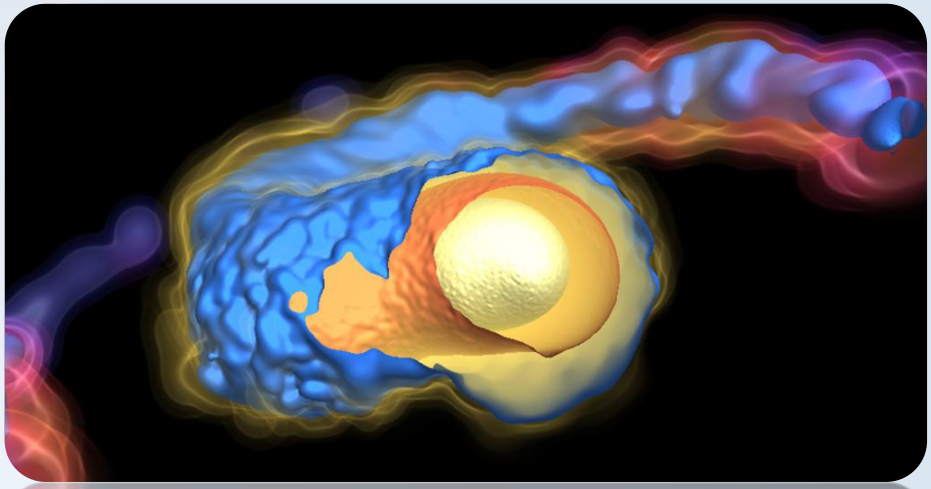

Efficient High-Quality Volume Rendering of SPH Data

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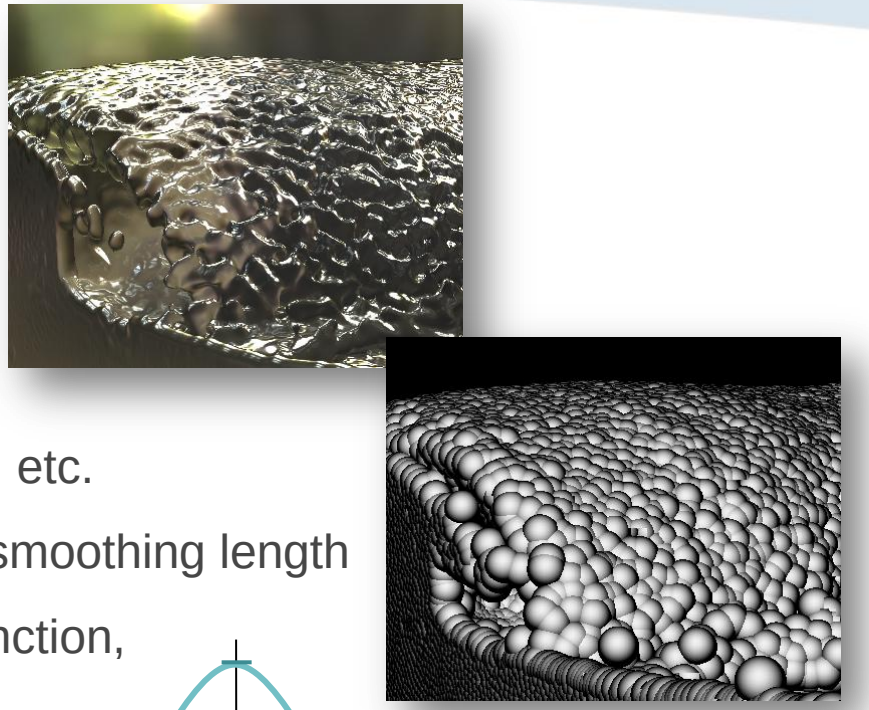
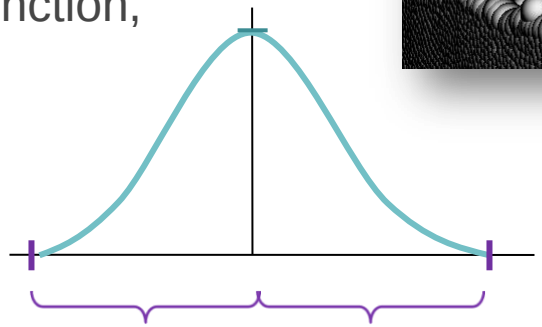
Smoothed Particle Hydrodynamics (SPH)

- What is SPH?
  - Mesh-free Lagrangian method to simulate fluid and gas dynamics
- Discrete elements: Particles
  - Quantities: mass, velocity, temperature, etc.
  - Spatial influence defined by position & smoothing length
  - Quantities are smoothed by a kernel function, e.g. cubic spline
- Common simulation size:
  - Millions to billions of particles





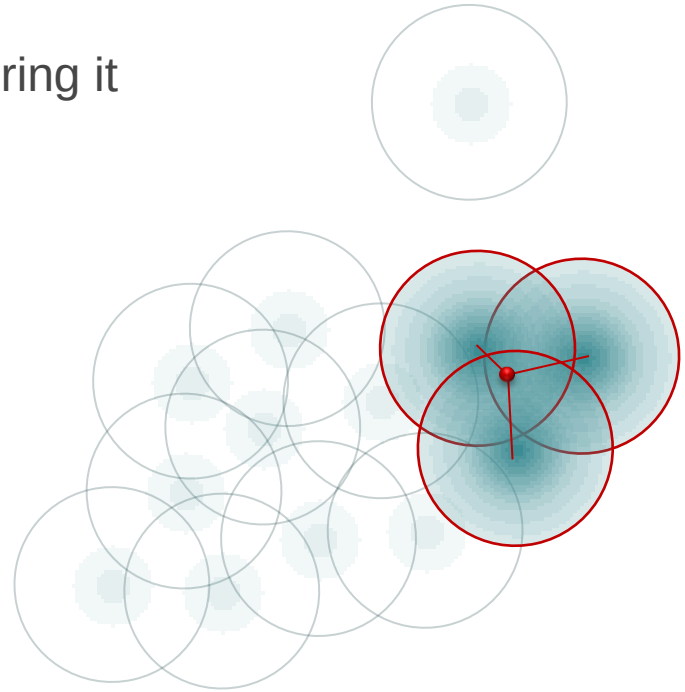
Smoothed Particle Hydrodynamics

- Interpolation within SPH data
  - Sampling point is influenced by all particles covering it
  - Interpolated quantity is a weighted sum of the particle quantities:

quantity mass distance

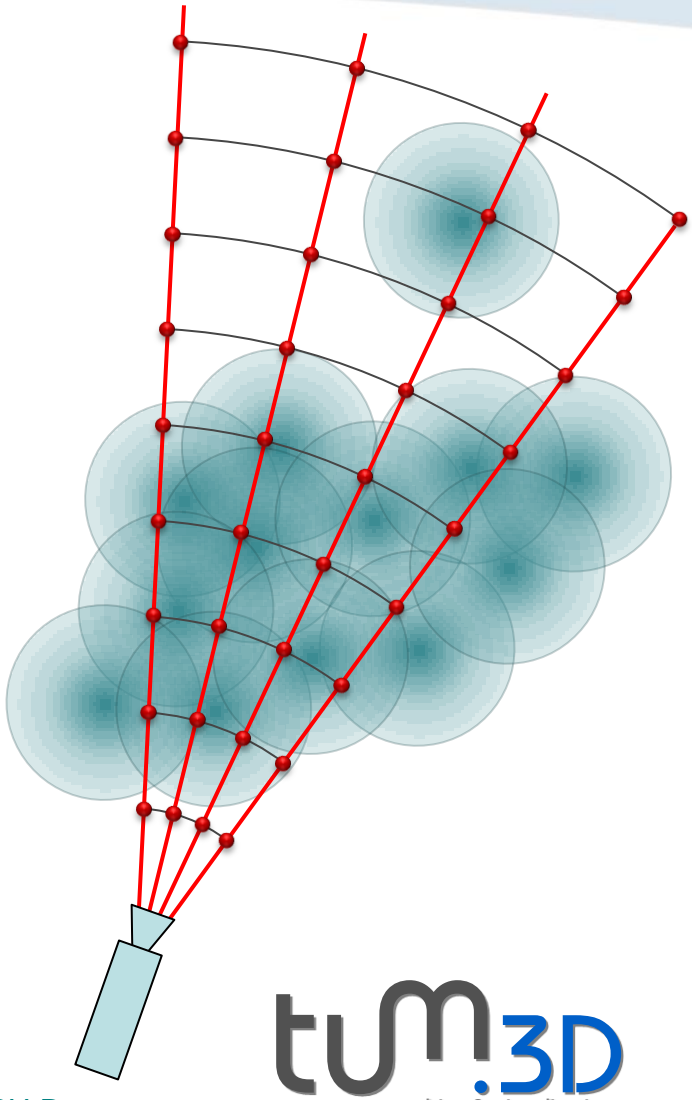
$$A(\mathbf{r}) = \sum_j A_j \frac{m_j}{\rho_j} W\left(|\mathbf{r} - \mathbf{r}_j|, h_j\right)$$

density kernel function smoothing length



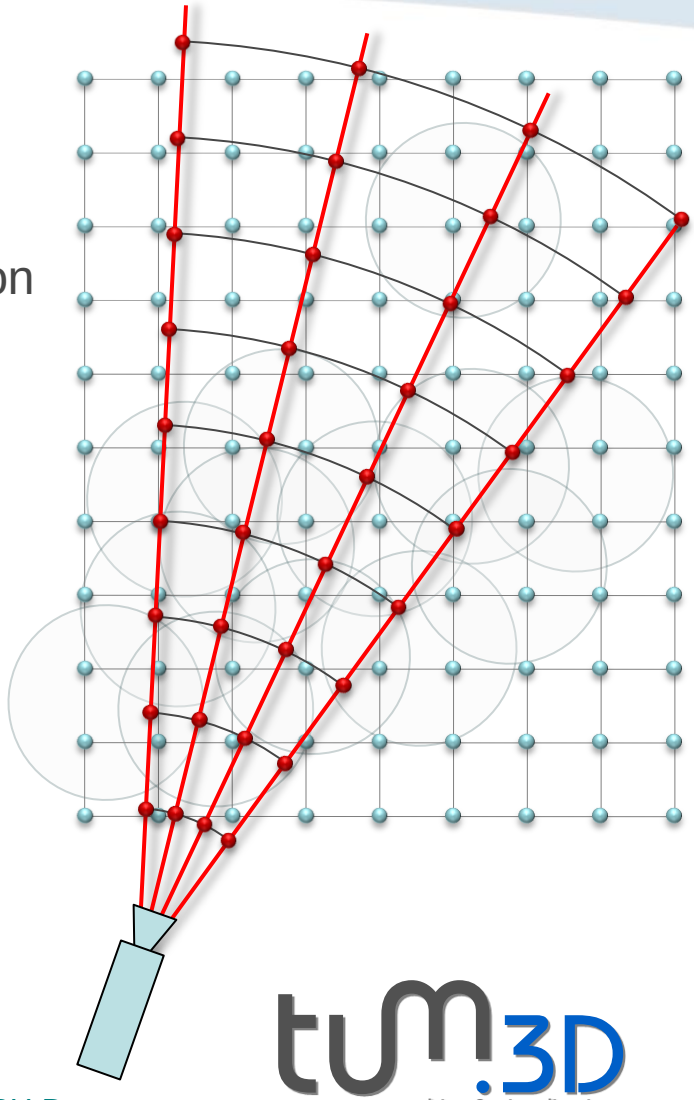
Visualization of SPH Data

- Direct Ray Casting
  - For each sample point
    - Interpolation of “neighboring“ particles
    - Neighbor search necessary
    - Accelerated by space-partitioning data structures (e.g. kd-tree)
- Advantage
  - High Rendering Quality
- Drawback
  - Currently no interactive rendering possible



Visualization of SPH Data

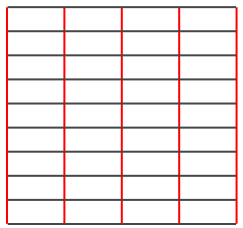
- Resampling and Volume Ray Casting
  - Data respampled into a cartesian grid
  - GPU-based ray casting using trilinear interpolation
- Advantage
  - Interactive rendering possible
- Drawback
  - Accuracy limited by GPU memory
  - Leads to undersampling with large data sets

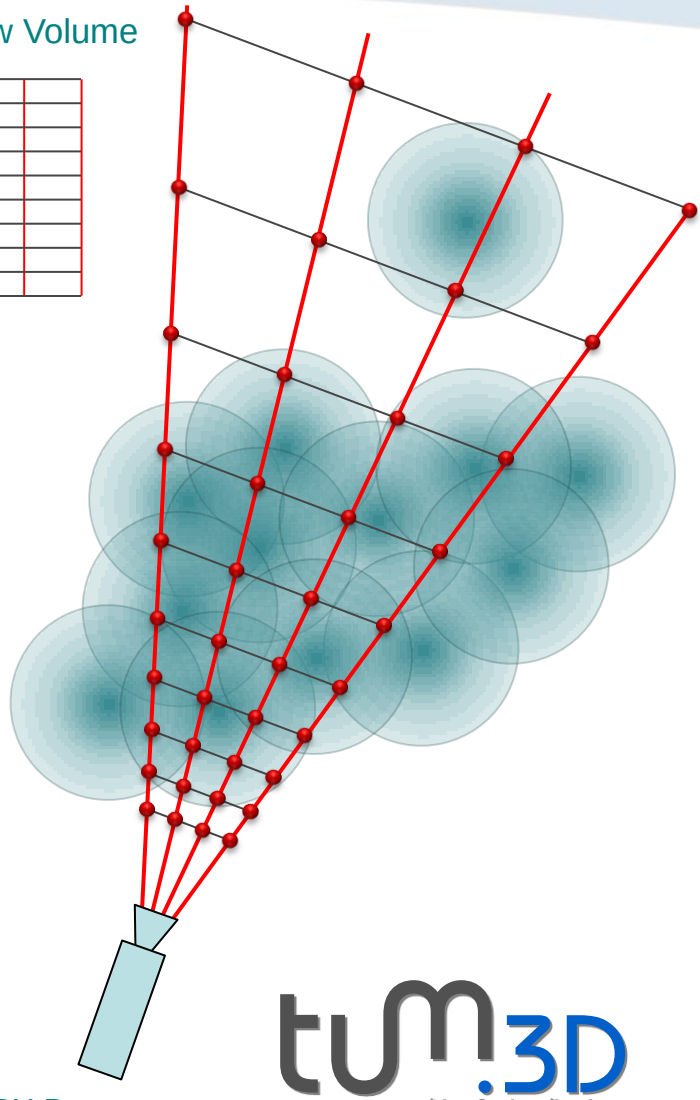


Novel Visualization Approach

- "Perspective Grid"
  - Regular grid fixed to the view volume
  - Stored in a 3D texture on GPU
  - Samples represent rays of ray casting
  - Adaptive sampling in viewing direction
    - → Almost isotropic Sampling in x/y/z-direction
- Advantages
  - High Rendering Quality
  - Interactive rendering possible

Canonical View Volume

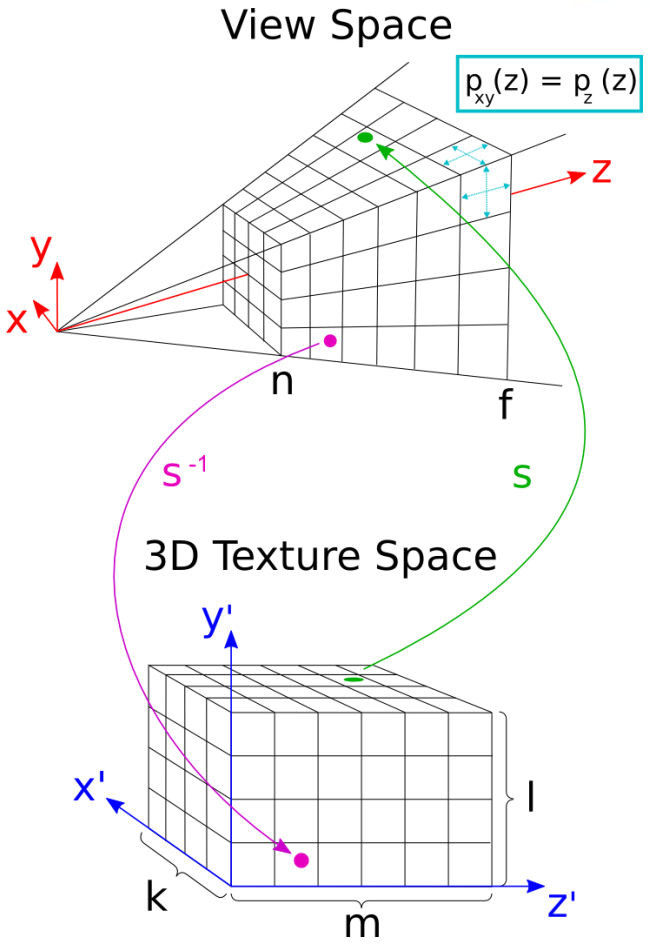




Perspective Grid

- Mapping Functions
  - $s_x^{-1}(x,z) = \left(\frac{x}{z \cdot \tan(fov_y/2)} + 1 \right) \cdot k$
  - $s_y^{-1}(y,z)$, respectively
  - $s_z^{-1}(z) = m \cdot \frac{\ln(z/n)}{\ln(f/n)}$
- Grid Resolution
  - k, l: given by viewport
  - m: derived by $p_{xy}(z) = p_z(z)$:

$$m = \frac{res_y}{2 \cdot \tan(fov_y/2)} \cdot \ln \frac{f}{n}$$

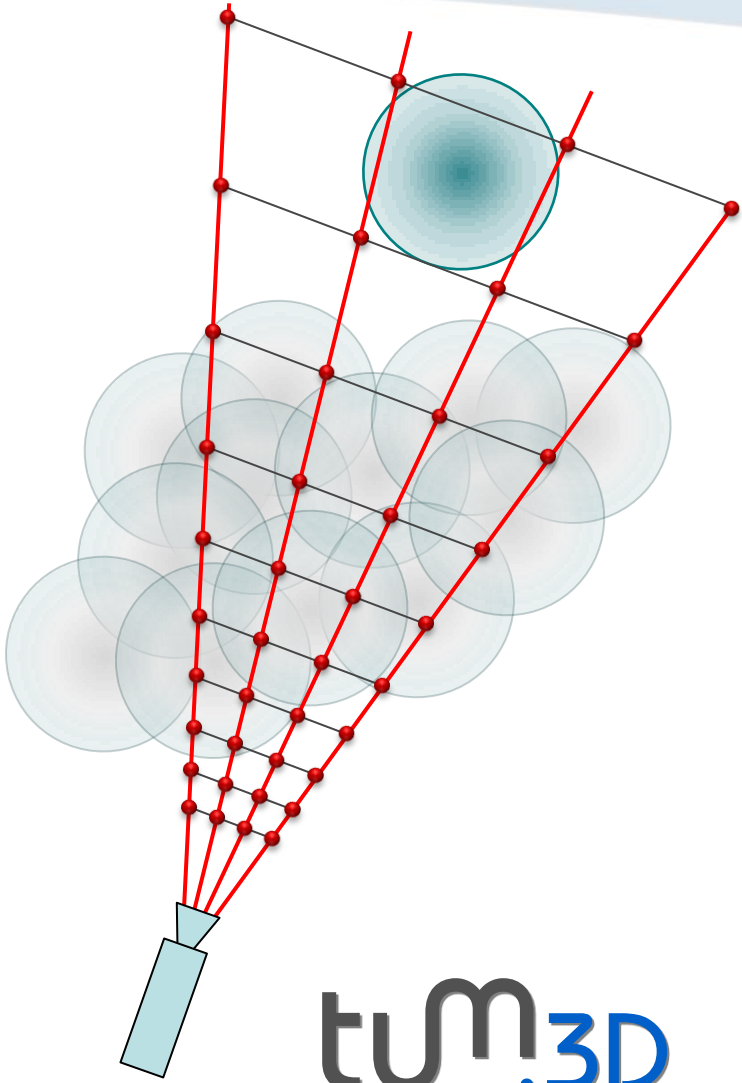


Aliasing

- Observations
  - Adaptive sampling leads to
    - Undersampling far away form the camera
    - Extreme case: Particles are entirely missed

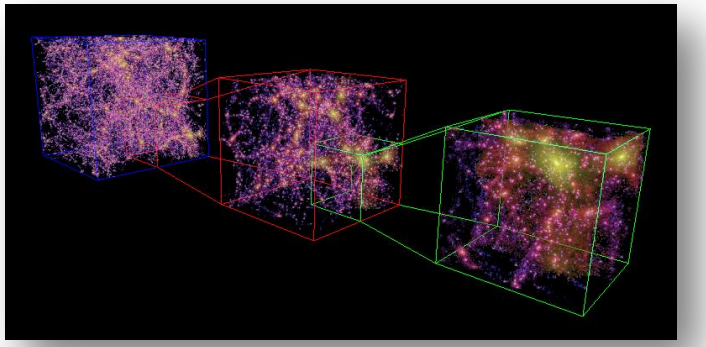
    → Aliasing artifacts
- Solution
  - Multi-resolution hierarchy
- Benefit
  - Less particles needed for rendering

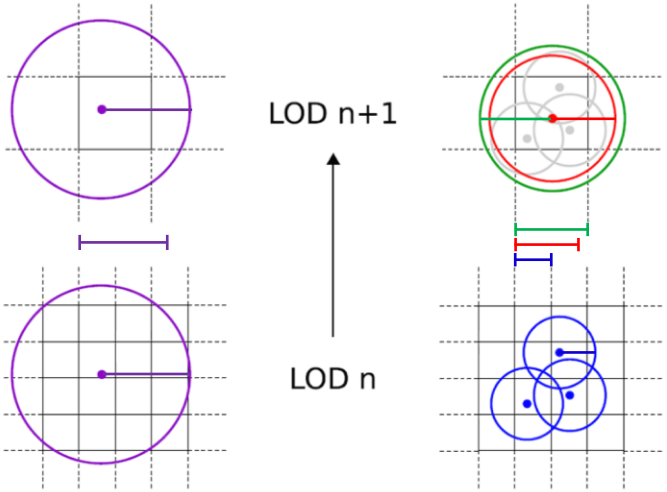
    → Performance gain



Hierarchical Particle Representation

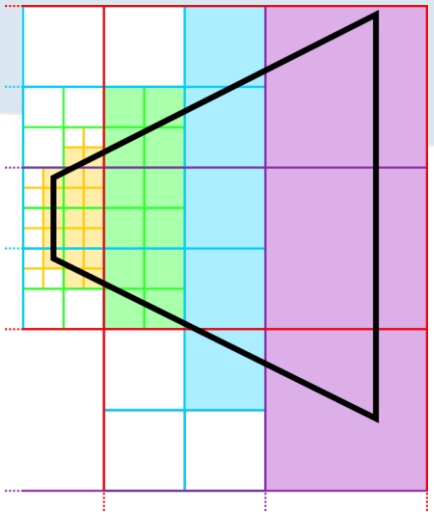
- Multi-resolution hierarchy
  - Octree-based data structure (see Fraedrich09)
  - Particles are sorted into 2^{n^3} bins per node
- Merging rule for particles
  - Particles are merged, iff radius < bin size
  - Merging (see Desbrun99, Hong08)
    - Volume preserving
    - Properties are averaged according to the particles' mass contribution
  - Particles radius is increased if still < bin size



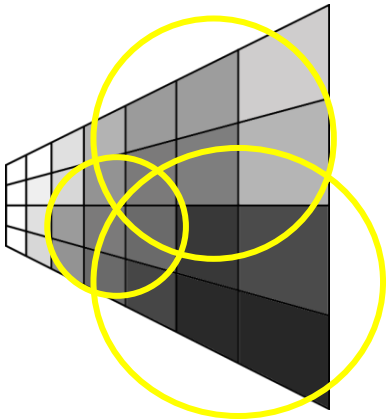


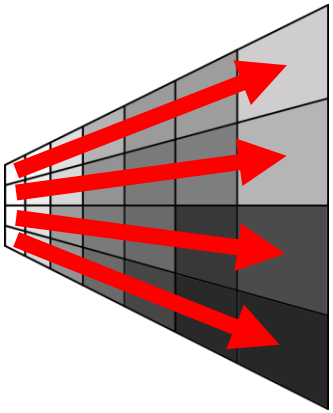
Fraedrich09: Fraedrich, Schneider, Westermann, „Exploring the Millennium Run...“
Desbrun99: Desbrun, Cani, „Space-time adaptive simulation of highly deformable substances.“
Hong08: Hong, House, Keyser, „Adaptive Particles for incompressible fluid dynamics“

Rendering



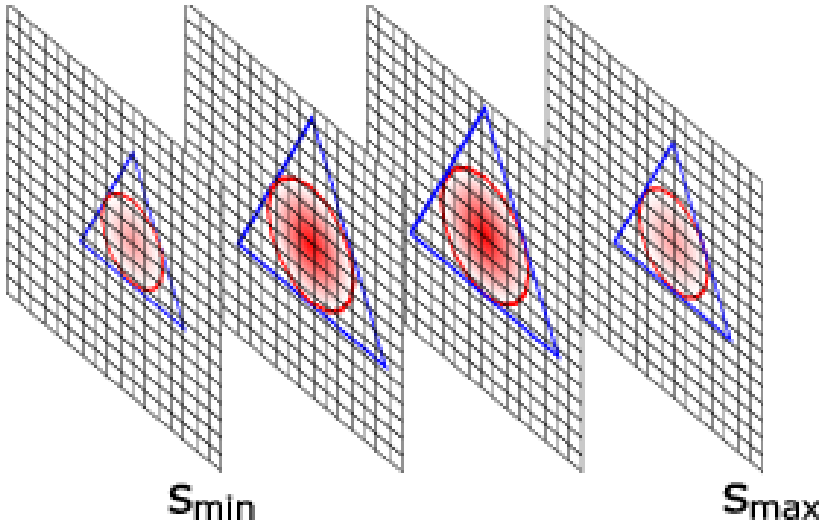
1. Octree traversal (CPU)
   - View frustum culling
   - LOD selection
2. Resampling (GPU)
3. Ray casting (GPU)





Resampling (GPU)

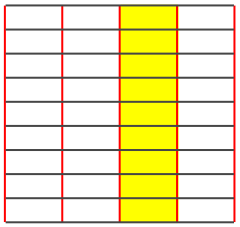
- For each slice covered by a particle determine:
  - Circular cross-section with particle sphere
  - Covering equilateral triangle



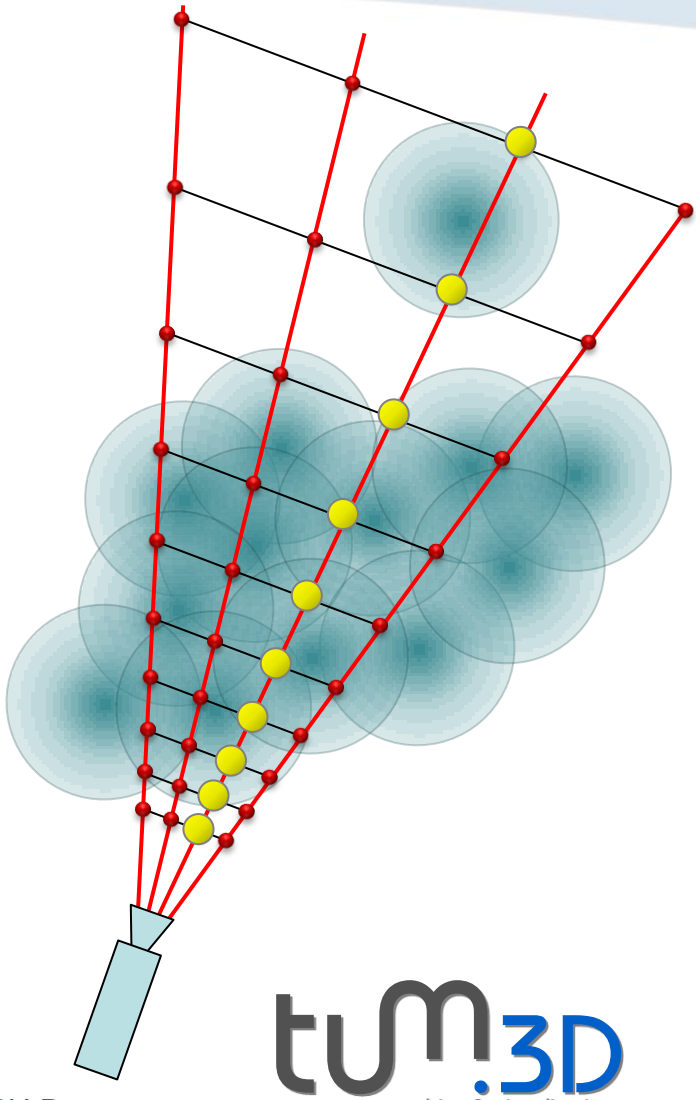
- For each fragment on cross-section calculate:
  - Vector to particle center
  - Attribute value acording to SPH kernel
  - Accumulative blending with existing grid values

Ray Casting (GPU)

- Texture-based volume ray casting
  - High speed
  - Flexible rendering options
    - Direct volume rendering
    - Iso-surface rendering
    - Both simultaneously
  - No interpolation needed for DVR
  - Opacity correction necessary however

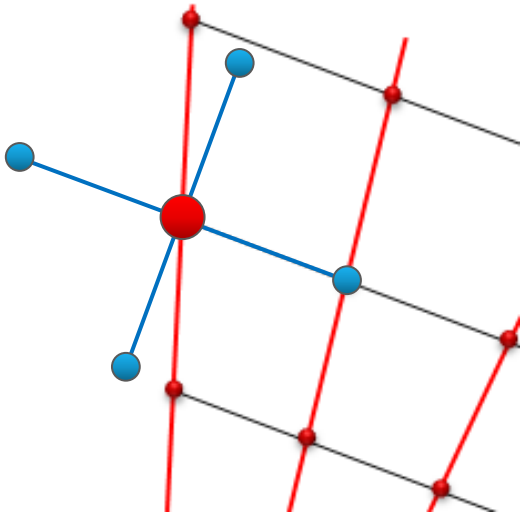


Ray

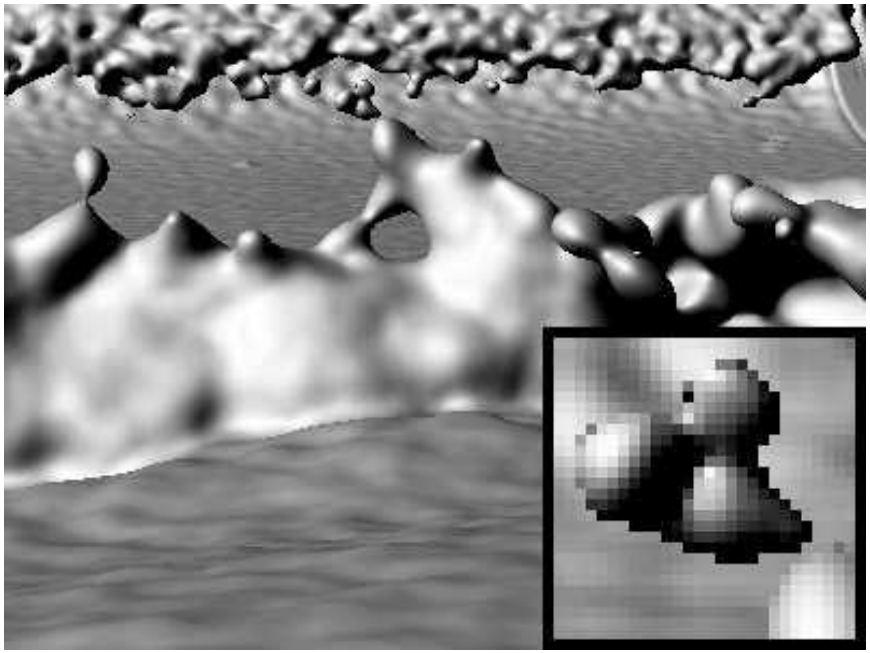


Gradient Computations

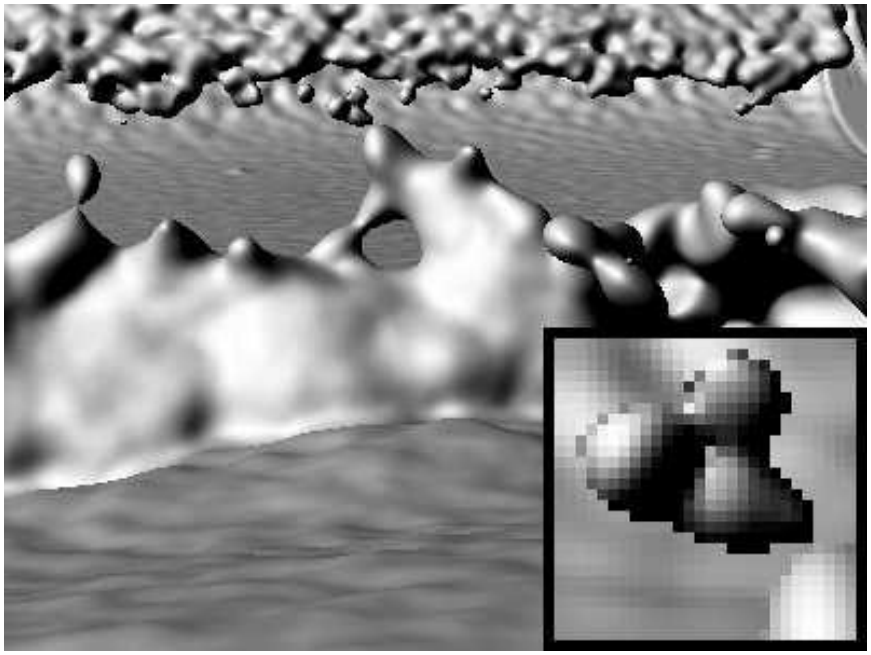
- For local illumination effects
- Central differences
- Additional samples at the borders required
- x and y components straightforward
- Samples for z component
  - Calculated in view space
  - Require interpolation



Gradient Computations



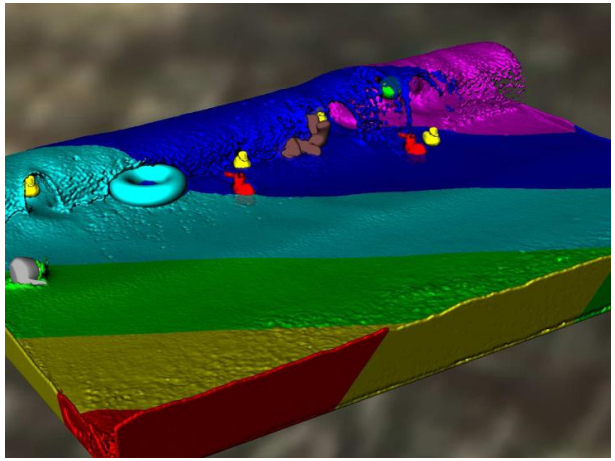
Trilinear interpolation
(hardware supported)

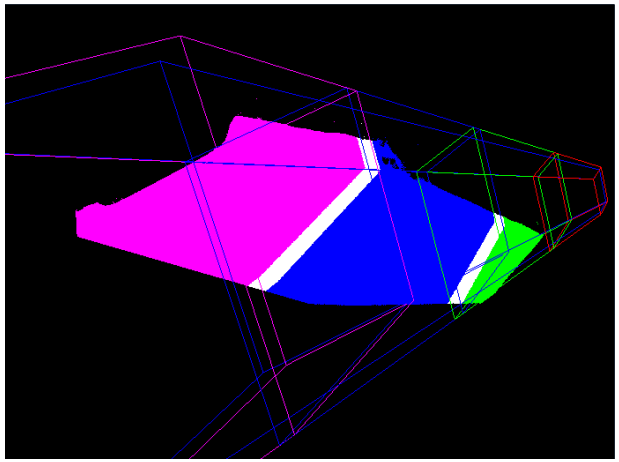


Distance based
interpolation

Grid Partitioning

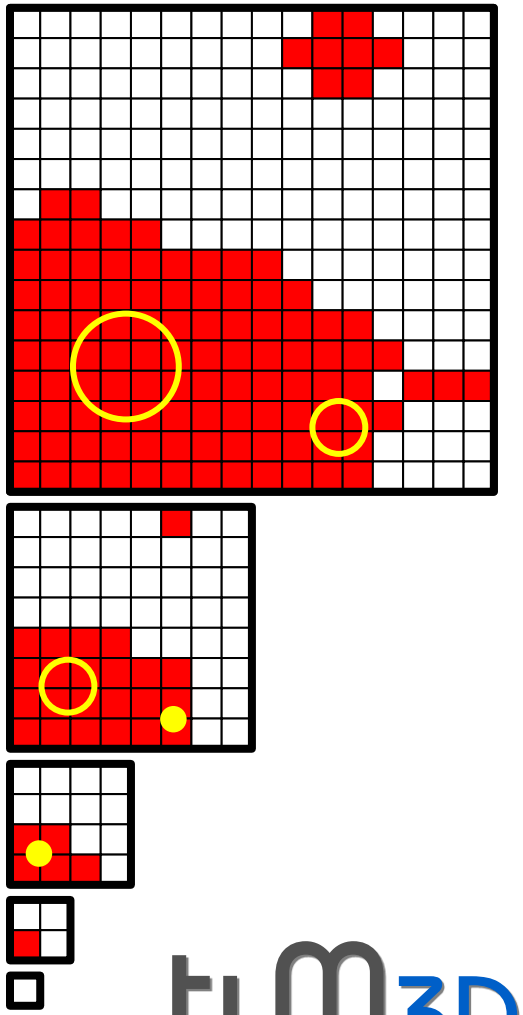
- Perspective grid too large for texture memory
- Divided along z axis into slabs
  - One rendering pass per slab
  - Front to back
  - Reusing the same volume texture
  - Gradient computation: overlap per slab
  - Slabs considered in hierarchy traversal to reduce GPU load during resampling and ray casting





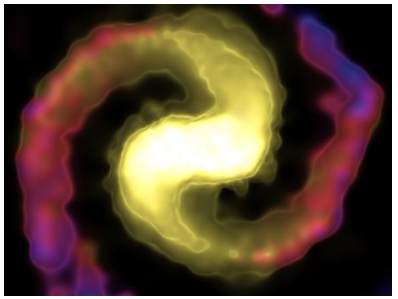
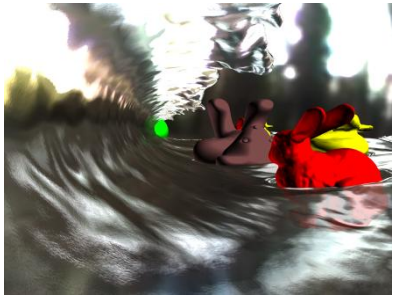
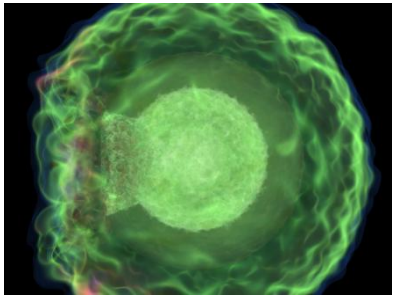
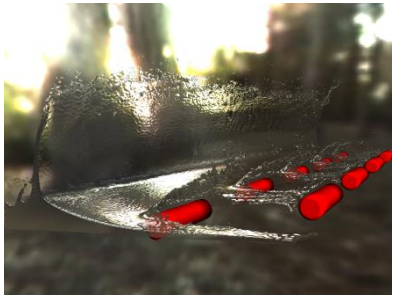
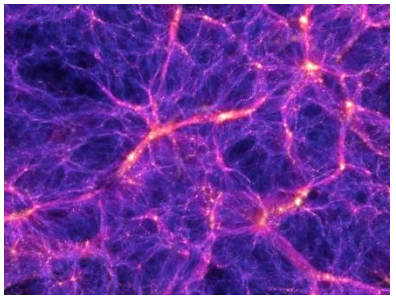
Occlusion Culling

- Opacity map generated after n slabs
- Boolean mipmap encodes opaque areas
  - Considers non-power-of-two resolutions
- Resampling skipped for nodes and particles overlapping only opaque areas
  - Mip level selection:
    - width of bounding circle < width of texel
  - 4 nearest texels opaque -> skip particle
    - Needs only one sampling instruction with bilinear filtering



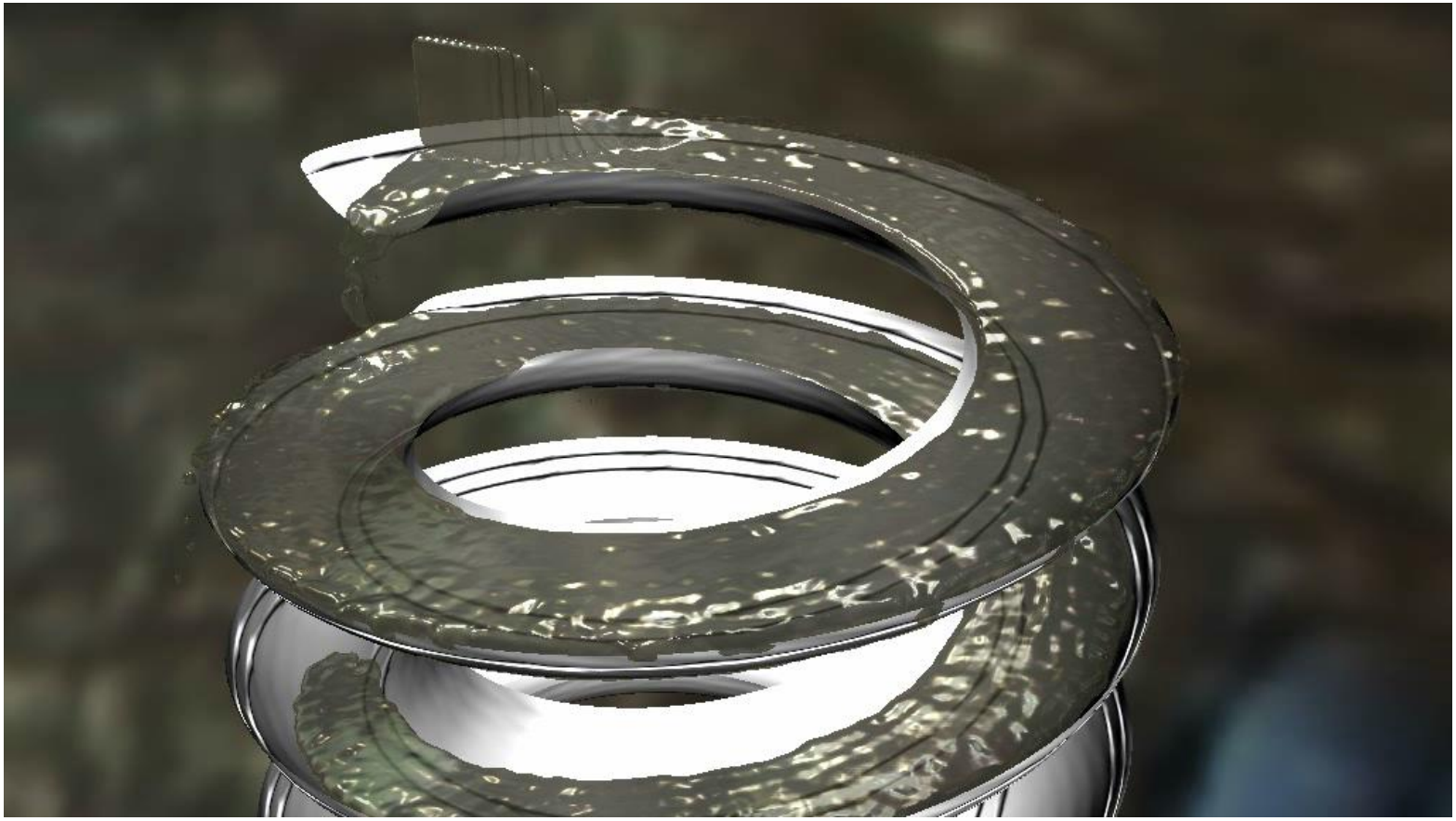
Results

- Datasets
  - 3 fluid dynamics, 3 astrophysics
  - Positions 32 bit float, Quantities 16 bit float
- Machine
  - 2.4 GHz Core 2 Duo CPU
  - NVIDIA GTX 280 GPU (1024 MB)
- Timings (all milliseconds)
  - Averages over all time steps
  - All particles within frustum
  - Millennium Run: Fly through

Results: Flume Dataset

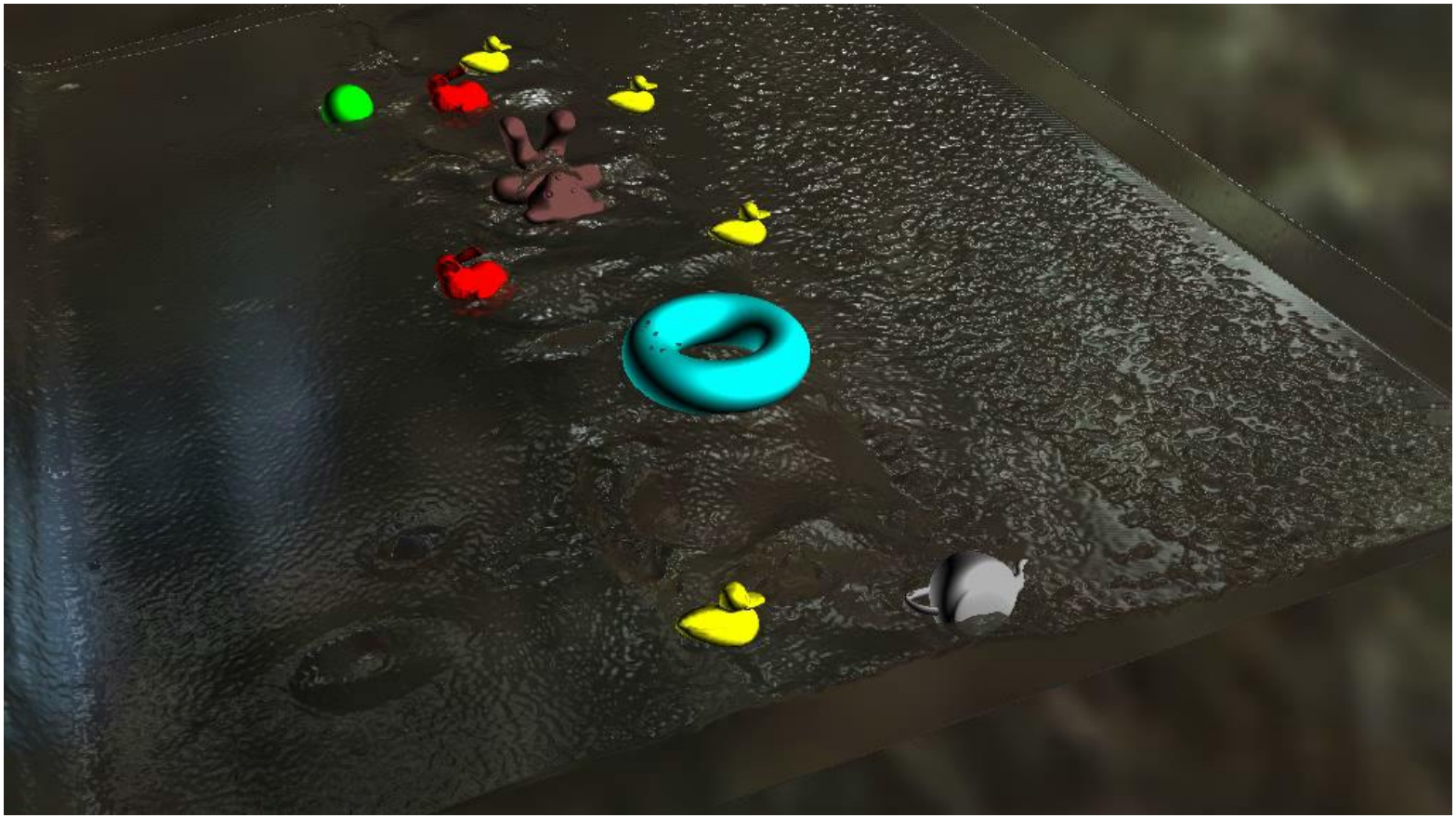
2209 Time Steps 100 to 80,000 Particles Density



Grid resolution	Resampling	Rendering	Total
512^2 x 364	6	43	49
1024^2 x 728	38	76	114

Results: LWMO Dataset

604 Time Steps 2.5 Million Particles Density



Grid resolution	Resampling	Rendering	Total
512^2 x 544	87	65	152
1024^2 x 1088	549	127	676

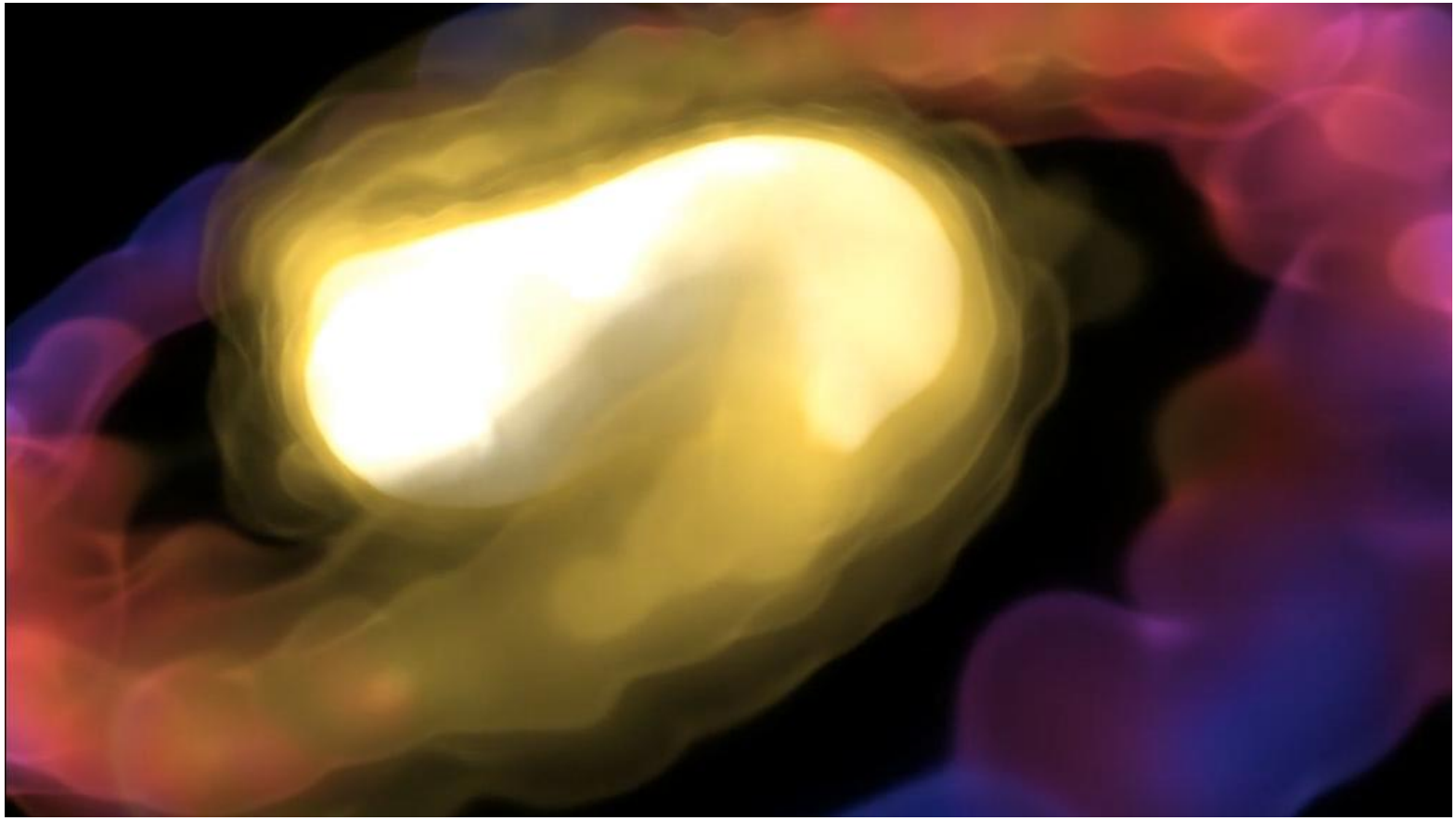
Results: LWSB Dataset

1232 Time Steps 3.2 Million Particles Density

Grid resolution	Resampling	Rendering	Total
512^2 x 664	135	79	214
1024^2 x 1328	804	178	982

Results: WDMerger Dataset

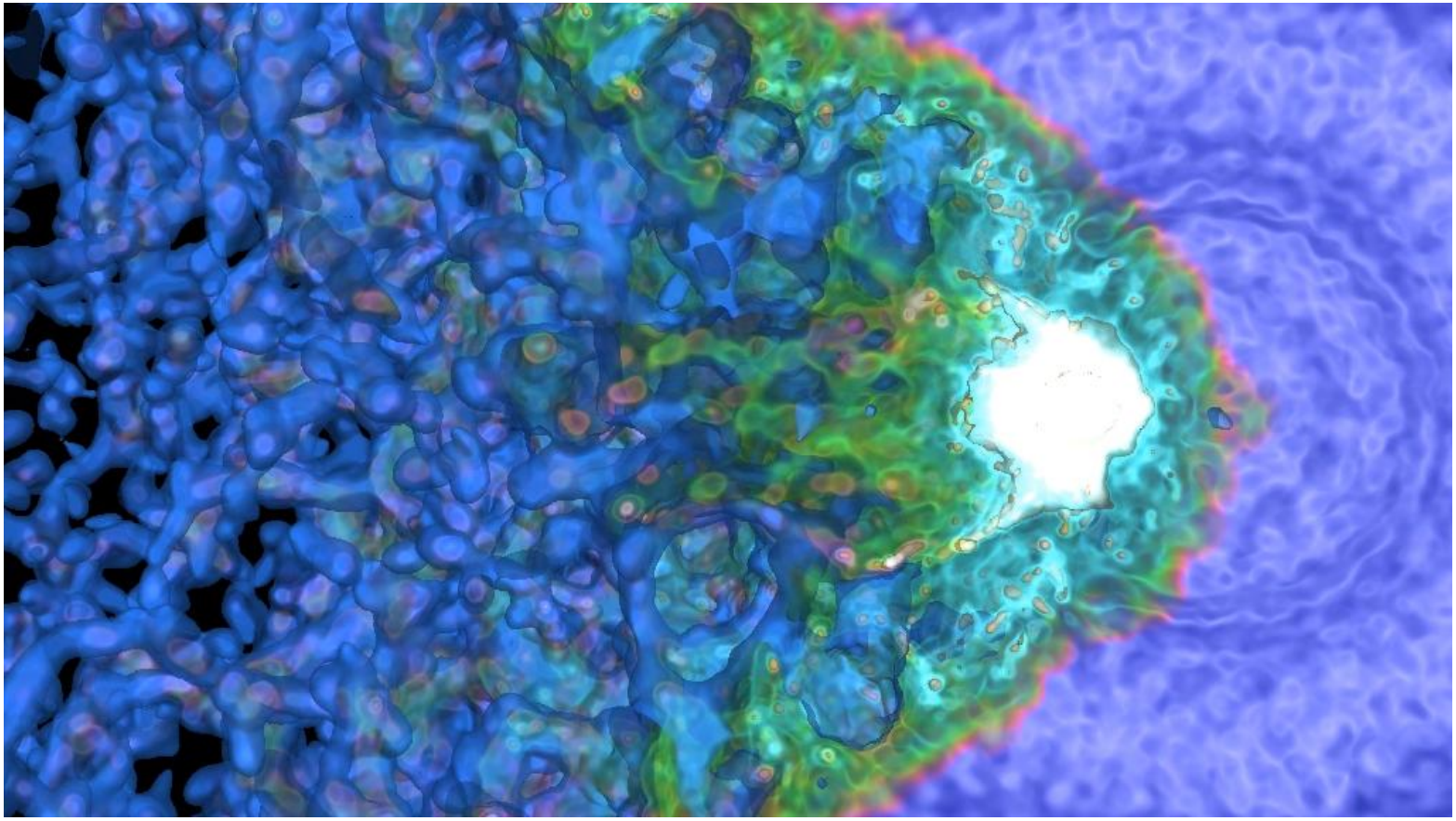
84 Time Steps 2 Million Particles Density + Temp.



Grid resolution	Resampling	Rendering	Total
512^2 x 292	642	40	682
1024^2 x 584	1492	81	1573

Results: SNIaEjecta Dataset

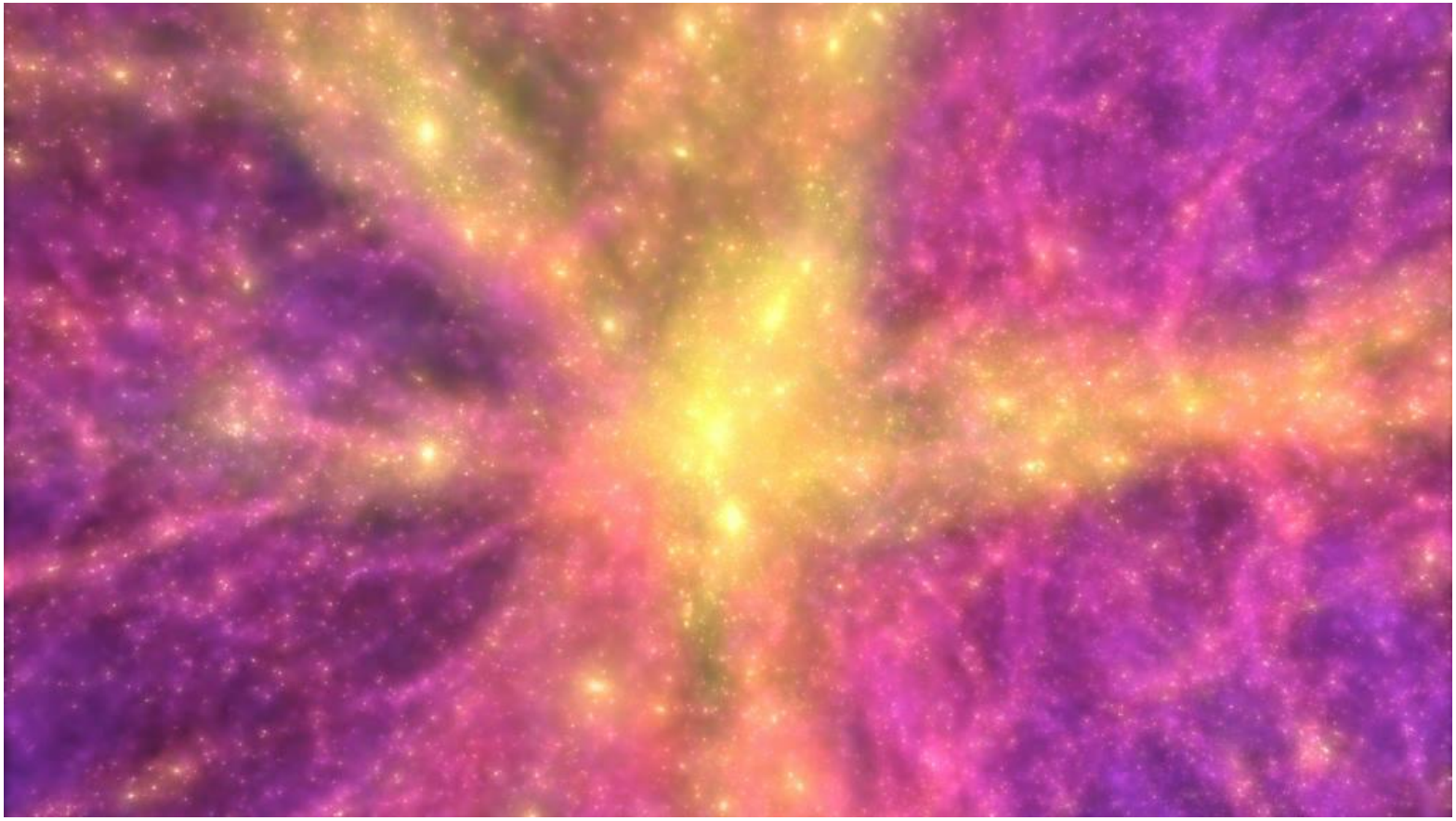
99 Time Steps 8.7 Million Particles Density + Temp.



Grid resolution	Resampling	Rendering	Total
512^2 x 396	1560	49	1609
1024^2 x 792	4574	100	4674

Results: Millennium Run Dataset

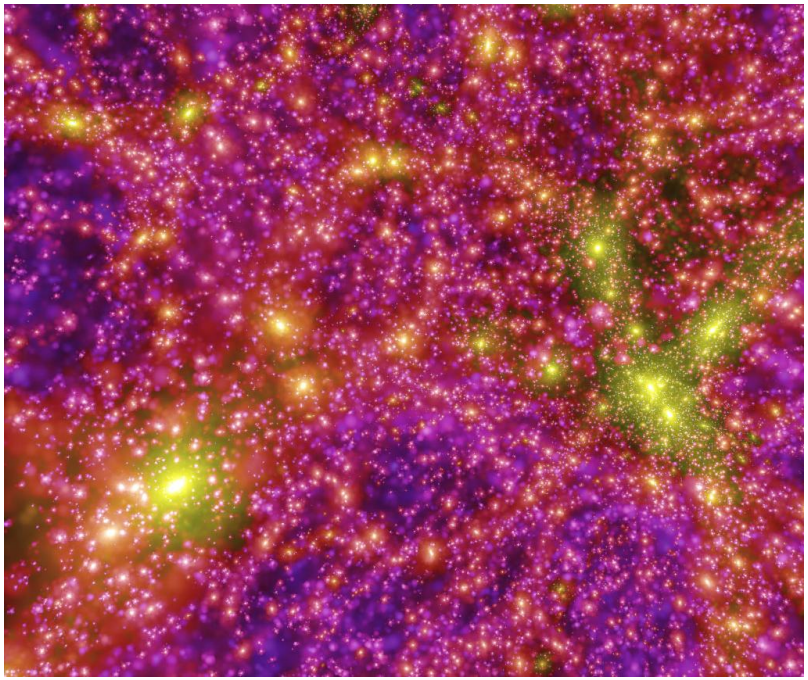
1 Time step 10 Billion Particles Total, 42 Million Visible Density + Vel. Disp.



Grid resolution	Resampling	Rendering	Total
512^2 x 480	2267	83	2350
1024^2 x 960	7771	162	7933

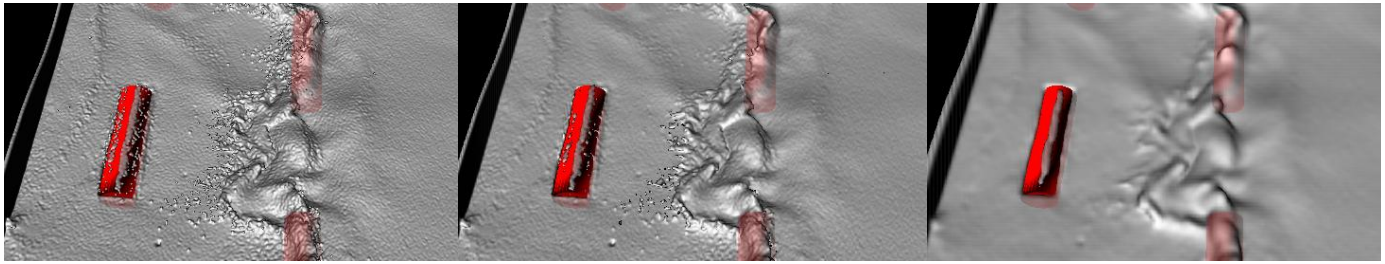
Millennium 2009 vs. 2010

Order independent 2D splatting

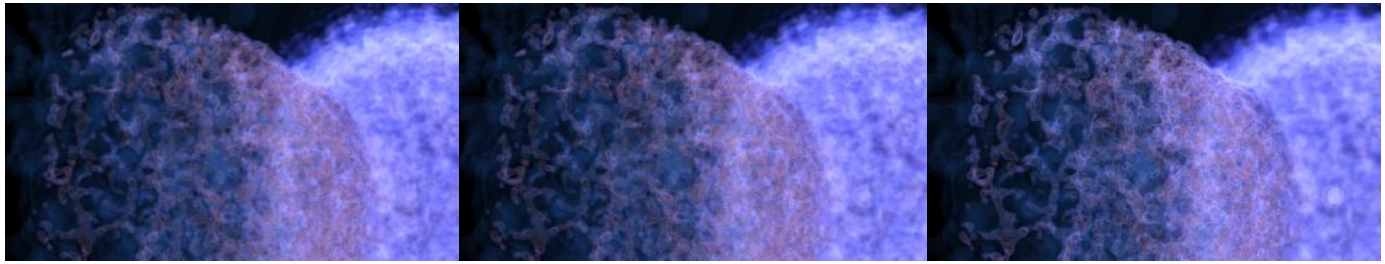


3D volume ray casting

Results: Multi-resolution hierarchy



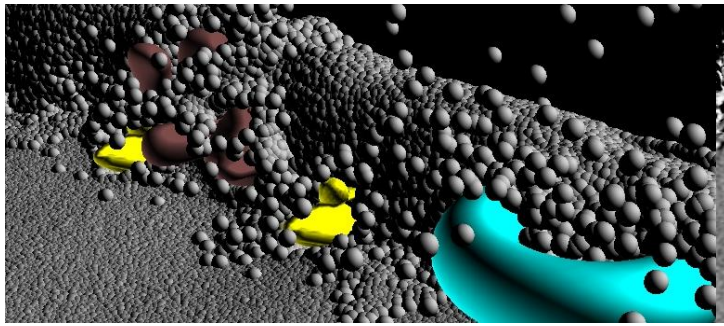
Grid resolution	1024^2 x 1324	512^2 x 664	256^2 x 364
Resampled Particles	3.2 Million	2.1 Million	0.7 Million
Speedup	1x	4.2x	10x

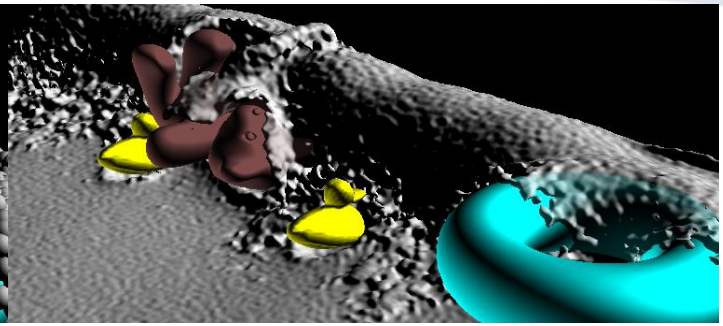


Grid resolution	1024^2 x 788	512^2 x 396	256^2 x 200
Resampled Particles	8.7 Million	4.6 Million	3.3 Million
Speedup	1x	2.9x	8.2x

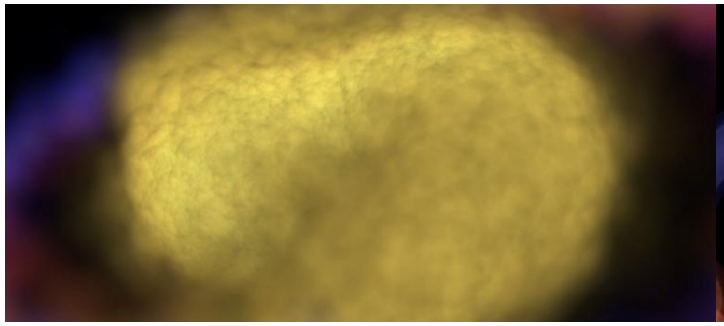
Viewport resolution 1024^2

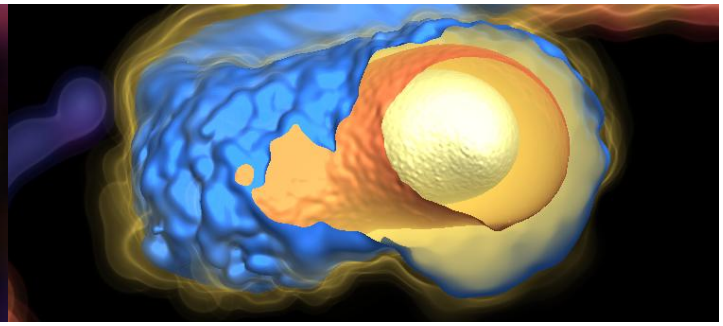
Results: Comparison to 2D Splatting





Technique	Depth buffer based (without smoothing)	Perspective grid iso-surface
Performance	12.5 fps	5.7 fps





Technique	Order dependent 2D accumulation	P. g. hybrid iso-surface / DVR
Performance	7.8 fps	1.7 fps

Conclusion

- Benefits
  - Suitable for large, high detail SPH data sets
  - Quality comparable to direct ray casting
  - Performance not far away from screen-space approaches
- Drawbacks
  - Secondary effects not possible
    - View volume discretization, optimized for primary rays
- Future Work
  - Curvature based smoothing to improve iso-surface appearance

Questions?