ZFP: Compressed Floating-Point Arrays for Exascale Computing

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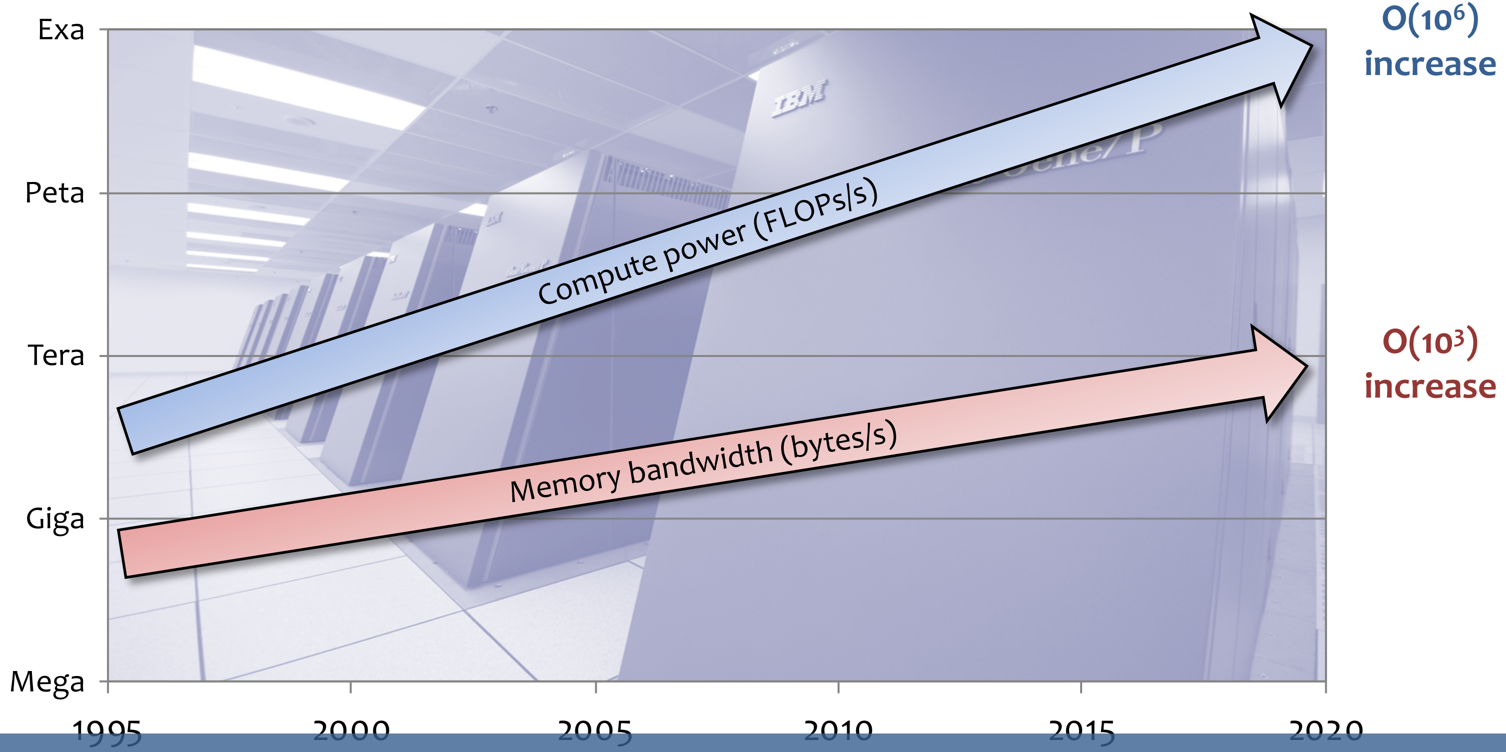
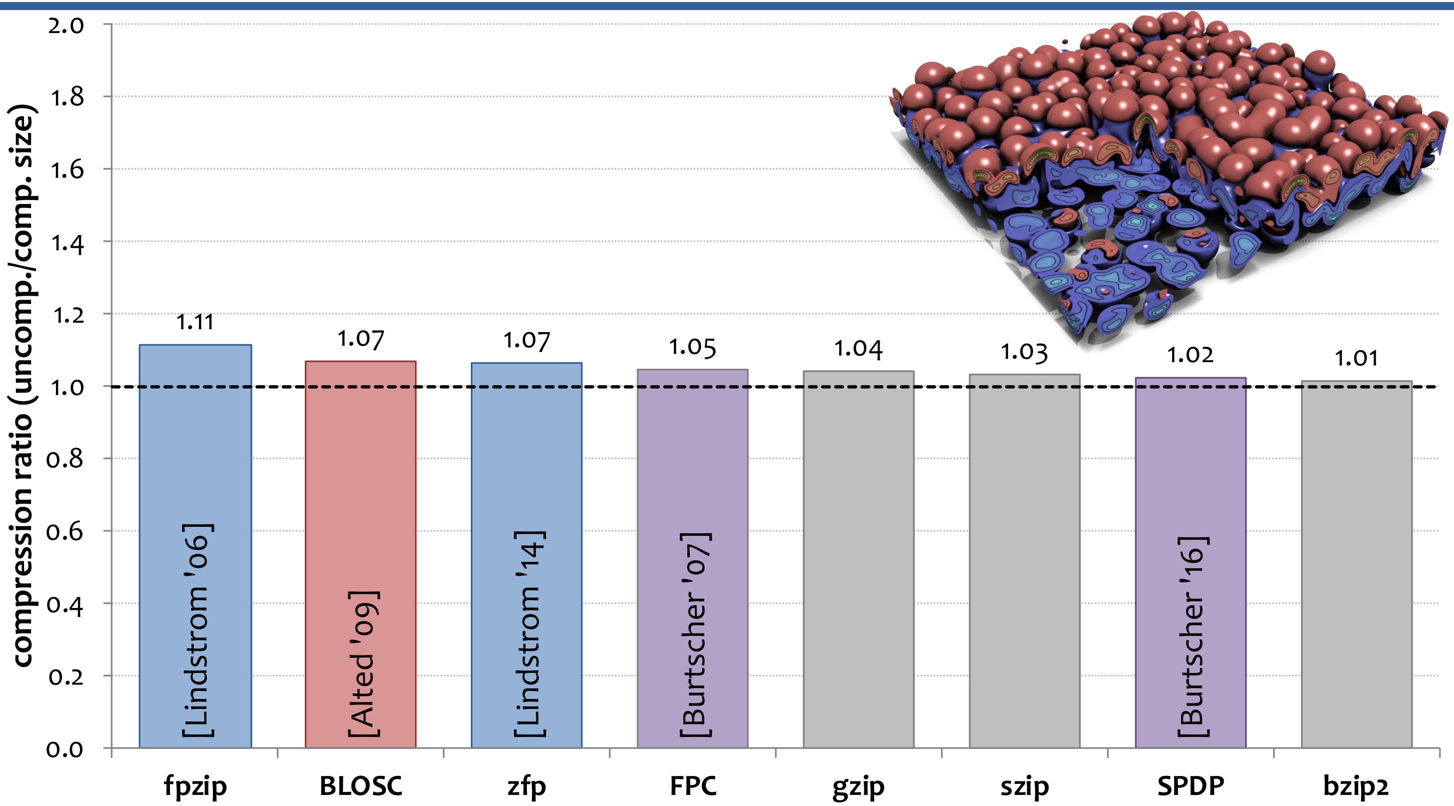
Data movement will dictate performance and power usage at exascale



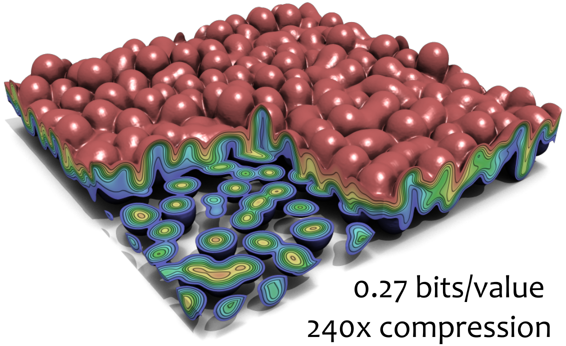
Otherwise idle compute cycles can be spent on data compression to reduce memory traffic

(64-bit) floating-point data does not compress well losslessly



Lossy compression enables greater reduction, but is often met with skepticism by scientists

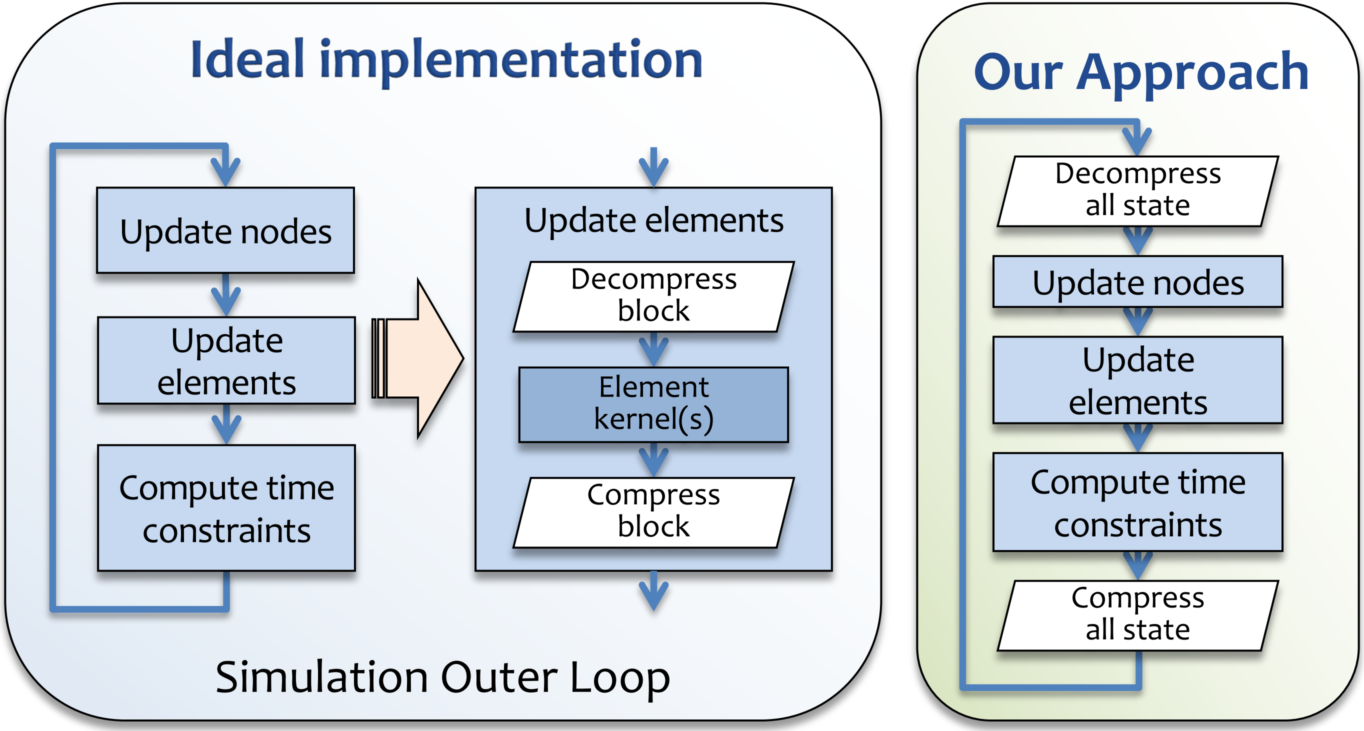
- Large improvements in compression are possible by allowing even small errors
  - Simulation often computes on meaningless bits
    - Round-off, truncation, iteration, model **errors abound**
    - Last few floating-point bits are effectively **random noise**



0.27 bits/value
240x compression

- Still, lossy compression often makes scientists nervous
  - Even though lossy **data reduction** is ubiquitous
    - **Decimation** in space and/or time (e.g., store every 100 time steps)
    - **Averaging** (hourly vs. daily vs. monthly averages)
    - **Truncation** to single precision (e.g., for history files)
  - State-of-the-art compressors support **error tolerances**

Can lossy-compressed in-memory storage of numerical simulation state be tolerated?

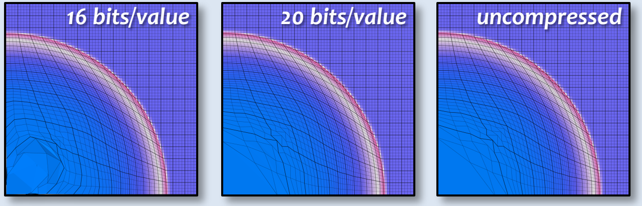


[Laney et al., "Assessing the effects of data compression in simulations using physically motivated metrics," SC 2013]

Using lossy FPZIP to store simulation state compressed, we have shown that 4x lossy compression can be tolerated

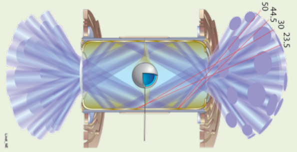
Lagrangian shock hydrodynamics

- QoI: *radial shock position*
- 25 state variables compressed over 2,100 time steps
- At **4x compression**, relative **error < 0.06%**



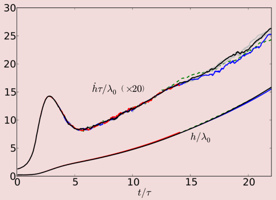
Laser-plasma multi-physics

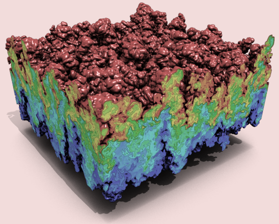
- QoI: *backscattered laser energy*
- At **4x compression**, relative **error < 0.1%**



High-order Eulerian hydrodynamics

- QoI: *Rayleigh-Taylor mixing layer thickness*
- 10,000 time steps
- At **4x compression**, relative **error < 0.2%**

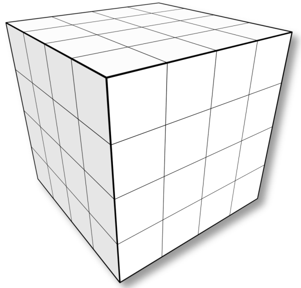




Lossy compression of state is viable, but streaming compression *increases* data movement—need inline compression

ZFP is an inline compressor for floating-point arrays

- ZFP provides a C++ *d*-dimensional compressed array primitive
  - Based on decomposition into independent **blocks of 4^d values**
  - *O*(1) read & write **random access** with user-defined memory footprint
  - **Replaces IEEE** as number format for numerical computations
  - Very fast: up to **150 GB/s** parallel throughput
    - H/w friendly: uses only integer additions and bitwise operations
  - **Conventional API:** C++ operator overloading hides complexity of (de)compression
    - double a[n] ⇔ std::vector<double> a(n) ⇔ zfp::array<double> a(n, **bits_per_value**)



- ZFP can also be used for streaming compression to reduce I/O and storage
  - Supports absolute and (local) relative **error tolerances**
  - Supports **spatially adaptive & progressive** compression
  - **Resilient** to data corruption

ZFP's C++ compressed arrays can replace STL vectors and C arrays with minimal code changes

// example using STL vectors

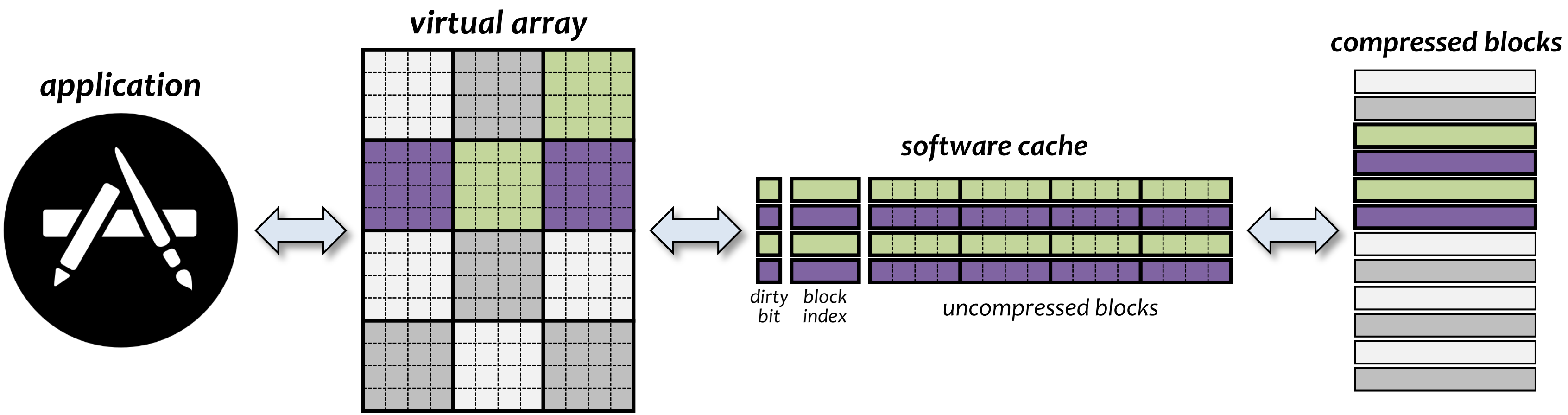
```
std::vector<double> u(nx * ny, 0.0);
u[x0 + nx*y0] = 1;
for (double t = 0; t < tfinal; t += dt) {
    std::vector<double> du(nx * ny, 0.0);
    for (int y = 1; y < ny - 1; y++)
        for (int x = 1; x < nx - 1; x++) {
            double uxx = (u[(x-1)+nx*y] - 2*u[x+nx*y] + u[(x+1)+nx*y]) / dxx;
            double uyy = (u[x+nx*(y-1)] - 2*u[x+nx*y] + u[x+nx*(y+1)]) / dyy;
            du[x + nx*y] = k * dt * (uxx + uyy);
        }
    for (int i = 0; i < u.size(); i++)
        u[i] += du[i];
}
```

// example using ZFP arrays

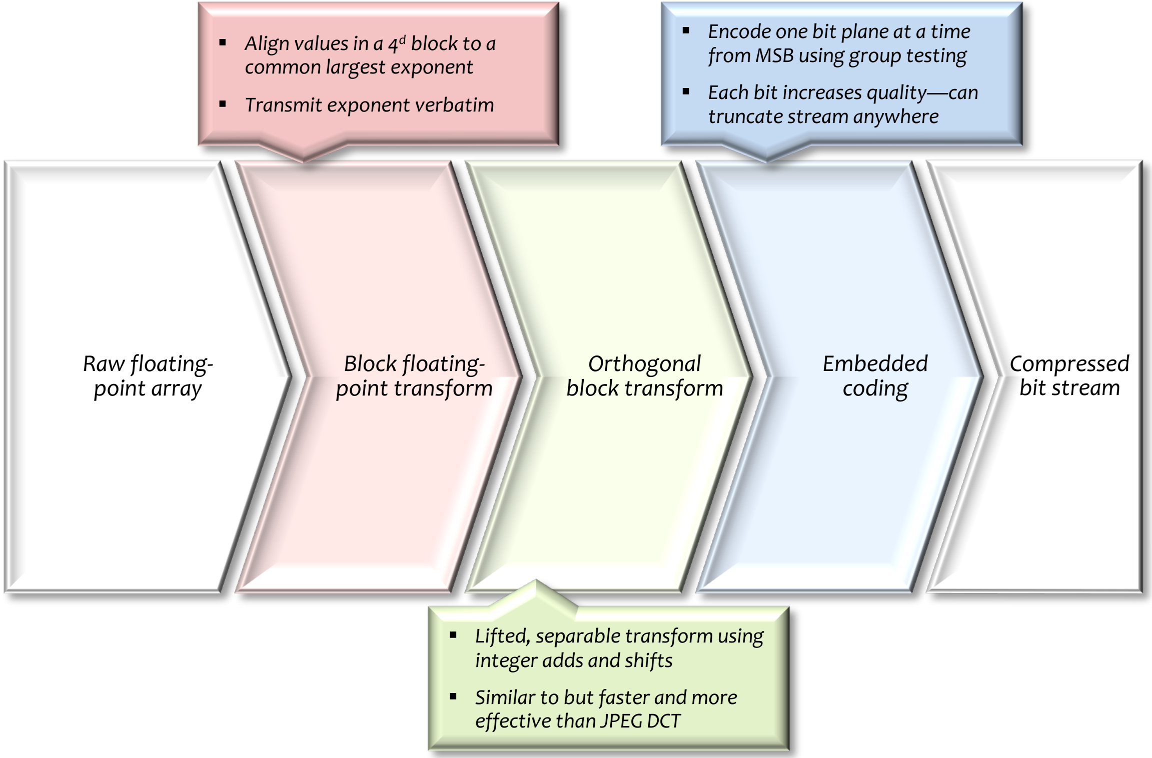
```
zfp::array2<double> u(nx, ny, bits_per_value);
u(x0, y0) = 1;
for (double t = 0; t < tfinal; t += dt) {
    zfp::array2<double> du(nx, ny, bits_per_value);
    for (int y = 1; y < ny - 1; y++)
        for (int x = 1; x < nx - 1; x++) {
            double uxx = (u(x-1, y) - 2*u(x, y) + u(x+1, y)) / dxx;
            double uyy = (u(x, y-1) - 2*u(x, y) + u(x, y+1)) / dyy;
            du(x, y) = k * dt * (uxx + uyy);
        }
    for (int i = 0; i < u.size(); i++)
        u[i] += du[i];
}
```

- required changes
- optional changes for improved readability

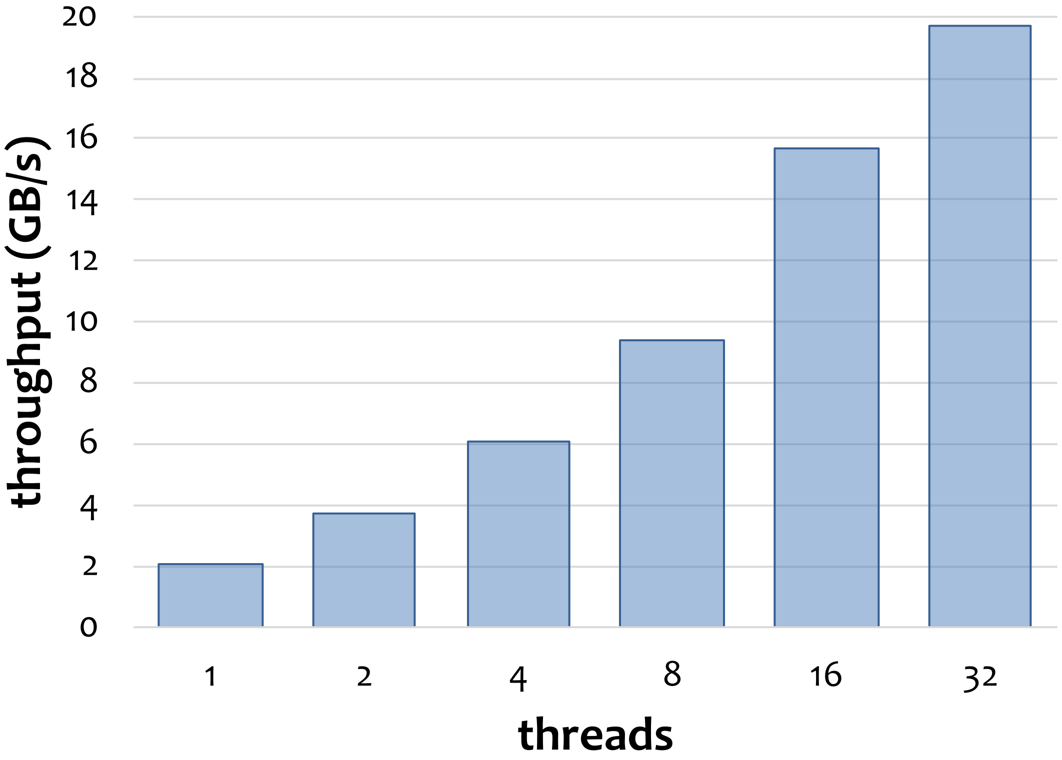
ZFP arrays limit data loss via a small write-back cache



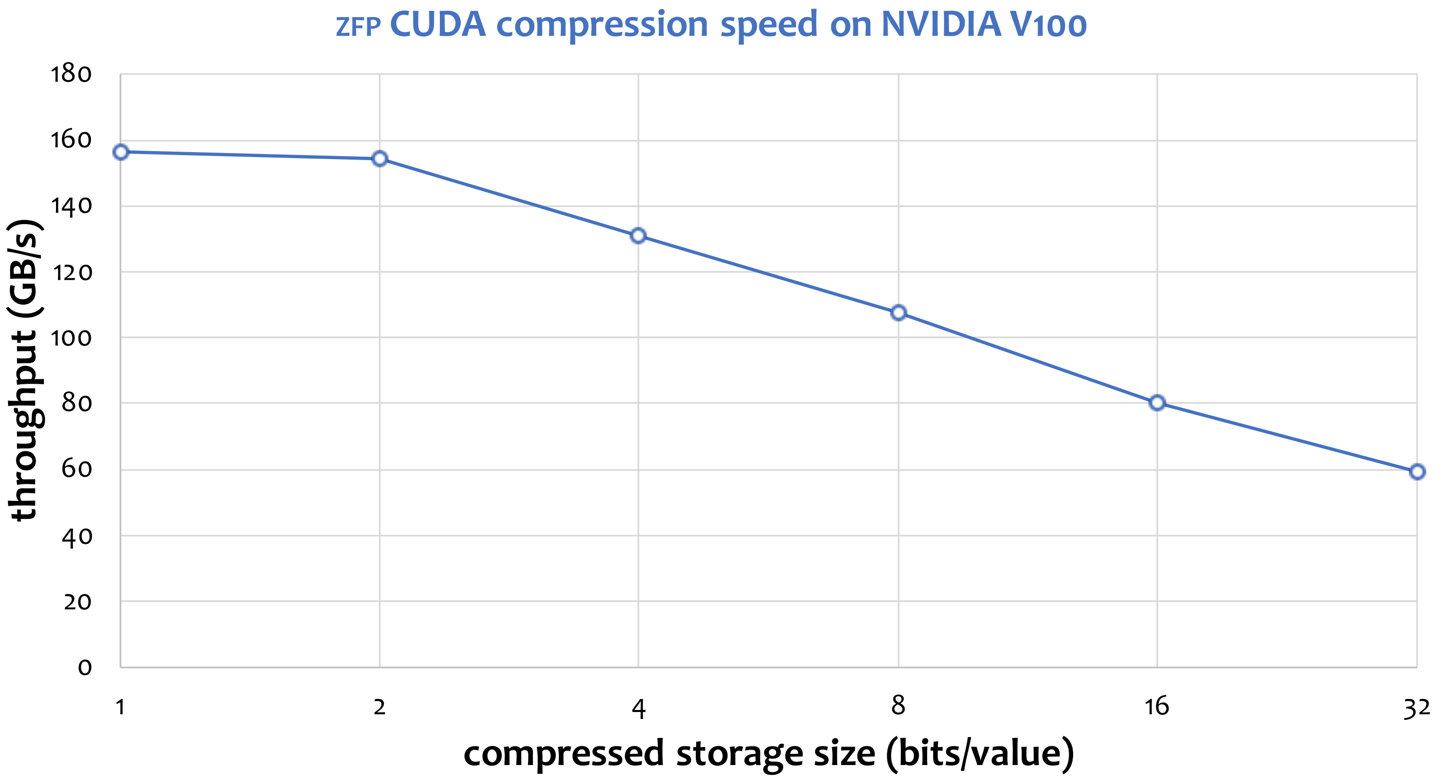
The ZFP compressor is comprised of three distinct components



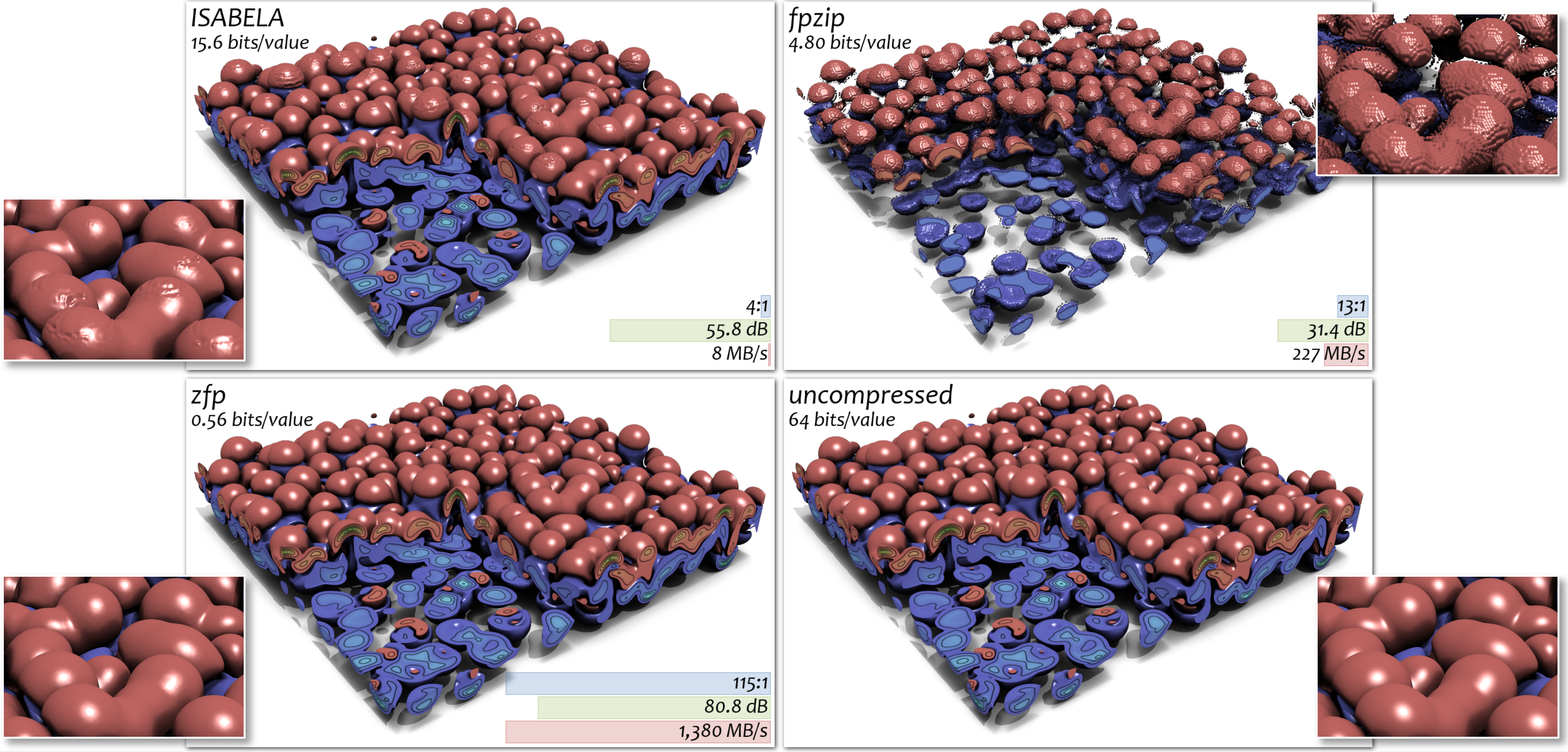
ZFP OpenMP compression achieves up to 20 GB/s throughput



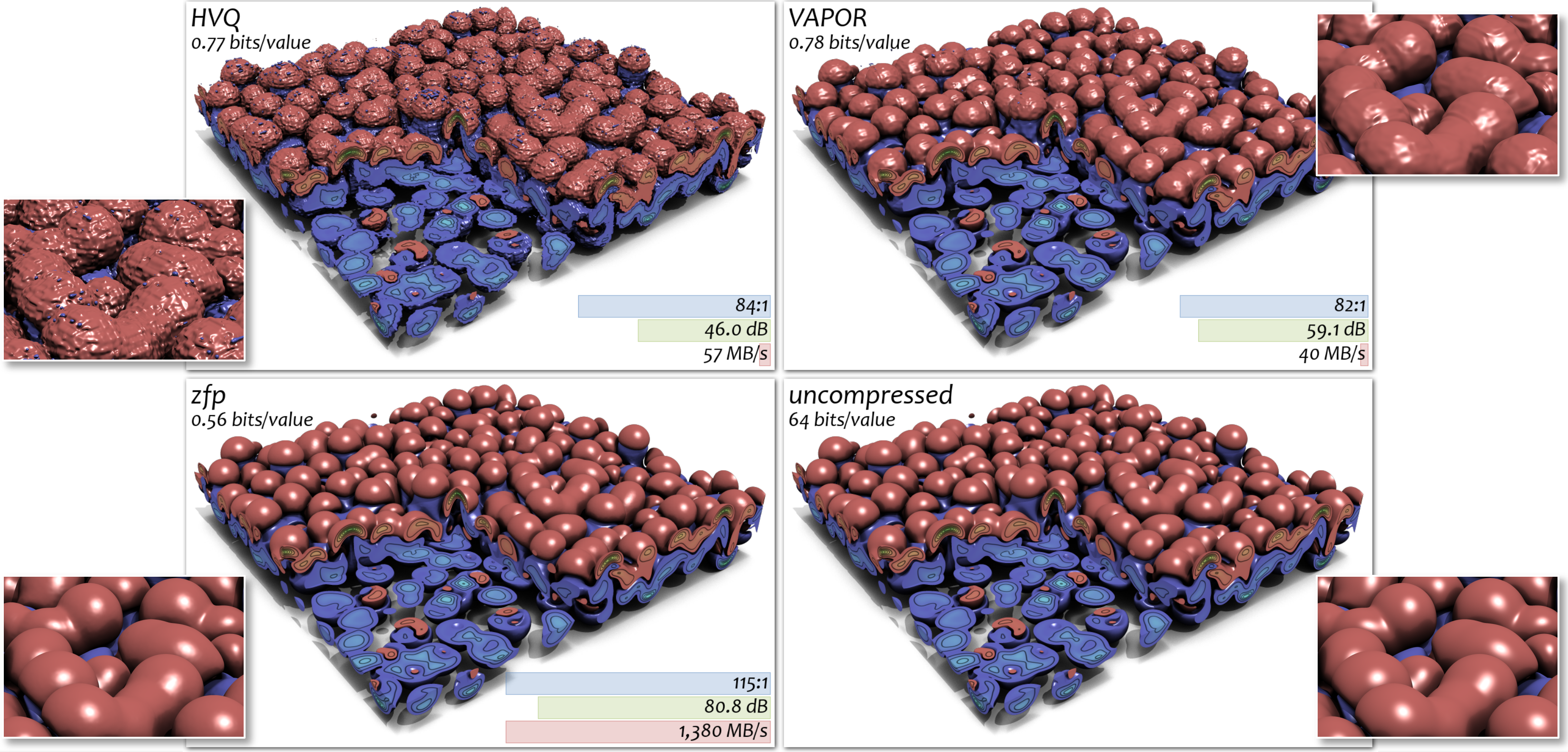
ZFP CUDA compression achieves up to 150 GB/s throughput



ZFP provides >100x compression with imperceptible loss in visual quality



ZFP provides >100x compression with imperceptible loss in visual quality



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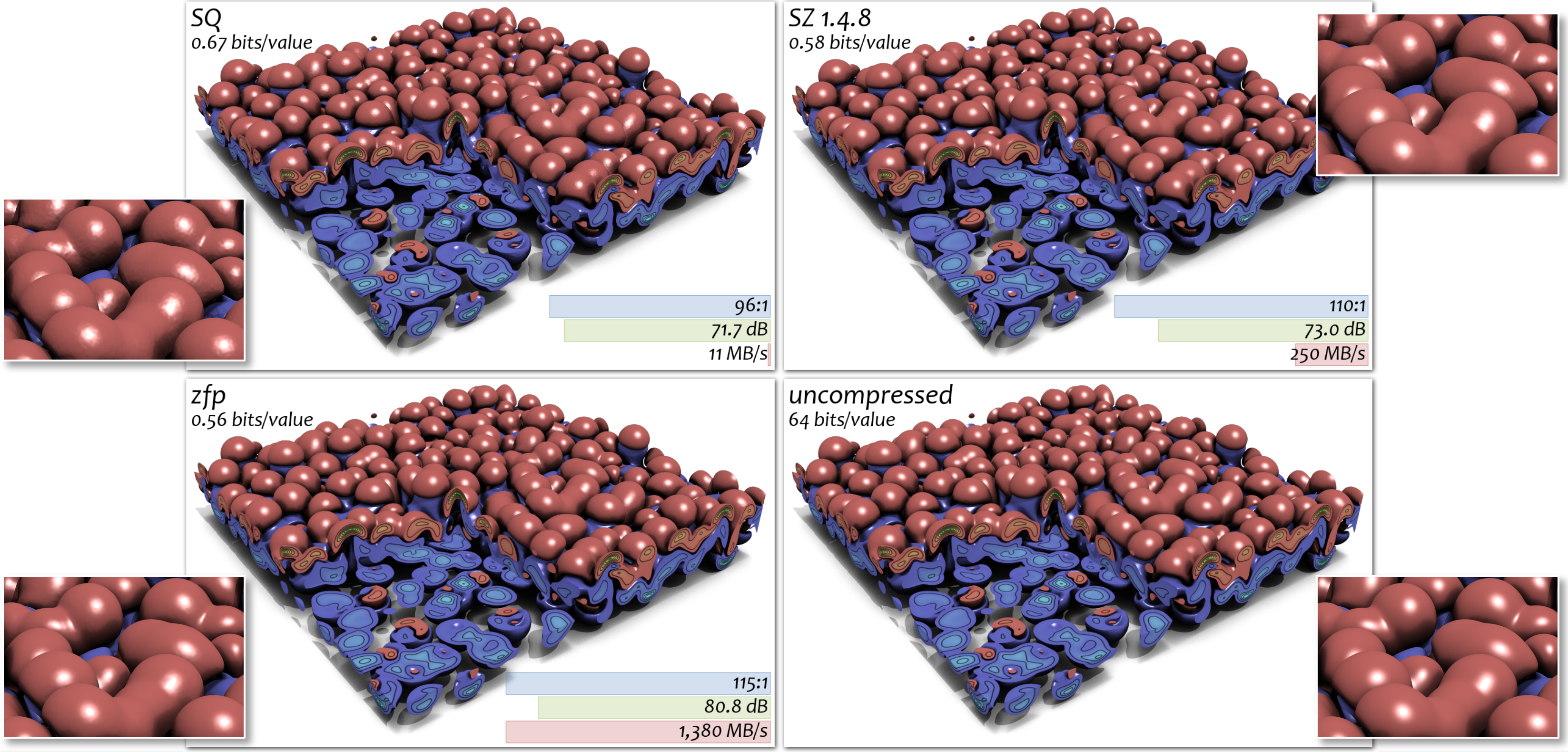
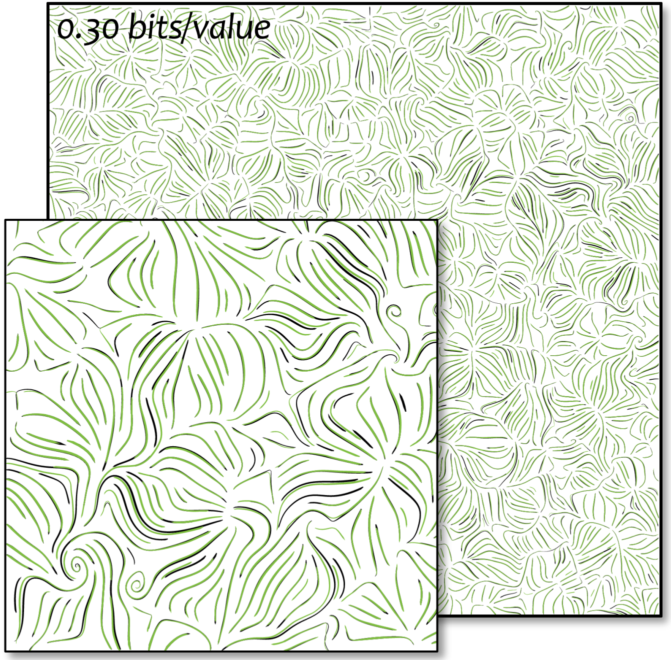
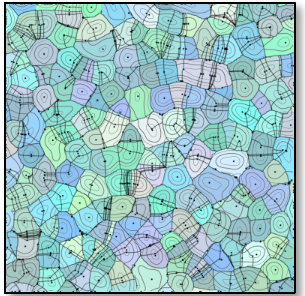


Got artifacts?

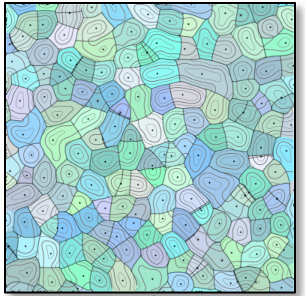
Velocity field Runge-Kutta integration shows good agreement with uncompressed field



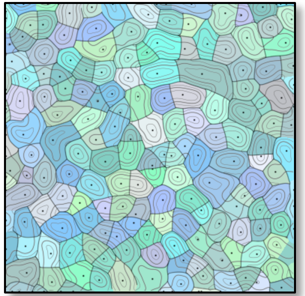
Morse segmentation at 16x compression shows lack of blocking artifacts



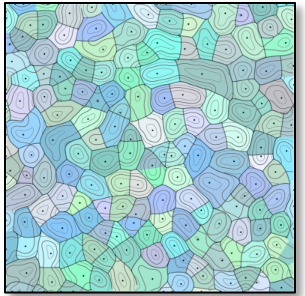
1 bit/value



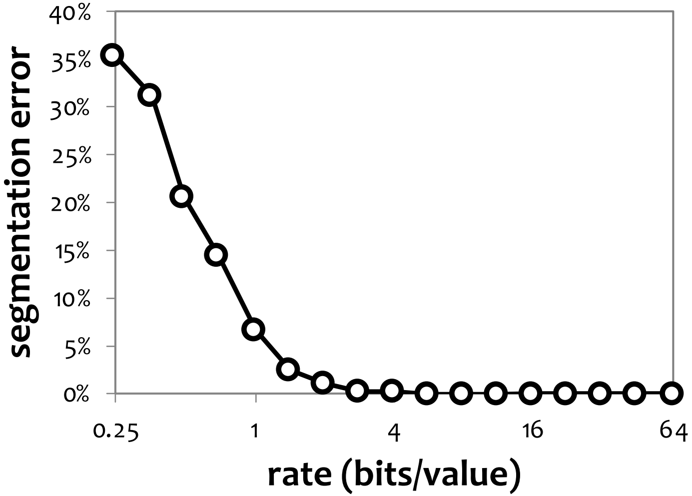
2 bits/value



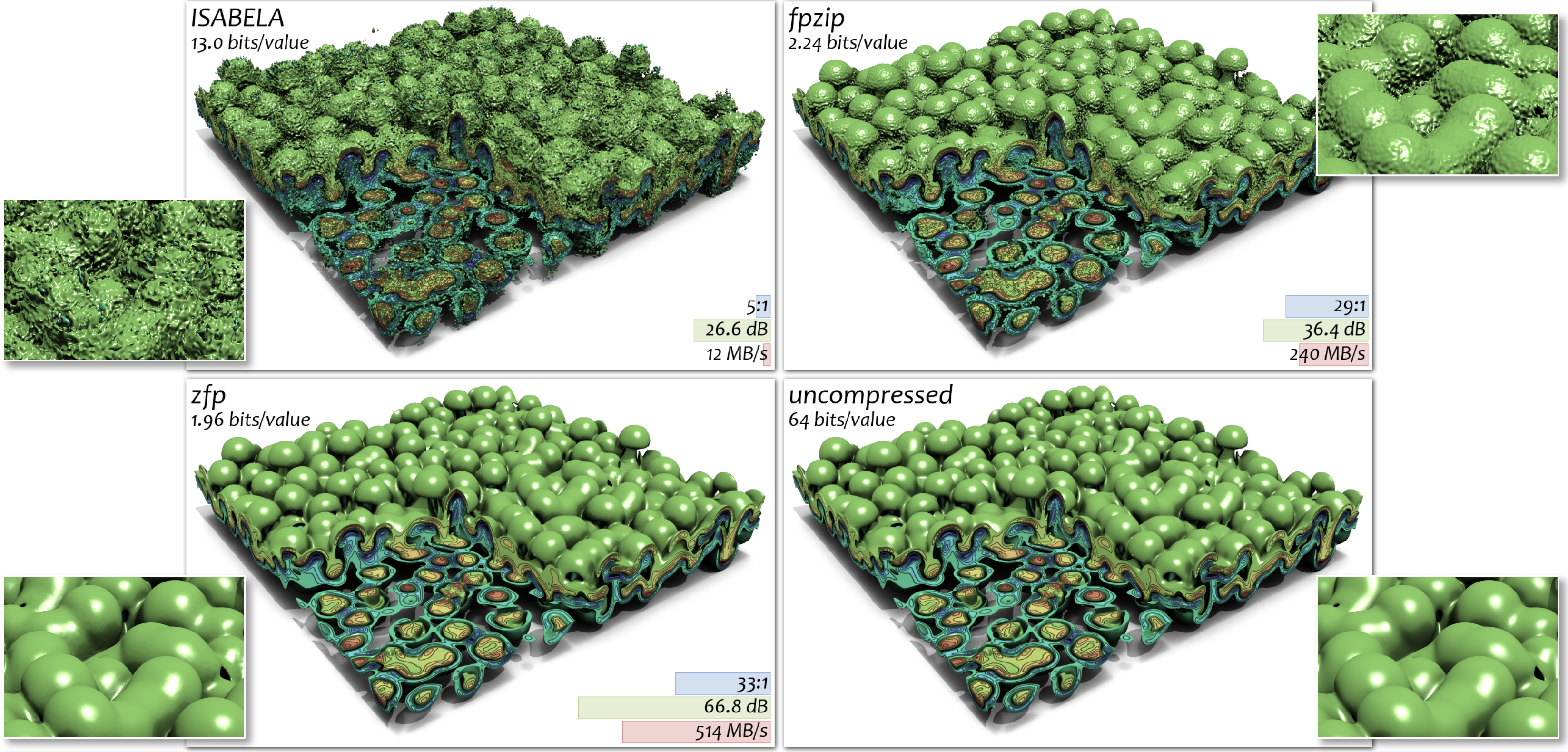
4 bits/value



64 bits/value



ZFP shows no artifacts in derivative computations (velocity divergence)



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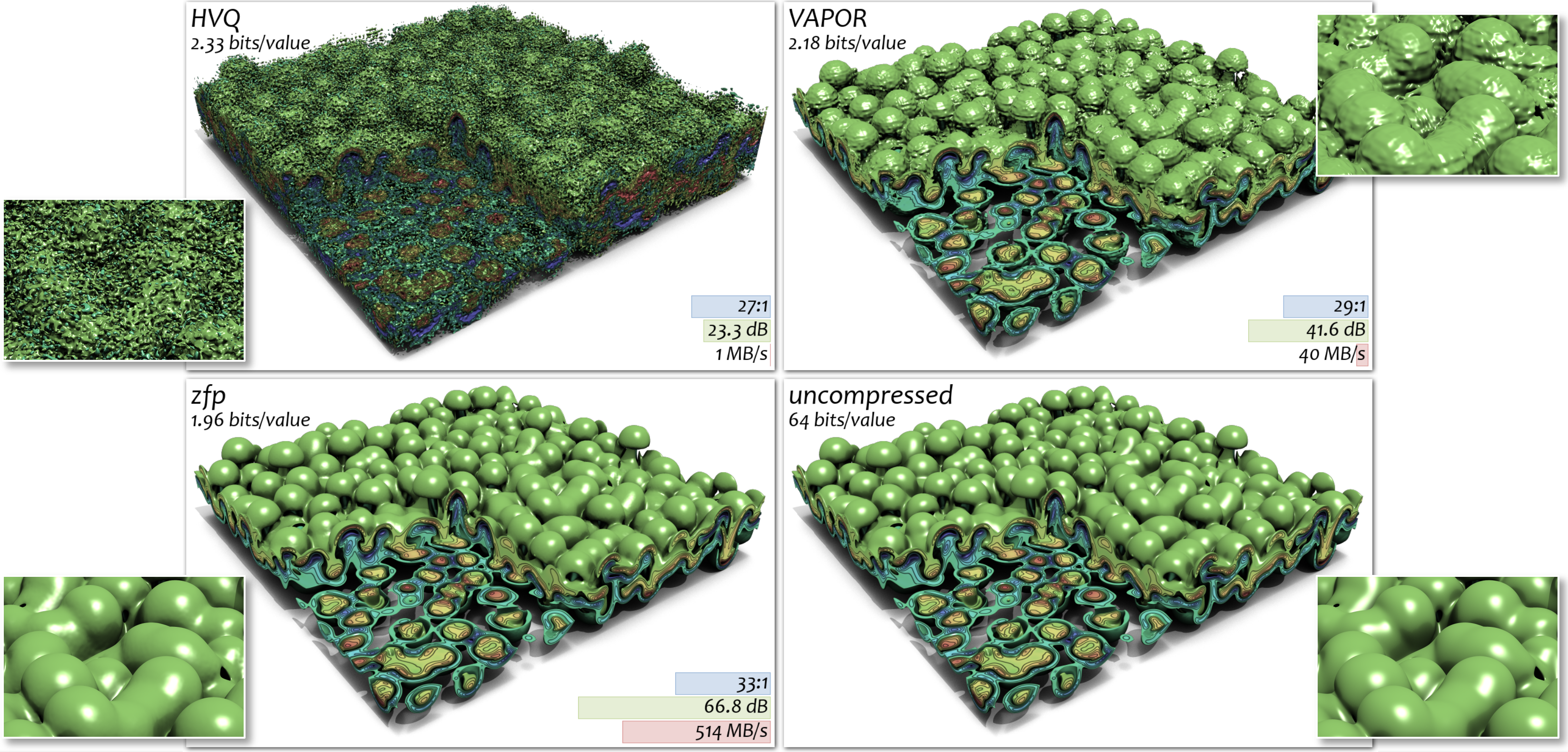
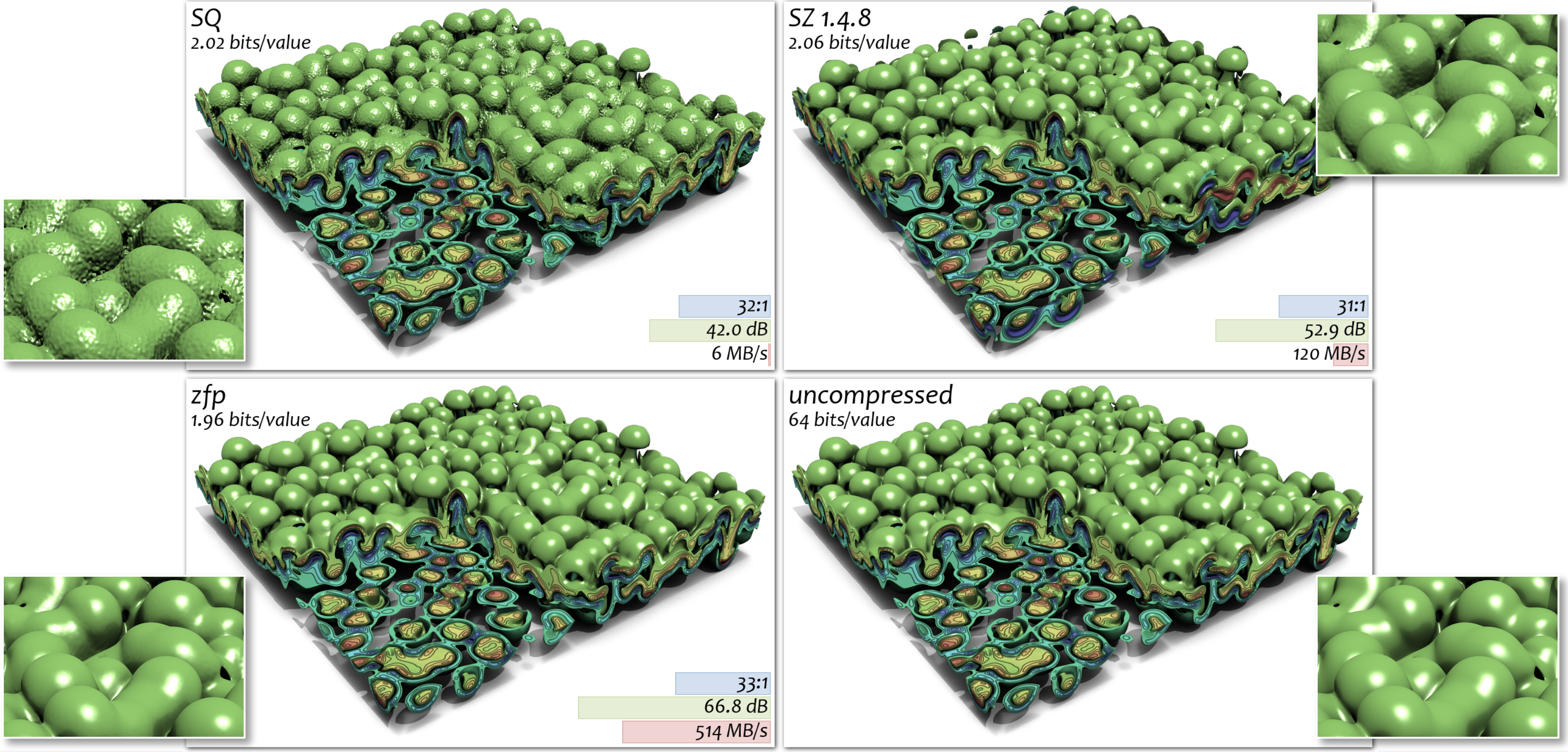
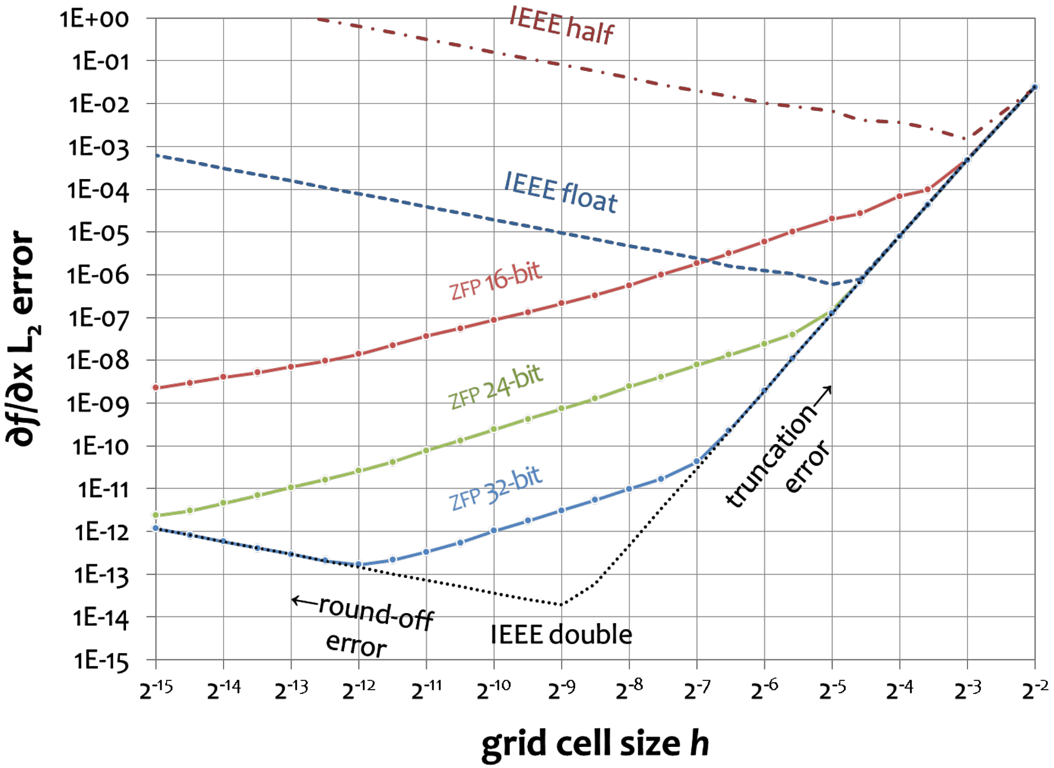


ZFP shows no artifacts in derivative computations (velocity divergence)

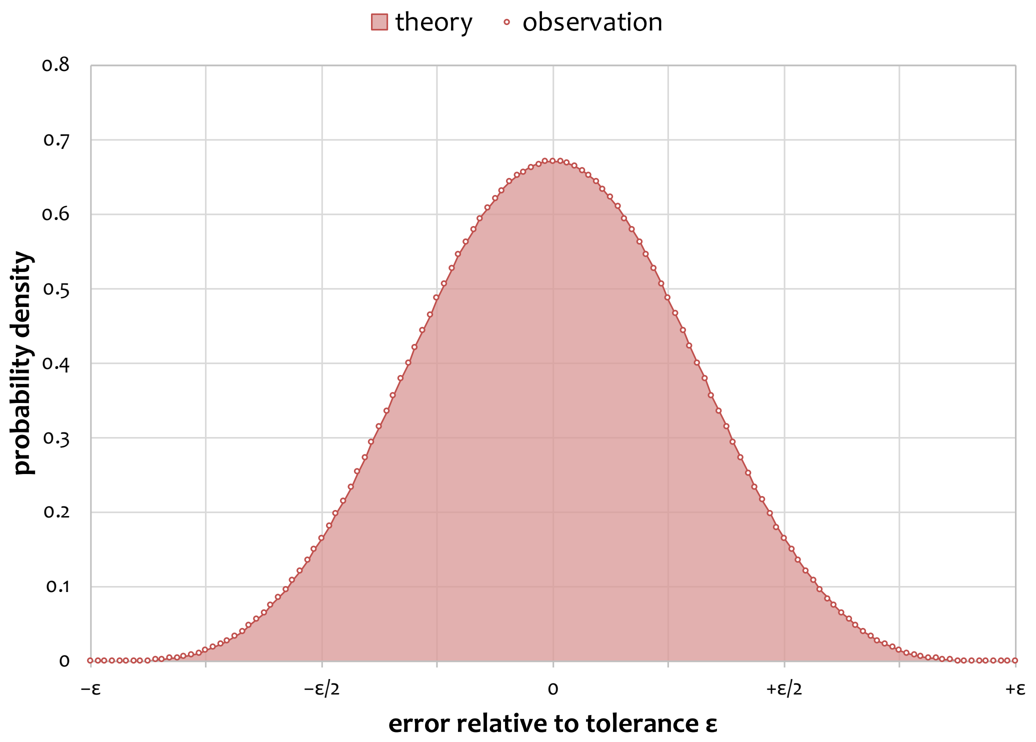


6-bit ZFP gives one more digit of accuracy than 32-bit IEEE in 2nd, 3rd derivative computations (Laplacian and highlight lines)

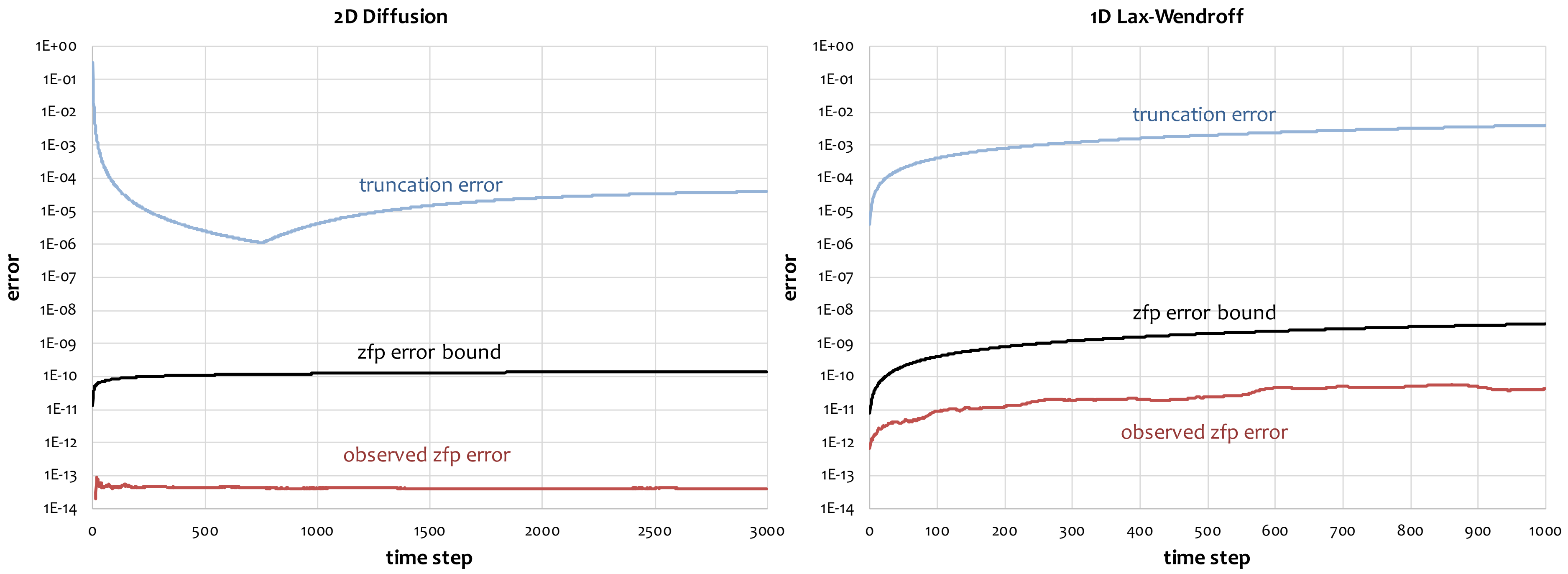
ZFP *improves* accuracy in finite difference computations using less precision than IEEE



ZFP compression errors are well behaved and follow a normal distribution

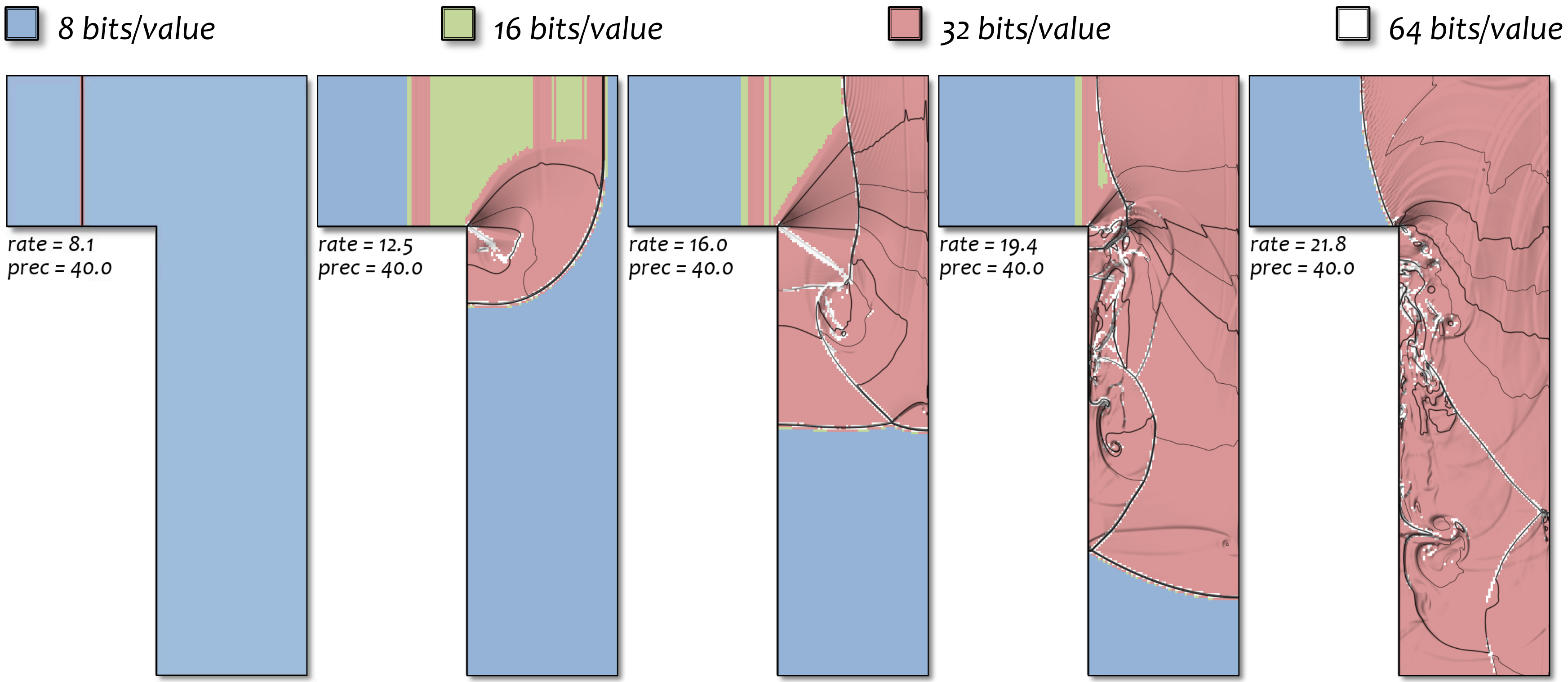


We have developed rigorous error bounds for ZFP, both for static data and in iterative methods

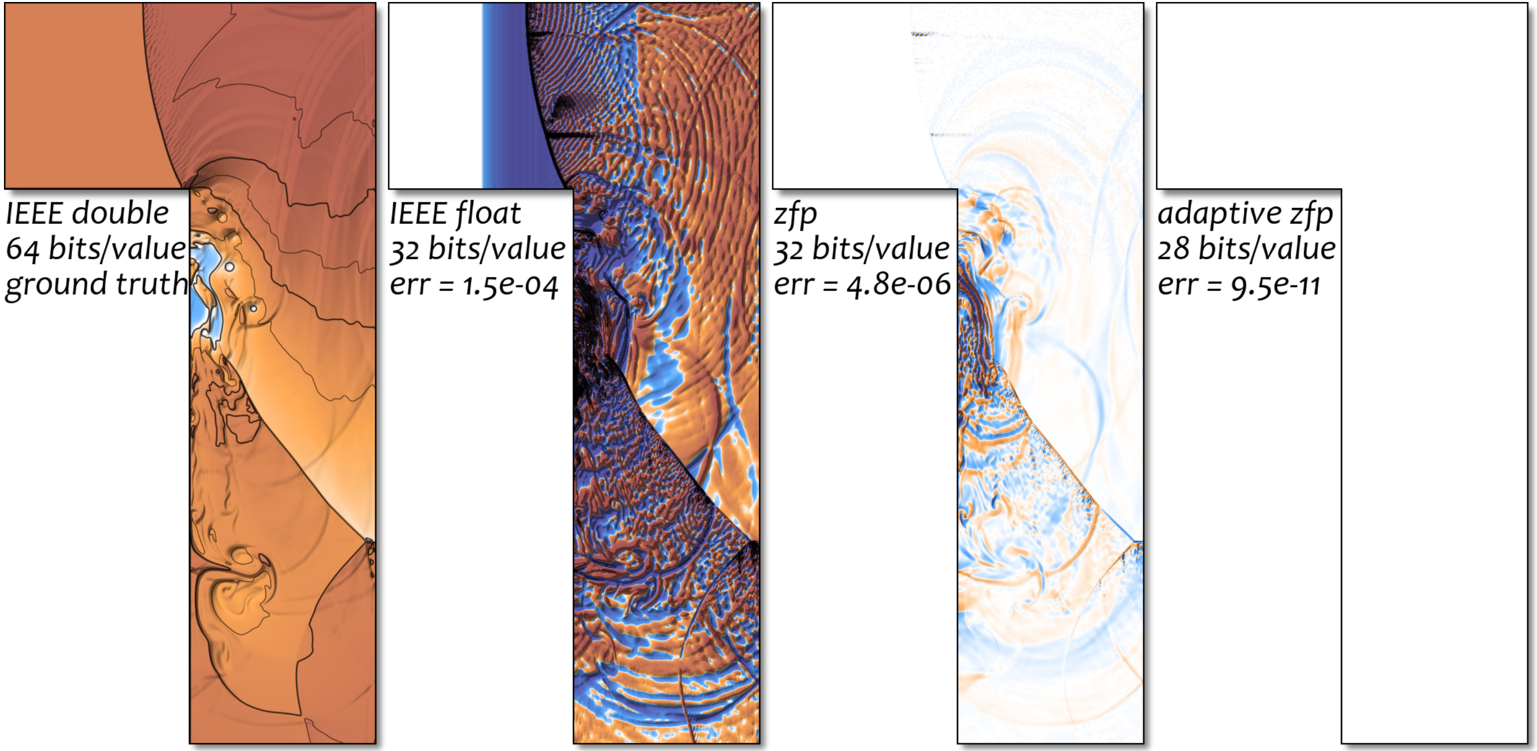


[Diffenderfer et al., "Error Analysis of ZFP Compression for Floating-Point Data," SIAM Journal on Scientific Computing, 2019]

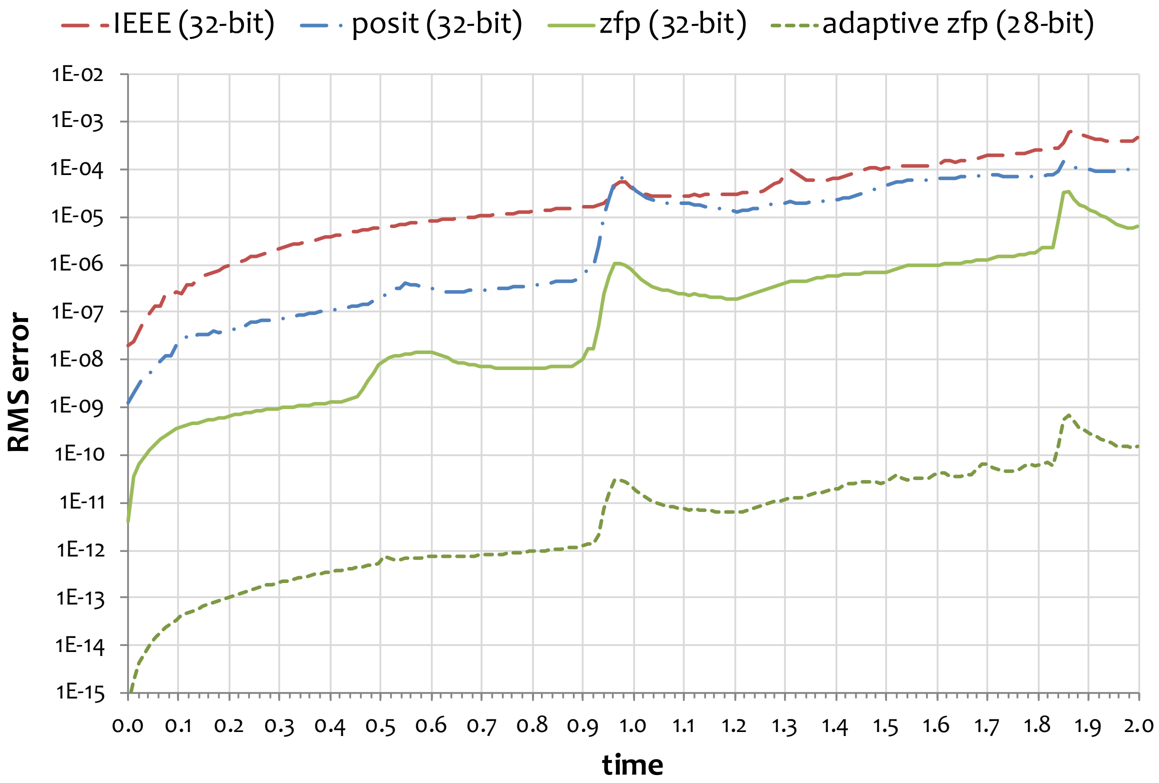
ZFP variable-rate arrays adapt storage spatially and allocate bits to regions where they are most needed



ZFP adaptive arrays improve accuracy in PDE solution over IEEE by 6 orders of magnitude using less storage

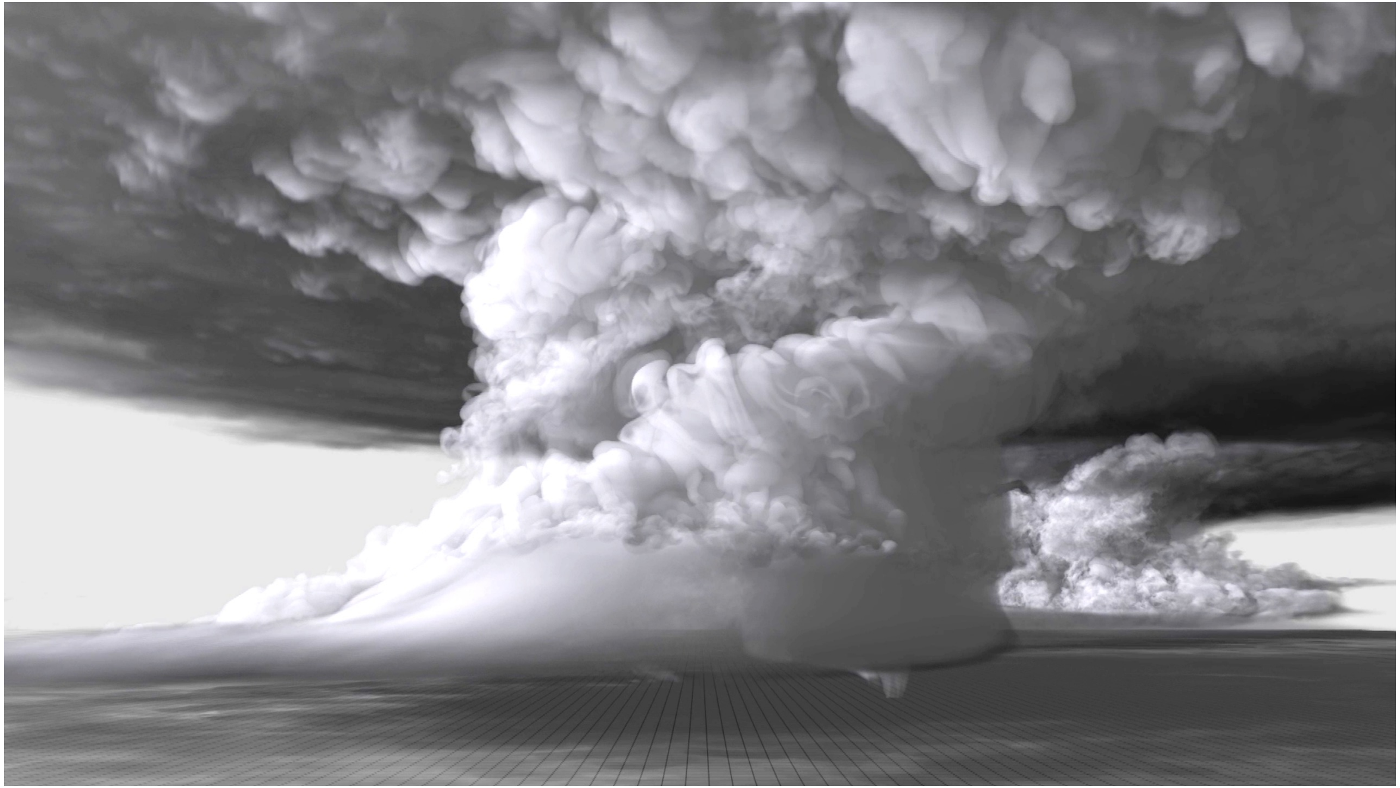


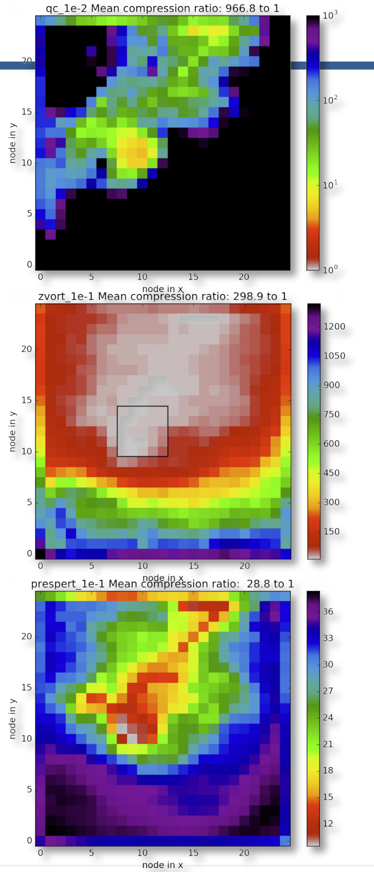
Adaptive-rate ZFP increases accuracy over IEEE float by 6 orders of magnitude while using less storage



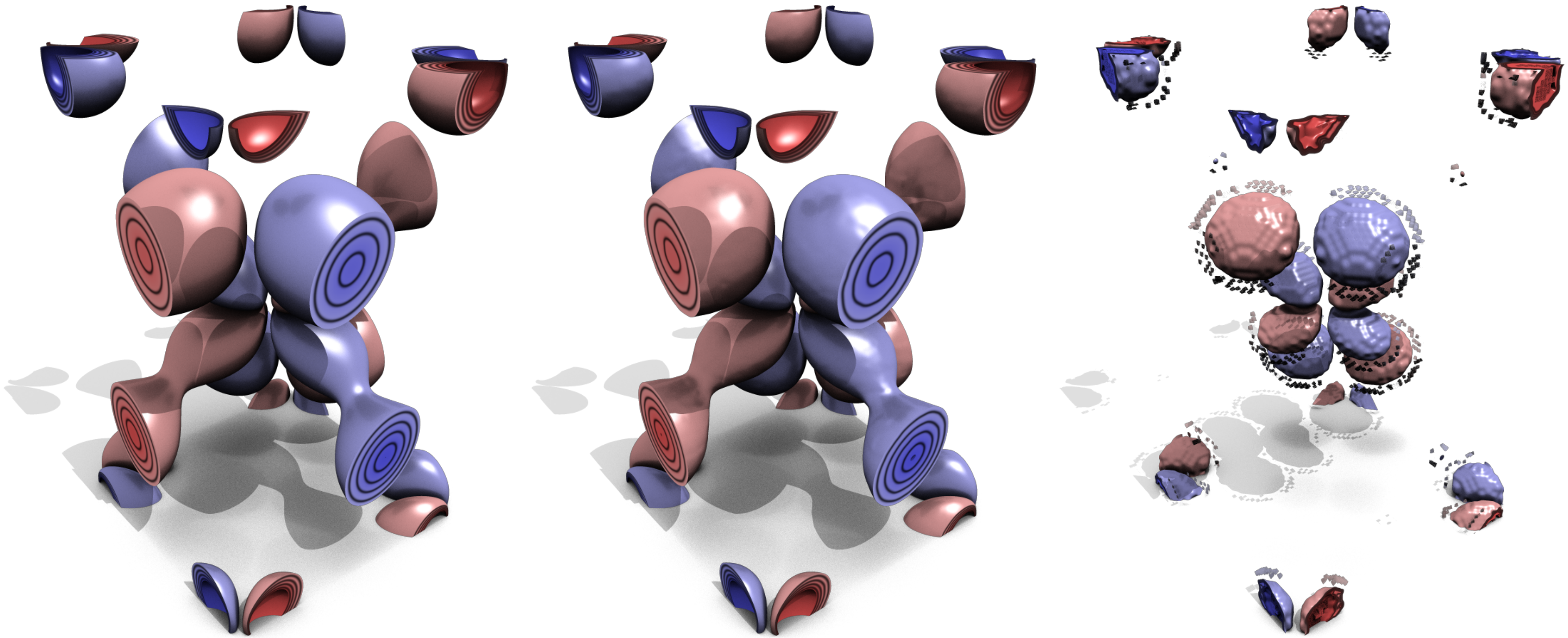
I/O Compression: ZFP reduces I/O by 30x on average in CM1

[Work done by Leigh Orf, UW-Madison]



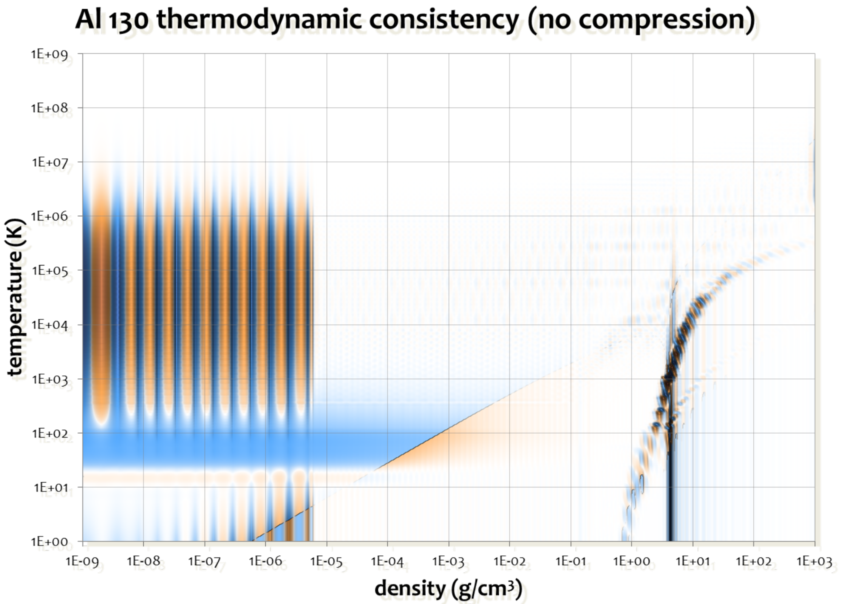


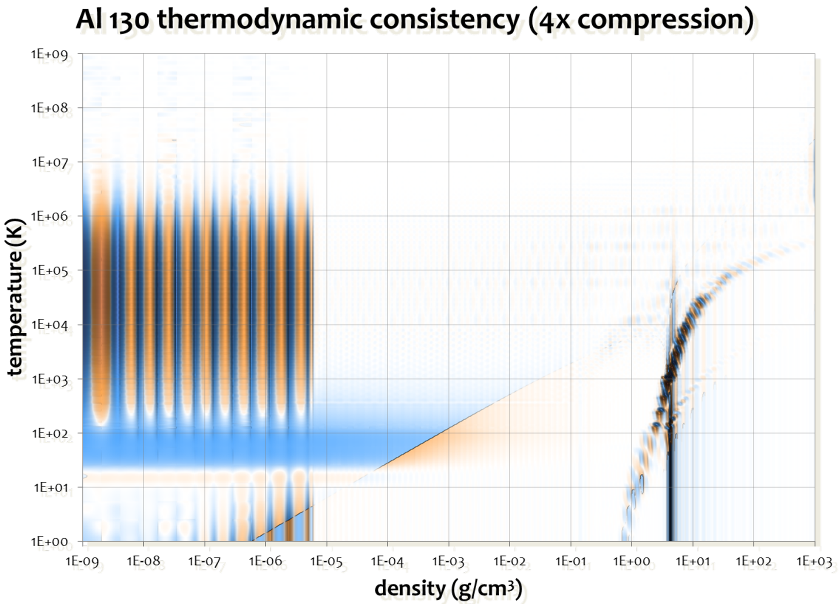
Tabular data: Compressed, pre-computed wavefunctions enable reduced memory footprint in QMCPACK code



uncompressed (32 bits/value) ZFP (1 bit/value) FPZIP (1 bit/value)

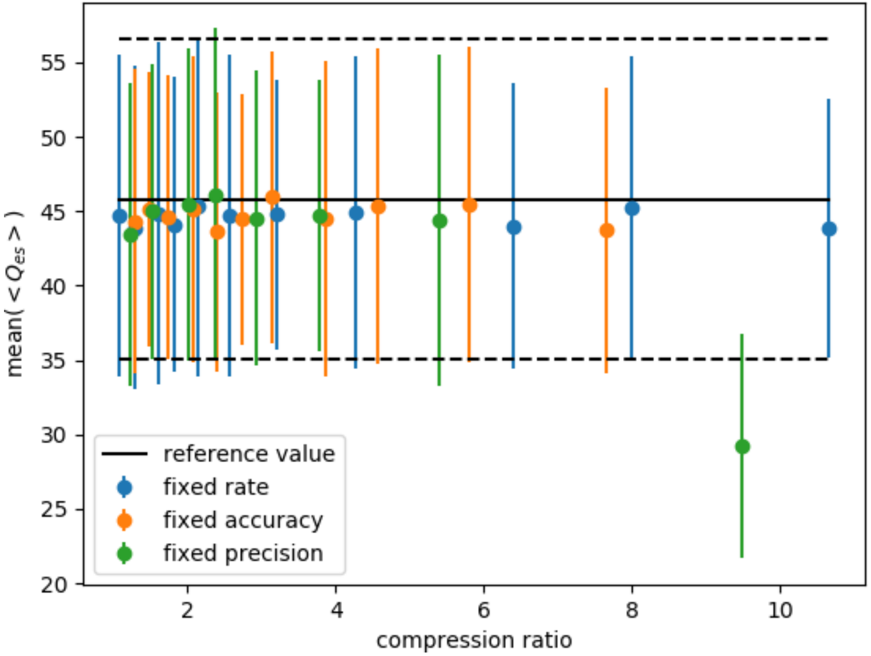
Tabular data: LEOS library reduces memory footprint of equation-of-state tables by 4-8x using ZFP

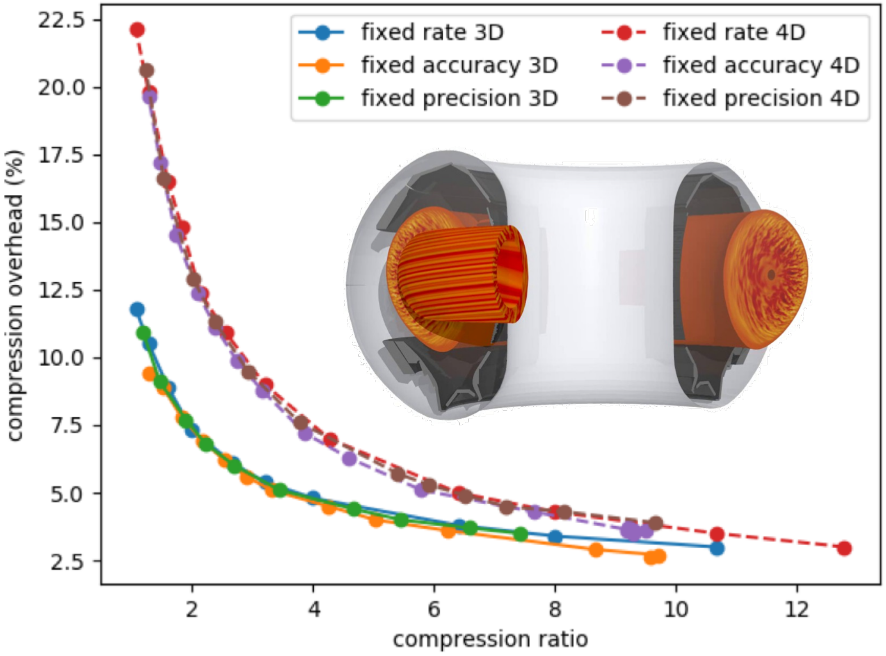




Inline compression: ZFP reduces 5D simulation state in GENE fusion code by 10x with acceptable loss in accuracy

[Work by Denis Jarema & Frank Jenko, MPI]

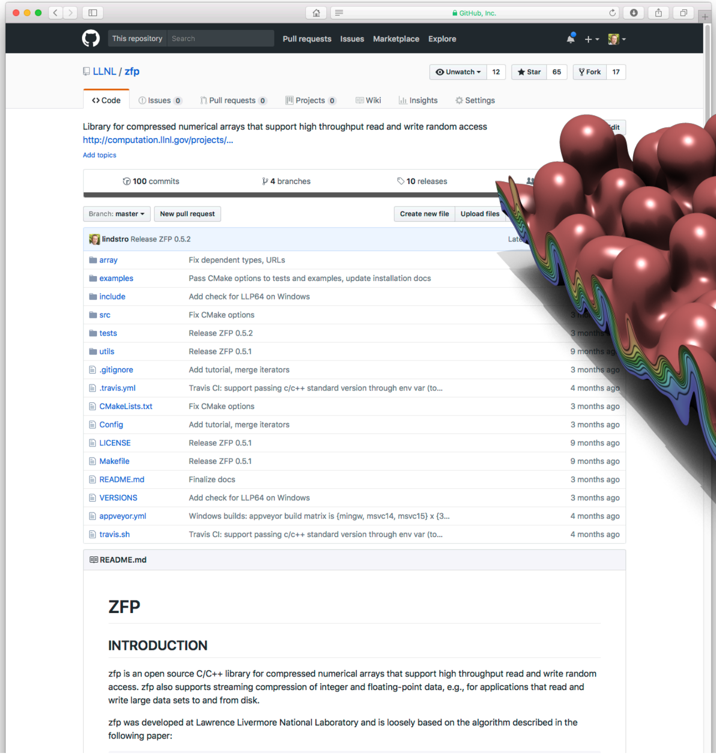


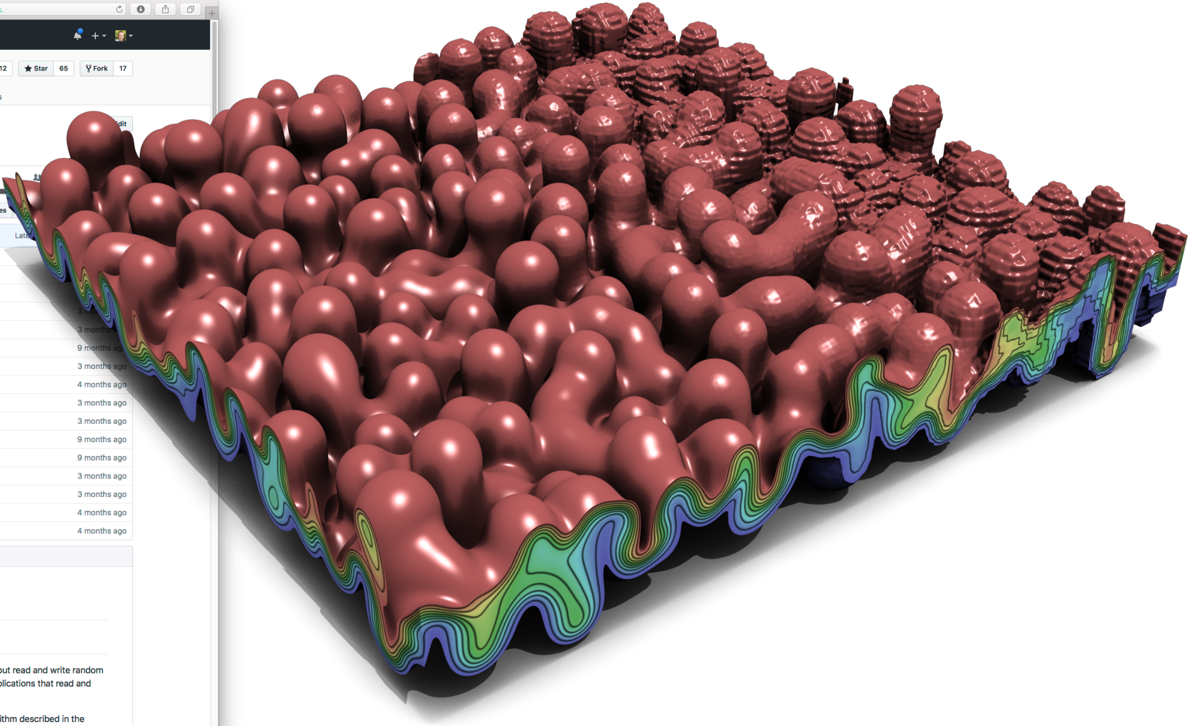


ZFP compression is available in I/O libraries and viz tools

- Registered compression filter in **HDF5**
  - H5Z-ZFP plugin: https://github.com/LLNL/H5Z-ZFP
- Available in **ADIOS** I/O library since version 1.11
  - AtoZ = ADIOS + ZFP: https://github.com/suchyta1/AtoZ
- Third-party I/O library in **VTK**
  - https://gitlab.kitware.com/third-party/zfp
- AVX implementation in **Intel IPP**
  - https://software.intel.com/ipp-dev-reference
- Available in **VTK-m** since December 2018
  - http://m.vtk.org/images/c/c8/VTKmUsersGuide.pdf

ZFP is BSD licensed and available on GitHub: https://github.com/LLNL/zfp





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