

Motivation

Why Boiling Matters?

A ubiquitous, stochastic, and chaotic form of multiphase heat transfer.

- **AI & Data Centers:** Critical for cooling high-density GPU clusters.
- **Nuclear Energy:** Central to reactor safety and efficiency.

Scientific Challenge:

We address four key questions:

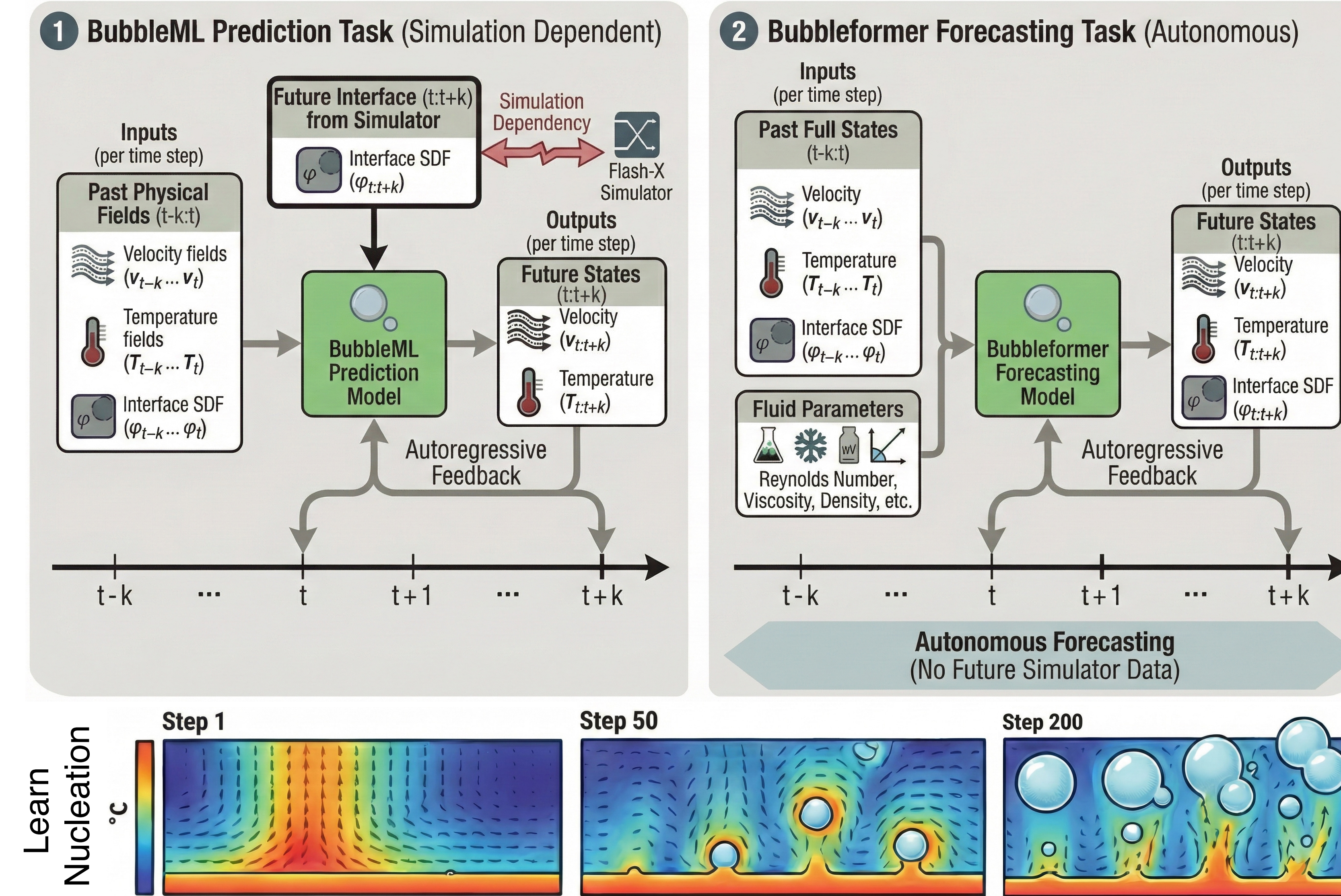
- **Generalization:** Can we forecast across different geometries and fluids?
- **Autonomy:** Can the model learn bubble nucleation for forecasting?
- **Stability:** Can the model stay stable during long autoregressive rollouts?
- **Physics Consistency:** Do the forecasts respect physical laws?

Contribution:

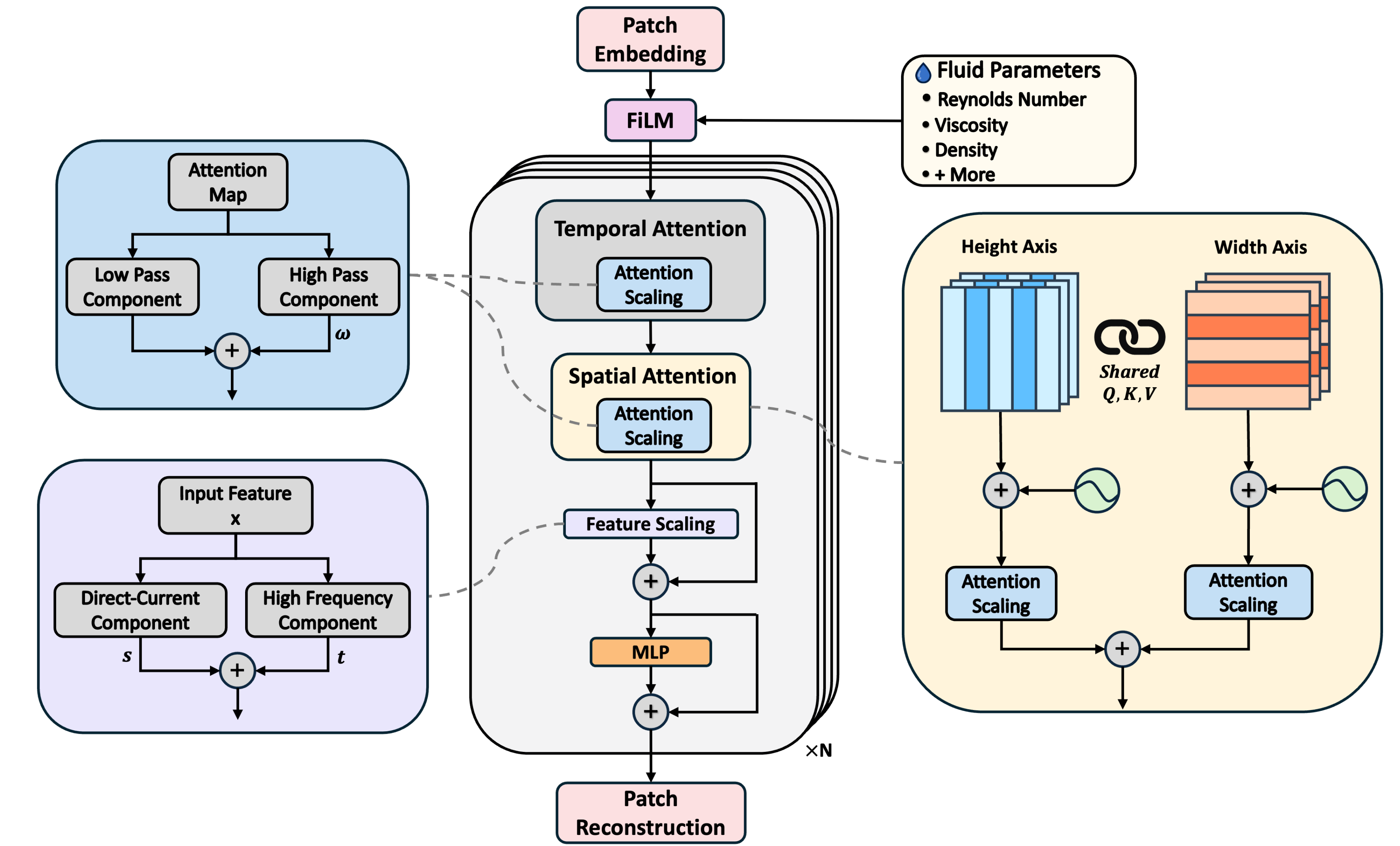
- Transformer-based **neural PDE solver** that **predicts and forecasts evolving physical fields** in boiling systems.
- Most comprehensive **open-source boiling dataset**.
- **Physics-based evaluation metrics** for forecasted fields.

Learning Tasks

Comparison of BubbleML Prediction vs. Bubbleformer Forecasting Tasks

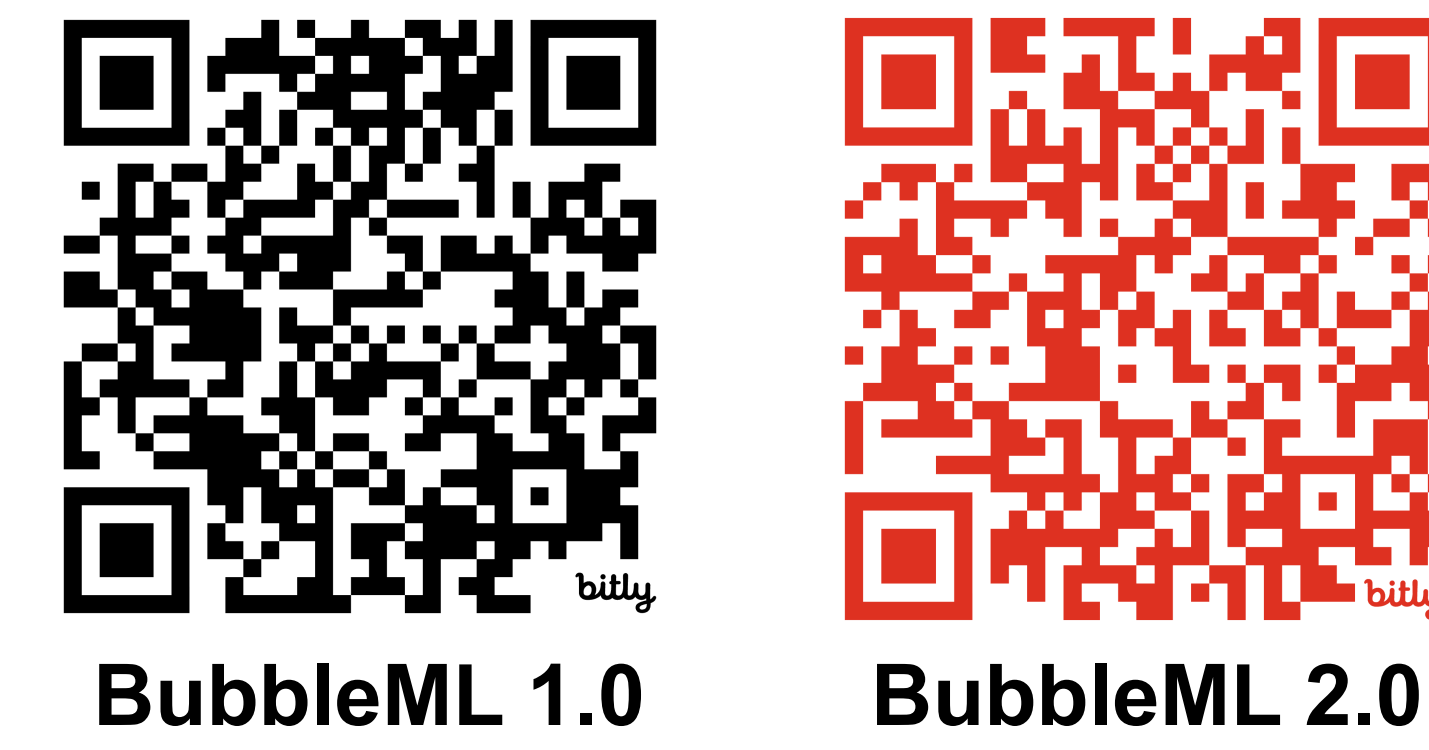


Bubbleformer Architecture



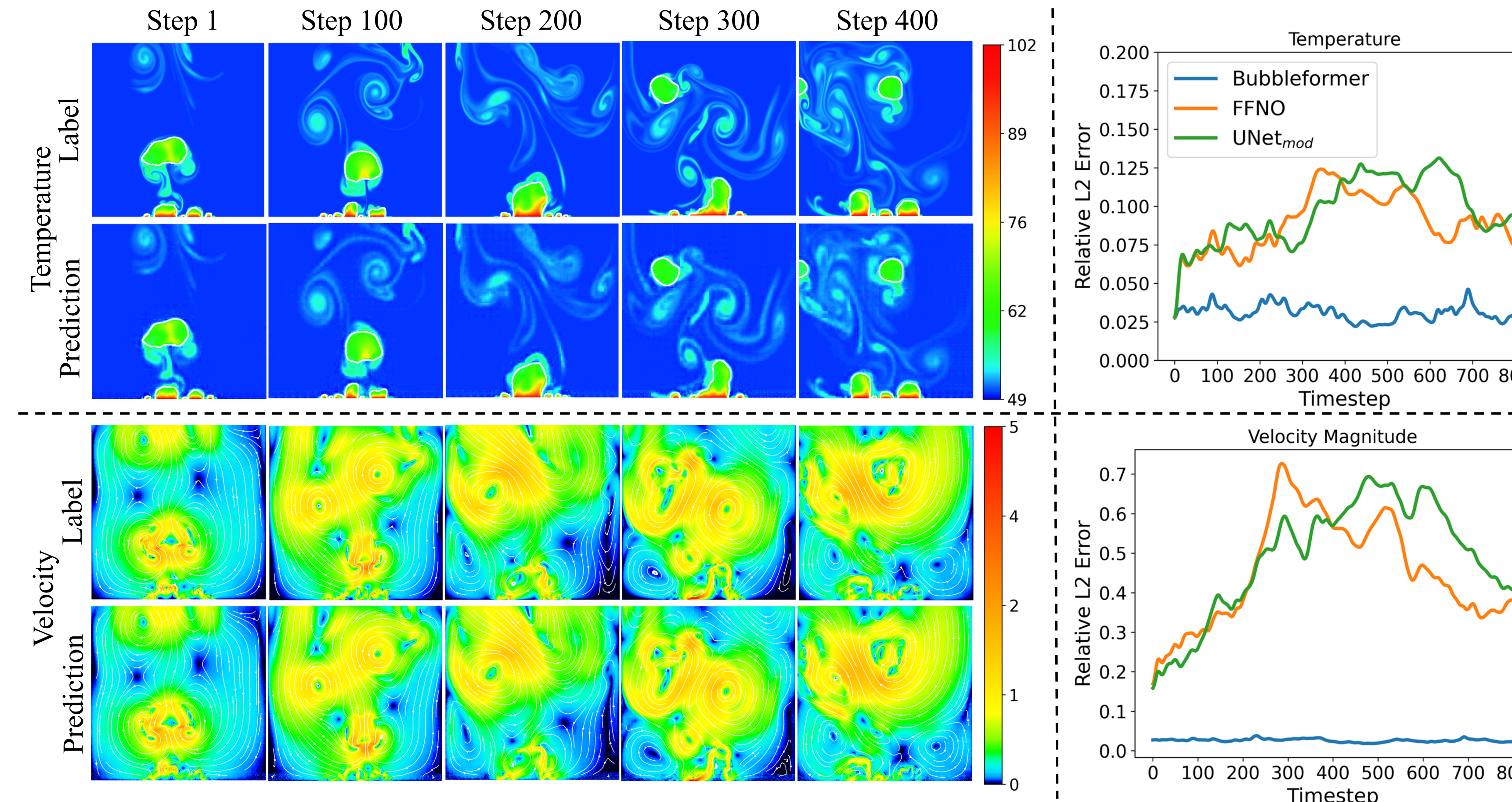
BubbleML 2.0 Dataset

- **Easy Access:** Hosted on Hugging Face with full metadata
- **Scale:** Over 160 high-fidelity simulations (~2.5 TB of data)
- **Diversity:** Covers a wide range of
 - **Fluids:** cryogenics, refrigerants, dielectrics
 - **Flow Regimes:** bubbly, slug, annular, post-dryout
 - **Geometries:** pool boiling & flow boiling

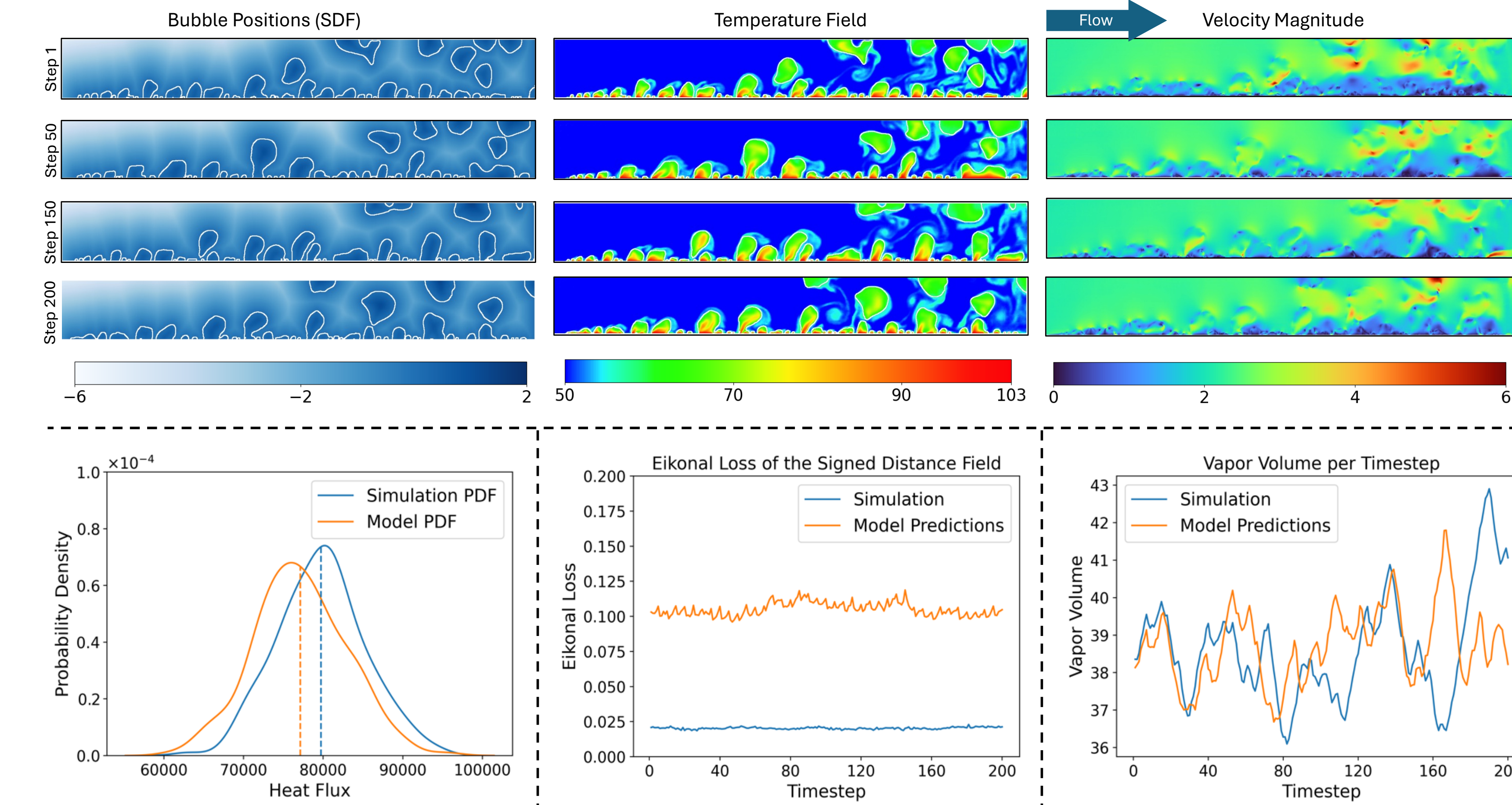


Main Results

Bubbleformer Predictions – Pool Boiling



Bubbleformer Forecasts – Flow Boiling



Model	Nucleation	Stable Forecast
UNet	✗	✓
FNO	✗	✗
MPP	✗	✓
Bubbleformer (Ours)	✓	✓

Heat Flux

Heat Flux is accumulated over the forecast window and its PDF is estimated to calculate the KL Divergence.

$$q^j = k_e \frac{\partial T^j}{\partial n} \bigg|_{\text{wall}}, \quad j \in \{t, \dots, t+k\} \quad \text{Fourier's Law}$$

$$D_{KL}(P_{GT} \| P_{ML}) = \int P_{GT}(q) \log \frac{P_{GT}(q)}{P_{ML}(q)} dq \quad \text{KL Divergence}$$

Eikonal Loss

Bubble positions (ϕ) are represented by a signed distance field and satisfy the Eikonal equation.

$$|\nabla \phi| = 1 \quad \text{Eikonal Equation}$$

$$\mathcal{L}_{\text{eik}}(\phi) = \frac{1}{k} \sum_{j=t}^{t+k} \frac{1}{N} \sum_{i=1}^N \left| |\nabla \phi_{ML}^j(x_i)| - 1 \right| \quad \text{Eikonal Loss}$$

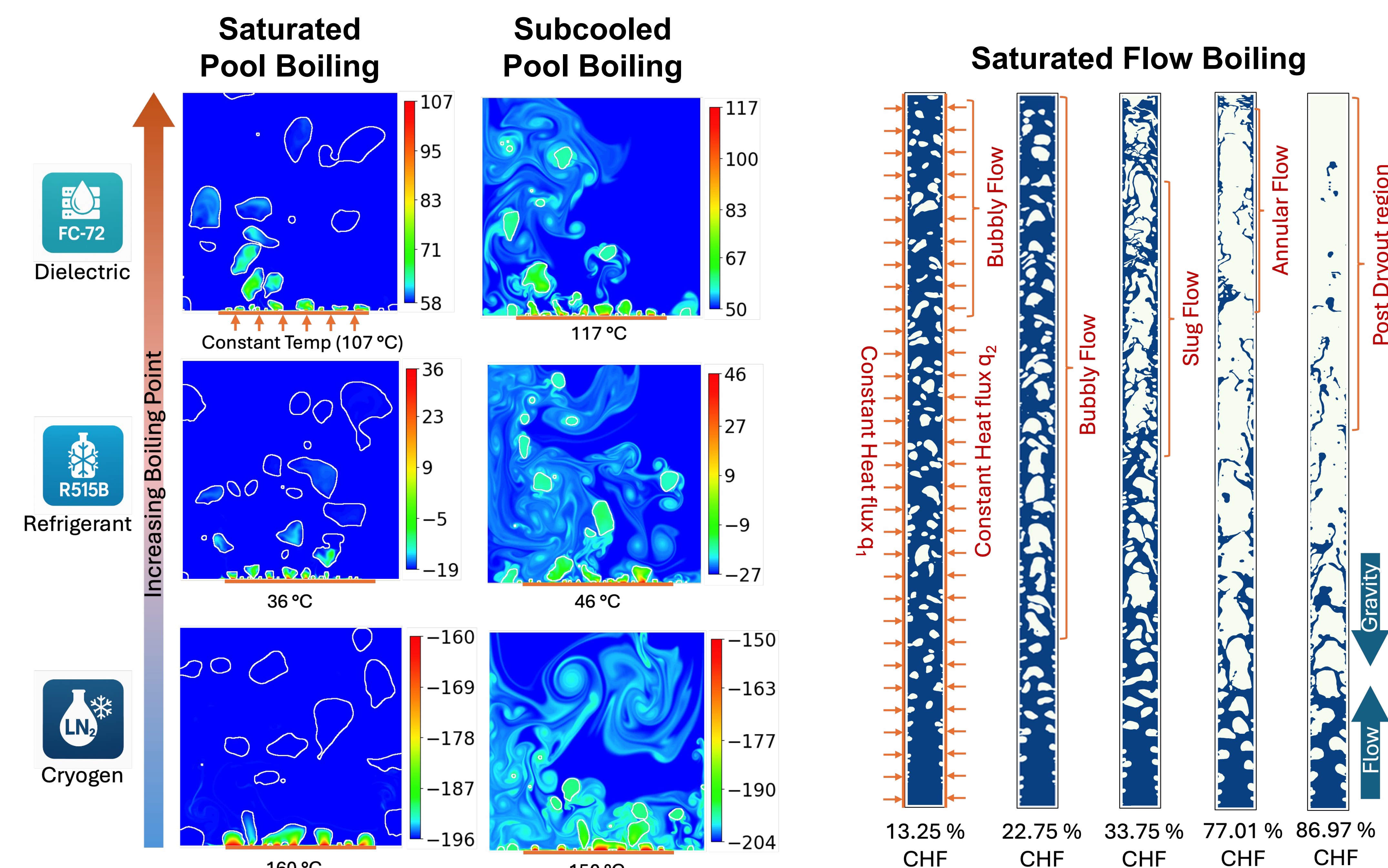
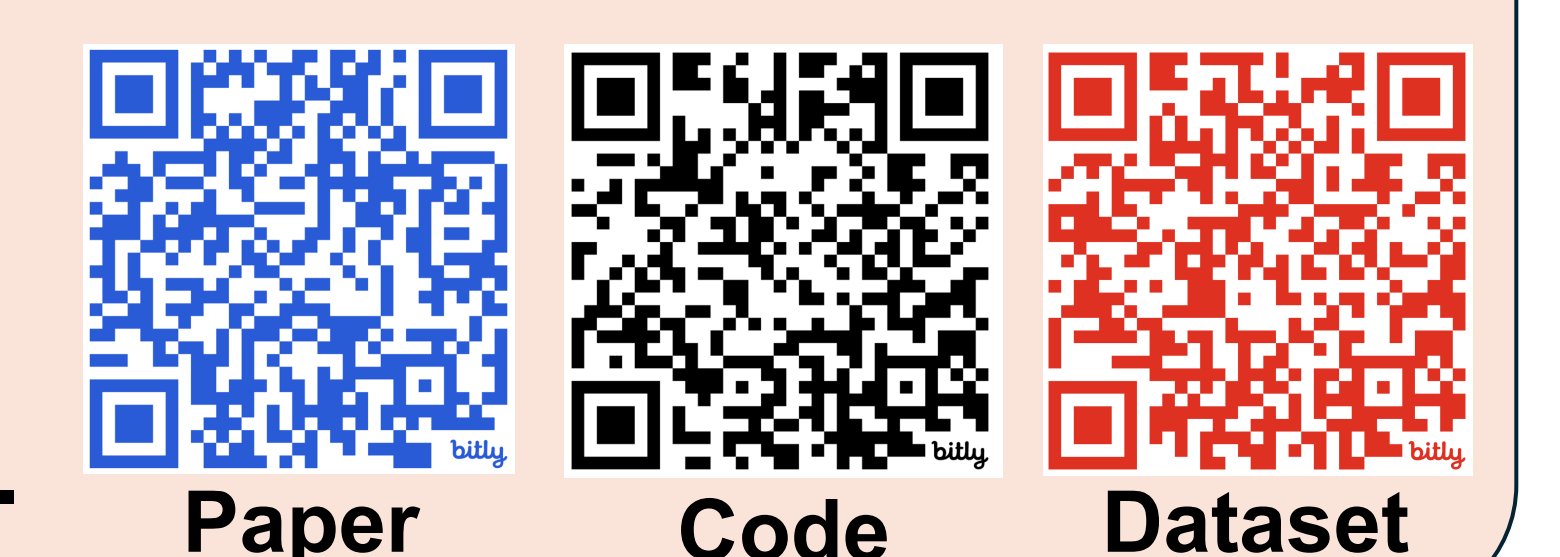
Relative Vapor Volume Error

Total vapor volume should be approximately conserved between simulation and model forecast. A low relative vapor volume error signifies that mass conservation laws are respected.

$$\mathcal{L}_{\text{vol}}(\phi) = \frac{1}{k} \sum_{j=t}^{t+k} \frac{\left| \sum_{i=1}^N \mathbf{1}_{\{\phi_{ML}^j(x_i) > 0\}} - \sum_{i=1}^N \mathbf{1}_{\{\phi_{GT}^j(x_i) > 0\}} \right|}{\sum_{i=1}^N \mathbf{1}_{\{\phi_{GT}^j(x_i) > 0\}}} \quad \text{RVV Error}$$

Take Home Message (TLDR)

- ❖ BubbleML 2.0 is a comprehensive, open-source boiling dataset covering diverse fluids, geometries and flow regimes.
- ❖ Bubbleformer is a spatiotemporal transformer that forecasts boiling dynamics across fluids, geometries, and boiling configurations, while preserving physical consistency.



Type - Physics - Fluid	Sims	Domain (mm^d)	Resolution Spatial	Δt	Time steps	Size (GB)
PB - Single Bubble - FC72	11	4.38×6.57	192×288	0.2	2000	50
PB - Single Bubble - R515B	11	6.48×9.72	192×288	0.2	2000	50
PB - Saturated - FC72	20	11.68×11.68	512×512	0.1	2000	320
PB - Saturated - R515B	20	17.28×17.28	512×512	0.1	2000	320
PB - Saturated - LN2	20	16.96×16.96	512×512	0.1	2000	320
PB - Subcooled - FC72	20	11.68×11.68	512×512	0.1	2000	320
PB - Subcooled - R515B	20	17.28×17.28	512×512	0.1	2000	320
PB - Subcooled - LN2	20	16.96×16.96	512×512	0.1	2000	320
FB - Inlet Velocity - FC72	15	30.66×3.65	1344×160	0.1	2000	320
FB - Constant Heat Flux - FC72	6	117.5×5.1	5152×224	0.1	1000	420