

Cohomology jump loci, Σ -invariants, and fundamental groups of algebraic varieties

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Topology Seminar
University of Oxford
November 16, 2009

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Characteristic varieties

- X connected CW-complex with finite k -skeleton ($k \geq 1$)
- $G = \pi_1(X, x_0)$: a finitely generated group
- \mathbb{k} field; $\text{Hom}(G, \mathbb{k}^\times)$ character variety

Definition

The *characteristic varieties* of X (over \mathbb{k}):

$$\mathcal{V}_d^i(X, \mathbb{k}) = \{\rho \in \text{Hom}(G, \mathbb{k}^\times) \mid \dim_{\mathbb{k}} H_i(X, \mathbb{k}_\rho) \geq d\},$$

for $0 \leq i \leq k$ and $d > 0$.

- For each i , get stratification $\text{Hom}(G, \mathbb{k}^\times) \supseteq \mathcal{V}_1^i \supseteq \mathcal{V}_2^i \supseteq \dots$
- Note: $1 \in \mathcal{V}_1^i(X, \mathbb{k}) \iff H_i(X, \mathbb{k}) \neq 0$
- If $\mathbb{k} \subseteq \mathbb{K}$ extension: $\mathcal{V}_d^i(X, \mathbb{k}) = \mathcal{V}_d^i(X, \mathbb{K}) \cap \text{Hom}(G, \mathbb{k}^\times)$
- For G of type F_k , set: $\mathcal{V}_d^i(G, \mathbb{k}) := \mathcal{V}_d^i(K(G, 1), \mathbb{k})$
- Note: $\mathcal{V}_d(X, \mathbb{k}) := \mathcal{V}_d^1(X, \mathbb{k}) = \mathcal{V}_d^1(\pi_1(X), \mathbb{k})$

Example (Torus)

Identify $\pi_1(T^n) = \mathbb{Z}^n$, and $\text{Hom}(\mathbb{Z}^n, \mathbb{k}) = (\mathbb{k}^\times)^n$. Then:

$$\mathcal{V}_d^i(T^n, \mathbb{k}) = \begin{cases} \{1\} & \text{if } d \leq \binom{n}{i}, \\ \emptyset & \text{otherwise.} \end{cases}$$

Example (Wedge of circles)

Identify $\pi_1(\bigvee^n S^1) = F_n$, and $\text{Hom}(F_n, \mathbb{k}) = (\mathbb{k}^\times)^n$. Then:

$$\mathcal{V}_d^1(\bigvee^n S^1, \mathbb{k}) = \begin{cases} (\mathbb{k}^\times)^n & \text{if } d < n, \\ \{1\} & \text{if } d = n, \\ \emptyset & \text{if } d > n. \end{cases}$$

Example (Orientable surface of genus $g > 1$)

$$\mathcal{V}_d^1(\Sigma_g, \mathbb{k}) = \begin{cases} (\mathbb{k}^\times)^{2g} & \text{if } d < 2g - 1, \\ \{1\} & \text{if } d = 2g - 1, 2g, \\ \emptyset & \text{if } d > 2g. \end{cases}$$

Alexander polynomial

- $G = \pi_1(X, x_0)$
- $X^{\text{ab}} \xrightarrow{p} X$ maximal torsion-free abelian cover, defined by $G \xrightarrow{\text{ab}} H = H_1(G)/\text{tors} \cong \mathbb{Z}^n$
- $A_G = H_1(X^{\text{ab}}, p^{-1}(x_0); \mathbb{Z})$ Alex. module / $\mathbb{Z}H \cong \mathbb{Z}[t_1^{\pm 1}, \dots, t_n^{\pm 1}]$
- $\Delta_G = \text{gcd}(E_1(A_G))$

Proposition (Dimca–Papadima–S.)

$$\check{\mathcal{V}}_1(G) \setminus \{1\} = V(\Delta_G) \setminus \{1\},$$

where

- $\check{\mathcal{V}}_1(G) = \text{union of codim. 1 components of } \mathcal{V}_1(G, \mathbb{C}) \cap \text{Hom}(G, \mathbb{C})^0$
- $V(\Delta_G) = \text{hypersurface in } \text{Hom}(G, \mathbb{C})^0 \text{ defined by } \Delta_G.$

Example

Let K be a non-trivial knot, $G = \pi_1(S^3 \setminus K)$. Then:

$$\mathcal{V}_1(G) = \{z \in \mathbb{C} \mid \Delta_G(z) = 0\} \cup \{1\}.$$

Tangent cones and exponential tangent cones

The homomorphism $\mathbb{C} \rightarrow \mathbb{C}^\times$, $z \mapsto e^z$ induces

$$\exp: \text{Hom}(G, \mathbb{C}) \rightarrow \text{Hom}(G, \mathbb{C}^\times), \quad \exp(0) = 1$$

Let $W = V(I)$ be a Zariski closed subset in $\text{Hom}(G, \mathbb{C}^\times)$.

Definition

- The *tangent cone* at 1 to W :

$$TC_1(W) = V(\text{in}(I))$$

- The *exponential tangent cone* at 1 to W :

$$\tau_1(W) = \{z \in \text{Hom}(G, \mathbb{C}) \mid \exp(tz) \in W, \forall t \in \mathbb{C}\}$$

Both types of tangent cones

- are homogeneous subvarieties of $\text{Hom}(G, \mathbb{C})$
- are non-empty iff $1 \in W$
- depend only on the analytic germ of W at 1
- commute with finite unions and arbitrary intersections

Moreover,

- $\tau_1(W) \subseteq TC_1(W)$
 - ▶ = if all irred components of W are subtori
 - ▶ \neq in general
- $\tau_1(W)$ is a finite union of rationally defined subspaces

Bieri–Neumann–Strebel–Renz invariants

G finitely generated group $\rightsquigarrow \mathcal{C}(G)$ Cayley graph.

$\chi: G \rightarrow \mathbb{R}$ homomorphism $\rightsquigarrow \mathcal{C}_\chi(G)$ induced subgraph on vertex set

$$G_\chi = \{g \in G \mid \chi(g) \geq 0\}.$$

Definition

$$\Sigma^1(G) = \{\chi \in \text{Hom}(G, \mathbb{R}) \setminus \{0\} \mid \mathcal{C}_\chi(G) \text{ is connected}\}$$

An open, conical subset of $\text{Hom}(G, \mathbb{R}) = H^1(G, \mathbb{R})$, independent of choice of generating set for G .

Definition

$$\Sigma^k(G, \mathbb{Z}) = \{\chi \in \text{Hom}(G, \mathbb{R}) \setminus \{0\} \mid \text{the monoid } G_\chi \text{ is of type } \text{FP}_k\}$$

Here, G is of type FP_k if there is a projective $\mathbb{Z}G$ -resolution $P_\bullet \rightarrow \mathbb{Z}$, with P_i finitely generated for all $i \leq k$.

- The BNSR invariants $\Sigma^q(G, \mathbb{Z})$ form a descending chain of *open* subsets of $\text{Hom}(G, \mathbb{R}) \setminus \{0\}$.
- $\Sigma^k(G, \mathbb{Z}) \neq \emptyset \implies G$ is of type FP_k .
- $\Sigma^1(G, \mathbb{Z}) = \Sigma^1(G)$.
- The Σ -invariants control the finiteness properties of normal subgroups $N \triangleleft G$ with G/N is abelian:

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

where $S(G, N) = \{\chi \in \text{Hom}(G, \mathbb{R}) \setminus \{0\} \mid \chi(N) = 0\}$.

- In particular:

$$\ker(\chi: G \rightarrow \mathbb{Z}) \text{ is f.g.} \iff \{\pm\chi\} \subseteq \Sigma^1(G)$$

Let X be a connected CW-complex with finite 1-skeleton, $G = \pi_1(X)$.

Definition

The *Novikov-Sikorav completion* of $\mathbb{Z}G$:

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

$\widehat{\mathbb{Z}G}_\chi$ is a ring, contains $\mathbb{Z}G$ as a subring $\implies \widehat{\mathbb{Z}G}_\chi$ is a $\mathbb{Z}G$ -module.

Definition

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

Bieri: G of type $\text{FP}_k \implies \Sigma^q(G, \mathbb{Z}) = \Sigma^q(K(G, 1), \mathbb{Z}), \forall q \leq k$.

Exponential tangent cone upper bound

Theorem (Papadima–S.)

If X has finite k -skeleton, then, for every $q \leq k$,

$$\Sigma^q(X, \mathbb{Z}) \subseteq \left(\tau_1^{\mathbb{R}} \left(\bigcup_{i \leq q} \mathcal{V}_1^i(X, \mathbb{C}) \right) \right)^c. \quad (*)$$

Thus: Each Σ -invariant is contained in the complement of a union of rationally defined subspaces. Bound is sharp:

Example

Let G be a finitely generated nilpotent group. Then

$$\Sigma^q(G, \mathbb{Z}) = \text{Hom}(G, \mathbb{R}) \setminus \{0\}, \quad \mathcal{V}_1^q(G, \mathbb{C}) = \{1\}, \quad \forall q$$

and so (*) holds as an equality.

Resonance varieties

Let X be a connected CW-complex with finite k -skeleton ($k \geq 1$).

Let \mathbb{k} be a field; if $\text{char } \mathbb{k} = 2$, assume $H_1(X, \mathbb{Z})$ has no 2-torsion.

Let $A = H^*(X, \mathbb{k})$. Then: $a \in A^1 \Rightarrow a^2 = 0$. Thus, get cochain complex

$$(A, \cdot a): A^0 \xrightarrow{a} A^1 \xrightarrow{a} A^2 \longrightarrow \dots$$

Definition

The *resonance varieties* of X (over \mathbb{k}) are the algebraic sets

$$\mathcal{R}_d^i(X, \mathbb{k}) = \{a \in A^1 \mid \dim_{\mathbb{k}} H^i(A, a) \geq d\},$$

defined for all integers $0 \leq i \leq k$ and $d > 0$.

- \mathcal{R}_d^i are homogeneous subvarieties of $A^1 = H^1(X, \mathbb{k})$
- $\mathcal{R}_1^i \supseteq \mathcal{R}_2^i \supseteq \dots \supseteq \mathcal{R}_{b_i+1}^i = \emptyset$, where $b_i = b_i(X, \mathbb{k})$.
- $\mathcal{R}_d^1(X, \mathbb{k})$ depends only on $G = \pi_1(X)$, so denote it by $\mathcal{R}_d^1(G, \mathbb{k})$.
- Set $\mathcal{R}_d(X) = \mathcal{R}_d^1(X, \mathbb{C})$ and $\mathcal{R}_d(G) = \mathcal{R}_d^1(G, \mathbb{C})$.

Equivalent definition:

$$\mathcal{R}_d(X, \mathbb{k}) = \left\{ a \in H^1(X, \mathbb{k}) \mid \begin{array}{l} \exists \text{ subspace } W \subset H^1(X, \mathbb{k}) \text{ such that} \\ \dim W = d + 1 \text{ and } a \cup W = 0 \end{array} \right\}$$

In particular, a non-zero $a \in H^1(X, \mathbb{k})$ belongs to $\mathcal{R}_1(X, \mathbb{k})$ iff there is $b \in H^1(X, \mathbb{k})$ not proportional to a , such that $a \cup b = 0$ in $H^2(X, \mathbb{k})$.

Example

- $\mathcal{R}_1(T^n) = \{0\}$, for all $n > 0$.
- $\mathcal{R}_1(\bigvee^n S^1) = \mathbb{C}^n$, for all $n > 1$.
- $\mathcal{R}_1(\Sigma_g) = \mathbb{C}^{2g}$, for all $g > 1$.

Theorem (Libgober 2002)

$$TC_1(\mathcal{V}_d^i(X, \mathbb{C})) \subseteq \mathcal{R}_d^i(X, \mathbb{C})$$

Equality does not hold in general (Matei–S. 2002)

Formality

Definition

- 1 A group G is *1-formal* if its Malcev Lie algebra, $\mathfrak{m}_G = \text{Prim}(\widehat{\mathbb{Q}G})$, is quadratic.
 - 2 A space X is *formal* if its minimal model is quasi-isomorphic to $(H^*(X, \mathbb{Q}), 0)$.
- X formal $\implies \pi_1(X)$ is 1-formal.
 - X_1, X_2 formal $\implies X_1 \times X_2$ and $X_1 \vee X_2$ are formal
 - G_1, G_2 1-formal $\implies G_1 \times G_2$ and $G_1 * G_2$ are 1-formal
 - M_1, M_2 formal, closed n -manifolds $\implies M_1 \# M_2$ formal

Tangent cone theorem

Theorem (Dimca–Papadima–S.)

If G is 1-formal, then $\exp: (\mathcal{R}_d^1(G, \mathbb{C}), 0) \xrightarrow{\cong} (\mathcal{V}_d^1(G, \mathbb{C}), 1)$. Hence

$$\tau_1(\mathcal{V}_d^1(G, \mathbb{C})) = TC_1(\mathcal{V}_d^1(G, \mathbb{C})) = \mathcal{R}_d^1(G, \mathbb{C})$$

In particular, $\mathcal{R}_d^1(G, \mathbb{C})$ is a union of rationally defined subspaces in $H^1(G, \mathbb{C}) = \text{Hom}(G, \mathbb{C})$.

Example

Let $G = \langle x_1, x_2, x_3, x_4 \mid [x_1, x_2], [x_1, x_4][x_2^{-2}, x_3], [x_1^{-1}, x_3][x_2, x_4] \rangle$. Then

$$\mathcal{R}_1^1(G, \mathbb{C}) = \{x \in \mathbb{C}^4 \mid x_1^2 - 2x_2^2 = 0\}$$

splits into subspaces over \mathbb{R} but not over \mathbb{Q} . Thus, G is *not* 1-formal.

Example

- $X = F(\Sigma_g, n)$: the configuration space of n labeled points of a Riemann surface of genus g (a smooth, quasi-projective variety).
- $\pi_1(X) = P_{g,n}$: the pure braid group on n strings on Σ_g .

Using computation of $H^*(F(\Sigma_g, n), \mathbb{C})$ by Totaro (1996), get

$$\mathcal{R}_1^1(P_{1,n}, \mathbb{C}) = \left\{ (x, y) \in \mathbb{C}^n \times \mathbb{C}^n \mid \begin{array}{l} \sum_{i=1}^n x_i = \sum_{i=1}^n y_i = 0, \\ x_i y_j - x_j y_i = 0, \text{ for } 1 \leq i < j < n \end{array} \right\}$$

For $n \geq 3$, this is an irreducible, non-linear variety (a rational normal scroll). Hence, $P_{1,n}$ is not 1-formal.

Resonance upper bound

Corollary

Suppose $\exp: (\mathcal{R}_1^i(X, \mathbb{C}), 0) \xrightarrow{\cong} (\mathcal{V}_1^i(X, \mathbb{C}), 1)$, for $i \leq q$. Then:

$$\Sigma^q(X, \mathbb{Z}) \subseteq \left(\bigcup_{i \leq q} \mathcal{R}_1^i(X, \mathbb{R}) \right)^c.$$

Corollary

Suppose G is a 1-formal group. Then $\Sigma^1(G) \subseteq \mathcal{R}_1^1(G, \mathbb{R})^c$.
 In particular, if $\mathcal{R}_1^1(G, \mathbb{R}) = H^1(G, \mathbb{R})$, then $\Sigma^1(G) = \emptyset$.

Example

The above inclusion may be strict: Let $G = \langle a, b \mid aba^{-1} = b^2 \rangle$.
 Then G is 1-formal, $\Sigma^1(G) = (-\infty, 0)$, yet $\mathcal{R}_1^1(G, \mathbb{R}) = \{0\}$.

Kähler and quasi-Kähler manifolds

- A compact, connected, complex manifold M is *Kähler* if there is a Hermitian metric h such that $\omega = \Im(h)$ is a closed 2-form.
- A manifold X is called *quasi-Kähler* if $X = \bar{X} \setminus D$, where \bar{X} is Kähler and D is a divisor with normal crossings.

Formality properties:

- M Kähler $\Rightarrow M$ is formal
(Deligne, Griffiths, Morgan, Sullivan 1975)
- $X = \mathbb{C}P^n \setminus \{\text{hyperplane arrangement}\} \Rightarrow X$ is formal
(Brieskorn 1973)
- X quasi-projective, $W_1(H^1(X, \mathbb{C})) = 0 \Rightarrow \pi_1(X)$ is 1-formal
(Morgan 1978)
- $X = \mathbb{C}P^n \setminus \{\text{hypersurface}\} \Rightarrow \pi_1(X)$ is 1-formal
(Kohno 1983)

Characteristic varieties of quasi-Kähler manifolds

Theorem (Arapura 1997)

Let $X = \bar{X} \setminus D$ be a quasi-Kähler manifold with $X = \bar{X}$ or $b_1(\bar{X}) = 0$. Then each component of $\mathcal{V}_d^i(X)$ is either an isolated unitary character, or of the form

$$\rho \cdot f^*(H^1(C, \mathbb{C}^\times))$$

for some unitary character ρ and some admissible map $f: X \rightarrow C$.

Here, $f: X \rightarrow C$ is *admissible* (or, a *pencil*) if f is a holomorphic, surjective map to a connected, smooth complex curve C , and there is a holomorphic, surjective extension $\bar{f}: \bar{X} \rightarrow \bar{C}$ with connected fibers.

Alexander polynomials of quasi-Kähler groups

Definition

A finitely-presented group G is called a (*quasi-*) Kähler group if there a (quasi-) Kähler manifold X with $G = \pi_1(X)$.

Theorem (Dimca–Papadima–S.)

Let G be a quasi-Kähler group. Set $n = b_1(G)$, and let Δ_G be the Alexander polynomial of G .

- If $n \neq 2$, then the Newton polytope of Δ_G is a line segment.
- If G is actually a Kähler group, then $\Delta_G \doteq \text{const}$.

If $n \geq 3$, we may write $\Delta_G(t_1, \dots, t_n) \doteq cP(t_1^{e_1} \cdots t_n^{e_n})$, for some $c \in \mathbb{Z}$, some polynomial $P \in \mathbb{Z}[t]$ equal to a product of cyclotomic polynomials, and some exponents $e_i \geq 1$ with $\gcd(e_1, \dots, e_n) = 1$.

Resonance varieties of quasi-Kähler manifolds

Theorem (Dimca–Papadima–S.)

Let X be a quasi-Kähler manifold, and $G = \pi_1(X)$. Let $\{L_\alpha\}_\alpha$ be the non-zero irred components of $\mathcal{R}_1(G)$. If G is 1-formal, then

- 1 Each L_α is a linear subspace of $H^1(G, \mathbb{C})$.
- 2 Each L_α is p -isotropic (i.e., restriction of \cup_G to L_α has rank p), with $\dim L_\alpha \geq 2p + 2$, for some $p = p(\alpha) \in \{0, 1\}$.
- 3 If $\alpha \neq \beta$, then $L_\alpha \cap L_\beta = \{0\}$.
- 4 $\mathcal{R}_d(G) = \{0\} \cup \bigcup_{\alpha: \dim L_\alpha > d + p(\alpha)} L_\alpha$.

Furthermore,

- 4 If X is compact, then G is 1-formal, and each L_α is 1-isotropic.
- 5 If $W_1(H^1(X, \mathbb{C})) = 0$, then G is 1-formal, and each L_α is 0-isotropic.

Σ -invariants

Let X be a quasi-Kähler manifold, $G = \pi_1(X)$.

Theorem (Papadima–S.)

- 1 $\Sigma^1(G) \subseteq TC_1^{\mathbb{R}}(\mathcal{V}_1^1(G, \mathbb{C}))^c$.
- 2 *If X is Kähler, or $W_1(H^1(X, \mathbb{C})) = 0$, then $\mathcal{R}_1^1(G, \mathbb{R})$ is a finite union of rationally defined linear subspaces, and $\Sigma^1(G) \subseteq \mathcal{R}_1^1(G, \mathbb{R})^c$.*

Example

Assumption from (2) is necessary. E.g., let X be the complex Heisenberg manifold: bundle $\mathbb{C}^\times \rightarrow X \rightarrow (\mathbb{C}^\times)^2$ with $e = 1$. Then:

- 1 X is a smooth quasi-projective variety;
- 2 $G = \pi_1(X)$ is nilpotent (and not 1-formal);
- 3 $\Sigma^1(G) = \mathbb{R}^2 \setminus \{0\}$ and $\mathcal{R}_1^1(G, \mathbb{R}) = \mathbb{R}^2$.

Thus, $\Sigma^1(G) \not\subseteq \mathcal{R}_1^1(G, \mathbb{R})^c$.

For Kähler manifolds, we can say precisely when the resonance upper bound for Σ^1 is attained.

Theorem (Papadima–S.)

Let M be a compact Kähler manifold with $b_1(M) > 0$, and $G = \pi_1(M)$. The following are equivalent:

- 1 $\Sigma^1(G) = \mathcal{R}_1^1(G, \mathbb{R})^c$.
- 2 *If $f: M \rightarrow C$ is an elliptic pencil, then f has no multiple fibers.*

Proof uses results of Arapura, DPS, and Delzant.

Toric complexes and right-angled Artin groups

- L simplicial complex on n vertices \rightsquigarrow *toric complex* T_L
(subcomplex of T^n obtained by deleting the cells corresponding to the missing simplices of L).
- $\pi_1(T_L)$ is the *right-angled Artin group* associated to graph $\Gamma = L^{(1)}$:

$$G_\Gamma = \langle v \in V(\Gamma) \mid vw = wv \text{ if } \{v, w\} \in E(\Gamma) \rangle.$$

- $K(G_\Gamma, 1) = T_{\Delta_\Gamma}$, where Δ_Γ is the *flag complex* of Γ .
- $H^*(T_L, \mathbb{k})$ is the *exterior Stanley-Reisner ring* of L , with generators the duals v^* , and relations the monomials corresponding to the missing simplices of L .
- T_L is formal, and so G_Γ is 1-formal.

Example

- $\Gamma = \overline{K}_n \Rightarrow G_\Gamma = F_n$
- $\Gamma = K_n \Rightarrow G_\Gamma = \mathbb{Z}^n$
- $\Gamma = \Gamma' \amalg \Gamma'' \Rightarrow G_\Gamma = G_{\Gamma'} * G_{\Gamma''}$
- $\Gamma = \Gamma' * \Gamma'' \Rightarrow G_\Gamma = G_{\Gamma'} \times G_{\Gamma''}$

Identify $A^1 = \mathbb{k}^V$ — the \mathbb{k} -vector space with basis $\{v \mid v \in V\}$.

Theorem (Papadima–S.)

$$\mathcal{R}_d^i(T_L, \mathbb{k}) = \bigcup_{\substack{W \subseteq V \\ \sum_{\sigma \in L_{V \setminus W}} \dim_{\mathbb{k}} \tilde{H}_{i-1-|\sigma|}(\mathrm{lk}_{L_W}(\sigma), \mathbb{k}) \geq d}} \mathbb{k}^W,$$

where L_W is the subcomplex induced by L on W , and $\mathrm{lk}_K(\sigma)$ is the link of a simplex σ in a subcomplex $K \subseteq L$.

In particular:

$$\mathcal{R}_1(G_\Gamma, \mathbb{k}) = \bigcup_{\substack{W \subseteq V \\ \Gamma_W \text{ disconnected}}} \mathbb{k}^W.$$

Similar formula holds for $\mathcal{V}_d^i(T_L, \mathbb{k})$, with \mathbb{k}^W replaced by $(\mathbb{k}^\times)^W$. Hence:

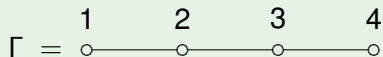
$$\exp: (\mathcal{R}_d^i(T_L, \mathbb{C}), 0) \xrightarrow{\cong} (\mathcal{V}_d^i(T_L, \mathbb{C}), 1).$$

Using (1) resonance upper bound, and (2) computation of $\Sigma^k(G_\Gamma, \mathbb{Z})$ by Meier, Meinert, VanWyk (1998), we get:

Corollary (Papadima-S.)

$$\begin{aligned} \Sigma^k(T_L, \mathbb{Z}) &\subseteq \left(\bigcup_{i \leq k} \mathcal{R}_1^i(T_L, \mathbb{R}) \right)^{\mathfrak{C}} \\ \Sigma^k(G_\Gamma, \mathbb{Z}) &= \left(\bigcup_{i \leq k} \mathcal{R}_1^i(T_{\Delta_\Gamma}, \mathbb{R}) \right)^{\mathfrak{C}} \end{aligned}$$

Example



Maximal disconnected subgraphs: $\Gamma_{\{134\}}$ and $\Gamma_{\{124\}}$. Thus:

$$\mathcal{R}_1(G_\Gamma, \mathbb{C}) = \mathbb{C}^{\{134\}} \cup \mathbb{C}^{\{124\}}.$$

Note that: $\mathbb{C}^{\{134\}} \cap \mathbb{C}^{\{124\}} = \mathbb{C}^{\{14\}} \neq \{0\}$

Since G_Γ is 1-formal $\Rightarrow G_\Gamma$ is not a quasi-Kähler group.

Theorem (Dimca–Papadima–S.)

The following are equivalent:

- | | |
|---|--------------------------------|
| ① G_Γ is a quasi-Kähler group | ① G_Γ is a Kähler group |
| ② $\Gamma = K_{n_1, \dots, n_r} := \bar{K}_{n_1} * \dots * \bar{K}_{n_r}$ | ② $\Gamma = K_{2r}$ |
| ③ $G_\Gamma = F_{n_1} \times \dots \times F_{n_r}$ | ③ $G_\Gamma = \mathbb{Z}^{2r}$ |

Bestvina–Brady groups

$N_\Gamma = \ker(\nu: G_\Gamma \rightarrow \mathbb{Z})$, where $\nu(v) = 1$, for all $v \in V(\Gamma)$.

Theorem (Dimca–Papadima–S.)

The following are equivalent:

- | | |
|---|--------------------------------|
| ① N_Γ is a quasi-Kähler group | ① N_Γ is a Kähler group |
| ② Γ is either a tree, or $\Gamma = K_{n_1, \dots, n_r}$, with some $n_i = 1$, or all $n_i \geq 2$ and $r \geq 3$. | ② $\Gamma = K_{2r+1}$ |
| | ③ $N_\Gamma = \mathbb{Z}^{2r}$ |

Example (answers a question of J. Kollár)

$\Gamma = K_{2,2,2} \rightsquigarrow G_\Gamma = F_2 \times F_2 \times F_2 \rightsquigarrow N_\Gamma =$ the Stallings group

N_Γ is finitely presented, but $\text{rank } H_3(N_\Gamma, \mathbb{Z}) = \infty$, so N_Γ not FP_3 .

Also, $N_\Gamma = \pi_1(\mathbb{C}^2 \setminus \{\text{an arrangement of 5 lines}\})$.

Thus, N_Γ is a quasi-projective group which is not commensurable (even up to finite kernels) to any group π having a finite $K(\pi, 1)$.

3-manifolds

Question (Donaldson–Goldman 1989, Reznikov 1993)

Which 3-manifold groups are Kähler groups?

Reznikov (2002) and Hernández-Lamóneda (2001) gave partial solutions.

Theorem (Dimca–S.)

Let G be the fundamental group of a closed 3-manifold. Then G is a Kähler group $\iff G$ is a finite subgroup of $O(4)$, acting freely on S^3 .

Idea of proof: compare the resonance varieties of (orientable) 3-manifolds to those of Kähler manifolds.

Proposition

Let M be a closed, orientable 3-manifold. Then:

- ① $H^1(M, \mathbb{C})$ is not 1-isotropic.
- ② If $b_1(M)$ is even, then $\mathcal{R}_1(M, \mathbb{C}) = H^1(M, \mathbb{C})$.

On the other hand, it follows from [Dimca–Papadima–S.] that:

Proposition

Let M be a compact Kähler manifold with $b_1(M) \neq 0$. If $\mathcal{R}_1(M, \mathbb{C}) = H^1(M, \mathbb{C})$, then $H^1(M, \mathbb{C})$ is 1-isotropic.

But $G = \pi_1(M)$, with M Kähler $\Rightarrow b_1(G)$ even.

Thus, if G is both a 3-mfd group and a Kähler group $\Rightarrow b_1(G) = 0$.

Using work of Fujiwara (1999) and Reznikov (2002) on Kazhdan's property (T), as well as Perelman (2003) $\Rightarrow G$ finite subgroup of $O(4)$.

Question

Which 3-manifold groups are quasi-Kähler groups?

Theorem (Dimca–Papadima–S.)

Let G be the fundamental group of a closed, orientable 3-manifold. Assume G is 1-formal. Then the following are equivalent:

- 1 $\mathfrak{m}(G) \cong \mathfrak{m}(\pi_1(X))$, for some quasi-Kähler manifold X .
- 2 $\mathfrak{m}(G) \cong \mathfrak{m}(\pi_1(M))$, where M is either S^3 , $\#^n S^1 \times S^2$, or $S^1 \times \Sigma_g$.

Boundary manifolds of line arrangements

Let $\mathcal{A} = \{\ell_0, \dots, \ell_n\}$ be an arrangement of lines in $\mathbb{C}\mathbb{P}^2$. The *boundary manifold* of \mathcal{A} is the closed, orientable 3-manifold $M = M(\mathcal{A})$ obtained by taking the boundary of a regular neighborhood of $\bigcup_{i=0}^n \ell_i$ in $\mathbb{C}\mathbb{P}^2$.

Theorem (Cohen–S., Dimca–Papadima–S.)

Let $\mathcal{A} = \{\ell_0, \dots, \ell_n\}$ be an arrangement of lines in $\mathbb{C}\mathbb{P}^2$, and let M be the corresponding boundary manifold. The following are equivalent:

- 1 The manifold M is formal.
- 2 The group $G = \pi_1(M)$ is 1-formal.
- 3 $TC_1(V_1(G, \mathbb{C})) = \mathcal{R}_1(G, \mathbb{C})$.
- 4 The group G is quasi-projective.
- 5 \mathcal{A} is either a pencil (and so $M = \sharp^n S^1 \times S^2$), or \mathcal{A} is a near-pencil (and so $M = S^1 \times \Sigma_{n-1}$).

BNS invariant and Thurston norm

Let M be a compact, connected 3-manifold, with $G = \pi_1(M)$.

Theorem (Bieri–Neumann–Strebel 1987)

- $\Sigma^1(G) = \bigcup_F \text{fibered face of Thurston norm unit ball}$ $\mathbb{R}_+ \cdot \overset{\circ}{F}$.
- $\Sigma^1(G) = -\Sigma^1(G)$.
- M fibers over $S^1 \iff \Sigma^1(G) \neq \emptyset$.

Using (1) upper bound $\Sigma^1(G) \subseteq \mathcal{R}_1(G, \mathbb{R})^{\circ}$ for 1-formal groups, and (2) description of $R_1(M^3, \mathbb{C})$ from above, we get:

Corollary (Papadima–S.)

Let M be a closed, orientable 3-manifold. If $b_1(M)$ is even, and $G = \pi_1(M)$ is 1-formal, then M does not fiber over the circle.

Formality and algebraic monodromy

Let M be a closed, orientable 3-manifold which fibers over the circle, with fiber F , and monodromy $h: F \rightarrow F$.

Combining the previous result with some further work on the “equivariant spectral sequence”, we get:

Theorem (Papadima–S.)

Suppose $G = \pi_1(M)$ is 1-formal. Then, for the eigenvalue $\lambda = 1$ of the monodromy operator $h_: H_1(F, \mathbb{C}) \rightarrow H_1(F, \mathbb{C})$, we have:*

- *The number of 1×1 Jordan blocks is even.*
- *There are no higher size Jordan blocks.*

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