The Geometry of the LARGE Volume Scenario

OR: What is SWISS CHEESE?

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Outline

1. Moduli Stabilization
2. The Large Volume Scenario
3. Swiss Cheese Geometry
4. Exploring the Swiss Cheese Landscape

In collaboration with

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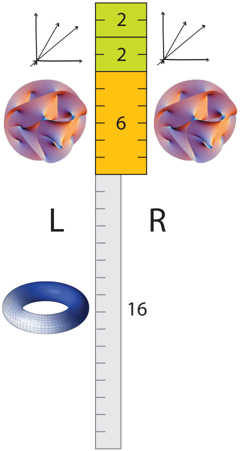
The Issue of Moduli Stabilization



To make contact with the observed world, 10d string theory needs to be compactified down to 4d.

→ **Various choices for 6d internal space** (topology, curvature, complex structure, ...)

Most common:
Compact Calabi-Yau threefolds
(complex Ricci-flat Kähler manifolds with $SU(3)$ holonomy/structure group)

Focus here: type IIB string theory

Moduli of Calabi-Yau threefolds

The geometric moduli of a Calabi-Yau 3-fold $\mathcal{X}$ are determined by the number of embedded 2- and 3-spheres.

$$
\begin{array}{ccccccc|c}
 & & & 1 & & & & b_0 \\
 & & 0 & & 0 & & & b_1 \\
 & 0 & & {\color{red}h^{1,1}} & & 0 & & b_2 \\
1 & & h^{1,2} & & {\color{green}h^{1,2}} & & 1 & b_3 \\
 & 0 & & h^{1,1} & & 0 & & b_4 \\
 & & 0 & & 0 & & & b_5 \\
 & & & 1 & & & & b_6
\end{array}
\quad \Longleftrightarrow
$$

- Kähler moduli U^k:
  $h^{1,1}(\mathcal{X}) = b_2$,
  ➙ 2-cycles
- complex structure mod. T_i:
  $h^{1,2}(\mathcal{X}) = \frac{b_3}{2} - 1$,
  ➙ 3-cycles

where the Betti numbers are cohomology dims. $b_i := \dim_{\mathbb{R}} H^i_{\mathrm{dR}}(\mathcal{X})$.

Unstabilized Moduli?

There is a further moduli, the axio-dilaton modulus S
➙ C_0 and string coupling

What happens to unstabilized moduli?
Compactification leaves effective 4d $\mathcal{N}=1$ supersymmetric theory.
Moduli fields appear as the massless scalar bosons in chiral superfields.

➙ Left "unstabilized" those massless superfields have no potential and would lead to 5th force effects or missing energy in colliders.

Not observed in nature! ➙ **Moduli must be stabilized!**

↓

General idea:
Use fluxes to generate a potential and a nonzero vev for moduli.

Effective Type IIB theory

The IIB theory's effective 4d $\mathcal{N}=1$ **Kähler potential** takes the form

$$K = -\log(S+\bar{S}) - \log\left(-\mathrm{i}\int_{\mathcal{X}} \Omega_3 \wedge \bar{\Omega}_3\right) - 2\log\left(\hat{\mathcal{V}} + \frac{\xi}{2g_s^{\frac{3}{2}}}\right)$$

where $(\alpha')^3$ corrections enter via the parameter ξ, i.e.

$$\xi = -\chi(\mathcal{X})\frac{\zeta(3)}{2(2\pi)^3}$$

Important: If the α' corrections are ignored (setting $\xi = 0$), the associated Kähler metric $K_{\alpha\beta} = \partial_\alpha\partial_\beta K$ becomes block-diagonal with respect to the three moduli types U^k, T_i and S.

➙ Assumed in the KKLT moduli stabilization scenario.

The KKLT Scenario

Using fluxes $F_3 = \mathrm{d}C_2$ and $H_3 = \mathrm{d}B_2$, consider the

Gukov-Vafa-Witten superpotential:
$$W_{\mathrm{GVW}} = \int_{\mathcal{X}} \Omega_3 \wedge G_3, \quad G_3 = \bar{F}_3 - \mathrm{i} S \bar{H}_3$$

$\downarrow$ F-terms

$$F_{U^k} = \int_{\mathcal{X}} \chi_k \wedge G_3, \quad F_{T_i} = K_{T_i} W_{\mathrm{GVW}}, \quad F_S = -\frac{1}{S + \bar{S}} \int_{\mathcal{X}} \Omega_3 \wedge \bar{G}_3.$$

The associated F-term potential V_F can be brought into the form

$$V_F = \mathrm{e}^K \left(K^{-1}_{U\bar{U}} F_U \bar{F}_{\bar{U}} + K^{-1}_{S\bar{S}} F_S \bar{F}_{\bar{S}} \right).$$

which does not depend on the Kähler moduli (cancellation due to the block-diagonal form of the (inverse) Kähler metric).

[Kachru-Kallosh-Linde-Trivedi 2003]

The KKLT Scenario

Minimizing V_F therefore only fixes the complex structure moduli and axio-dilaton. What about the Kähler moduli?

In addition to W_{GVW}, the superpotential W also involves non-perturbative contributions from e.g. E3-brane instantons:

$$W_{\mathrm{np}} = \sum_{\rho} A_{\rho}(U^k, S)\mathrm{e}^{-a_{\rho} T_{\rho}} \quad \text{where} \quad T_{\rho} = \sum_{i=1}^{h^{1,1}(\mathcal{X})} m_{\rho}^{i} T_i$$

Here $A_{\rho}(U^k, S)$ are treshold prefactors and the coefficients a_{ρ} determine the type of the contribution.

Define $W_0 = W_{\mathrm{GVW}}|_{\mathrm{min}}$ to be the minimum of the GVW superpotential for fixed complex structure moduli and axio-dilaton.

The KKLT Scenario

Consider the full superpotential $W = W_0 + \sum_\rho A_\rho(U^k, S)\mathrm{e}^{-a_\rho T_\rho}$.

$$\Downarrow$$

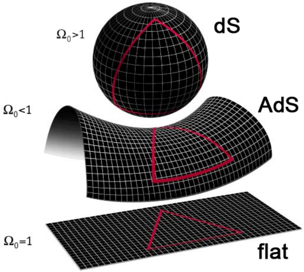
F-term potential: $V_F = \mathrm{e}^K \left(K^{-1}_{T\bar{T}} F_T \bar{F}_{\bar{T}} - 3|W|^2 \right)$
Minimizing this potential stabilizes the Kähler moduli as well.

So, we have two-step moduli stabilization:

1. Stabilize the complex structure and axio-dilaton by the Gukov-Vafa-Witten superpotential, i.e. via G_3-flux.
2. Then consider the non-perturbative contributions as a perturbation around this minimum and stabilize the Kähler structure.

The KKLT Scenario... the BUTs

- KKLT only stabilizes to supersymmetric **anti-de Sitter minima** (not exactly phenomenologically favoured...)



- **Conceptual issues:**
  since W_{np} depends on U^k and S, the 2-step procedure is not always justified
- **Problematic assumption:**
  neglecting α' corrections made the 2-step procedure viable in the first place (block-diagonal Kähler metric)

$\Downarrow$

Can we do better?

Beyond KKLT

...well, at least somewhat.

LET US...

- take α' corrections into account
- neglect open string sector for the moment, such that the D-term potential $V_D = 0$
- assume a specific kind of Calabi-Yau manifold

$$\Downarrow$$

Essentially, we aim to get a better handle on the interplay between the perturbative and non-perturbative contributions.

Swiss Cheese geometry

Let $D_1, \ldots, D_n$ be a divisor basis via $\mathrm{Div}(\mathcal{X}) \cong H^{1,1}(\mathcal{X}; \mathbb{Z})$, where $D_i \subset \mathcal{X}$ is a **4-cycle** of the Calabi-Yau threefold $\mathcal{X}$. $[D_i]$ denotes the Poincaré-dual (1,1)-form of the divisor D_i.

Define triple intersection numbers

$$\kappa_{ijk} = \int_{\mathcal{X}} [D_i] \wedge [D_j] \wedge [D_k]$$

to encode the topology. The Kähler structure is expressed by the expansion of the symplectic form $J \in \Omega^{1,1}(\mathcal{X})$

$$J = \sum_{i=1}^{n} t^i [D_i],$$

with t^i being equivalent to the Kähler parameters.

Swiss Cheese geometry

Note that complex structure and Kähler structure are not entirely independent, which becomes apparent when expressing the overall Calabi-Yau threefold volume

$$\mathcal{V} = \int_{\mathcal{X}} \Omega_3 \wedge \bar{\Omega}_3 = \frac{1}{3!} \int_{\mathcal{X}} J \wedge J \wedge J = \frac{1}{6} \kappa_{ijk} t^i t^j t^k$$

The volumes of the 4-cycle divisors D_i are given by

$$\tau_i = \frac{\partial \mathcal{V}}{\partial t^i} = \frac{1}{2!} \int_{\mathcal{X}} [D_i] \wedge J \wedge J = \frac{1}{2} \kappa_{ijk} t^j t^k$$

Note that the 4-cycle volumes serve as a Kähler structure parameter basis as well, which is non-linearly related to the t^i:

$$T_i = \tau_i + \mathrm{i} b_i \quad \text{where} \quad b_i = \int_{\mathcal{X}} C_4$$

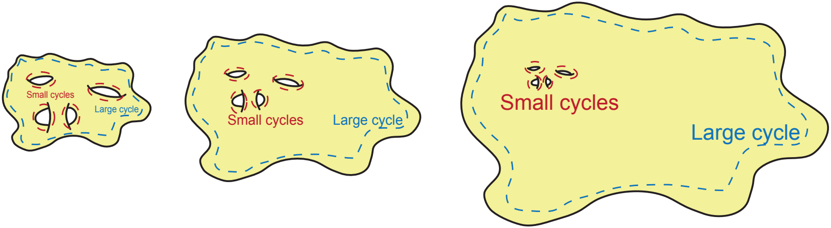
Swiss Cheese geometry

The assumed type of Calabia-Yau threefold then requires that there is

- one 4-cycle that can get LARGE ➙ τ_{L}
- $N_{\mathrm{small}} = h^{1,1}(\mathcal{X}) - 1$ small 4-cycles to generate non-perturbative effects ➙ τ_{s_i}

such that the overall volume takes the form

$$\mathcal{V} = \tau_{\mathrm{L}}^{\frac{3}{2}} - \sum_{i=1}^{N_{\mathrm{small}}} \tau_{\mathrm{s}_i}^{\frac{3}{2}}$$



The LARGE Volume Scenario

By taking the overall volume $\mathcal{V}$ large, we have $\frac{1}{\mathcal{V}} \ll 1$ such that we can expand in the inverse volume. We are now taking the full superpotential with the **large 4-cycle contributions neglected** (since $\tau_{\mathrm{L}} \gg \tau_{\mathrm{s}_i}$):

$$W = \int_{\mathcal{X}} \Omega_3 \wedge G_3 + \sum_{\rho} A_\rho(U^k) \mathrm{e}^{-a_\rho T_\rho} \quad \text{where} \quad T_\rho = \sum_{i=1}^{N_{\mathrm{small}}} m_\rho^i T_{\mathrm{s}_i}$$

$$\Downarrow$$

The expansion of the V_F contributions in $\frac{1}{\mathcal{V}}$ shows the following:

- $K^{-1}_{U\bar{U}} F_U \bar{F}_{\bar{U}} \sim \mathcal{O}(\frac{1}{\mathcal{V}^0})$
- $K^{-1}_{S\bar{S}} F_S \bar{F}_{\bar{S}} \sim \mathcal{O}(\frac{1}{\mathcal{V}^0})$
- $K^{-1}_{S\bar{T}} F_S \bar{F}_{\bar{T}} \sim \mathcal{O}(\frac{1}{\mathcal{V}^1})$
- $K^{-1}_{T\bar{T}} F_T \bar{F}_{\bar{T}} - 3|W|^2 \sim \mathcal{O}(\frac{1}{\mathcal{V}^1})$

The LARGE Volume Scenario

To leading order we then obtain the F-term potential:

$$V_F = \mathrm{e}^K \left(K^{-1}_{U\bar{U}} F_U \bar{F}_{\bar{U}} + K^{-1}_{S\bar{S}} F_S \bar{F}_{\bar{S}} \right) + \mathcal{O}(\tfrac{1}{\mathcal{V}^3})$$

$$\Big\downarrow$$

Same potential as in the 1st KKLT step!
(and only the W_{GVW} part of W contributes)

Once again use $W_0 = W_{\mathrm{GVW}}|_{\mathrm{min}}$ to stabilize U^k and S. The $\mathcal{O}(\frac{1}{\mathcal{V}^3})$ term of V_F as a perturbation then stabilizes the T_i moduli.

→ The benefit of the LARGE Volume Scenario is therefore a **$\mathcal{V}$-controlled separation of the two moduli stabilization steps**.

The Swiss Cheese Landscape

Swiss Cheese geometry is crucial for the LARGE Volume Scenario.

➙ Understand the actual LARGE Volume Limit!

[Cicoli-Conlon-Quevedo 2008]

At the moment there are less than 20 Swiss Cheese manifolds known.

- $\tilde{\mathbb{P}}^4_{1,1,1,6,9}[18]$
- $\tilde{\mathbb{P}}^4_{1,1,3,10,15}[30]$
- $M_n^{(dP_1)^n}$, $n = 0, \ldots, 8$
- $\tilde{\mathbb{P}}^4_{1,3,3,3,5}[15]$
- $\mathcal{F}_{11} = \mathrm{CY}^{h^\bullet=3,111}/\mathbb{Z}_2$

$\Downarrow$

GOAL: Improve on that situation.

Towards a Scanning Algorithm

What goes into the Swiss Cheese definition?

- The (topological) intersection form, which in the end defines the 4-cycle volumes τ_i and overall volume $\mathcal{V}$.

$\downarrow$

The entire Swiss Cheese geometry is essentially encoded in the intersection form.

Biggest issue:
How to make the distinction between the large cycle divisor and the small cycle divisor?

In the literature, this distinction has always been made by hand by considering only a simple geometry...

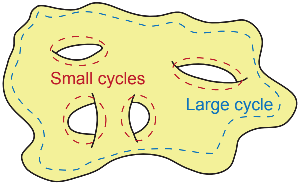
Towards a Scanning Algorithm

Let $\mathcal{X}$ be a Calabi-Yau 3-fold and $D_{\mathrm{L}}, D_{\mathrm{s}_1}, \ldots, D_{\mathrm{s}_n}$ be a "convenient" divisor basis—the assumed situation in the literature.

- $D_{\mathrm{s}_i} + D_{\mathrm{s}_j}$ gives another small divisor
- $D_{\mathrm{L}} + D_{\mathrm{s}_i}$ gives a new (fake) "large" divisor

↓

For a generic intersection form κ_{ijk} and the implied divisor basis D_i is NOT in a "convenient" basis.
A general base changes the number of apparently large 4-cycles.



↓

Identify the minimal number of large 4-cycles... *EFFICIENTLY*

Attempt 0: Straight diagonalization

So, **basic goal**:
In order to bring the volume form to

$$\mathcal{V} = \tau_{\mathrm{L}}^{\frac{3}{2}} - \sum_{i=1}^{N_{\mathrm{small}}} \tau_{\mathrm{s}_i}^{\frac{3}{2}}$$

all we need to do is diagonalize the intersection matrix κ_{ijk}.

$\Downarrow$

Naively, $\kappa_{ijk} \to A_{i\tilde{\imath}} A_{j\tilde{\jmath}} A_{k\tilde{k}} \kappa_{\tilde{\imath}\tilde{\jmath}k}$ gives you
$\binom{h^{1,1}+2}{3}$ cubic equations for the
$(h^{1,1})^2 - 1$ components of the base change matrix.

$\Downarrow$

Doesn't scale too well...

Attempt 1: General base change

Express the Kähler parameters t^i in terms of the volumes τ_i:

$$\tau_i = \frac{1}{2}\kappa_{ijk}t^j t^k \iff t^i = t^i(\sqrt{\tau_1}, \dots, \sqrt{\tau_n})$$

Recall that t^i and τ_i are equivalent and non-linearly related.

➙ A base change on the D_i is equivalent to a base change on the τ_i.

Assume an arbitrary base change $\tau_i \to \tilde{\tau}_i = \sum_{\tilde{j}} A_{i\tilde{j}}\tau_{\tilde{j}}$.

Compute the overall volume with respect to the new basis $\tilde{\tau}_i$:

$$\mathcal{V}(\tilde{\tau}_i) = \frac{1}{6}\kappa_{ijk}t^i(\sqrt{\tilde{\tau}})t^j(\sqrt{\tilde{\tau}})t^k(\sqrt{\tilde{\tau}})$$

Solve for the A_{ij} such that $\mathcal{V}$ has prototype form of $\tilde{\tau}$ dependency.

Attempt 1: Example for $\mathbb{P}^4_{1,1,1,6,9}[18]$

Consider $\mathcal{X} = \mathbb{P}^4_{1,1,1,6,9}[18]$ which has $h^{1,1} = 2$.

$$\kappa_{ijk} = \begin{pmatrix} \{0,1\} & \{1,6\} \\ \{1,6\} & \{6,36\} \end{pmatrix} \quad \rightarrow \quad \begin{cases} \mathcal{V} = \frac{1}{6}\left(3t_1^2 t_2 + 18 t_1 t_2^2 + 36 t_2^3\right) \\ \tau_1 = t_1 t_2 + 3t_2^2 \\ \tau_2 = \frac{1}{2}\left(t_1^2 + 12 t_1 t_2 + 36 t_2^2\right) \end{cases}$$

Question: Swiss Cheese or not?

Hint:

$$\tau_1 = (t_1 + 3t_2)t_2$$
$$\tau_2 = \frac{1}{2}(t_1 + 6t_2)^2$$

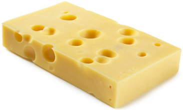
Attempt 1: Example for $\mathbb{P}^4_{1,1,1,6,9}[18]$

Base change: $$\begin{pmatrix} \tilde{\tau}_1 \\ \tilde{\tau}_2 \end{pmatrix} = \begin{pmatrix} -6 & 1 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} \tau_1 \\ \tau_2 \end{pmatrix} = \begin{pmatrix} \frac{1}{2} t_1^2 \\ \frac{1}{2}\left(t_1 + 6t_2^2\right)^2 \end{pmatrix}$$

$$\Downarrow$$

$$\mathcal{V} = \frac{1}{9\sqrt{2}}\left(\tilde{\tau}_2^{\frac{3}{2}} - \tilde{\tau}_1^{\frac{3}{2}}\right)$$

$$\Downarrow$$



Attempt 1: General base change

Problem:

This is also just a *little* bit slow...

Can't even scan $h^{1,1} = 2$ manifolds (simplest case) in any reasonable amount of time...

➙ No chance for a large scale scan.

Thoughts:

- An arbitrary base change seems to be necessary.
- Do we really need to involve the t^i Kähler parameters?
- Do we need to express the t^is in terms of the τ_js?

➙ Back to the drawing board...

Attempt 2: "Dyadization" simplification

What about a simplifying assumption?
$\kappa^{(i)} = \kappa_{i\bullet\bullet}$ is the symmetric intersection form on each divisor $D_i \subset \mathcal{X}$

Assume that each $\kappa^{(i)}$ is a dyadic tensor, i.e.

$$\kappa^{(i)}_{uv} = \kappa_{iuv} = a^{(i)}_u a^{(i)}_v \iff \kappa^{(i)} = a^{(i)} \otimes a^{(i)}$$

$$\Downarrow$$

$$\tau_i = \frac{1}{2} \sum_{u,v} \kappa_{iuv} t^u t^v = \frac{1}{2} \left(\sum_u a^{(i)}_u t^u \right)^2$$

This assumption automatically takes care of producing the squared form of the 4-cycle volumes, that guided in the previous example.

$\rightarrow$ Faster, but quite restrictive...

Attempt 3: Faster base change

Need to rewrite the problem in a more base-invariant fashion and need to make the equation system structurally simpler.

Notation: $\vec{t} = (t^1, \ldots, t^n)$ are the Kähler parameters.

➞ Express 4-cycle volume by $\tau_i = \vec{t}^* \kappa^{(i)} \vec{t}$.

Assuming that there is only one large cycle D_{L} whose volume is taken $\tau_{\mathrm{L}} \to \infty$ means that there is only one corresponding direction $\vec{t}_{\mathrm{L}}$ in the Kähler parameter space.

$$\text{splitting: } \vec{t} = \lambda \vec{t}_{\mathrm{L}} + \vec{t}_{\mathrm{s}} \quad ➞ \quad \text{LVL: } \tau_{\mathrm{L}} \to \infty \iff \lambda \to \infty$$

With respect to a convenient basis $D_{\mathrm{L}}, D_{\mathrm{s}_1}, \ldots, D_{\mathrm{s}_n}$ the large and small cycles are then characterized by

$$\vec{t}^*_{\mathrm{L}} \kappa^{(\mathrm{L})} \vec{t}_{\mathrm{L}} \neq 0 \qquad \vec{t}^*_{\mathrm{L}} \kappa^{(\mathrm{s}_i)} \vec{t}_{\mathrm{L}} = 0 \qquad \vec{t}^*_{\mathrm{s}} \kappa^{(\mathrm{s}_i)} \vec{t}_{\mathrm{s}} \neq 0$$

PRELIMINARY

Attempt 3: Faster base change

Now consider switching to an arbitrary basis: $\tau_i = \sum_{\tilde{j}=1}^{h^{1,1}(\mathcal{X})} A_{i\tilde{j}} \tilde{\tau}_{\tilde{j}}$

Note: $A_{i\tilde{j}} \kappa^{(\tilde{j})}_{\tilde{u}\tilde{v}} = A_{i\tilde{j}} \int_{\tilde{D}_{\tilde{j}}} [\tilde{D}_{\tilde{u}}] \wedge [\tilde{D}_{\tilde{v}}] = \int_{A_{i\tilde{j}} \tilde{D}_{\tilde{j}}} [\tilde{D}_{\tilde{u}}] \wedge [\tilde{D}_{\tilde{v}}] = \kappa^{(i)}_{\tilde{u}\tilde{v}}$

➙ Need to solve:

$$\begin{cases} \text{large 4-cycle:} & \vec{t}^{\,*}_{\mathrm{L}} A_{\mathrm{L}\tilde{j}} \kappa^{(\tilde{j})} \vec{t}_{\mathrm{L}} \neq 0 \\ \text{small 4-cycles:} & \vec{t}^{\,*}_{\mathrm{L}} A_{\mathrm{s}_i\tilde{j}} \kappa^{(\tilde{j})} \vec{t}_{\mathrm{L}} = 0 \\ & \vec{t}^{\,*}_{\mathrm{s}} A_{\mathrm{s}_i\tilde{j}} \kappa^{(\tilde{j})} \vec{t}_{\mathrm{s}} \neq 0 \\ \text{base change:} & \det A_{i\tilde{j}} \neq 0 \end{cases}$$

Also need to stay within the Kähler cone:

$$\begin{cases} (\vec{t}_{\mathrm{L}})_{\tilde{j}} \geq 0 \\ (\vec{t}_{\mathrm{s}_i})_{\tilde{j}} \geq 0 \end{cases}$$

PRELIMINARY

Attempt 3: Faster base change

Recall from the LVL characterization that we need the superpotential

$$W = W_0 + \sum_{i=1}^{N_{\mathrm{small}}} A_i(U^k, S)\mathrm{e}^{-a_i T_i}$$

Note that this implies that the **assumed divisor basis is effective**, i.e. at least the small base divisors D_{s_i} are within the Kähler cone.

$\downarrow$

- Make certain we start with an arbitrary basis of effective divisors.
- Only allow for basis transformations $A_{i\tilde{\jmath}}$ that keep the basis effective, i.e. $A_{i\tilde{\jmath}} \geq 0$.

PRELIMINARY

Attempt 3: Faster base change

- Check if the equation system

$$\begin{cases} \text{large 4-cycle:} & \vec{t}_{\mathrm{L}}^{*} A_{\mathrm{L}\tilde{\jmath}} \kappa^{(\tilde{\jmath})} \vec{t}_{\mathrm{L}} \neq 0 \\ \text{small 4-cycles:} & \vec{t}_{\mathrm{L}}^{*} A_{\mathrm{s}_i\tilde{\jmath}} \kappa^{(\tilde{\jmath})} \vec{t}_{\mathrm{L}} = 0 \\ & \vec{t}_{\mathrm{s}}^{*} A_{\mathrm{s}_i\tilde{\jmath}} \kappa^{(\tilde{\jmath})} \vec{t}_{\mathrm{s}} \neq 0 \\ \text{base change:} & \det A_{i\tilde{\jmath}} \neq 0 \\ \text{keep effective:} & A_{i\tilde{\jmath}} \geq 0 \\ \text{Kähler cone:} & (\vec{t}_{\mathrm{L}})_{\tilde{\jmath}} \geq 0 \\ & (\vec{t}_{\mathrm{s}_i})_{\tilde{\jmath}} \geq 0 \end{cases}$$

is solveable in $\vec{t}_{\mathrm{L}}$, $\vec{t}_{\mathrm{s}}$ and $A_{i\tilde{\jmath}}$...

- **Surprisingly fast!**

PRELIMINARY

Attempt 3: Faster base change

Furthermore, for an arbitrary effective basis, the Kähler cone will not correspond to $t_{\tilde{\imath}} \geq 0$, as used earlier. In general the Kähler cone is a subset thereof, which requires a proper redefinition of the parameters.

➞ Yet to be done...

↓

A generic and *efficient* Swiss Cheese identification algorithm is much harder to obtain than originally anticipated.

1. Redefine the basis / Kähler parameters, such that the basis divisors are effective and $t_{\tilde{\imath}} \geq 0$ corresponds to the Kähler cone.
2. Test if the prior outlined equation system is solveable.

PRELIMINARY

Outlook

Some further question:

- How generic is the Swiss Cheese condition in the landscape?
- Check if the small 4-cycles are del Pezzo.
- Study implications for inflation scenarios.
- What about D-term potentials / open string sector.
- Study hierarchy implications.

The Alternate Swiss Cheese Landscape