A Massively-Parallel, Fault-Tolerant Solver for Time-Dependent PDEs in High Dimensions

Euro-Par 2016: Resilience

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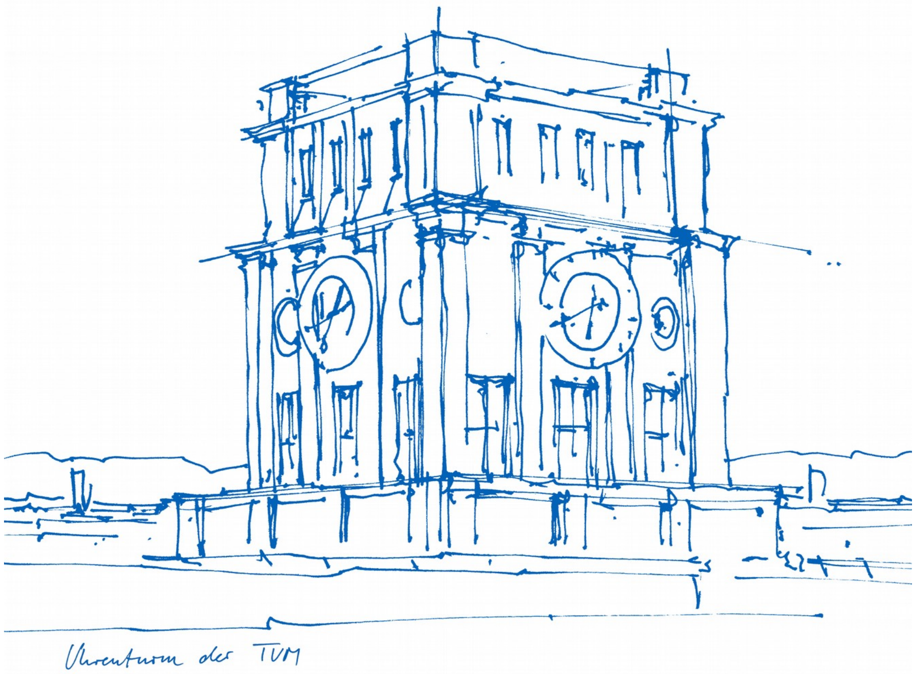
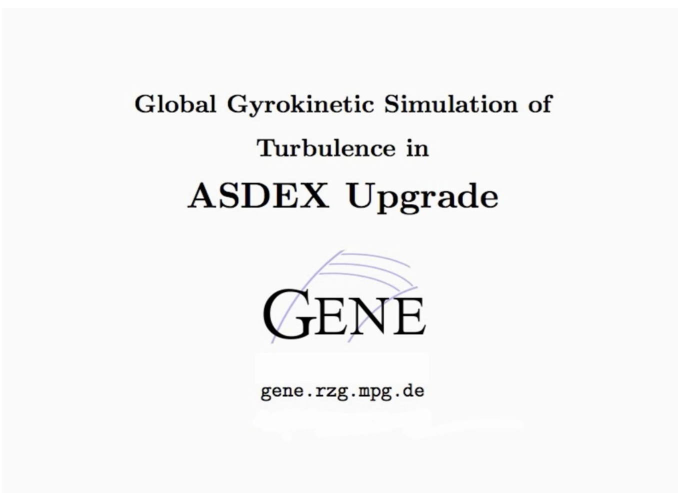


EXAHD Project

- Goal: (exa)scalable solution of high-dimensional PDEs
- Main challenge: *curse of dimensionality*
  - 2^n discretization points per dimension → $(2^n)^d$ total points



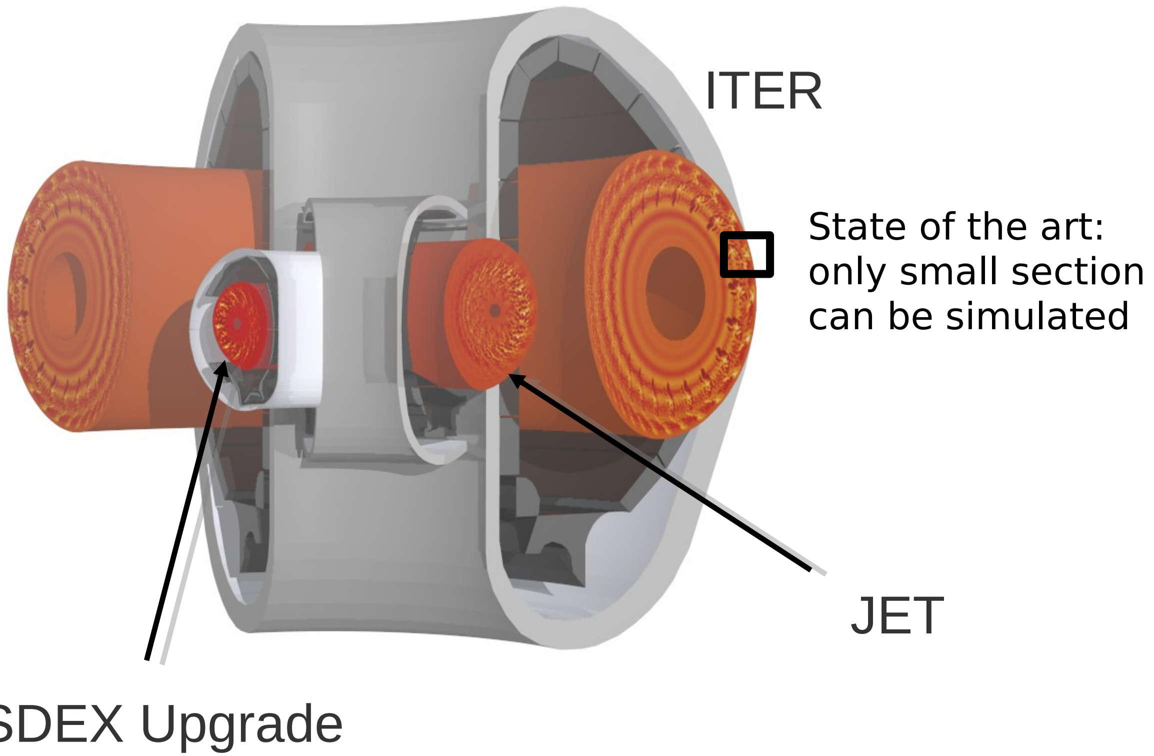
Example: *GENE* Code [1]

- Plasma simulations
- 5D + time nonlinear PDE (Vlasov equations):

$$u(t; x, y, z, \mu, \nu) \rightarrow 2^{n_x} \times 2^{n_y} \times 2^{n_z} \times 2^{n_\mu} \times 2^{n_\nu}$$

- Production runs: billions of grid points!
- ~10^7 core-hours; several TB of short-term storage
- Future of clean energy?

Problem 1: Computational resolution limit reached



Gyrokinetic Electromagnetic Numerical Experiment

Problem 2: *GENE* is not fault tolerant

- 100,000's lines of Fortran code!
- Replace MPI with ULFM?
- Implement efficient checkpointing
- Redefine communicators
- Implement restart / recovery routines
- 1.5 Post Doc years later + 1,000's lines of code changed + 10's of E-Mails with ULFM devs
  → Little progress...

Goal 1: Increase computational resolution of high-dimensional PDE solvers

Goal 2: Resilience

Our approach: New *algorithmic* approaches

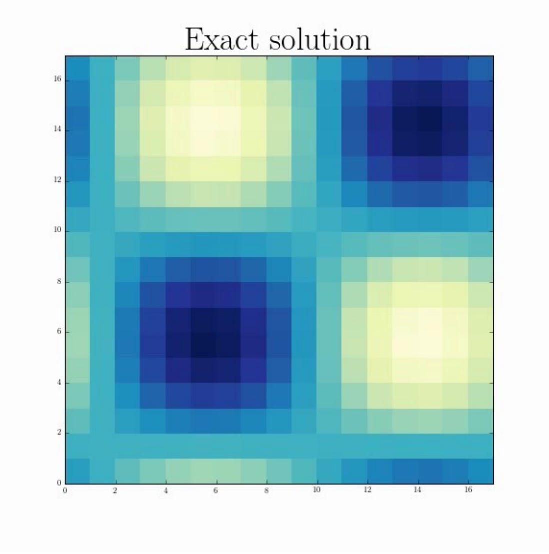
→ The Sparse Grid Combination Technique

The Sparse Grid Combination Technique

- Extrapolation method to solve high-dimensional problems
- Simple example in 2D

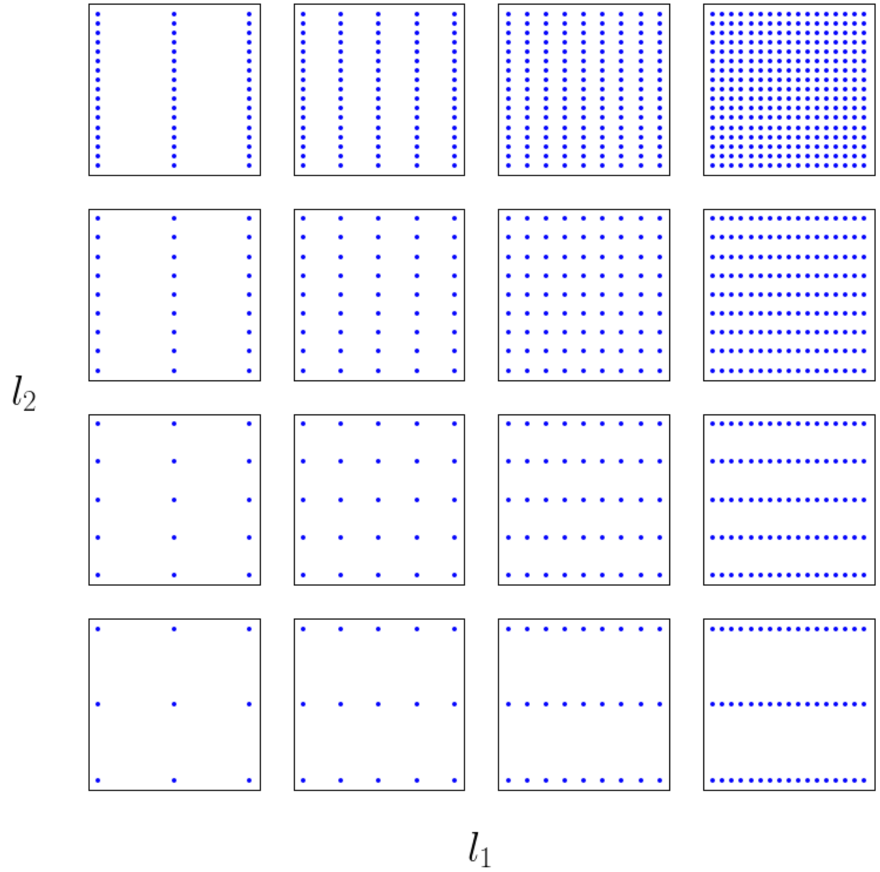
$$\frac{\partial u}{\partial t} + \frac{\partial u}{\partial x} + \frac{\partial u}{\partial y} = 0$$

with $u(x, y, t = 0) = \sin(2\pi x)\sin(2\pi y)$



The Sparse Grid Combination Technique

- Each grid has $(2^{l_1}+1)\times(2^{l_2}+1)$ grid points



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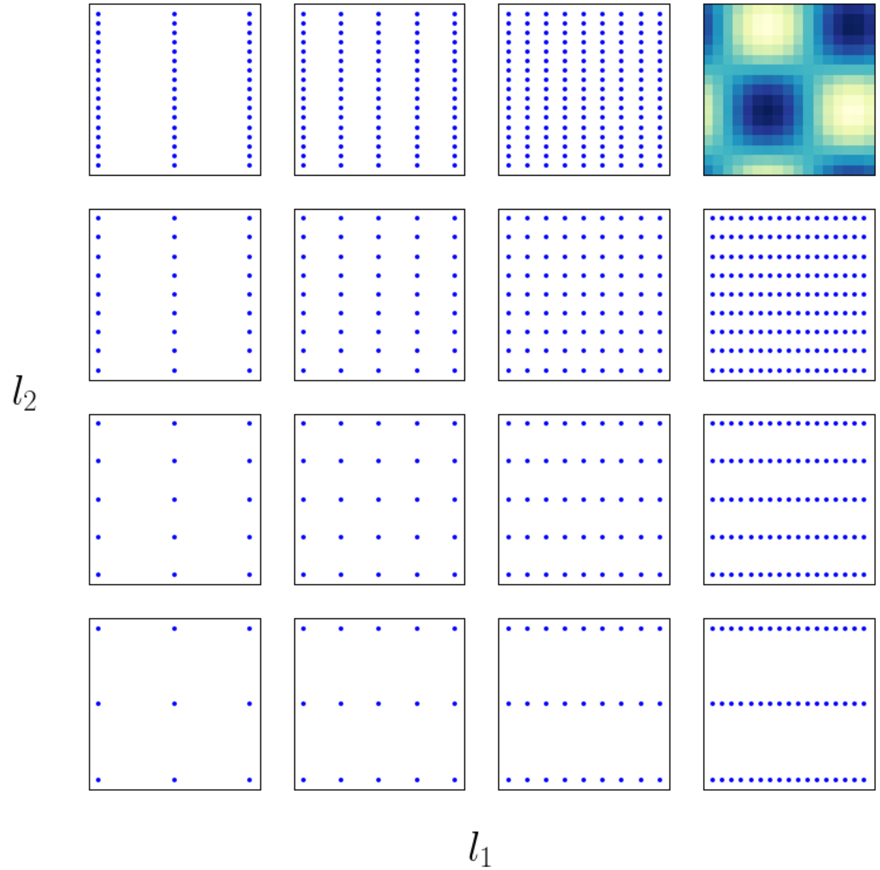
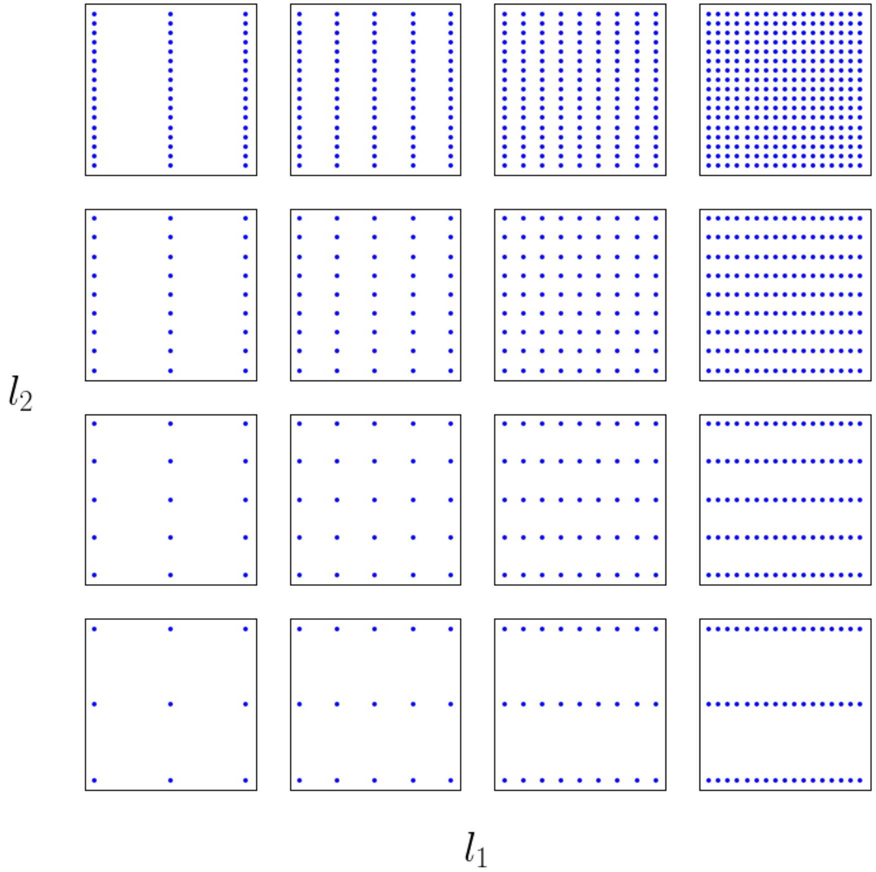


The Sparse Grid Combination Technique

- A very simple extrapolation scheme



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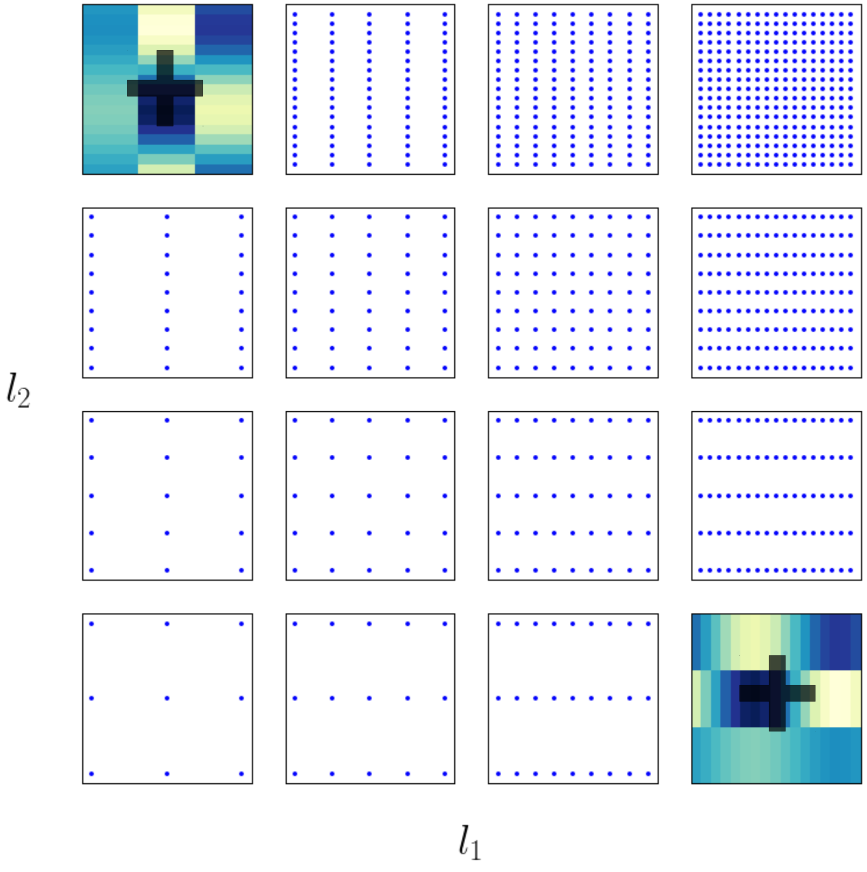

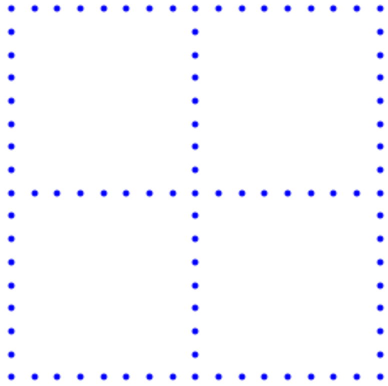

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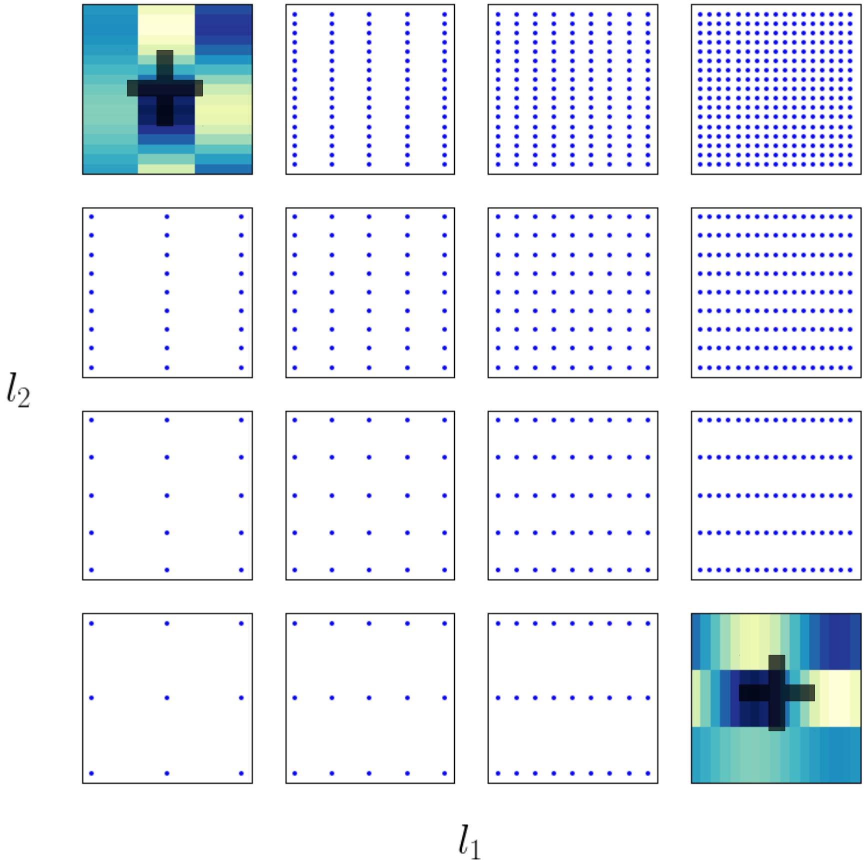

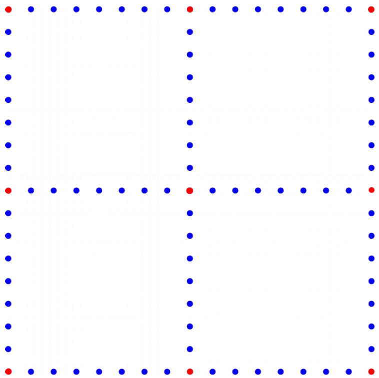

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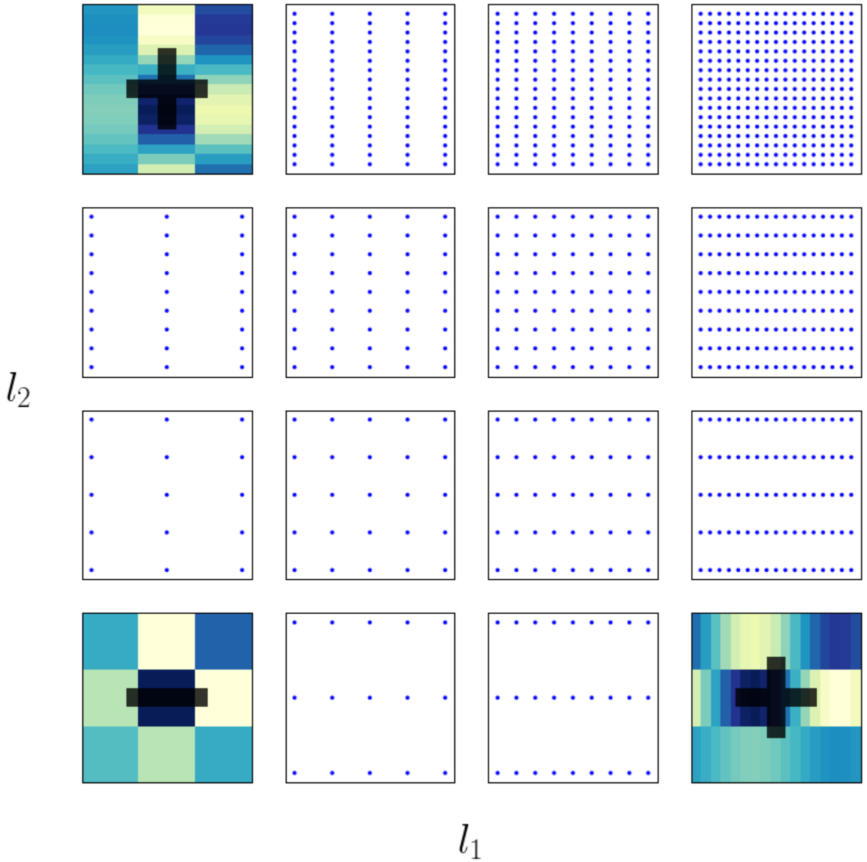

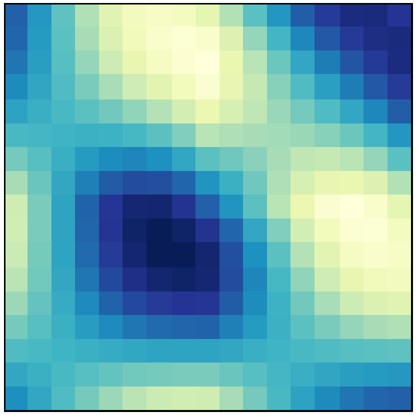

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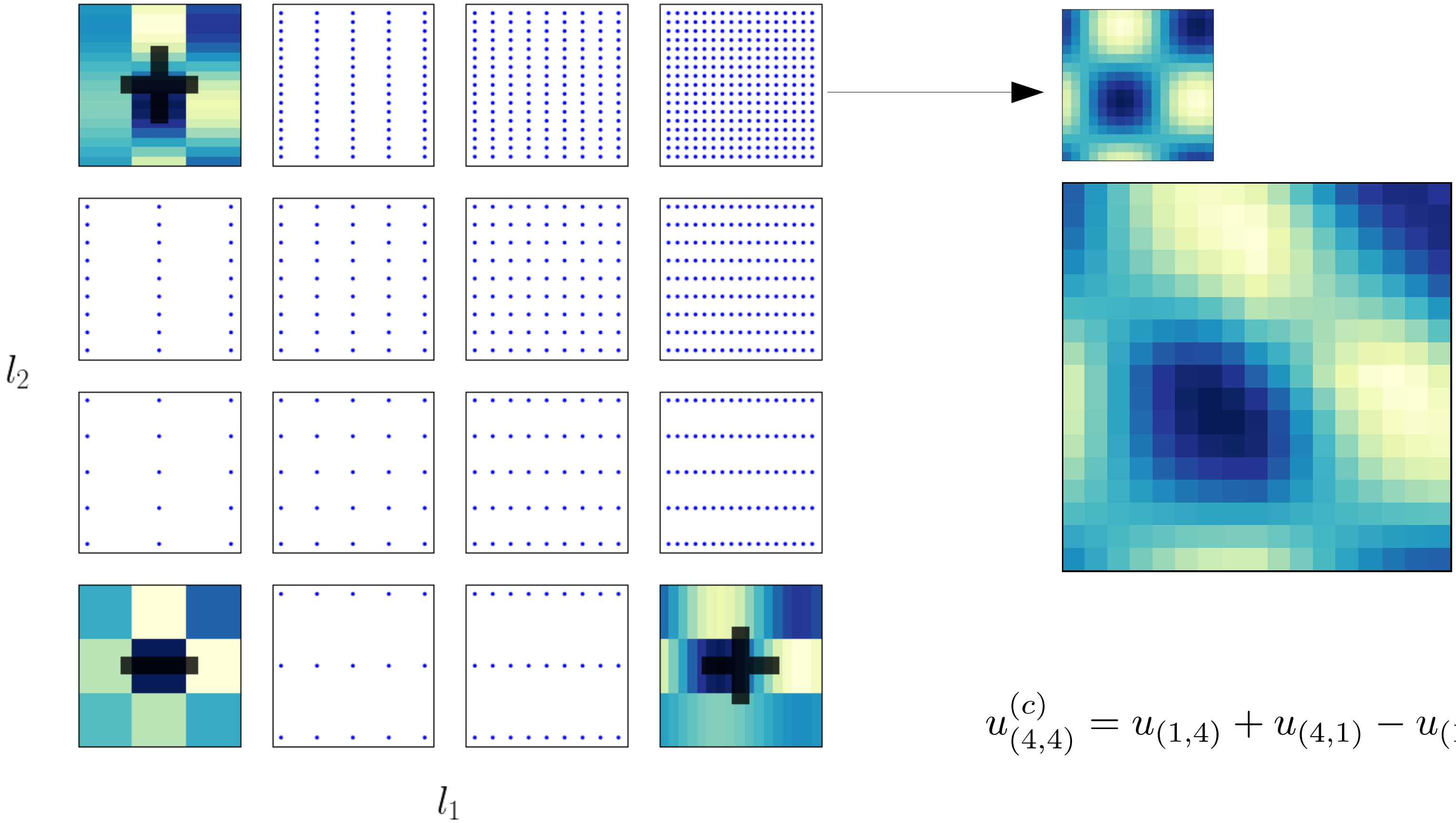

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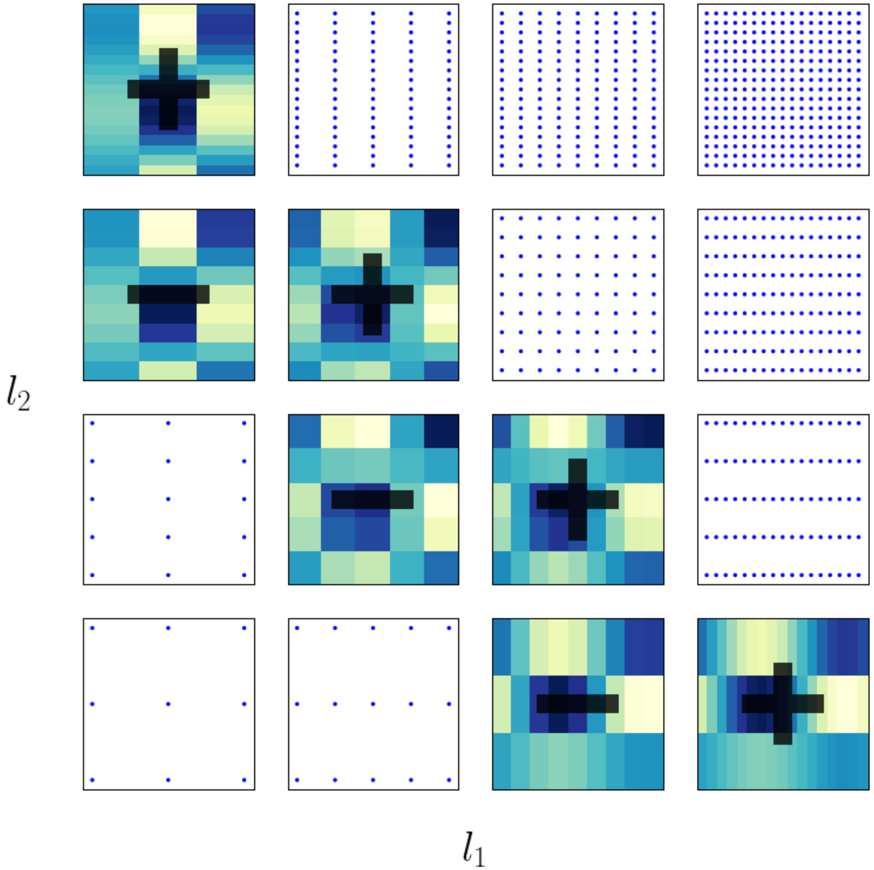
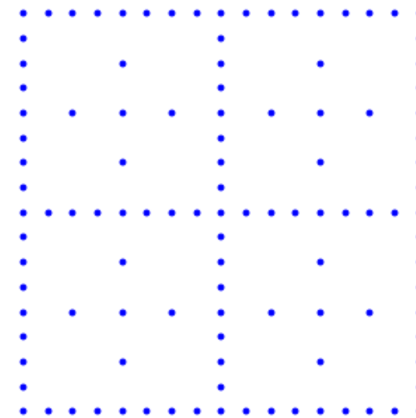
The Sparse Grid Combination Technique

- The *Classical Combination Technique*





$$u^{(c)}_{(4,4)} = u_{(1,4)} + u_{(2,3)} + u_{(3,2)} + u_{(4,1)} - u_{(1,3)} - u_{(2,2)} - u_{(3,1)}$$

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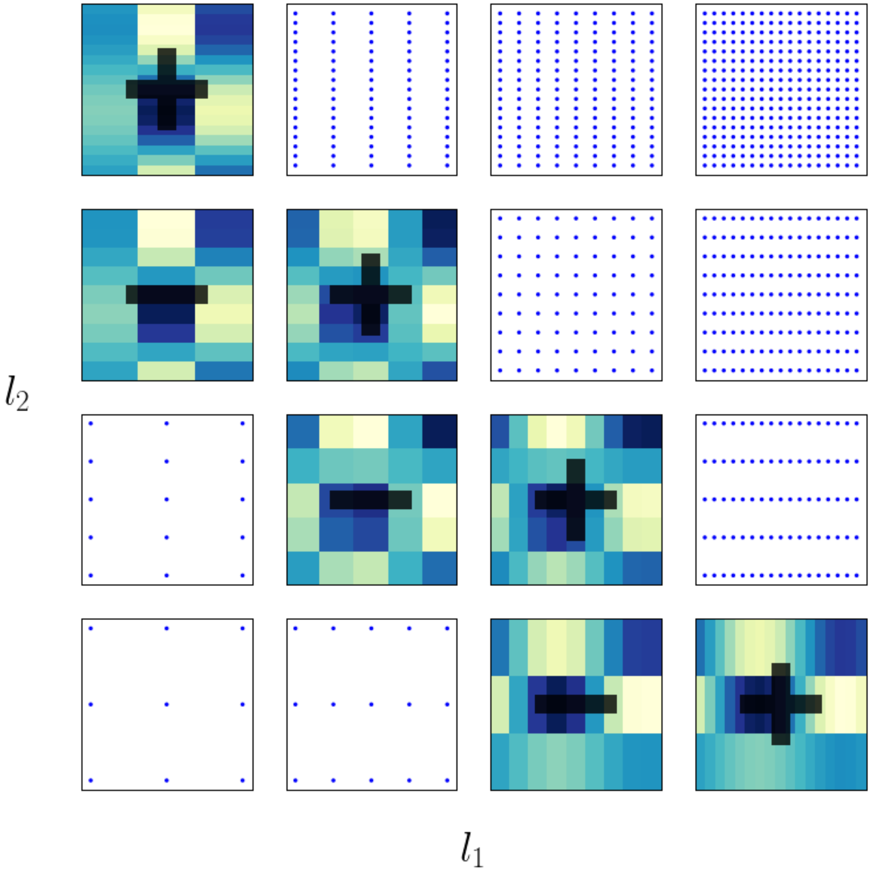

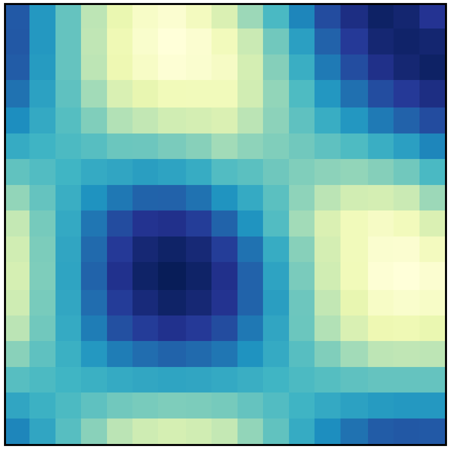

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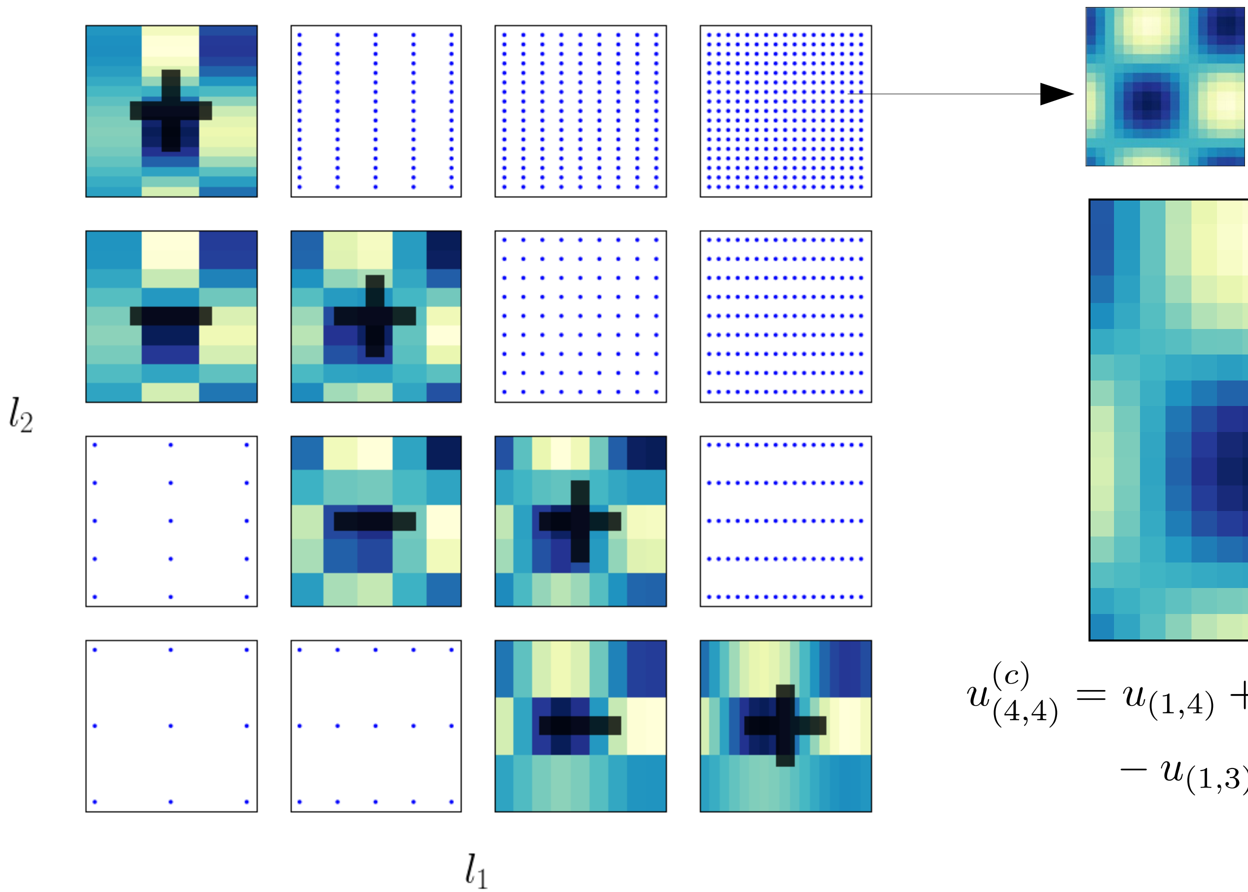

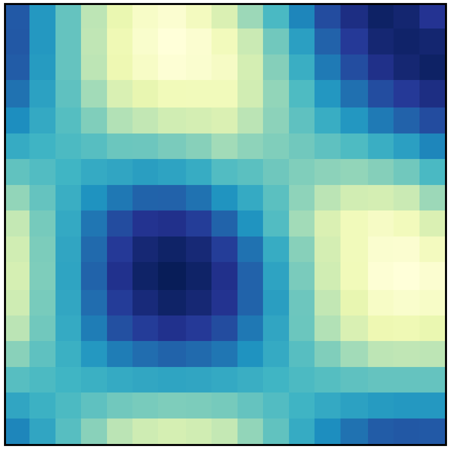

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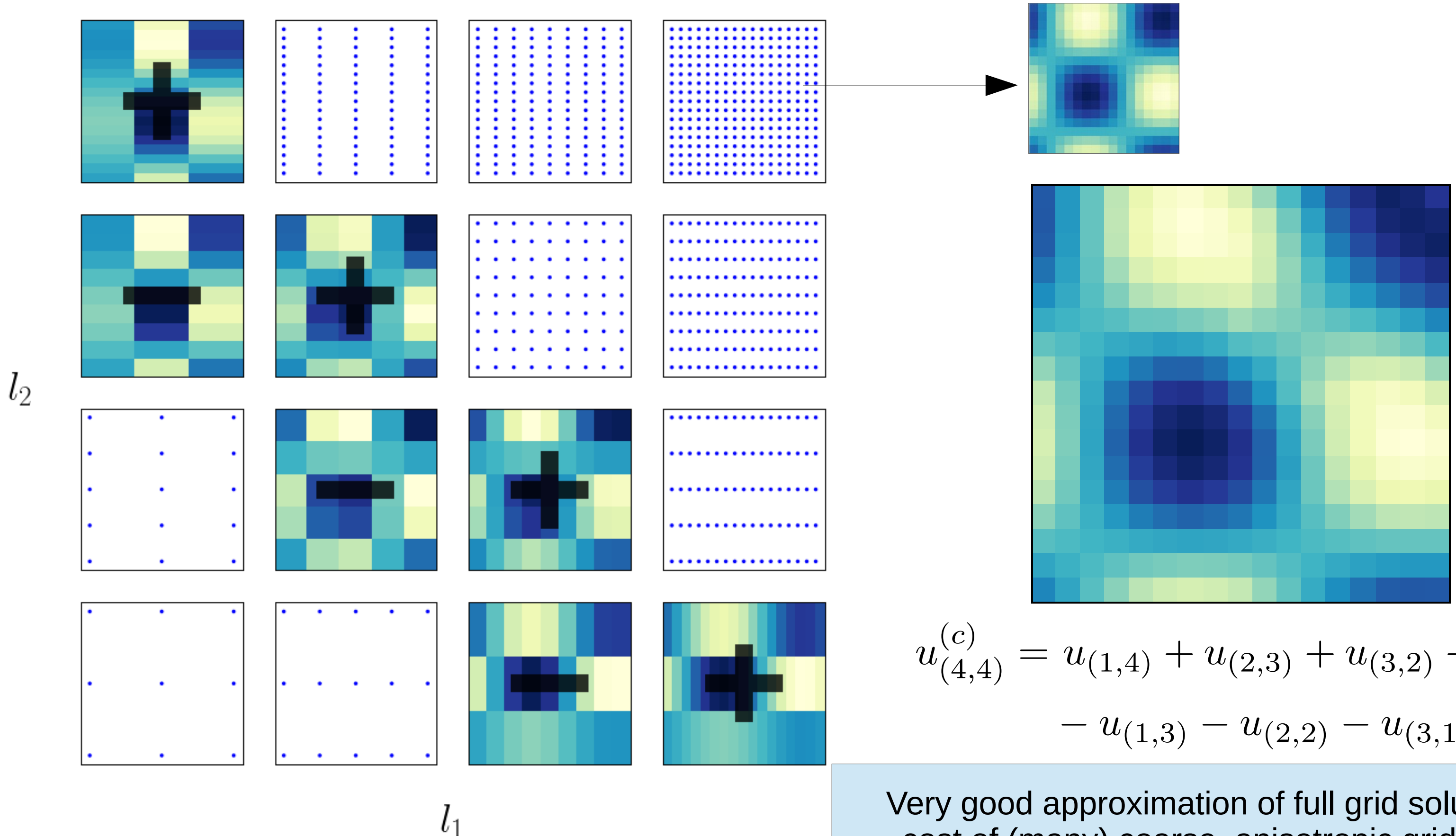
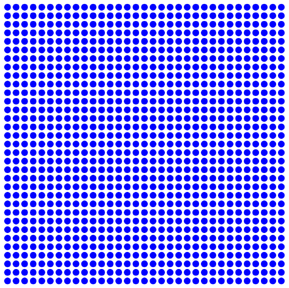


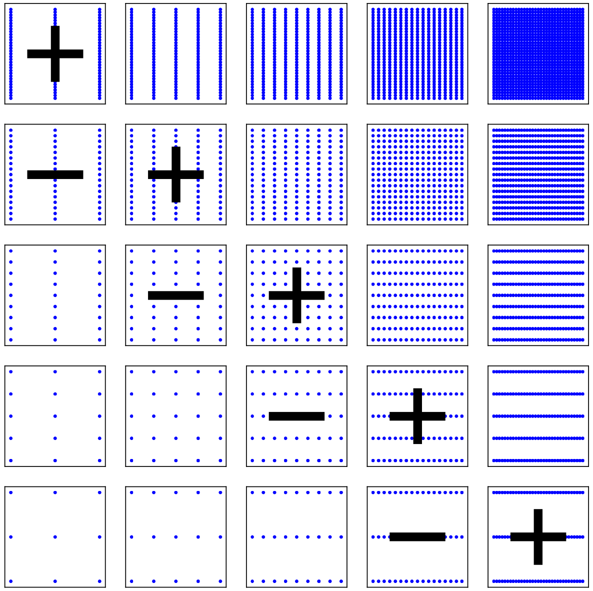
$$u^{(c)}_{(4,4)} = u_{(1,4)} + u_{(2,3)} + u_{(3,2)} + u_{(4,1)} - u_{(1,3)} - u_{(2,2)} - u_{(3,1)}$$

Very good approximation of full grid solution at the cost of (many) coarse, anisotropic grids (cheap!)

The Sparse Grid Combination Technique

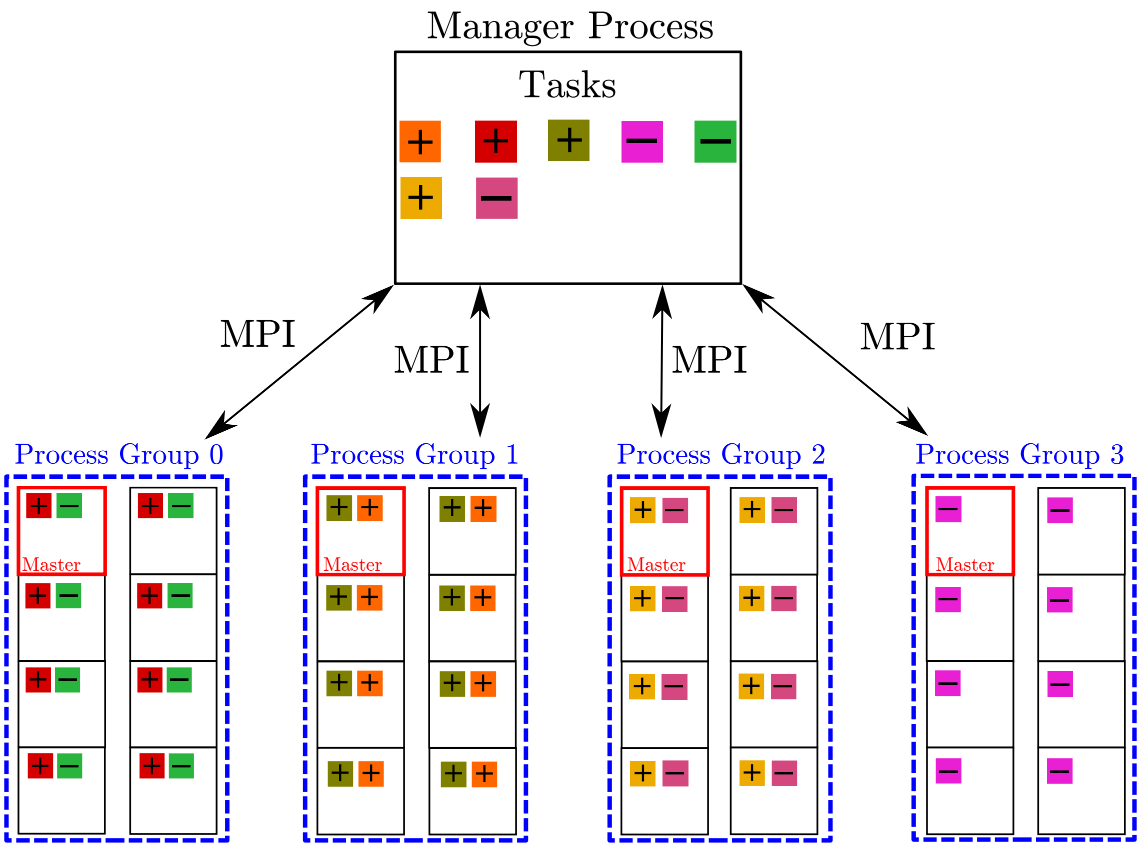
Dimension	# points per dimension	# points full grid	# points Combination Technique
6	2^{10}	$> 10^{18}$	4,096 × 249,000
10	2^{12}	$> 10^{37}$	352,705 × 80,641,000





Parallelizing the Combination Technique

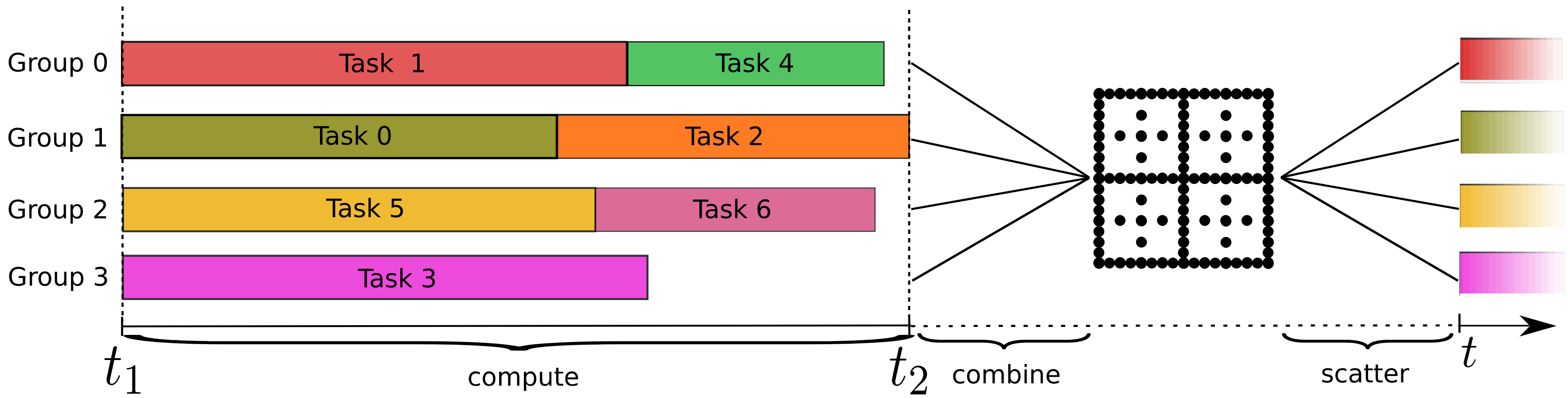
Manager-Worker Model



Parallelizing the Combination Technique

Basic algorithm:

1. Distribute tasks among groups and set initial conditions
2. Each group solves N timesteps of each task
3. Combine tasks to obtain sparse grid
4. Use combined sparse grid solution as initial condition for next N timesteps



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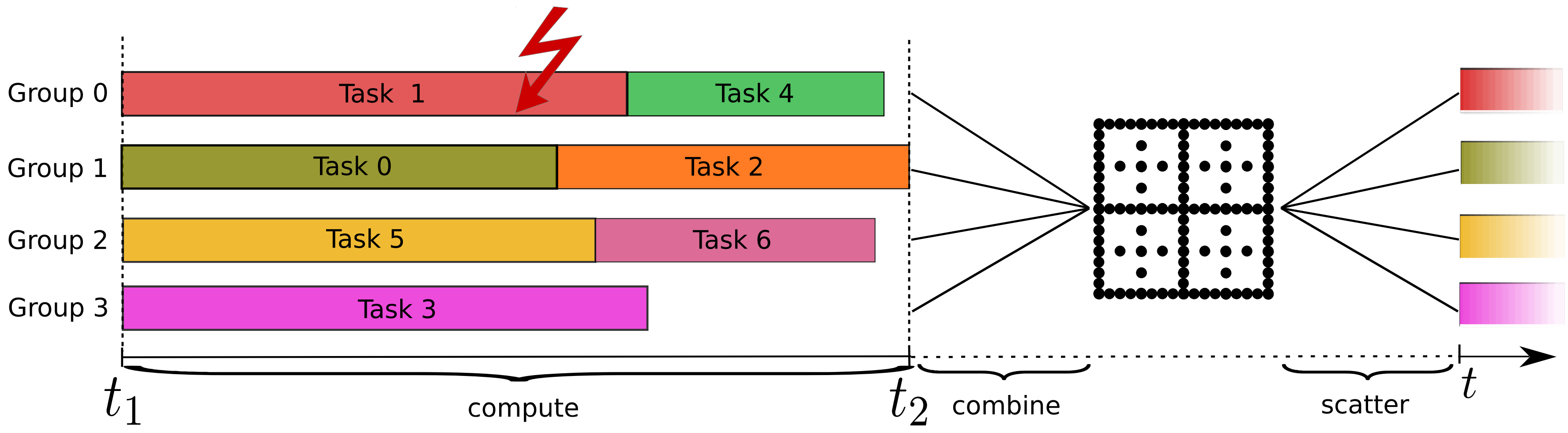
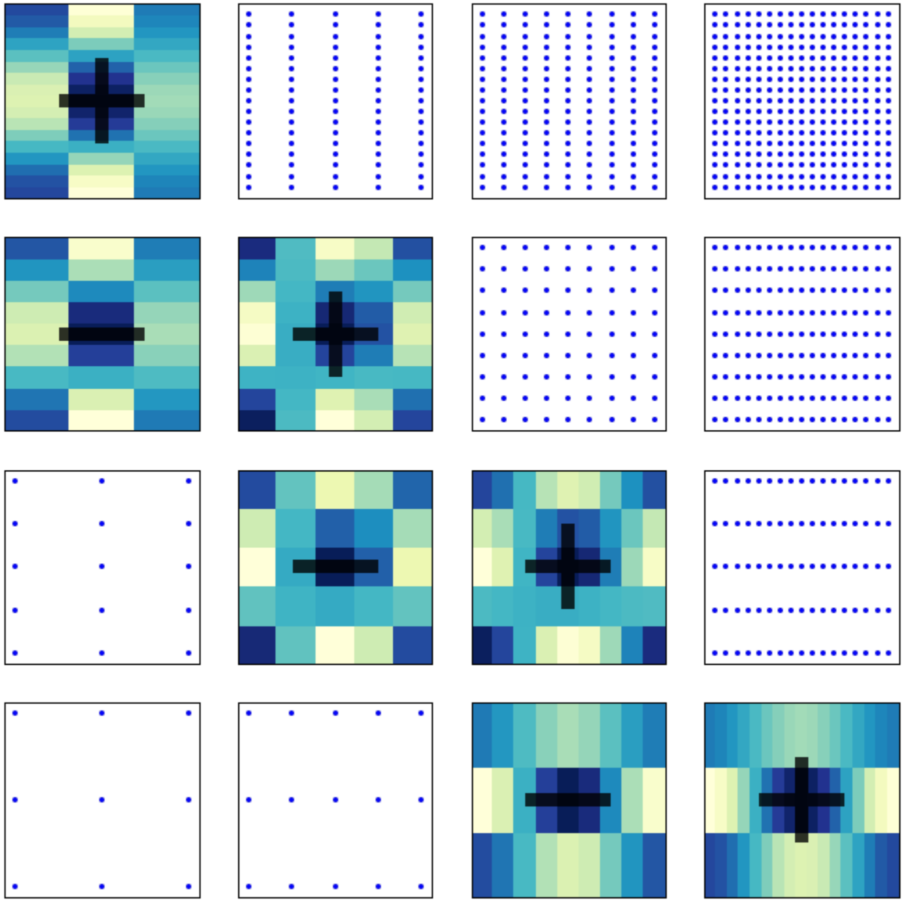
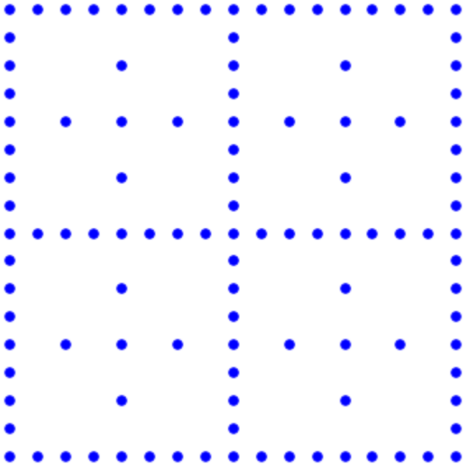


Algorithmic approach to fail-stop failures [2]





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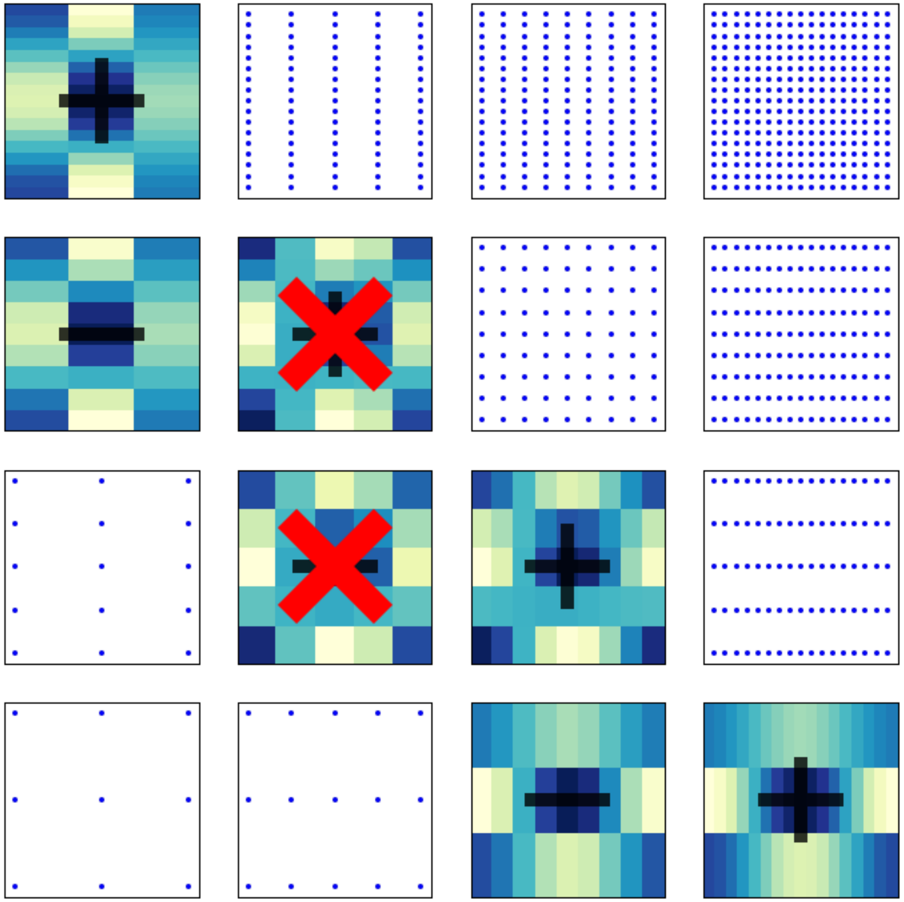

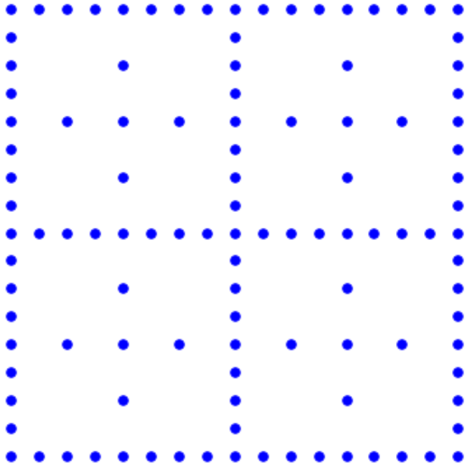

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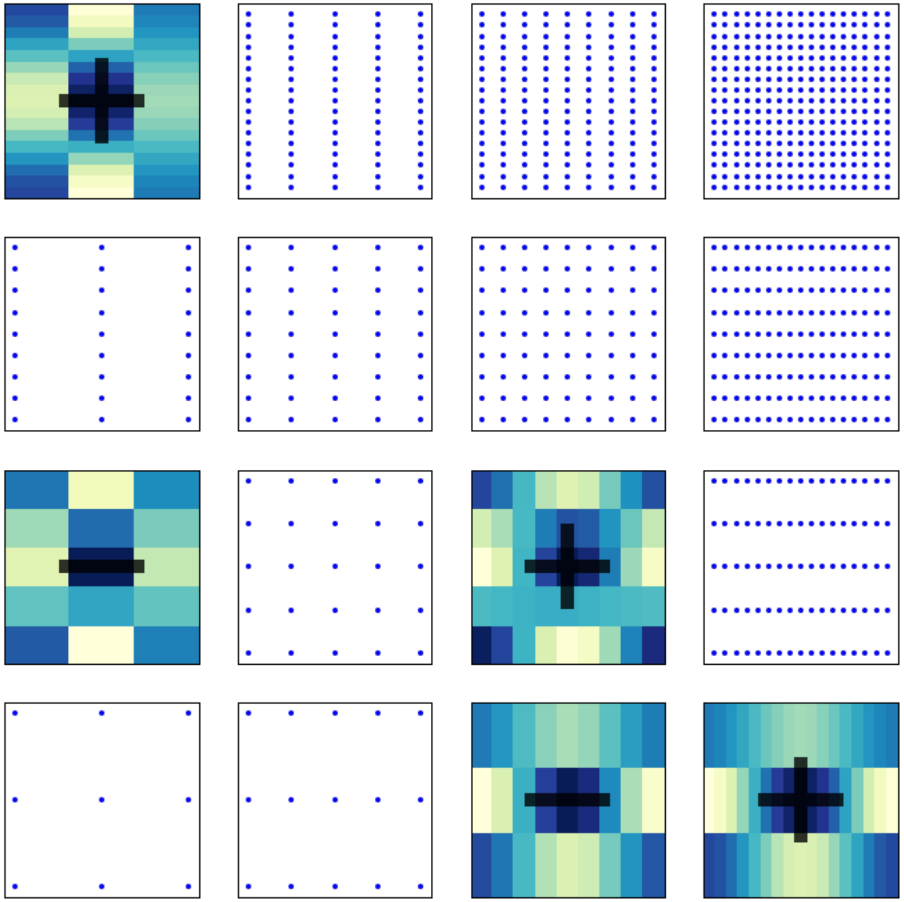
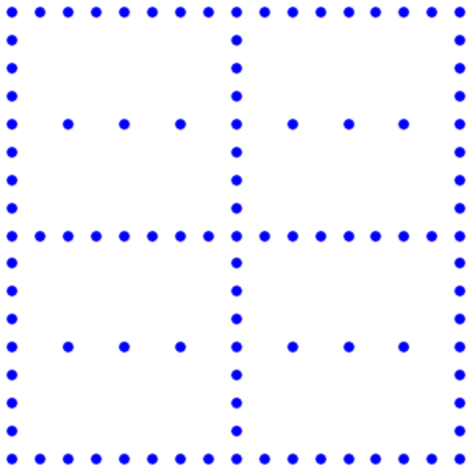
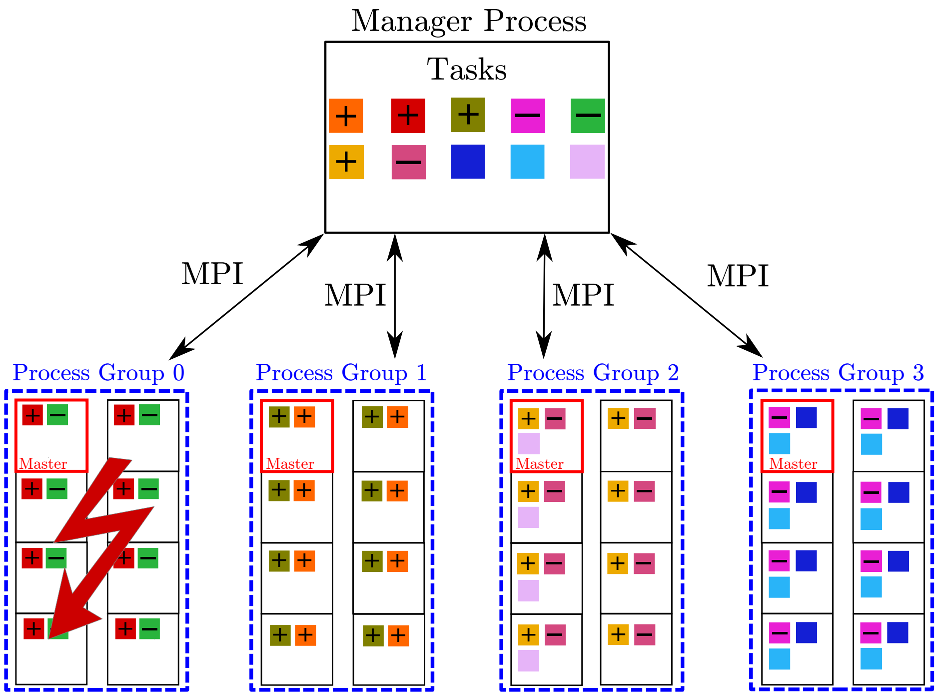




Recovery strategy (ULFM-like)

- Detect failed group during collective operation (combine)



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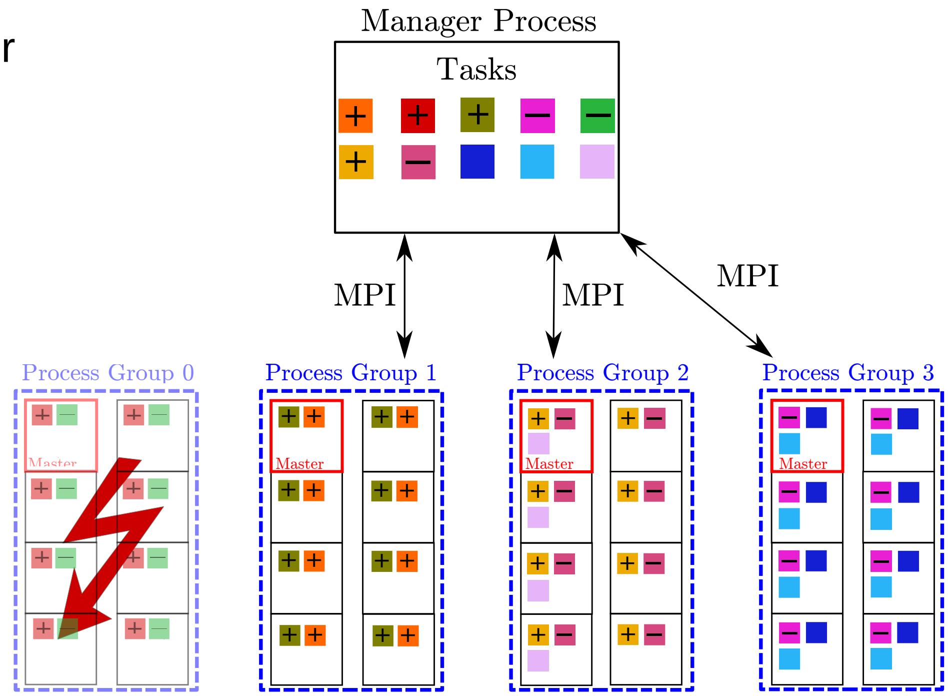

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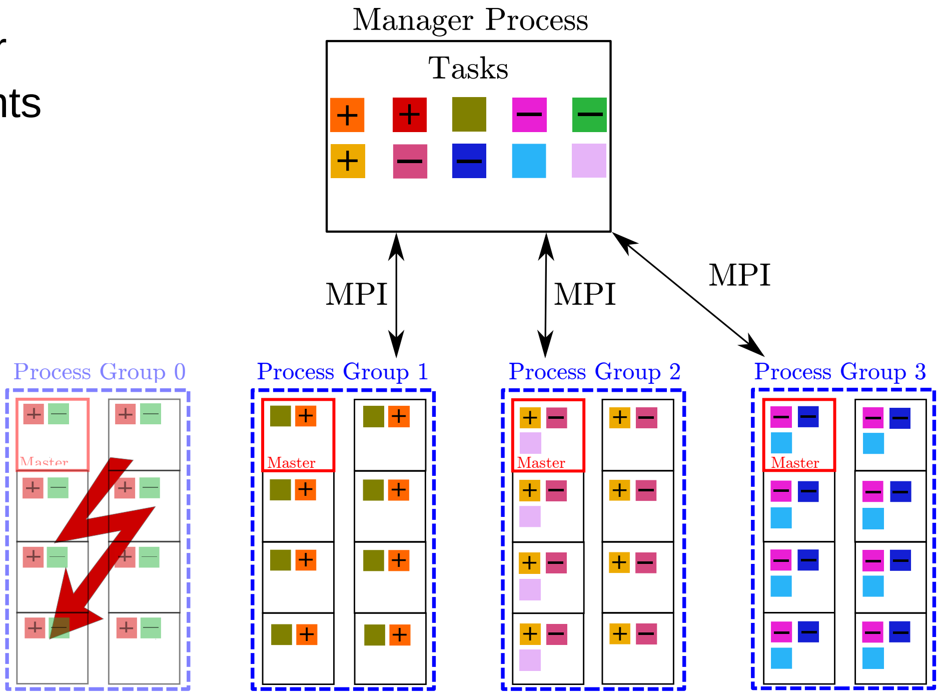

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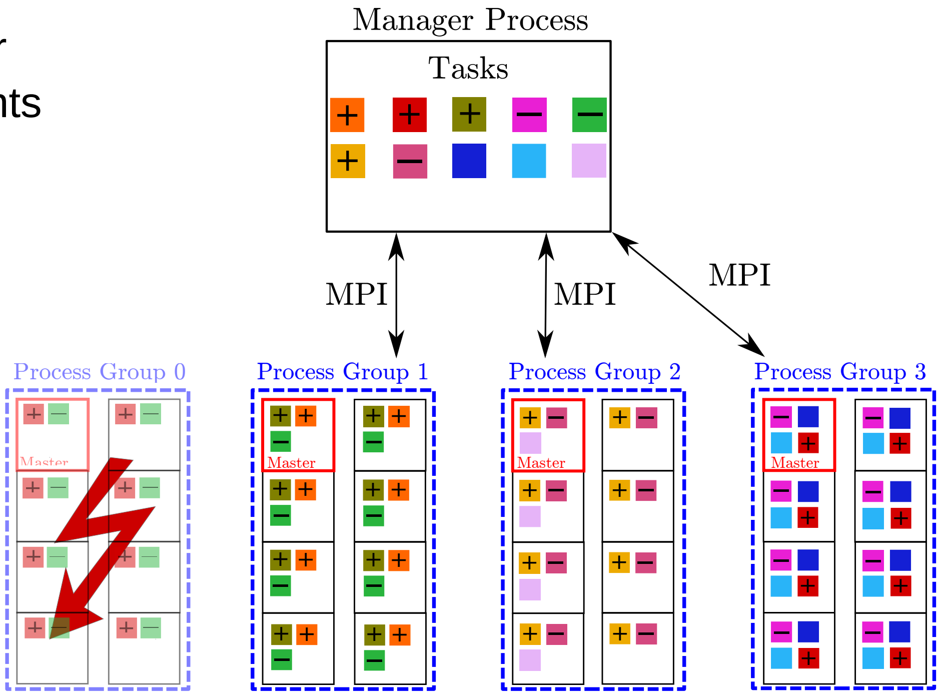

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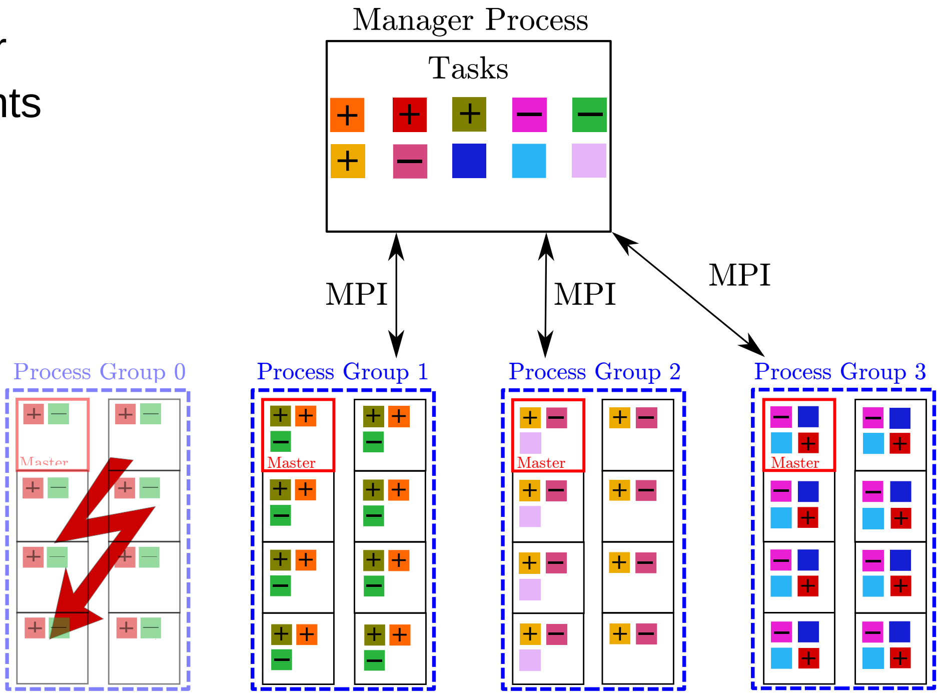


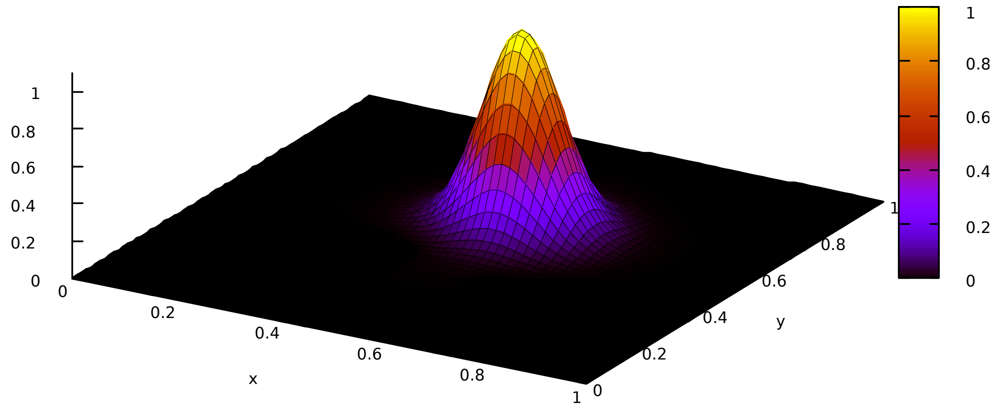
- Key questions:
  1) How good is the solution after faults compared to the solution without faults?
  2) What is the overhead of the fault tolerance functions? Does it scale?

Simulation scenario

- Solve *d*-dimensional advection-diffusion equation using *DUNE*[5]

$$\begin{aligned} \partial_t u - \Delta u + \vec{a} \cdot \nabla u &= f && \text{in } \Omega \times [0,T) \\ u(\cdot,t) &= 0 && \text{in } \partial\Omega \end{aligned}$$

with $\Omega = [0,1]^d$, $\vec{a} = (1,1,...,1)^T$ and $u(\cdot,0) = e^{-100\sum_{i=1}^{d}(x_i-0.5)^2}$



Simulation scenario

- Supercomputer *Hazel Hen (CRAY XC40)* at the *High-Performance Computing Center,* Stuttgart (#9 in Top 500, 2016)

Convergence experiments

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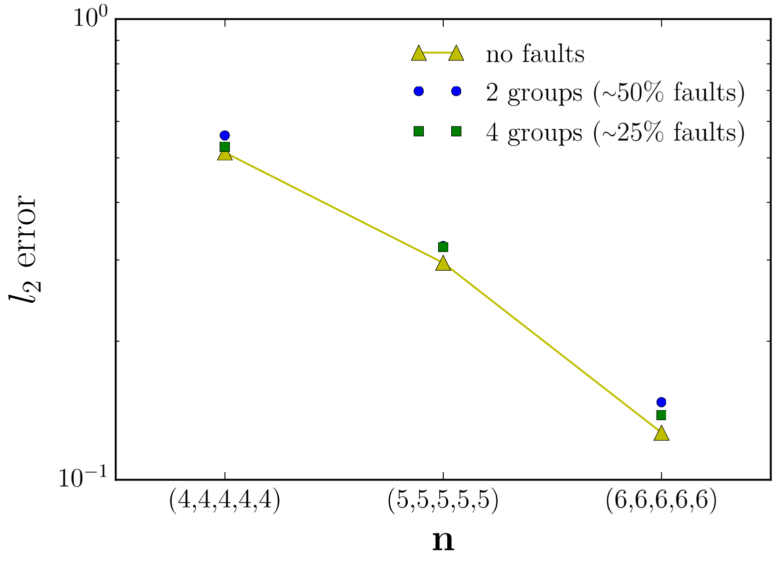
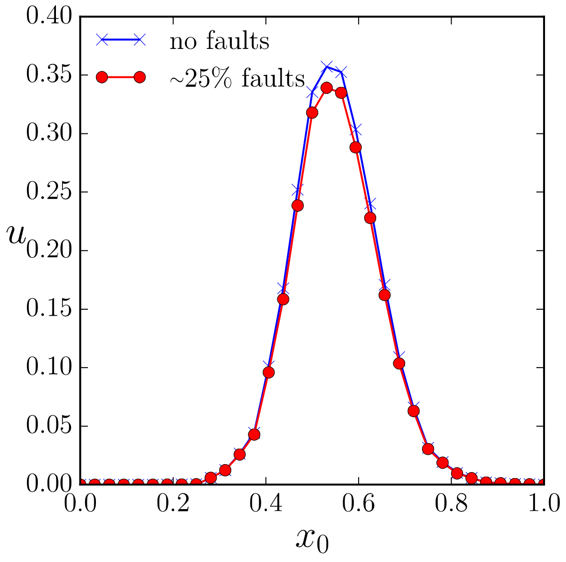


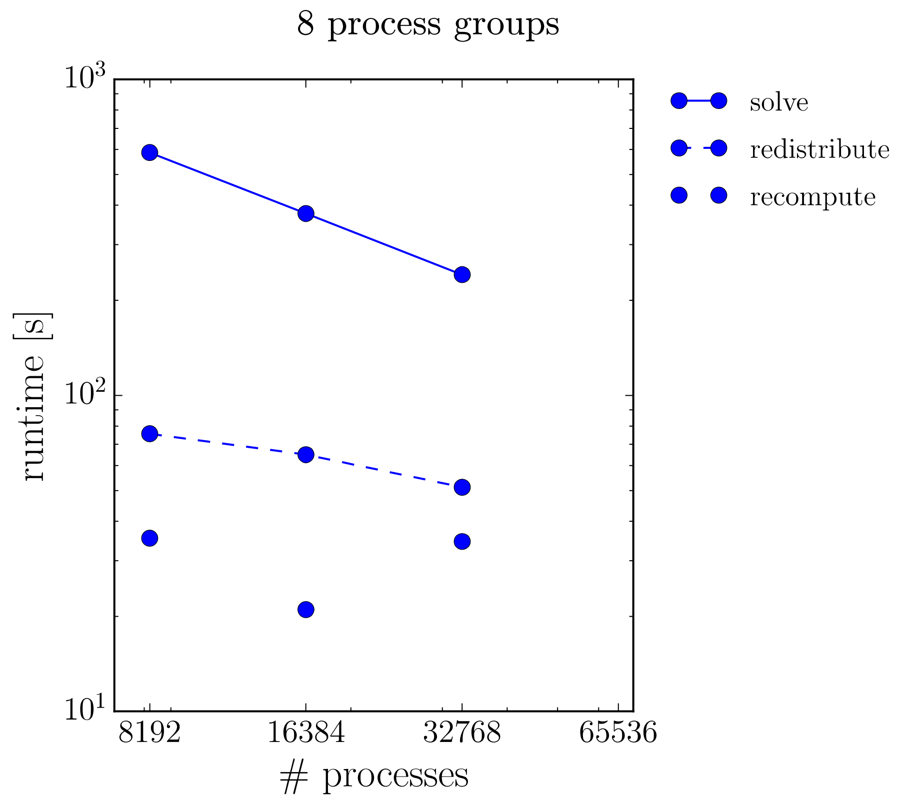
5D convergence



Cross section of 5D solution with and without faults

Strong scaling experiments

- Compare time to ***solve*** one timestep vs time to ***redistribute*** (and reinitialize) tasks vs time to ***recompute*** some tasks



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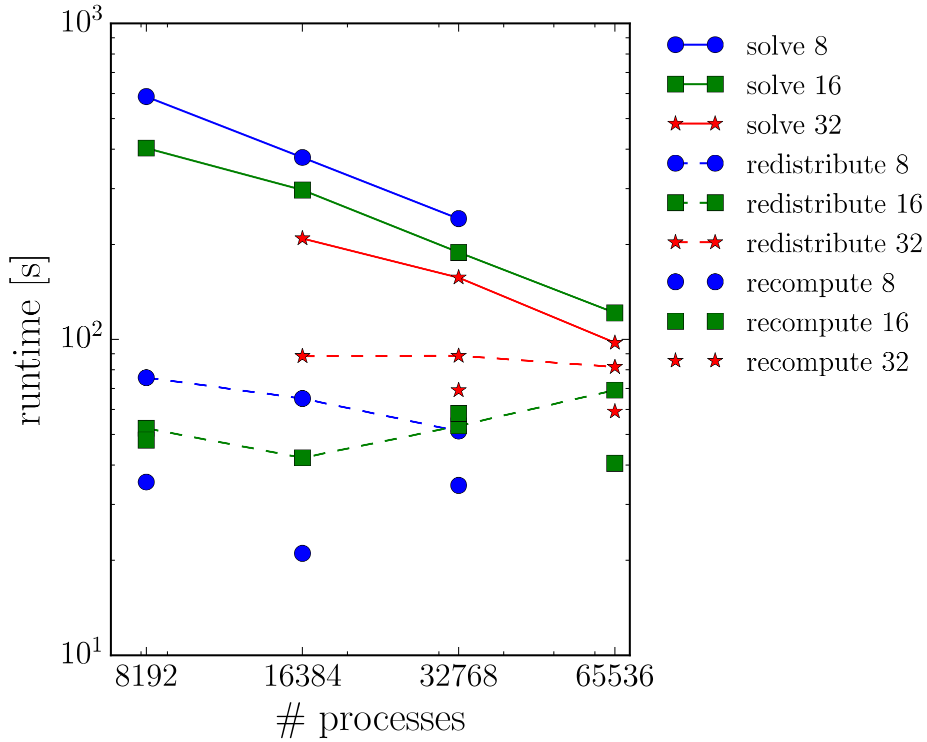
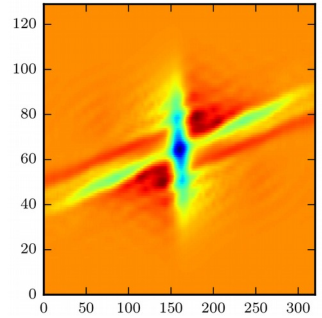
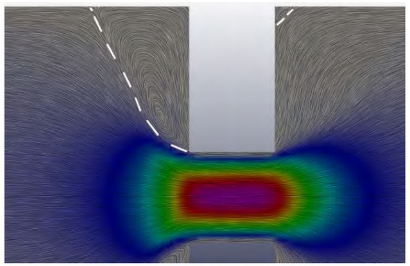
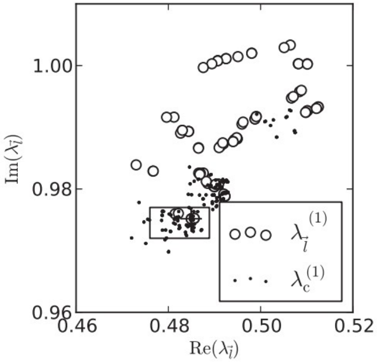


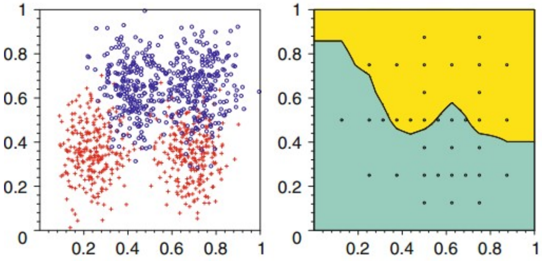
Takeaways

- Combination Technique is attractive for peta-/exascale:
  1. Solve PDEs (approximately) with high resolution (impossible with full grids) at the cost of many cheap solves (in parallel!)
  2. Offers algorithmic fault tolerance: no checkpoint/restarting, duplication, etc.









Ongoing: detection of silent data corruption [6]

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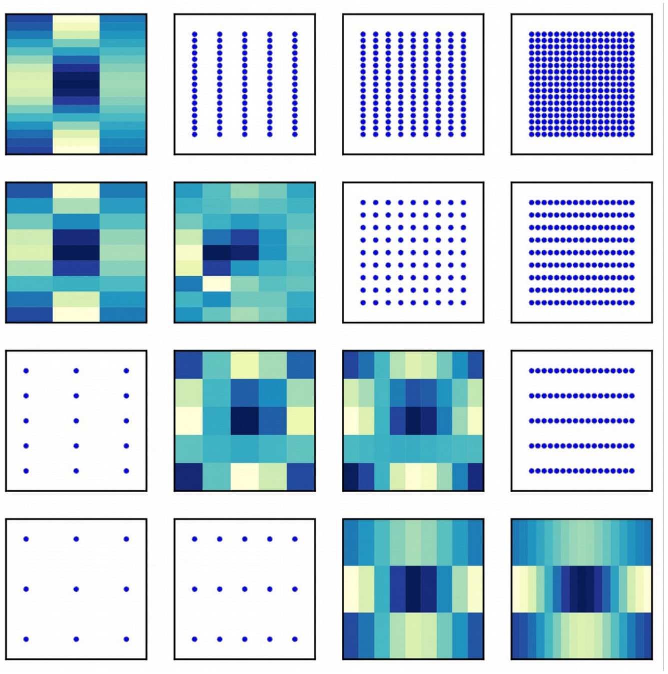

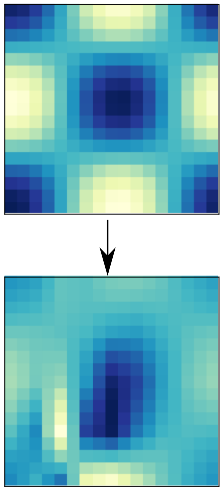

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