Warped Dimensions & the LHC

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OUTLINE

- A non-supersymmetric, but extra-dimensional approach to Hierarchy Problem.
- Comprehensively developed & studied
- Deep principles are at stake
- An unusual, challenging phenomenology to prepare for:

Heavy Resonances $\longrightarrow$ highly boosted $t, b, W, Z, \text{higgs}^{2}$.

(Mostly $\hbar = c = 1$ units)

HIERARCHY PUZZLES of the SM

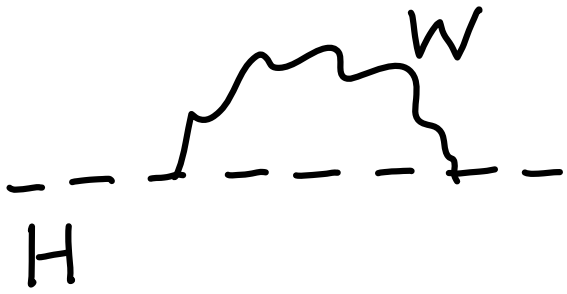
$$m_\nu \ll m_e \ll m_c \ll m_Z \ll M_{GUT}, M_{Pl}$$

$$V_{td}^{CKM} \ll V_{ud}^{CKM}$$

Flavor Hierarchies

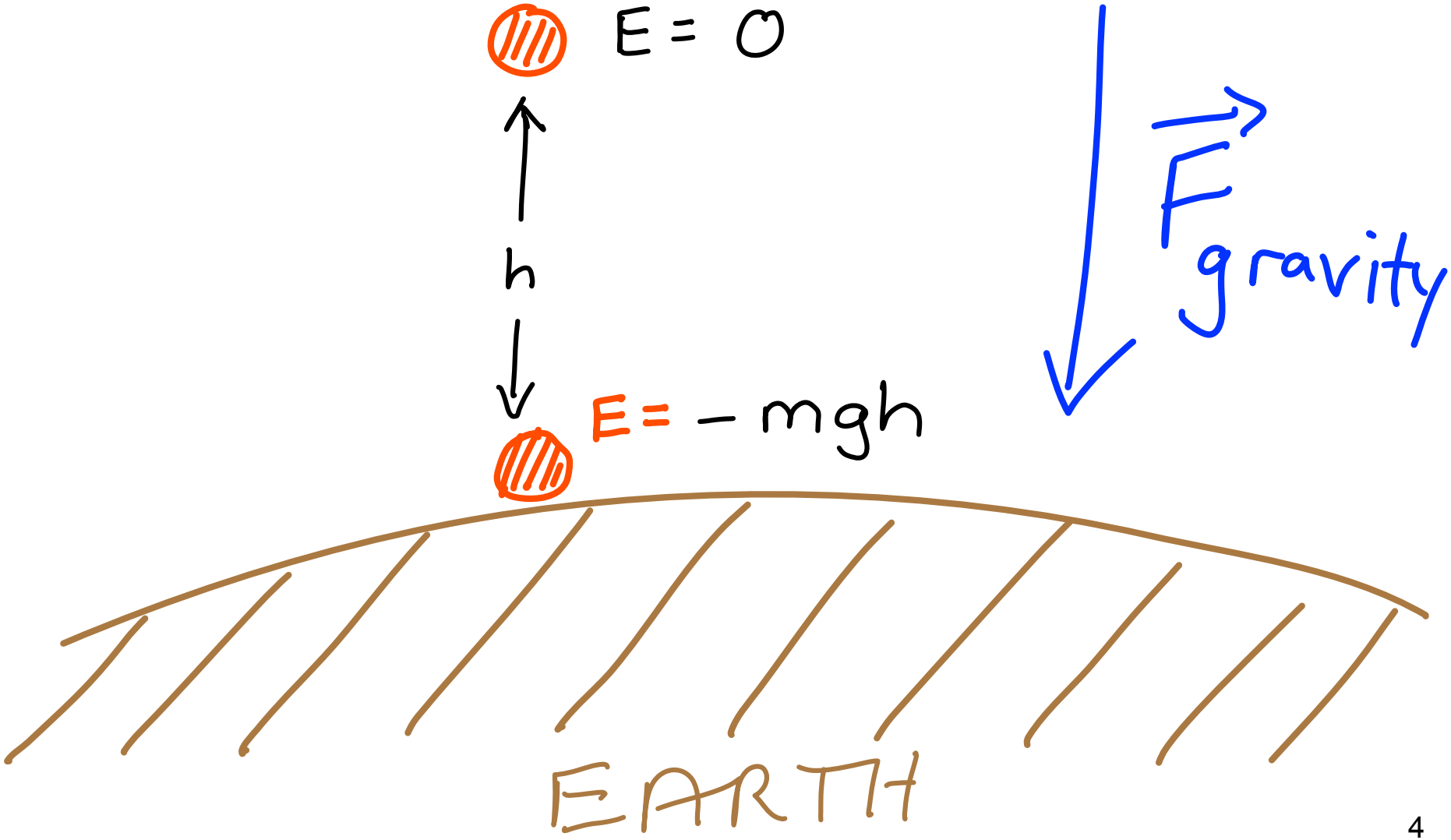
The Hierarchy Problem:

Radiative Corrections,



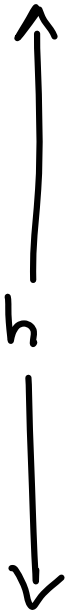
, tend to drive m_Z to the highest scales.

NEWTONIAN GRAVITY



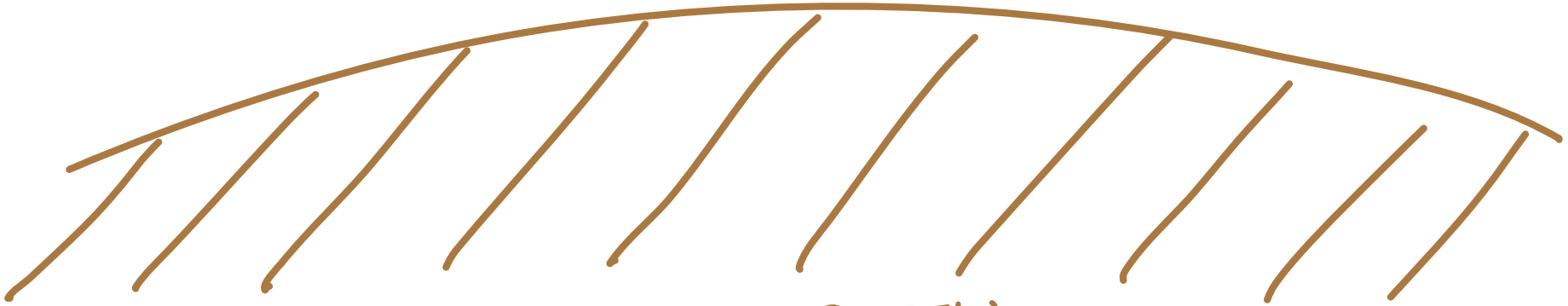
GENERAL RELATIVITY

tick, tick, tick



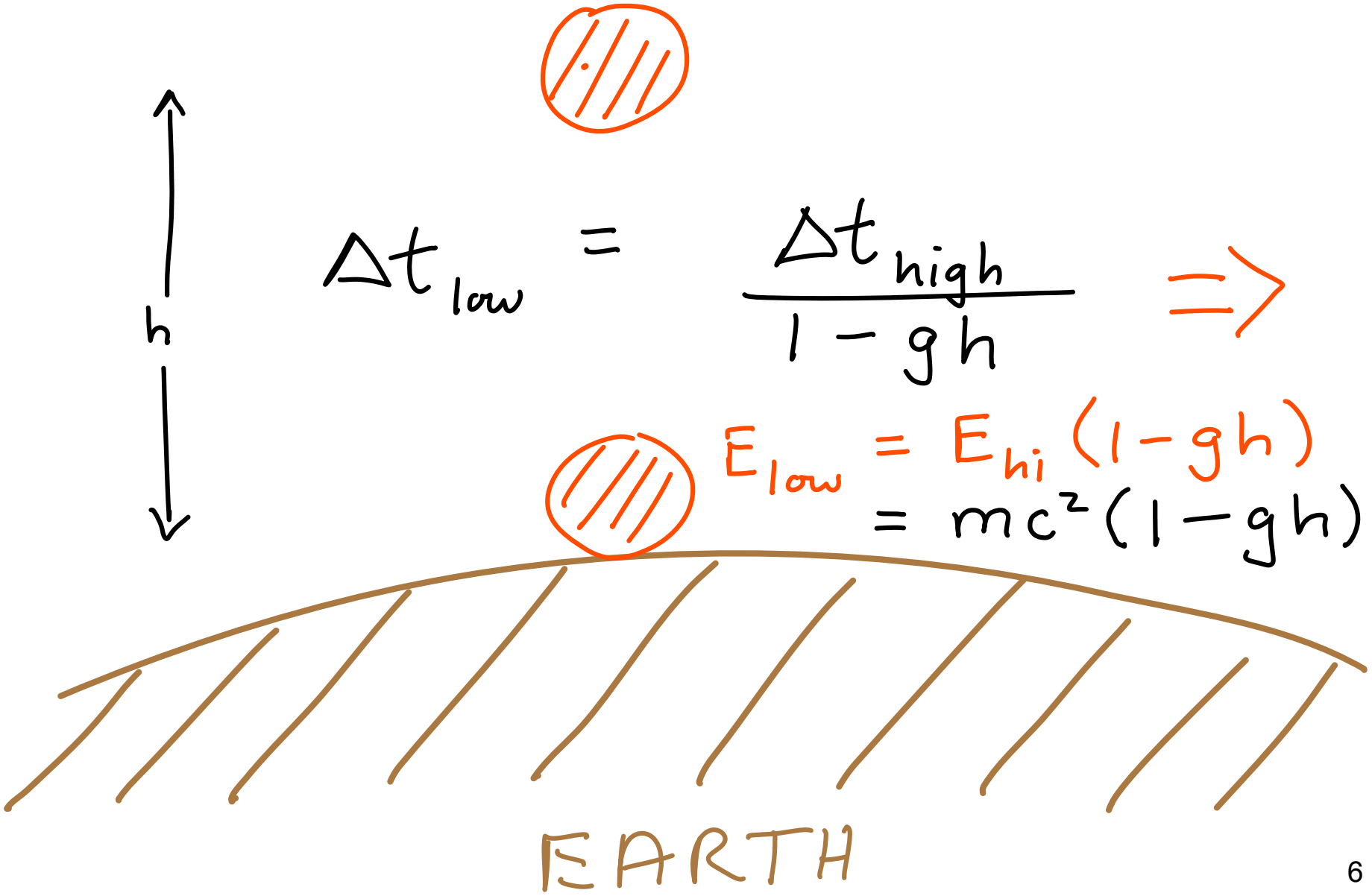
$$\Delta t_{low} = \frac{\Delta t_{high}}{1 - gh}$$

tick – tick – tick

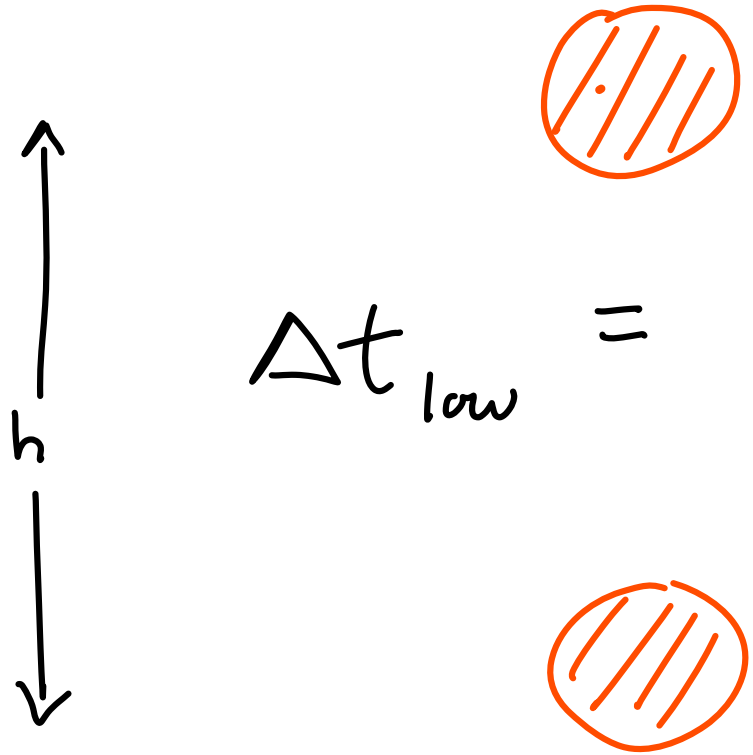


EARTH

GRAVITATIONAL REDSHIFT



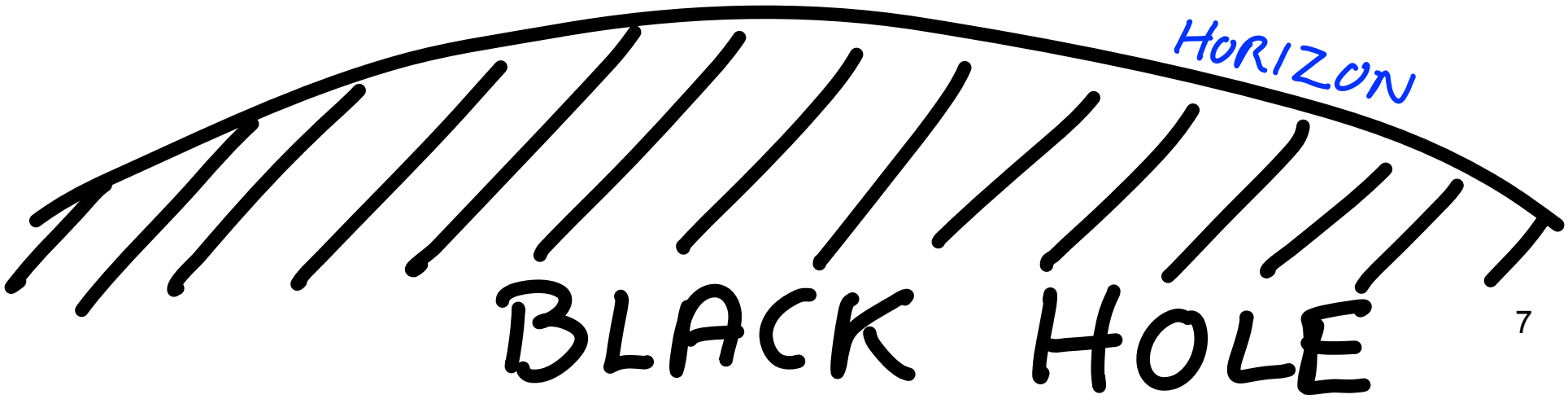
GRAVITATIONAL REDSHIFTS CAN BE BIG!



$$\Delta t_{low} = \frac{\Delta t_{high}}{\sqrt{1 - \frac{R_{horizon}}{r}}} \Rightarrow$$

$$E_{low} = E_{hi}\sqrt{1 - \frac{R_{horizon}}{r}}$$

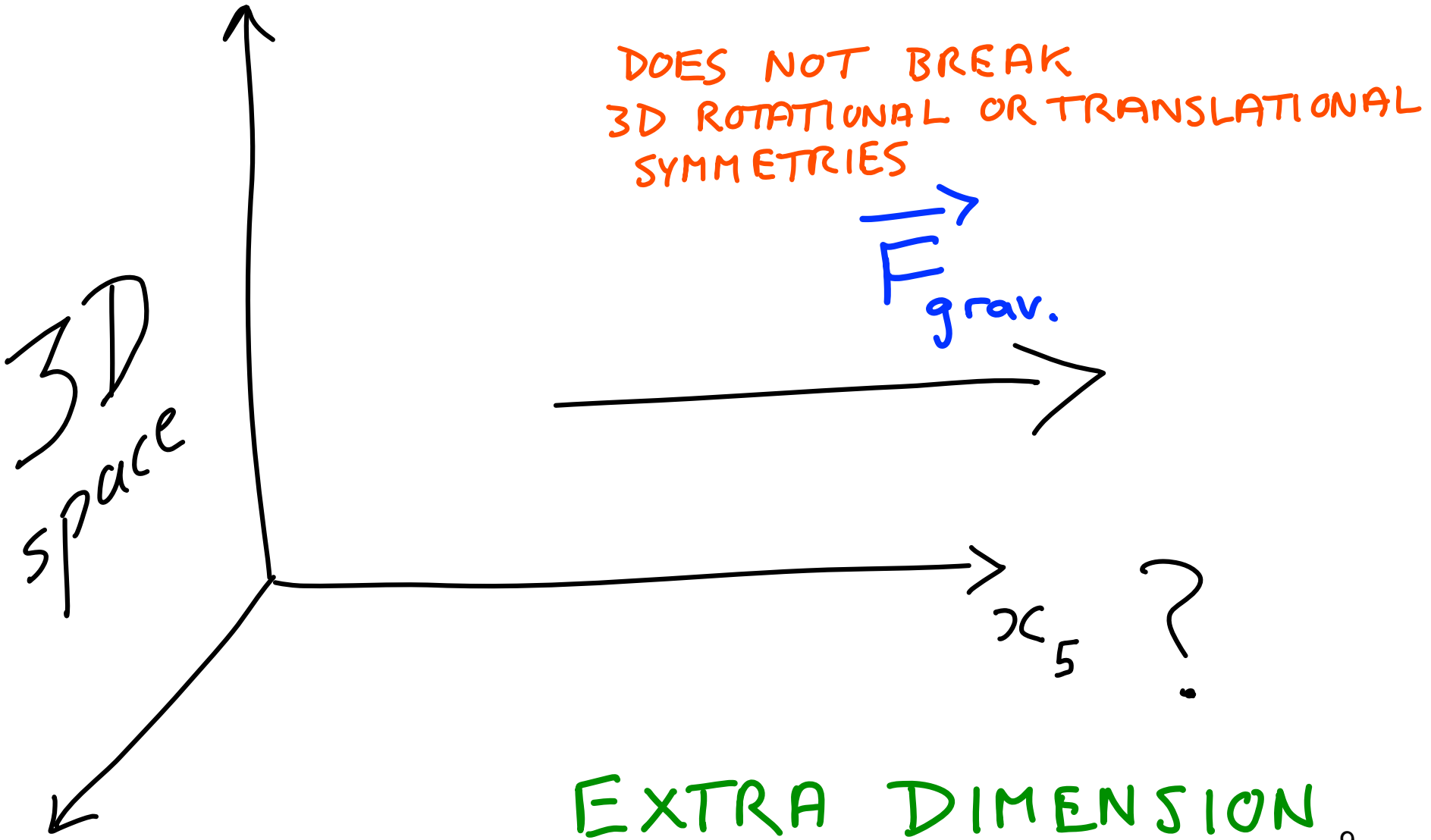
$$= mc^2\sqrt{1 - R_{horizon}/r}$$



CAN BIG REDSHIFTS EXPLAIN BIG MASS HIERARCHIES?

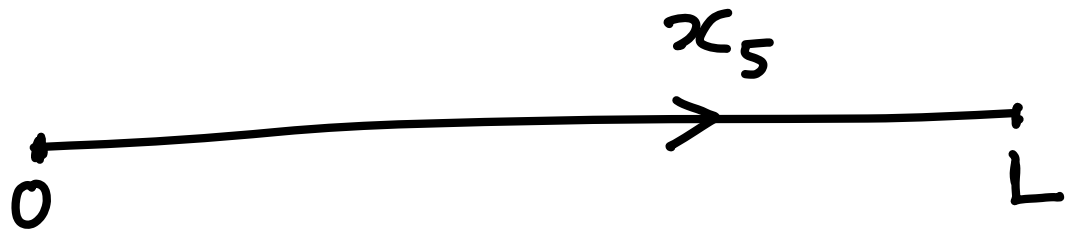
BUT WHICH WAY IS DOWN?

A NEW DIRECTION

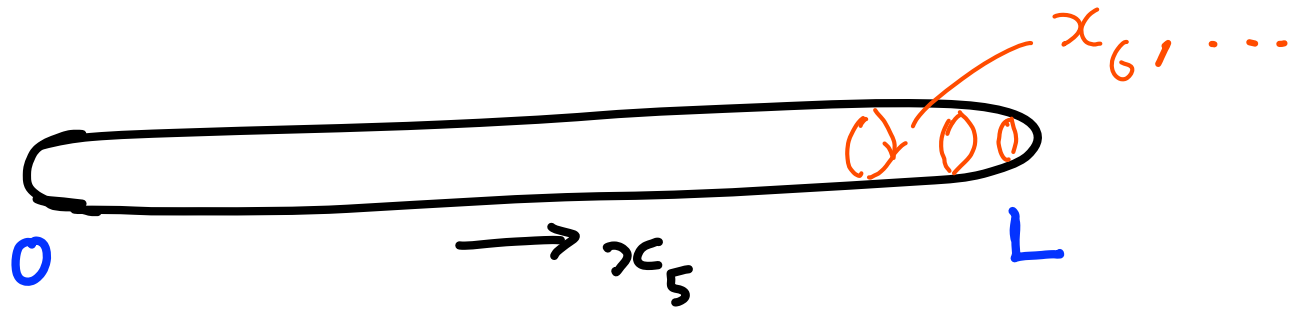


EXTRA DIMENSION

THE ENDS OF THE UNIVERSE



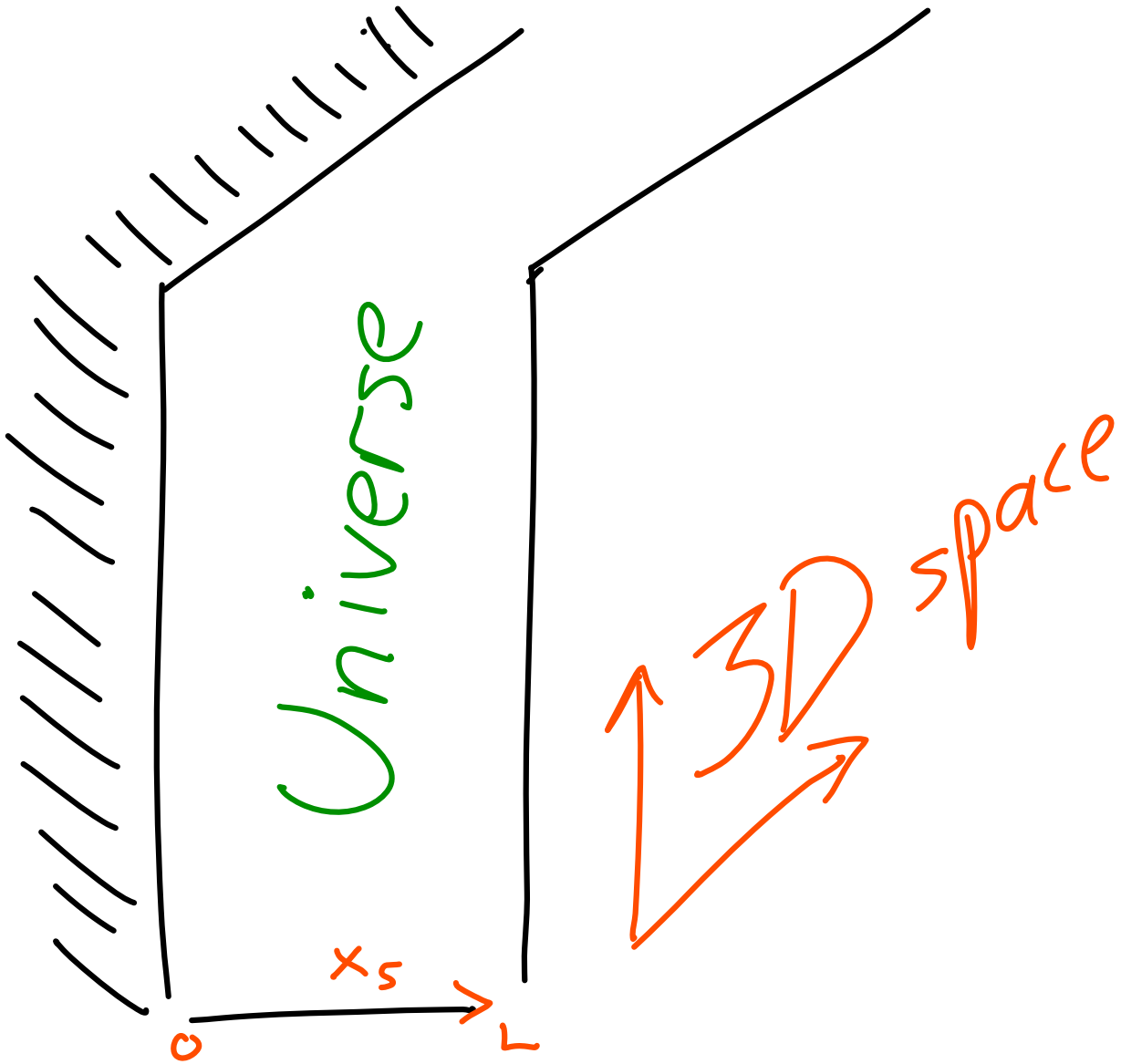
THE ENDS OF THE UNIVERSE



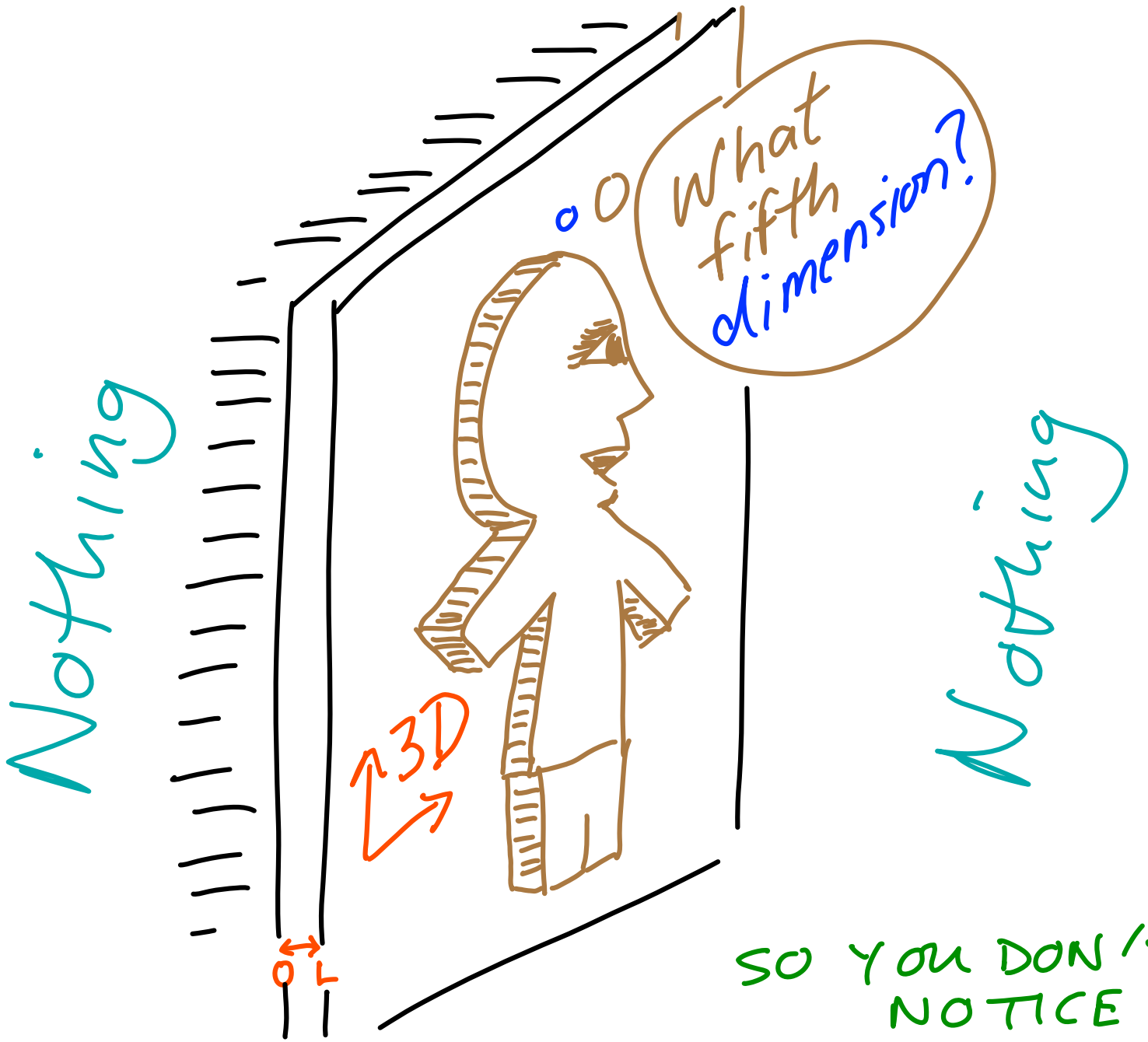
CAN BE SMOOTH

SUCH AS IN SOME
STRING THEORY CONSTRUCTIONS

THE ENDS OF THE UNIVERSE

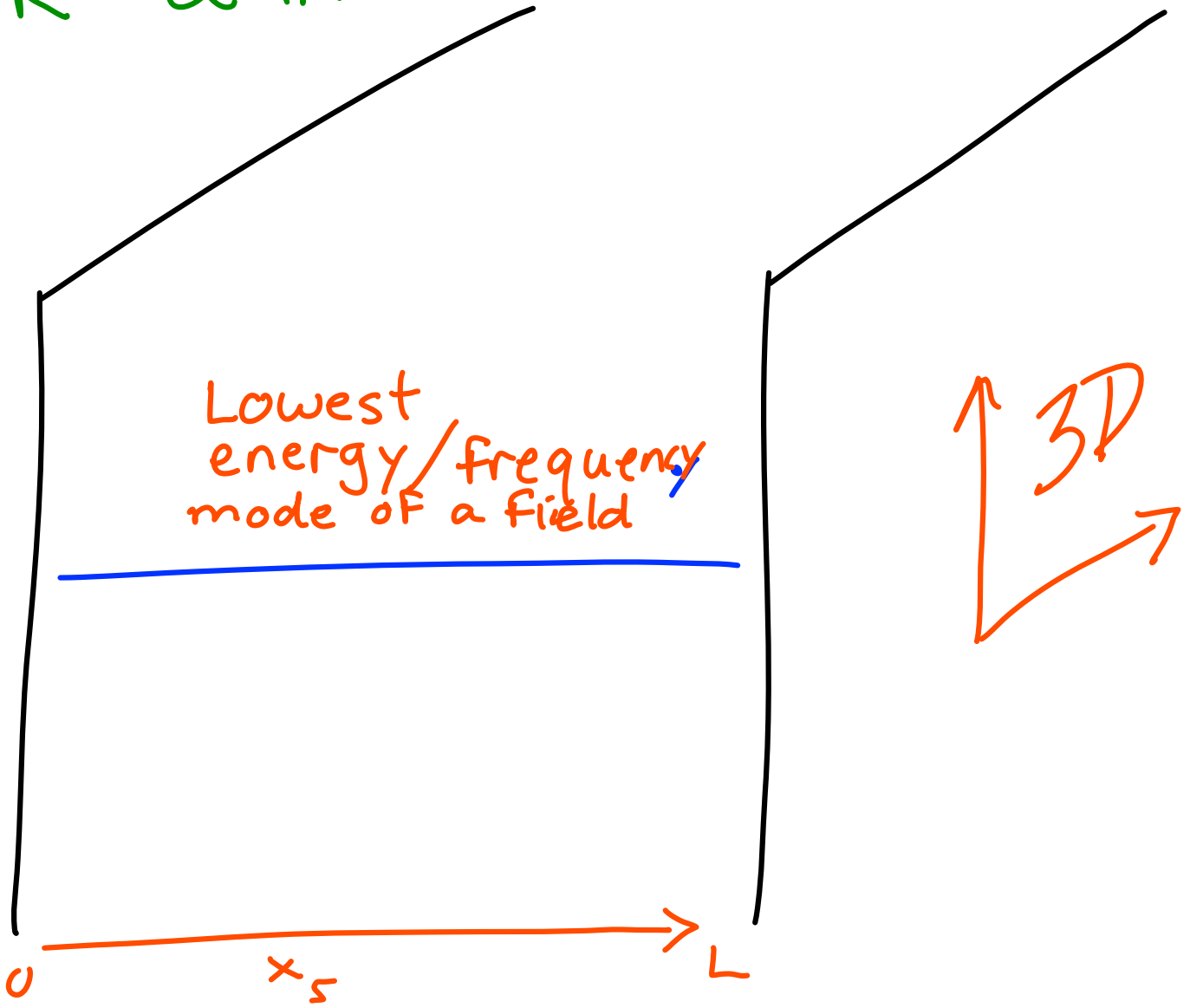


THE FIFTH DIMENSION IS SMALL...



SO YOU DON'T NOTICE IT

A COSMIC WAVE GUIDE FOR QUANTUM FIELDS



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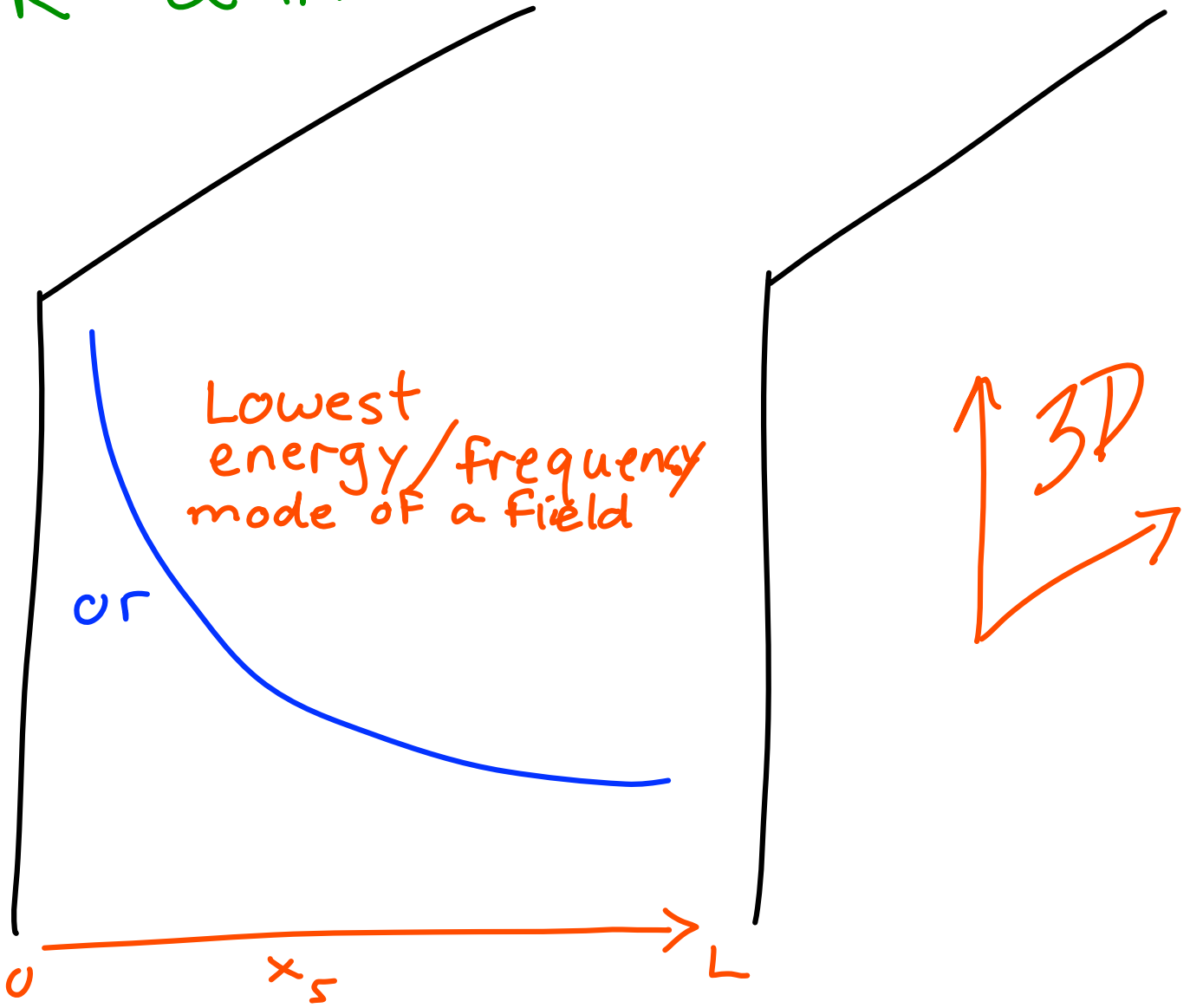

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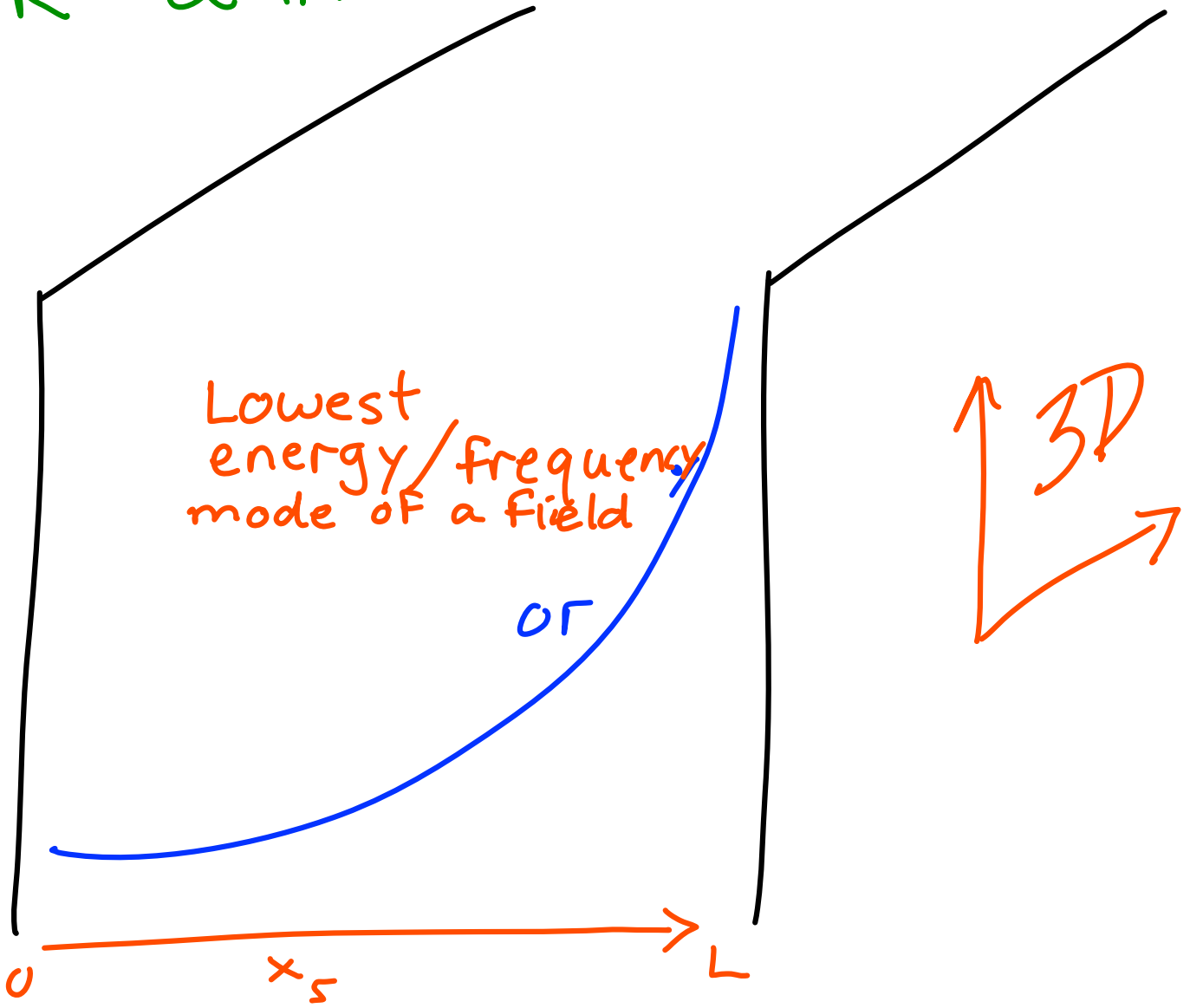

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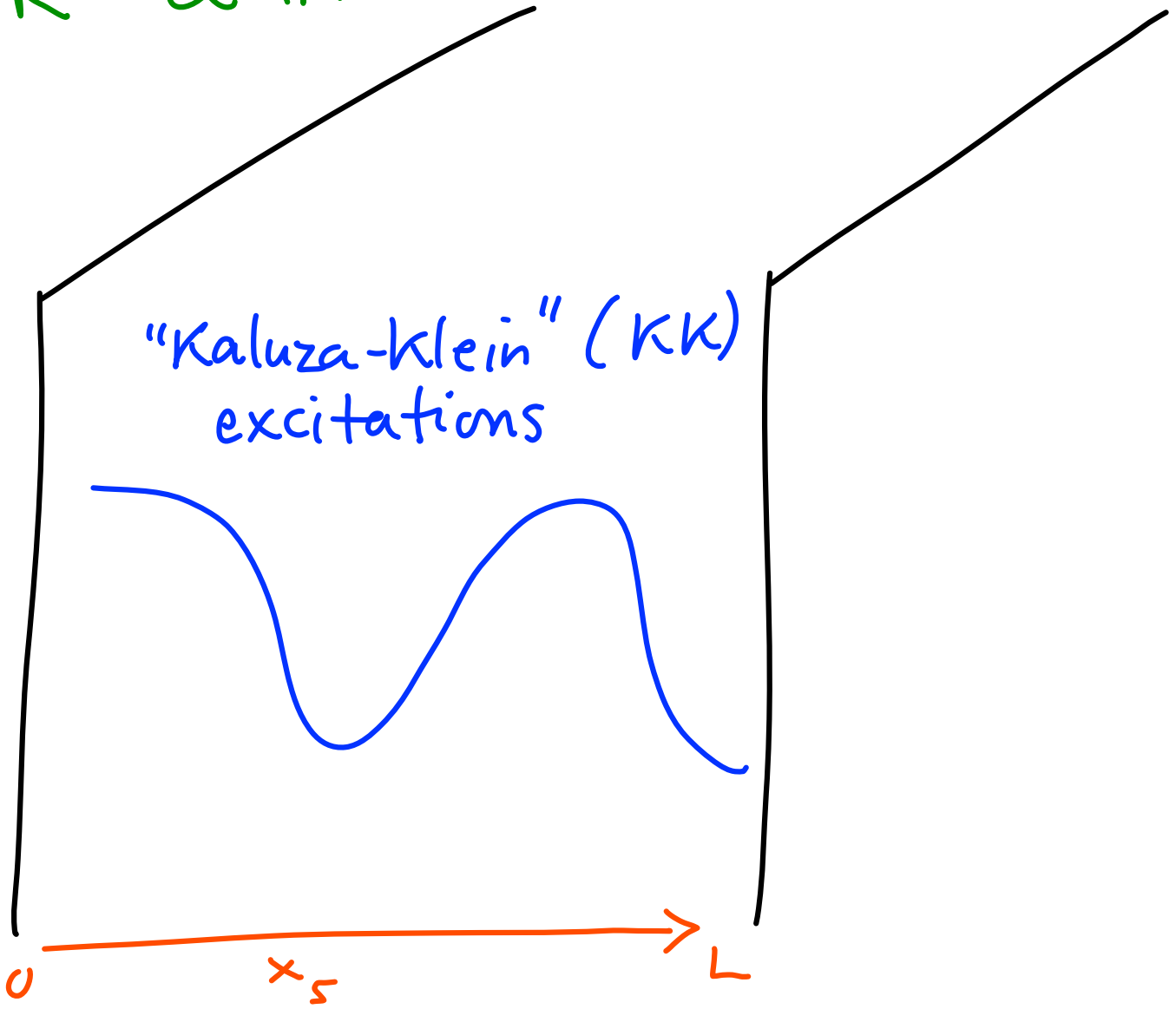

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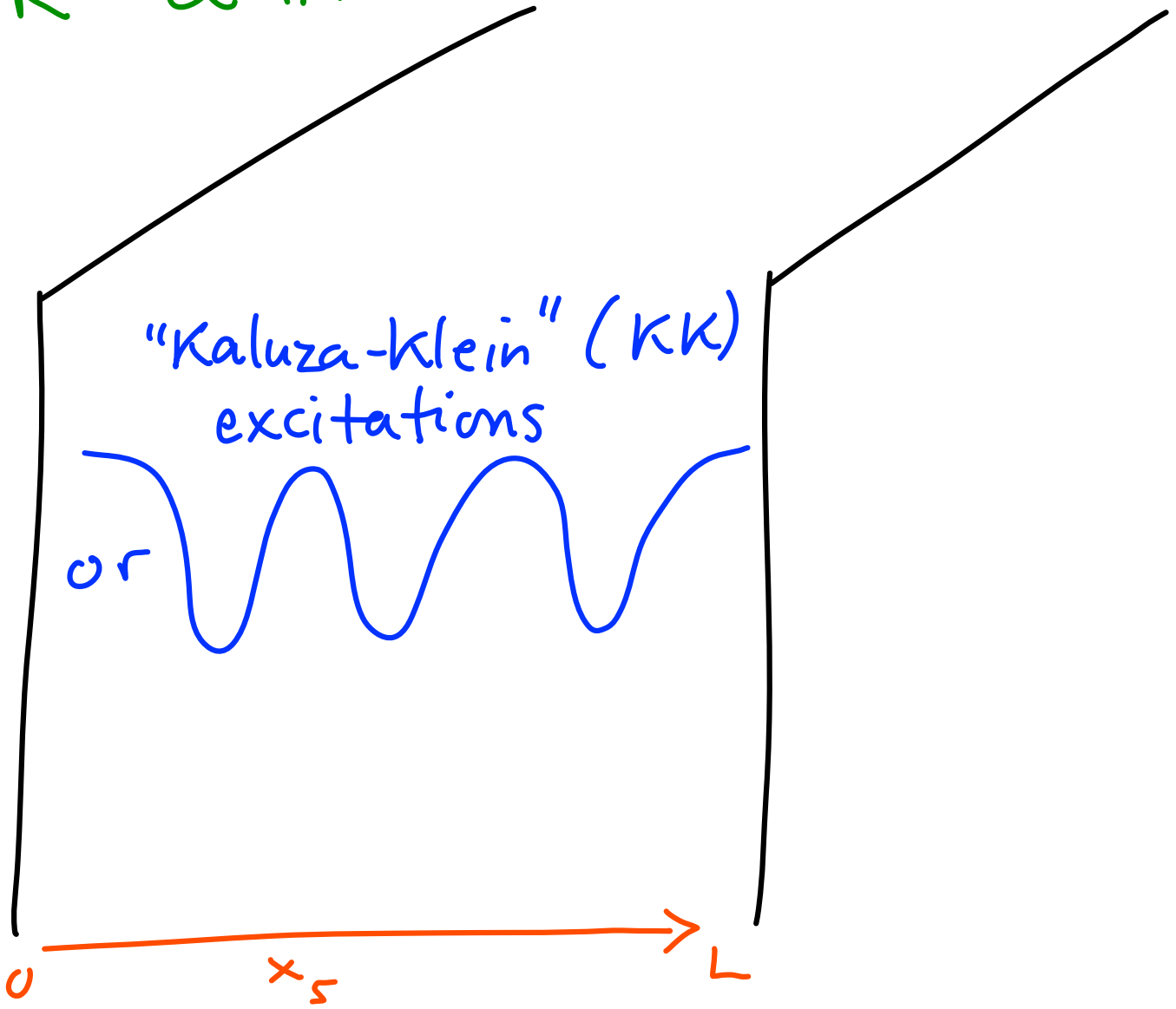

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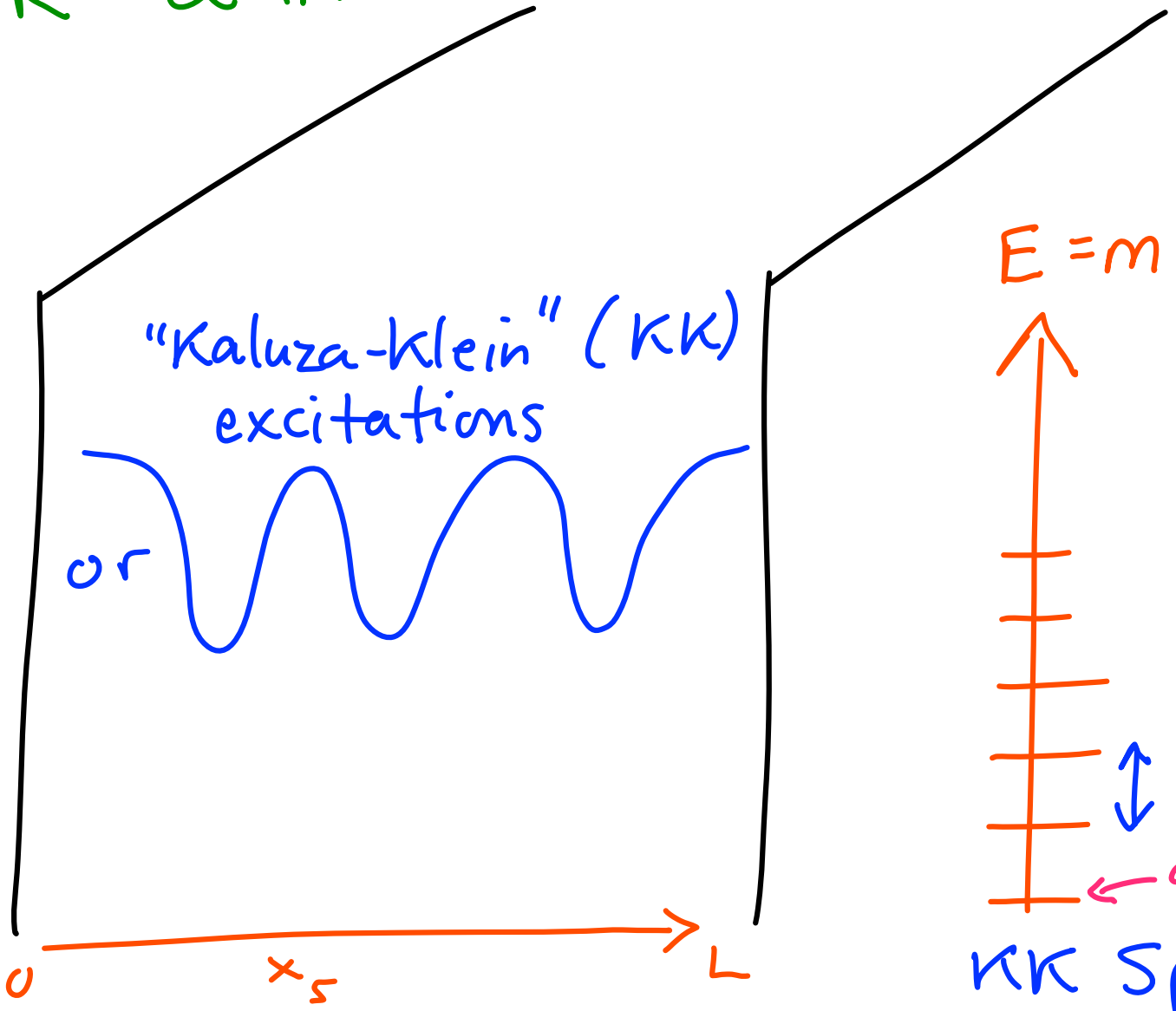
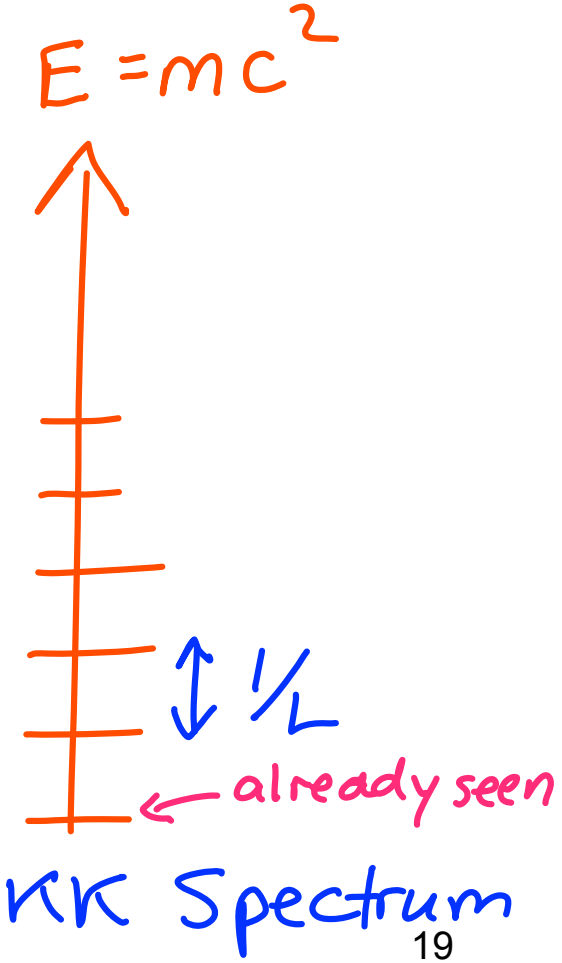
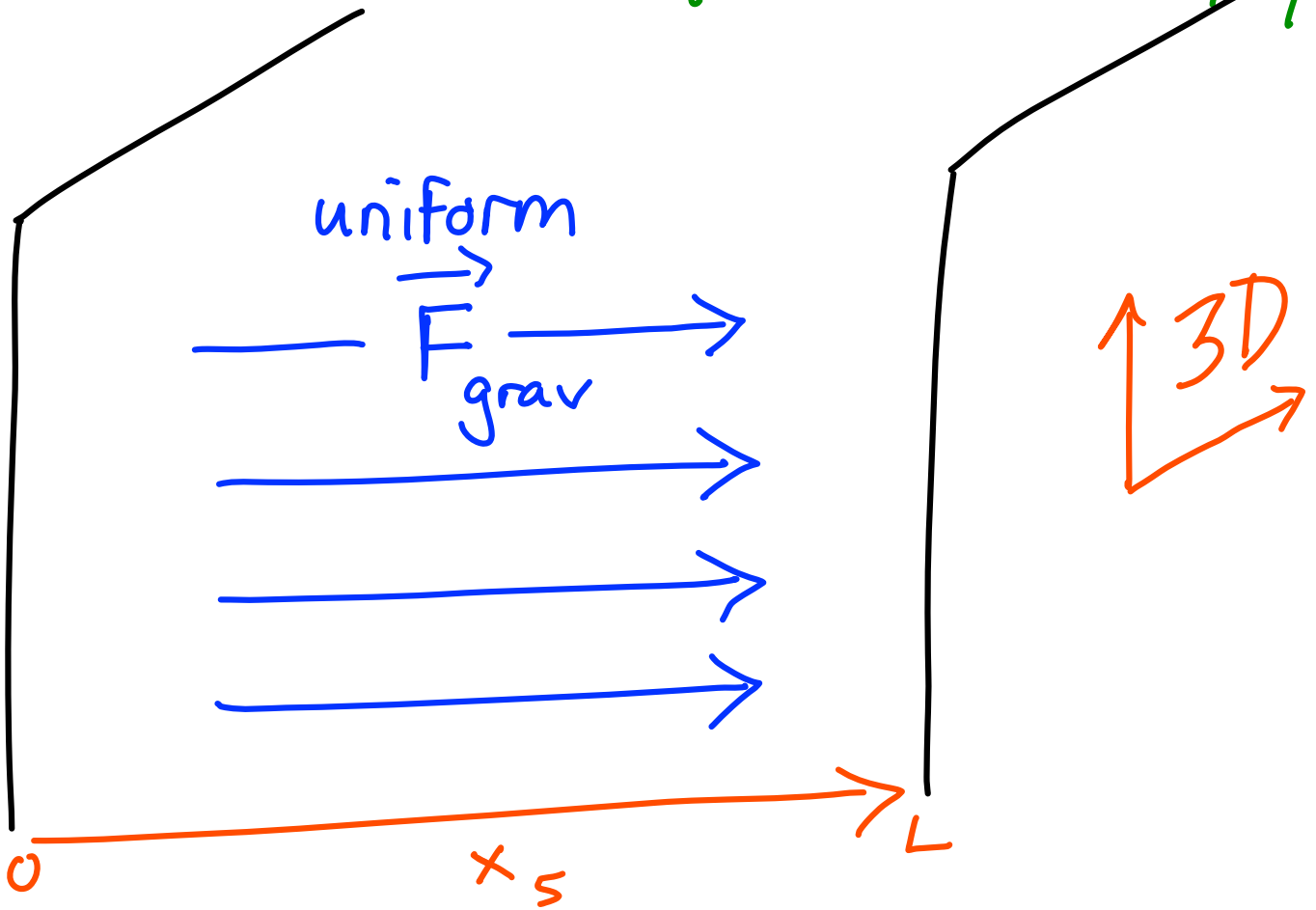




RANDALL-SUNDRUM I MODEL (RS1)

Randall, Sundrum '99

Higher-dimensional Einstein Equations robustly yield...



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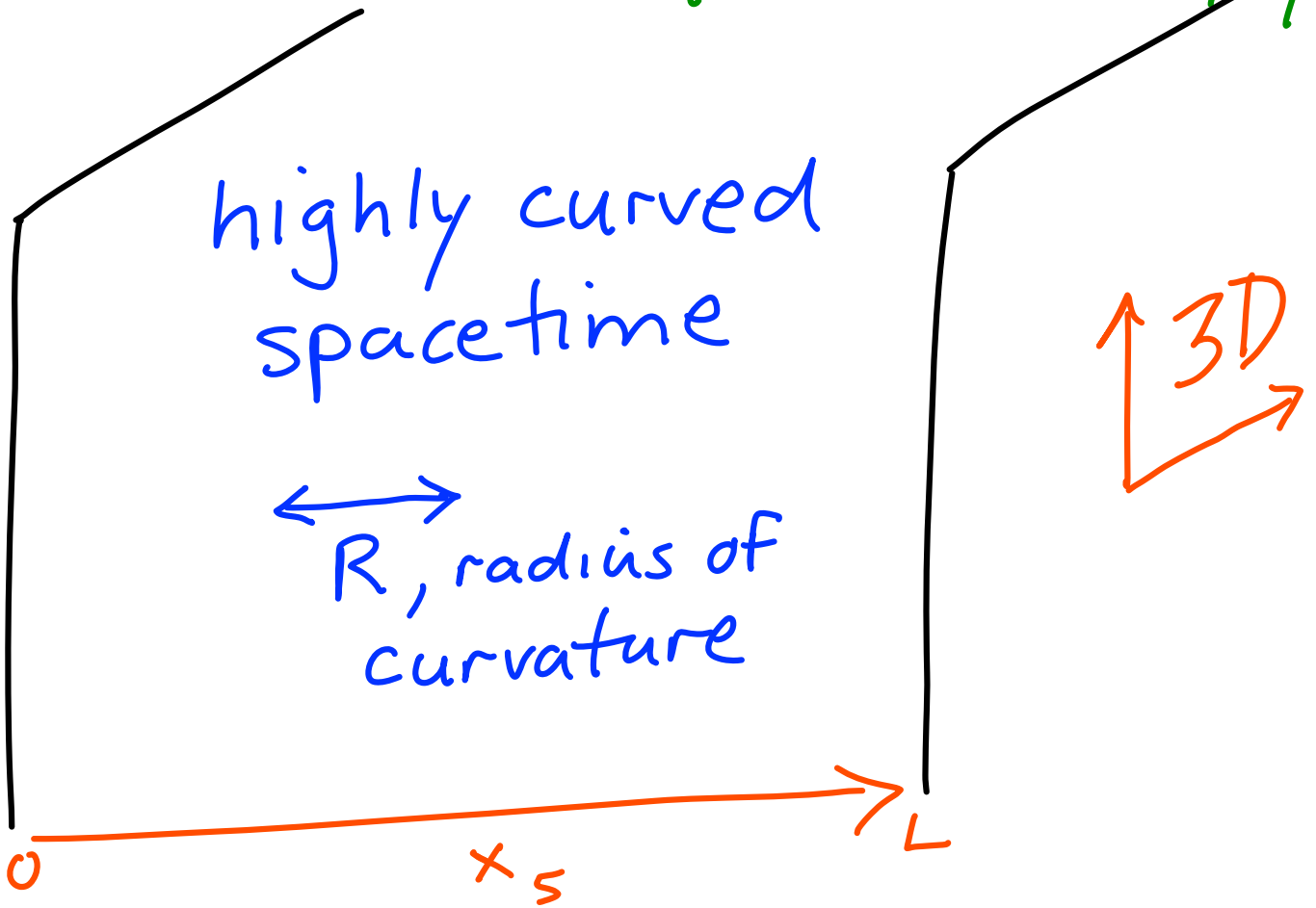

$L \sim 10/s \times R$ readily occurs in solutions

Goldberger, Wise '99

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Randall, Sundrum '99

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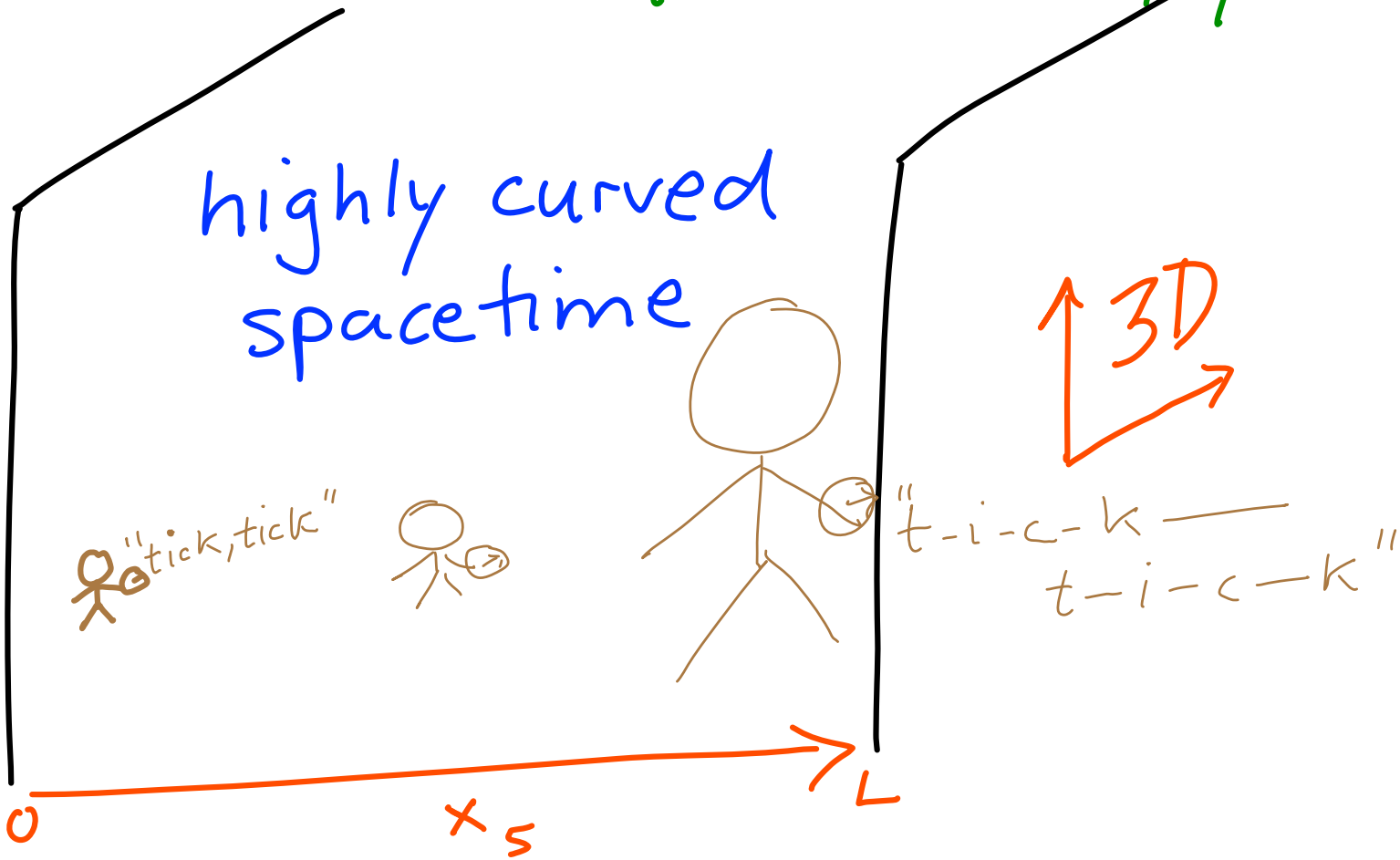

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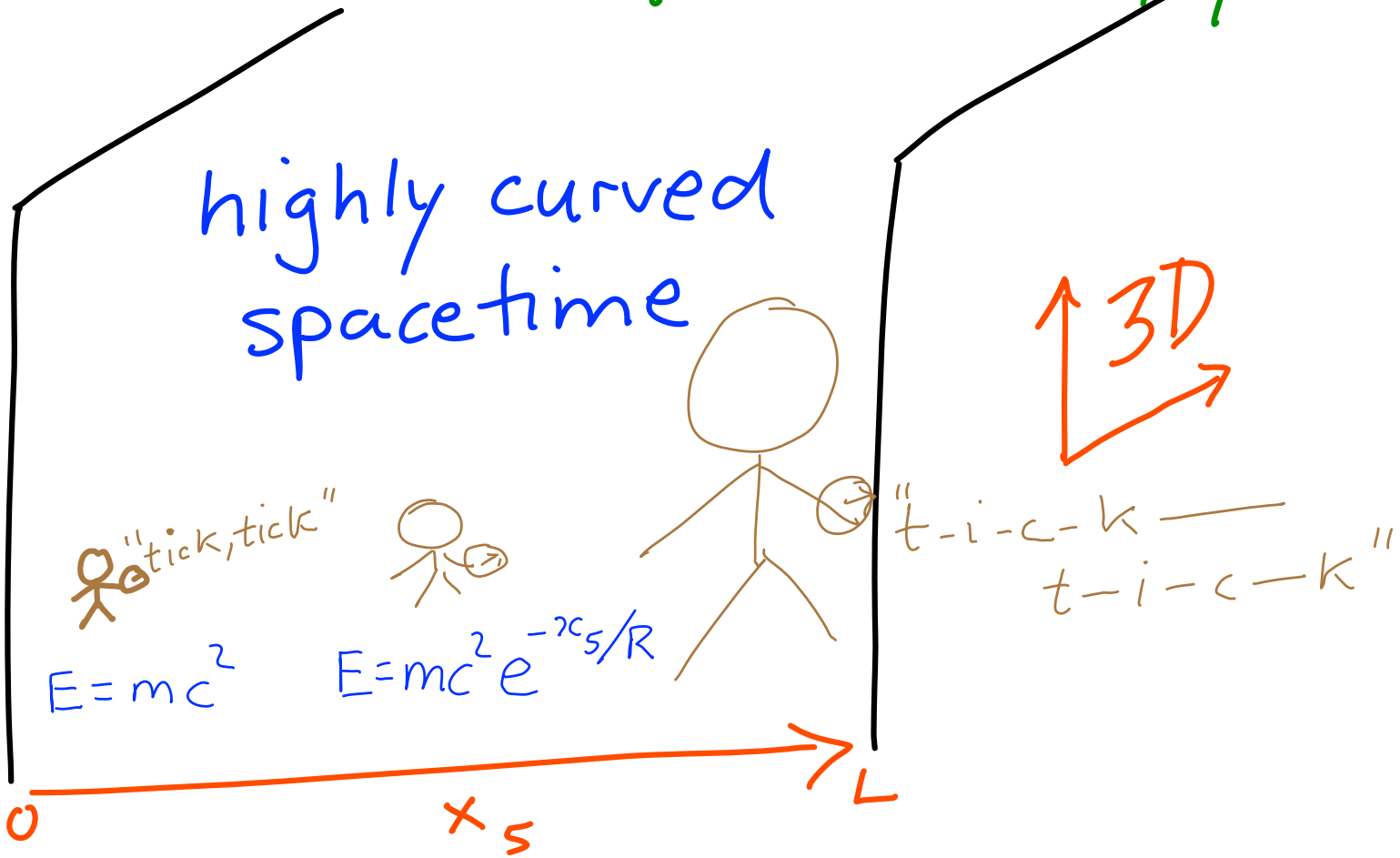
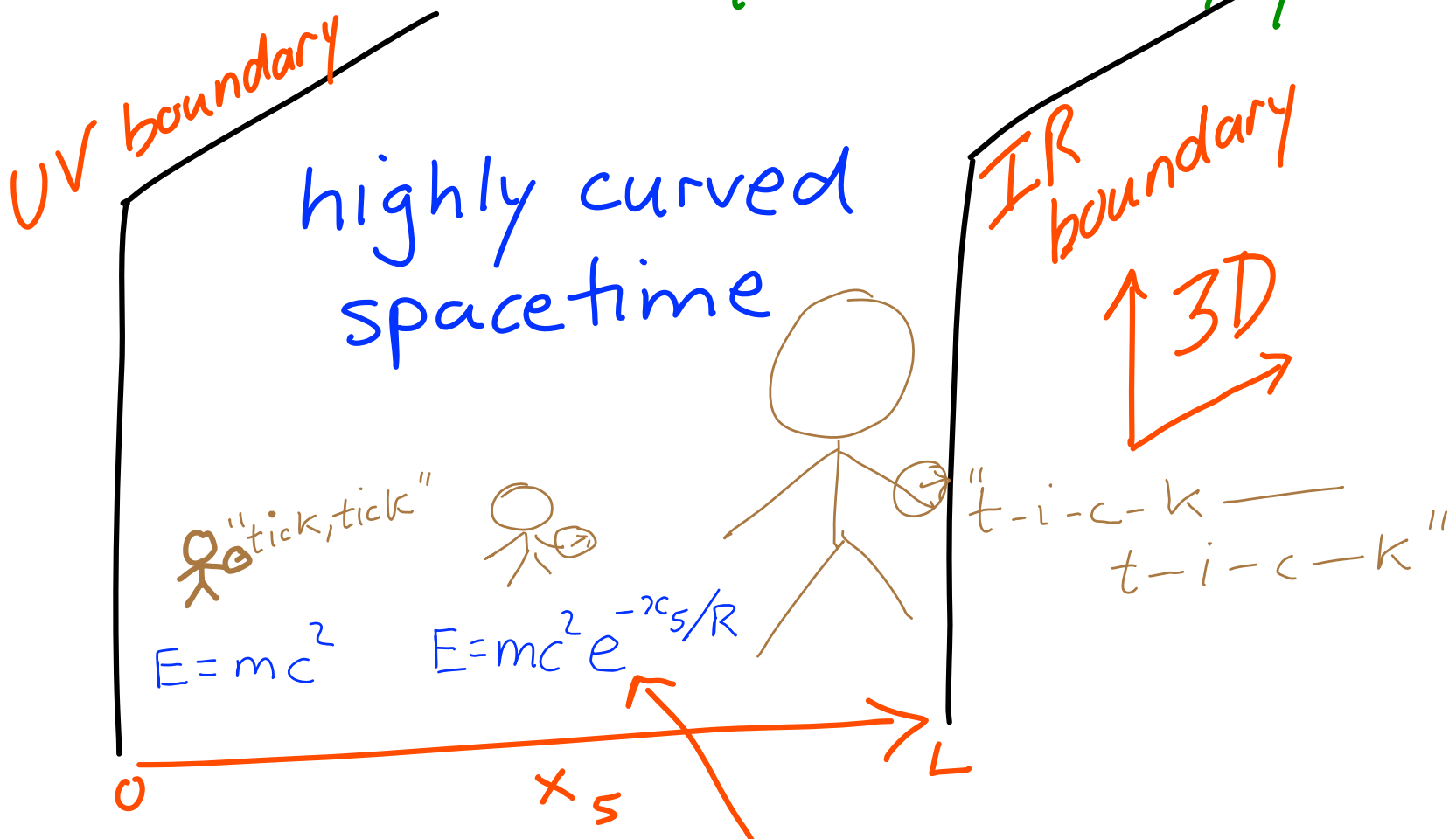


... Exponential Gravitational Redshifts

RANDALL-SUNDRUM I MODEL (RS1)

Randall, Sundrum '99

Higher-dimensional Einstein Equations robustly yield...

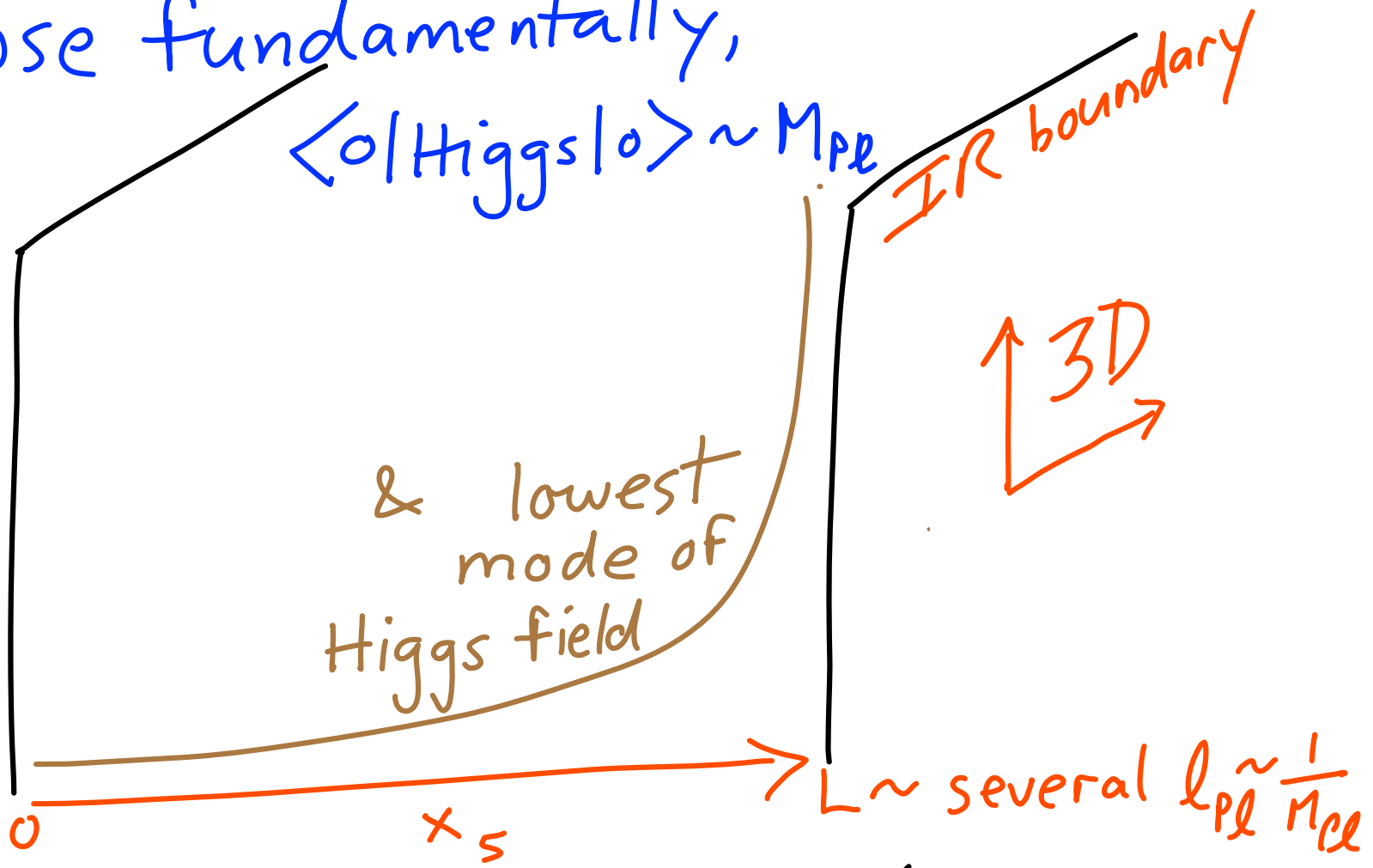


... Exponential Redshift "Warp factor"

RANDALL-SUNDRUM I MODEL (RS1)

Randall, Sundrum '99

Suppose fundamentally, $\langle 0|\text{Higgs}|0\rangle \sim M_{Pl}$



Effectively $\langle 0|\text{Higgs}|0\rangle \sim M_{Pl}\, e^{-L/R}$

sets max. SM masses (m_Z, m_{top})

RANDALL-SUNDRUM I MODEL (RS1)

Randall, Sundrum '99

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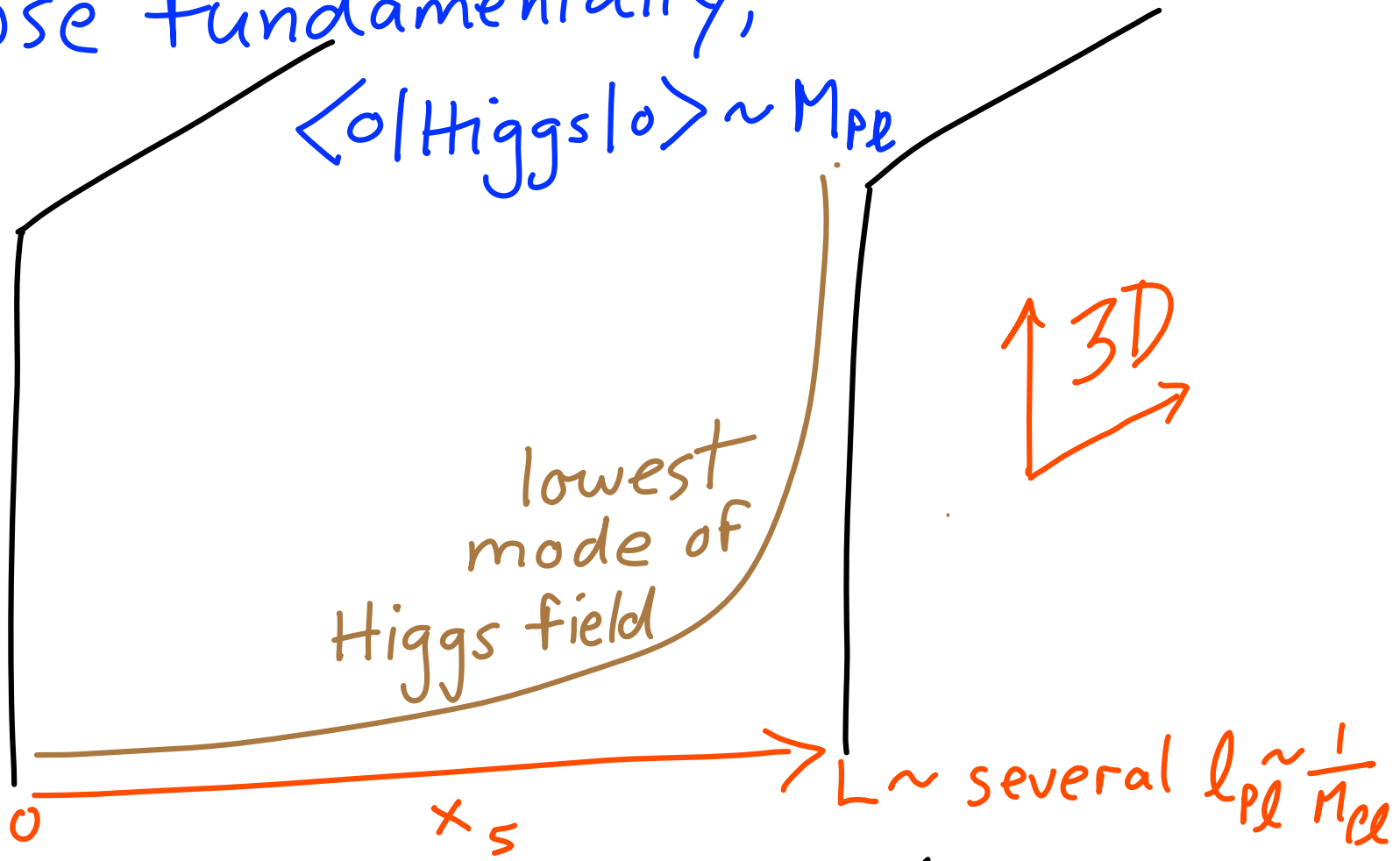
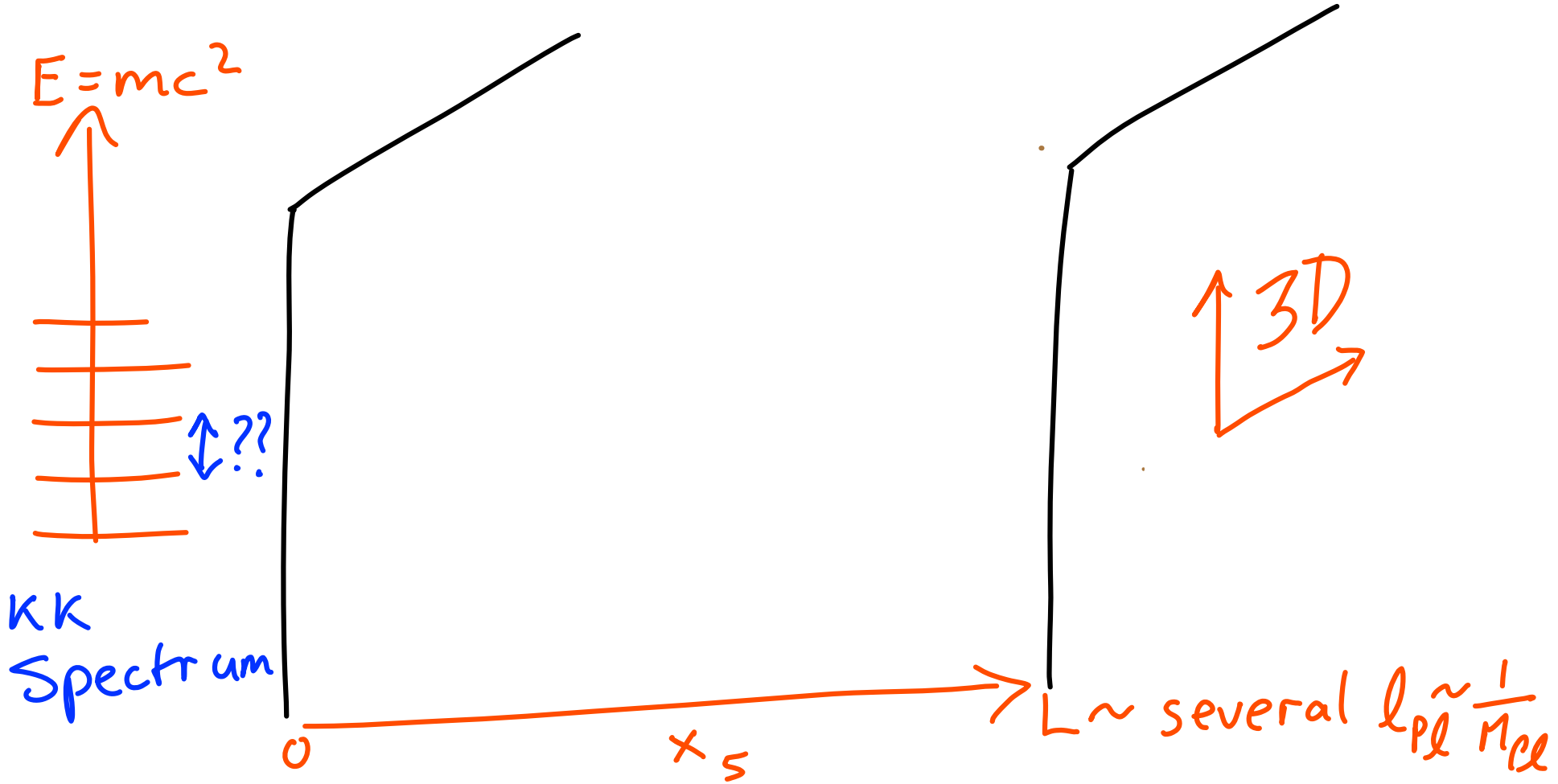


Effectively $\langle 0|\text{Higgs}|0\rangle \sim M_{Pl}\, e^{-L/R} \sim 100$'s GeV

sets max. SM masses (m_Z, m_{top}) for $L/R \approx 30$

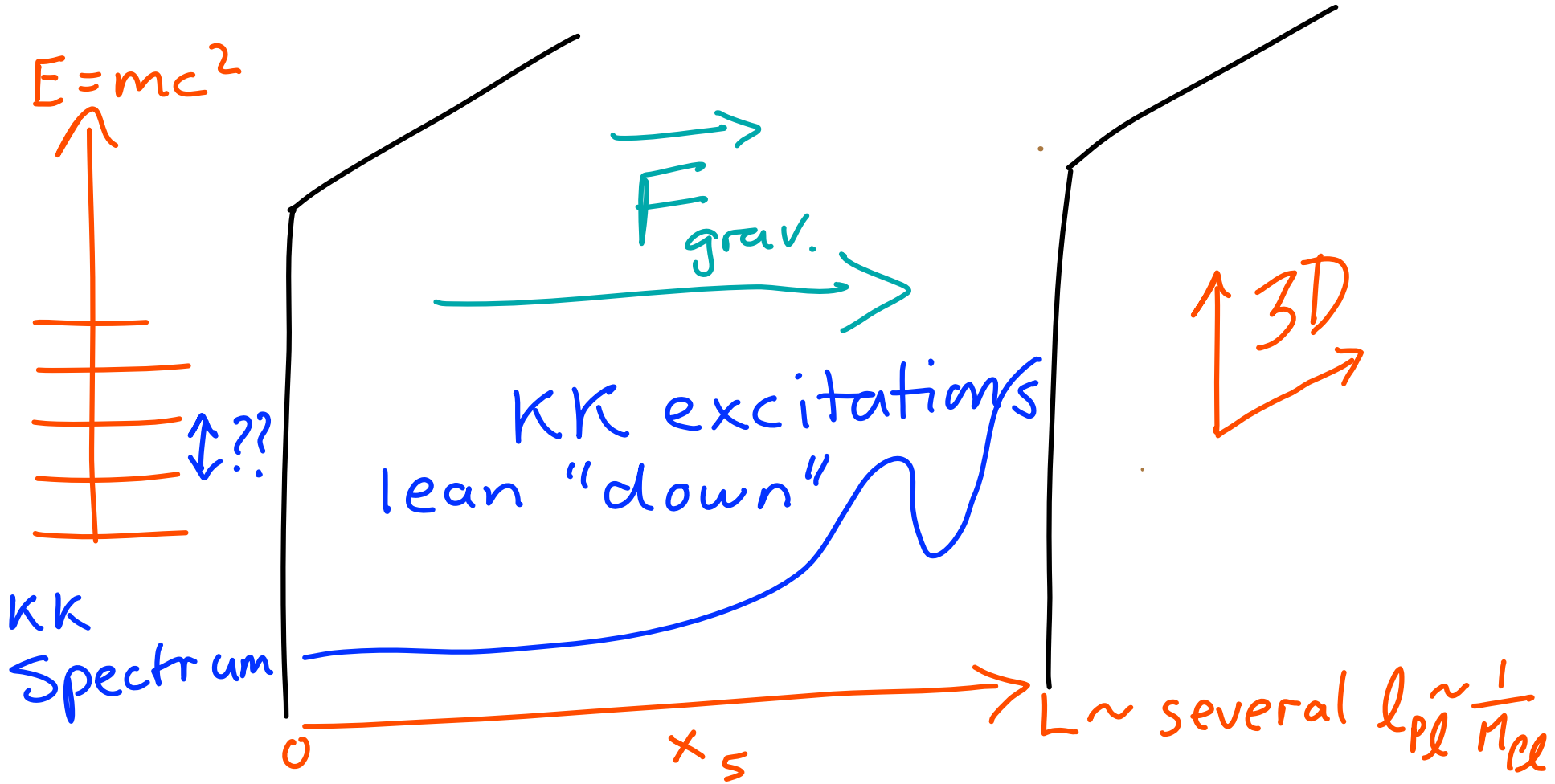
KALUZA-KLEIN EXCITATIONS IN RS1

are not at $1/L \lesssim 1/\ell_{Pl} \equiv M_{Pl}$



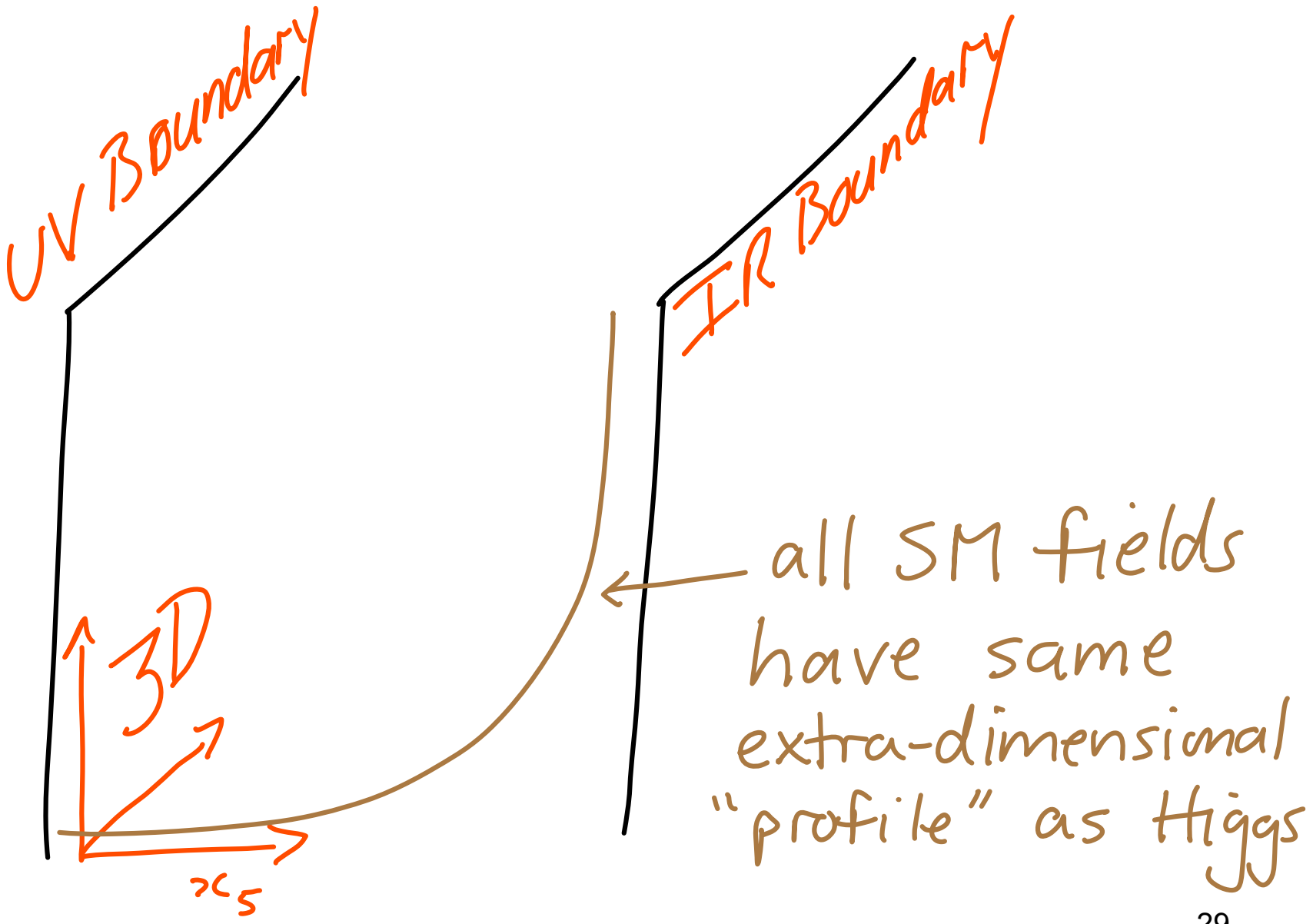
KALUZA-KLEIN EXCITATIONS IN RS1

are not at $1/L \lesssim 1/\ell_{Pl} \equiv M_{Pl}$

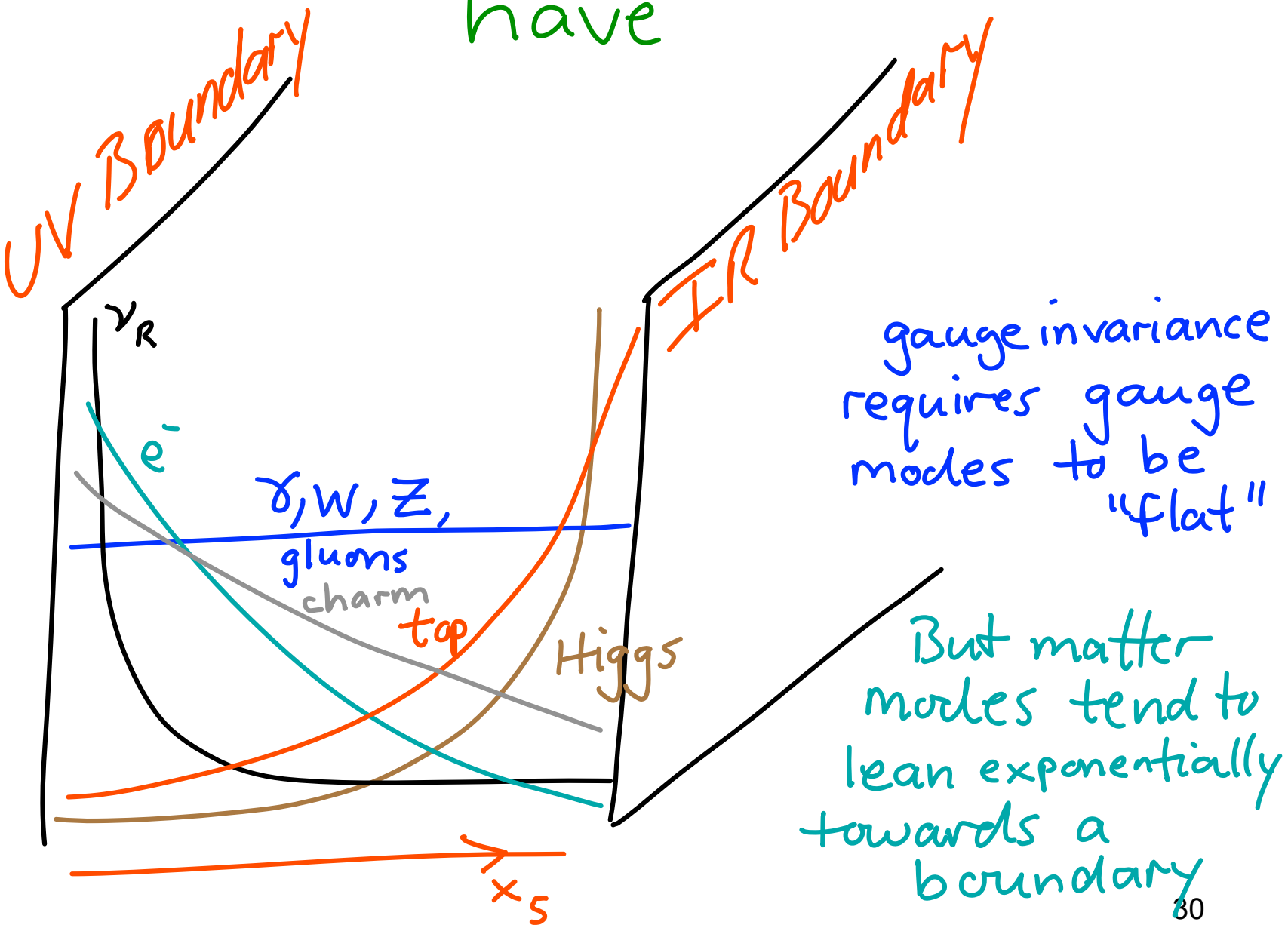


& are redshifted, $E_{KK} = m_{KK}c^2 \sim \frac{e^{-L/R}}{R} \sim$ TeV

ORIGINAL RS1



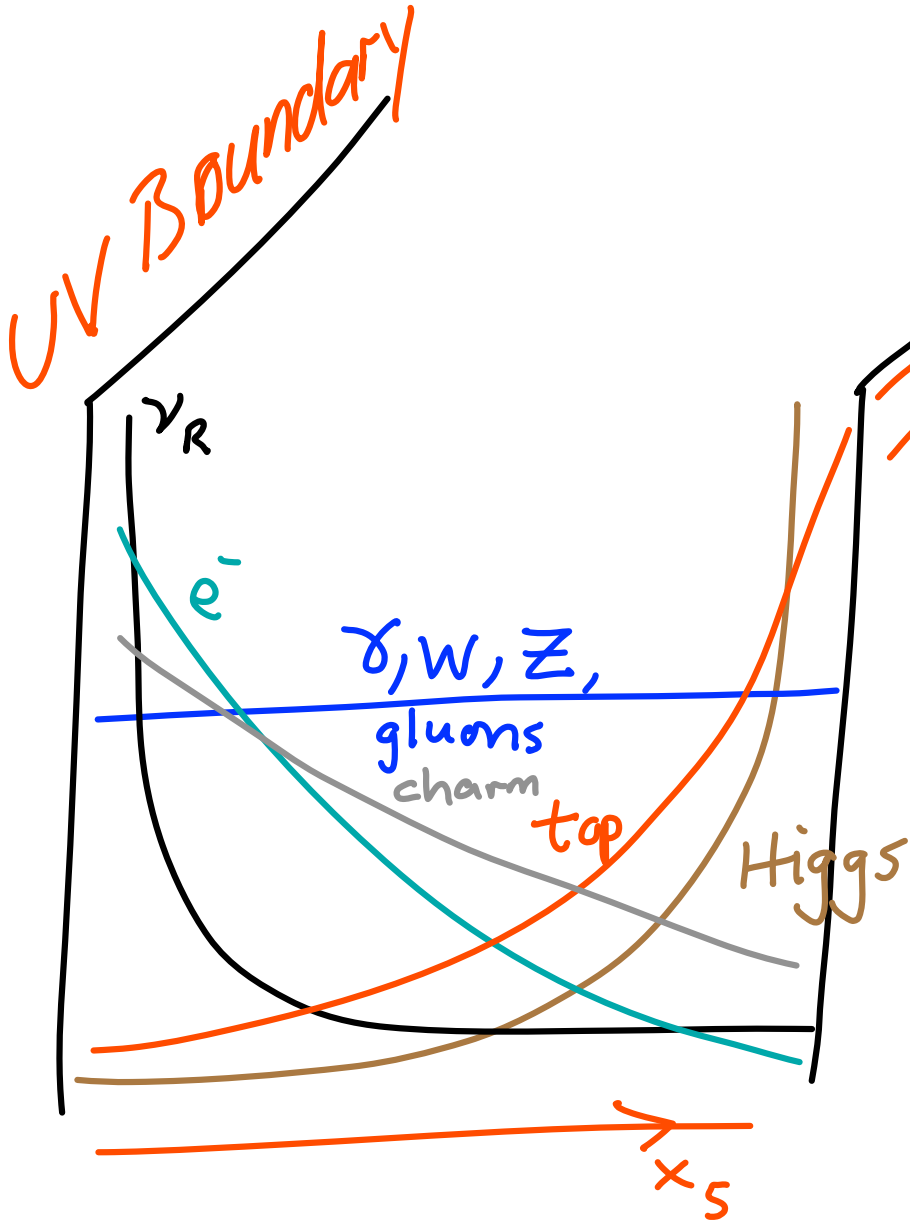
MODERN VARIANTS have



gauge invariance requires gauge modes to be "flat"

But matter modes tend to lean exponentially towards a boundary

5D CHAOS = 4D COSMOS



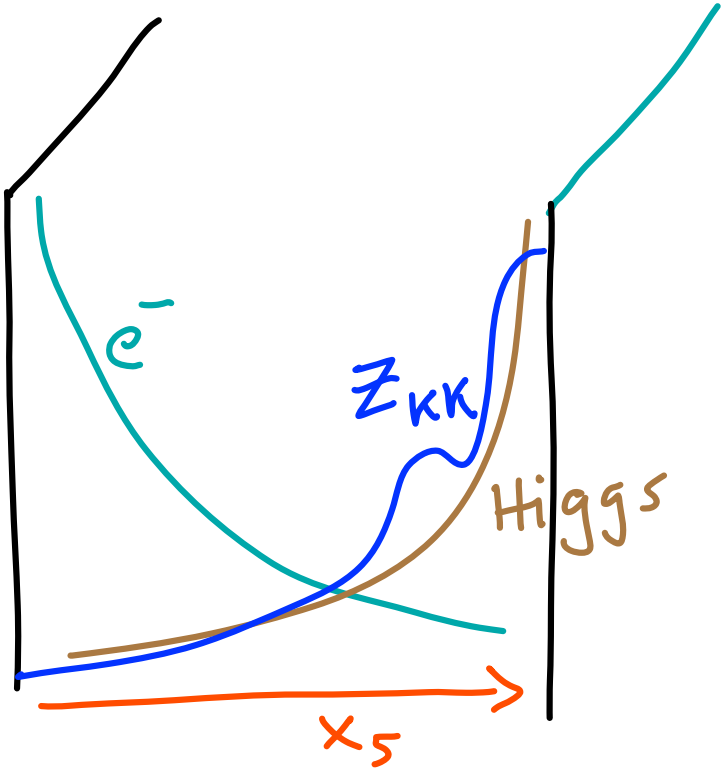
Flavor Hierarchies from extra-dimensional wavefunction overlaps with Higgs

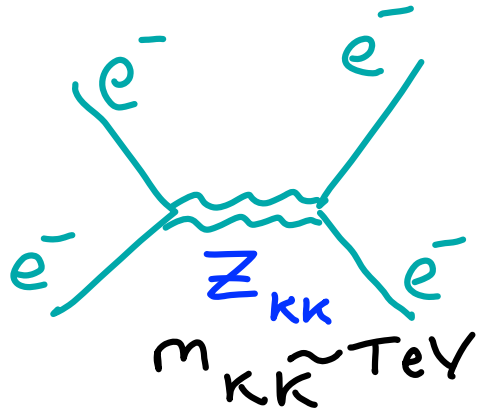
(Arkani-Hamed, Schmaltz '00)
Grossman, Neubert '00
Gherghetta, Pomarol '00
Huber, Shafi '01
Agashe, Okui, Sundrum '08
⋮

PRECISION TESTS

≡ virtual sensitivity to KK excitations

Compositeness tests





$m_{KK} \sim$ TeV

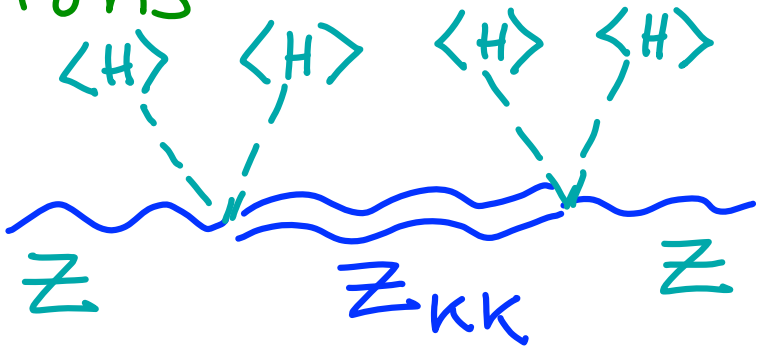
suppressed by small $e^- - Z_{KK}$ overlap

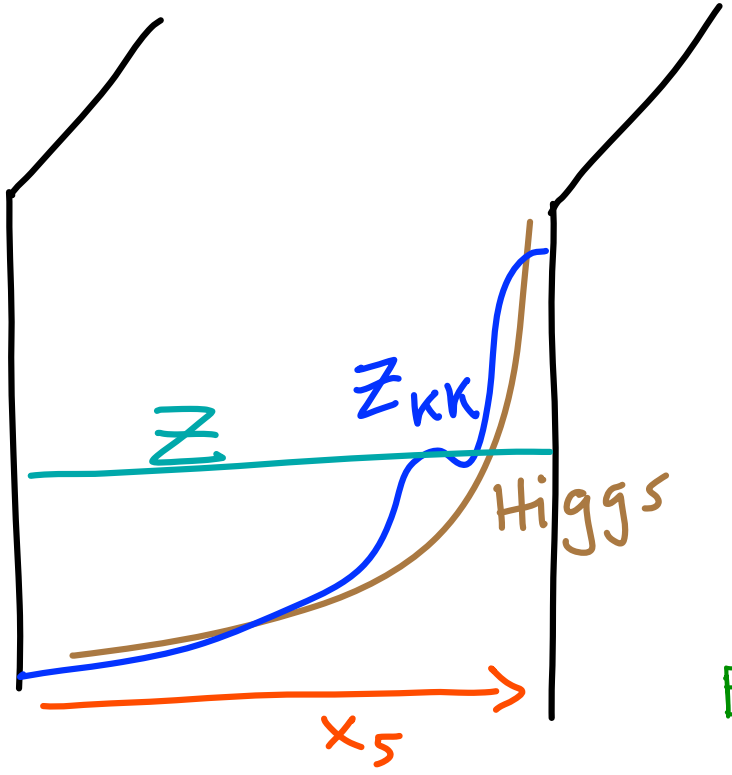
$\sim e^-$–Higgs overlap.

PRECISION TESTS

≡ virtual sensitivity to KK excitations

Electroweak tests:





requires extending 5D gauge symmetry

$SU(3) \times SU(2)_L \times U(1)_Y$

$\rightarrow SU(3) \times SU(2)_L \times SU(2)_R \times U(1)_X$

Agashe, Delgado, May, Sundrum '03

Even then, $m_{KK} \gtrsim 3\,\text{TeV}$.

based on long history...

Davoudiasl, Hewett, Rizzo '00

Chang et. al '00

Huber, Shafi '01

Huber, Lee, Shafi '02

Csaki, Erlich, Terning '02

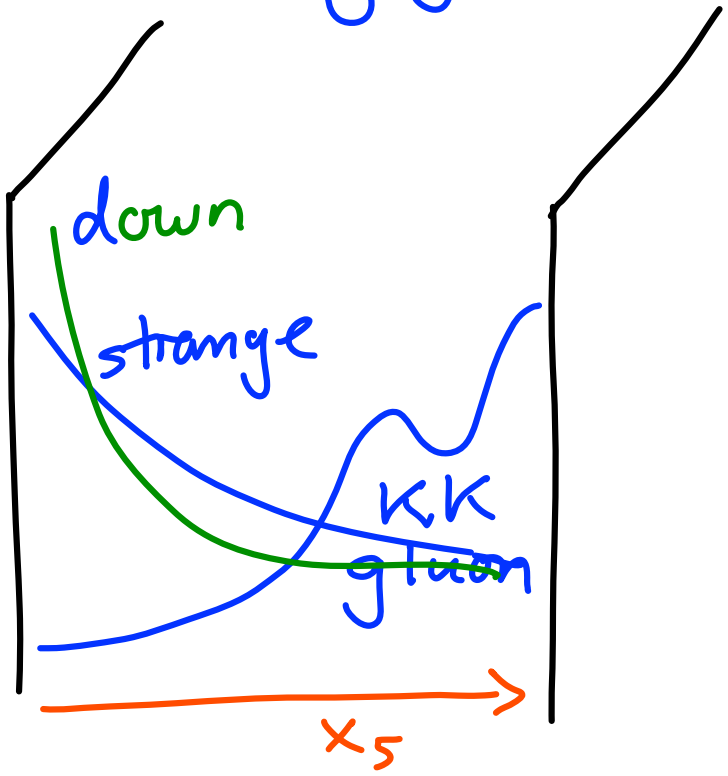
Hewett, Petriello, Rizzo '02

Burdman '02

PRECISION TESTS

≡ virtual sensitivity to KK excitations

Flavor-changing tests : have virtual sensitivity to extremely high mass scales



suppressed again by wavefunction overlaps

Agashe, Perez, Soni '04

$m_{KK} \gtrsim 3\,\text{TeV}$

PRECISION TESTS

$\equiv$ virtual sensitivity to KK excitations

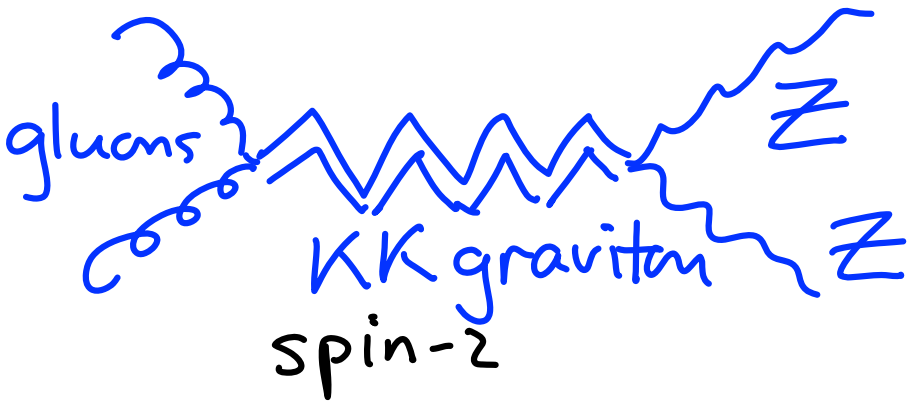
~~CP~~ tests in flavor-changing + edm's (also worrying for SUSY)

Agashe, Perez, Soni '05
Csaki, Falkowski, Weiler '08
Casagrande, Goertz, Haisch, Neubert, Pfoh '08
Blanke, Buras, Duling, Gori, Weiler '09; Agashe, Azatov, Zhu '09
Gedalia, Isidori, Perez; Blum, Grossman, Nir, Perez '09

$m_{KK} \gtrsim 5\text{-}10$ TeV in dominant part of parameter space,

OR still missing some special ~~CP~~ mechanism.

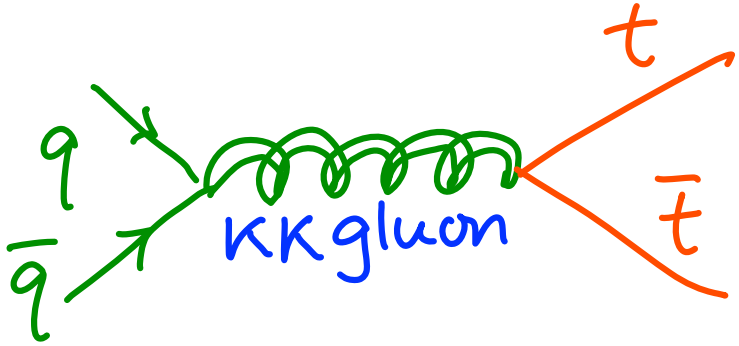
KK RESONANCES $\lesssim$ 3TeV @ LHC$_{14\text{TeV}}$



$\sigma(pp \to {}^{2\text{TeV}}_{KK} \to ZZ) \sim 5\text{-}10\,\text{fb}$

Fitzpatrick, J. Kaplan, Randall, L. Wang '07

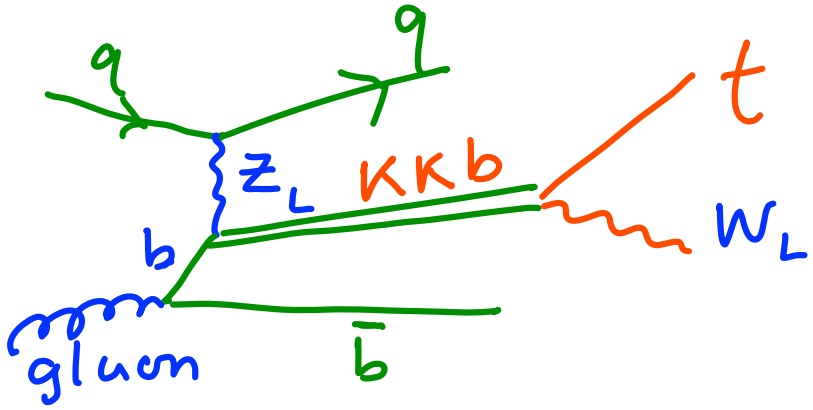
Agashe, Davoudiasl, Perez, Soni '07



$\sigma(pp \to {}^{3\text{TeV}}_{KK} \to t_R \bar{t}_R) \sim 100\,\text{fb}$

Agashe, Belyaev, Krupovnickas, Perez, Virzi '06

Lillie, Randall, Wang '07

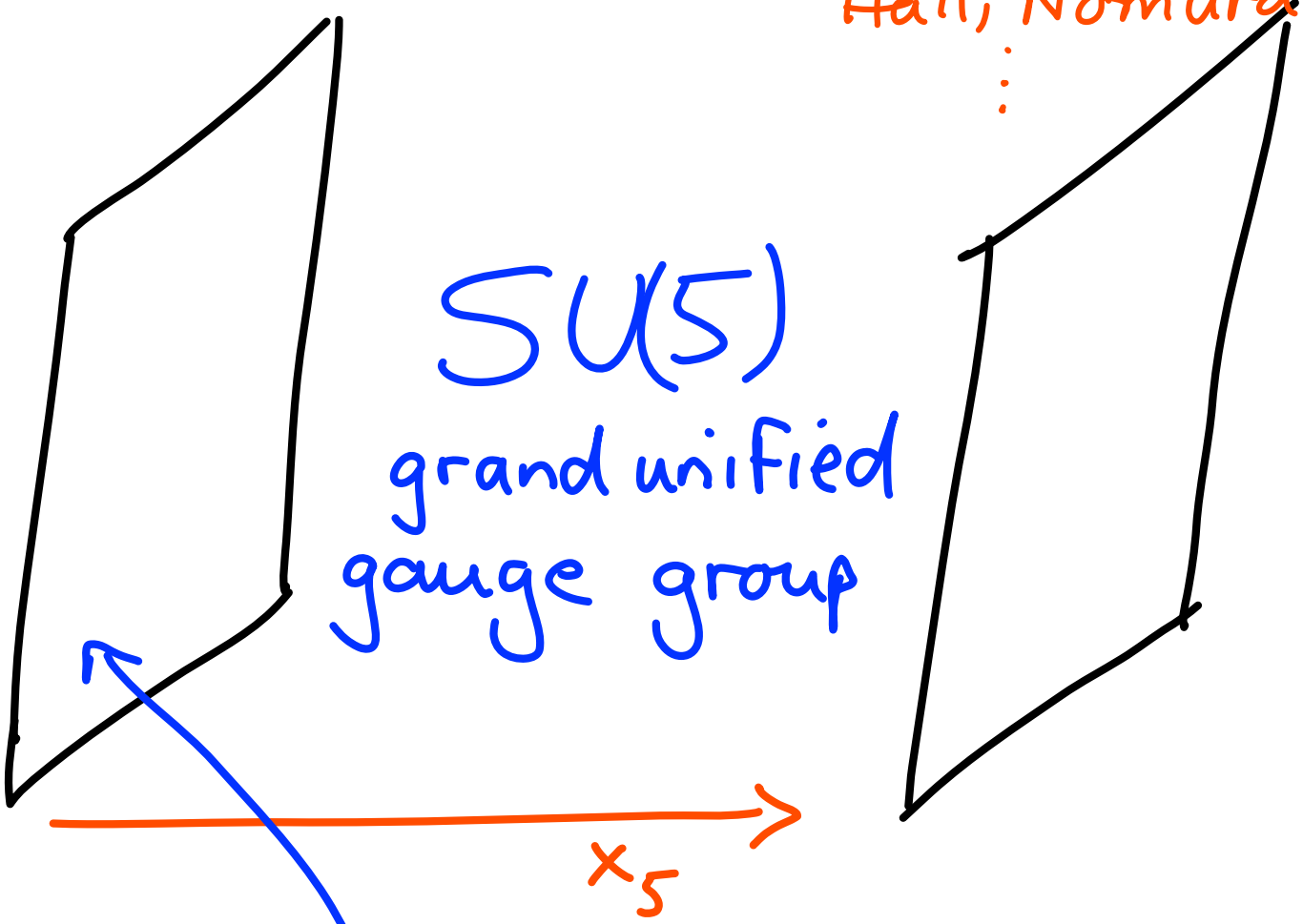


$\sigma(pp \to \bar{b}\, b^{1.5\text{TeV}}_{KK} \to \bar{b}\, t\, W_L) \sim 10\,\text{fb}$

similar to Little Higgs "top partner".

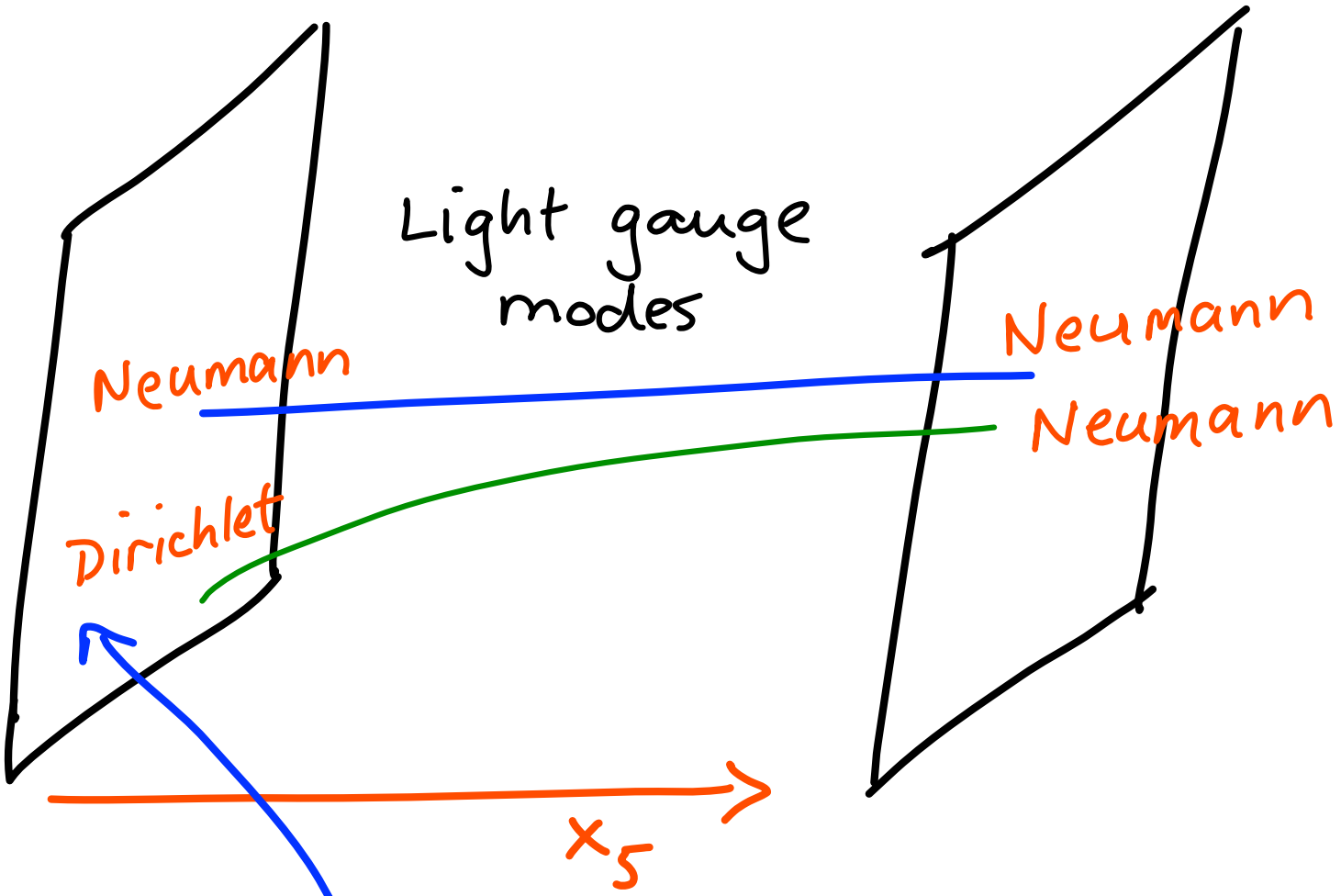
(ORBIFOLD) UNIFICATION

Kawamura '00
Hall, Nomura '01



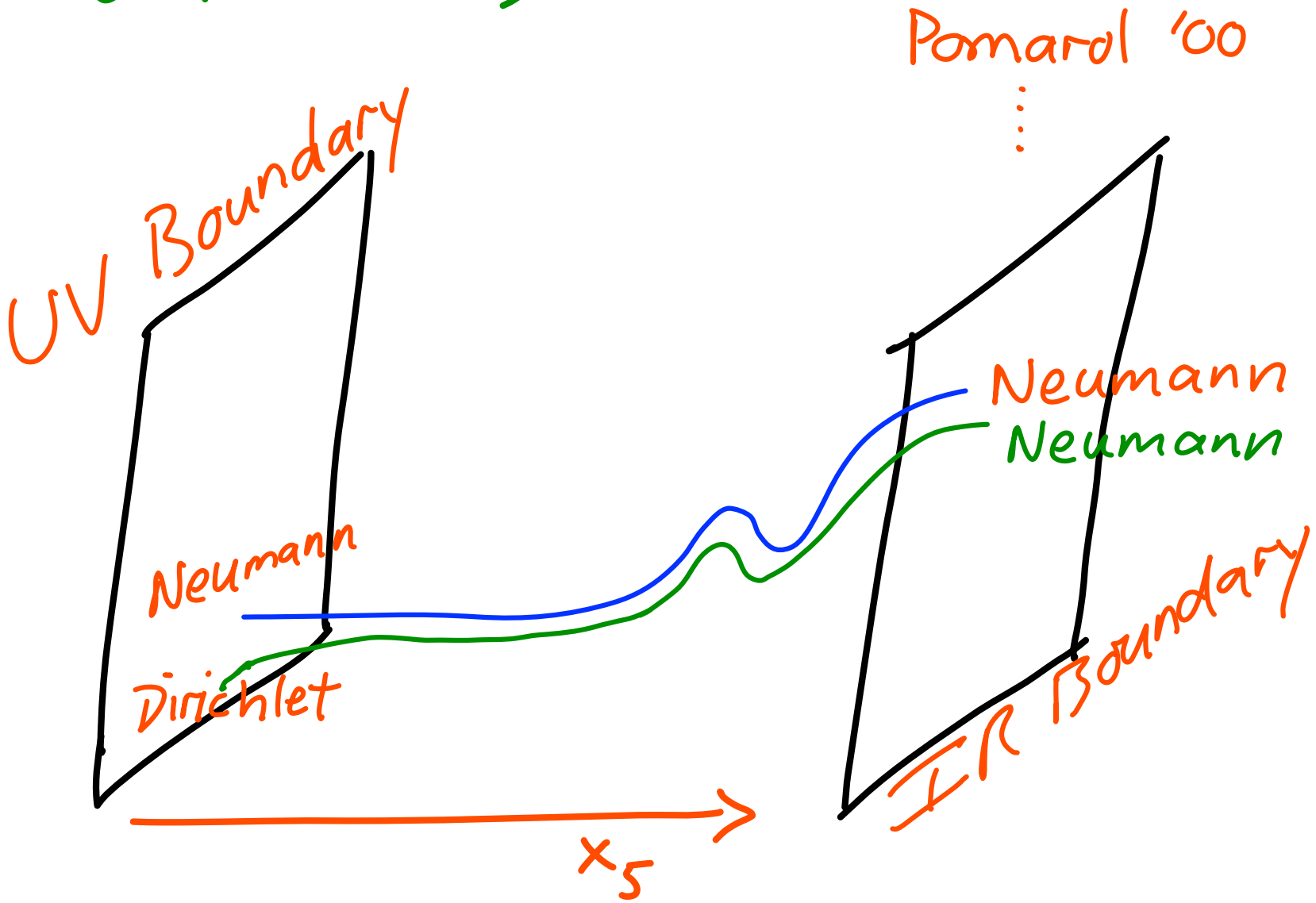
broken by extra-dimensional boundary condition $\longrightarrow SU(3) \times SU(2)_L \times {}^{3}U(1)_Y$

(ORBIFOLD) UNIFICATION



broken by extra-dimensional boundary condition $\rightarrow SU(3)_C \times SU(2)_L \times^{3\theta} U(1)_Y$

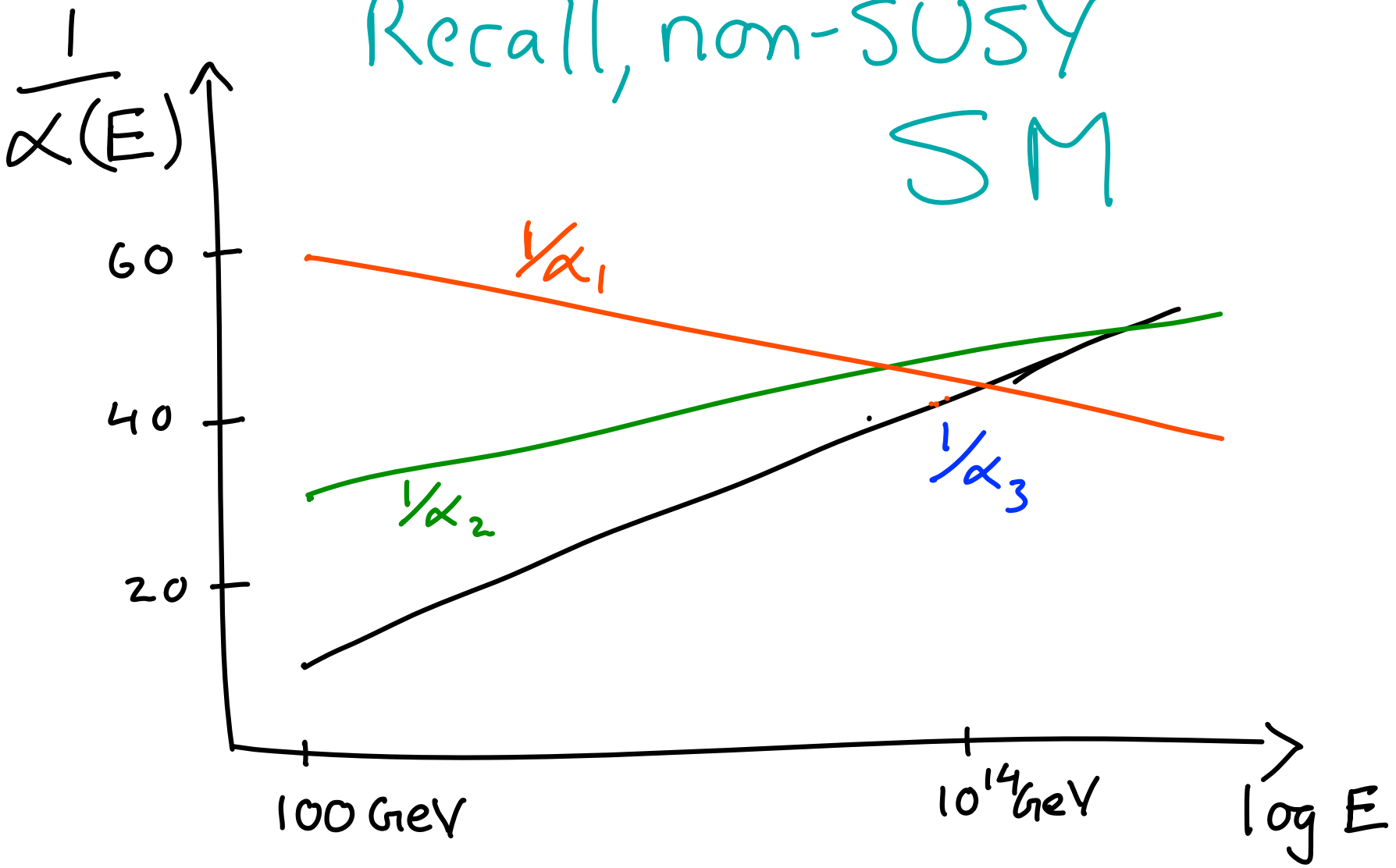
WARPED UNIFICATION



KK modes remain $\approx$ unified at several TeV, insensitive to UV boundary.

Gauge Coupling Unification

Recall, non-SUSY SM

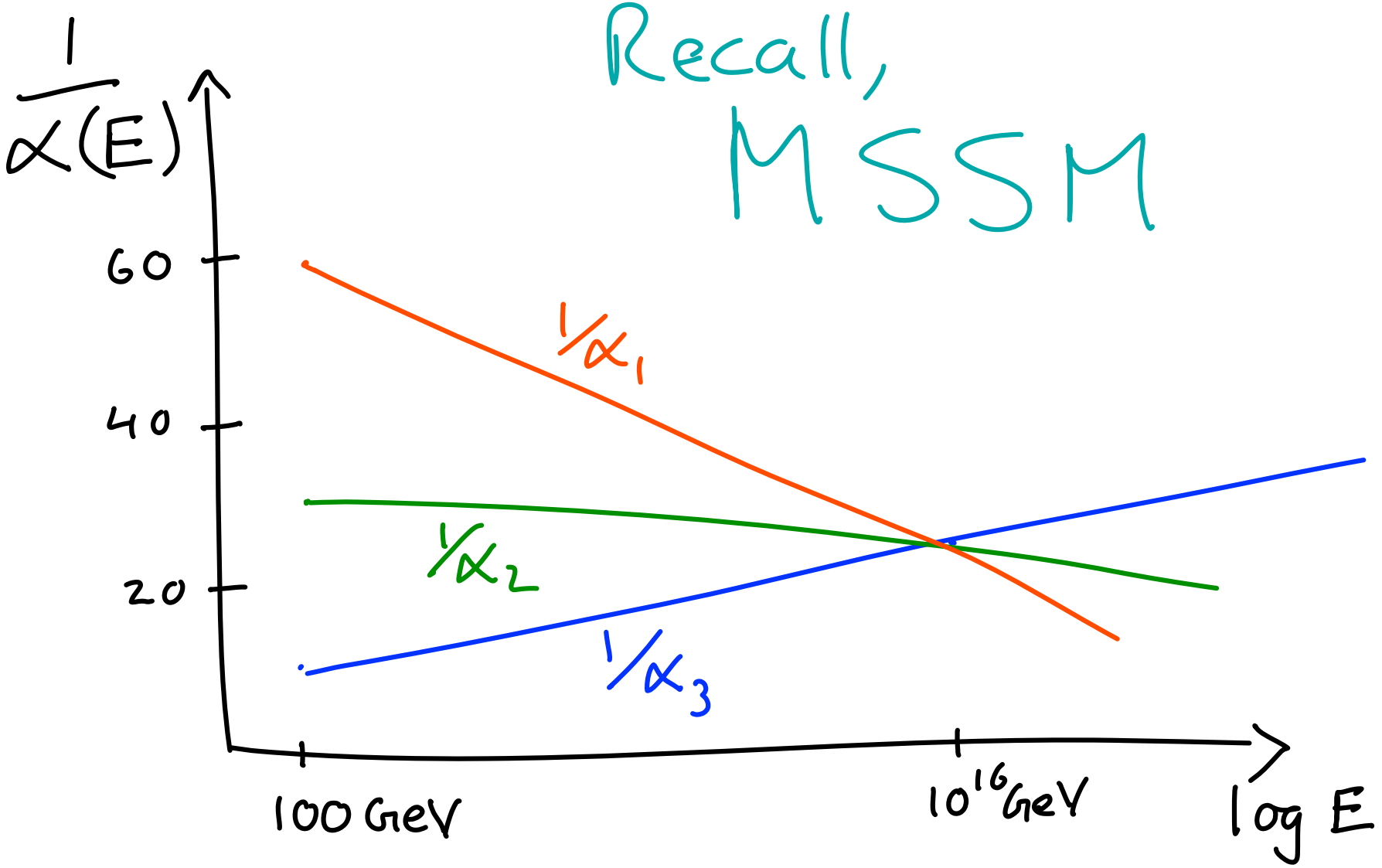


intriguing but not precise

Gauge Coupling Unification

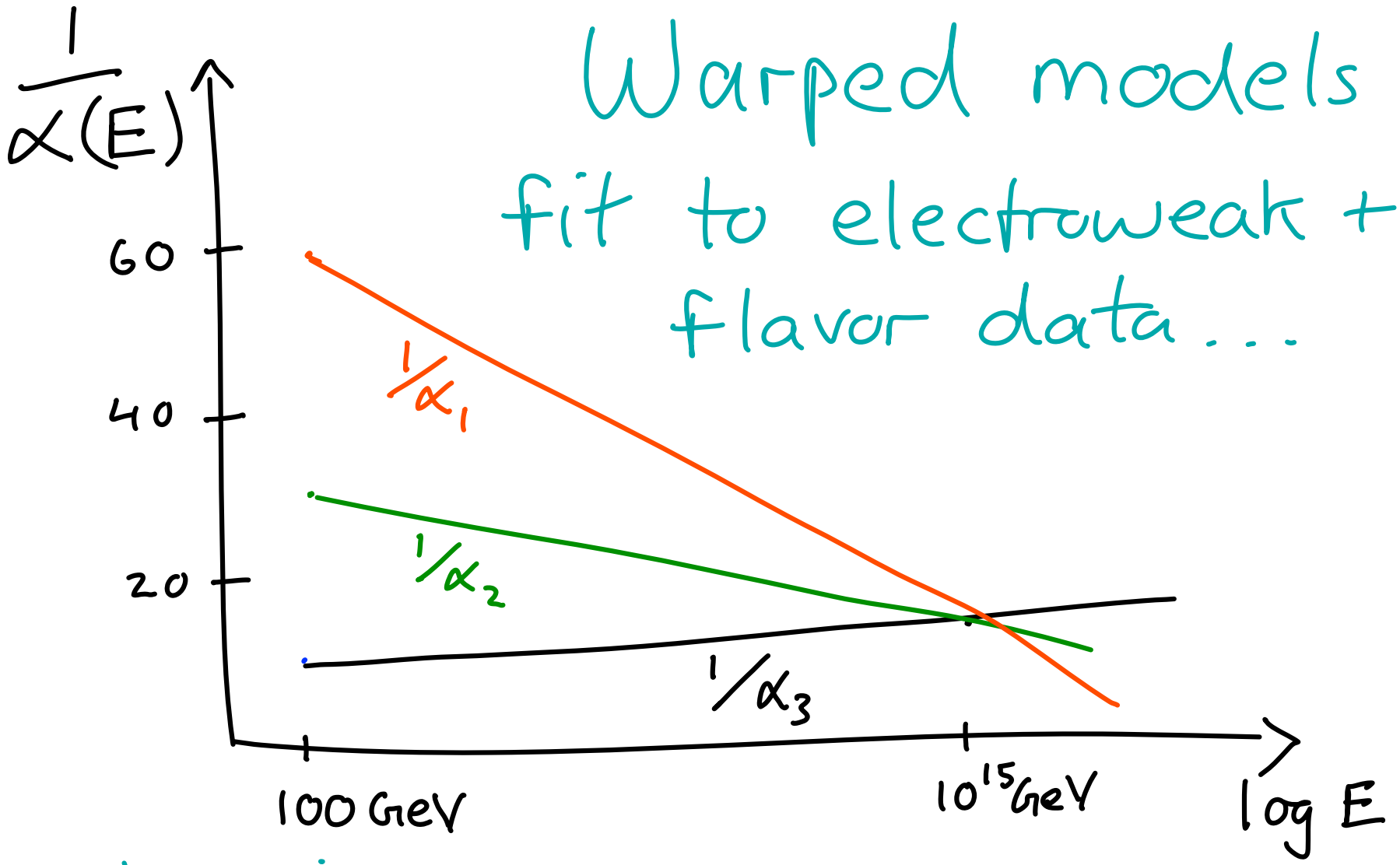
Recall,

MSSM



gives precision unification

Gauge Coupling Unification

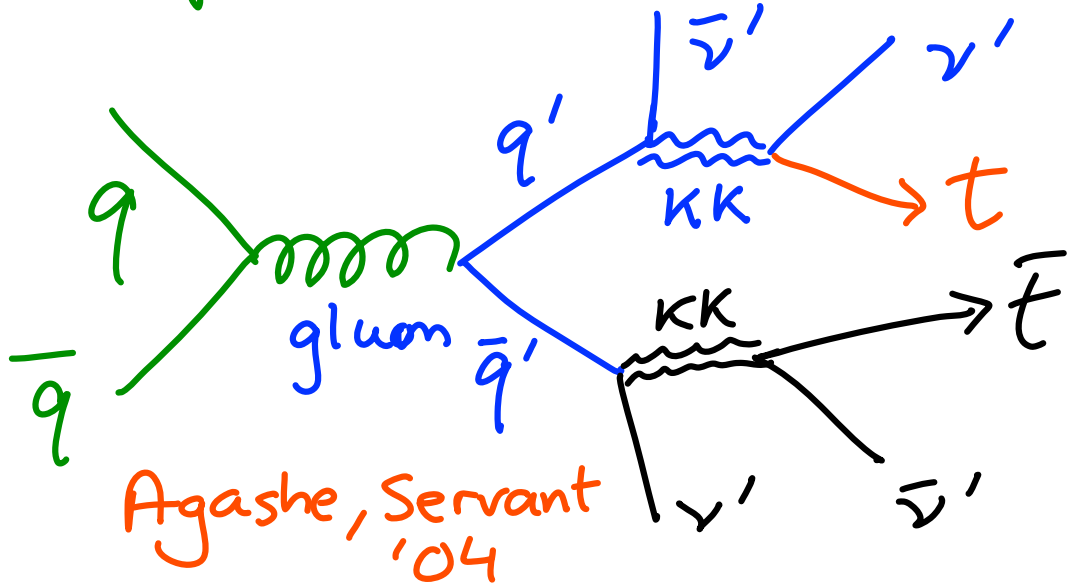


Warped models fit to electroweak + flavor data...

... also give precision unification!

Agashe, Contino, Sundrum '05

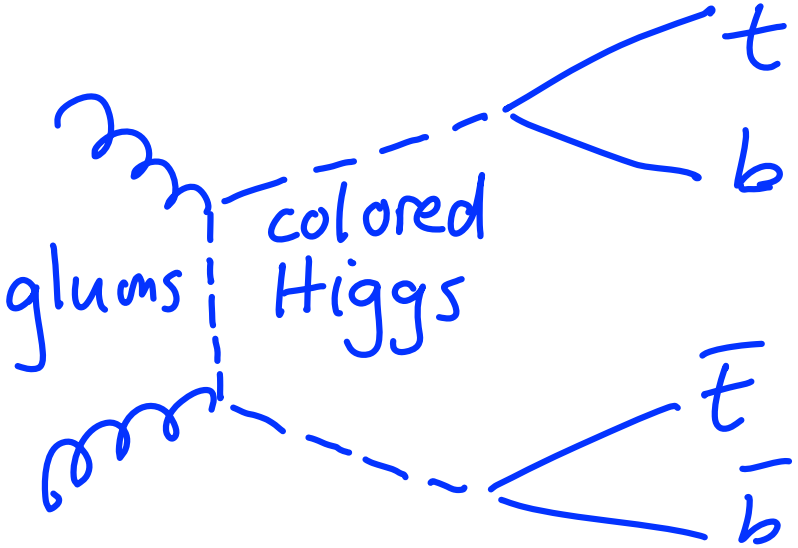
Such extra structure in Warped theory ⟶ "Light" exotics < TeV



Agashe, Servant '04

$\sigma(pp \to \underset{\text{500 GeV each}}{\bar{q}'q'} \to \bar{t}t + \not{E}) \sim 3000\,fb$

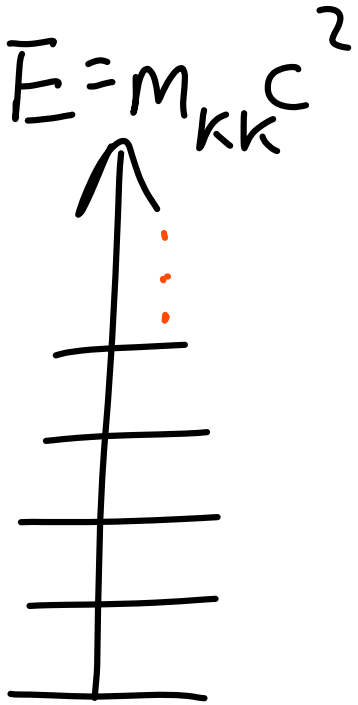
Exotic ν' stable, good WIMP dark matter



$\sigma(pp \to \underset{\text{500 GeV each}}{\bar{H}_{col.} H_{col.}} \to t\bar{b}\bar{t}b) \sim 500\,fb$

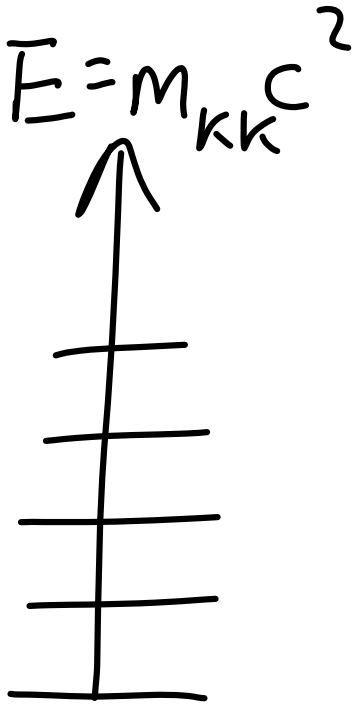
Contino, Kramer, Son, Sundrum (in progress)

AdS/CFT DUALITY

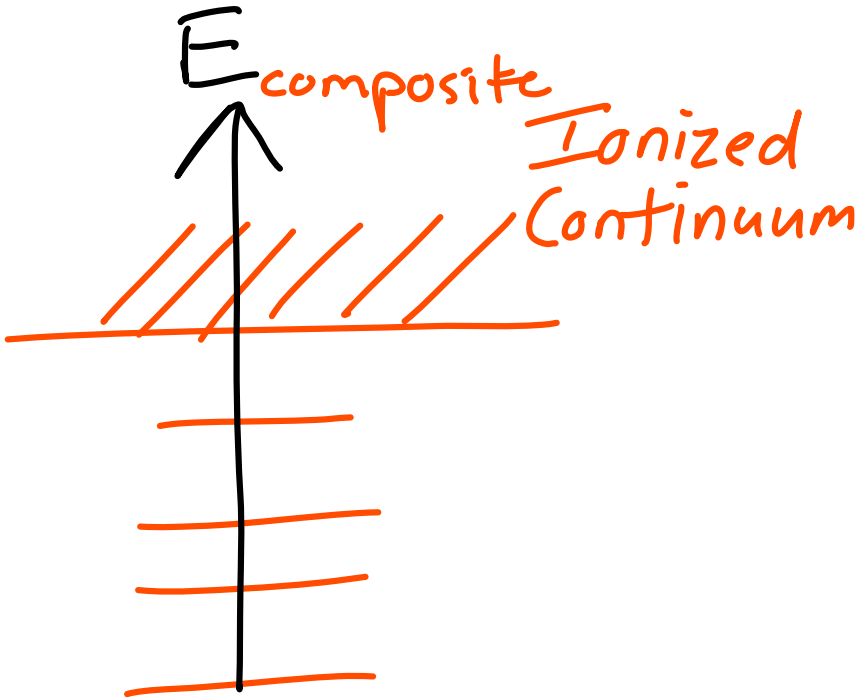


Warped
KK Spectrum

AdS/CFT DUALITY

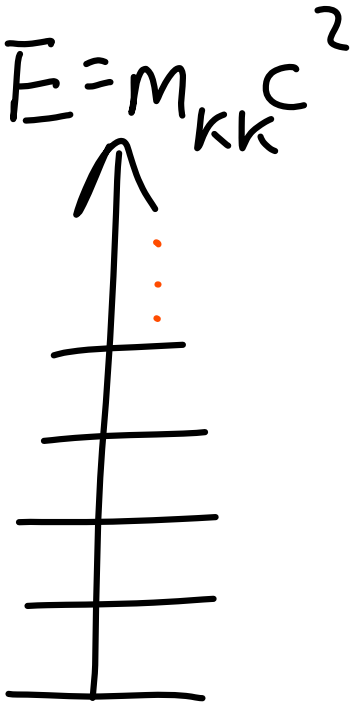


Warped KK Spectrum

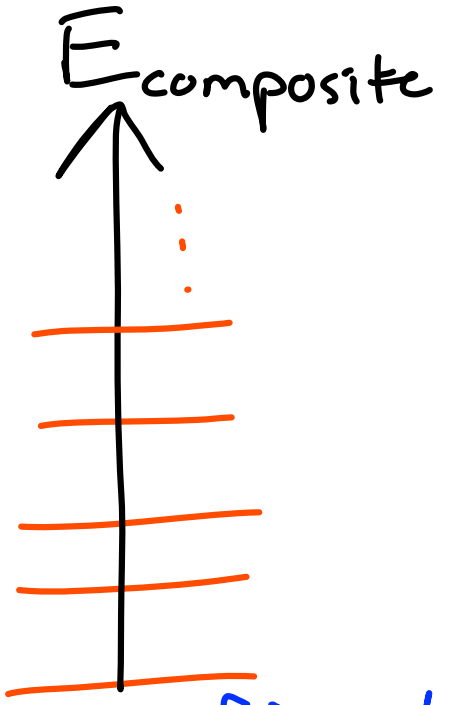


Bound State Spectrum

AdS/CFT DUALITY

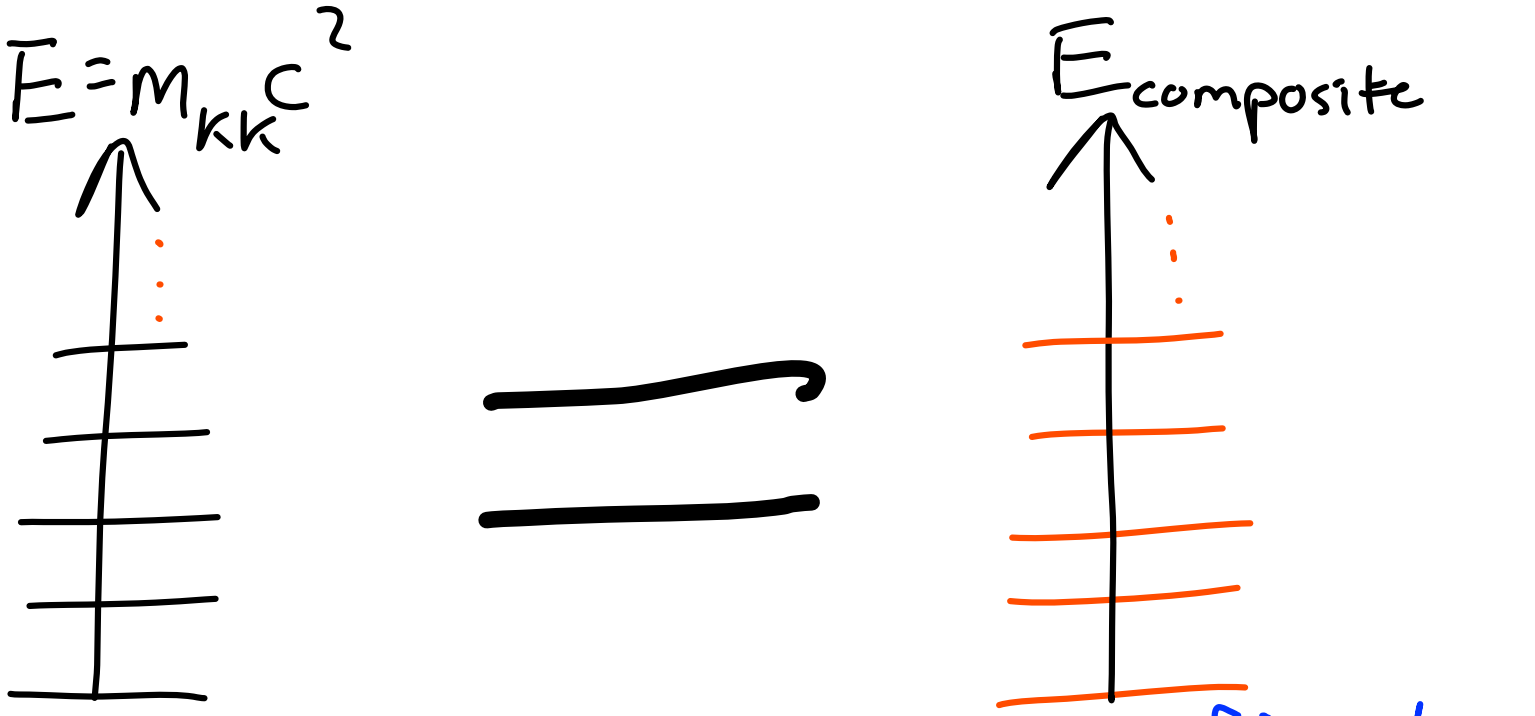


Warped KK Spectrum



Confined Bound State Spectrum

AdS/CFT DUALITY



Warped KK Spectrum

Confined Bound State Spectrum

Maldacena '98; Gubser, Klebanov, Polyakov '98; Witten '98
Hi Verlinde '00; Gubser '01; Arkani-Hamed, Porrati, Randall '01
Rattazzi, Zaffaroni '01; Perez-Victoria '01

AdS/CFT DUALITY

Theories of Warped Dimensions have very similar "DNA" to Theory of Strong Nuclear Force, despite appearances.

Warped Dimensions ≡ calculable variants of theories of Higgs Compositeness

see eg. Georgi, Kaplan '84
D.B. Kaplan '91

CONCLUSIONS

- Warped extra dimensions provide non-SUSY geometric approach to Hierarchy Problem
- Flexible framework, rather than single model (like SUSY)
- LHC phenomenology of excitations with SM charges, decays to heaviest SM particles.