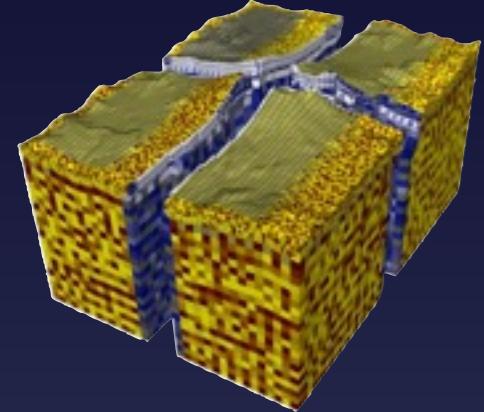
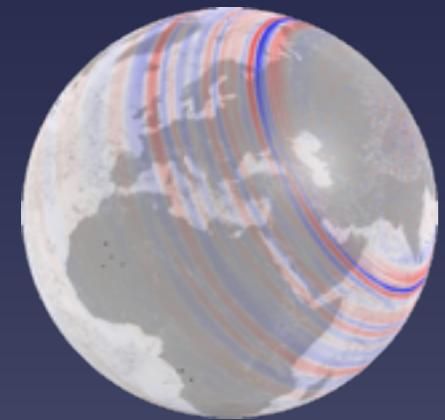


SPECFEM3D codes



SPECFEM3D_Cartesian



SPECFEM3D_GLOBE

Spectral-element method

Equation of motion:

$$\rho \partial_t^2 \mathbf{s} - \nabla \cdot \mathbf{T} = \mathbf{f}$$

Weak form:

$$\int_{\Omega} \rho \mathbf{w} \cdot \partial_t^2 \mathbf{s} d^3x = \int_{\Omega} \nabla \mathbf{w} : \mathbf{T} d^3x + \mathbf{M} : \nabla \mathbf{w}(\mathbf{x}_s) S(t)$$

- implicitly accounts for free-surface boundary condition
- fluid-solid coupling terms may be explicitly added

Spectral-element method

Weak-form of the elastodynamic momentum equation:

$$\int_{\Omega} [\rho \mathbf{w} \cdot \partial_t^2 \mathbf{u} + \nabla \mathbf{w} : \mathbf{C} : \nabla \mathbf{u}] d^3 \mathbf{x} = \int_{\Omega} \mathbf{w} \cdot \mathbf{f} d^3 \mathbf{x}$$

Continuous Galerkin discretization:

$$\mathbf{M} \ddot{\mathbf{u}}(t) + \mathbf{K} \mathbf{u}(t) = \mathbf{F}(t)$$

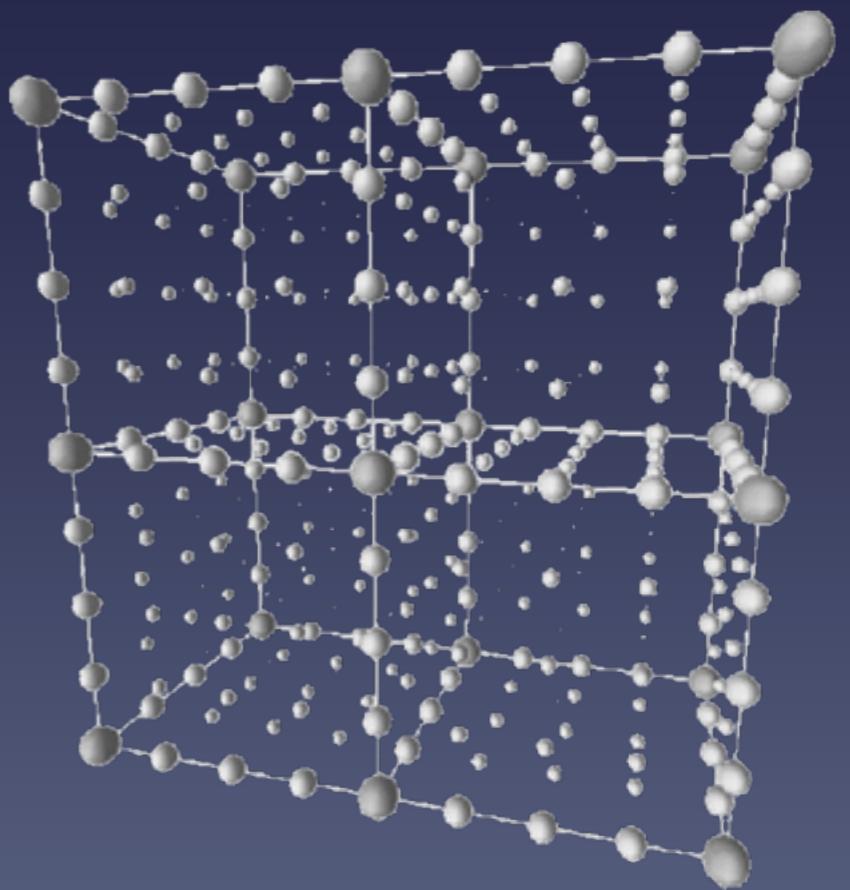
$$\ddot{\mathbf{u}} = -\mathbf{M}^{-1}(\mathbf{K} \mathbf{u} + \mathbf{F}) = \mathbf{B} \mathbf{u} + \tilde{\mathbf{F}}$$

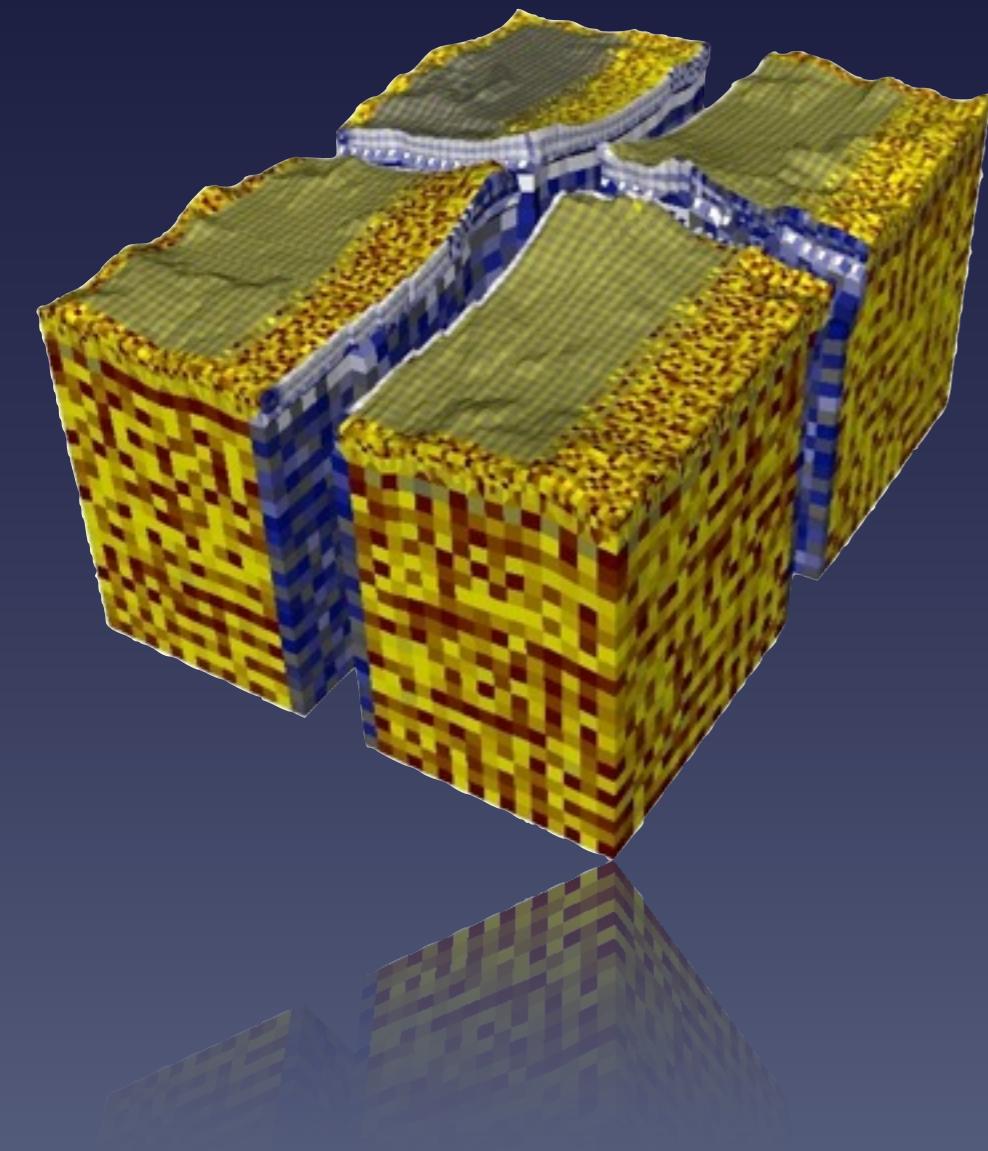
temporal: Newmark time scheme (2nd-order)

spatial : Gauss-Lobatto-Legendre (GLL) basis (4th-order)

Spectral-element method

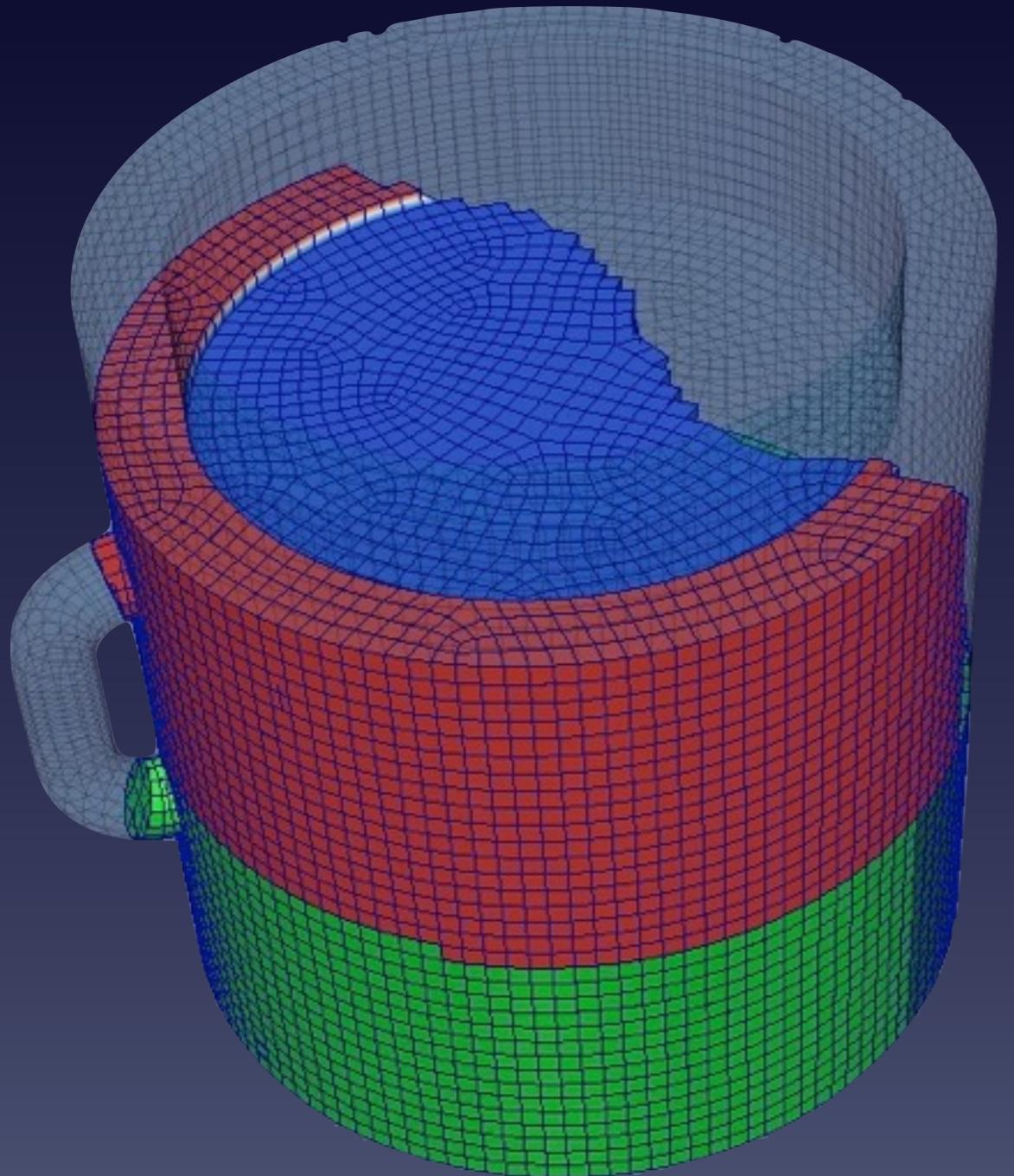
- hexahedral finite-elements
- Gauss-Lobatto-Legendre quadrature
- diagonal mass matrix
- explicit time-marching scheme



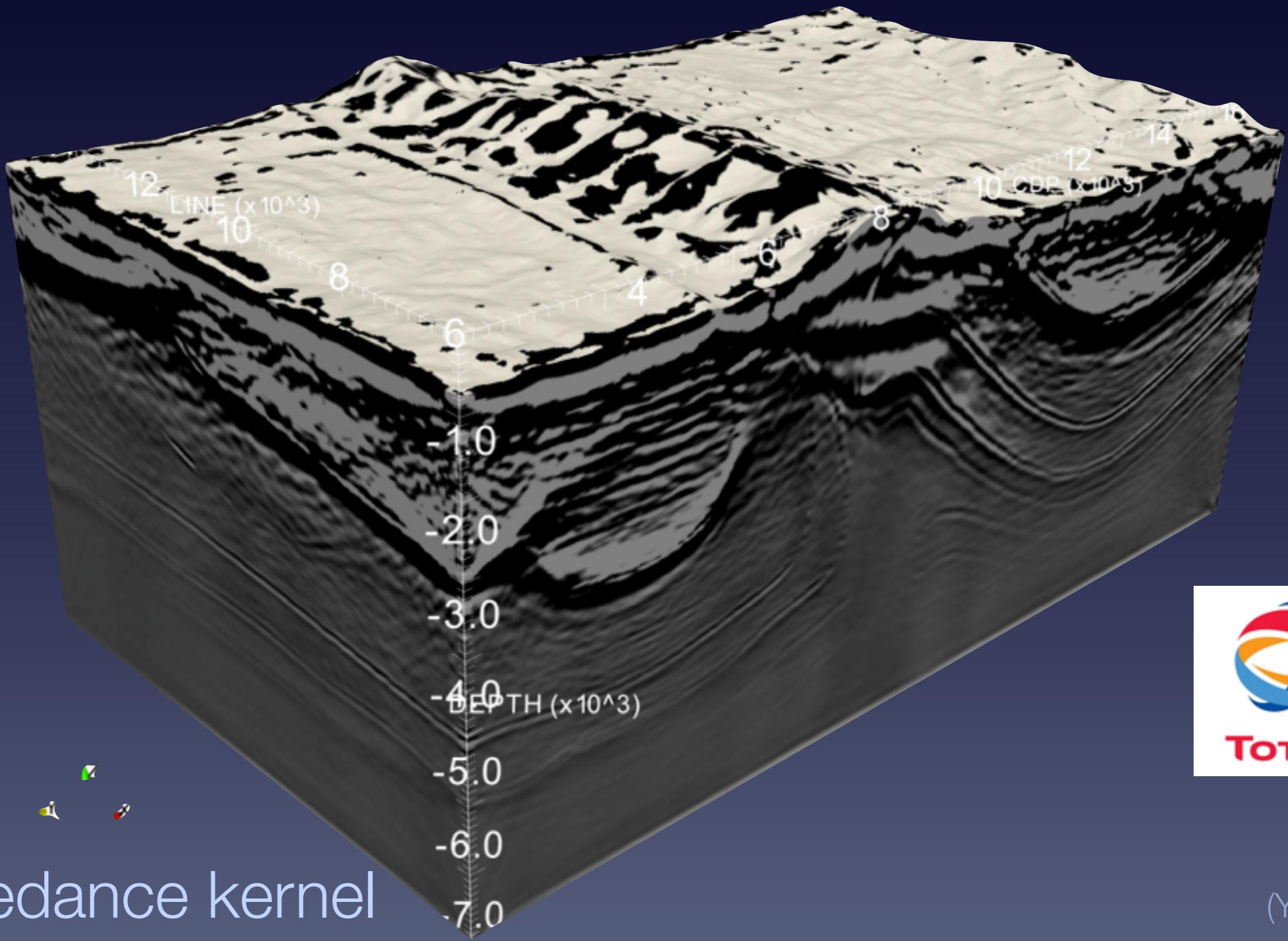


SPECFEM3D_Cartesian

SPECFEM3D



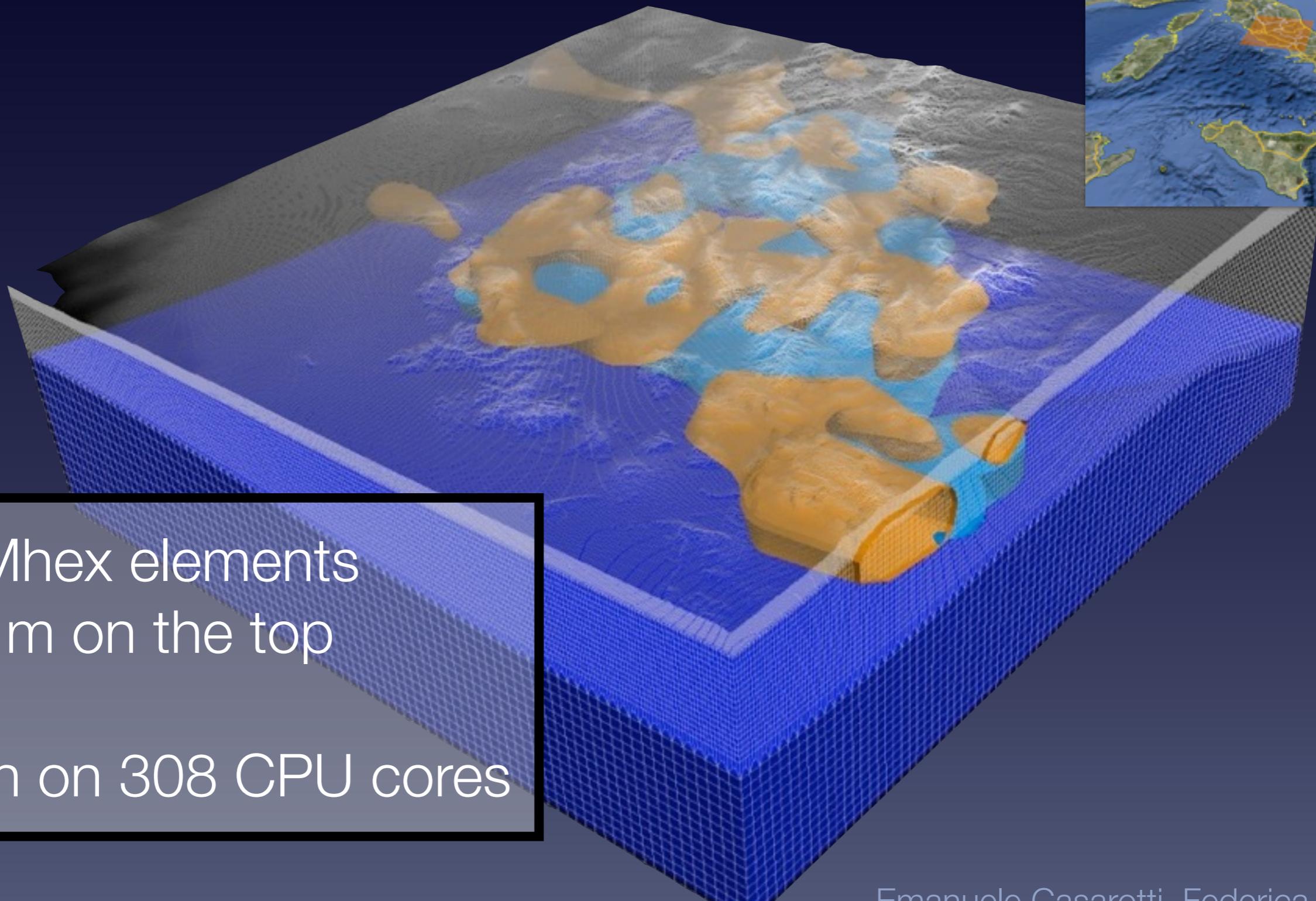
SPECFEM3D



Impedance kernel

(Yang Luo)

SPECFEM3D

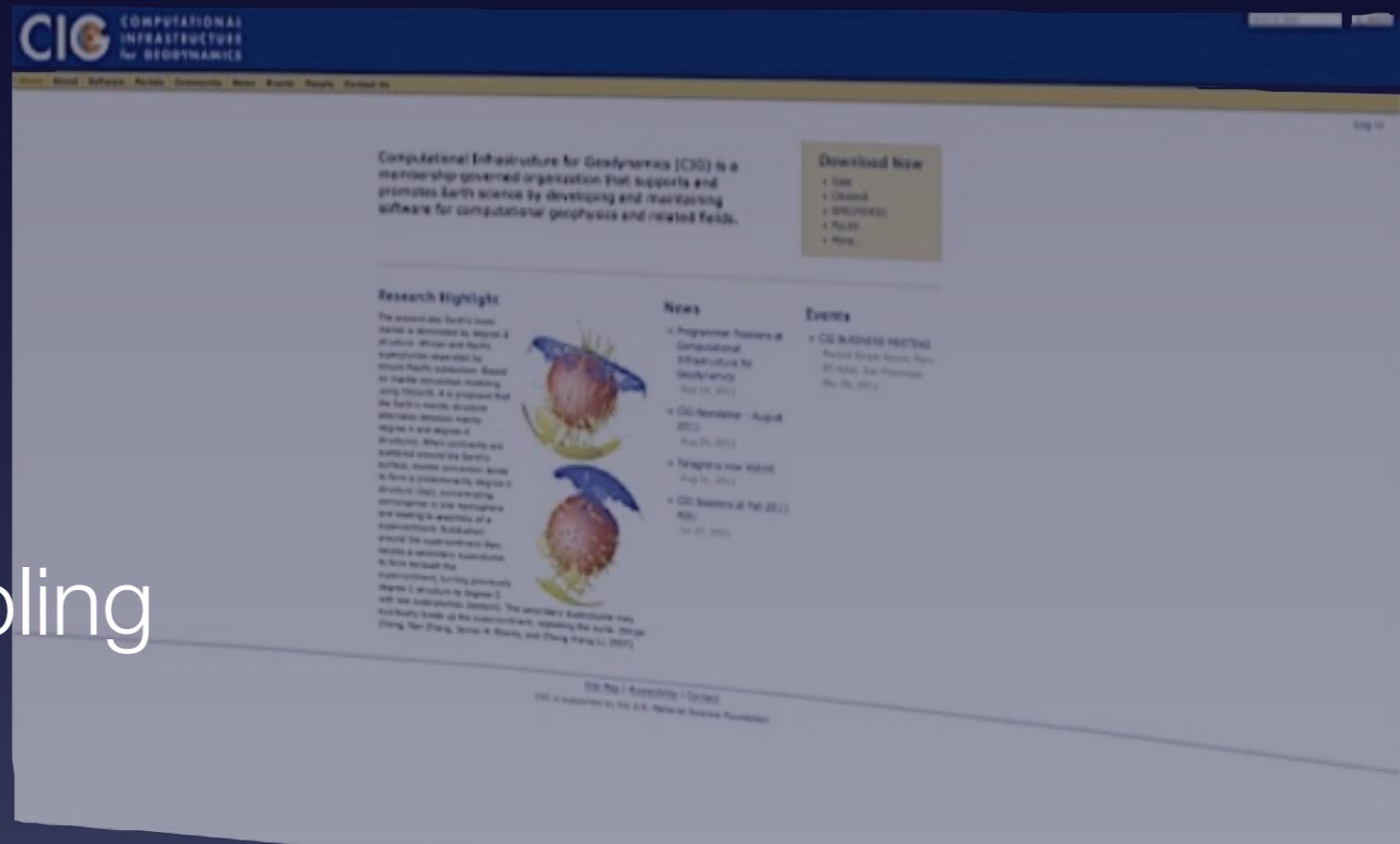


Emanuele Casarotti, Federica Magnoni
(INGV)

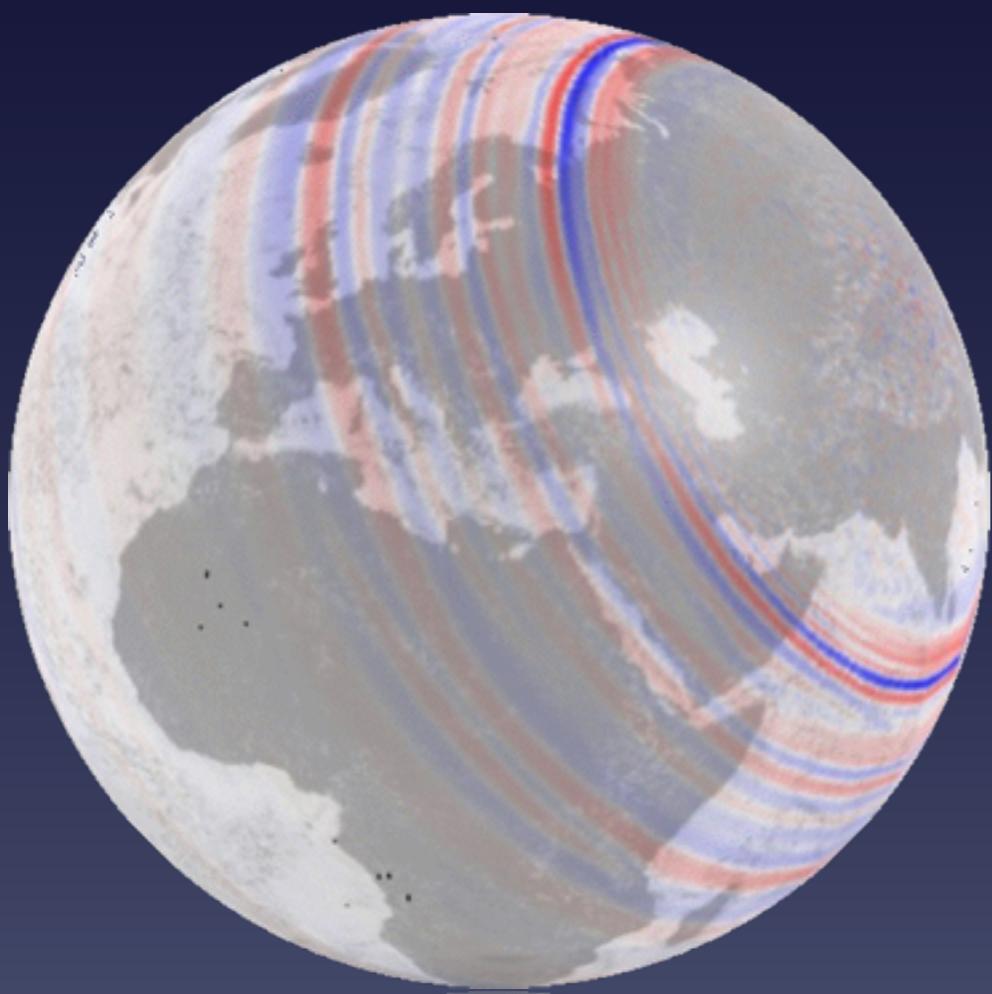
SPECFEM3D

Open-Source

- Unstructured meshes
- Load-balanced mesh partitioning
- Acoustic & Elastic coupling
- Anisotropy
- Attenuation
- Adjoint kernels

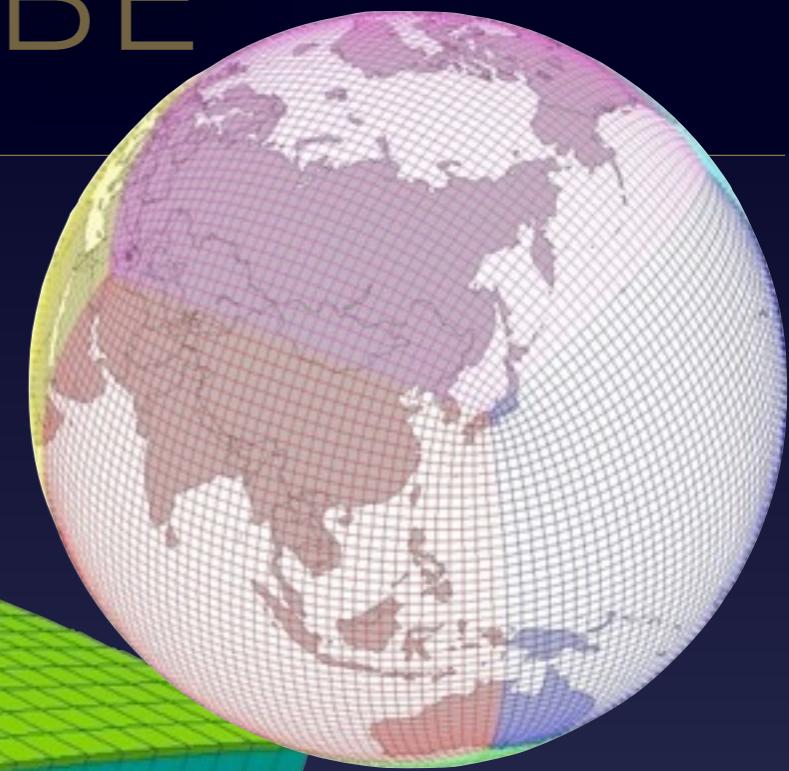
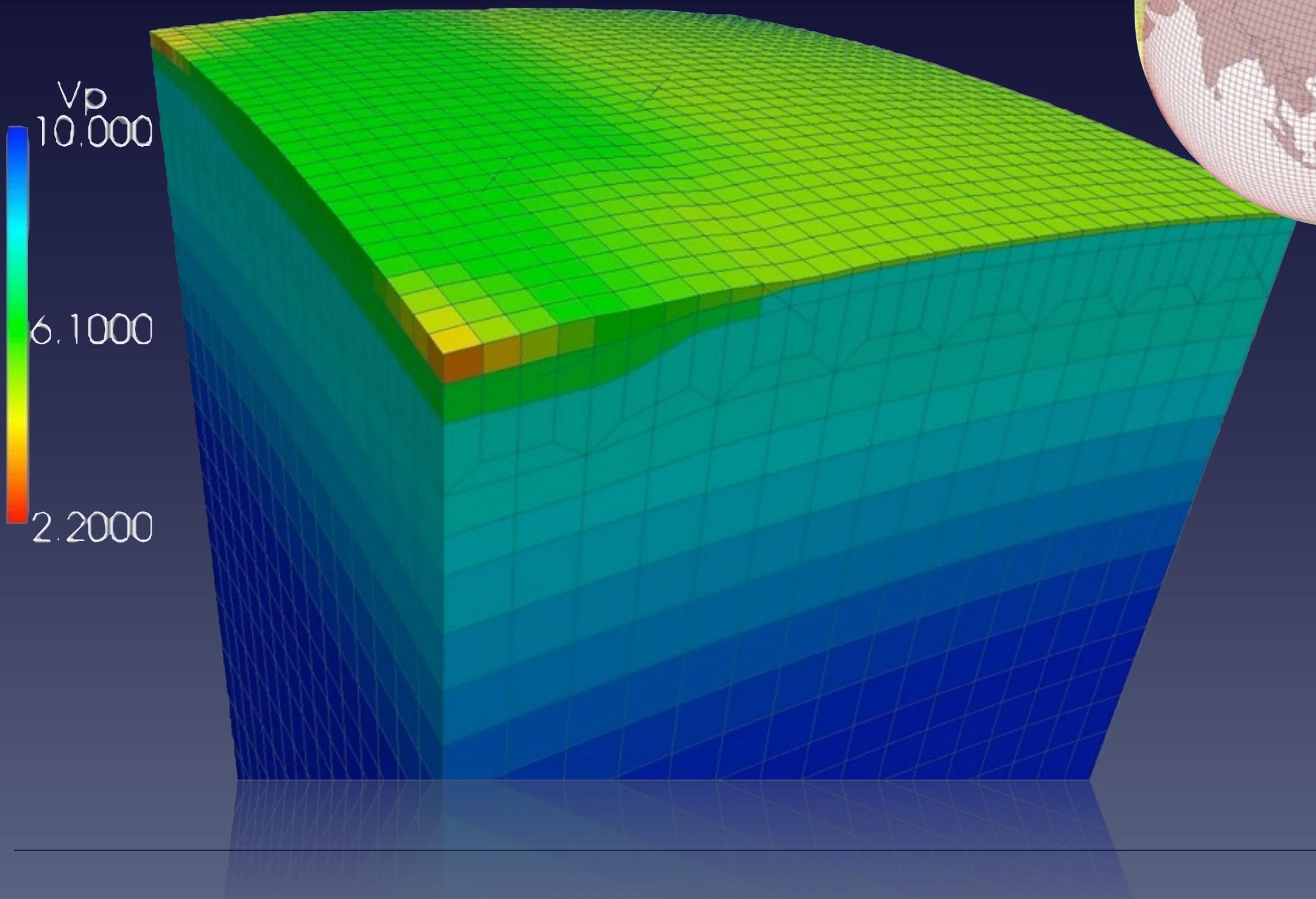


www.geodynamics.org



SPECFEM3D_GLOBE

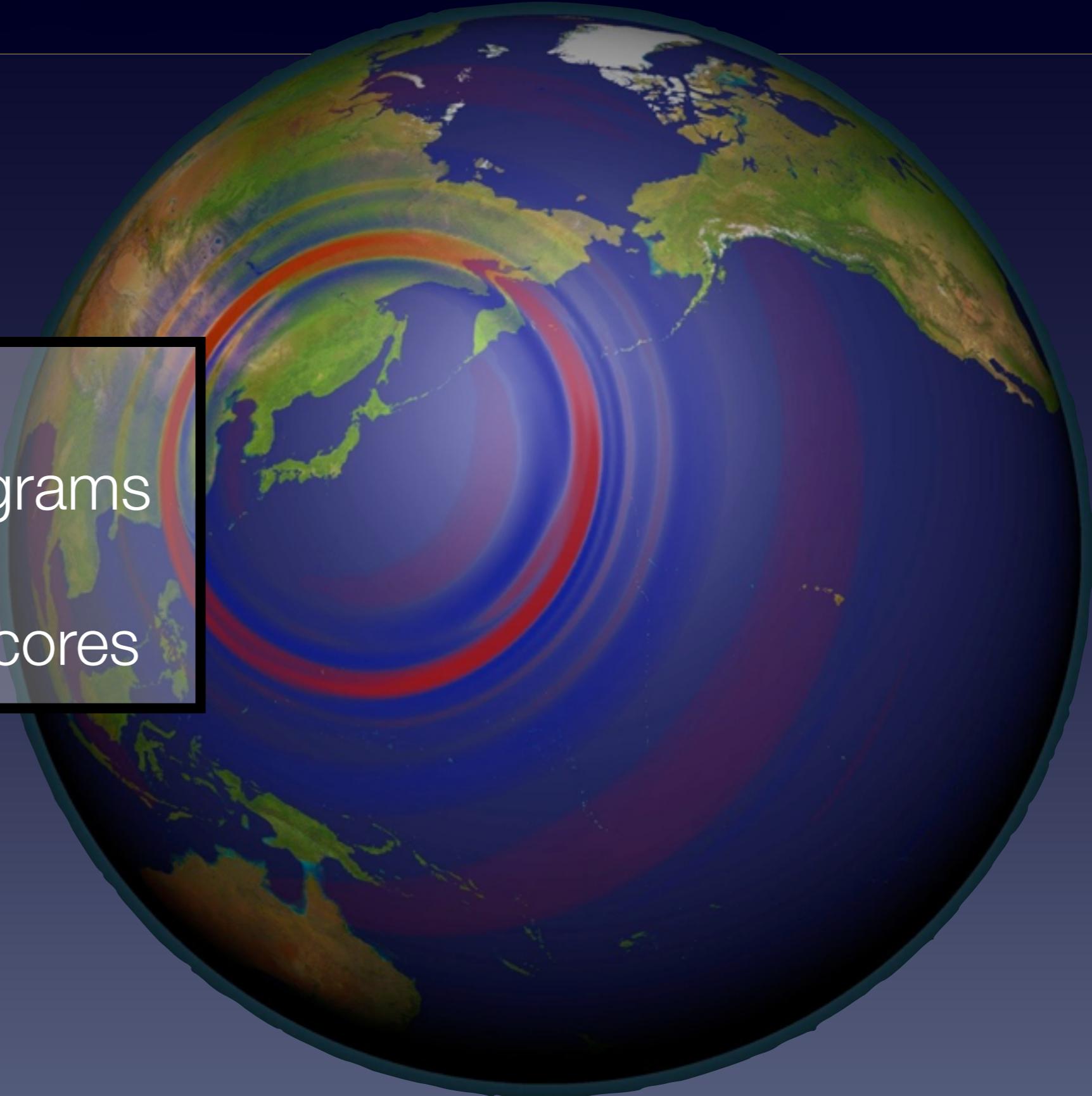
SPECFEM3D_GLOBE



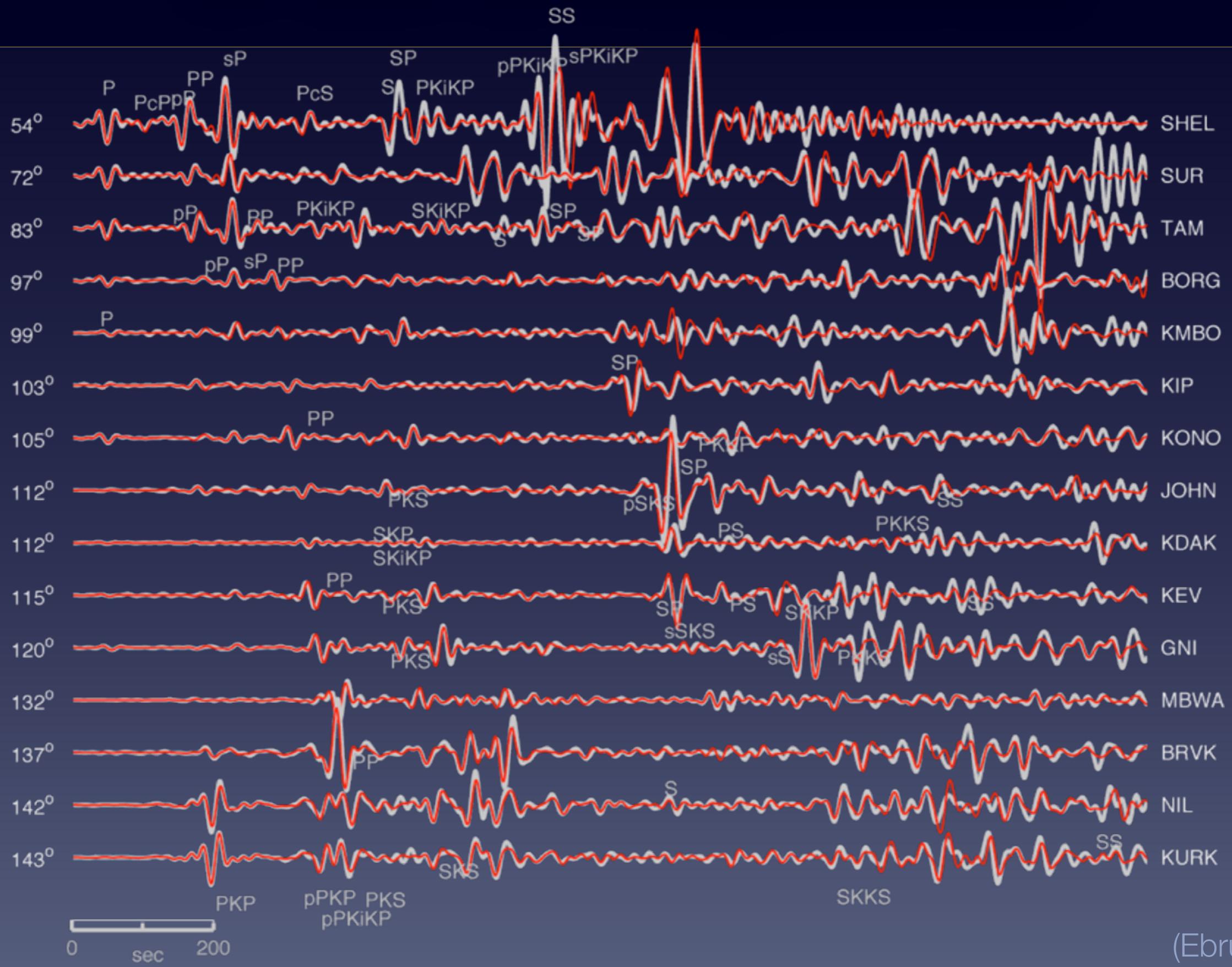
SPECFEM3D_GLOBE

resolution 17 s
100 min seismograms

5h on 384 CPU cores



SPECFEM3D_GLOBE

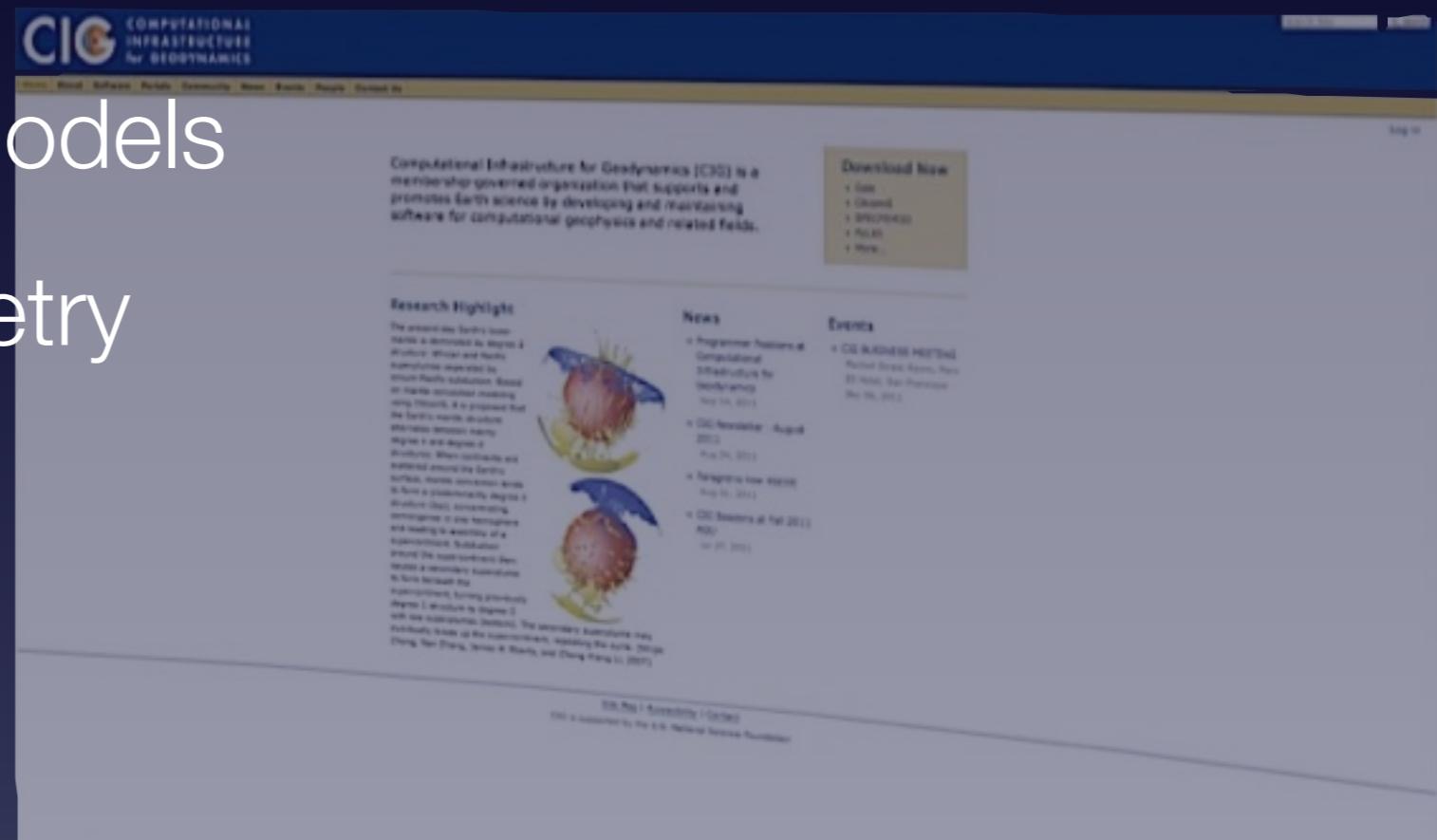


(Ebru Bozdag)

SPECFEM3D_GLOBE

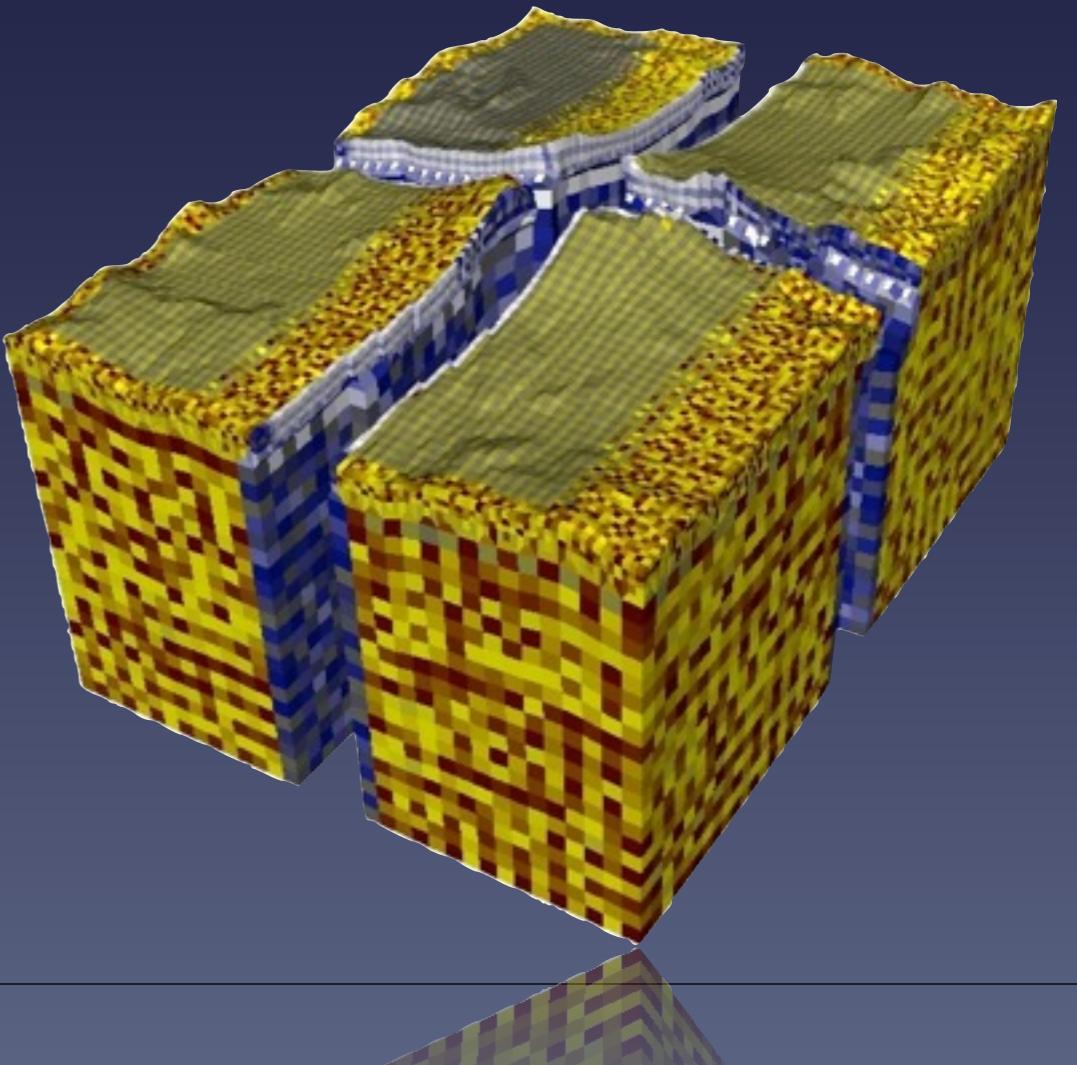
Open-Source

- 3D crust and mantle models
- Topography & Bathymetry
- Rotation
- Ellipticity
- Gravitation
- Anisotropy
- Attenuation
- Adjoint kernels

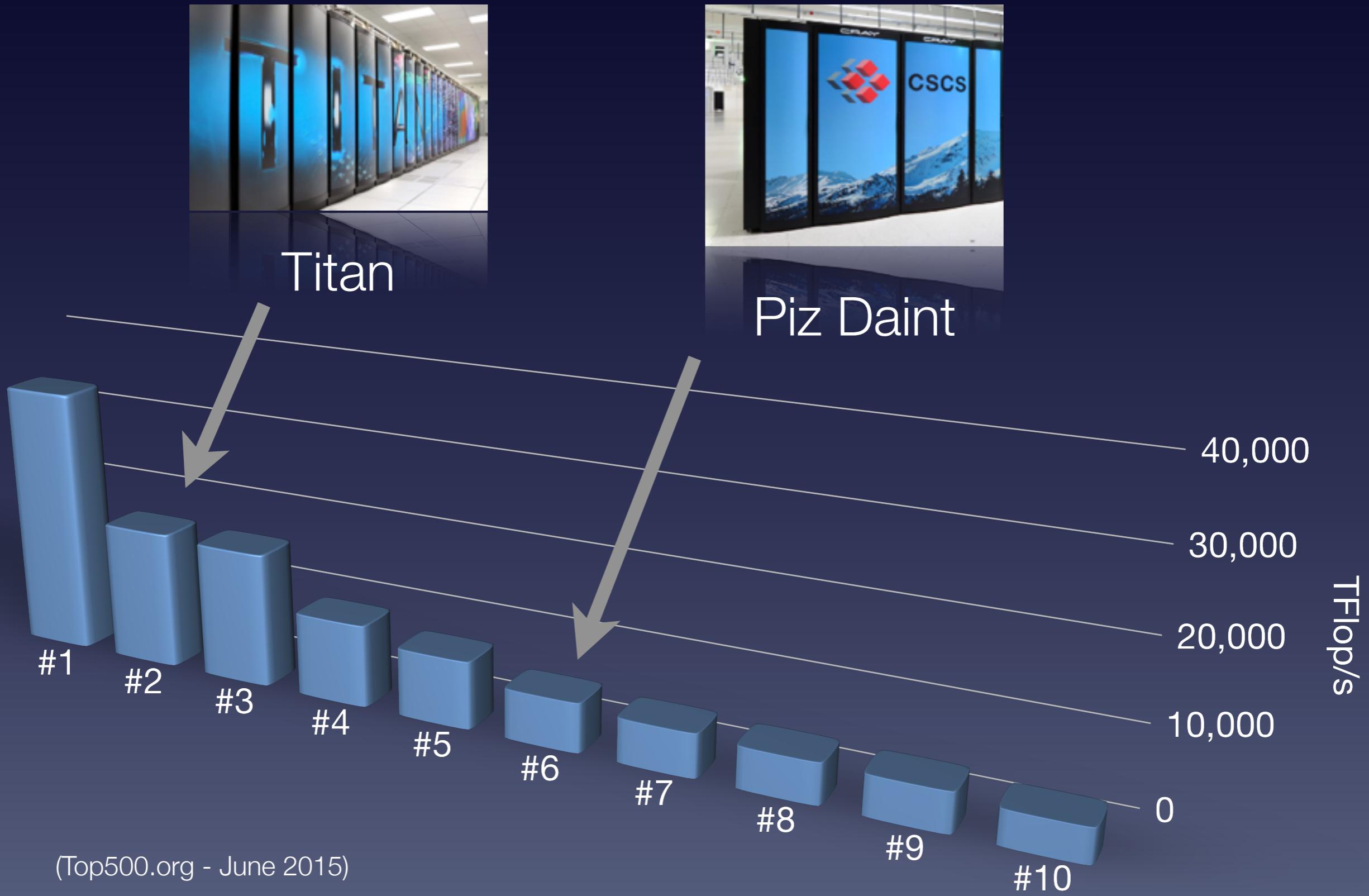


www.geodynamics.org

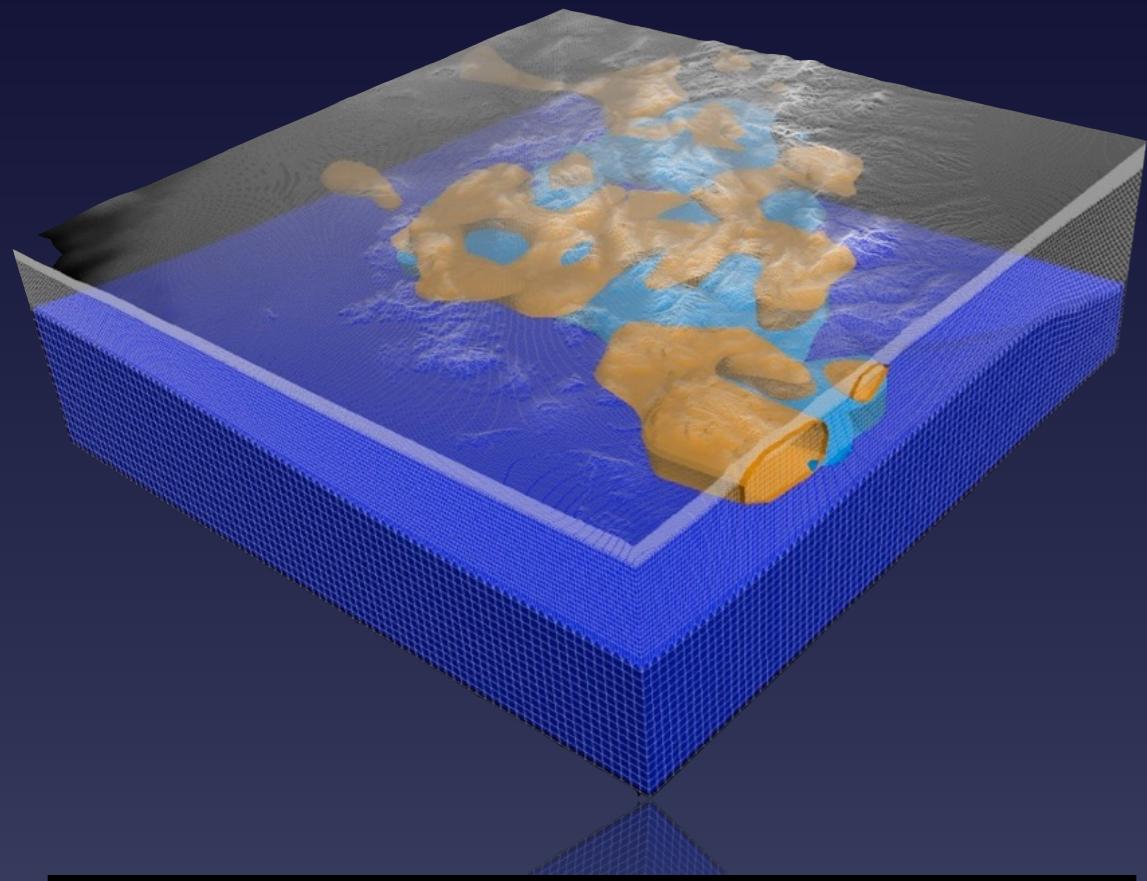
High-performance computing



GPU



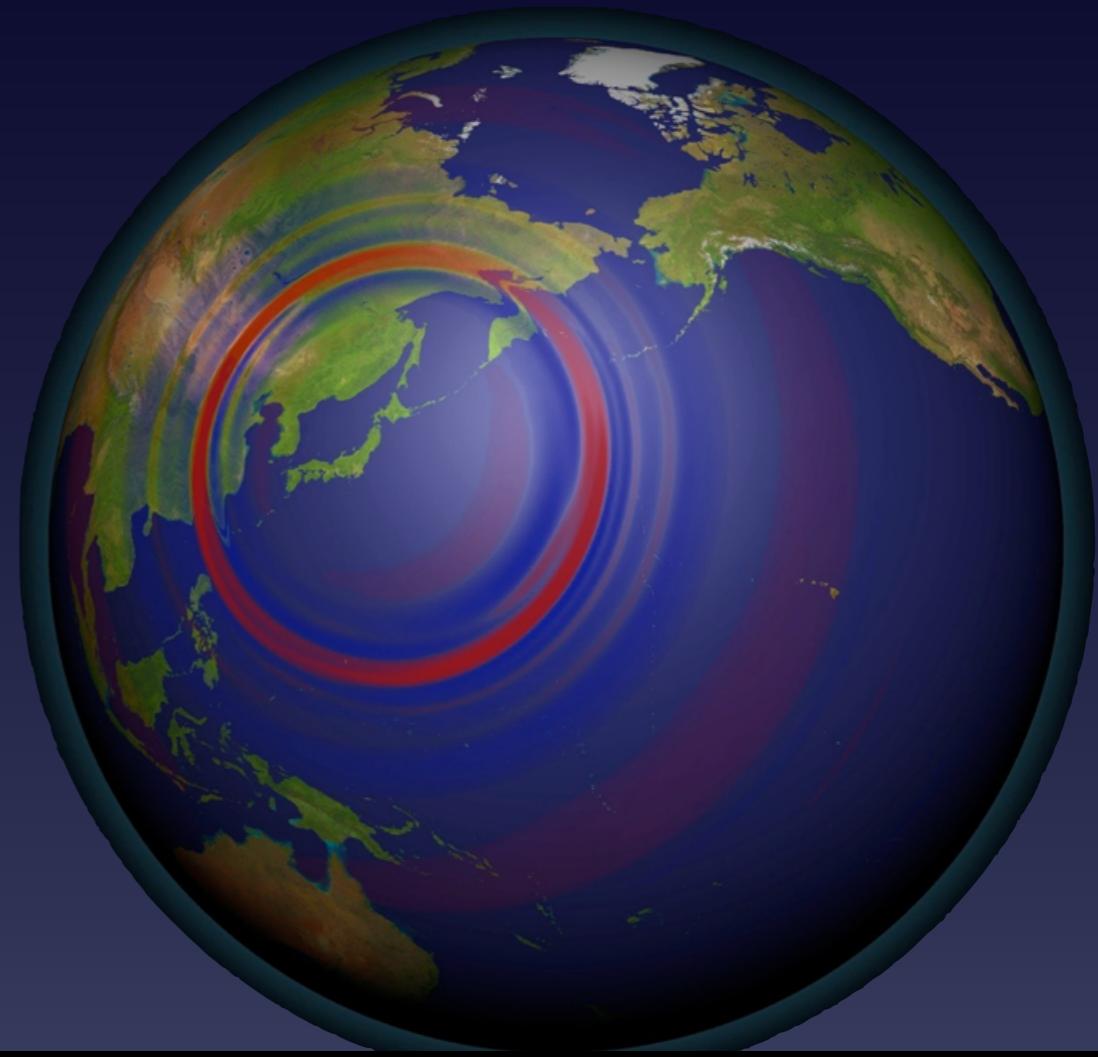
GPU computing



SPECFEM3D

~70,000 lines of code

Fortran90 / C / Cuda

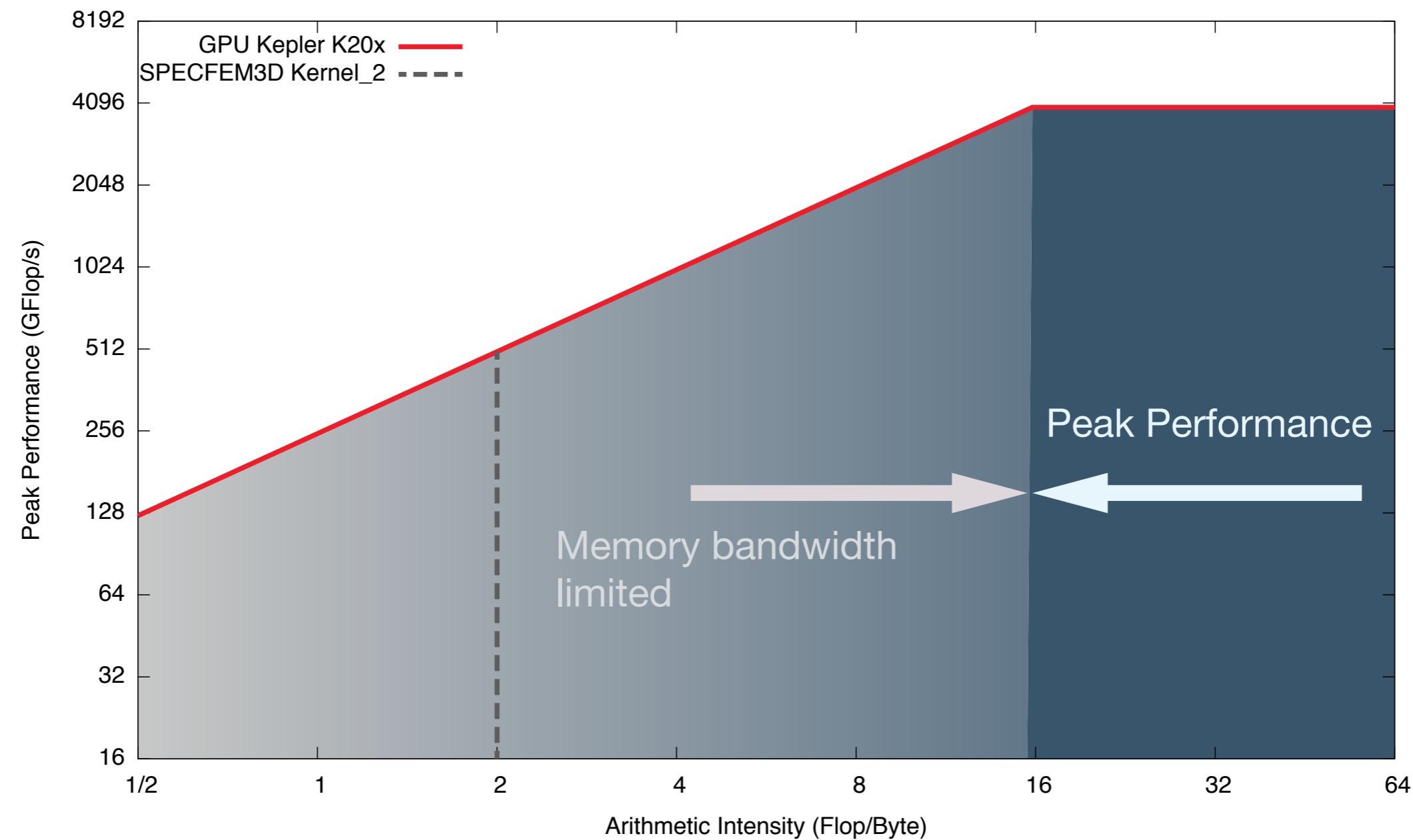


SPECFEM3D_GLOBE

~100,000 lines of code

Fortran90 / C / Cuda / OpenCL

GPU



CUDA/OpenCL

BOAST source-to-source transformation library:

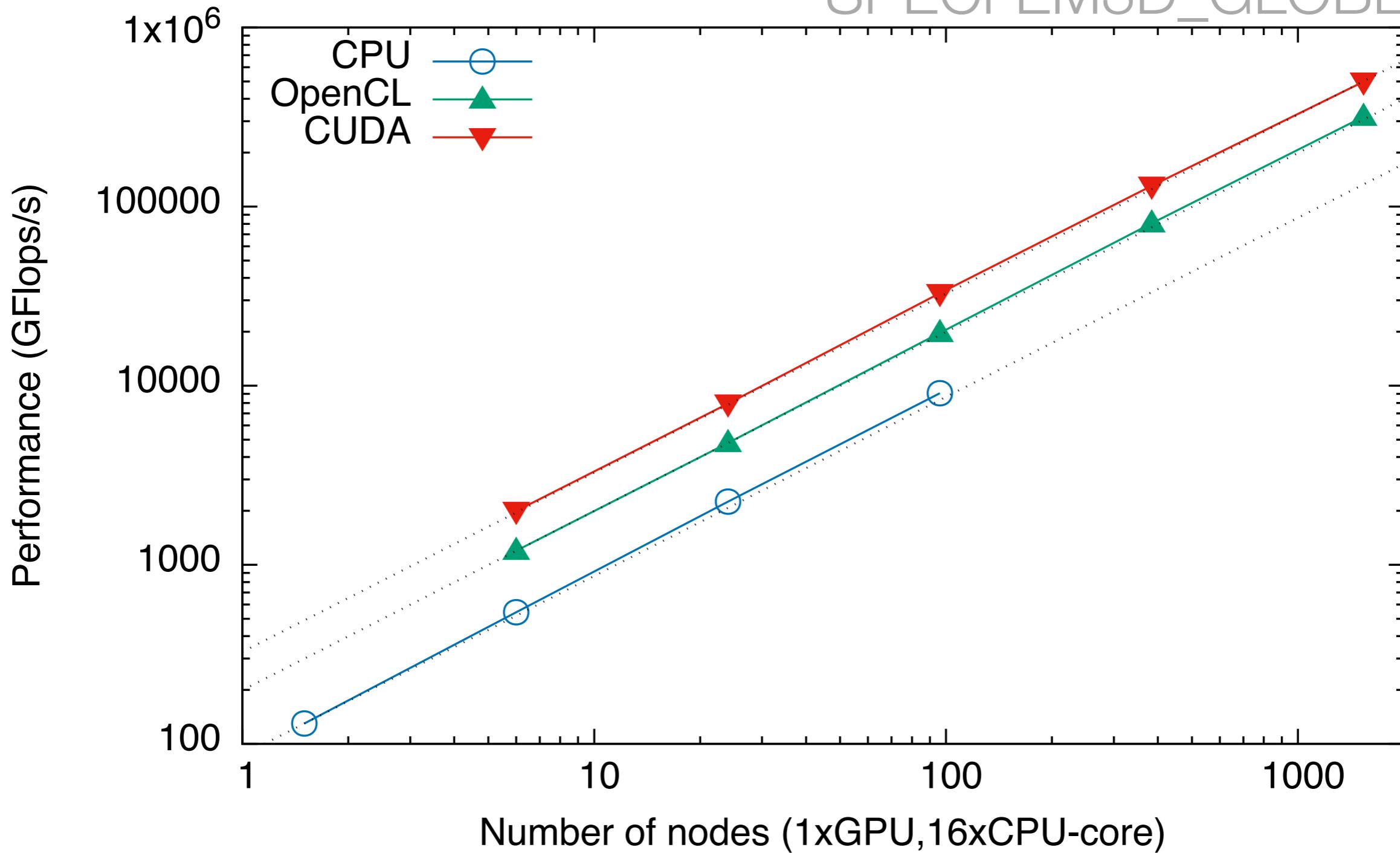
```
module BOAST
    def BOAST::compute_rho_kernel(ref = true, n_gll3 = 125)
        push_env( :array_start => 0 )
        kernel = CKernel::new
        function_name = "compute_rho_kernel"
        accel = Real("accel", :dir => :in, :dim => [Dim(3), Dim()])
        ..

        p = Procedure(function_name, [ibool, accel, b_displ, rho_kl, nspec, deltat])
        if (get_lang == CL or get_lang == CUDA) then
            make_specfem3d_header( :ngll3 => n_gll3 )
            open p
            decl ispec = Int("ispec")
            ..

            print ispec === get_group_id(0) + get_group_id(1)*get_num_groups(0)
            print If(ispec < nspec ) {
                print ijk_ispec === get_local_id(0) + ngll3*ispec
                print iglob === ibool[ijk_ispec] - 1
                print rho_kl[ijk_ispec] === rho_kl[ijk_ispec] + deltat * ( accel[0, iglob] * b_displ[0, iglob]+.. )
            close p
        end
        pop_env( :array_start )
        kernel.procedure = p
        return kernel
    end
end
```

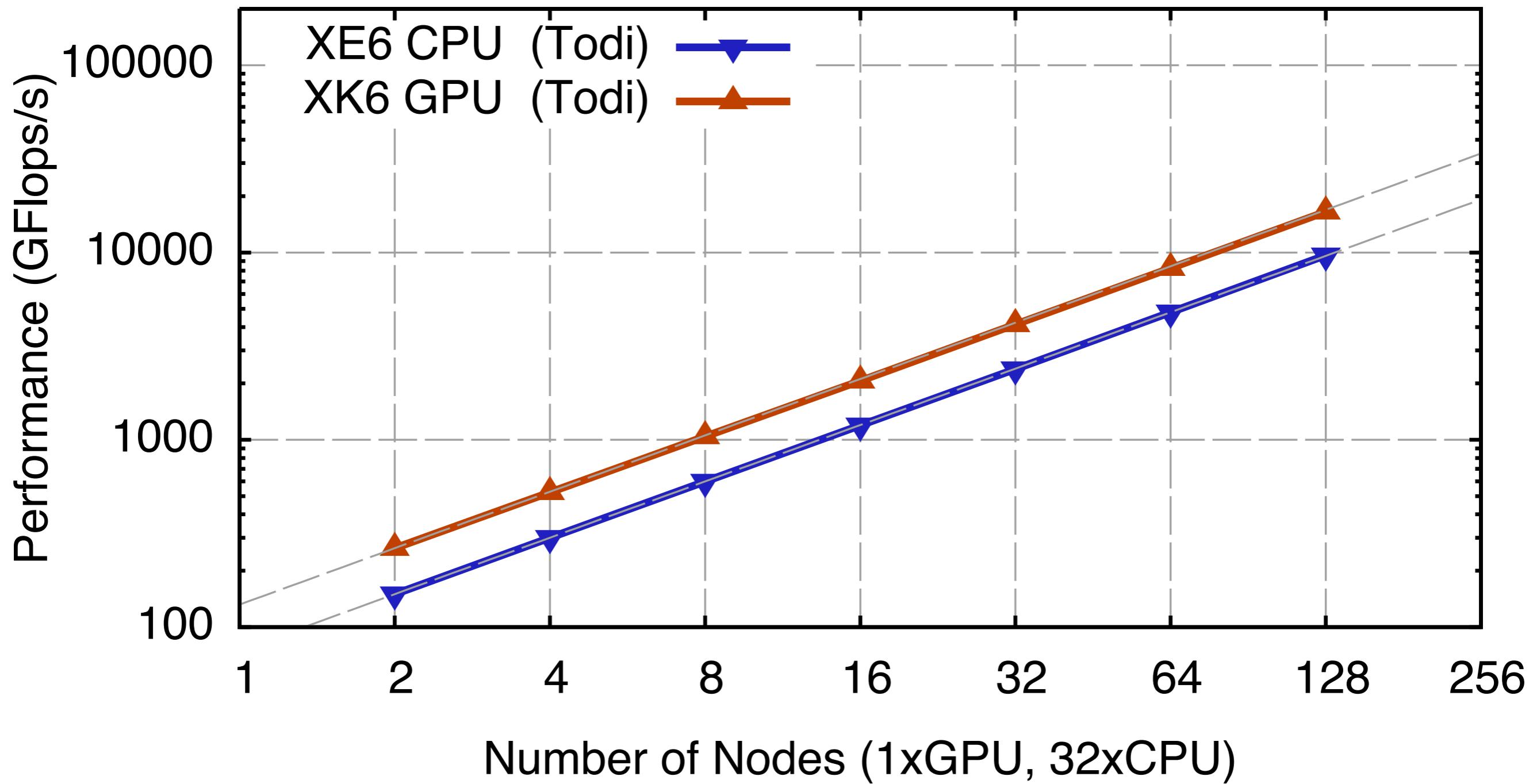
Weak scaling

SPECFEM3D_GLOBE



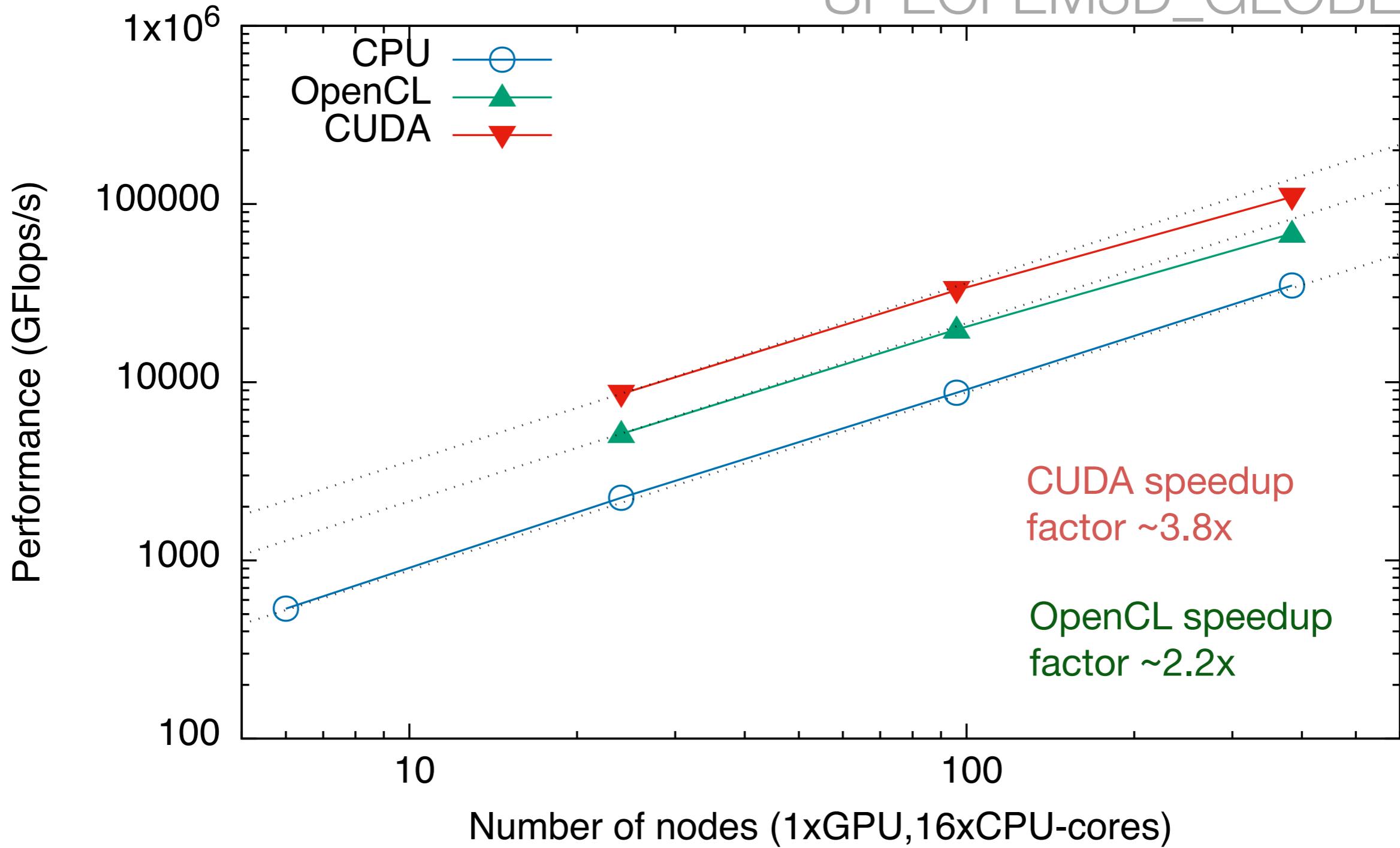
Weak scaling

SPECFEM3D_Cartesian



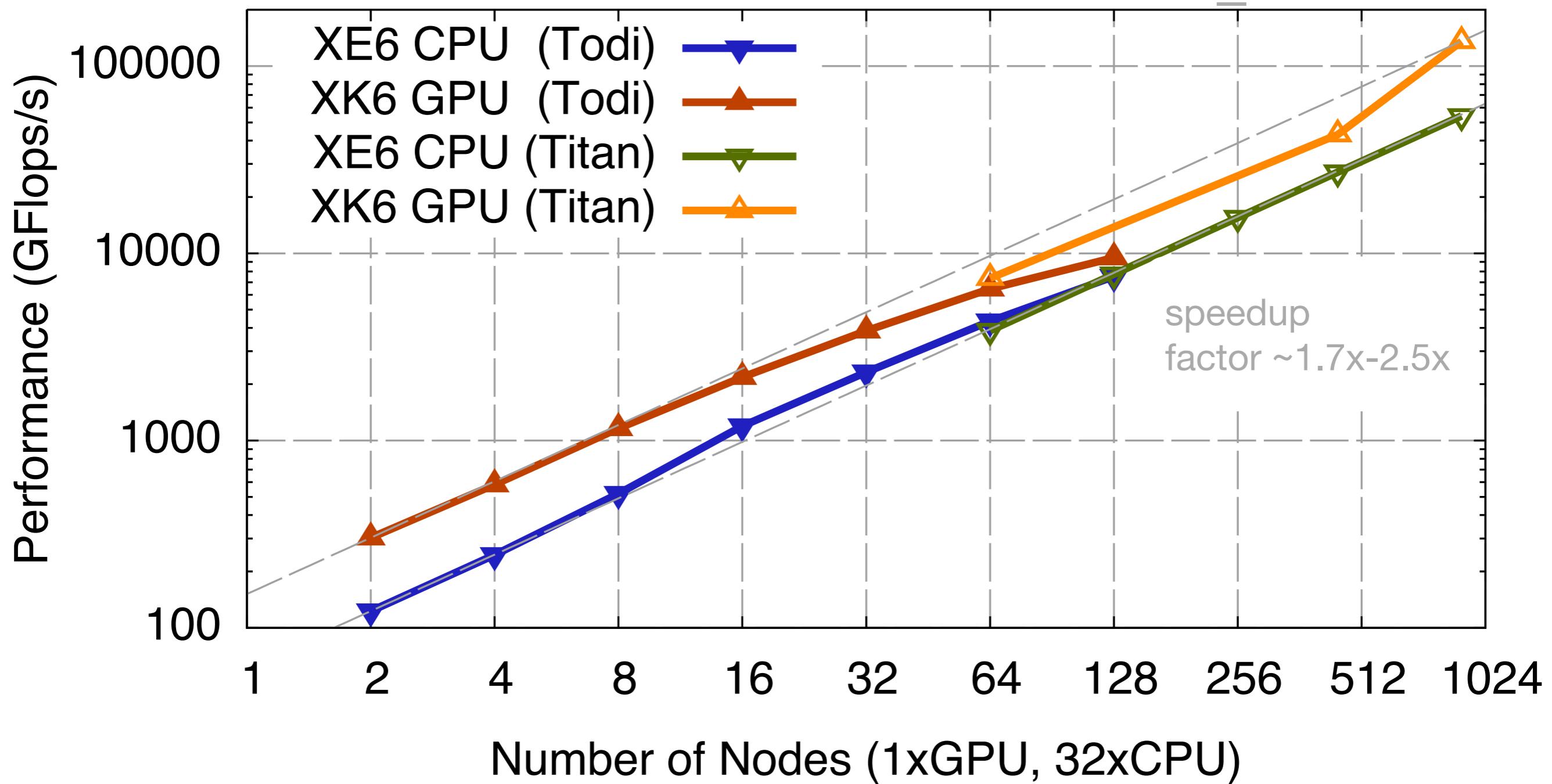
Strong scaling

SPECFEM3D_GLOBE



Strong scaling

SPECFEM3D_Cartesian



SPECFEM - Awards



2010 **BULL Joseph Fourier Prize winner**
for the partial GPU port of SPECFEM3D_GLOBE



2008 **ACM Gordon Bell Finalist**
for SPECFEM3D_GLOBE simulation reaching resolution of 1.72s shortest period



2003 **ACM Gordon Bell Award for Best Performance**
for SPECFEM3D_GLOBE simulation on the Earth Simulator

Milestone simulations

SPECFEM3D_GLOBE - Milestones



2015 **K computer simulation > 1.24 PFlops** (shortest period ~ 1.2 s)
on 82,134 nodes, 82,134 MPI ranks w/ 8 OpenMP threads, 657,072 cores

2013 **Blue Waters XE6 simulation > 1 PFlops** (shortest period < 2 s)
on 21,675 XE nodes, 693,600 MPI ranks, 693,600 cores

2008 **Kraken XT5 simulation > 160 TFlops** (shortest period ~1.72 s)
on 149,784 cores

2003 **Earth Simulator simulation > 5 TFlops** (shortest period ~5 s)
on 243 nodes, 1,944 MPI ranks, 1,944 cores

Impact / Outreach

SPECFEM - press releases



SGI - “(..) It enables the Department of Geosciences to report on seismic activity, via the Global Seismicity Portal, in 15-30 minutes as compared to two to eight hours previously...” (June, 2013)

http://www.sgi.com/company_info/newsroom/press_releases/2013/june/princeton.html



BULL - “(..) Bull helps its customers optimize their accelerator utilization, with very varied codes such as BIGDFT (nano-sciences), SPECFEM3D (seismic), NAMD (biochemistry), but also for oil and gas research with the porting of RTM (Reverse Time Migration) codes to accelerators.” (2014)

<http://www.bull.com/bullx/accelerators.html>



NVIDIA - “(..) Equipped with 12 GB of memory and powerful features like GPU Boost, Tesla K40 delivers up to 40% more performance compared to the Tesla K20X.”
— table: Earth Science represented by SPECFEM3D (2014)

<http://www.nvidia.com/object/gpu-test-drive.html?cid=gputestdrive>

ShakeMovie

<http://global.shakemovie.princeton.edu>

- automatically triggered by global CMTs
- 1D & 3D synthetics
- public outreach movies
- provided by IRIS





Development Team

Michael Afanasiev, Jean-Paul (Pablo) Ampuero, Kangchen Bai, Piero Basini, Céline Blitz, Alexis Bottero, Ebru Bozdag, Emanuele Casarotti, Joseph Charles, Min Chen, Paul Cristini, Clément Durochat, Percy Galvez, Dominik Göddeke, Vala Hjörleifsdóttir, Sue Kientz, Dimitri Komatitsch, Jesús Labarta, Nicolas Le Goff, Pieyre Le Loher, Matthieu Lefebvre, Qinya Liu, David Luet, Yang Luo, Alessia Maggi, Federica Magnoni, Roland Martin, René Matzen, Dennis McRitchie, Matthias Meschede, Peter Messmer, David Michéa, Vadim Monteiller, Surendra Nadh Somalia, Tarje Nissen-Meyer, Daniel Peter, Kevin Pouget, Max Rietmann, Elliott Sales de Andrade, Brian Savage, Bernhard Schuberth, Anne Sieminski, James Smith, Leif Strand, Carl Tape, Jeroen Tromp, Brice Videau, Jean-Pierre Vilotte, Zhinan Xie, Chang- Hua Zhang, Hejun Zhu