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# HPC Simulations of Microturbulence in Fusion Plasmas

Roman Hatzky  
High Level Support Team  
Max-Planck-Institut für Plasmaphysik

With contributions from:  
CEA-Cadarache, France; IPP, Germany; TKK, Finland

International Supercomputing Conference 2010



# What and what for

Controlled fusion has the potential to give a major contribution to the energy production of the future.

Net gain from fusion devices needs a sufficiently large energy confinement time, i.e. the ratio between the total energy stored in the plasma and the power flowing out via conduction and convection.

Extensive computer codes have to be used for realistically simulating the complex transport dynamics driven by (micro)turbulence in plasmas.

# Multi-scale problems in space and time



MICROTURBULENCE

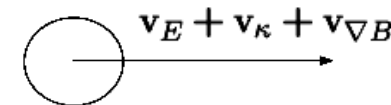
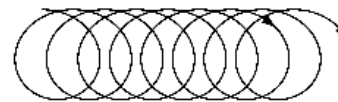
MHD EVOLUTION

TRANSPORT

fluid transport

extended MHD

gyrokinetic



Alfvén  
transit time

sound  
transit time

MHD  
evolution time

transport  
time

resistive  
time

$$t_A \ll$$

$$t_s \ll$$

$$t_{\text{evol}} \ll$$

$$t_{\text{trans}} \ll$$

$$t$$

$$10^{-6}$$

$$10^{-5}$$

$$10^{-4}$$

$$10^{-3}$$

$$10^{-2}$$

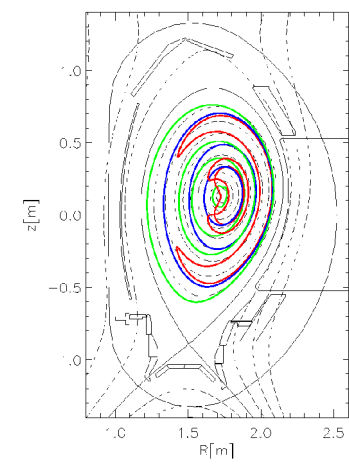
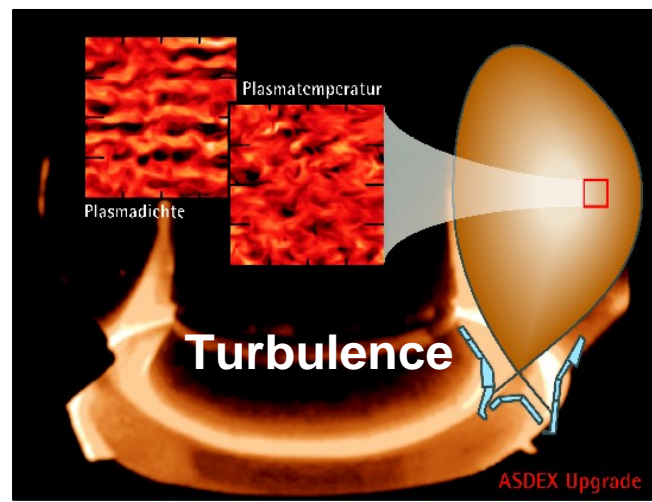
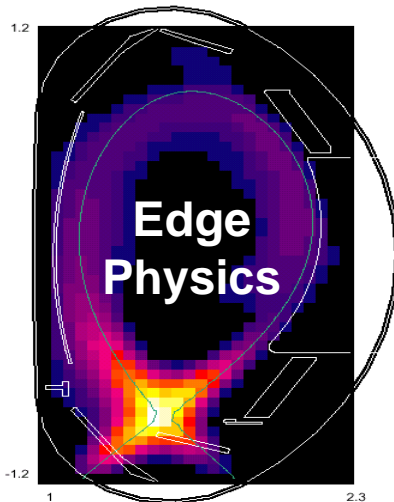
$$10^{-1}$$

$$10^0$$

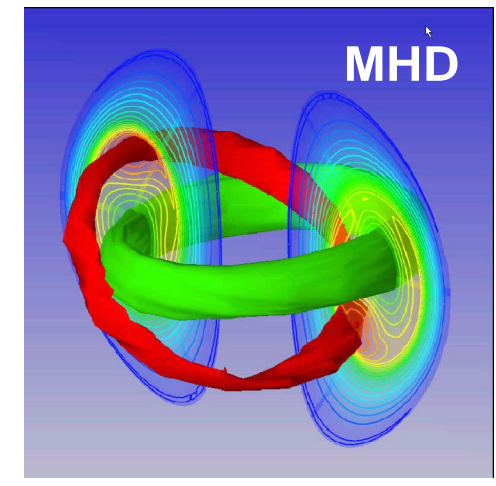
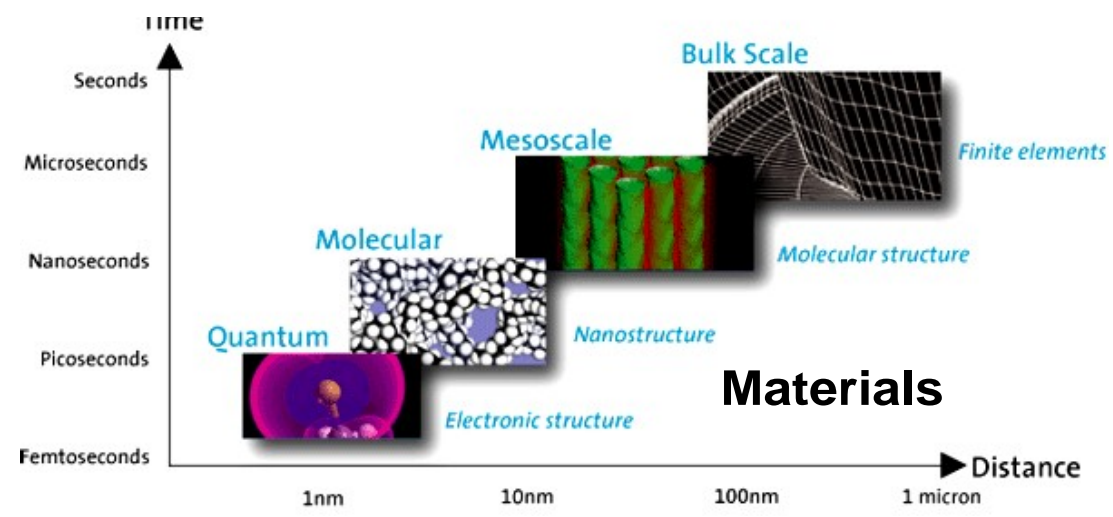
$$10^1$$

problem time (s)

# High-performance computing in fusion needed for ...



Fast Particles





# Numerical Algorithms



## Three classes of numerical methods

- Eulerian
  - Fixed grid in 5-dim phase space
  - Finite difference discretization of differential operators
- Semi-Lagrangian
  - Fixed grid in 5-dim phase space
  - Trace characteristics back in time to evolve distribution function
- Lagrangian: Particle-in-Cell (PIC), i.e. Monte Carlo method
  - Follow particle trajectories in 5-dim phase space
  - Project particles to real space to compute density and current

All three methods need a Poisson and parallel Ampère field solver

- Discretization with e.g. finite differences, finite elements, FFT



# Numerical Algorithms

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- Gyrofluid vs. gyrokinetic model
  - Choice of the most realistic physical model
- Local approximation vs. global model
  - Covering just a local “flux-tube” or the whole physical domain
- Adiabatic vs. kinetic electrons
  - Taking the full kinetics of all species into account
- Electrostatic vs. electromagnetic model
  - Taking self generated currents and Ampère’s law into account
- Collisionless vs. collisional plasma
  - Taking all values of collisionality into account

**So far none of the codes covers all physical aspects!**



# Numerical Algorithms

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- The number of relevant self-consistent (non-linear) gyrokinetic codes worldwide is between 10 and 15.
- The development of the relevant codes took typically many man-years (>5 years) and is still not finished.
- The codes are usually developed by more than one person.
- The codes run on massively parallel computers.
- The limited physical models still result from a lack of computational resources.

**More powerful computers with efficient code implementations are needed!**

# Distributed European Infrastructure for Supercomputing Applications



## Joint Research Activities in Plasma Physics + eDEISA (2004-2009)

Application enabling and support for important codes of the European plasma physics community.



## DEISA Extreme Computing Initiative

The DEISA Extreme Computing Initiative (DECI) is a scheme through which European computational scientists can apply for single-project access to world-leading computational resources in the European HPC infrastructure, operated by DEISA.



> 10 million hours of computer resources for fusion under DEISA

# The EFDA HPC project



## HPC-FF



- 1080 nodes @ 8 cores, peak performance 101 TFlop/s
- Start of production: August 2009

- numerical algorithms
- efficient parallelization strategies
- visualization
- education

core team (5 persons)



+ 4 ppy in other Associations



# HPC-FF at JSC



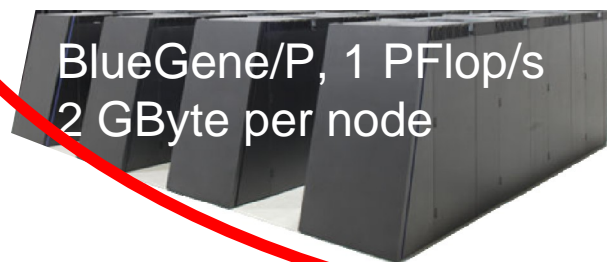
Jülich's General Purpose Supercomputer

- 2208 nodes @ 8 cores
- 24 GB per node
- Intel Nehalem-EP
- Network: Infiniband QDR
- Peak Performance 207 TFlop/s

Supercomputer for  
Fusion Science HPC-FF

- 1080 nodes @ 8 cores  
of same architecture
- Peak Performance 101 TFlop/s

**Flexible swapping  
of resources**





# High Level Support Team



## Main tasks for HLST

The HLST team is a **support unit** to ensure optimal exploitation of HPC-FF, i.e. it is **not focused on its own academic research**.

## Support for code development

- Single processor **performance optimization**
- Parallelization & optimization of codes for massively parallel computers
- Improvement of the **parallel scalability** of existing codes already ported to parallel platforms
- Implementation of **algorithms and mathematical library routines** to improve the efficiency of codes
- **Visualization** of large data sets

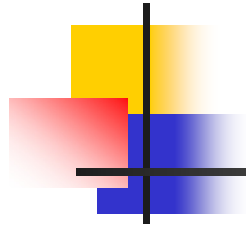


# Relevant European Codes



- ELMFIRE
  - TKK – Aalto University School of Science and Technology
  - VTT – Technical Research Centre of Finland
- GEMR
  - Max-Planck-Institut für Plasmaphysik (IPP)
- GENE
  - Max-Planck-Institut für Plasmaphysik (IPP)
  - Centre de Recherches en Physique des Plasmas (CRPP)
- GYSELA
  - Commissariat à l'énergie atomique (CEA) – Centre de Cadarache
- ORB5
  - Centre de Recherches en Physique des Plasmas (CRPP)
  - Max-Planck-Institut für Plasmaphysik (IPP)

This list is not exhaustive!



# ELMFIRE

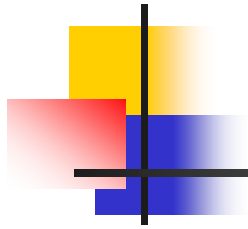


- Guiding-center orbit following gyrokinetic PIC method
- The global tokamak geometry is covered
- Electrostatic model
- Electrons and ions treated kinetically
- Momentum and energy conserving binary collisions included

Strong scaling of ELMFIRE code for the [Cyclone base case](#)

Numerical parameters:

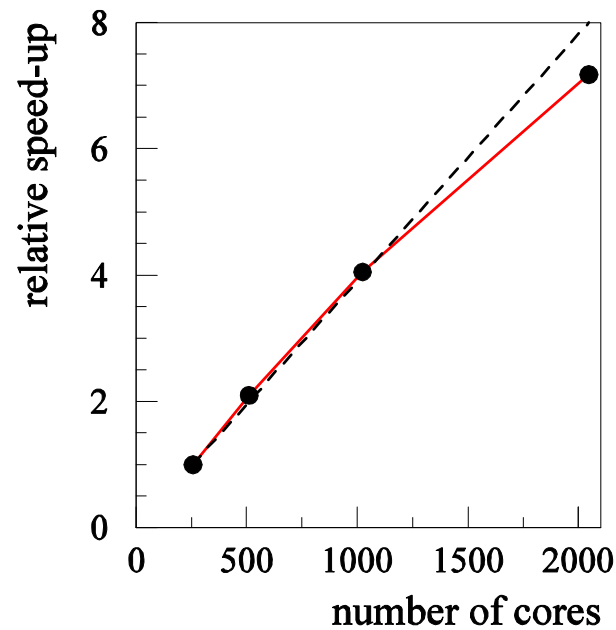
- $N=900,000,000$  particles are used to sample the 5-dim phase space
- A grid of  $N_s=8$ ,  $N_\theta=150$ ,  $N_\phi=91$  discretizes the potential equation



# ELMFIRE

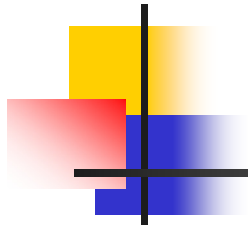


## Strong scaling



The job was executed on the [Cray XT5](#) machine with AMD Opteron Barcelona Quad-Core processors and 2.3 GHz clock rate at CSC.

data contributed by [S. Janhunen](#), TKK



# GEMR

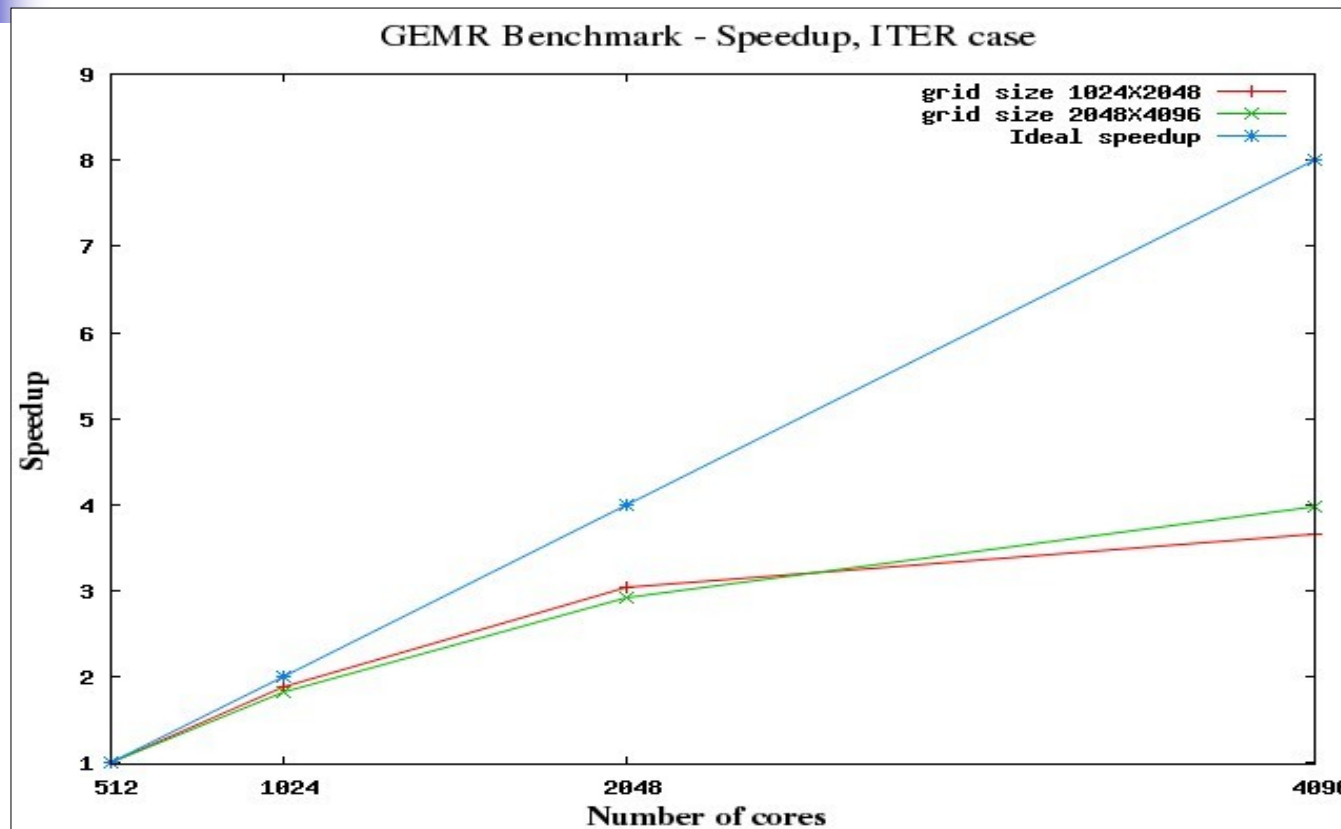


- Gyrofluid model
- The global tokamak geometry is covered
- Electromagnetic model
- Electrons and one or more ion species
- Momentum and energy conserving binary collisions included

Strong scaling of GEMR code:

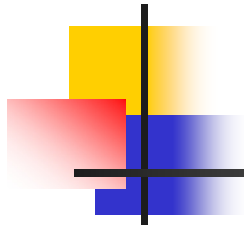
- With a grid of  $N_x=1024$ ,  $N_y=2048$ ,  $N_s=32$
- With a grid of  $N_x=2048$ ,  $N_y=4096$ ,  $N_s=32$

# GEMR



The job was executed on the [Bull HPC-FF](#) machine with Intel Xeon X5570 Quad-Core processors and 2.93 GHz clock rate at JSC.

figure contributed by N. Hariharan and B.D. Scott, IPP



# GENE



- Gyrokinetic Eulerian method
- Local “flux-tube” or global code version
- Electromagnetic model
- Electrons and one or more ion species treated kinetically
- Momentum and energy conserving binary collisions included

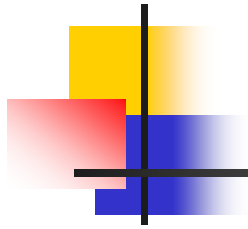
Strong scaling of GENE code:

Multiscale parameters:

- 5-dim grid of  $N_{x_0}=1024$ ,  $N_{ky}=512$ ,  $N_{z_0}=24$ ,  $N_{v_0}=96$ ,  $N_{w_0}=64$   
problem size of  $\approx 20$  TByte

Stellarator parameters:

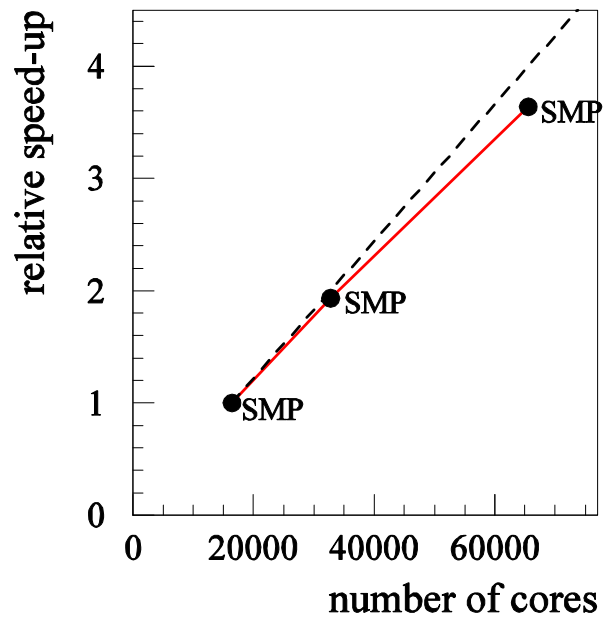
- 5-dim grid of  $N_{x_0}=128$ ,  $N_{ky}=64$ ,  $N_{z_0}=512$ ,  $N_{v_0}=64$ ,  $N_{w_0}=16$   
relatively small problem size of  $\approx 2$  TByte



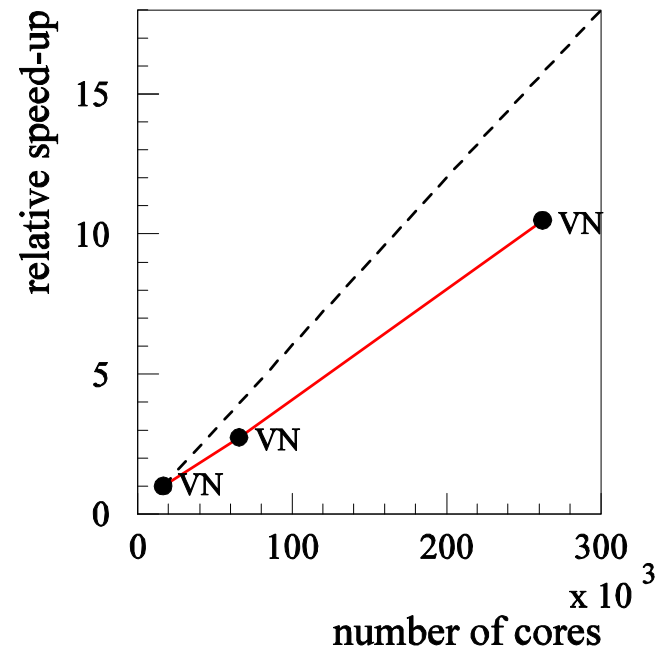
# GENE



Strong scaling for multiscale parameters

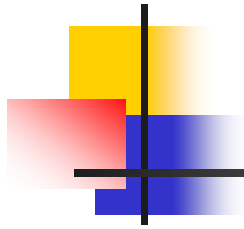


Strong scaling for stellarator parameters



The job was executed on the [IBM BlueGene/P](#) machine with PowerPC 450 quad-core processors ([SMP/VN mode](#)) and 850 MHz clock rate at JSC.

data contributed by T. Dannert, RZG and F. Jenko, IPP



# GYSELA



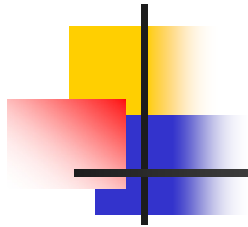
- Gyrokinetic Semi-Lagrangian method
- The global tokamak geometry is covered
- Electrostatic model
- Kinetic ions and adiabatic electrons
- Reduced ion-ion collisions operator

Strong scaling of GYSELA code:

- With a grid of  $N_r=512$ ,  $N_\theta=256$ ,  $N_\varphi=256$ ,  $N_{vpar}=48$ ,  $N_\mu=32$

Weak scaling of GYSELA code:

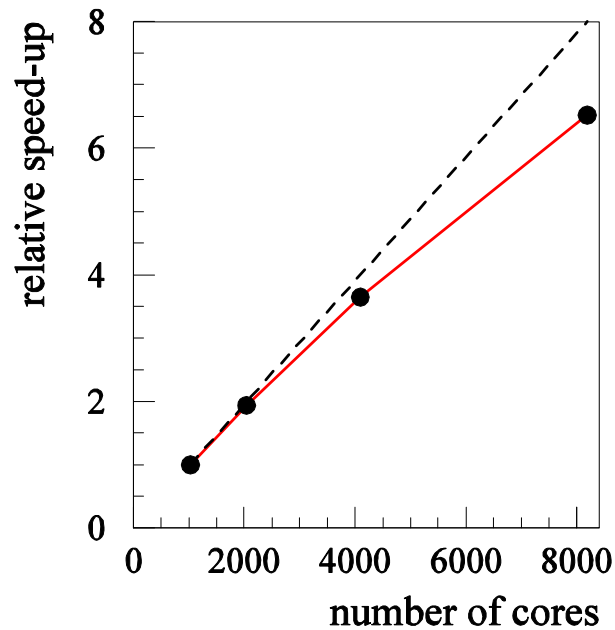
- With a grid of  $N_r=512$ ,  $N_\theta=512$ ,  $N_\varphi=64$ ,  $N_{vpar}=124$ ,  $N_\mu=2,4,8,16,32,64$



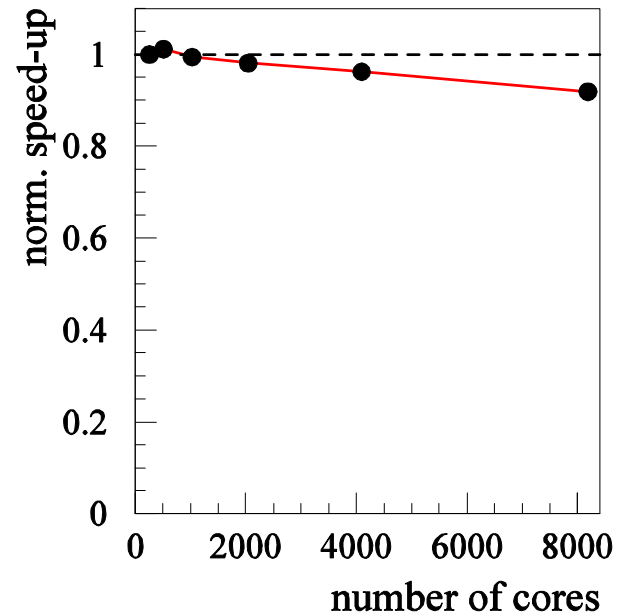
# GYSELA



## Strong scaling

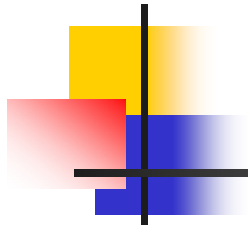


## Weak Scaling



The job was executed on the [SGI Altix ICE 8200](#) machine with Intel Xeon E5472 Quad-Core processors and 3 GHz clock rate at CINES.

data contributed by G. Latu and V. Grandgirard, CEA



# ORB5

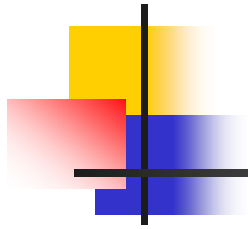


- Guiding-center orbit following gyrokinetic PIC method
- The global tokamak geometry is covered
- Electromagnetic model
- Electrons and one or more ion species treated kinetically

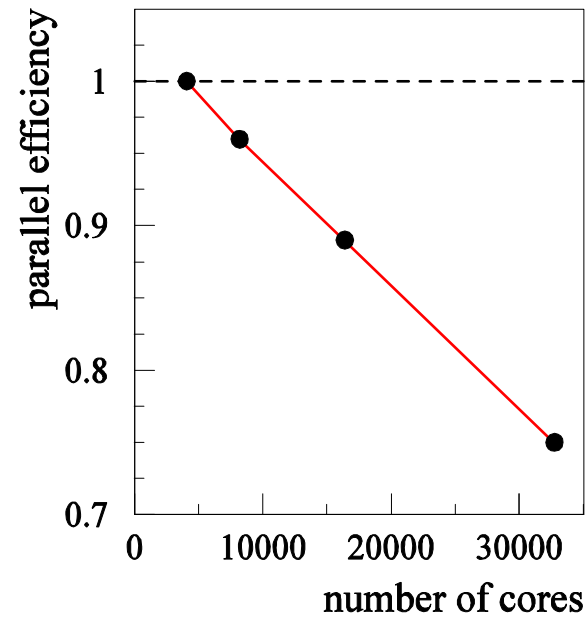
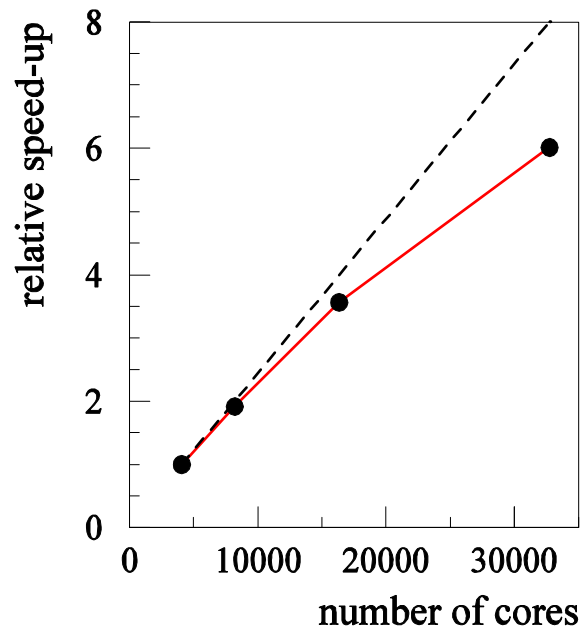
Strong scaling of ORB5 code for the [Cyclone base case](#)

Numerical parameters:

- $N=3,145,728,000$  particles are used to sample the 5-dim phase space
- A grid of  $N_s=128$ ,  $N_\theta=512$ ,  $N_\varphi=256$  discretizes the potential equation



# ORB5



The job was executed on the [IBM BlueGene/P](#) machine with PowerPC 450 quad-core processors ([VN mode](#)) and 850 MHz clock rate at IDRIS.

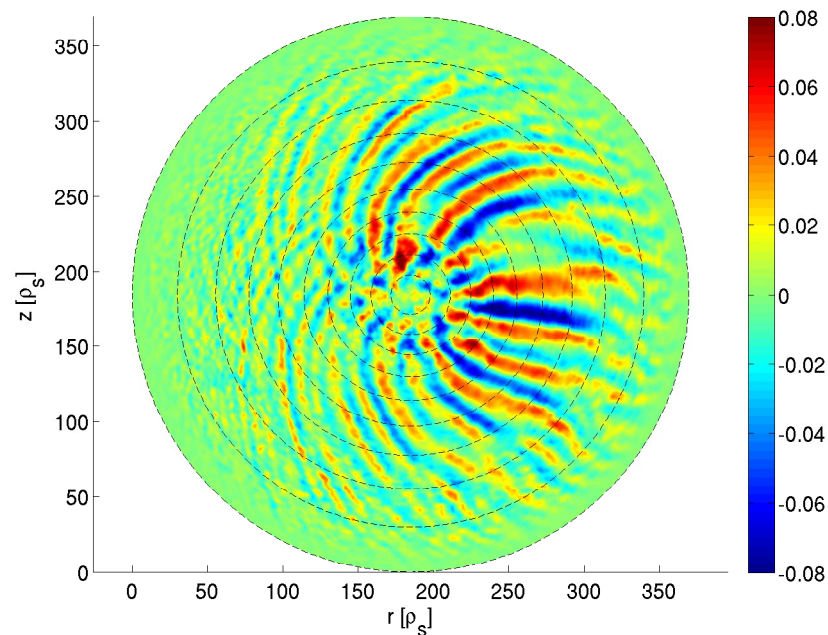
data contributed by R. Tisma, RZG and A. Bottino, IPP

# Zonal Flow interaction with turbulence

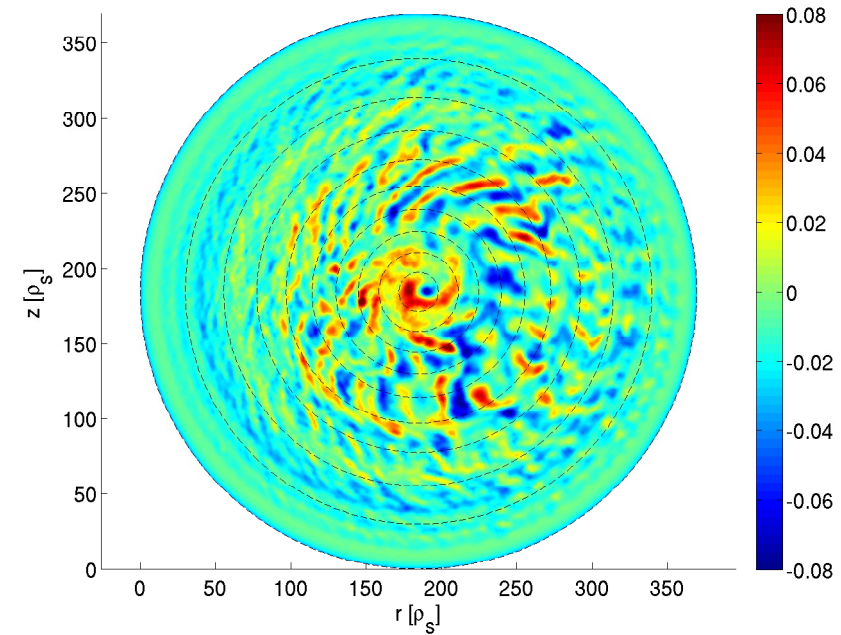


The **zonal flow** means a plasma flow along the circular contours. It arises via a self-organization phenomenon driven by plasma modes.

without zonal flow



with zonal flow



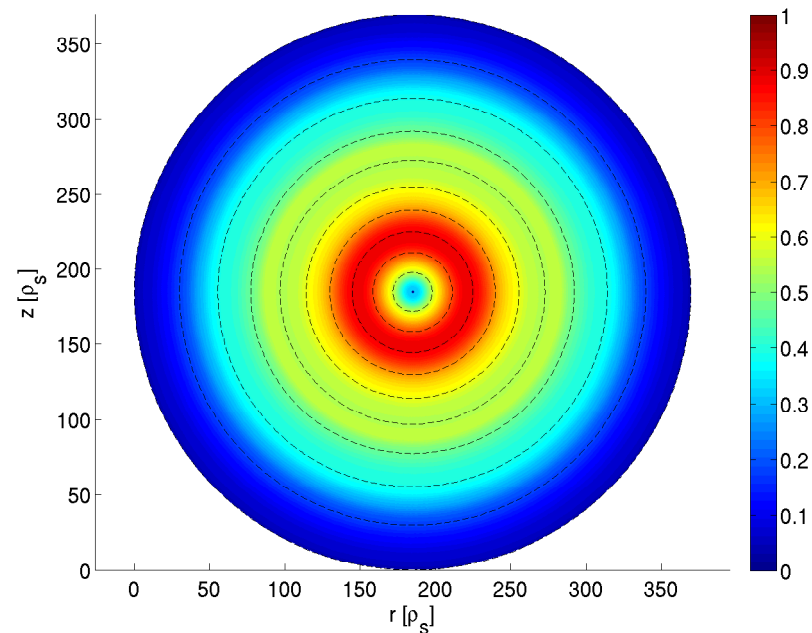
→ The zonal flow brakes up the radial streamers (ORB5 simulation)

figures contributed by A. Bottino, IPP

# Zonal Flow interaction with turbulence



The  $m=0$ ,  $n=0$  Fourier mode of the **electrostatic potential** drives the zonal flow via the  $\mathbf{E} \times \mathbf{B}$  drift.



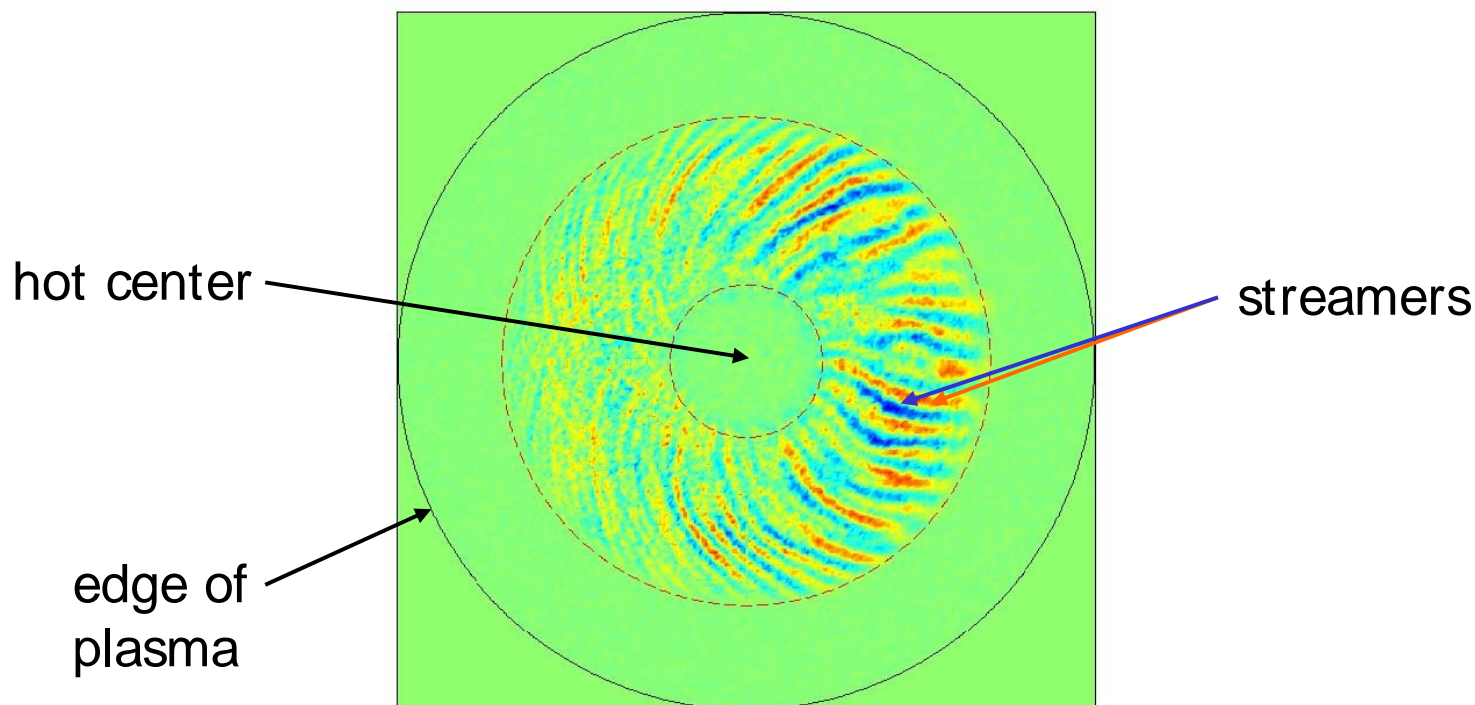
→ The zonal flow depends on the gradient of the contours (ORB5 simulation)

figure contributed by A. Bottino, IPP

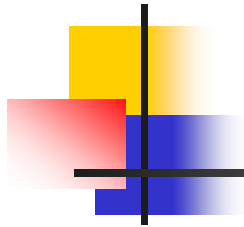
# ETG driven turbulence



Electron temperature gradient (ETG) driven turbulence can contribute to heat flux due to **elongated radial streamers**.



A. Bottino et al., PoP **14**, Art.No: 010701, 2007 (ORB5 simulation)



# Summary

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- European scientists are **quite active** in the field of gyrokinetic turbulence simulations
- They use **complementary** numerical methods
- They are supported by the EFDA HPC project:
  - With a 100 TFlop/s machine (**HPC-FF**) for computing
  - The **High Level Support Team** for code optimization
- Further progress in the field will depend on **algorithmic development** and access to **Petaflop computers**
- The **IFERC-CSC** will provide such computational power in 2012