

# Width, Ricci Curvature, and Bisecting Surfaces

Parker Glynn-Adey

University of Toronto

`parker.glynn.adey@utoronto.ca`

`www.pgadey.ca`

June 15, 2016

# Outline

## ① Ricci Curvature and Width

# Outline

① Ricci Curvature and Width

② Bisecting Surfaces

# Outline

- ① Ricci Curvature and Width
- ② Bisecting Surfaces
- ③ Sponges

## Acknowledgements

- Alex Nabutovsky, Regina Rotman, and Robert Young
- Yevgeney Liokumovich and Zhifei Zhu
- Alfonso Gracia-Saz and Raymond Grinnell
- Almut Burchard and Kasra Rafi
- Stefan Bilaniuk, Marcus Pivato, David Poole, and Reem Yassawi.
- The Entire Tenth Floor of Huron
- Megan Shaw
- KC and Lesley Wynne
- Kathleen Schmidt-Hertzberg, Norman Taylor, Raja Rajagopal, and John Karsemeyer
- Sam Chapin, Derek Krickhan, and Nick Saika

## $(n - 1)$ -Width

Let  $(M^n, g)$  be a compact Riemannian manifold.

## $(n - 1)$ -Width

Let  $(M^n, g)$  be a compact Riemannian manifold.

Metrize the space of Lipschitz  $(n - 1)$ -cycles in  $M$ .

## $(n - 1)$ -Width

Let  $(M^n, g)$  be a compact Riemannian manifold.  
Metrize the space of Lipschitz  $(n - 1)$ -cycles in  $M$ .

### Definition

A continuous loop

$$z : S^1 \rightarrow \mathcal{Z}_{n-1}(M, \mathbb{Z}/2\mathbb{Z})$$



## $(n - 1)$ -Width

Let  $(M^n, g)$  be a compact Riemannian manifold.  
Metrize the space of Lipschitz  $(n - 1)$ -cycles in  $M$ .

### Definition

A continuous loop

$$z : S^1 \rightarrow \mathcal{Z}_{n-1}(M, \mathbb{Z}/2\mathbb{Z})$$

of  $(n - 1)$ -cycles *sweeps out*  $M$  if  $z$  assembles to  $[M]$

## $(n - 1)$ -Width

Let  $(M^n, g)$  be a compact Riemannian manifold.  
Metrize the space of Lipschitz  $(n - 1)$ -cycles in  $M$ .

### Definition

A continuous loop

$$z : S^1 \rightarrow \mathcal{Z}_{n-1}(M, \mathbb{Z}/2\mathbb{Z})$$

of  $(n - 1)$ -cycles *sweeps out*  $M$  if  $z$  assembles to  $[M]$   
under Almgren's isomorphism:

## $(n - 1)$ -Width

Let  $(M^n, g)$  be a compact Riemannian manifold.  
Metrize the space of Lipschitz  $(n - 1)$ -cycles in  $M$ .

### Definition

A continuous loop

$$z : S^1 \rightarrow \mathcal{Z}_{n-1}(M, \mathbb{Z}/2\mathbb{Z})$$

of  $(n - 1)$ -cycles *sweeps out*  $M$  if  $z$  assembles to  $[M]$   
under Almgren's isomorphism:  $\pi_1(\mathcal{Z}_{n-1}(M)) \simeq H_n(M)$ .

## $(n - 1)$ -Width

Let  $(M^n, g)$  be a compact Riemannian manifold.  
Metrize the space of Lipschitz  $(n - 1)$ -cycles in  $M$ .

### Definition

A continuous loop

$$z : S^1 \rightarrow \mathcal{Z}_{n-1}(M, \mathbb{Z}/2\mathbb{Z})$$

of  $(n - 1)$ -cycles *sweeps out*  $M$  if  $z$  assembles to  $[M]$   
under Almgren's isomorphism:  $\pi_1(\mathcal{Z}_{n-1}(M)) \simeq H_n(M)$ .

### Definition

The *width* of  $(M, g)$  is

## $(n - 1)$ -Width

Let  $(M^n, g)$  be a compact Riemannian manifold.  
Metrize the space of Lipschitz  $(n - 1)$ -cycles in  $M$ .

### Definition

A continuous loop

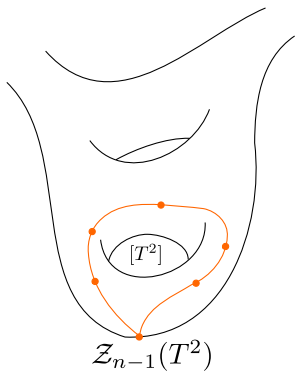
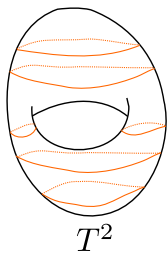
$$z : S^1 \rightarrow \mathcal{Z}_{n-1}(M, \mathbb{Z}/2\mathbb{Z})$$

of  $(n - 1)$ -cycles *sweeps out*  $M$  if  $z$  assembles to  $[M]$   
under Almgren's isomorphism:  $\pi_1(\mathcal{Z}_{n-1}(M)) \simeq H_n(M)$ .

### Definition

The *width* of  $(M, g)$  is

$$W(M) = \inf_z \left( \sup_p [\text{vol}_{n-1}(z_p)] \right)$$



# The $(n - 1)$ -Width-Volume Inequality

Theorem (Guth 2007)

*There are universal constants  $C(n)$  such that:*

# The $(n - 1)$ -Width-Volume Inequality

Theorem (Guth 2007)

*There are universal constants  $C(n)$  such that:  
Every open bounded subset  $U \subset \mathbb{R}^n$  satisfies*



# The $(n - 1)$ -Width-Volume Inequality

Theorem (Guth 2007)

*There are universal constants  $C(n)$  such that:  
Every open bounded subset  $U \subset \mathbb{R}^n$  satisfies*

$$W(U) \leq C(n) \operatorname{vol}_n(U)^{\frac{n-1}{n}}$$

# The $(n - 1)$ -Width-Volume Inequality

## Theorem (Guth 2007)

*There are universal constants  $C(n)$  such that:  
Every open bounded subset  $U \subset \mathbb{R}^n$  satisfies*

$$W(U) \leq C(n) \text{vol}_n(U)^{\frac{n-1}{n}}$$

## Theorem (Burago & Ivanov 1995)

*The 3-torus admits a metrics  $T_k = (T^3, g_k)$  with:*

# The $(n - 1)$ -Width-Volume Inequality

## Theorem (Guth 2007)

*There are universal constants  $C(n)$  such that:  
Every open bounded subset  $U \subset \mathbb{R}^n$  satisfies*

$$W(U) \leq C(n) \text{vol}_n(U)^{\frac{n-1}{n}}$$

## Theorem (Burago & Ivanov 1995)

*The 3-torus admits a metrics  $T_k = (T^3, g_k)$  with:*

$$\text{vol}(T_k) = 1$$

# The $(n - 1)$ -Width-Volume Inequality

## Theorem (Guth 2007)

*There are universal constants  $C(n)$  such that:  
Every open bounded subset  $U \subset \mathbb{R}^n$  satisfies*

$$W(U) \leq C(n) \text{vol}_n(U)^{\frac{n-1}{n}}$$

## Theorem (Burago & Ivanov 1995)

*The 3-torus admits a metrics  $T_k = (T^3, g_k)$  with:*

$$\text{vol}(T_k) = 1 \text{ and } W(T_k) > k$$

# The $(n - 1)$ -Width-Volume Inequality

## Theorem (Guth 2007)

*There are universal constants  $C(n)$  such that:  
Every open bounded subset  $U \subset \mathbb{R}^n$  satisfies*

$$W(U) \leq C(n) \text{vol}_n(U)^{\frac{n-1}{n}}$$

## Theorem (Burago & Ivanov 1995)

*The 3-torus admits a metrics  $T_k = (T^3, g_k)$  with:*

$$\text{vol}(T_k) = 1 \text{ and } W(T_k) > k$$

*(The Width-Volume Inequality doesn't hold for general manifolds.)*

## Definition (Hassannezhad 2011)

Let  $M^n$  be a compact Riemannian  $n$ -manifold.

## Definition (Hassannezhad 2011)

Let  $M^n$  be a compact Riemannian  $n$ -manifold.

$$\text{MCV}(M, g) = \inf_{\varphi} \{ \text{vol}_n(M, \varphi g) : \text{Ricci}(M, \varphi g) \geq -(n-1) \}$$

## Definition (Hassannezhad 2011)

Let  $M^n$  be a compact Riemannian  $n$ -manifold.

$$\text{MCV}(M, g) = \inf_{\varphi} \{ \text{vol}_n(M, \varphi g) : \text{Ricci}(M, \varphi g) \geq -(n-1) \}$$

is the **minimal conformal volume** of  $M$ .



## Definition (Hassannezhad 2011)

Let  $M^n$  be a compact Riemannian  $n$ -manifold.

$$\text{MCV}(M, g) = \inf_{\varphi} \{ \text{vol}_n(M, \varphi g) : \text{Ricci}(M, \varphi g) \geq -(n-1) \}$$

is the **minimal conformal volume** of  $M$ .

## Theorem (G-A & Liokumovich)

## Definition (Hassannezhad 2011)

Let  $M^n$  be a compact Riemannian  $n$ -manifold.

$$\text{MCV}(M, g) = \inf_{\varphi} \{ \text{vol}_n(M, \varphi g) : \text{Ricci}(M, \varphi g) \geq -(n-1) \}$$

is the **minimal conformal volume** of  $M$ .

## Theorem (G-A & Liokumovich)

$$W(M) \leq C(n) \max\{1, \text{MCV}(M)^{\frac{1}{n}}\} \text{vol}_n(M)^{\frac{n-1}{n}}$$

## Definition (Hassannezhad 2011)

Let  $M^n$  be a compact Riemannian  $n$ -manifold.

$$\text{MCV}(M, g) = \inf_{\varphi} \{ \text{vol}_n(M, \varphi g) : \text{Ricci}(M, \varphi g) \geq -(n-1) \}$$

is the **minimal conformal volume** of  $M$ .

## Theorem (G-A & Liokumovich)

$$W(M) \leq C(n) \max\{1, \text{MCV}(M)^{\frac{1}{n}}\} \text{vol}_n(M)^{\frac{n-1}{n}}$$

## Corollary (G-A & L)

*If  $(M^n, g)$  is conformally non-negatively Ricci curved then:*

## Definition (Hassannezhad 2011)

Let  $M^n$  be a compact Riemannian  $n$ -manifold.

$$\text{MCV}(M, g) = \inf_{\varphi} \{ \text{vol}_n(M, \varphi g) : \text{Ricci}(M, \varphi g) \geq -(n-1) \}$$

is the **minimal conformal volume** of  $M$ .

## Theorem (G-A & Liokumovich)

$$W(M) \leq C(n) \max\{1, \text{MCV}(M)^{\frac{1}{n}}\} \text{vol}_n(M)^{\frac{n-1}{n}}$$

## Corollary (G-A & L)

*If  $(M^n, g)$  is conformally non-negatively Ricci curved then:*

$$W(M) \leq C(n) \text{vol}_n(M)^{\frac{n-1}{n}}$$

## Definition (Hassannezhad 2011)

Let  $M^n$  be a compact Riemannian  $n$ -manifold.

$$\text{MCV}(M, g) = \inf_{\varphi} \{ \text{vol}_n(M, \varphi g) : \text{Ricci}(M, \varphi g) \geq -(n-1) \}$$

is the **minimal conformal volume** of  $M$ .

## Theorem (G-A & Liokumovich)

$$W(M) \leq C(n) \max\{1, \text{MCV}(M)^{\frac{1}{n}}\} \text{vol}_n(M)^{\frac{n-1}{n}}$$

## Corollary (G-A & L)

*If  $(M^n, g)$  is conformally non-negatively Ricci curved then:*

$$W(M) \leq C(n) \text{vol}_n(M)^{\frac{n-1}{n}}$$

(The Width-Volume Inequality holds for *these* manifolds.)

## MCV and Surfaces

Consider  $M = \Sigma_n$  an oriented Riemannian surface of genus  $n$ .

## MCV and Surfaces

Consider  $M = \Sigma_n$  an oriented Riemannian surface of genus  $n$ .

When the genus  $n < 2$  we obtain:  $\text{MCV}(\Sigma_n) = 0$ .

## MCV and Surfaces

Consider  $M = \Sigma_n$  an oriented Riemannian surface of genus  $n$ .

When the genus  $n < 2$  we obtain:  $\text{MCV}(\Sigma_n) = 0$ .

When  $n \geq 2$ :



## MCV and Surfaces

Consider  $M = \Sigma_n$  an oriented Riemannian surface of genus  $n$ .

When the genus  $n < 2$  we obtain:  $\text{MCV}(\Sigma_n) = 0$ .

When  $n \geq 2$ : By Gauss-Bonnet

$$\text{area}(\Sigma_n, g) \geq 4\pi(n - 1)$$

## MCV and Surfaces

Consider  $M = \Sigma_n$  an oriented Riemannian surface of genus  $n$ .

When the genus  $n < 2$  we obtain:  $\text{MCV}(\Sigma_n) = 0$ .

When  $n \geq 2$ : By Gauss-Bonnet

$$\text{area}(\Sigma_n, g) \geq 4\pi(n - 1)$$

Apply hyperbolic uniformization to obtain  $(\Sigma_n, \varphi g)$ .

## MCV and Surfaces

Consider  $M = \Sigma_n$  an oriented Riemannian surface of genus  $n$ .

When the genus  $n < 2$  we obtain:  $\text{MCV}(\Sigma_n) = 0$ .

When  $n \geq 2$ : By Gauss-Bonnet

$$\text{area}(\Sigma_n, g) \geq 4\pi(n - 1)$$

Apply hyperbolic uniformization to obtain  $(\Sigma_n, \varphi g)$ .

Thus,  $\text{MCV}(\Sigma_n) = 4\pi(n - 1)$ .

## MCV and Surfaces

Consider  $M = \Sigma_n$  an oriented Riemannian surface of genus  $n$ .

When the genus  $n < 2$  we obtain:  $\text{MCV}(\Sigma_n) = 0$ .

When  $n \geq 2$ : By Gauss-Bonnet

$$\text{area}(\Sigma_n, g) \geq 4\pi(n - 1)$$

Apply hyperbolic uniformization to obtain  $(\Sigma_n, \varphi g)$ .

Thus,  $\text{MCV}(\Sigma_n) = 4\pi(n - 1)$ .

### Theorem (G-A & L)

$W(\Sigma_n) \leq 220\sqrt{(n - 1) \text{area}(\Sigma_n)}$  for any closed oriented surface.

## MCV and Surfaces

Consider  $M = \Sigma_n$  an oriented Riemannian surface of genus  $n$ .

When the genus  $n < 2$  we obtain:  $\text{MCV}(\Sigma_n) = 0$ .

When  $n \geq 2$ : By Gauss-Bonnet

$$\text{area}(\Sigma_n, g) \geq 4\pi(n - 1)$$

Apply hyperbolic uniformization to obtain  $(\Sigma_n, \varphi g)$ .

Thus,  $\text{MCV}(\Sigma_n) = 4\pi(n - 1)$ .

**Theorem (G-A & L)**

$W(\Sigma_n) \leq 220\sqrt{(n - 1)\text{area}(\Sigma_n)}$  for any closed oriented surface.

(Balacheff & Sabourau 2010 for oriented  $\Sigma_n$  with an improved constant.)

# Sketch of the Sweep-Out Construction

## Sketch of the Sweep-Out Construction

- Use an isoperimetric inequality to subdivide  $M$  into parts.

## Sketch of the Sweep-Out Construction

- Use an isoperimetric inequality to subdivide  $M$  into parts.
- Iterate the subdivision process until all parts are small volume.



## Sketch of the Sweep-Out Construction

- Use an isoperimetric inequality to subdivide  $M$  into parts.
- Iterate the subdivision process until all parts are small volume.
- Estimate width of small parts by the area of their boundaries.

## Sketch of the Sweep-Out Construction

- Use an isoperimetric inequality to subdivide  $M$  into parts.
- Iterate the subdivision process until all parts are small volume.
- Estimate width of small parts by the area of their boundaries.
- Assemble the sweep outs of parts to global sweep out.

## Sketch of the Sweep-Out Construction

- Use an isoperimetric inequality to subdivide  $M$  into parts.
- Iterate the subdivision process until all parts are small volume.
- Estimate width of small parts by the area of their boundaries.
- Assemble the sweep outs of parts to global sweep out.

We needed:

## Sketch of the Sweep-Out Construction

- Use an isoperimetric inequality to subdivide  $M$  into parts.
- Iterate the subdivision process until all parts are small volume.
- Estimate width of small parts by the area of their boundaries.
- Assemble the sweep outs of parts to global sweep out.

We needed:

- Control over the isoperimetric constant.

## Sketch of the Sweep-Out Construction

- Use an isoperimetric inequality to subdivide  $M$  into parts.
- Iterate the subdivision process until all parts are small volume.
- Estimate width of small parts by the area of their boundaries.
- Assemble the sweep outs of parts to global sweep out.

We needed:

- Control over the isoperimetric constant.
- An estimate of multiplicities of covers by balls

# Sketch of the Sweep-Out Construction

- Use an isoperimetric inequality to subdivide  $M$  into parts.
- Iterate the subdivision process until all parts are small volume.
- Estimate width of small parts by the area of their boundaries.
- Assemble the sweep outs of parts to global sweep out.

We needed:

- Control over the isoperimetric constant.
- An estimate of multiplicities of covers by balls

of small volume and boundary area.

# Subdivision Area and Homological Filling

# Subdivision Area and Homological Filling

## Definition



# Subdivision Area and Homological Filling

## Definition

Let  $M$  be a Riemannian 3-sphere with volume  $V$ .

# Subdivision Area and Homological Filling

## Definition

Let  $M$  be a Riemannian 3-sphere with volume  $V$ .

An embedded surface  $\Sigma \subset M$  is  $\eta$ -subdividing if:

# Subdivision Area and Homological Filling

## Definition

Let  $M$  be a Riemannian 3-sphere with volume  $V$ .

An embedded surface  $\Sigma \subset M$  is  $\eta$ -subdividing if:

$$M \setminus \Sigma = X_1 \sqcup X_2 \text{ and } \text{vol}(X_i) > \eta V \text{ for } i = 1, 2$$

# Subdivision Area and Homological Filling

## Definition

Let  $M$  be a Riemannian 3-sphere with volume  $V$ .

An embedded surface  $\Sigma \subset M$  is  $\eta$ -subdividing if:

$$M \setminus \Sigma = X_1 \sqcup X_2 \text{ and } \text{vol}(X_i) > \eta V \text{ for } i = 1, 2$$

We define the **subdivision area of  $M$**  to be:

# Subdivision Area and Homological Filling

## Definition

Let  $M$  be a Riemannian 3-sphere with volume  $V$ .

An embedded surface  $\Sigma \subset M$  is  $\eta$ -subdividing if:

$$M \setminus \Sigma = X_1 \sqcup X_2 \text{ and } \text{vol}(X_i) > \eta V \text{ for } i = 1, 2$$

We define the **subdivision area of  $M$**  to be:

$$SA_\epsilon(M) = \inf \left\{ \text{area}(\Sigma) : \Sigma \text{ is } \left( \frac{1}{4} - \epsilon \right)\text{-subdividing} \right\}$$

# Subdivision Area and Homological Filling

## Definition

Let  $M$  be a Riemannian 3-sphere with volume  $V$ .

An embedded surface  $\Sigma \subset M$  is  $\eta$ -subdividing if:

$$M \setminus \Sigma = X_1 \sqcup X_2 \text{ and } \text{vol}(X_i) > \eta V \text{ for } i = 1, 2$$

We define the **subdivision area of  $M$**  to be:

$$SA_\epsilon(M) = \inf \left\{ \text{area}(\Sigma) : \Sigma \text{ is } \left( \frac{1}{4} - \epsilon \right)\text{-subdividing} \right\}$$

## Definition

$$\text{HF}_1(\ell) = \sup_{\text{length}(z) \leq \ell} \left( \inf_{\partial c = z} \text{area}(c) \right)$$

# Subdivision Area and Homological Filling

## Definition

Let  $M$  be a Riemannian 3-sphere with volume  $V$ .

An embedded surface  $\Sigma \subset M$  is  $\eta$ -subdividing if:

$$M \setminus \Sigma = X_1 \sqcup X_2 \text{ and } \text{vol}(X_i) > \eta V \text{ for } i = 1, 2$$

We define the subdivision area of  $M$  to be:

$$SA_\epsilon(M) = \inf \left\{ \text{area}(\Sigma) : \Sigma \text{ is } \left( \frac{1}{4} - \epsilon \right)\text{-subdividing} \right\}$$

## Definition

$$\text{HF}_1(\ell) = \sup_{\text{length}(z) \leq \ell} \left( \inf_{\partial c = z} \text{area}(c) \right)$$

is the first homological filling function of  $M$ .

# Subdivision Area and Homological Filling

## Definition

Let  $M$  be a Riemannian 3-sphere with volume  $V$ .

An embedded surface  $\Sigma \subset M$  is  $\eta$ -subdividing if:

$$M \setminus \Sigma = X_1 \sqcup X_2 \text{ and } \text{vol}(X_i) > \eta V \text{ for } i = 1, 2$$

We define the subdivision area of  $M$  to be:

$$SA_\epsilon(M) = \inf \left\{ \text{area}(\Sigma) : \Sigma \text{ is } \left( \frac{1}{4} - \epsilon \right)\text{-subdividing} \right\}$$

## Definition

$$\text{HF}_1(\ell) = \sup_{\text{length}(z) \leq \ell} \left( \inf_{\partial c = z} \text{area}(c) \right)$$

is the first homological filling function of  $M$ .



# Geometric Bisection

Theorem (G-A & Zhu)

*For any Riemannian 3-sphere*

# Geometric Bisection

Theorem (G-A & Zhu)

*For any Riemannian 3-sphere*

$$SA(M) \leq 3 HF_1(2d)$$

# Geometric Bisection

Theorem (G-A & Zhu)

*For any Riemannian 3-sphere*

$$SA(M) \leq 3 HF_1(2d)$$

*where  $d$  is the diameter of  $M$ .*

# Geometric Bisection

Theorem (G-A & Zhu)

*For any Riemannian 3-sphere*

$$SA(M) \leq 3 HF_1(2d)$$

*where  $d$  is the diameter of  $M$ .*

Theorem (Papasoglu & Swenson 2016)

# Geometric Bisection

## Theorem (G-A & Zhu)

*For any Riemannian 3-sphere*

$$SA(M) \leq 3 HF_1(2d)$$

*where  $d$  is the diameter of  $M$ .*

## Theorem (Papasoglu & Swenson 2016)

*There exist Riemannian 3-spheres  $M_k = (S^3, g_k)$  such that:*

# Geometric Bisection

## Theorem (G-A & Zhu)

*For any Riemannian 3-sphere*

$$SA(M) \leq 3 HF_1(2d)$$

*where  $d$  is the diameter of  $M$ .*

## Theorem (Papasoglu & Swenson 2016)

*There exist Riemannian 3-spheres  $M_k = (S^3, g_k)$  such that:*

$$\text{vol}_3(M_k) = 1,$$

# Geometric Bisection

## Theorem (G-A & Zhu)

*For any Riemannian 3-sphere*

$$SA(M) \leq 3 \text{HF}_1(2d)$$

*where  $d$  is the diameter of  $M$ .*

## Theorem (Papasoglu & Swenson 2016)

*There exist Riemannian 3-spheres  $M_k = (S^3, g_k)$  such that:*

$$\text{vol}_3(M_k) = 1, \text{diam}(M_k) = 1,$$

# Geometric Bisection

## Theorem (G-A & Zhu)

*For any Riemannian 3-sphere*

$$SA(M) \leq 3 HF_1(2d)$$

*where  $d$  is the diameter of  $M$ .*

## Theorem (Papasoglu & Swenson 2016)

*There exist Riemannian 3-spheres  $M_k = (S^3, g_k)$  such that:*

$$\text{vol}_3(M_k) = 1, \text{diam}(M_k) = 1, \text{ and } SA(M_k) > k.$$



# Sketch for Bisecting Surfaces

## Sketch for Bisecting Surfaces

- Suppose there are no such bisecting surfaces.

## Sketch for Bisecting Surfaces

- Suppose there are no such bisecting surfaces.
- Small volume fillings  $M \setminus \Sigma$  for lots of  $\Sigma \subset M$

## Sketch for Bisecting Surfaces

- Suppose there are no such bisecting surfaces.
- Small volume fillings  $M \setminus \Sigma$  for lots of  $\Sigma \subset M$
- Construct a chain map from a contractible complex to  $C_*(M)$ .

## Sketch for Bisecting Surfaces

- Suppose there are no such bisecting surfaces.
- Small volume fillings  $M \setminus \Sigma$  for lots of  $\Sigma \subset M$
- Construct a chain map from a contractible complex to  $C_*(M)$ .
- Obtain a contradiction to  $H_3(M) \neq 0$ .

## Sketch for Bisecting Surfaces

- Suppose there are no such bisecting surfaces.
- Small volume fillings  $M \setminus \Sigma$  for lots of  $\Sigma \subset M$
- Construct a chain map from a contractible complex to  $C_*(M)$ .
- Obtain a contradiction to  $H_3(M) \neq 0$ .
- Desingularize the cycle to obtain a surface.

# Planar Sponges

Question (Guth 2007)

*Are there universal constants  $\epsilon(n)$  such that:*

# Planar Sponges

## Question (Guth 2007)

*Are there universal constants  $\epsilon(n)$  such that:*

*Every open bounded subset  $U \subset \mathbb{R}^n$  with  $\text{vol}_n(U) < \epsilon(n)$*



# Planar Sponges

## Question (Guth 2007)

*Are there universal constants  $\epsilon(n)$  such that:*

*Every open bounded subset  $U \subset \mathbb{R}^n$  with  $\text{vol}_n(U) < \epsilon(n)$  admits an expanding embedding  $U \xrightarrow{\text{e.e.}} B^n(1)$ ?*

# Planar Sponges

## Question (Guth 2007)

*Are there universal constants  $\epsilon(n)$  such that:*

*Every open bounded subset  $U \subset \mathbb{R}^n$  with  $\text{vol}_n(U) < \epsilon(n)$  admits an expanding embedding  $U \xrightarrow{\text{e.e.}} B^n(1)$ ?*

*(This would imply the W-V Inequality in  $\mathbb{R}^n$ .)*

# Planar Sponges

## Question (Guth 2007)

*Are there universal constants  $\epsilon(n)$  such that:*

*Every open bounded subset  $U \subset \mathbb{R}^n$  with  $\text{vol}_n(U) < \epsilon(n)$  admits an expanding embedding  $U \xrightarrow{\text{e.e.}} B^n(1)$ ?*

*(This would imply the W-V Inequality in  $\mathbb{R}^n$ .)*

## Theorem (G-A)

*If  $U$  is an open bounded Jordan measurable set in the plane and*

# Planar Sponges

## Question (Guth 2007)

*Are there universal constants  $\epsilon(n)$  such that:*

*Every open bounded subset  $U \subset \mathbb{R}^n$  with  $\text{vol}_n(U) < \epsilon(n)$  admits an expanding embedding  $U \xrightarrow{e.e.} B^n(1)$ ?*

*(This would imply the W-V Inequality in  $\mathbb{R}^n$ .)*

## Theorem (G-A)

*If  $U$  is an open bounded Jordan measurable set in the plane and  $\text{area}(U) < 1/10$  then*

# Planar Sponges

## Question (Guth 2007)

Are there universal constants  $\epsilon(n)$  such that:

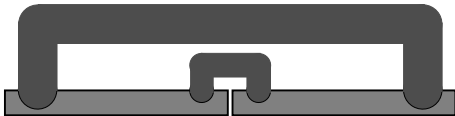
Every open bounded subset  $U \subset \mathbb{R}^n$  with  $\text{vol}_n(U) < \epsilon(n)$  admits an expanding embedding  $U \xrightarrow{\text{e.e.}} B^n(1)$ ?

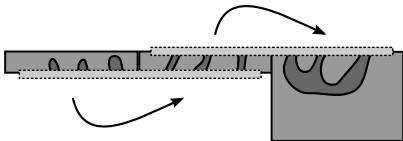
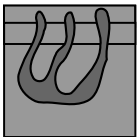
(This would imply the W-V Inequality in  $\mathbb{R}^n$ .)

## Theorem (G-A)

If  $U$  is an open bounded Jordan measurable set in the plane and  $\text{area}(U) < 1/10$  then

$$U \xrightarrow{\text{e.e.}} \mathbb{R} \times [0, 1]$$









Questions? Comments?

# Questions? Comments?

parker.glynn.adey@utoronto.ca

# Questions? Comments?

`parker.glynn.adey@utoronto.ca`

`www.pgadey.ca`