Fluid Simulation in the Movies

NAVIER AND STOKES MUST BE CIRCULATING IN THEIR GRAVES

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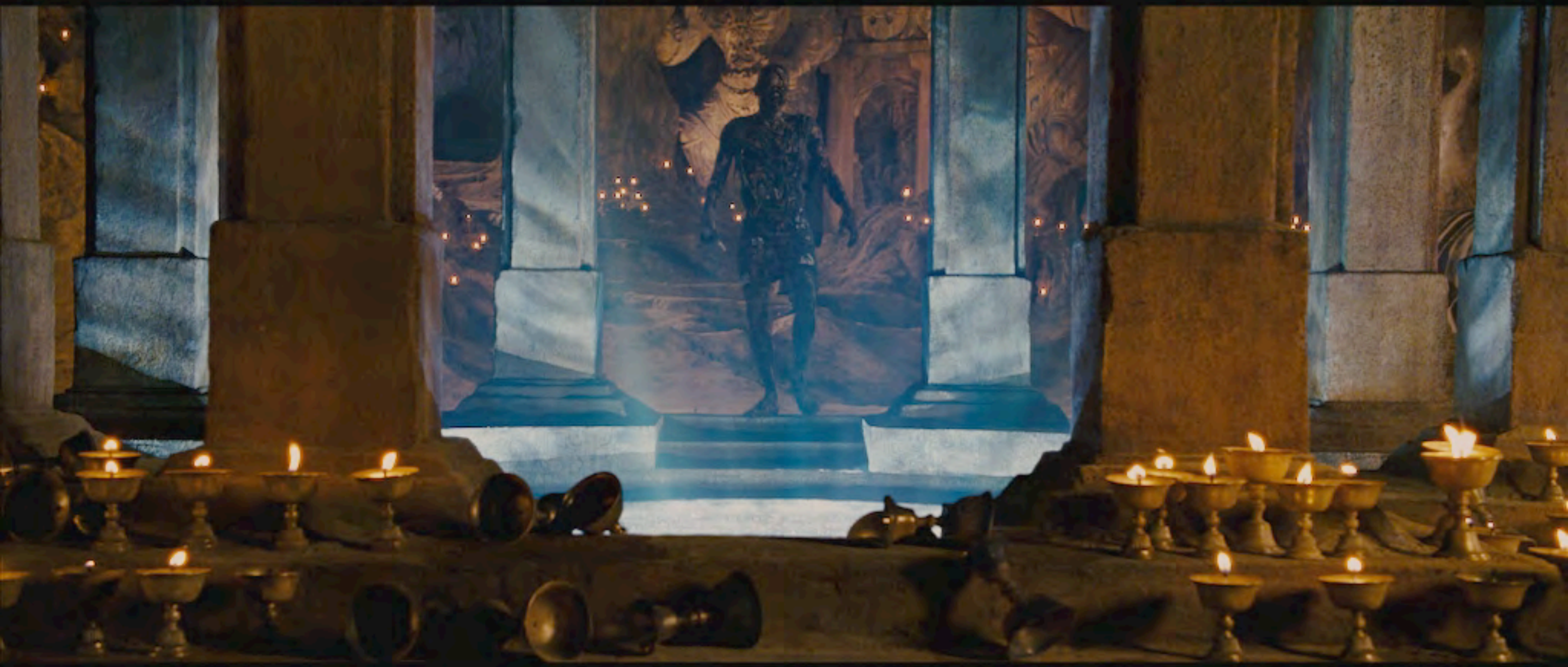
THE MUMMY : TOMB OF THE DRAGON EMPEROR



THE MUMMY : TOMB OF THE DRAGON EMPEROR

THE A-TEAM


#1657221 : ef175.964.CmpMain.Main-0043 - hhoyland
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EF_175X_964_v043.qt

The wolfman

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Production Issues

- CFD and Production workflows do not fit together well
- The language of visual effects is imprecise

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Golden Compass

0021

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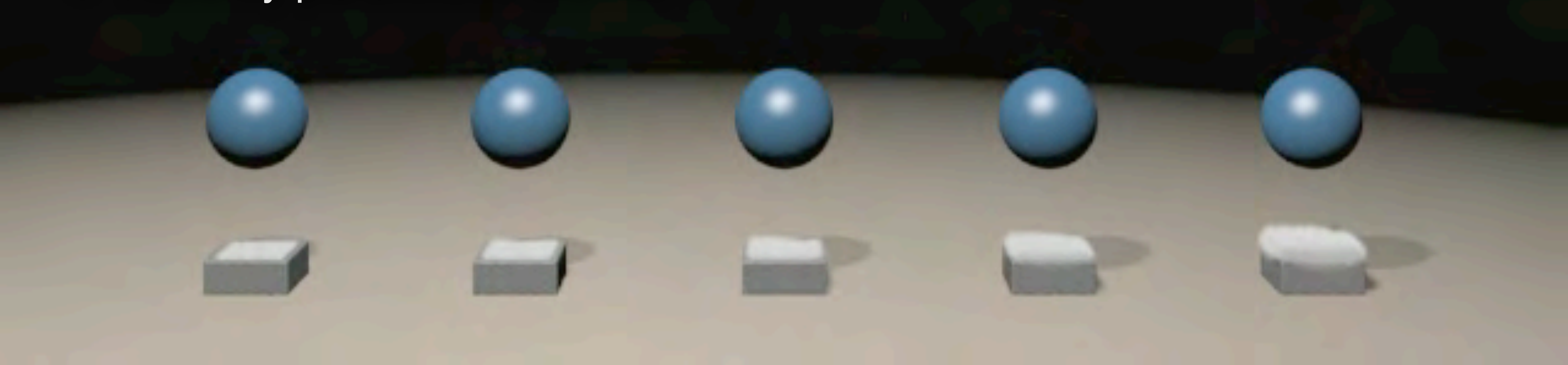
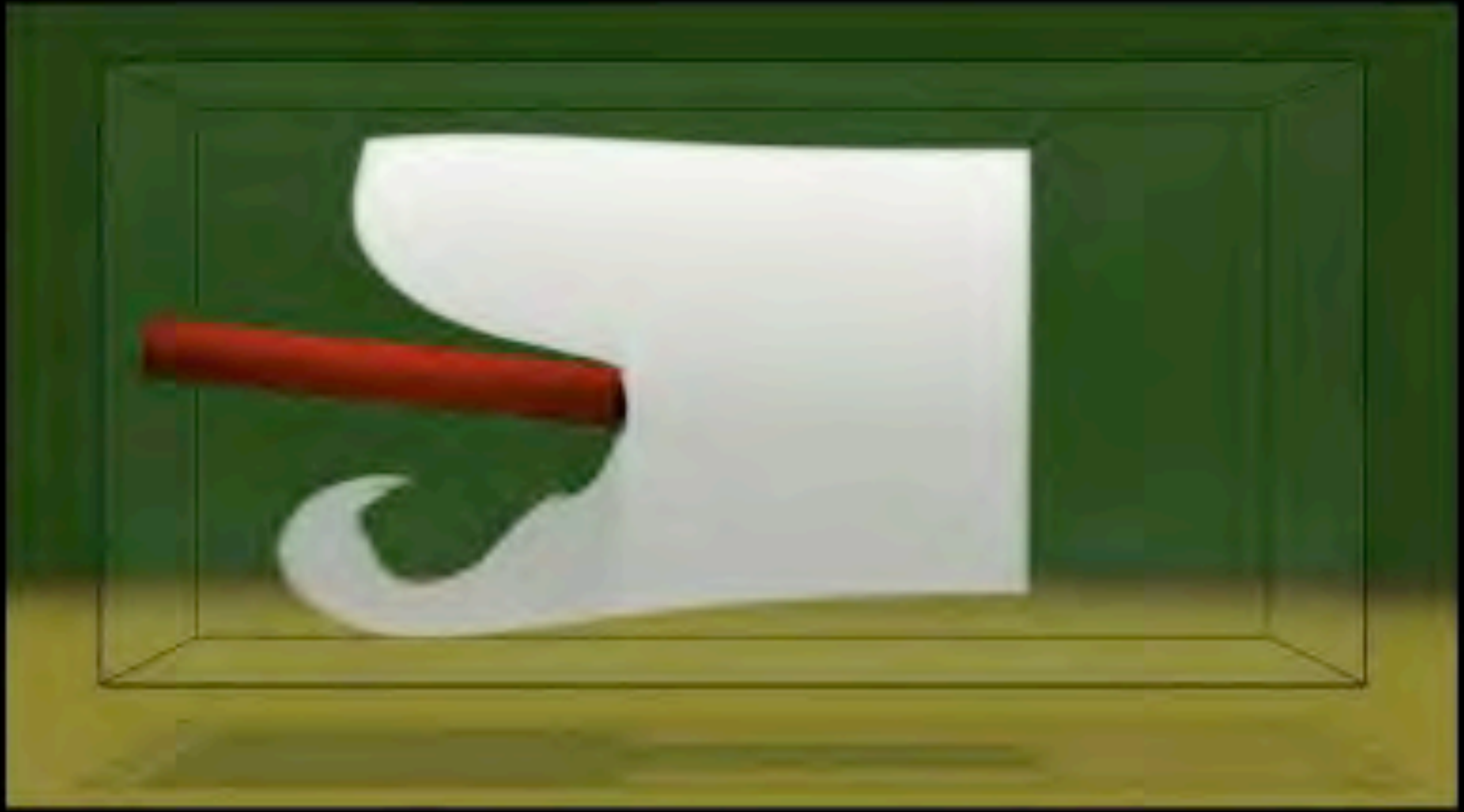
3D Gas Solver

- Incompressible Navier-Stokes
- Fixed rectangular Eulerian grid
- Multiple Advection Schemes
  - QUICK (space) + 2nd order Adams-Bashforth (time)
  - FLIP
  - Semi-Lagrangian
- Pressure Projection
  - Multigrid
  - Iterated Orthogonal Projections for complex boundaries
- Recently parallelized with MPI



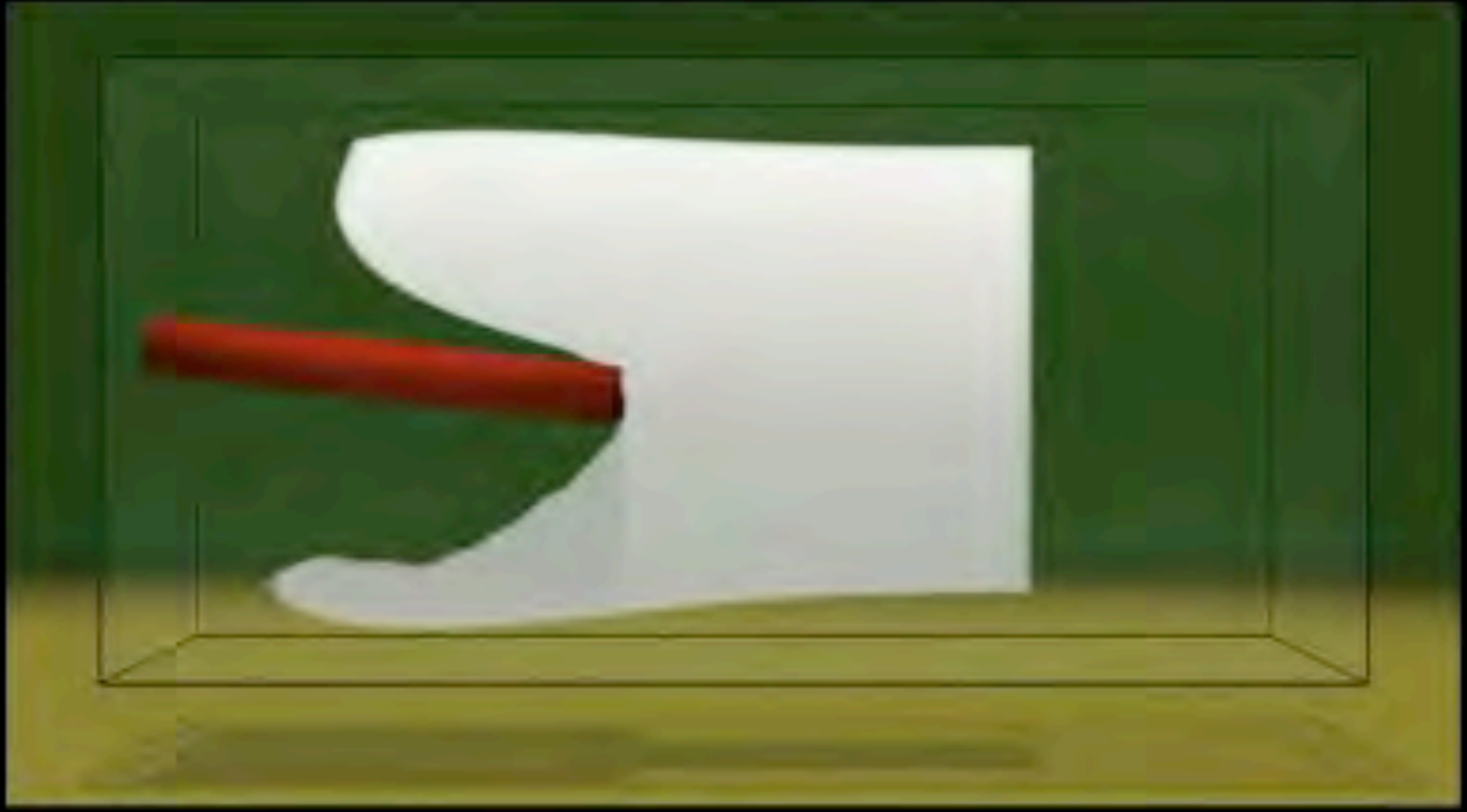
Low numerical viscosity

(QUICK)



High numerical viscosity

(SEMI-LAGRANGIAN)



X2 - XMen United

swirly smokey puffy

Routine Simulation Workflow

- Technical Directors (artists) run simulation software
- Many iterations per day, daily feedback
- Single machine (2-4 cores, 2-32 GB RAM)
- Low-res sims for quick approval, hi-res maybe
- “Sweetening” via gridless advection

Advection via Characteristic

$$\frac{\partial C(\mathbf{x},t)}{\partial t} + \mathbf{u}(\mathbf{x},t)\cdot\nabla C(\mathbf{x},t) = S(\mathbf{x},t)$$

- Integral solution in terms of a characteristic function $\mathbf{X}$

$$\mathbf{X}(\mathbf{x},t') = \mathbf{x} - \int_0^{t'} dt''\ \mathbf{u}\left(\mathbf{X}(\mathbf{x},t'-t''),t''\right)$$

$$C(\mathbf{x},t) = C(\mathbf{X}(\mathbf{x},t))\ + \int_0^{t} dt'\ S(\mathbf{X}(\mathbf{x},t-t'),t')$$

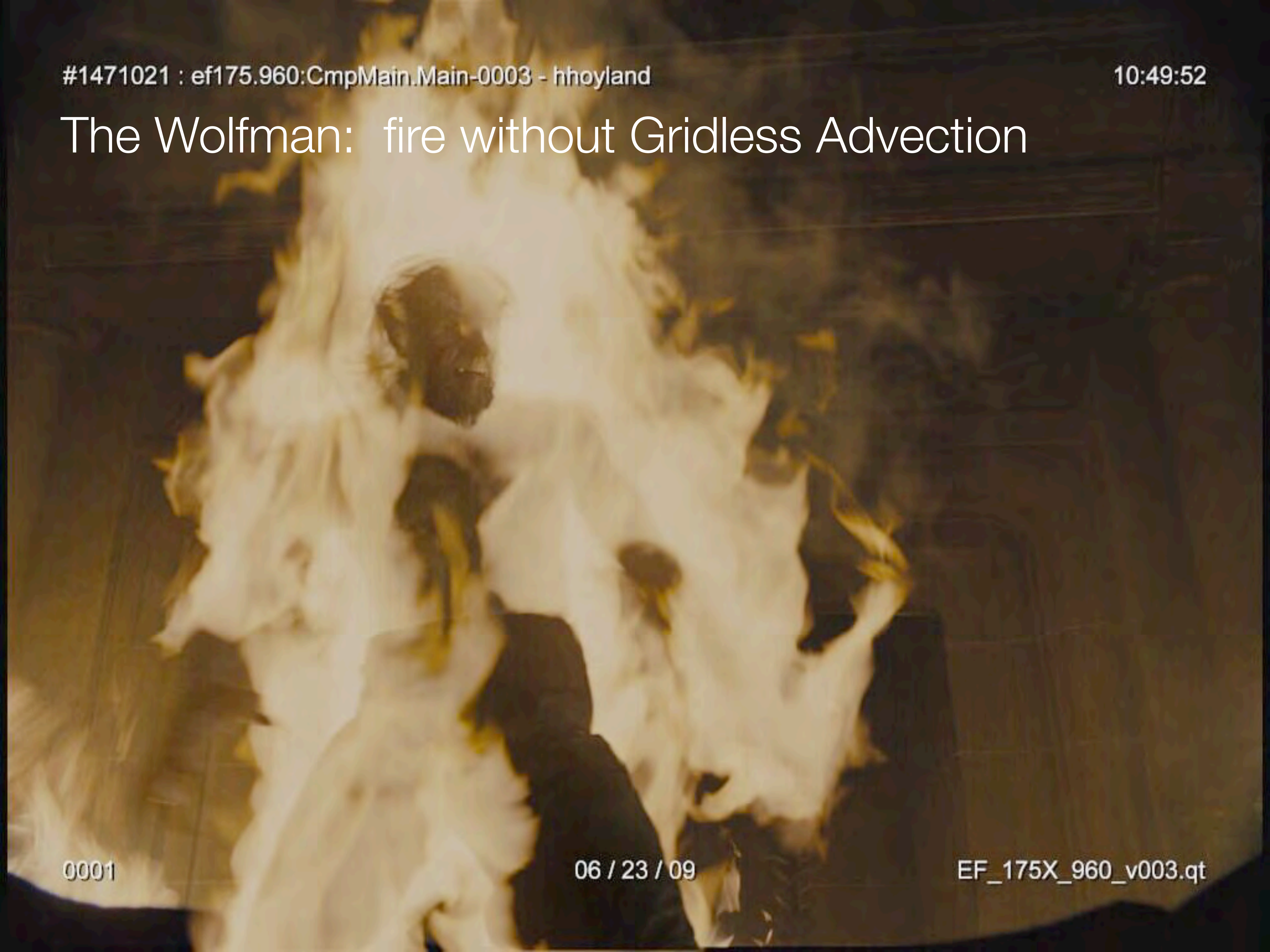
Multiple advection steps

$$C(\mathbf{x}, n\Delta t) = C_0(\mathbf{X}_n(\mathbf{x}))$$

$$\mathbf{X}_n(\mathbf{x}) = \mathbf{X}_{n-1}\left(\mathbf{x} - \mathbf{u}(\mathbf{x}, t + (n-1)\Delta t)\Delta t\right)$$

- Map generated post simulation
- Evaluating at render time is very slow for $n > 4$
- Artistic tool for “sharpening” density and color fields
- “Gridless advection”

The Wolfman: fire without Gridless Advection

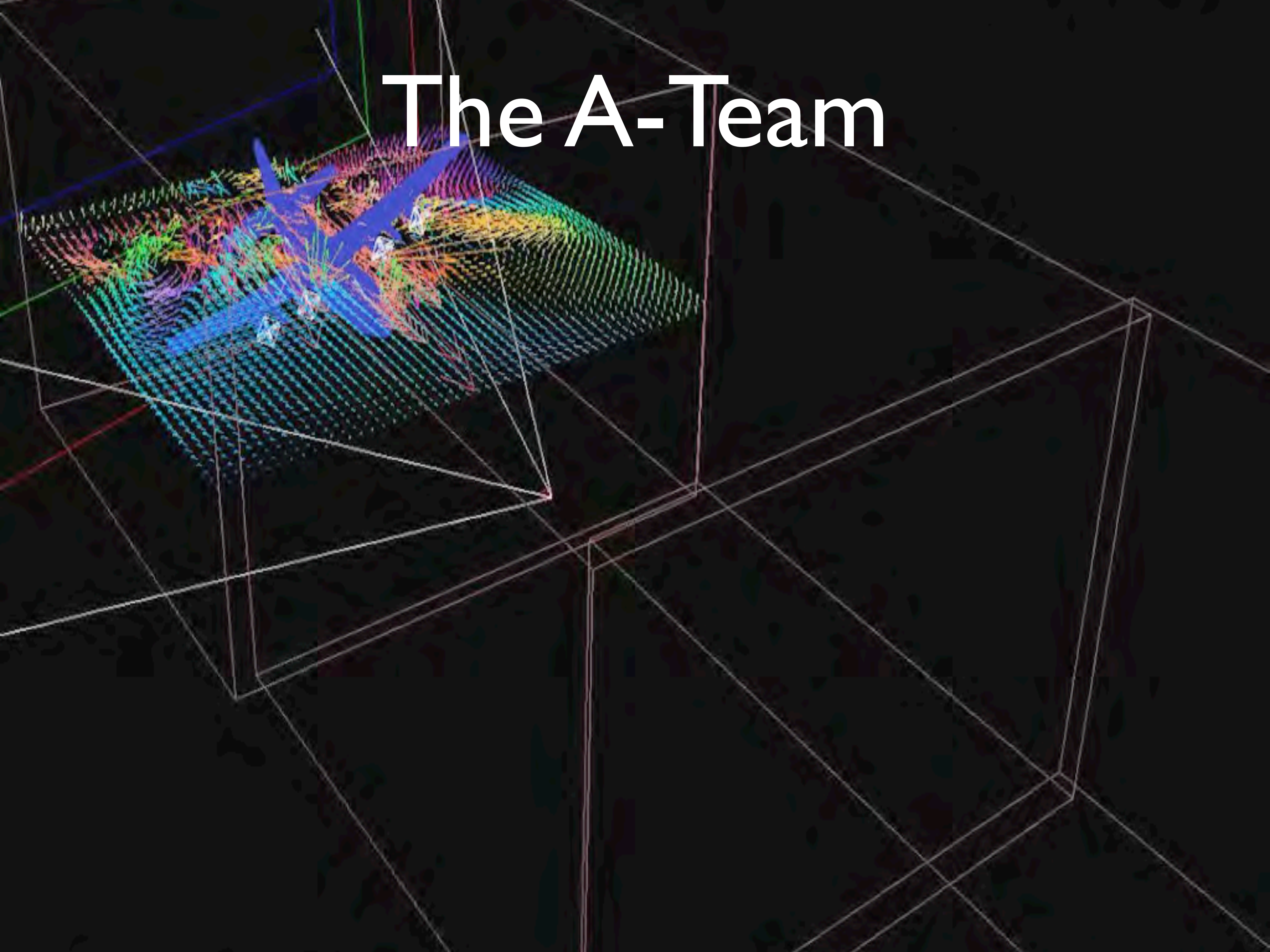


The Wolfman: fire with Gridless Advection

A-Team
Foreground cloud gridless advection

The A-Team

The A-Team



Semi-Lagrangian Mapping (SELMA)

- Characteristic mapping function is the central object of advection

$$\mathbf{X}_n(\mathbf{x}) = \mathbf{X}_{n-1}\left(\mathbf{x} - \mathbf{u}_n(\mathbf{x})\Delta t\right)$$

- Applying this for more than 4-5 steps takes a lot of cpu time and memory
- Sampling the mapping function onto a grid each step reduces both resource issues

$$\mathbf{X}_n(\mathbf{x}_i) = \sum_j \omega_j \, \mathbf{X}_{n-1}\left(\mathbf{x}_j\right)$$

$$\mathbf{x}_j \in \text{Neighborhood}\left(\mathbf{x}_i - \mathbf{u}_n(\mathbf{x}_i)\Delta t\right)$$

- Preserves detail
- Causes numerical dissipation of the mapping function, but not the density

The A-Team

The A-Team

The A-Team

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0089

The A-Team

The A-Team

3D Liquid Solver

- Incompressible Navier-Stokes
- Fixed rectangular Eulerian grid
- Advection via QUICK
  - 3rd order upwind advection
  - 2nd order Adams-Bashforth in time
- Pressure projection via conjugate gradient
- Free-surface tracking via levelset (gridded signed distance function)
  - Smooth Particle Hydrodynamics initiated at surface erosion
- One-phase only (liquid and vacuum)

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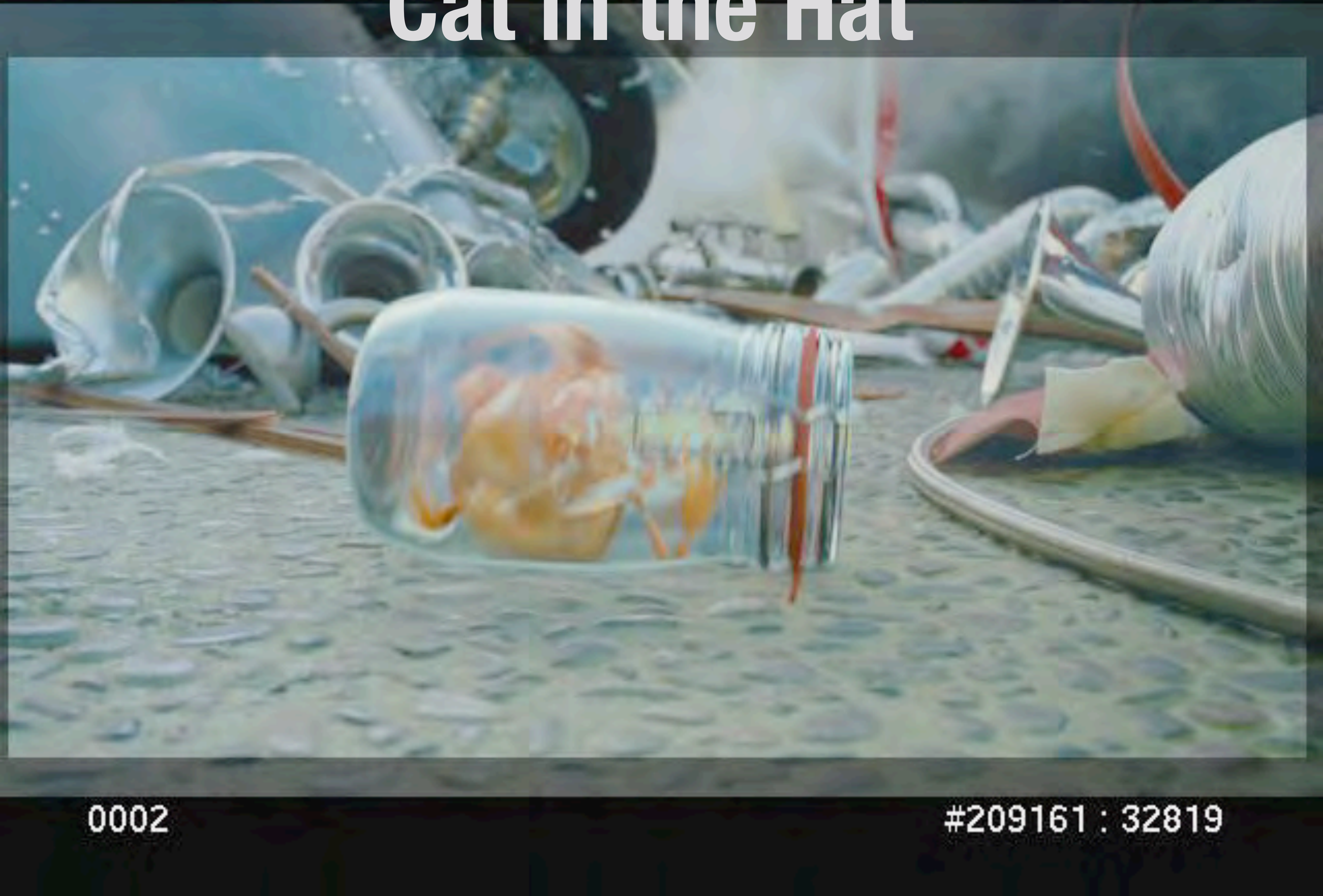
Cat in the Hat



Happy Feet


1250
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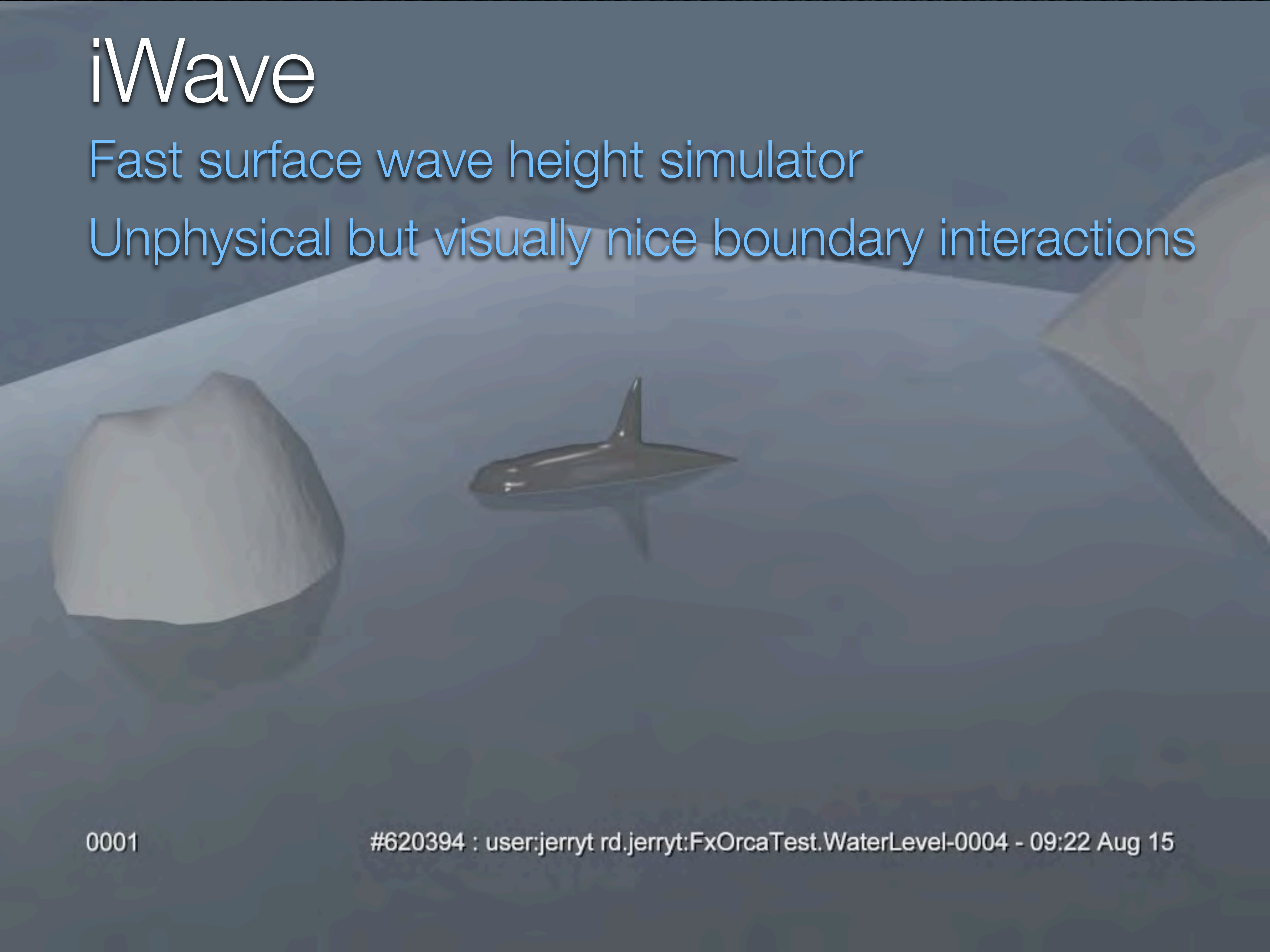
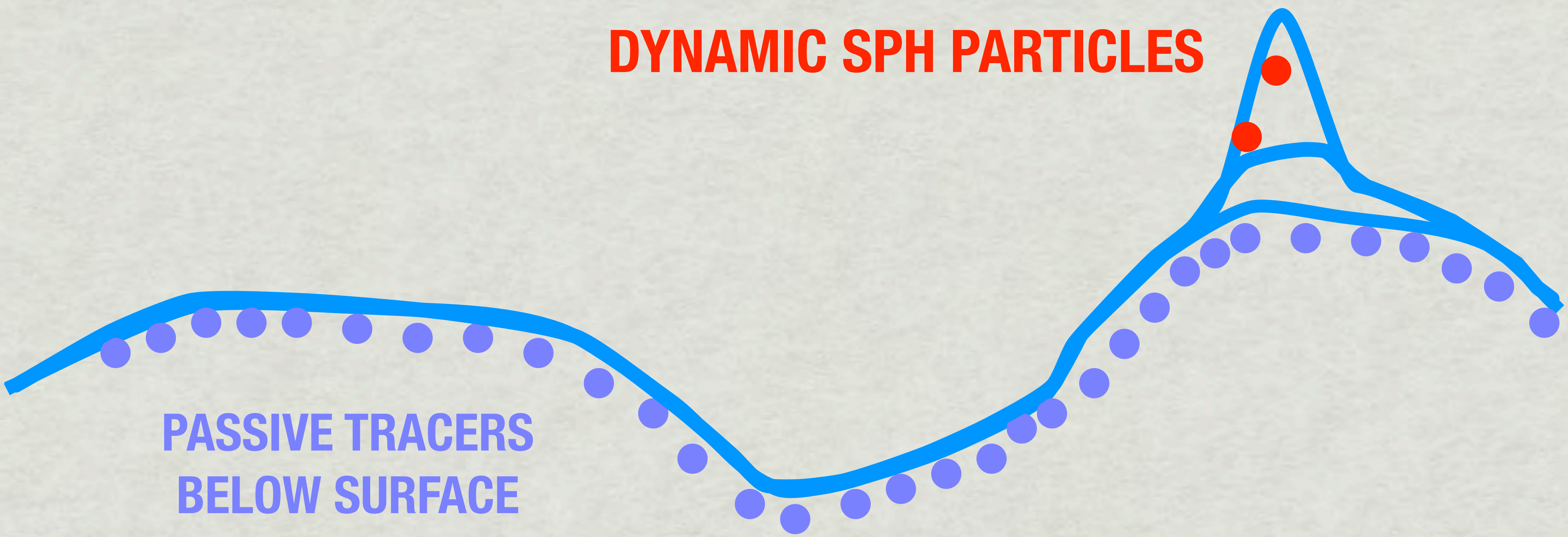
iWave

- Fast surface wave height simulator
- Unphysical but visually nice boundary interactions



Hybrid Eulerian Grid and SPH



- Levelset surface advected
- Passive tracers advected
- Levelset surface regridded - EROSION OCCURS
- Exposed tracers converted to SPH particles with momentum & mass from eroded volume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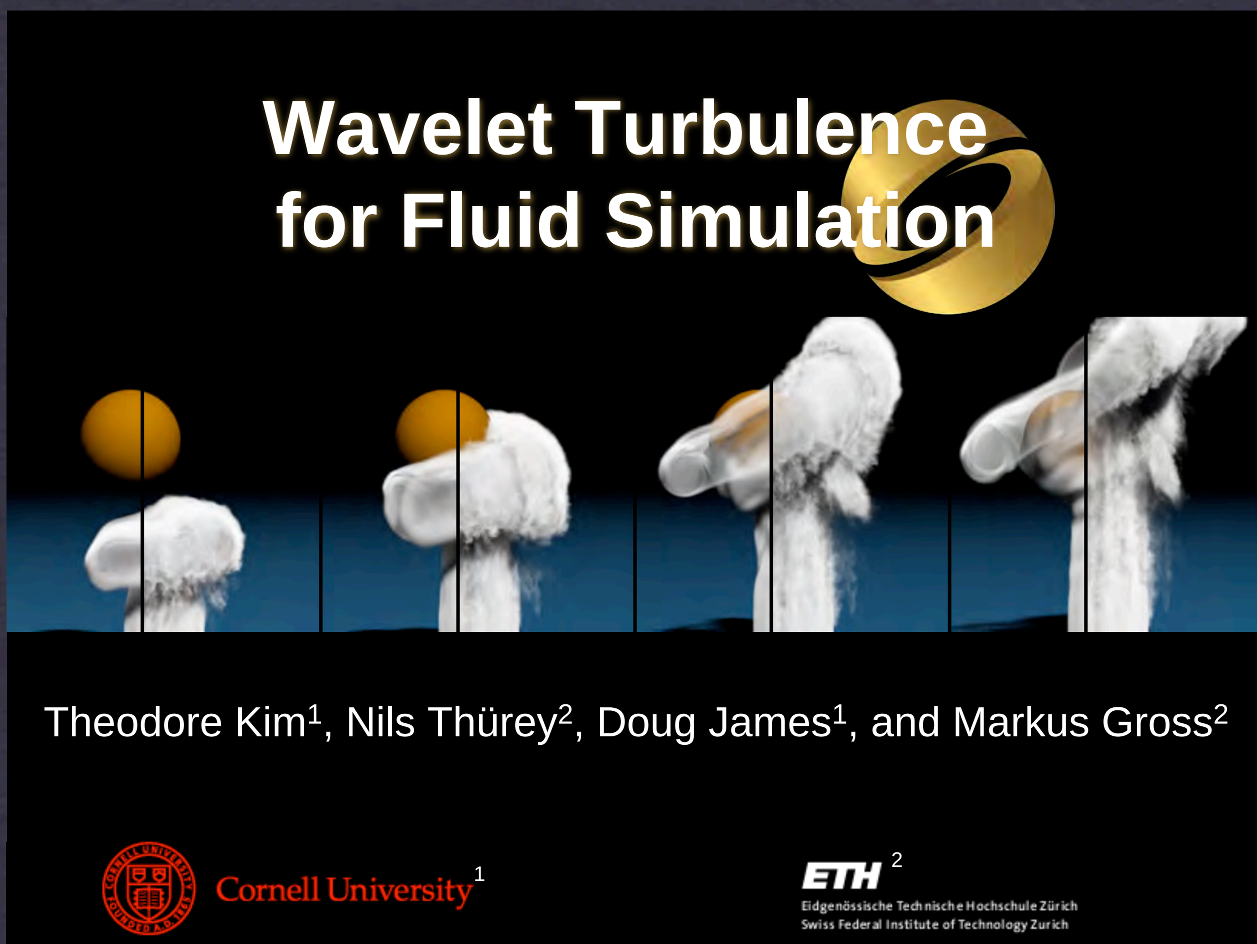
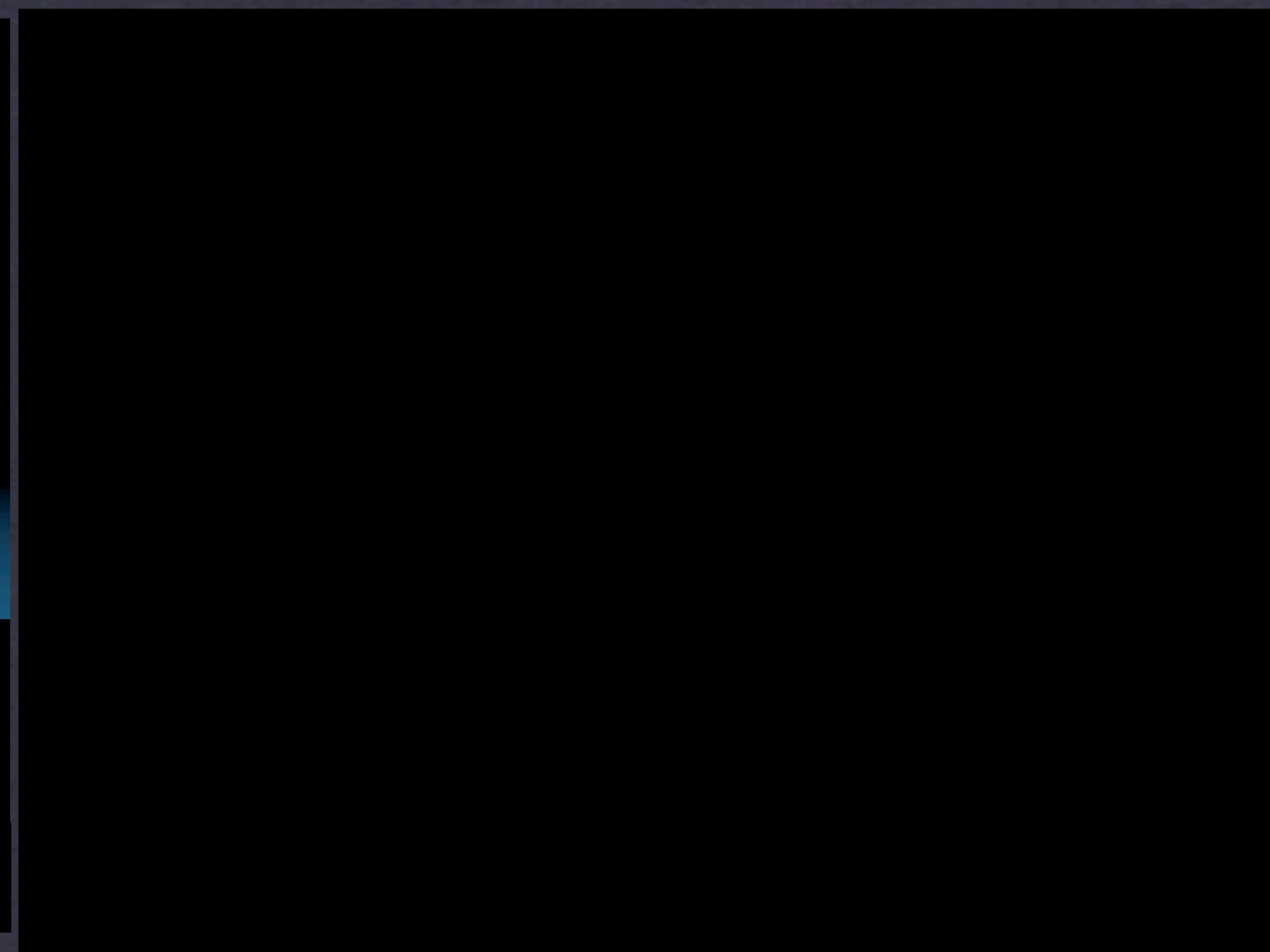
Coupled Simulations
3D HYBRID + IWAVE SURFACE + SPLASHES & FOAM TEXTURES

Marmaduke

Graphics Research on CFD





New Directions

- Iterate on simulations without full re-simulation
  - iterate on a subregion of the full simulation
  - inject density/velocity changes
  - inject objects
  - move objects around
  - local changes in dynamics or resolution
  - more external forcing
- Focus on characteristic function in simulation
  - recast Navier-Stokes

Iterative NS Simulation

- Assume pre-existing velocity, density, pressure

$$\mathbf{U}_0(\mathbf{x},t)$$
$$\rho_0(\mathbf{x},t)$$
$$p_0(\mathbf{x},t)$$

$$\begin{aligned}
\frac{\partial \mathbf{U}_0}{\partial t} + \mathbf{U}_0 \cdot \nabla \mathbf{U}_0 + \nabla p_0 &= f_0 \\
\nabla \cdot \mathbf{U}_0 &= 0 \\
\frac{\partial \rho_0}{\partial t} + \mathbf{U}_0 \cdot \nabla \rho_0 &= 0
\end{aligned}$$

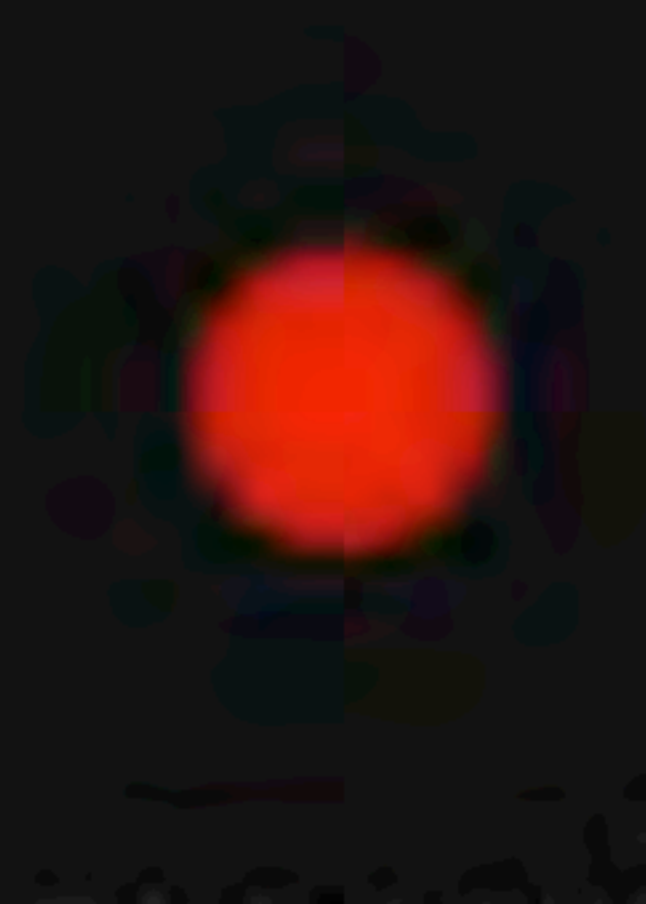
Perturbing Simulation

$$\begin{aligned}\mathbf{U}_0(\mathbf{x},t) &\quad + \quad \mathbf{U}'(\mathbf{x},t)\\ \rho_0(\mathbf{x},t) &\quad + \quad \rho'(\mathbf{x},t)\\ p_0(\mathbf{x},t) &\quad + \quad p'(\mathbf{x},t)\end{aligned}$$

$$\begin{aligned}\frac{\partial \mathbf{U}'}{\partial t} + (\mathbf{U}_0 + \mathbf{U}') \cdot \nabla \mathbf{U}' + \mathbf{U}' \cdot \nabla \mathbf{U}_0 + \nabla p' &= f'\\ \nabla \cdot \mathbf{U}' &= 0\\ \frac{\partial \rho'}{\partial t} + (\mathbf{U}_0 + \mathbf{U}') \cdot \nabla \rho' + \mathbf{U}' \cdot \rho_0 &= 0\end{aligned}$$

Last night's Sim

Supervisor comment:
"Make it veer to the right"



Iterated Sim

Recast Navier-Stokes

- Characteristic function is the critically important feature
- Write NS equations to work directly with it
- Production benefits
  - conceptually similar to surface displacement
  - artistic modifications more controllable

$$
\begin{aligned}
\frac{\partial \mathbf{U}}{\partial t} + \mathbf{U} \cdot \nabla \mathbf{U} + \nabla p &= f \\
\nabla \cdot \mathbf{U} &= 0 \\
\frac{\partial \rho}{\partial t} + \mathbf{U} \cdot \nabla \rho &= 0
\end{aligned}
$$

$$
\begin{aligned}
\frac{\partial \mathbf{U}}{\partial t} + \mathbf{U} \cdot \nabla \mathbf{U} + \nabla p &= f \\
\det(\nabla \mathbf{X}) &= 1 \\
\frac{\partial \mathbf{X}}{\partial t} + \mathbf{U} \cdot \nabla \mathbf{X} &= 0 \\
\mathbf{U}(\mathbf{x}, t + \Delta t) &= \mathbf{X}(\mathbf{x}, t) - \mathbf{X}(\mathbf{x}, t + \Delta t)
\end{aligned}
$$