Deformetrica 4: an open-source software for statistical shape analysis

ARAMIS LAB
BRAIN DATA SCIENCE

ShapeMI workshop

MICCAI conference

20 September 2018

Granada, Spain

Alexandre Bône, Maxime Louis, Benoît Martin, Stanley Durrleman

Deformetrica 4: an open-source software for statistical shape analysis

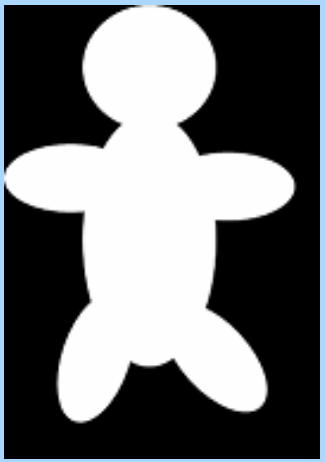
ARAMIS LAB
BRAIN DATA SCIENCE

I. Registration demo

II. Atlas

III. Regression

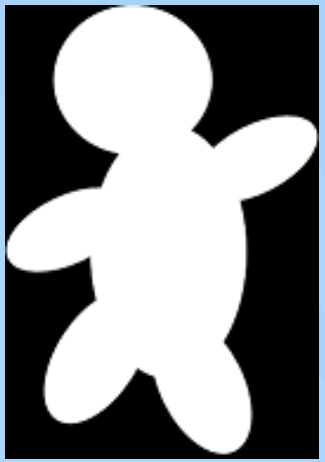
Registration



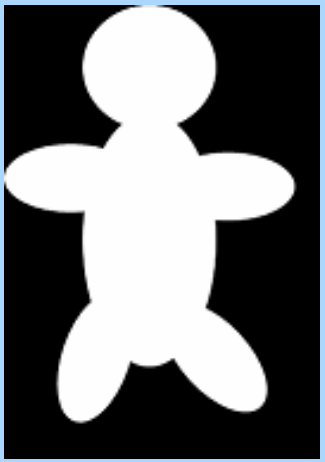
S

Φ

T

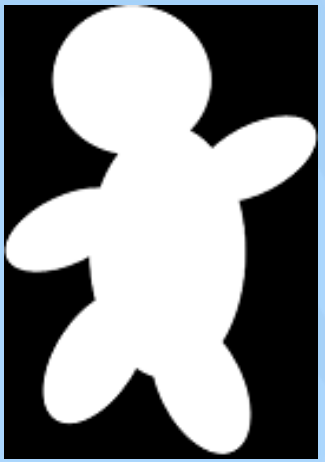


Registration



S

$$\Phi_{c,\alpha}^{\sigma}$$



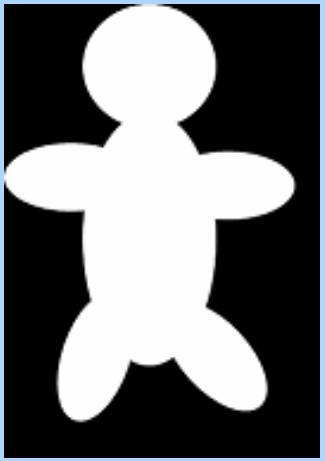
T

Registration

ARAMIS LAB
BRAIN DATA SCIENCE

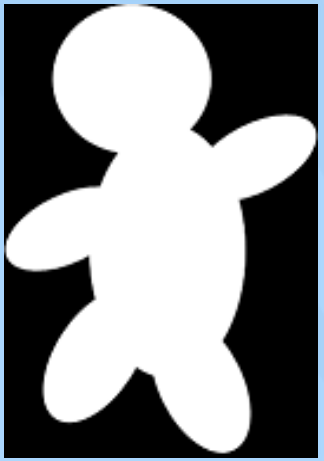
cost function = **attachment cost** + **regularization cost**

$$E(c,\alpha) = \frac{1}{\sigma_\varepsilon^2}\left\|\Phi_{c,\alpha}^{\sigma} \star S - T\right\|_{\varepsilon}^{2} + R(c,\alpha)$$



S

$\boldsymbol{\Phi_{c,\alpha}^{\sigma}}$



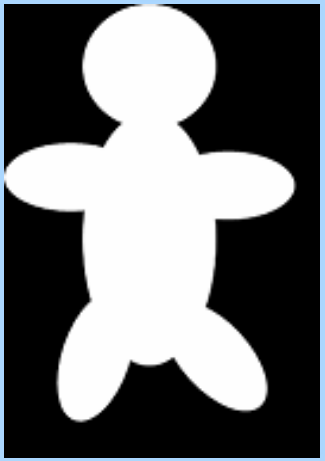
T

Registration

ARAMIS LAB
BRAIN DATA SCIENCE

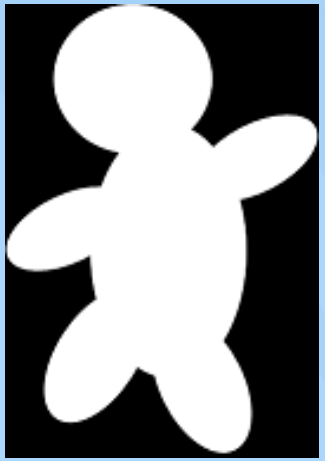
inputs

$$E(c,\alpha) = \frac{1}{\sigma_\varepsilon^2}\left\|\Phi_{c,\alpha}^{\sigma} \star S - T\right\|_\varepsilon^2 + R(c,\alpha)$$



S

$\boldsymbol{\Phi_{c,\alpha}^{\sigma}}$



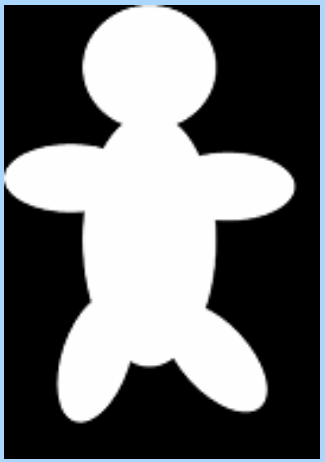
T

Registration

ARAMIS LAB
BRAIN DATA SCIENCE

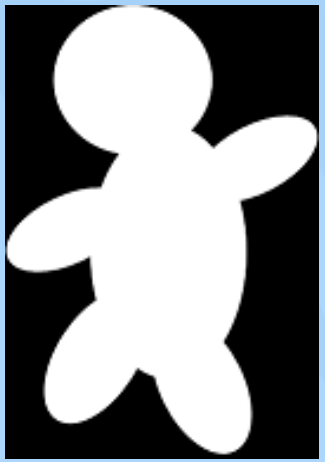
inputs **outputs**

$$E(c,\alpha) = \frac{1}{\sigma_\varepsilon^2}\left\|\Phi_{c,\alpha}^{\sigma} \star S - T\right\|_\varepsilon^2 + R(c,\alpha)$$



S

$\Phi_{c,\alpha}^{\sigma}$



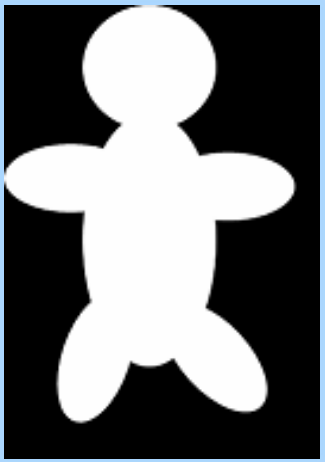
T

Registration

ARAMIS LAB
BRAIN DATA SCIENCE

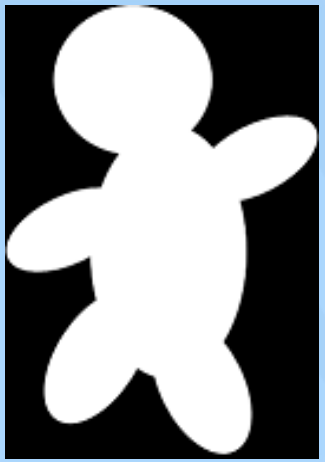
inputs **outputs** **Hyper-parameters**

$$E(c,\alpha) = \frac{1}{\sigma_\varepsilon^2}\left\|\Phi_{c,\alpha}^{\sigma} \star S - T\right\|_\varepsilon^2 + R(c,\alpha)$$



S

$\Phi_{c,\alpha}^{\sigma}$



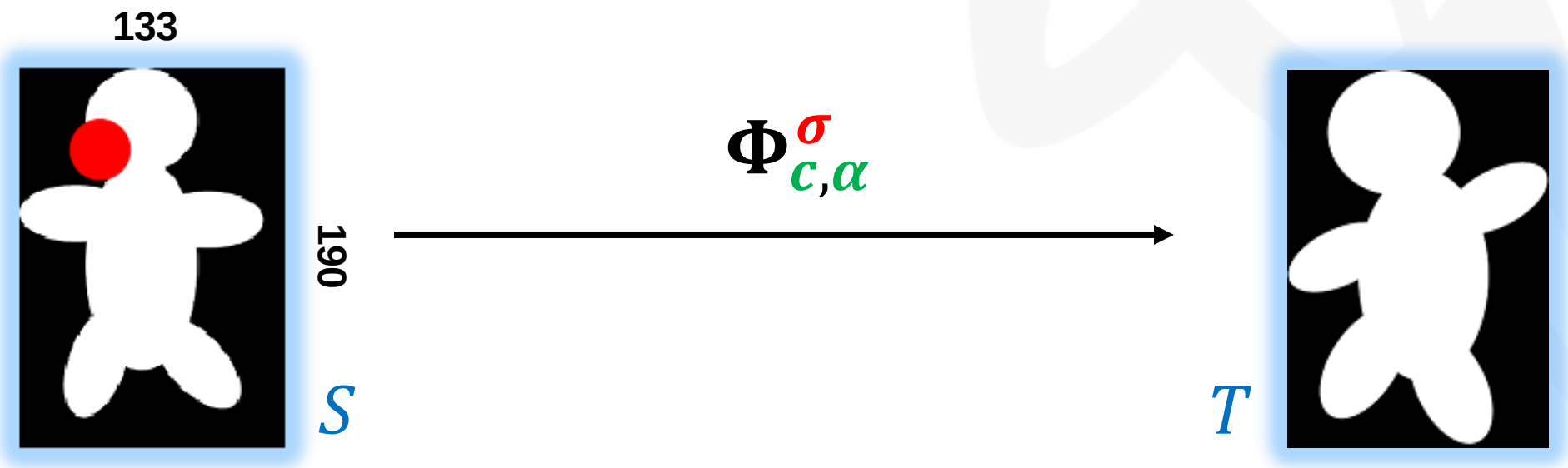
T

Registration

ARAMIS LAB
BRAIN DATA SCIENCE

inputs **outputs** **Hyper-parameters**

$$E(c,\alpha) = \frac{1}{\sigma_\varepsilon^2}\left\|\Phi_{c,\alpha}^{\sigma} \star S - T\right\|_\varepsilon^2 + R(c,\alpha)$$



Registration

ARAMIS LAB
BRAIN DATA SCIENCE

inputs

outputs

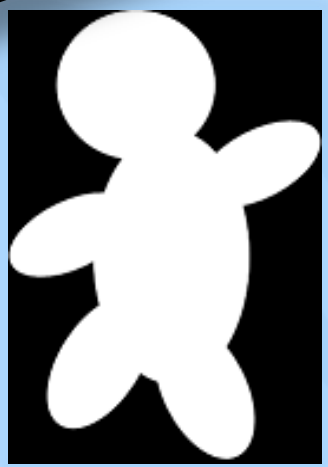
r-
ers

$E($

DEMO

S

T

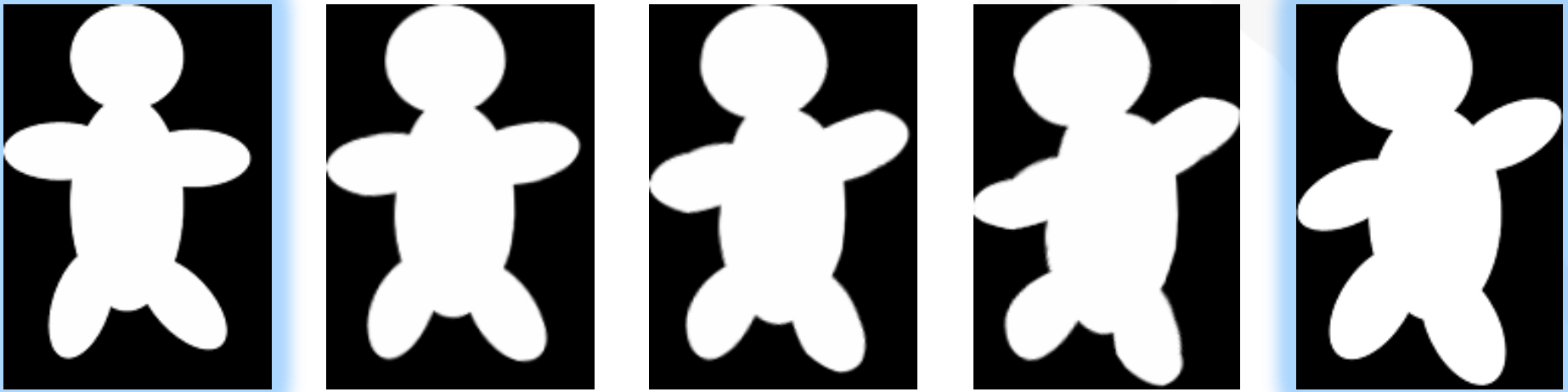


Registration

ARAMIS LAB
BRAIN DATA SCIENCE

inputs **outputs** **Hyper-parameters**

$$E(c,\alpha) = \frac{1}{\sigma_\varepsilon^2}\left\|\Phi_{c,\alpha}^{\sigma} \star S - T\right\|_\varepsilon^2 + R(c,\alpha)$$

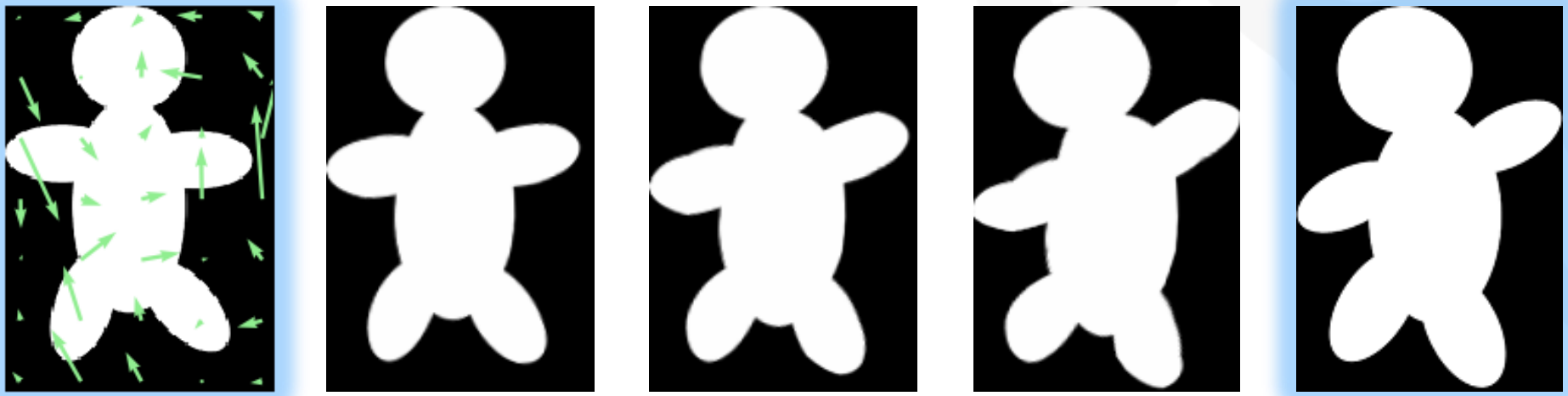


Registration

ARAMIS LAB
BRAIN DATA SCIENCE

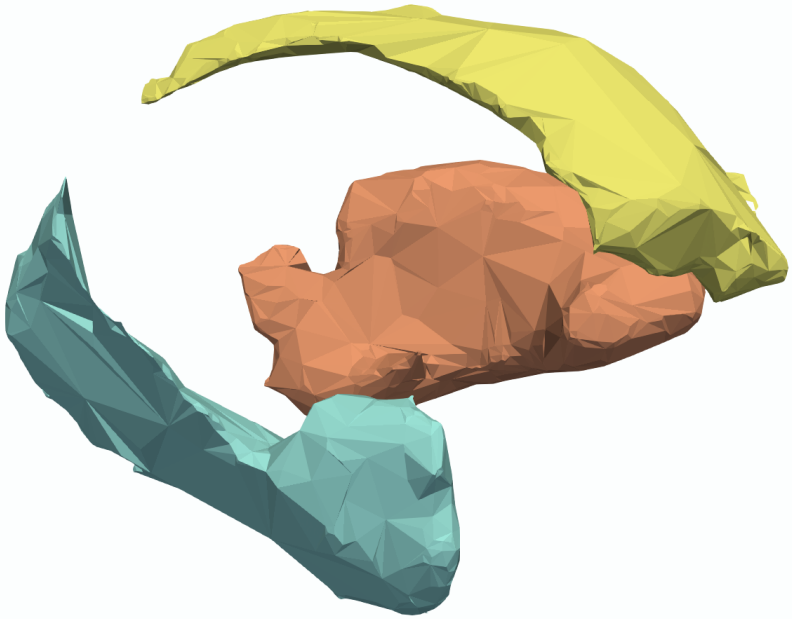
inputs **outputs** **Hyper-parameters**

$$E(c,\alpha) = \frac{1}{\sigma_\varepsilon^2}\left\|\Phi_{c,\alpha}^{\sigma} \star S - T\right\|_\varepsilon^2 + R(c,\alpha)$$

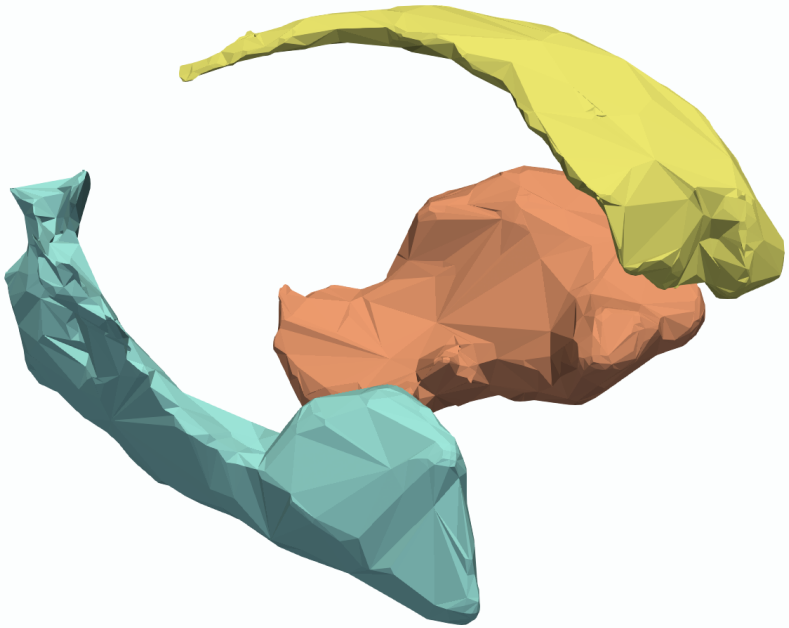


Registration

ARAMIS LAB
BRAIN DATA SCIENCE



T



S

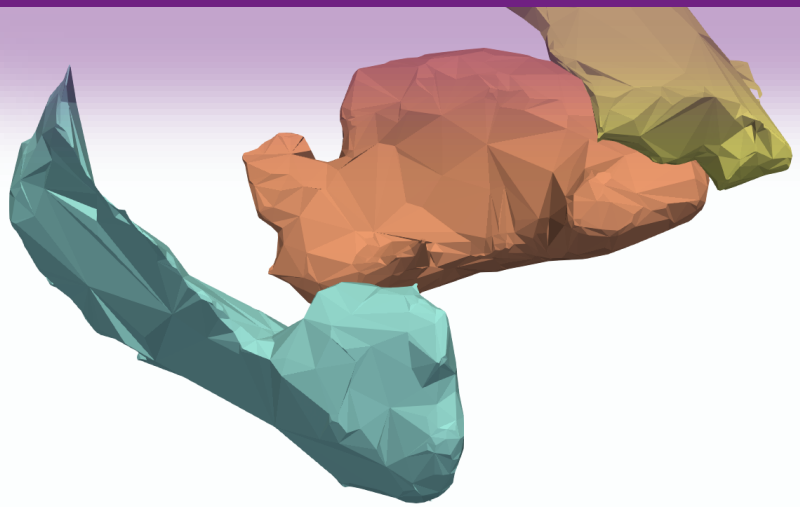
Reg

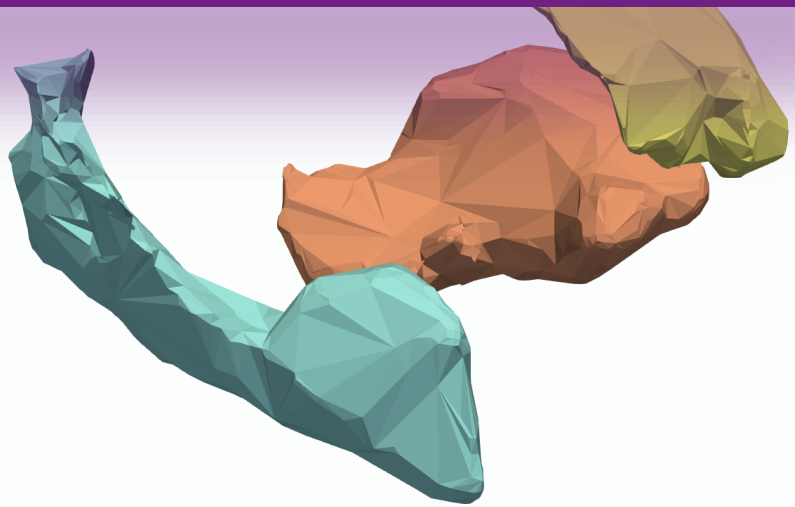

```
<?xml Version="1.0"?>
<model>
    <model-type>Registration</model-type>

    <template>
        <object Id="leftCaudate">
            <deformable-object-type>SurfaceMesh</deformable-object-type>
            <attachment-type>Current</attachment-type>
            <kernel-width>10</kernel-width>
            <noise-std>1</noise-std>
            <filename>data/s0906_654_0_leftCaudate.vtk</filename>
        </object>

        <object Id="leftHippocampus">
            <deformable-object-type>SurfaceMesh</deformable-object-type>
            <attachment-type>Varifold</attachment-type>
            <kernel-width>10</kernel-width>
            <noise-std>1</noise-std>
            <filename>data/s0906_654_0_leftHippocampus.vtk</filename>
        </object>

        <object Id="leftPutamen">
            <deformable-object-type>SurfaceMesh</deformable-object-type>
            <attachment-type>Varifold</attachment-type>
            <kernel-width>10</kernel-width>
            <noise-std>1</noise-std>
            <filename>data/s0906_654_0_leftPutamen.vtk</filename>
        </object>
    </template>

    <deformation-parameters>
        <kernel-width>15</kernel-width>
    </deformation-parameters>
</model>
```

Registration

ARAMIS LAB
BRAIN DATA SCIENCE

```
<data-set>
    <subject Id="s0671">
        <visit Id="baseline">
            <filename Object_id="leftCaudate">data/s0671_612_0_leftCaudate.vtk</filename>
            <filename Object_id="leftHippocampus">data/s0671_612_0_leftHippocampus.vtk</filename>
            <filename Object_id="leftPutamen">data/s0671_612_0_leftPutamen.vtk</filename>
        </visit>
    </subject>
</data-set>
```





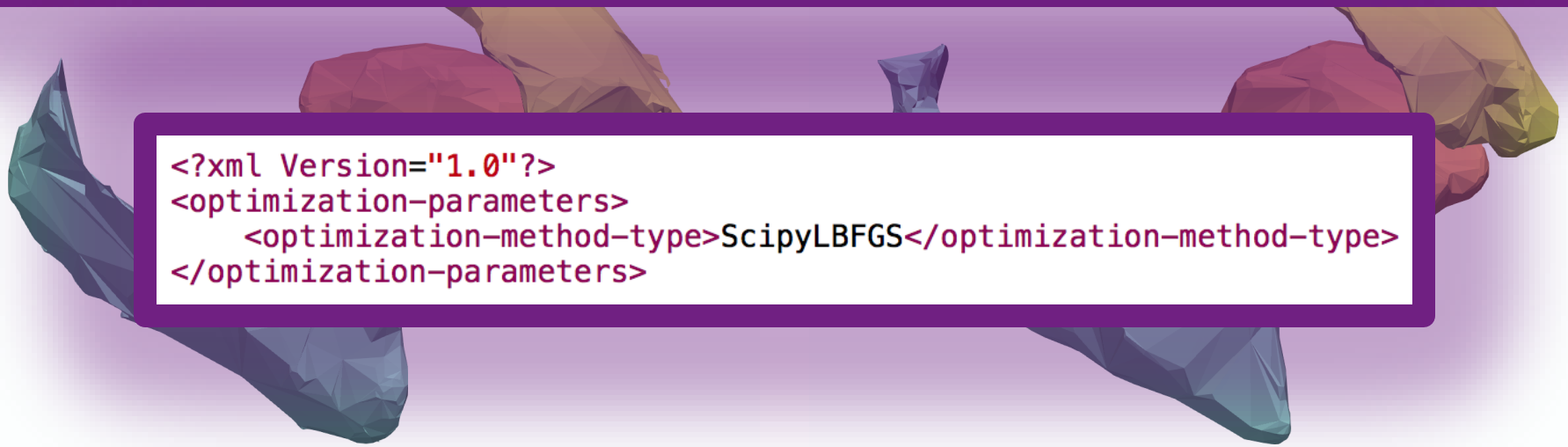
T

S

Registration

ARAMIS LAB
BRAIN DATA SCIENCE

```
<data-set>
    <subject Id="s0671">
        <visit Id="baseline">
            <filename Object_id="leftCaudate">data/s0671_612_0_leftCaudate.vtk</filename>
            <filename Object_id="leftHippocampus">data/s0671_612_0_leftHippocampus.vtk</filename>
            <filename Object_id="leftPutamen">data/s0671_612_0_leftPutamen.vtk</filename>
        </visit>
    </subject>
</data-set>
```



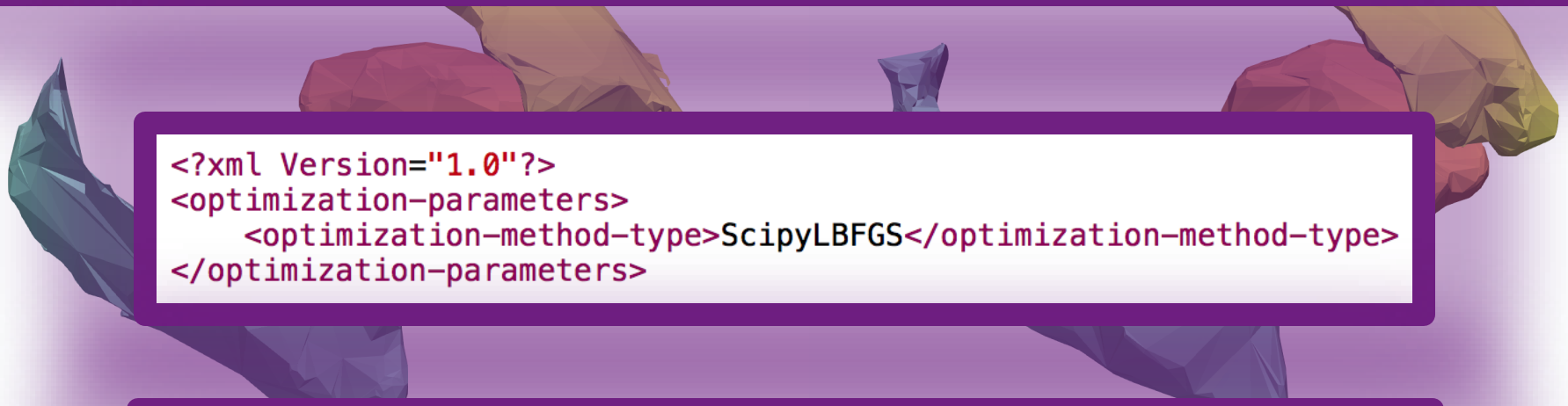
```
<?xml Version="1.0"?>
<optimization-parameters>
    <optimization-method-type>ScipyLBFGS</optimization-method-type>
</optimization-parameters>
```

T S

Registration

ARAMIS LAB
BRAIN DATA SCIENCE

```
<data-set>
    <subject Id="s0671">
        <visit Id="baseline">
            <filename Object_id="leftCaudate">data/s0671_612_0_leftCaudate.vtk</filename>
            <filename Object_id="leftHippocampus">data/s0671_612_0_leftHippocampus.vtk</filename>
            <filename Object_id="leftPutamen">data/s0671_612_0_leftPutamen.vtk</filename>
        </visit>
    </subject>
</data-set>
```

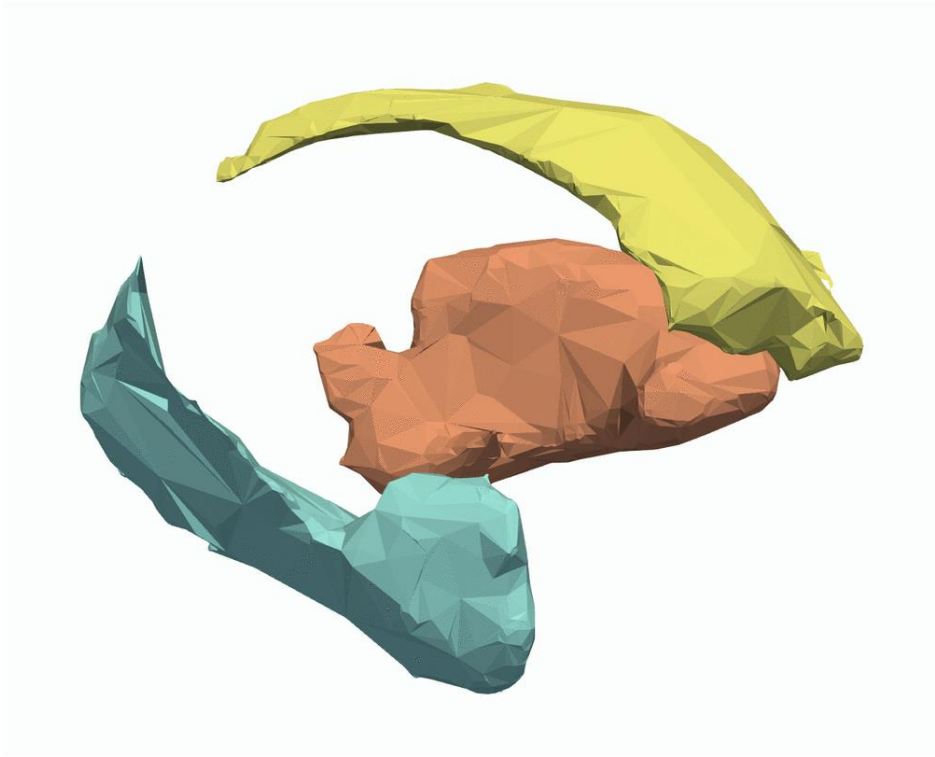


```
<?xml Version="1.0"?>
<optimization-parameters>
    <optimization-method-type>ScipyLBFGS</optimization-method-type>
</optimization-parameters>
```

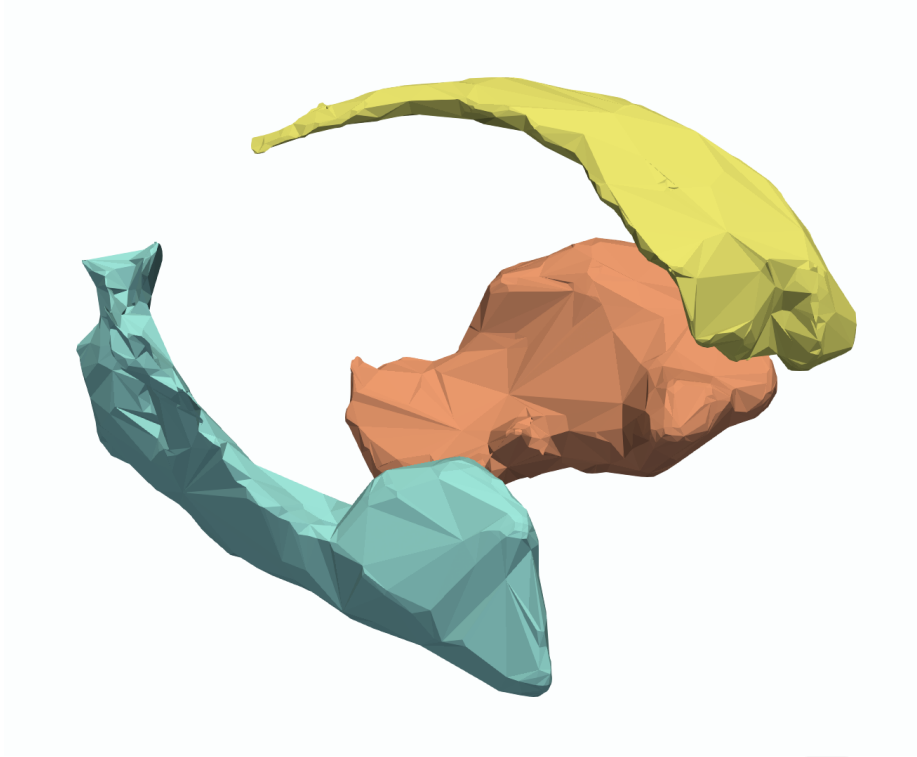
```
>> deformetrica estimate
model.xml data_set.xml -p
optimization_parameters.xml
```

Registration

ARAMIS LAB
BRAIN DATA SCIENCE



T



S

Deformetrica 4: an open-source software for statistical shape analysis

ARAMIS LAB
BRAIN DATA SCIENCE

I. Registration demo

II. Atlas

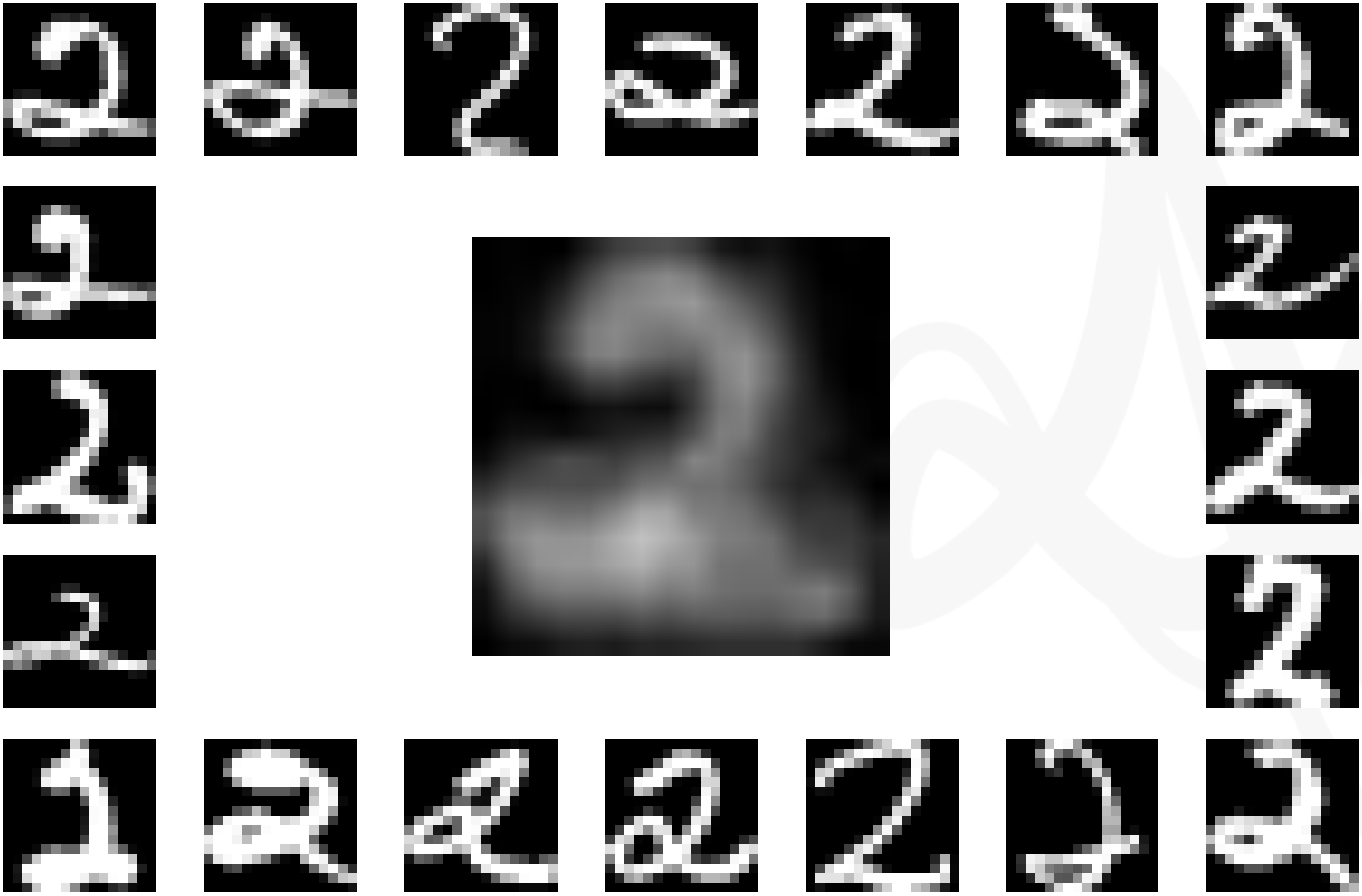
III. Regression

Deterministic atlas

ARAMIS LAB
BRAIN DATA SCIENCE

Deterministic atlas

ARAMIS LAB
BRAIN DATA SCIENCE



Deterministic atlas

ARAMIS LAB
BRAIN DATA SCIENCE

inputs **outputs** **Hyper-parameters**

$$E(S, c, (\alpha_i)_i) = \frac{1}{\sigma_\varepsilon^2} \sum_{i=1}^{n} \left\| \Phi^{\sigma}_{c,\alpha_i} \star S - T_i \right\|_\varepsilon^2 + R(c, \alpha_i)$$

Deterministic atlas

ARAMIS LAB
BRAIN DATA SCIENCE

```
<?xml Version="1.0"?>
<model>

    <model-type>DeterministicAtlas</model-type>

    <template>
        <object Id="img">
            <deformable-object-type>Image</deformable-object-type>
            <filename>data/digit_2_mean.png</filename>
            <noise-std>1</noise-std>
        </object>
    </template>

    <deformation-parameters>
        <kernel-width>5</kernel-width>
    </deformation-parameters>

</model>
```

Deterministic atlas

ARAMIS LAB
BRAIN DATA SCIENCE

```
<?xml Version="1.0"?>
<data-set>

    <subject Id="sub1">
        <visit Id="t0">
            <filename Object_id="img">data/digit_2_sample_1.png</filename>
        </visit>
    </subject>


    <subject Id="sub2">
        <visit Id="t0">
            <filename Object_id="img">data/digit_2_sample_2.png</filename>
        </visit>
    </subject>


    <subject Id="sub3">
        <visit Id="t0">
            <filename Object_id="img">data/digit_2_sample_3.png</filename>
        </visit>
    </subject>


    <subject Id="sub4">
```

$E($ ... $\alpha_i)$

Deterministic atlas

ARAMIS LAB
BRAIN DATA SCIENCE

```
<?xml Version="1.0"?>
<optimization-parameters>

    <convergence-tolerance>1e-3</convergence-tolerance>

</optimization-parameters>
```

$$E(\ldots) \propto \sigma_\varepsilon^2 \sum_{i=1}^{n} \ldots \alpha_i)$$

Deterministic atlas

ARAMIS LAB
BRAIN DATA SCIENCE

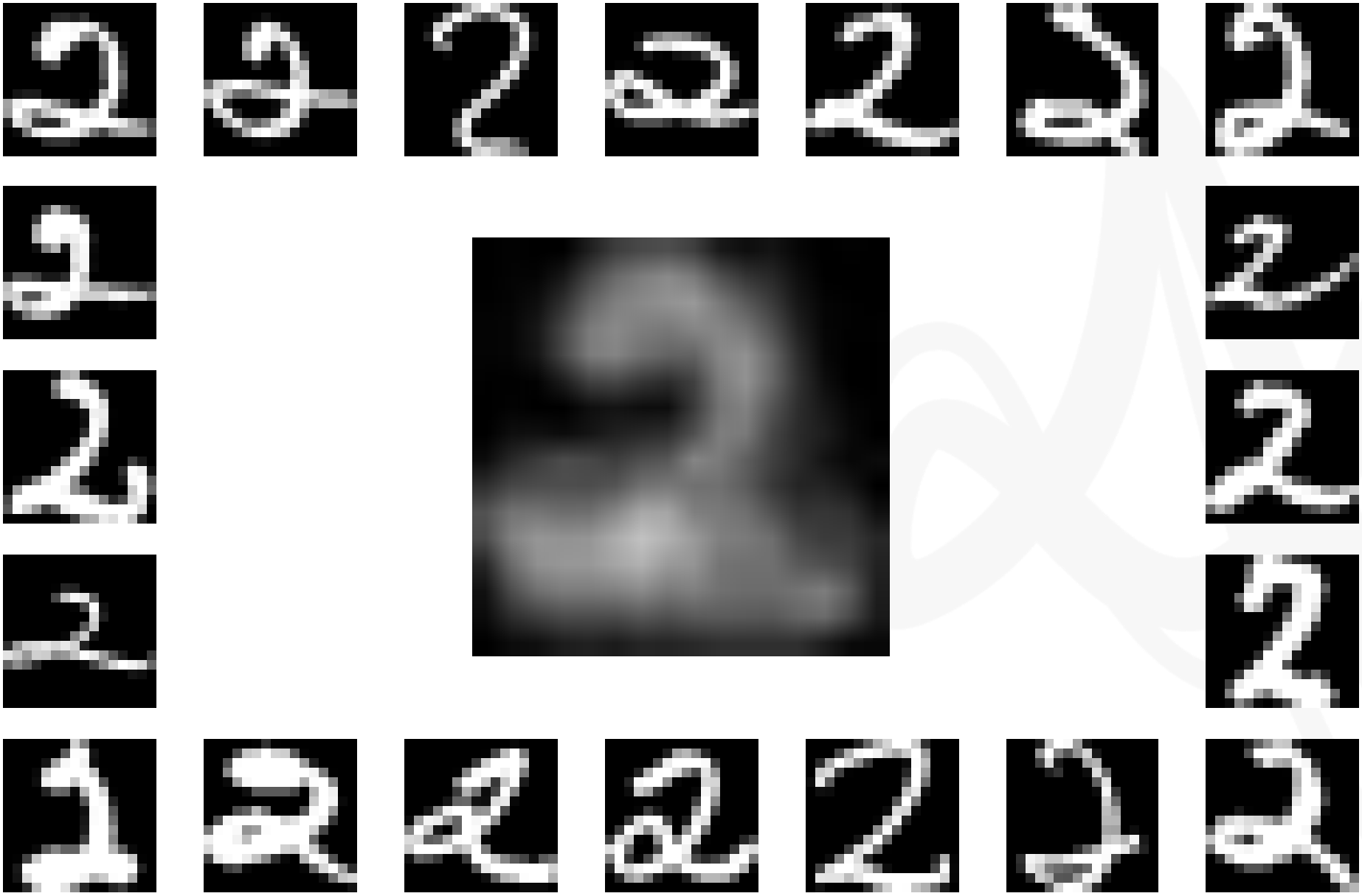
```
<?xml Version="1.0"?>
<optimization-parameters>

    <convergence-tolerance>1e-3</convergence-tolerance>

</optimization-parameters>
```

$$\sigma_\varepsilon^2 \sum_{i=1}^{n}$$

```
>> deformetrica estimate
model.xml data_set.xml -p
optimization_parameters.xml
```

Deterministic atlas

ARAMIS LAB
BRAIN DATA SCIENCE

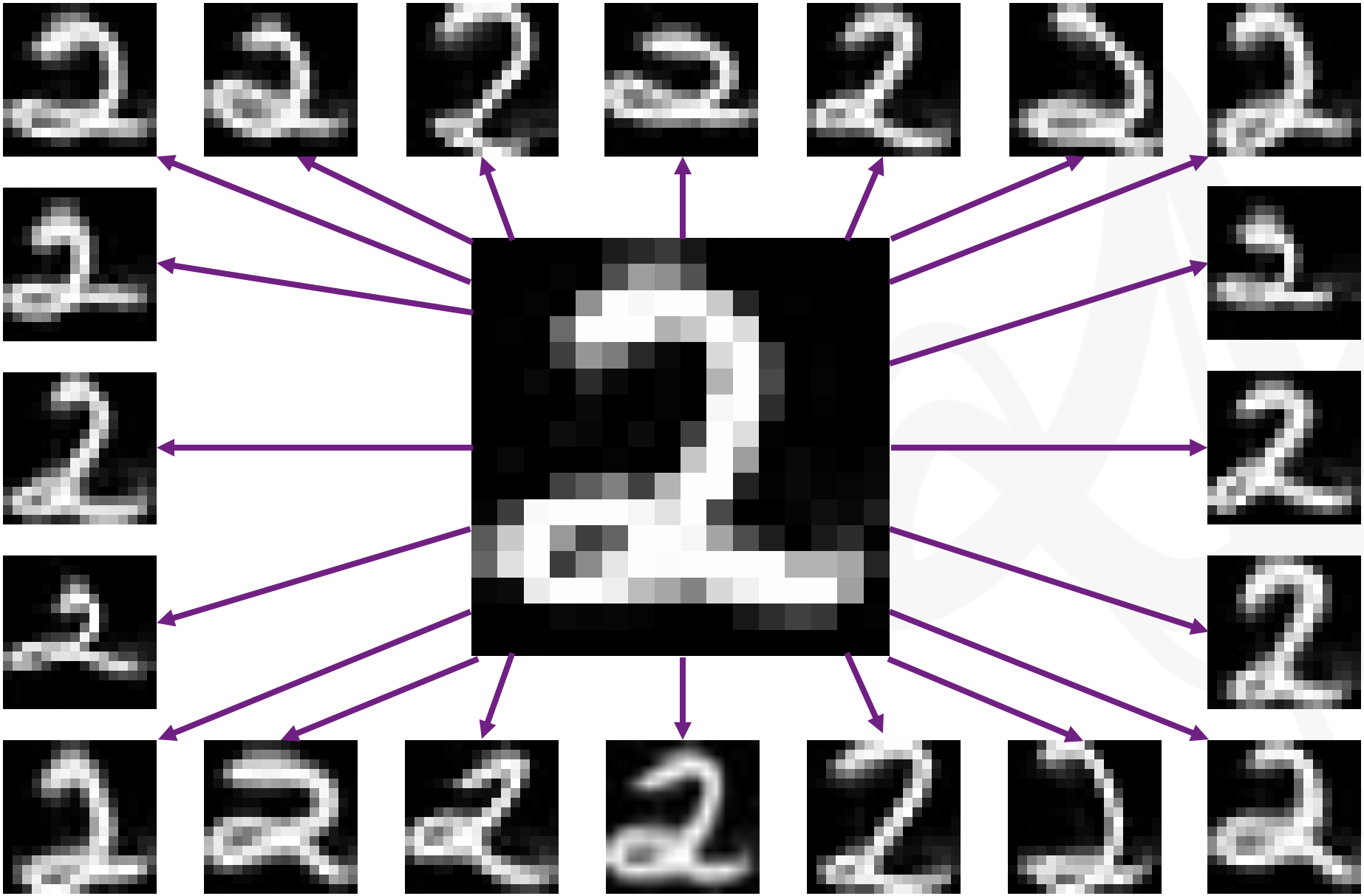


Deterministic atlas

ARAMIS LAB
BRAIN DATA SCIENCE

Deterministic atlas

ARAMIS LAB
BRAIN DATA SCIENCE



Deformetrica 4: an open-source software for statistical shape analysis

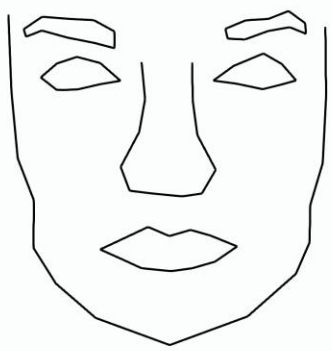
ARAMIS LAB
BRAIN DATA SCIENCE

I. Registration demo

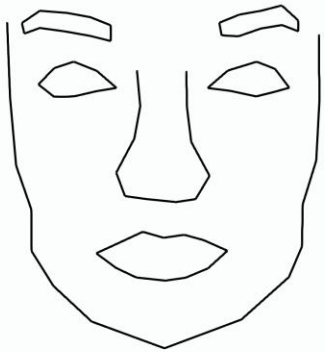
II. Atlas

III. Regression

Geodesic regression



$t_1 = 5$



$t_2 = 15$

$t_3 = 25$

$t_4 = 35$

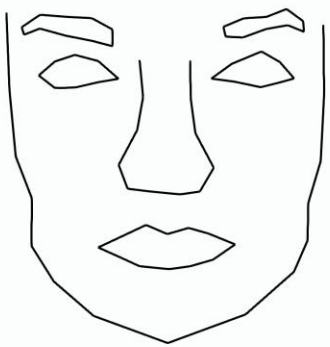
Yin et al. 2008, “A High- Resolution 3D Dynamic Facial Expression Database”

Geodesic regression

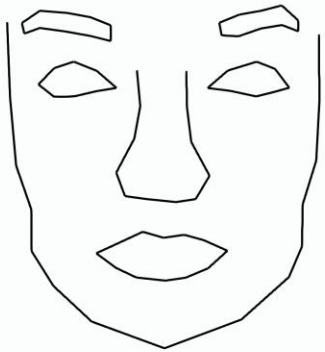
ARAMIS LAB
BRAIN DATA SCIENCE

inputs **outputs** **Hyper-parameters**

$$E(S, c, \alpha) = \frac{1}{\sigma_\varepsilon^2} \sum_{j=1}^{p} \left\| \Phi^{\sigma}_{c, t_j \cdot \alpha} \star S - T_j \right\|_\varepsilon^2 + R(c, \alpha)$$



$t_1 = 5$



$t_2 = 15$

$t_3 = 25$

$t_4 = 35$

Yin et al. 2008, “A High- Resolution 3D Dynamic Facial Expression Database”

Geodesic regression

ARAMIS LAB
BRAIN DATA SCIENCE

```
<?xml Version="1.0" ?>
<model>

    <model-type>Regression</model-type>

    <template>
        <dense-mode>On</dense-mode>
        <object Id="FaceLandmarks">
            <deformable-object-type>PolyLine</deformable-object-type>
            <attachment-type>Landmark</attachment-type>
            <filename>data/sub-F001_ses-015.vtk</filename>
            <noise-std>0.0035</noise-std>
        </object>
    </template>

    <deformation-parameters>
        <kernel-width>0.015</kernel-width>
        <concentration-of-timepoints>1</concentration-of-timepoints>
    </deformation-parameters>

</model>
```

$t_1 = 5$ $t_2 = 15$ $t_3 = 25$ $t_4 = 35$

Yin et al. 2008, “A High- Resolution 3D Dynamic Facial Expression Database”

Geodesic regression

ARAMIS LAB
BRAIN DATA SCIENCE

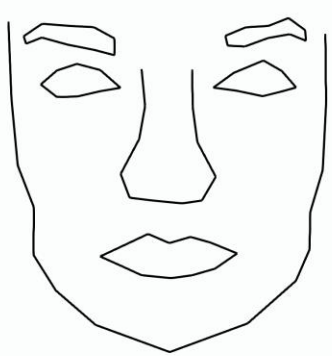
```
<?xml Version="1.0" ?>
<data-set>
    <subject Id="sub-F001">
        <visit Id="ses-000">
            <age>0</age>
            <filename Object_id="FaceLandmarks">data/sub-F001_ses-000.vtk</filename>
        </visit>
        <visit Id="ses-005">
            <age>5</age>
            <filename Object_id="FaceLandmarks">data/sub-F001_ses-005.vtk</filename>
        </visit>
        <visit Id="ses-010">
            <age>10</age>
            <filename Object_id="FaceLandmarks">data/sub-F001_ses-010.vtk</filename>
        </visit>
        <visit Id="ses-015">
            <age>15</age>
            <filename Object_id="FaceLandmarks">data/sub-F001_ses-015.vtk</filename>
        </visit>
        <visit Id="ses-020">
            <age>20</age>
            <filename Object_id="FaceLandmarks">data/sub-F001_ses-020.vtk</filename>
        </visit>
        <visit Id="ses-025">
```

$t_1 = 5$ $t_2 = 15$ $t_3 = 25$ $t_4 = 35$

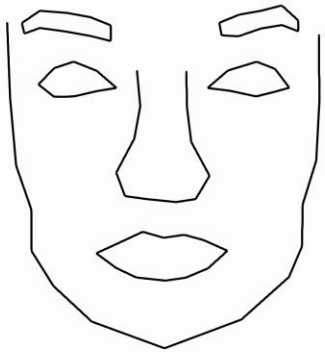
Yin et al. 2008, “A High- Resolution 3D Dynamic Facial Expression Database”

Geodesic regression

```
>> deformetrica estimate
model.xml data_set.xml
```



$t_1 = 5$



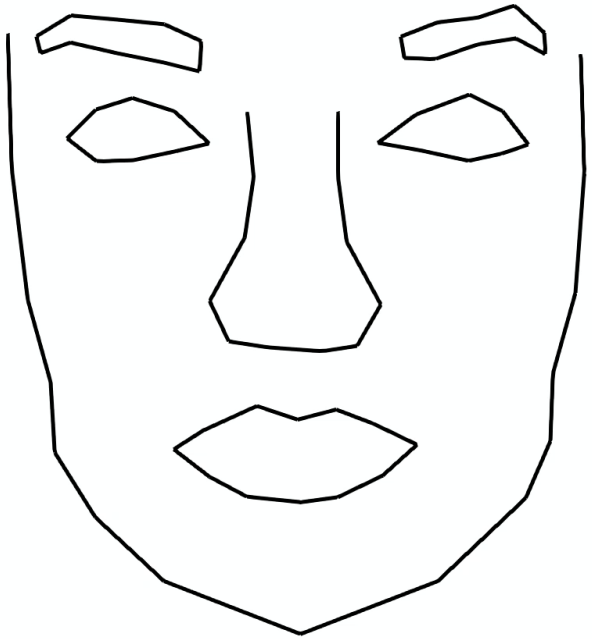
$t_2 = 15$

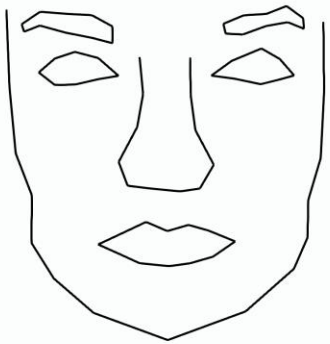
$t_3 = 25$

$t_4 = 35$

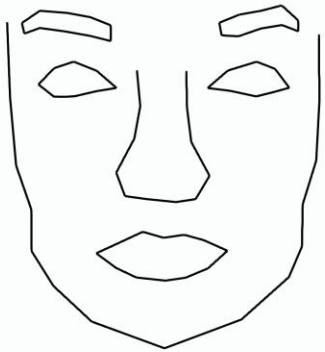
Yin et al. 2008, “A High- Resolution 3D Dynamic Facial Expression Database”

Geodesic regression





$t_1 = 5$



$t_2 = 15$

$t_3 = 25$

$t_4 = 35$

Yin et al. 2008, “A High- Resolution 3D Dynamic Facial Expression Database”

Parallel transport

ARAMIS LAB
BRAIN DATA SCIENCE

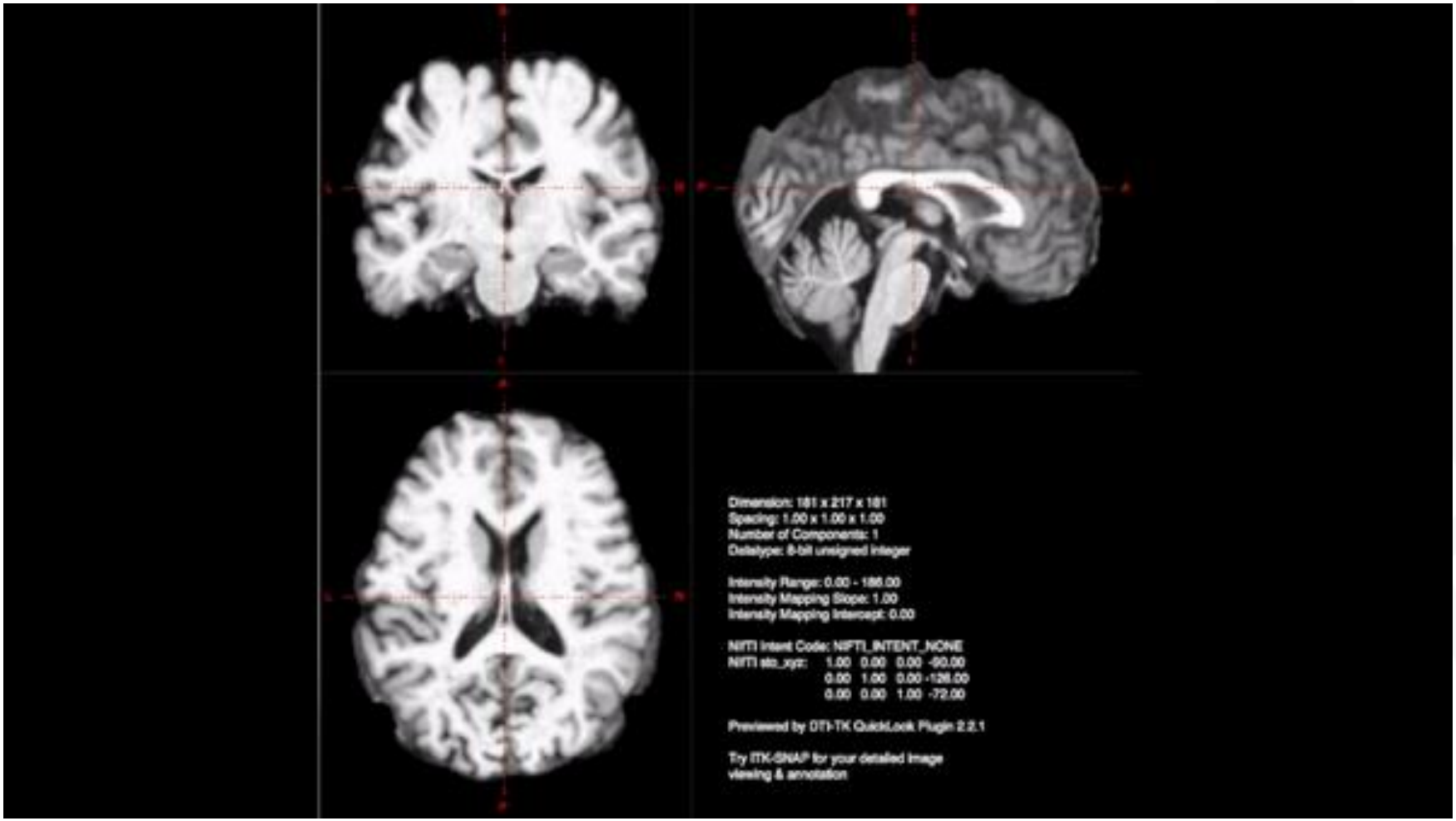
Transfer a reference temporal evolution towards a new target geometry

Data courtesy of Paolo Piras, Sapienza Università di Roma, Italy

MR image registration performance

ARAMIS LAB
BRAIN DATA SCIENCE

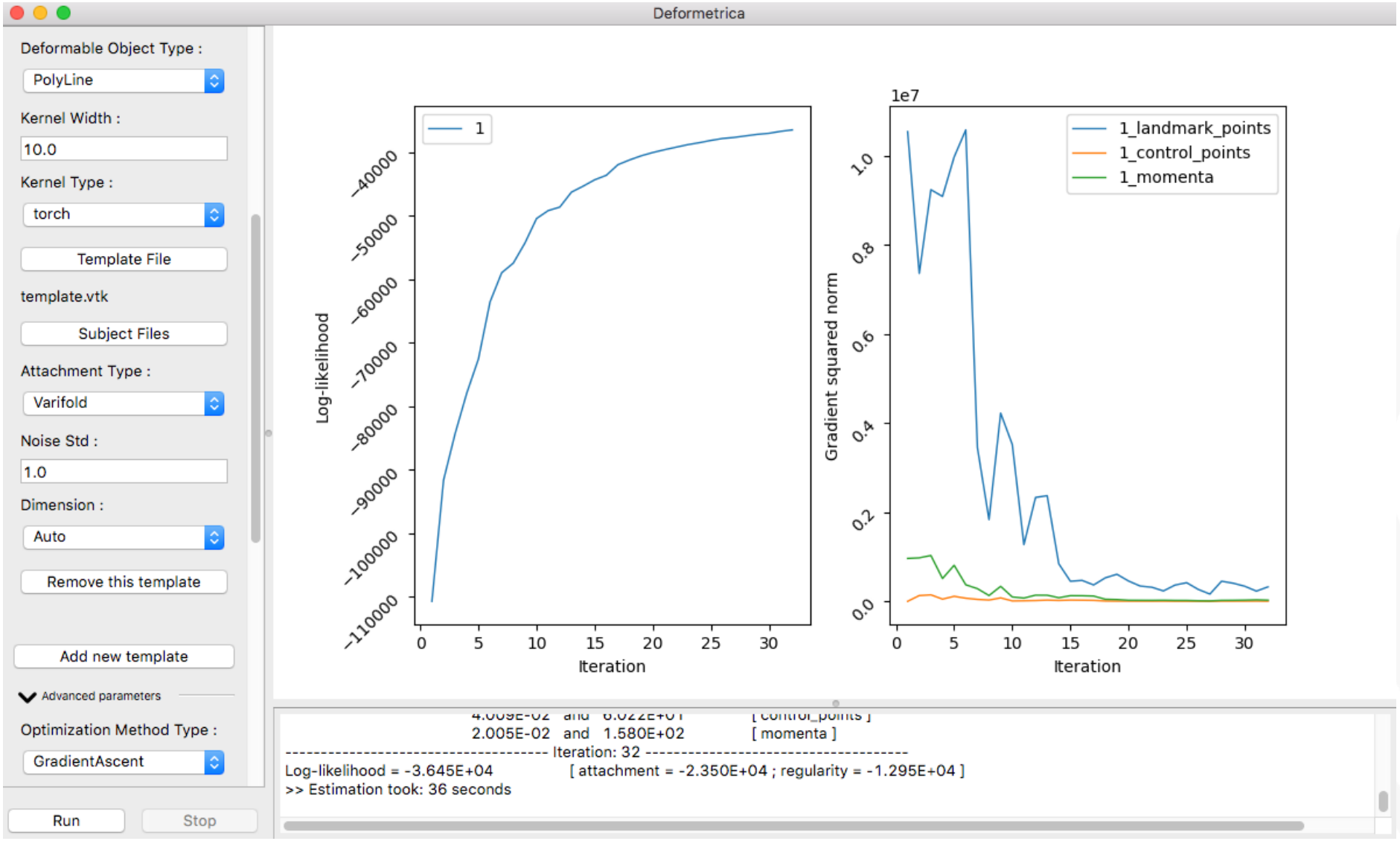
Registration of full-resolution MR images (7 millions voxels) in 2-3 minutes, with low GPU memory usage



Teaser: graphical user interface

alpha

ARAMIS LAB
BRAIN DATA SCIENCE



Teaser: python API

beta

ARAMIS LAB
BRAIN DATA SCIENCE

```
# Import.
from deformetrica.api import Deformetrica

# Estimate a Bayesian atlas model.
deformetrica = Deformetrica()
bayesian_atlas = deformetrica.estimate_bayesian_atlas(...)

# Perform post-processing tasks.
bayesian_atlas.write(output_dir='~/Desktop/output')
sampled_momenta = bayesian_atlas.individual_random_effects['momenta'].sample()
```

PyTorch

ARAMIS LAB
BRAIN DATA SCIENCE

- **Auto-differentiation**

- **Seamless CUDA code**

PyTorch + PyKeops

ARAMIS LAB
BRAIN DATA SCIENCE

- **Auto-differentiation, without memory overflows**

- **Seamless CUDA code**

Thanks to Benjamin Charlier, Jean Feydy & Joan Glaunès

Conclusion

ARAMIS LAB
BRAIN DATA SCIENCE

Implements many statistical shape analysis tasks ...

- **Registration**
- **Deterministic atlas**
- **Bayesian atlas**
- **Geodesic regression**
- **Parallel transport**
- Longitudinal atlas beta
- Principal geodesic analysis alpha

Conclusion

ARAMIS LAB
BRAIN DATA SCIENCE

Implements many statistical shape analysis tasks ...

- **Registration**
- **Deterministic atlas**
- **Bayesian atlas**
- **Geodesic regression**
- **Parallel transport**
- Longitudinal atlas beta
- Principal geodesic analysis alpha

... with very few requirements about the data

- **Image**
- **Meshes**
- **No required point correspondence**
- **Multi-object**
- **Cross-sectional or longitudinal datasets**

Thanks!

ARAMIS LAB
BRAIN DATA SCIENCE

Requirements

- **Linux or Mac**
- **Anaconda 3**

www.deformetrica.org

Install

```
conda install -c pytorch -c conda-forge
-c anaconda -c aramislab deformetrica
```

Come see us at the lunch & demo session!

Future work

ARAMIS LAB
BRAIN DATA SCIENCE

Grow the pool of users

- **Graphical user interface (GUI)**
- **Python API**
- **Windows platform**

Add functionalities

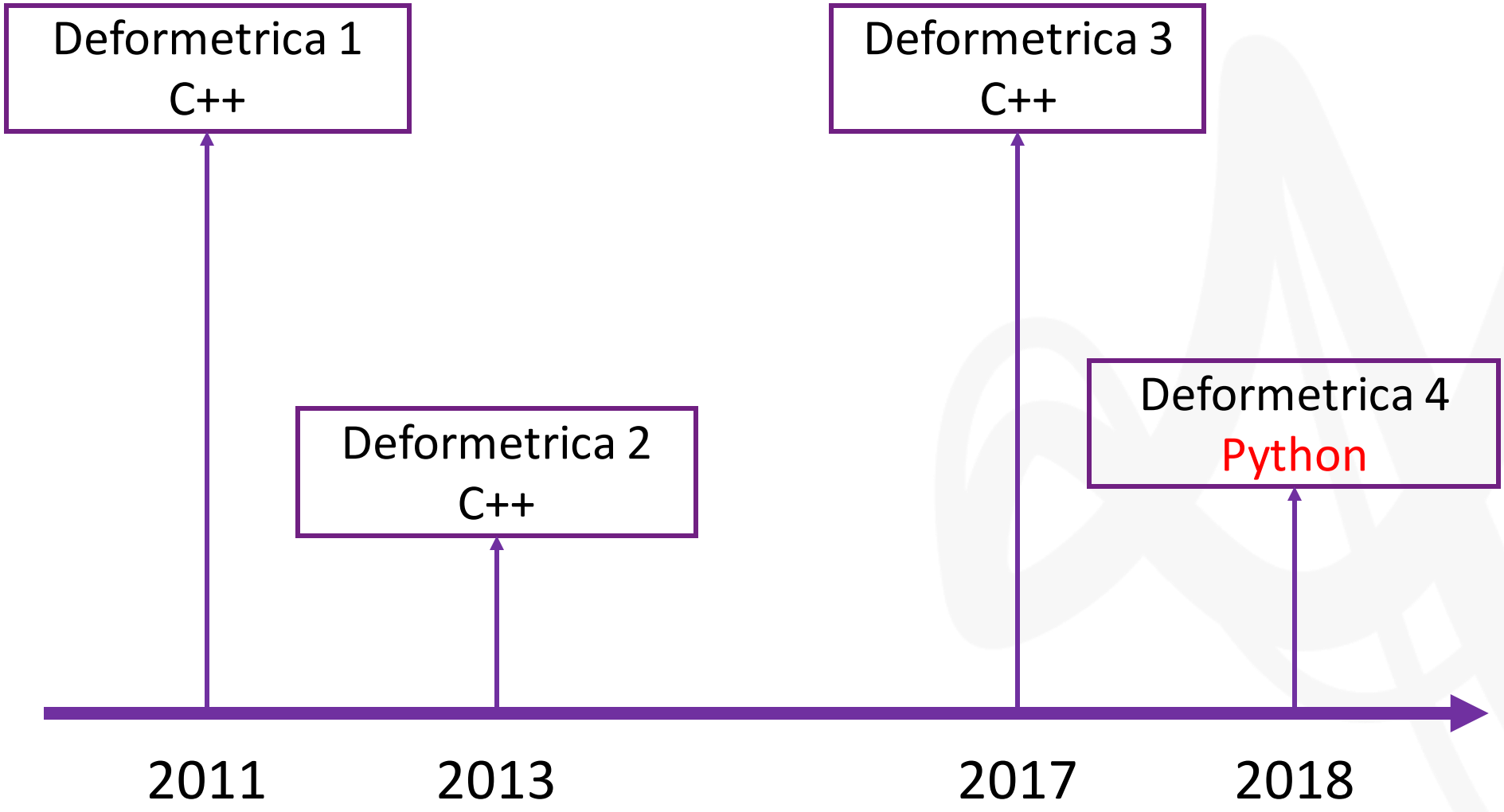
- **Longitudinal atlas**
- **Principal geodesic analysis**
- **MCMC-SAEM estimation algorithm**

Improve performance

- **Achieve massive parallelization on large clusters**
- **Emphasis on GPU-specific optimizations**

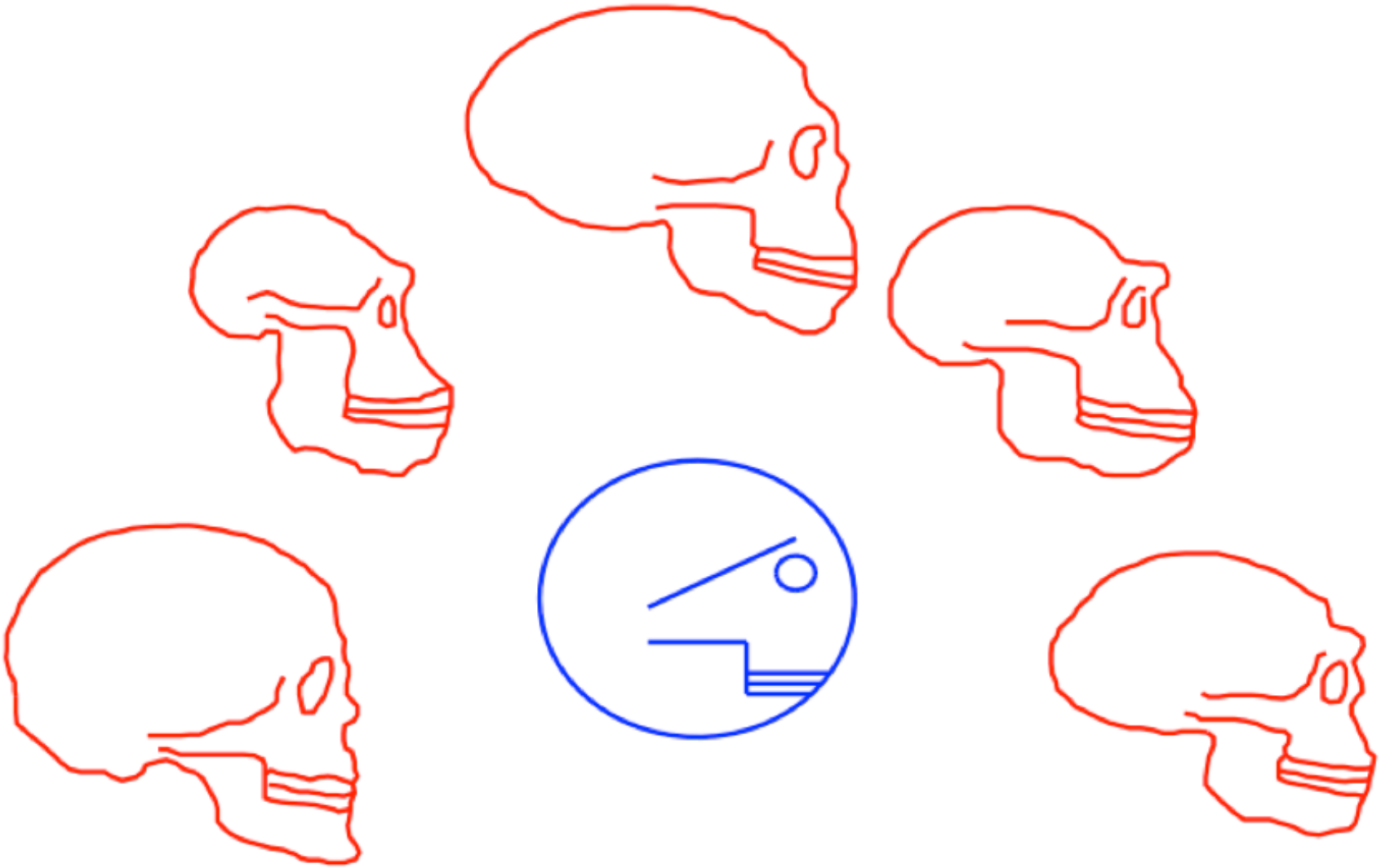
A decade of development

ARAMIS LAB
BRAIN DATA SCIENCE



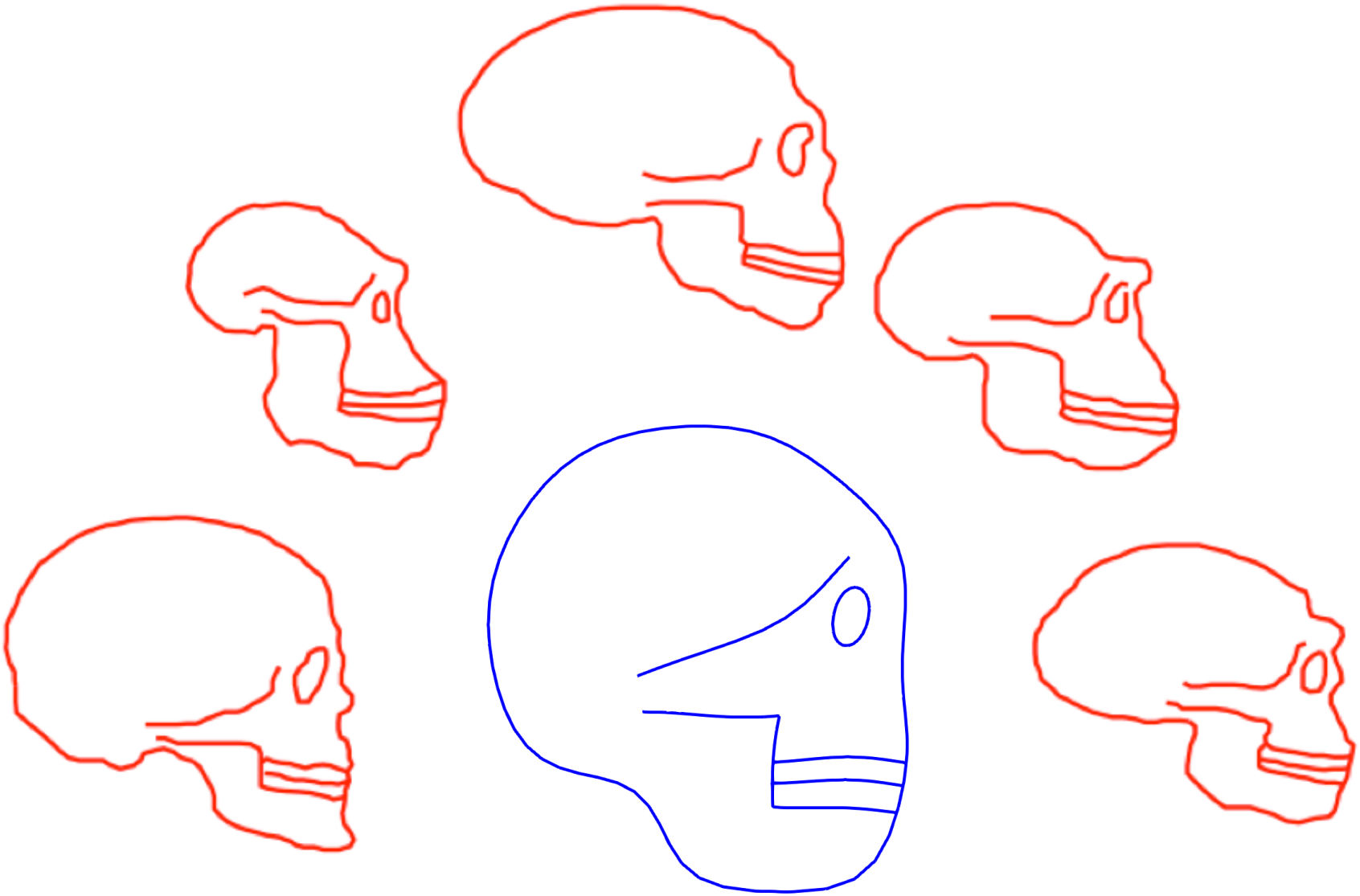
Deterministic atlas: *landmark/2d/skulls*

ARAMIS LAB
BRAIN DATA SCIENCE



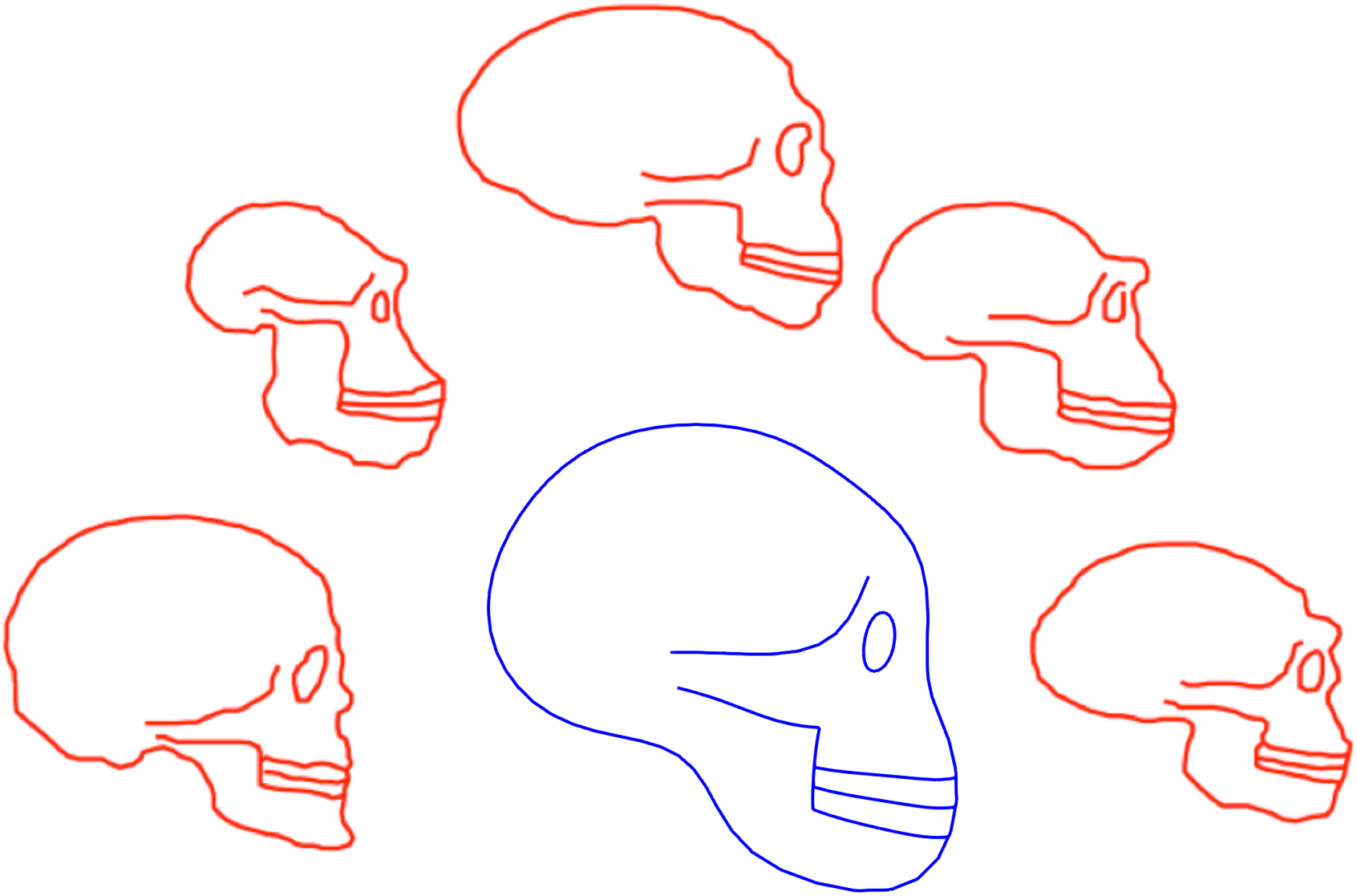
Deterministic atlas: *landmark/2d/skulls*

ARAMIS LAB
BRAIN DATA SCIENCE



Deterministic atlas: *landmark/2d/skulls*

ARAMIS LAB
BRAIN DATA SCIENCE



A note on the Bayesian atlas

ARAMIS LAB
BRAIN DATA SCIENCE

cost function = **attachment cost** + **regularization cost**

$$C(T,(\mu_i)_i,\sigma_\varepsilon^2) = \frac{1}{\sigma_\varepsilon^2}\sum_{i=1}^{n}\left\|\Phi_{\mu_i}\star T - S_i\right\|_\varepsilon^2 + R(\mu_i,\sigma_\varepsilon^2)$$

A note on the Bayesian atlas

ARAMIS LAB
BRAIN DATA SCIENCE

The optimal tradeoff between attachment and regularity terms is estimated from the data

$$C(T, (\mu_i)_i, \sigma_\varepsilon^2) = \frac{1}{\sigma_\varepsilon^2} \sum_{i=1}^{n} \left\| \Phi_{\mu_i} \star T - S_i \right\|_{\mathcal{E}}^2 + R(\mu_i, \sigma_\varepsilon^2)$$

Gives a statistical interpretation of the regularization term, which arises from assumed underlying random structures on the momenta and residuals

In practice, no need to specify σ_ε^2 anymore!

Bayesian atlas

ARAMIS LAB
BRAIN DATA SCIENCE

cost function = **attachment cost** + **regularization cost**

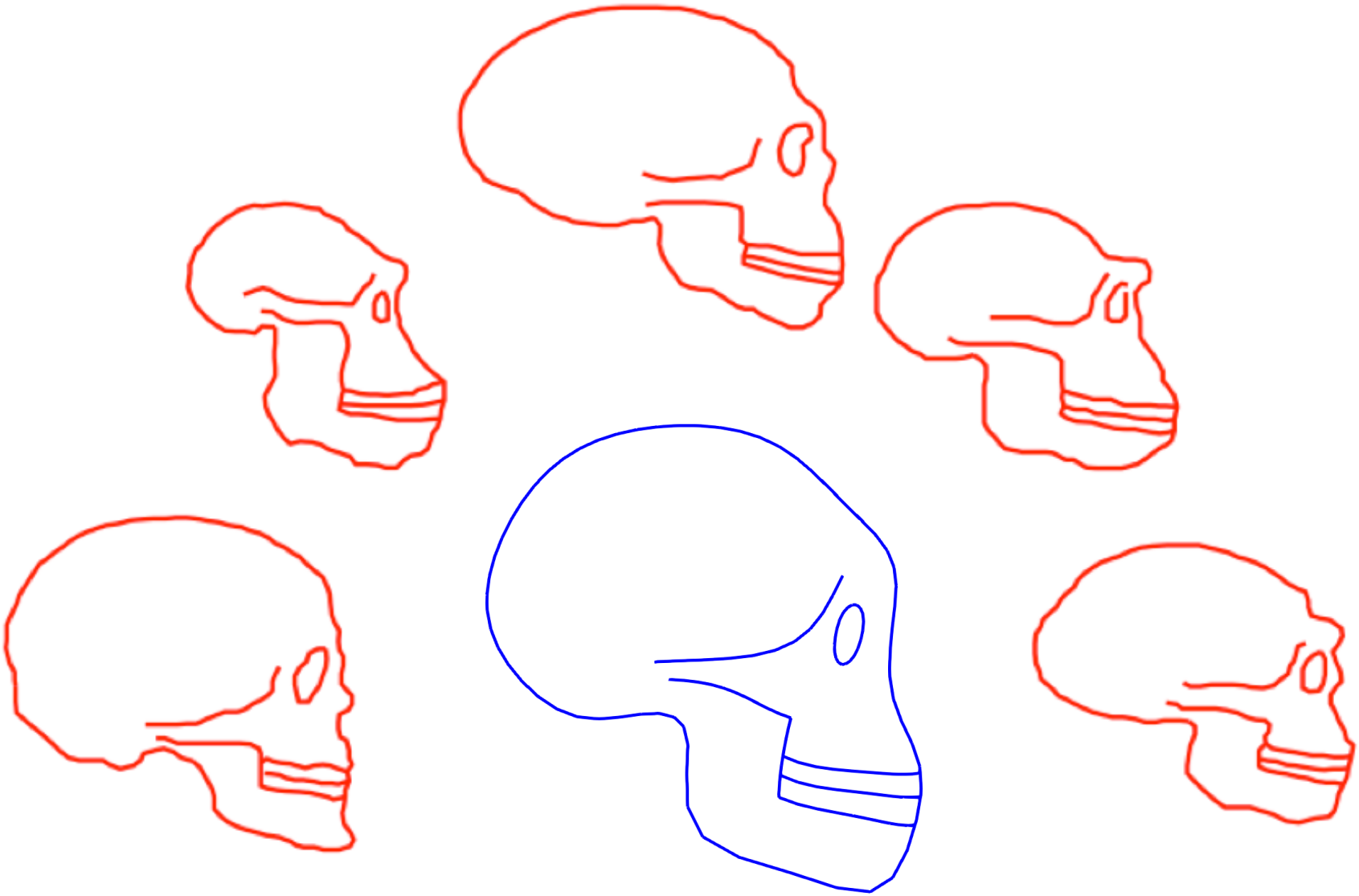
$$C(T,(\mu_i)_i,\sigma_\varepsilon^2) = \frac{1}{\sigma_\varepsilon^2}\sum_{i=1}^{n}\left\|\Phi_{\mu_i}\star T - S_i\right\|_{\mathcal{E}}^2 + R(\mu_i,\sigma_\varepsilon^2)$$

Statistical interpretation of the regularization term, which arises from assumed underlying random structures on the momenta and residuals

In practice, no need to specify σ_ε^2 anymore!

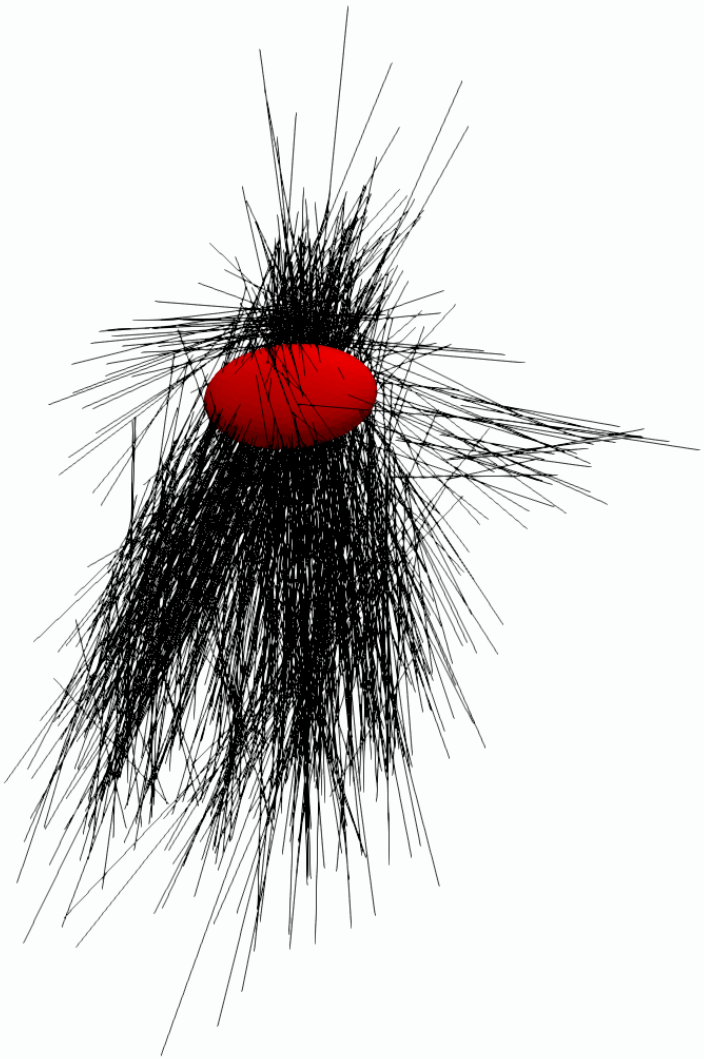
Bayesian atlas

ARAMIS LAB
BRAIN DATA SCIENCE

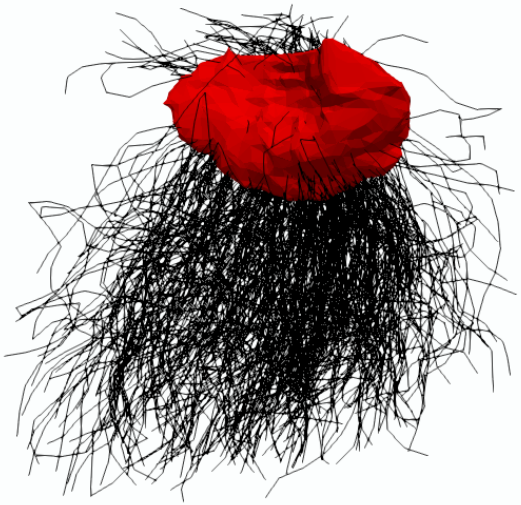


Registration

ARAMIS LAB
BRAIN DATA SCIENCE



T

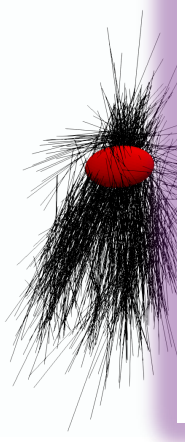


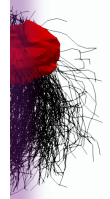
S

Registration

ARAMIS LAB
BRAIN DATA SCIENCE

```
<?xml Version="1.0"?>
<model>
    <model-type>Registration</model-type>
    <dimension>3</dimension>

    <template>

        <object Id="bundle">
            <deformable-object-type>PolyLine</deformable-object-type>
            <attachment-type>Varifold</attachment-type>
            <noise-std>1</noise-std>
            <kernel-width>11</kernel-width>
            <filename>data/bundle_prototype.vtk</filename>
        </object>

        <object Id="putamen">
            <deformable-object-type>SurfaceMesh</deformable-object-type>
            <attachment-type>Varifold</attachment-type>
            <noise-std>0.1</noise-std>
            <kernel-width>11</kernel-width>
            <filename>data/putamen_prototype.vtk</filename>
        </object>

    </template>

    <deformation-parameters>
        <kernel-width>15</kernel-width>
    </deformation-parameters>

</model>
```

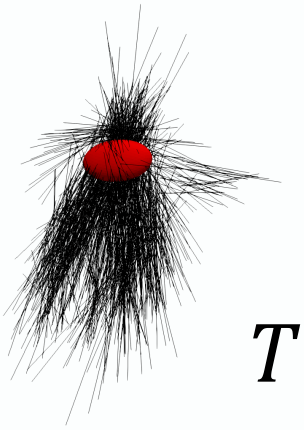




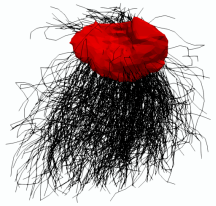
Registration

ARAMIS LAB
BRAIN DATA SCIENCE

```
<?xml Version="1.0"?>
<data-set>
    <subject Id="subj1">
        <visit Id="experiment">
            <filename Object_id="bundle">data/subject_bundle.vtk</filename>
            <filename Object_id="putamen">data/subject_putamen.vtk</filename>
        </visit>
    </subject>
</data-set>
```



T

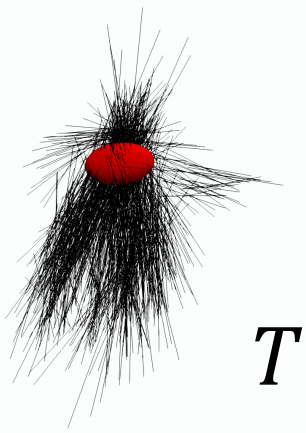


S

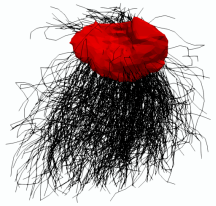
Registration

ARAMIS LAB
BRAIN DATA SCIENCE

```
<?xml Version="1.0"?>
<optimization-parameters>
    <optimization-method-type>ScipyLBFGS</optimization-method-type>
</optimization-parameters>
```



T



S

Registration

ARAMIS LAB
BRAIN DATA SCIENCE

```
>> deformetrica estimate model.xml
data_set.xml -p
optimization_parameters.xml
```