Uniqueness of Weak Solutions to the Ricci Flow and Topological Applications

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(joint work with Bruce Kleiner, NYU)

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Online class on Ricci flow this fall semester
(August 27 – December 3)

- **UCB students:** Math 277
- **other students:** email me (`rbamler@berkeley.edu`) or check my webpage (`https://math.berkeley.edu/~rbamler`) for further details

Structure of Talk

- Part I: Topological Results
- Part II: Ricci flow, Weak solutions, Uniqueness,
  Continuous dependence
- Part III: Applications to Topology

Part I: Topological Results

Basic definitions

M (mostly) 3-dimensional, compact, orientable manifold

Recall: The topology of 3-manifolds is sufficiently well understood due to the resolution of the Poincaré and Geometrization Conjectures by Perelman, using Ricci flow.

Main objects of study:

- $\mathrm{Met}(M)$: space of Riemannian metrics on M
- $\mathrm{Met}_{PSC}(M) \subset \mathrm{Met}(M)$: subset of metrics with positive scalar curvature
- $\mathrm{Diff}(M)$: space of diffeomorphisms $\phi : M \to M$

. . . each equipped with the C^∞-topology.

Goal: Classify these spaces up to homotopy (using Ricci flow)!

$\mathrm{Met}(M)$ is contractible

Space of PSC-metrics

Main Result 1:

Ba., Kleiner 2019

$\mathrm{Met}_{PSC}(M)$ is either contractible or empty.

History:

- true in dimension 2 (via Uniformization Theorem or Ricci flow (see later))
- Hitchin 1974; Gromov, Lawson 1984; Botvinnik, Hanke, Schick, Walsh 2010: Further examples with $\pi_i(\mathrm{Met}_{PSC}(M^n)) \neq 1$ for certain (large) i, n.
- Marques 2011 (using Ricci flow with surgery):
  $\mathrm{Met}_{PSC}(M^3)/\,\mathrm{Diff}(M^3)$ is path-connected,
  $\mathrm{Met}_{PSC}(S^3)$ is path-connected

Diffeomorphism groups

Smale 1958: $O(3) \simeq \mathrm{Diff}(S^2)$

Smale Conjecture: $O(4) \simeq \mathrm{Diff}(S^3)$
proven by Hatcher in 1983

For a general spherical space form $M = S^3/\Gamma$ consider the injection

$$\mathrm{Isom}(M) \longrightarrow \mathrm{Diff}(M)$$

Generalized Smale Conjecture

This map is a homotopy equivalence.

- Verified for a handful of other spherical space forms, but open e.g. for $\mathbb{R}P^3$.
- All proofs so far are purely topological and technical. No uniform treatment.

Main Result 2:

Theorem (Ba., Kleiner 2019)

The Generalized Smale Conjecture is true.

Remarks:

- Proof via Ricci flow (first purely topological application of Ricci flow since Perelman's work ~ 15 years ago).
- Uniform treatment of all cases.
- Alternative proof in the S^3-case (Smale Conjecture).
- There are two proofs:
    - "Short" proof (Ba., Kleiner 2017): GSC if $M \not\approx S^3, \mathbb{R}P^3$, M hyperbolic
    - Long proof (Ba., Kleiner 2019): full GSC and $S^2 \times \mathbb{R}$-cases

Similar techniques imply results in non-spherical case:

- If M is closed and hyperbolic, then $\mathrm{Isom}(M) \simeq \mathrm{Diff}(M)$.
  (topological proof by Gabai 2001)
- If (M, g) is aspherical and geometric and g has maximal symmetry, then $\mathrm{Isom}(M) \simeq \mathrm{Diff}(M)$.
  (new in non-Haken infranil case)
- $\mathrm{Diff}(S^2 \times S^1) \simeq O(2) \times O(3) \times \Omega O(3)$
  (topological proof by Hatcher)
- $\mathrm{Diff}(\mathbb{R}P^3 \# \mathbb{R}P^3) \simeq O(1) \times O(3)$
  (topological proof by Hatcher)

Connection to Ricci flow

Lemma

For any $g \in \mathrm{Met}_{K\equiv\pm1}(M)$:

$$\mathrm{Isom}(M,g) \simeq \mathrm{Diff}(M) \qquad \Longleftrightarrow \qquad \mathrm{Met}_{K\equiv\pm1}(M) \;\text{ contractible}$$

Proof: Fiber bundle

$$\begin{aligned} \mathrm{Isom}(M,g) \longrightarrow \mathrm{Diff}(M) &\longrightarrow \mathrm{Met}_{K\equiv\pm1}(M) \\ \phi &\longmapsto \phi^* g \end{aligned}$$

Apply long exact homotopy sequence.

This reduces both results to:

Theorem (Ba., Kleiner 2019)

$\mathrm{Met}_{PSC}(M)$ and $\mathrm{Met}_{K\equiv1}(M)$ are each either contractible or empty.

Part II: Ricci flow, Weak solutions, Uniqueness, Continuous dependence

Ricci flow

Ricci flow: $(M, g(t))$, $t \in [0, T)$

$$\partial_t g(t) = -2\,\mathrm{Ric}_{g(t)}, \qquad g(0) = g_0 \qquad (*)$$

Short-time existence (Hamilton):

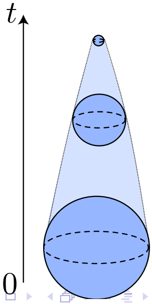
- For every initial condition g_0 the initial value problem $(*)$ has a unique solution for maximal $T \in (0, \infty]$.
- If $T < \infty$, then "singularity at time T". Curvature $|\mathrm{Rm}|$ blows up as $t \nearrow T$.

Example: Round shrinking sphere

$M = S^n$

$T = \frac{1}{2(n-1)}$

$g(t) = 2(n-1)(T-t)g_{S^n}$.

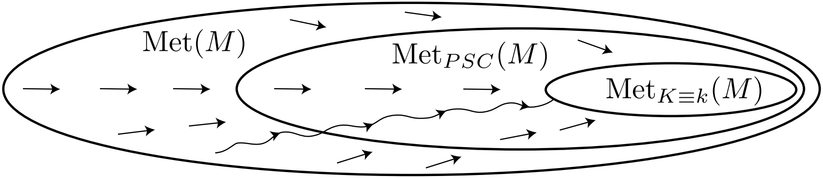


Ricci flow in 2D

Hamilton, Chow: On $M = S^2$ for any initial condition g_0 we have

$$T = \frac{\mathrm{vol}(S^2, g_0)}{8\pi}, \qquad (T-t)^{-1} g(t) \longrightarrow g_{\mathrm{round}}$$

Interpretation on the space of metrics:



- Preservation of positive scalar curvature (in all dimensions)
- $\rightsquigarrow$ deformation retractions from $\mathrm{Met}(S^2)$ and $\mathrm{Met}_{PSC}(S^2)$ onto $\mathrm{Met}_{K\equiv 1}(S^2)$

Theorem

$\mathrm{Met}_{PSC}(S^2) \simeq \mathrm{Met}_{K\equiv 1}(S^2) \simeq \mathrm{Met}(S^2) \simeq *$
Therefore $\mathrm{Diff}(S^2) \simeq O(3)$.

Ricci flow in 3D

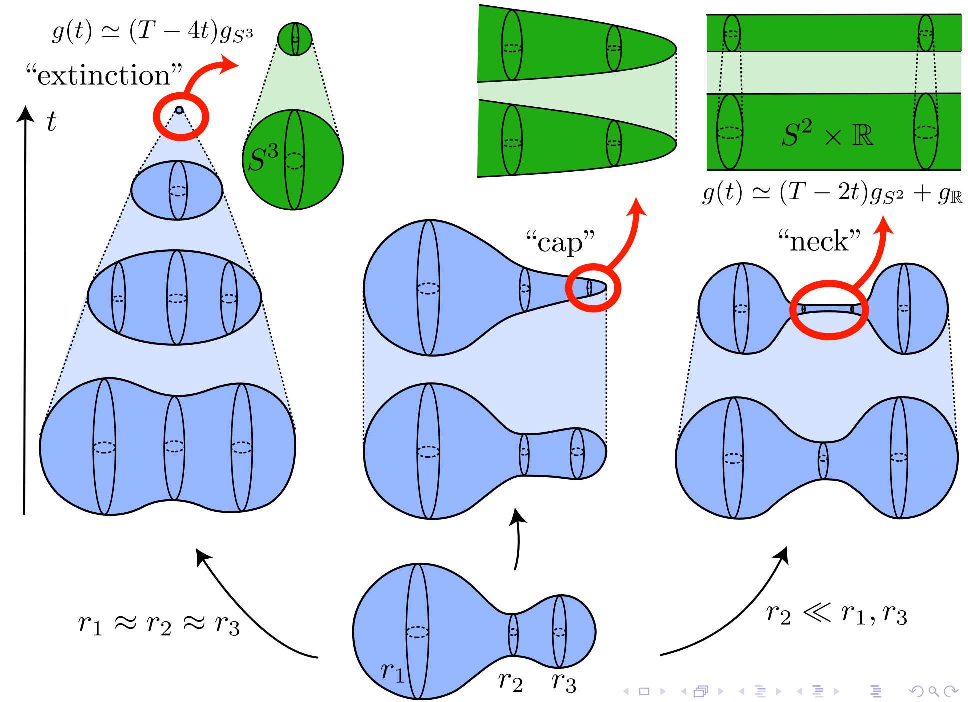
Difficulties:

- Flow may incur non-round and non-global singularities.
- Necessary to extend the flow past the first singular time (surgeries).
- Continuous dependence on initial data?

Results:

- Perelman: Qualitative classification of singularity models (κ-solutions)
- Brendle 2018 / Ba., Kleiner 2019: Further classification / rotational symmetry of κ-solutions

Example: rotationally symmetric dumbbell


$g(t) \simeq (T-4t) g_{S^3}$
"extinction"
t
S^3
$S^2 \times \mathbb{R}$
$g(t) \simeq (T-2t) g_{S^2} + g_{\mathbb{R}}$
"cap"
"neck"
$r_1 \approx r_2 \approx r_3$
$r_2 \ll r_1, r_3$
r_1
r_2
r_3

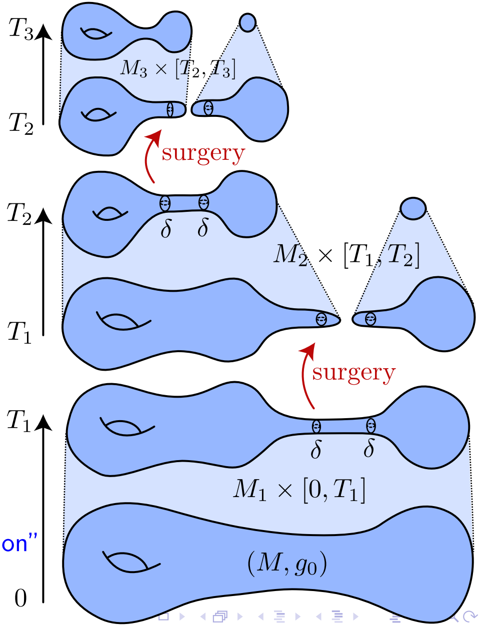
Ricci flow with surgery

Given (M, g_0) construct
Ricci flow with surgery:

$$(M_1, g_1(t)), t \in [0, T_1],$$

$$(M_2, g_2(t)), t \in [T_1, T_2],$$

$$(M_3, g_3(t)), t \in [T_2, T_3], \quad \ldots$$



Observations:

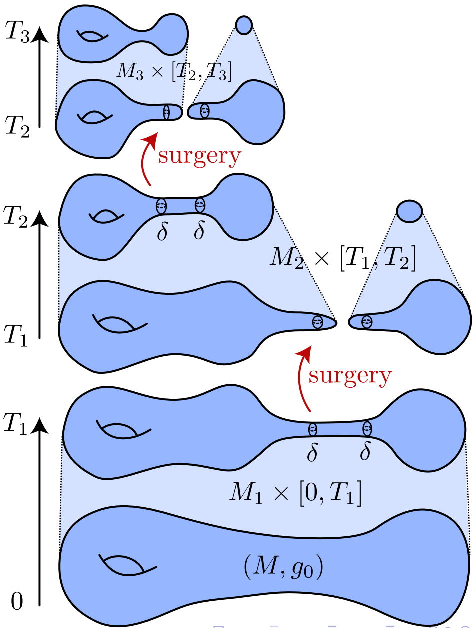
- surgery scale $\approx \delta \ll 1$
- high curvature regions are ε-close to singularity models from before: "ε-canonical neighborhood assumption"

RF with surgery was used to prove Poincaré & Geometrization Conjectures

Drawback:
surgery process is not canonical (depends on surgery parameters)

Perelman:

- *It is likely that [. . .] one would get a canonically defined Ricci flow through singularities, but at the moment I don't have a proof of that.*
- *Our approach [. . .] is aimed at eventually constructing a canonical Ricci flow, [. . .] - a goal, that has not been achieved yet in the present work.*



Theorem (Ba., Kleiner, Lott)

Perelman's "conjecture" is true:

- There is a notion of a weak Ricci flow "through singularities" and we have existence and uniqueness within this class.
- This weak flow is a limit of Ricci flows with surgery, where surgery scale $\delta \to 0$.

Comparison with Mean Curvature Flow:

- Notions of weak flows: Level Set Flow, Brakke Flow
- General case: fattening $\cong$ non-uniqueness
- Mean convex case: non-fattening $\cong$ uniqueness
- 2-convex case: uniqueness + weak flow is limit of MCF with surgery as surgery scale $\delta \to 0$

How to take limits of sequences of Ricci flows with surgery?

RF with surgery

- Consider the spacetimes

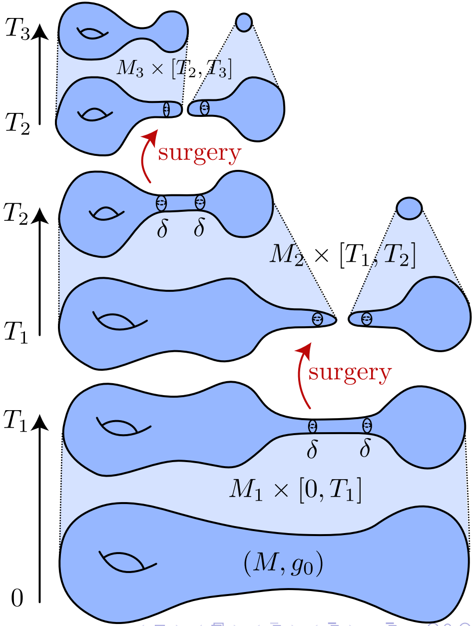
$$M_1 \times [0, T_1], \quad M_2 \times [T_1, T_2], \quad \ldots$$

- Identify:

$$M_1 \times \{T_1\} \setminus \{\text{surgery points}\} \leftrightarrow M_2 \times \{T_1\} \setminus \{\text{surgery points}\},$$

$$M_2 \times \{T_2\} \setminus \{\text{surgery points}\} \leftrightarrow M_3 \times \{T_2\} \setminus \{\text{surgery points}\},$$

$\ldots$



Spacetime picture

Spacetime 4-manifold:

$$\mathcal{M}^4 = \big(M_1 \times [0, T_1] \;\cup\; M_2 \times [T_1, T_2] \;\cup\; M_3 \times [T_2, T_3] \;\cup\; \ldots \big) - \text{surgery points}$$

Time function: $\mathfrak{t} : \mathcal{M} \to [0, \infty)$

Time-slices: $\mathcal{M}_t = \mathfrak{t}^{-1}(t)$

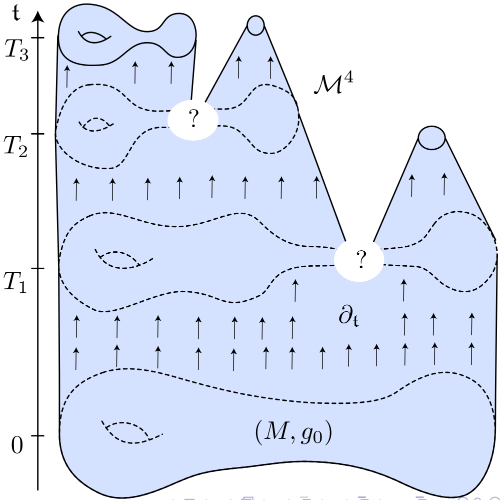
Time vector field:
$\partial_{\mathfrak{t}}$ on $\mathcal{M}$ (with $\partial_{\mathfrak{t}} \cdot \mathfrak{t} = 1$)

Metric g: on the distribution $\ker d\mathfrak{t} \subset T\mathcal{M}$

Ricci flow equation:
$\mathcal{L}_{\partial_{\mathfrak{t}}} g = -2 \operatorname{Ric}_g$

$\mathcal{M} = (\mathcal{M}, \mathfrak{t}, \partial_{\mathfrak{t}}, g)$ is called a Ricci flow spacetime.

Note: there are "holes" at scale $\approx \delta$
space-time is δ-complete



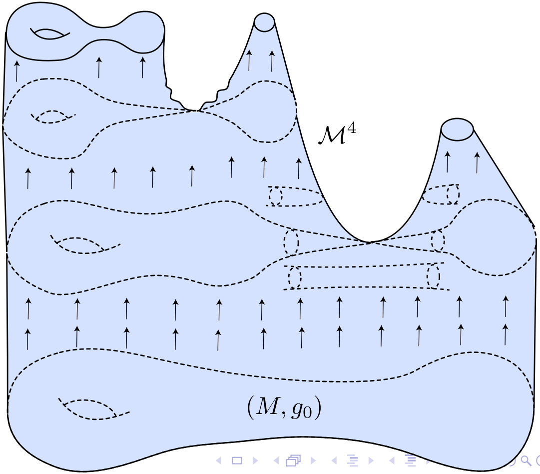
Kleiner, Lott 2014: Compactness theorem and $\delta_i \to 0$
$\Longrightarrow$ existence of (weak) singular Ricci flow starting from any (M, g_0)

Singular Ricci flow: Ricci flow spacetime $\mathcal{M}$ that:

- is 0-complete (i.e. "surgery scale $\delta = 0$")
- satisfies the ε-canonical neighborhood assumption for small ε.

Remarks:

- $\mathcal{M}$ is smooth everywhere and not defined at singularities
- singular times may accummulate



Uniqueness

Theorem (Ba., Kleiner 2016)

$\mathcal{M}$ is uniquely determined by its initial time-slice $(\mathcal{M}_0, g_0)$ up to isometry.

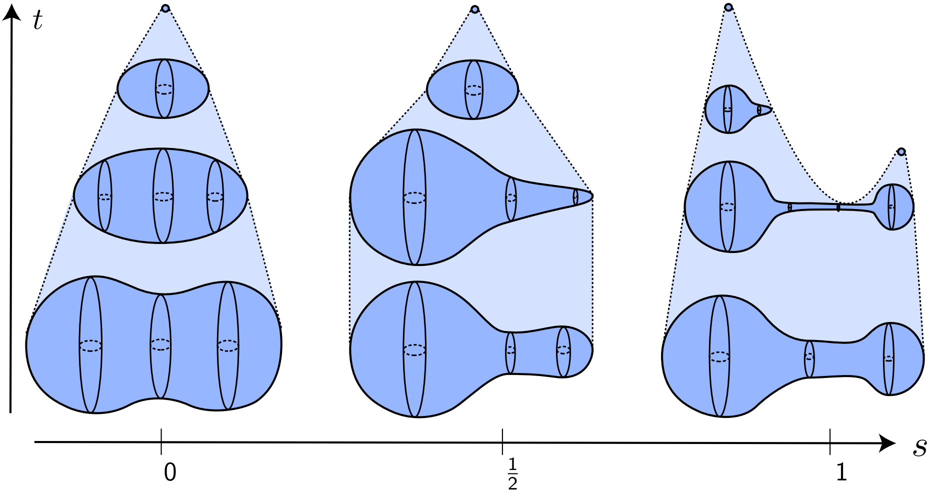
So for any (M, g) there is (up to isometry) a canonical singular Ricci flow $\mathcal{M}$ with initial time-slice $(\mathcal{M}_0, g_0) \cong (M, g)$.

Write: $\mathcal{M}^g$.

Uniqueness $\longrightarrow$ Continuous dependence

continuous family of metrics $(g^s)_{s\in[0,1]}$ on M

$\rightsquigarrow \quad \{\mathcal{M}^s := \mathcal{M}^{g^s}\}_{s\in[0,1]}$ singular RFs



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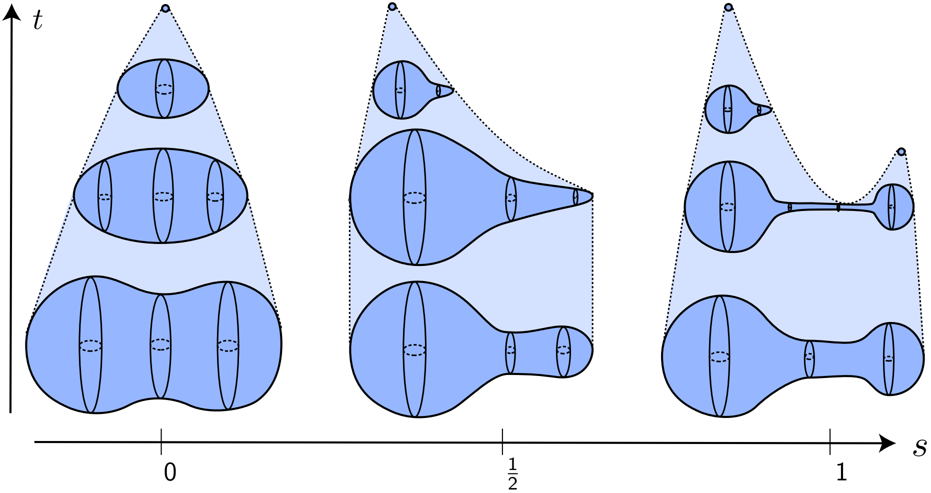


Continuity of singular RFs

Vague statement: $\mathcal{M}^g$ depends continuously on its initial metric g.

Precise statement:

Theorem (Ba., Kleiner 2019)

Given a continuous family $(g^s)_{s\in X}$ of Riemannian metrics on M over some topological space X, there is a continuous family of singular RFs $(\mathcal{M}^s = \mathcal{M}^{g^s})_{s\in X}$. That is:

- A topology on $\sqcup_{s\in X}\mathcal{M}^s$ such that the projection
$$\bigsqcup_{s\in X} \mathcal{M}^{g^s} \longrightarrow X$$
is a topological submersion.
- A compatible lamination structure on $\sqcup_{s\in X}\mathcal{M}^s$ with leaves $\mathcal{M}^s$ with respect to which all objects $\mathfrak{t}^s, \partial_{\mathfrak{t}}^s, g^s$ are transversely continuous.

Part III: Applications to Topology

Generalized Smale Conjecture

Let $M \approx S^3/\Gamma$, then $\mathrm{Diff}(M) \simeq \mathrm{Isom}(M)$.

Goal: As in 2D, construct a retraction

$$* \simeq \mathrm{Met}(M) \longrightarrow \mathrm{Met}_{K\equiv 1}(M)$$

Strategy:

$$\mathrm{Met}(M) \xrightarrow{\qquad\qquad} \{\text{singular RFs}\} \overset{?}{\dashrightarrow} \mathrm{Met}_{K\equiv 1}(M)$$

Short proof (30 pages): if $M \not\approx S^3, \mathbb{R}P^3$ and assuming the Smale Conj. for S^3

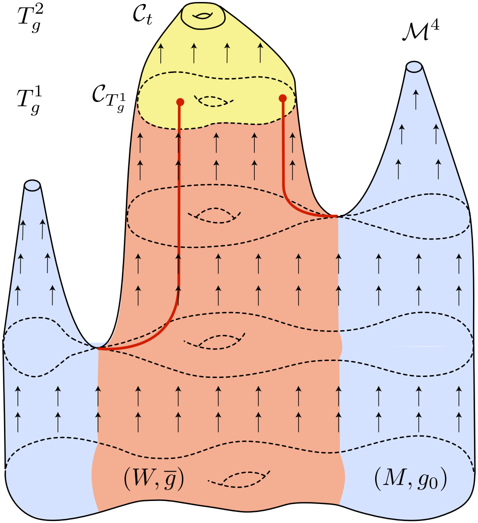
2 Observations:

1. Distinguished end $\mathcal{C} \approx M \times [T^1_g, T^2_g) \subset \mathcal{M}^g$ on which metric converges to $K \equiv 1$ metric modulo rescaling.
2. Every component of every time-slice only has finitely many bad points.

   (bad point $x \in \mathcal{M}$: trajectory of $-\partial_t$ through x does not exists up to time 0.)

$(W, \overline{g}_t) :=$ push-forward of $(\mathcal{C}_t, g_t)$ via flow of $-\partial_t$

$(W, \overline{g} := \lim_{t \nearrow T^2_g} \lambda_t \overline{g}_t) \cong S^3/\Gamma \setminus \{p_1, \ldots, p_N\}$



$\rightsquigarrow$ continuous, canonical map

$$\mathrm{Met}(M) \longrightarrow \mathrm{PartMet}_{K\equiv 1}(M), \qquad g \longmapsto \mathcal{M}^g \longmapsto (W, \overline{g})$$

Obstruction theory $\quad \rightsquigarrow \quad \mathrm{PartMet}_{K\equiv 1}(M) \longrightarrow \mathrm{Met}_{K\equiv 1}(M).$