Massively Parallel Simulation of Plasma Turbulence with the Sparse Grid Combination Technique

Mario Heene[1], Alfredo Parra Hinojosa[2] and Dirk Pflüger[1]
[1] {mario.heene,dirk.pflueger}@ipvs.uni-stuttgart.de, Institute of parallel and distributed Systems, University of Stuttgart
[2] hinojosa@in.tum.de, Chair of Scientific Computing, Technische Universität München

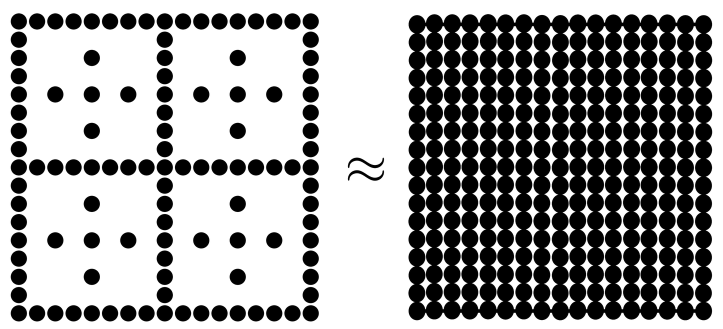
Universität Stuttgart

Motivation

Size of **higher dimensional problems** is severely limited by **curse of dimensionality**
→ computational effort grows exponentially with dimension $\mathcal{O}\left((2^n)^d\right)$

Sparse Grids mitigate curse of dimensionality
- drastically **reduce number of grid points** (degrees of freedom) from $\mathcal{O}\left((2^n)^d\right)$ to $\mathcal{O}\left(2^n n^{d-1}\right)$
- accuracy only slightly deteriorated

Sparse Grid ≈ Regular Grid



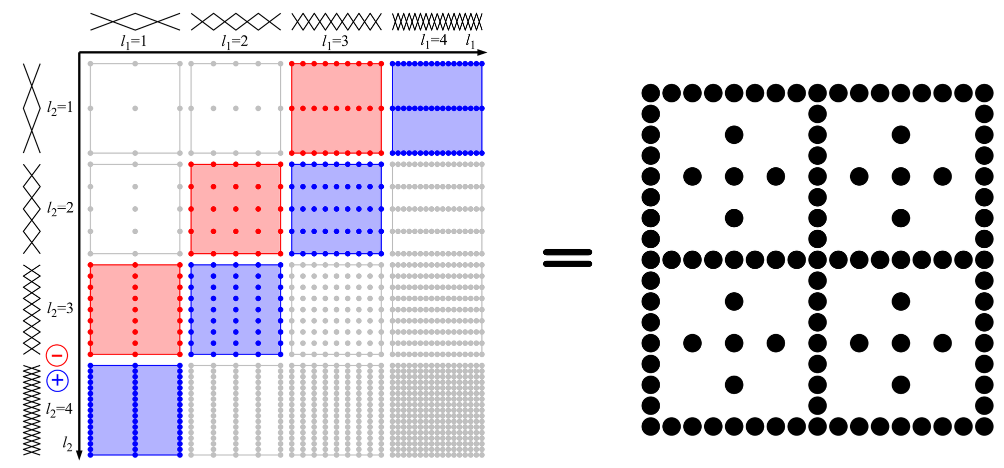
$159 \cdot 10^9$ $> 10^{37}$
(#grid points for d=10, discretization level n=12)

Tackle **exascale software challenges:**
- scalability
- load balancing
- fault tolerance

Sparse Grid Combination Technique

Idea:
- solve problem on different **coarse and anisotropic regular grids**
- combine component solutions to obtain sparse grid approximation

$$u(\boldsymbol{x}) \approx \sum_{l \in I} c_l u_l(\boldsymbol{x})$$



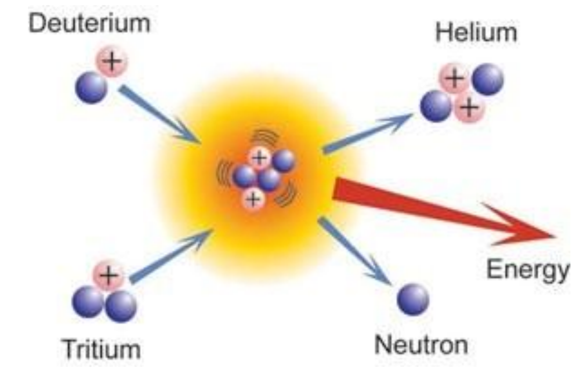
component grids and the resulting sparse grid for d=2 and n=4

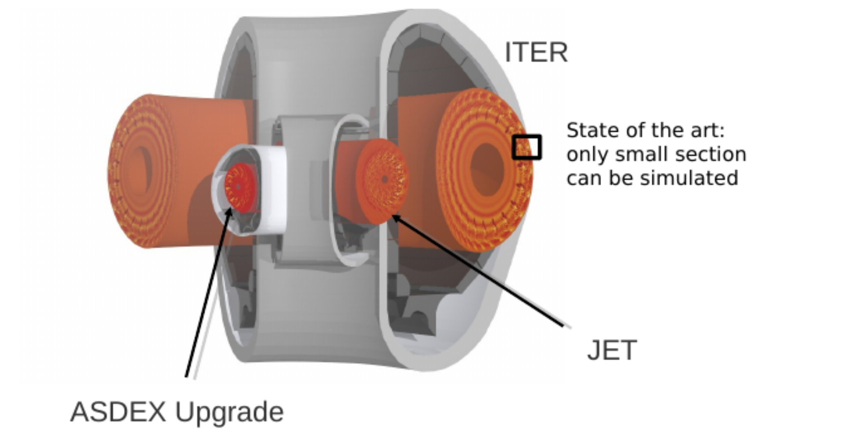
- **independent and asynchronous** computation of component solutions → **second level of parallelism**
- existing solvers can be used
- certain degree of inherent redundancy → **resilience**

Application: GENE

Simulation of microturbulence in hot, magnetized fusion plasmas
- **five-dimensional** gyrokinetic equations:

$$\frac{\partial F_\sigma}{\partial t} + \frac{\mathrm{d}X}{\mathrm{d}t} \cdot \nabla F_\sigma + \frac{\mathrm{d}v_\parallel}{\mathrm{d}t}\frac{\partial F_\sigma}{\partial v_\parallel} = 0$$



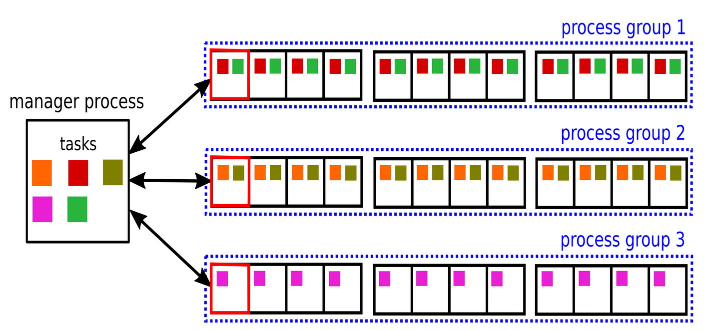


Gyrokinetic Electromagnetic Numerical Experiment
(www.genecode.org)

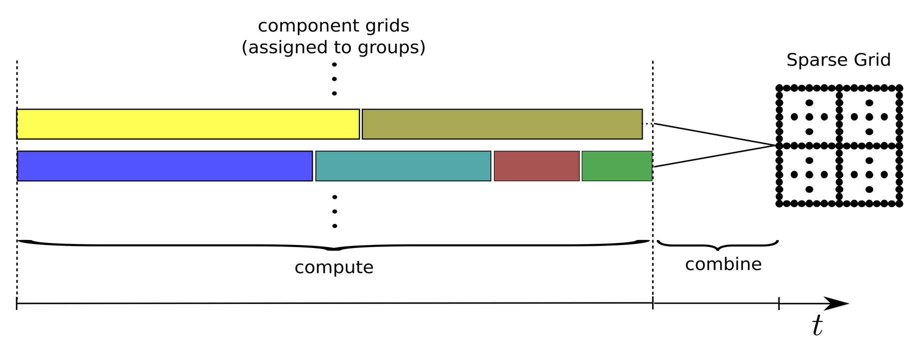
Goal: large-scale simulations of ITER
- global, non-linear runs
- more than 10^{11} grid points, 10^6 time steps
- **exascale performance** necessary

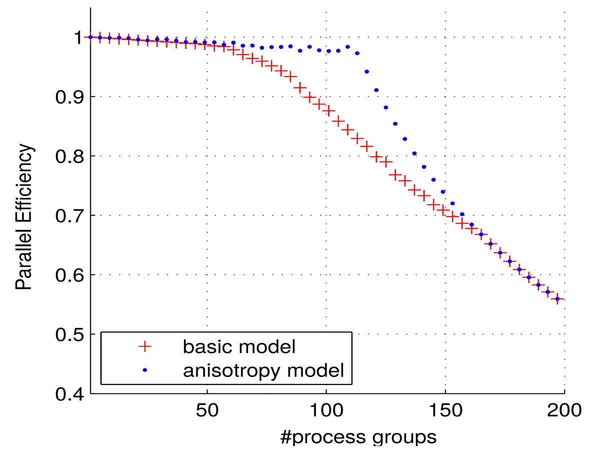
Scalable Parallelization

Parallelization concept: manager-worker model
- arrange processes in groups
- distribute component grids to different process groups



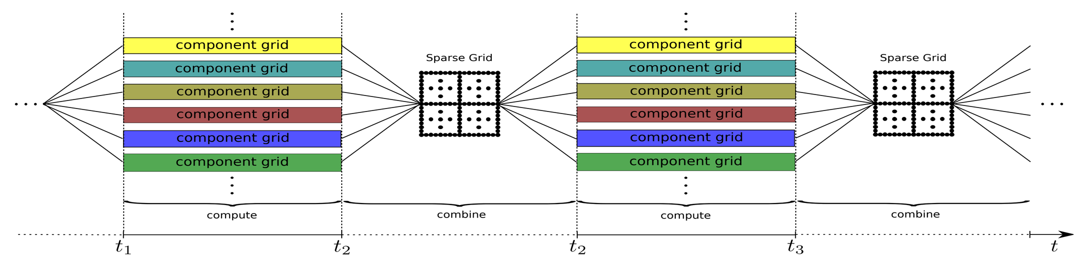
Anisotropic discretizations cause severe **load imbalance**
- developed load model to **estimate execution time** of component solution which considers anisotropy
- ensures **good load balancing** for high numbers of process groups



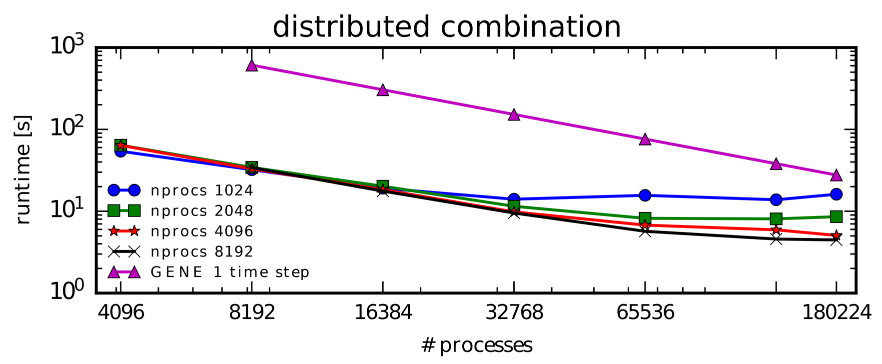


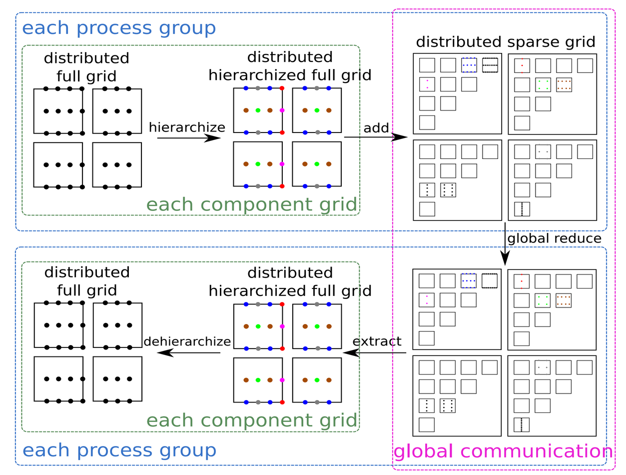
Efficient Global Communication

Time-dependent problems:
- require to **combine** component grids **in sparse grid space** very frequently (in the worst case: after each time step)
  → scalable and efficient global communication is crucial for performance



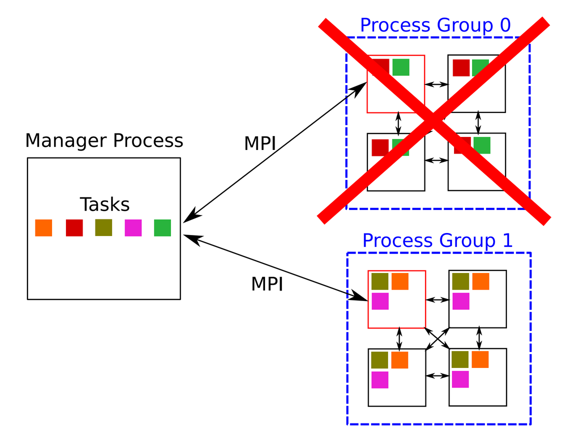
Scalable and efficient combination algorithm:
- exploits hierarchical structure
- scales up to **more than 180 000 cores** (*Hazel Hen*)
- faster than single time step of application

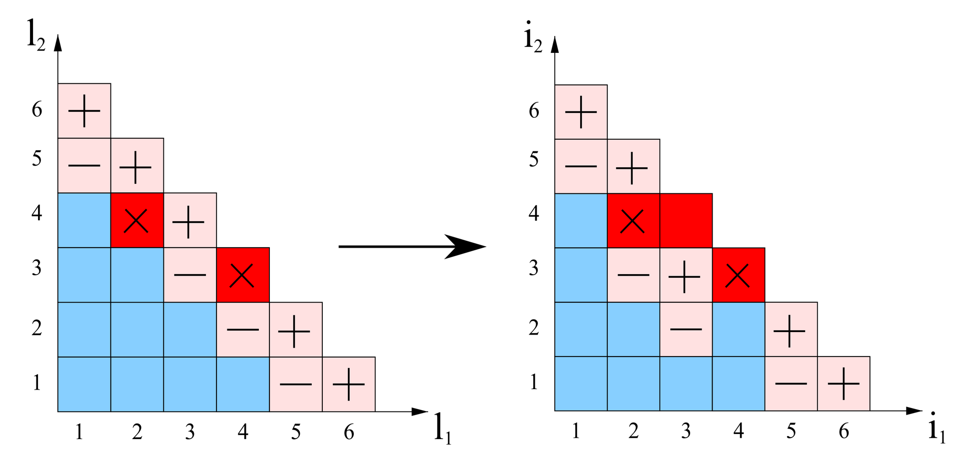




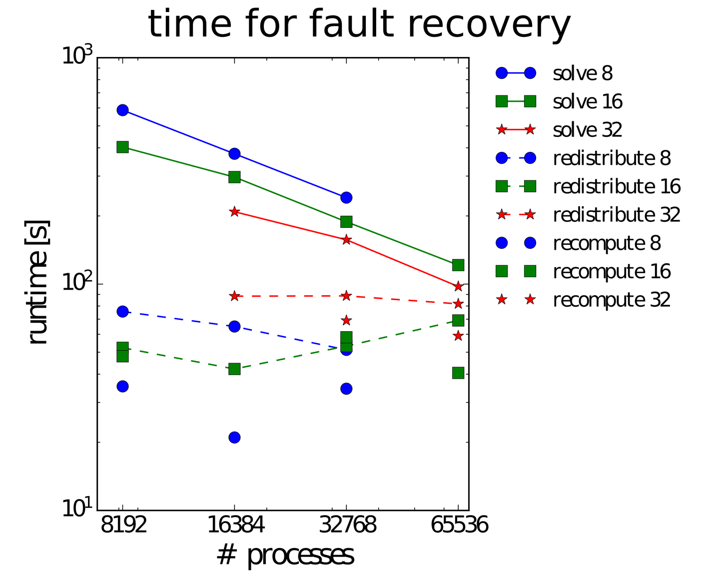
Algorithm-based Fault Tolerance

Algorithm-based fault tolerance at **low cost:**
- node failure → we only lose a subset of our component solutions





- our algorithm chooses a different set of partial solutions that avoids the missing ones
  → **no recomputation necessary**
- **approximation quality only slightly degraded**



[1] M. Heene, C. Kowitz, D. Pflüger. Load Balancing for Massively Parallel Computations with the Sparse Grid Combination Technique. Advances in Parallel Comp., Vol. 25, 2014
[2] P. Hupp, M. Heene, R. Jacob, D. Pflüger. Global Communication Schemes for the Numerical Solution of High-Dimensional PDEs. Parallel Computing, Vol. 52, 2016
[3] M. Heene, D. Pflüger. Efficient and scalable distributed-memory hierarchization algorithms for the sparse grid combination technique. Advances in Parallel Comp., Vol. 27, 2016
[4] M. Heene, D. Pflüger. Scalable algorithms for the solution of higer-dimensional PDEs. Lecture Notes in Computational Science and Engineering (LNCSE), accepted
[5] M. Heene, A. Parra Hinojosa, D. Pflüger, H.-J. Bungartz. A Massively-Parallel, Fault-Tolerant Solver for High-Dimensional PDEs. Euro-Par 2016 Resilience Workshop, accepted

SimTech Cluster of Excellence

SPPEXA Project **EXAHD**