Simulating acoustic and gravity waves in ForestClaw

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SIAM Parallel Processing

Feb 23-26, 2022

Seattle,WA (Virtual)

AirWaves project

- **AIRWaveS** : Atmosphere-Ionosphere Response to Wave Signals

  -- Project to simulate nonlinear waves and detect signals in the upper atmosphere triggered by natural hazards (tsunamis, earthquakes, thunder storms and so on).

  -- Funded under the DARPA (Defense Advanced Research Projects Agency) **AtmoSense** program (funding received January, 2021)

  -- **PI** : Jonathan Snively, Embry-Riddle Aeronautic University (ERAU), (FL).

  -- Three **technical areas** (TA1, TA2, TA3). TA1 is the modeling and simulation group and the focus of this talk.

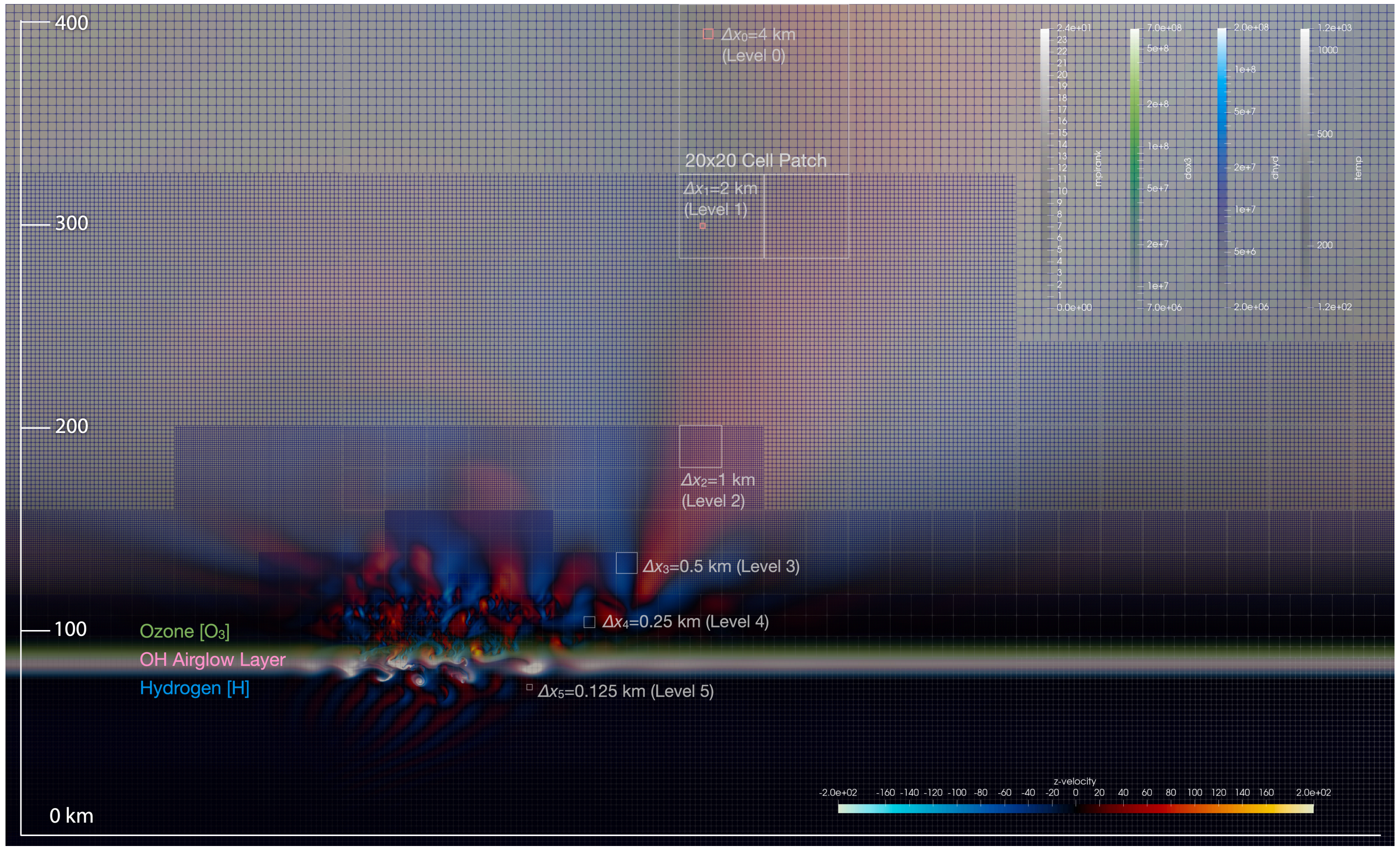
  -- Involves five additional university partners (BSU, UNH, ASU, Duke, Univ. Bonn)

A key component in the simulation and modeling group is the coupling of three modeling components using the **ForestClaw** (DC, C. Burstedde) platform.

AirWaveS

Using MAGICForest

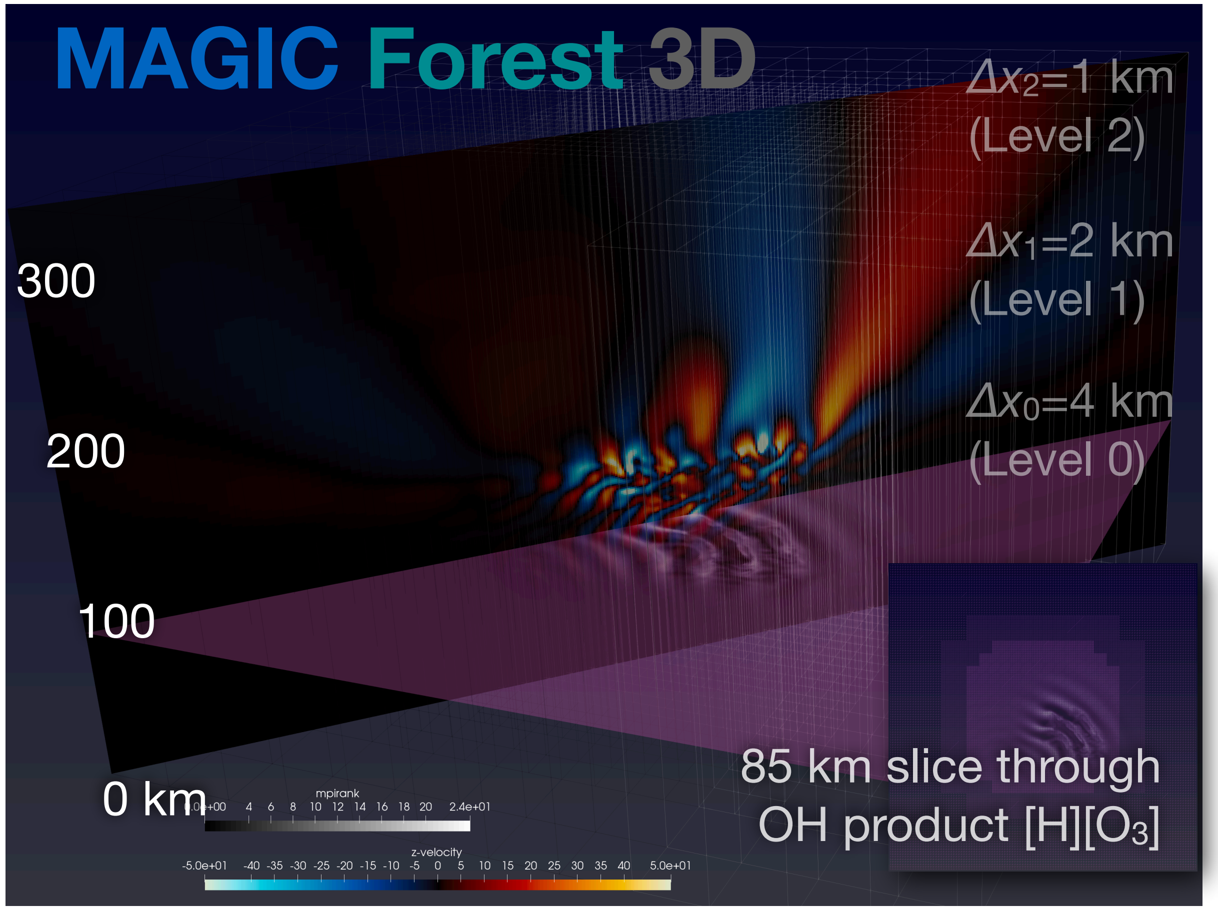
(MAGIC = **M**odel for **A**coustic **G**ravity wave **I**nteractions and **C**oupling



2D: ~200x speed-up using MAGIC Forest.

* Research was supported by DARPA Cooperative Agreement HR00112120003 with ERAU. This work is approved for public release; distribution is unlimited. The content of the information does not necessarily reflect the position or the policy of the Government, and no official endorsement should be inferred.

MagicForest



3D MAGIC in ForestClaw “extruded mesh”

J. B. Snively and D. A. Calhoun (AGU Fall 2021 Meeting)

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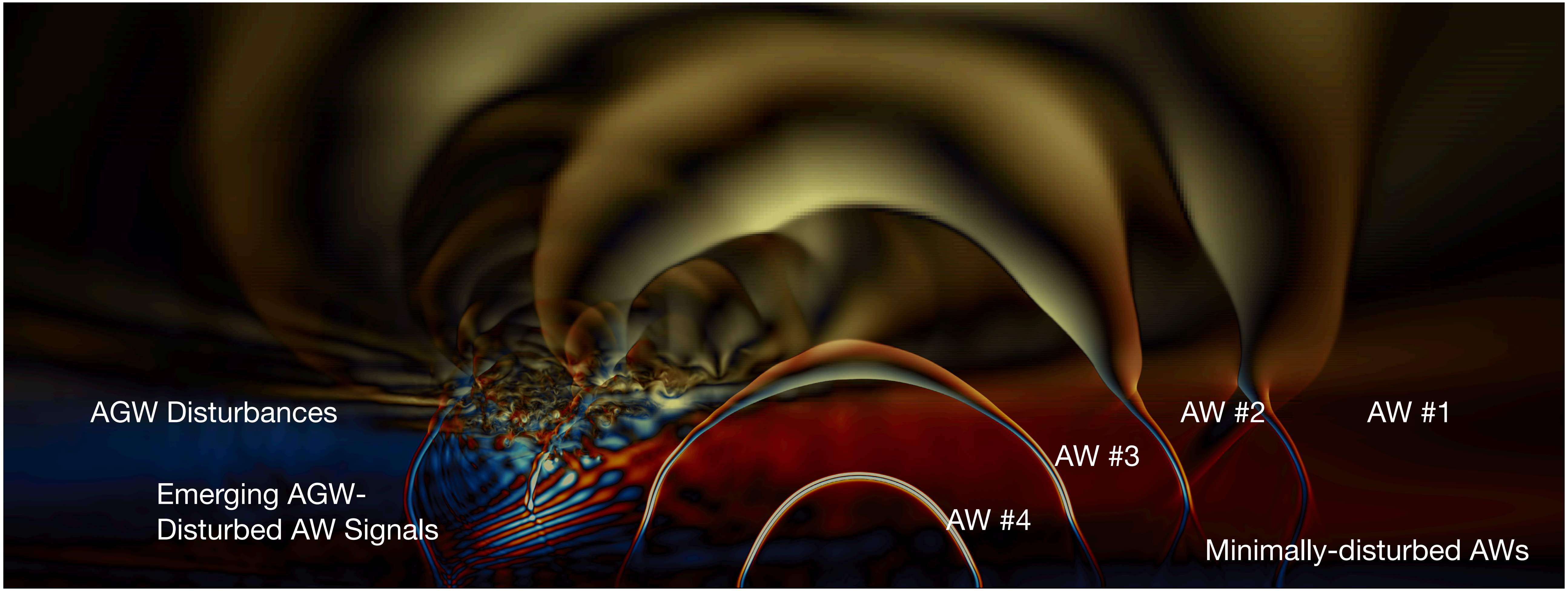
One AIRWaves Application:
Nonlinear Acoustic-Gravity Wave (AGW) Interactions



Energy-release source (Sabatini et al., 2019), triggered 4 times at 200 s intervals in a Demo acoustic-gravity wave (AGW) field (2D) to address question of “How do ambient wave fields influence AW signals of natural hazard events?”

images and caption: Jonathan Snively (Poster : Snively and Calhoun, AGU Fall 2021 Meeting)

ForestClaw Project

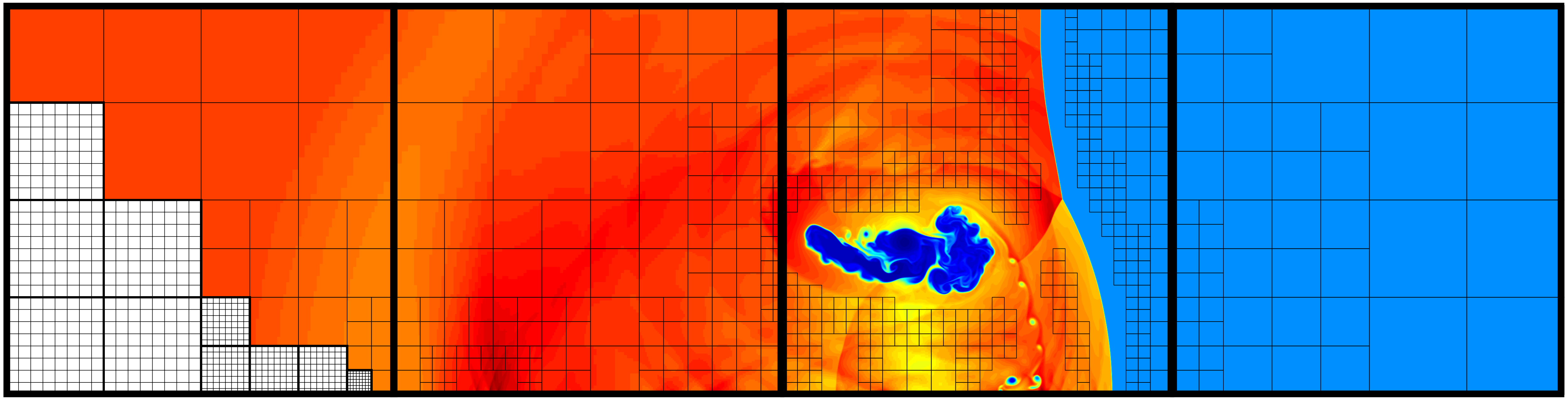
A parallel, adaptive library for logically Cartesian, mapped, multi-block domains

Features of ForestClaw include :

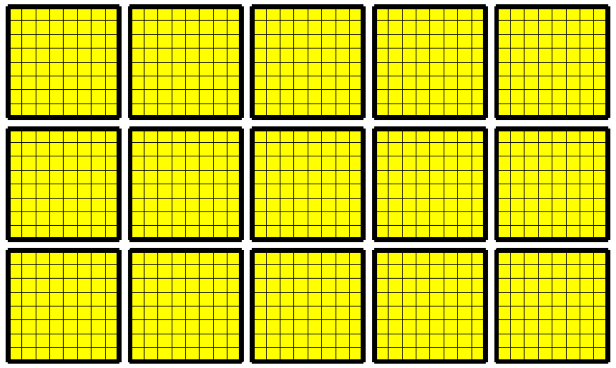
- Uses the highly scalable **p4est** dynamic grid management library (C. Burstedde, Univ. of Bonn, Germany)
- Each leaf of the **quadtree/octree** contains a fixed, uniform grid,
- Optional **multi-rate time stepping strategy**,
- Has **mapped, multi-block capabilities**, (cubed-sphere, for example) to allow for flexibility in physical domains,
- Modular design gives user flexibility in **extending ForestClaw** with Cartesian grid based solvers and packages.
- Uses essentially the same numerical components as patch-based AMR (e.g. Berger-Oliger-Colella)

www.github.com/ForestClaw

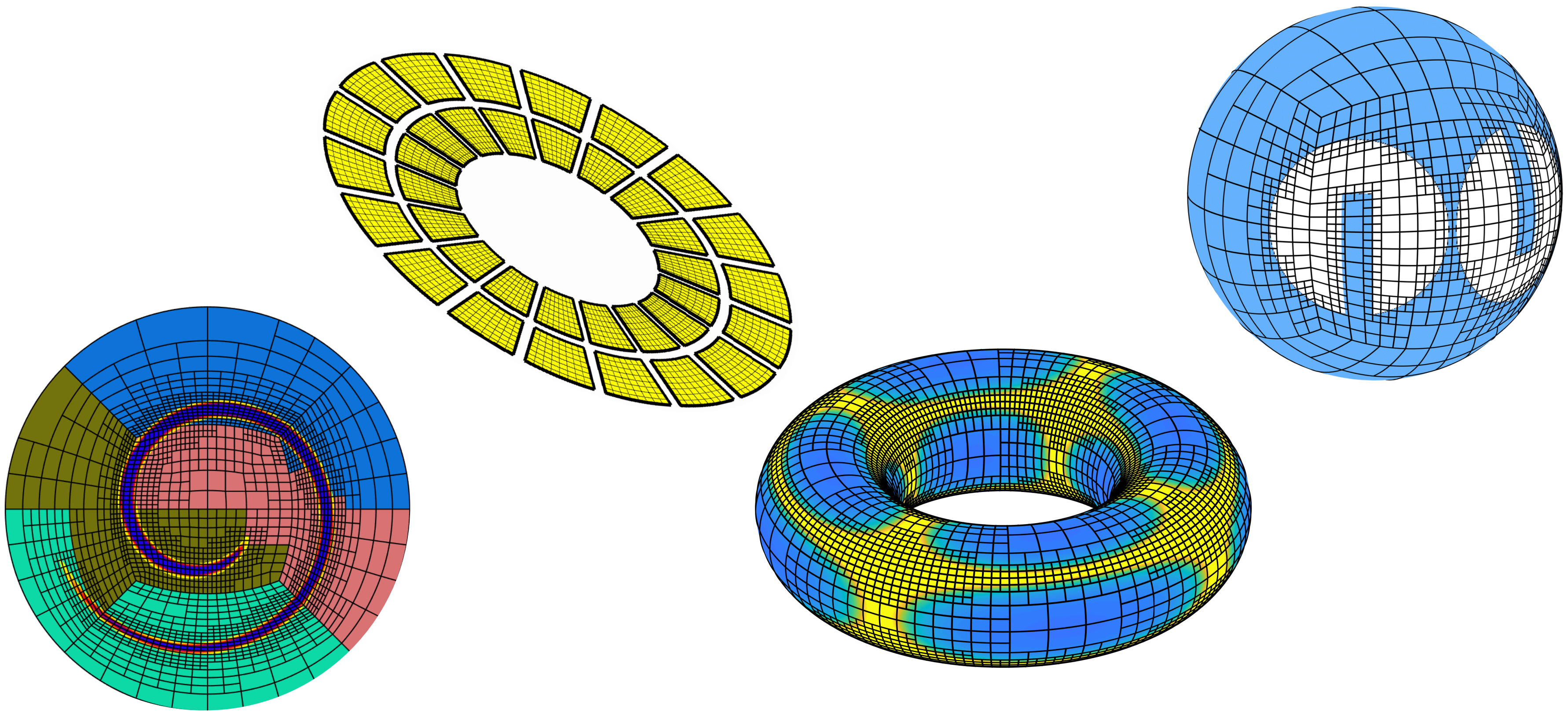
ForestClaw meshes



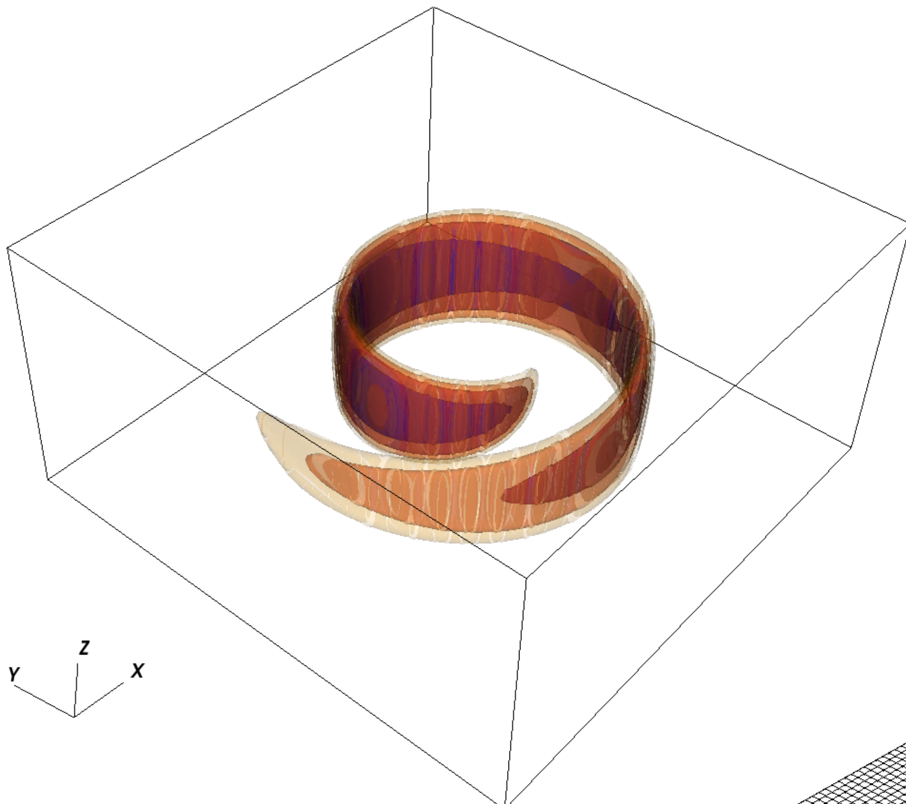
Shockbubble simulation using Clawpack (www.clawpack.org) extension of ForestClaw on 4x1 multi block domain

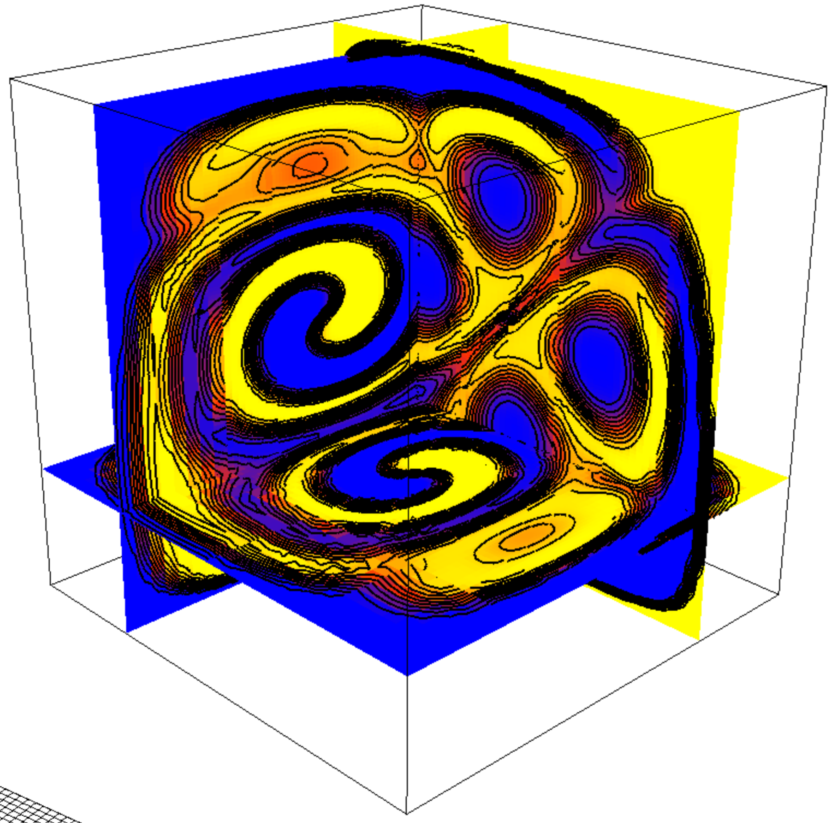


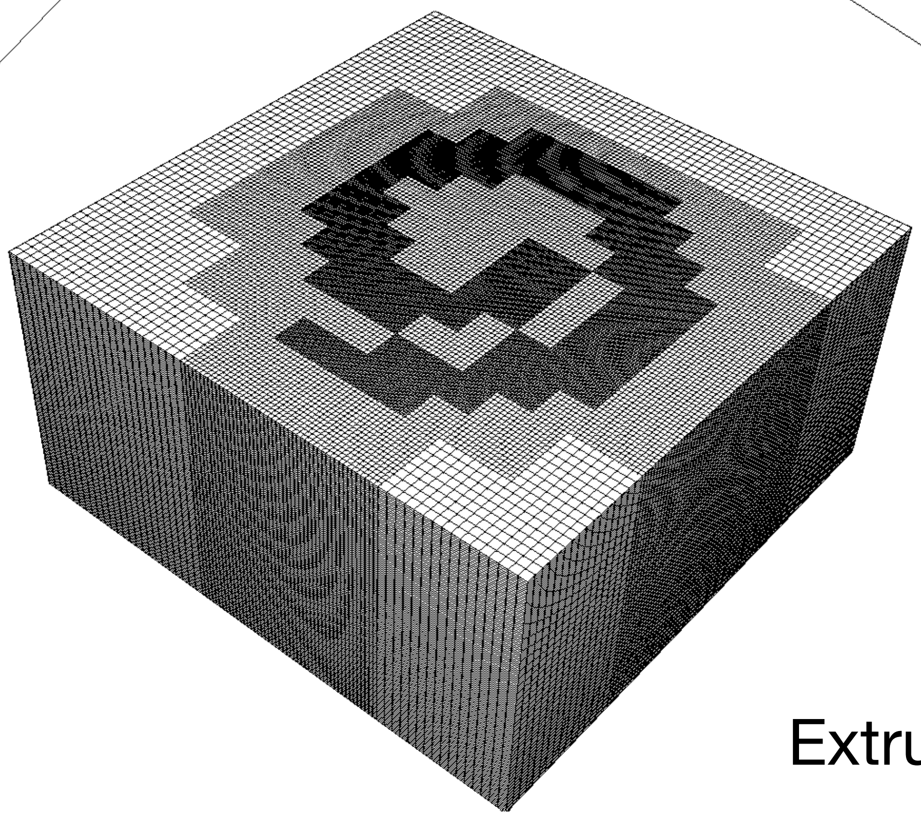
Solvers based on finite volume wave propagation algorithms in Clawpack (R. J. LeVeque)



ForestClaw Meshes

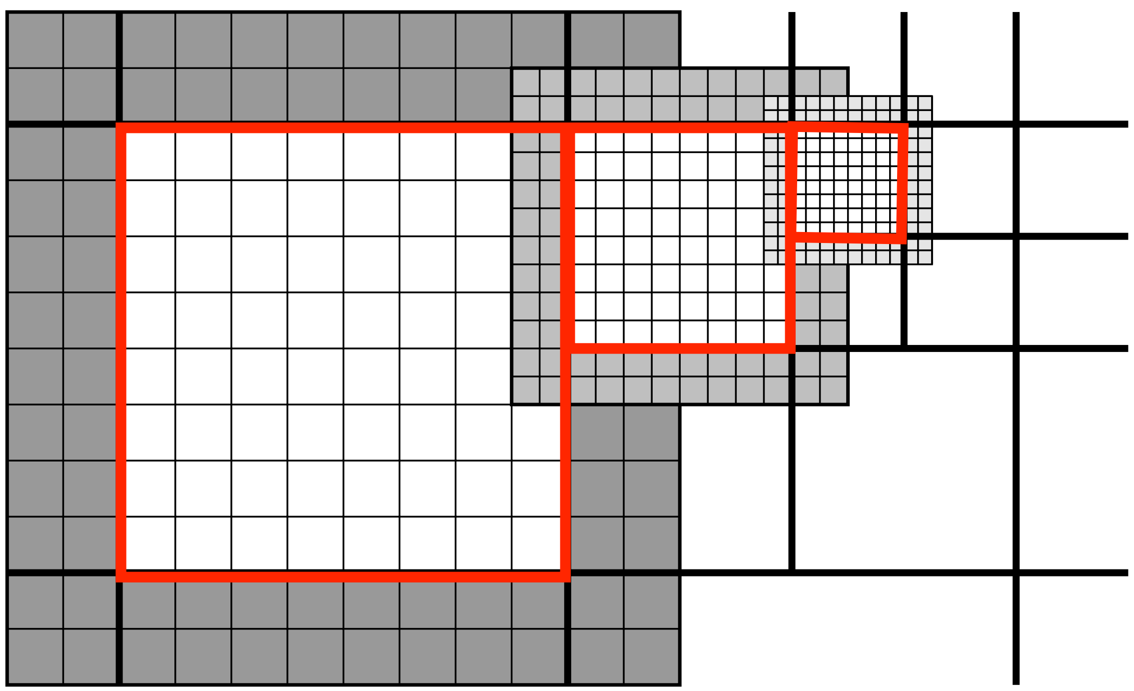




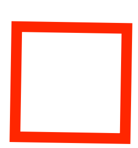


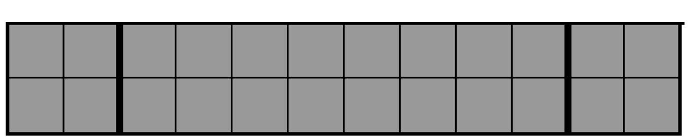
Extruded mesh

How does ForestClaw use p4est?



Each p4est quadrant is occupied by a single logically Cartesian grid, stored in contiguous memory (with ghost cells).

 p4est quadrant

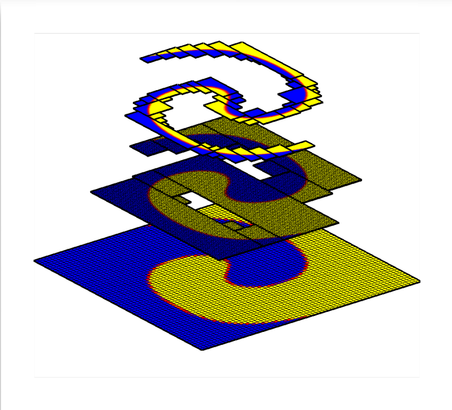
 Ghost (halo) cells in a ForestClaw patch

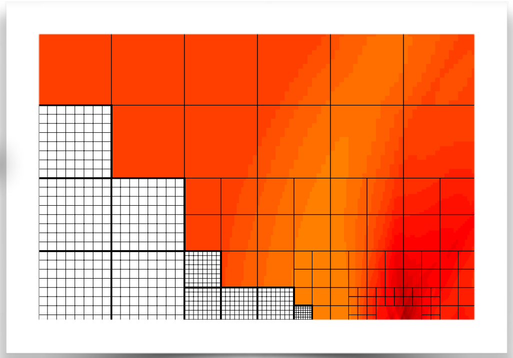
ForestClaw is a **p4est PDE layer**.

- Written mostly in object-oriented C
- Core routines are agnostic as to patch data, solvers used, etc.
- Most aspects of the PDE layer, including type of patch used, solver, interpolation and averaging, ghost-filling, can be customized
- Support for legacy codes
- Several extensions include Clawpack extension, GeoClaw, Ash3d and others.
- FV solvers and meshes are available as applications.

ForestClaw in the AMR* eco-system

*AMR = Adaptive Mesh Refinement





ForestClaw, **FLASH** (PARAMESH), Racoon II, Nirvana, Orchard,

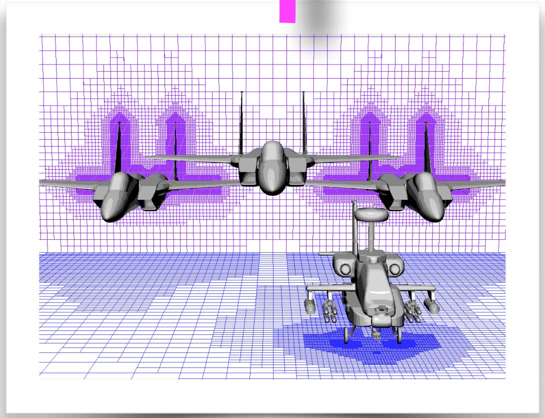
Hybrid “block-based” AMR

Share Cartesian “patch/grid” philosophy and algorithms

Share common tree-based mesh philosophy

AMReX, AMRClaw, GeoClaw, Chombo, Unintah, Amroc, SAMRAI, ...

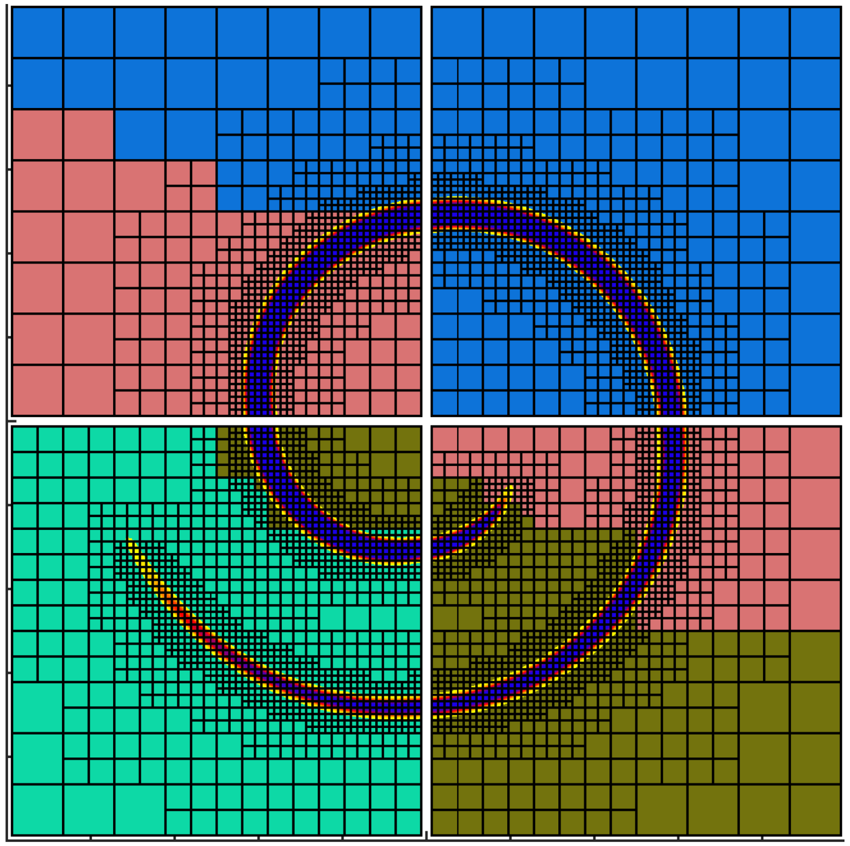
Patch-based AMR



Cart3d, RAMSES, Basilisk, deal.ii, **p4est**, NUMA/NUMO, ...

Cell-based AMR

ForestClaw : Parallel capabilities



Distribution of patches on four processors using space-filling curve

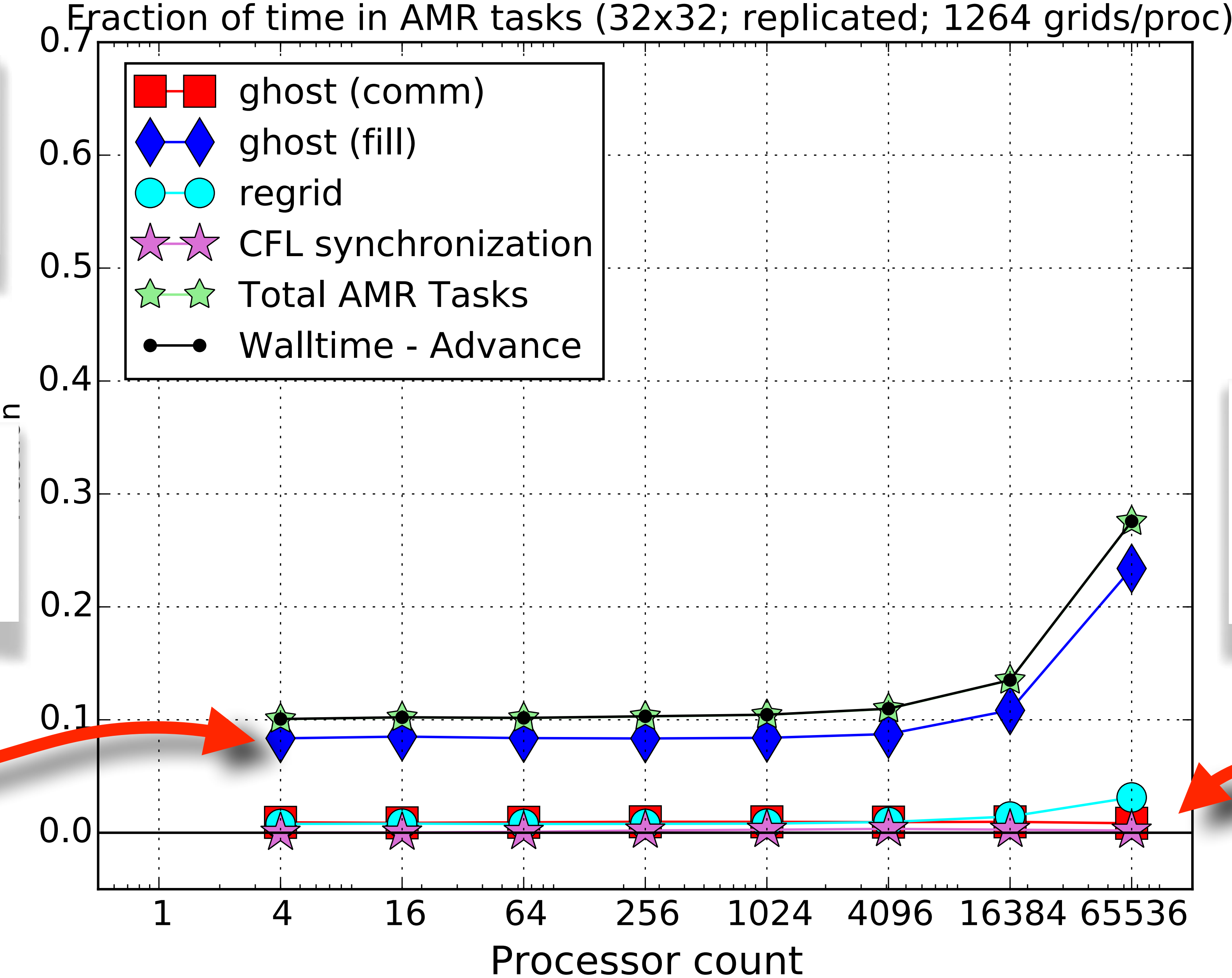
- Distributed (MPI) parallelism handled by p4est using **space-filling-curve** with Morton ordering
- Good scaling up to 65K cores on using 32x32 blocks on JUQUEEN (Juelich, Germany) (now de-commissioned)
- Communication and re-partitioning done after each time step, after new domain has been created and updated.

ForestClaw : Parallel capabilities

Scalar advection on a replicated domain with 32×32 patches

90% of wall time : advancing the solution on patches

~8% of wall time : Ghost-filling between patches



Regridding, communication CFL sync. are negligible (< 5%)

Results from Juqueen, Jülich, Germany (now decommissioned)

ForestClaw : Current capabilities

- 2d and **3d extruded mesh** capabilities
- Build ForestClaw can be built using either GNU autotools build tools, or **CMake**
- Visualization done through VTK files for use with Parkview, VisIt. Output can also be formatted for visualization with Matlab
- **Continuous Integration through GitHub Actions**
- User defined options, ForestClaw options and solver options can read in through configuration files (i.e. *.ini files) or from the command line
- Most features of related to refinement can be customized
- Features for several 2d mapped, multi-block domains (e.g. torus, sphere, polar, spherical, cubed-sphere, “brick” domains)
- Most of ForestClaw is written in C (minimal dependence on C++)
- Available patch type is a cell-centered finite volume patch. Users can easily define their own patches, however.
- **Stand-alone build system** so that users can use ForestClaw as a library for their application.
- **Doxygen-style documentation**

New features implemented by S. Aiton (Research Assistant, BSU) and supported by DARPA funding

ForestClaw applications and extensions

- **Clawpack** Wave propagation algorithm for solving hyperbolic conservation laws (www.clawpack.org). Examples for scalar advection, acoustics, Burgers, Euler equations, shallow water wave equations and so on) (R. J. LeVeque, M. Berger, K. Mandli and many others)
- **GeoClaw** library extension for depth averaged geophysical flows (tsunamis, overland flooding, debris flows, landslides, storm surge). (www.clawpack.org) (M. Shih, D. George, R. J. LeVeque, M. Berger, and many others)
- **Volcanic ash cloud** modeling using USGS code Ash3d. (example of legacy code port.) (H. Schwaiger, Y-S Shih,DC)
- **MAGIC-Forest** - Using the atmosphere for remote sensing (J. Snively, C. Burstedde, DC, Embry-Riddle, FL)
- **ThunderEgg** Elliptic solver for adaptive block-based meshes based on multi-grid preconditioned BiCGStab (S. Aiton, BSU, G. Wright, BSU, DC)
- **Serre-Green-Naghdi** solver (D. Chipman, S. Aiton, DC)
- **CUDA solvers** for Clawpack available (5x-7x speed-up) (Y-S. Shih, S. Aiton, X. Qin, DC)

ForestClaw : What is still needed

- Full 3d octree refinement
- Increased composability :

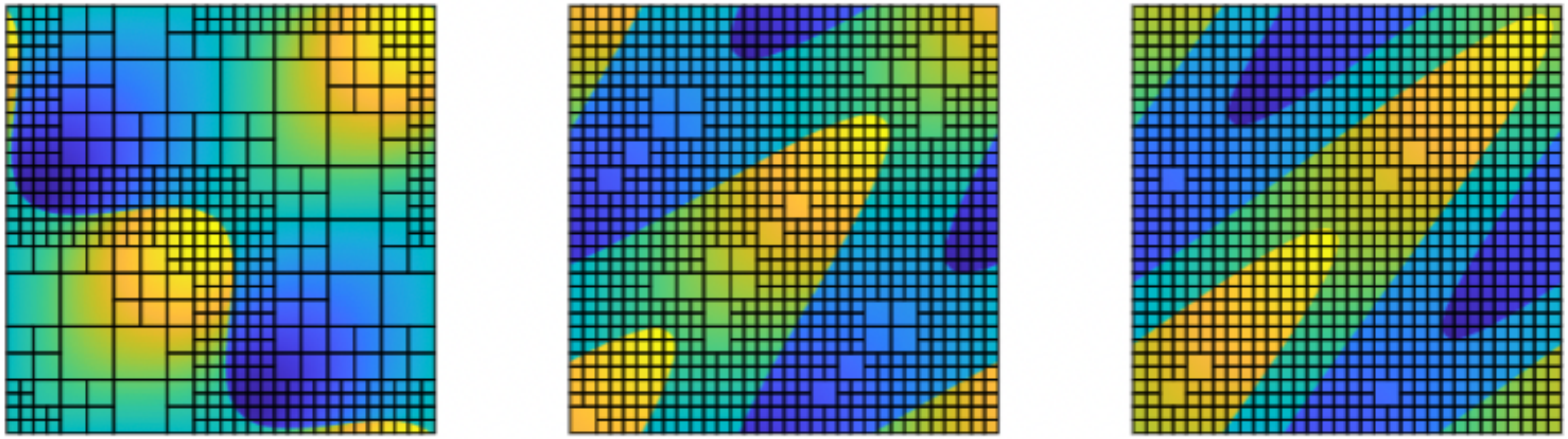
  -- Ability to run more than one ForestClaw application at a time

  -- Communication between between applications and their meshes
- Restart capabilities
- Higher order solvers
- 3d mapped grids (e.g. spherical shells)
- More sophisticated time stepping (e.g. stabilized RK methods) for diffusion problems.

Progress : Higher order methods

with Christiane Helzel, Erik Chudzik (Univ. of Düsseldorf, Germany)

- Implement the Active Flux method (T. Eymann, P. Roe et al, 2011) for ForestClaw AMR meshes
  - -- Solver working for advection, and variable coefficient advection, Burgers equation and acoustics
  - -- shows third order accuracy, with and without limiters, on AMR grids
  - -- Supports local sub-cycling



Burgers Equation using the Active Flux Method extension of Forest Claw

Progress : Composability

- Forestclaw application encapsulation
  -- Each application has their own option “packages” (stored as C-structs)
  -- Virtual tables (also stored as C-structs) contain pointers to functions defining patch and solver behavior.

```
struct fclaw2d_patch_vtable { /* In core ForestClaw routines */
   ....
   fclaw2d_patch_tag4refinement_t    tag4refinement;
  ....
}
/* Cell-centered “clawpatch” routines */
void fclaw2d_clawpatch_vtable_initialize(int claw_version) {
    ...
     patch_vt->tag4refinement = clawpatch_tag4refinement;  // C routine
   ...
     clawpatch_vt->fort_tag4refinement = CLAWPATCH46_FORT_TAG4REFINEMENT;
}
```

Tagging routine might call a (virtualized) Fortran routine under the hood to allow for easy tagging on individual patches.

Multiple options packages can exist in the same program. However, virtual tables exist in global name space, limiting our composability, currently.

Composability with other codes

- Achieving composability between different ForestClaw applications can be done using existing paradigms within ForestClaw.
- Outside applications must provide an “interface” layer to access ForestClaw functionality.

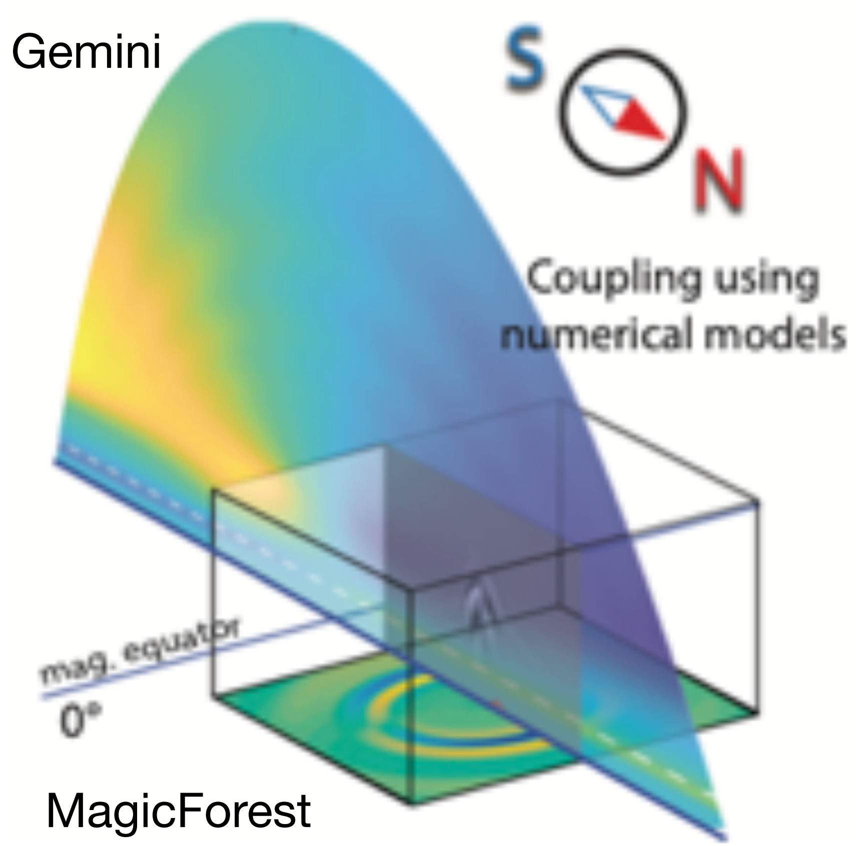
  -- C-wrapper code can be used to wrap various algorithmic patch components (patch initialization, patch updates and so on).
- Biggest challenge is getting two build systems to work together so that ForestClaw and outside applications can be built together

  -- Stand-alone framework will allow us to link ForestClaw as a library.

AIRWaveS: AGW Effects in Atmosphere & Ionosphere

Current goal of this project :

- Use ForestClaw to couple **MAGIC** Forest (MAGIC = **M**odel for **A**coustic **G**ravity wave **I**nteractions and **C**oupling, J. B. Snively, ERAU) atmosphere with **GEMINI** (**G**eospace **E**nvironment **M**odel of **I**on-**N**eutral **I**nteractions, M. D. Zettergren, ERAU) ionosphere.



Meshing and solver challenges

- Multiple 2d/3d p4est meshes will need to communicate (MAGIC to GEMINI, and vice-versa).
- Full 3d octree meshing (current 3d capabilities are for extruded meshes only)
- Coupling several large multiphysics codes

Images : Jonathan Snively

Thank you!

for the invitation to speak at this mini symposium