# A physics-informed machine learning approach to super-resolution of 4D-flow MRI in the left ventricle

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[5] Philips Electronics UK Limited, Surrey, UK

# Clinical Motivation: Impact of Cardiovascular Disease

- WHO estimates that cardiovascular disease (CVD) kills **>17 million** yearly worldwide
  - Heart failure is a major contributor to CVD
- Estimated yearly cost of CVD is **$219 billion** in US alone
  - In UK, this figure currently stands at **£7.4 billion**
  - Additional indirect costs incur **£15.8 billion**

***CVD in UK:***

- **£23 billion**
- **160,000 deaths**

***CVD in USA:***

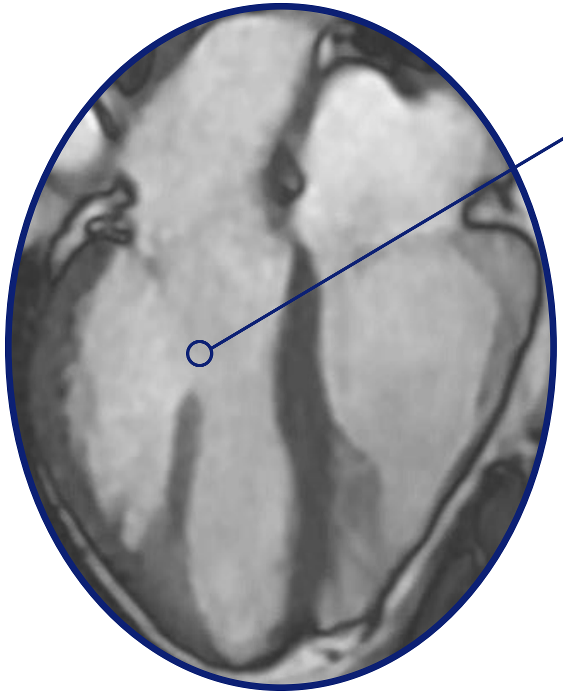
- **$219 billion**
- **655,000 deaths**

# Haemodynamics in the Heart Chambers

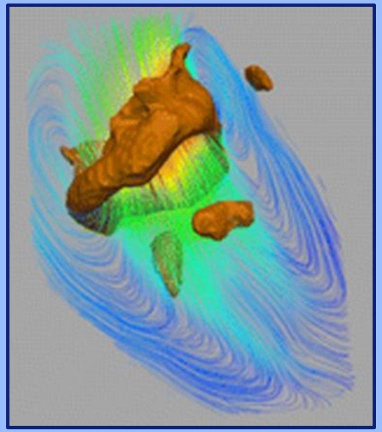


*Hanson, C, https://statenews.com/article/2022/02/heart-healthy-cardiovascular-mri-imaging-is-now-at-sparrow-hospital?ct=content_open&cv=cbox_featured*

# Haemodynamics in the Heart Chambers



**Vorticity**
*Demirkiran et al. (2022)*





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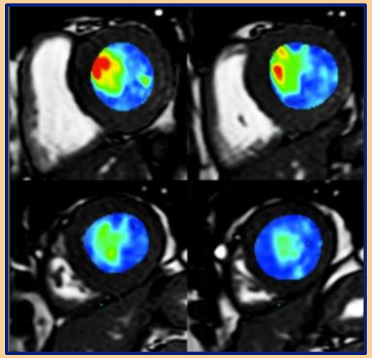
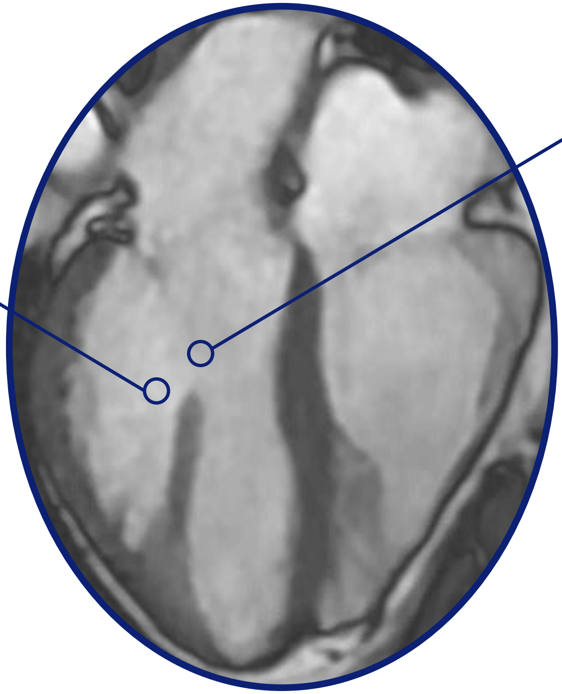
# Haemodynamics in the Heart Chambers

**Kinetic energy**
*Garg et al.*
*(2018)*





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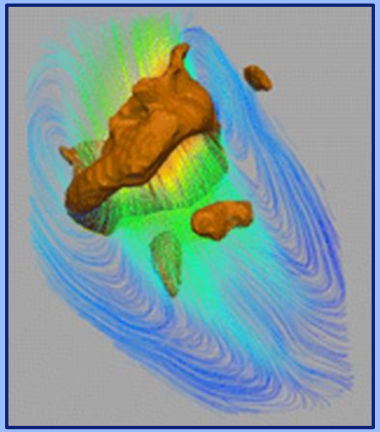



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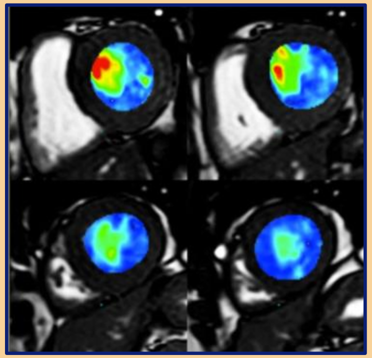

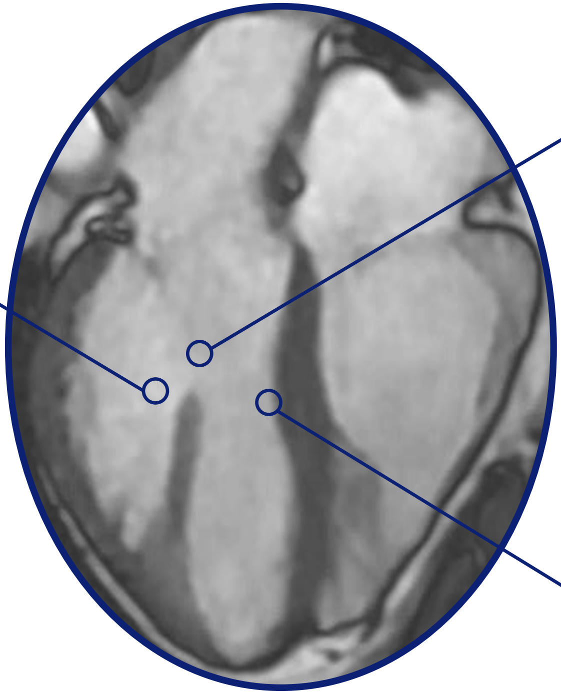

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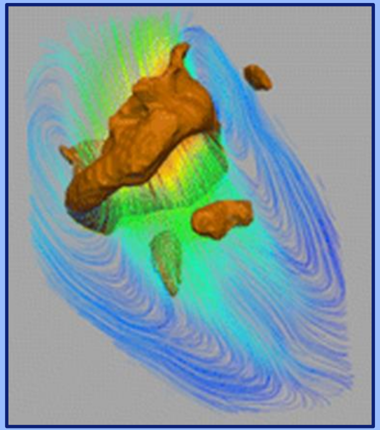
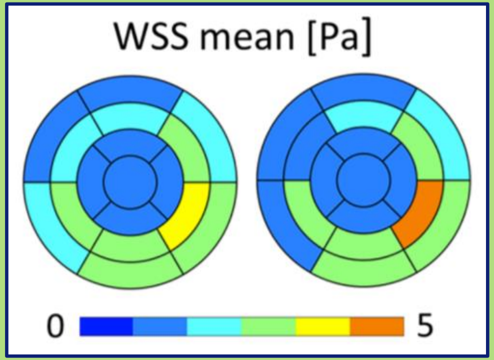


**Wall shear stress**
*Canè et al. (2022)*



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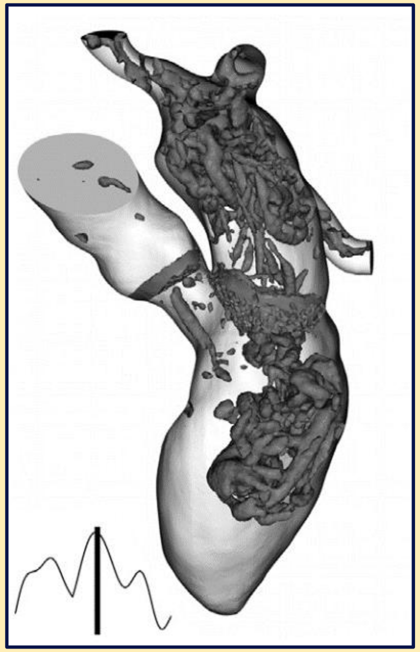
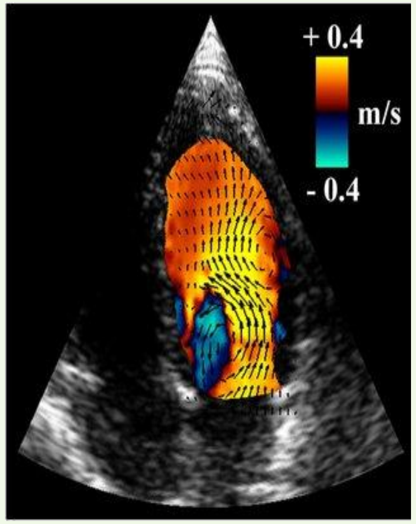
# Quantifying Haemodynamics in the Heart

## CFD

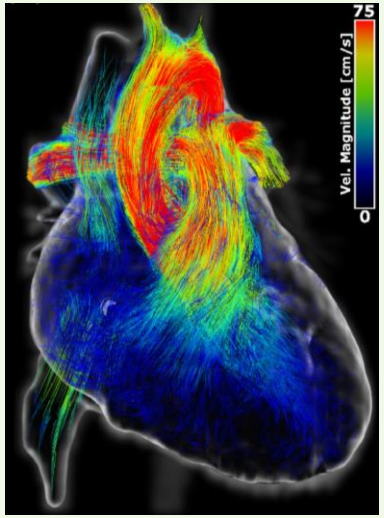


## Imaging

### Doppler echocardiography




### 4D-flow MRI






Chnafa, C, Image-based large-eddy simulation in a realistic left heart, 2016

Faurie, J. et al., IEE transactions on ultrasonics, ferroelectrics, and frequency control, 2016
Pruitt, A. et al., Fully self-gated whole-heart 4D flow imaging from a 5-minute scan, 2021

# Quantifying Haemodynamics in the Heart

CFD

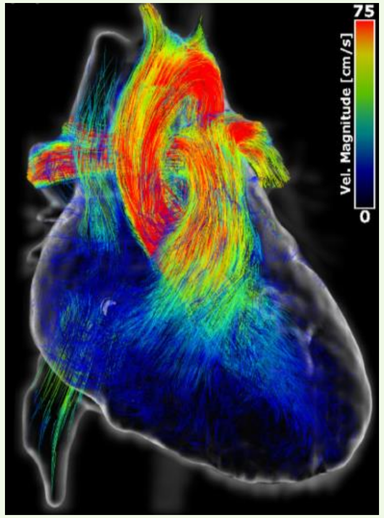


Imaging

Doppler echocardiography




4D-flow MRI



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# Quantifying Haemodynamics in the Heart

*CFD*

***Low spatial resolution:***
$2.5 - 3\text{mm}^3$

***Noise artifacts:***
Non-Gaussian spatial distribution

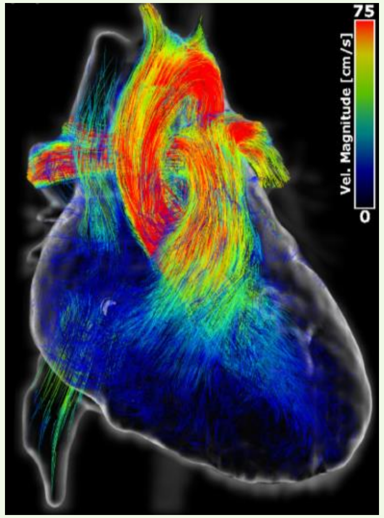
***Temporal averaging:***
Over scan duration

## *Imaging*

***Doppler echocardiography***




***4D-flow MRI***



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# Quantifying Haemodynamics in the Heart

CFD

## Imaging

**_Low spatial resolution:_**
$2.5 - 3\text{mm}^3$

**_Noise artifacts:_**
Non-Gaussian spatial distribution

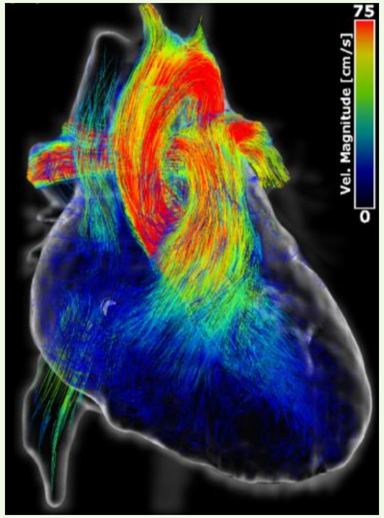
**_Temporal averaging:_**
Over scan duration

**_Poor accuracy of derivatives:_**
Relevant variables such as vorticity and stresses

**_Near-wall flow not captured well_**

**_Small-scale flow features missed:_**
Particularly important in analysis of vortex dissipation

**_4D-flow MRI_**



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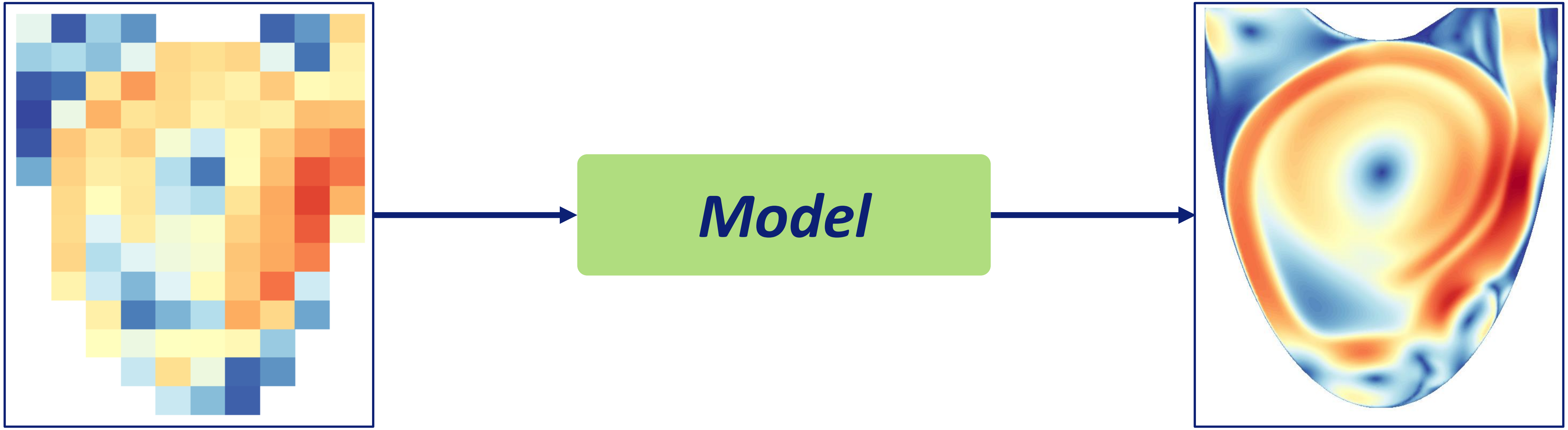
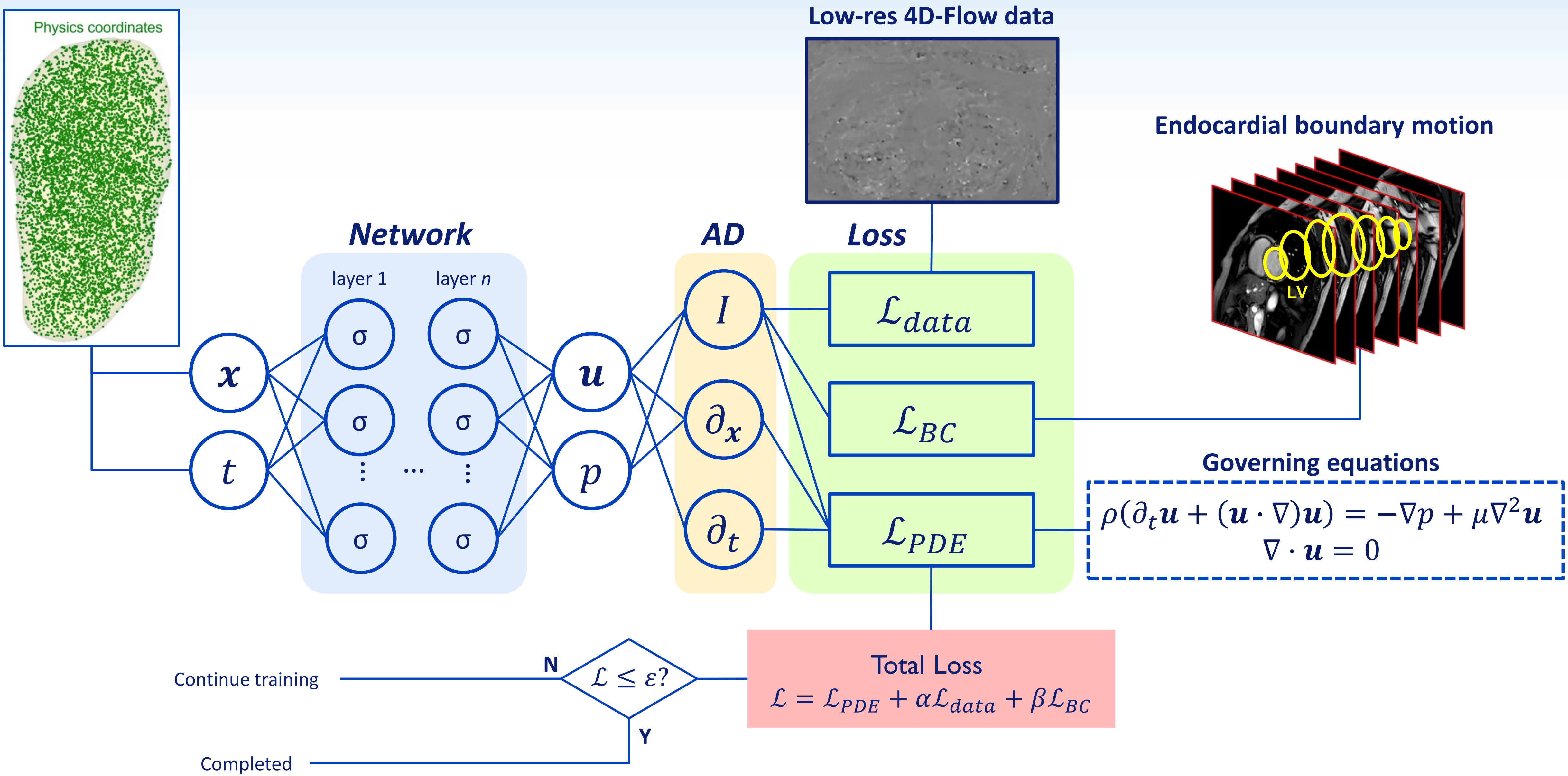
# Improving 4D-Flow MRI – Super-Resolution



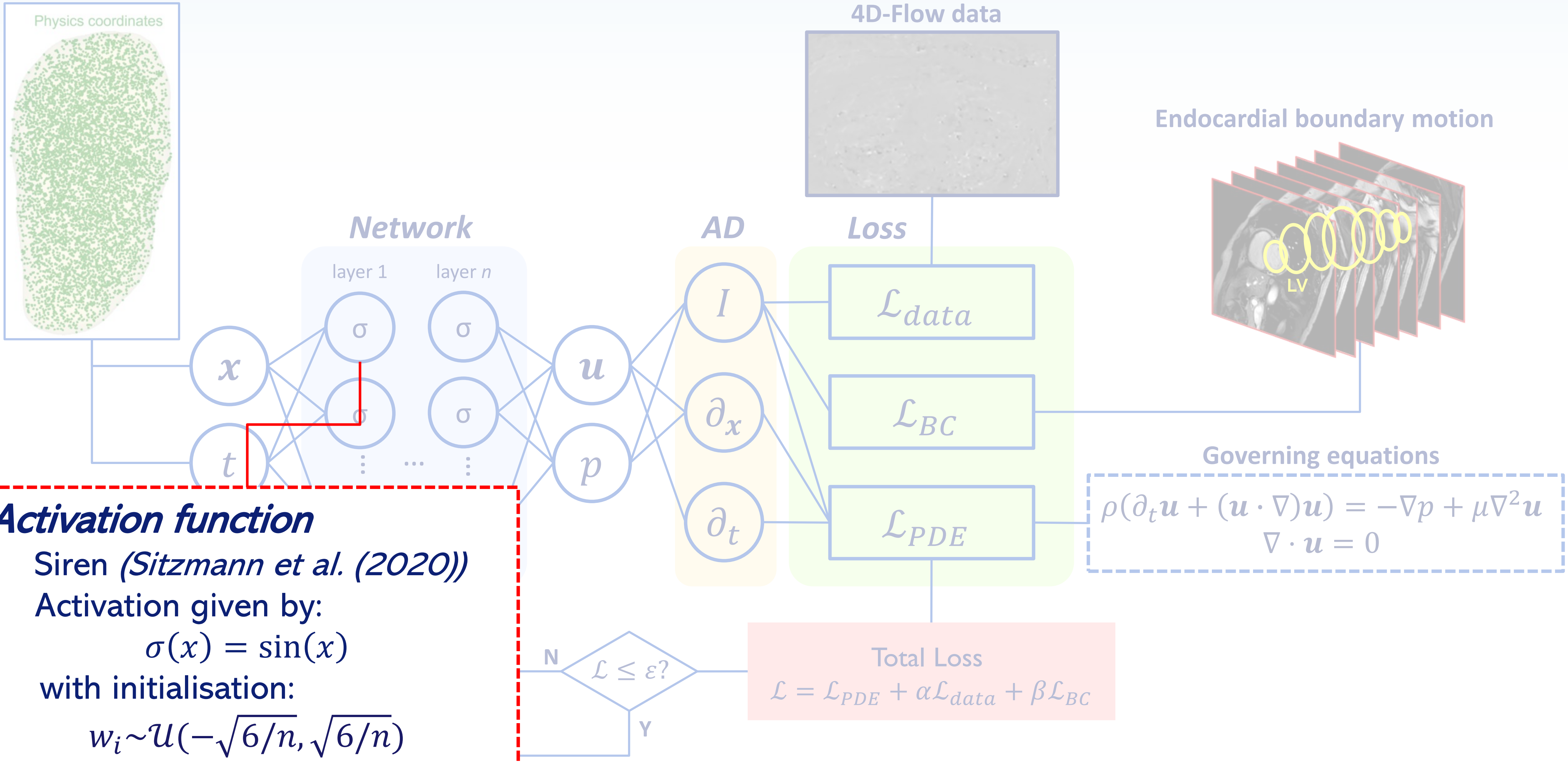

Low-resolution, corrupted velocity data

High-resolution velocity field

# Our Super-Resolution Model – Physics-Informed Neural Network



# Key Ingredients




## *Activation function*

- Siren *(Sitzmann et al. (2020))*
- Activation given by:

$$\sigma(x) = \sin(x)$$

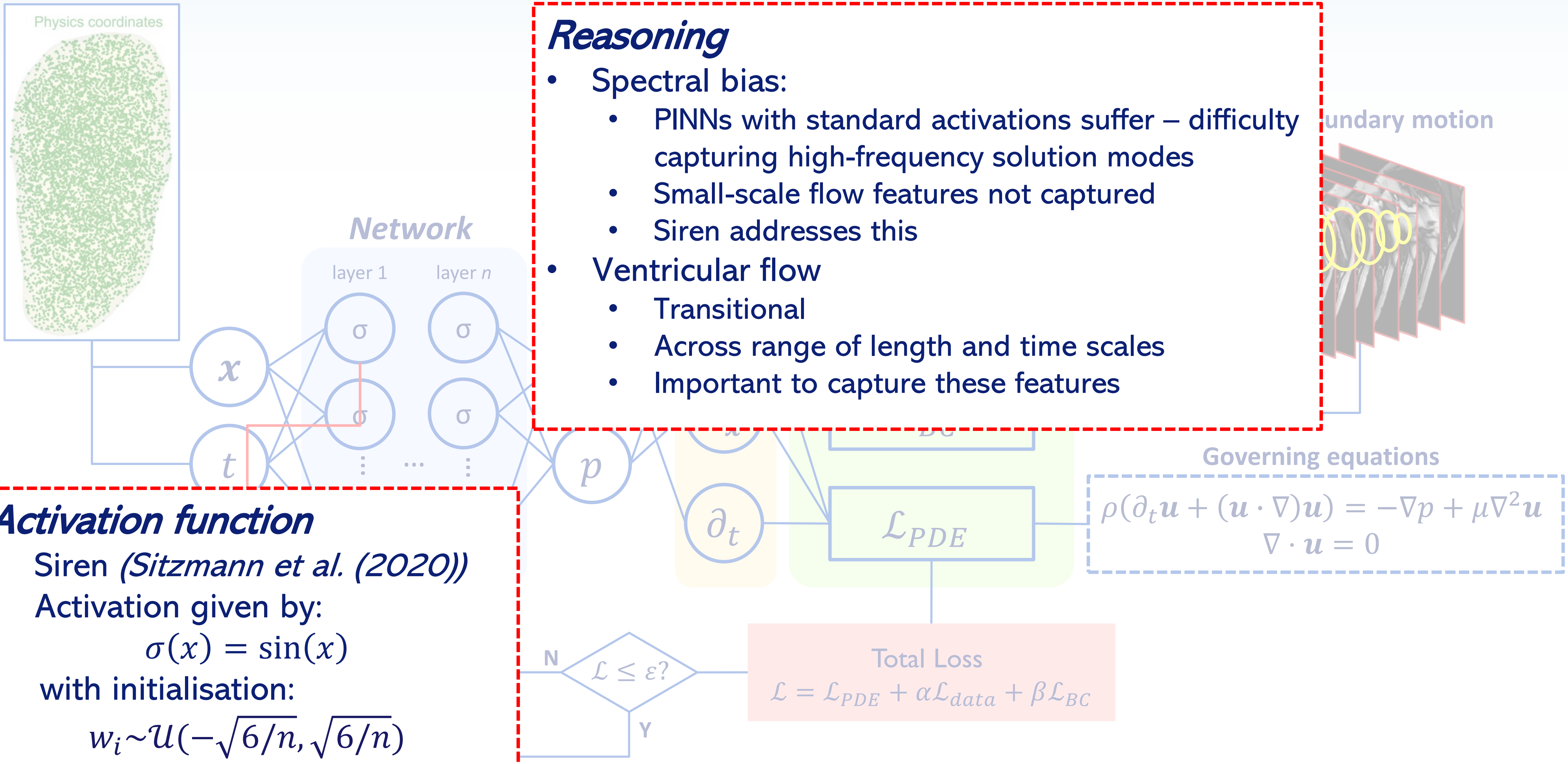
with initialisation:

$$w_i \sim \mathcal{U}(-\sqrt{6/n}, \sqrt{6/n})$$



Sitzmann, V & Martel, J & Bergman, A et al. (2020)

# Key Ingredients




## *Reasoning*

- Spectral bias:
  - PINNs with standard activations suffer – difficulty capturing high-frequency solution modes
  - Small-scale flow features not captured
  - Siren addresses this
- Ventricular flow
  - Transitional
  - Across range of length and time scales
  - Important to capture these features

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*Sitzmann, V & Martel, J & Bergman, A et al. (2020)*

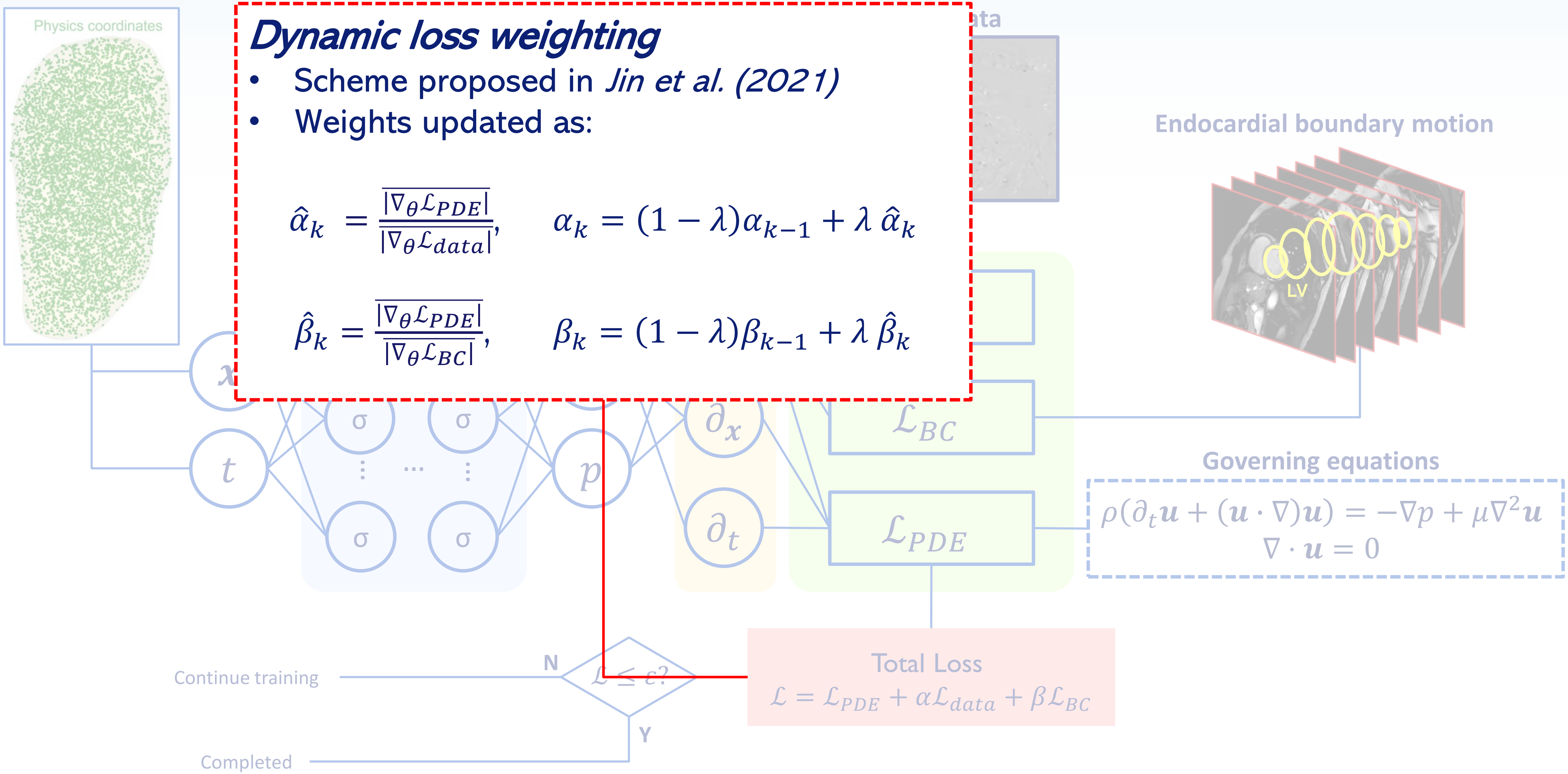
# Key Ingredients

## *Dynamic loss weighting*

- Scheme proposed in *Jin et al. (2021)*
- Weights updated as:

$$\hat{\alpha}_k = \frac{\overline{|\nabla_\theta \mathcal{L}_{PDE}|}}{\overline{|\nabla_\theta \mathcal{L}_{data}|}}, \qquad \alpha_k = (1-\lambda)\alpha_{k-1} + \lambda\,\hat{\alpha}_k$$

$$\hat{\beta}_k = \frac{\overline{|\nabla_\theta \mathcal{L}_{PDE}|}}{\overline{|\nabla_\theta \mathcal{L}_{BC}|}}, \qquad \beta_k = (1-\lambda)\beta_{k-1} + \lambda\,\hat{\beta}_k$$



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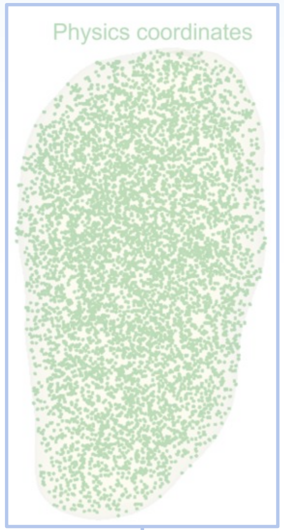
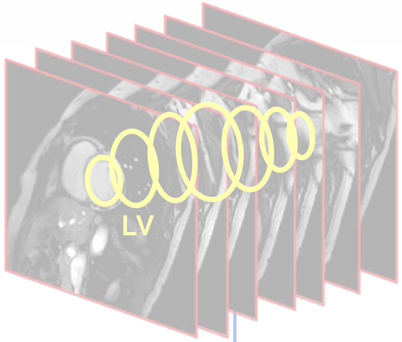



Endocardial boundary motion

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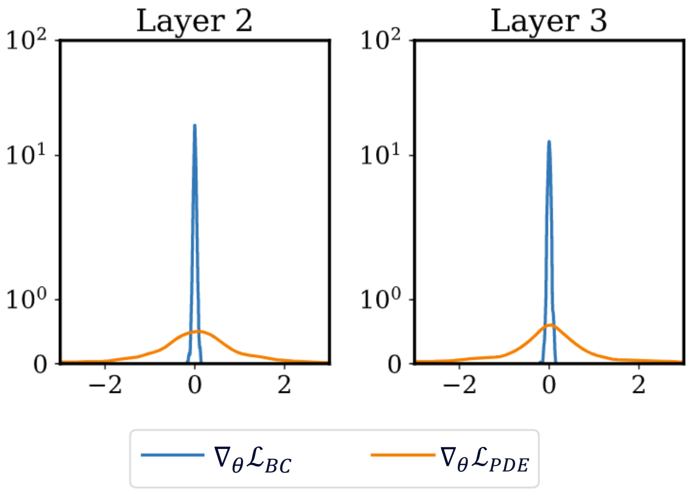
## *Reasoning*

- Different loss terms provide different gradient contributions
- Term contributing smaller gradients may not be satisfied during training
- E.g. boundary condition loss in figure
- More complex PDEs (like Navier-Stokes equations) tend to contribute larger gradients

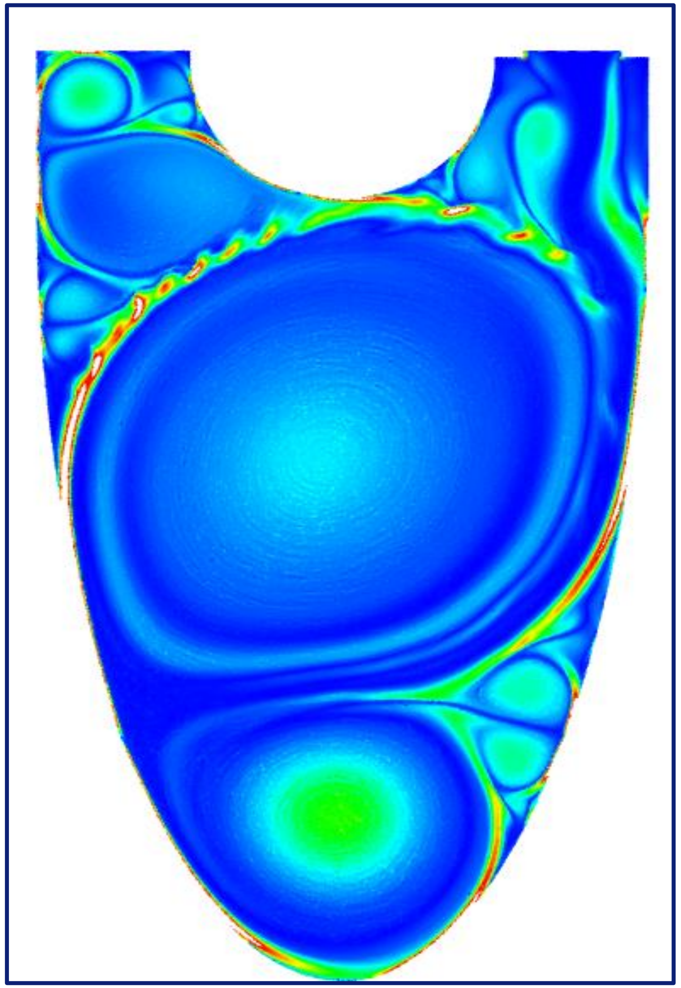




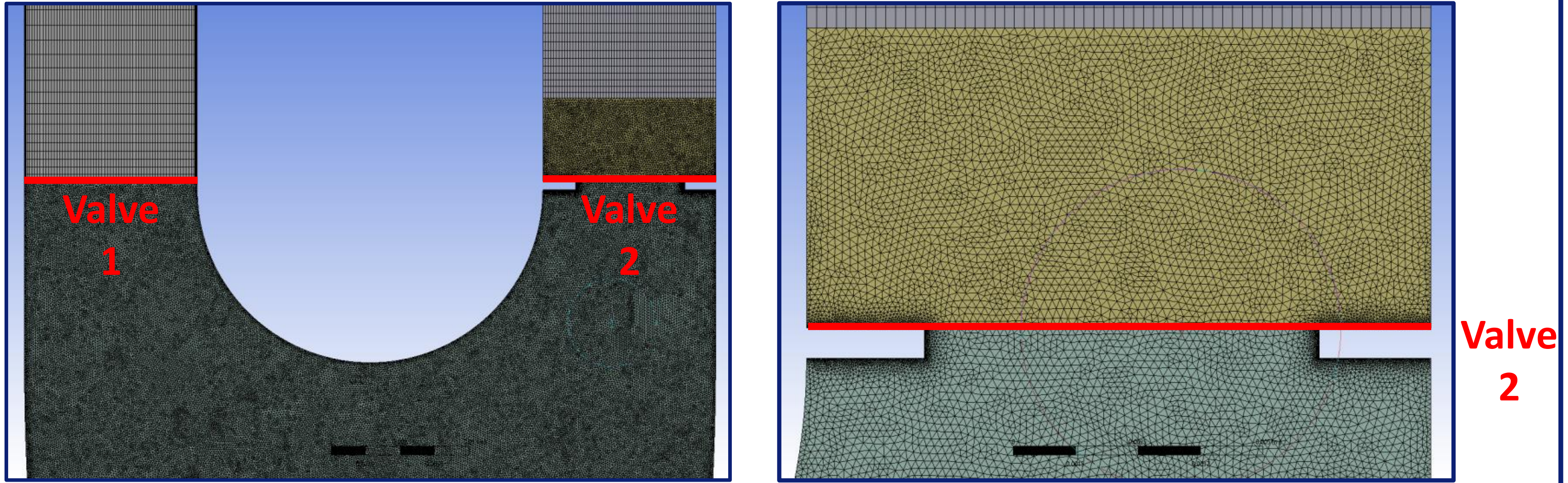

*Jin et al (2021)*
*Wang,S & Teng, Y & Peridakis, P. (2020)*

# Experiments: 2D Idealised Ventricle

- Synthetic study designed to validate model
- Simplified, 2D CFD-generated ventricle
    - Flow driven by moving boundary
    - Highly-resolved mesh
    - Small adaptive time-step
    - Results in complex flow simulated



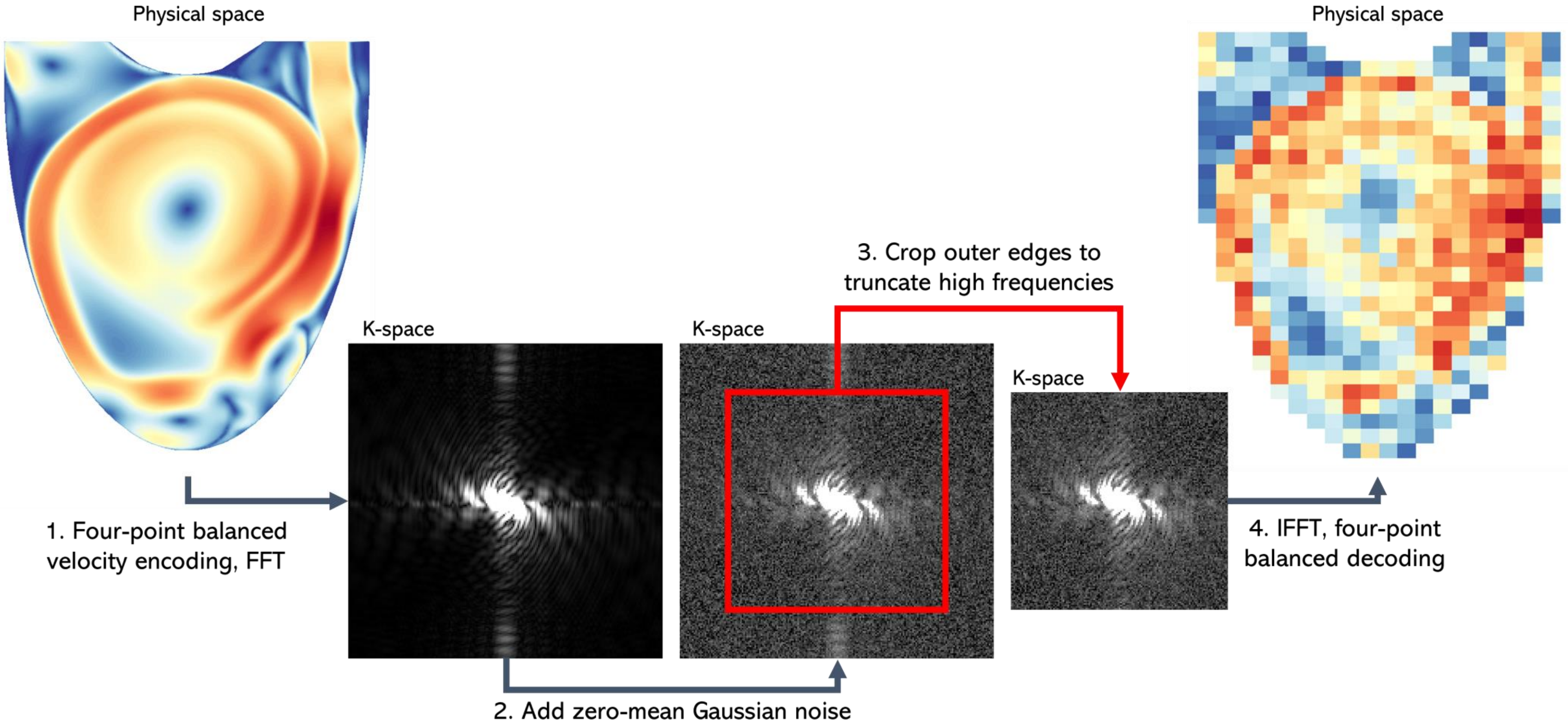
Vorticity contour plot of CFD results




Mesh details

# 2D Idealised Ventricle: Synthetic Data Generation

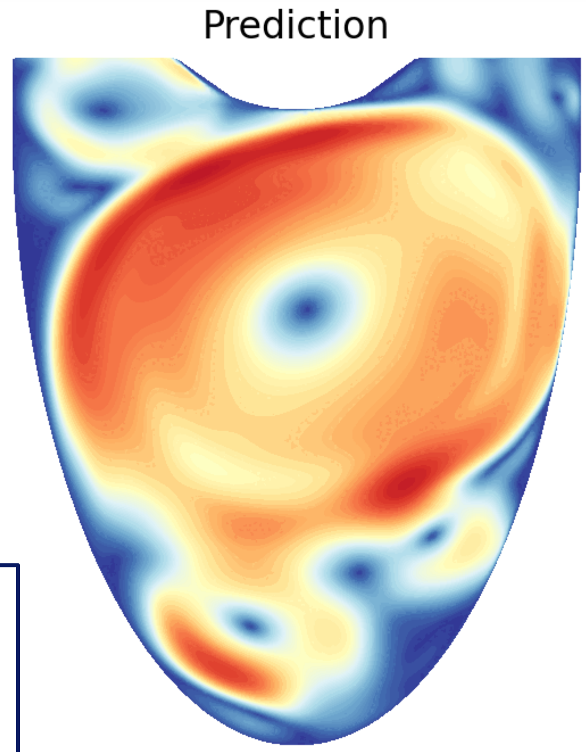
- Downsample data to match 4D-flow characteristics

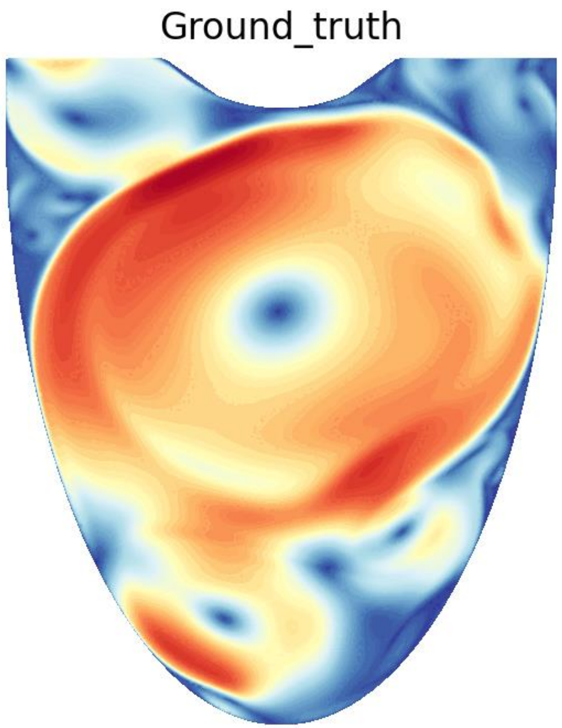


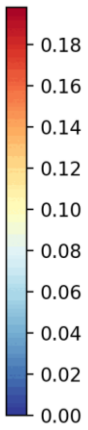
# 2D Idealised Ventricle: Setup

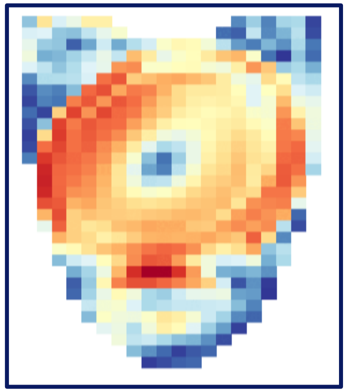
- Network width: **900** neurons
- Network depth: **9** layers
- Dropout rate: **0.55**
- Number of epochs: **30**
- Initial learning rate: $\mathbf{1 \times 10^{-5}}$ (annealing based on plateau of validation loss)
- Optimiser: **ADAM**
- Total collocation (physics) sample count: **5,986,116**
- Total wall data sample count: **346,572**
- Total training time: <3 hours

# Results: Velocity Magnitude



Training data

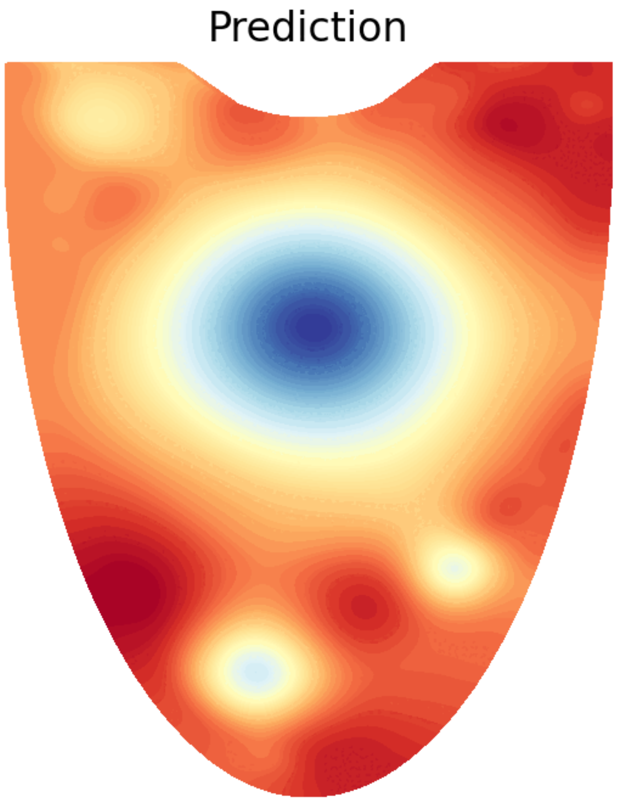
Prediction

nRMSE: **8.49%**

Ground truth

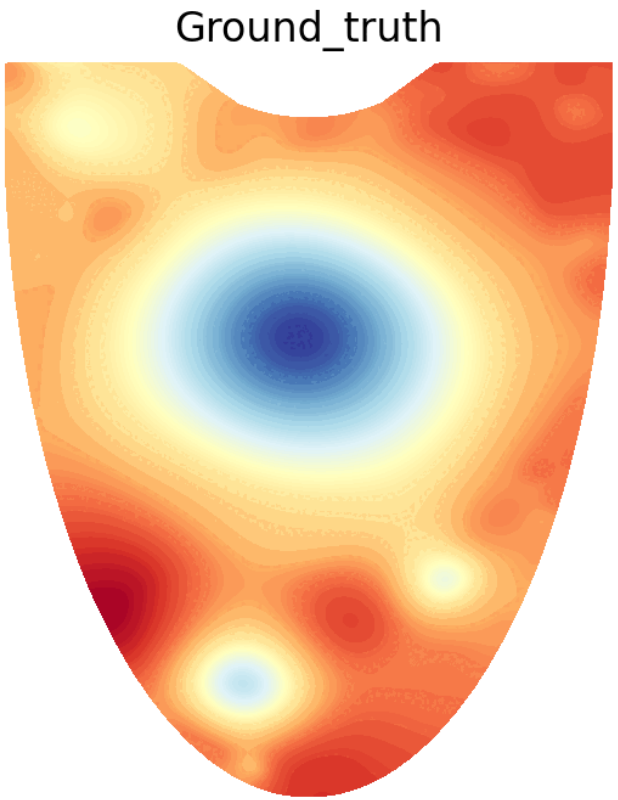
Velocity magnitude throughout cardiac cycle

# Results: Pressure




Prediction

nRMSE: **2.66%**

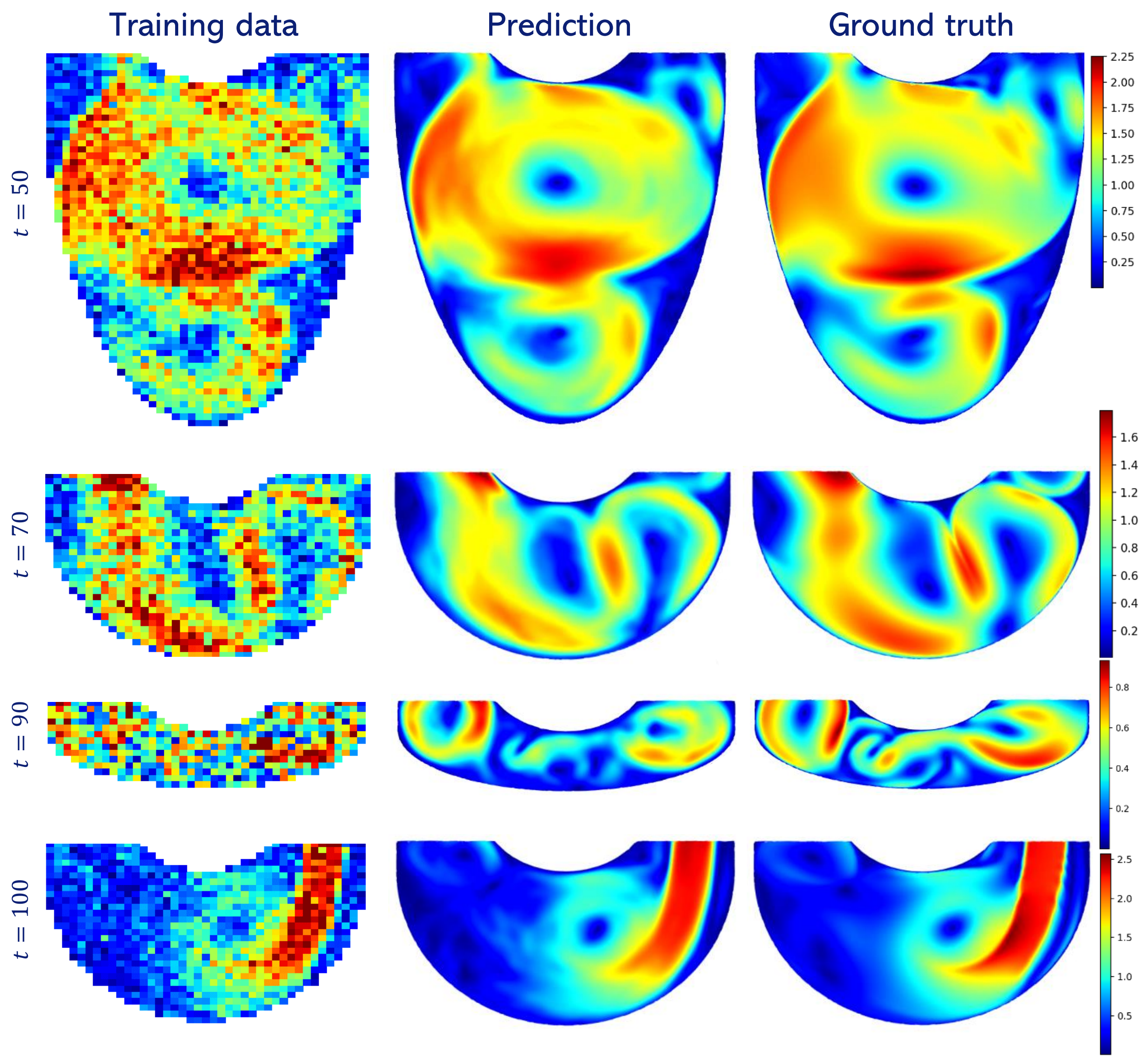



Ground truth

Velocity magnitude throughout cardiac cycle

# Results: Velocities

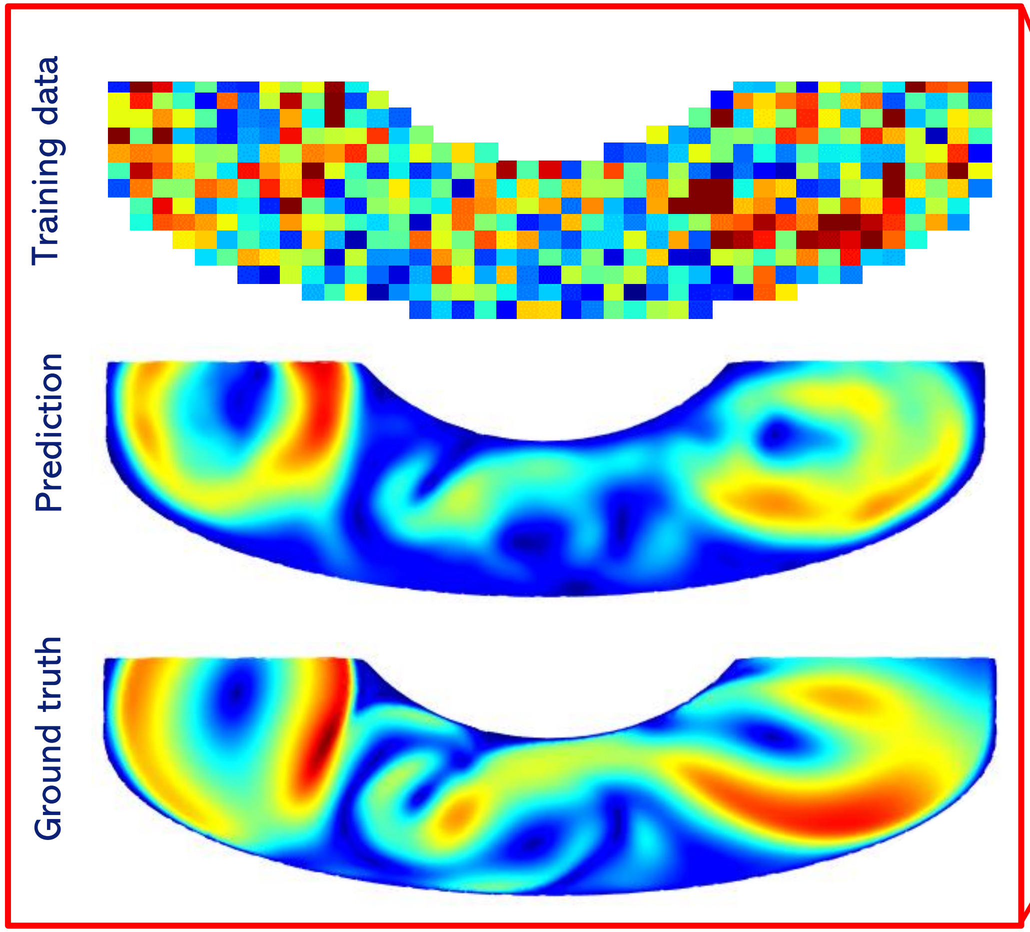
- Training data used
  - Spatial downsampling factor (each dim): **4**
  - Temporal downsampling factor: **5**
  - Signal-to-noise ratio: **6.6 (15%** std dev)
- Error:
  - Velocity max-normalised RMSE: **6.5%**
  - Interpolation (cubic spline) RMSE: **11.9%**

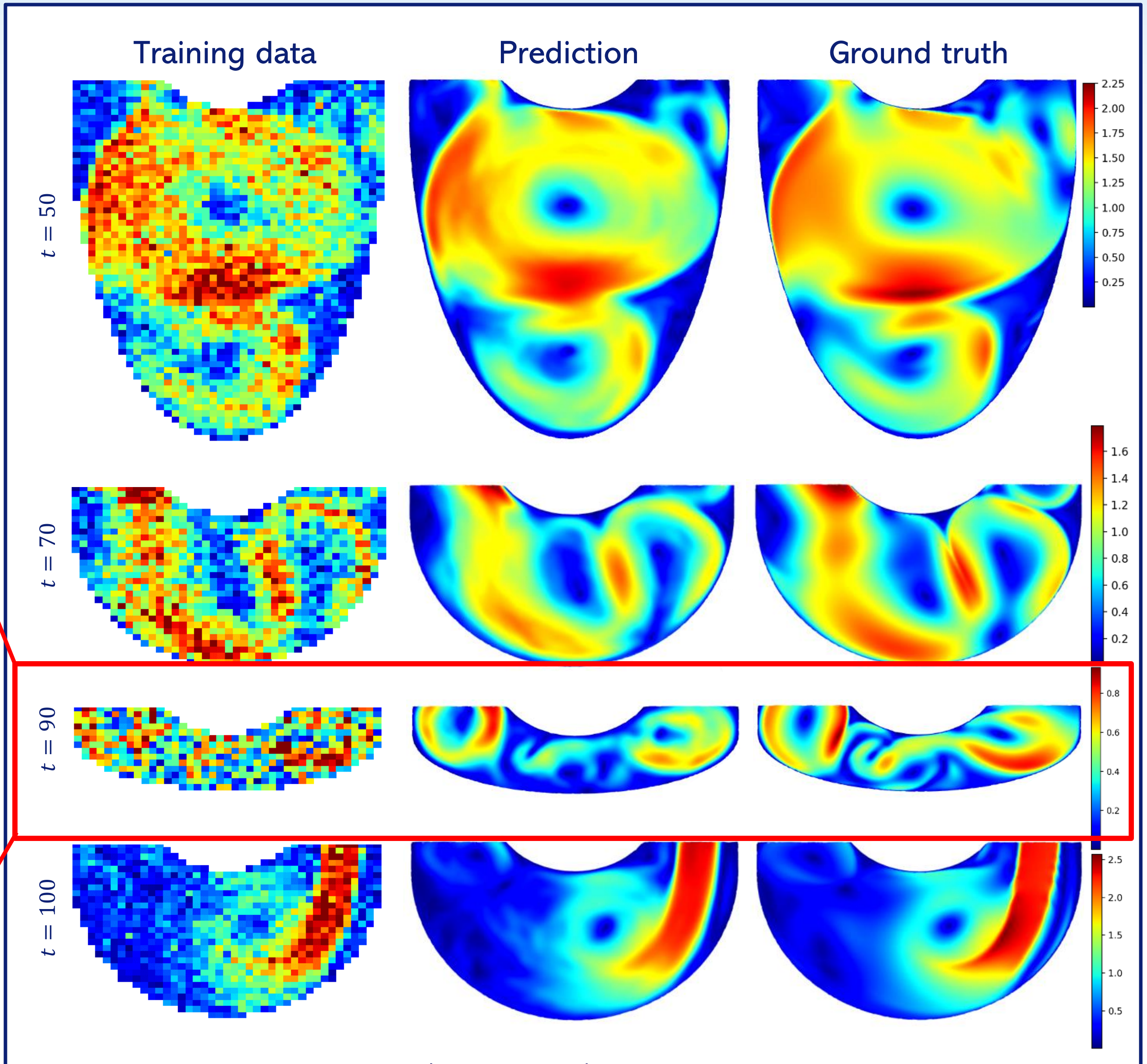



Velocity magnitude at various time steps

# Results: Velocities

- Captures features not visible in data!

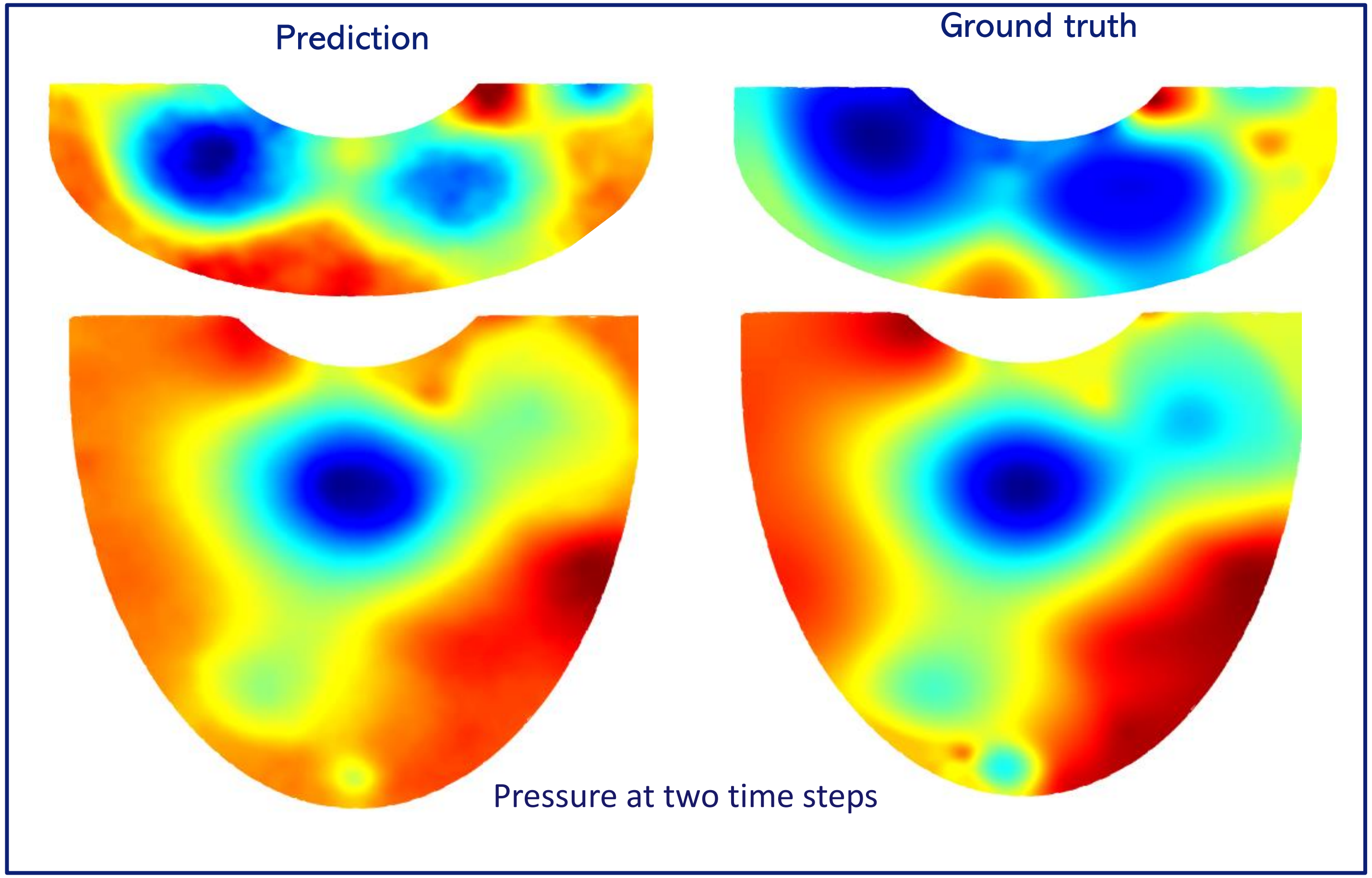


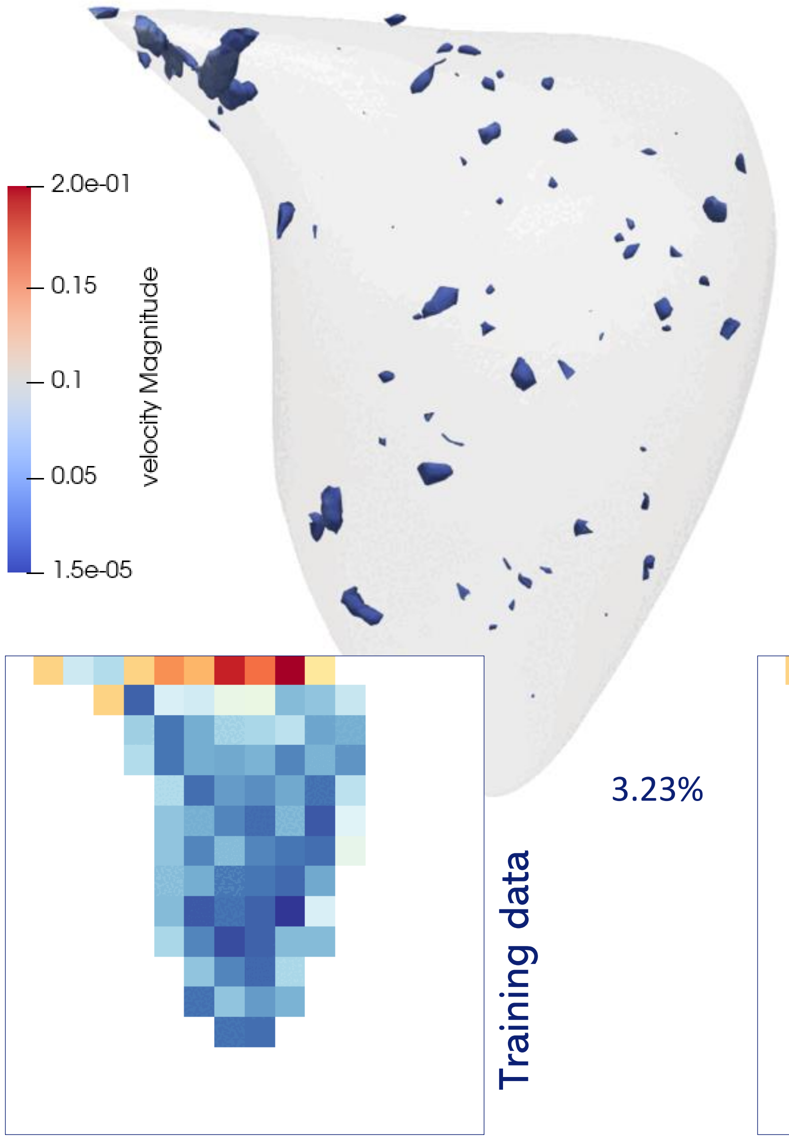

Velocity magnitude at various time steps

# Results: Pressure

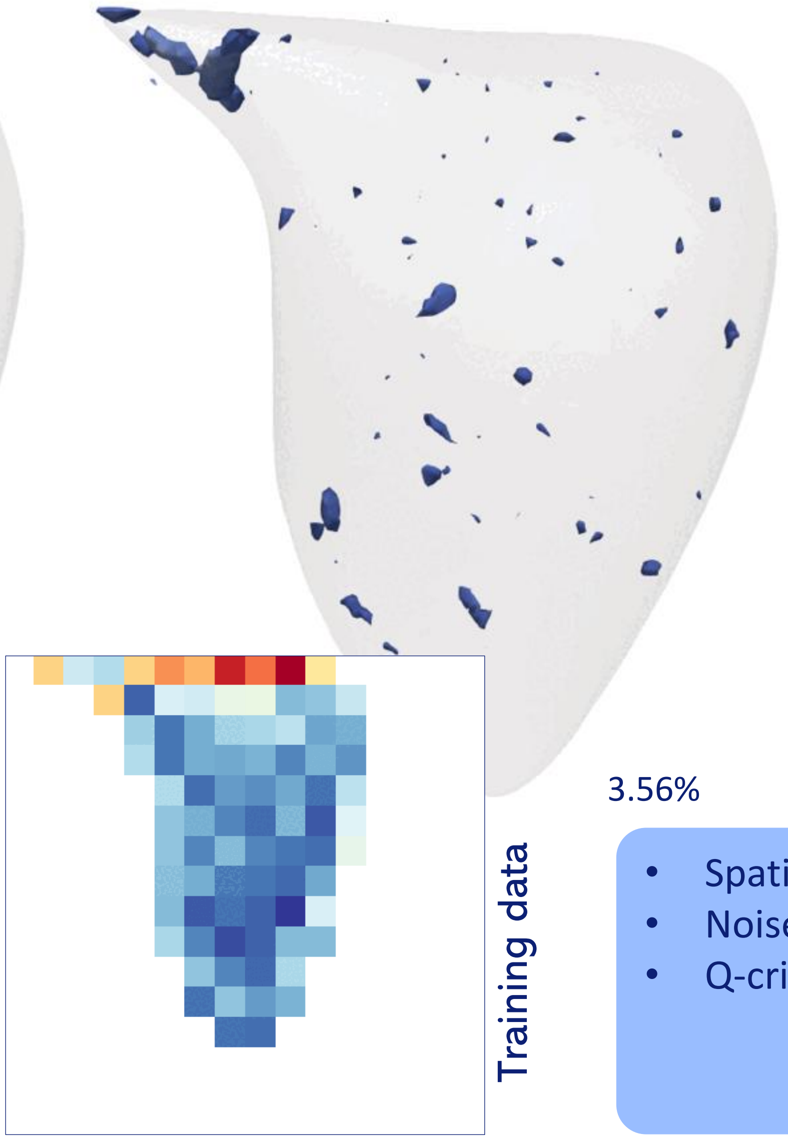
- No pressure data used in training
- Only constrained by Navier-Stokes equations!
  - Only accurate up to a constant
- Error:
  - Pressure nRMSE: **5.3%**



5x temporal upsampling




10x temporal upsampling




Ground truth

- Spatial downsampling rate: **8x**
- Noise: SNR **10** (**10%** std dev)
- Q-criterion:

$$Q = \frac{1}{2}\left(\|\boldsymbol{\Omega}\|^2 - \|\boldsymbol{S}\|^2\right)$$

# Outlook and Challenges

- We have shown:
  - PINNs provide effective super-resolution in the presence of significant data corruption
  - We are validating this in 2D and 3D synthetic studies

- Clinical challenges:
  - Large uncertainty in boundary motion and location
  - Rigorous *in vivo* validation is required, but challenging
    - 4D-flow MRI is already the gold standard blood flow imaging modality
  - We have planned a study to acquire 4D-flow MRI at two spatial resolutions

Thank you for listening!