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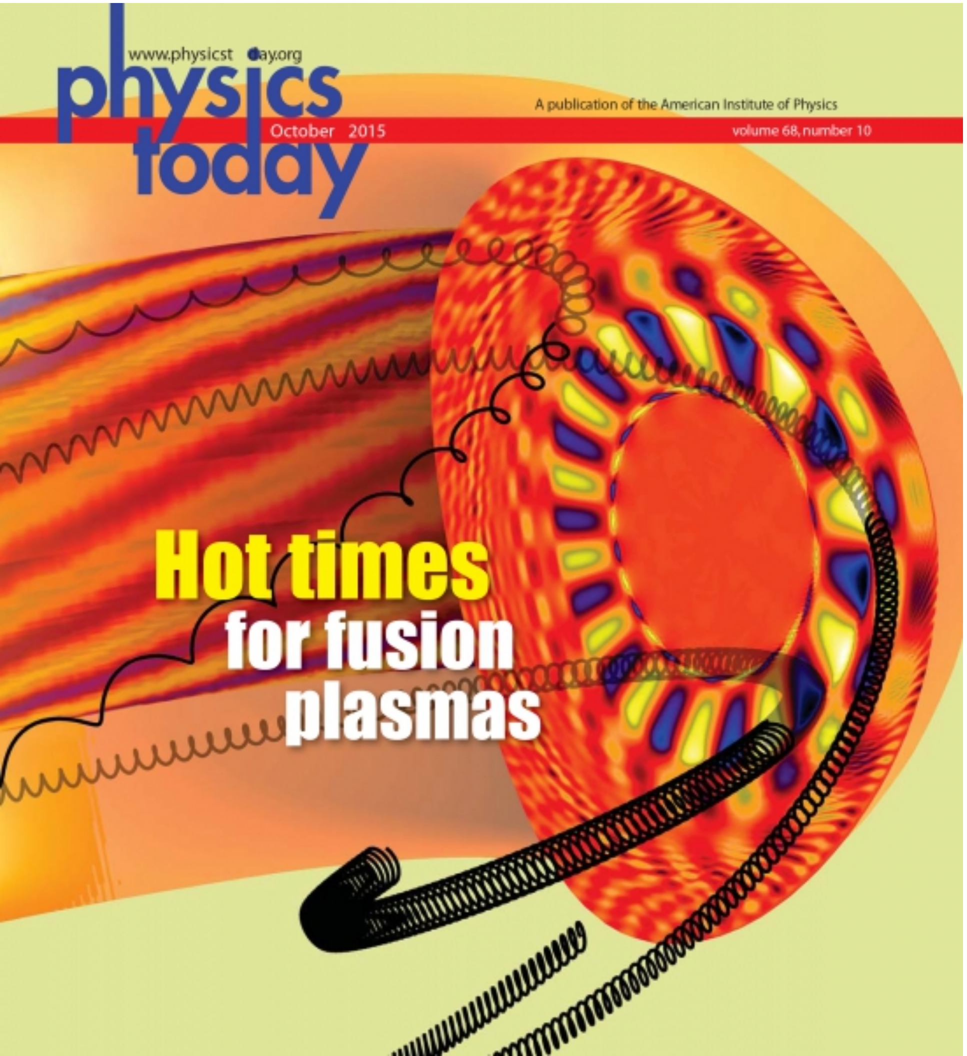
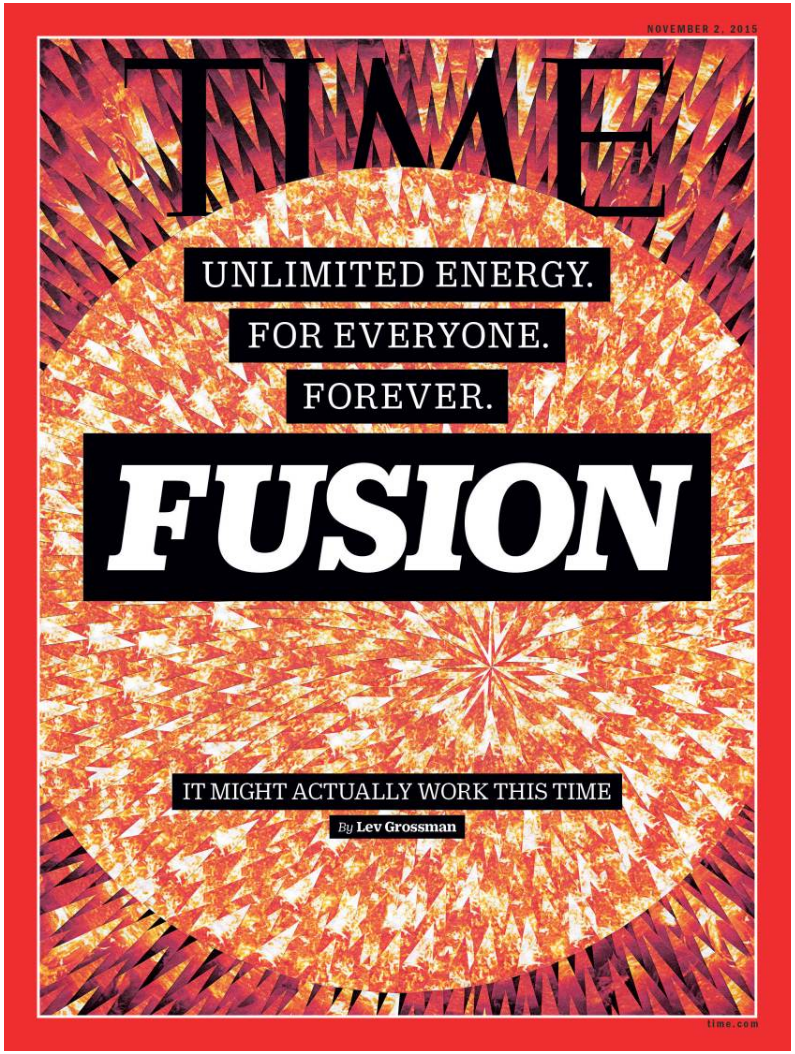
BOOSTING PLASMA SCIENCE THROUGH BIG DATA & HPC

Long Program „Science at Extreme Scales“

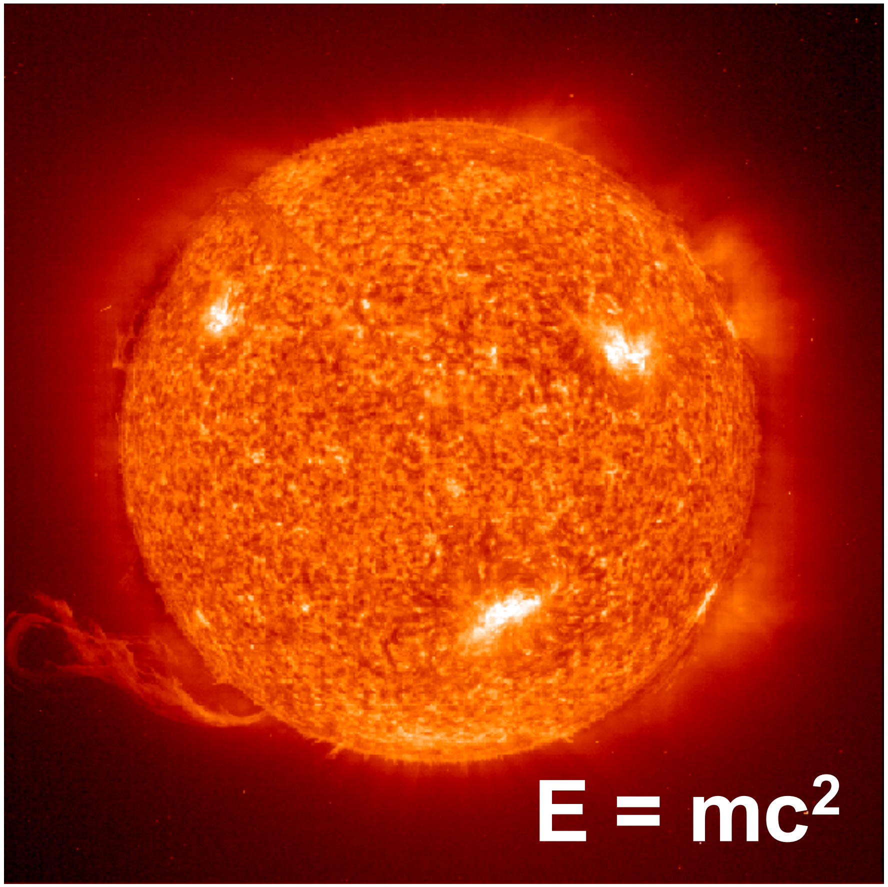
Los Angeles, September 12, 2018

FUSION ENERGY IN THE NEWS (JUST TWO EXAMPLES)

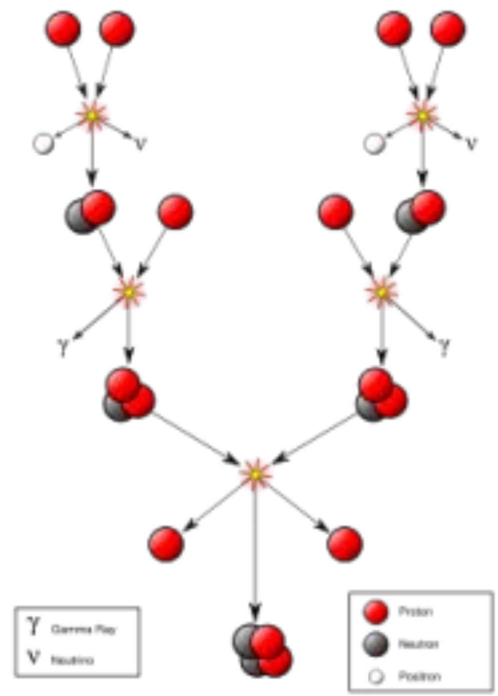




How the Sun shines



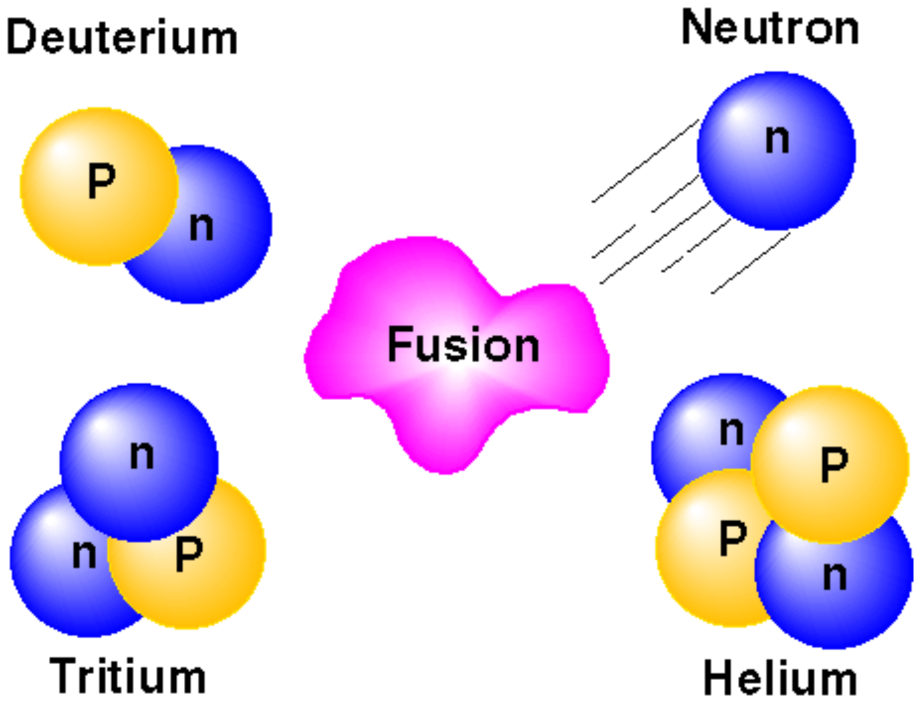
Fusion of 4 protons (in steps)



Idea: Carbon-free energy source for the 21st century and well beyond

Fusion Energy in the Laboratory

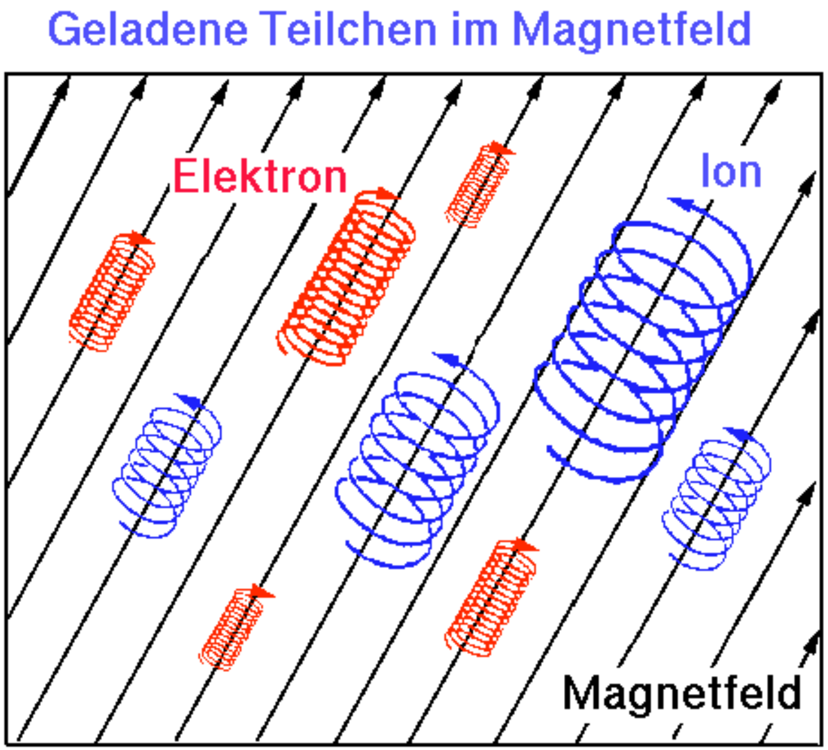
This process has by far the highest reaction rate under experimentally accessible conditions:



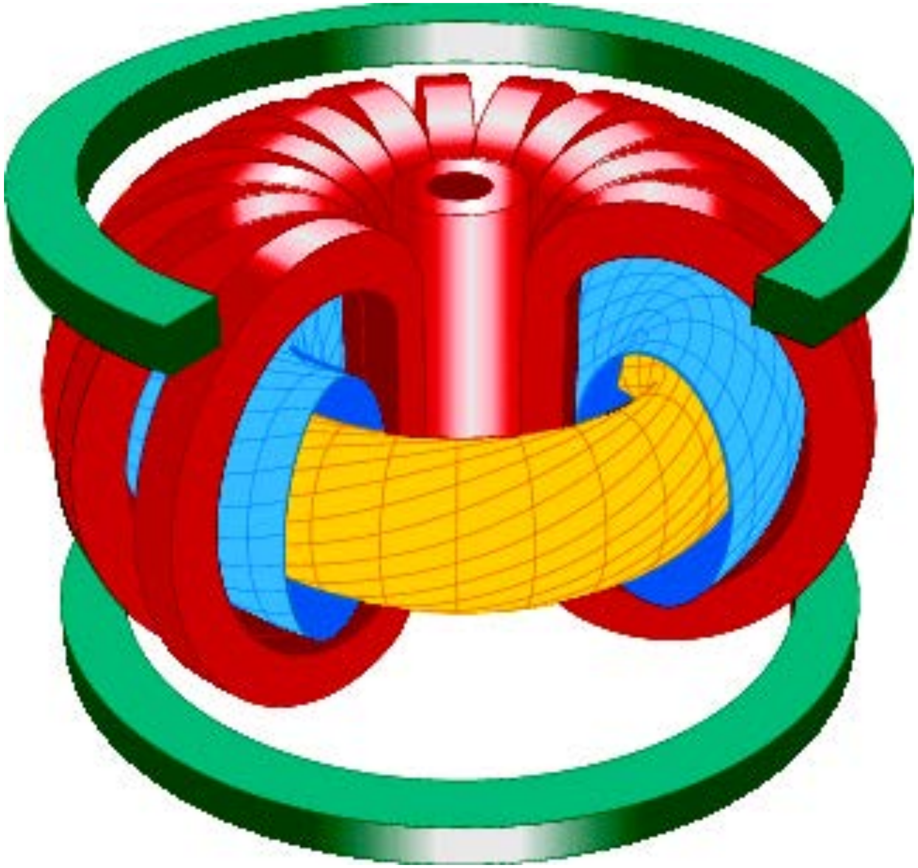
Still, temperatures of about 100 million degrees are required! Thus, we are dealing with a fully ionized gas (plasma).

Magnetic Confinement of Plasmas

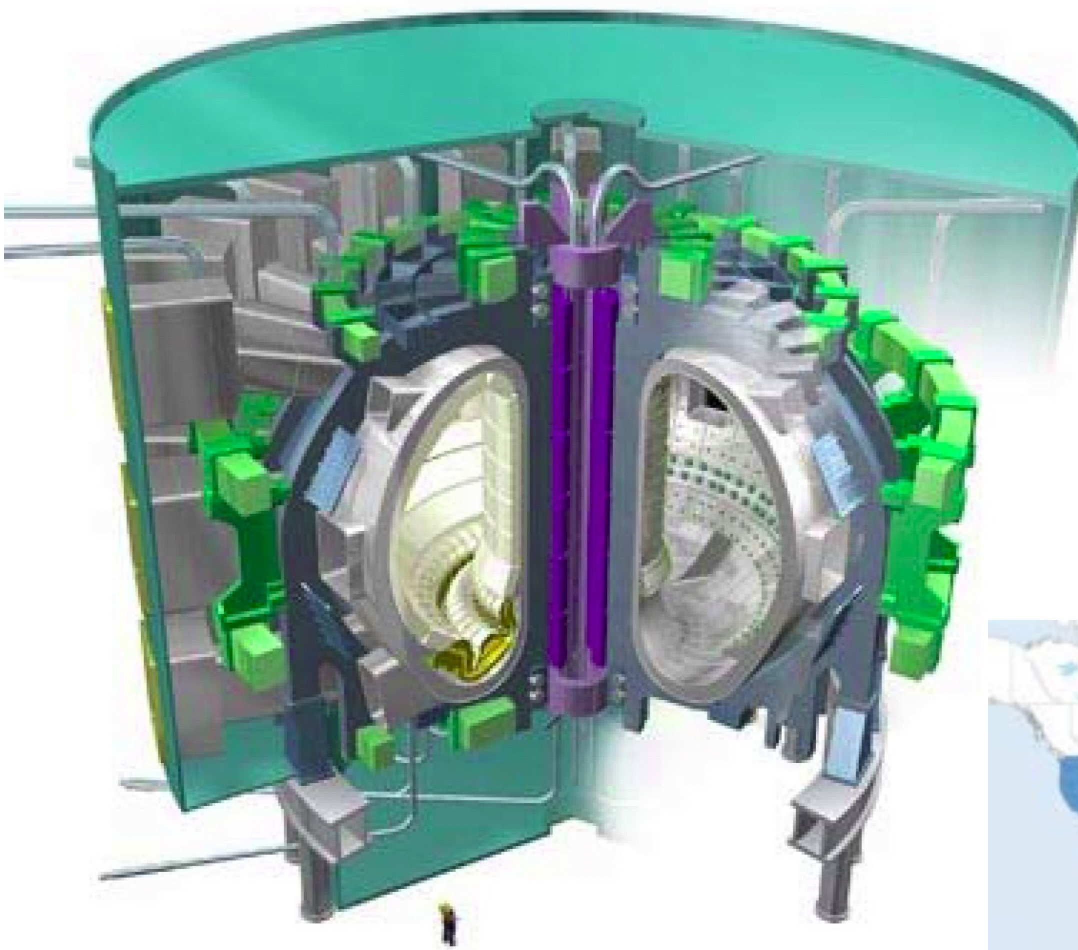
Charged particles basically follow magnetic field lines



Axisymmetric “tokamak”: Nested magnetic surfaces



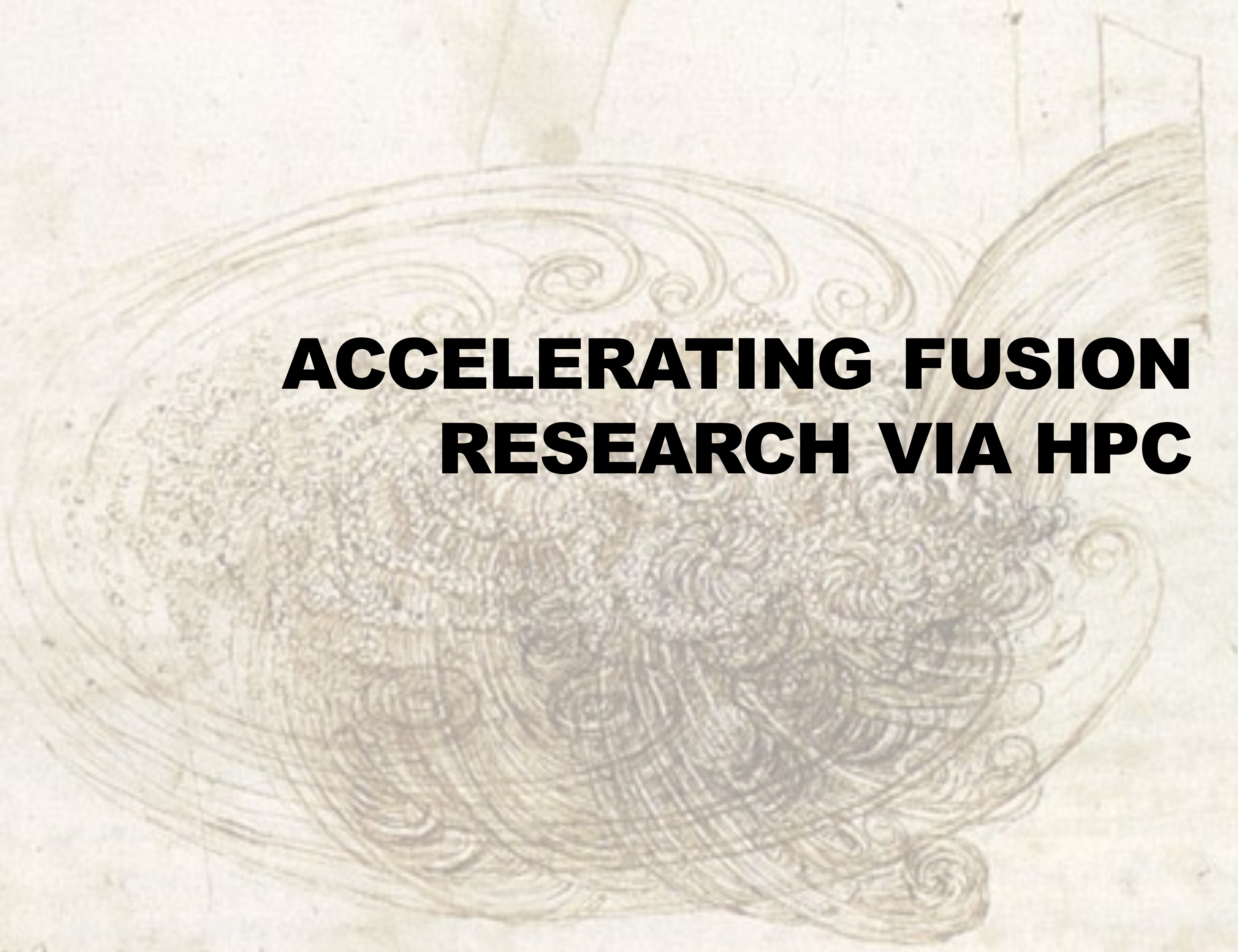
The crucial next step: ITER



Goals:
- 500 MW of fusion power for 50 MW of external heating
- „Burning“ plasma

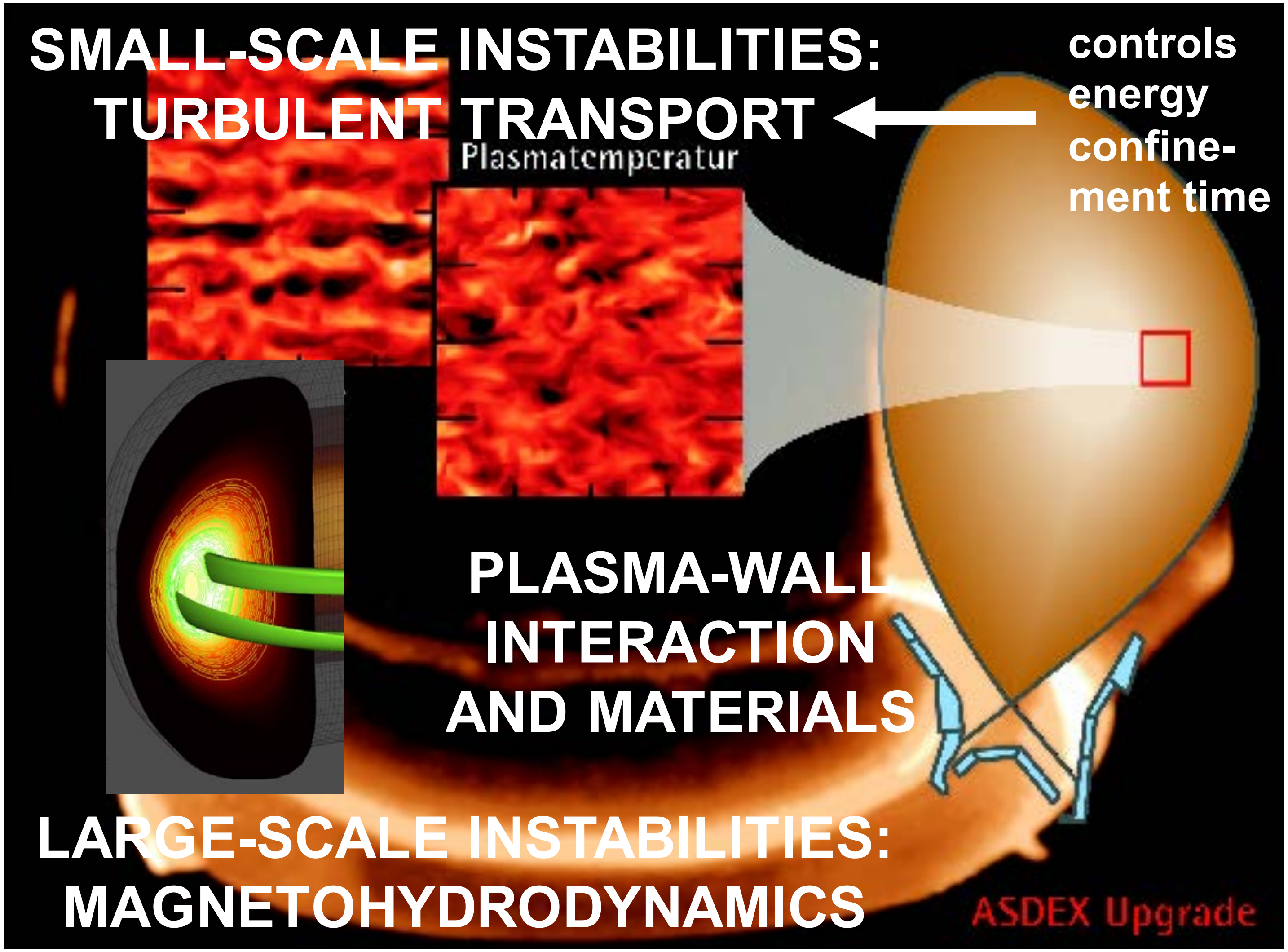
More info:
www.iter.org

ITER CONSTRUCTION SITE IN SOUTHERN FRANCE

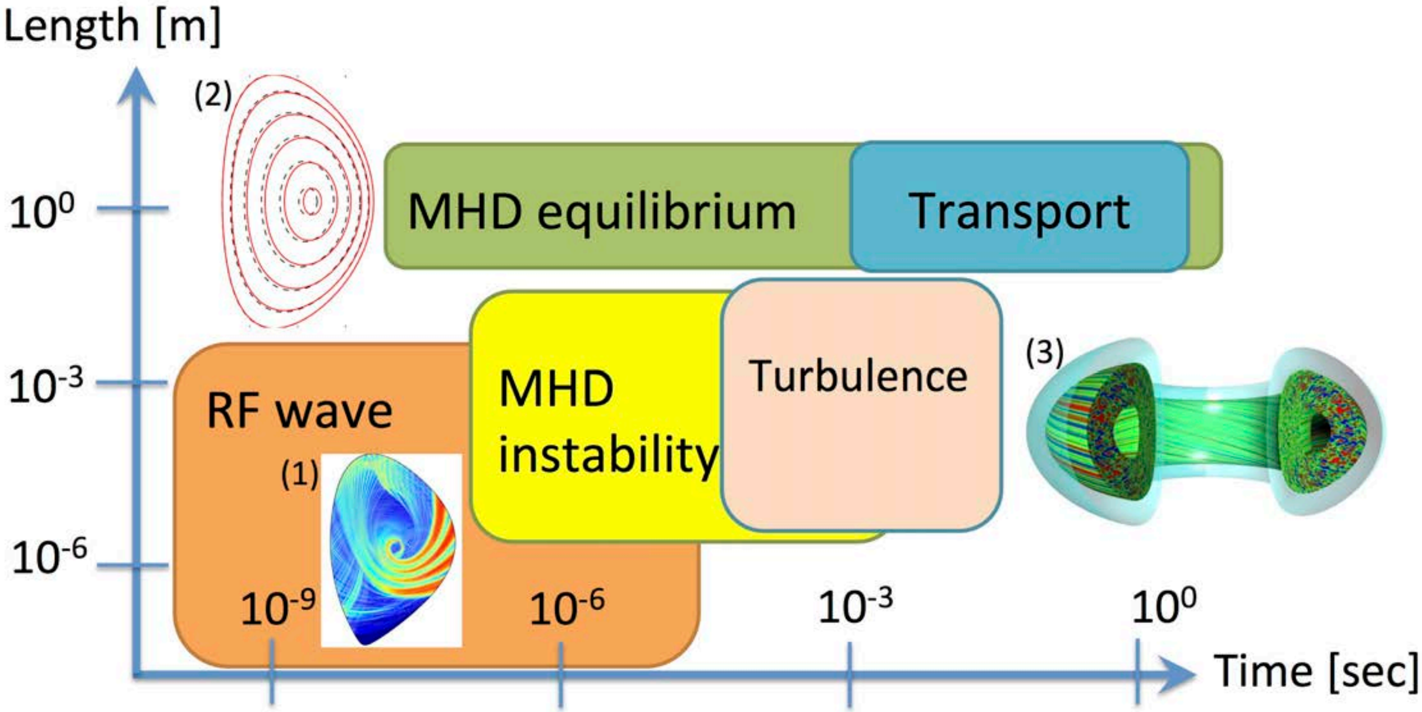


ACCELERATING FUSION RESEARCH VIA HPC

3 key challenges for fusion physics



KEY THEME: INTEGRATION



Applied mathematics

Computer science

Plasma astrophysics

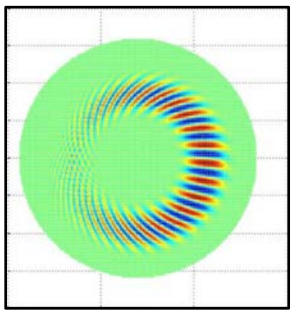
Complex systems

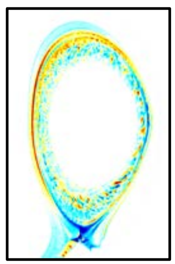
incl. **High Performance Computing** *and* **Data Analytics**

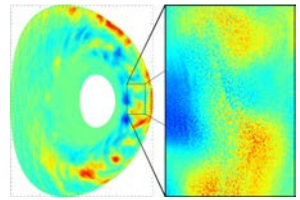
TOWARDS A "VIRTUAL" TOKAMAK

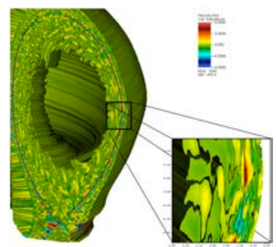
Goals: prepare and interpret **ITER** discharges, guide the development of **power plants**

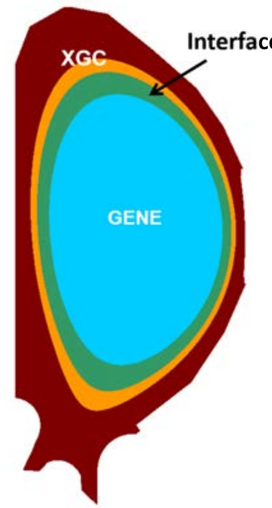
Increasing fidelity & modeling capability with increasing computing power →

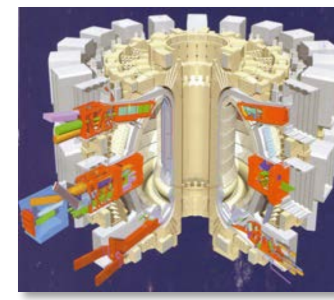












Gigaflops

Core: ion-scale electrostatic physics in simplified geometry

Teraflops

Core: adding kinetic electron electromagnetic physics in a torus

Edge: ion+neutral electrostatic physics in a torus

Petaflops

Core: adding electron-scale physics

Edge: adding kinetic electron electrostatic physics

Exaflops

Core-edge coupled studies of whole-device ITER, incl. turbulence, MHD instability, fast particles, heating, and plasma-wall interactions

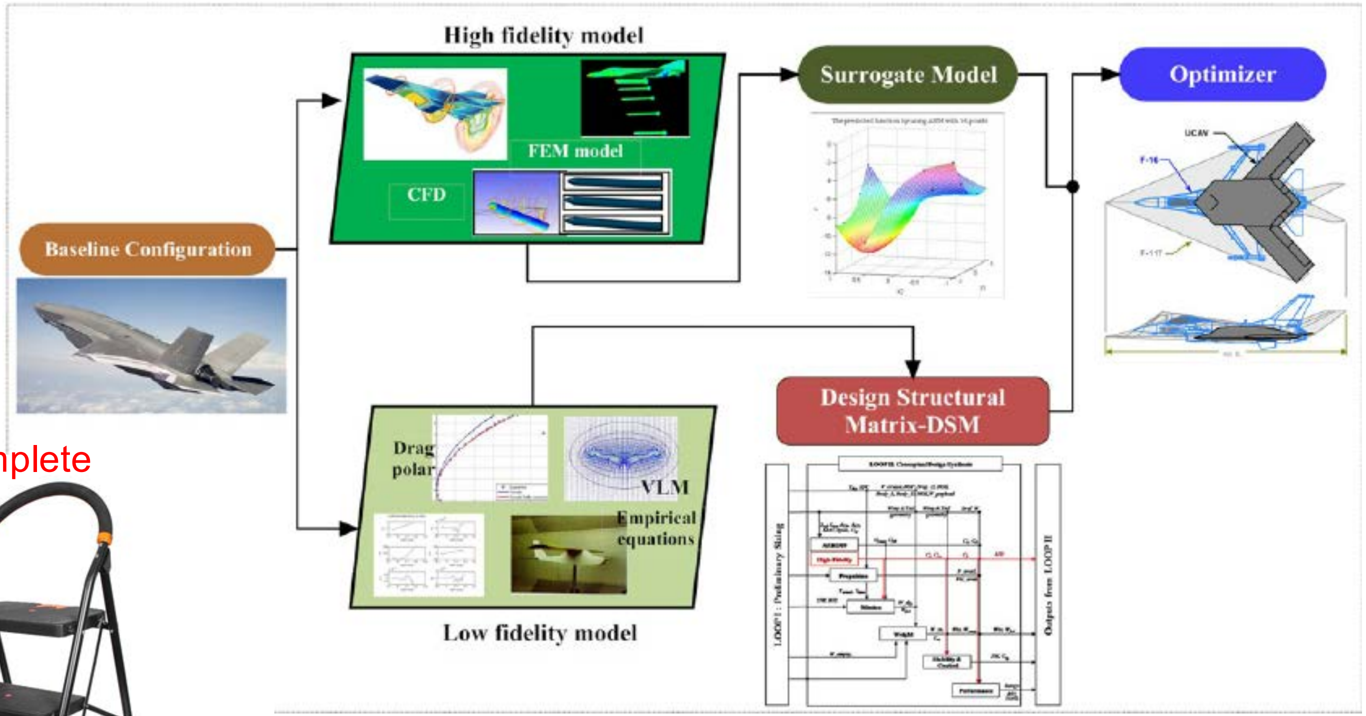
Beyond

Whole device modeling of all relevant fusion science

Acknowledgements: ECP

MULTI-FIDELITY APPROACH

An example:



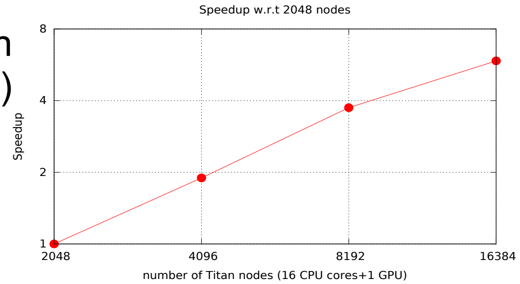
- High-fidelity models provide reliable **predictive capability**
- Lower-fidelity models foster **high-throughput computing**
- Both are needed – together

Vital role of **theory** (for deriving fundamental equations, analytical solutions in limiting cases, reduced models etc.) and **modern data analytics**

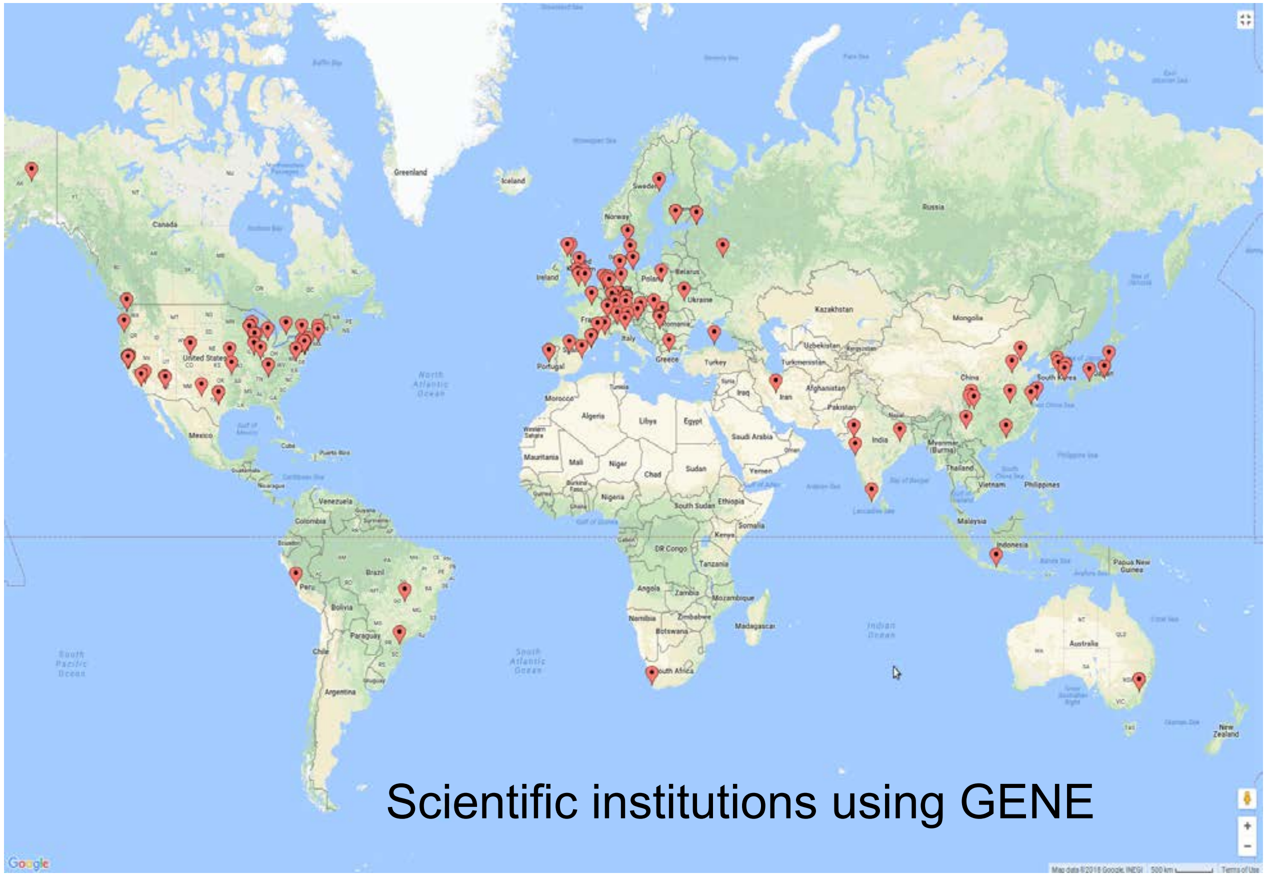
The gyrokinetic Vlasov code GENE

Some background on GENE

Almost linear scaling on Titan
(up to ~90% of the machine size)

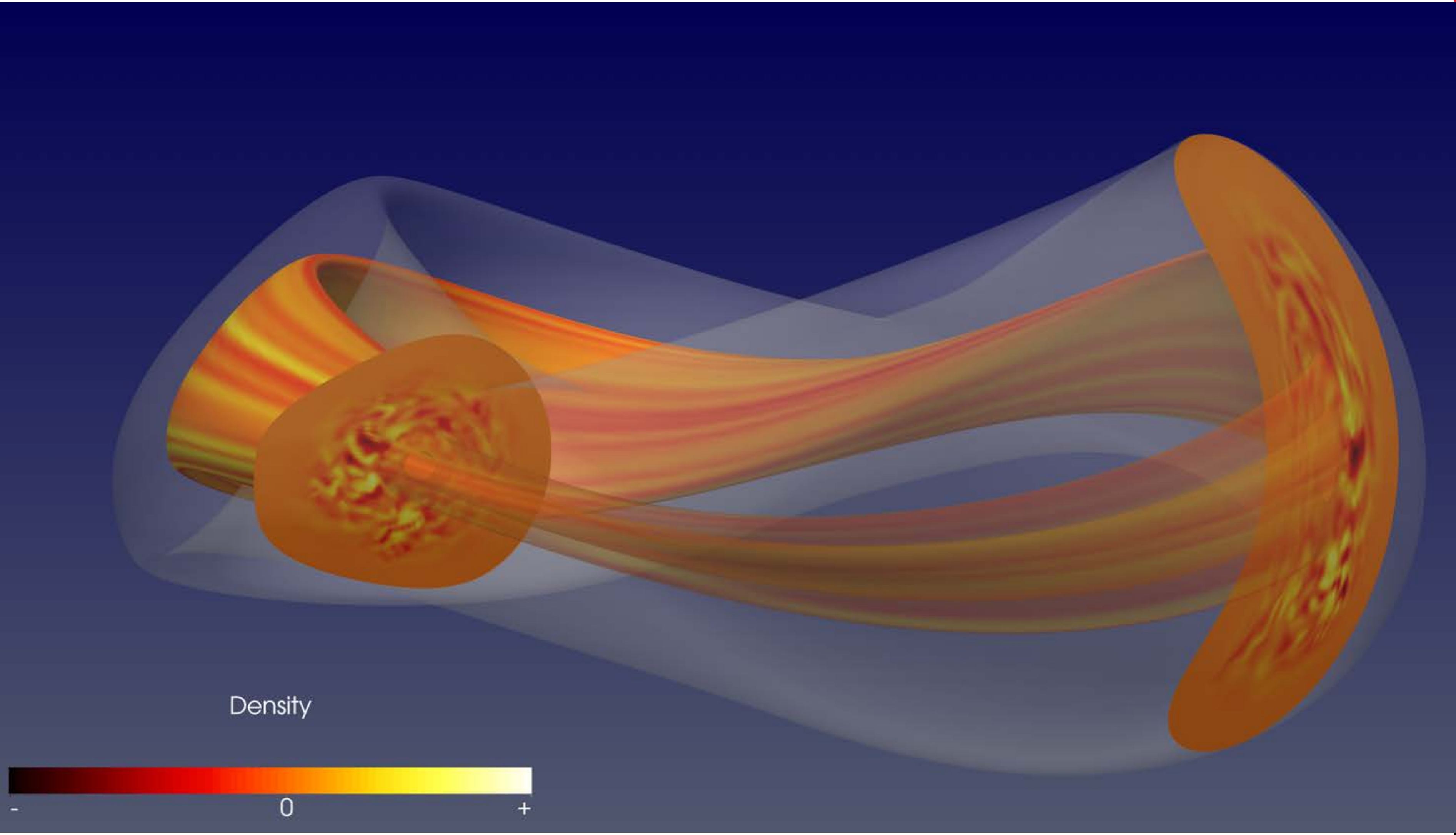


- First GENE publication: Jenko PoP 2000 (> 550 citations)
- More than 100,000 lines of source code, plus 200,000 lines for pre-/post-processing
- Single repository: version control via Git
- Open source policy
- Significant user base: ~300 registered users
- Active user support via support@genecode.org
- Website: genecode.org ~50,000 views



Scientific institutions using GENE

New GENE-3D code: Applications to a QA stellarator



(Pre-)Exascale supercomputers provide unprecedented opportunities for designing turbulence-optimized stellarators (via reduced models)

DATA ANALYTICS FOR FUSION

INTEGRATED DATA ANALYSIS

R. Fischer

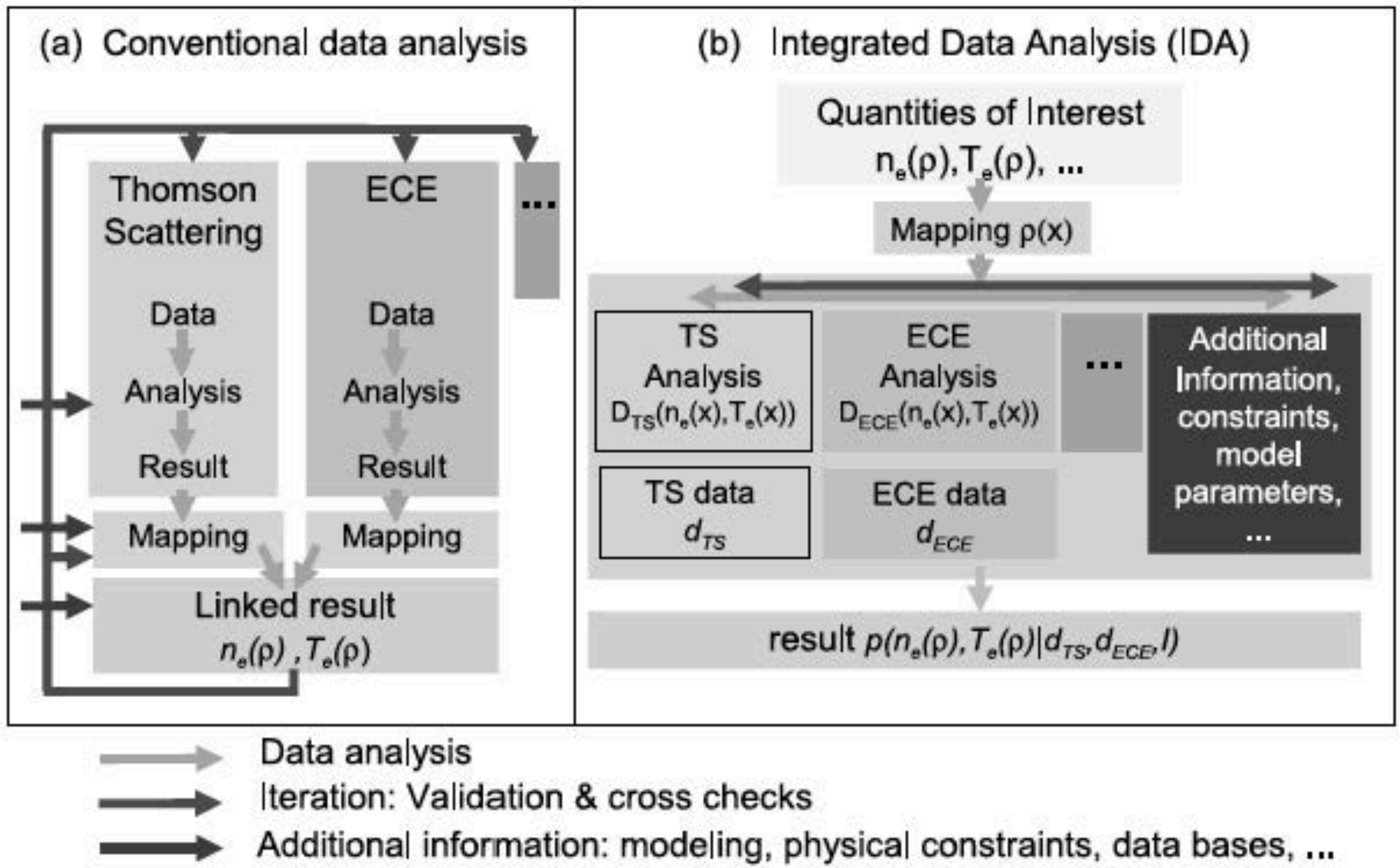
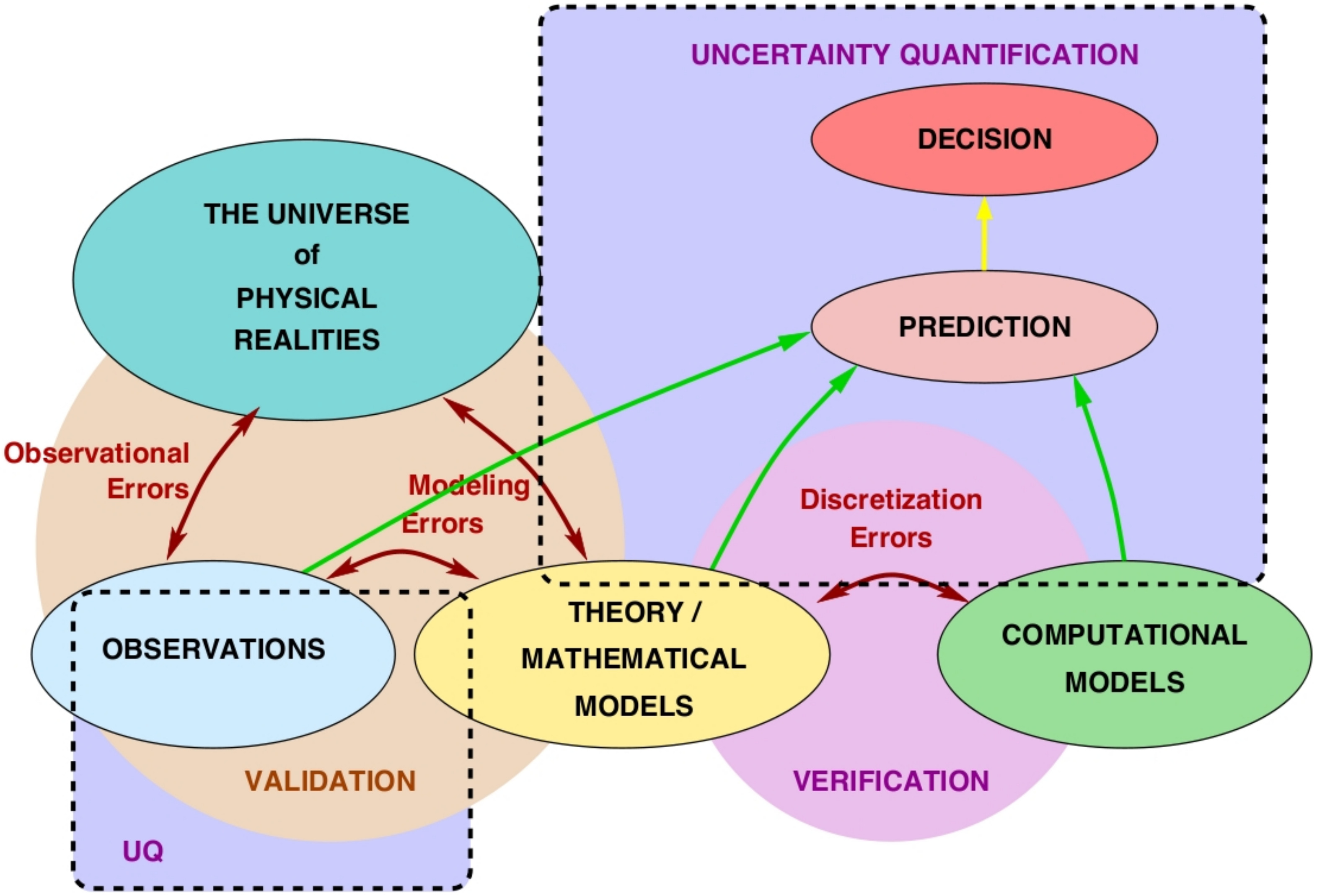


Fig. 1. Schematic comparison of the conventional data analysis with the IDA approach.

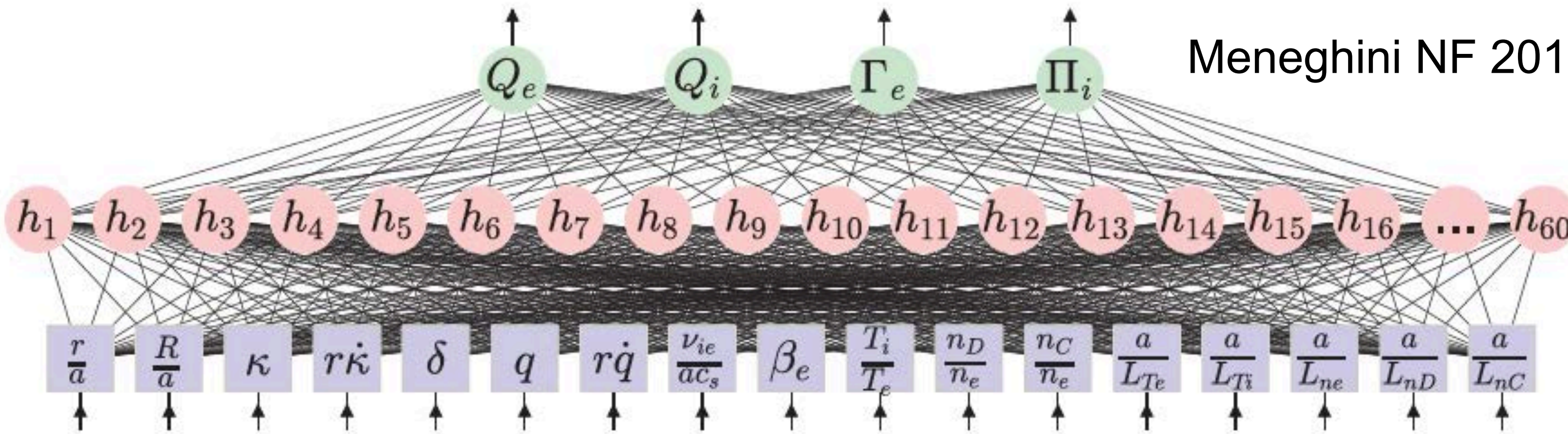
UNCERTAINTY QUANTIFICATION

A truly **predictive computational capability** must include UQ

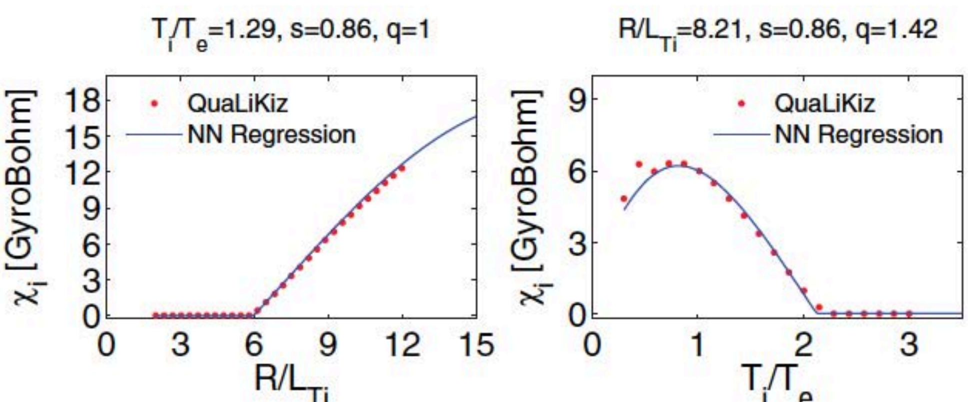


REAL-TIME PLASMA PREDICTION

From *nonlinear* gyrokinetics to *quasilinear* gyrokinetics/gyrofluids to NNs:
Calls for **deep understanding of turbulence** in plasmas



Meneghini NF 2017



Citrin+ NF 2015

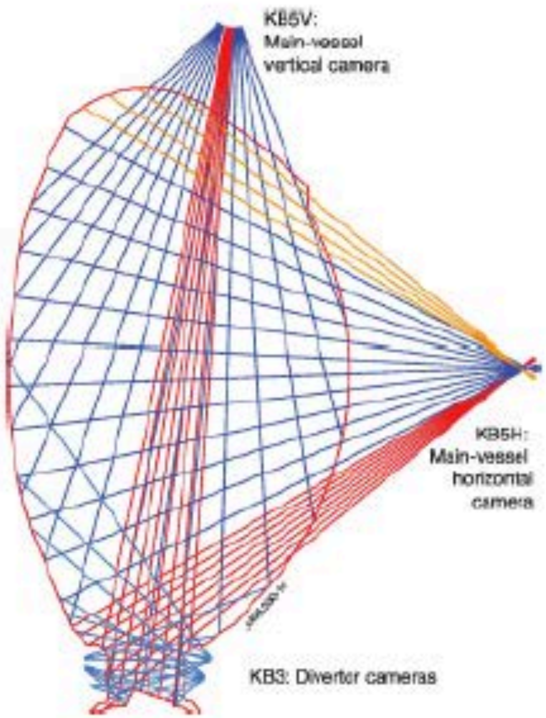
NL gyrokinetics: ~10^5 core-h

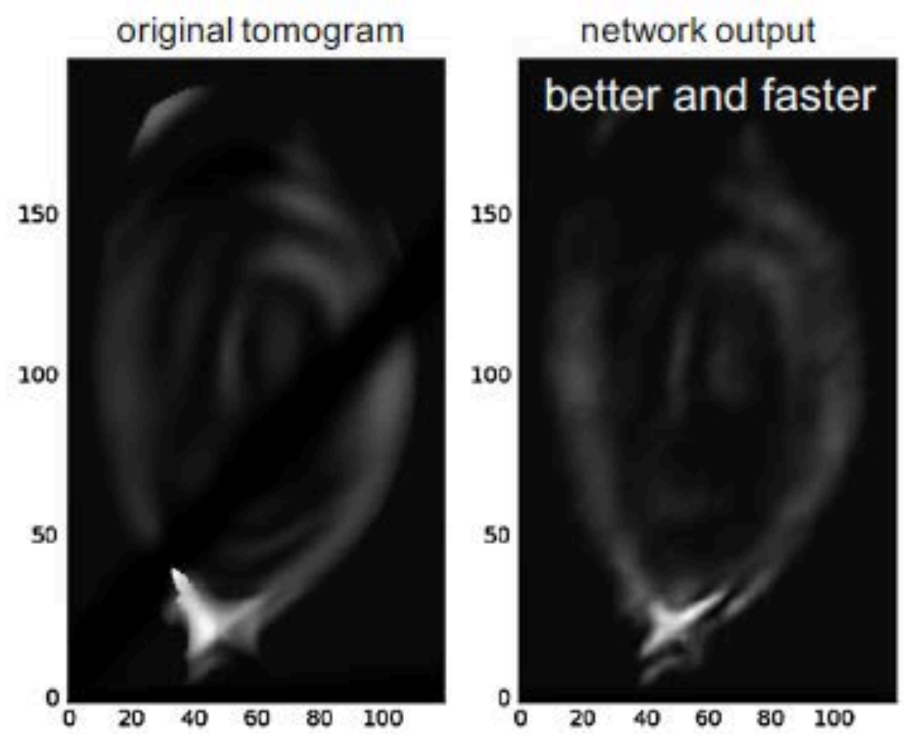
QL gyrokinetics: ~10^{-3} core-h

NNs: real-time capability

DEEP LEARNING FOR REAL-TIME PLASMA CONTROL

Plasma tomography: Use CNNs to reconstruct cross-section from projections



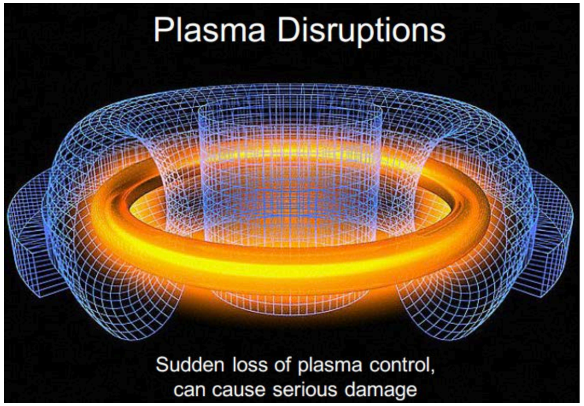


Deep learning for plasma tomography using the bolometer system at JET

PhD student at IPP

Francisco A. Matos[a], Diogo R. Ferreira[a,*], Pedro J. Carvalho[b], JET Contributors[1]

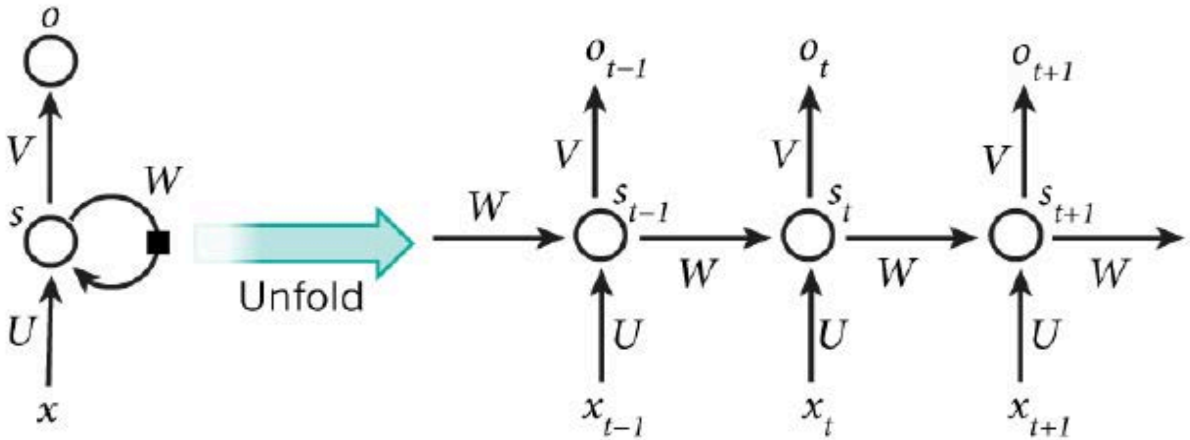
REAL-TIME EVENT DETECTION



Time series predictions via Deep Learning

Examples: Financial data, earthquakes, plasma disruptions etc.

Possible approach: **Recurrent Neural Networks (RNNs)**



Long Short-Term Memory (LSTM) Deep Learning method, developed at the TUM by Hochreiter & Schmidhuber in 1997

HPC MEETS BIG DATA

Two recent waves of innovations affecting science (= main drivers of the expansion of the role of the mathematical sciences[1]):

High Performance Computing & Big Data

[1]emphasized by the NRC

Currently, these themes are usually addressed rather independently – but they are intrinsically linked:

- **HPC needs Big Data** for dealing with increasingly large data sets
  - ✓ Communication bottleneck on the path to exascale computing
  - ✓ Develop novel ways of representing, reducing, reconstructing, and transferring huge amounts of data *(need new algorithms!)*
- **Big Data needs HPC** for analyzing increasingly large data sets
  - ✓ Data analytics becomes ever more compute-intensive