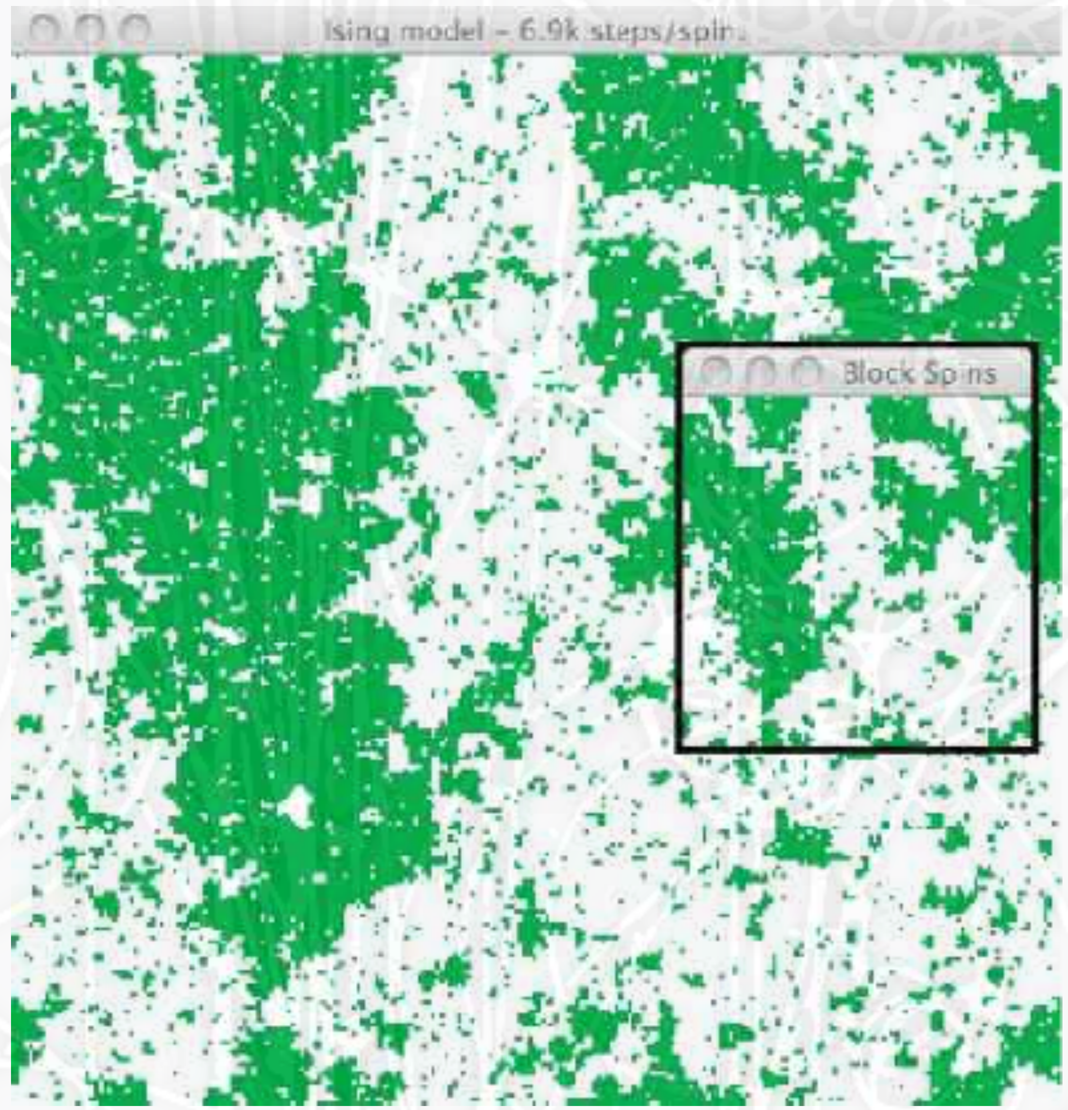


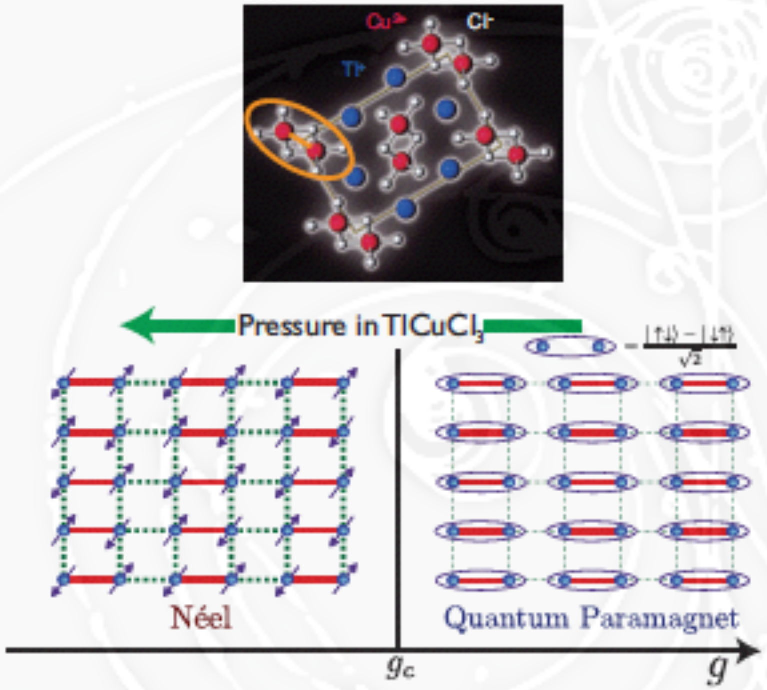
at $T=T_c$ $$\langle s(0)s(x)\rangle \propto \frac{1}{|x|^{2\Delta-1}} = \int d^3p\, \frac{e^{ip\cdot x}}{|p|^{4-2\Delta}}$$

critical exponent

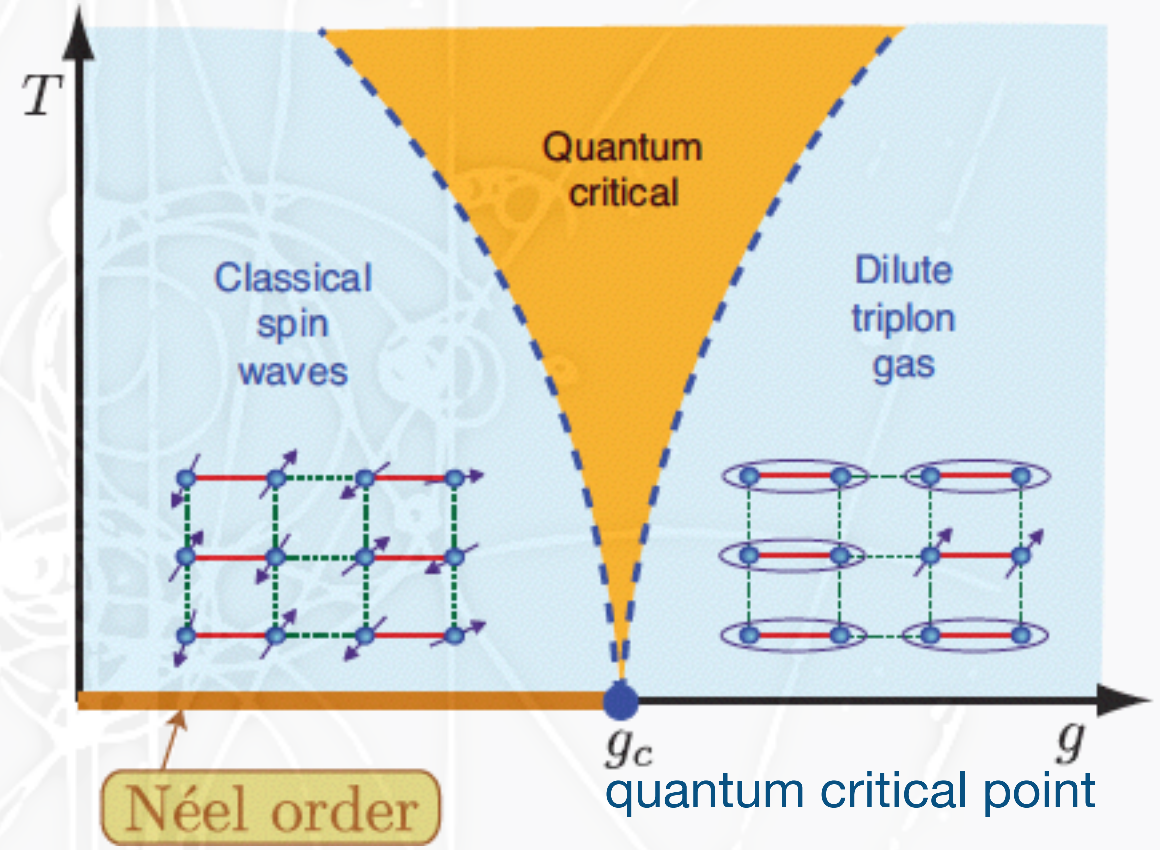
Courtesy of J. Terning

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



Bellazzini, Csaki, Hubisz, SL, Serra, Terning (PRX 2016)

Higgs & Quantum Phase Transition

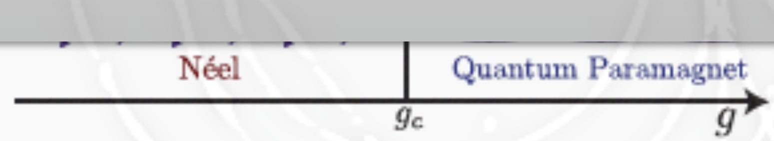
Condensed matter systems can produce a light scalar by tuning the parameters close

rs.

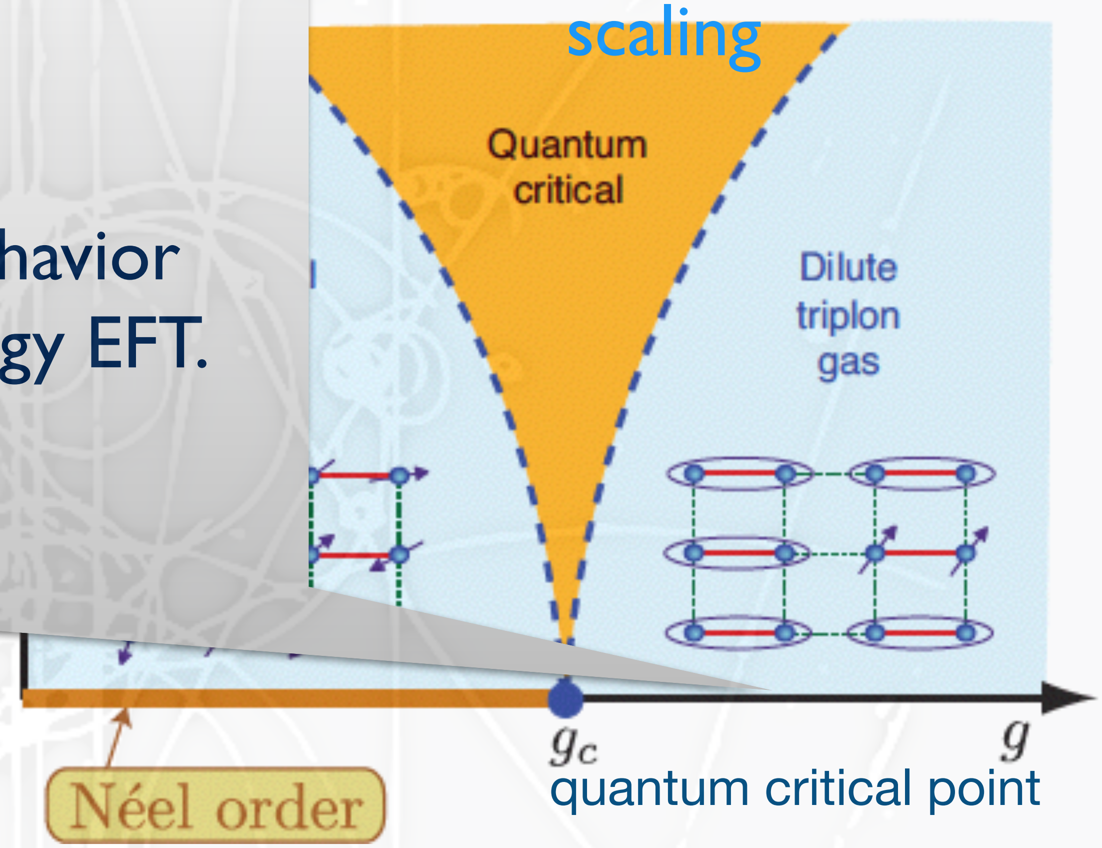
@2nd order QPT, @ critical point, all masses vanish & the theory is scale invariant, characterized by the dimensions of the field,

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

scaling



Sachdev, arXiv:1102.4268



quantum critical point

Bellazzini, Csaki, Hubisz, SL, Serra, Terning (PRX 2016)

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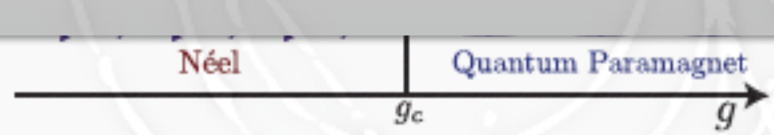

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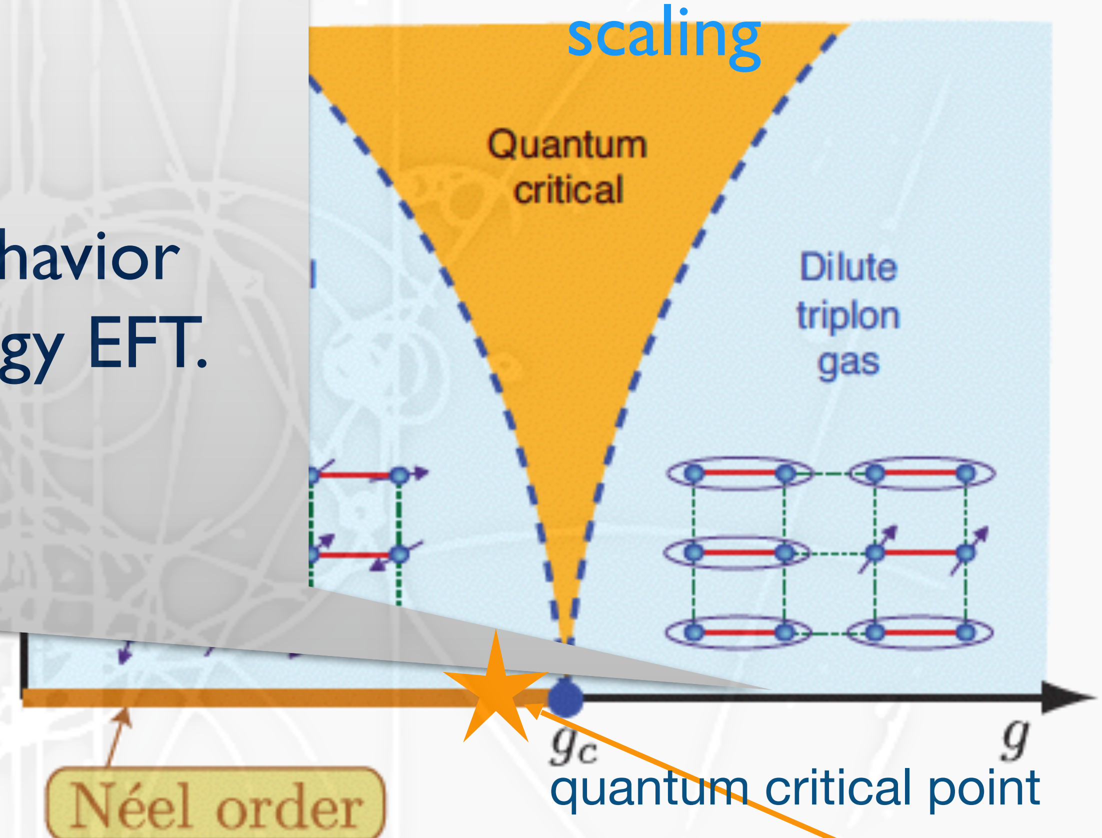

We are here

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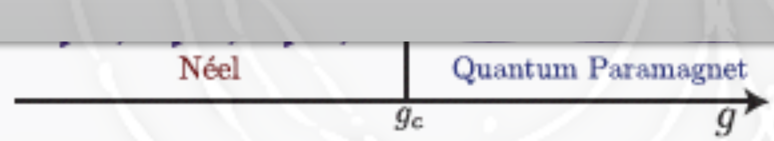

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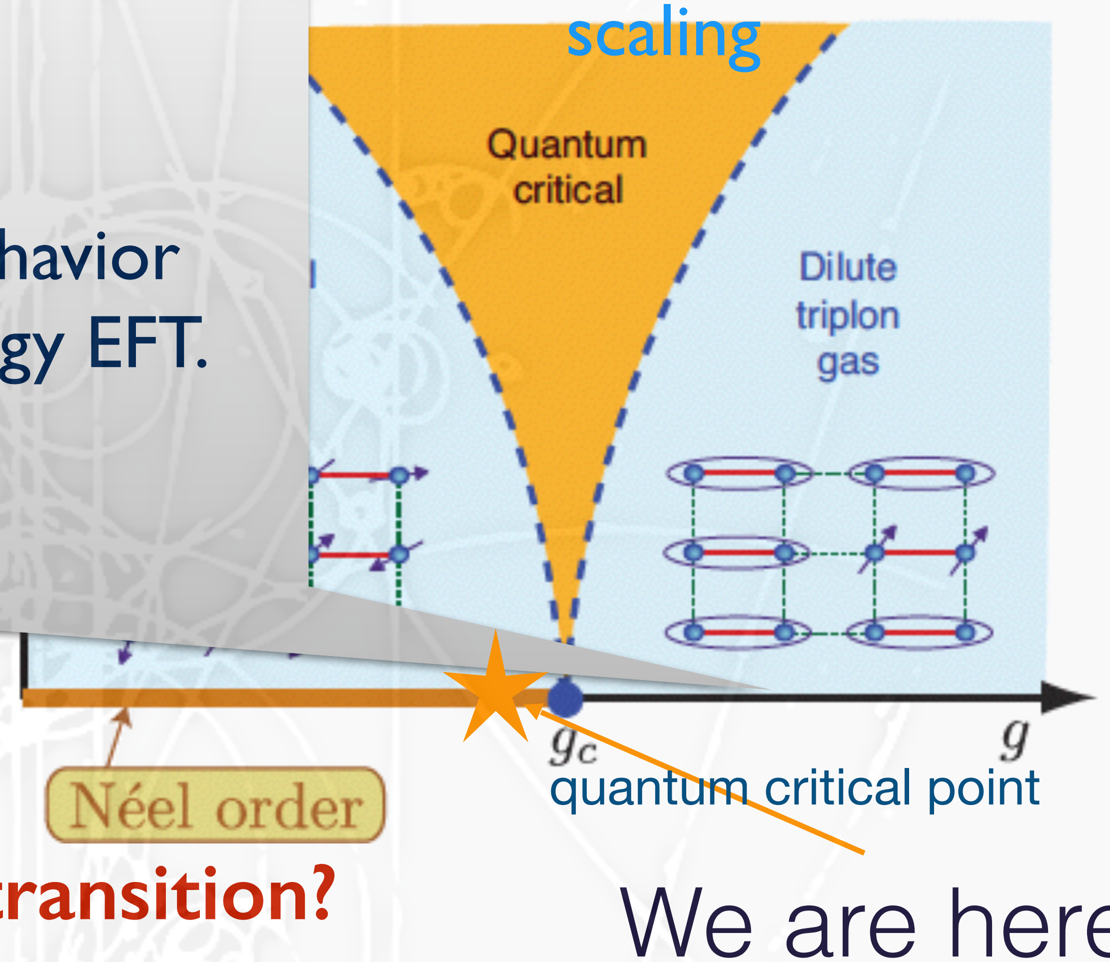

What is the nature of electroweak phase transition?

Does the underlying theory also have a QPT?

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

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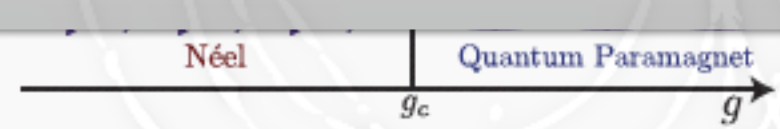

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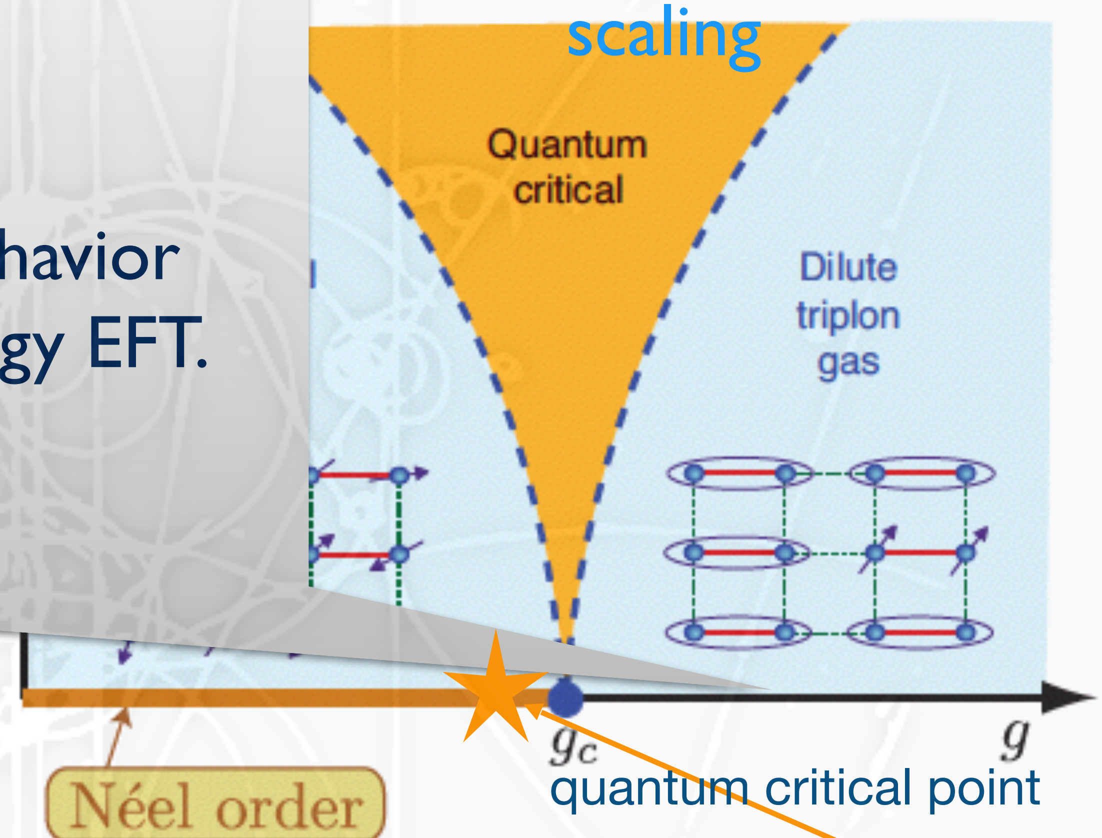

We are here

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

AdS/CFT

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

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

$\mathcal{O} \subset \mathrm{CFT} \leftrightarrow \phi$ AdS_5 field

AdS/CFT

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

$$z > \epsilon$$

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

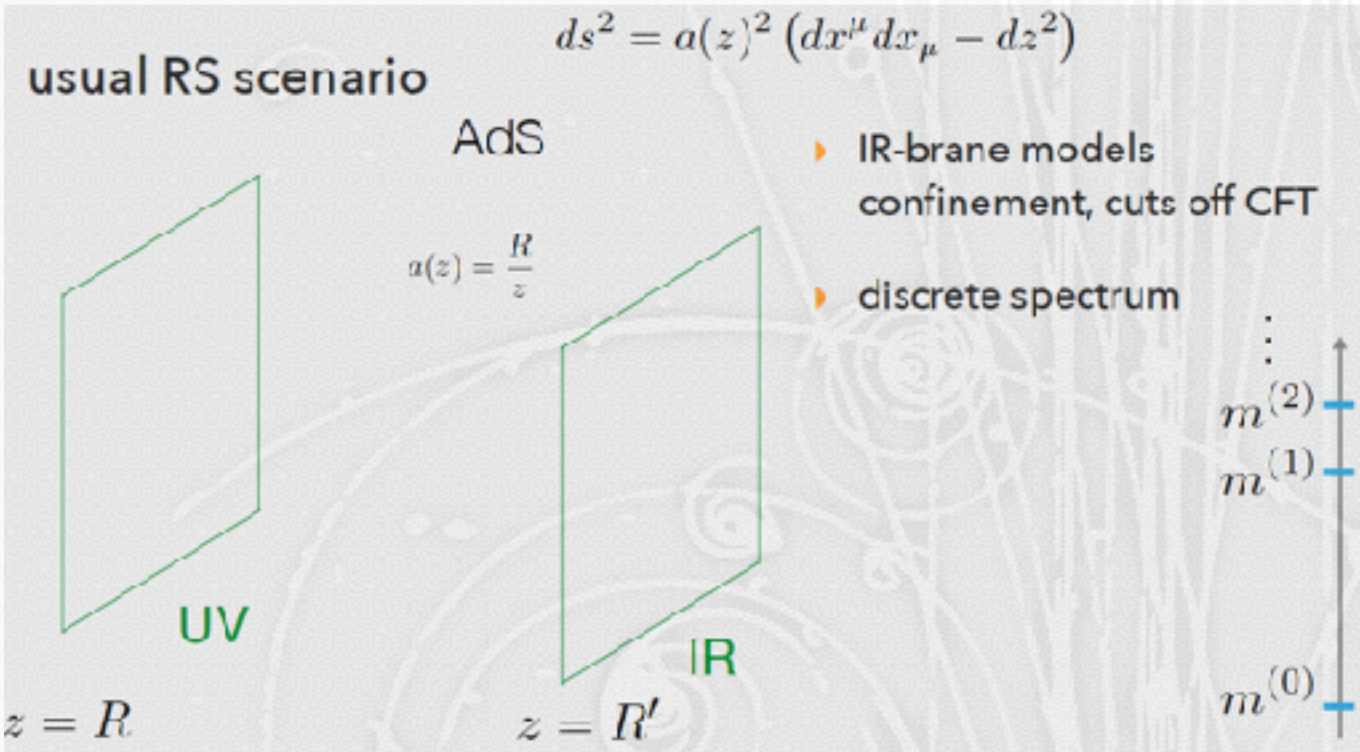
$$\phi(p,z) = az^2 J_\nu(pz) + bz^2 J_{-\nu}(pz)$$

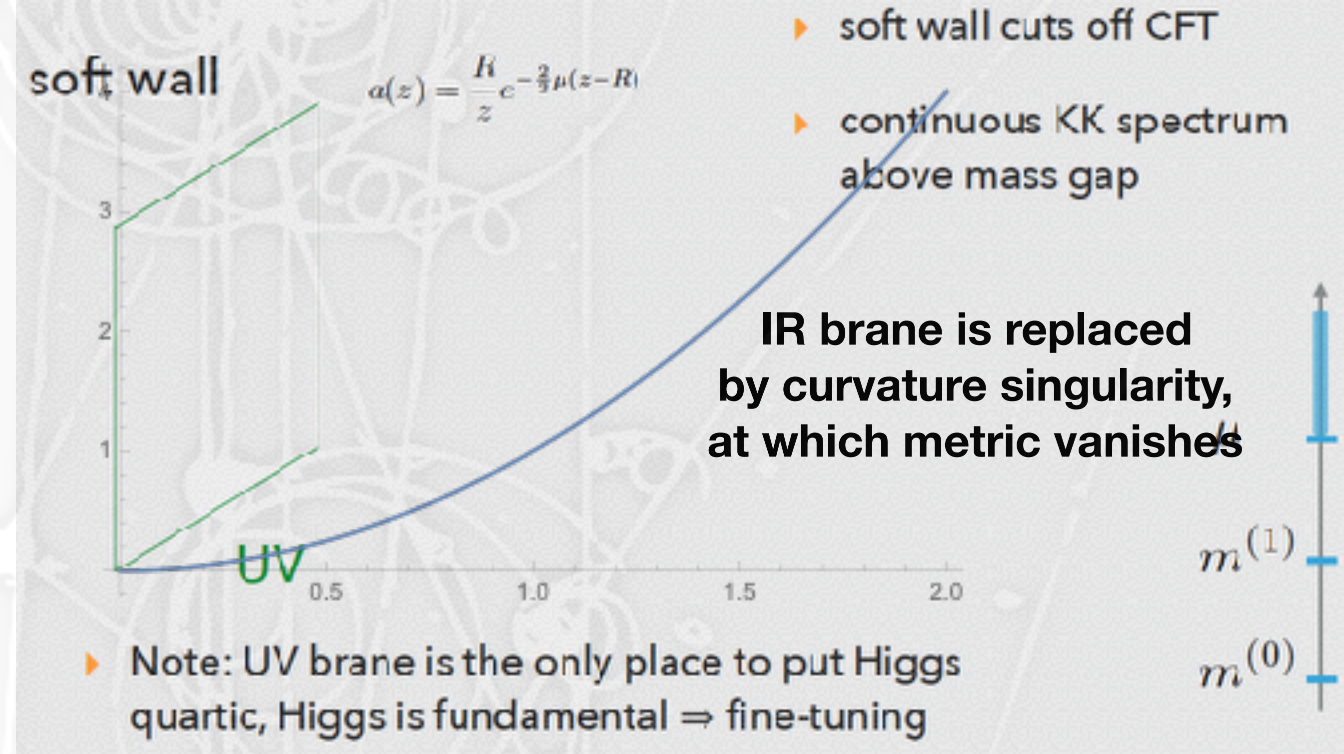
$$\Delta[\mathcal{O}] = 2 \pm \nu = 2 \pm \sqrt{4 + m^2R^2}$$

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

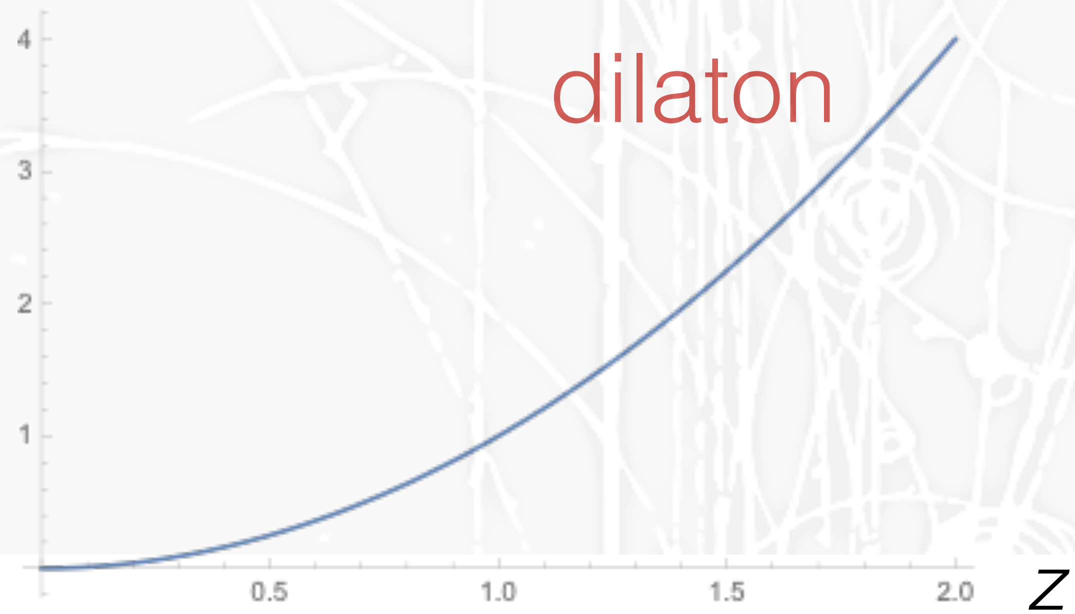
Witten, Klebanov 99'

broken CFT



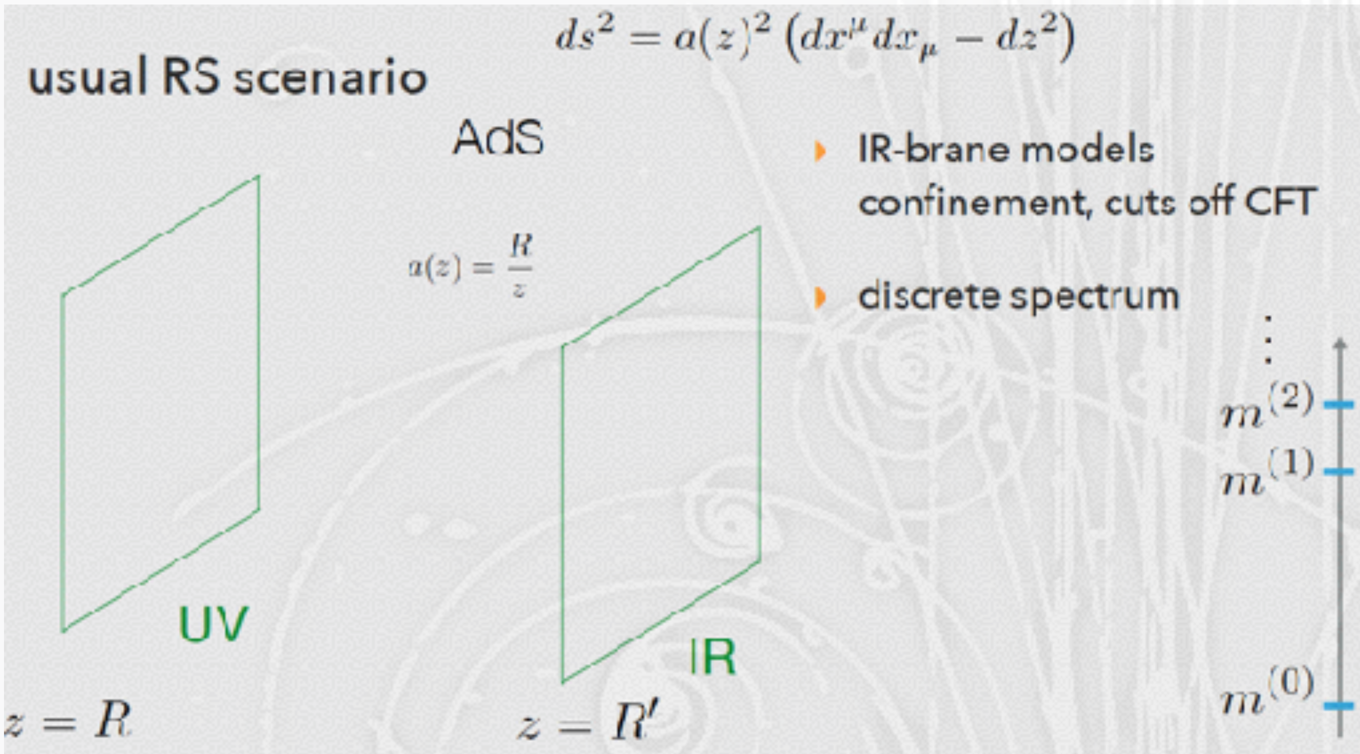


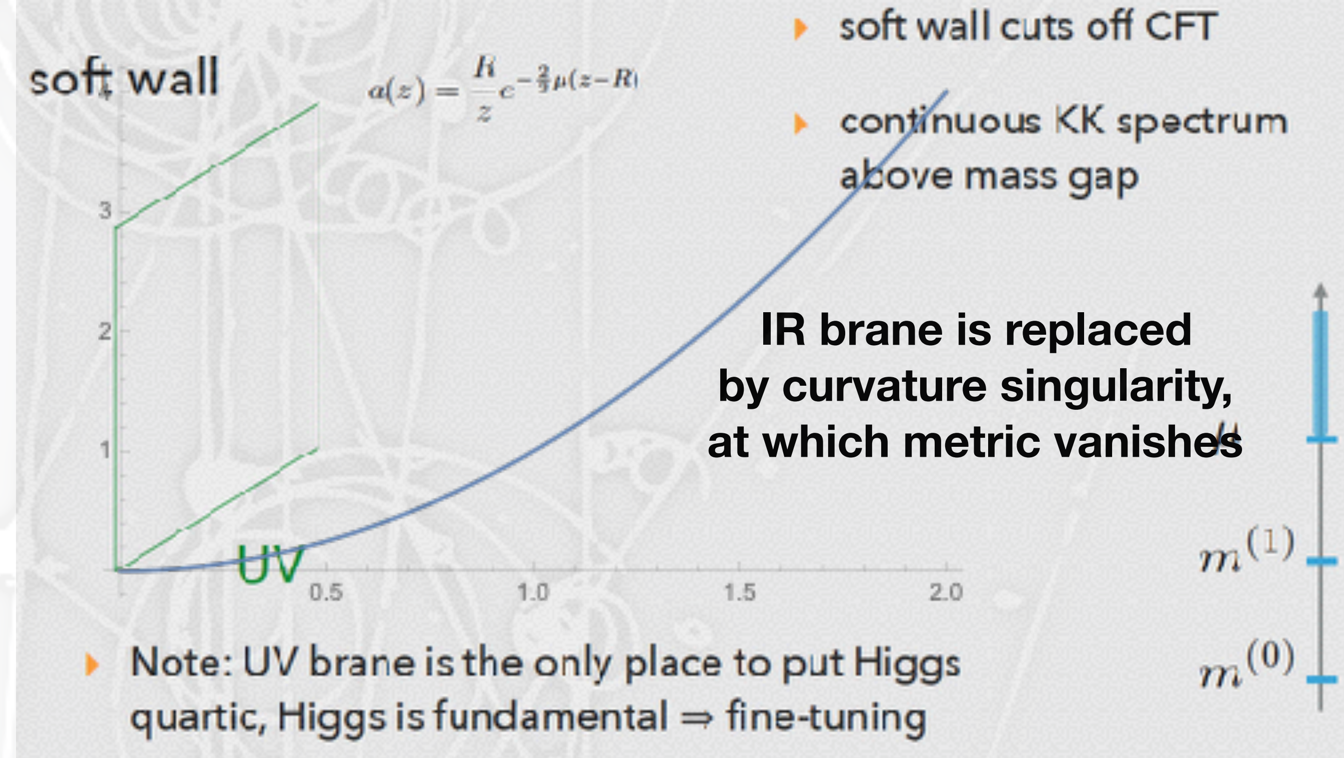
- Randall Sundrum 2 (only UV brane and bulk): cuts from 0 (CFT)
- RS1: putting IR cutoff at TeV
- New type of IR cutoff (soft wall) gives rise to a different phenomenology



Karch, Katz, Son, Stephaniv 06`

broken CFT





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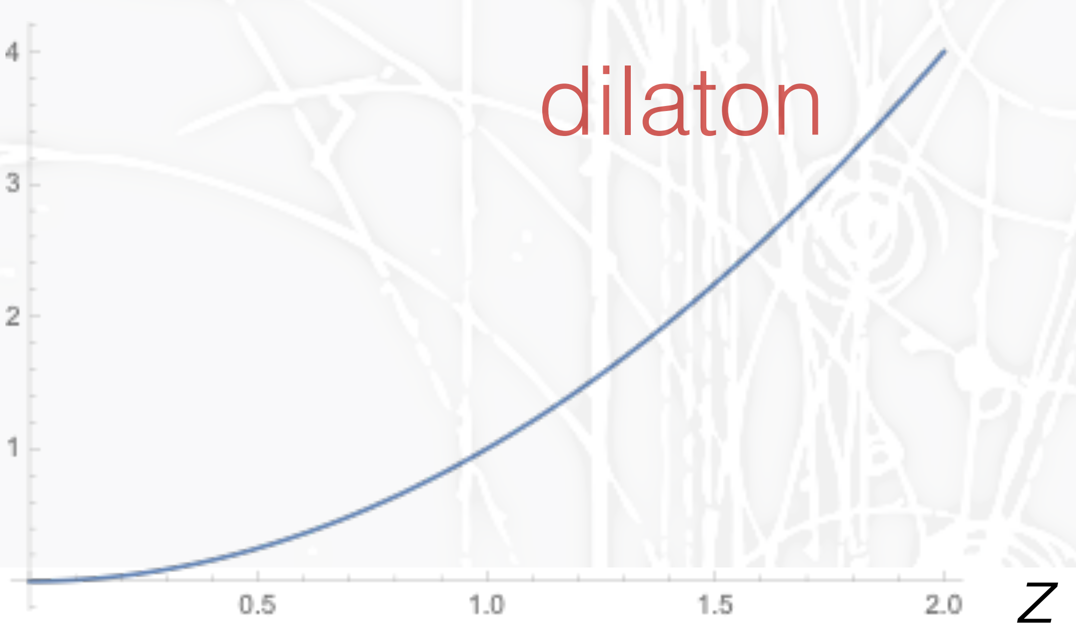

scalar getting VEV => marginal deformation of CFT

Karch, Katz, Son, Stephaniv 06`

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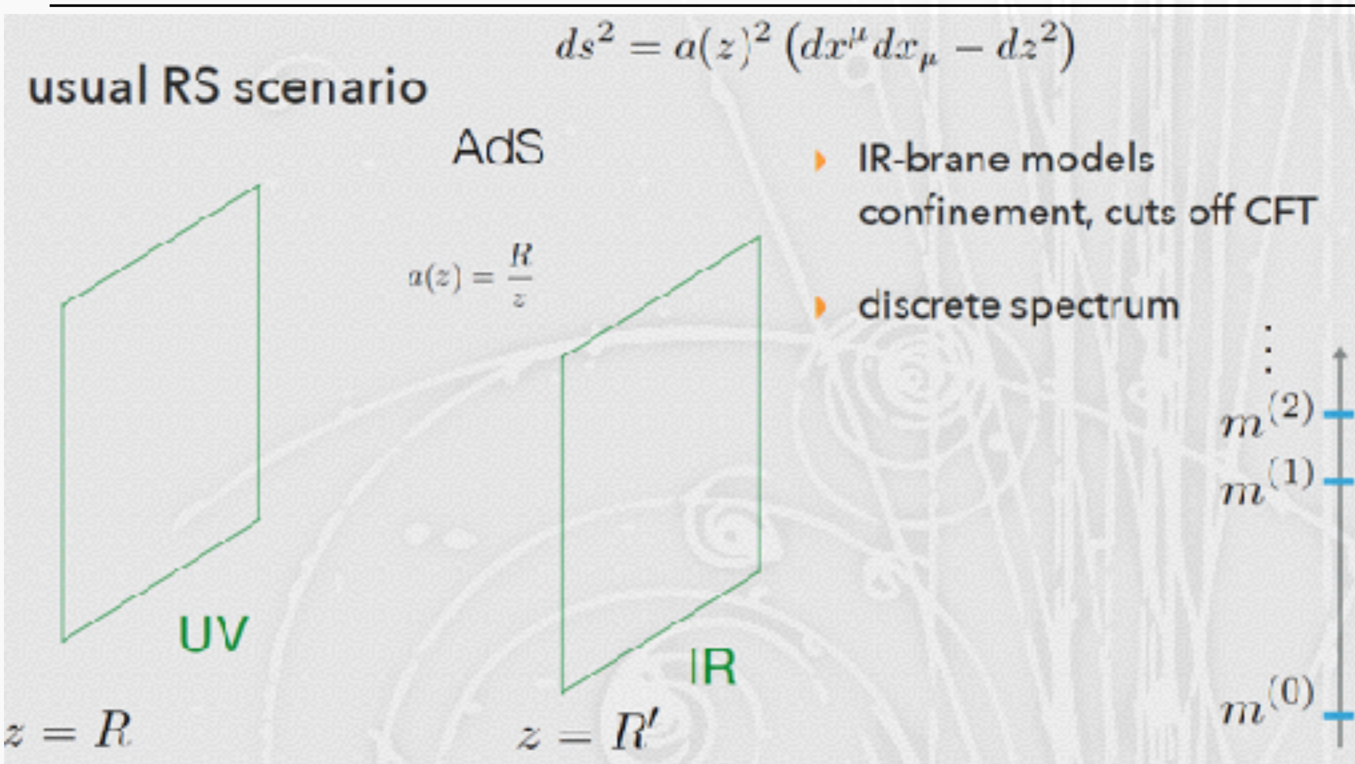

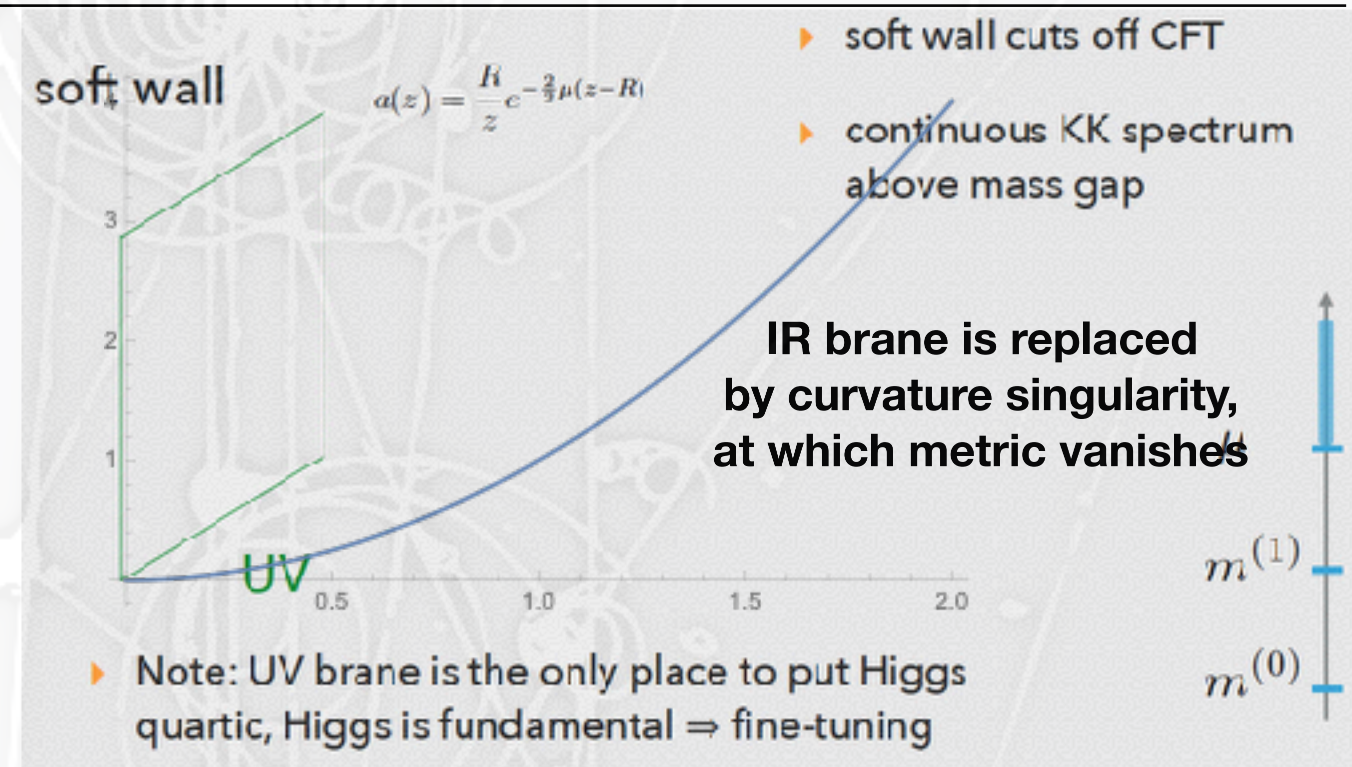

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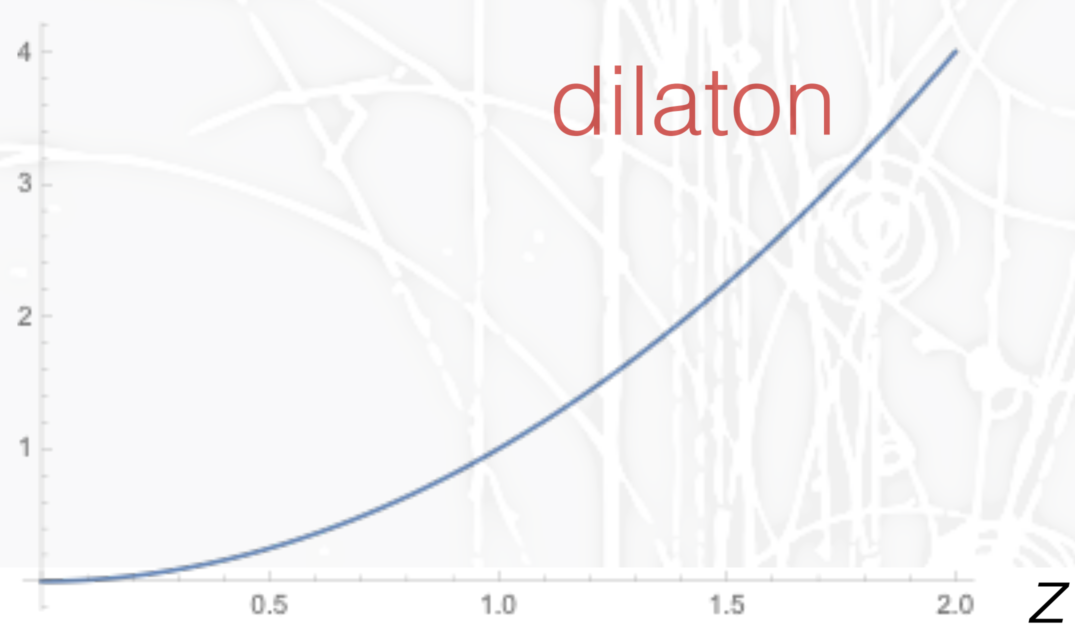


Karch, Katz, Son, Stephaniv 06`

broken CFT by IR cutoff

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

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

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

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

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

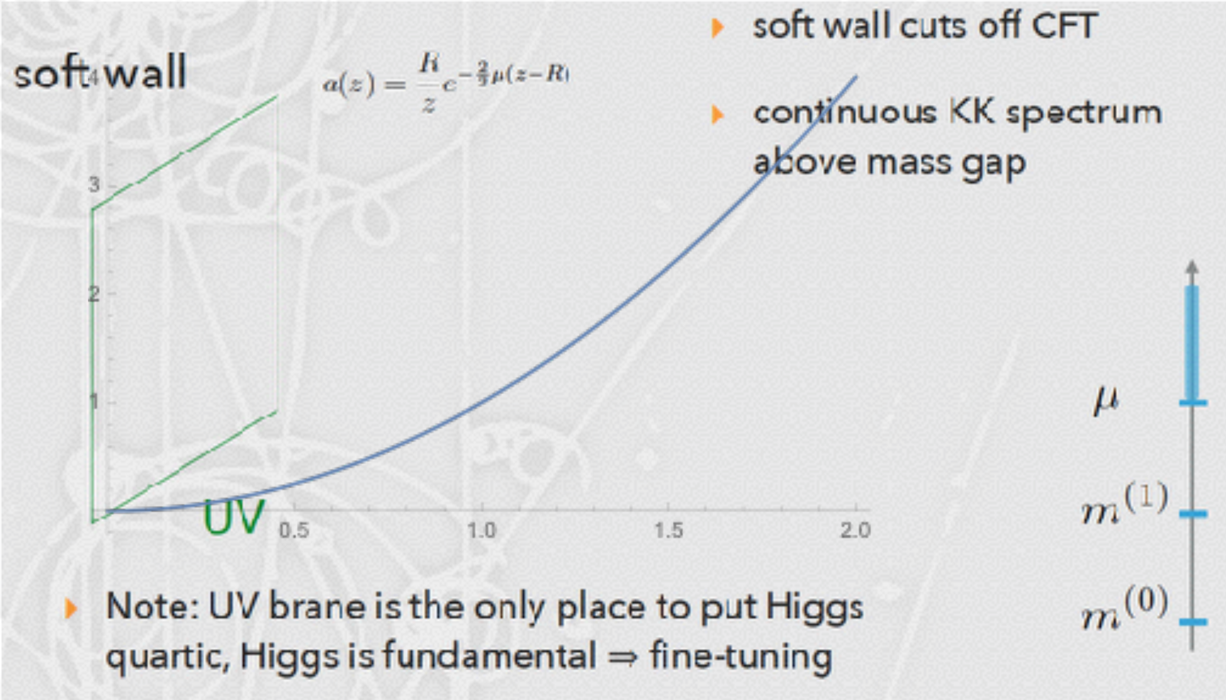
5D UnHiggs: Falkowski, Perez-Victoria

soft wall (AdS/QCD)

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

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

$$S_{\text{gauge}} = \int d^5x\, -\frac{1}{4} a(z) F^{a2}_{MN}$$

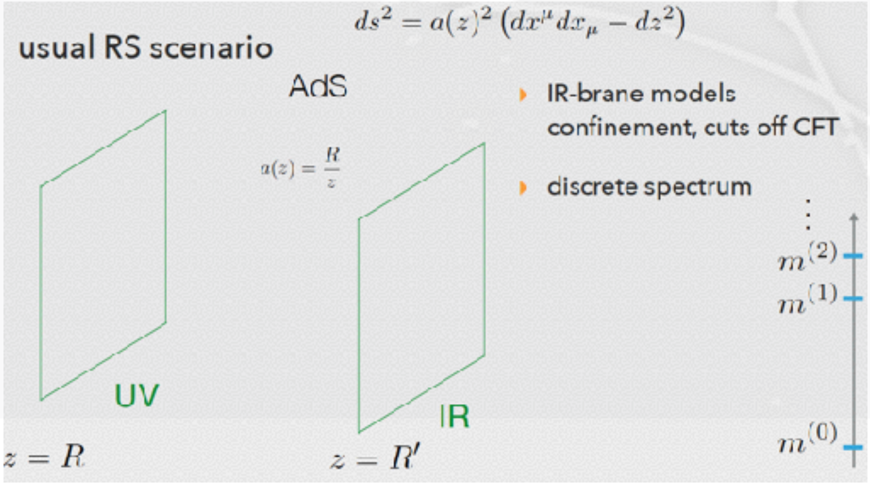


EOM: $\left(a^{-1}\partial_z(a\partial_z) + p^2\right) f = 0$ $\quad f = a^{-\frac{1}{2}}\Psi$

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

$$V(z)\big|_{z\to\infty} \to \left(\frac{\mu}{3}\right)^2$$

=> continuum begins at: $p^2 = (\mu/3)^2$



$\to \infty$ (infinite well) => KK towers

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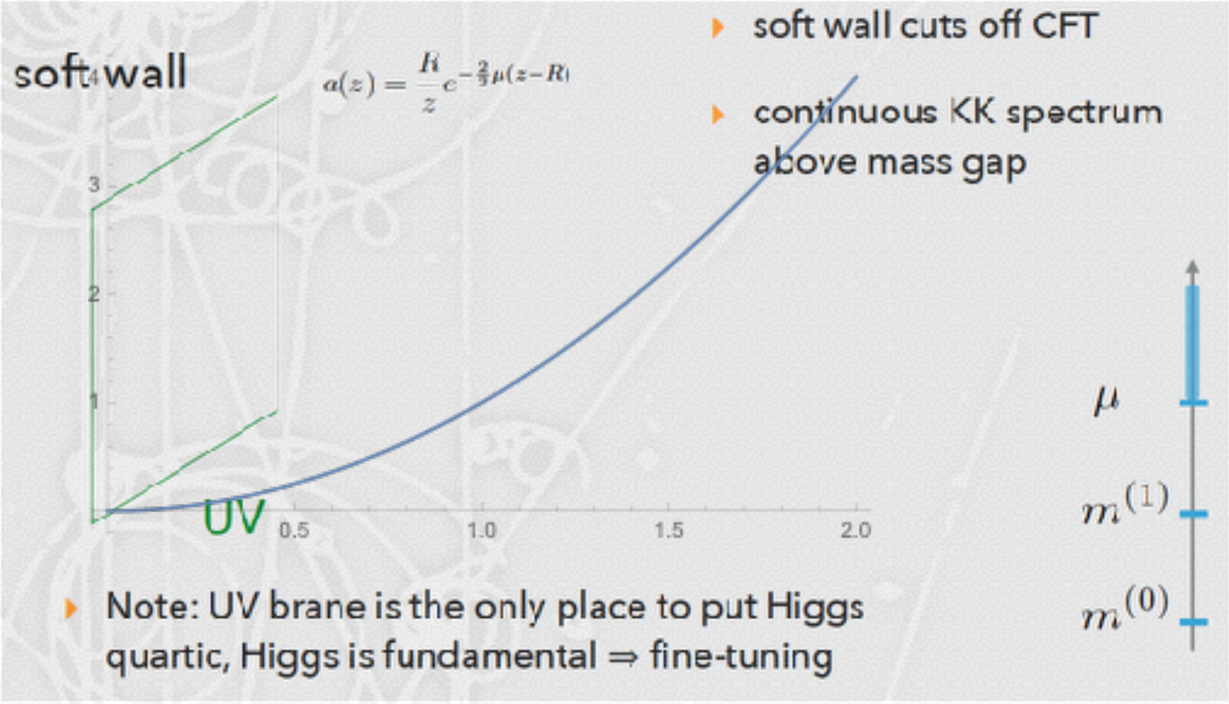

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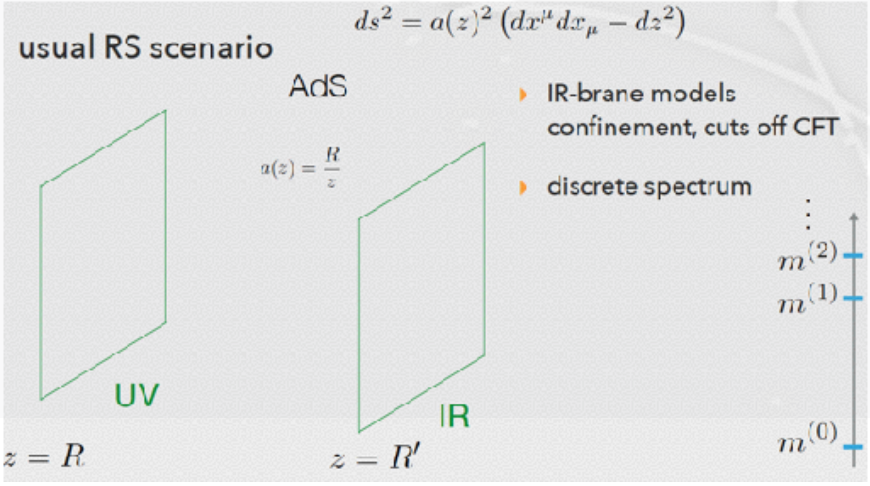

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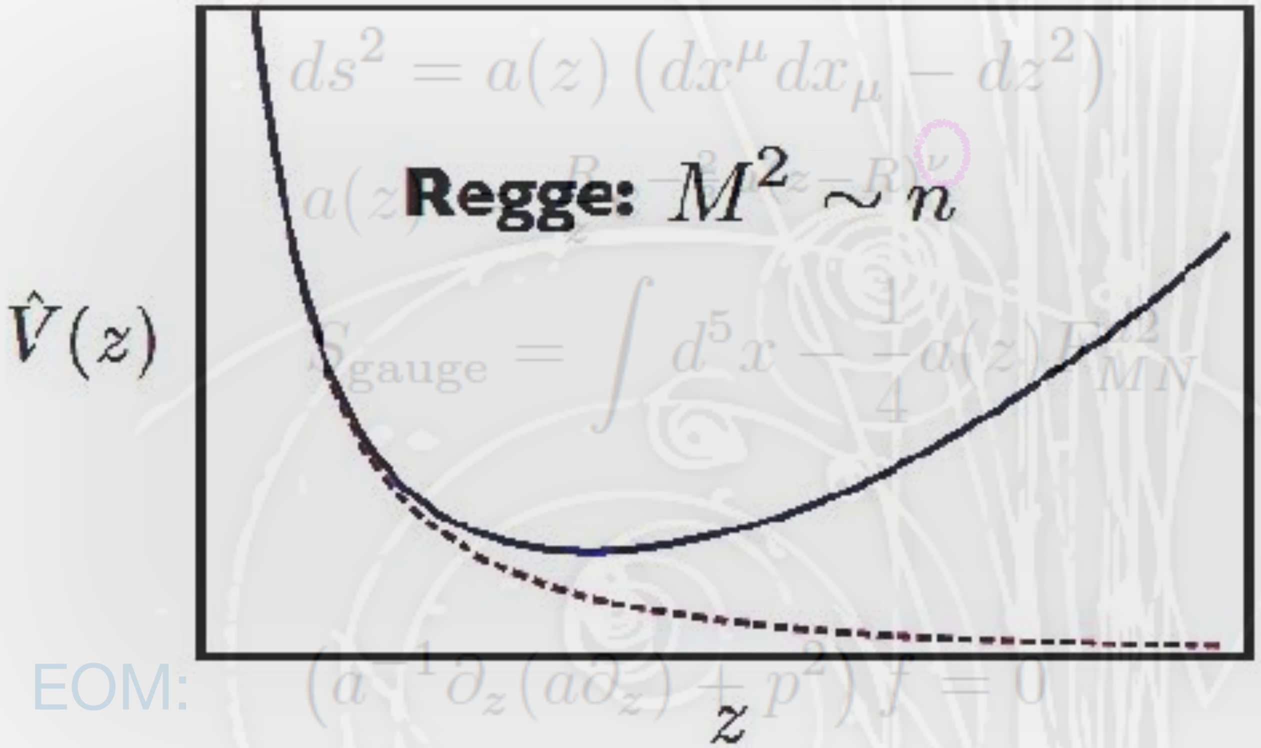

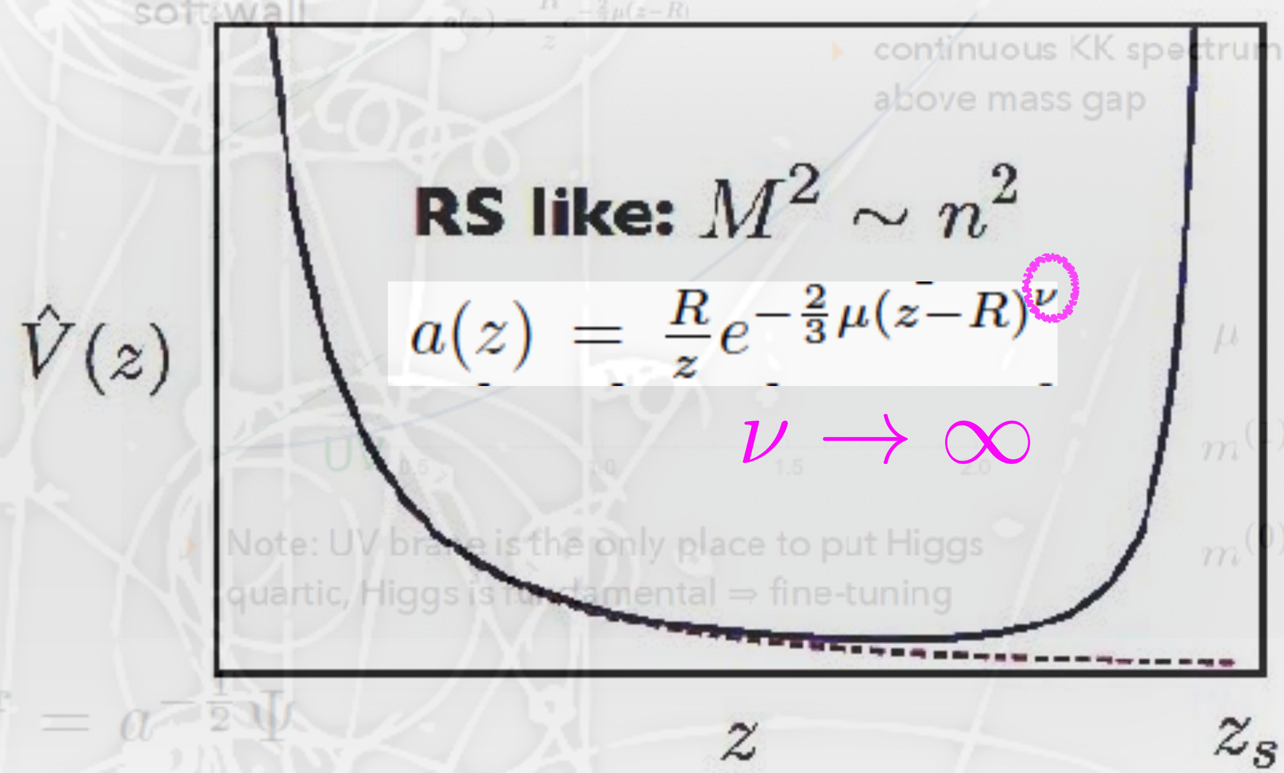

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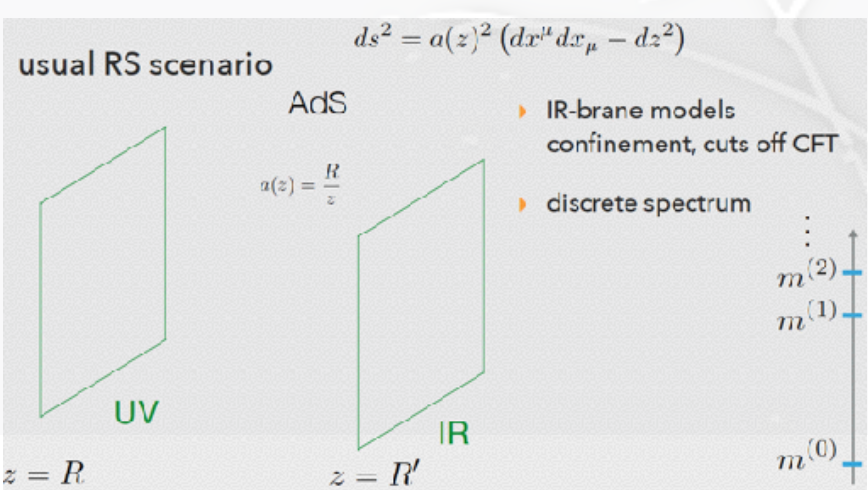

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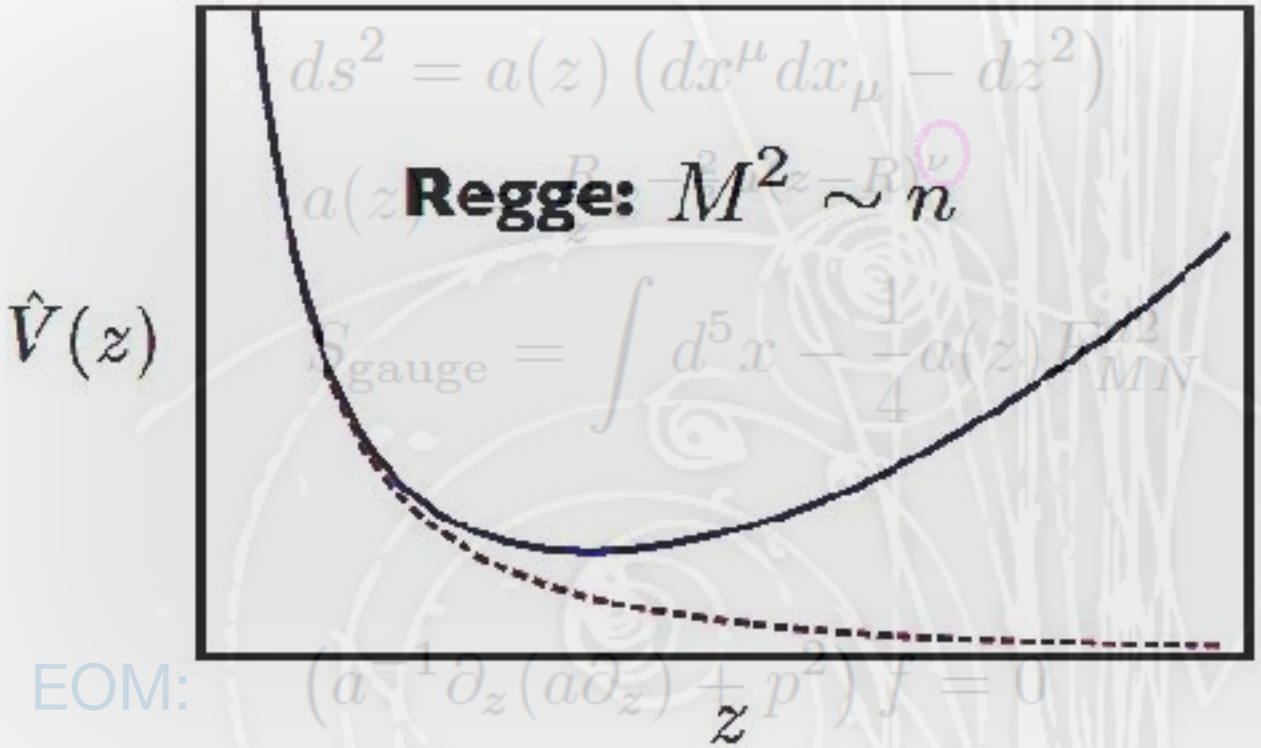

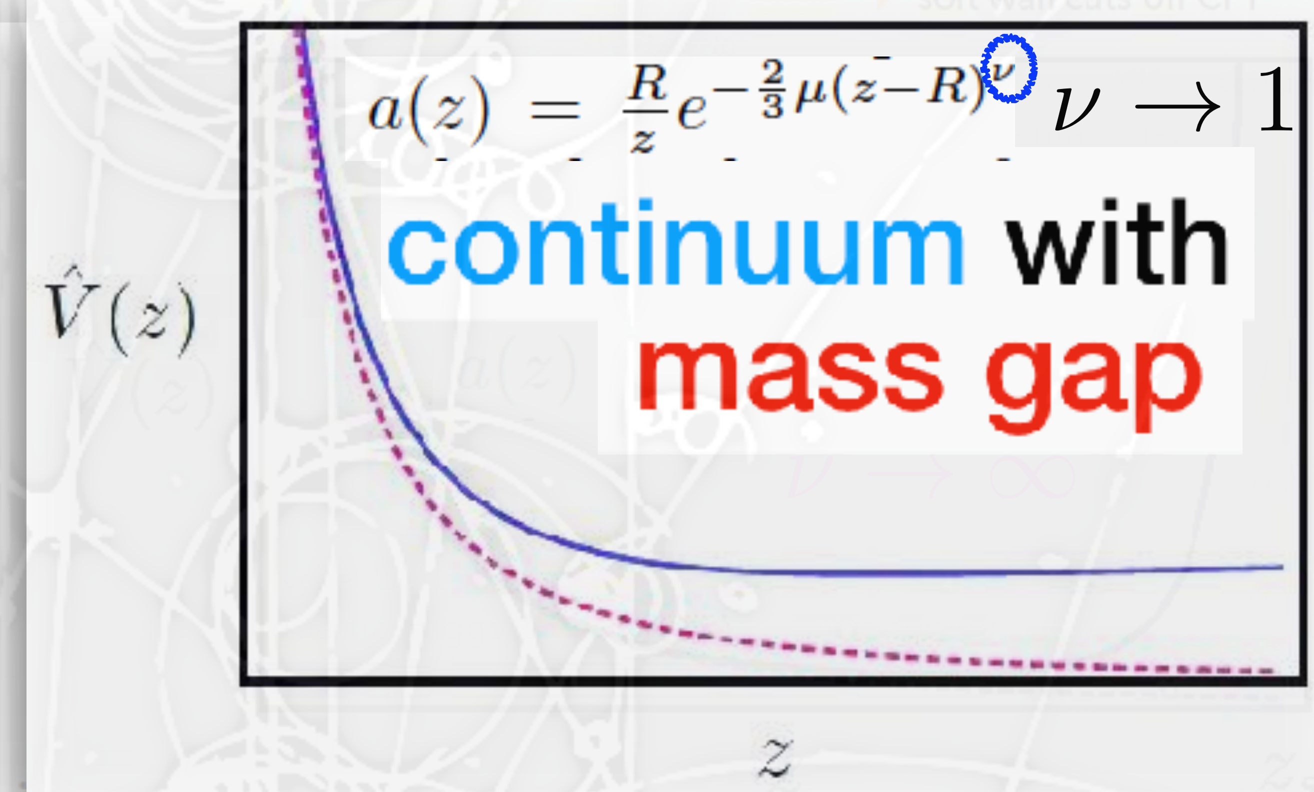

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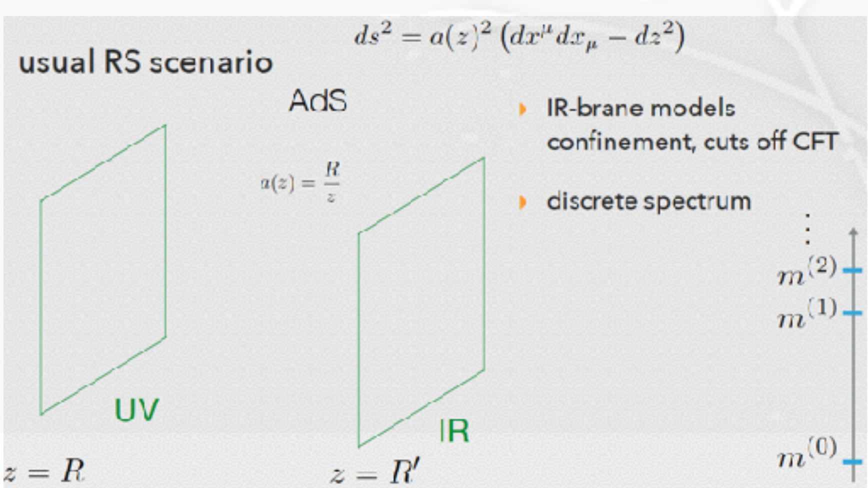

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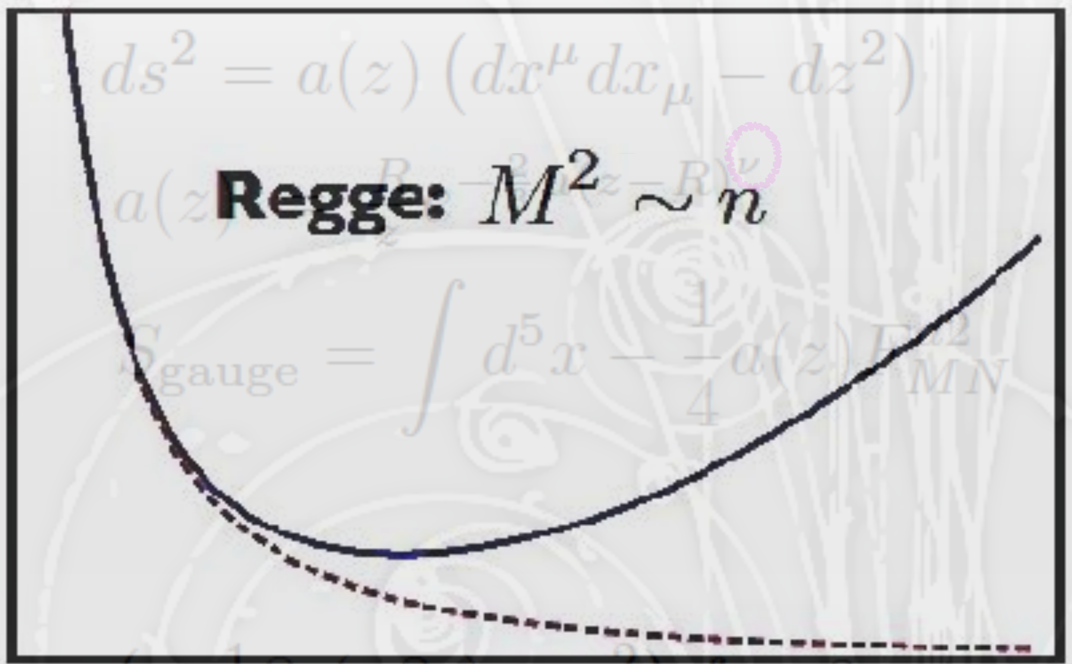

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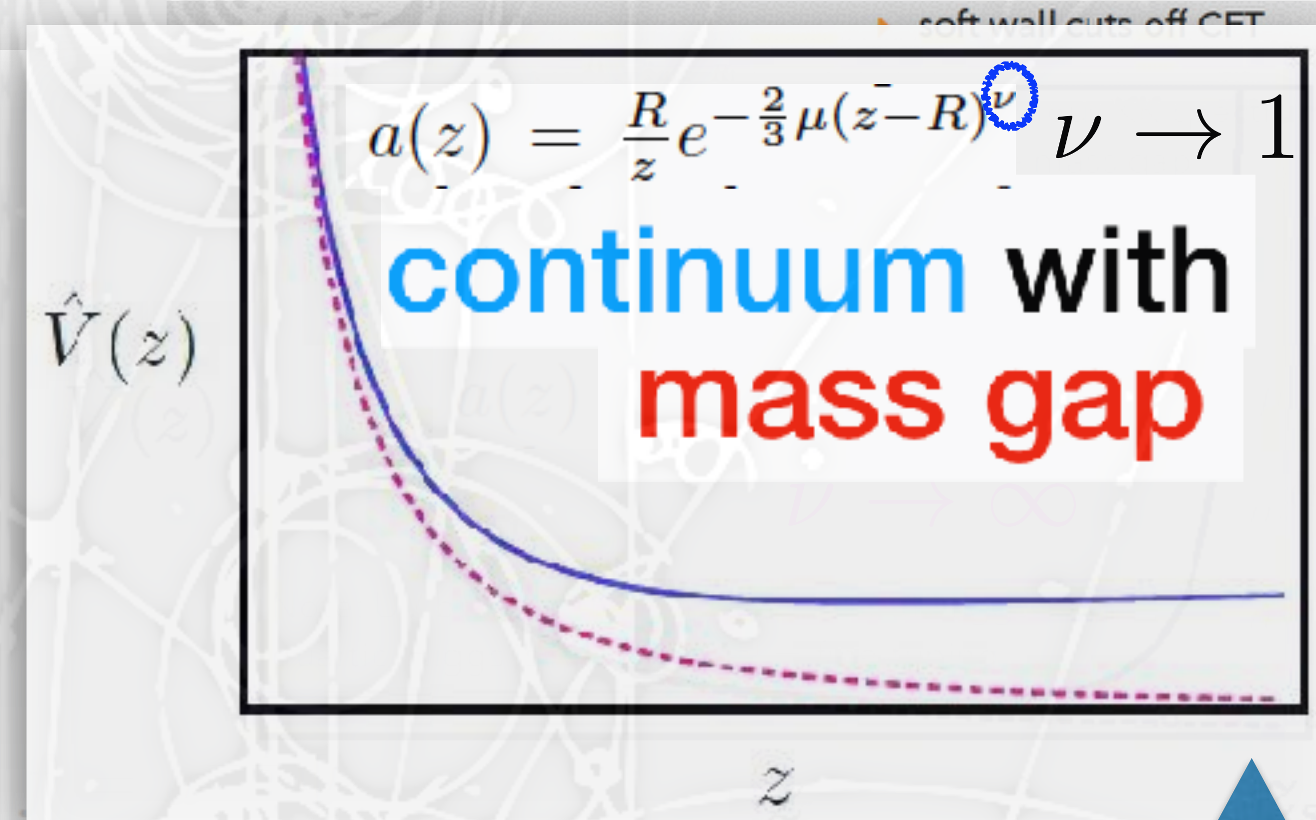

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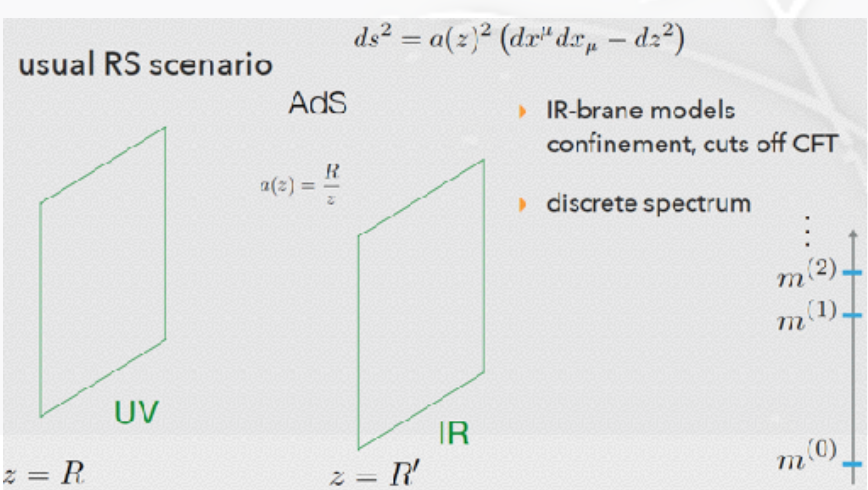
Stabilization of this setting:

Batell, Gherghetta, Sword '08
Cabrer, Gersdorff , Quiros '09

$$V(z)\big|_{z\to\infty} \to \left(\frac{\mu}{3}\right)^2$$ => co



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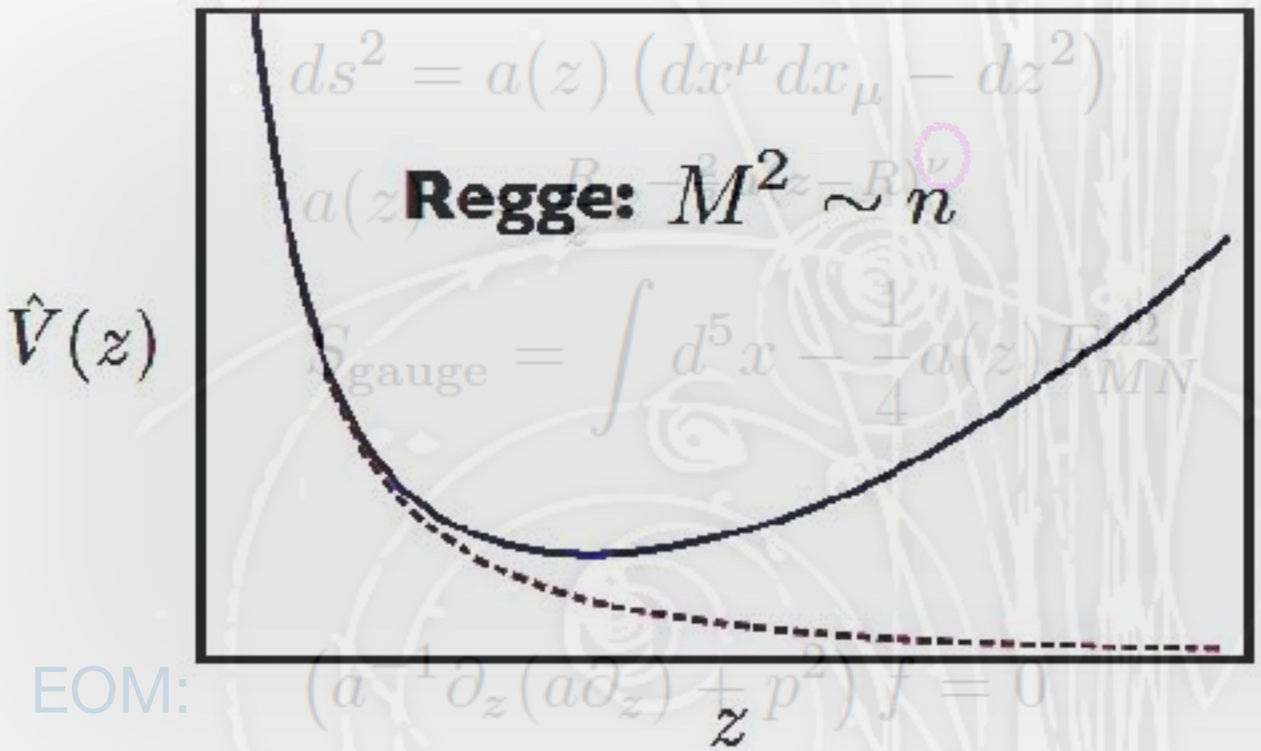

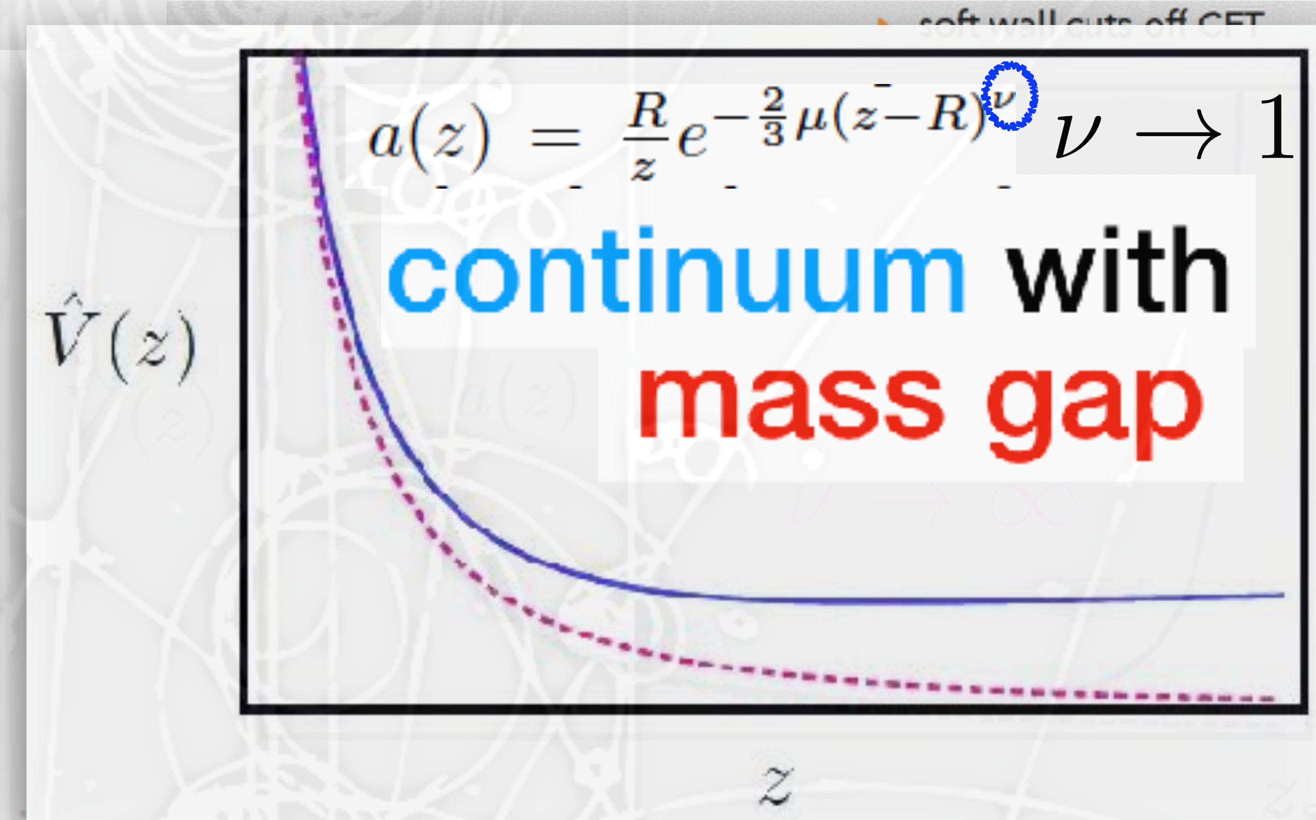

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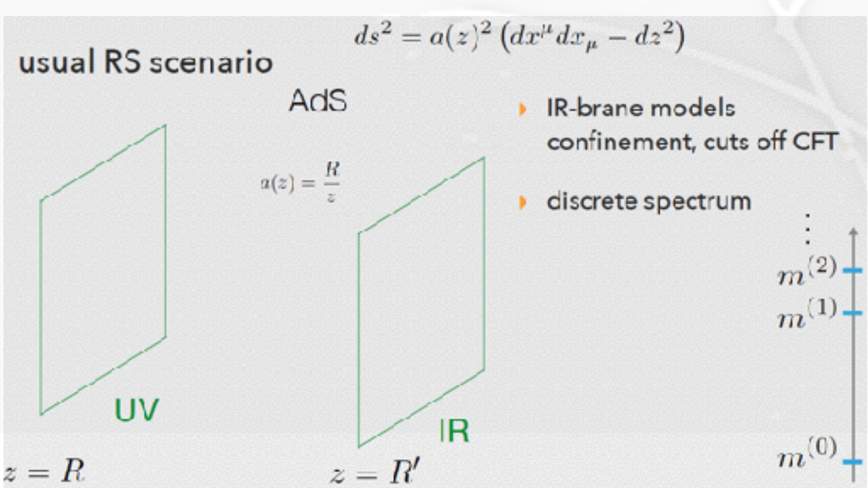

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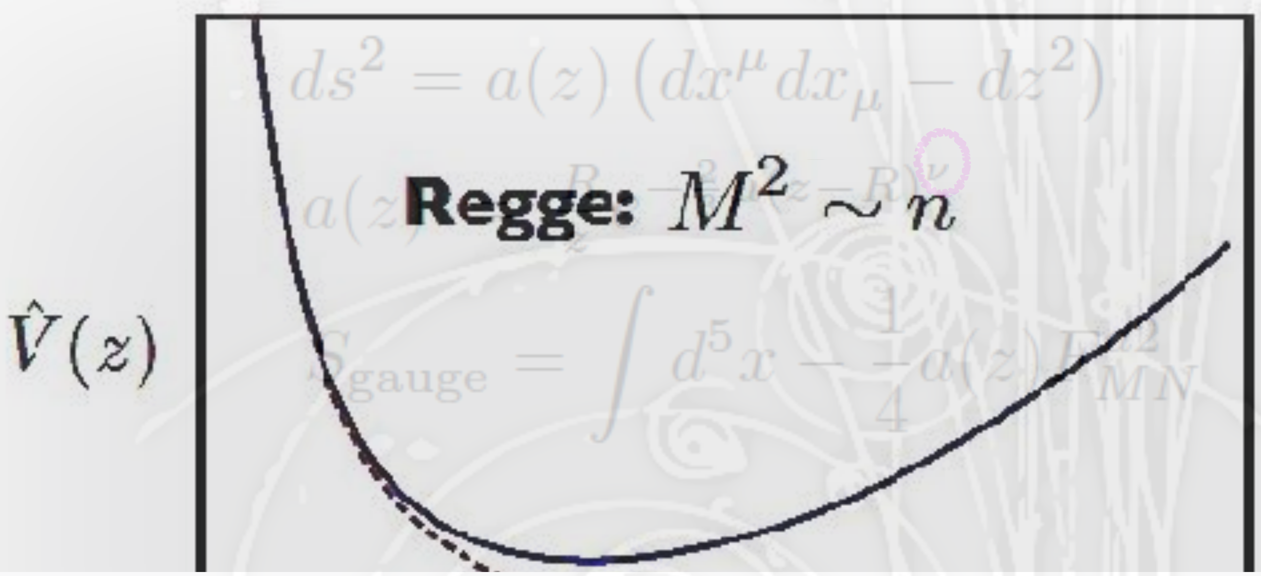
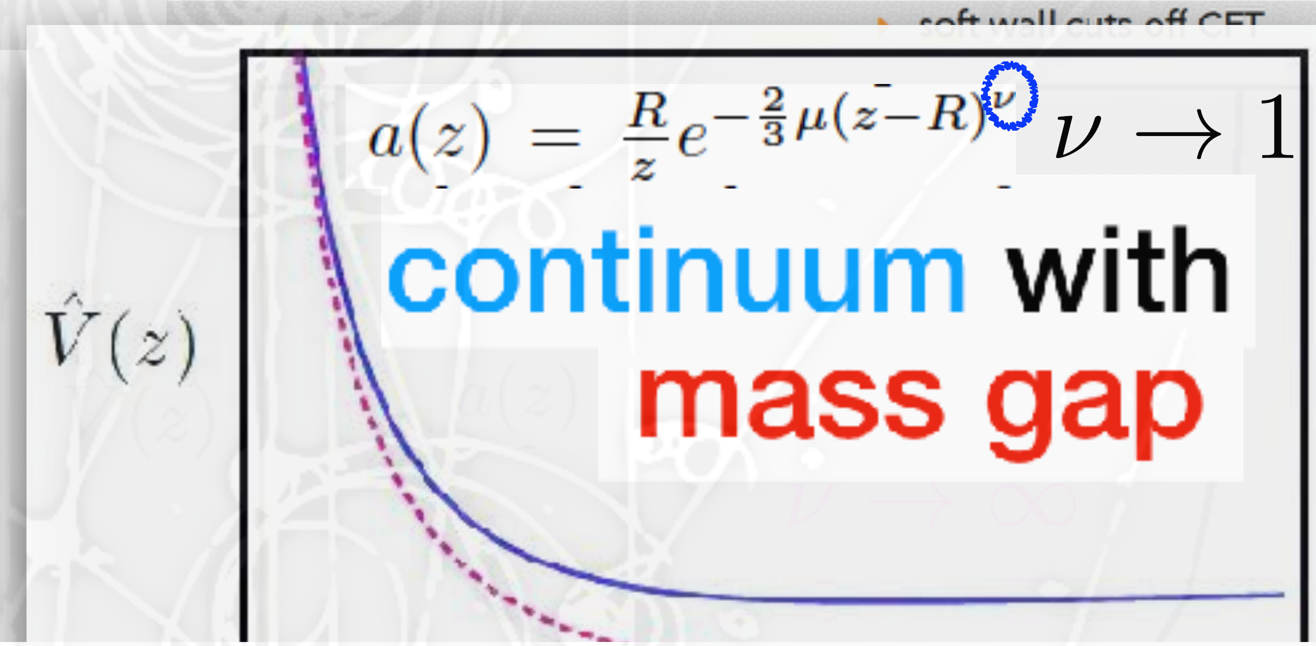
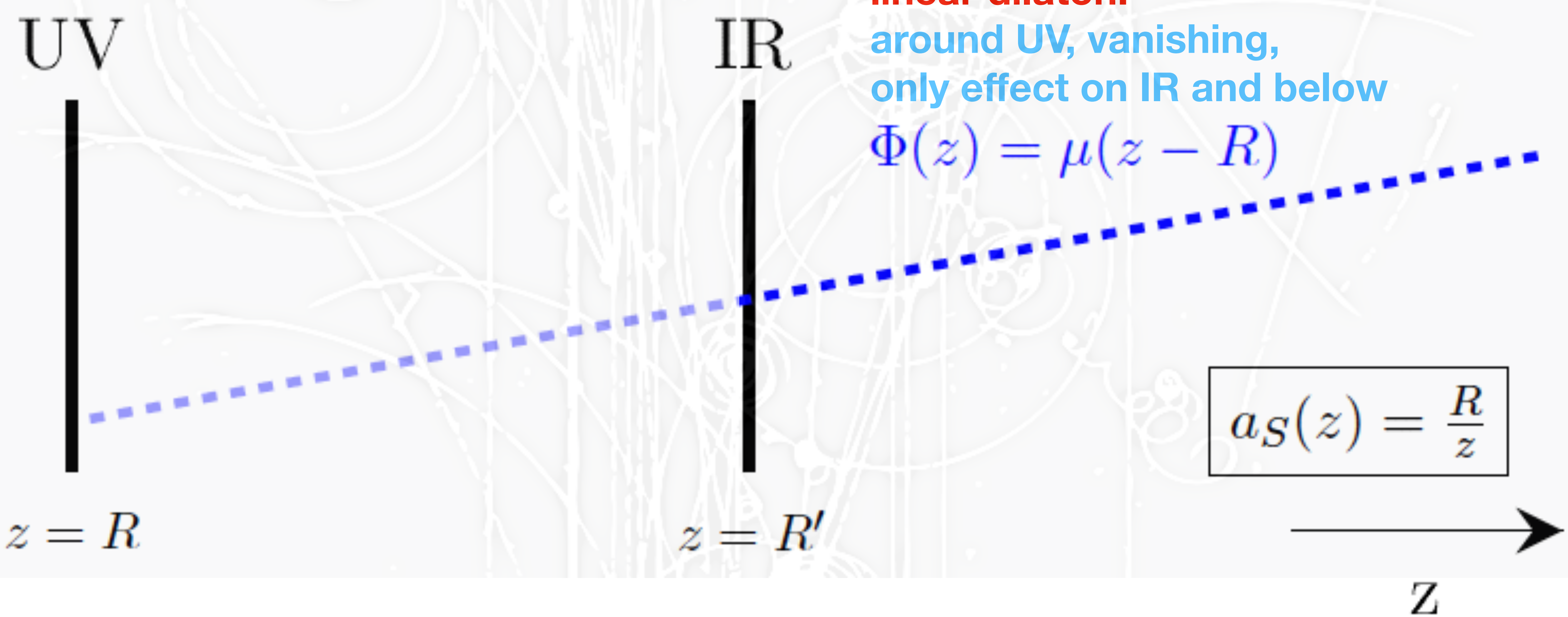




linear dilaton:

around UV, vanishing,
only effect on IR and below

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



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

The Quantum Critical higgs

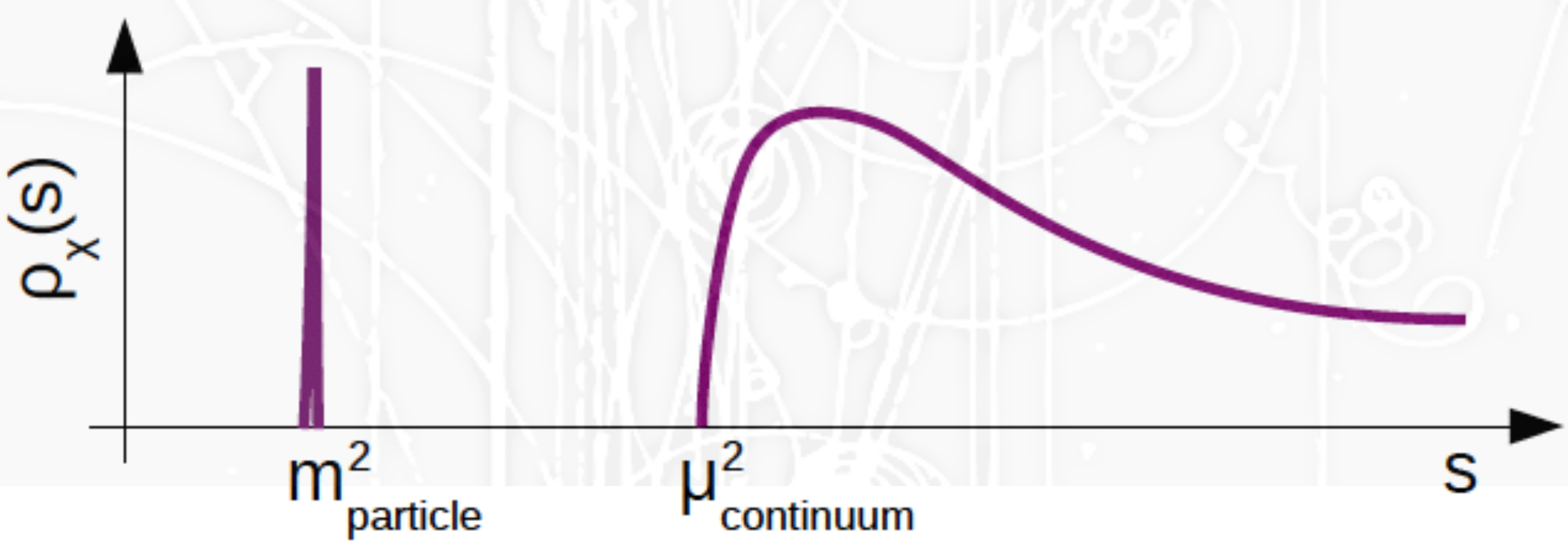
- At a QPT the approximate scale invariant theory is characterized by the scaling dimension Δ of the gauge invariant operators.

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

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



Modeling the QCH: generalized free fields

Generalized Free Fields

Polyakov, early '70s- skeleton expansions

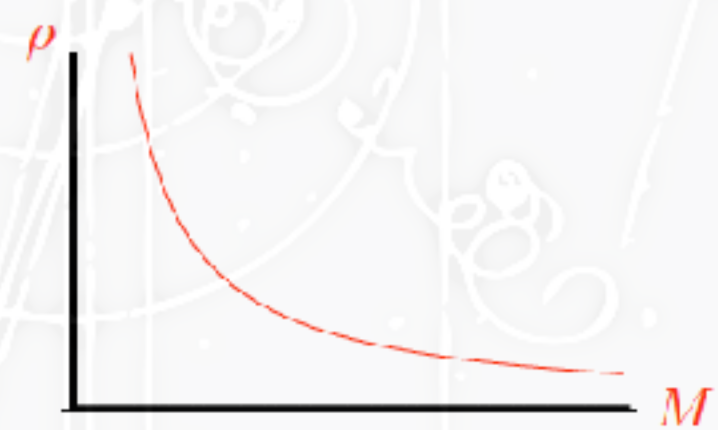
CFT completely specified by 2-point function - rest vanish

Scaling - 2-point function: $G(p^2) = -\frac{i}{(-p^2+i\epsilon)^{2-\Delta}}$

Can be generated from: $\mathcal{L}_{\mathrm{GFF}} = -h^\dagger \left(\partial^2\right)^{2-\Delta} h$ Georgi **hep-ph/0703260**

Branch cut starting at origin - spectral density purely a continuum:

$$G(p) \sim \int_{\mu^2}^{\infty} dM^2 \frac{\rho(M^2)}{p^2 - M^2}$$

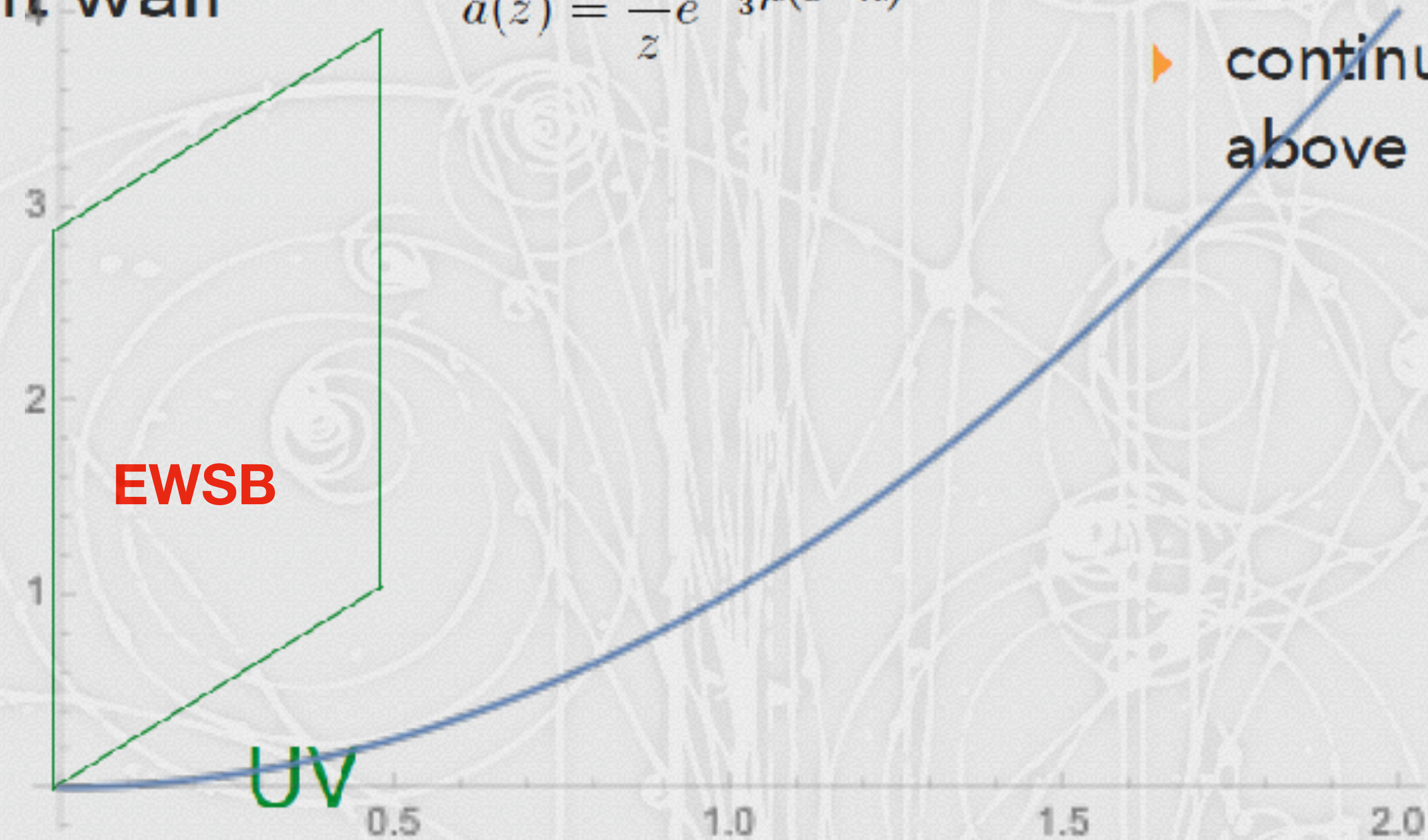


Bellazzini, Csaki, Hubisz, SL, Serra, Terning (PRX 2016)

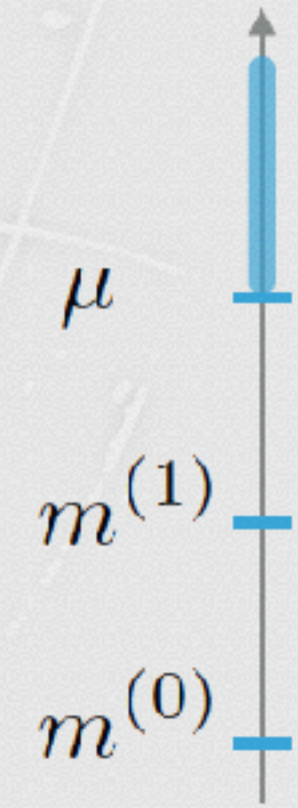
Quantum Critical Higgs

soft wall

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



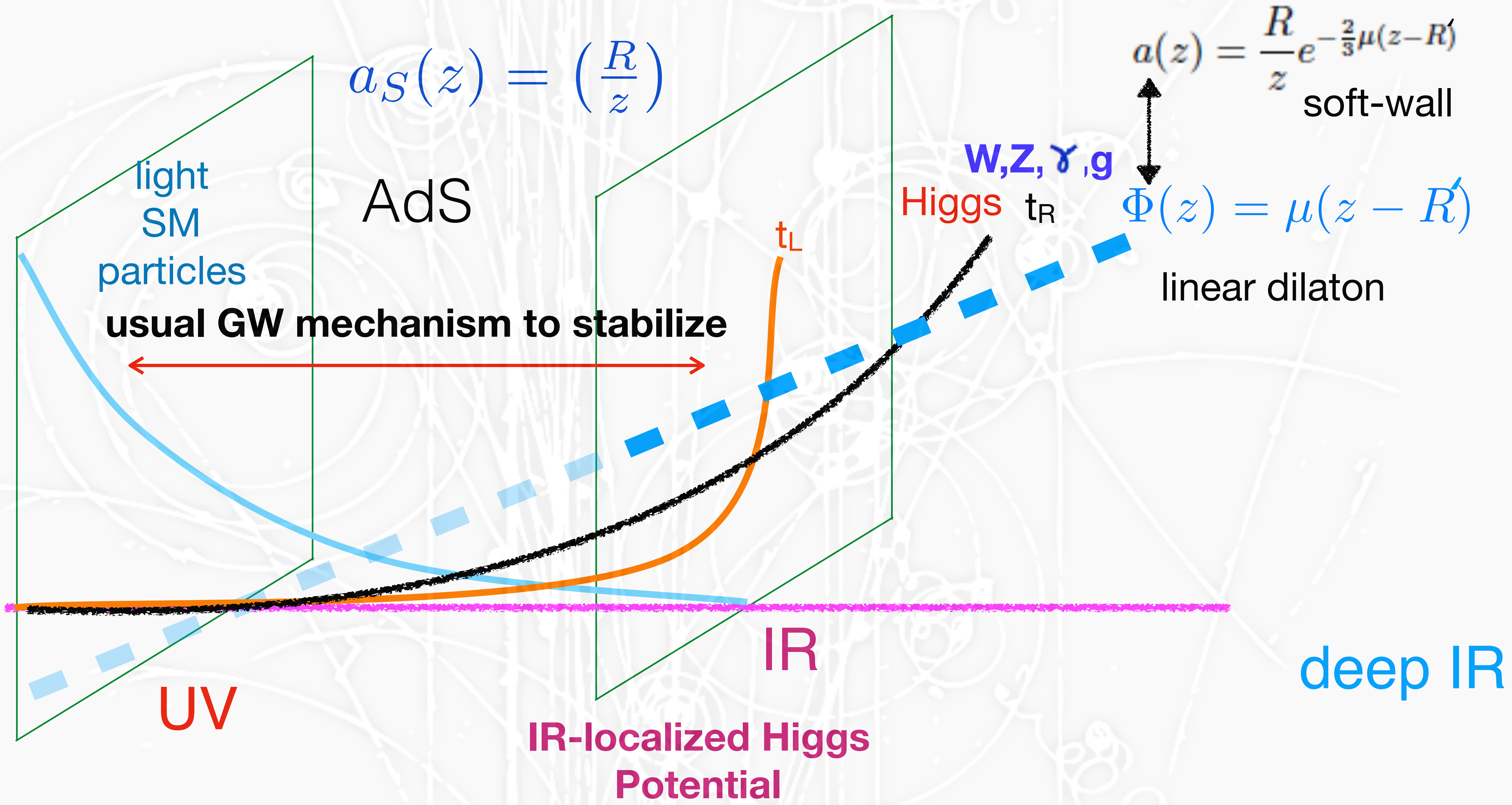
- soft wall cuts off CFT
- continuous KK spectrum above mass gap



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

Csaki, SL, Lombardo, work in progress

A Natural Quantum Critical Higgs: 5D linear dilaton



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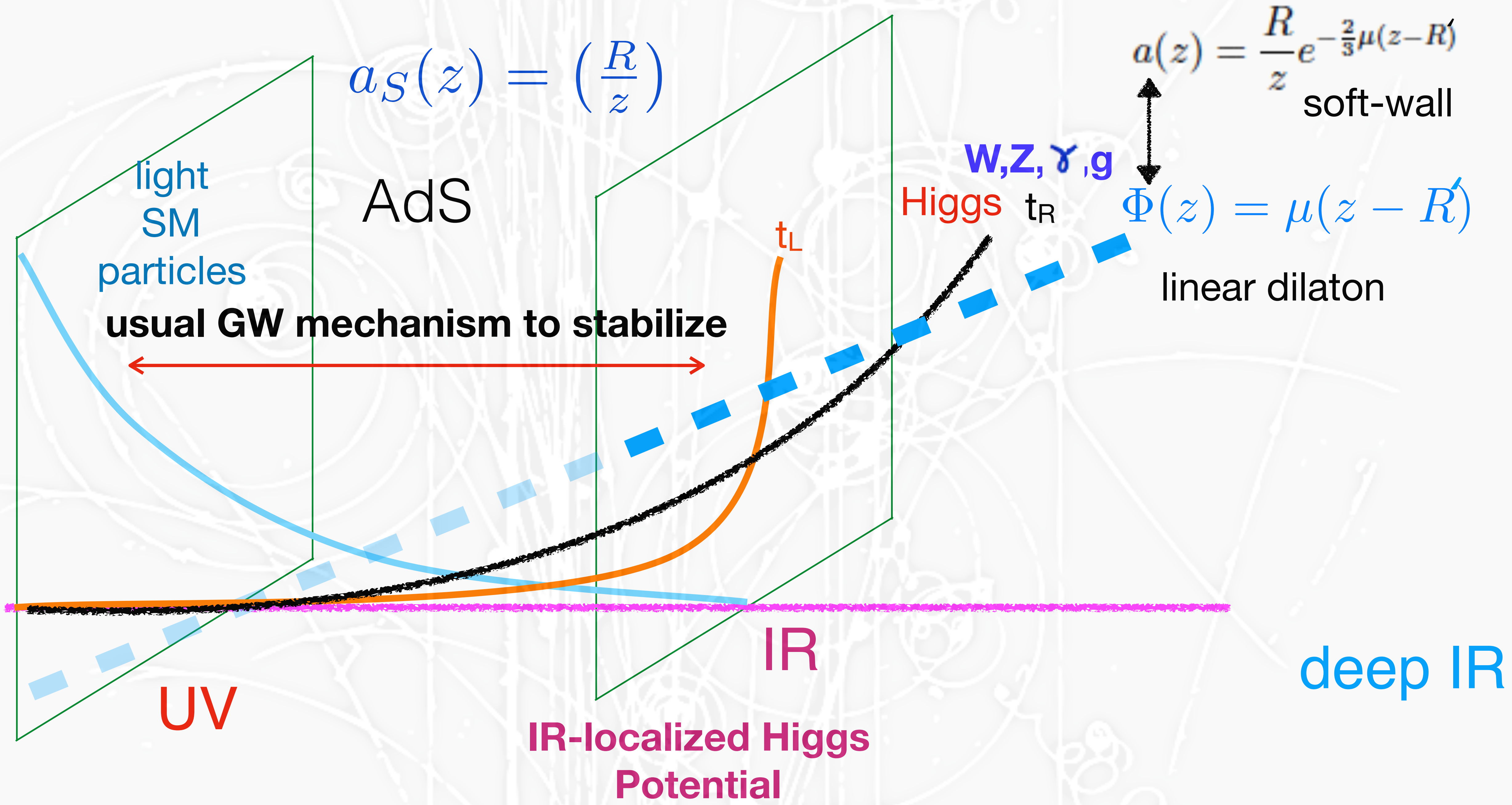
Higgs arises from CFT with a domain wall (IR brane)



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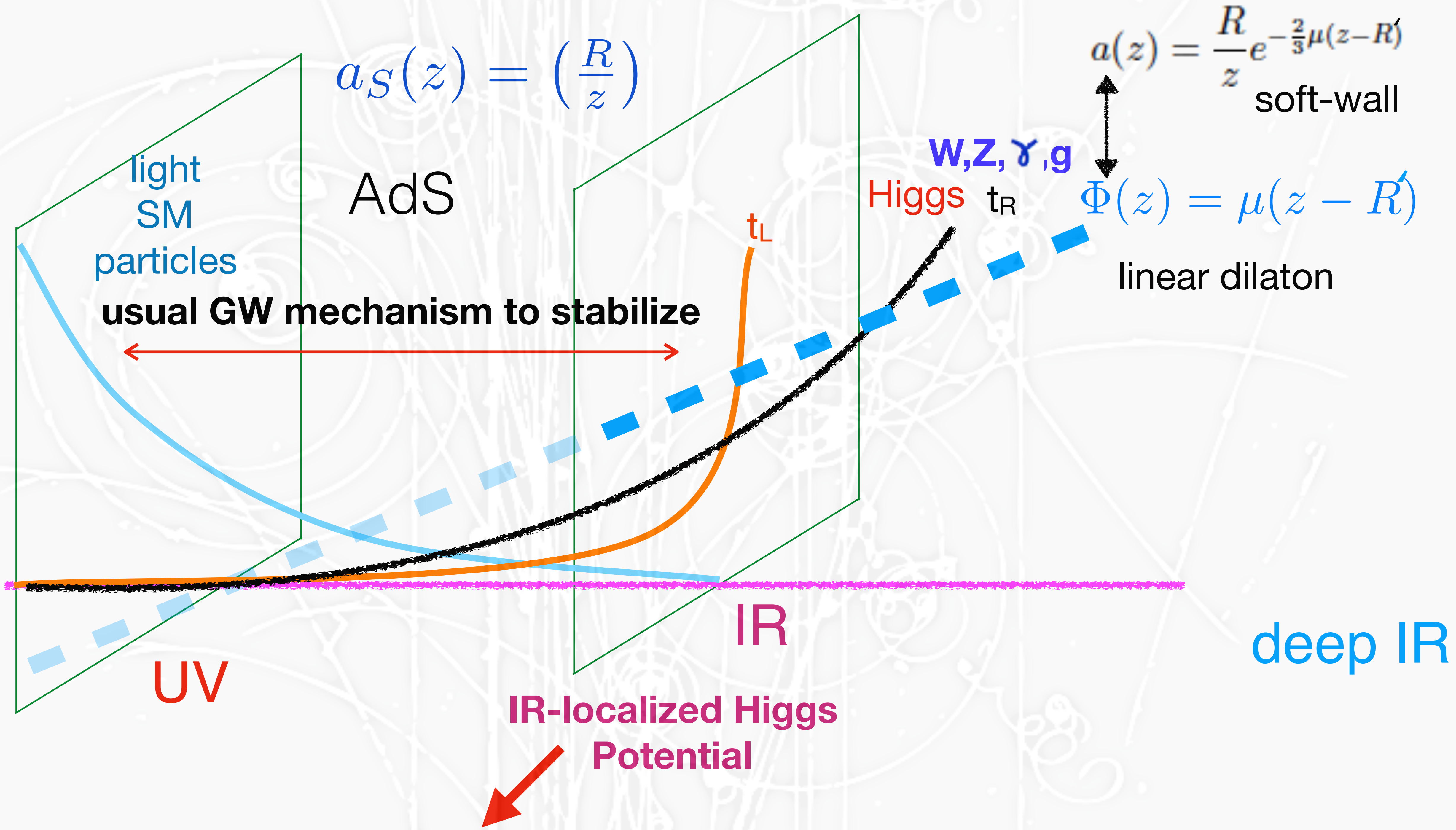
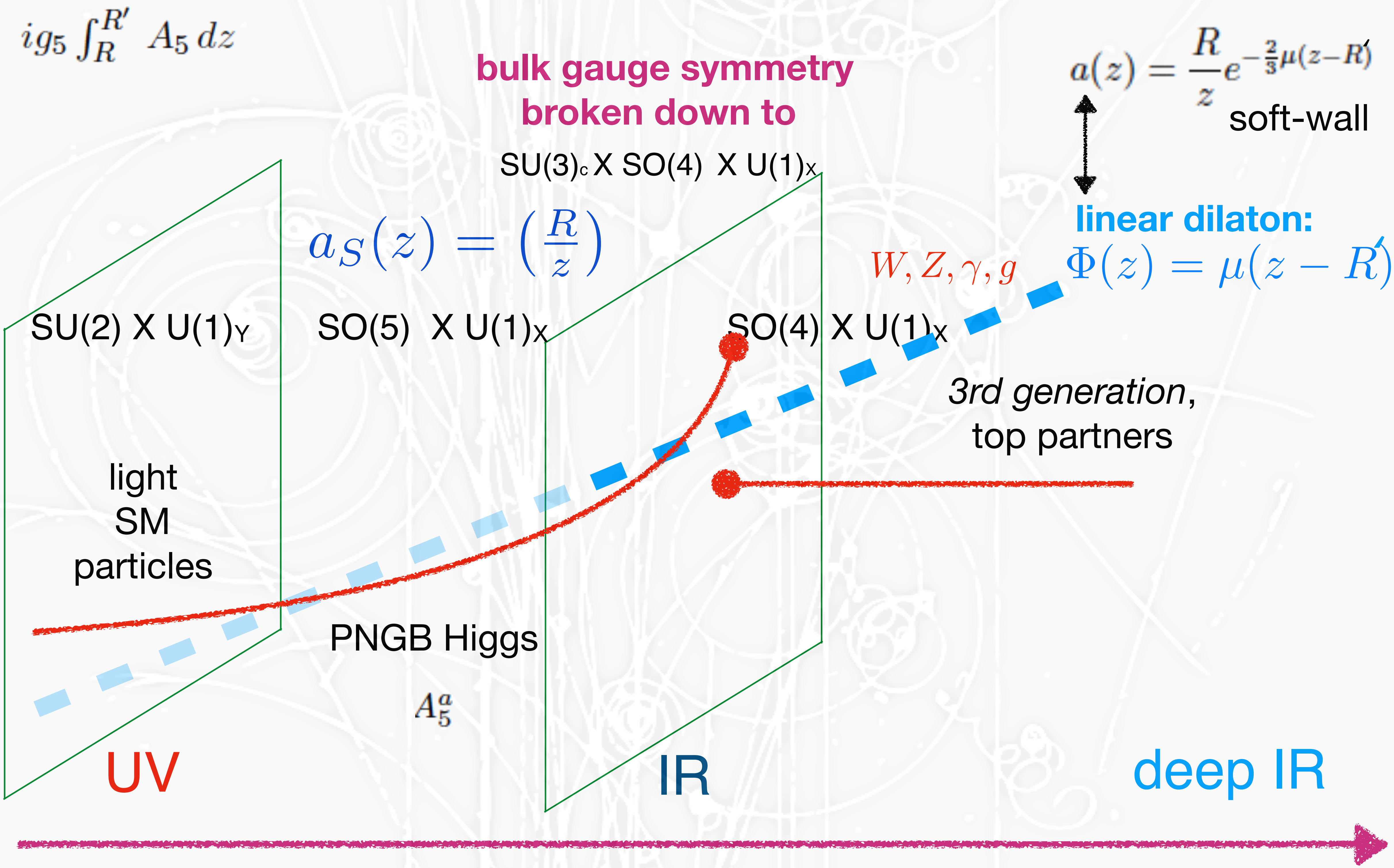


taking a pole (physical Higgs) out of CFT

=> arises as a composite bound state of CFT

Csaki, Lombardo, Lee, SL, Telem

A “more” Natural model: Linear Dilaton



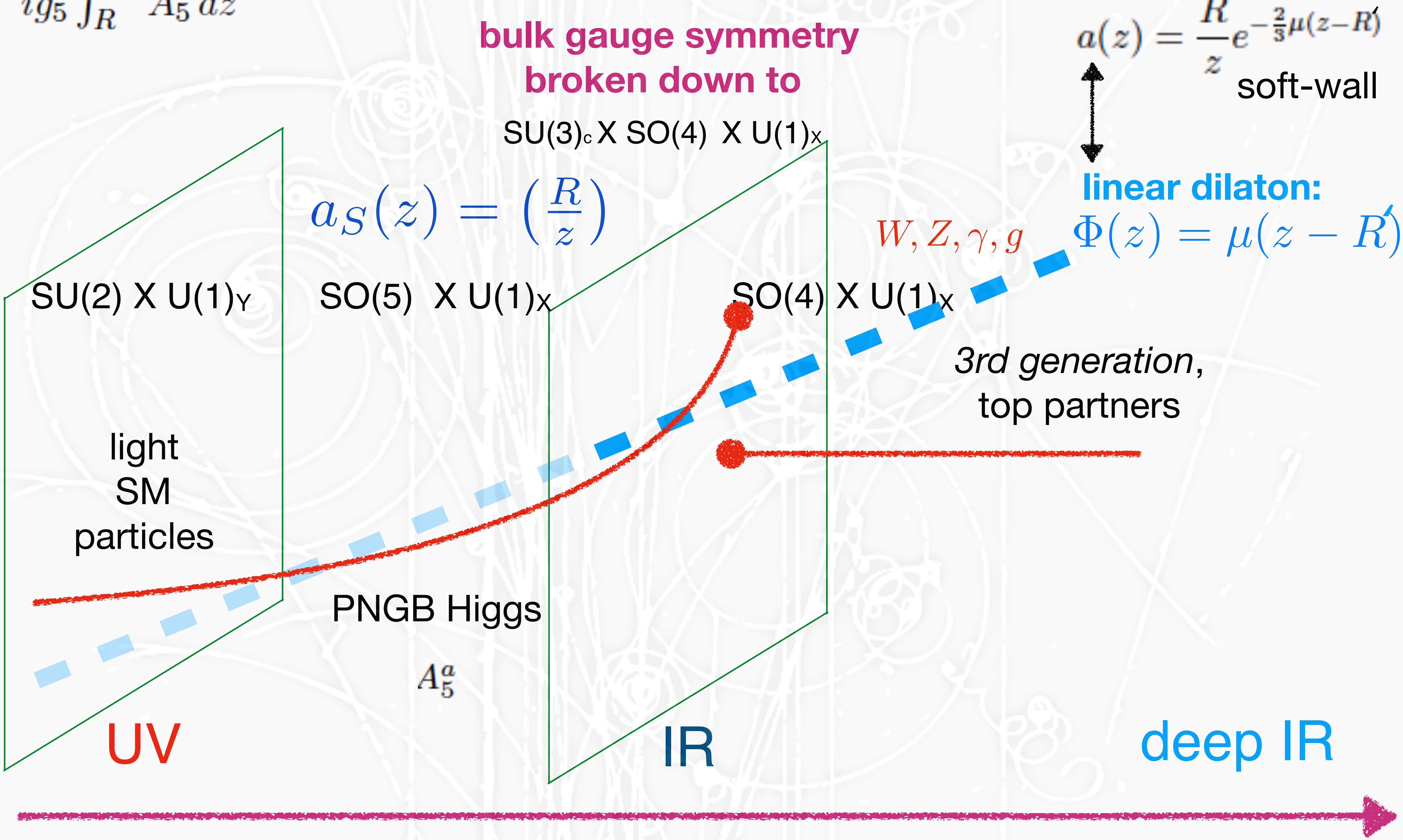
theory gets closed to a fixed point, but then gets a mass gap

Csaki, Lombardo, Lee, SL, Telem

A “more” Natural model: Linear Dilaton

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

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



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

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

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

Unparticle Spectral densities (5D model)

- In principle could just input the ρ(s) spectral density, but don't know if it provides unitary, causal QFT

- To make sure we don't use inconsistent ρ's get them from 5D

- Old story: RS2 gives a model of continuum fermions without a gap (Cacciapaglia, Marandella, Terning)

$$G_{5D}(p^2) \propto \frac{\Gamma\left(\frac{1}{2}-c\right)}{4^c\Gamma\left(\frac{1}{2}+c\right)} \frac{1}{(-p^2)^{\frac{1}{2}-c}} \qquad G_{4D}(p^2) \propto \frac{\Gamma\left(\frac{5}{2}-d\right)}{4^{d-2}\Gamma\left(d-\frac{3}{2}\right)} \frac{1}{(-p^2)^{\frac{5}{2}-d}}$$

- Boundary RS2 Green's fn = 4D ungapped continuum fermion ("unparticle")

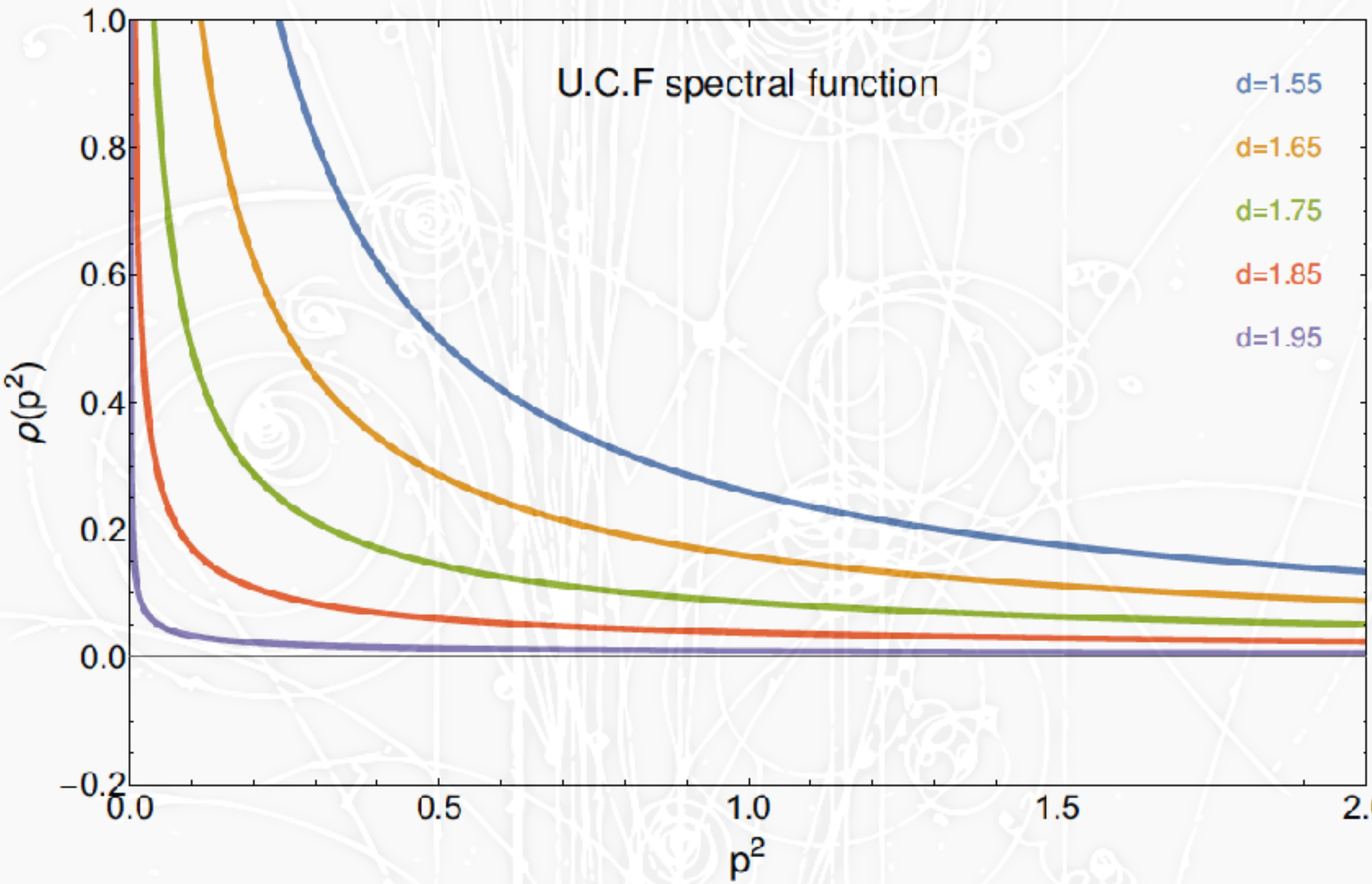
Unparticle Spectral densities (5D model)

♦ I… …ow if it …

♦ T…

♦ C… …ap (Cac…

G_5… $\frac{5}{2}-d$

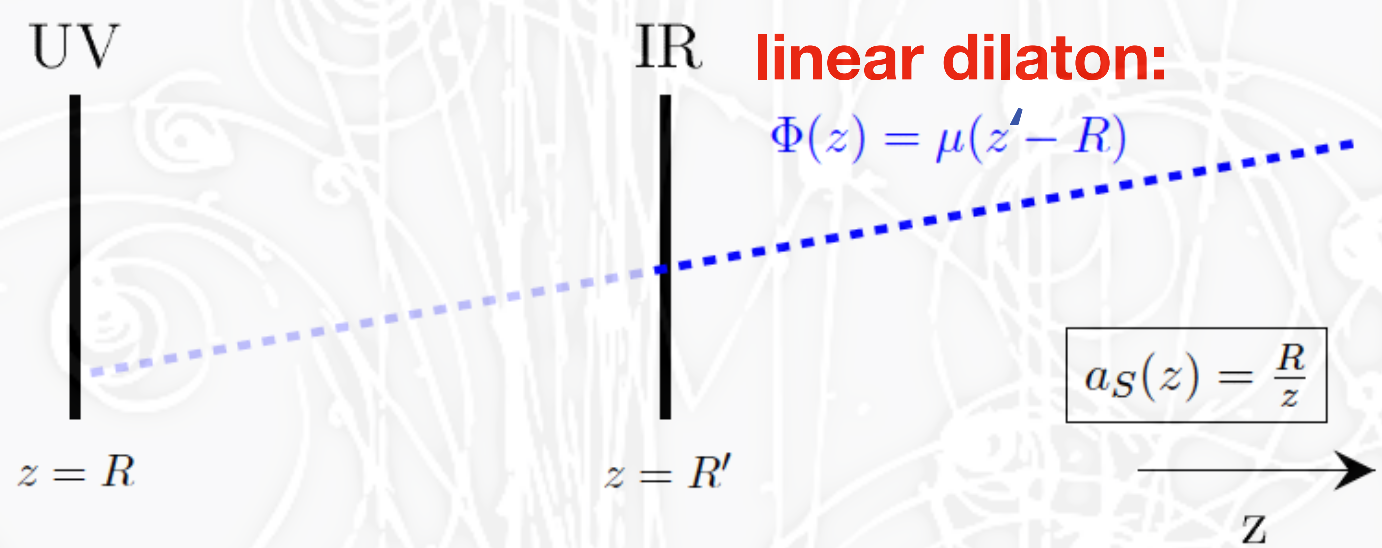


♦ Boundary RS2 Green's fn = 4D ungapped continuum fermion ("unparticle")

Gapped Continuum

Csaki, Lombardo, Lee, SL, Telem

- To introduce mass gap, we need to modify the 5D background
- Introduce linear dilaton into AdS



- ***Φ***(z) linear dilaton - around the UV brane vanishing

➡ won't have effect until IR (z~1/**μ**)

- Linear dilaton models the details of the IR dynamics (e.g. theory modified by dynamics of some composite mesons bellow IR scale, leading into gapped continuum)

Gapped Continuum

Csaki, Lombardo, Lee, SL, Telem

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

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

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

bulk Yukawa coupling between the dilaton and the bulk fermion

- Kinetic term conventional

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

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

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

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

Solutions to the bulk equations

Csaki, Lombardo, Lee, SL, Telem

- Schrödinger form for the EOM

$$-\hat{\chi}''(z) + V_{\text{eff}}(z)\,\hat{\chi}(z) \;=\; p^2\hat{\chi}(z)\,, \qquad \hat{\chi}(z) = \left(\tfrac{R}{z}\right)^2 \chi(z)$$

- Effective potential

$$V_{\text{eff}}(z) = \frac{c(c+1) + y\Phi(z)(2c + y\Phi(z) + 1) - yz\Phi'(z)}{z^2}$$

- Gapped continuum if $V_{\text{eff}}(z \to \infty) = \text{const} > 0$

- To achieve that, need a linear dilaton

$$\Phi(z) \;=\; \mu(z - R) \;\text{ with }\; \mu \sim 1\,\text{TeV}$$

- will give: $V_{\text{eff}}(z \to \infty) = y^2\mu^2$

→ **gap will show at** $y\mu$

Gapped Continuum

Csaki, Lombardo, Lee, SL, Telem

- 5D holographic model with a linear dilaton

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

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

$$-i\bar{\sigma}^\mu \partial_\mu \chi - \partial_5 \bar{\psi} - 2\frac{a'}{a}\bar{\psi} + \frac{ac}{R}\bar{\psi} = 0$$

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

$$\chi = g(z)\chi(z)$$

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

$$\chi(z) = A\, a^{-2}(z)\; W\left(-\frac{c\mu y}{\Delta}, c + \frac{1}{2}, 2\Delta z\right),$$

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Gapped Continuum

Csaki, Lombardo, Lee, SL, Telem

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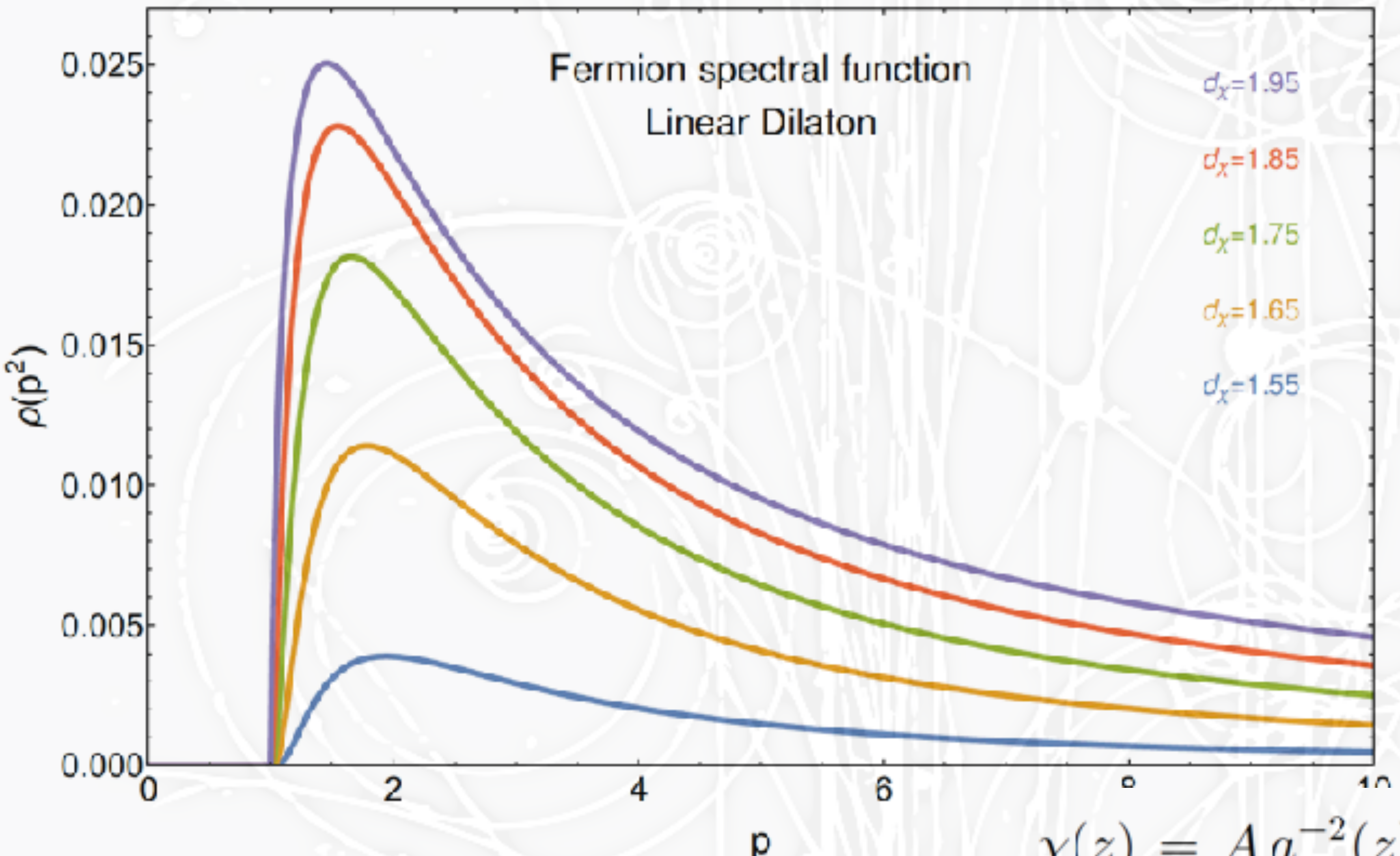
- profile of continuum depends

on the scaling dimension of the fields

Gapped Continuum

Csaki, Lombardo, Lee, SL, Telem



$$\frac{a(z)c(z)}{R}\Big)$$

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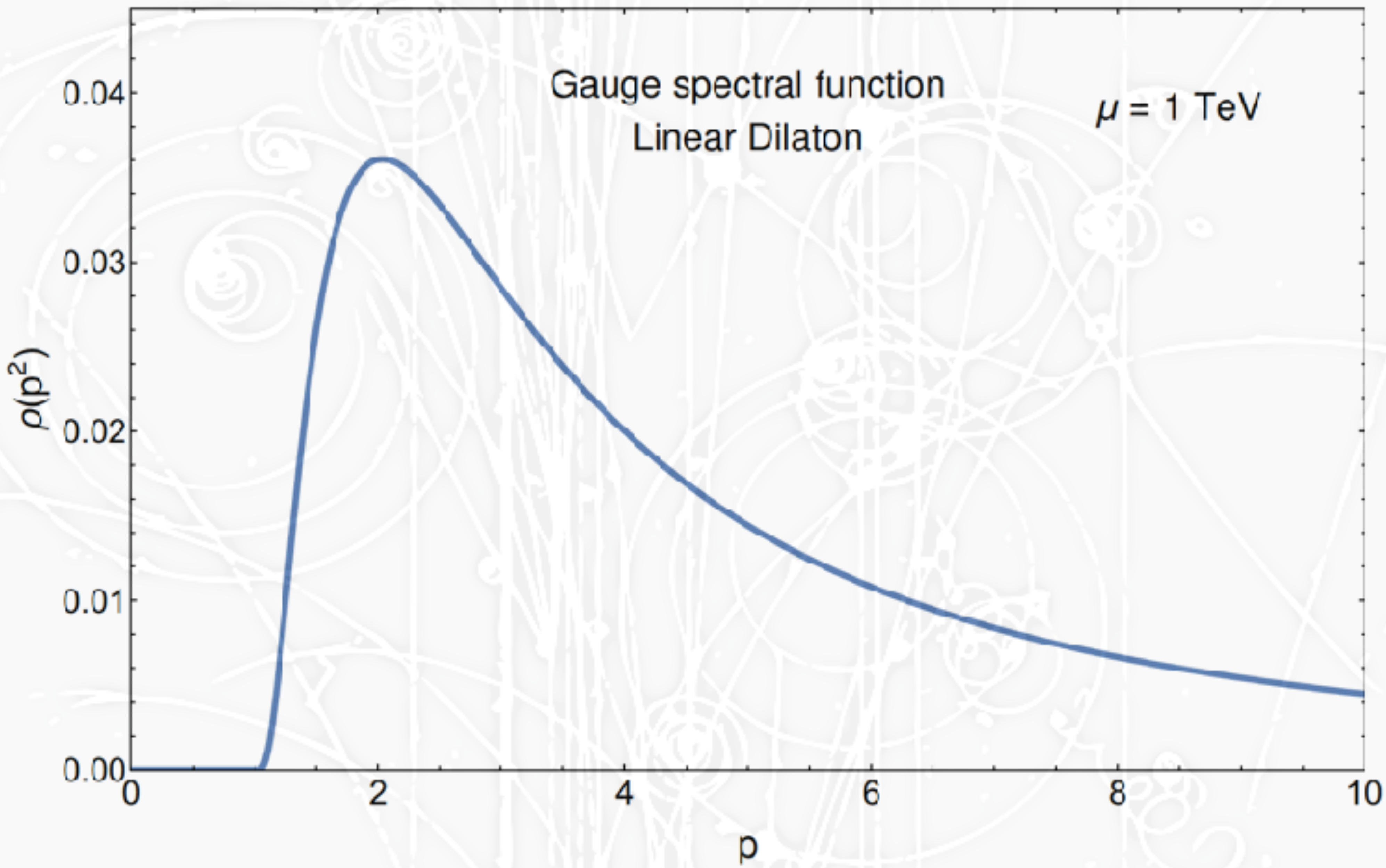
Gapped Continuum

Csaki, Lombardo, Lee, SL, Telem

- Similar story for Gauge Boson



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

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: $i g_5 \int_R^{R'} A_5 \, dz$

  (No other physical Wilson line beyond IR brane)
- Bulk fermions

$$
\begin{aligned}
Q_L(\mathbf{5})_{\frac{2}{3}} &\rightarrow q_L(\mathbf{2})_{\frac{1}{6}} + \tilde{q}_L(\mathbf{2})_{\frac{7}{6}} + y_L(\mathbf{1})_{\frac{2}{3}} , \\
T_R(\mathbf{5})_{\frac{2}{3}} &\rightarrow q_R(\mathbf{2})_{\frac{1}{6}} + \tilde{q}_R(\mathbf{2})_{\frac{7}{6}} + t_R(\mathbf{1})_{\frac{2}{3}} , \\
B_R(\mathbf{10})_{\frac{2}{3}} &\rightarrow q'_R(\mathbf{2})_{\frac{1}{6}} + \tilde{q}'_R(\mathbf{2})_{\frac{7}{6}} + x_R(\mathbf{3})_{\frac{2}{3}} + y_R(\mathbf{1})_{\frac{7}{6}} + \tilde{y}_R(\mathbf{1})_{\frac{1}{6}} + b_R(\mathbf{1})_{-\frac{1}{3}}
\end{aligned}
$$

A Realistic Model

- To generate Yukawa couplings, need localized mass terms

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

- A realistic benchmark point

$$R/R' = 10^{-16},\ 1/R' = 2.81\ \mathrm{TeV},\ \mu = 1\ \mathrm{TeV},\ y = 1.75,$$
$$r = 0.975,\ \sin\theta = 0.39,$$
$$c_Q = 0.2,\ c_T = -0.22,\ c_B = -0.03,$$
$$M_1 = 1.2,\ M_4 = 0,\ M_b = 0.017\,.$$

- 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

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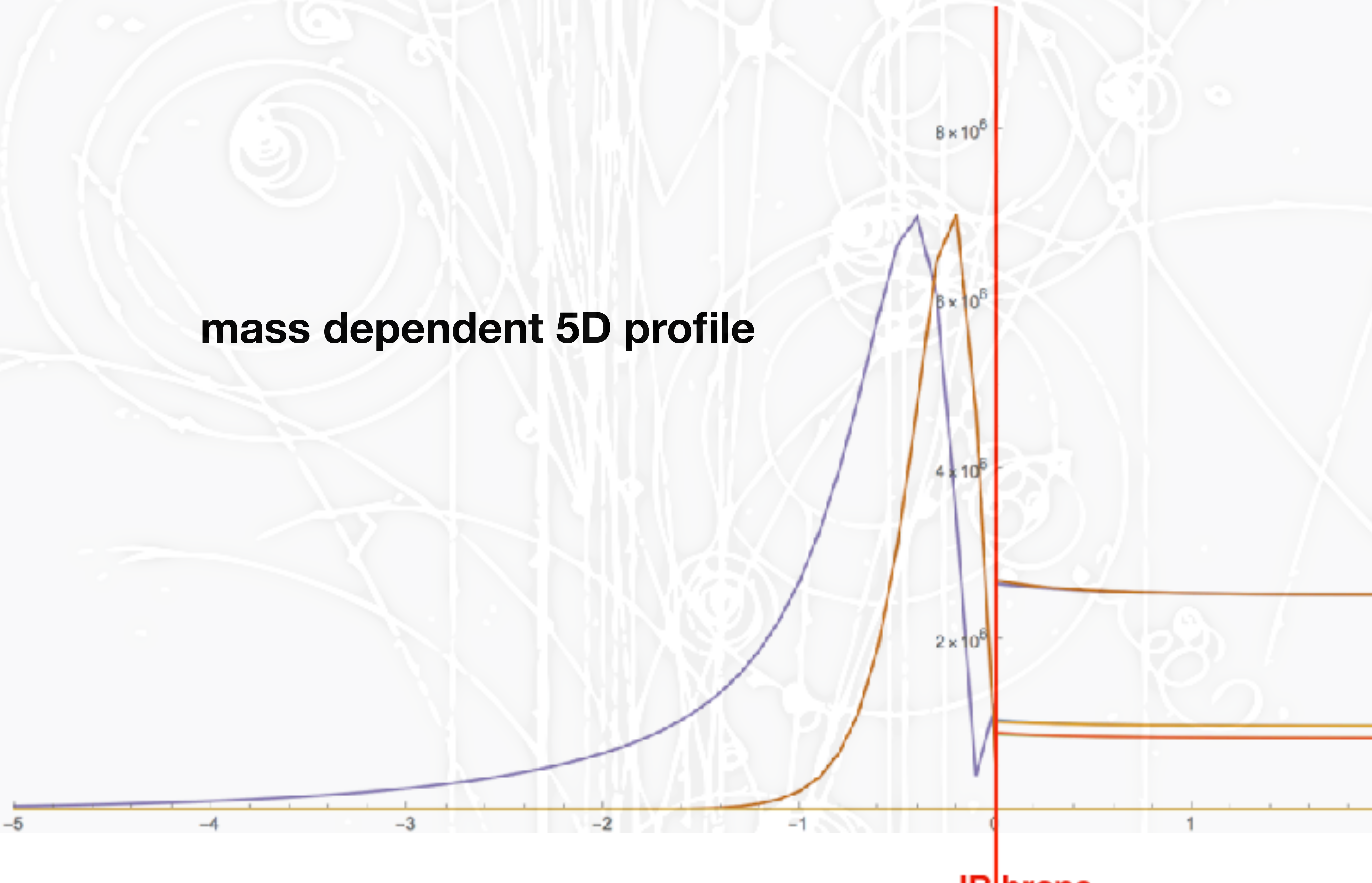
$$S_{\rm IR} = \int d^4x \sqrt{g_{\rm ind}} \left[M_1 \bar{z}_L t_R + M_4 \left(\bar{q}_L q_R + \bar{\tilde{q}}_L \tilde{q}_R \right) + M_b \left(\bar{q}_L q'_R + \bar{\tilde{q}}_L \tilde{q}'_R \right) \right]$$

- A re

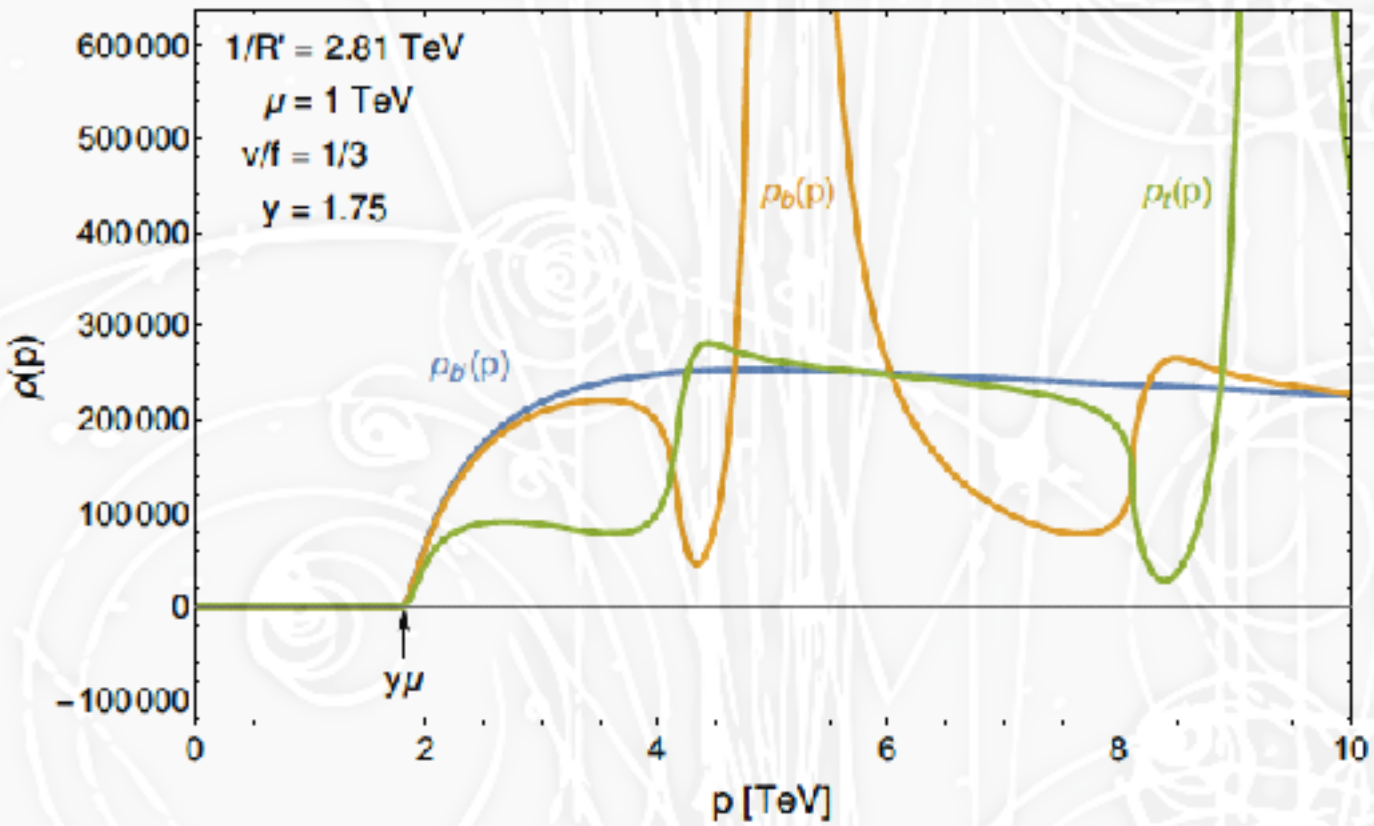


- All … bit light

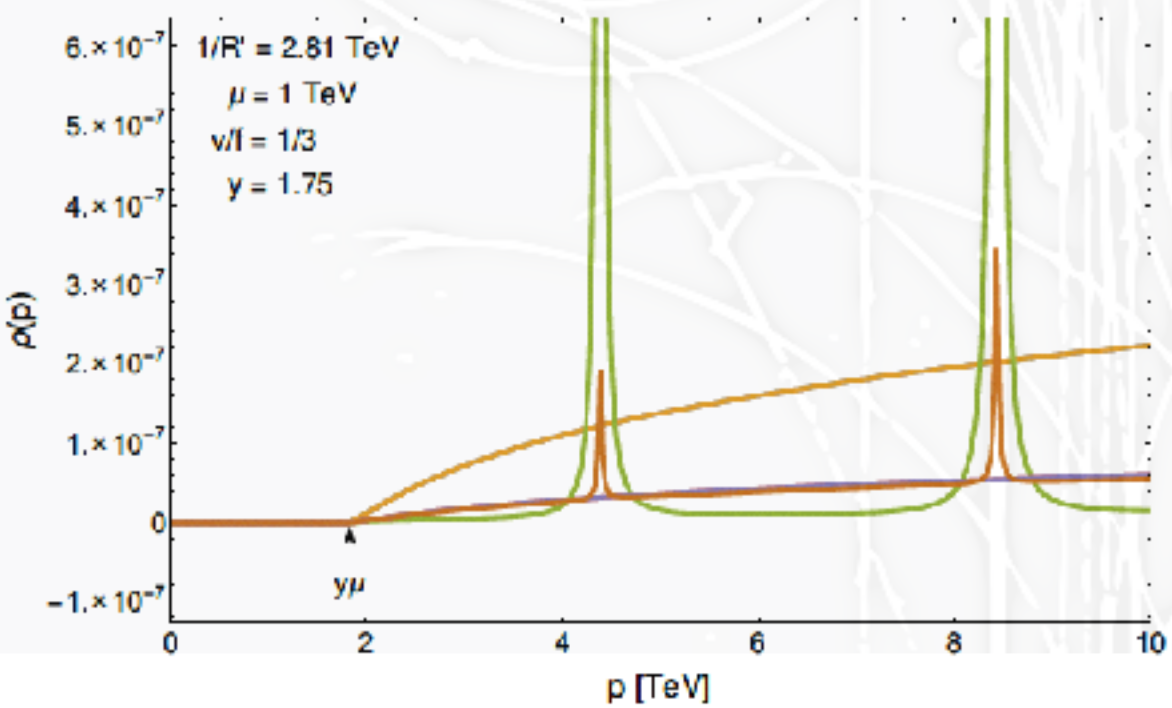
- Cho … 75 TeV

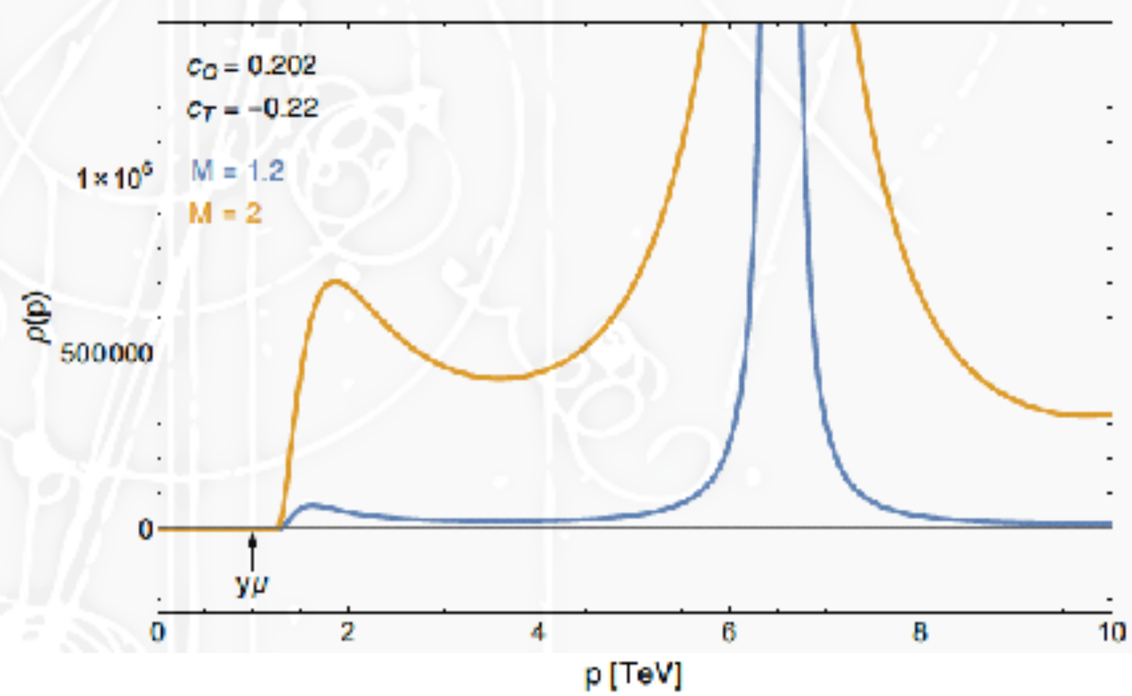
Fermionic Spectrum

- Fermion spectral densities. 3rd generation all very broad



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



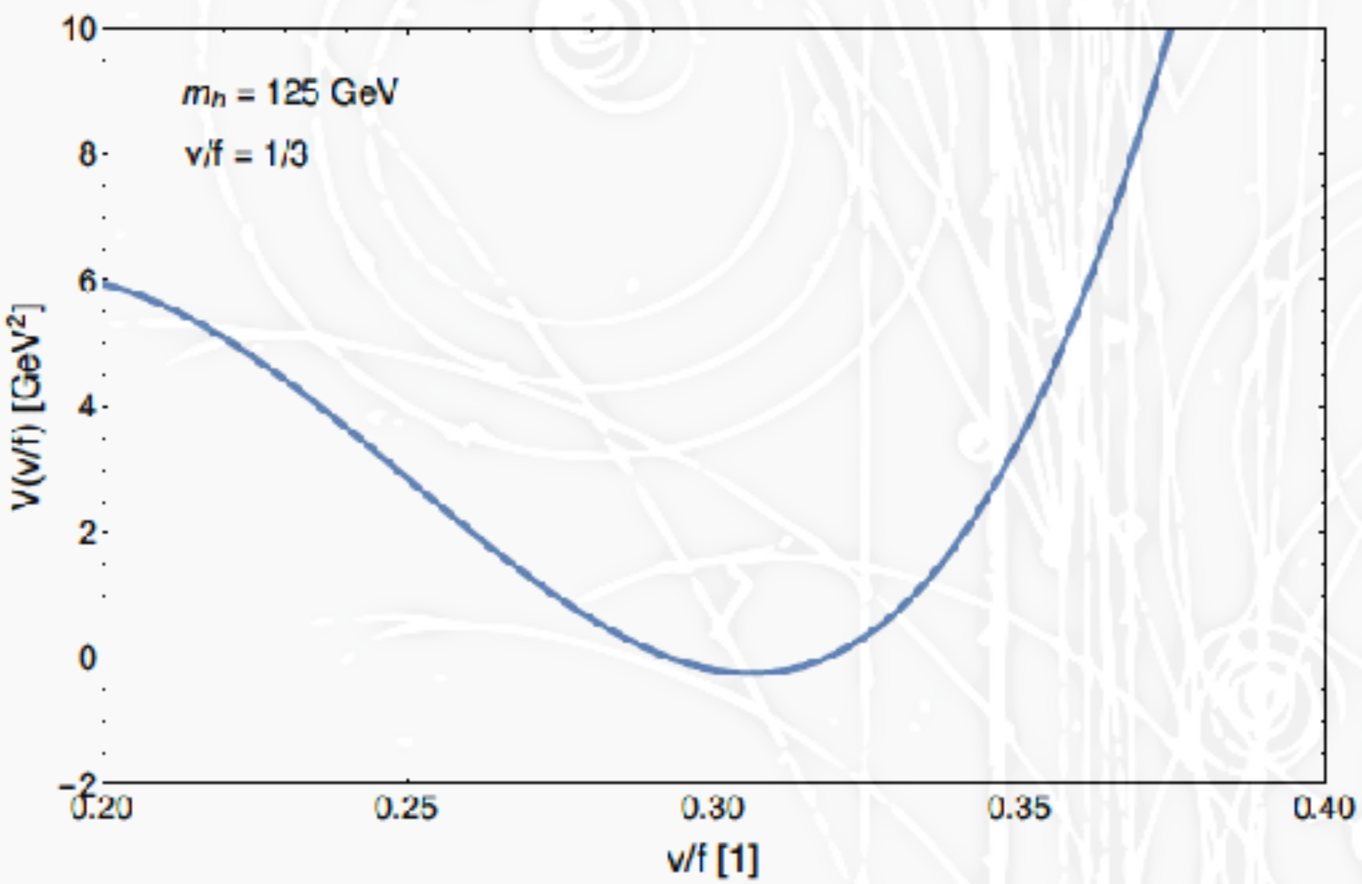


Continuum Top Partners

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

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

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



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fermion continuum starts at $y\mu = 1.75$ TeV

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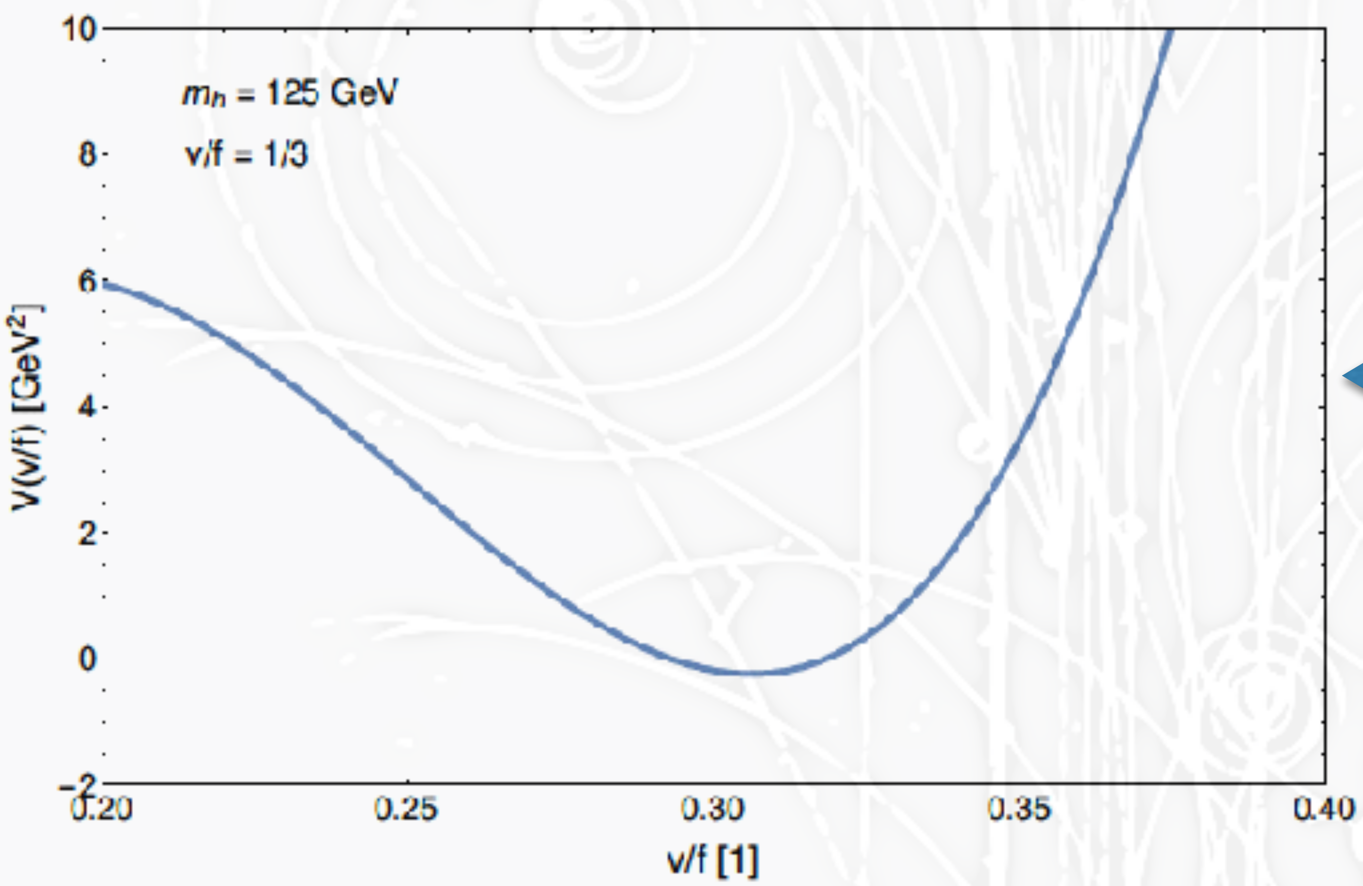

→ usual 1% tuning

with our conservative choice of parameters

fermion continuum starts at $y\mu = 1.75$ TeV

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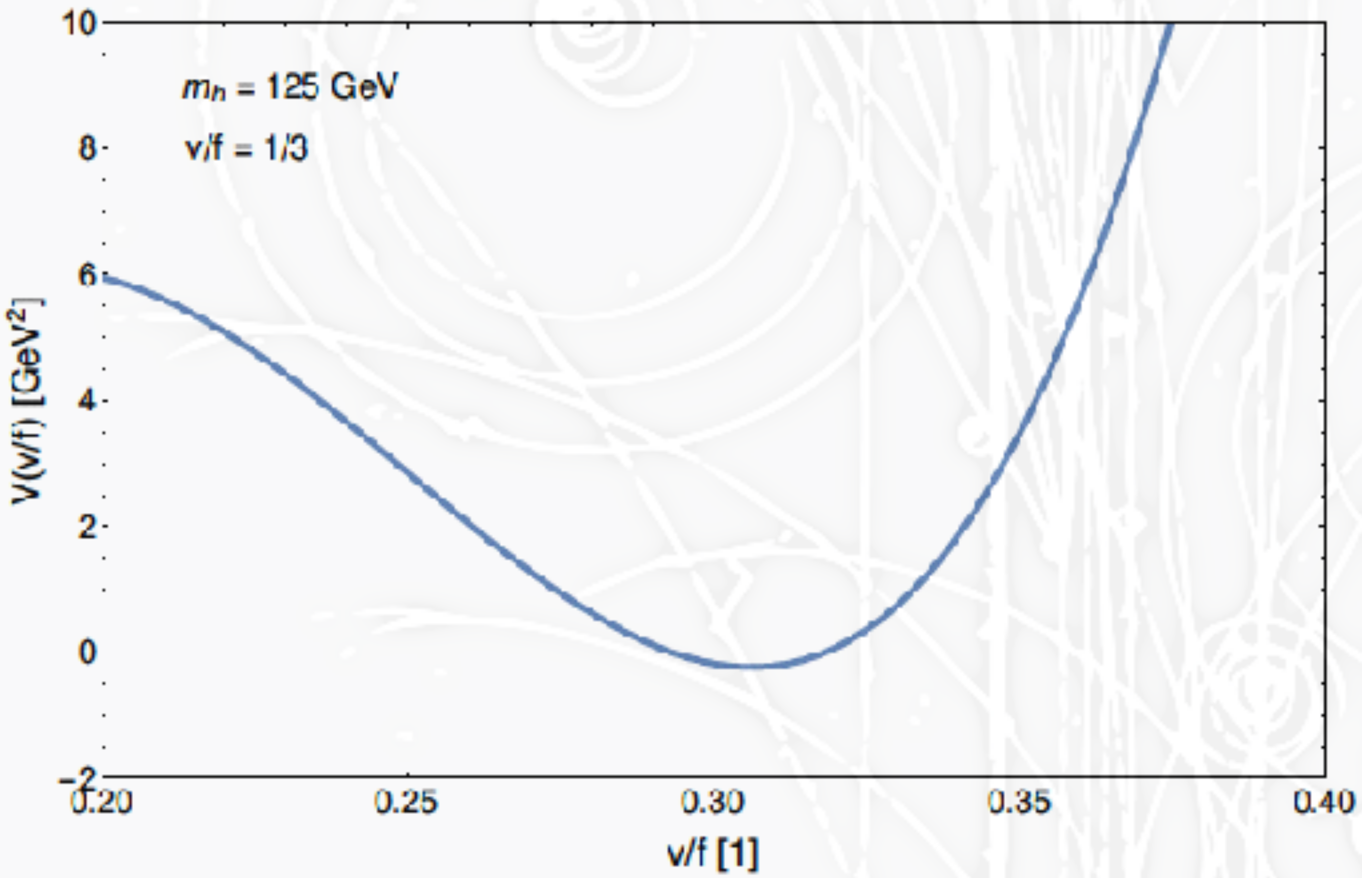

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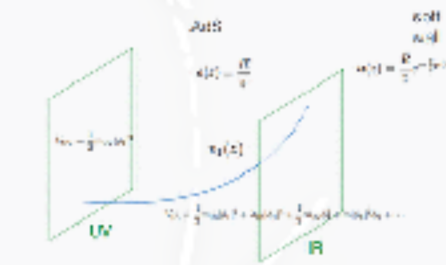
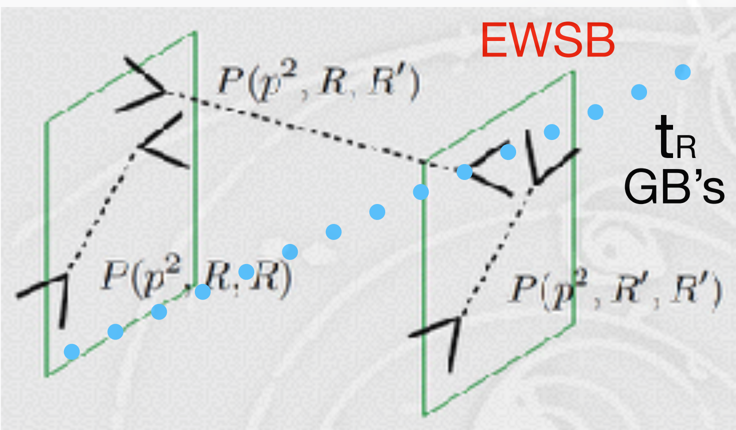
Continuum Naturalness?

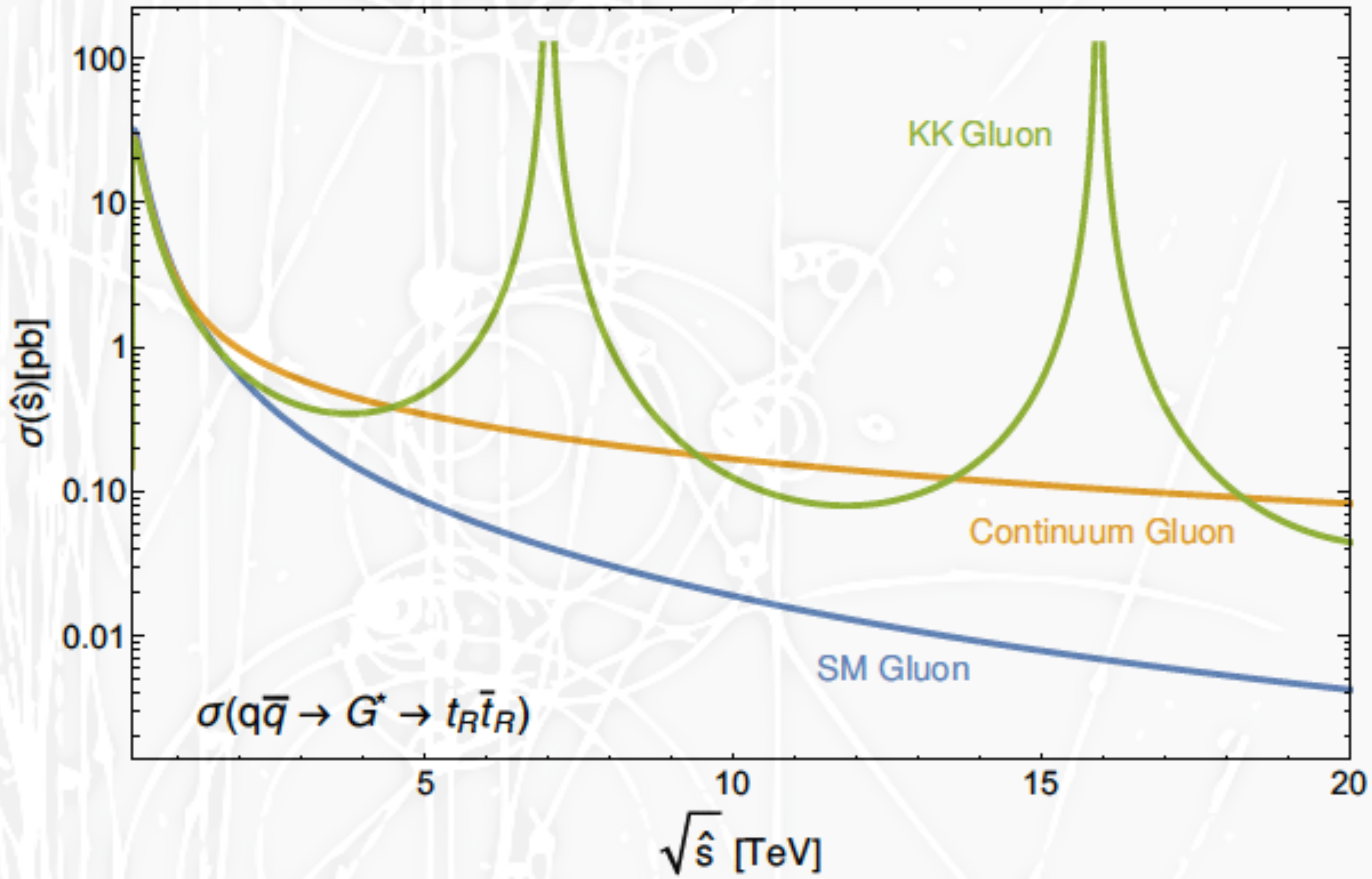


Csaki, Lombardo, Lee, SL, Telem

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



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



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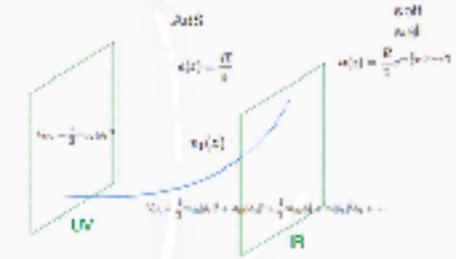

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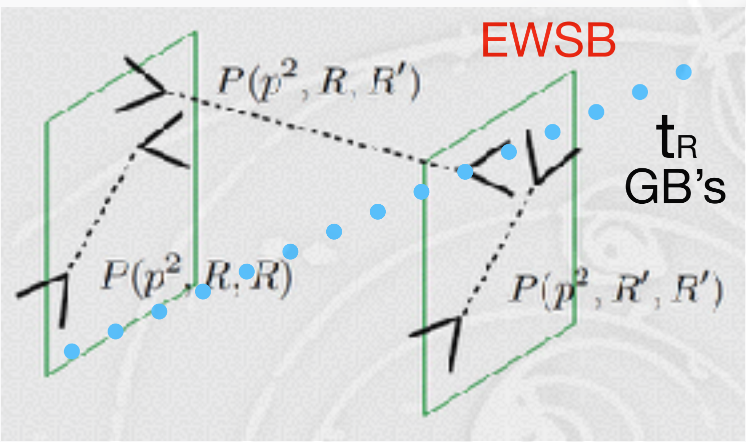

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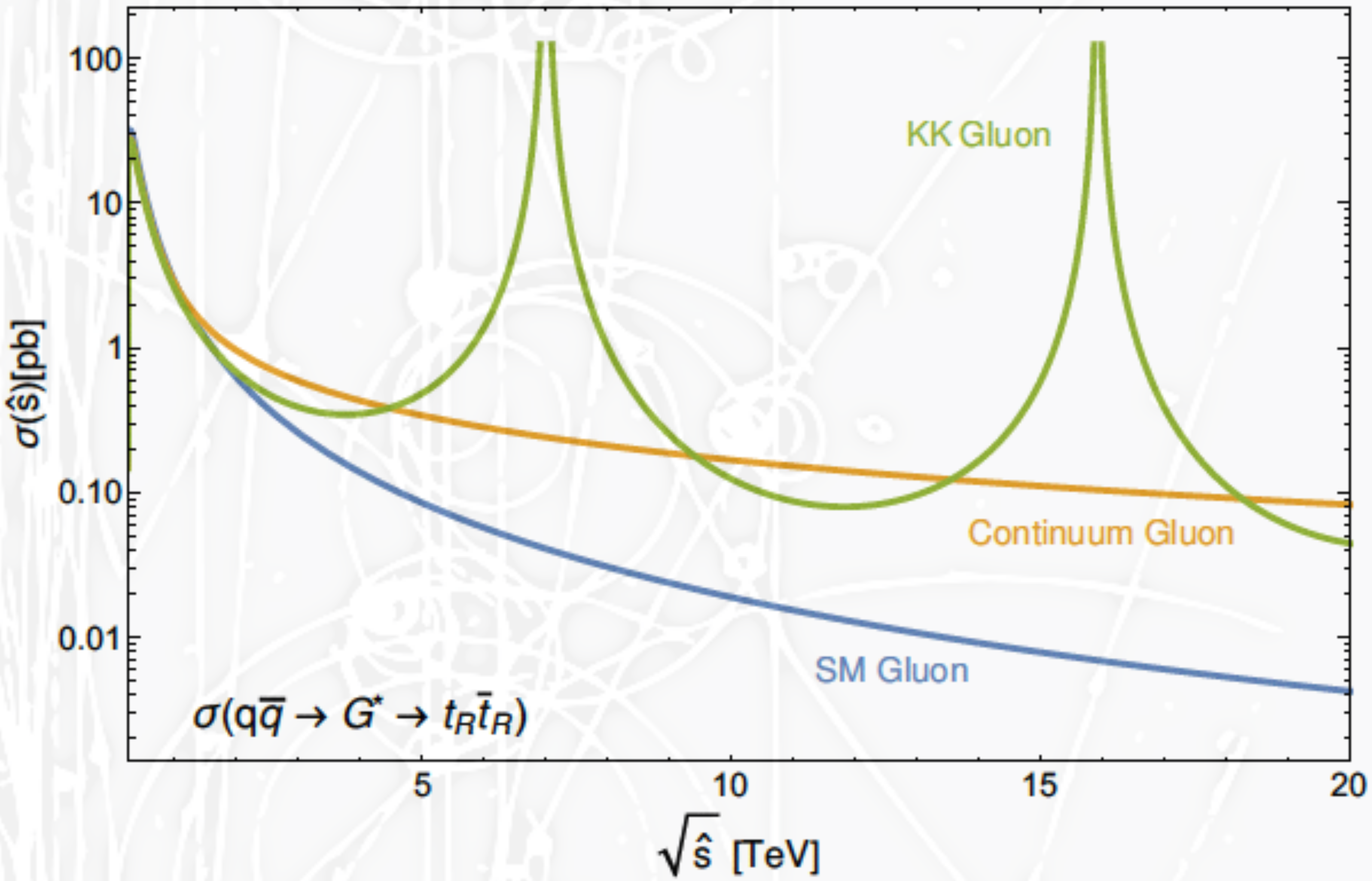

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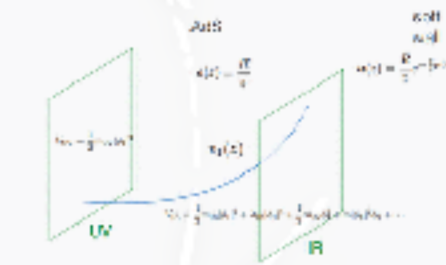

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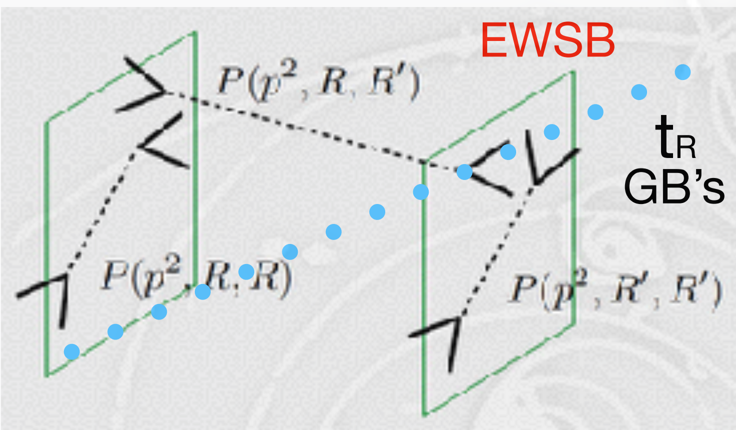

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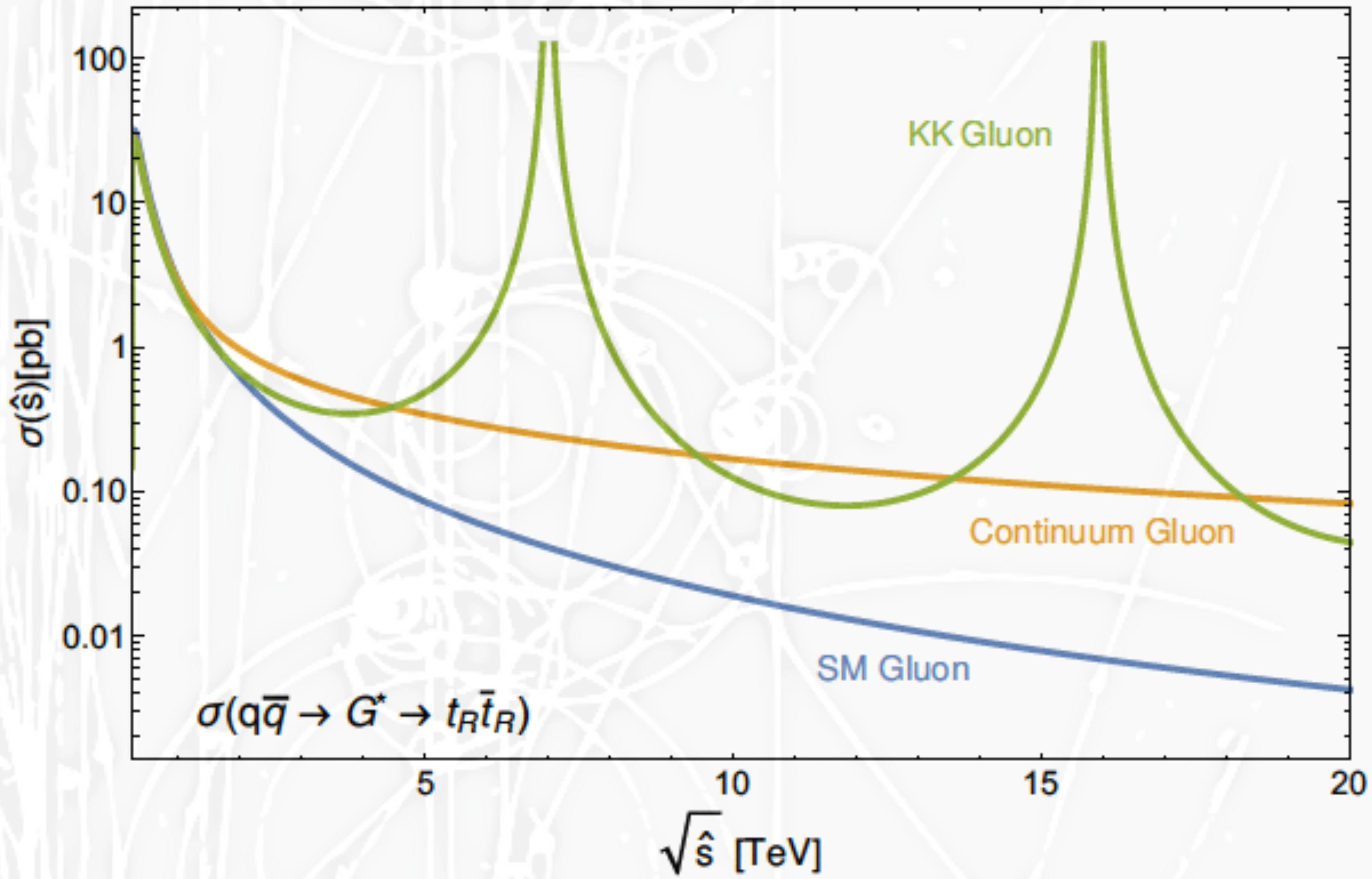

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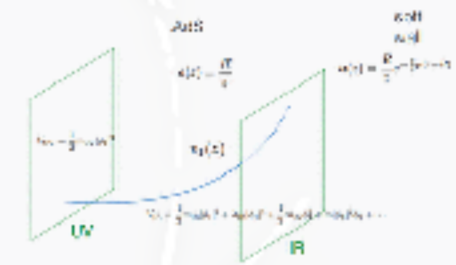

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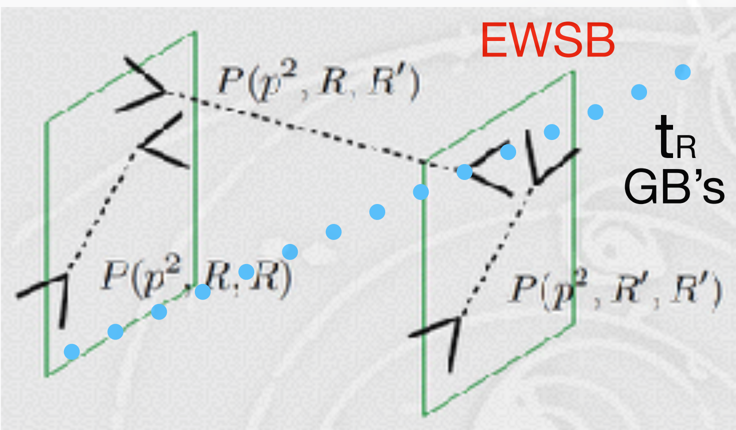

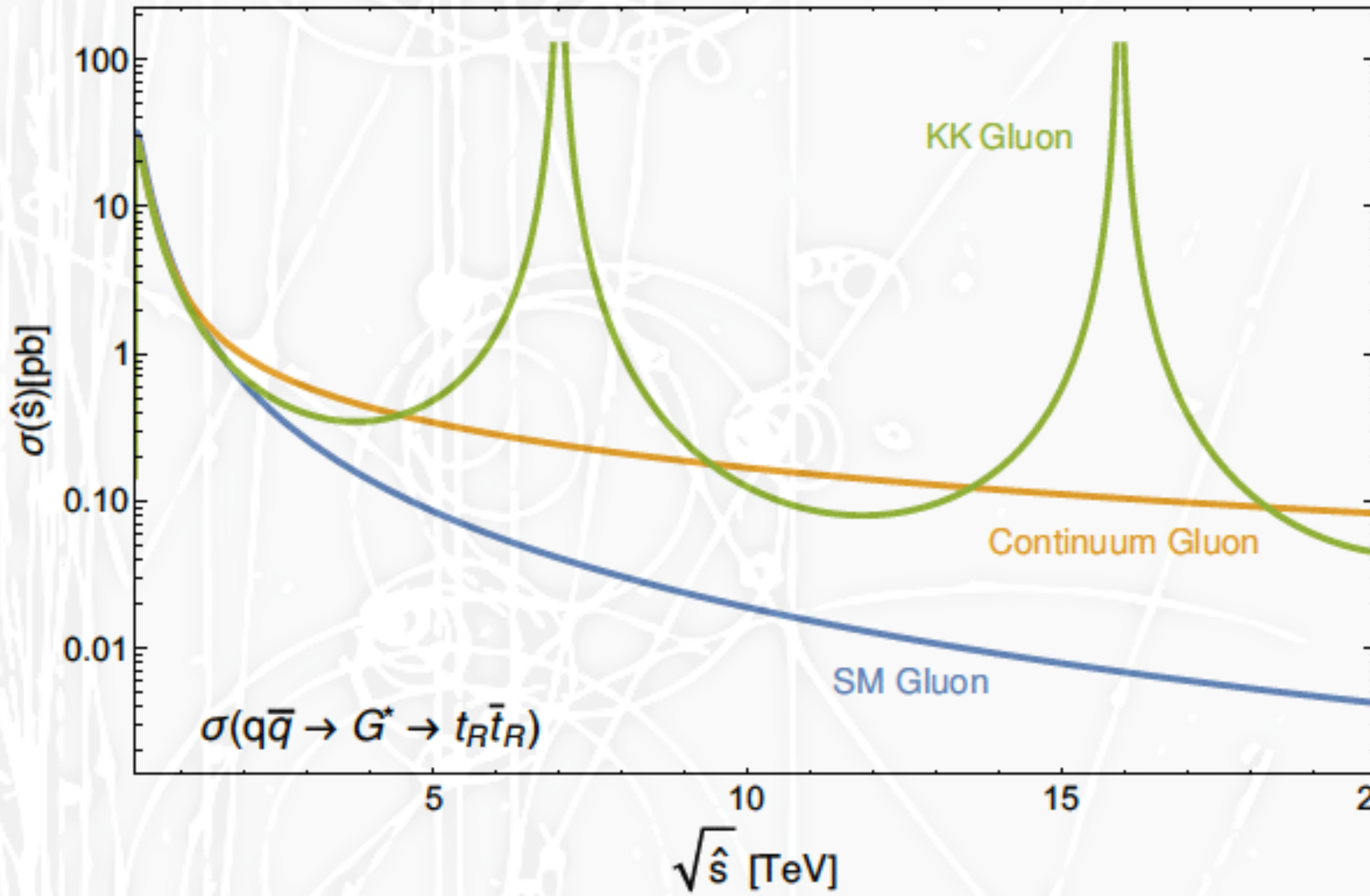

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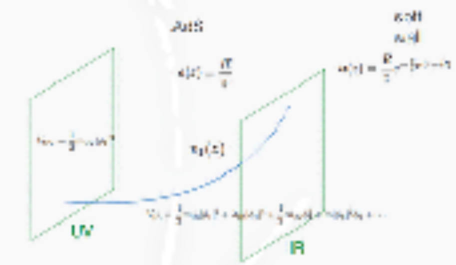

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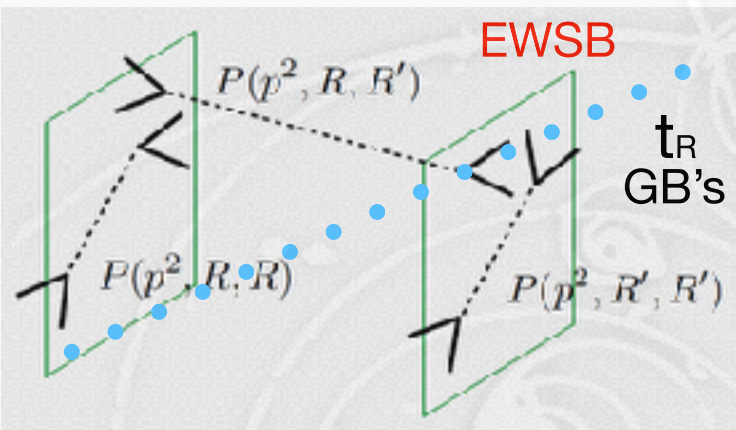

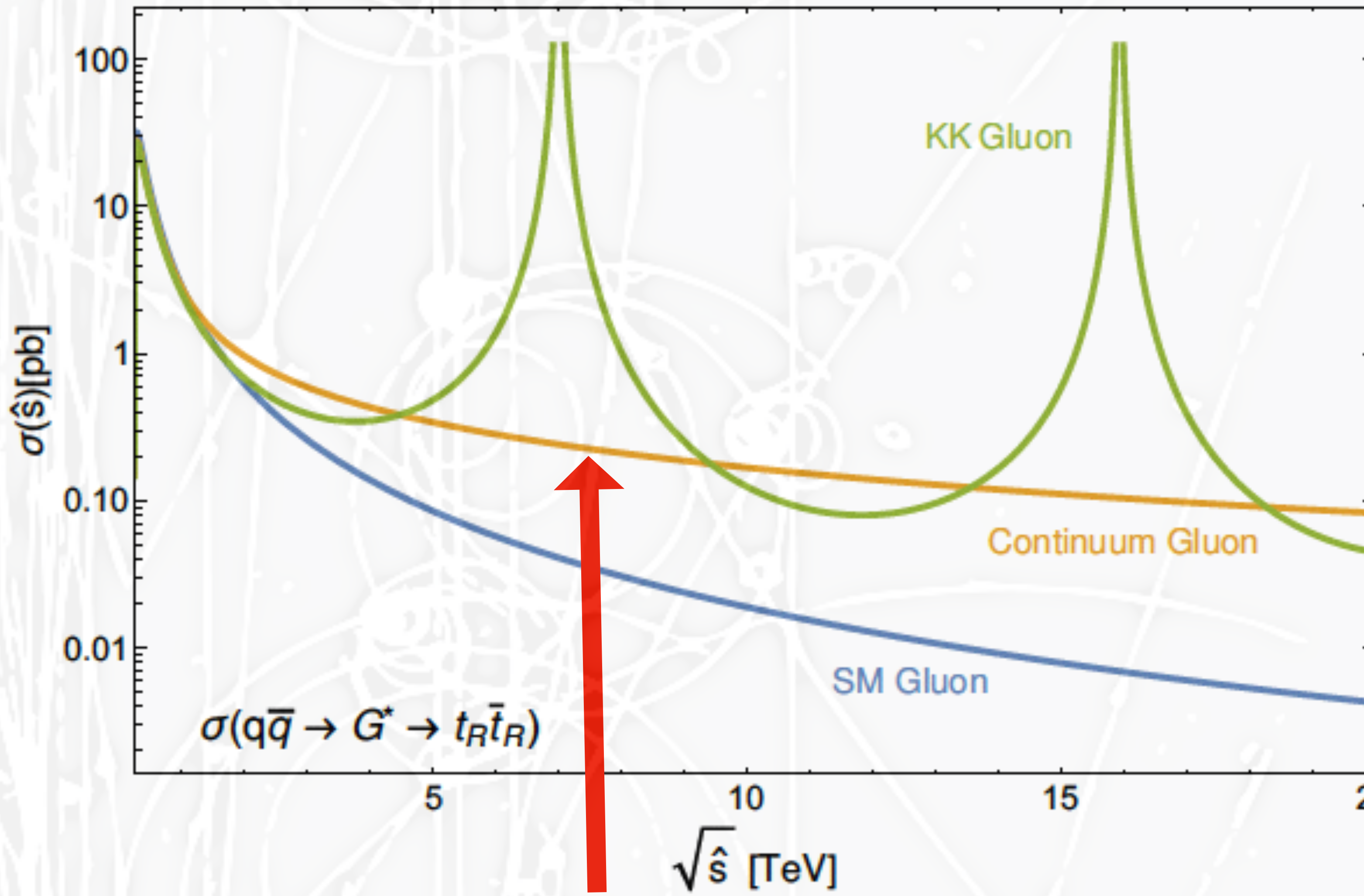

New Physics is hidden in the tail region!!

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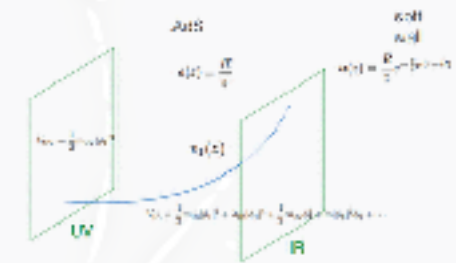
Continuum Naturalness?

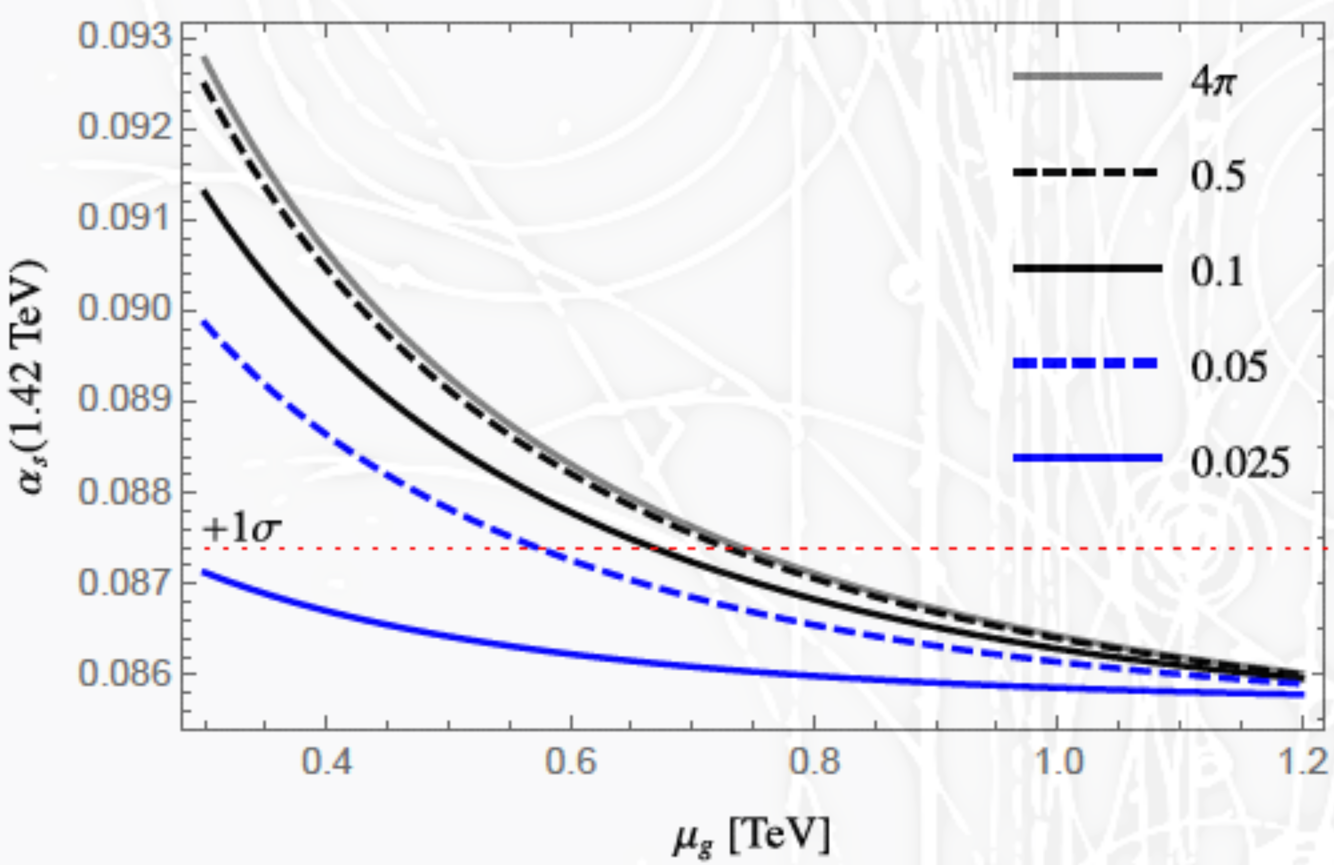
Csaki, Lombardo, Lee, SL, Telem



- 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

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



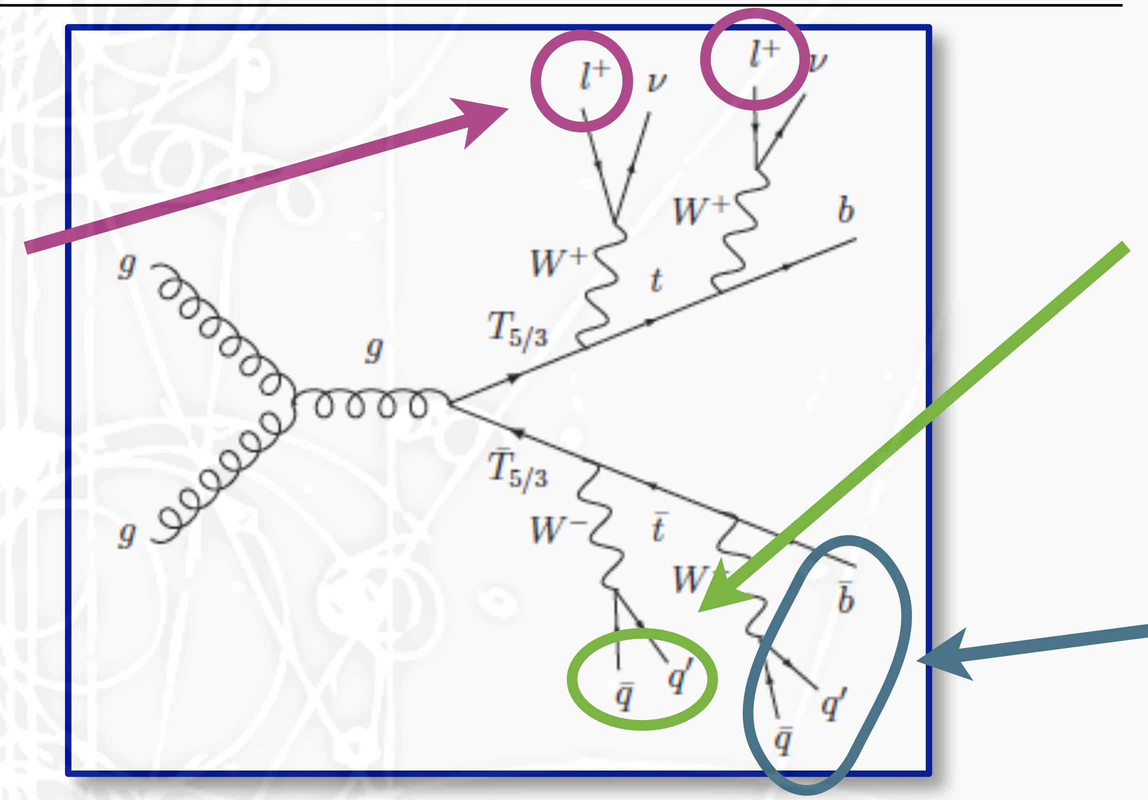
$$\mu_g > 600 - 700 \text{ GeV}$$

Continuum Top Partners

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

- Can we hide top partners at the LHC?

same-sign dileptons



$$\sigma(q\bar{q} \to \chi^\dagger \chi) = \frac{32\pi\alpha_s}{9s} \mathrm{Im}\Pi(s)$$

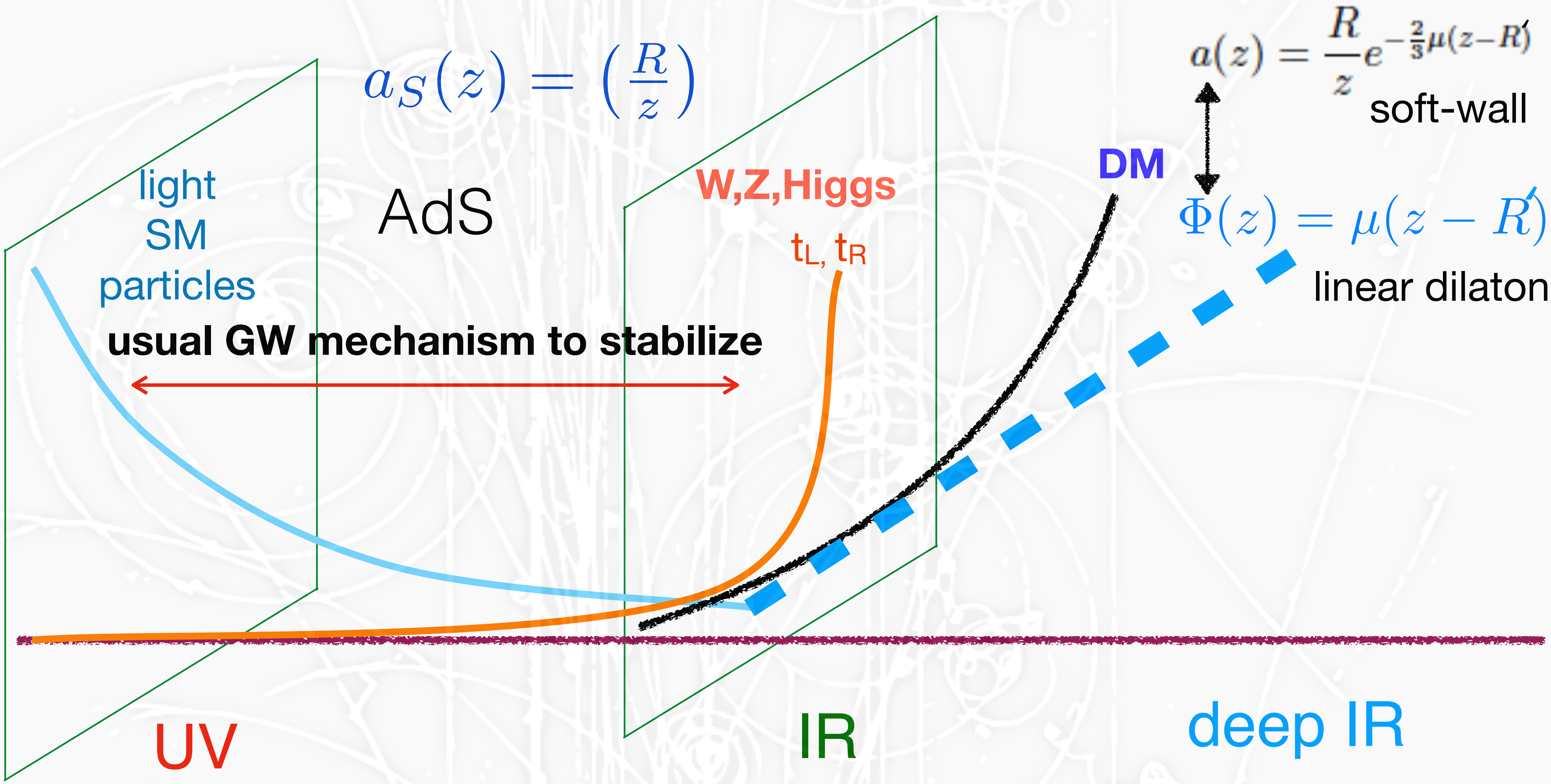
$$i\Pi^{\mu\nu,ab}(q) = \left(-g^{\mu\nu} + \frac{q^\mu q^\nu}{q^2}\right)\delta^{ab} i\Pi(q^2)$$

- depending on profile of the spectral density
- calculate top partner production for a given

- need to calculate loop with continuum states (work in progress)

Csaki, SL, Xue, work in progress

Continuum Dark Matter



Summary

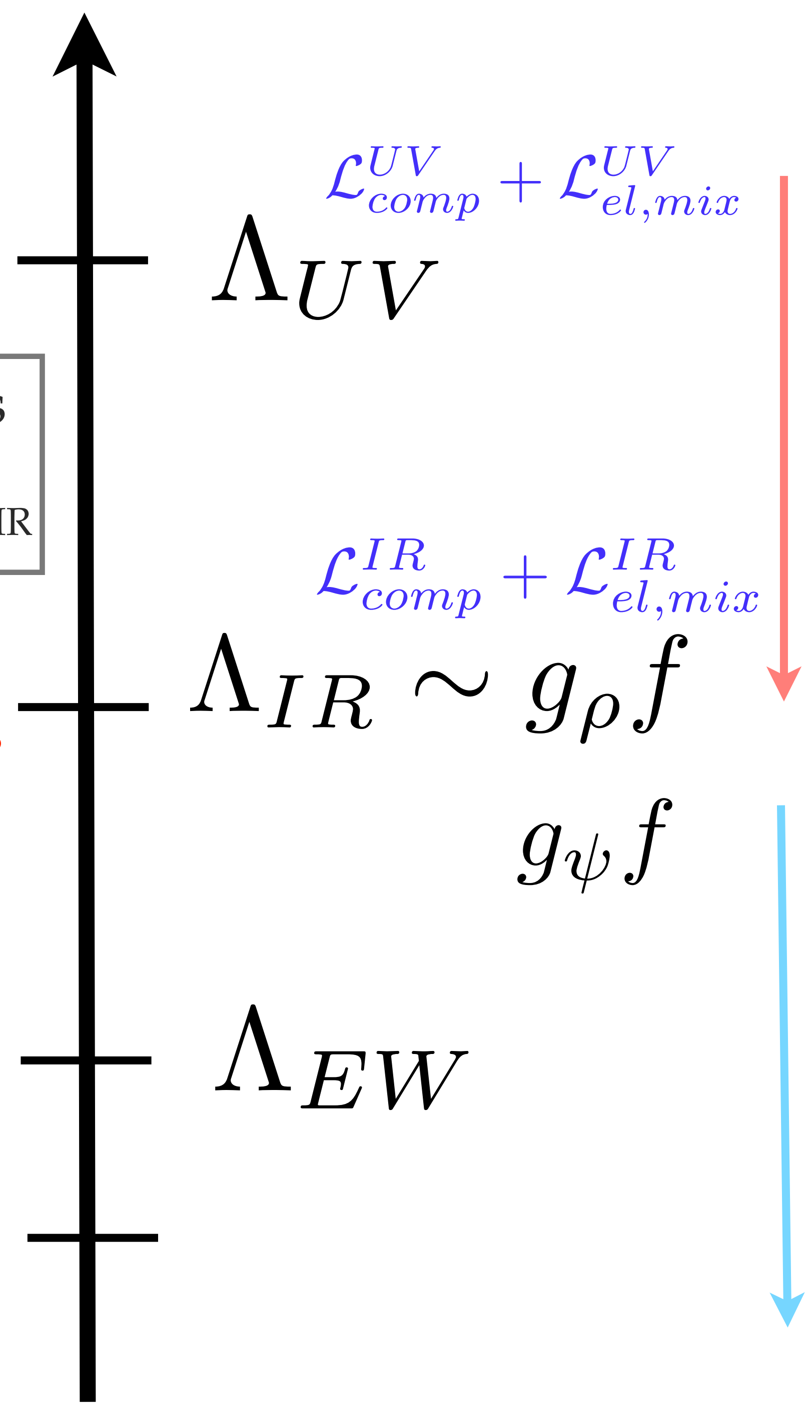
- Searches at the LHC have placed the naturalness paradigm under pressure
- We provided a natural model (continuum composite Higgs model), where top and gauge partners could be continuum states from the strong dynamics of confinement
- The new continuum states in this scenario cannot be described as Breit-Wigner resonances, drastically changing their LHC pheno
- No bounds from bump huntings, but still bounds from running of alpha, and pair production (work in progress).


Thank You

Composite Higgs

Georgi, Kaplan '84; Kaplan '91; Agashe, Contino, Pomarol '05; Agashe et al '06; Giudice et al '07; Contino et al '07; Csaki, Falkowski, Weiler '08; Contno, Servant '08; Mrazek, Wulzer '10; Panico, Wulzer '11; De Curtis, Redi, Tesi '11, Marzocca, Serone, Shu '12; Pomarol, Riva '12; Bellazini et al '12; De Simone et al '12, Grojean, Matsedonskyi, Panico "13,...

composite sector originated at some UV scale: e.g. assuming a conformal fixed point below UV, ...



Higgs mass term is irrelevant above Λ_{IR}

heavy resonances

strong dynamics

IR scale is dynamically generated
f ⇔ a symmetry breaking scale

PNGB model often requires $g_\psi f \neq g_\rho f$ for less fine-tuning to get ~125 GeV higgs

weak dynamics

$$m_h^2 \sim \frac{N_c}{2\pi^2}\frac{v^2}{f^2}M_T$$