thrive
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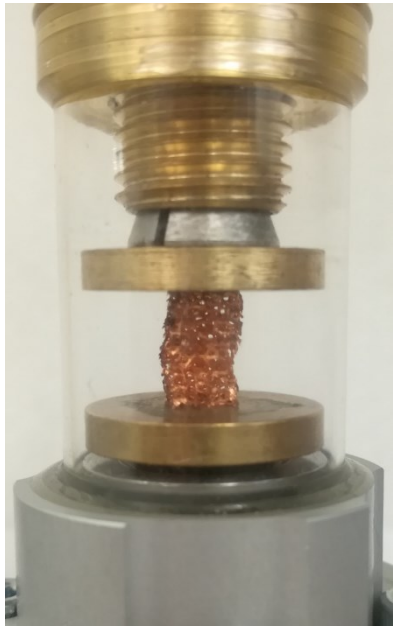
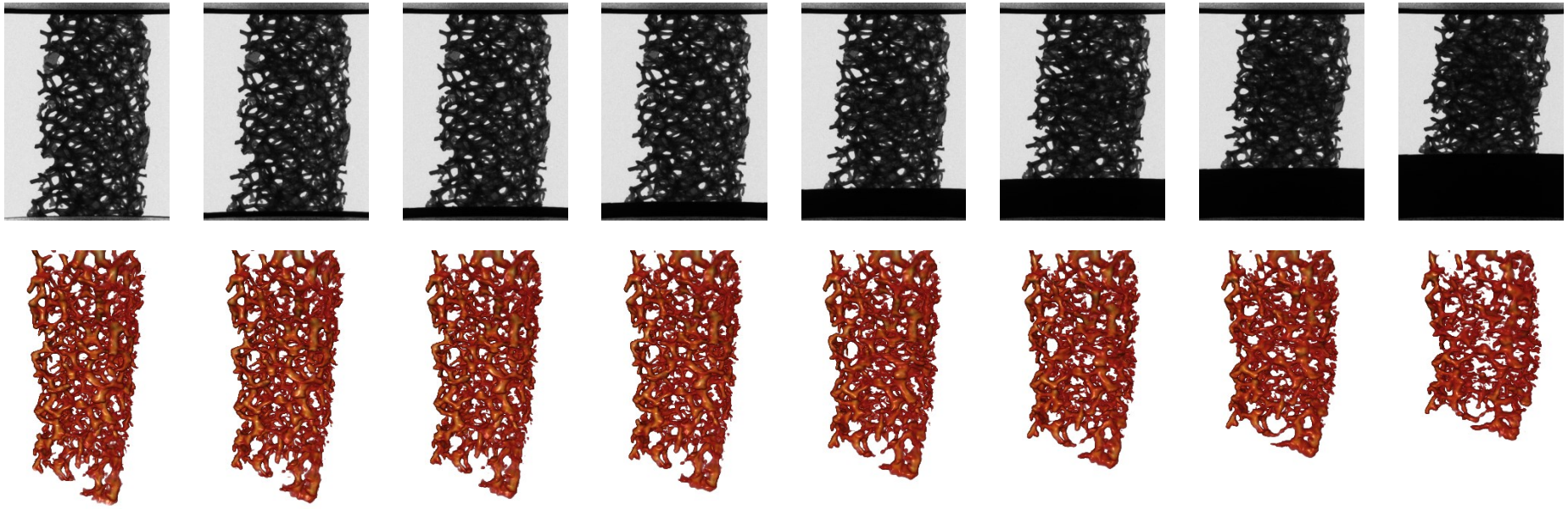
للعلوم والتقنية
King Abdullah University of
Science and Technology

Warp-and-Project Tomography for Rapidly Deforming Objects

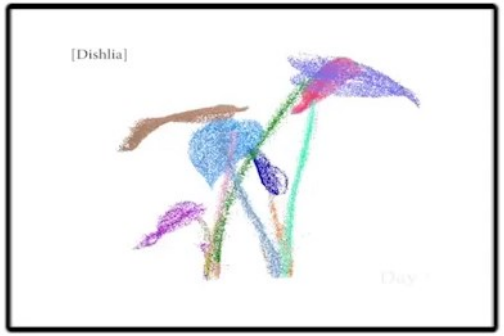
Guangming Zang, Ramzi Idoughi, Ran Tao, Gilles Lubineau, Peter Wonka, Wolfgang Heidrich,
King Abdullah University of Science And Technology





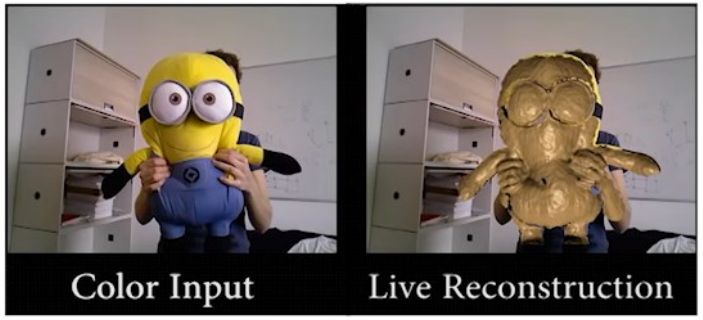
Dynamic scene reconstruction

[Wang et al. 2009]

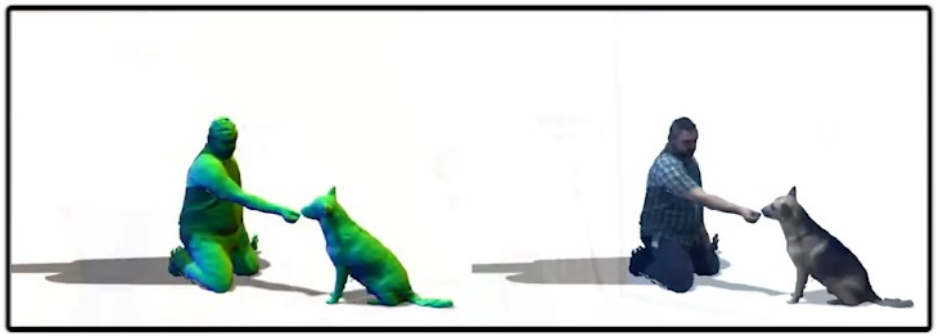


[Li et al. 2013]

[Zheng et al. 2017]

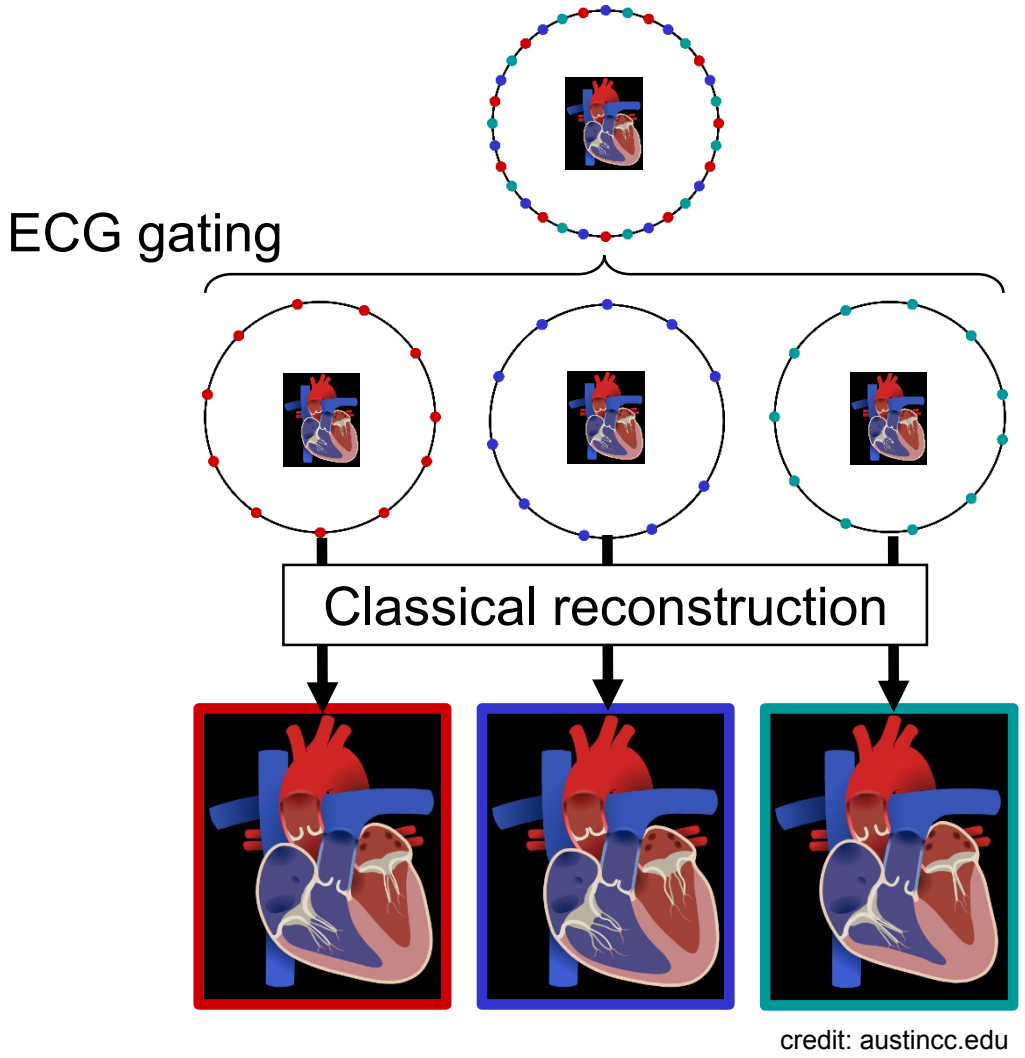


[Innmann et al. 2016]



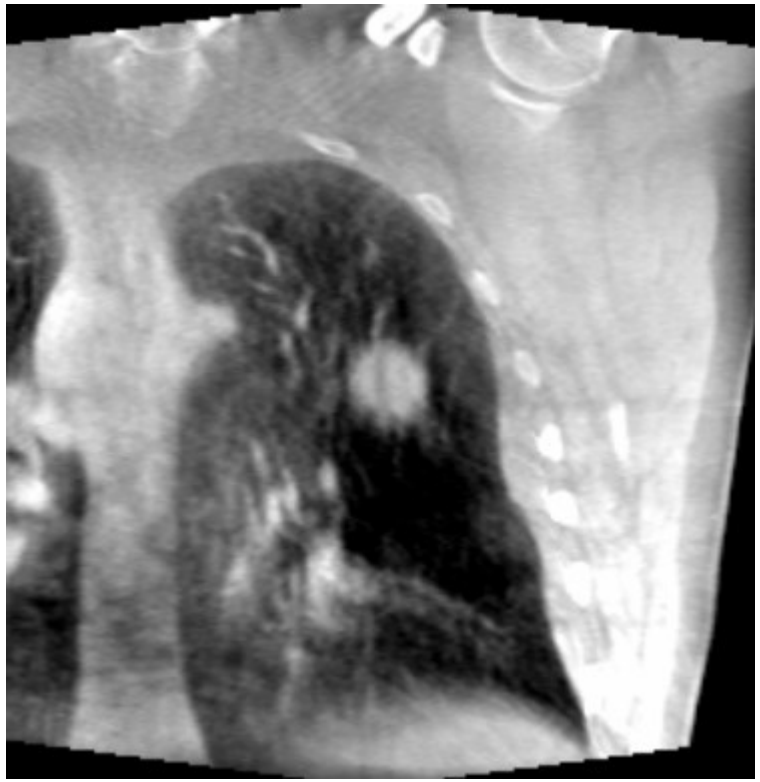
[Dou et al. 2016]

Dynamic X-ray tomography



credit: austincc.edu

[Chen et al. 2012]



credit: RTK

[Mory et al. 2016]

Dynamic scene reconstruction

	Optical means	X-ray tomography
Cameras/ sensors	One or more	**One**
Resolution	Low	**High**
Reconstruction	Surface	**Surface + internal structures**
Capture Speed	**Fast**	Slow
Deformation type	**General**	Periodic or with Pattern
Application fields	**General**	Medical, Security, Industry

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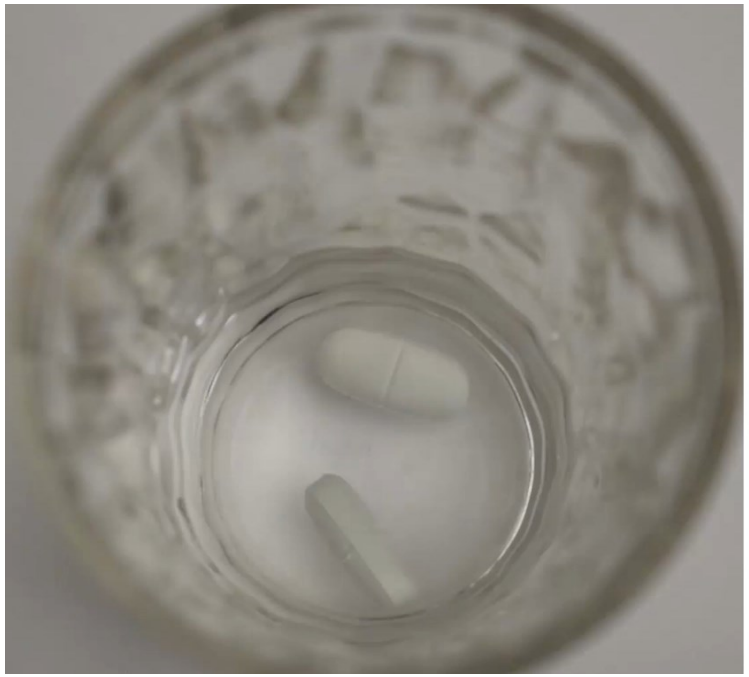
High quality surface and internal reconstruction for fast deforming objects with general motion

Motivation

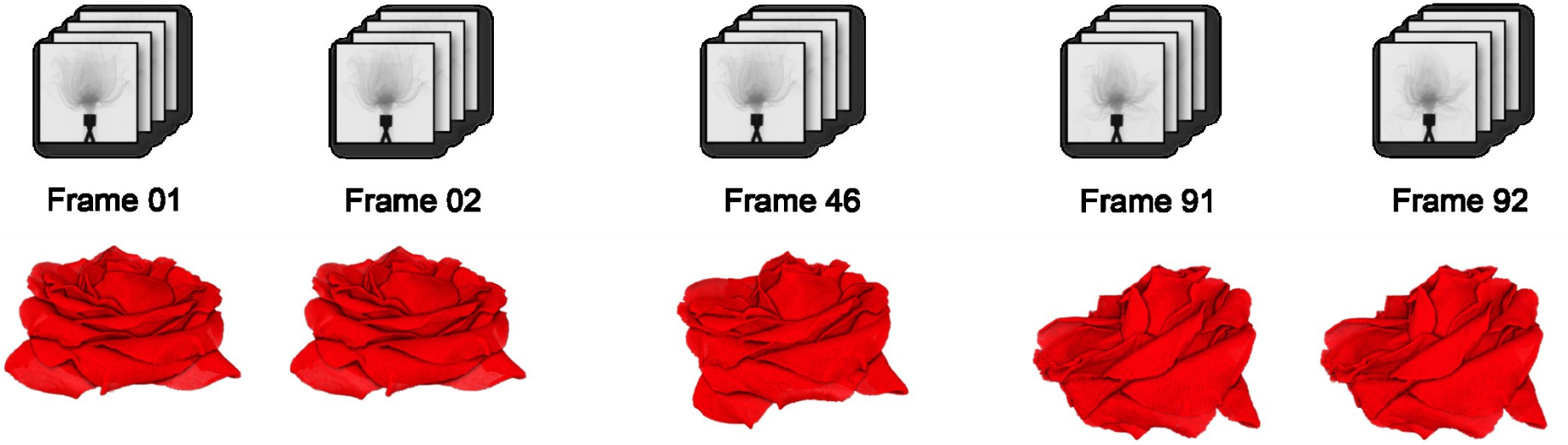
Is it possible to scan rapidly deforming objects with internal details?



Pills dissolving

Hydro-gel balls

Motivation



Space time tomography
[Zang et al. SIGGRAPH18]

Shortcomings ?

- **Assumption:** slow and smooth motion fields
- **Trade-off:** spatial *VS.* temporal reconstruction quality
- **Sampling:** costly uniform temporal sampling

Motivation

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SART-ROF
[Getreuer 2012]

ST-Tomography
[Zang et al. 2018]

Warp-and-Project
[Ours]

Image formation model

Ω_i: X-ray path

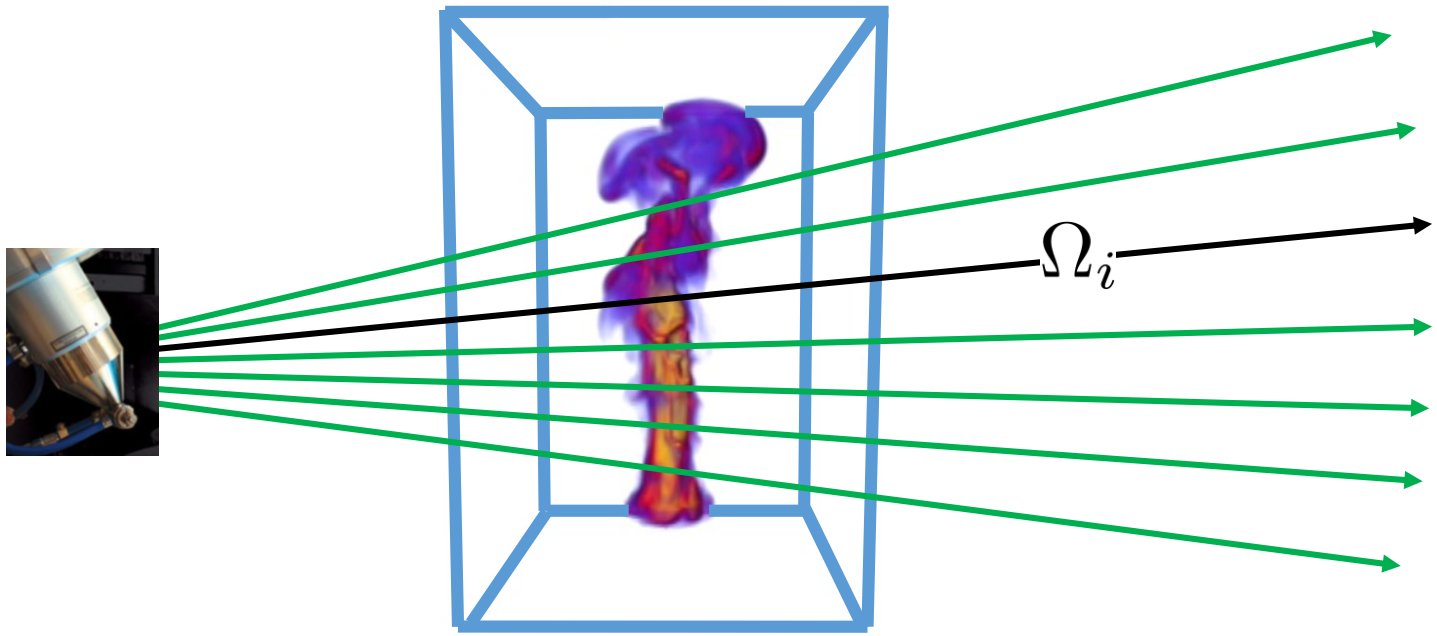


Image formation model

Ω_i: X-ray path $h(x)$: Unknown field

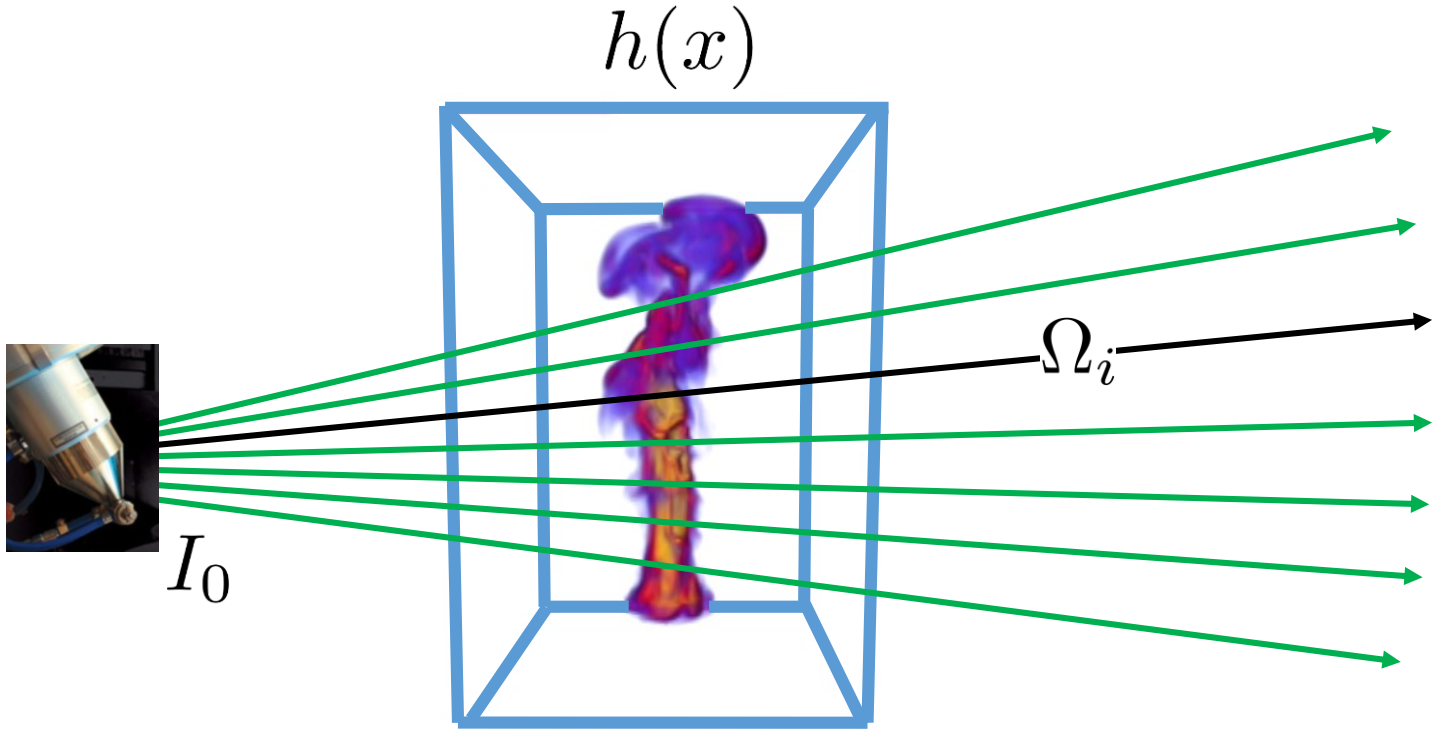
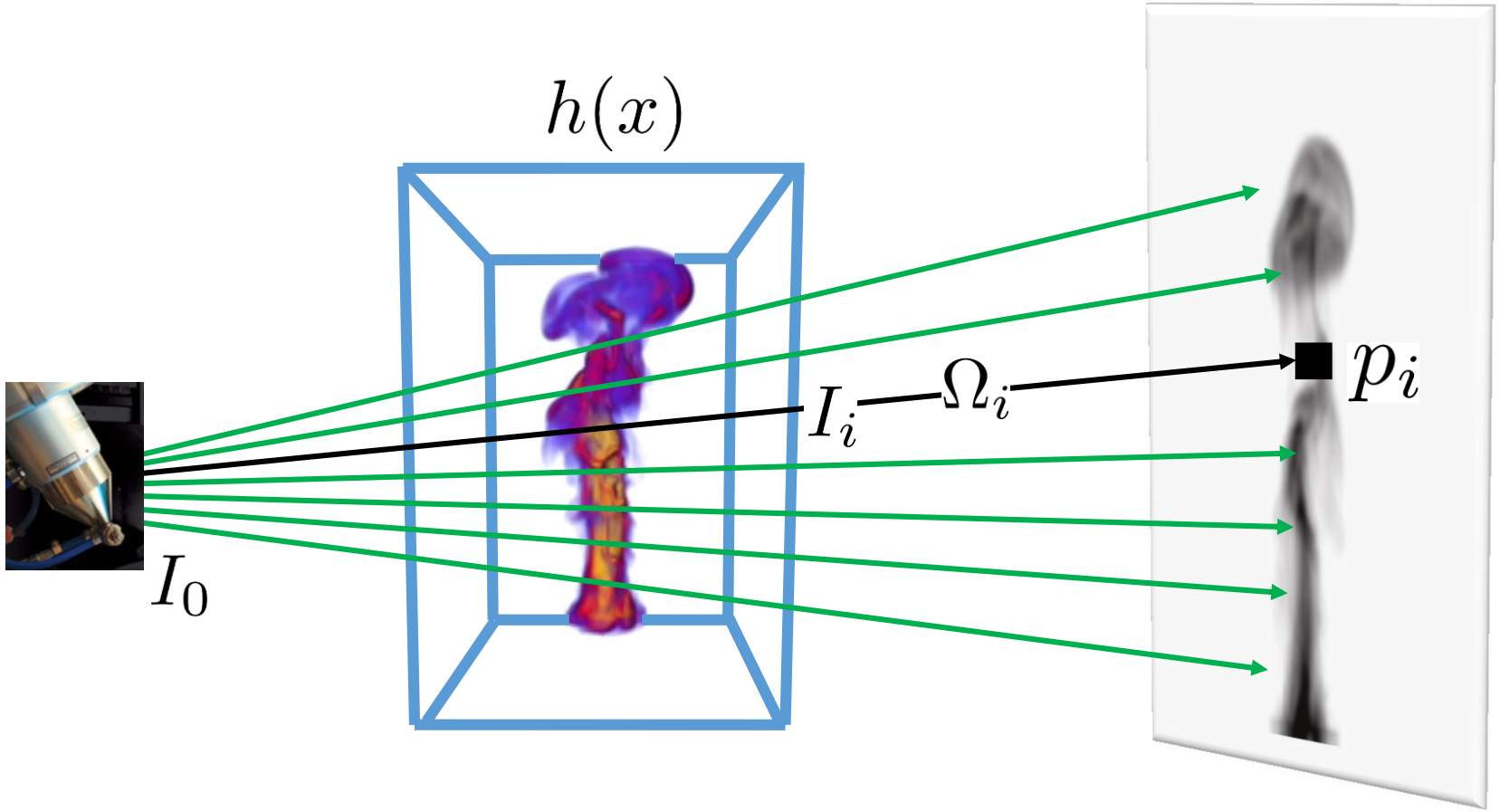


Image formation model

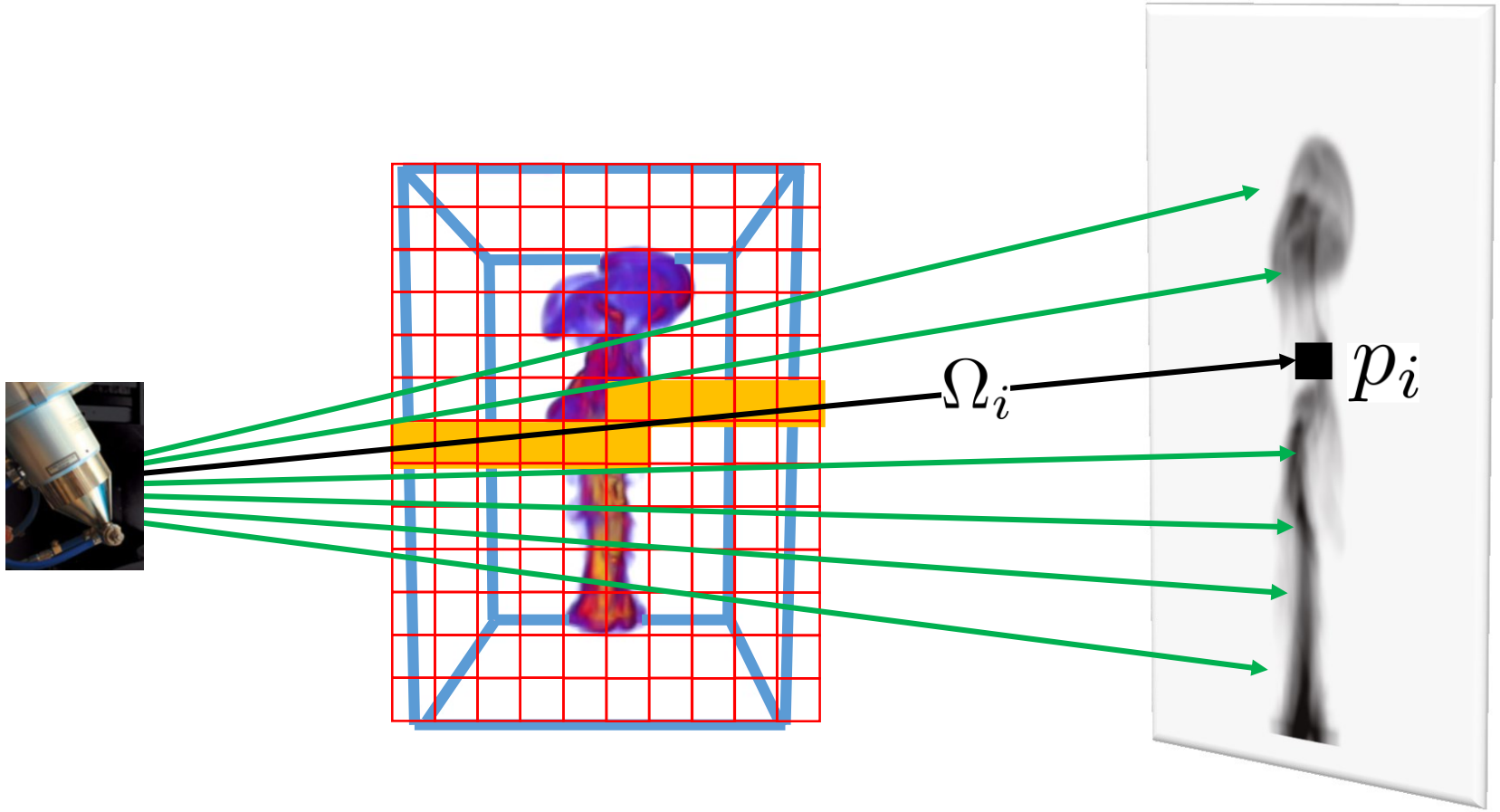
Ω_i: X-ray path $h(x)$: Unknown field p_i : Measurement



$$\int_{\Omega_i} h(x)\, d\Omega_i = \underbrace{-log\,(I_i/I_0)}_{p_i}$$

Image formation model

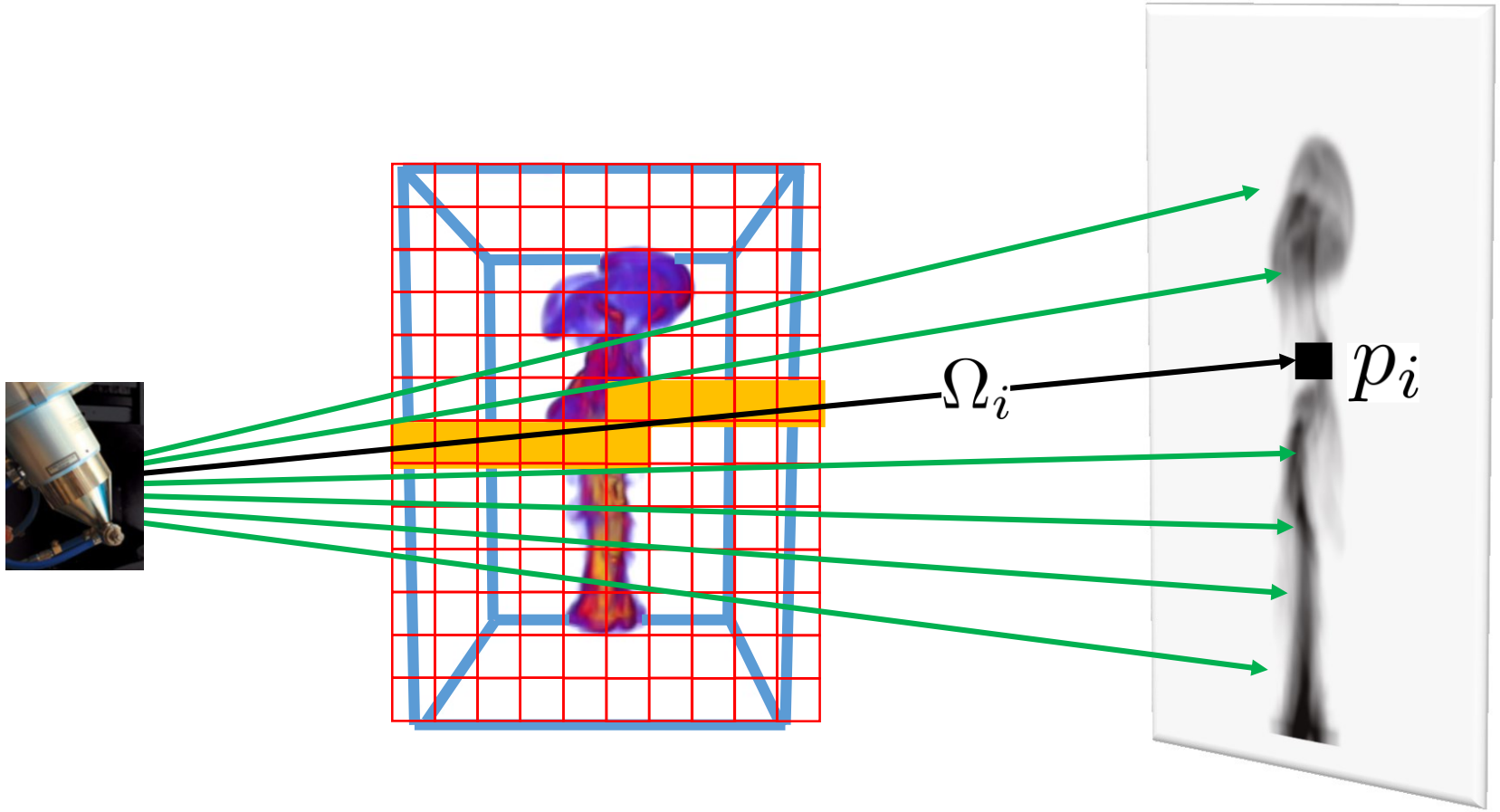
Ω_i: X-ray path $h(x)$: Unknown field p_i : Measurement



$$\sum_j h_j A_{ij} = p_i$$

Image formation model

Ω_i: X-ray path $h(x)$: Unknown field p_i : Measurement



$$\sum_j h_j A_{ij} = p_i$$

$$A_t h_t = \mathrm{p}_t$$

Each projection image has its own time stamp!

Linear system

- Sparse system
- Memory consuming
- Ill-posed problem

$$\underbrace{\begin{pmatrix} \mathbf{A}_1 & & & \\ & \ddots & & \\ & & \mathbf{A}_j & \\ & & & \ddots \\ & & & \mathbf{A}_{N_p} \end{pmatrix}}_{\mathbf{A}} \cdot \underbrace{\begin{pmatrix} \mathbf{h}_1 \\ \vdots \\ \mathbf{h}_j \\ \vdots \\ \mathbf{h}_{N_p} \end{pmatrix}}_{\mathbf{h}} = \underbrace{\begin{pmatrix} \mathbf{p}_1 \\ \vdots \\ \mathbf{p}_j \\ \vdots \\ \mathbf{p}_{N_p} \end{pmatrix}}_{\mathbf{p}},$$

Radon Transform Frames Measurements

Warp and project tomography

- Non-parametric and matrix-free
- No assumption of the motion
- A non-uniform temporal up-sampling

Objective function

$$\min_{\mathbf{f},\mathbf{u}} \sum_{j=1}^{N_p} \left\| \mathbf{A}_j \mathbf{W}_j^f(\mathbf{f}_{j^-}) - \mathbf{p}_j \right\|_2^2 + \sum_{j=1}^{N_p} \left\| \mathbf{A}_j \mathbf{W}_j^b(\mathbf{f}_{j^+}) - \mathbf{p}_j \right\|_2^2$$

$$+\kappa_1 \sum_{k=1}^{N_k-1} \|\nabla_T \mathbf{f}_k + \nabla_S \mathbf{f}_k \cdot \mathbf{u}_k\|_1$$

$$+ \sum_{k=1}^{N_k} \left[\kappa_2 \|\nabla_S \mathbf{f}_k\|_{\mathrm{H}_\epsilon} + \kappa_3 \|\nabla_T \mathbf{f}_k\|_2^2 \right]$$

$$+ \sum_{k=1}^{N_k-1} \sum_{i=x,y,z} \left[\kappa_4 \left\|\nabla_S \mathbf{u}_{k,i}\right\|_{\mathrm{H}_\tau} + \kappa_5 \left\|\nabla_T \mathbf{u}_{k,i}\right\|_2^2 \right]$$

Objective function

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Data fitting
(Forward / backward warping)

$$+\kappa_1 \sum_{k=1}^{N_k-1} \|\nabla_T \mathbf{f}_k + \nabla_S \mathbf{f}_k \cdot \mathbf{u}_k\|_1$$

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Data fitting
(Forward / backward warping)

Volume correlation

Objective function

$$\min_{\mathbf{f},\mathbf{u}} \sum_{j=1}^{N_p} \left\| \mathbf{A}_j \mathbf{W}_j^f(\mathbf{f}_{j^-}) - \mathbf{p}_j \right\|_2^2 + \sum_{j=1}^{N_p} \left\| \mathbf{A}_j \mathbf{W}_j^b(\mathbf{f}_{j^+}) - \mathbf{p}_j \right\|_2^2$$

Data fitting
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$$+\kappa_1 \sum_{k=1}^{N_k-1} \|\nabla_T \mathbf{f}_k + \nabla_S \mathbf{f}_k \cdot \mathbf{u}_k\|_1$$

Volume correlation

$$+ \sum_{k=1}^{N_k} \left[\kappa_2 \|\nabla_S \mathbf{f}_k\|_{\mathrm{H}_\epsilon} + \kappa_3 \|\nabla_T \mathbf{f}_k\|_2^2 \right]$$

Volume smoothness

$$+ \sum_{k=1}^{N_k-1} \sum_{i=x,y,z} \left[\kappa_4 \left\|\nabla_S \mathbf{u}_{k,i}\right\|_{\mathrm{H}_\tau} + \kappa_5 \left\|\nabla_T \mathbf{u}_{k,i}\right\|_2^2 \right]$$

Objective function

$$\min_{\mathbf{f},\mathbf{u}} \sum_{j=1}^{N_p} \left\| \mathbf{A}_j \mathbf{W}_j^f(\mathbf{f}_{j^-}) - \mathbf{p}_j \right\|_2^2 + \sum_{j=1}^{N_p} \left\| \mathbf{A}_j \mathbf{W}_j^b(\mathbf{f}_{j^+}) - \mathbf{p}_j \right\|_2^2$$

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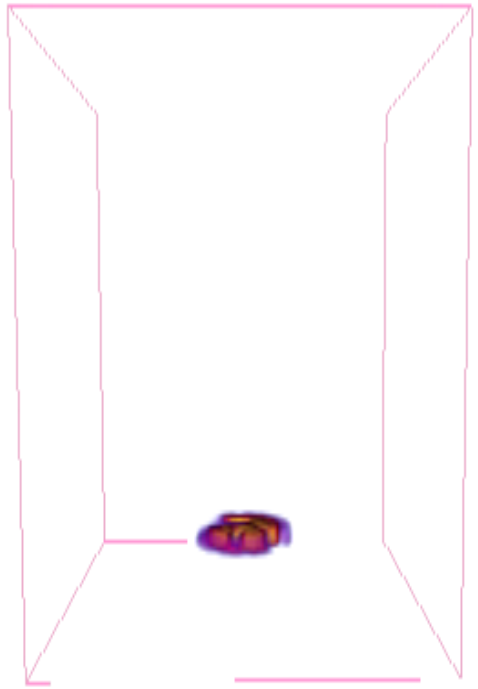
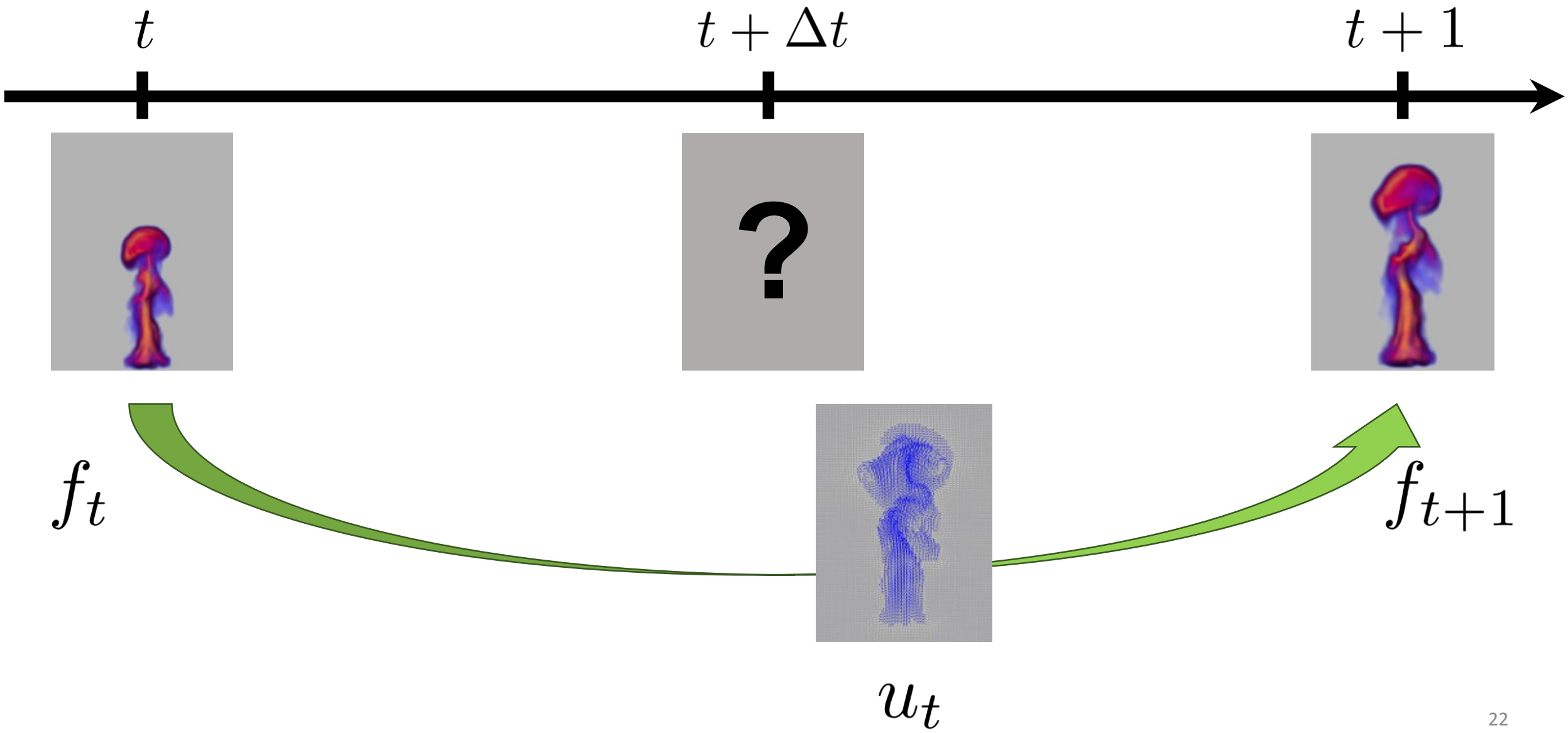
Deformation field smoothness

Optimization framework

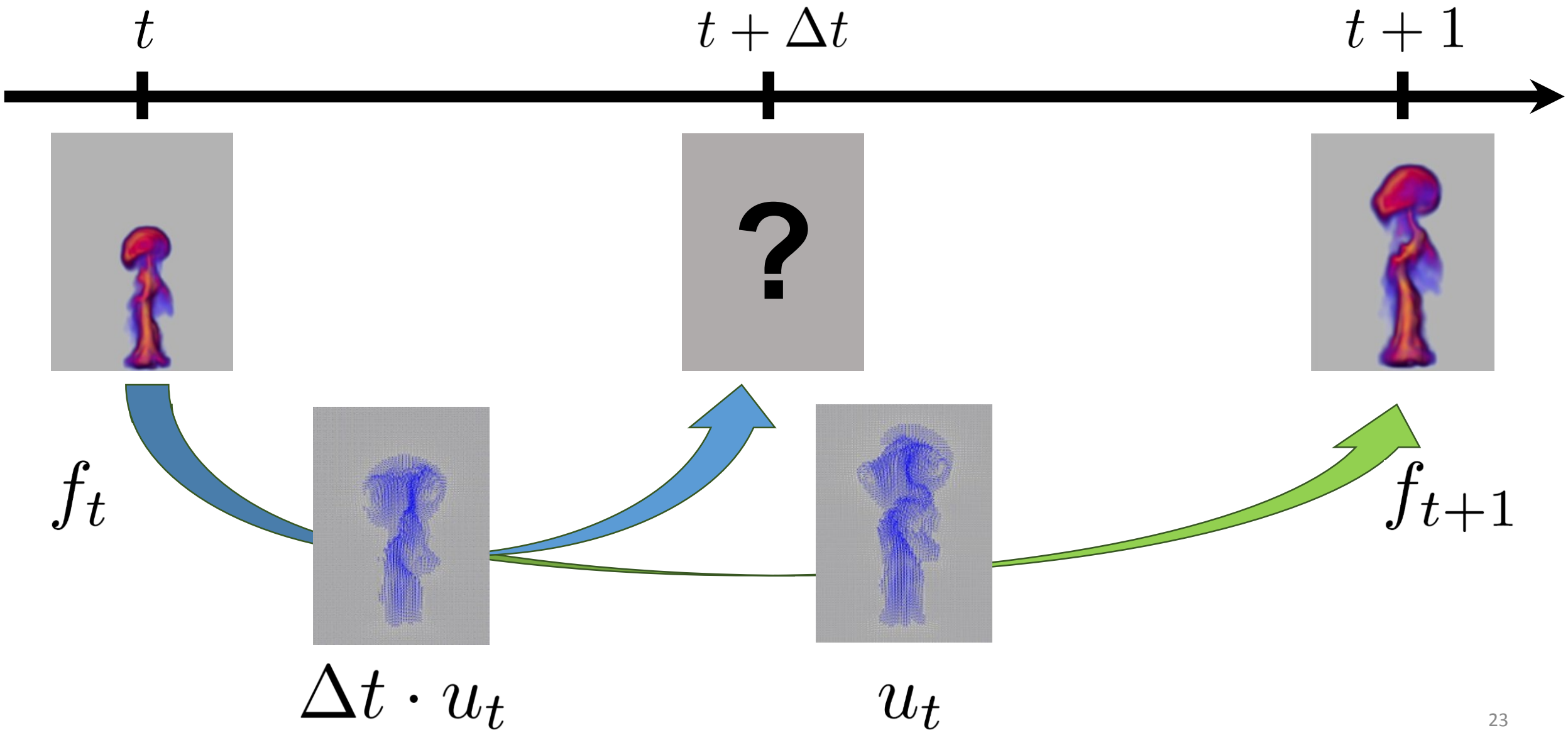
Simulated plume data
Volume size: 100x150x100
Time frames: 300



Warping operator



Warping operator



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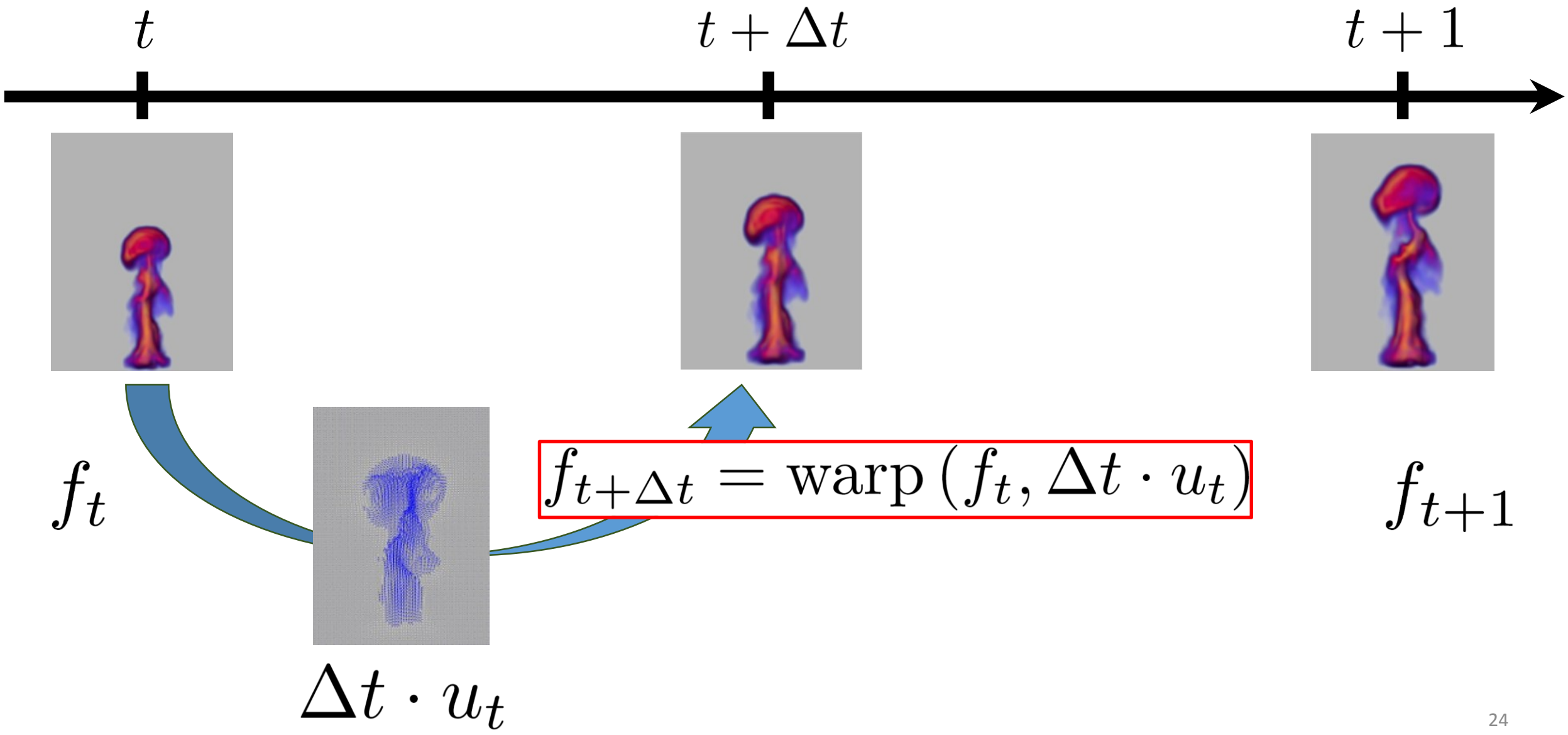
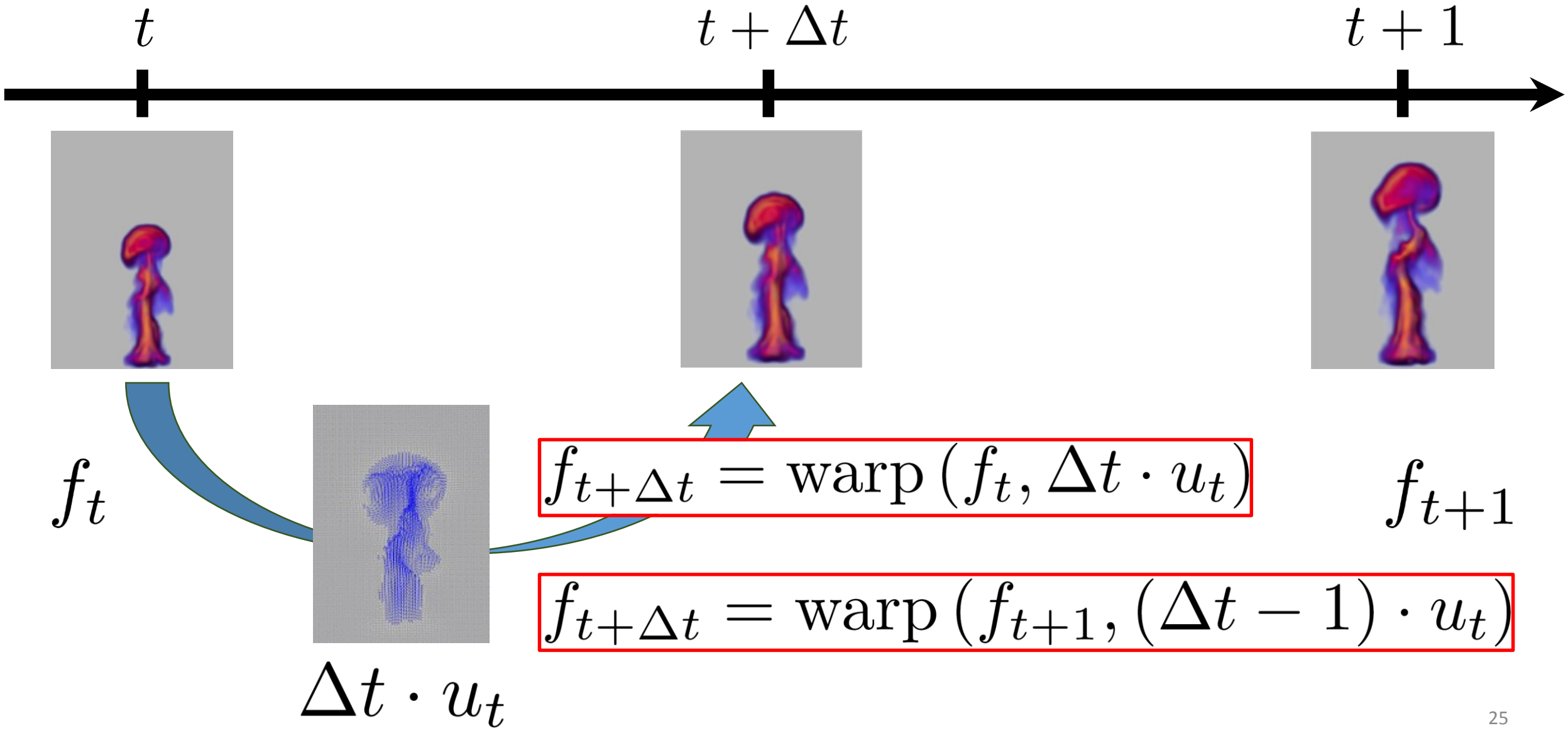
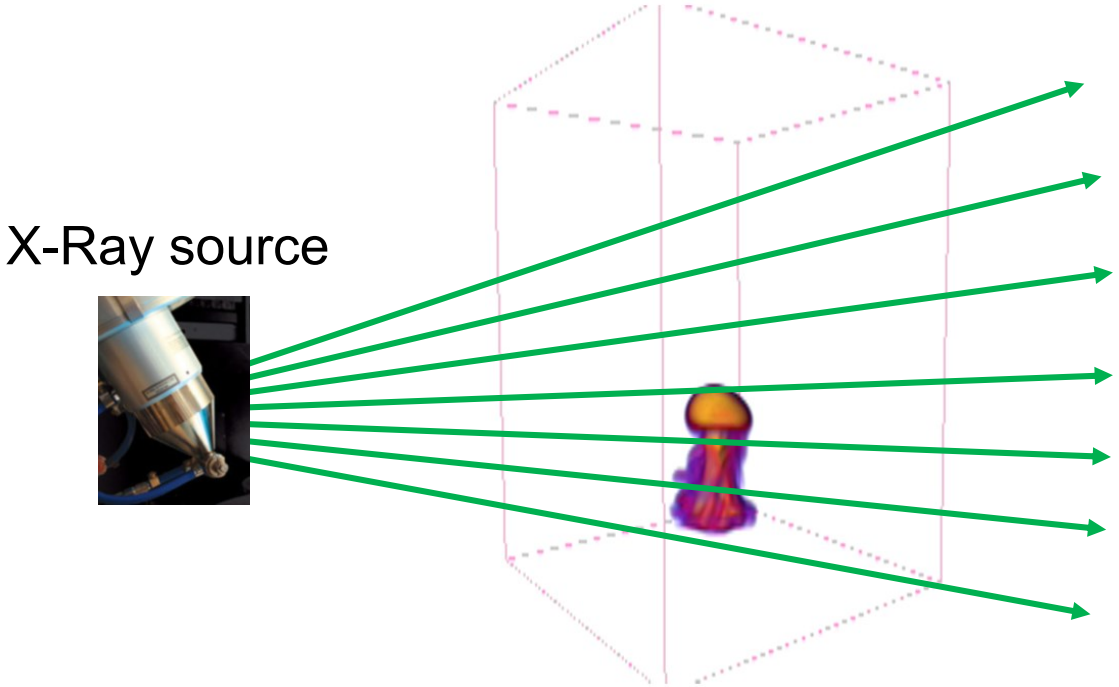


Warping operator



Optimization framework

t_1



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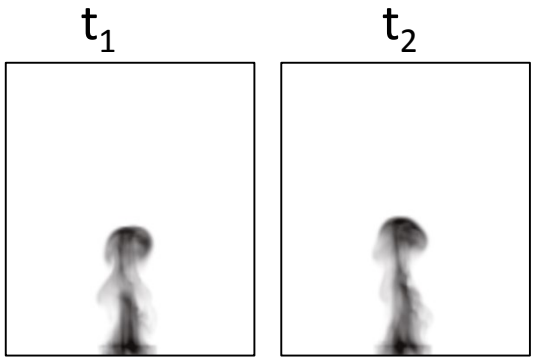

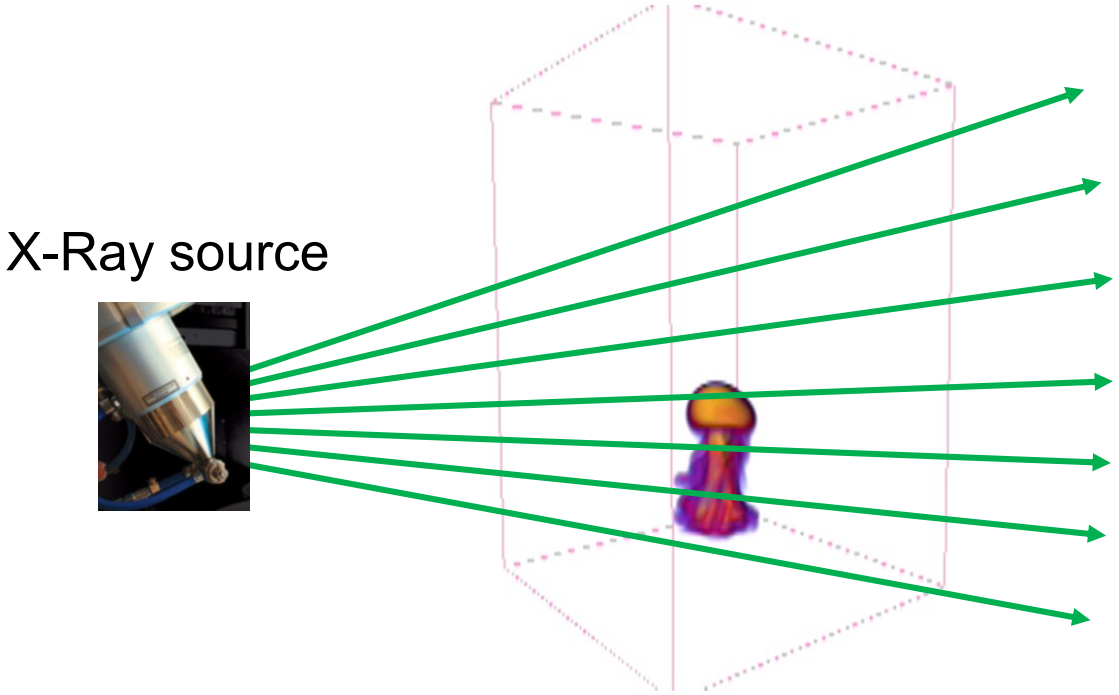

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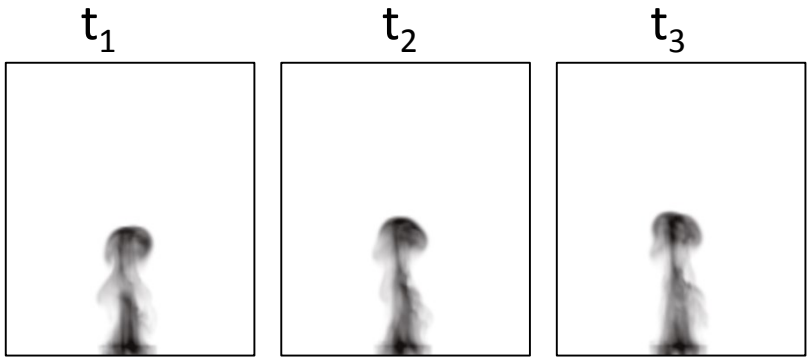

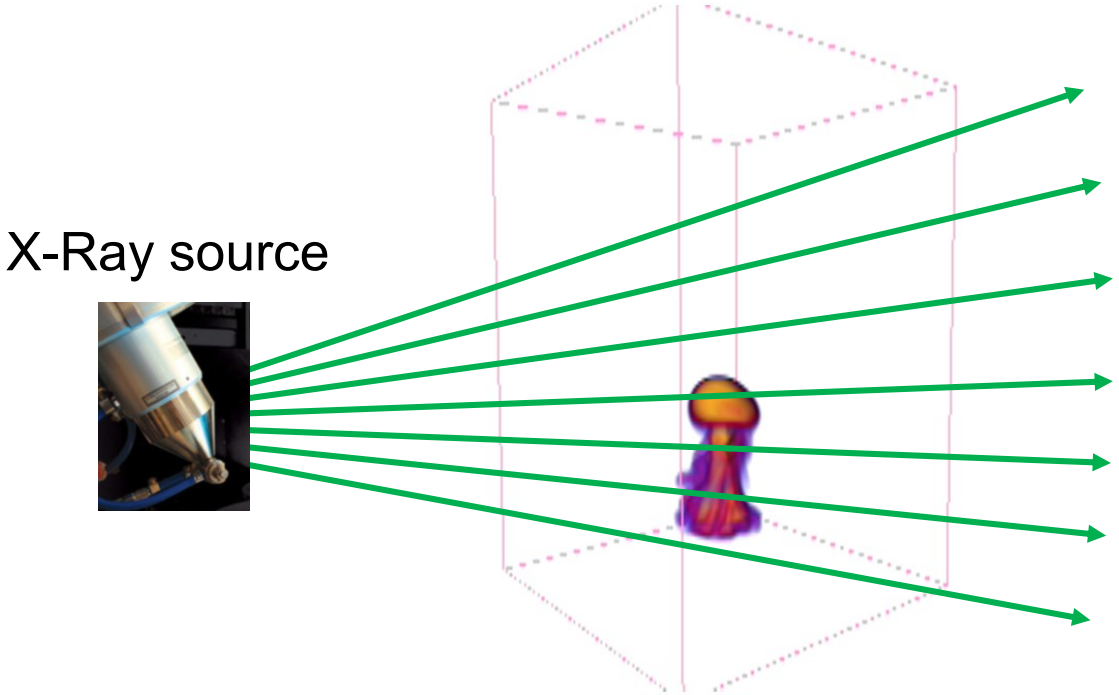

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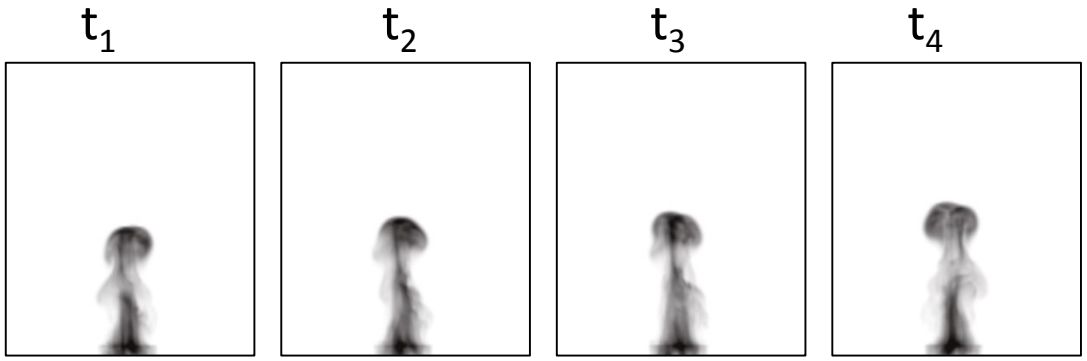

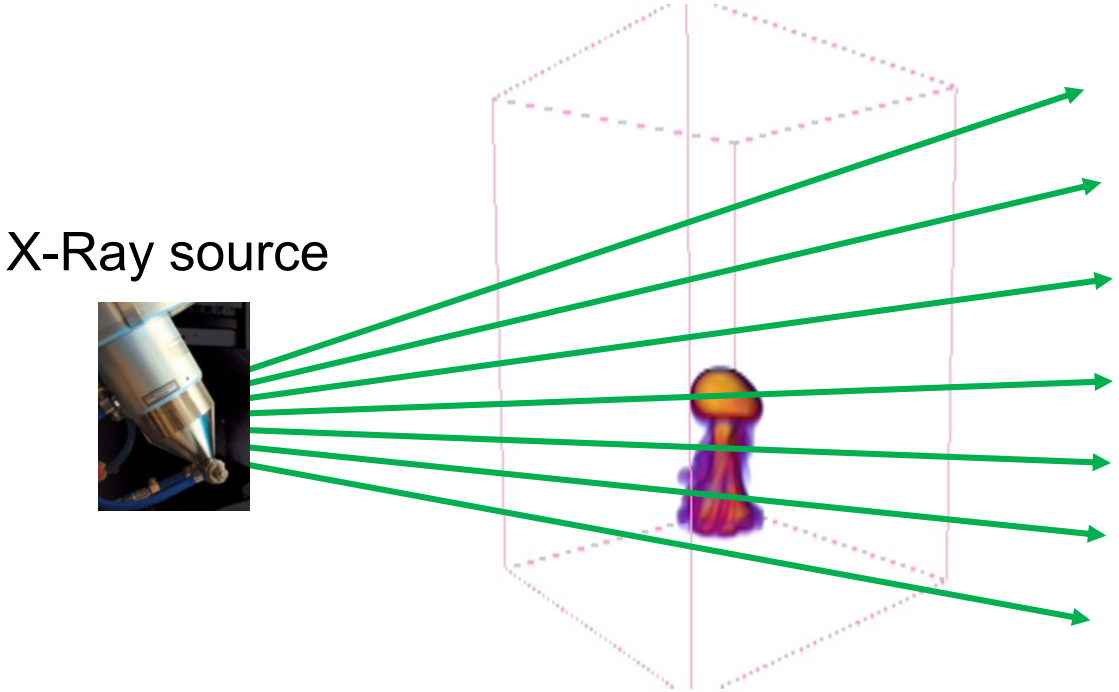

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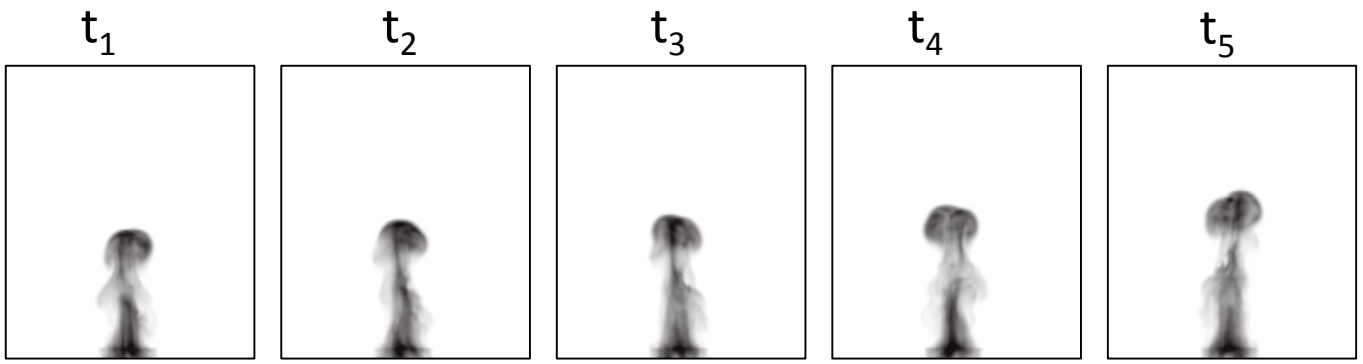

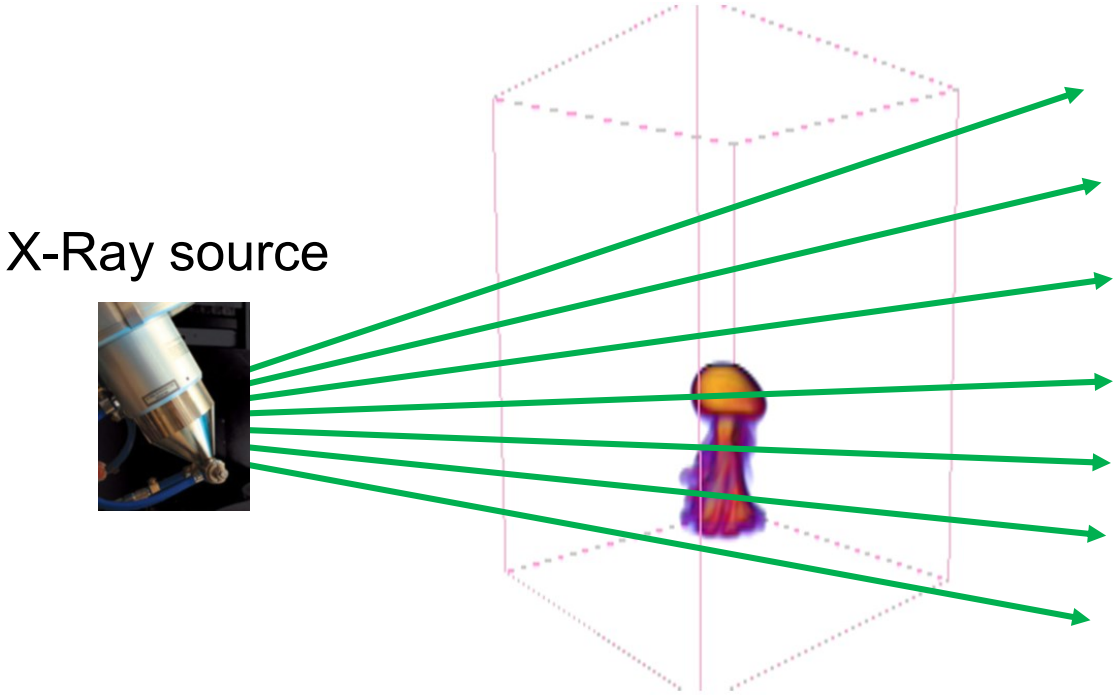

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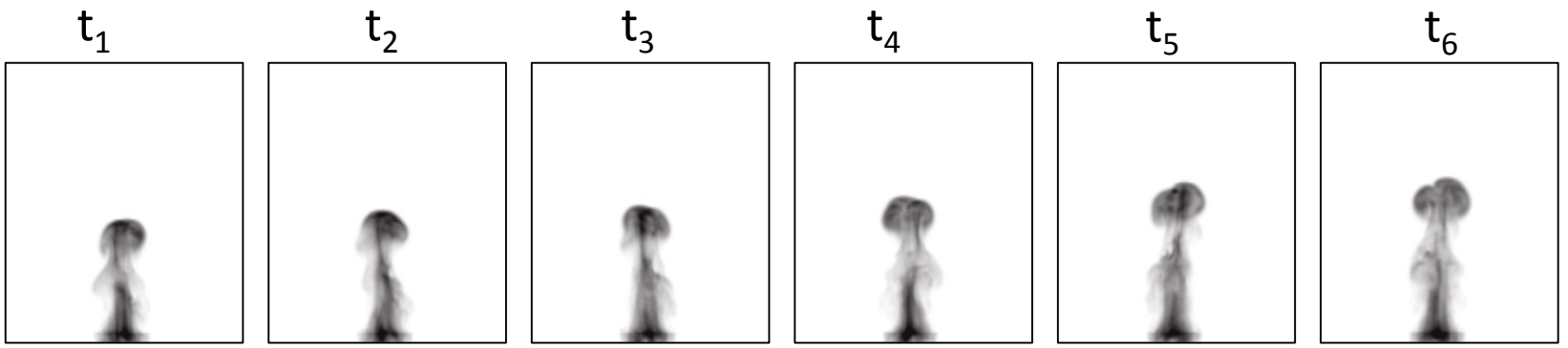

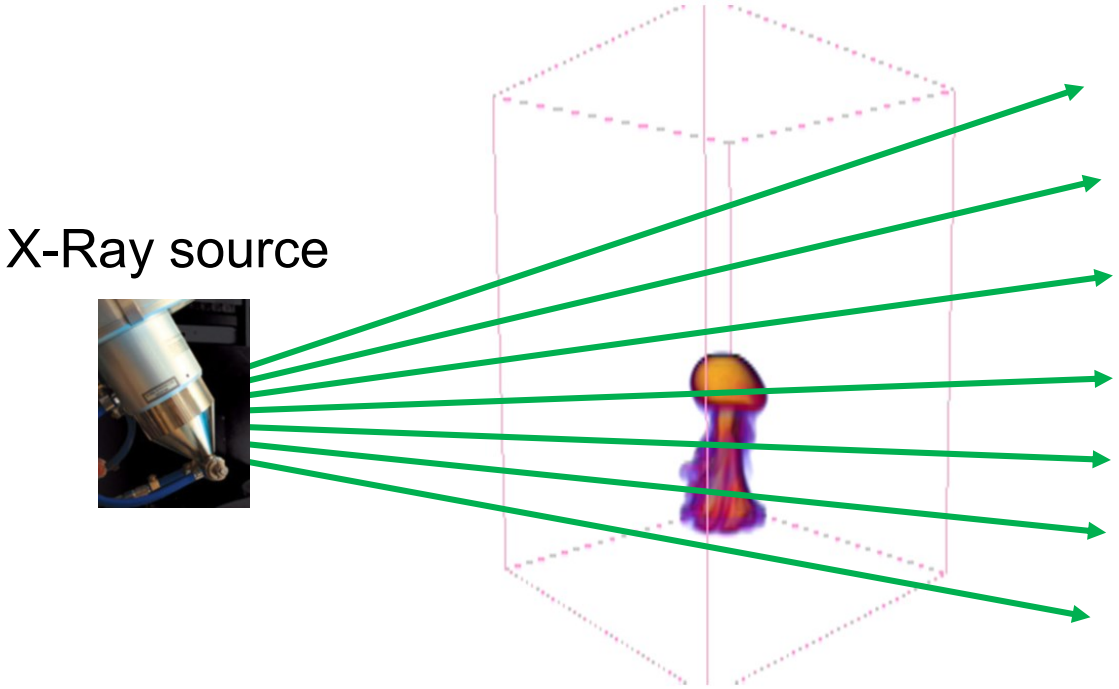

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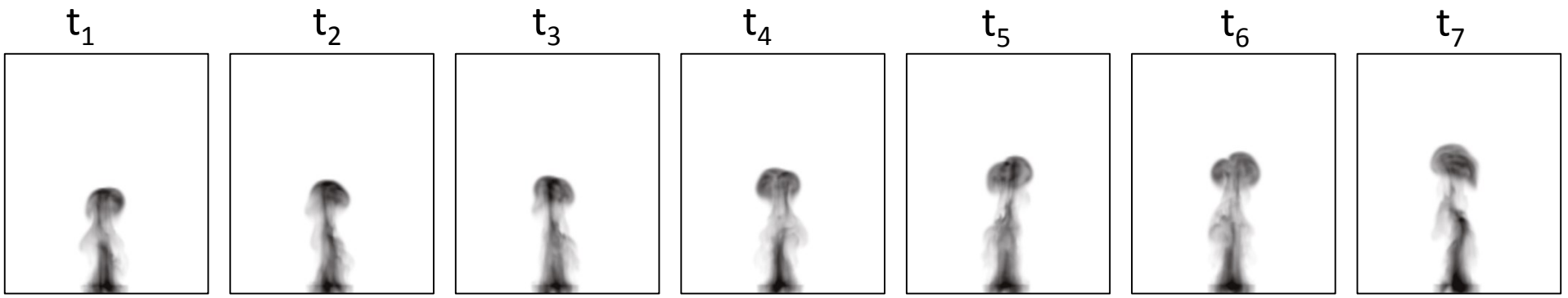

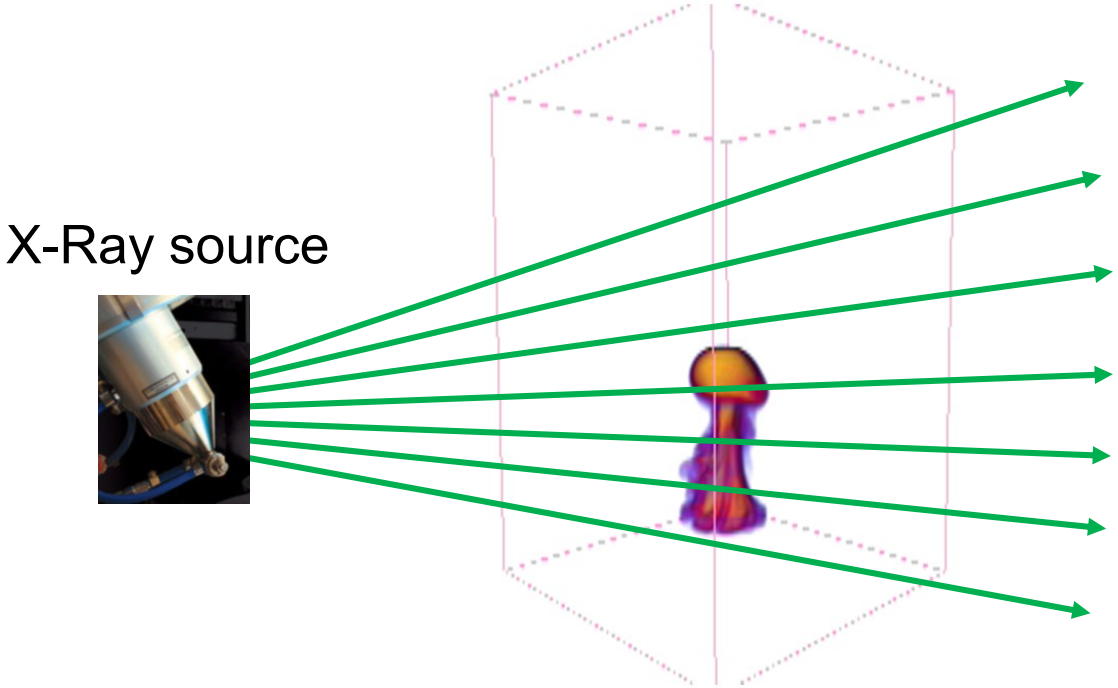

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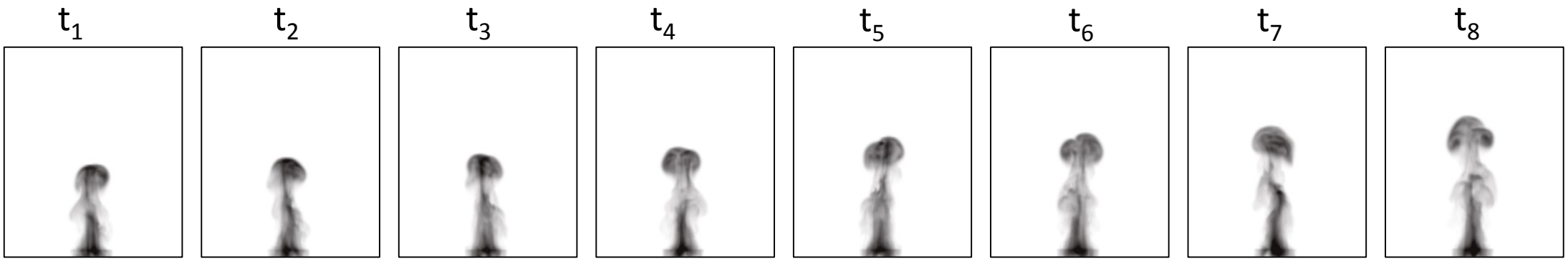

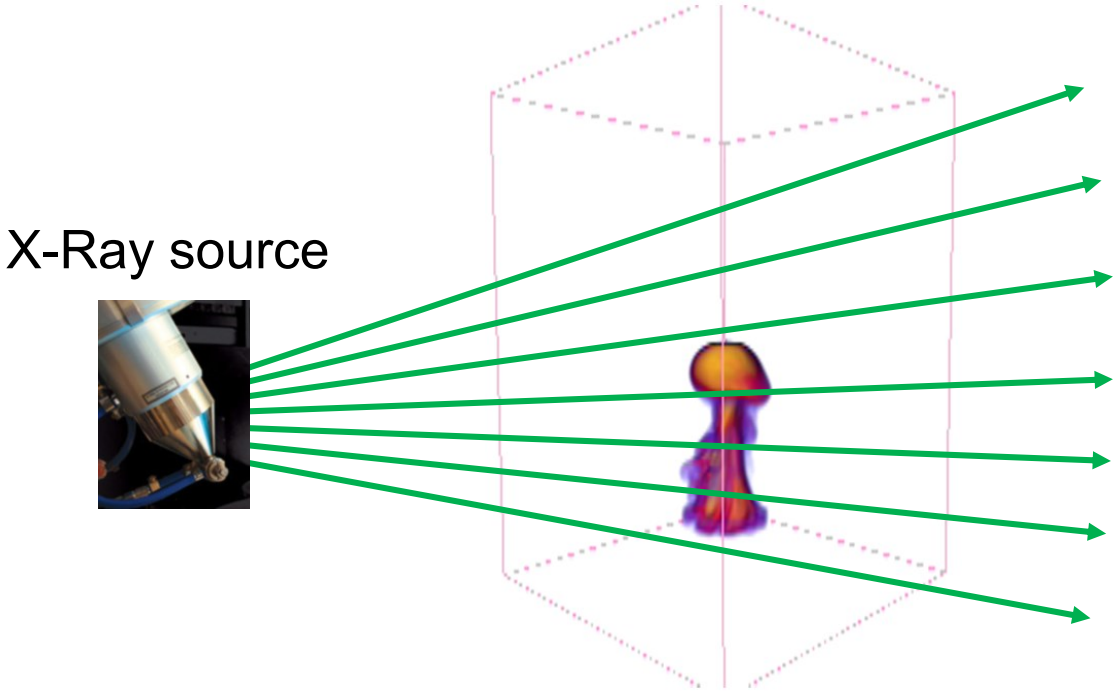

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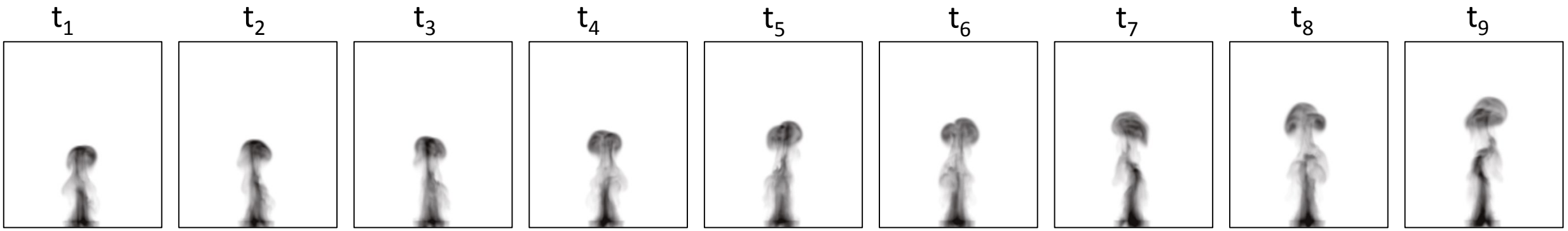

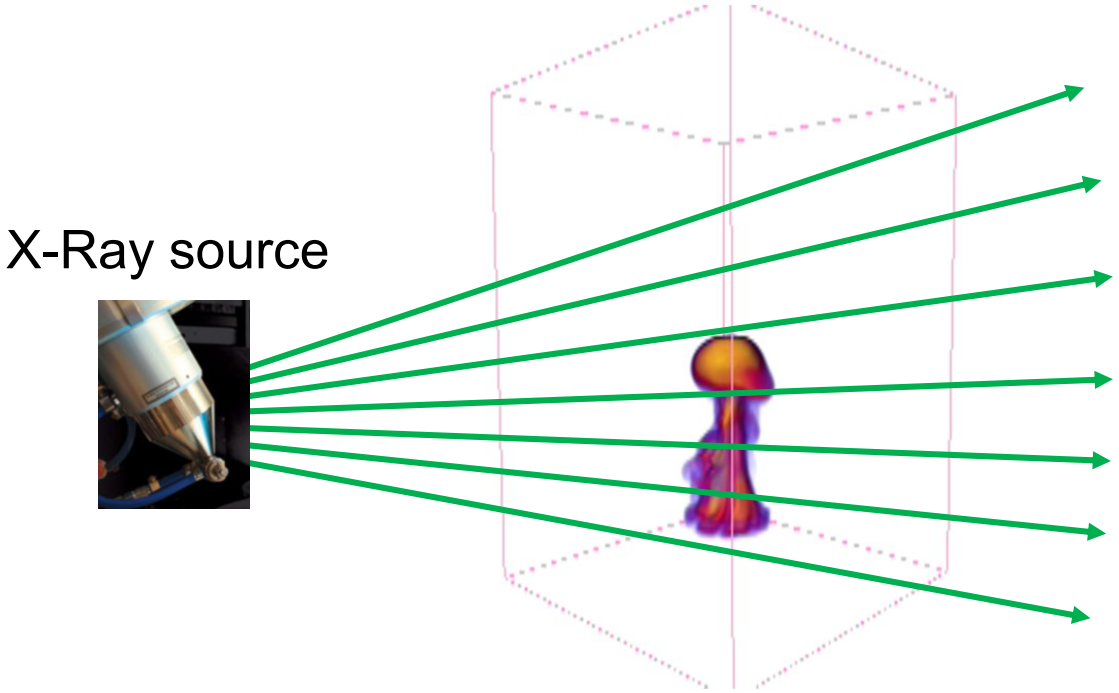

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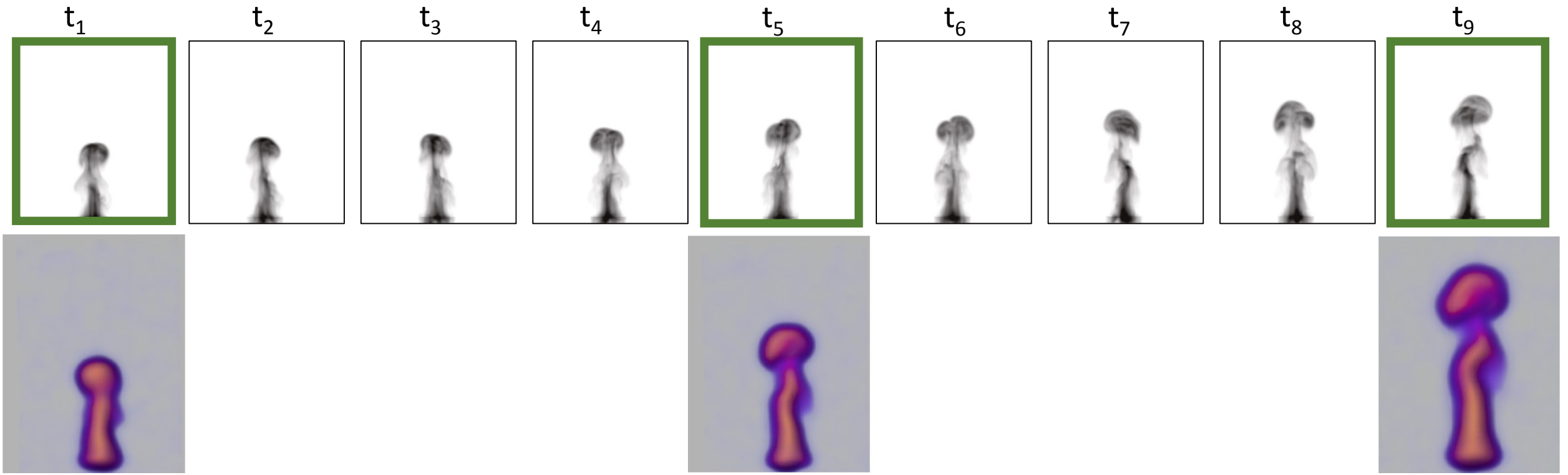

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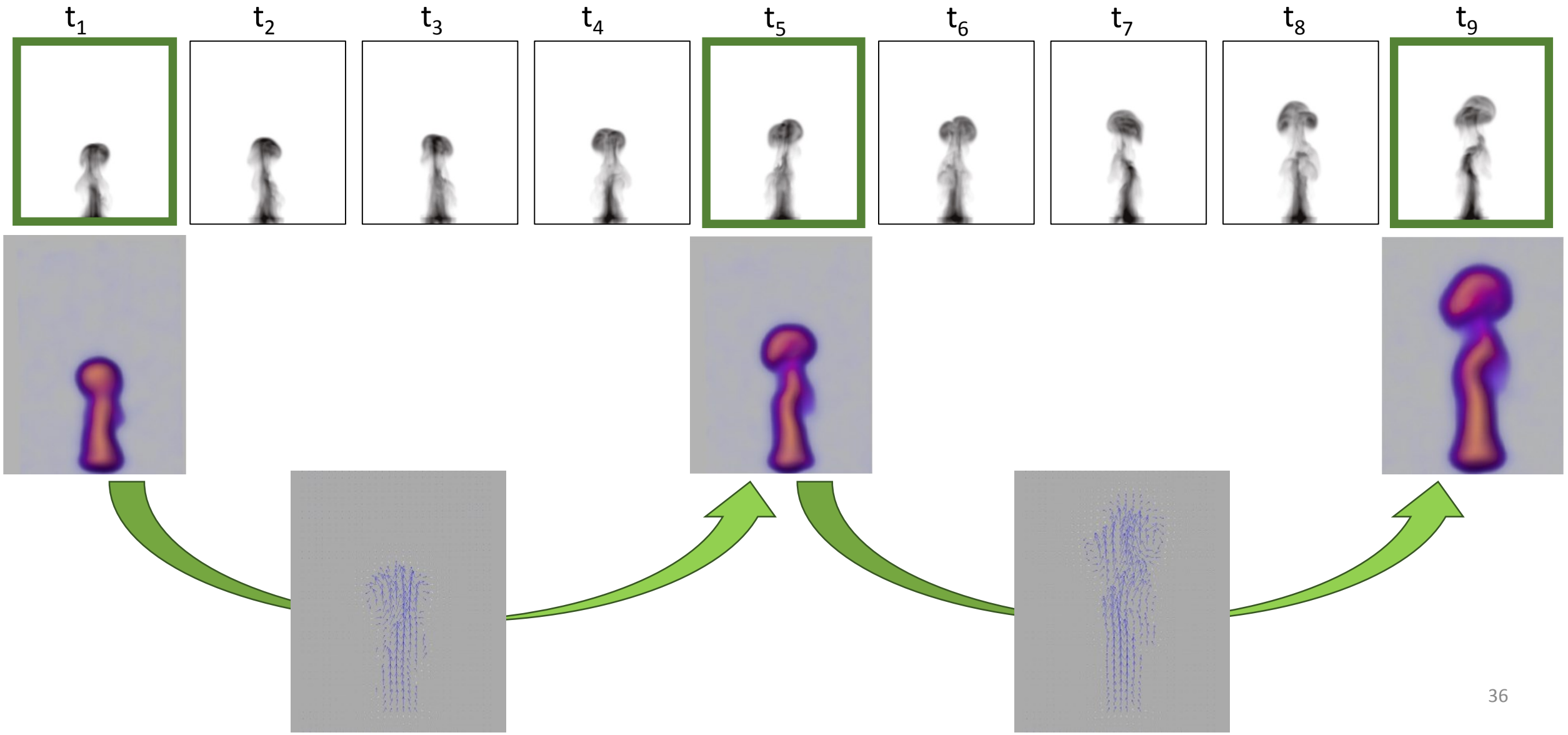

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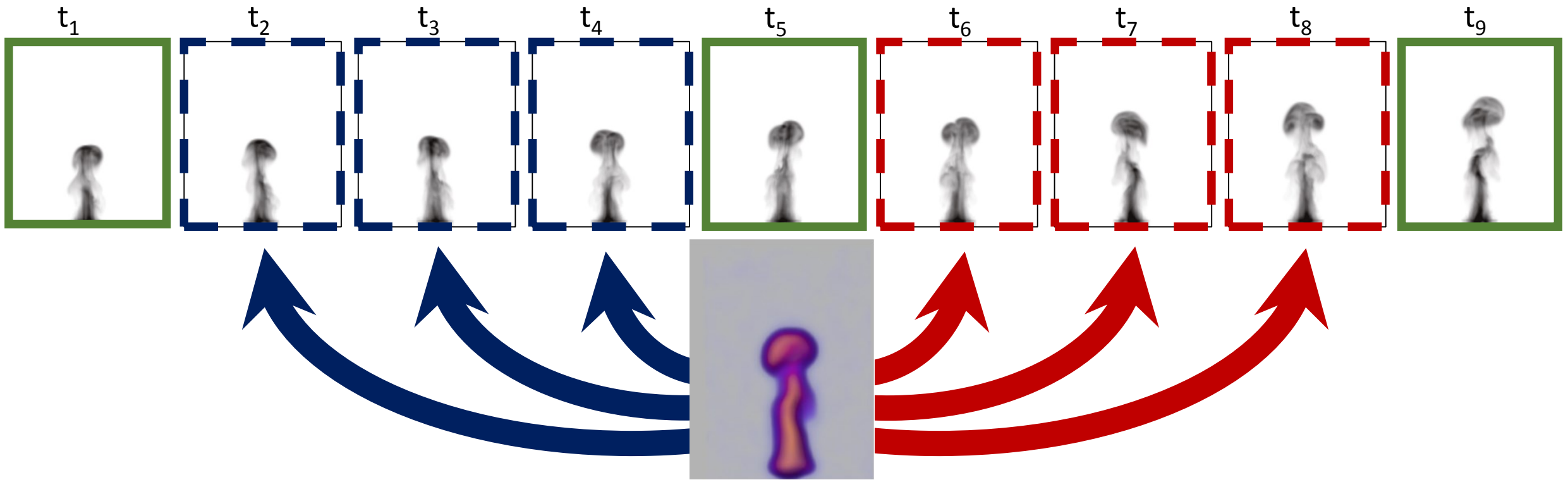

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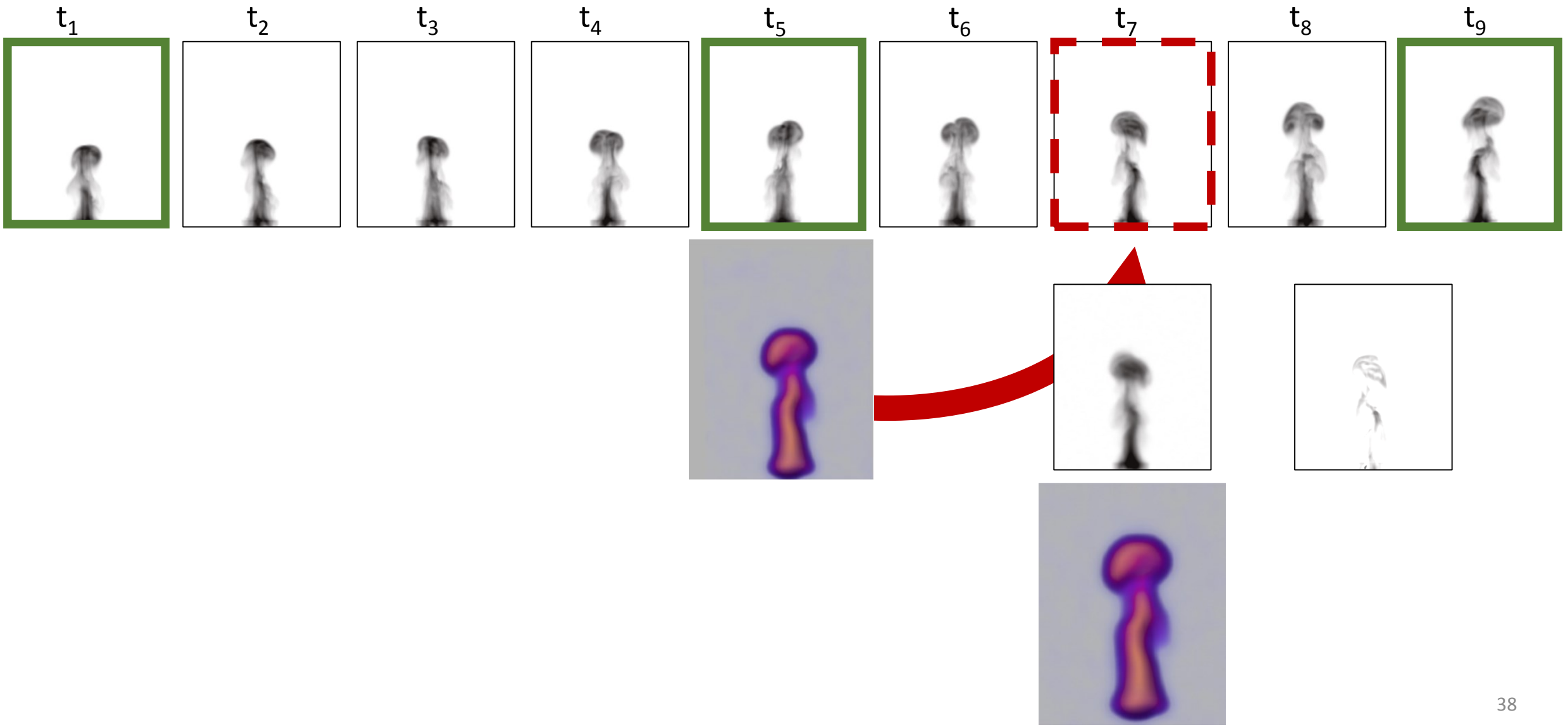

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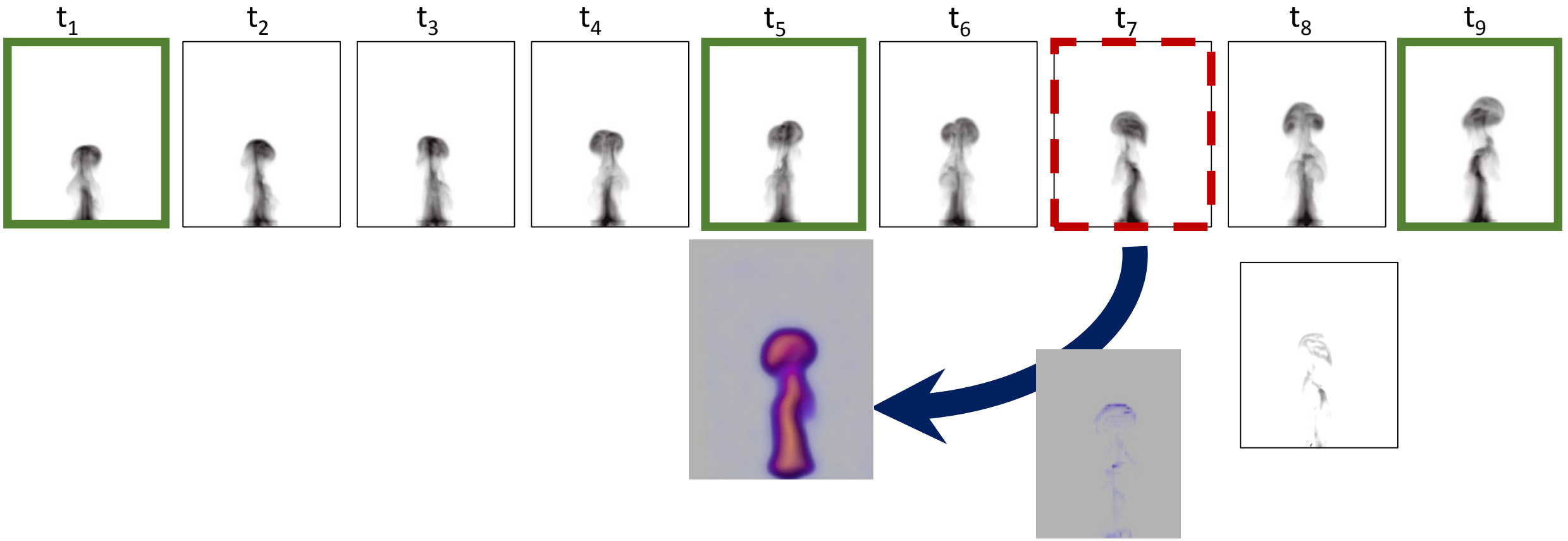
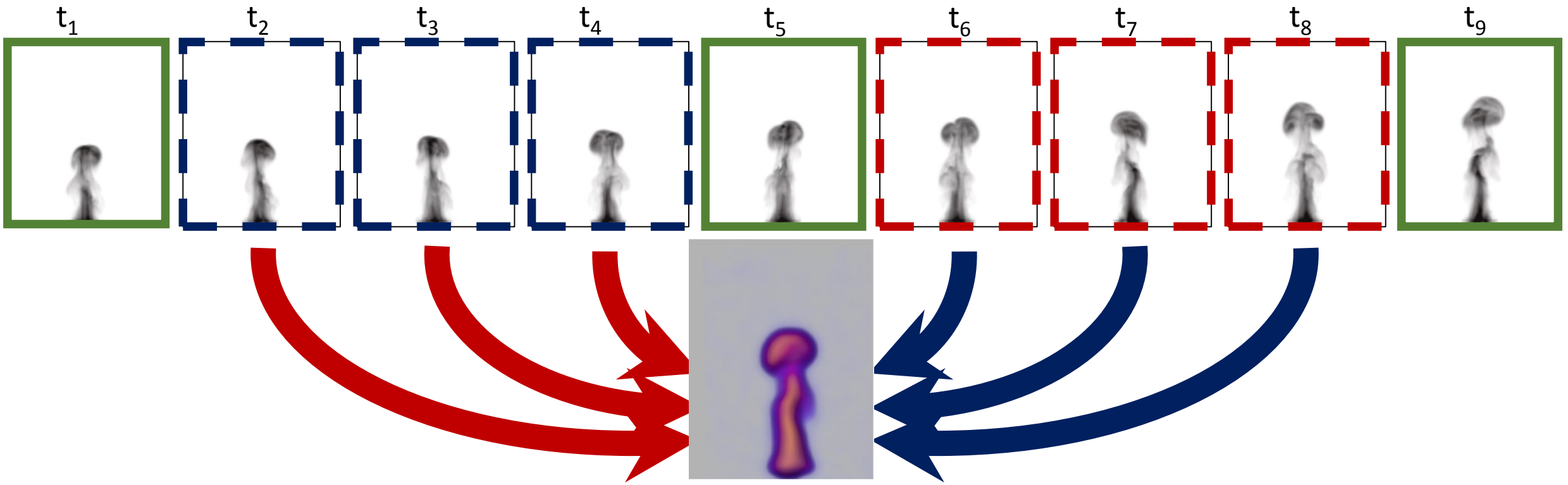
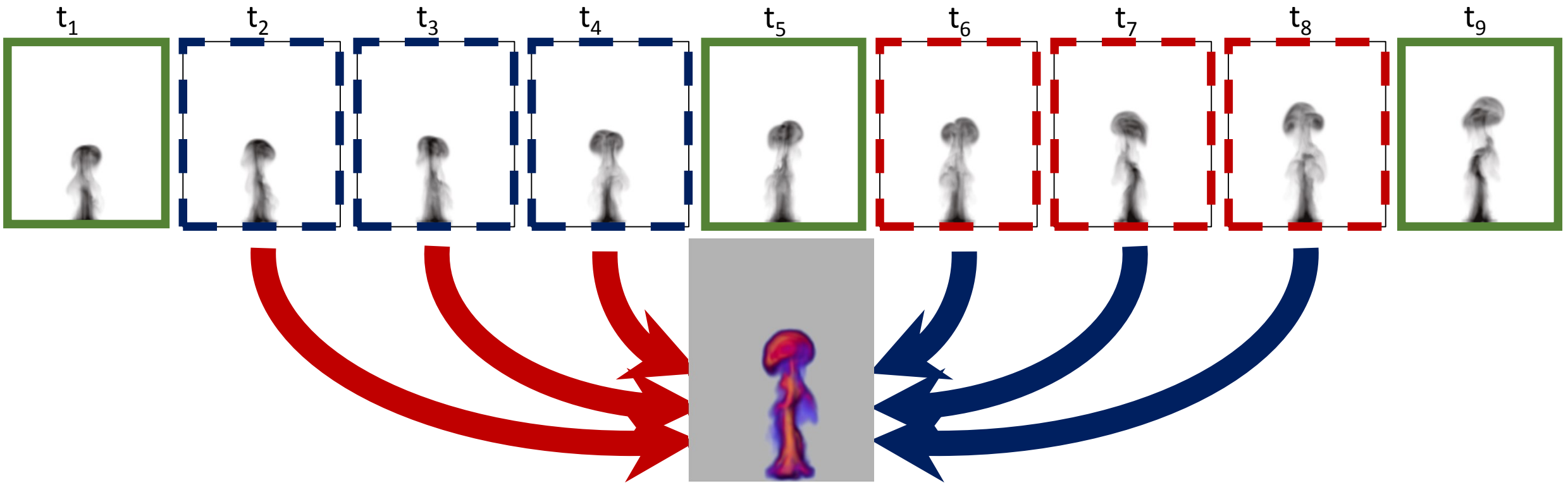


Optimization framework



Forward warping **Backward warping**

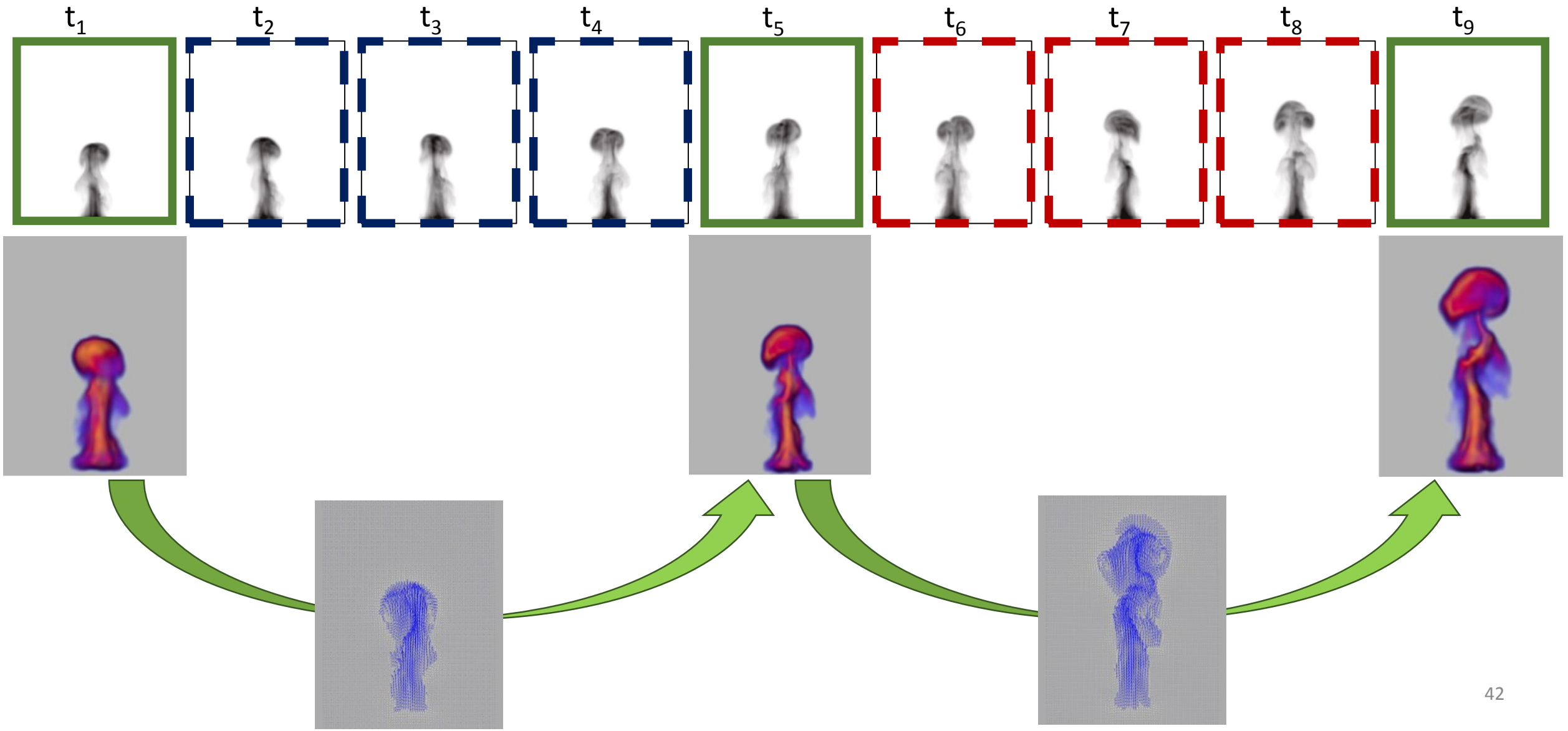
Optimization framework



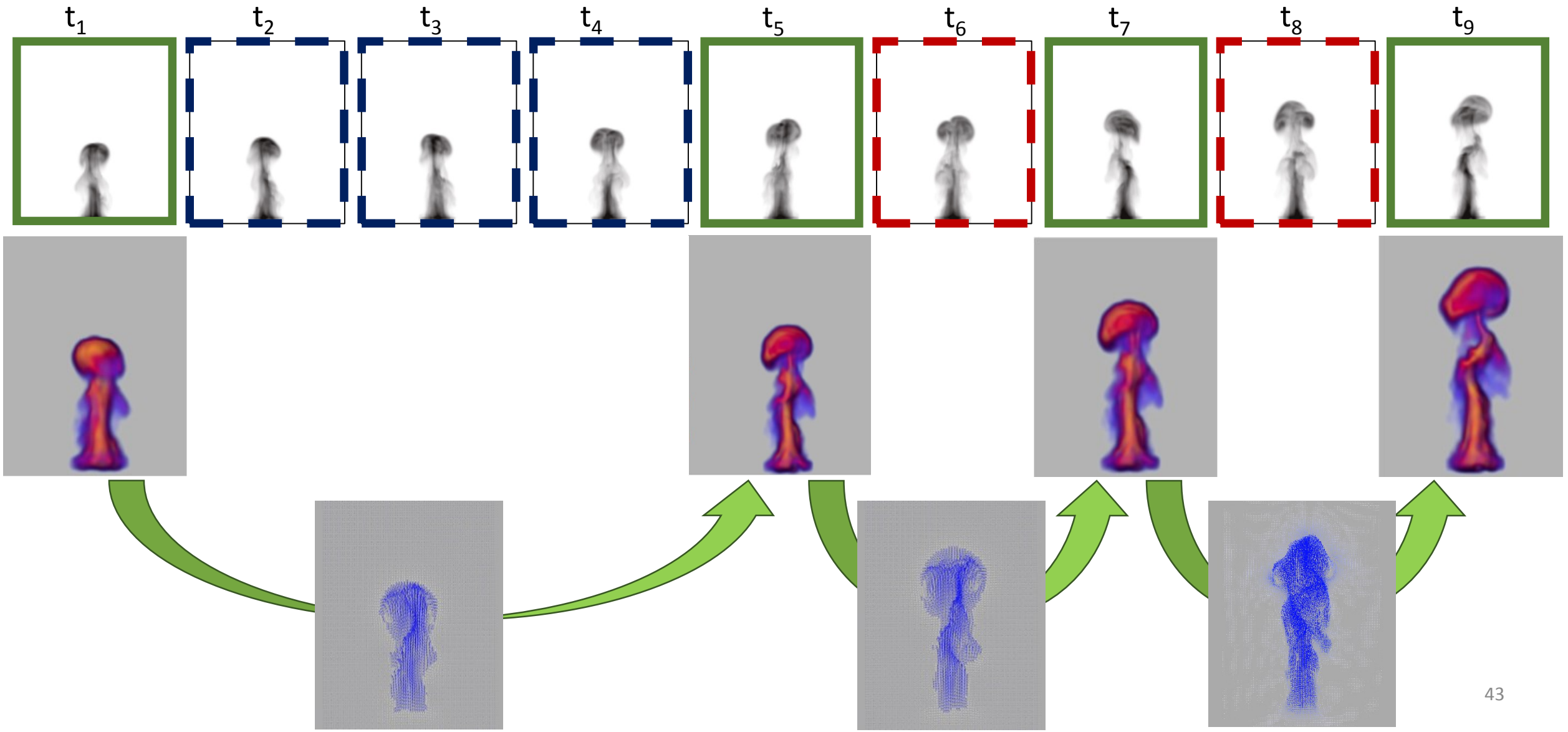
Forward warping

Backward warping

Optimization framework

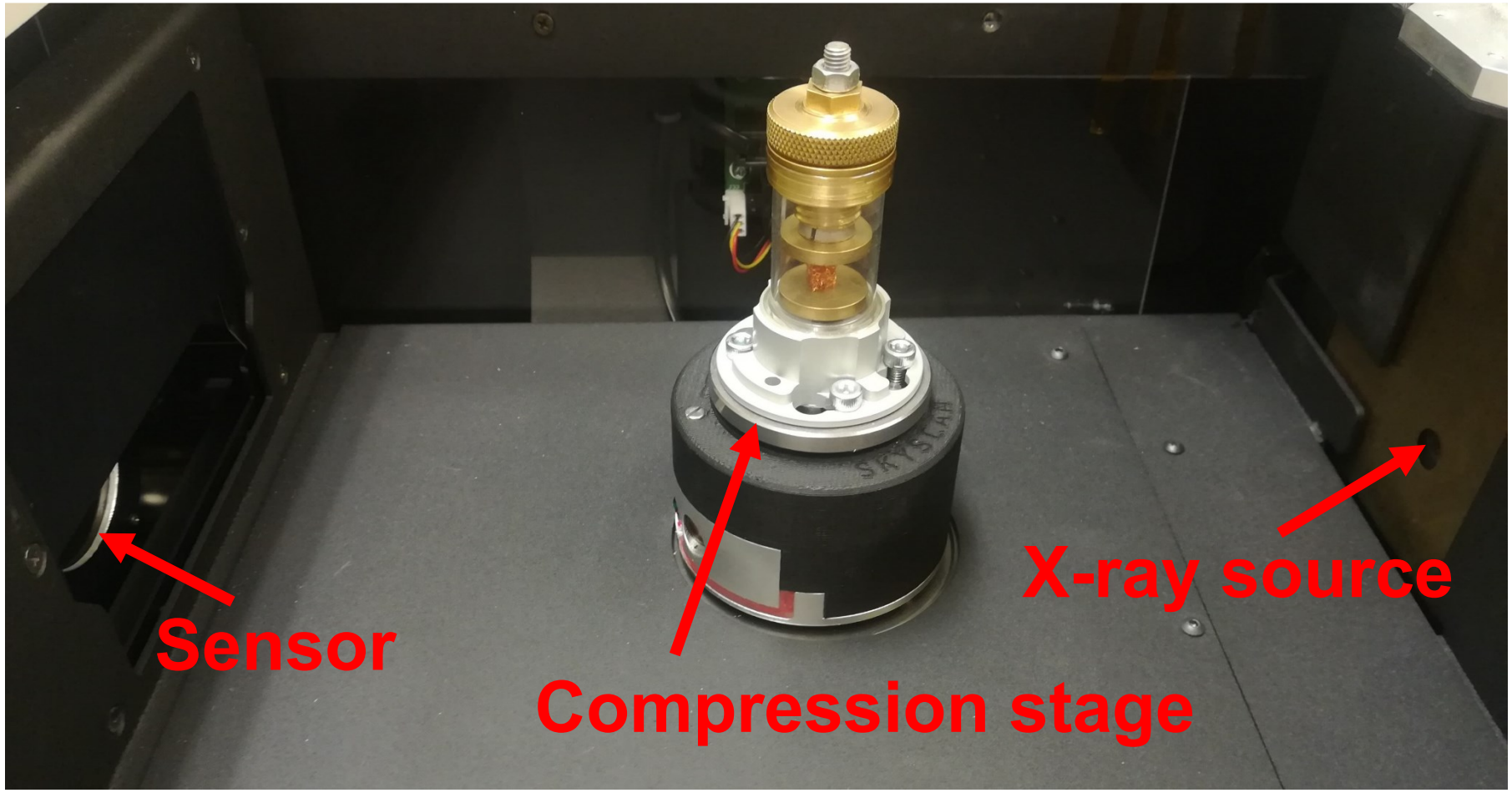


Optimization framework

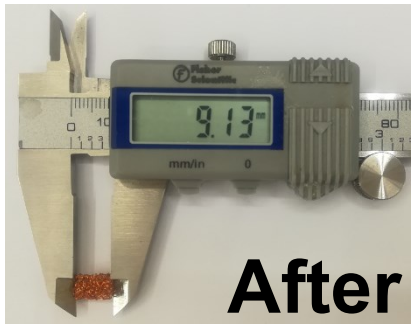


Material deformation analysis

Controlled compression of a copper foam



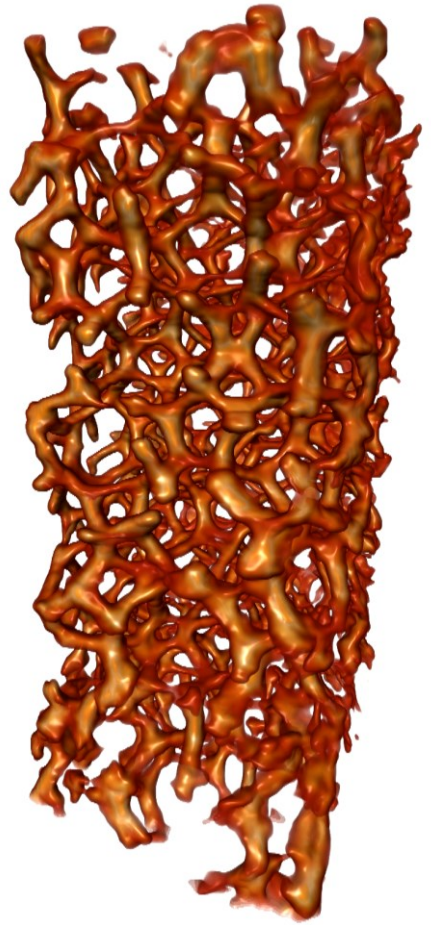
Material deformation analysis



Stop-motion capture
- Controlled compression
- 192 intermediate states
- 60 projections for each state

Reconstruction
- Ground truth: 192*60 projections
- Other reconstructions: only 192 projections

Ground truth reconstruction



Material deformation analysis

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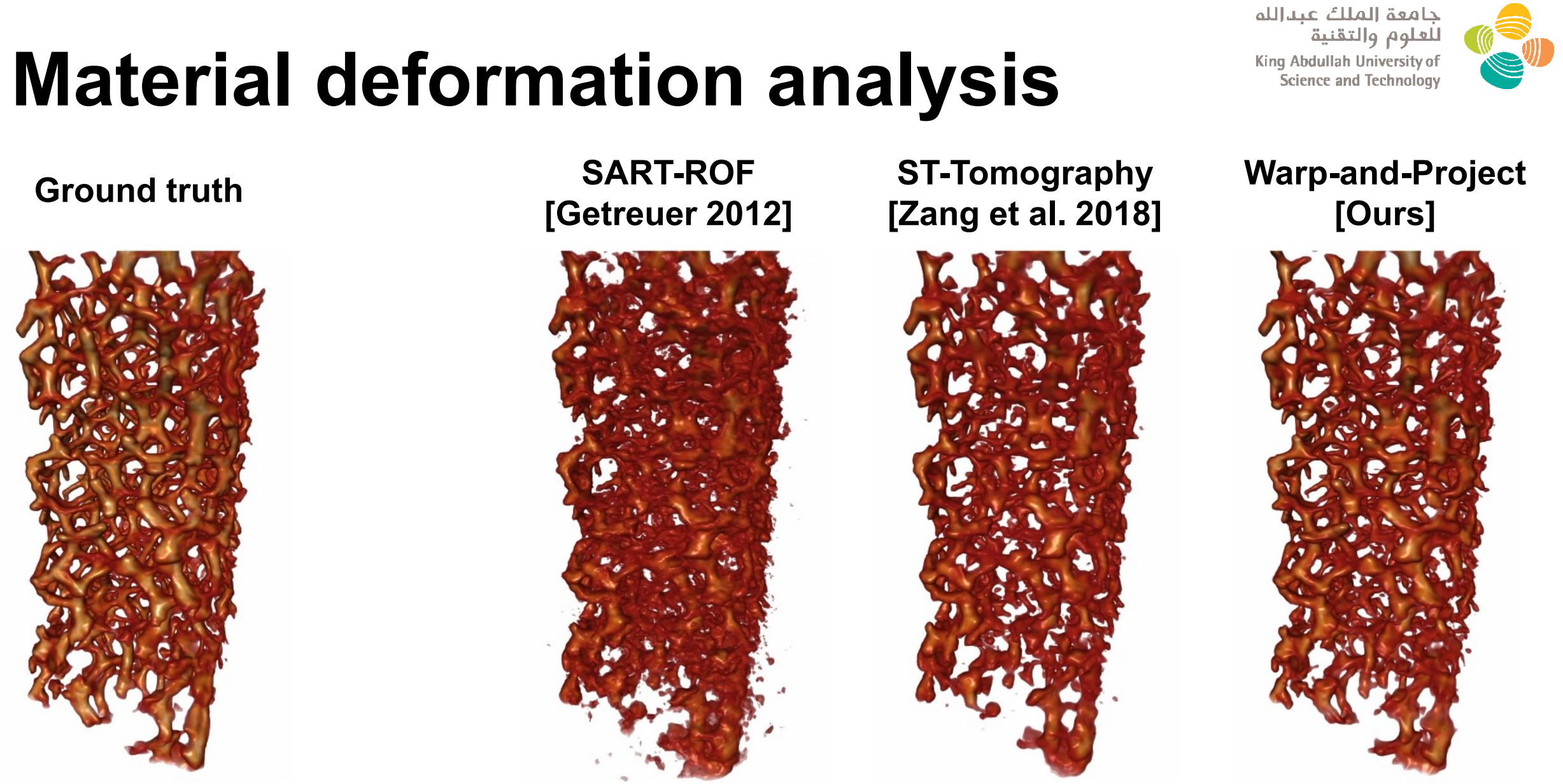

Material deformation analysis

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للعلوم والتقنية
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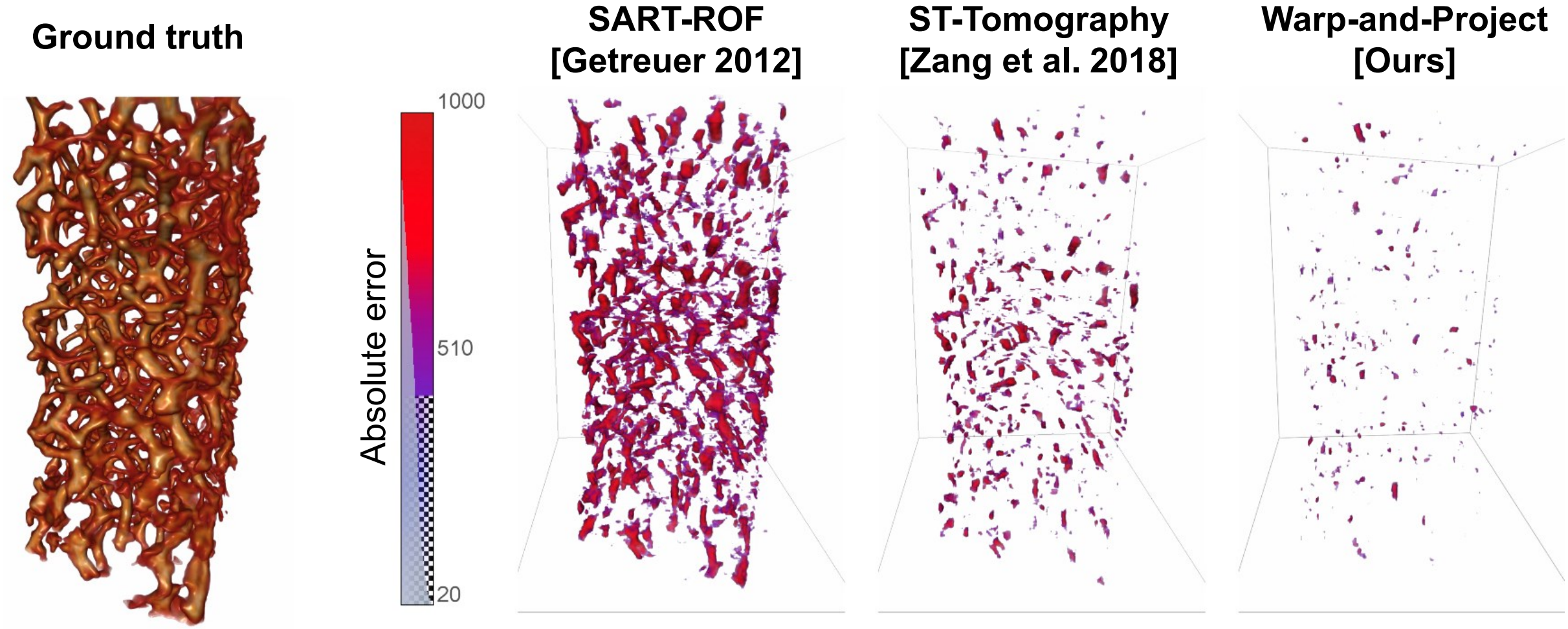
Science and Technology



Rock porosity characterization

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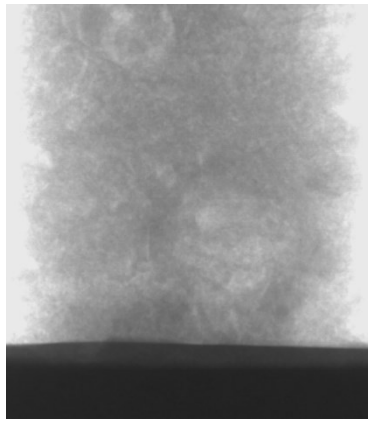
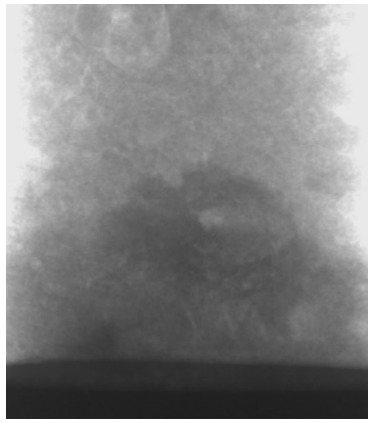
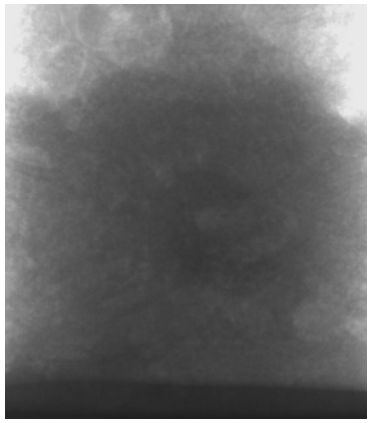
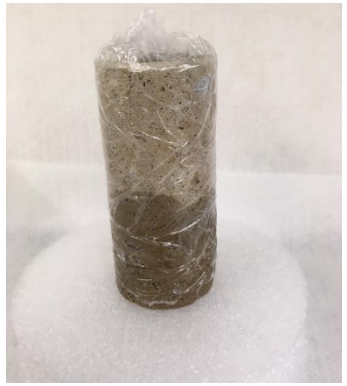
Before

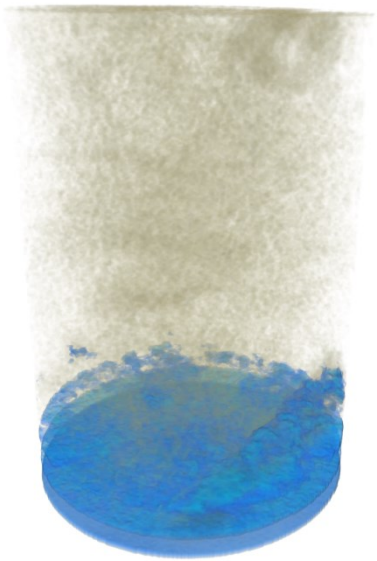


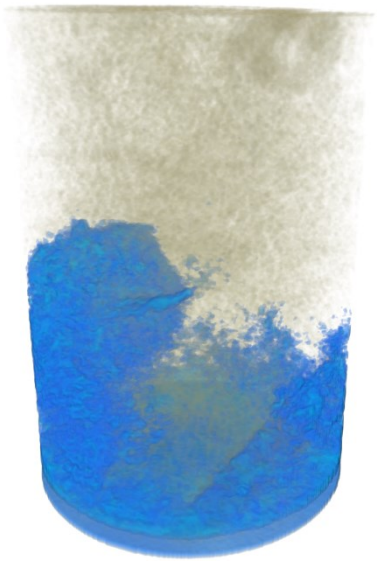




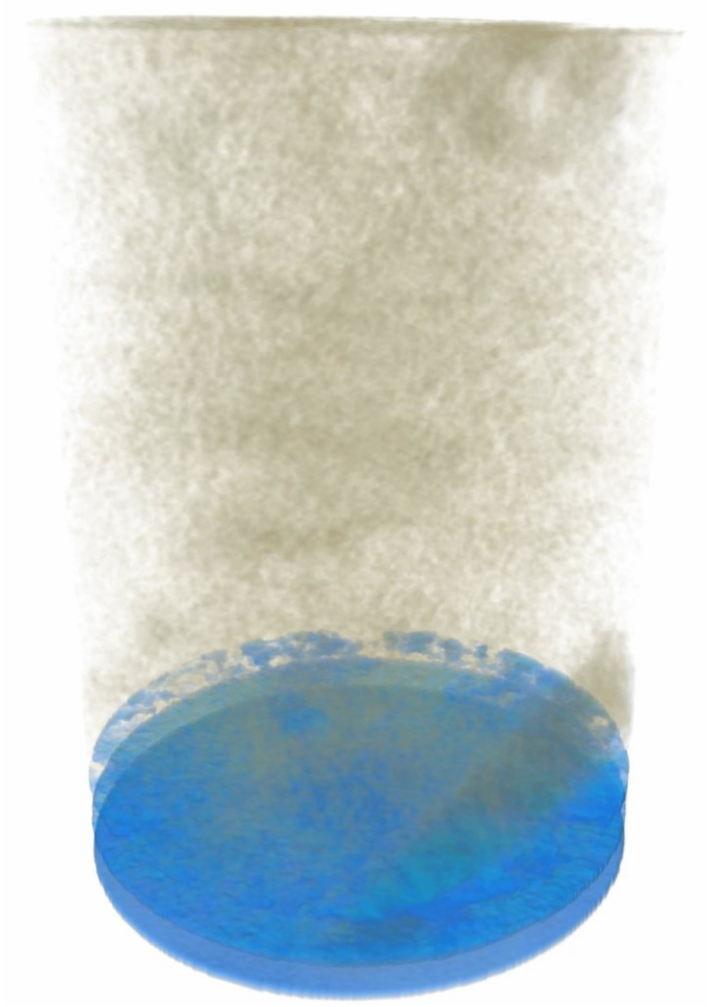
After







Rock porosity characterization



Fungus re-hydration

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Before

After

Capture duration: 38min
projections: 600

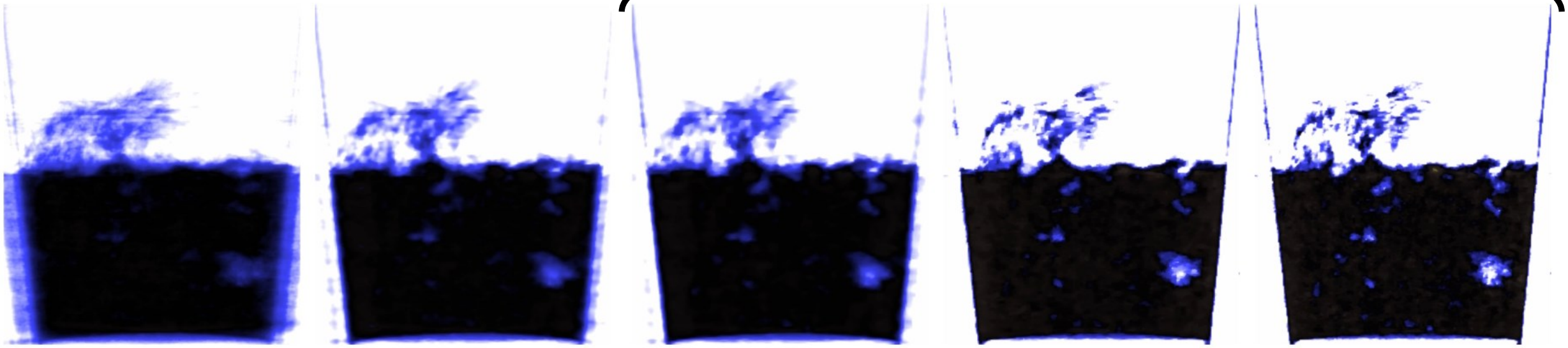
Fungus re-hydration

Temporal sampling

SART-ROF
[Getreuer 2012]

ST-Tomography
[Zang et al. 2018]

Warp-and-Project
[Ours]



30 key frames | 30 key frames | 30 key frames | 64 key frames | 128 key frames

Hydro-gel balls

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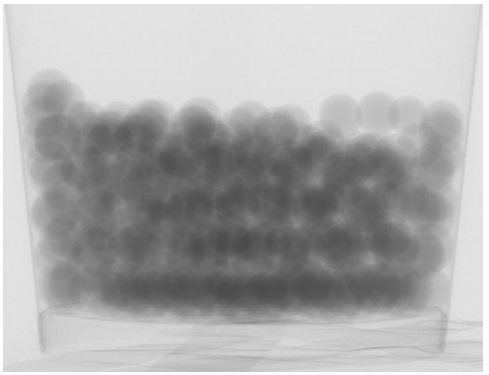
Before

After

Capture duration: 43min
projections: 640



Hydro-gel balls

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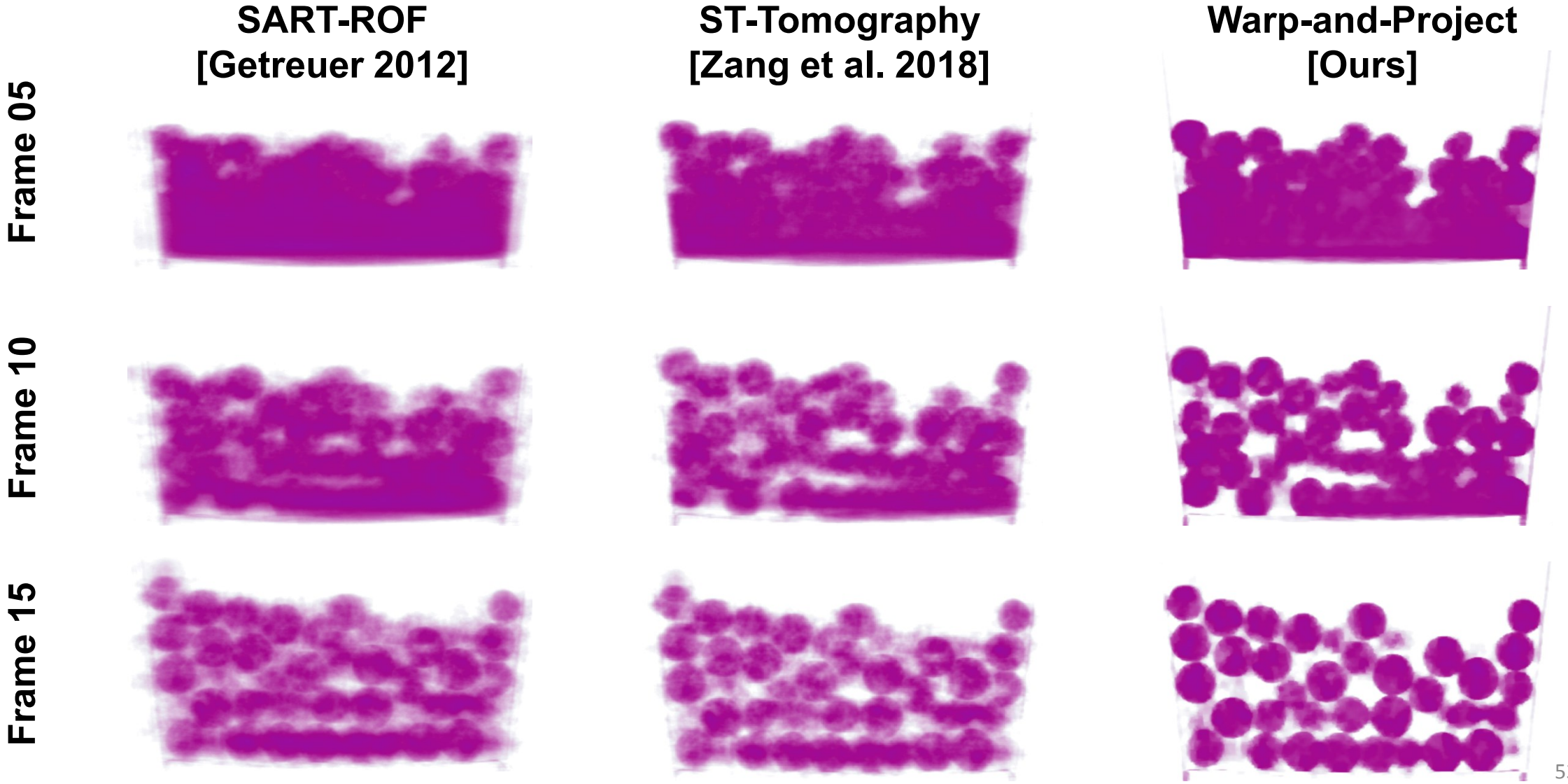
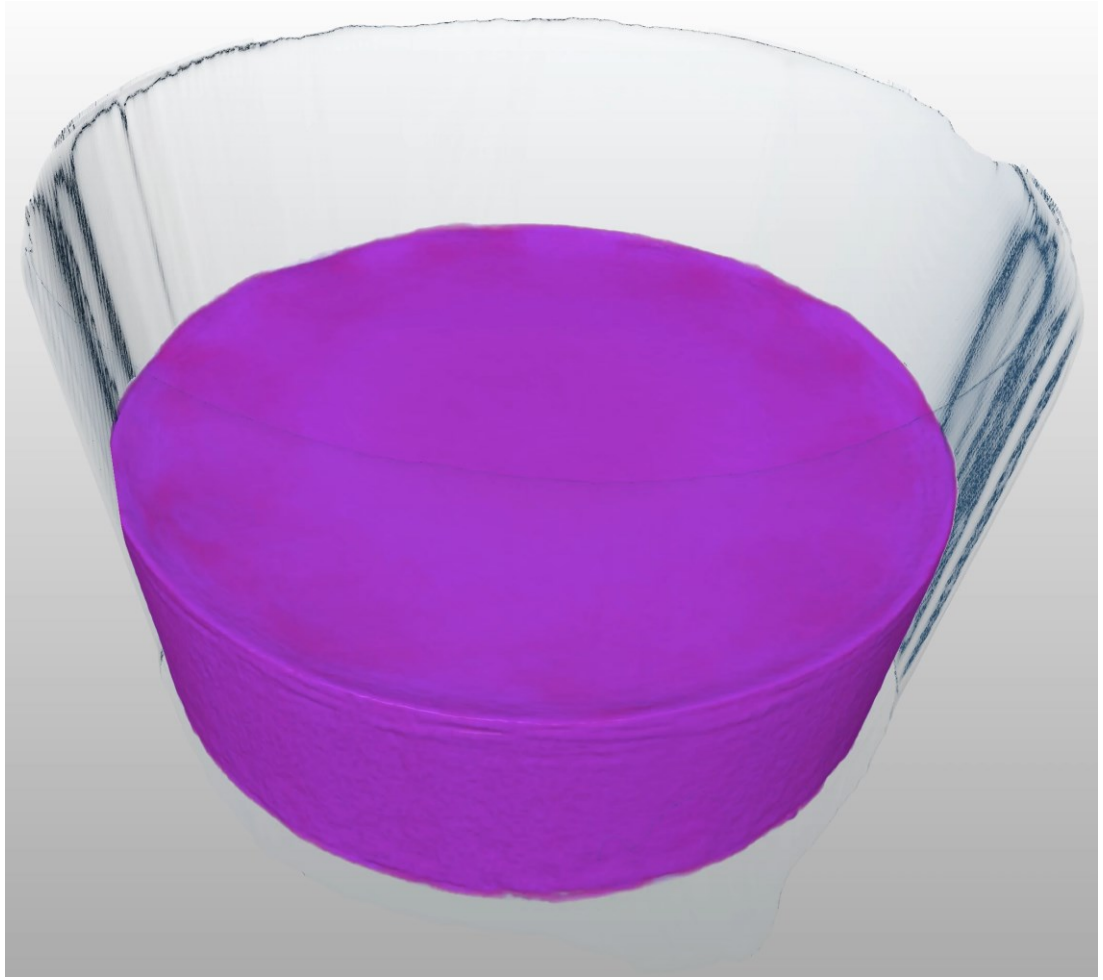
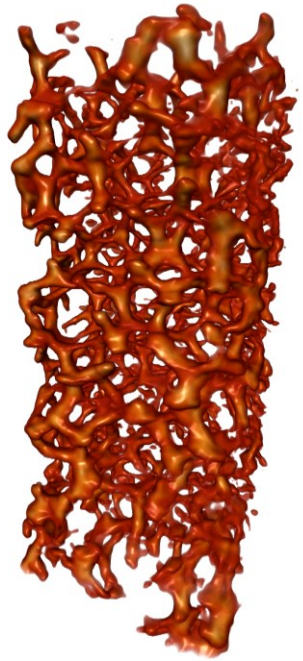


Hydro-gel balls

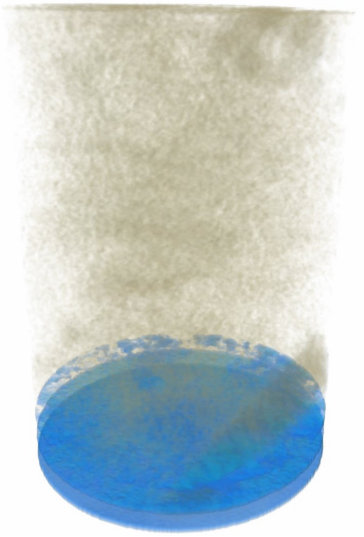


Summary

- A new 4D tomographic reconstruction for rapidly deforming objects
- Well suited to graphics, and several scientific applications



Material deformation analysis



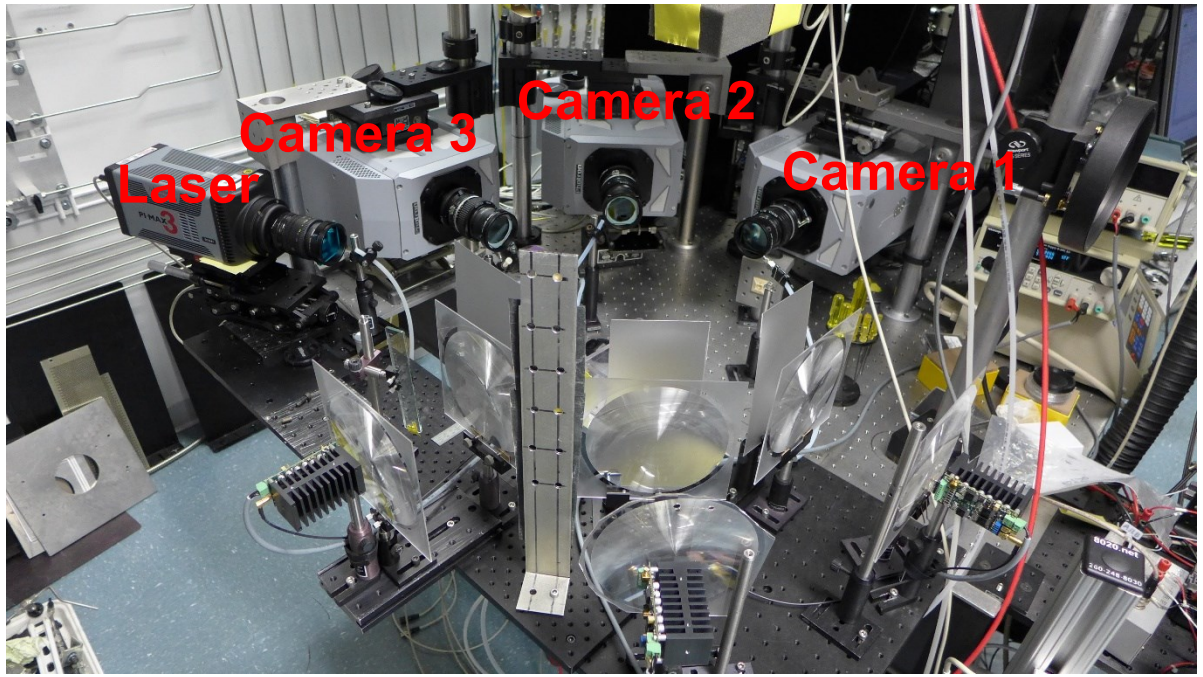
Porosity characterization

What is next ?

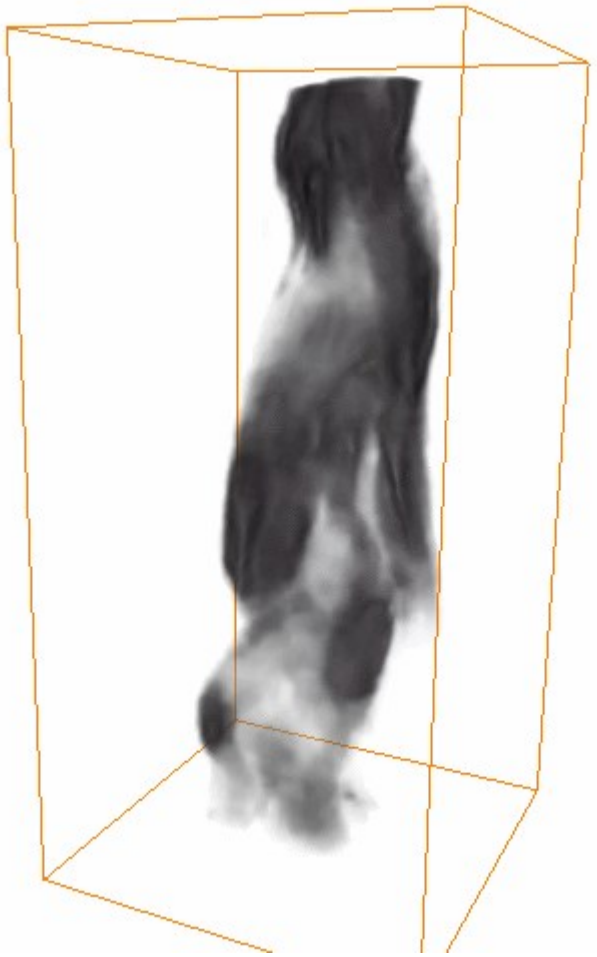
- Software engineering (memory, computation speed, etc.)
- Combination with other tomography techniques (e.g. phase contrast tomography)
- Extension to other imaging modalities (e.g. electron microscopy)

What is next ?

Applications: High speed 3D soot imaging



Camera 2



Thank you !

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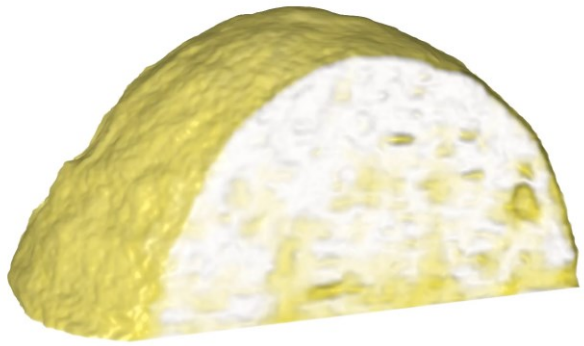
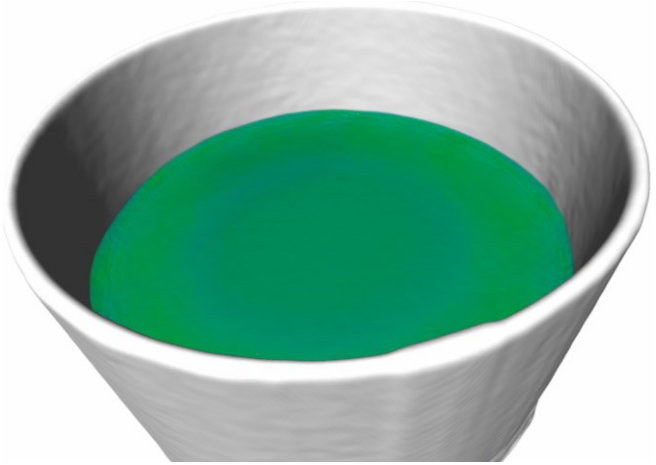
Project webpage:

Code and data available soon





Sponsorship: KAUST as part of VCC Center Competitive Funding.