On the physics and prospects of fusion energy - an exciting journey

Prof. Frank Jenko

Max Planck Institute for Plasma Physics

Monday
March 20th
16:15
Room CE 2

APERO
after the colloquium

Fusion energy - based on the physical processes that power billions of stars in our galaxy - holds the promise of becoming an attractive key player in covering the world's continuously growing electricity needs. The realization of this ambitious idea requires us to understand and control the extremely complex behavior of magnetically confined plasmas at more than 100 million degrees. In our quest to unravel the fascinating nonlinear dynamics at play, simulations on the world's largest supercomputers as well as modern machine learning techniques prove to be invaluable. Recent breakthroughs and novel developments will be highlighted.

Host: Christian Theiler

Organized by the Institute of Physics, EPFL

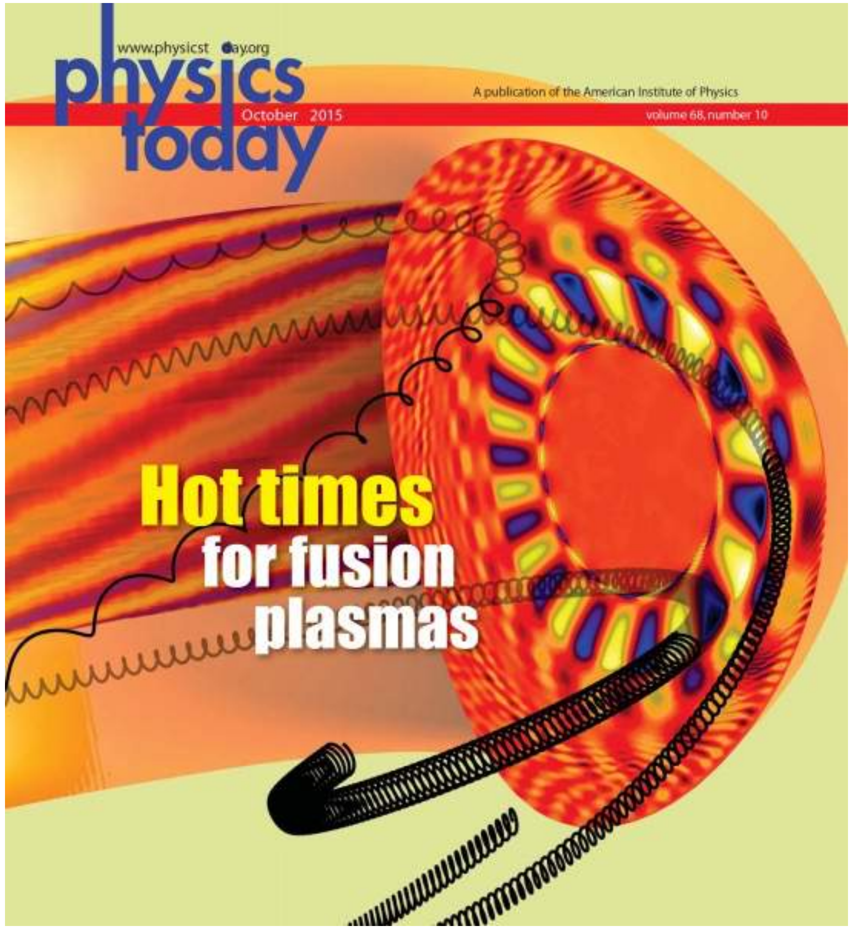
On the Physics & Prospects of Fusion Energy

Frank Jenko

Max Planck Institute for Plasma Physics, Garching
Technical University of Munich
The University of Texas at Austin

EPFL – March 20, 2023

Fusion energy in the news



www.physicstoday.org

physics today

A publication of the American Institute of Physics

October 2015

volume 68, number 10

Hot times for fusion plasmas

Technology Review

DAS MAGAZIN FÜR INNOVATION

Luftfahrt

Die Elektroflieger kommen

Shopping

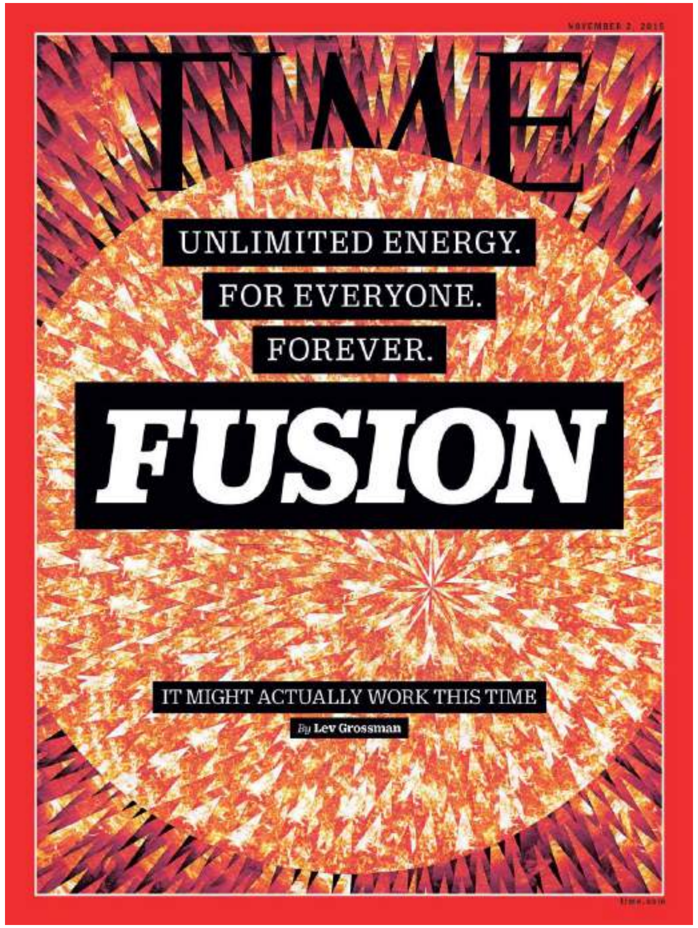
Warum die Trennung von Offline und Online verschwindet

Biografie-Vorabdruck

Die zwei Gesichter des Steve Jobs

Zündung!

Auf der Überholspur zur Fusionsenergie: Unternehmen wollen das Milliardenprojekt ITER abhängen



TIME

UNLIMITED ENERGY.

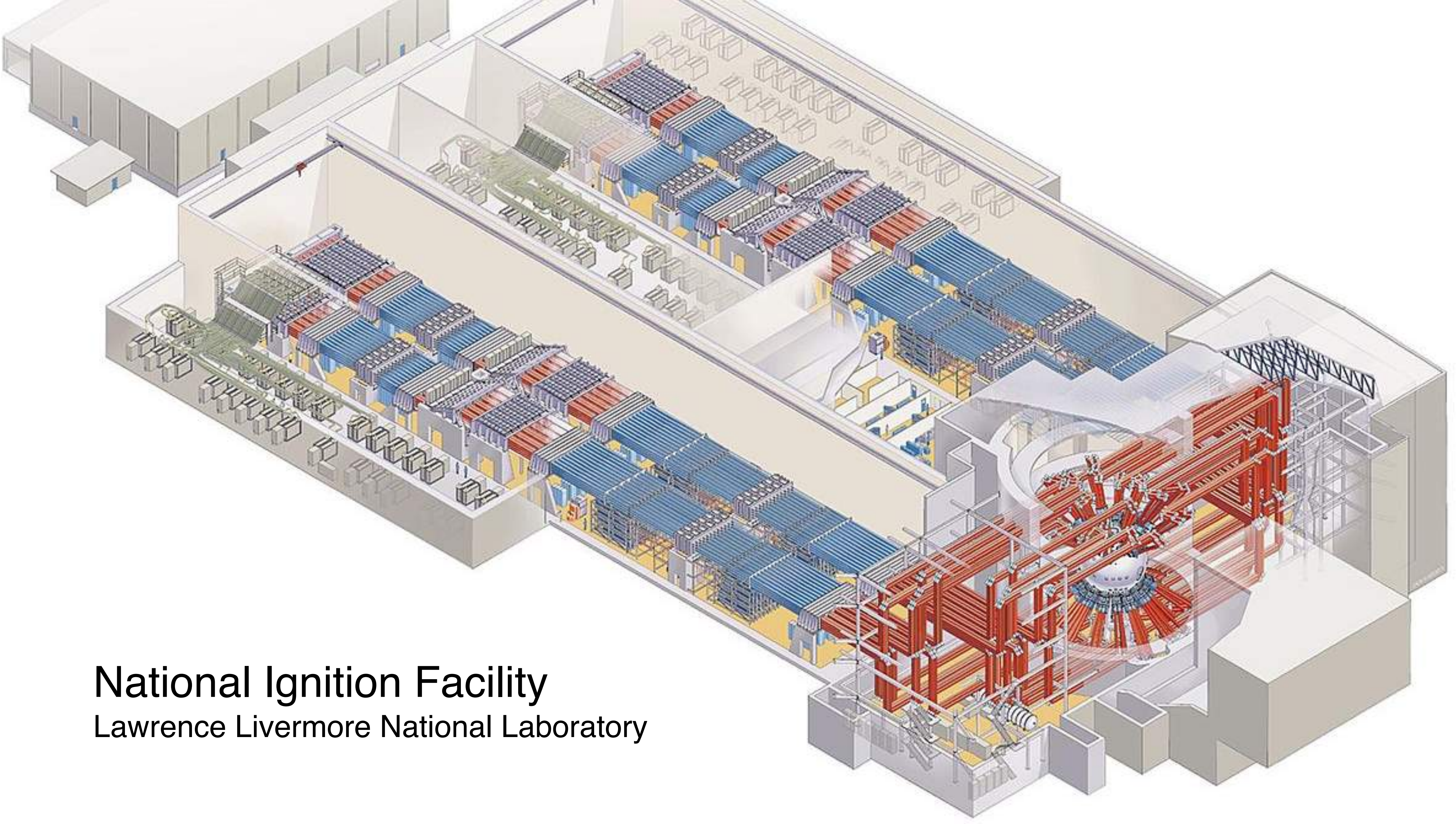
FOR EVERYONE.

FOREVER.

FUSION

IT MIGHT ACTUALLY WORK THIS TIME

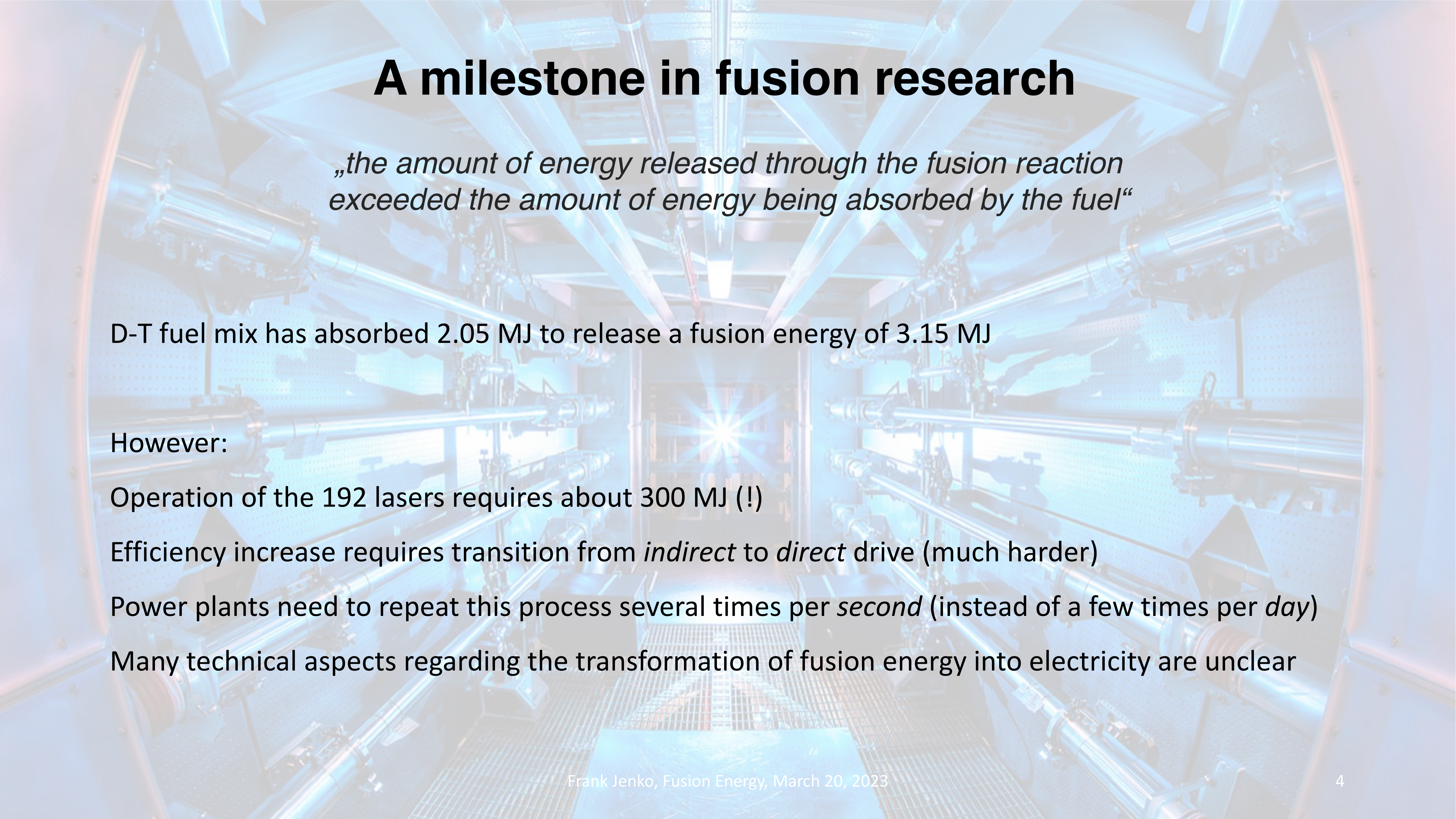
By Lev Grossman



National Ignition Facility

Lawrence Livermore National Laboratory

A milestone in fusion research



„the amount of energy released through the fusion reaction exceeded the amount of energy being absorbed by the fuel“

D-T fuel mix has absorbed 2.05 MJ to release a fusion energy of 3.15 MJ

However:

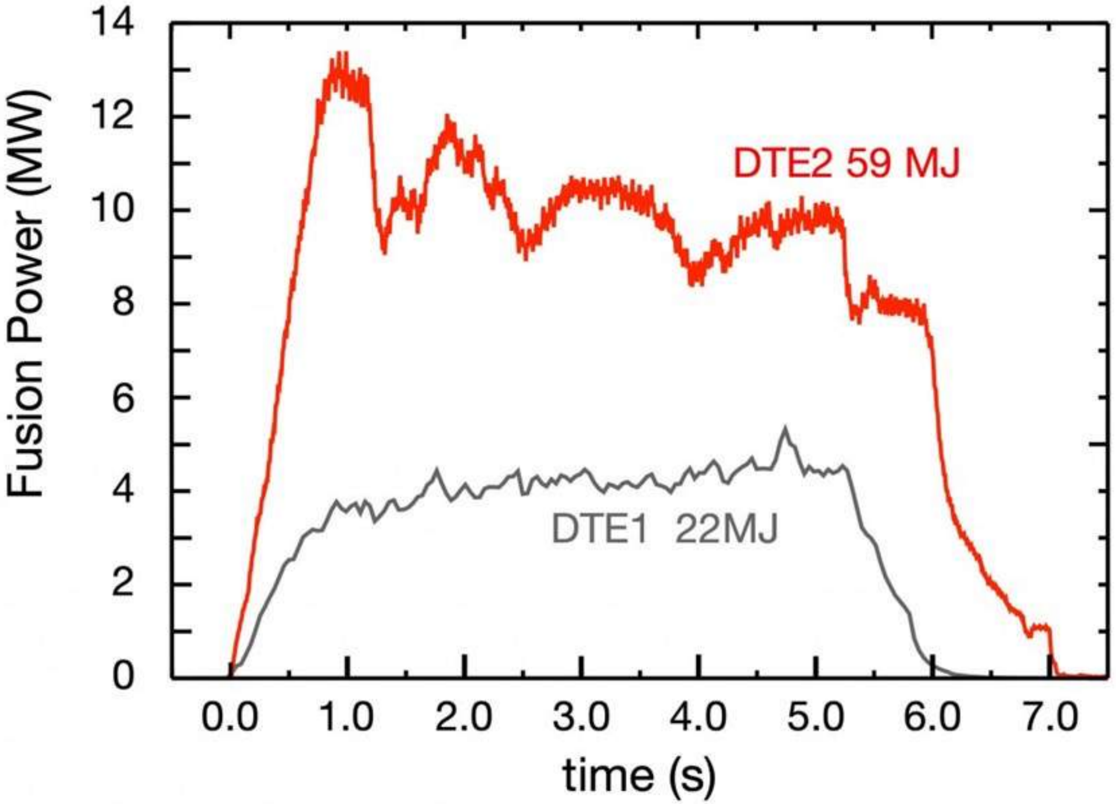
Operation of the 192 lasers requires about 300 MJ (!)

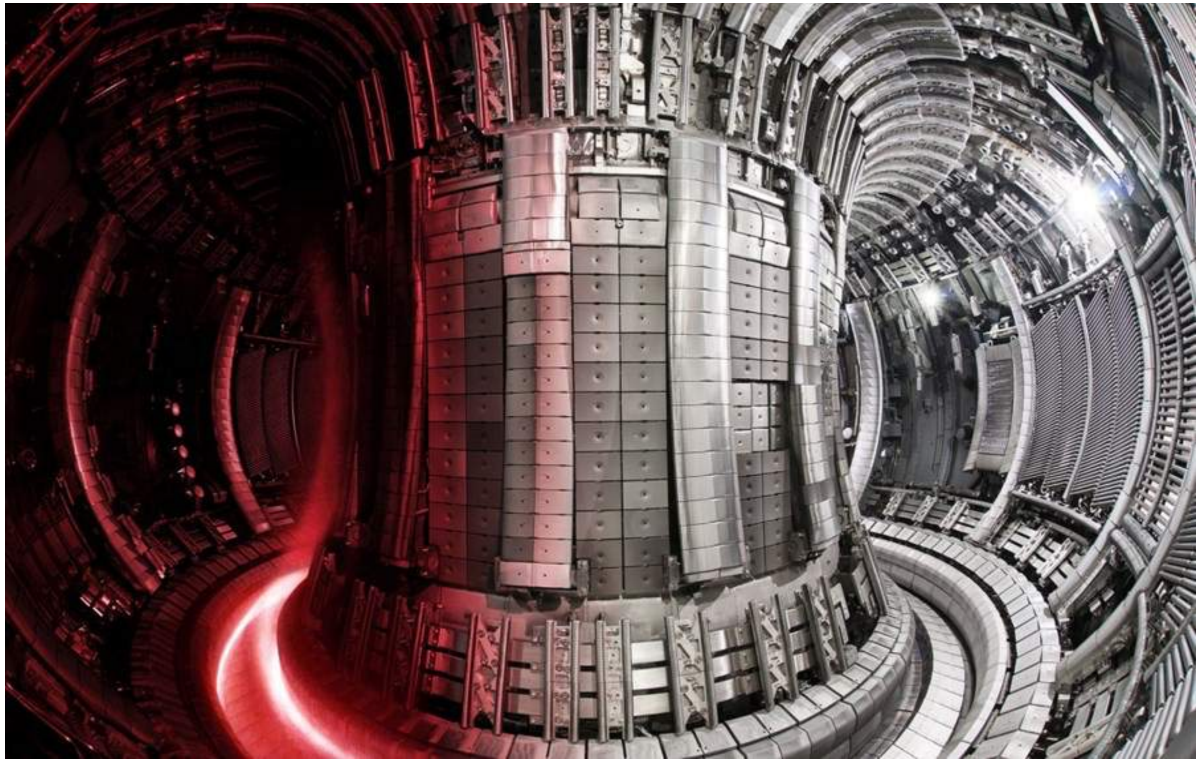
Efficiency increase requires transition from *indirect* to *direct* drive (much harder)

Power plants need to repeat this process several times per *second* (instead of a few times per *day*)

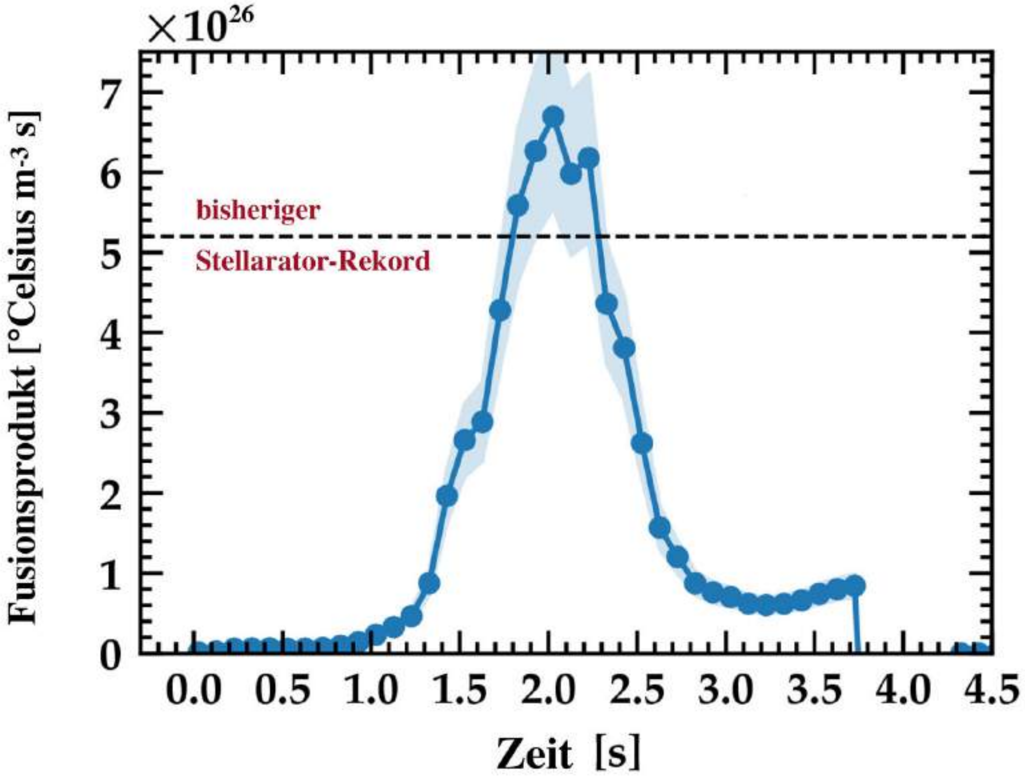
Many technical aspects regarding the transformation of fusion energy into electricity are unclear

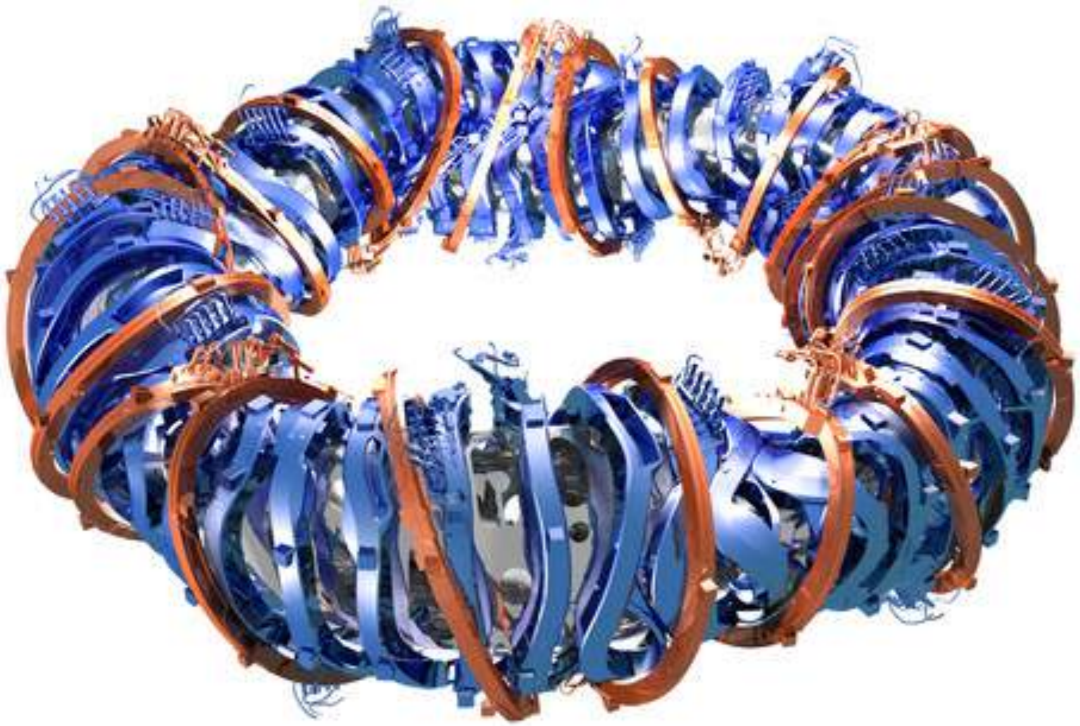
New world record at the JET tokamak (Oxford, UK)





New world record at the W7-X stellarator (IPP)

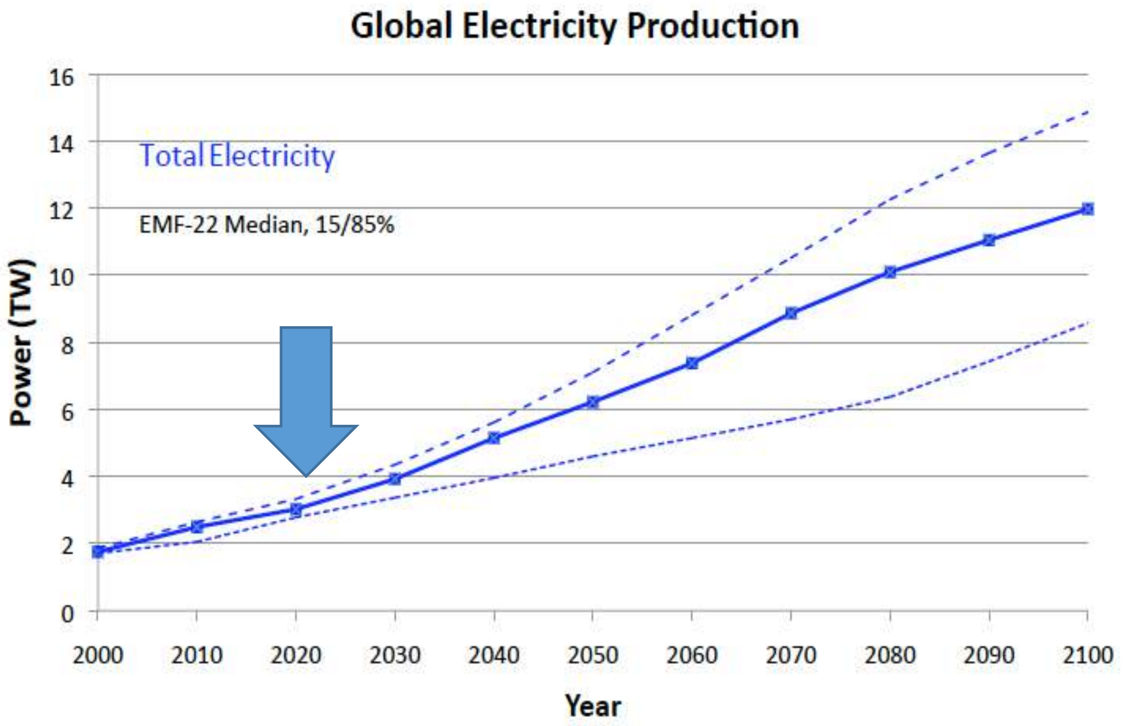




Fusion energy: Some context

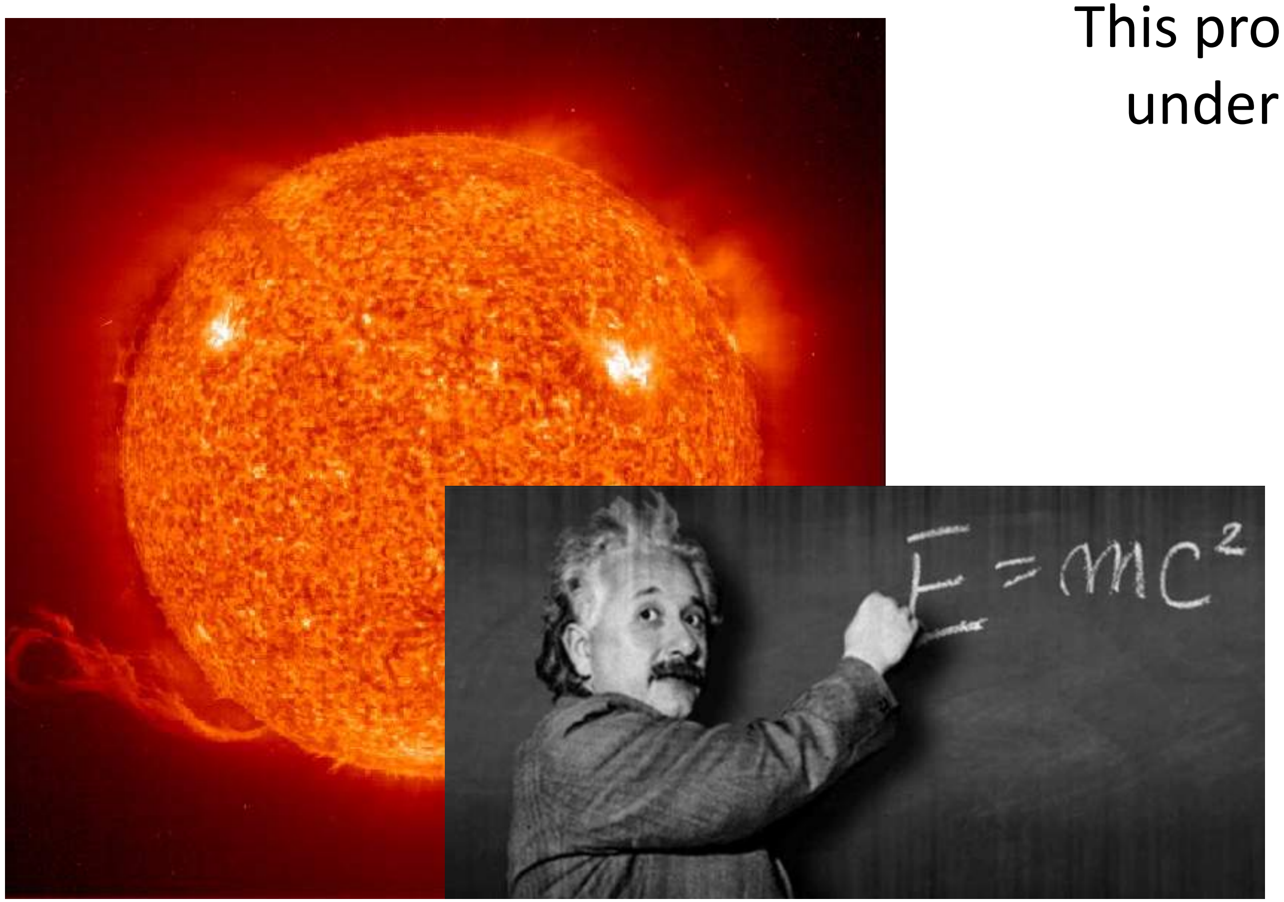
Global electricity needs will keep increasing

Energy Modeling Forum 22
100 models from 15 research groups (Clarke 2009)

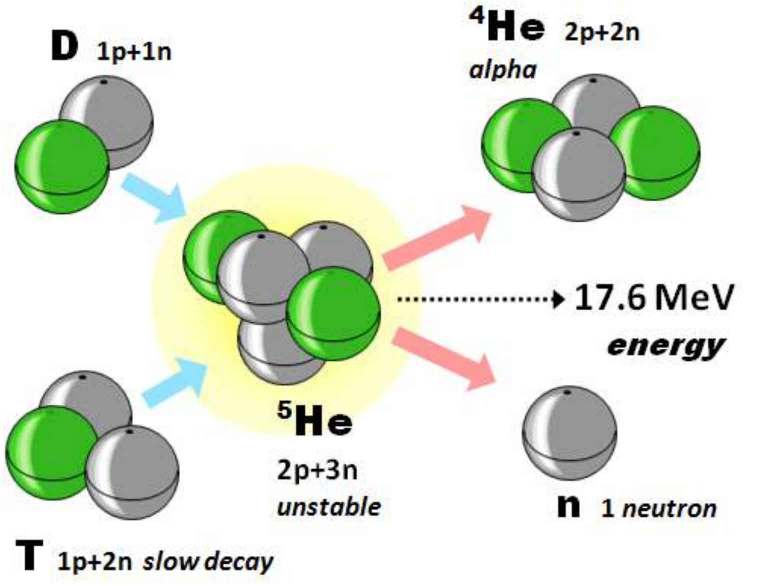


Factor of 3-5 until the end of this century

Fusion energy in nature and in the laboratory



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



LastTechAge.wordpress.com

Optimal temp: 145–330 M °C

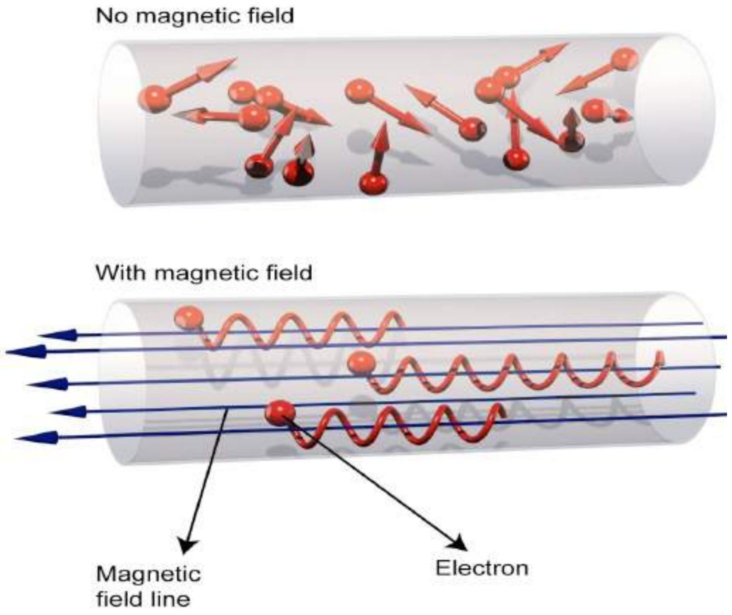
Still, temperatures of about 100 million degrees are required!
Thus, we are dealing with a fully ionized gas (plasma).

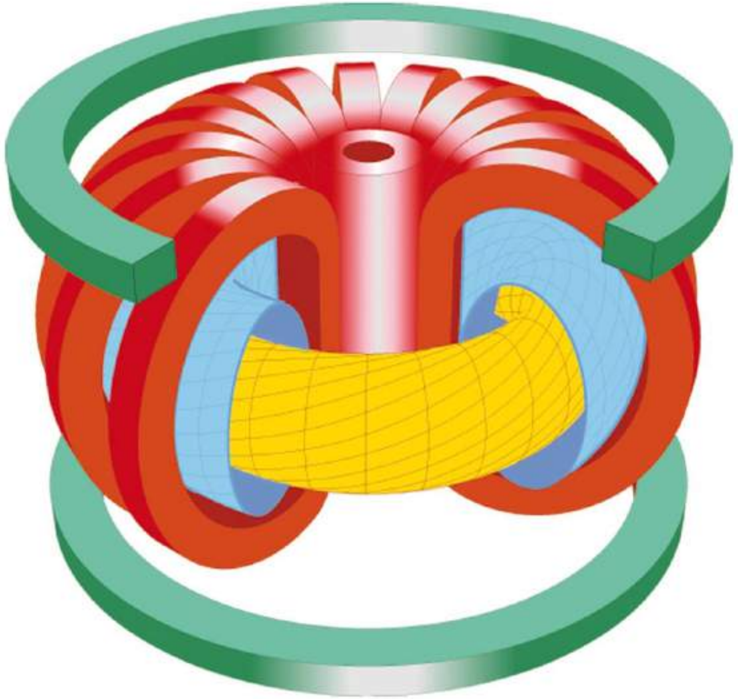
Magnetic confinement of fusion plasmas

Charged particles basically follow magnetic field lines

Helically twisted field lines span nested magnetic surfaces

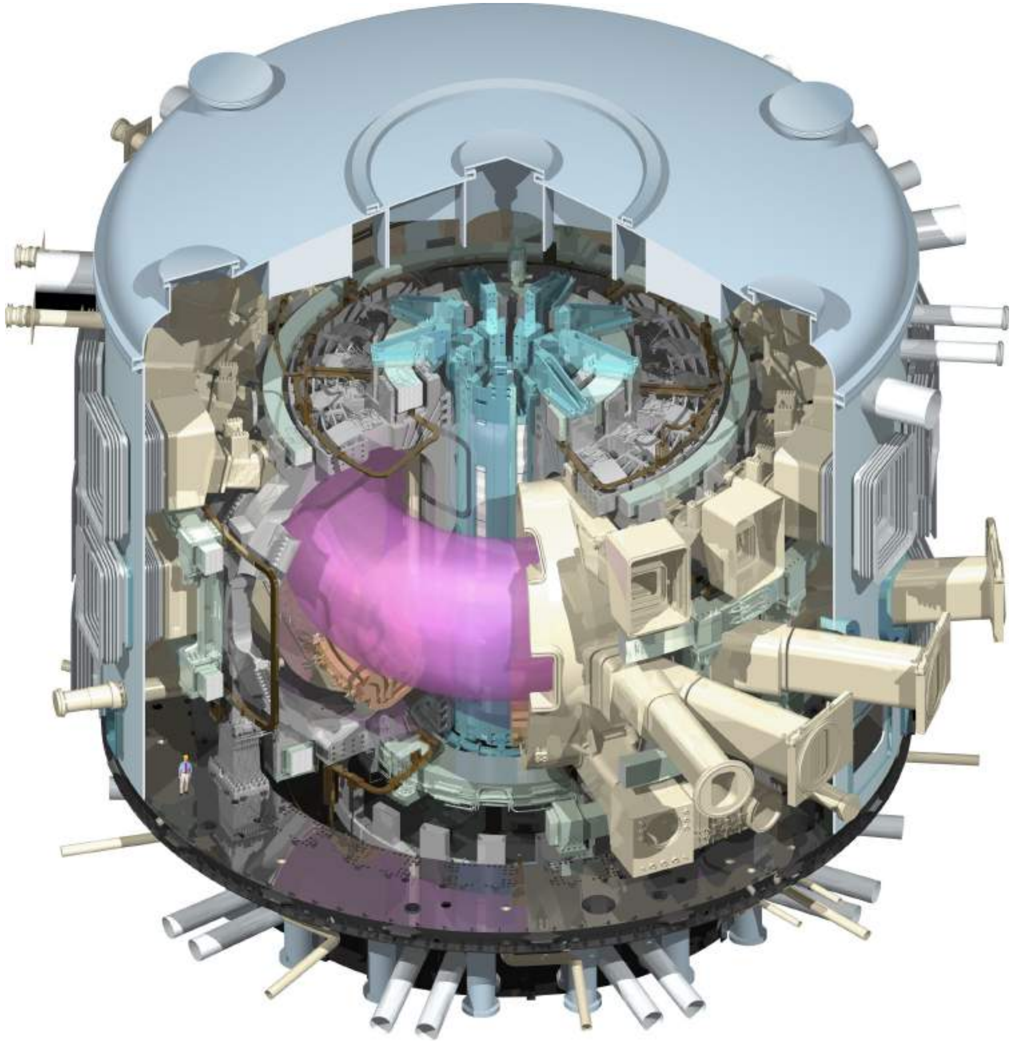
Such an axisymmetric device is called “tokamak”





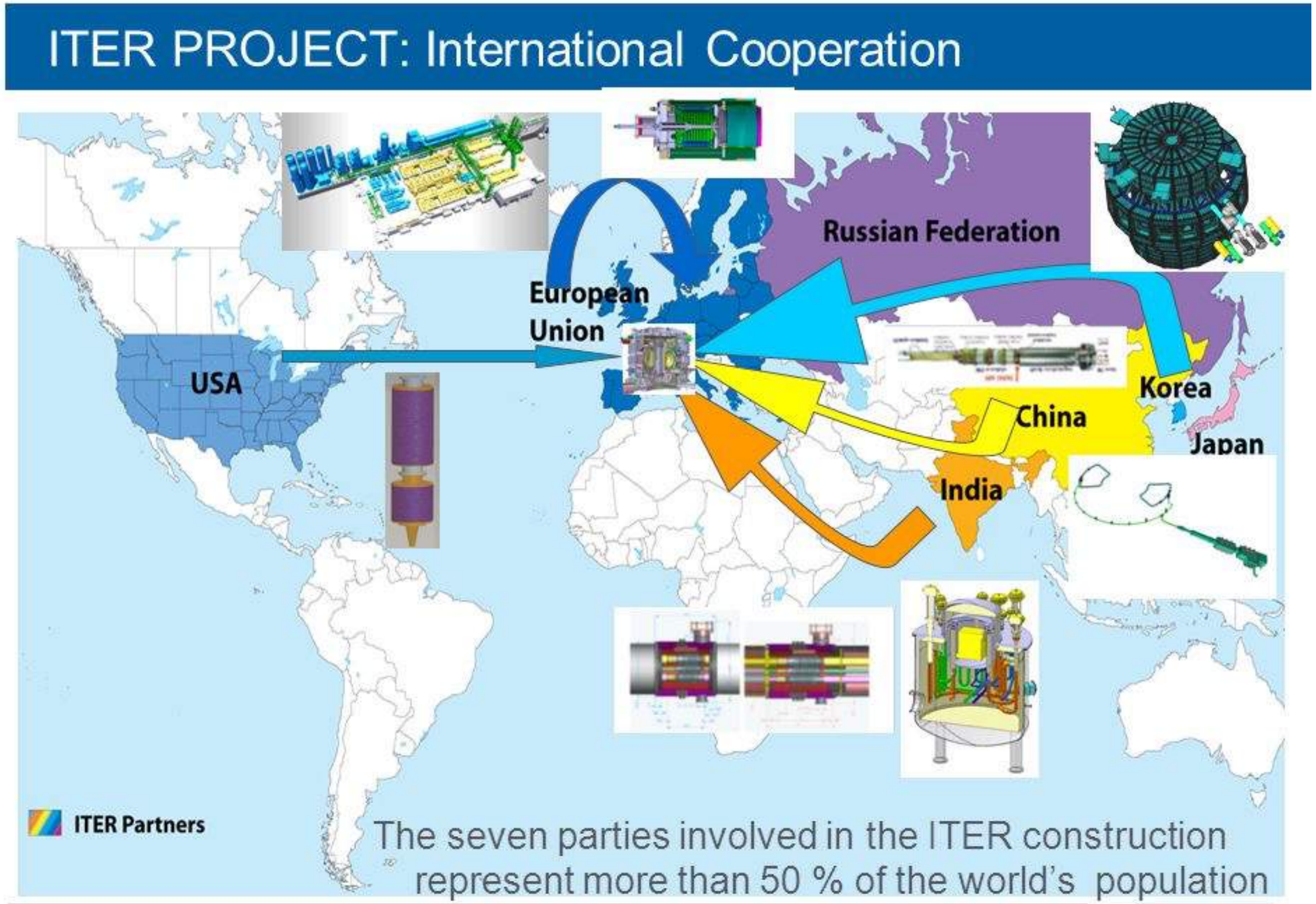

ASDEX Upgrade (IPP Garching)

The international ITER project



Goal: 500 MW of fusion power

www.iter.org



ITER PROJECT: International Cooperation

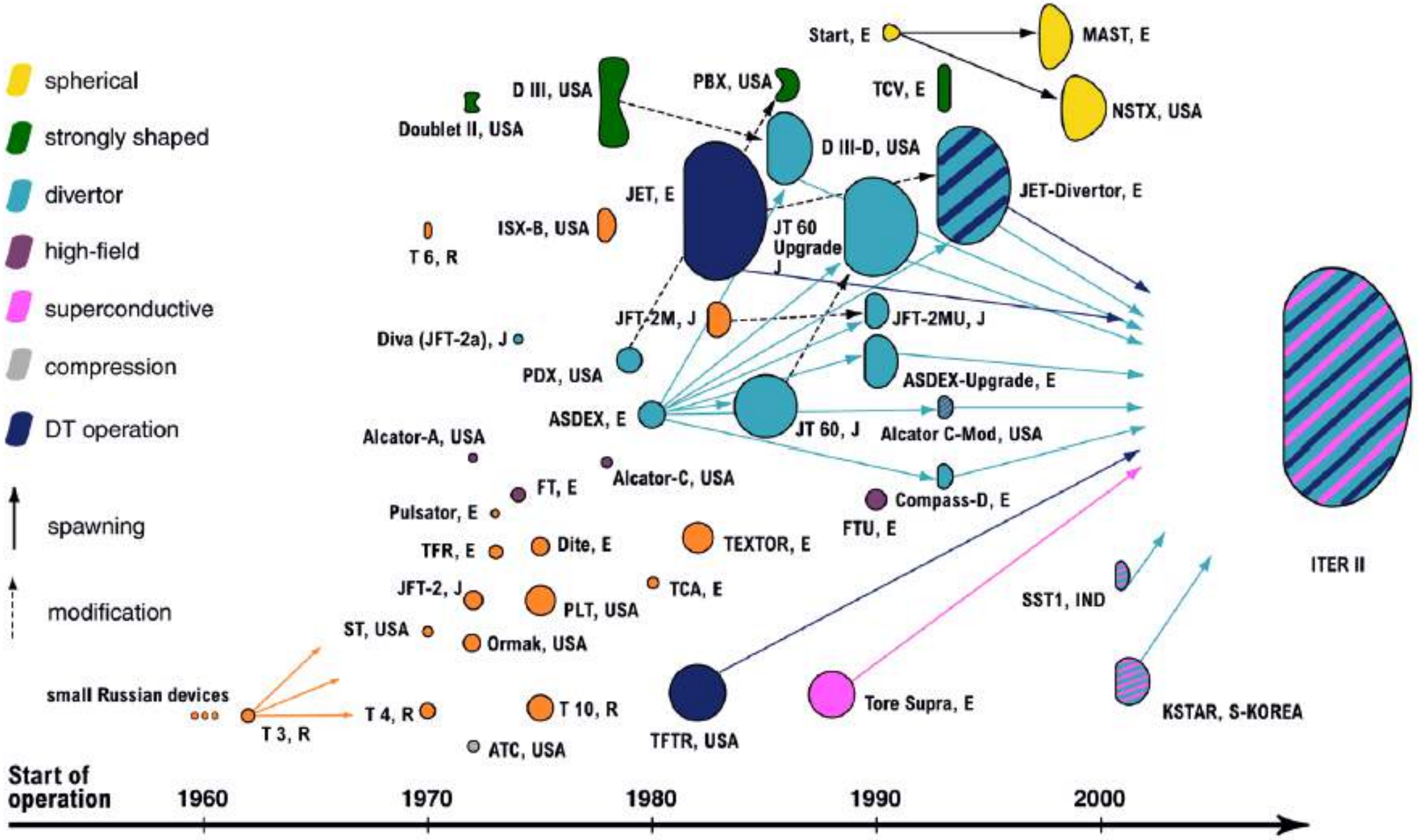
The seven parties involved in the ITER construction represent more than 50 % of the world's population

ITER construction site in Southern France

Operation is scheduled to begin in a few years
www.iter.org

From ‘trial-and-error’ to ‘predict first’

Evolution of tokamaks



Fusion research: On the path towards burning plasmas

Self-heating must compensate energy losses:

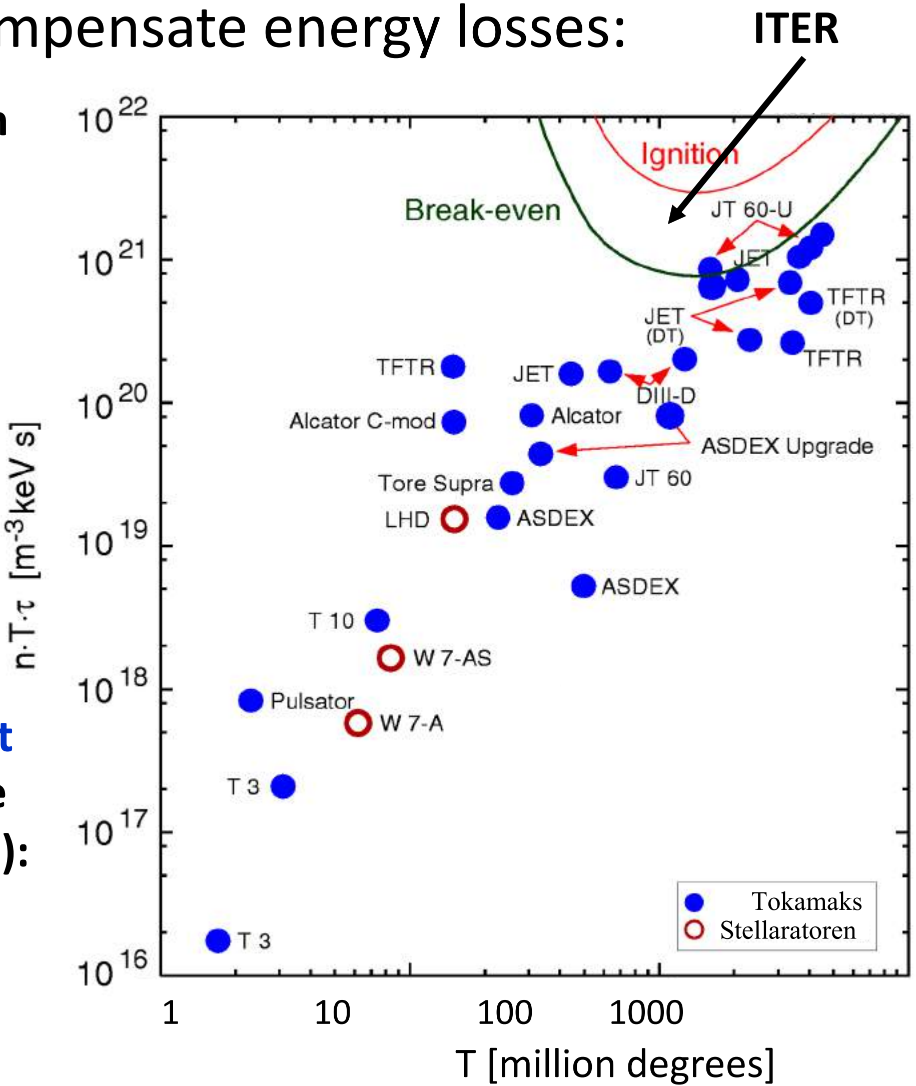
- **Electromagnetic radiation**
- **Turbulent transport**

Key requirements:

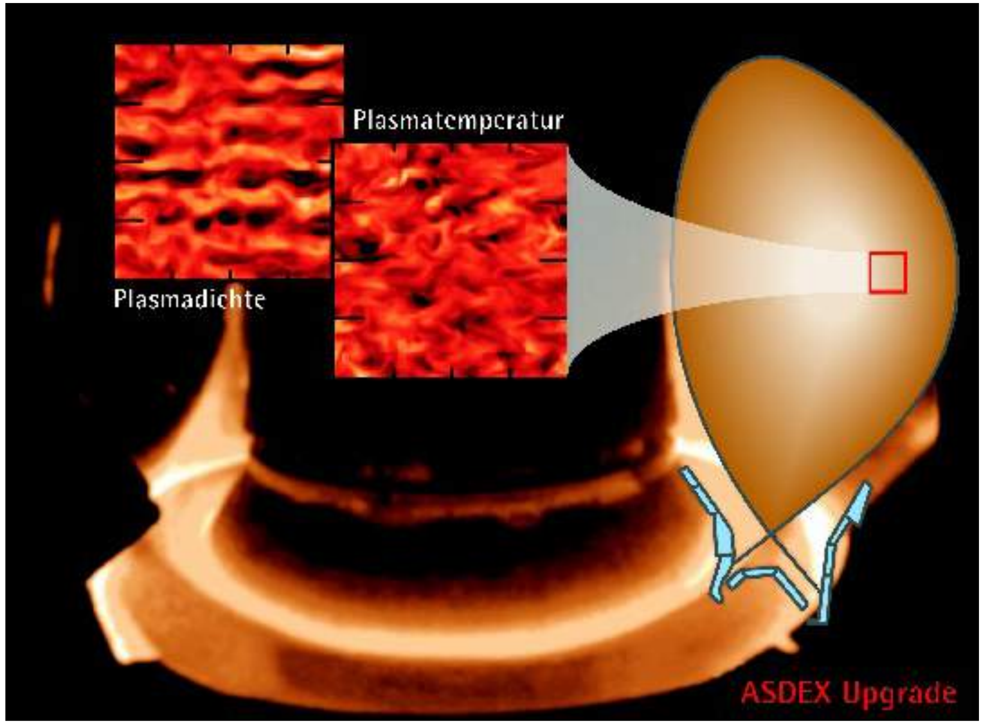
- **Large central pressure** **(limited by onset of large-scale instabilities)**

- **Large energy confinement time** **(limited by small-scale instabilities, i.e. turbulence):**

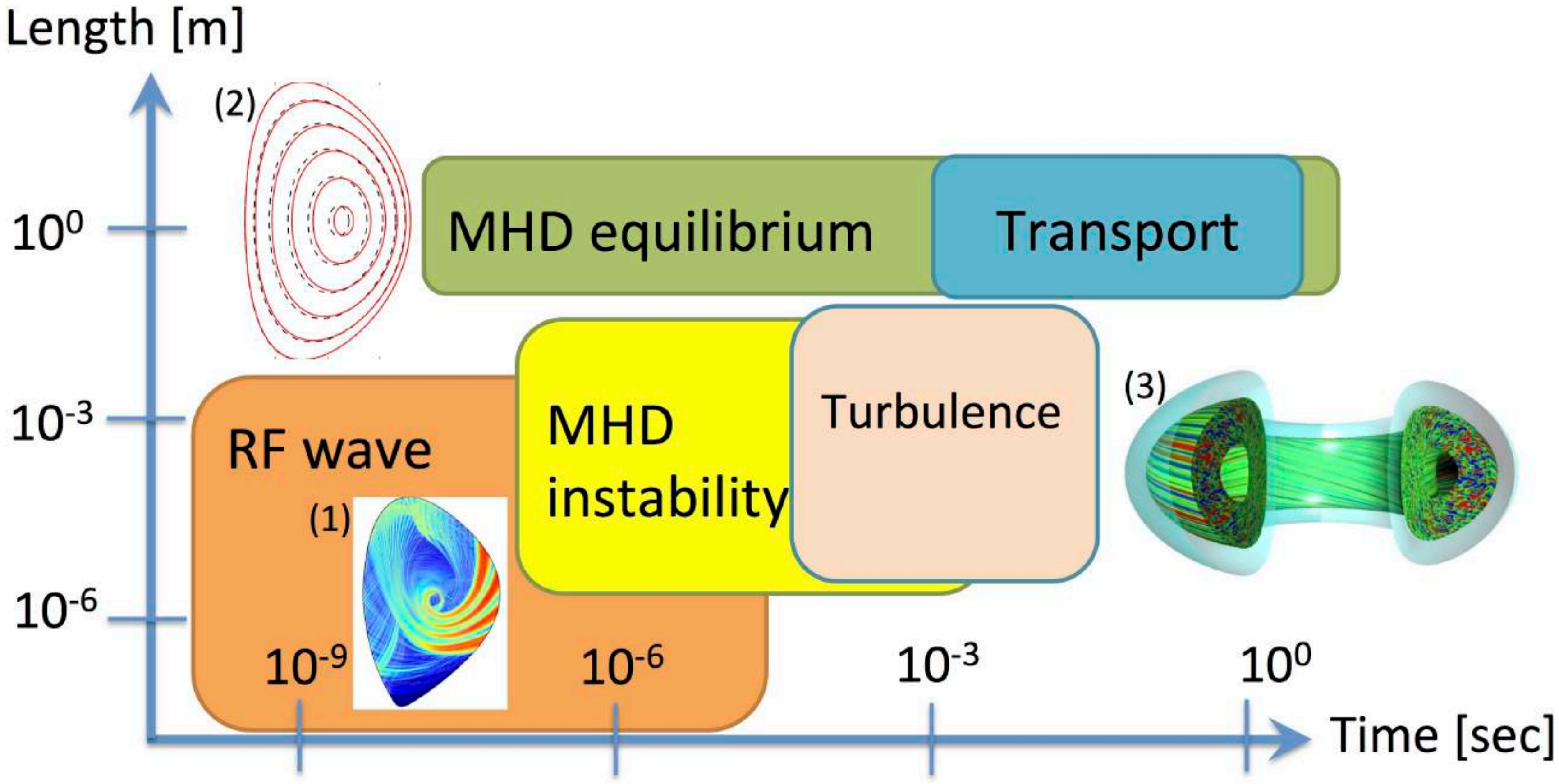
$$\tau_E = E_{plasma} / P_{loss}$$



Radial heat transport due to small-scale turbulence controls energy confinement time



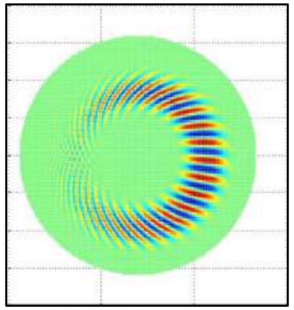
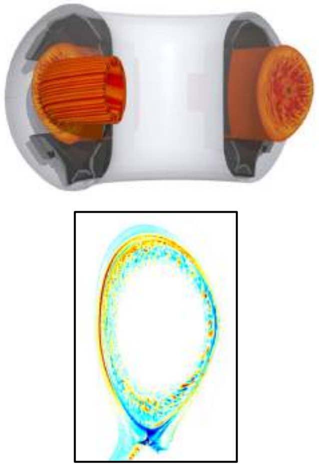
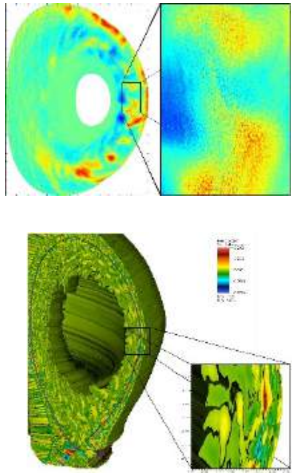
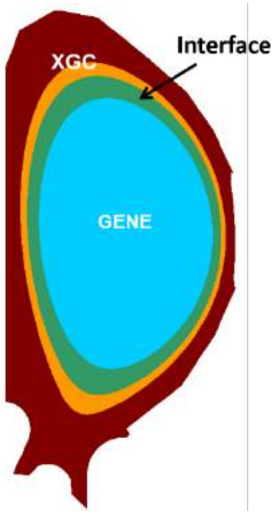
The multiscale, multiphysics challenge

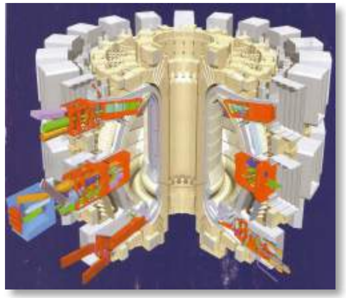


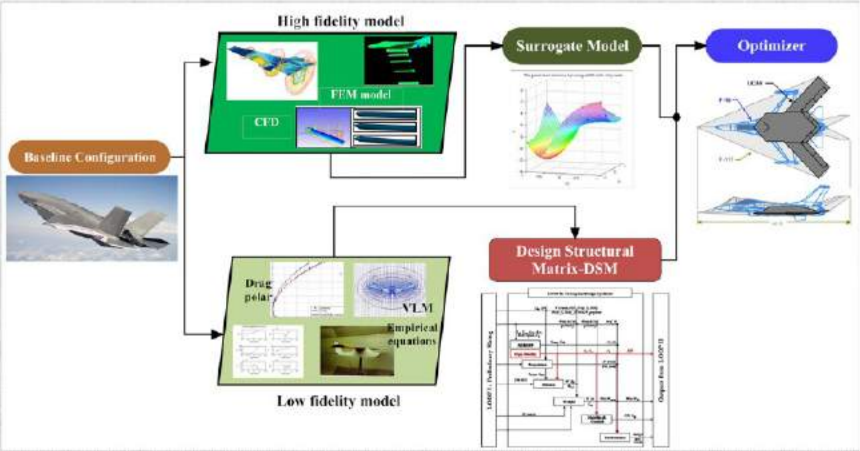
Many nonlinear interactions; we cannot use a simple "superposition principle"

From highly idealized models towards digital twins

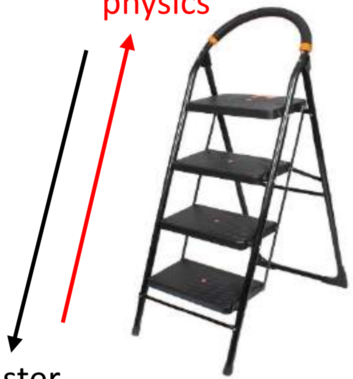
Increasing fidelity & modeling capability with increasing computing power





more complete physics



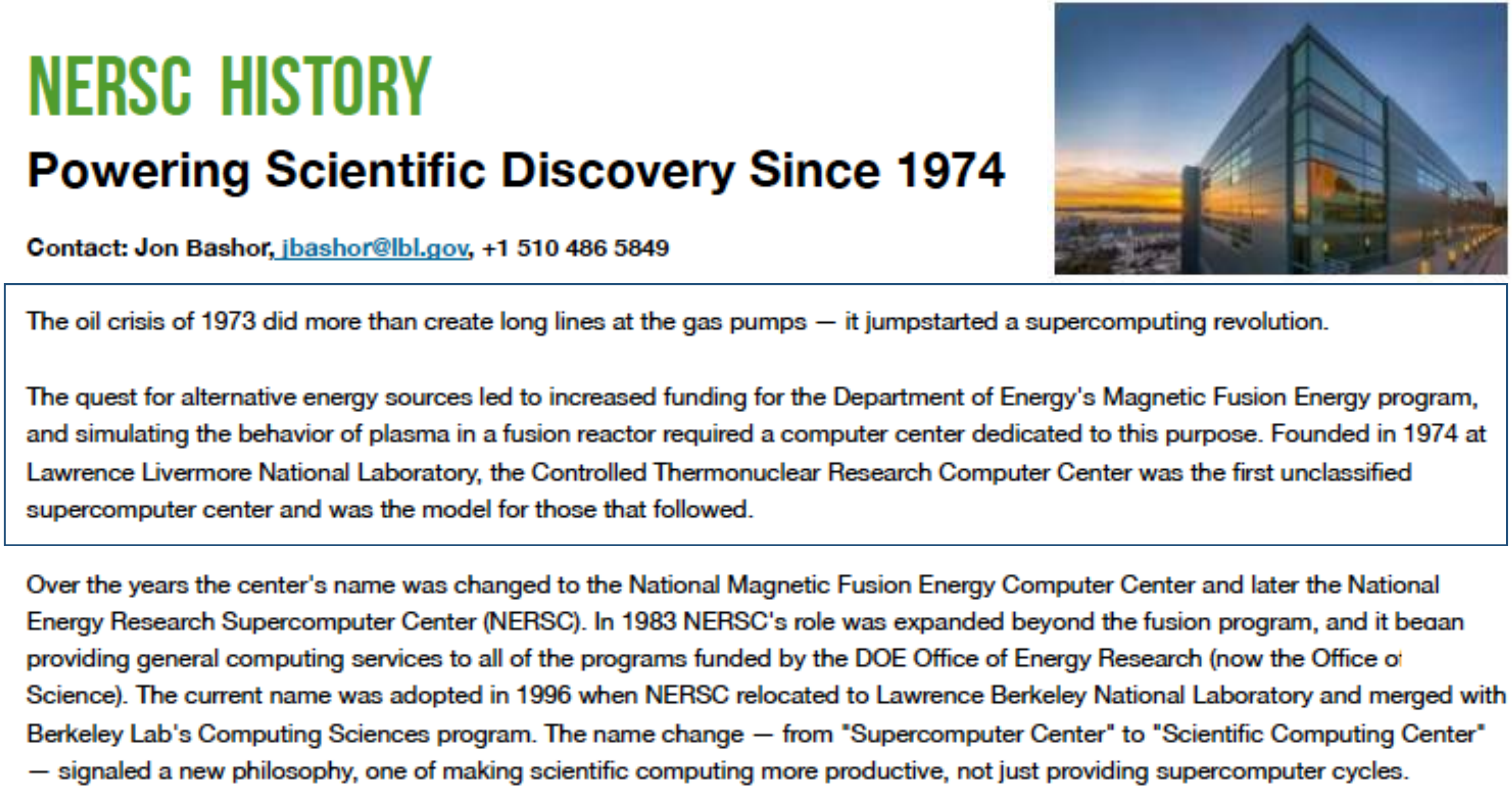
faster

Multi-fidelity approach:

- HiFi models for reliable extrapolation/prediction
- LoFi models (based on HiFi models) for high-throughput computing & real-time applications (incl. control)

Both are needed – together

Fusion: At the forefront of supercomputing since the 70s



NERSC HISTORY

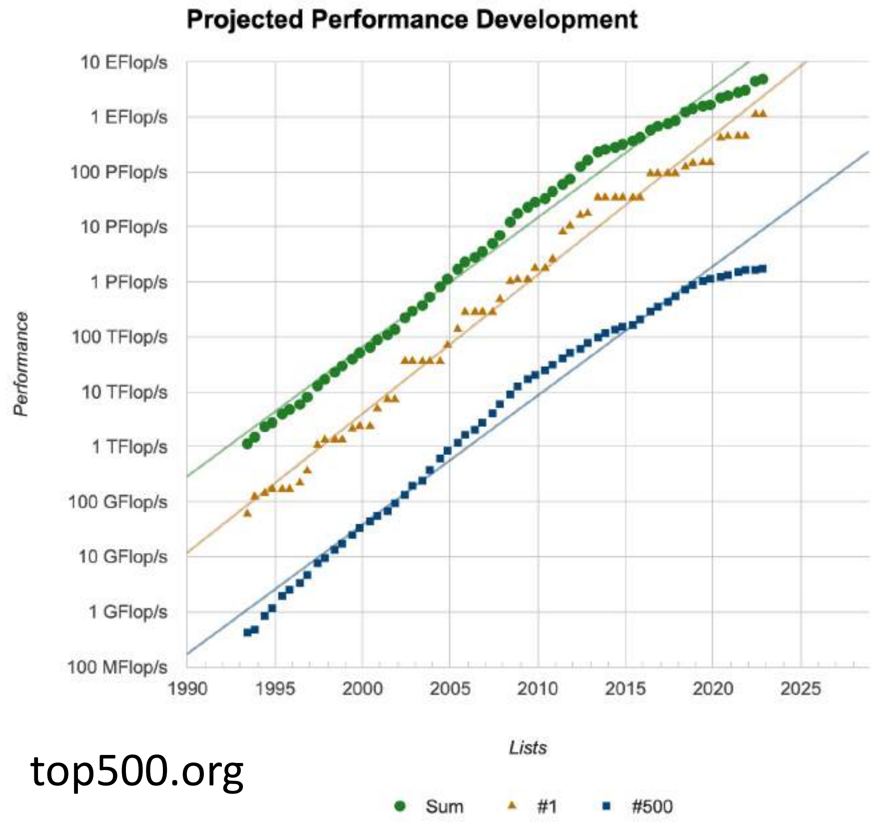
Powering Scientific Discovery Since 1974

Contact: Jon Bashor, jbashor@lbl.gov, +1 510 486 5849

The oil crisis of 1973 did more than create long lines at the gas pumps — it jumpstarted a supercomputing revolution.

The quest for alternative energy sources led to increased funding for the Department of Energy's Magnetic Fusion Energy program, and simulating the behavior of plasma in a fusion reactor required a computer center dedicated to this purpose. Founded in 1974 at Lawrence Livermore National Laboratory, the Controlled Thermonuclear Research Computer Center was the first unclassified supercomputer center and was the model for those that followed.

Over the years the center's name was changed to the National Magnetic Fusion Energy Computer Center and later the National Energy Research Supercomputer Center (NERSC). In 1983 NERSC's role was expanded beyond the fusion program, and it began providing general computing services to all of the programs funded by the DOE Office of Energy Research (now the Office o Science). The current name was adopted in 1996 when NERSC relocated to Lawrence Berkeley National Laboratory and merged with Berkeley Lab's Computing Sciences program. The name change — from "Supercomputer Center" to "Scientific Computing Center" — signaled a new philosophy, one of making scientific computing more productive, not just providing supercomputer cycles.



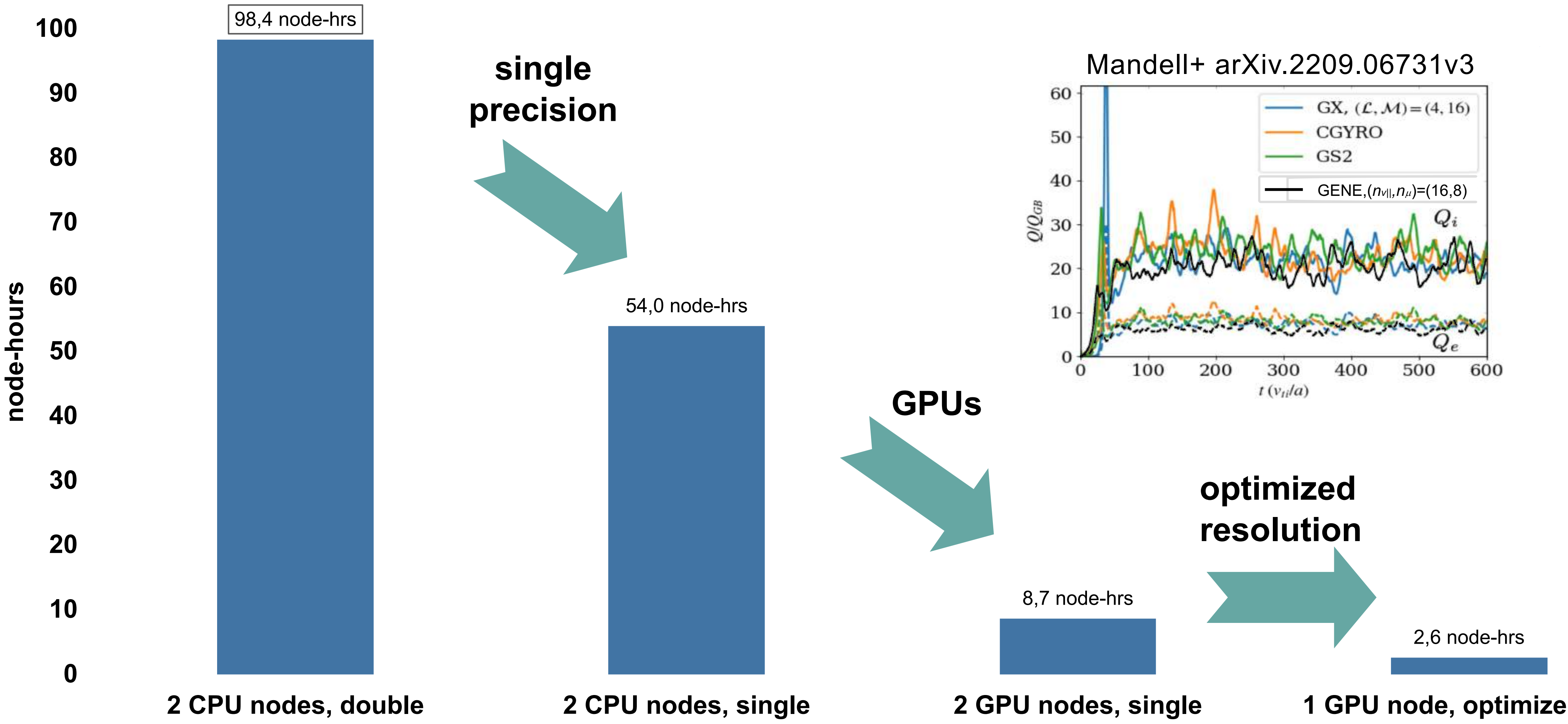
top500.org

> 1.000.000.000.000.000.000 floating point operations per second

Entering the era of exascale computing

Beyond brute force: Smart algorithms and implementations

Cyclone Base Case with kinetic electrons & collisions (T = 600 a/cs)

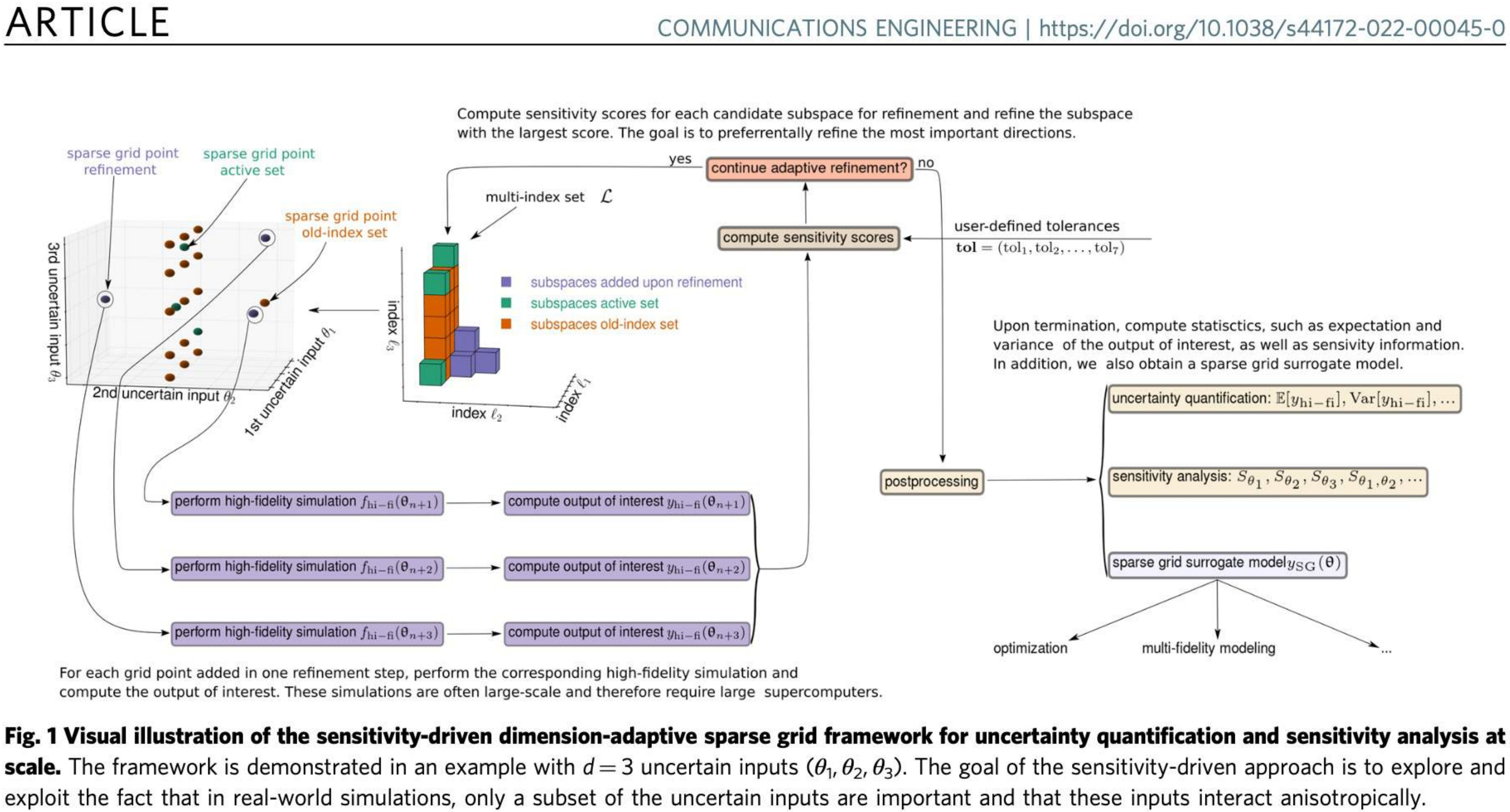


Mandell+ arXiv.2209.06731v3

38x more efficient

CPU node: Intel Xeon IceLake-SP with 72 cores (using 64)
GPU node: 4 NVIDIA A100 GPUs using 4 CPUs

Exploring high-dimensional parameter spaces efficiently



ARTICLE

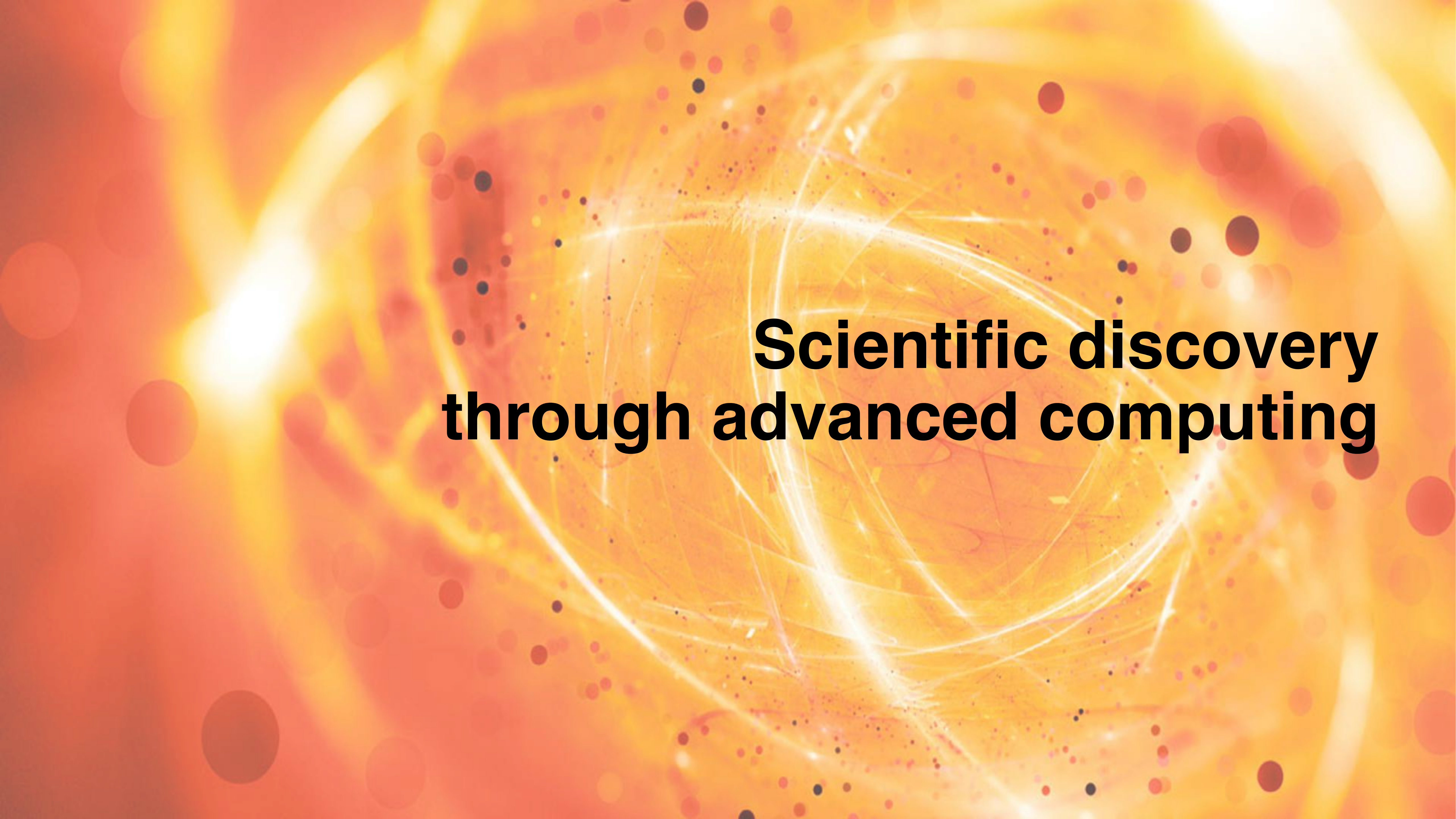
COMMUNICATIONS ENGINEERING | https://doi.org/10.1038/s44172-022-00045-0

Compute sensitivity scores for each candidate subspace for refinement and refine the subspace with the largest score. The goal is to preferrentally refine the most important directions.

Upon termination, compute statisctics, such as expectation and variance of the output of interest, as well as sensivity information. In addition, we also obtain a sparse grid surrogate model.

For each grid point added in one refinement step, perform the corresponding high-fidelity simulation and compute the output of interest. These simulations are often large-scale and therefore require large supercomputers.

Fig. 1 Visual illustration of the sensitivity-driven dimension-adaptive sparse grid framework for uncertainty quantification and sensitivity analysis at scale. The framework is demonstrated in an example with $d = 3$ uncertain inputs $(\theta_1, \theta_2, \theta_3)$. The goal of the sensitivity-driven approach is to explore and exploit the fact that in real-world simulations, only a subset of the uncertain inputs are important and that these inputs interact anisotropically.

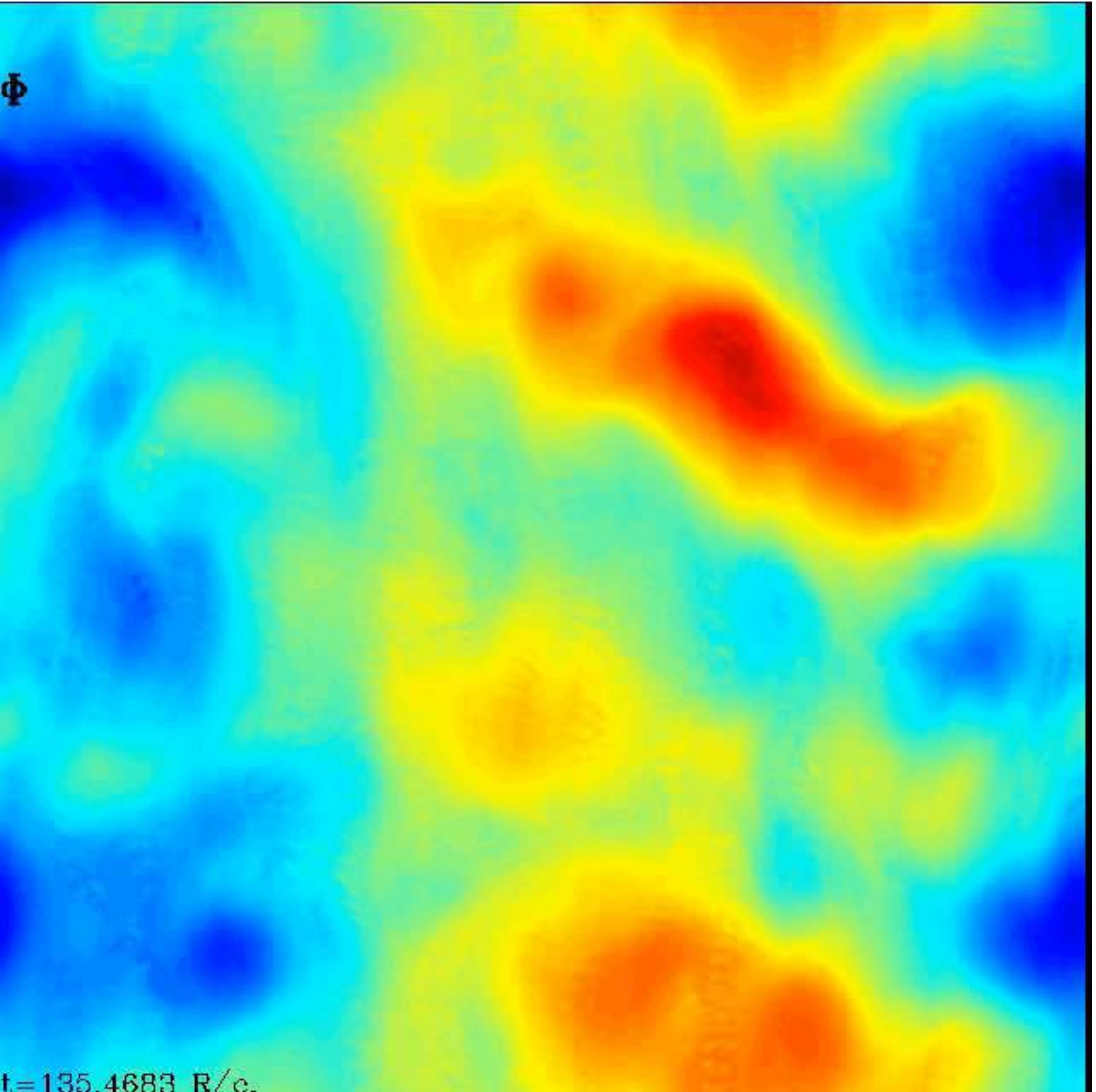


Scientific discovery through advanced computing

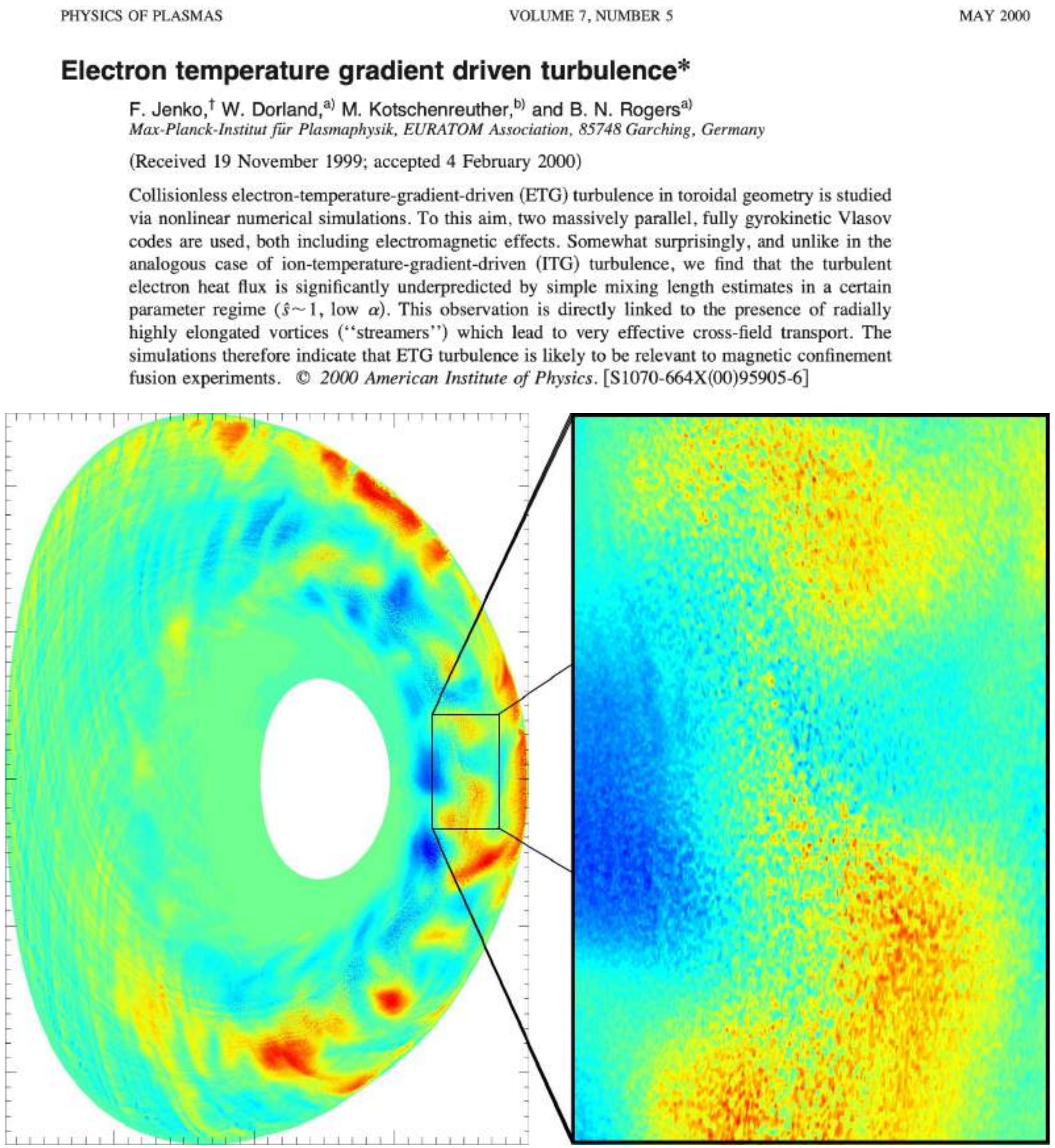
Global Gyrokinetic Simulation of Turbulence in ASDEX Upgrade

GENE

gene.rzg.mpg.de



From interpretation to prediction



PHYSICS OF PLASMAS VOLUME 7, NUMBER 5 MAY 2000

Electron temperature gradient driven turbulence*

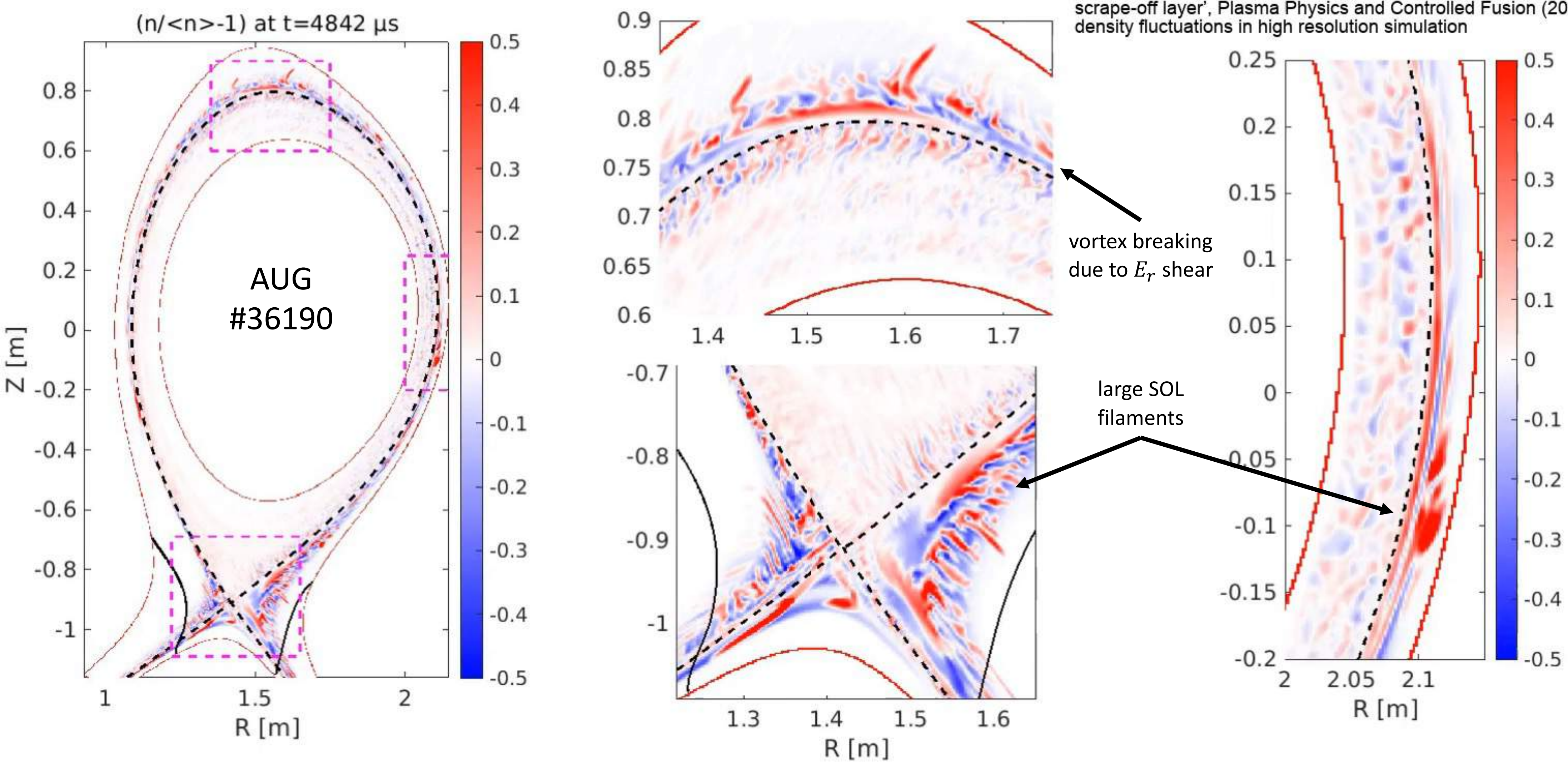
F. Jenko,† W. Dorland,[a] M. Kotschenreuther,[b] and B. N. Rogers[a]
Max-Planck-Institut für Plasmaphysik, EURATOM Association, 85748 Garching, Germany

(Received 19 November 1999; accepted 4 February 2000)

Collisionless electron-temperature-gradient-driven (ETG) turbulence in toroidal geometry is studied via nonlinear numerical simulations. To this aim, two massively parallel, fully gyrokinetic Vlasov codes are used, both including electromagnetic effects. Somewhat surprisingly, and unlike in the analogous case of ion-temperature-gradient-driven (ITG) turbulence, we find that the turbulent electron heat flux is significantly underpredicted by simple mixing length estimates in a certain parameter regime ($\hat{s}\sim 1$, low α). This observation is directly linked to the presence of radially highly elongated vortices (''streamers'') which lead to very effective cross-field transport. The simulations therefore indicate that ETG turbulence is likely to be relevant to magnetic confinement fusion experiments. © *2000 American Institute of Physics.* [S1070-664X(00)95905-6]

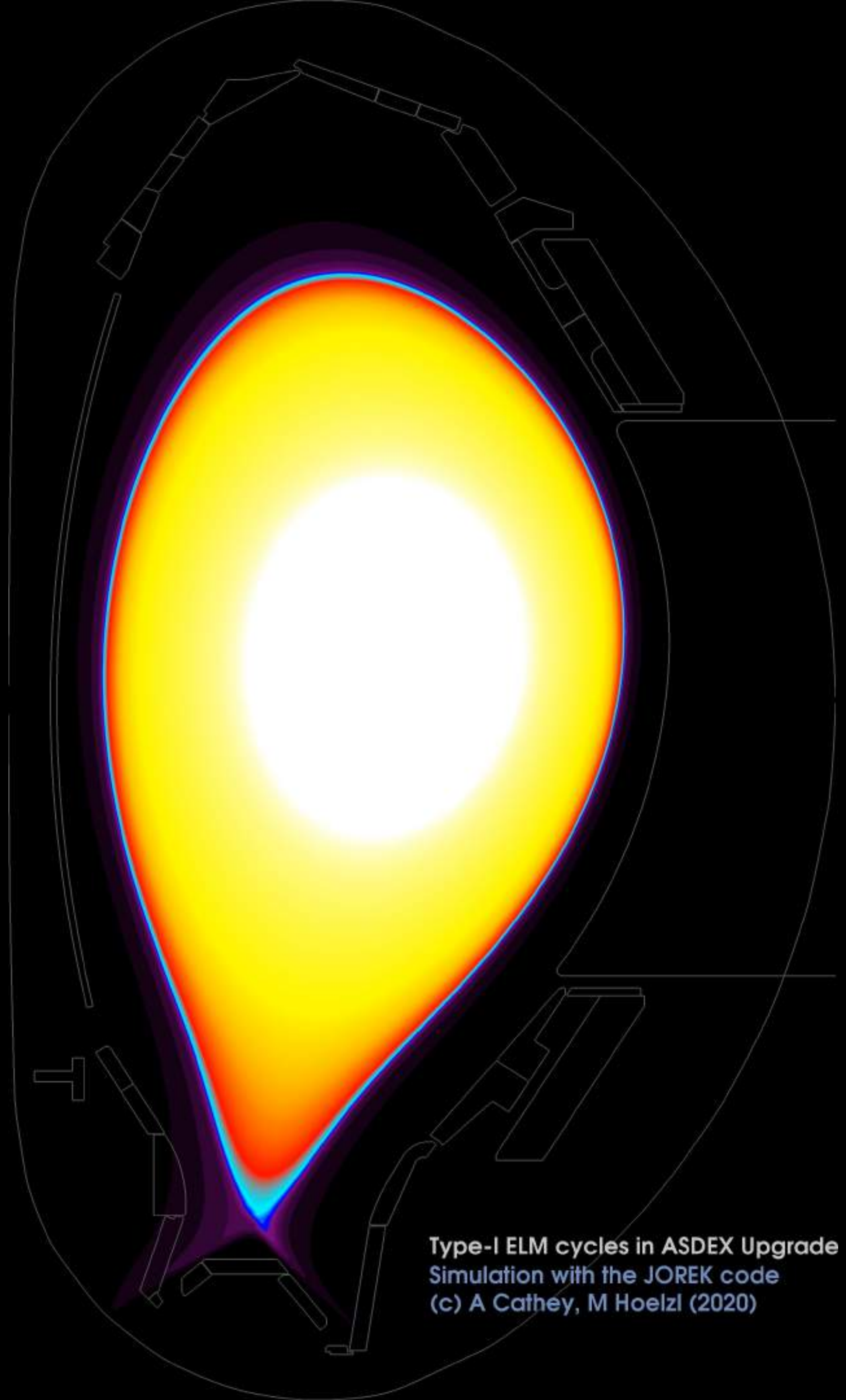
Exploring the physics of edge transport barriers

Wladimir Zholobenko et al., ‘Electric field and turbulence in global Braginskii simulations across ASDEX Upgrade edge and scrape-off layer’, Plasma Physics and Controlled Fusion (2020), density fluctuations in high resolution simulation



vortex breaking due to E_r shear

large SOL filaments

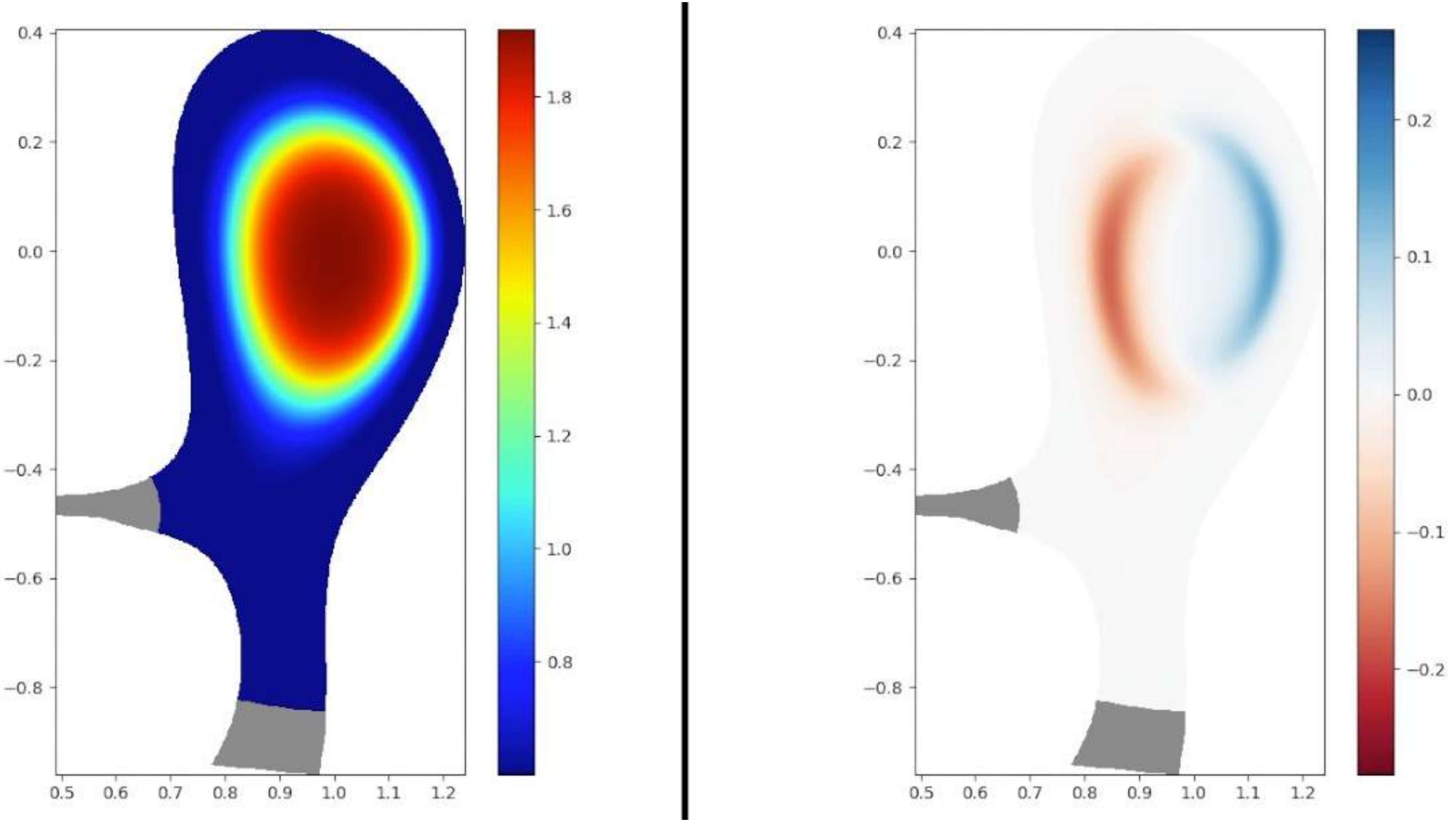


Type-I ELM cycles in ASDEX Upgrade

Simulation with the JOREK code

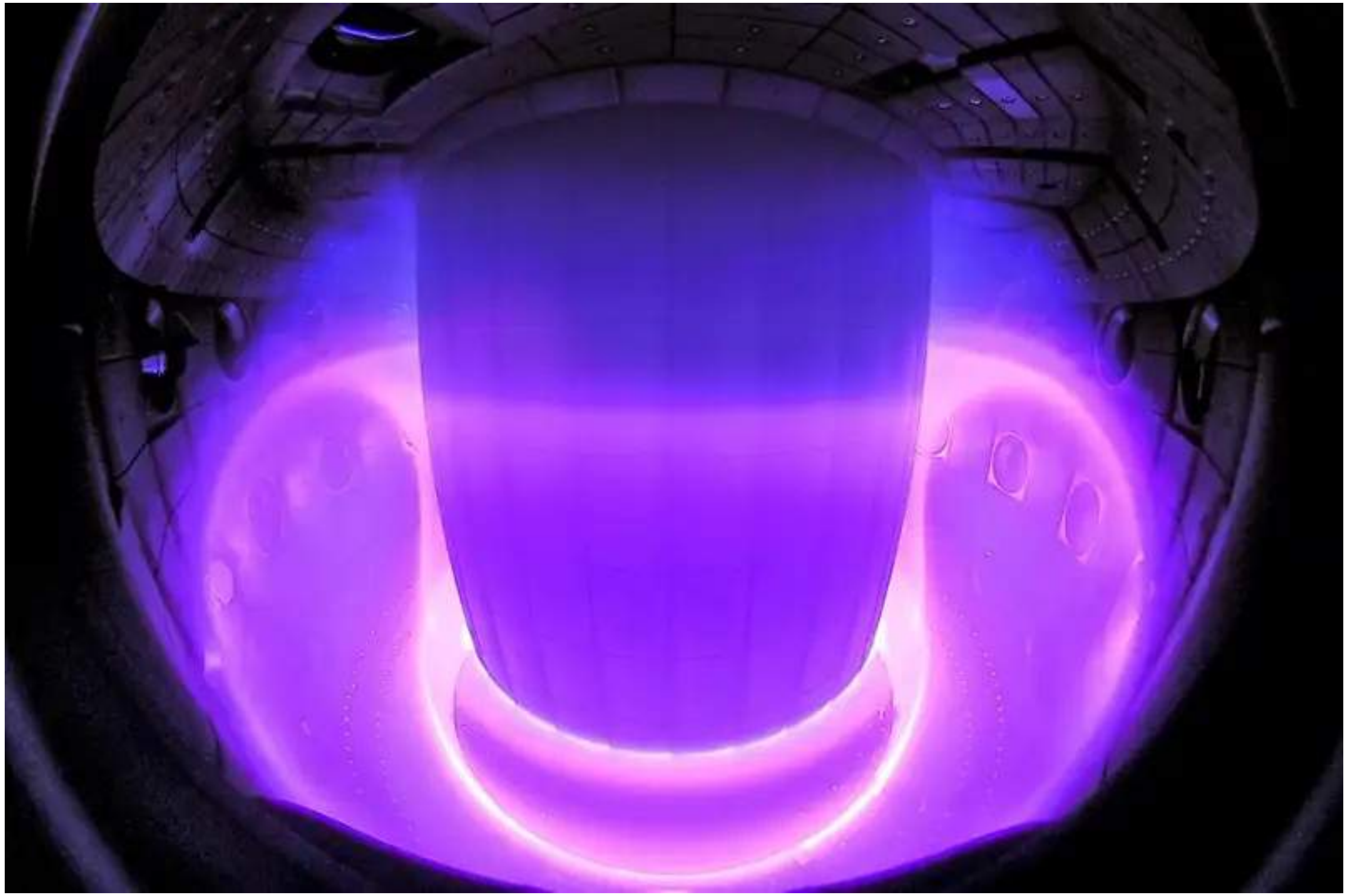
(c) A Cathey, M Hoelzl (2020)

First whole-device simulations (of the TCV tokamak) with GENE-X

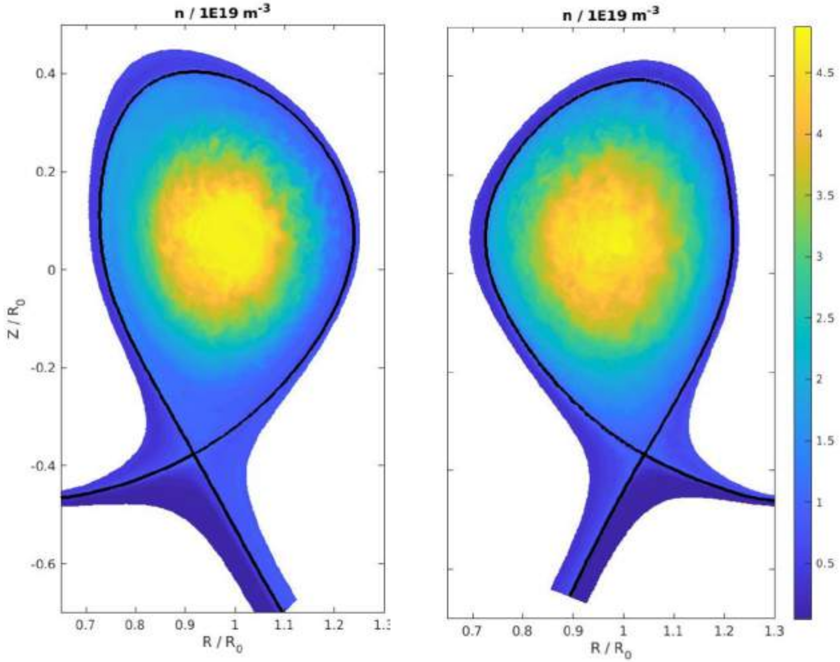


TCV studies: Optimized plasma shaping

Enhanced confinement w/o periodic edge instabilities:
Negative triangularity plasmas



Tokamak à configuration variable (TCV) at SPC/EPFL

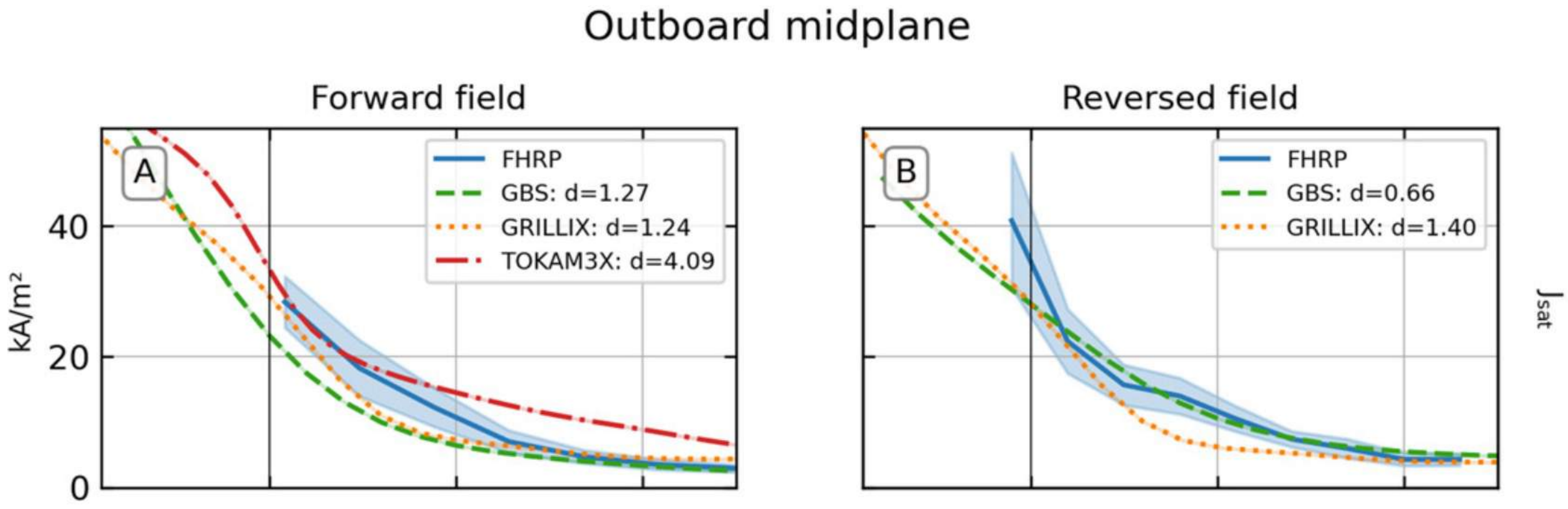


GENE-X simulations

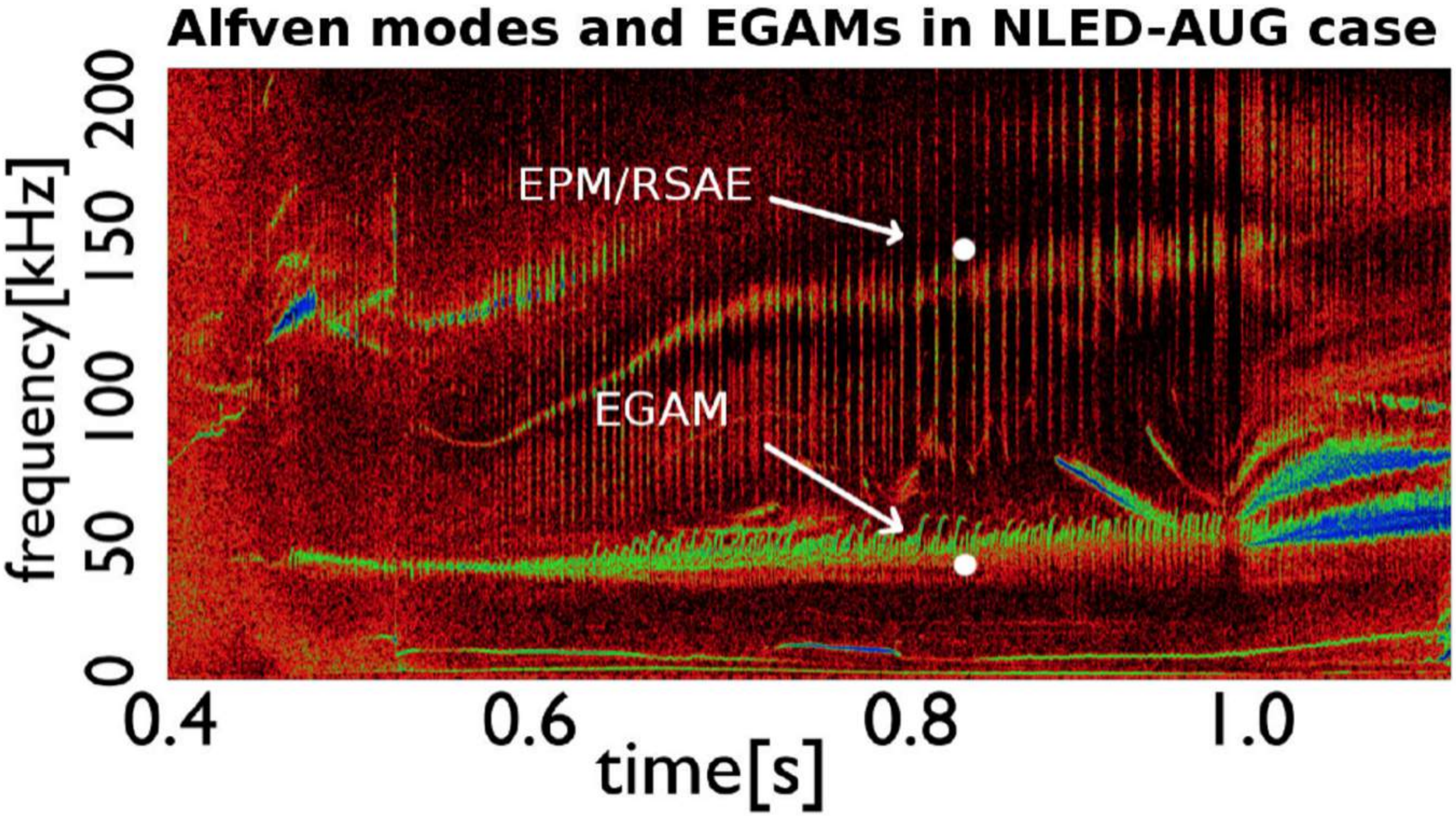
Validation of edge turbulence codes against TCV

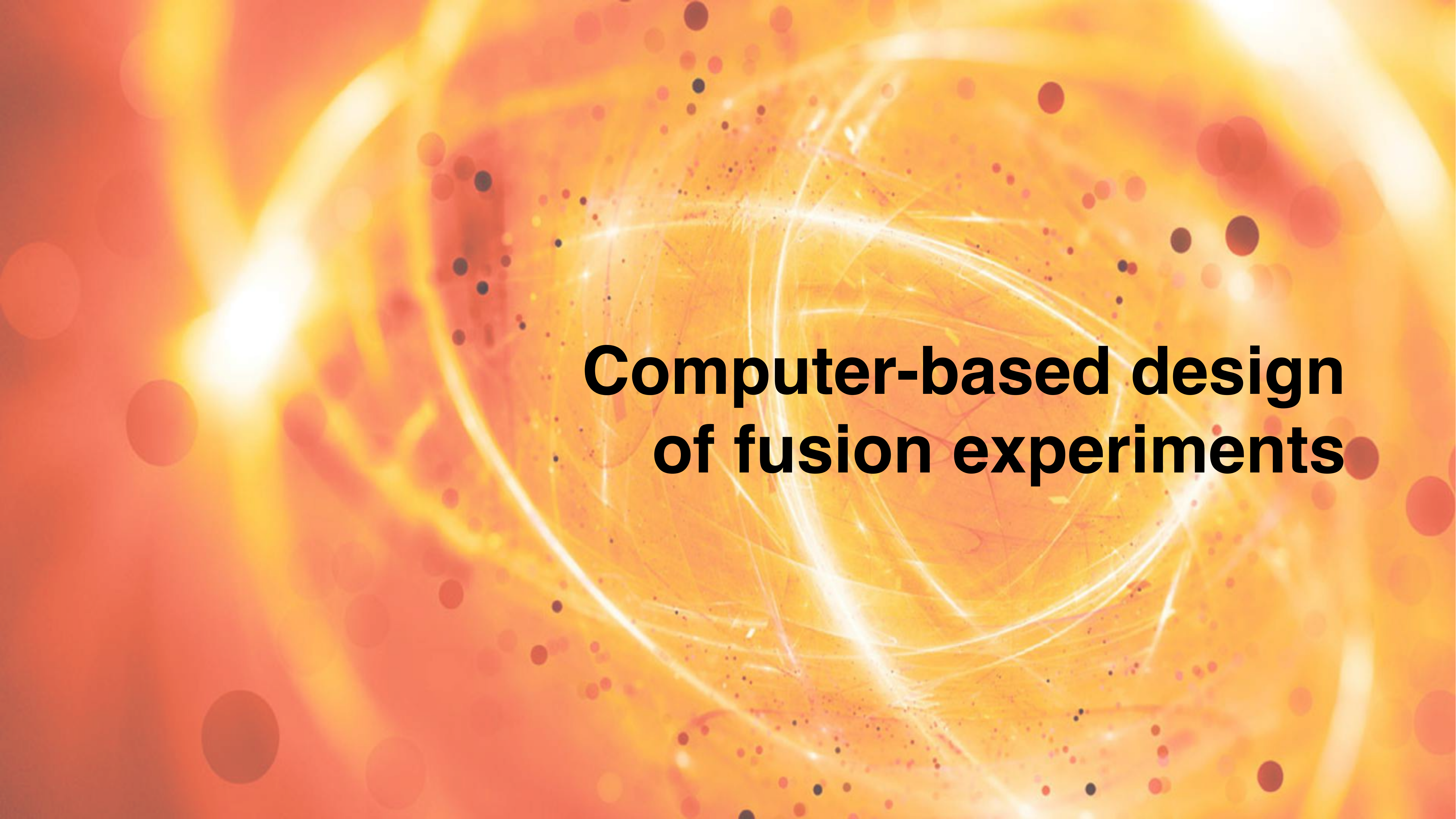
European community effort to match TCV-X21 diverted L-mode reference case

Nucl. Fusion **62** (2022) 096001 D.S. Oliveira, T. Body *et al*



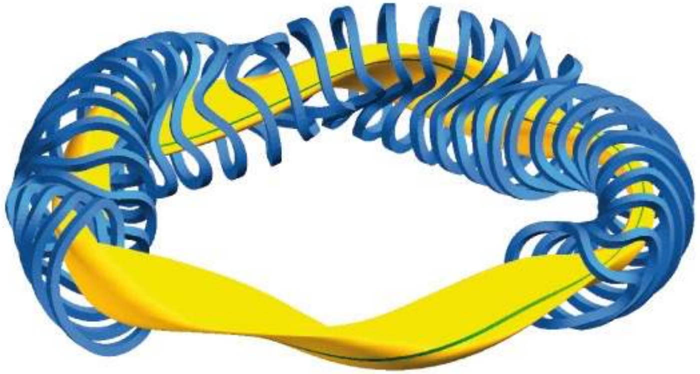
Global modes: ORB5 simulations matching experiments

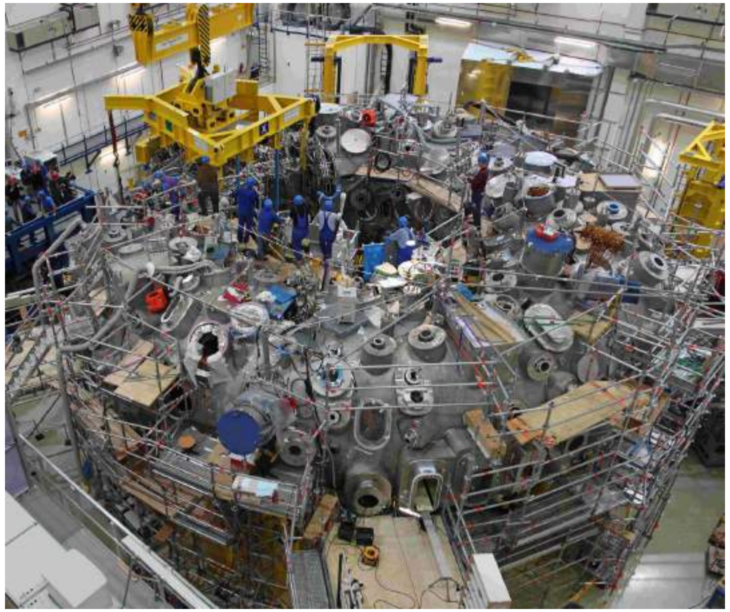




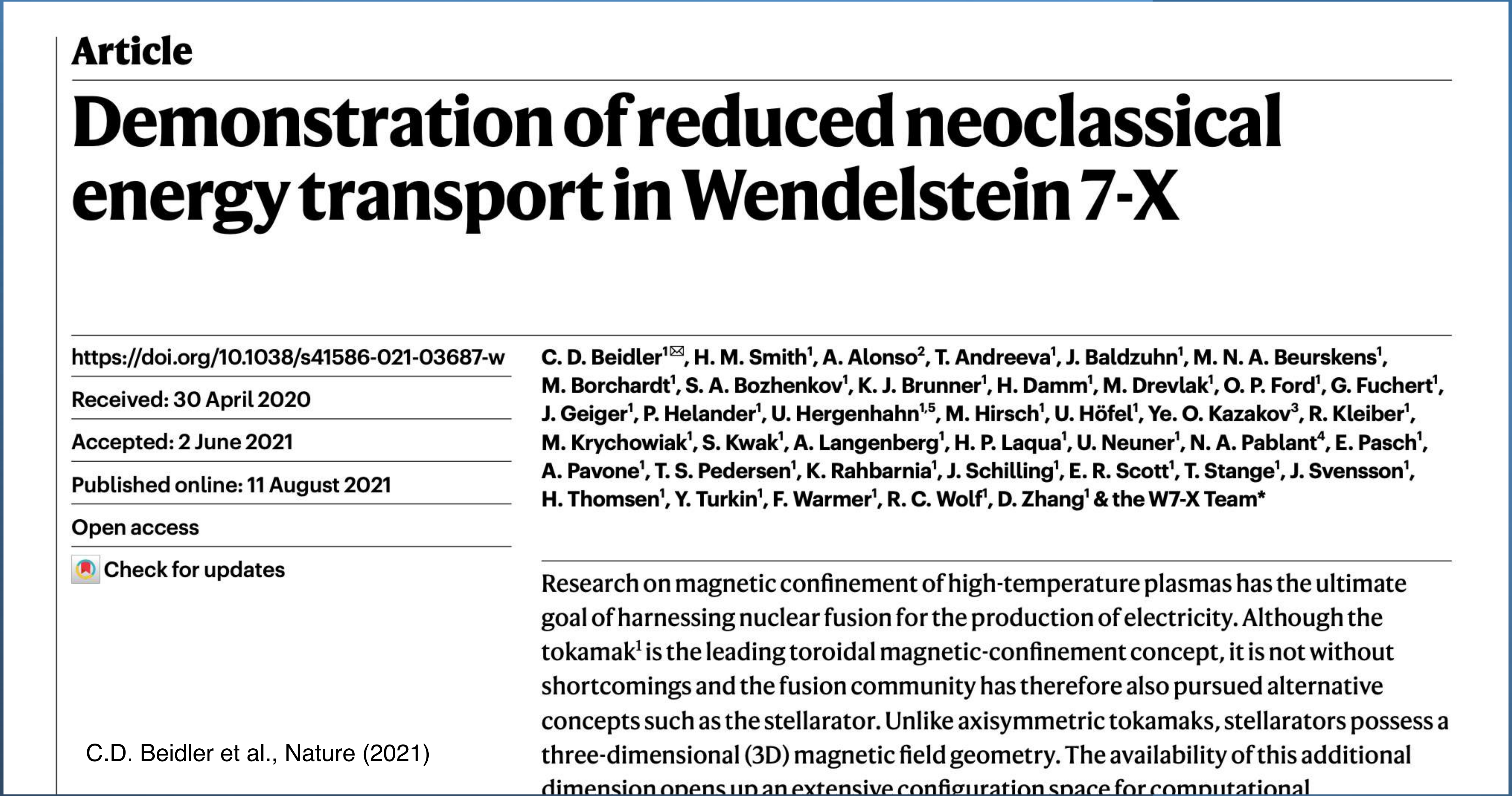
Computer-based design of fusion experiments


Cray-1 am IPP





Stellarator Wendelstein 7-X at IPP Greifswald



Article

Demonstration of reduced neoclassical energy transport in Wendelstein 7-X

https://doi.org/10.1038/s41586-021-03687-w

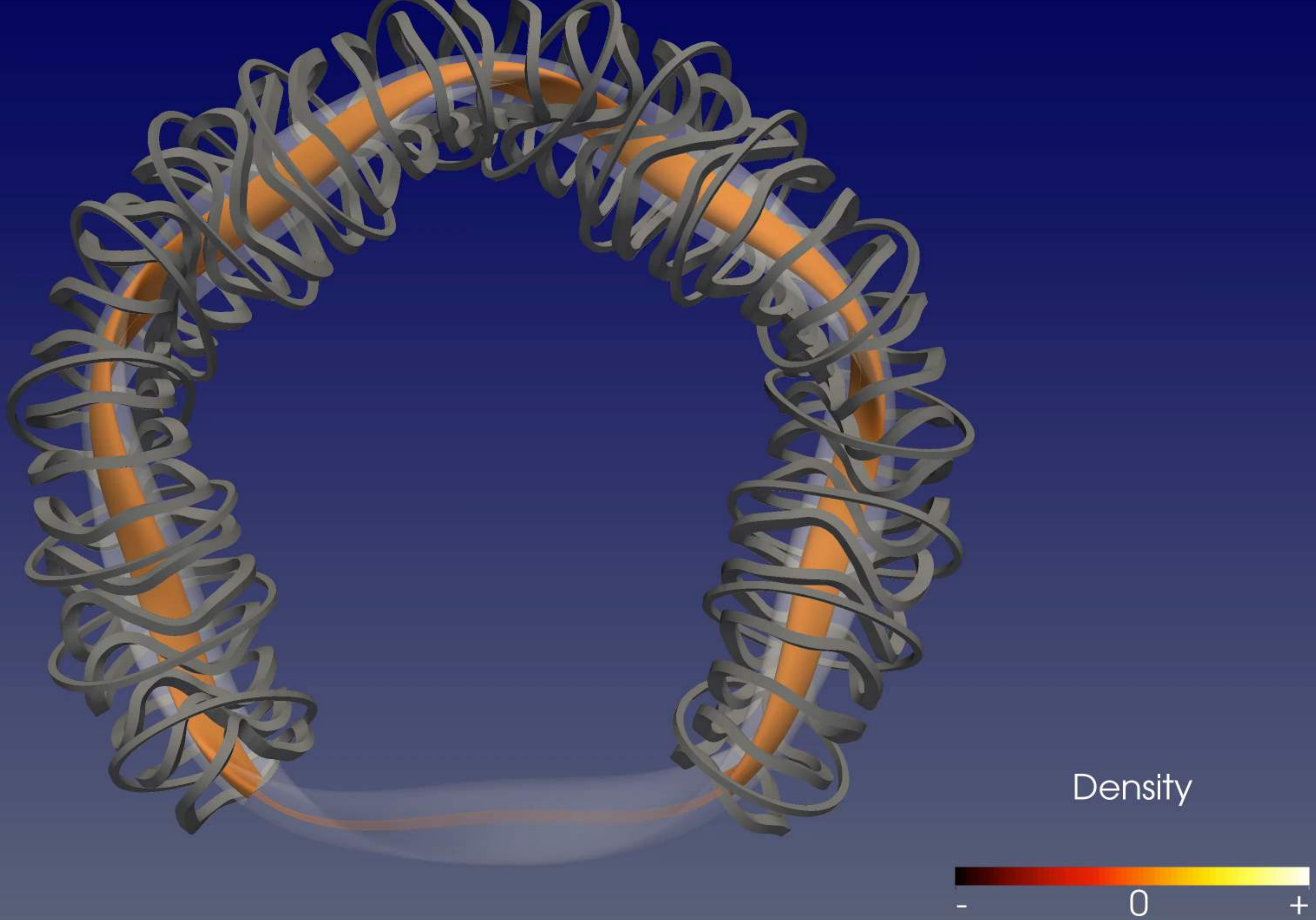
Received: 30 April 2020

Accepted: 2 June 2021

C. D. Beidler[1]✉, H. M. Smith[1], A. Alonso[2], T. Andreeva[1], J. Baldzuhn[1], M. N. A. Beurskens[1], M. Borchardt[1], S. A. Bozhenkov[1], K. J. Brunner[1], H. Damm[1], M. Drevlak[1], O. P. Ford[1], G. Fuchert[1], J. Geiger[1], P. Helander[1], U. Hergenhahn[1,5], M. Hirsch[1], U. Höfel[1], Ye. O. Kazakov[3], R. Kleiber[1], M. Krychowiak[1], S. Kwak[1], A. Langenberg[1], H. P. Laqua[1], U. Neuner[1], N. A. Pablant[4], E. Pasch[1], A. Pavone[1], T. S. Pedersen[1], K. Rahbarnia[1], J. Schilling[1], E. R. Scott[1], T. Stange[1], J. Svensson[1], H. Thomsen[1], Y. Turkin[1], F. Warmer[1], R. C. Wolf[1], D. Zhang[1] & the W7-X Team*

Research on magnetic confinement of high-temperature plasmas has the ultimate goal of harnessing nuclear fusion for the production of electricity. Although the tokamak[1] is the leading toroidal magnetic-confinement concept, it is not without shortcomings and the fusion community has therefore also pursued alternative concepts such as the stellarator. Unlike axisymmetric tokamaks, stellarators possess a three-dimensional (3D) magnetic field geometry. The availability of this additional dimension opens up an extensive configuration space for computational

C.D. Beidler et al., Nature (2021)



Density
-
0
+

On the role of AI

An important, timely topic of broad interest

"Science at extreme scales: Where big data meets large-scale computing"

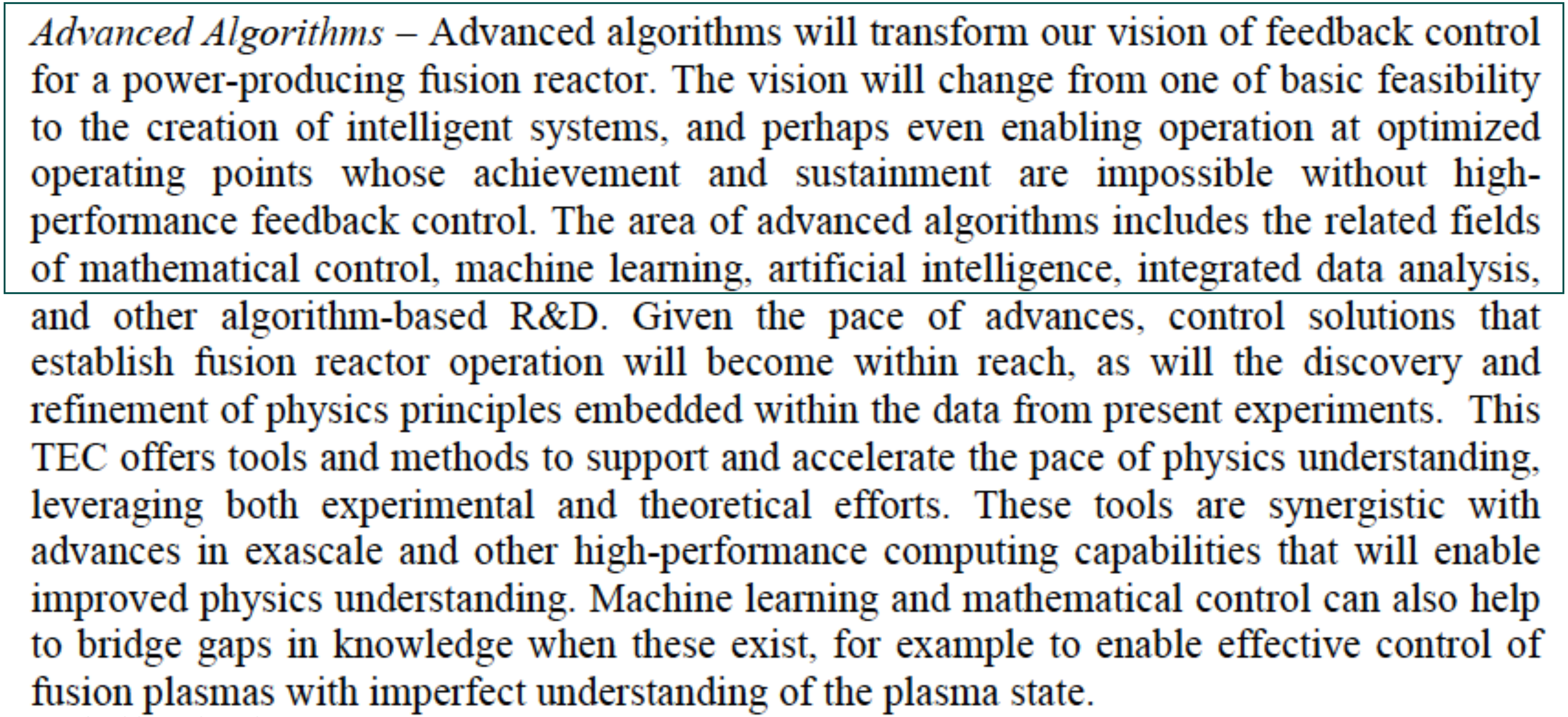
Interdisciplinary Long Program @UCLA
September 12 - December 14, 2018
200+ participants, 50+ long-term participants

Speaker list includes:

- Yann LeCun (Director of AI Research @Facebook)
- Emmanuel Candes (Stanford University)
- Rajat Monga (Google)
- Matthias Troyer (Microsoft)
- James Sexton (IBM)
- Adrian Tate (Cray)
- Alan Lee (AMD)

Transformative Enabling Capabilities for fusion

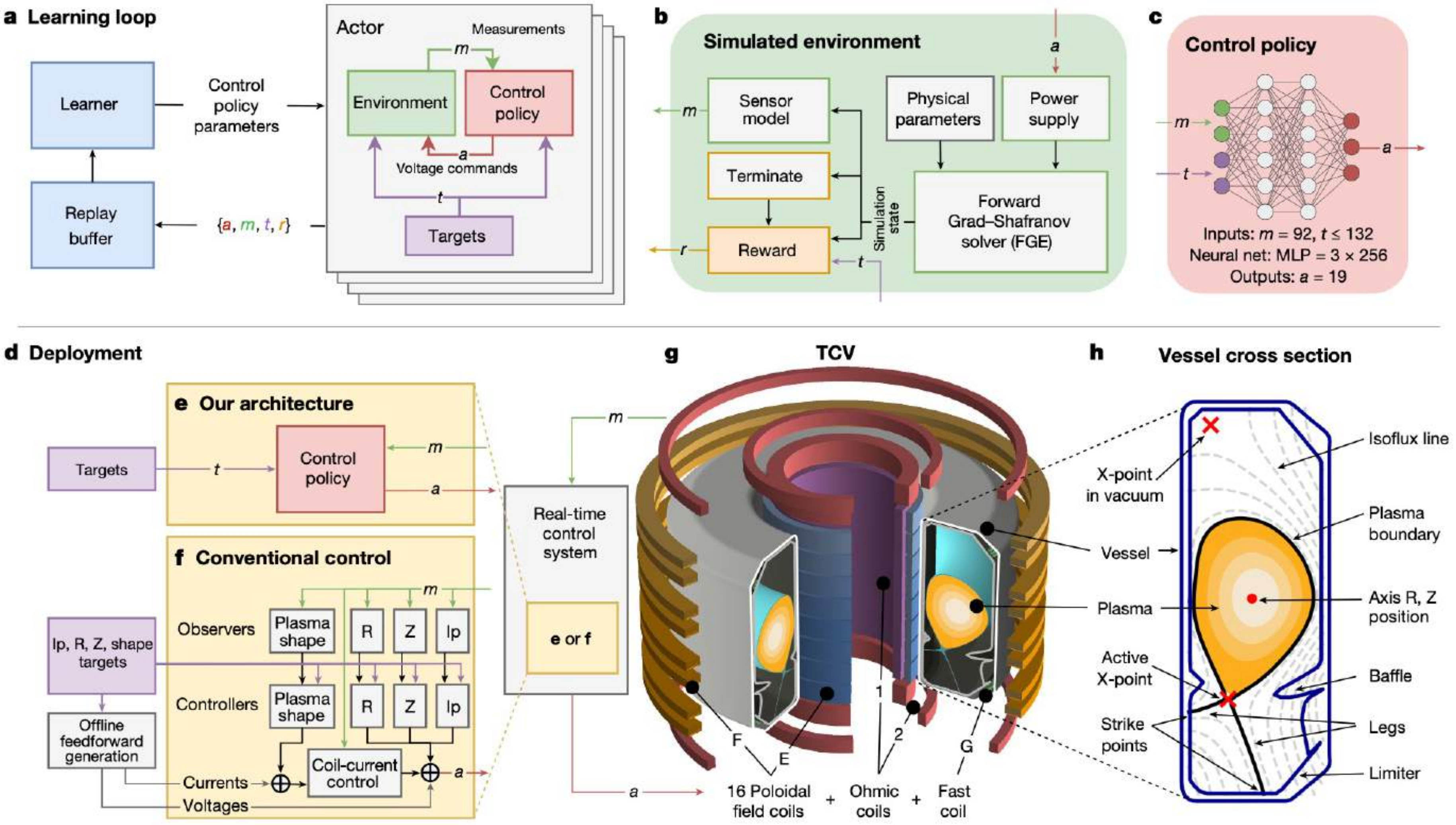
FESAC Report (2018)



Advanced Algorithms – Advanced algorithms will transform our vision of feedback control for a power-producing fusion reactor. The vision will change from one of basic feasibility to the creation of intelligent systems, and perhaps even enabling operation at optimized operating points whose achievement and sustainment are impossible without high-performance feedback control. The area of advanced algorithms includes the related fields of mathematical control, machine learning, artificial intelligence, integrated data analysis, and other algorithm-based R&D. Given the pace of advances, control solutions that establish fusion reactor operation will become within reach, as will the discovery and refinement of physics principles embedded within the data from present experiments. This TEC offers tools and methods to support and accelerate the pace of physics understanding, leveraging both experimental and theoretical efforts. These tools are synergistic with advances in exascale and other high-performance computing capabilities that will enable improved physics understanding. Machine learning and mathematical control can also help to bridge gaps in knowledge when these exist, for example to enable effective control of fusion plasmas with imperfect understanding of the plasma state.

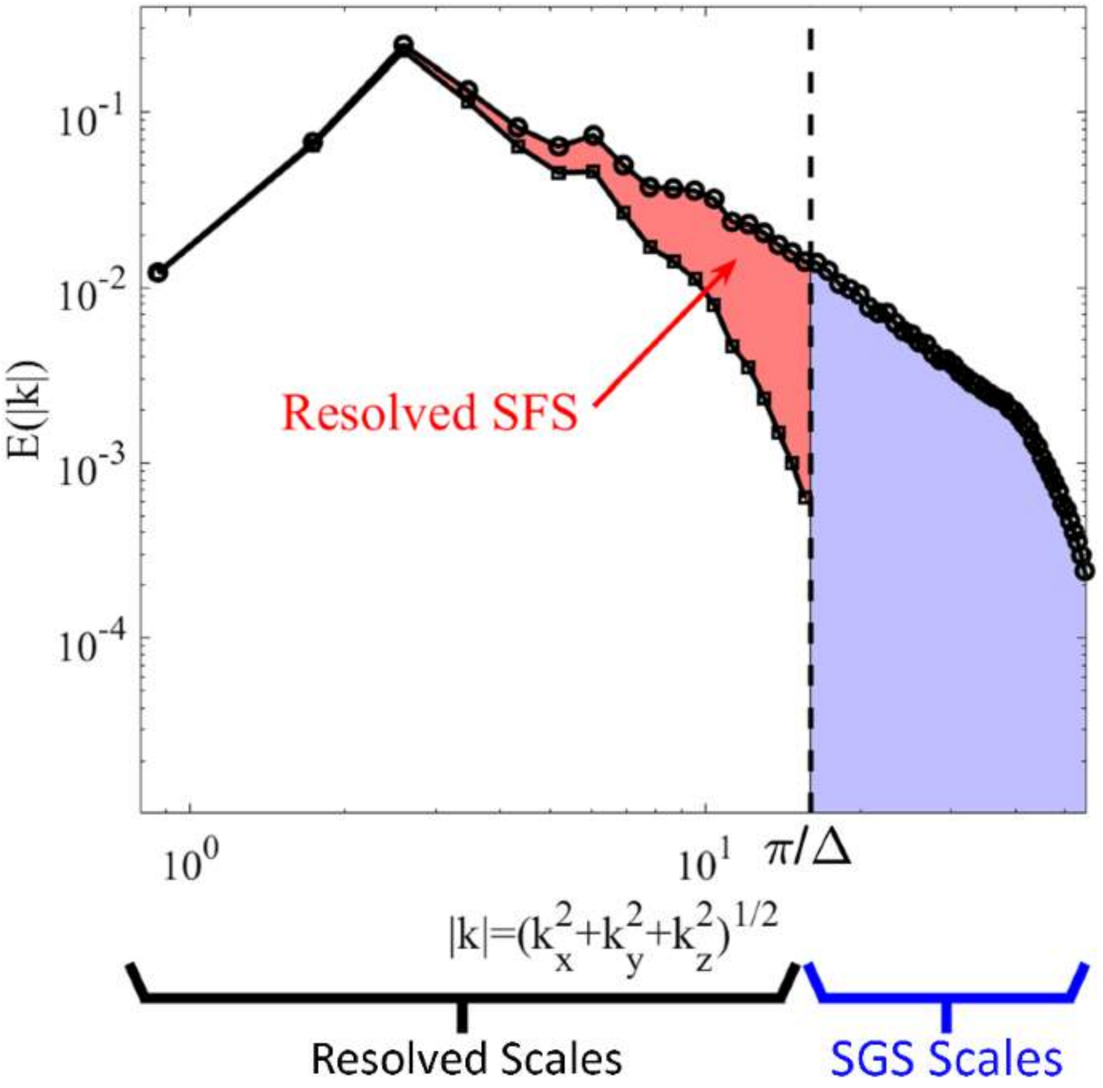
Deep Learning for plasma control

SPC @ EPFL
DeepMind @ London



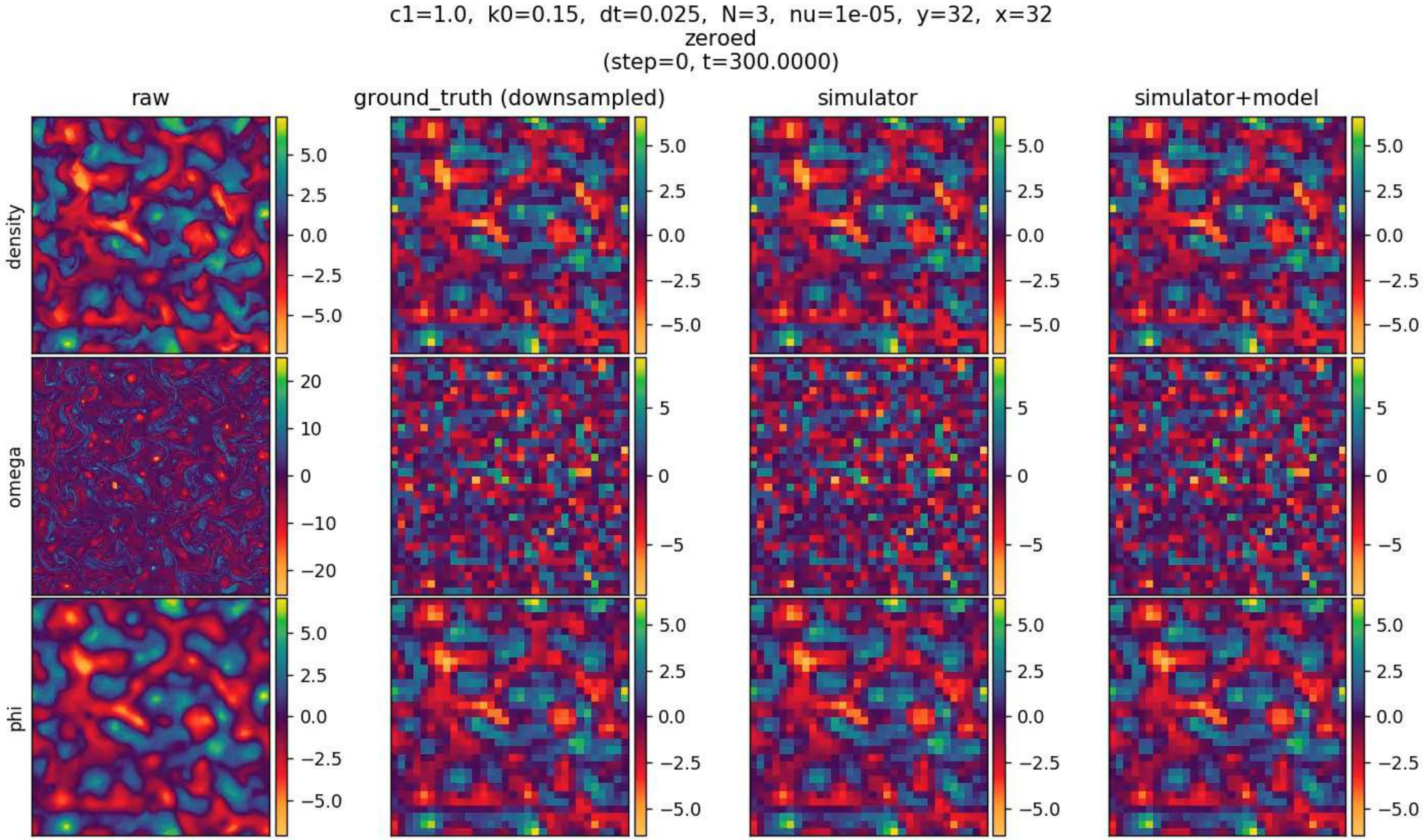
https://doi.org/10.1038/s41586-021-04301-9

Large Eddy Simulations



AI-accelerated plasma turbulence simulations

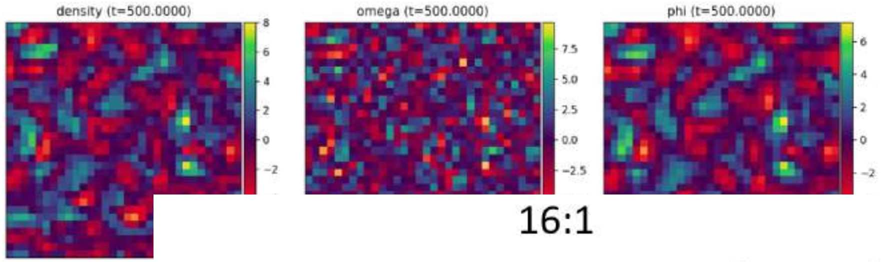
Hasegawa-Wakatani equations



Accuracy vs efficiency

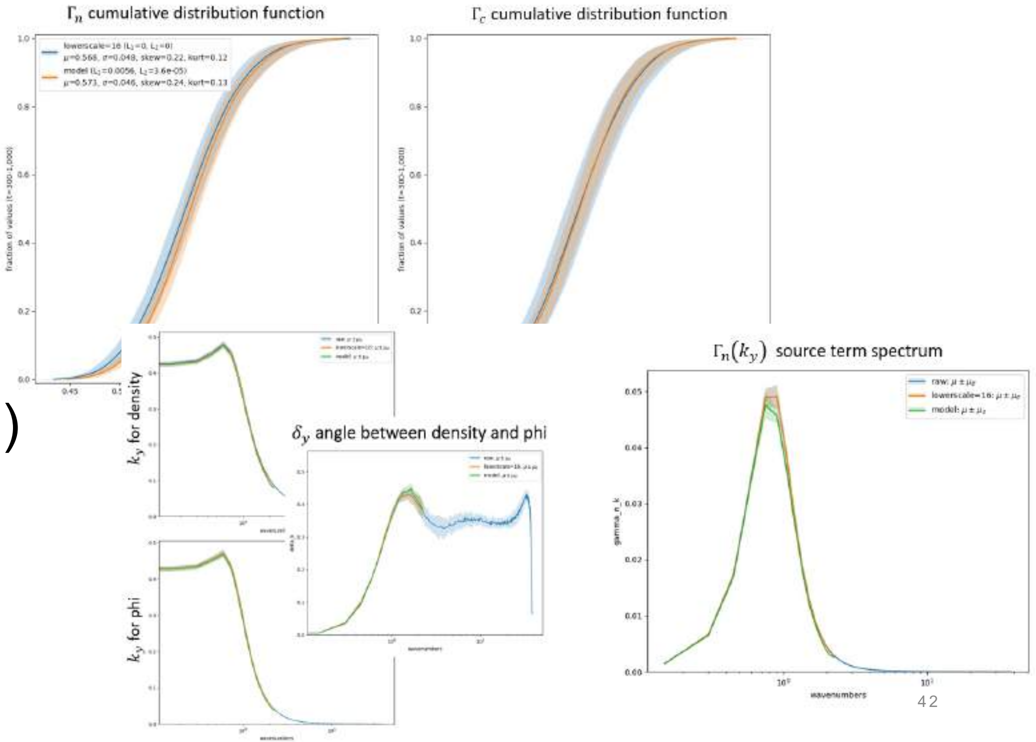
- **Preserved visual dynamics***
- **Preserved physical metrics***
- **Preserved statistical distributions***
- **Preserved spectral properties***
- **Speedup:**
  - Network scales O(n)
  - Downsampling in x and y, 16x each: 256x
  - Using fewer gradients, $\mathrm{RK4} \rightarrow \mathit{Euler}$: 4x
  - Increasing time step compared to $\mathrm{RK4}$: 5x
  - Up to $\sim 5{,}000$x faster in theory
  - **Speedup of ~ 700x** in practice (from ~ 12 h to ~ 1 min)

*within 1σ of the mean value



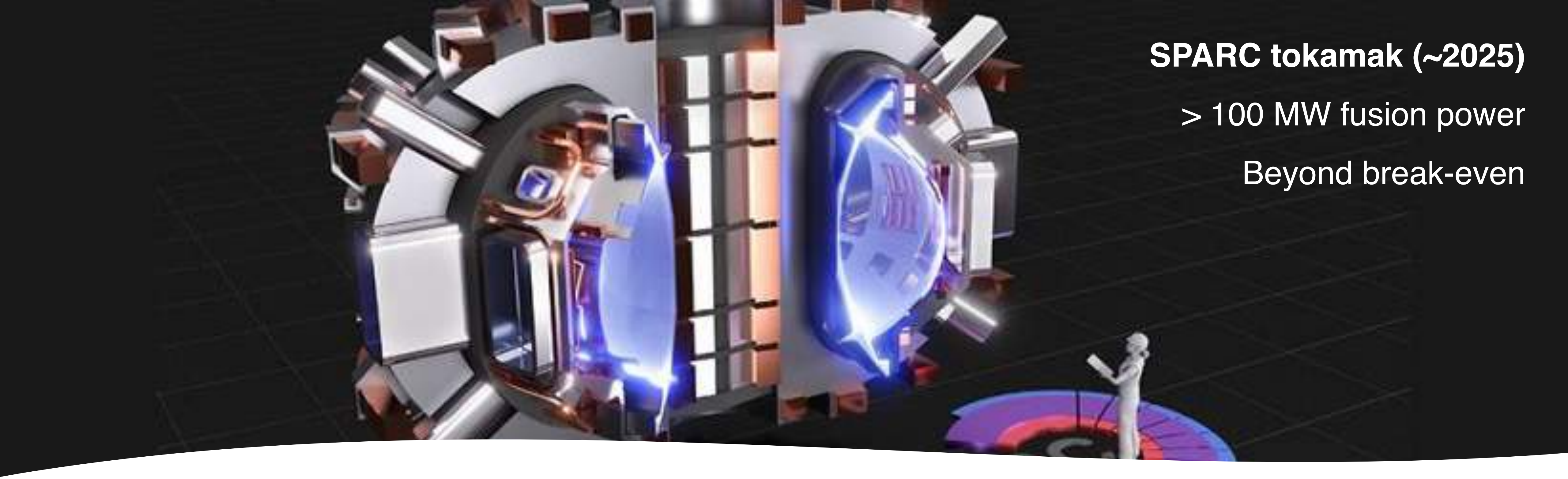
16:1

High Resolution	$\Gamma_n = 0.60 \pm 0.01$	$\delta\Gamma_n = 0.05 \pm 0.004$
Downsampled	$\Gamma_n = 0.57 \pm 0.01$	$\delta\Gamma_n = 0.05 \pm 0.004$
Greif et al.	$\Gamma_n = 0.58 \pm 0.01$	$\delta\Gamma_n = 0.05 \pm 0.005$



On the prospects of fusion energy

Many specific steps towards a fusion power plant



SPARC tokamak (~2025)

> 100 MW fusion power

Beyond break-even

Public Private Partnerships

New developments:

- More than **40 new fusion startups** during the last 10-15 years
- Significant interest from private investors (more than **$5B**)
- **New technologies** (high-temperature superconductors, 3D printing, advanced materials, exascale computing, AI etc.)

Our ambitious goal

„We choose to go to the moon in this decade and do the other things, not because they are easy, but because they are hard, because that goal will serve to organize and measure the best of our energies and skills, because that challenge is one that we are willing to accept, one we are unwilling to postpone, and one which we intend to win.“