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# GigaVoxels, Real-time Voxel-based Library to Render Large and Detailed Objects

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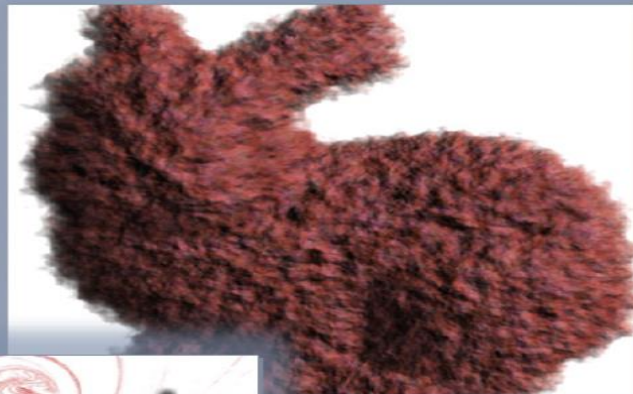
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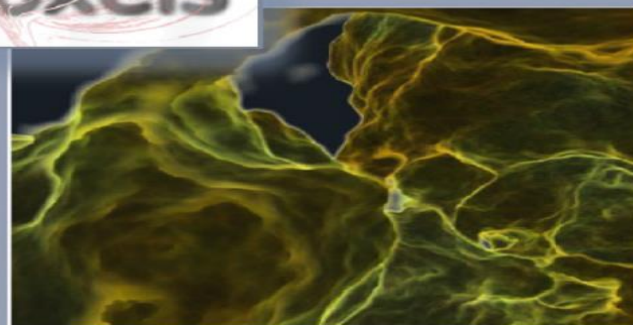
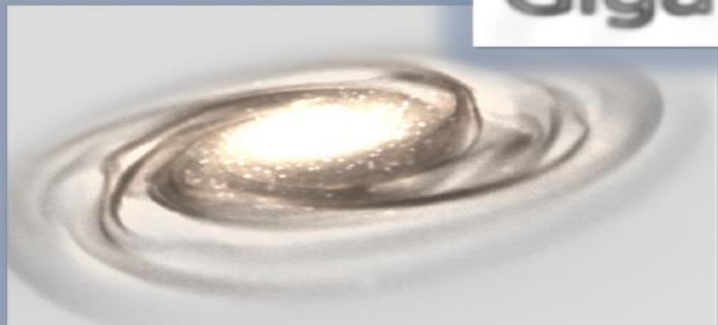


A voxel-based rendering pipeline  
for efficient exploration  
of large and detailed scenes

Pascal GUEHL  
R&D Engineer



**GigaVoxels**



*Videos Games*

*Special Effects*

*Scientific  
Visualization*



*Between Research & Industry*

<http://gigavoxels.inrialpes.fr/>

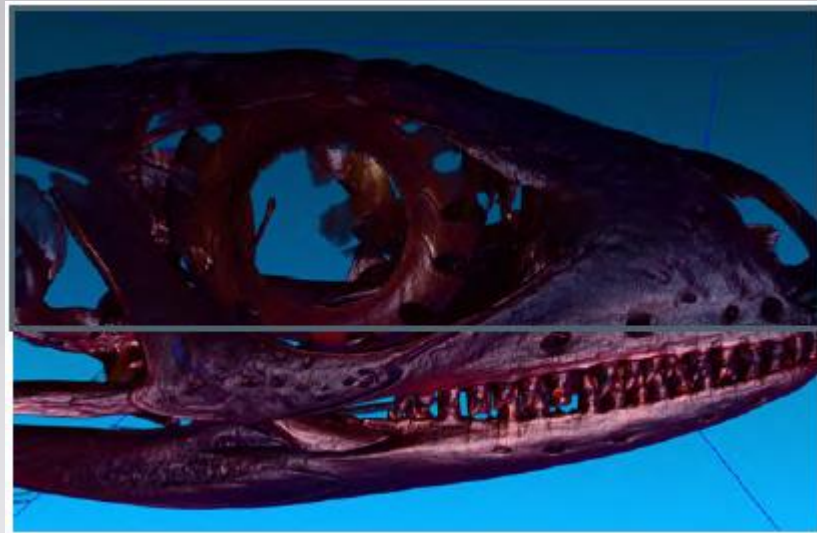
## What is all about ?

R&D project about real-time exploration of

- ▶ large and detailed objects/scenes
- ▶ eventually generated on the fly
- ▶ visually realistic

## Target audience

- ▶ Video games
- ▶ Special effects
- ▶ Special case : scientific visualization



voxel based medical dataset generated from CT scan (2048x2048x2048, 32GB on disc)



## Goal

Present our implementation of the « GigaVoxels » technology

- [ 1 ] - Reminder : what is GigaVoxels ? – Key Concepts / Features
- [ 2 ] - Show fonctionnalités through examples of the SDK
- [ 3 ] - A survey : explain how to program

# PART 1 - GigaVoxels

## Exploratory Research phase

- ▶ PhD Thesis : « GigaVoxels: A Voxel-Based Rendering Pipeline For Efficient Exploration Of Large And Detailed Scenes »
- ▶ Team : INRIA/CNRS/LJK (Cyril Crassin, Fabrice Neyret)
- ▶ Based on an OpenGL / GLSL + CUDA prototype

## Engineering phase

- ▶ Started in 2011 : clean, maintain, add fonctionnalités, ...
- ▶ SDK (tutorials), doc, tools, ...

## Partnership

- ▶ RSA Cosmos : planetariums [funded by French ANR, 4 years research project]

# GigaVoxels

## Website

- image gallery
- videos
- publications
- documentation
- source code (not yet)
- **contact**

<http://gigavoxels.inrialpes.fr/>

- D A W N -  
V E R S I O N 1 . 0

GigaVoxels

Welcome to the GigaVoxels website

GigaVoxels is a ray-guided streaming library used for efficient 3D real-time rendering of highly detailed volumetric scenes.



Dawn Version

- ▶ **Software SDK**
  - > Data Structure (N-tree) + User Defined Data (color, normal, density...)
  - > Cache Mecanism
  - > Renderer (ray casting with OpenGL interoperability)
  - > Producer Mecanism (on host and device)
- ▶ **Documentation**
  - > Classes (doxygen)
  - > User / Developer Manuel
- ▶ **Tutorials**
- ▶ **Tools**
  - > Viewer
  - > Voxelizier (pre-process)

# Key Ideas

[x] Rendering only dependent on what is visible

- ▶ ray-tracing approach

[x] Load only needed data, at the needed resolution

- ▶ occlusion + LOD (level of details)
- ▶ ray-guided streaming

[x] Reuse loaded data as much as possible

- ▶ cache mechanism on GPU

[x] Minimize computation, minimize memory transfers

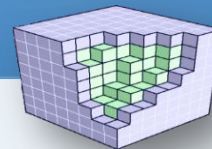
# Key Features

- **Tree Data Management** (space partitioning) to store and organize data (octree or generalized N3-tree, + SDK example kd-tree)
- **Cache System on GPU** : LRU mechanism (least recently used) (to get temporal coherency)
- **Data Production Management** : on host, GPU, or hybrid mode  
Goal : produced data are kept in cache on GPU
- **Visit algorithm** : traverse your data (loaded in cache) as could be done for rendering
- **Renderer** (hierarchical volume ray-casting, cone tracing, emission of requests, brick marching)



# Data Structure

## Spare Voxel Mipmap Pyramid



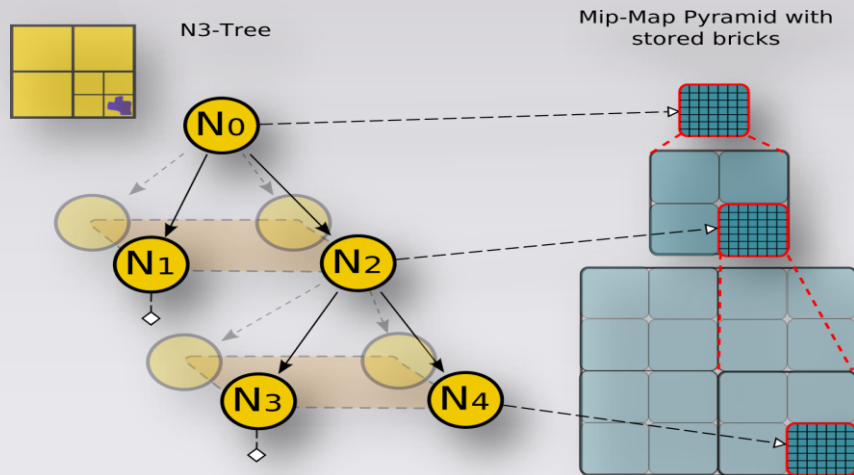
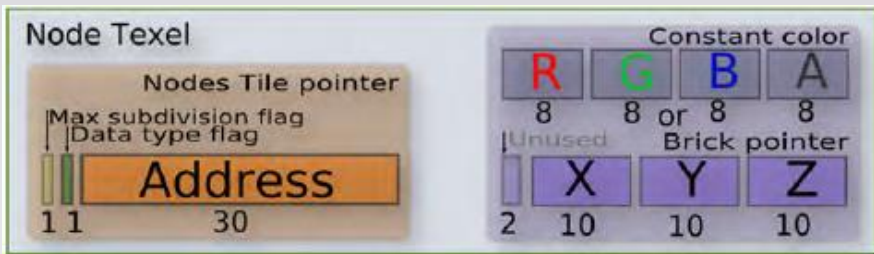
### Generalized N<sub>3</sub>-tree (octree)

- Space partitioning
- Empty space compaction

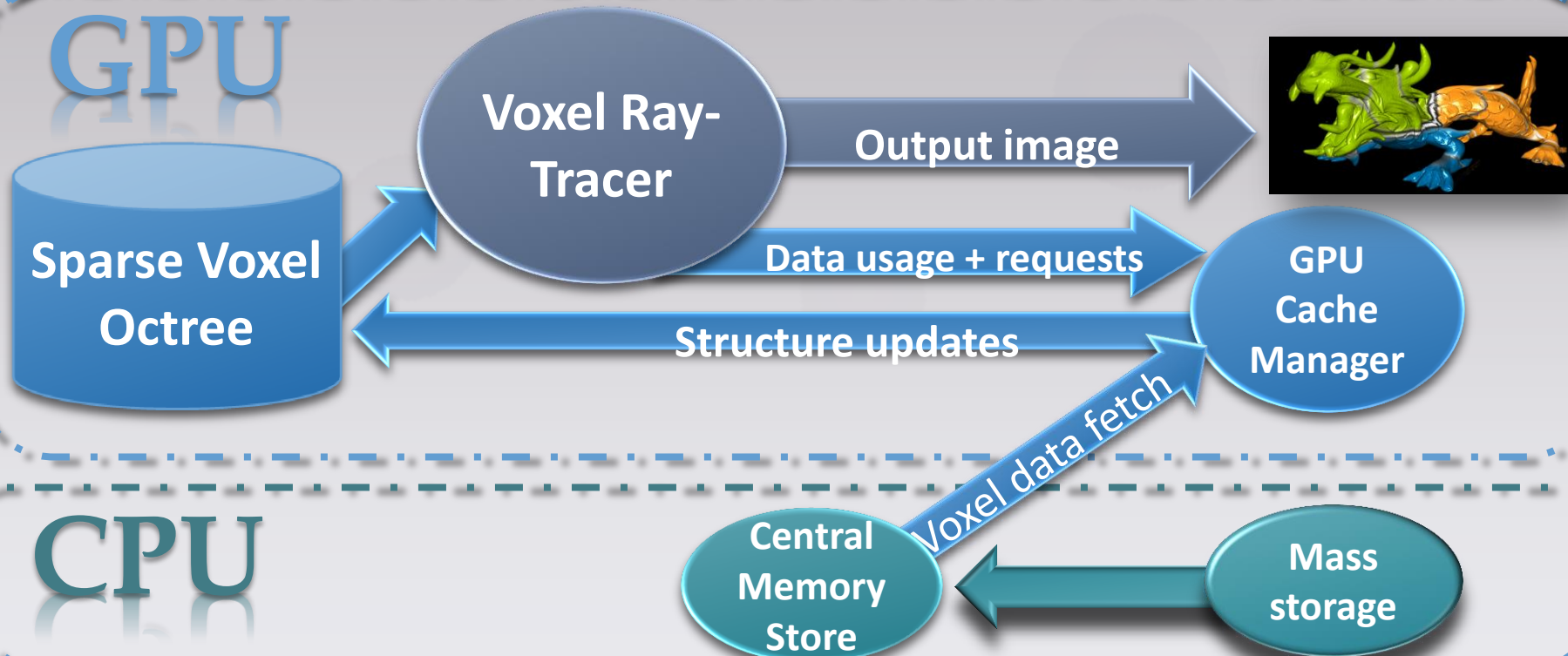
### Bricks of voxels

- Linked by octree nodes
- Store opacity, color, normal,...

### “Node pointer based” data structure

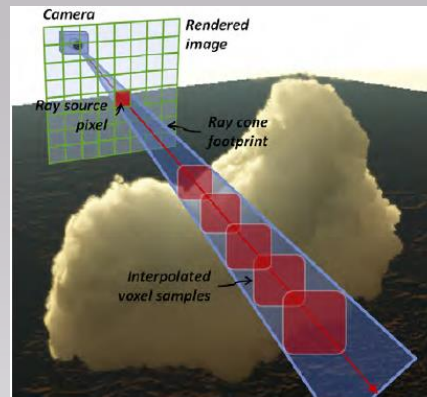


# GigaVoxels Pipeline

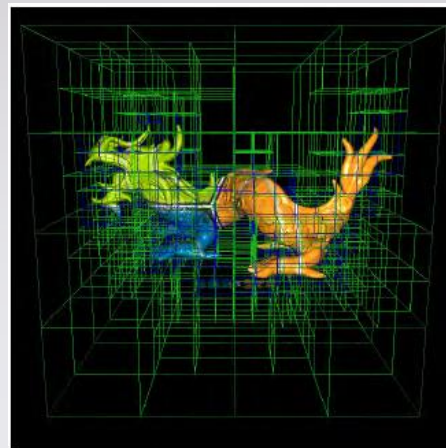
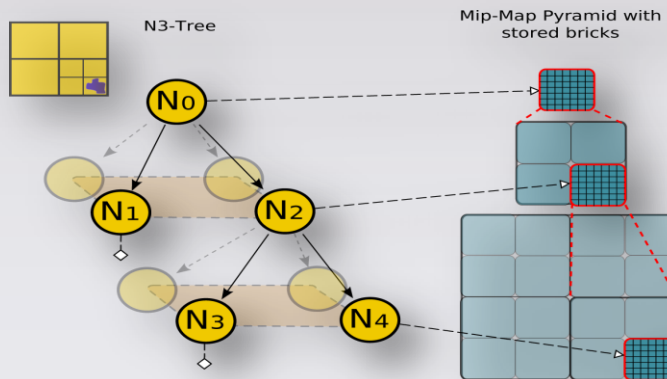


# GigaVoxels Pipeline + data structure

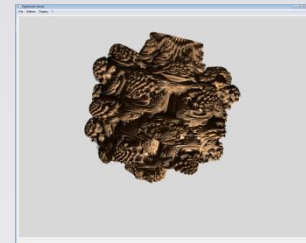
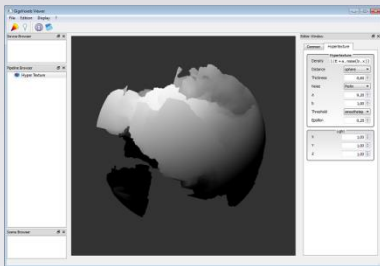
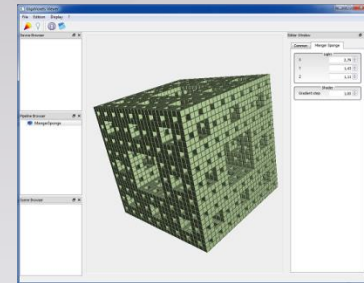
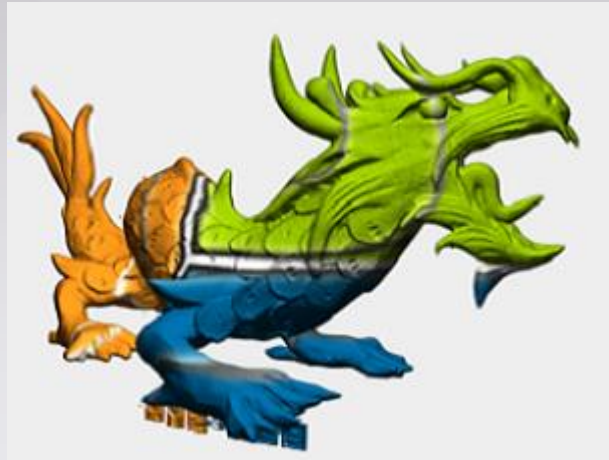
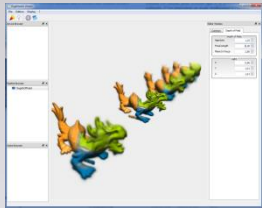
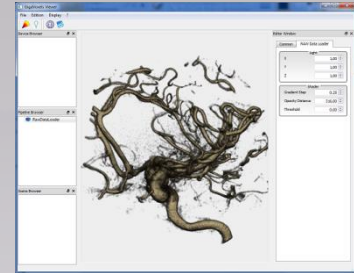
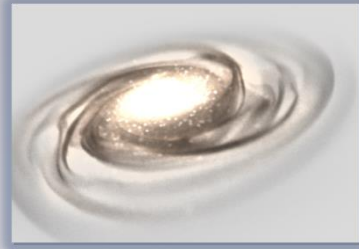
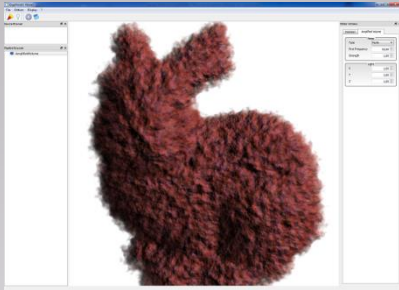
- unified data structure (geometry + texture)
- load only needed data at needed resolution
- smooth transitions and continuously reveals details
- Handle semi-transparent objects
- Alias free filtered images ( cone tracing )



Cone tracing



# PART 2 - Fonctionnalités through SDK examples



# Data loading

## Data streaming

Load data « on demand ». Two modes :

- ▶ level by level (from coarse to fine) [ speed trade-off ]
- ▶ directly max level of resolution [ quality before ]

## File format

By level of resolution and by data types

- ▶ 1 - nodes (spatial structure)
- ▶ 2 - bricks of voxels

no header, no meta-file...



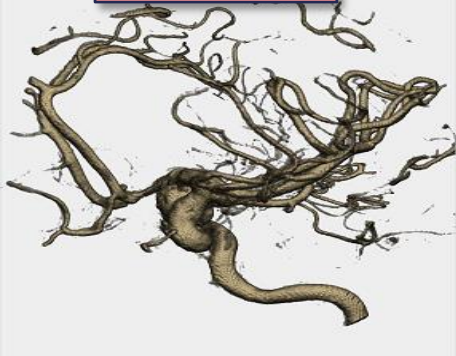
# Import your own data

## Custom file importer

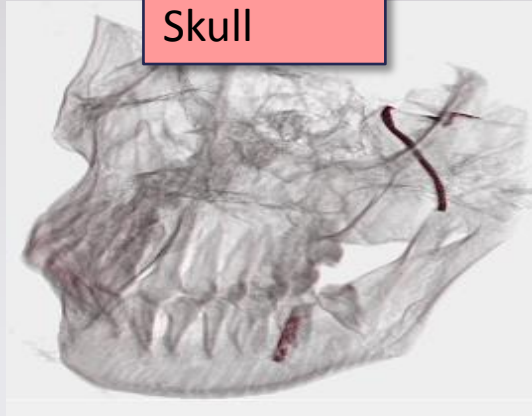
RAW data [scientific visualization]

- ▶ apply transfer function
- ▶ threshold data
- ▶ clipping plane [region of interest]

Aneurism



Skull



Foot  
+ threshold





# Procedural data generation

## Mandelbulb

Goal : generate environments

Fractal object : 3D extension of Mandelbrot set

$$\langle x, y, z \rangle^n = r^n \langle \cos(n\theta) \cos(n\phi), \sin(n\theta) \cos(n\phi), \sin(n\phi) \rangle$$

$$\text{où } \left\{ \begin{array}{l} r = \sqrt{x^2 + y^2 + z^2} \\ \theta = \arctan(y/x) \\ \phi = \arctan(z/\sqrt{x^2 + y^2}) = \arcsin(z/r) \end{array} \right\}$$

pour la nième puissance du nombre hypercomplexe 3D.  
Les points sont calculés par itération de  $z \mapsto z^n + c$  où  $z$  et  $c$  sont des nombres hypercomplexes dans un espace de dimension 3 et  $z \mapsto z^n$  l'application définie ci-dessus. Ici  $n = 8$ .



Mandelbulb

# Procedural data generation



Mandelbulb



# Noise - Hypertextures

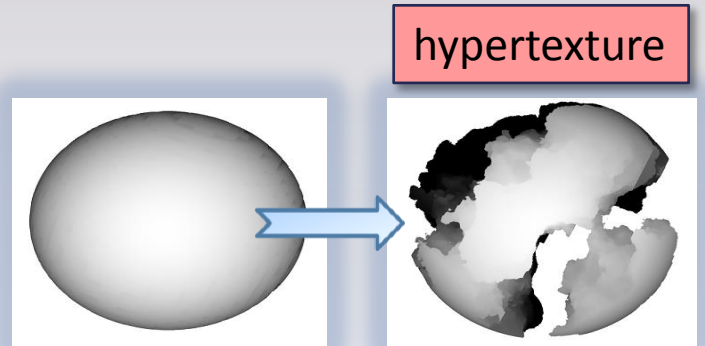
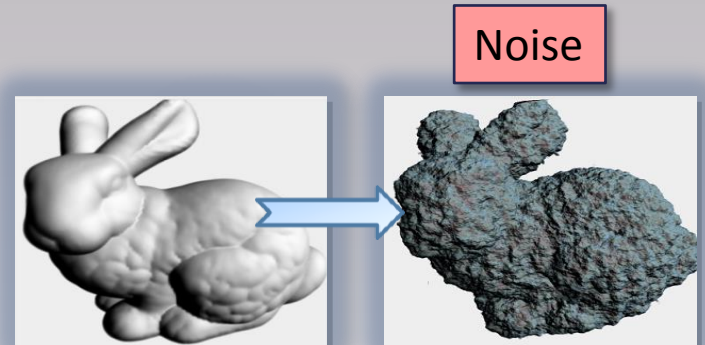
## Goals

Add details on 3D models

- smooth transitions and continuously reveals details
- alias free filtered images
- handle parallax effect

## Theory

- Ken Perlin
- book : « Texturing and Modeling, a procedural approach », chapter 12

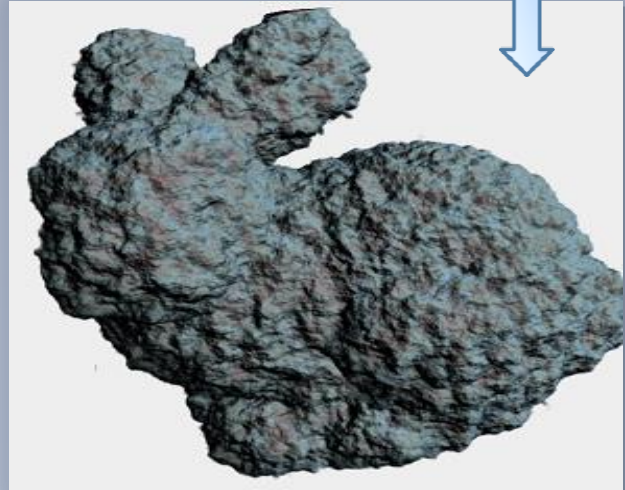
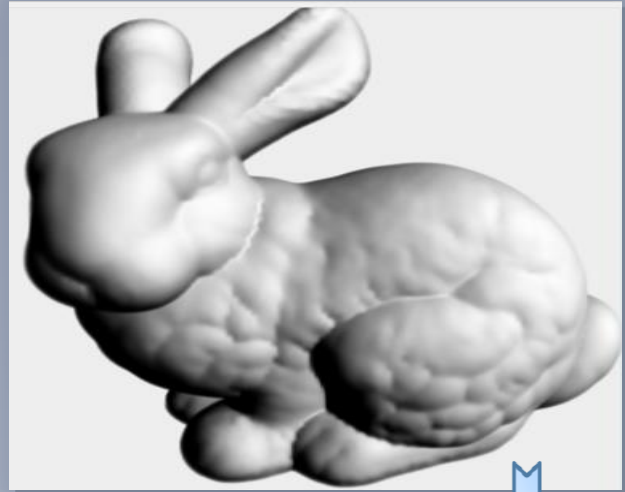


# Noise

## Input

3D model : Signed Distance Field

- ▶ Noise : applied on distance and normal
- ▶ Transfer Function : convert distance to RGBA color



# Noise : optimisation(s)

Idea : (use cache)

Mimic the LOD mechanism that continuously add details :

➔ Re-use noise computation at previous resolution level

- noise : sum of octaves (frequencies)
- compute only one octave by level of resolution
- store them in GPU cache
- reproduce the sum :
- $F(\text{level } N) = \text{currentNoise}(\text{level } N) + \text{previousNoise}(\text{level } N-1)$
- Finally : replace “noise computation” by “data fetch in cache”

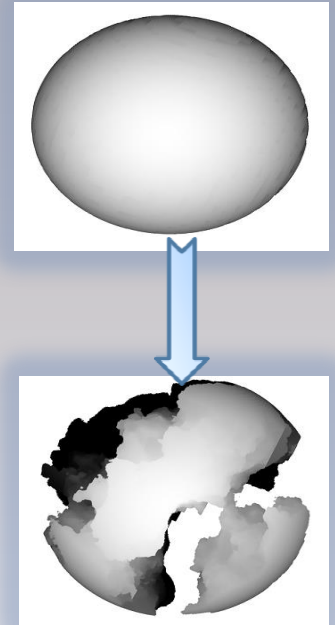
# Hypertextures

## Hypertexture (shape + solid texturing)

- $F(x)=0$  : outside the object
- $F(x)=1$  : strictly inside the object
- $0 < F(x) < 1$  : inside a fuzzy region

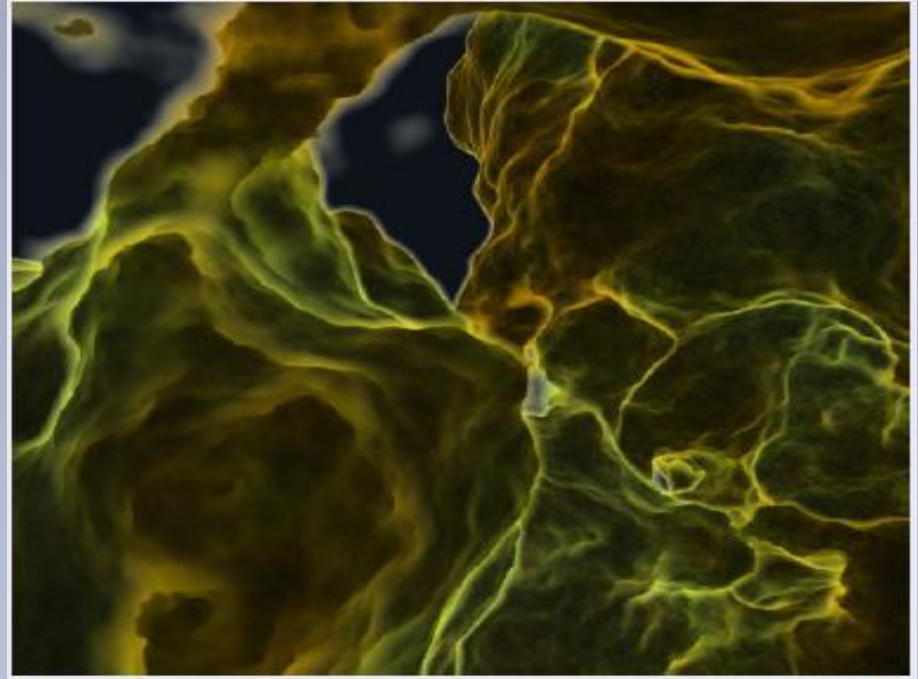
Idea : add details on armor soldier

- Distance function : sphere
- Thickness : fuzzy region (Perlin noise)
- Current work : optimizations
  - Stop adding noise components if density is outside



hypertexture

# Hypertextures



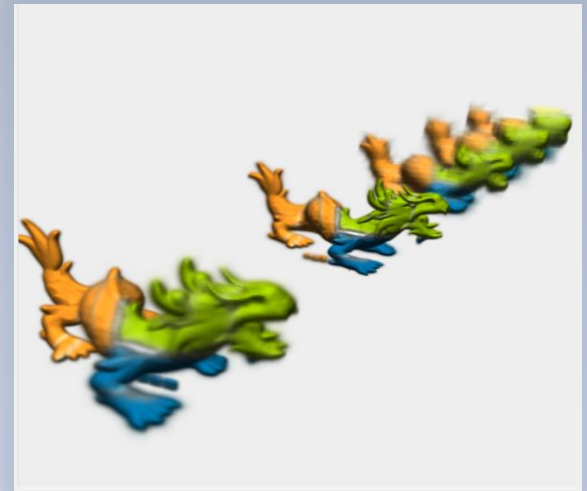
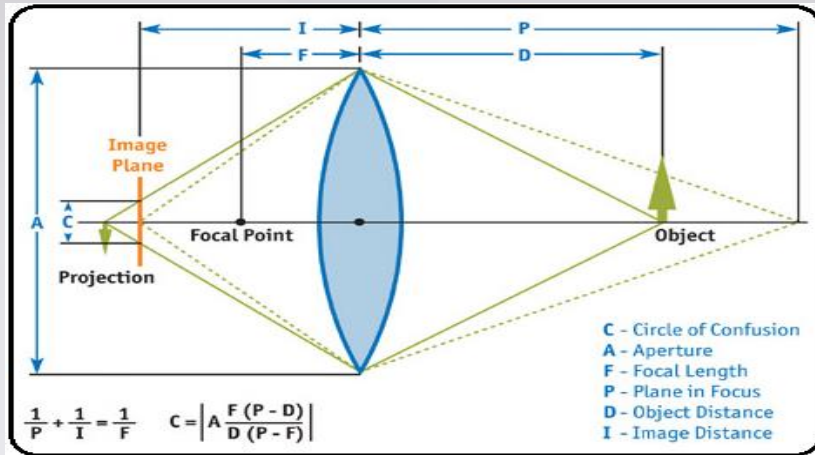
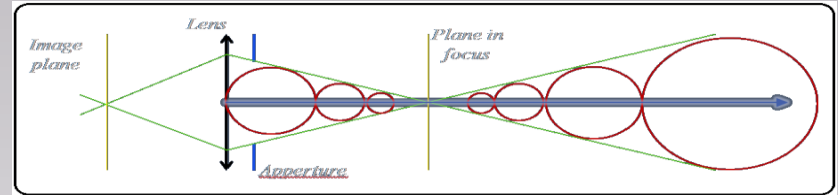
# Depth of Field

## Goal

Add more realism to images

- ▶ mimic camera lens (focus plane)
- ▶ double lens cone

Depth of Field

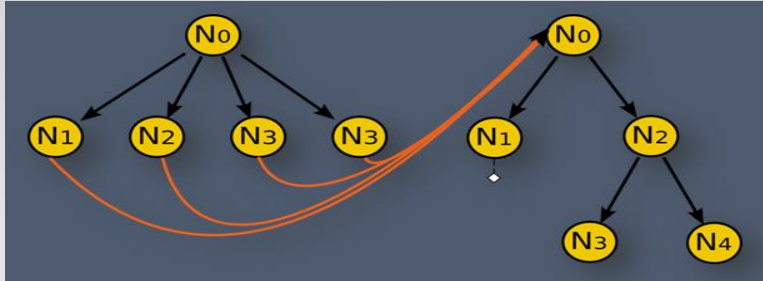


# Voxel data synthesis

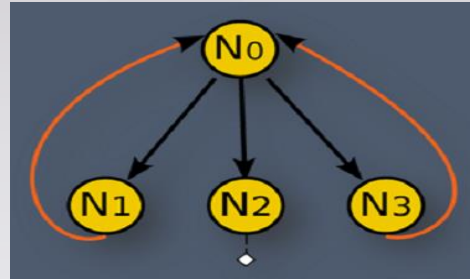
Goal : Simulate environments

## Instanciacion and recursion

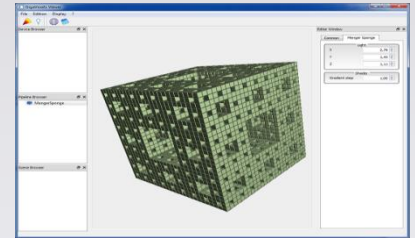
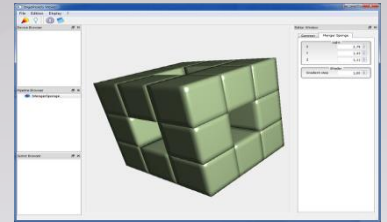
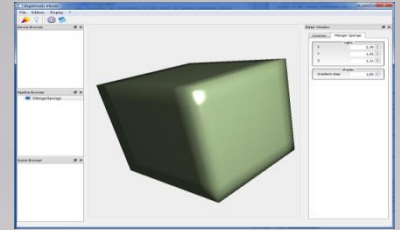
node pointers based system



Instanciacion



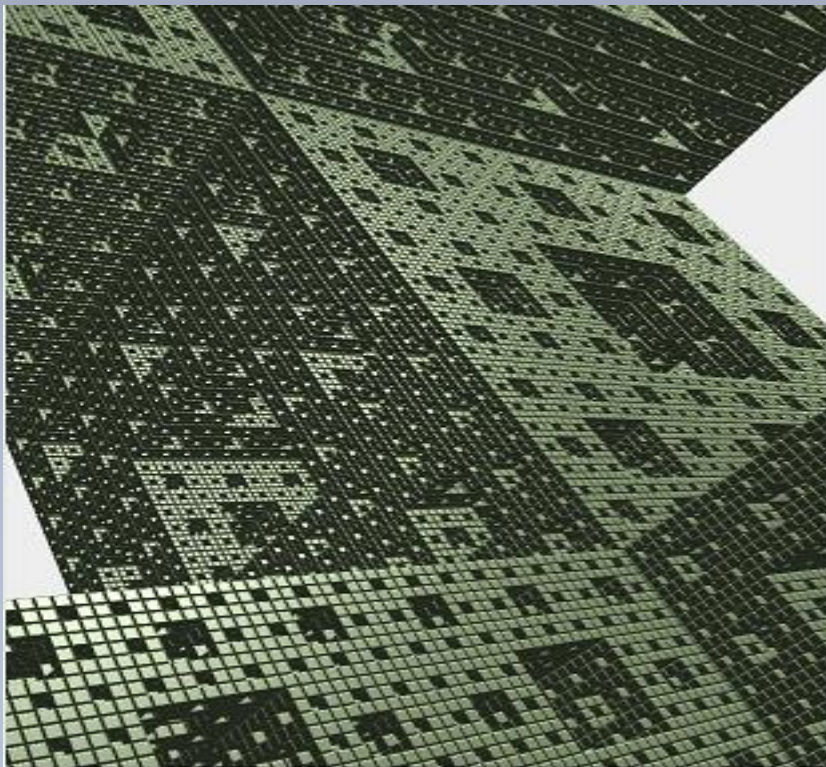
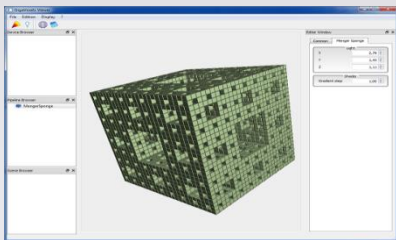
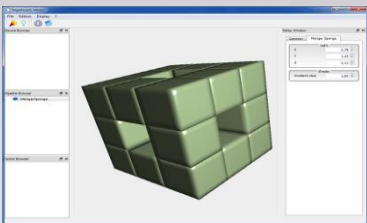
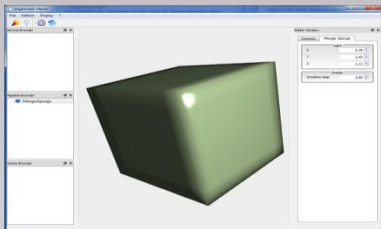
Recursivity





# Voxel data synthesis

## Menger/Serpinski Sponge

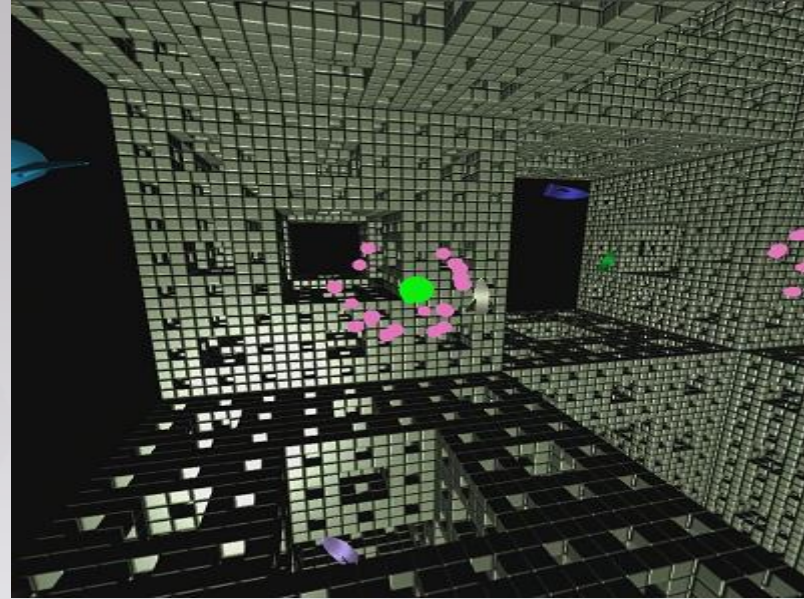




# OpenGL interoperability

## Mix triangles and voxels

- integration with traditional CG rasterized scenes (or compositing)
- renderer takes color and depth buffer as input and updates them with voxels



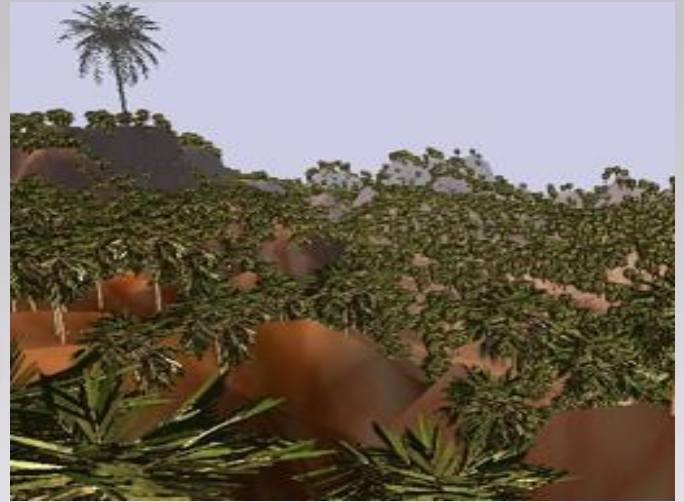
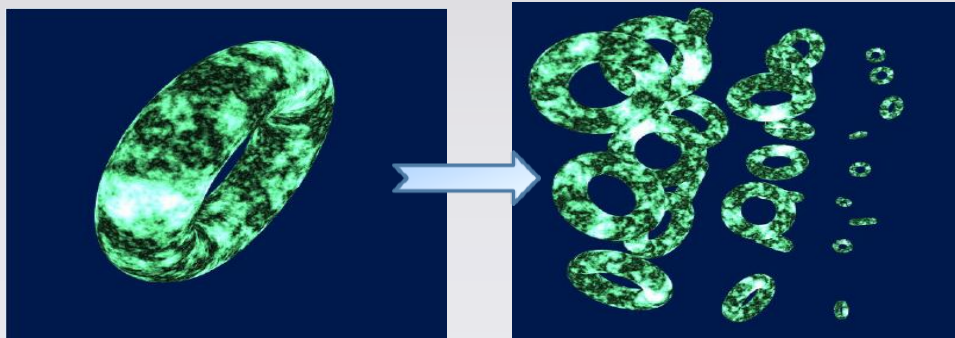
OpenGL  
interoperability

# Voxel-based Instancing

**Goal** (not yet, in study/progress)

Have several GigaVoxels entities (forest)

- Need proxy geometry
- Render projected 2D BBox
- Use GLSL fragment shader
- (rays start + direction)



Instancing

# Tools : Viewer

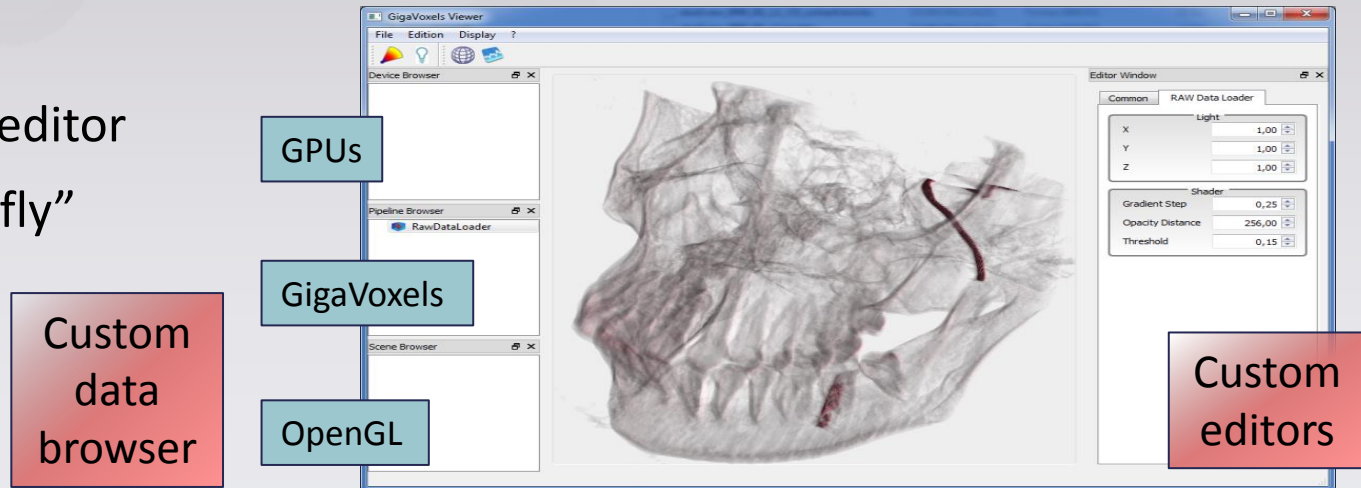
## Goal

Environment to study, test, profile, debug...

- Kind of “generic” API : browsers, editors, etc...
- Tools : transfer function, performance monitor, etc...
- 3D models importer (+ GLSL shaders editor)
- Futur hope :

CUDA functions editor

“recompile on the fly”



# Outils : Viewer

## Goal

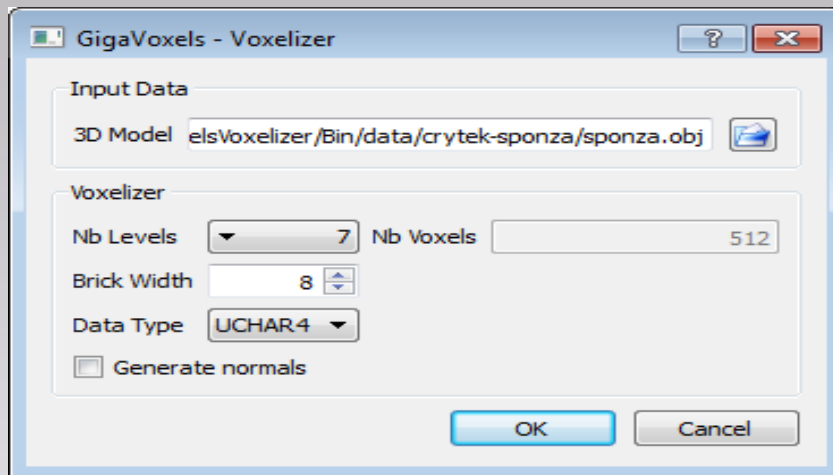
Plugin « GigaVoxels Pipeline » : dynamic library (.dll, .so)

=> kind of « effect »

- Idea : plug this “node” in a scene graph à la OpenSceneGraph (see the “ppu” project) or Ogre3D
- Not yet finished : it has been “polluted” with Qt to have USER custom editors.

# Outils : Voxelizer

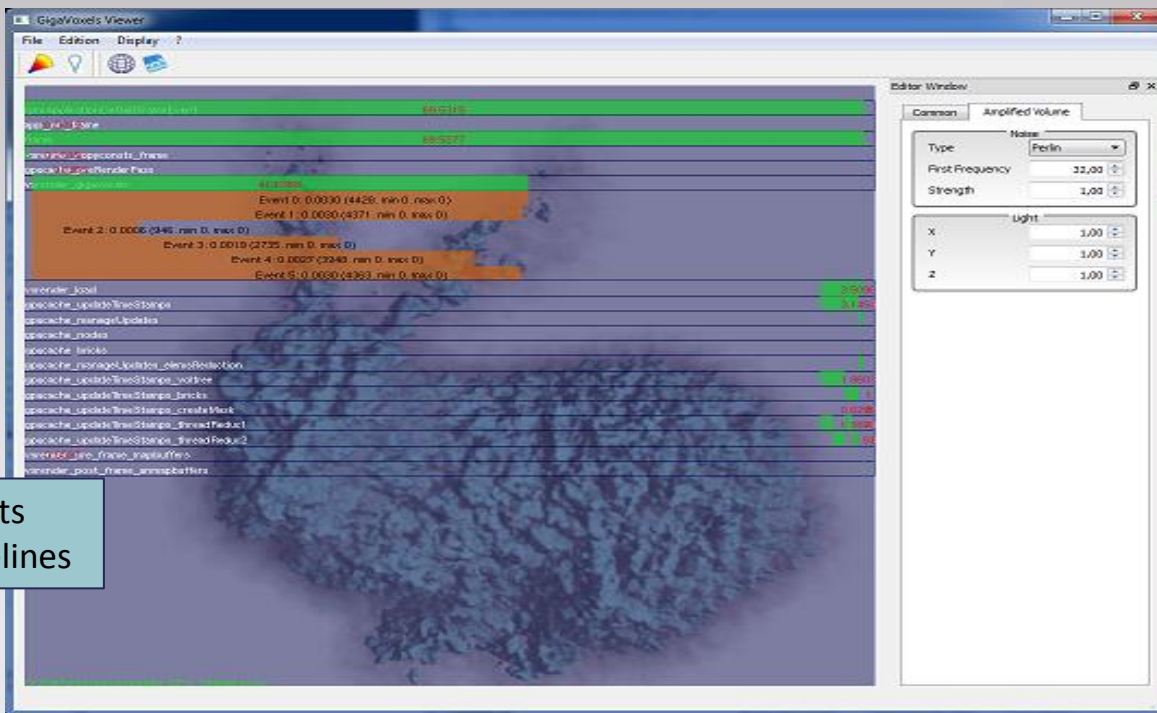
- Pre-process step
  - Futur work :
    - - optimize code
    - - smooth resulting data
    - - idea : voxelize data
- “on the fly” in the producers



Voxelizer  
Tool

# Outils : Performance Monitor (still in debug...)

- Use events to record time between kernel functions
- Special case : record “device” functions (1 thread per pixel)



Performance  
Monitor

# Outils : Performance Monitor

- Record device function for Rendering kernel (1 thread per pixel), then compute average time on all pixels

```
#ifdef WIN32
    typedef unsigned __int64    uint64;
#else
    typedef unsigned long long   uint64;
#endif

__device__ uint64 getClock()
{
    uint64 result;
    // Using inline PTX assembly in CUDA.
    // Target ISA Notes : %clock64 requires sm_20 or higher.
    //
    // The constraint on output is "=l" :
    // - '=' modifier specified that the register is written to
    // - 'l' modifier refers to the register type ".u64 reg"
    asm volatile ("mov.u64 %0,%clock64;" : "=l"(result) : : );
    return result;
}
```

# RTIGE

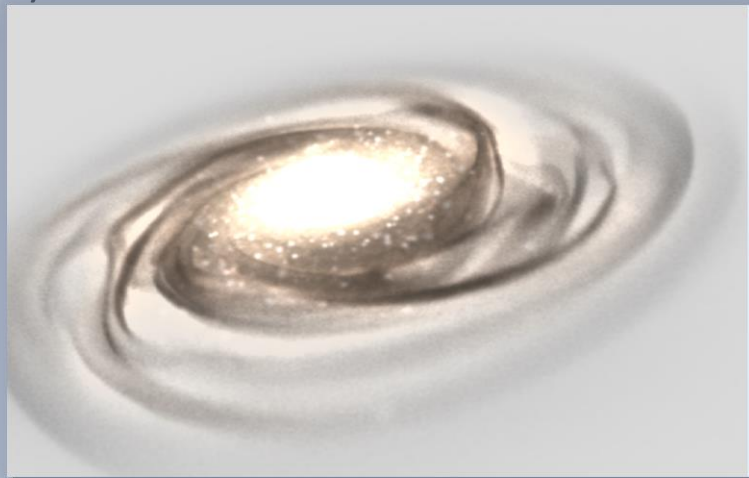
## French ANR Research Project

RSA Cosmos : planetariums [2010-2014]

- “Real-Time and Interactive Galaxy for Edutainment”
- I. Visualize static galaxies
- II. Data amplification (procedural generation)
- III. Animate galaxies

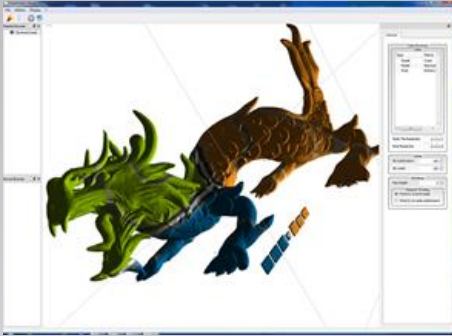
## Optimisations

- use OpenGL billboards to stop rays (VBO)
- multi-GPUs ?
- time budget ?, priority on bricks ?

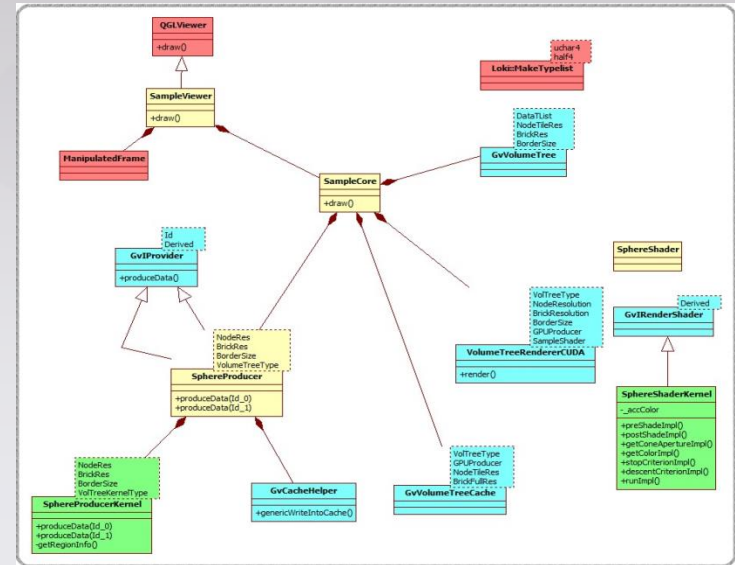
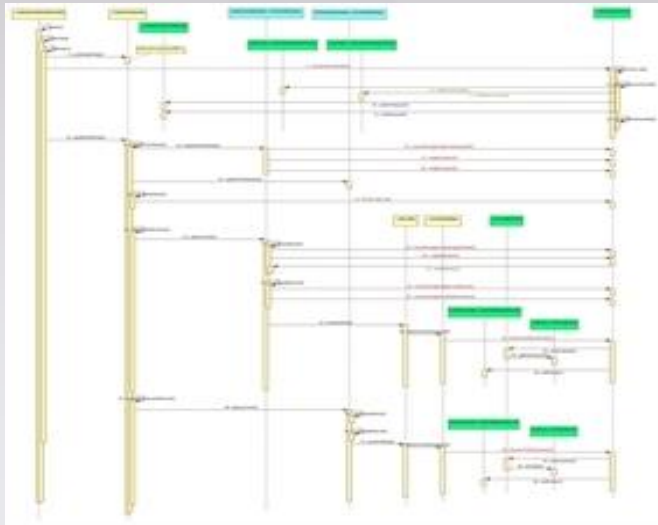
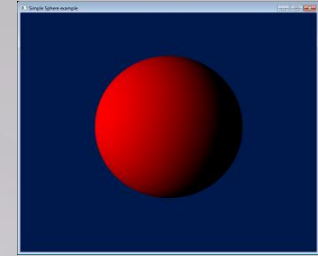




# PART 3 - The library



- [ 1 ] - Core library
- [ 2 ] - User custom API



# The library

## Goal

- Capitalize on the knowledge of the team
- Continue research on the subject
- Hide the complexity of the underlying « core » library (cache mechanism, data structure management, etc...)
- Give USER access to customize the « data production » and the « shader »

# The library

## Technologies

- C++ (template)
- GPU Computing : CUDA + libraries (cudpp / thrust)
- CMake
- IHM : Qt
- Viewer : QGLViewer
- 3D : OpenGL (GLSL)
- Others : Loki, Assimp, Cimg, ImageMagick
- OS : Windows (7), Linux (Ubuntu) + 32/64 bits
- Requirements : Cuda 4.x and Compute Capability SM at least 2.0

# Library

## [ 1 ] - Common API : « hidden » generic mechanisms

- **Tree Data Management** (space partitioning) to store and organize data (octree or generalized N3-tree, + SDK example kd-tree)
- **Cache System on GPU** : LRU mechanism (least recently used) (to get temporal coherency)
- **Data Production Management** : on host, GPU, or hybrid mode  
Goal : produced data are kept in cache on GPU
- **Visit algorithm** : traverse your data (loaded in cache) as could be done for rendering
- **Renderer** (hierarchical volume ray-casting, cone tracing, emission of requests, brick marching)

# Library

## [ 2 ] – USER access

### USER Customizable API

- ▶ **Producer** (load or produce our own data)
  - ➡ used during Data Production Management
- ▶ **Shader** (write your custom shader)
  - ➡ used during Visit algorithm and Rendering

# Library

## Data Production Management :

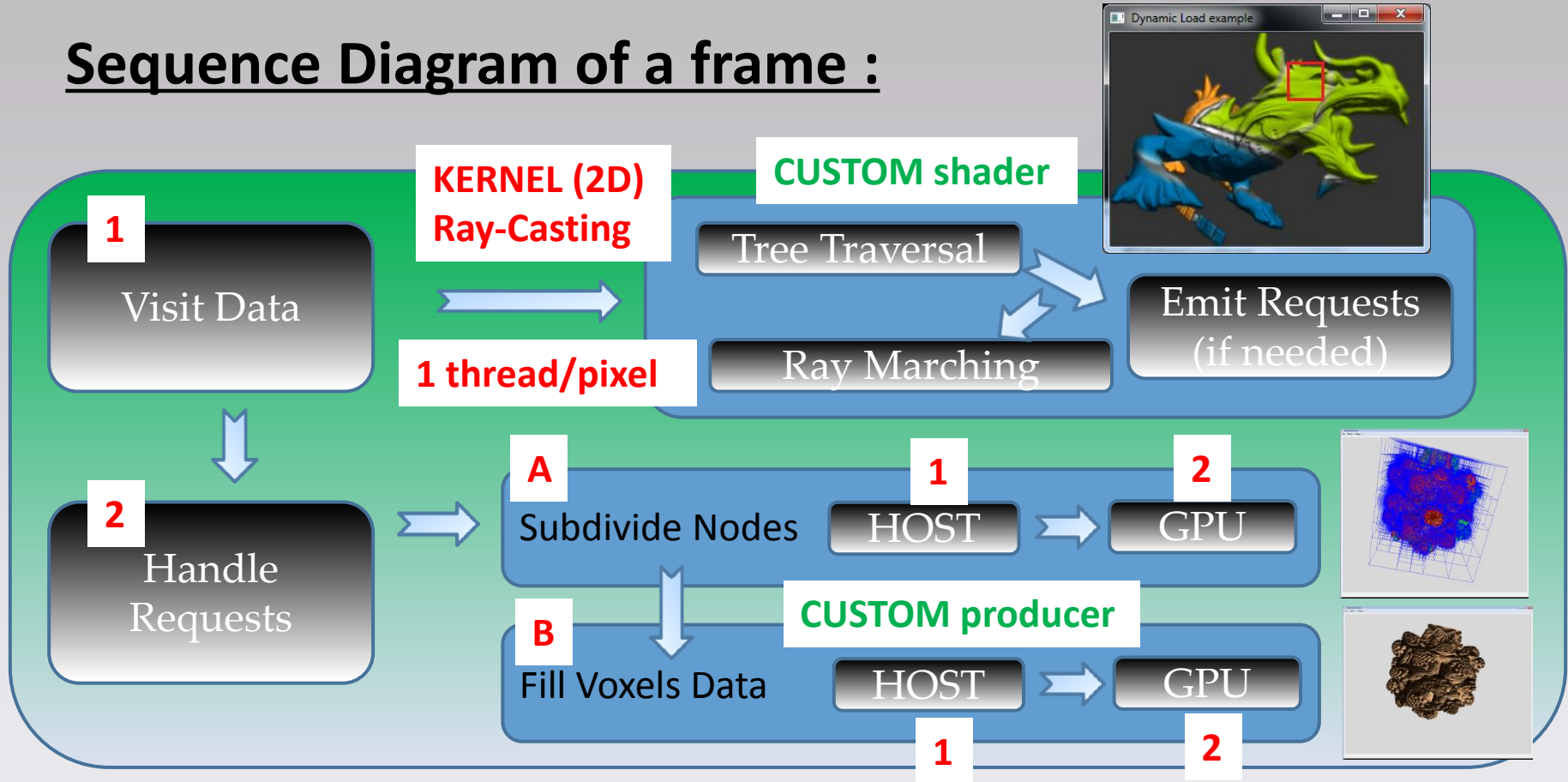
- Nodes subdivision (data refinement)
- Load or compute bricks of voxels (fill data)

USER has to write :

- a HOST producer
- and its associated GPU producer

# Data Production Management

## Sequence Diagram of a frame :



# Sequence

**Frame 1**

Produce Nodes



Produce Bricks

**Frame 2**

Produce Nodes



Produce Bricks

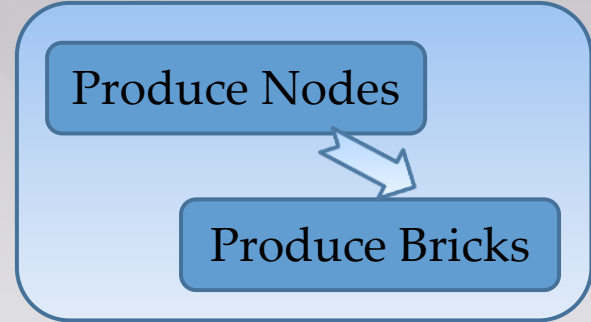
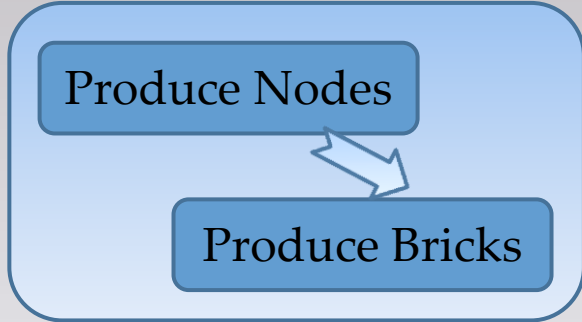
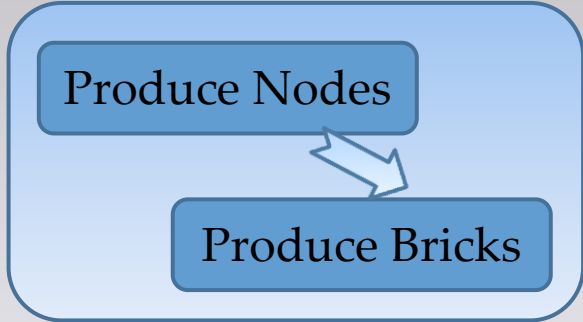
...

**Frame N**

Produce Nodes



Produce Bricks



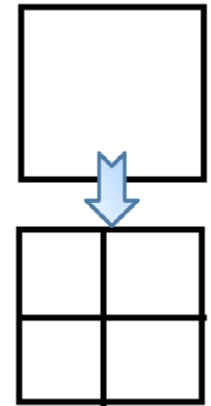


# Ex : sphere on GPU

Parent

## Nodes subdivision :

- KERNEL : 1 bloc/node and 1 thread/child\_node
- Each node has to say what's inside each of its child
- INPUT : localization info of current node (LOD depth and spatial index pos)
- INPUT : address in “node cache” where to write new child nodes
- Test if it is in a sphere (analytically)
- Write nodes in cache

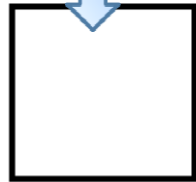


Children

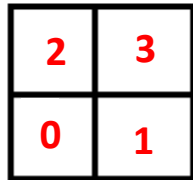
# Ex : sphere on GPU

## Nodes subdivision :

**WORLD : sphere**



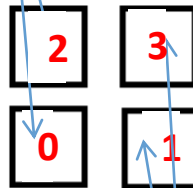
**Parent**



**Children  
- what's inside ?**



**empty**



**data**

**1st step**

### FLAG Children

- EMPTY
- DATA inside
- MAX RESOLUTION reached

**Retrieve 3D world position with help of INPUT localization info (depth, index position)**



**2nd step**

### Write result in cache

- Next frame, render will ask for the node data production ( brick of voxels)

# Ex : sphere on GPU

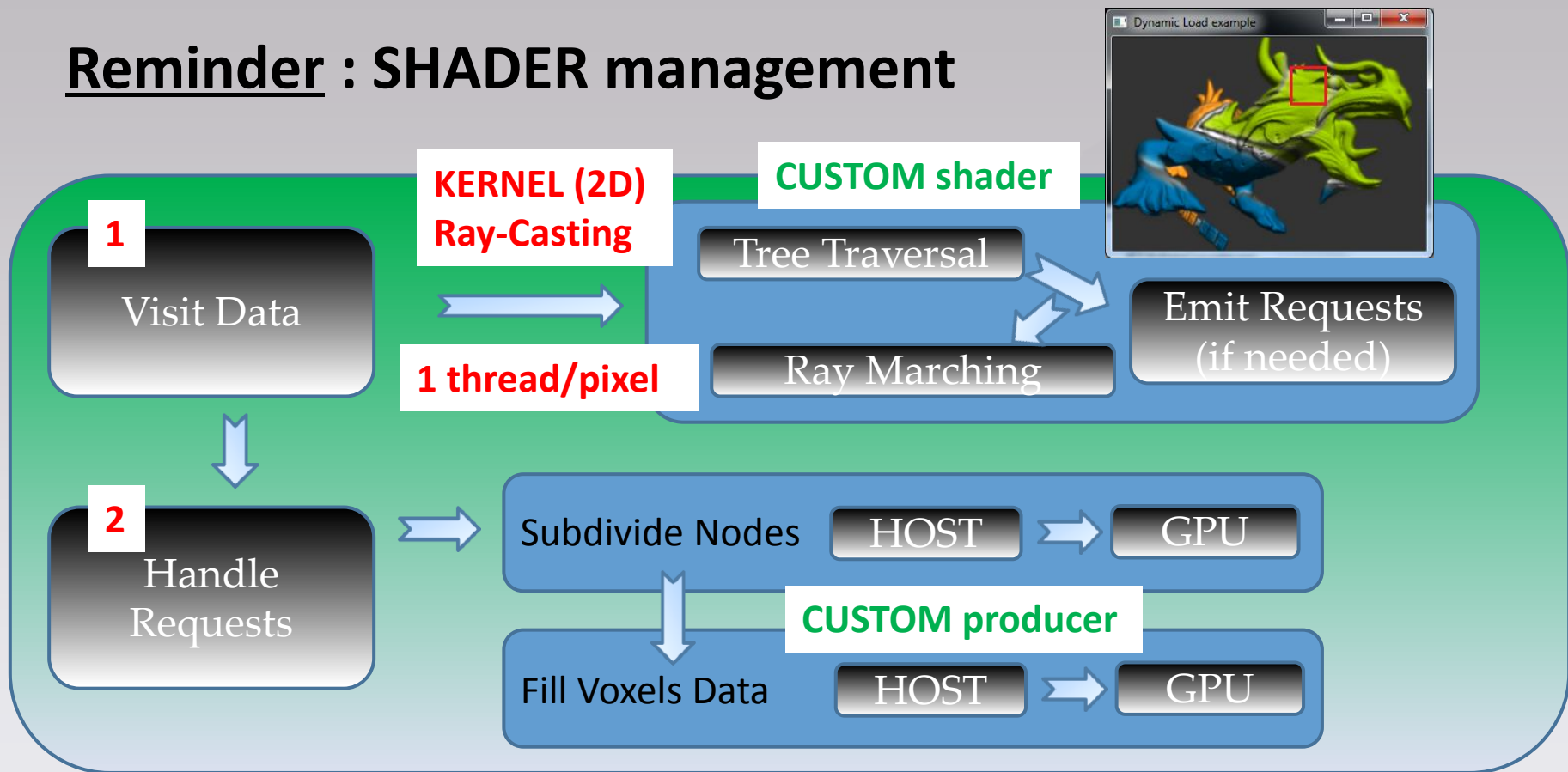
## Bricks of voxels production :

(same principe as for nodes)

- KERNEL : 1 bloc/brick and thread is as you want
- USER is in 1 brick and has to populate its voxels
- INPUT : localization info of current node (LOD depth and spatial index pos)
- INPUT : address in “data cache” where to write new voxels
- Write voxels in cache

# Ex : sphere on GPU

## Reminder : SHADER management



# Ex : sphere on GPU

## SHADER :

- ▶ INPUT : “data sampler” and current position
- ▶ Sample data, retrieve USER defined channel (color, normal, etc...) and accumulate color along the current ray

```
// Retrieve first channel element : color
__device__ void ShaderKernel::run( const SamplerType& brickSampler, ... )
{
    float4 color = brickSampler.getValue< 0 >( coneAperture );    // channel 0 is color

    If ( color.w > 0.0f ) { _accumulatedColor = _accumulatedColor + ( 1.0f - _accumulatedColor.w ) * color; }
}
```

# Sphere on GPU

## SHADER :

- ▶ CUSTOM api provide “other entry points” :
- ▶ `getConeAperture()` [modify cone aperture]
- ▶ `getStopCritrion()` [ ex :  $\text{accumulatedColor.w} \geq 0,98f$  ]
- ▶ `getDescentCriterion()` [ used during “visit” traversal ]
- ▶ ...



GigaVoxels Sequence Diagram

# Library

## Tips and tricks :

- Template meta-programmation : curiously recursive template pattern (to avoid polyphormism on GPU)

This technique achieves a similar effect to the use of [virtual functions](#), without the costs (and some flexibility) of [dynamic polymorphism](#).

- Data cache : 3D texture to read, and bind with surfaces to write data
- Loki : use to access different textures types
- Cudpp(/thrust) : cache mechanism on GPU (stream compaction to get “used” and “non-used” elements at current frame)
- Write Z-buffer : slow => idea => use color and do conversion

# OpenGL interoperability

## Mix triangles and voxels :

- integration with traditional CG rasterized scenes (or compositing)
- renderer takes color and depth buffer as input and updates them with voxels
- Opaque objects rendered first (depth buffer) to skip occluded parts
- GigaVoxels registers « textures, renderBuffer, PBO, ... » with optimized flags

(see GTC 2013 : S3070 – « Part 1 – Configuring, Programming and Debugging Applications for Multi-GPUs » from Wil Braithwaite [NVIDIA])

`cudaGraphicsRegisterFlagsReadOnly, cudaGraphicsRegisterFlagsWriteDiscard, ...`

)



# OpenGL interoperability

## Mix triangles and voxels

Simple mode : [ no input ] + [ only write color ]

**// [ 1 ] - Init texture (with window size)**

```
glGenTextures( 1, &colorTex );
```

```
glBindTexture( GL_TEXTURE_RECTANGLE_EXT, colorTex );
```

```
glTexImage2D( GL_TEXTURE_RECTANGLE_EXT, 0, GL_RGBA8, width, height, 0, GL_RGBA, GL_UNSIGNED_BYTE, NULL );
```

**// [ 2 ] - Register texture in WRITE ONLY slot in GigaVoxels**

```
renderer->connect( Gv::eColorWriteSlot, colorTex, GL_TEXTURE_RECTANGLE_EXT );
```

**// Launch GigaVoxels rendering engine**

```
renderer->render( /*OpenGL matrices*/ );
```

**// Draw a full screen textured quad**

```
glBindTexture( GL_TEXTURE_RECTANGLE_EXT, colorTex );
```

```
glBegin( GL_QUADS );
```

```
...
```

```
enum GraphicsResourceSlot
{
    eColorReadSlot,
    eColorWriteSlot,
    eColorReadWriteSlot,
    eDepthReadSlot,
    eDepthWriteSlot,
    eDepthReadWriteSlot,|
    eNbGraphicsResourceSlots
};
```

**Slots**

# OpenGL interoperability

Current work

[ 1 ] - Proxy geometry

“rasterized (approximate) geometry” containing non-empty areas of volume, providing starting and exit point for each ray, speeding-up the skipping of empty spaces

- Help skip empty regions
- Can add volumetric details on a triangle mesh

[ 2 ] – kind of Geometry Instancing

- Would like to have demo with forest



# OpenGL interoperability

Current work : based on a galaxy visualization research project

Number of stars represented by points (VBO) can be very huge :

## [ 1 ] Sphere Ray-Tracing (change representation)

- When bricks are near empty, generate spheres coordinates in « producer »
- Replace brick-marching by Ray-Tracing at rendering phase (fetch positions)

## [ 2 ] -VBO generation

- add details by generating stars (OpenGL vbo points) in a GigaVoxels « producer »
- dump result in VBO dynamically (only visible nodes)
- => kind of view frustum culling

# ... the futur...

## Ideas

- Working on performance (Visual Profiler, NSight)
  - + Handle time budget for a frame, priority on bricks
- Use CUDA 5 : linker (recompile USER functions on the fly ?)
- Store points inside voxel (VBO generation according to visibility)
- ✓ Geometry instancing (forest)
- ✓ Voxel animation (with shellmaps)
- ...

# User / developer guide

## Library / SDK content

- Core library documented
- SDK tutorials fully documented
- Developer guide : soon
  - kind of “behind the scene”) : technical implementations detailed

# Thanks

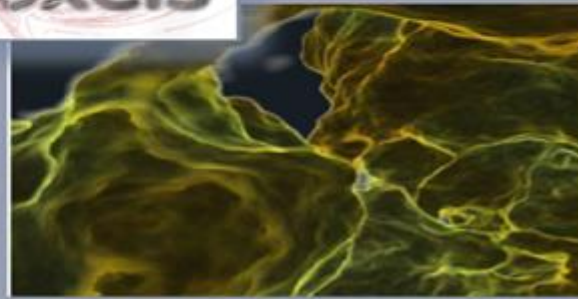
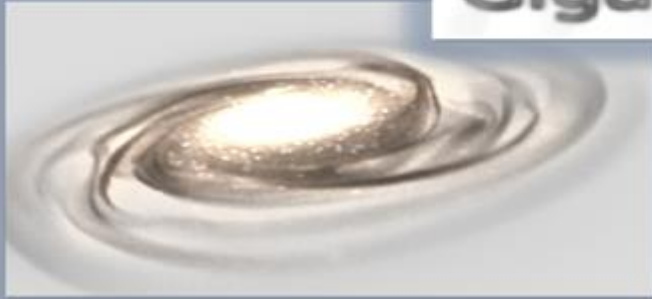
- Fabrice Neyret ( CNRS, INRIA, LJK), M. Armand, E. Heitz, E. Eisemann, ...
- Cyril Crassin ( NVidia )
- Nvidia : for cards donation (Chandra Cheij)
- ✓ RSA Cosmos : for testing the library
- ✓ French Research ANR :

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ANR "RTIGE" (Real-Time Interactive & Galaxy for Edutainment)  
of reference ANR-10-CORD-0006

# Questions



GigaVoxels



Thanks  
for  
your  
attention

<http://gigavoxels.inrialpes.fr/>