# Challenges for particle physics from strings

Michael Ratz

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Based on collaborations with:
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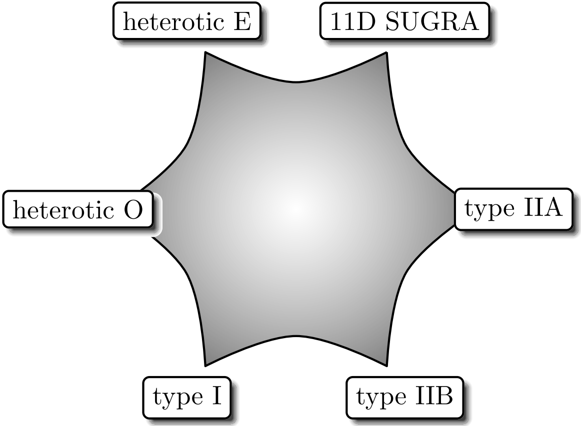

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- ☞ Superstring theory requires 10 space–time dimensions
- ➥ 6 dimensions need to be compact

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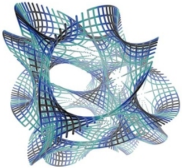

☞ String compactification: twist the string in such a way that the excitations carry the quantum numbers of the standard model particles

# From strings to the real world?

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- heterotic orbifolds
- intersecting $D$–branes
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**main theme of the rest of this talk:**

orbifold compactifications of the heterotic string

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  Buchmüller, Dierigl, Oehlmann & Ruehle (2017b)

  *"However, despite the remarkable progress in F–theory model building in recent years, a number of important conceptual and phenomenological questions still remain open. In fact, to the best of our knowledge, at present there is no fully satisfactory F–theory GUT model, which would have to account for symmetry breaking to the standard model gauge group, the matter content of the (supersymmetric) standard model, doublet–triplet splitting, sufficiently suppressed proton decay, supersymmetry breaking and semi–realistic quark and lepton mass matrices."*

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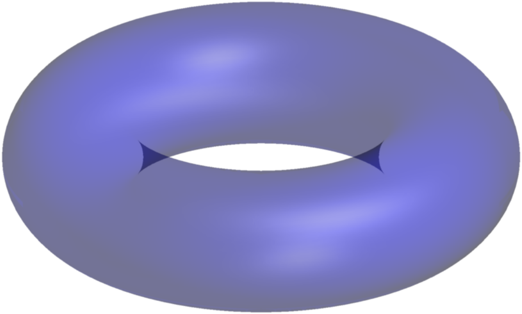
- ☞ Complete classification of heterotic orbifold geometries

  Fischer, M.R., Torrado & Vaudrevange (2013b); Fischer, Ramos-Sánchez & Vaudrevange (2013a)

# $\mathbb{Z}_2$ orbifold pillow

- Starting point: torus



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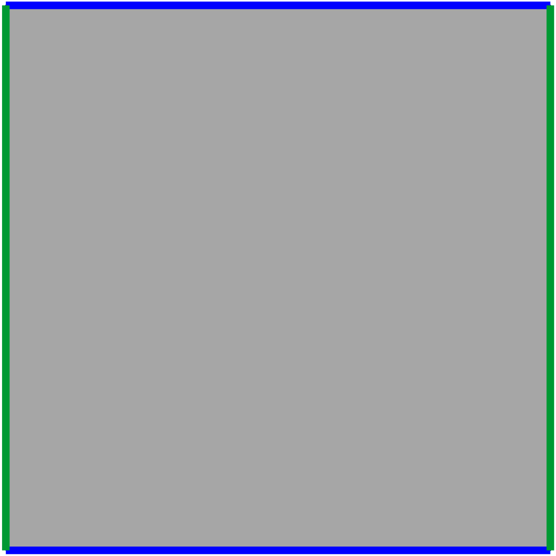

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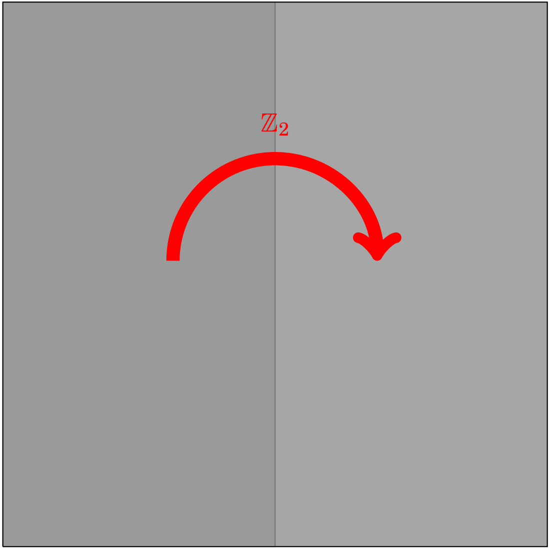

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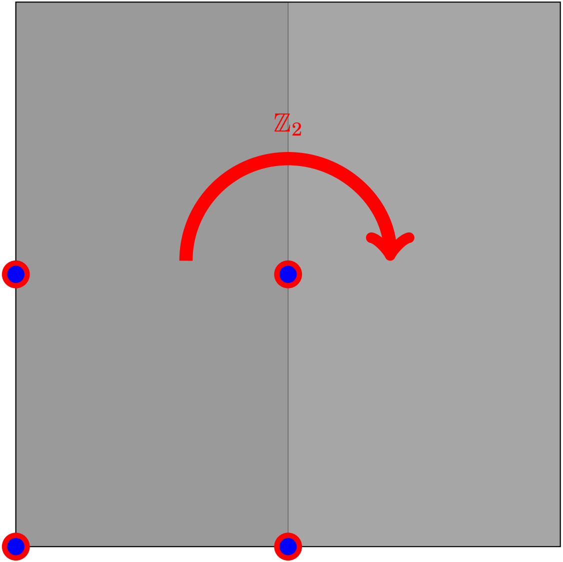

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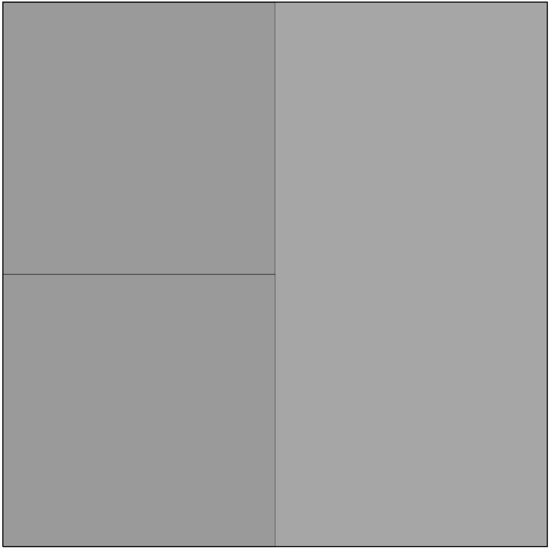

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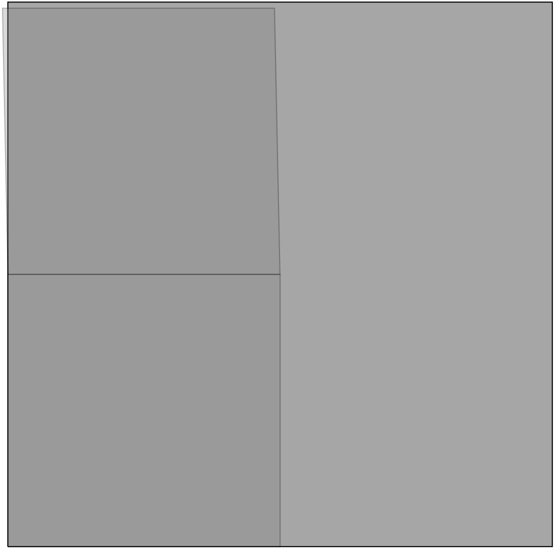

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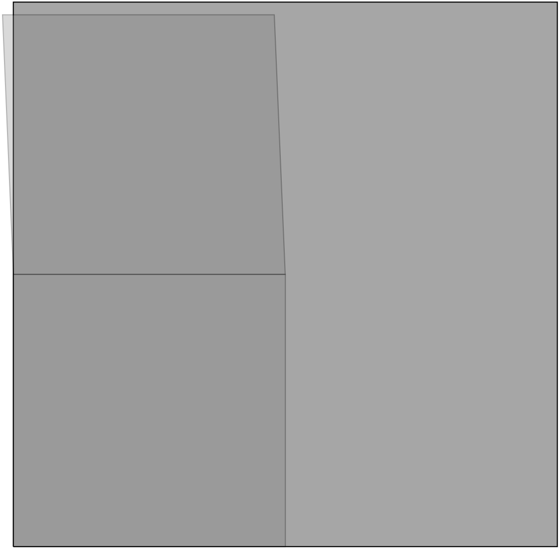

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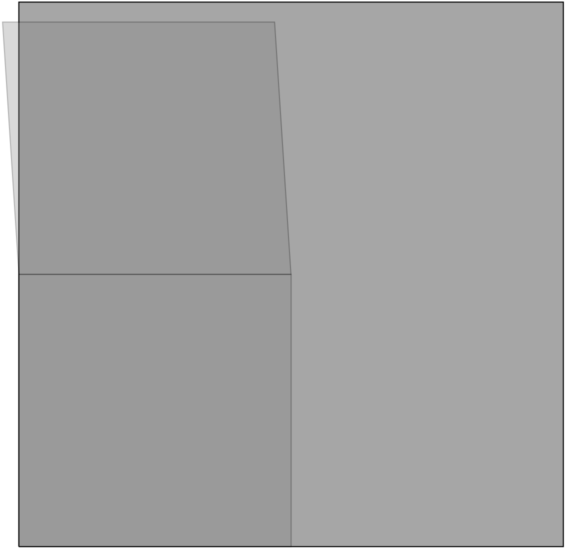

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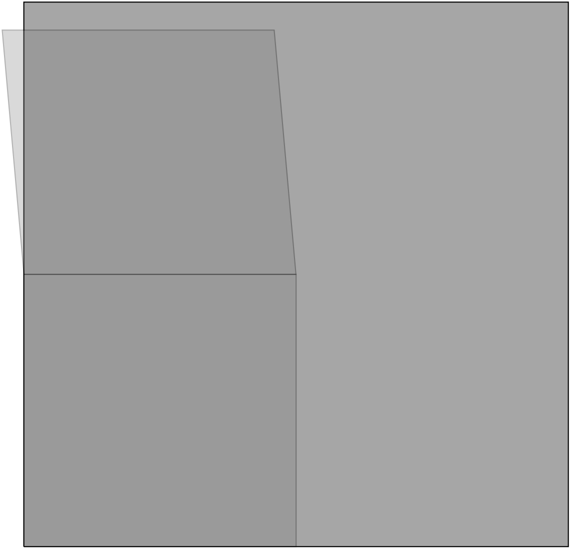

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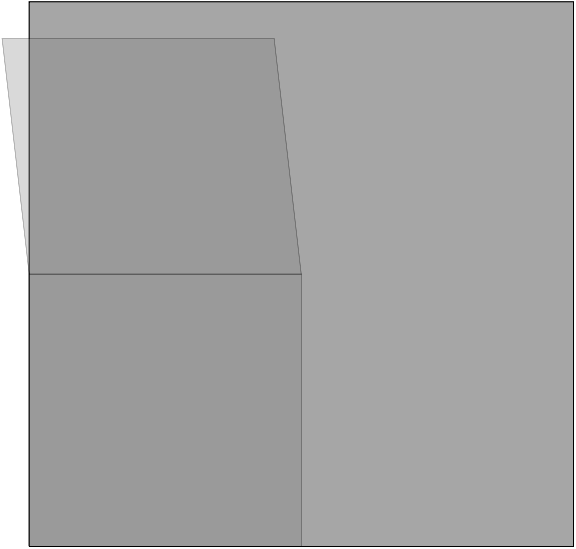

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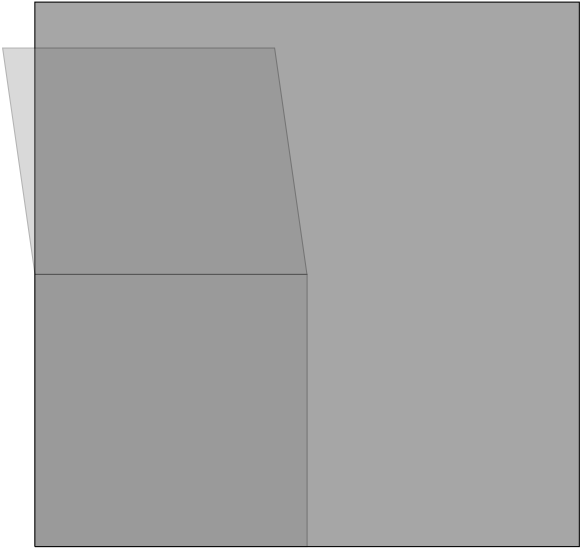

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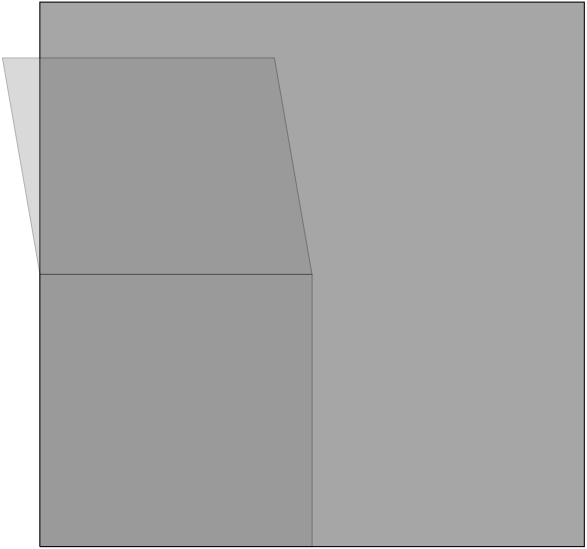

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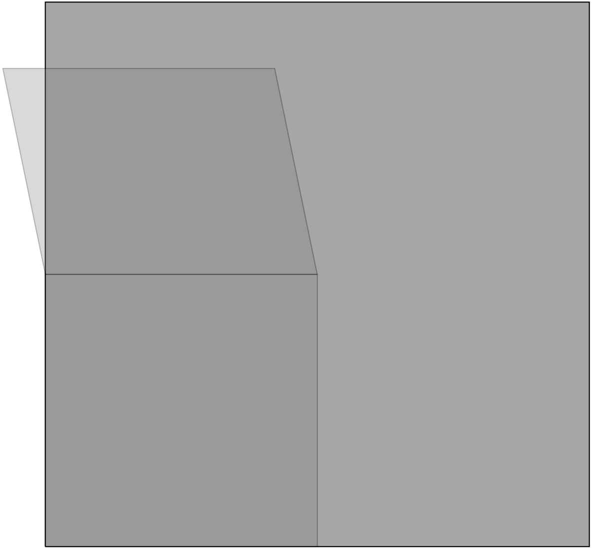

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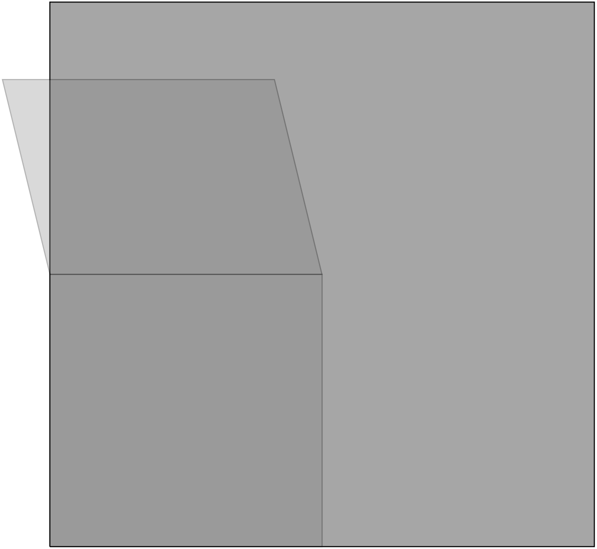

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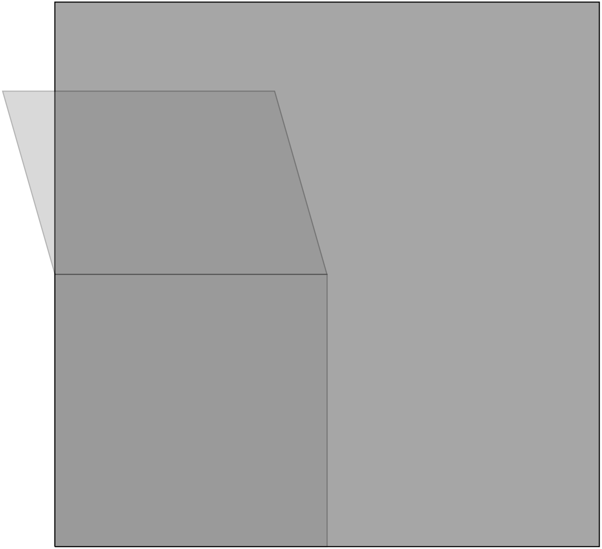

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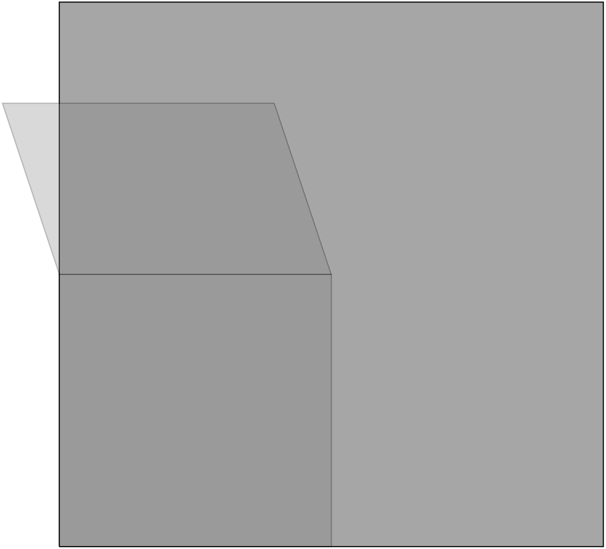

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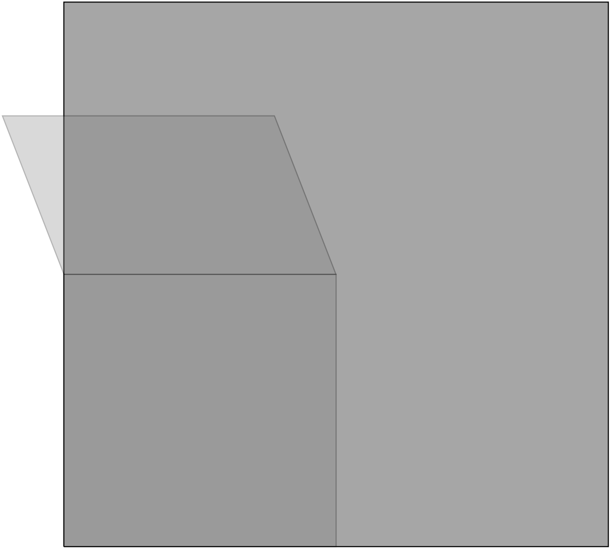

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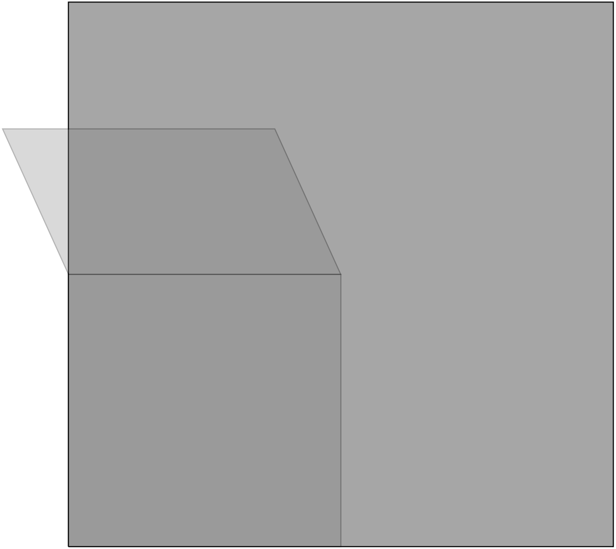

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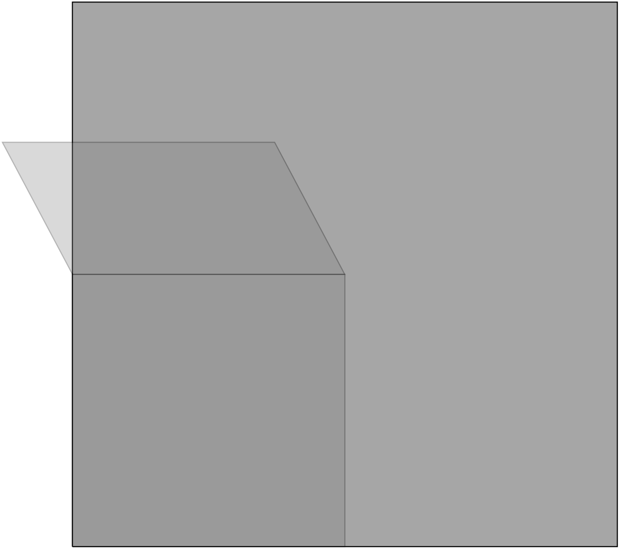

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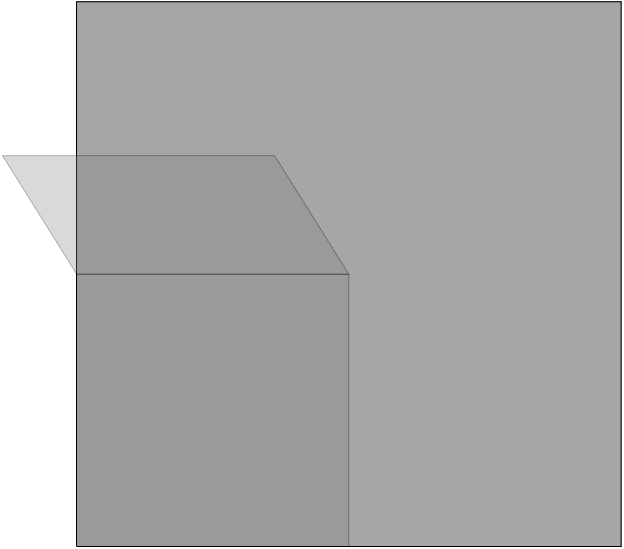

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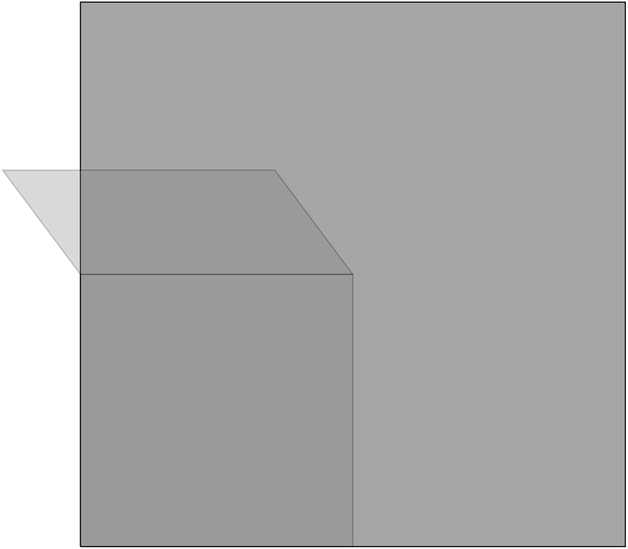

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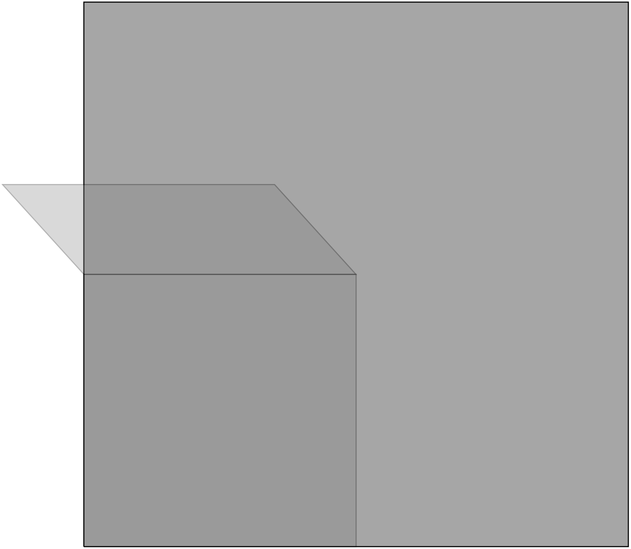

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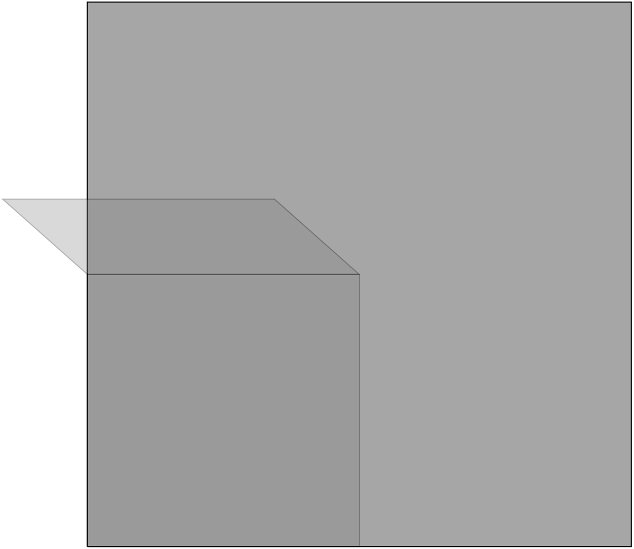

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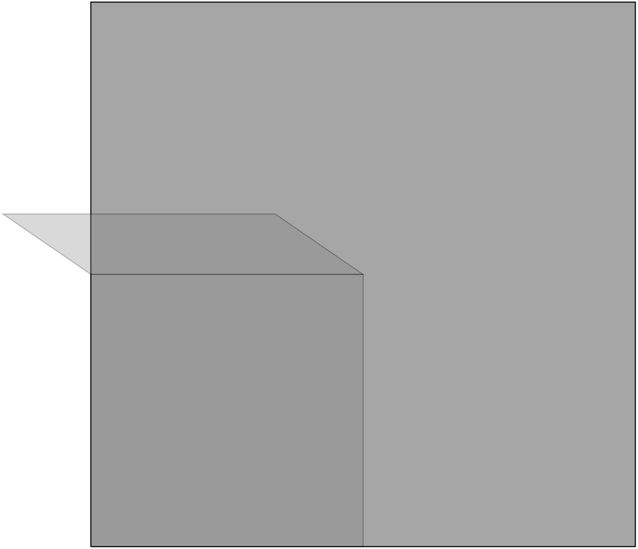

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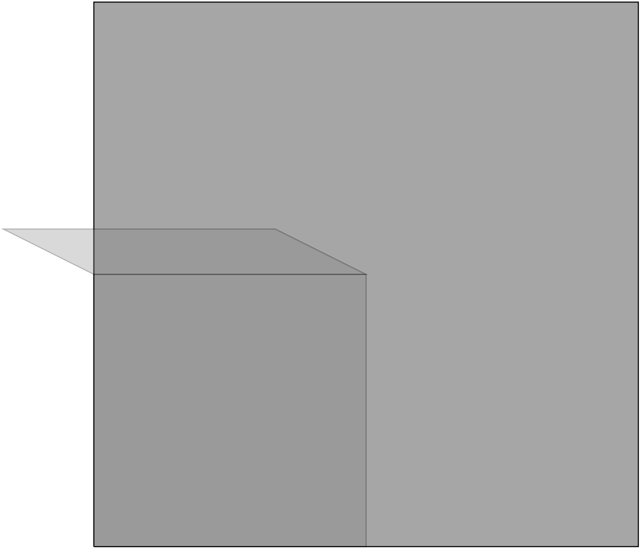

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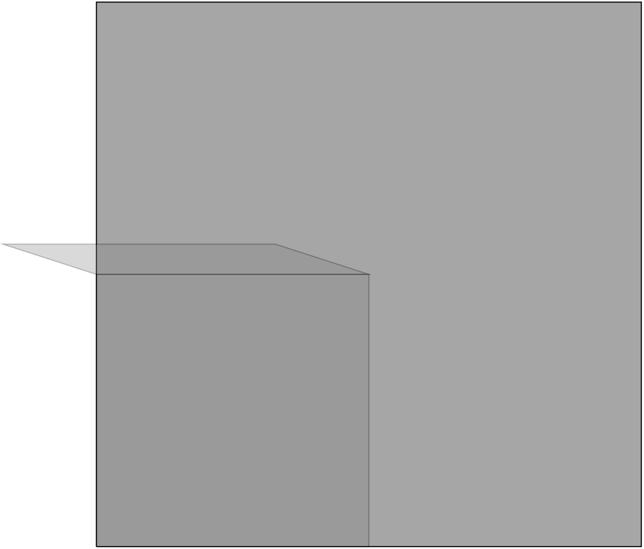

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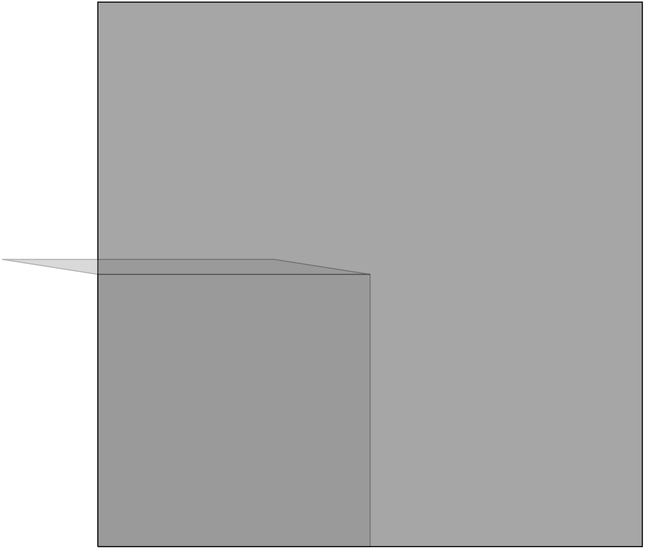

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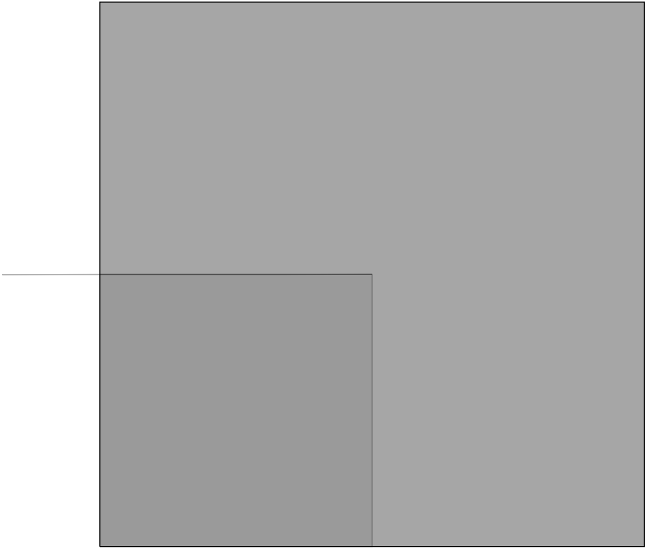

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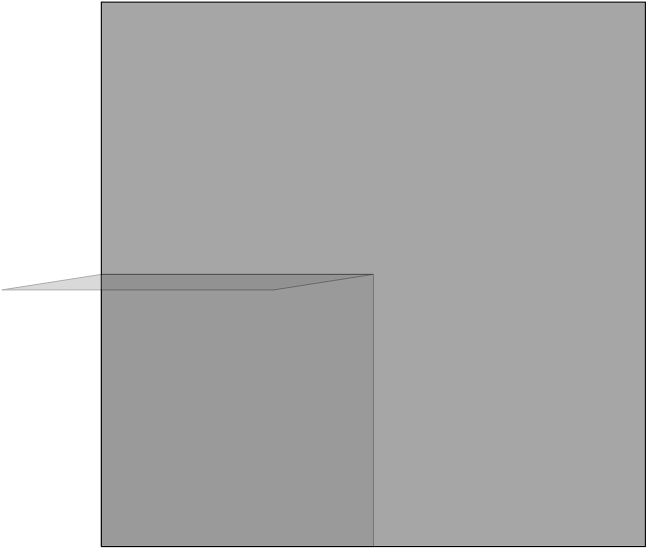

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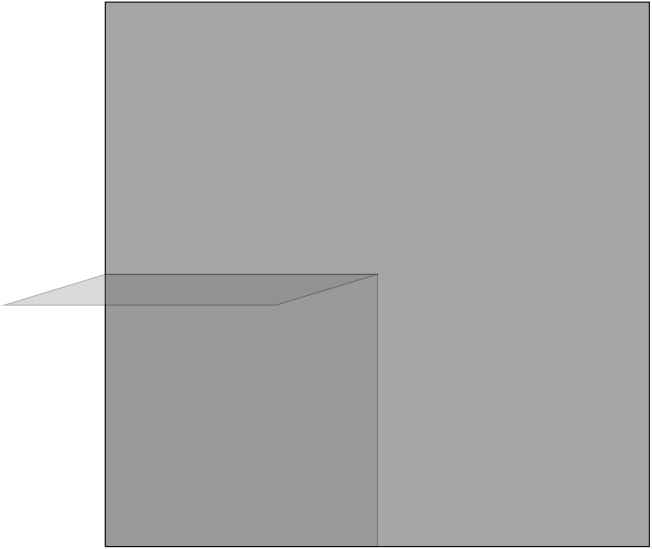

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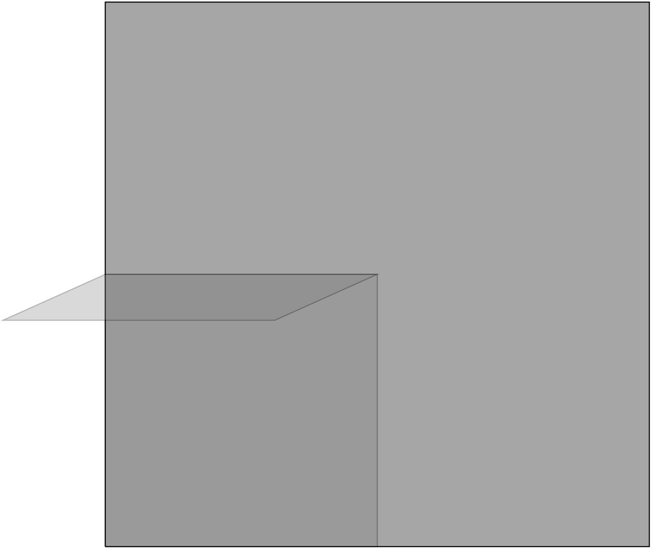

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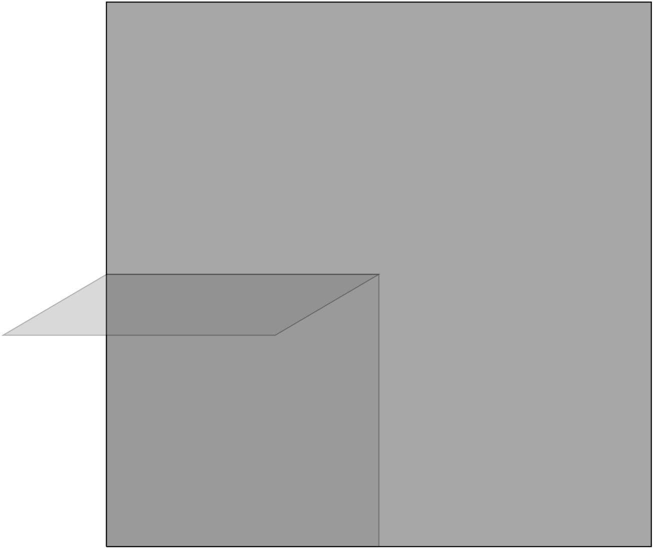

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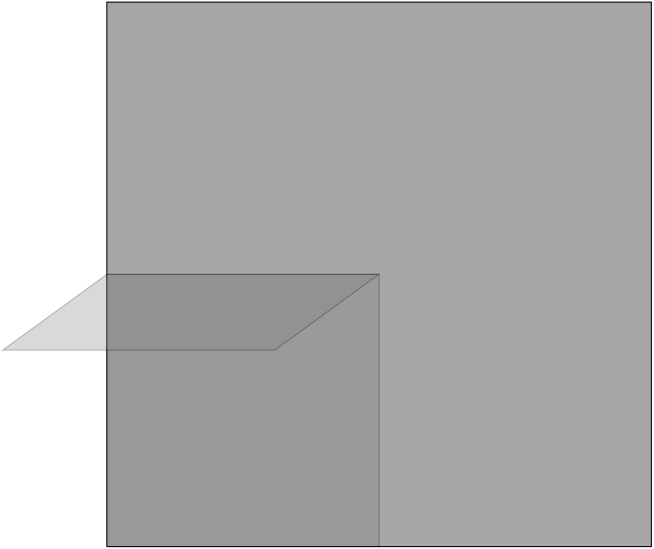

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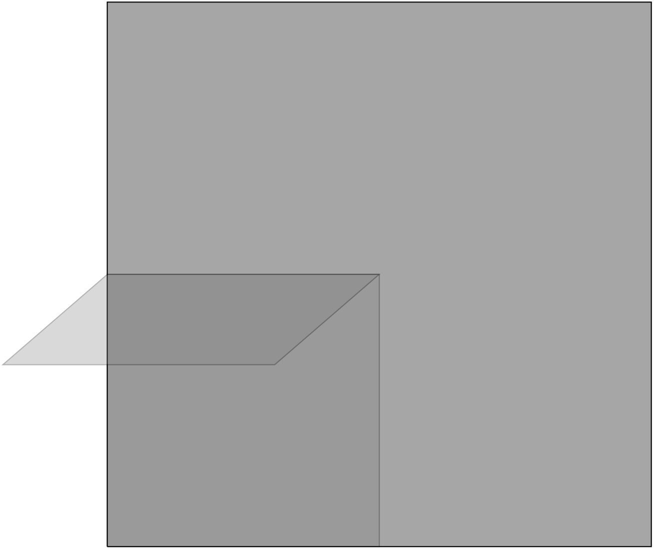

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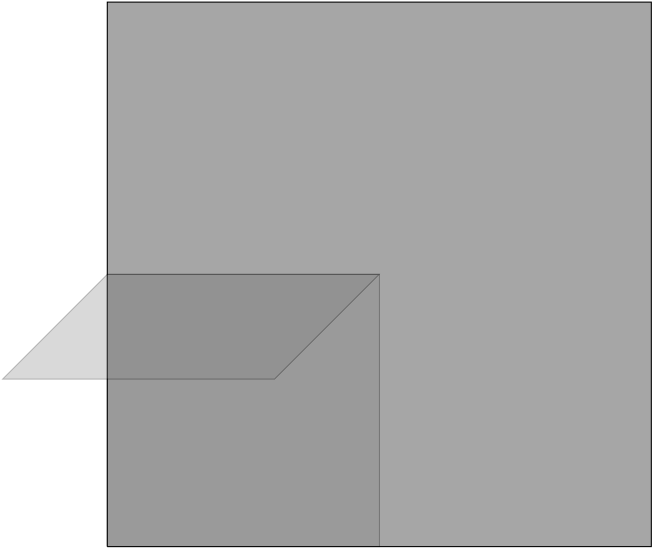

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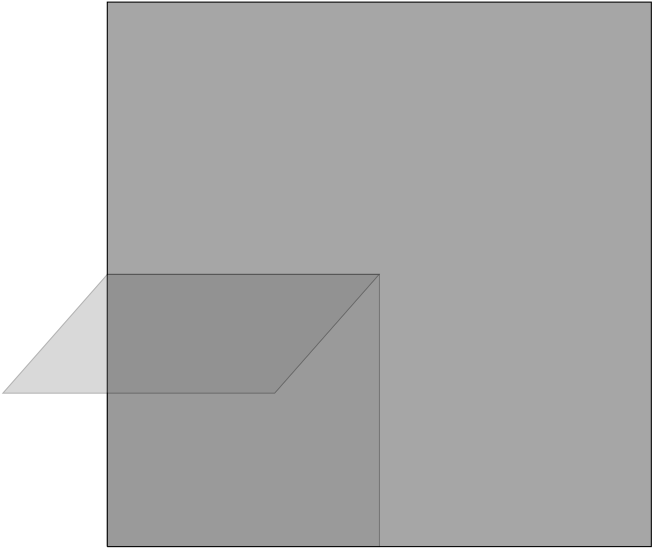

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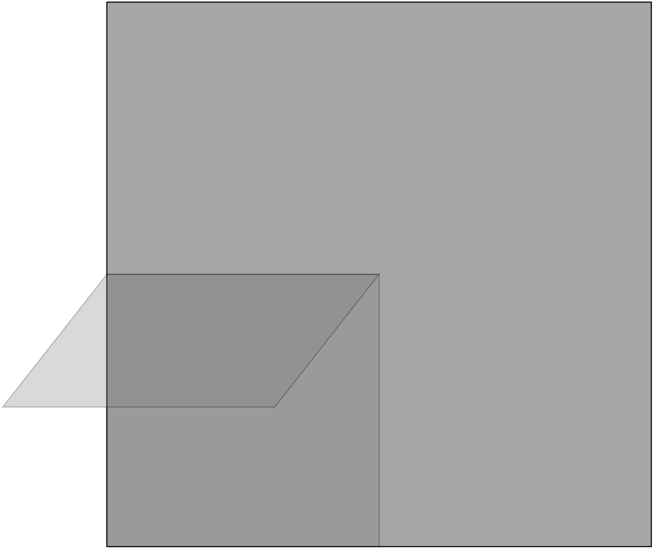

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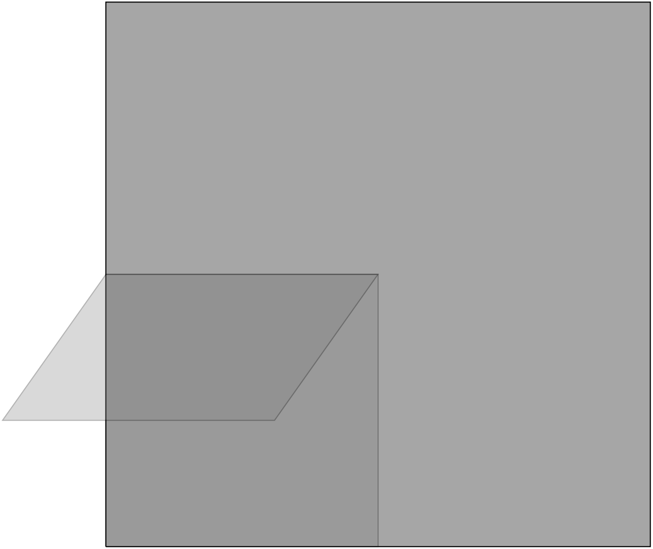

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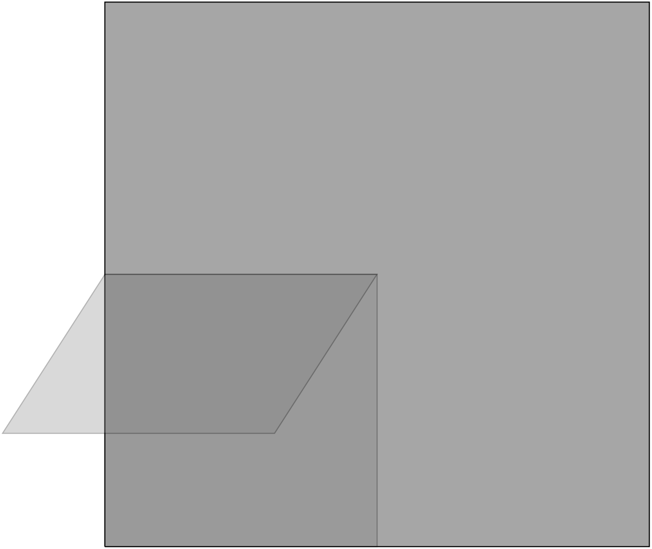

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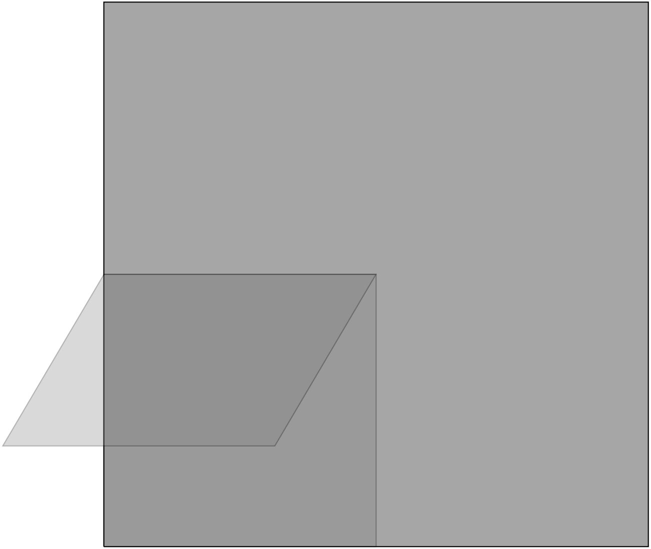

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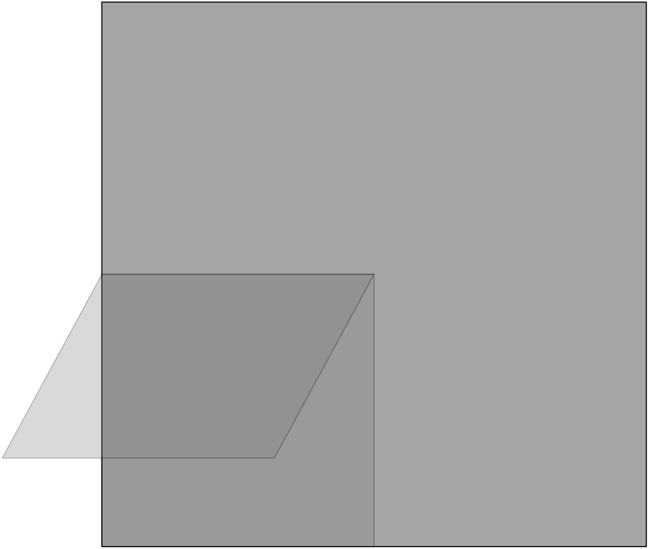

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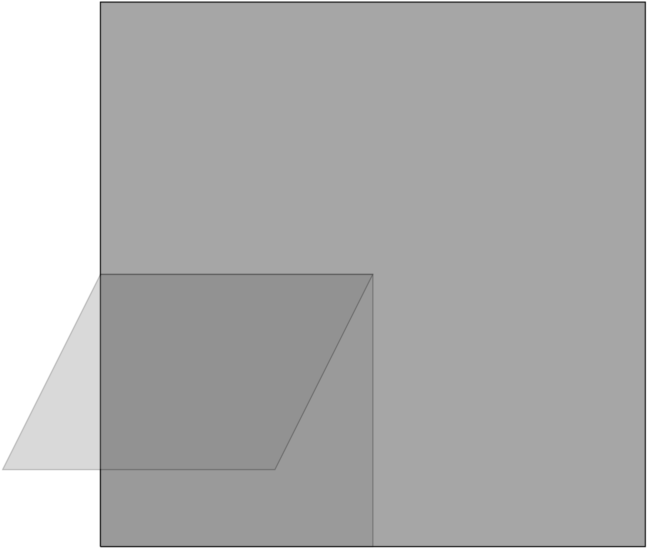

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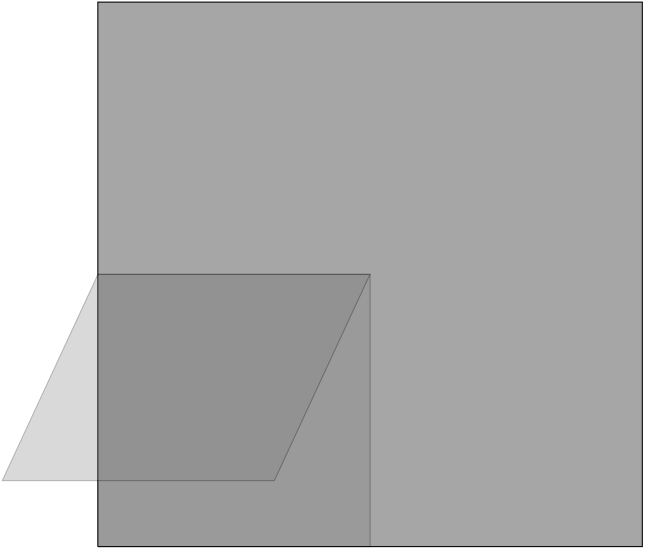

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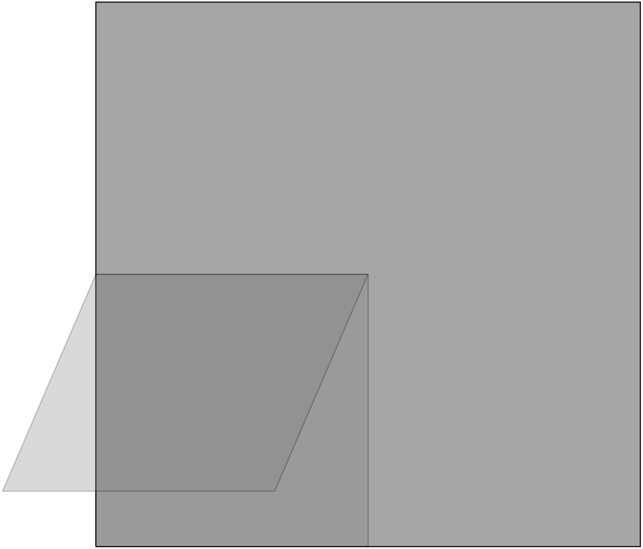

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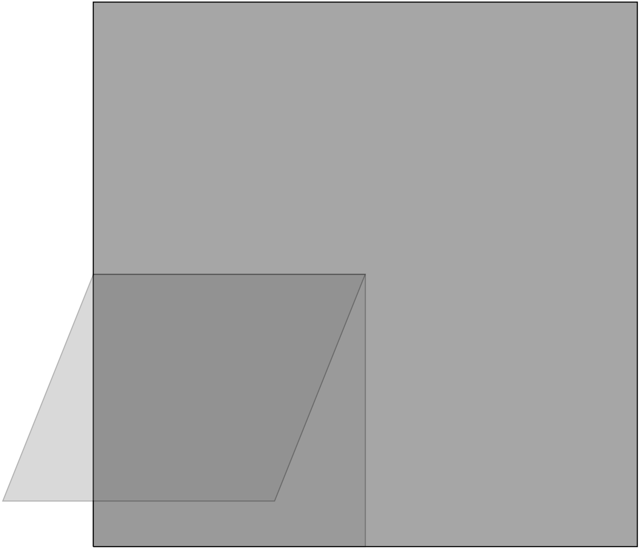

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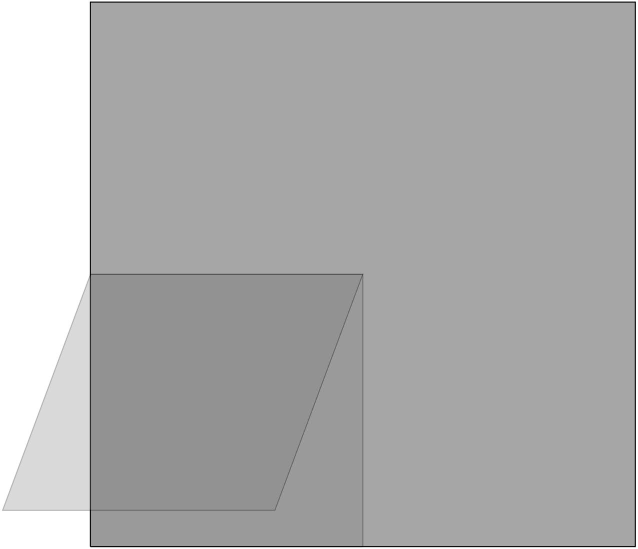

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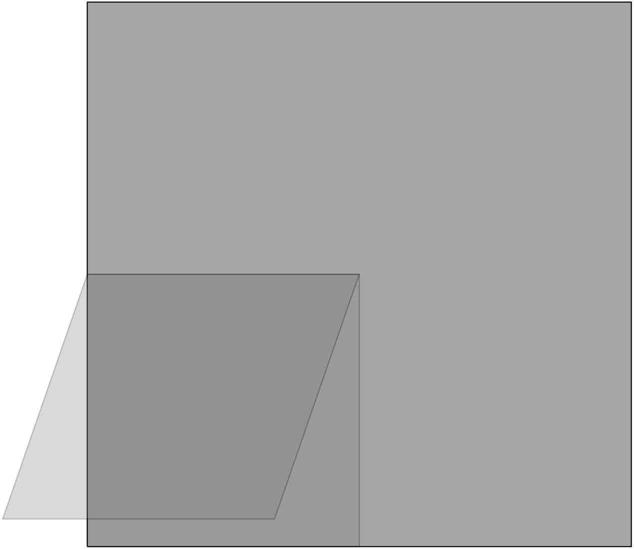

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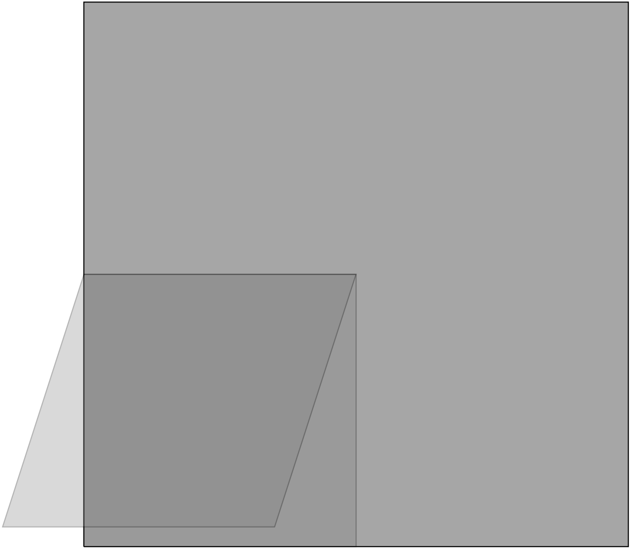

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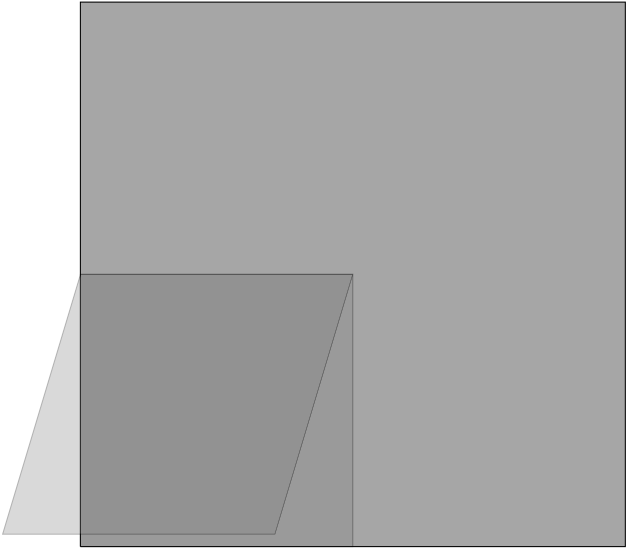

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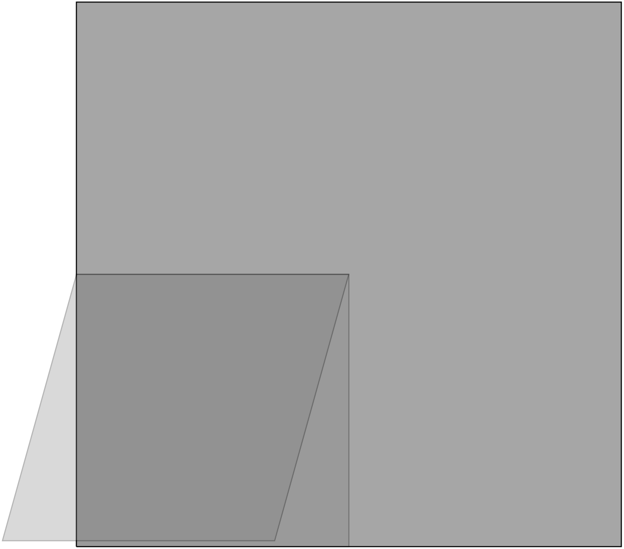

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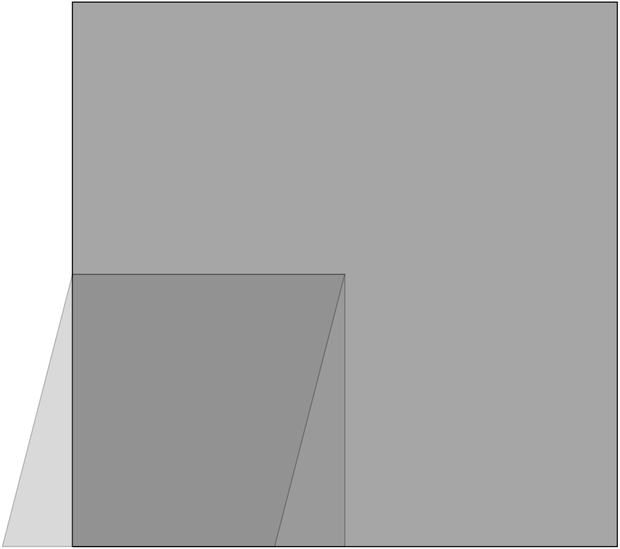

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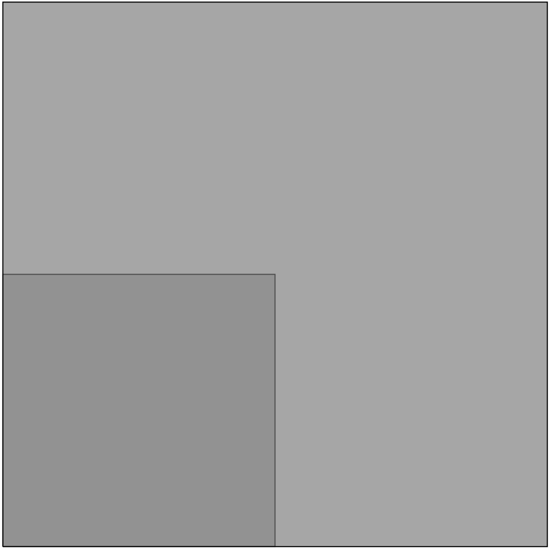
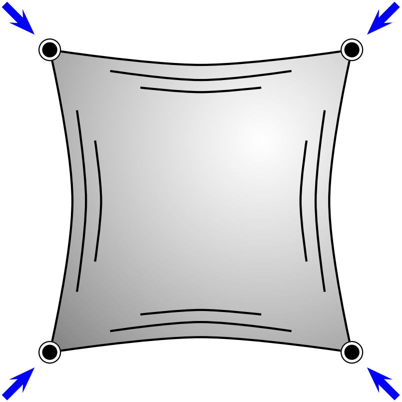


back

# What is an orbifold?



☞ An orbifold is a space which is smooth/flat everywhere except for special (orbifold fixed) points

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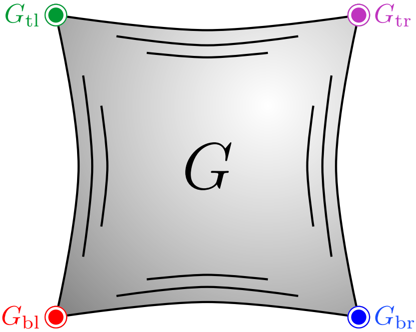


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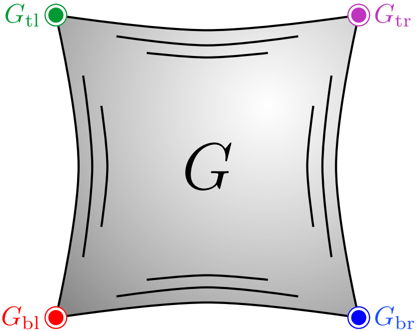


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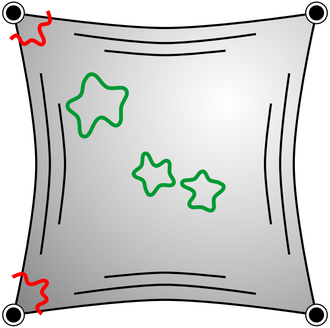
- 'Bulk' gauge symmetry $G$ is broken to (different) subgroups (local GUTs) at the fixed points
- Low–energy gauge group : $G_{\mathrm{low-energy}} = G_{\mathrm{bl}} \cap G_{\mathrm{br}} \cap G_{\mathrm{tl}} \cap G_{\mathrm{tr}}$

# Strings on orbifolds

| heterotic string | field theory |
|---|---|
| untwisted sector = strings closed on the torus | extra components of gauge fields |
| 'twisted' sectors = strings which are only closed on the orbifold | 'brane fields' (hard to understand in field–theoretical framework) |



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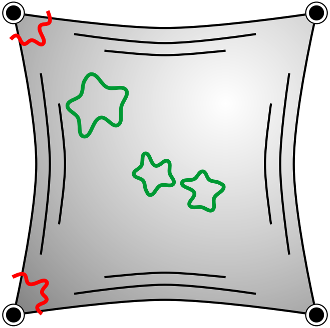

☞ ('Brane') Fields living at a fixed point with a certain symmetry appear as complete multiplet of that symmetry

➥ E.g. if the electron lives at a point with SO(10) symmetry also $u$ and $d$ quarks live there

# String compactifications with local $SO(10)$ GUTs

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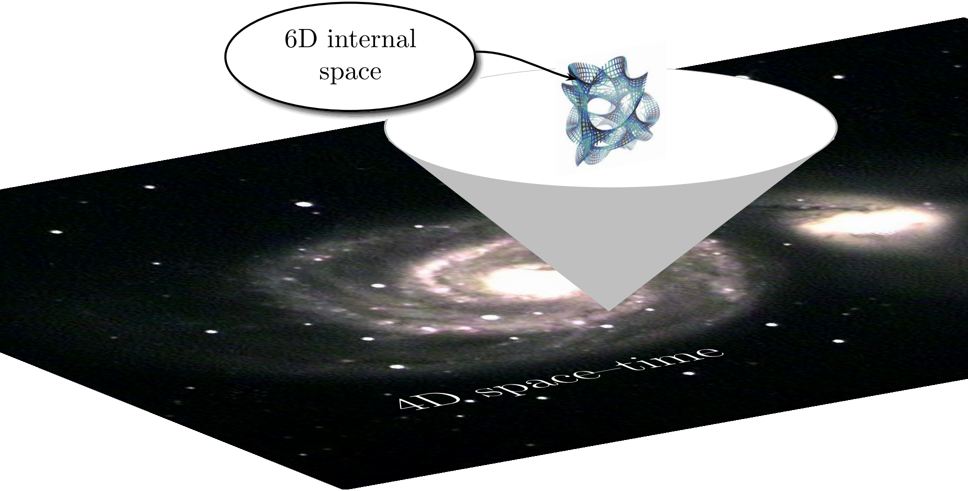

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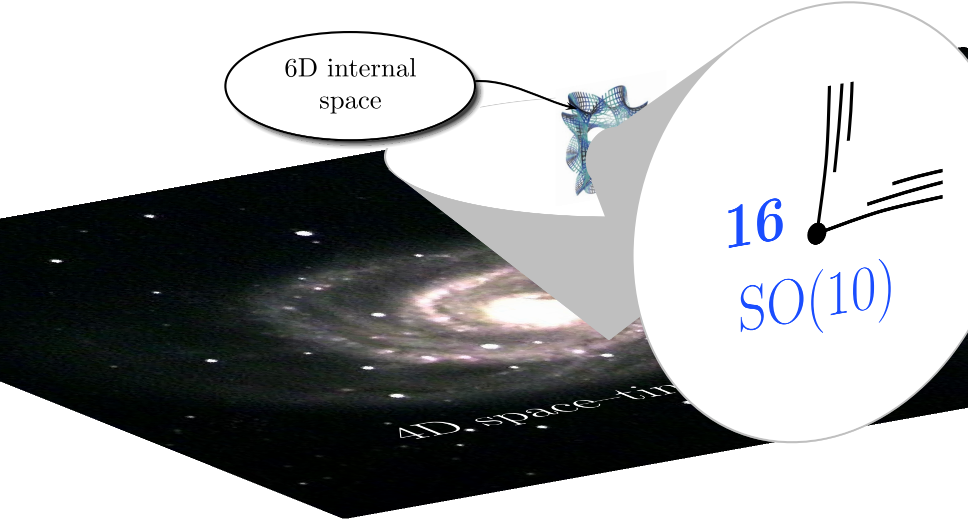

# The mini–landscape search

# Results

1. $3 \times \mathbf{16}$ + Higgs + nothing

No exotics


Lebedev, Nilles, Raby, Ramos-Sánchez, M.R., Vaudrevange & Wingerter (2007b)

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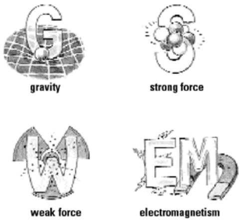


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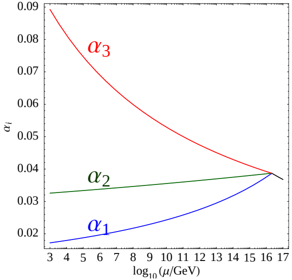
3. unification
   precision gauge unification (PGU)
   from non–local GUT breaking




Raby, M.R. & Schmidt-Hoberg (2010); Krippendorf, Nilles, M.R. & Winkler (2013)

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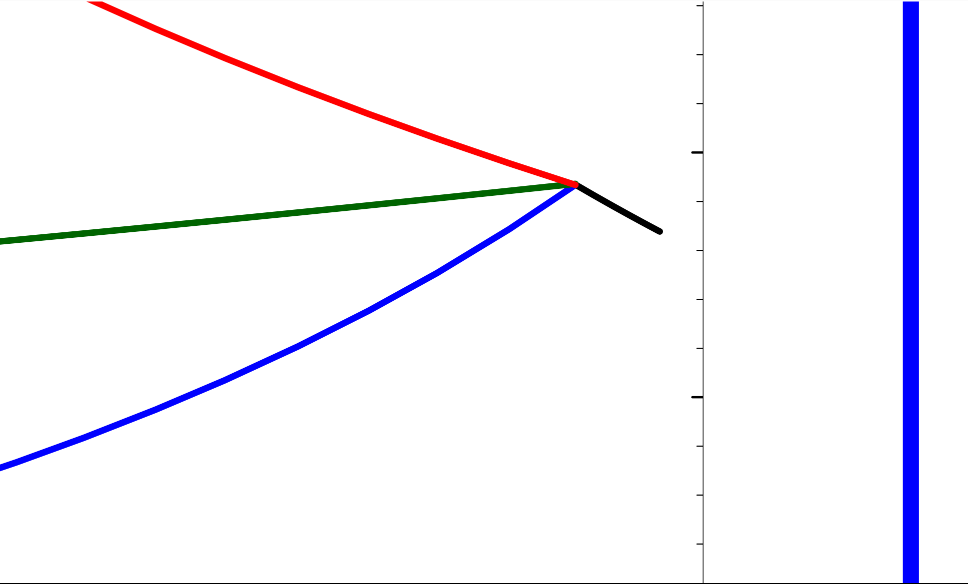

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$\cancel{\bar{u}\,\bar{d}\,\bar{d}}$ $\cancel{q\,\bar{d}\,\ell}$

$\cancel{\ell\,\ell\,\bar{e}}$ $\cancel{\ell\,H_u}$

$\curvearrowright$ proton long–lived

$\curvearrowright$ DM stable

Lebedev, Nilles, Raby, Ramos-Sánchez, M.R., Vaudrevange & Wingerter (2007c); Kappl, Petersen, Raby, M.R., Schieren & Vaudrevange (2011)

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$\curvearrowright$ suppressed $\nu$ masses

Buchmüller, Hamaguchi, Lebedev, Ramos-Sánchez & M.R. (2007)

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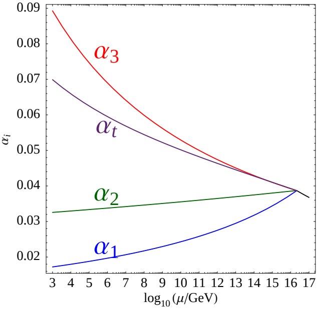


$\curvearrowright$ realistic top mass

Hosteins, Kappl, M.R. & Schmidt-Hoberg (2009)

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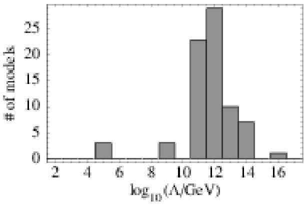
   scale of hidden sector strong dynamics is consistent with TeV–scale soft masses

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8. solution to the $\mu$ problem

$$\mu \sim \langle \mathscr{W} \rangle$$

$\langle \mathscr{W} \rangle \ll 1$ from approximate $\mathrm{U}(1)_R$ symmetries

$\curvearrowright$ light Higgs

Kappl, Nilles, Ramos-Sánchez, M.R., Schmidt-Hoberg & Vaudrevange (2009); Brümmer, Kappl, M.R. & Schmidt-Hoberg (2010)

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that’s what we searched for. . .

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. . . that’s what we got ‘for free’

“stringy surprises”

# Open questions & challenges

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☞ Hard to disprove

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see, however, Kaloper & Terning (2017)

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- A new version of "why now problem": why did questions in the old days have non–anthropic explanations and only the newer problems not?

**Note:**

Even if one believes in the landscape, one still needs to understand the string models, i.e. construct at least some of them explicitly

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- ☞ Example 1:
  Groot Nibbelink, Loukas, Ruehle & Vaudrevange (2015)
  - infinite sets of models allowed by the usual consistency conditions of Calabi–Yau model building by adding fluxes. . .
  - . . . but these models would have an arbitrarily large number of massless states and cannot be UV complete

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- ☞ Example 1: constraints on fluxes???

- ☞ Example 2: Blaszczyk, Groot Nibbelink, M.R., Ruehle, Trapletti, et al. (2010)
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  - . . . but in Calabi–Yau model building there appear to be no analogous constraints

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- Swampland: constructions which resemble string constructions but are not Vafa (2005)
- Example 1: constraints on fluxes???
- Example 2: constraints on Wilson lines?
- Question: how many of the Calabi–Yau and F–theory models are truly consistent string models?
- Question: are there additional consistency conditions at the level of field theory that ensure that a given model has a stringy completion?
- . . . obviously globally consistent string compactifications fulfill this . . .

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see talk by Yessenia Olguin–Trejo
Bailin & Love (1992) . . . Olguin-Trejo & Ramos-Sánchez (2017)

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- New ways to address the hierarchy problem?

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- Tension between non–supersymmetric compactifications and a small cosmological constant Groot Nibbelink, Loukas, Mütter, Parr & Vaudrevange (2017)

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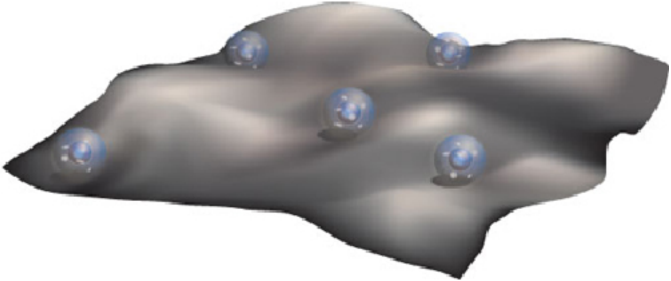

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- Moduli VEVs determine couplings of the low–energy effective theory

$$\mathscr{L}_{\mathrm{QCD}} \xrightarrow[\text{hard}]{\text{very}} \text{proton mass}$$

$$\text{string model} \xrightarrow[\text{harder}]{\text{much}} \text{electron mass}$$

# Issue 6: potential absence of smoking gun signatures

Mütter, M.R. & Vaudrevange (2016)

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**however:**

proton decay is considered to be THE smoking gun signature of unification

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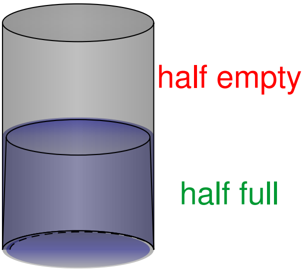

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# Muchas gracias!
# Enjoy the conference!

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