# Finiteness properties, cohomology jump loci, and tropical varieties

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## The Bieri–Neumann–Strebel–Renz invariants

- Let $G$ be a finitely generated group, $n = b_1(G) > 0$. Let $S(G) = S^{n-1}$ be the unit sphere in $\mathrm{Hom}(G, \mathbb{R}) = \mathbb{R}^n$.

- (Bieri–Neumann–Strebel 1987)

  $$\Sigma^1(G) = \{\chi \in S(G) \mid \mathrm{Cay}_\chi(G) \text{ is connected}\},$$

  where $\mathrm{Cay}_\chi(G)$ is the induced subgraph of $\mathrm{Cay}(G)$ on vertex set $G_\chi = \{g \in G \mid \chi(g) \geq 0\}$.

- (Bieri–Renz 1988)

  $$\Sigma^q(G, \mathbb{Z}) = \{\chi \in S(G) \mid \text{the monoid } G_\chi \text{ is of type } \mathrm{FP}_q\},$$

  i.e., there is a projective $\mathbb{Z}G_\chi$-resolution $P_\bullet \to \mathbb{Z}$, with $P_i$ finitely generated for all $i \leq q$. Moreover, $\Sigma^1(G, \mathbb{Z}) = -\Sigma^1(G)$.

- The BNSR-invariants of form a descending chain of open subsets,

$$S(G) \supseteq \Sigma^1(G,\mathbb{Z}) \supseteq \Sigma^2(G,\mathbb{Z}) \supseteq \cdots .$$

- The $\Sigma$-invariants control the finiteness properties of normal subgroups $N \triangleleft G$ for which $G/N$ is free abelian:

$$N \text{ is of type } \mathrm{FP}_q \iff S(G,N) \subseteq \Sigma^q(G,\mathbb{Z})$$

  where $S(G,N) = \{\chi \in S(G) \mid \chi(N) = 0\}$.

- In particular: $\ker(\chi\colon G \twoheadrightarrow \mathbb{Z})$ is f.g. $\iff \{\pm\chi\} \subseteq \Sigma^1(G)$.

- More generally, let $X$ be a connected CW-complex with finite $q$-skeleton, for some $q \geq 1$.
- Let $G = \pi_1(X, x_0)$. For each $\chi \in S(X) := S(G)$, let

$$\widehat{\mathbb{Z}G}_\chi = \left\{ \lambda \in \mathbb{Z}^G \mid \{g \in \operatorname{supp} \lambda \mid \chi(g) \geq c\} \text{ is finite, } \forall c \in \mathbb{R} \right\}$$

be the Novikov–Sikorav completion of $\mathbb{Z}G$.

- (Farber–Geoghegan–Schütz 2010)

$$\Sigma^q(X, \mathbb{Z}) = \{\chi \in S(X) \mid H_i(X, \widehat{\mathbb{Z}G}_{-\chi}) = 0, \ \forall\, i \leq q\}.$$

- (Bieri 2007) If $G$ is $\text{FP}_k$, then $\Sigma^q(G, \mathbb{Z}) = \Sigma^q(K(G,1), \mathbb{Z})$, $\forall q \leq k$.

## Characteristic varieties

- Let $\mathbb{T}_G := \mathrm{Hom}(G, \mathbb{C}^*)$ be the character group of $G = \pi_1(X)$, also denoted by $\mathrm{Char}(X) := H^1(X, \mathbb{C}^*)$.
- The *characteristic varieties* of $X$ are the sets

$$\mathcal{V}^i(X) = \{\rho \in \mathbb{T}_G \mid H_i(X, \mathbb{C}_\rho) \neq 0\}.$$

- If $X$ has finite $q$-skeleton, then $\mathcal{V}^i(X)$ is Zariski closed for all $i \leq q$.
- We may define similarly $\mathcal{V}^i(X, \Bbbk) \subset H^1(X, \Bbbk^*)$ for any field $k$.
- These constructions are compatible with restriction and extension of the base field. Namely, if $\Bbbk \subset \mathbb{L}$ is a field extension, then

$$\mathcal{V}^i(X, \Bbbk) = \mathcal{V}^i(X, \mathbb{L}) \cap H^1(X, \Bbbk^\times),$$

$$\mathcal{V}^i(X, \mathbb{L}) = \mathcal{V}^i(X, \Bbbk) \times_\Bbbk \mathbb{L}.$$

- Let $X^{\mathrm{ab}} \to X$ be the maximal abelian cover. View $H_*(X^{\mathrm{ab}}, \mathbb{C})$ as a module over $\mathbb{C}[G_{\mathrm{ab}}]$. Then

$$\bigcup_{i\leq q} \mathcal{V}^i(X) = \bigcup_{i\leq q} V\big(\operatorname{ann}\big(H_i(X^{\mathrm{ab}}, \mathbb{C})\big)\big).$$

- Let $\exp\colon \mathbb{C}^n \to (\mathbb{C}^*)^n$. Given a subvariety $W \subset (\mathbb{C}^*)^n$, define its *exponential tangent cone* at 1 (identity of $(\mathbb{C}^*)^n$) as

$$\tau_1(W) = \{z \in \mathbb{C}^n \mid \exp(\lambda z) \in W,\ \forall \lambda \in \mathbb{C}\}.$$

- $\tau_1(W)$ depends only on $W_{(1)}$; it is non-empty iff $1 \in W$.
- If $T \cong (\mathbb{C}^*)^r$ is an algebraic subtorus, then $\tau_1(T) = T_1(T) \cong \mathbb{C}^r$
- (Dimca–Papadima–S. 2009) $\tau_1(W)$ is a finite union of rationally defined linear subspaces.
- Set $\tau_1^{\Bbbk}(W) = \tau_1(W) \cap \Bbbk^n$, for a subfield $\Bbbk \subset \mathbb{C}$.

## Resonance varieties

- Let $A = H^*(X, \mathbb{C})$. For each $a \in A^1$, we have that $a^2 = 0$. Thus, there is a cochain complex

$$(A, \cdot a)\colon\ A^0 \xrightarrow{a} A^1 \xrightarrow{a} A^2 \longrightarrow \cdots .$$

- The *resonance varieties* of $X$ are the homogeneous algebraic sets

$$\mathcal{R}^i(X) = \{a \in A^1 \mid H^i(A, a) \neq 0\}.$$

- Identify $A^1 = H^1(X, \mathbb{C})$ with $\mathbb{C}^n$, where $n = b_1(X)$. The map $\exp\colon H^1(X, \mathbb{C}) \to H^1(X, \mathbb{C}^*)$ has image $\mathbb{T}^0_G = (\mathbb{C}^*)^n$.
- (Dimca–Papadima–S. 2009)

$$\tau_1(\mathcal{V}^i(X)) \subseteq \mathcal{R}^i(X).$$

- (DPS-2009, DP-2014) If $X$ is a $q$-formal space, then, for all $i \leq q$,

$$\tau_1(\mathcal{V}^i(X)) = \mathcal{R}^i(X).$$

## Bounding the $\Sigma$-invariants

THEOREM (PAPADIMA–S. 2010)

*Let $X$ be a connected CW-complex with finite $q$-skeleton. Let $\chi\colon \pi_1(X) \to \mathbb{R}$ be a non-zero homomorphism, and let $b_i(X,\chi)$ be the corresponding $i$-th Novikov–Betti number. Then,*

- $-\chi \in \Sigma^q(X,\mathbb{Z}) \implies b_i(X,\chi) = 0,\ \forall i \le q.$
- $\chi \notin \tau_1^{\mathbb{R}}(\mathcal{V}^{\le q}(X)) \iff b_i(X,\chi) = 0,\ \forall i \le q.$

COROLLARY

$$\Sigma^q(X,\mathbb{Z}) \subseteq S\left(\tau_1^{\mathbb{R}}\left(\mathcal{V}^{\le q}(X)\right)\right)^{\mathrm{c}}$$

- Thus, $\Sigma^q(X,\mathbb{Z})$ is contained in the complement of a finite union of rationally defined great subspheres.
- If $X$ is $q$-formal, then $\Sigma^i(X,\mathbb{Z}) \subseteq S\left(\mathcal{R}^{\le i}(X)\right)^{\mathrm{c}}$ for all $i \le q$.

## Tropical varieties

- Let $\mathbb{K} = \mathbb{C}\{\{t\}\} = \bigcup_{n\geq 1} \mathbb{C}((t^{1/n}))$ be the field of Puiseux series $/\mathbb{C}$.
- A non-zero element of $\mathbb{K}$ has the form $c(t) = c_1 t^{a_1} + c_2 t^{a_2} + \cdots$, where $c_i \in \mathbb{C}^*$ and $a_1 < a_2 < \cdots$ are rational numbers with a common denominator.
- The (algebraically closed) field $\mathbb{K}$ admits a valuation $v\colon \mathbb{K}^* \to \mathbb{Q}$, given by $v(c(t)) = a_1$.
- Let $v\colon (\mathbb{K}^*)^n \to \mathbb{Q}^n \subset \mathbb{R}^n$ be the $n$-fold product of the valuation.
- The *tropicalization* of a subvariety $W \subset (\mathbb{K}^*)^n$, denoted $\operatorname{Trop}(W)$, is the closure (in the Euclidean topology) of $v(W)$ in $\mathbb{R}^n$.
- This is a rational polyhedral complex in $\mathbb{R}^n$. For instance, if $W$ is a curve, then $\operatorname{Trop}(W)$ is a graph with rational edge directions.

- If $T$ be an algebraic subtorus of $(\mathbb{K}^*)^n$, then $\mathrm{Trop}(T)$ is the linear subspace $\mathrm{Hom}(\mathbb{K}^*, T) \otimes \mathbb{R} \subset \mathrm{Hom}(\mathbb{K}^*, (\mathbb{K}^*)^n) \otimes \mathbb{R} = \mathbb{R}^n$.
- Moreover, if $z \in (\mathbb{K}^*)^n$, then $\mathrm{Trop}(z \cdot T) = \mathrm{Trop}(T) + v(z)$.
- For a variety $W \subset (\mathbb{C}^*)^n$, we may define its tropicalization by setting $\mathrm{Trop}(W) = \mathrm{Trop}(W \times_{\mathbb{C}} \mathbb{K})$.
- In this case, the tropicalization is a polyhedral fan in $\mathbb{R}^n$.
- If $W = V(f)$ is a hypersurface, defined by a Laurent polynomial $f \in \mathbb{C}[t_1^{\pm 1}, \dots, t_n^{\pm 1}]$, then $\mathrm{Trop}(W)$ is the positive-codimensional skeleton of the inner normal fan to the Newton polytope of $f$.

## Tropicalizing the characteristic varieties

- Recall $\mathbb{K} = \mathbb{C}\{\{t\}\}$ comes with a valuation map, $v\colon \mathbb{K}^* \to \mathbb{Q}$.
- Let $\nu_X\colon \operatorname{Char}_{\mathbb{K}}(X) \to \mathbb{Q}^n \subset \mathbb{R}^n$ be the composite

$$H^1(X, \mathbb{K}^*) \xrightarrow{v_*} H^1(X, \mathbb{Q}) \longrightarrow H^1(X, \mathbb{R}).$$

- I.e., if $\rho\colon \pi_1(X) \to \mathbb{K}^*$ is a $\mathbb{K}$-valued character, then the morphism $v \circ \rho\colon \pi_1(X) \to \mathbb{Q}$ defines $\nu_X(\rho) \in H^1(X, \mathbb{Q}) = \mathbb{Q}^n \subset \mathbb{R}^n$.
- Given an algebraic subvariety $W \subset H^1(X, \mathbb{C}^*)$ we define its *tropicalization* as the closure in $H^1(X, \mathbb{R}) \cong \mathbb{R}^n$ of the image of $W \times_{\mathbb{C}} \mathbb{K} \subset H^1(X, \mathbb{K}^*)$ under $\nu_X$,

$$\operatorname{Trop}(W) := \overline{\nu_X(W \times_{\mathbb{C}} \mathbb{K})}.$$

- Applying this definition to the characteristic varieties $\mathcal{V}^i(X)$, and recalling that $\mathcal{V}^i(X, \mathbb{K}) = \mathcal{V}^i(X) \times_{\mathbb{C}} \mathbb{K}$, we have that

$$\operatorname{Trop}(\mathcal{V}^i(X)) = \overline{\nu_X\big(\mathcal{V}^i(X, \mathbb{K})\big)}.$$

## Lemma

*Let $W \subset (\mathbb{C}^*)^n$ be an algebraic variety. Then $\tau_1^{\mathbb{R}}(W) \subseteq \operatorname{Trop}(W)$.*

Sketch of proof.

- Every irreducible component of $\tau_1^{\mathbb{R}}(W)$ is of the form $L \otimes_{\mathbb{Q}} \mathbb{R}$, for some linear subspace $L \subset \mathbb{Q}^n$.
- The complex torus $T := \exp(L \otimes_{\mathbb{Q}} \mathbb{C})$ lies inside $W$.
- Thus, $\operatorname{Trop}(T) = L \otimes_{\mathbb{Q}} \mathbb{R}$ lies inside $\operatorname{Trop}(W)$. □

## Proposition

- *$\tau_1^{\mathbb{R}}(\mathcal{V}^i(X)) \subseteq \operatorname{Trop}(\mathcal{V}^i(X))$, for all $i \le q$.*
- *If there is a subtorus $T \subset \operatorname{Char}^0(X)$ such that $T \not\subset \mathcal{V}^i(X)$, yet $\rho T \subset \mathcal{V}^i(X)$ for some $\rho \in \operatorname{Char}(X)$, then $\tau_1^{\mathbb{R}}(\mathcal{V}^i(X)) \subsetneq \operatorname{Trop}(\mathcal{V}^i(X))$.*

## A tropical bound for the $\Sigma$-invariants

THEOREM (PS-2010, S-2021)

*Let $\rho\colon \pi_1(X) \to \Bbbk^*$ be a character such that $\rho \in \mathcal{V}^{\leq q}(X, \Bbbk)$. Let $\upsilon\colon \Bbbk^* \to \mathbb{R}$ be the homomorphism defined by a valuation on $\Bbbk$, and write $\chi = \upsilon \circ \rho$. If the homomorphism $\chi\colon \pi_1(X) \to \mathbb{R}$ is non-zero, then $\chi \notin \Sigma^q(X, \mathbb{Z})$.*

Sketch of proof.

- Let $\hat{\Bbbk}$ be the topological completion of $\Bbbk$ with respect to the absolute value $|c| = \exp(-\upsilon(c))$. Get a field extension, $\iota\colon \Bbbk \hookrightarrow \hat{\Bbbk}$.
- Let $G = \pi_1(X)$. Extend $\rho\colon G \to \Bbbk^\times$ to a ring map, $\bar{\rho}\colon \mathbb{Z}G \to \Bbbk$.
- Since $\chi = \upsilon \circ \rho$, we can extend $\bar{\rho}$ to a morphism of topological rings, $\hat{\rho}\colon \widehat{\mathbb{Z}G}_{-\chi} \to \hat{\Bbbk}$, making $\hat{\Bbbk}$ into a $\widehat{\mathbb{Z}G}_{-\chi}$-module, denoted $\hat{\Bbbk}_{\hat{\rho}}$.
- Restricting scalars via the inclusion $\mathbb{Z}G \hookrightarrow \widehat{\mathbb{Z}G}_{-\chi}$ yields the $\mathbb{Z}G$-module $\hat{\Bbbk}_{\iota\circ\rho}$, defined by the character $\iota \circ \rho\colon G \to \hat{\Bbbk}^\times$.

- For a ring $R$, a bounded below chain complex of flat right $R$-modules $K_*$, and a left $R$-module $M$, there is a (right half-plane, boundedly converging) Künneth spectral sequence,

$$E^2_{ij} = \operatorname{Tors}^R_i(H_j(K), M) \Rightarrow H_{i+j}(K \otimes_R M)\,.$$

- Use ring $R = \widehat{\mathbb{Z}G}_{-\chi}$, chain complex of free $R$-modules $K_* = C_*(\widetilde{X}, \mathbb{Z}) \otimes_{\mathbb{Z}G} \widehat{\mathbb{Z}G}_{-\chi}$, and $R$-module $M = \hat{\Bbbk}_{\hat{\rho}}$.
- Now let $\rho \in \mathcal{V}^{\leq q}(X, \Bbbk)$, and suppose $\chi = \upsilon \circ \rho \in \Sigma^q(X, \mathbb{Z})$.
- This is equivalent to $H_j(X, \widehat{\mathbb{Z}G}_{-\chi}) = 0$ for all $j \leq q$; that is, $H_j(K) = 0$ for $j \leq q$. Therefore, $E^2_{ij} = 0$ for $j \leq q$.
- Hence, $H_{i+j}(X, \hat{\Bbbk}_{\iota\circ\rho}) = 0$ for $j \leq q$, and so $H_j(X, \hat{\Bbbk}_{\iota\circ\rho}) = 0$ for $j \leq q$.
- This is equivalent to $\iota \circ \rho \notin \mathcal{V}^{\leq q}(X, \hat{\Bbbk})$. Hence, $\rho \notin \mathcal{V}^{\leq q}(X, \Bbbk)$, contradicting our hypothesis on $\rho$.
- Therefore, $\chi \notin \Sigma^q(X, \mathbb{Z})$. $\square$

THEOREM (S-2021)

$$\Sigma^q(X,\mathbb{Z}) \subseteq S(\operatorname{Trop}(\mathcal{V}^{\leq q}(X)))^{\mathrm{c}}$$

Sketch of proof.

- Let $\rho\colon \pi_1(X) \to \mathbb{K}^\times$ and set $\chi = v \circ \rho\colon \pi_1(X) \to \mathbb{Q}$, a rational point on $H^1(X,\mathbb{R})$.
- Suppose $\rho \in \mathcal{V}^{\leq q}(X,\mathbb{K}) = \mathcal{V}^{\leq q}(X) \times_{\mathbb{C}} \mathbb{K}$.
- Then $\chi$ is a rational point on $\operatorname{Trop}(\mathcal{V}^{\leq q}(X)) = \overline{\nu_X(\mathcal{V}^{\leq q}(X,\mathbb{K}))}$.
- Conversely, all rational points on $\operatorname{Trop}(\mathcal{V}^{\leq q}(X))$ are of the form $\nu_X(\rho) = v \circ \rho$, for some $\rho \in \mathcal{V}^{\leq q}(X,\mathbb{K})$.
- Finally, assume that $\chi \neq 0$, so that $\chi$ represents an (arbitrary) rational point in $S(\operatorname{Trop}(\mathcal{V}^{\leq q}(X))$.
- By the previous theorem, $\chi \in \Sigma^q(X,\mathbb{Z})^{\mathrm{c}}$.
- But the rational points are dense in $S(\operatorname{Trop}(\mathcal{V}^{\leq q}(X)))$, and $\Sigma^q(X,\mathbb{Z})^{\mathrm{c}}$ is closed in $S(X)$, so we're done. □

## Corollary

$$\Sigma^q(X,\mathbb{Z}) \subseteq S(\operatorname{Trop}(\mathcal{V}^{\le q}(X)))^{\mathrm{c}} \subseteq S(\tau_1^{\mathbb{R}}(\mathcal{V}^{\le q}(X)))^{\mathrm{c}}.$$

$$\Sigma^1(G) \subseteq -S(\operatorname{Trop}(\mathcal{V}^1(G)))^{\mathrm{c}} \subseteq S(\tau_1^{\mathbb{R}}(\mathcal{V}^1(G)))^{\mathrm{c}}.$$

## Corollary

*If $\mathcal{V}^{\le q}(X)$ contains a component of $\operatorname{Char}(X)$, then $\Sigma^q(X,\mathbb{Z}) = \emptyset$.*

## Theorem

*Let $f_\alpha \colon G \to G_\alpha$ be a finite collection of epimorphisms. If each $\mathcal{V}^1(G_\alpha)$ contains a component of $\mathbb{T}_{G_\alpha}$, then*

$$\Sigma^1(G) \subseteq \Big(\bigcup_\alpha S(f_\alpha^*(H^1(G_\alpha,\mathbb{R})))\Big)^{\mathrm{c}}.$$

## The Alexander polynomial

- Let $H = G_{\text{ab}}/\operatorname{tors}(G_{\text{ab}})$ be the maximal torsion-free abelian quotient of $G = \pi_1(X)$ and $q\colon X^H \to X$ the respective cover.
- Set $A_X := H_1(X^H, q^{-1}(x_0), \mathbb{Z})$, viewed as a $\mathbb{Z}[H]$-module.
- Let $E_1(A_X) \subseteq \mathbb{Z}[H]$ be the ideal of codimension $1$ minors in a presentation for $A_X$.
- $\Delta_X := \gcd(E_1(A_X)) \in \mathbb{Z}[H]$ is the *Alexander polynomial* of $X$. It only depends on $G$, so also write it as $\Delta_G$.
- Suppose $I_H^p \cdot (\Delta_G) \subseteq E_1(A_G)$, for some $p \geq 0$. Then

$$\mathcal{V}^1(X) \cap \mathbb{T}_G^0 = \{1\} \cup V(\Delta_G).$$

- This condition is satisfied if $G$ is a $1$-relator group, or $G = \pi_1(M)$, where $M$ is a closed, orientable $3$-manifold with empty or toroidal boundary (C. McMullen, D. Eisenbud–W. Neumann).

- Let $\mathrm{Newt}(\Delta_G) \subset H_1(G,\mathbb{R})$ be the Newton polytope of $\Delta_G$.
- Given $\phi \in H^1(G;\mathbb{Z}) \cong \mathrm{Hom}(H,\mathbb{Z})$, its *Alexander norm*, $\|\phi\|_A$, is the length of $\phi(\mathrm{Newt}(\Delta_G))$.
- This defines a semi-norm on $H^1(G,\mathbb{R})$, with unit ball

$$B_A = \{\phi \in H^1(G;\mathbb{R}) \mid \|\phi\|_A \le 1\}.$$

- If $\Delta_G$ is symmetric (i.e., invariant under $t_i \mapsto t_i^{-1}$), then $B_A$ is, up to a scale factor of $1/2$, the polar dual of the Newton polytope of $\Delta_G$,

$$2B_A = \mathrm{Newt}(\Delta_G)^*.$$

PROPOSITION

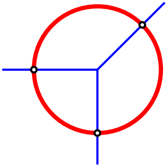
*If $\Delta_G$ is symmetric and $I_H^p \cdot (\Delta_G) \subseteq E_1(A_G)$, for some $p \ge 0$, then*

$$\Sigma^1(G) \subseteq \bigcup_{F \text{ an open facet of } B_A} S(F).$$

## Two-generator, one-relator groups

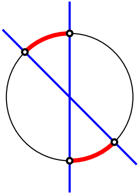
- Let $G = \langle x, y \mid r \rangle$, with $b_1(G) = 2$. K. Brown gave a combinatorial algorithm for computing $\Sigma^1(G)$.

### Example



- Let $G = \langle a, b \mid b^2(ab^{-1})^2 a^{-2} \rangle$.
- Then $\Sigma^1(G) = S^1 \setminus \{(\frac{1}{\sqrt{2}}, \frac{1}{\sqrt{2}}), (0, -1), (-1, 0)\}$.
- On the other hand, $\Delta_G = 1 + a + b$.
- Thus, $\Sigma^1(G) = -S(\mathrm{Trop}(V(\Delta_G)))^{\mathrm{c}}$, though $\tau_1 \mathcal{V}^1(G) = \{0\}$.

### Example



- Let $G = \langle a, b \mid a^2ba^{-1}ba^2ba^{-1}b^{-3}a^{-1}ba^2ba^{-1}ba$ $b^{-1}a^{-2}b^{-1}ab^{-1}a^{-2}b^{-1}ab^3ab^{-1}a^{-2}b^{-1}ab^{-1}a^{-1}b \rangle$.
- Then $\Delta_G = (a-1)(ab-1)$, and so $S(\mathrm{Trop}(V(\Delta_G)))$ consists of two pairs of points.
- Yet $\Sigma^1(G)$ consists of two open arcs joining those points.

## Compact 3-manifolds

- Let $M$ be a compact, connected, orientable 3-manifold with $b_1(M) > 0$.
- A non-zero class $\phi \in H^1(M;\mathbb{Z}) = \operatorname{Hom}(\pi_1(M),\mathbb{Z})$ is a *fibered* if there exists a fibration $p\colon M \to S^1$ such that the induced map $p_*\colon \pi_1(M) \to \pi_1(S^1) = \mathbb{Z}$ coincides with $\phi$.
- The *Thurston norm* $\|\phi\|_T$ of a class $\phi \in H^1(M;\mathbb{Z})$ is the infimum of $-\chi(\hat{S})$, where $S$ runs though all the properly embedded, oriented surfaces in $M$ dual to $\phi$, and $\hat{S}$ denotes the result of discarding all components of $S$ which are disks or spheres.
- Thurston showed that $\| - \|_T$ defines a seminorm on $H^1(M;\mathbb{Z})$, which can be extended to a continuous seminorm on $H^1(M;\mathbb{R})$.
- The unit norm ball, $B_T = \{\phi \in H^1(M;\mathbb{R}) \mid \|\phi\|_T \le 1\}$, is a rational polyhedron with finitely many sides and symmetric in the origin.

- There are facets of $B_T$, called the *fibered faces* (coming in antipodal pairs), so that a class $\phi \in H^1(M;\mathbb{Z})$ fibers if and only if it lies in the cone over the interior of a fibered face.
- Bieri, Neumann, and Strebel showed that the BNS invariant of $G = \pi_1(M)$ is the projection onto $S(G)$ of the open fibered faces of the Thurston norm ball $B_T$; in particular, $\Sigma^1(G) = -\Sigma^1(G)$.

PROPOSITION

*Let $M$ be a compact, connected, orientable, $3$-manifold with empty or toroidal boundary. Set $G = \pi_1(M)$ and assume $b_1(M) \geq 2$. Then*

1. $\operatorname{Trop}\left(\mathcal{V}^1(G) \cap \mathbb{T}^0_G\right)$ *is the positive-codimension skeleton of $\mathcal{F}(B_A)$, the face fan of the unit ball in the Alexander norm.*
2. $\Sigma^1(G)$ *is contained in the union of the open cones on the facets of $B_A$.*

Part (2) is inspired by, and partly recovers a theorem of C. McMullen.

## Kähler manifolds

- Let $M$ be a compact Kähler manifold. Then $M$ is formal.
- (Beauville, Catanese, Green–Lazarsfeld, Simpson, Arapura, B. Wang) $\mathcal{V}^i(M)$ are finite unions of torsion translates of algebraic subtori of $H^1(M, \mathbb{C}^*)$.

THEOREM (DELZANT 2010)

$$\Sigma^1(M) = S(M) \setminus \bigcup_\alpha S(f_\alpha^*(H^1(C_\alpha, \mathbb{R}))),$$

*where the union is taken over those orbifold fibrations* $f_\alpha \colon M \to C_\alpha$ *with the property that either* $\chi(C_\alpha) < 0$, *or* $\chi(C_\alpha) = 0$ *and* $f_\alpha$ *has some multiple fiber.*

In degree $1$, we may recast this result in the tropical setting, as follows.

COROLLARY

$$\Sigma^1(M) = S(\operatorname{Trop}(\mathcal{V}^1(M))^{\mathrm{c}}.$$

## Hyperplane arrangements

- Let $\mathcal{A} = \{H_1, \dots, H_n\}$ be an (essential, central) arrangement of hyperplanes in $\mathbb{C}^d$.
- Its complement, $M(\mathcal{A}) \subset (\mathbb{C}^*)^d$, is a smooth, quasi-projective Stein manifold; thus, it has the homotopy type of a finite, $d$-dimensional CW-complex.
- $H^*(M(\mathcal{A}), \mathbb{Z})$ is the Orlik–Solomon algebra of $L(\mathcal{A})$.
- (Arapura) The characteristic varieties $\mathcal{V}^i(\mathcal{A}) := \mathcal{V}^i(M(\mathcal{A})) \subset (\mathbb{C}^*)^n$. are unions of translated subtori.
- Consequently, $\operatorname{Trop}(\mathcal{V}^i(\mathcal{A})) = -\operatorname{Trop}(\mathcal{V}^i(\mathcal{A}))$.
- (DSY 2016/17) $M(\mathcal{A})$ is an “abelian duality space"; thus, its jump loci propagate: $\mathcal{V}^1(\mathcal{A}) \subseteq \mathcal{V}^2(\mathcal{A}) \subseteq \cdots \subseteq \mathcal{V}^{d-1}(\mathcal{A})$.
- (Arnol'd, Brieskorn) $M(\mathcal{A})$ is formal. Thus, $\tau_1(\mathcal{V}^i(\mathcal{A})) = \mathcal{R}^i(\mathcal{A})$.

### Theorem

*Let $M$ be the complement of an arrangement of $n$ hyperplanes in $\mathbb{C}^d$. Then, for each $1 \leq q \leq d-1$:*

- $\operatorname{Trop}(\mathcal{V}^q(M))$ *is the union of a subspace arrangement in* $\mathbb{R}^n$.
- $\Sigma^q(M, \mathbb{Z}) \subseteq S(\operatorname{Trop}(\mathcal{V}^q(M)))^{\mathrm{c}}$.

### Question (MFO Miniworkshop 2007)

Given an arrangement $\mathcal{A}$, do we have

$$\Sigma^1(M(\mathcal{A})) = S(\mathcal{R}^1(\mathcal{A}, \mathbb{R}))^{\mathrm{c}}? \qquad (\star)$$

## Example (Koban–McCammond–Meier 2013)

- Let $\mathcal{A}$ be the braid arrangement in $\mathbb{C}^n$, defined by $\prod_{1\leq i<j\leq n}(z_i - z_j) = 0$. Then $M(\mathcal{A}) = \operatorname{Conf}(n, \mathbb{C}) \simeq K(P_n, 1)$.
- Answer to ($\star$) is yes: $\Sigma^1(M(\mathcal{A}))$ is the complement of the union of $\binom{n}{3} + \binom{n}{4}$ planes in $\mathbb{C}^{\binom{n}{2}}$, intersected with the unit sphere.

## Example

- Let $\mathcal{A}$ be the "deleted $B_3$" arrangement, defined by $z_1 z_2(z_1^2 - z_2^2)(z_1^2 - z_2^2)(z_2^2 - z_3^2) = 0$.
- (S. 2002) $\mathcal{V}^1(\mathcal{A})$ contains a (1-dimensional) translated torus $\rho \cdot T$.
- Thus, $\operatorname{Trop}(\rho \cdot T) = \operatorname{Trop}(T)$ is a line in $\mathbb{C}^8$ which is *not* contained in $\mathcal{R}^1(\mathcal{A}, \mathbb{R})$. Hence, the answer to ($\star$) is no.

## Question (Revised)

$$\Sigma^1(M(\mathcal{A})) = S(\operatorname{Trop}(\mathcal{V}^1(\mathcal{A}))^{\mathrm{c}}? \qquad (\star\star)$$

# REFERENCE

Alexander I. Suciu, *Sigma-invariants and tropical varieties*, arXiv:2010.07499. To appear in Math. Annalen, doi:10.1007/s00208-021-02172-z.