# IL CALCOLO HPC NELLA FISICA TEORICA INFN: STATO E PROSPETTIVE

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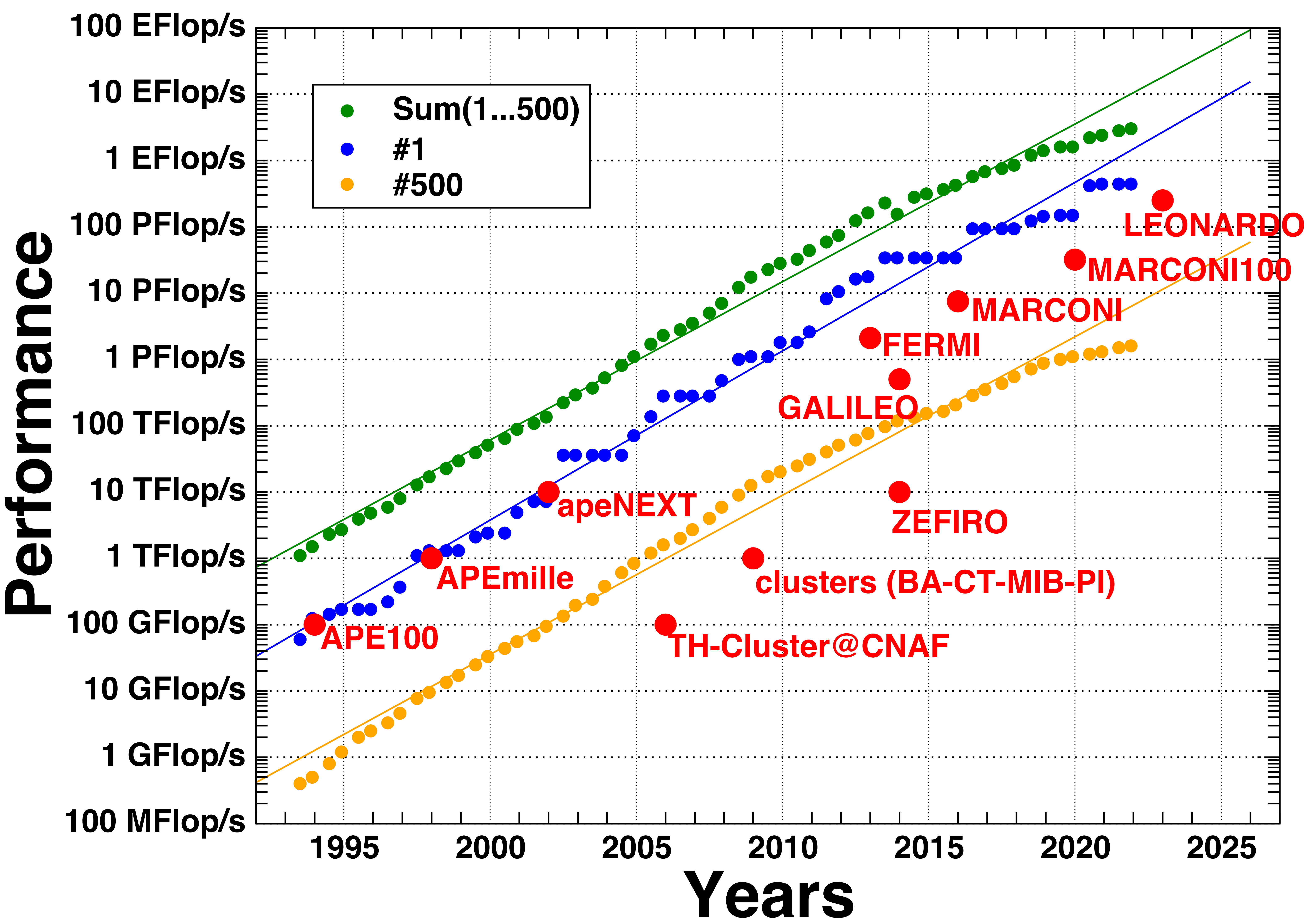
INFN

Commissione Calcolo Reti

*Workshop sul Calcolo nell'INFN*, Paestum, 23 maggio 2022

# HPC & THEORETICAL PHYSICS @ INFN:   A LONG HISTORY

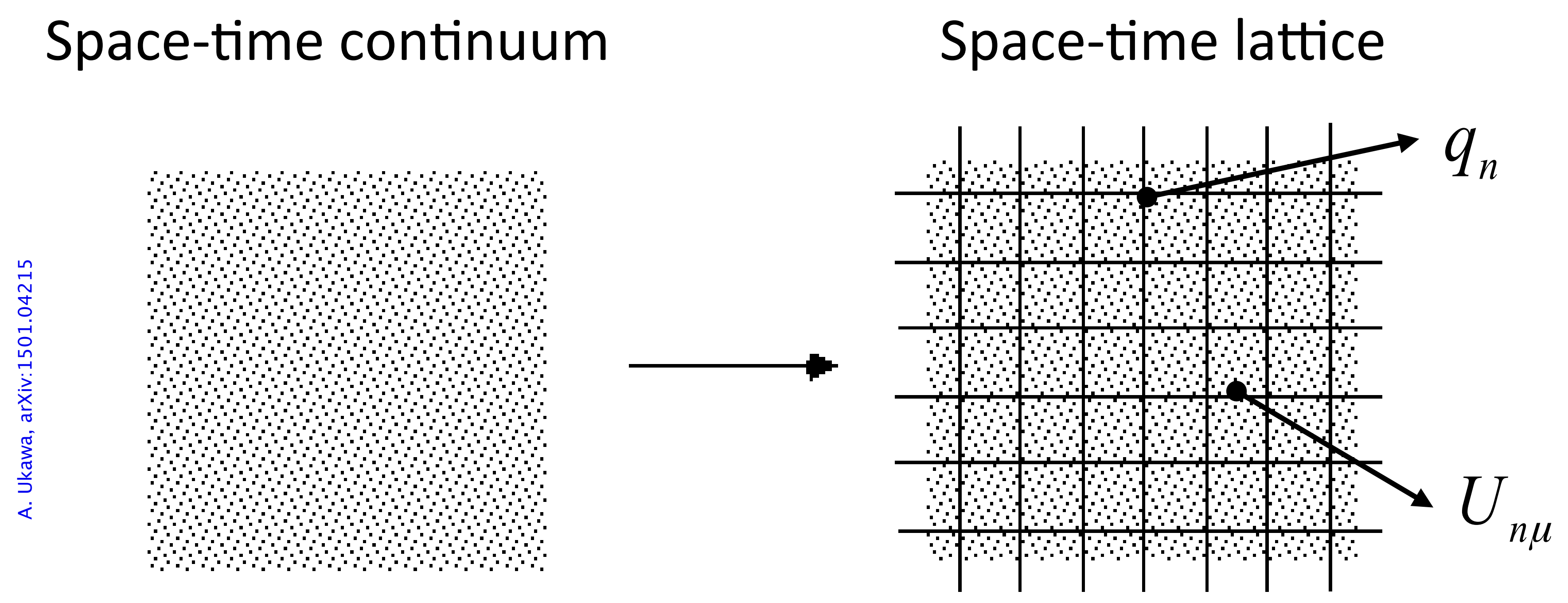



Storico:

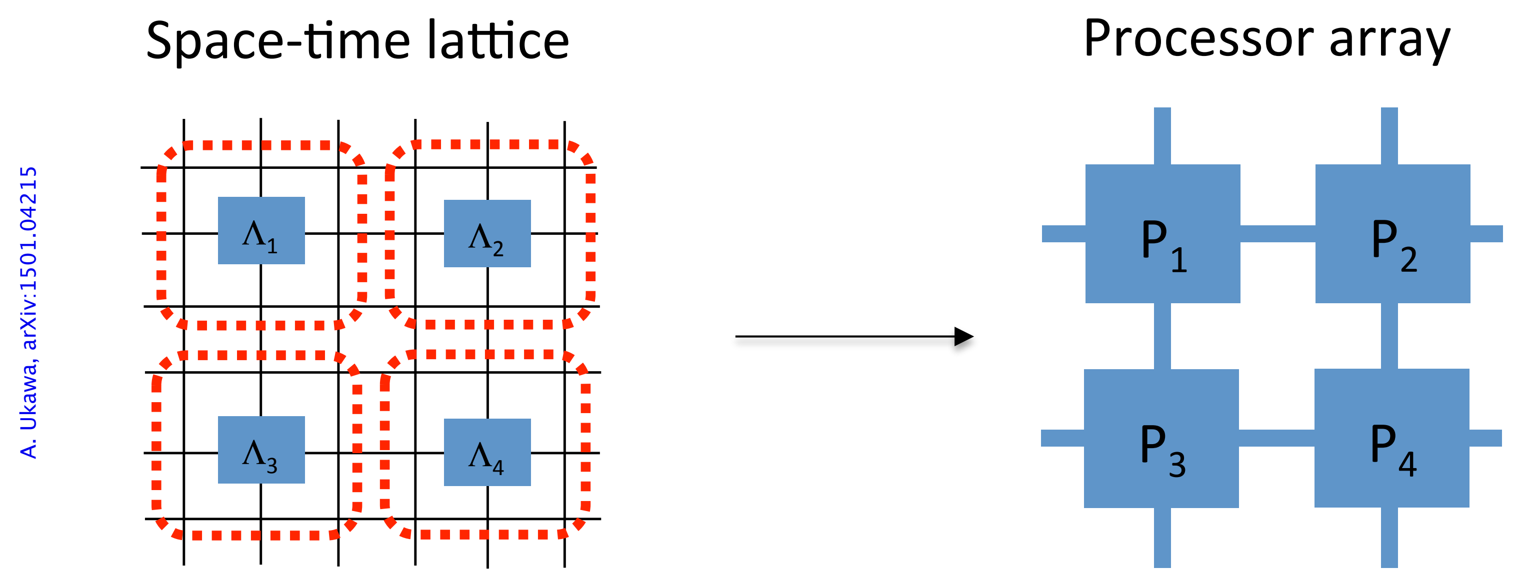
- ~1985-1995:  Cray 1M, Cray X-MP/12-48, Cray Y-MP, Cray T3D/64  (CINECA)
- ~1985-2010:  APE, APE100, APEmille, apeNEXT
- ~2010-…:  cluster locali (BA-CT-MIB-PI), cluster CSN4 (Zephiro)
- ~2012: nuova convenzione CINECA: BlueGene/Q (FERMI), IBM cluster (GALILEO), Lenovo cluster (MARCONI),…

# HIGH PERFORMANCE COMPUTING & LQCD: a paradigmatic use case

Formulation of QCD on a space-time lattice → a framework for understanding the dynamics of non-Abelian gauge fields




Massive parallelism and Lattice QCD →




Lattice QCD drove the development of HPC hardware

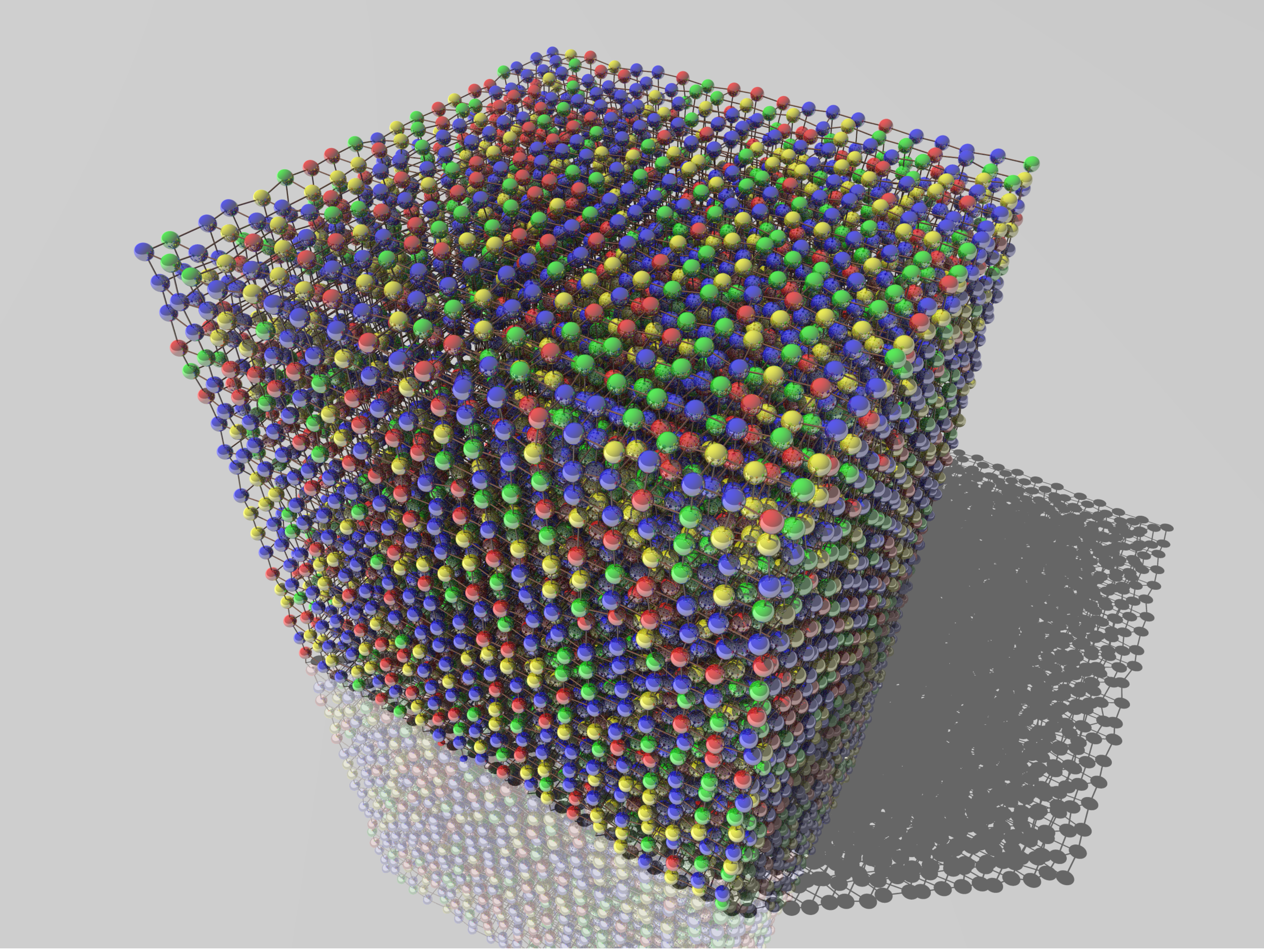
| *name* | *year* | *authors* | *peak speed* |
|---|---|---|---|
| Columbia | 1984 | Christ-Terrano | - |
| Colmbia-16 | 1985 | Christ et al | 0.25 GFlop/s |
| Columbia-64 | 1987 | Christ et al | 1 GFlop/s |
| **APE1** | **1988** | **Cabibbo-Parisi** | **1 GFlop/s** |
| Columbia-256 | 1989 | Christ et al | 16 GFlop/s |
| ACPMAPS | 1991 | Mackenzie et al | 5 GFlop/s |
| QCDPAX | 1991 | Iwasaki-Hoshino | 14 GFlop/s |
| GF11 | 1992 | Weingarten | 11 GFlop/s |
| **APE100** | **1994** | **APE Collab.** | **0.1 TFlop/s** |
| CP-PACS | 1996 | Iwasaki et al | 0.6 TFlop/s |
| QCDSP | 1998 | Christ et al | 0.6 TFlop/s |
| **APEmille** | **2000** | **APE Collab.** | **0.8 TFlop/s** |
| **apeNEXT** | **2004** | **APE Collab.** | **10 TFlop/s** |
| QCDOC | 2005 | Christ et al | 10 TFlop/s |
| PACS-CS | 2006 | Ukawa et al | 14 TFlop/s |
| QCDCQ | 2011 | Christ et al | 500 TFlop/s |
| QPACE | 2012 | Wettig et al | 200 TFlop/s |

# HIGH PERFORMANCE COMPUTING & LQCD: a paradigmatic use case

Lattice QCD calculations typically require multidimensional integration over the gauge fields

The integration dimension in state-of-the-art calculations is $\mathcal{O}(10^{10})$

Markov Chain Monte Carlo methods are used to perform the multidimensional integrations



"Colored lattice" fdecomite (flickr.com)

Generation of ensembles of configurations with importance sampling via Monte Carlo methods is an essential step in numerical simulations of the path-integral of statistical mechanics systems and field theories.

The development of numerical algorithms is crucial: over the history of lattice gauge theory calculations, the improvement from algorithm development has been similar to the gain from Moore's law.

# HIGH PERFORMANCE COMPUTING & LQCD: a paradigmatic use case

## The Lattice QCD workflow

**Monte Carlo sampling phase**

$$P_{\mathrm{eq}}(U) = \frac{1}{\mathcal{Z}} \mathrm{Det}(M^{\dagger}M) e^{-S(U)}$$

- Generates an ensemble of gluon field configurations $U$ distributed according to the QCD action (using the hybrid Monte Carlo algorithm): $\mathrm{Cost} \propto V^{9/8} a^{-2}$
- This ensemble generation is serially dependent and represents a **strong scaling computational problem**.
- A large number of computing nodes is required. On the largest scales this becomes a **halo-exchange communication problem** since the local data bandwidths vastly exceed those of inter-node communication.

**Hadronic observables are calculated on each sampled configuration $U$:**

$$\langle \mathcal{O} \rangle \approx \overline{\mathcal{O}} = \frac{1}{N} \sum_{U} \mathcal{O}(U)$$

- High degree of trivial parallelism: computer interconnect limitations are more easily avoided by exploiting this trivial parallelism.

**Physics goals**:
calculations with ensembles of gauge fields with physical volumes $V$ large enough to ensure that finite-volume effects are under control.

- Example at the ***exascale frontier:***

  Simulation with up/down, strange, charm and bottom quarks at their physical masses with physical volume $V = (10\,\mathrm{fm})^4$ at a lattice spacing $a = 0.04\,\mathrm{fm}$ ($a^{-1} \sim 5\,\mathrm{GeV}$) (lattice size $256^3 \times 512$)

  $\sim$ 12,000 Exaflop hours = 12,000 $\times$ ($3600 \times 10^{18}$) floating-point operations

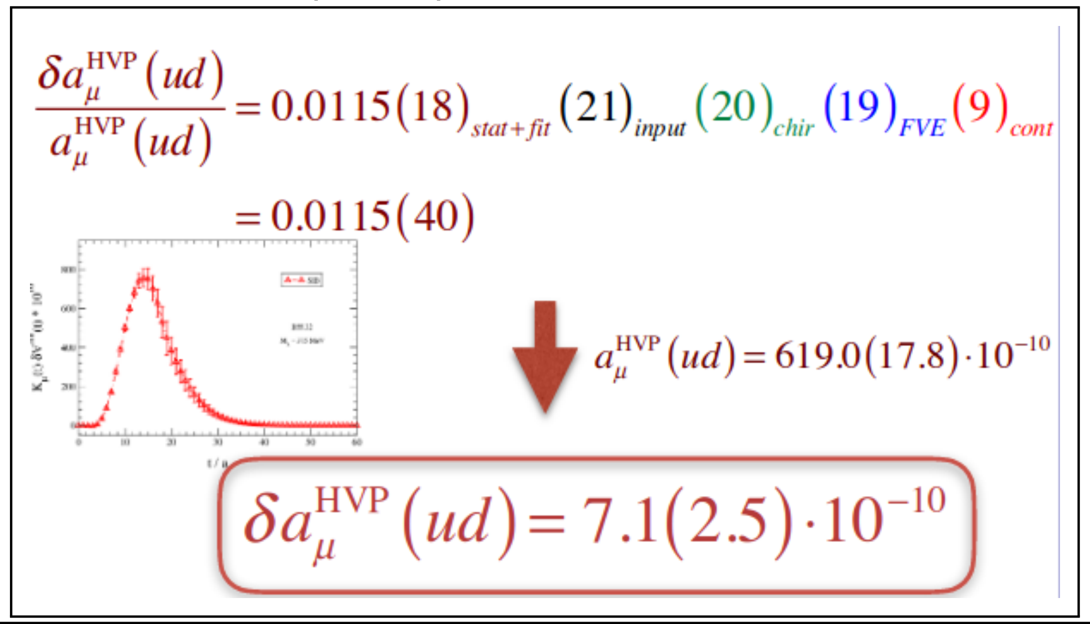
# AN OVERVIEW OF SOME PROJECTS IN LATTICE QCD

## LQCD123 *(F. Sanfilippo)* *r.n. V. Lubicz*

### Physics activity: QCD + QED phenomenology

**QED CORRECTIONS TO LEADING HADRONIC CONTRIB. ($a_\mu$) OF $g_\mu - 2$**

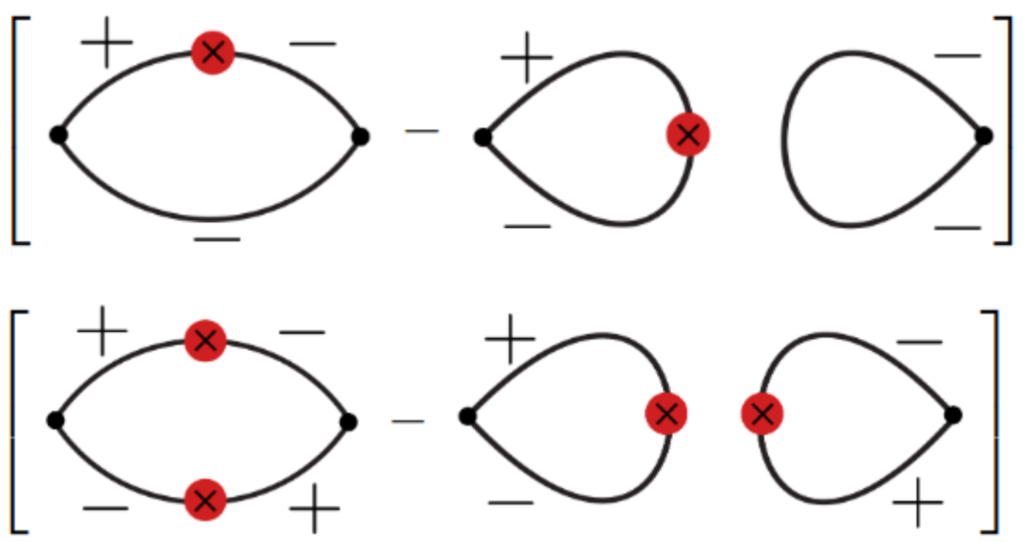
PRD99(**2019**) + update in progress




**$\ell_7$ low energy constant**

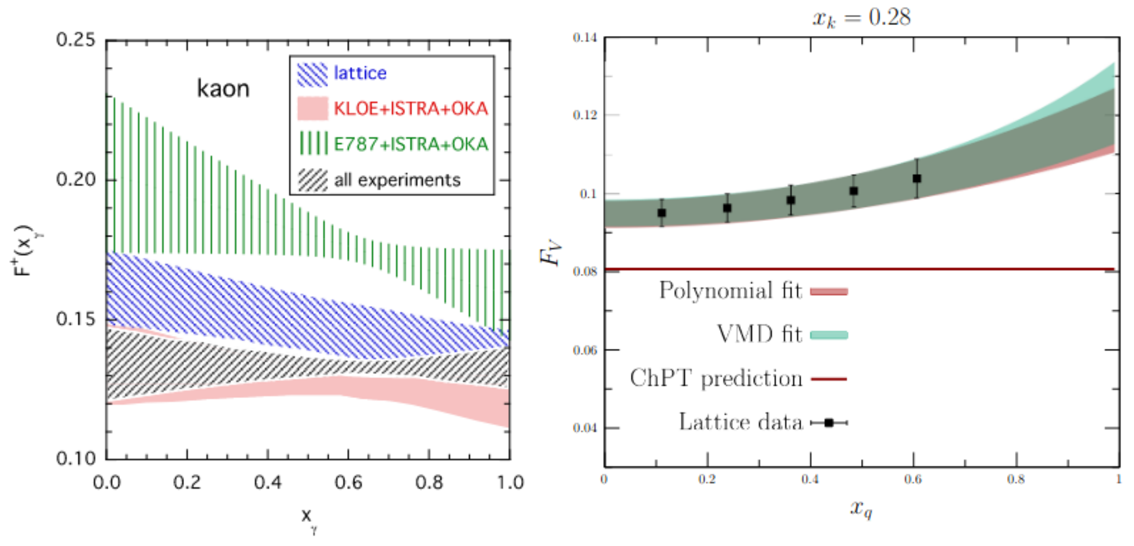
PRD 104, 074513 **(2021)**

ISCRA22B - E$\pi$C



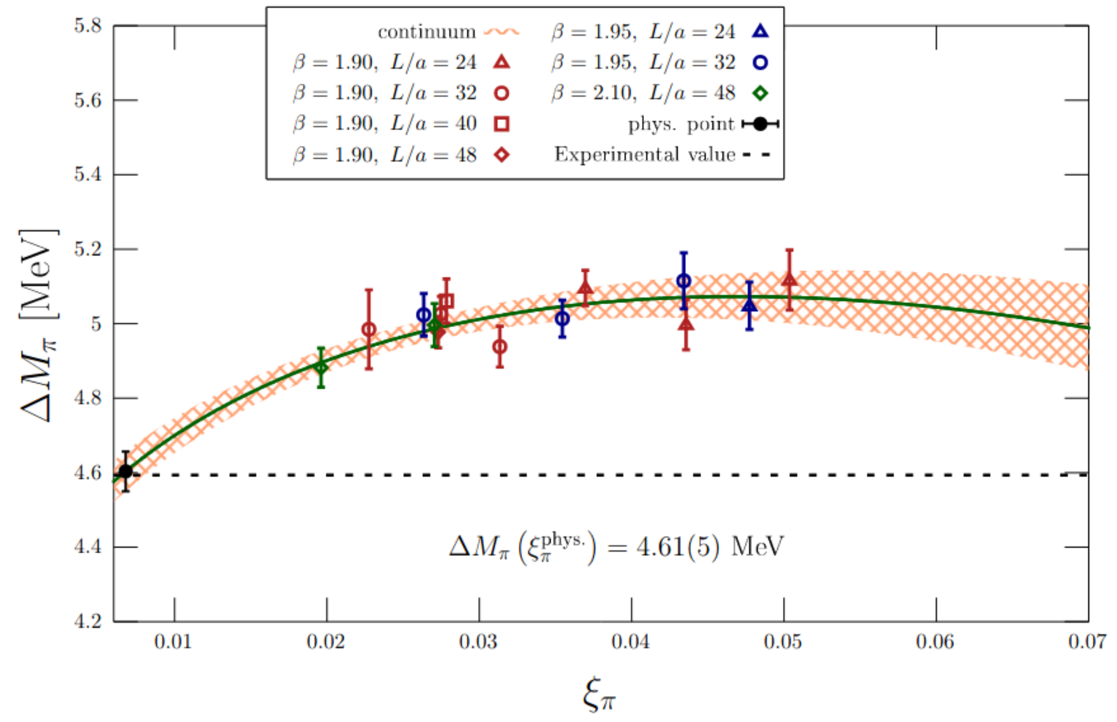
**REAL & VIRTUAL PHOTON EMISSION**

PRD103,1 (**2021**), PRD103,5 (**2021**) and arXiv:2202.03833 (to appear on PRD)




**$M_{\pi^+} - M_{\pi^0}$ theoretical prediction to $\mathcal{O}(\alpha)$**

arXiv:2202.11970




### Simulations within ETM collaboration: LQCD at the physical point

**$Nf = 2 + 1 + 1$ Physical pion mass simulations - arXiv:2111.14710**

| ensemble | $\beta$ | $V/a^4$ | $a$ (fm) | $a\mu_\ell$ | $M_\pi$ (MeV) | $L$ (fm) | $M_\pi L$ |
|---|---|---|---|---|---|---|---|
| cA211.53.24 | 1.726 | $24^3 \times 48$ | 0.0947 (4) | 0.00530 | 346.4 (1.6) | 2.27 | 3.99 |
| cA211.40.24 | | $24^3 \times 48$ | | 0.00400 | 301.6 (2.1) | 2.27 | 3.47 |
| cA211.30.32 | | $32^3 \times 64$ | | 0.00300 | 261.1 (1.1) | 3.03 | 4.01 |
| cA211.12.48 | | $48^3 \times 96$ | | 0.00120 | 167.1 (0.8) | 4.55 | 3.85 |
| cB211.25.24 | 1.778 | $24^3 \times 48$ | 0.0816 (3) | 0.00250 | 259.2 (3.0) | 1.96 | 2.57 |
| cB211.25.32 | | $32^3 \times 64$ | | 0.00250 | 253.3 (1.4) | 2.61 | 3.35 |
| cB211.25.48 | | $48^3 \times 96$ | | 0.00250 | 253.0 (1.0) | 3.92 | 5.02 |
| cB211.14.64 | | $64^3 \times 128$ | | 0.00140 | 189.8 (0.7) | 5.22 | 5.02 |
| cB211.072.64 | | $64^3 \times 128$ | | 0.00072 | 136.8 (0.6) | 5.22 | 3.62 |
| cB211.072.96 | | $96^3 \times 192$ | | 0.00072 | 136.0 (0.3) | 7.83 | 5.43 |
| cC211.06.80 | 1.836 | $80^3 \times 160$ | 0.0694 (3) | 0.00060 | 134.2 (0.5) | 5.55 | 3.78 |
| cD211.054.96 | 1.9 | $96^3 \times 192$ | 0.0576 (2) | 0.00054 | 138.0 (0.5) | 5.53 | 3.87 |

PRACE projects: **PRA17-4394, PRA20-5171, PRA22-5171**

Non perturbative renormalization,

Quark masses and meson decay constant determination

- Phys. Rev. D 104, 074515 (2021)
- Phys. Rev. D 104, 074520 (2021)

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PRA17-4394:  45M core hours su MARCONI (KNL)

PRA20-5171:  76M core hours su Marconi100

PRA22-5171: 66M core hours su Marconi100
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# AN OVERVIEW OF SOME PROJECTS IN LATTICE QCD

**NPQCD** *(M. D'Elia)* *r.n. L.Cosmai* Non-perturbative Quantum Chromodynamics

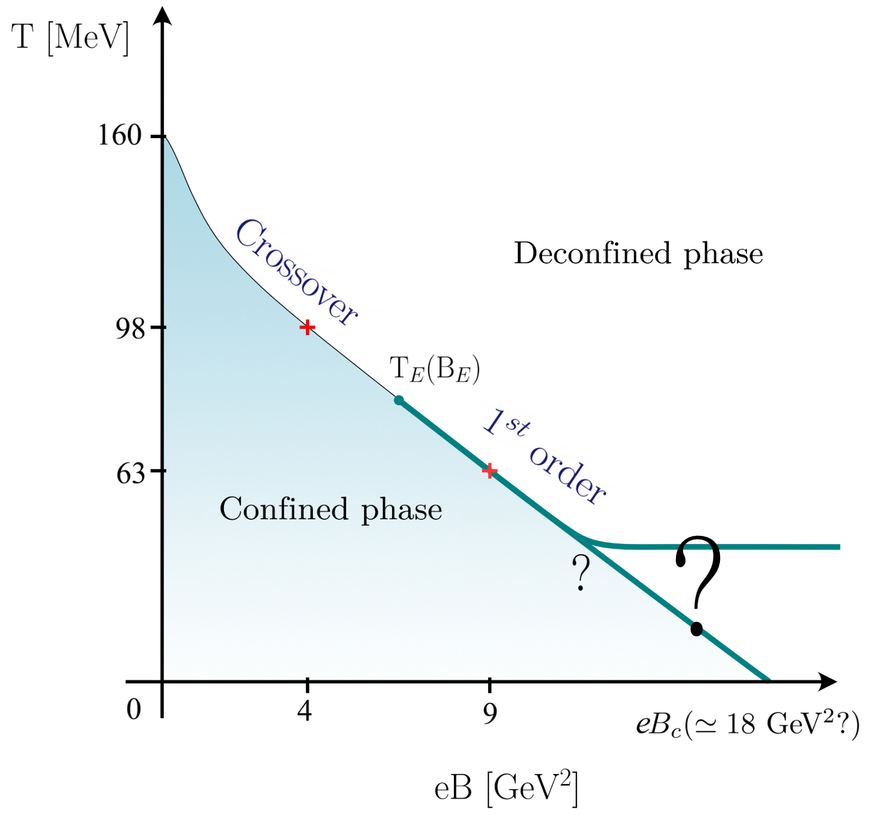
## Research activities and HPC in NPQCD

1. **QCD in extreme conditions**
   - **finite temperature and density**
   - **phase diagram in strong magnetic backgrounds**
   - **color confinement and deconfinement**
   - **topological properties and axion phenomenology**
2. **QCD-like theories (Large-N limit, universality)**
3. **Numerical approaches to quantum gravity (CDT)**
4. **Exploratory exercises in Quantum Computing**

**Large scale HPC resources mostly dedicated to item 1)**
**Lists of PRACE and ISCRA-B projects:**

- **PRACE:** **AXTRO (call 13) and SISMAF (call 9)**
- **ISCRA-B:** **HP10BWSSLC, HP10BLQLBY, HP10BQMUVT, HP10B36BYO, HP10BA76RL, HP10BX8GQE, HP10BZV1G1, HP10BA5QTA, HP10BSRSMS, HP10B4P9OZ, HP10B9REXC, HP10B2J1PH, HP10CIN32X (last 4 in the last 3 years)**

## Highlights on most recent results

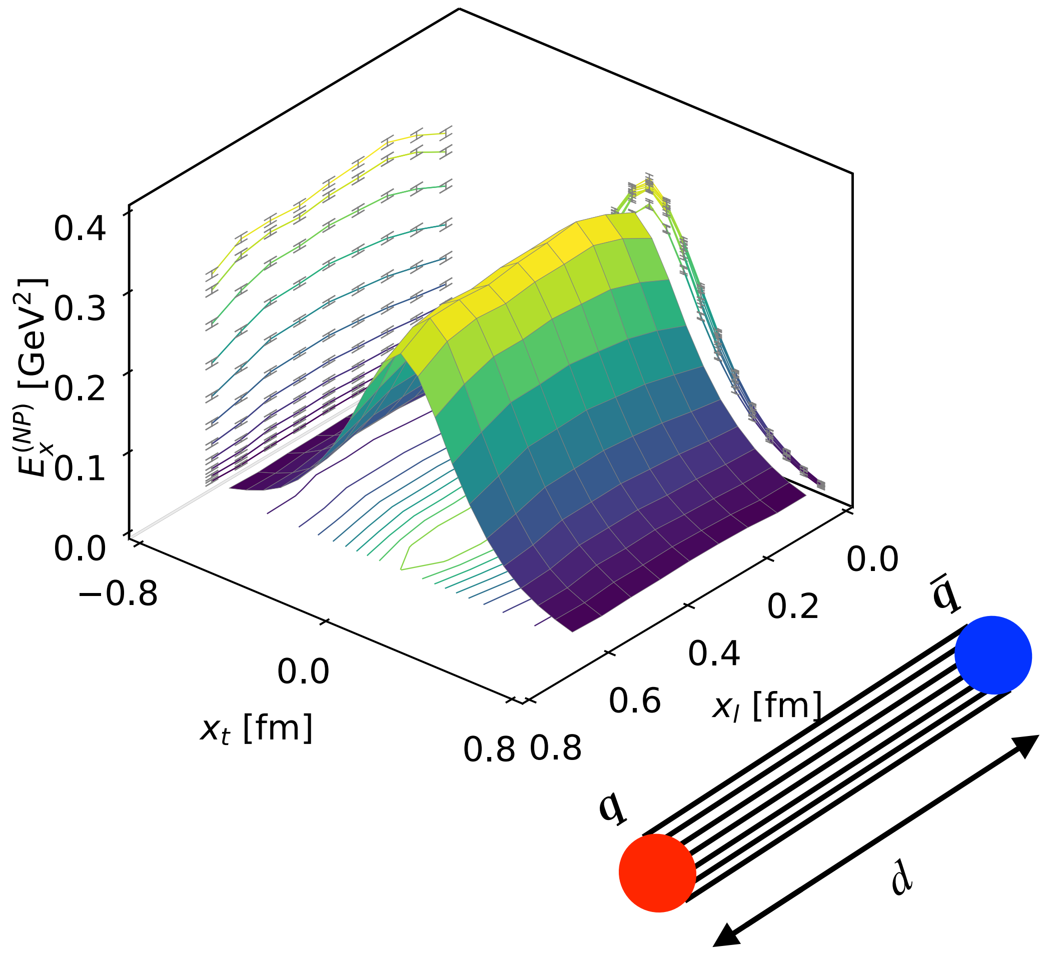



**Critical endpoint found in the QCD Phase Diagram in a magnetic background**

M. D'Elia, L. Maio, F. Sanfilippo and A. Stanzione, "Phase diagram of QCD in a magnetic background," Phys. Rev. D 105, 034511 (2022)

Editors' suggestion

based on NPQCD and Iscra-B QGPSMF HP10B9REXC




**The non-perturbative chromoelectric field obtained by subtracting the perturbative contribution**

M. Baker, V. Chelnokov, L. Cosmai, F. Cuteri, and A. Papa, "The flux tube profile in full QCD", POS Lattice 2021

based on NPQCD and Iscra-B HP10BUL8OZ

# QCDLAT *(L. Giusti)*

*r.n. L. Giusti*

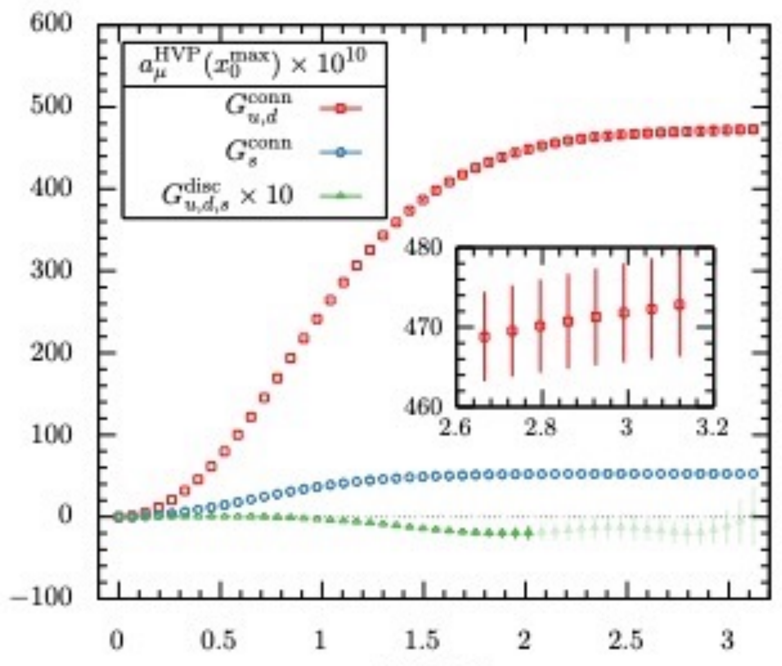
# QCDLAT: Next generation lattice field theory for searching new phenomena in particle physics

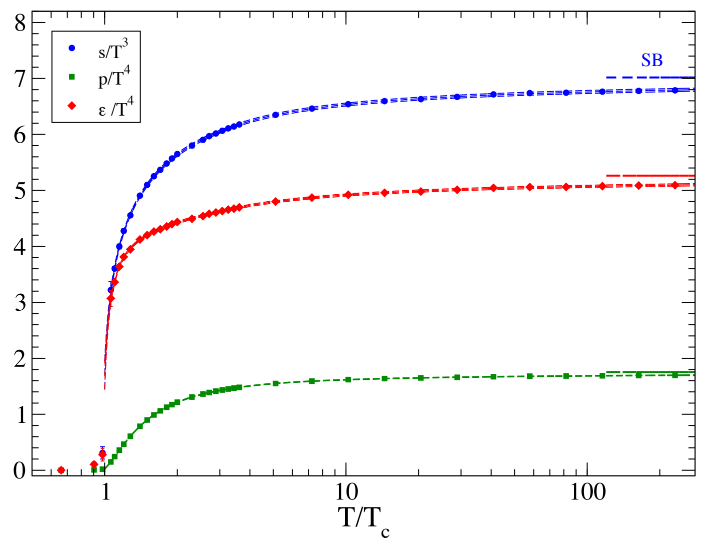
## The Physics

- **Theme 1: QCD and flavour physics in the SM and beyond**
  $(g-2)_\mu$, ΔF=2 in SM and beyond, CP violation in K, D and B mixing and decays

- **Theme 2: QCD at high temperature**
  Equation of State, screening masses, transport coefficients, topology (axions)…
  Study of QCD phase diagram by simulations with an imaginary chemical potential

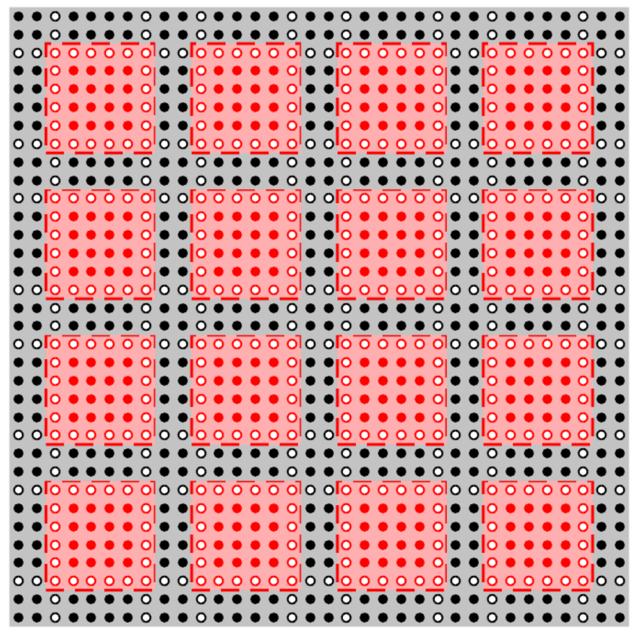
- **Theme 3**: **Theoretical developments**
  NP renormalization: quark masses, energy-momentum tensor, ΔF=2 operators in SM and beyond, …., . NSPT, improvement, . . .

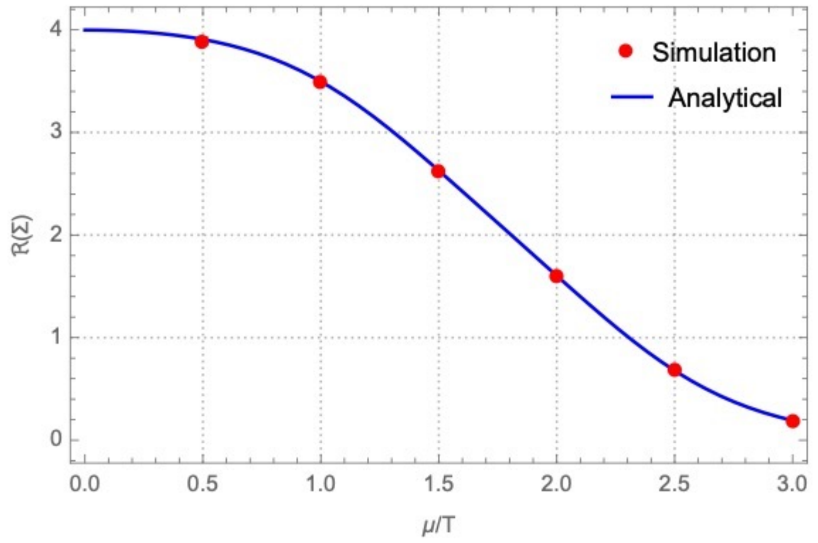





## Computational strategies (theme 4)

- Local factorization of determinant, multi-level integration with fermions, signal-to-noise ratio, master field simulations,…
- Development of algorithms for solving the sign problem in the presence of a non-zero chemical potential: simulations of toy-models in the Lefschetz thimble regularization
- Thermal field theories in a moving reference frame
- The challenge: HPC exascale, domain decomposition and factorization for the extreme parallelization of algorithms






**PRACE:**

Title: EoSQCD – Equation of State of QCD
Allocation Period: 1.4.2019 -- 31.3.2020
Allocation: **80 MChours** SKL Marenostrum

Title: MLHVP - Multi-Level measurement of the Hadron Vacuum Polarization in Lattice QCD
Allocation Period: 01.04.2020 -- 31.03.2021
Allocation: **40 MChours** SKL JUWELS

Title: QCD2EW – Finite temperature QCD up to the Electro-Weak scale
Allocation Period: 01.10.2021 -- 30.09.2022
Allocation: **45 MChours** SKL JUWELS

Title: Lee-Yang edge singularities in QCD
Allocation Period: 1.10.2021-30.9.2022
Allocation: **1.6 MChours** Marconi100

**ISCRA:**

Title: The anomalous magnetic moment of the muon with a multi-level algorithm
Allocation Period: 16.1.2019 -- 15.1.2020
Allocation: **14 MChours** KNL Marconi

Title: LqcdPADE
Allocation Period: 27.10.2021-26.10.2022
Allocation: **0.64 MChours** Marconi100

Approximatively 180 MChours granted by PRACE and ISCRA

# QCDLAT *(L. Giusti)*

## Dall'R&D alle simulazioni su grande scala

**HPC piccolo**: R&D algoritmi. **O(0.1M€).** In casa.

**HPC medio**: R&D, studi di fattibilità. **O(1M€).**
Convenzioni: INFN/Cineca

**HPC grande (top 500):** produzione. **O(10M€)** → **O(100M€)** con Leonardo (CINECA)**.**

Bandi competitivi Europei e Nazionali, Bicocca ultimi 2 anni: 4 PRACE, 2 ISCRA per 180 MChours (~1.8 **M€**)

Coordinated Lattice Simulation (CLS): condividiamo dati a livello Europeo ( ) nata al CERN nel 2008, QCDLAT membro fondatore.

## SFT *(M. Panero)*

*r.n. G. Mussardo*

### INFN_SFT: Statistical Field Theory

Research focus: Strongly interacting quantum theories describing *condensed matter* and *elementary particles*:

- Statistical field theories in and out of equilibrium
- Entanglement in quantum systems
- Topological phases of matter
- Conformal field theory
- Integrable models

HPC-intensive activities:

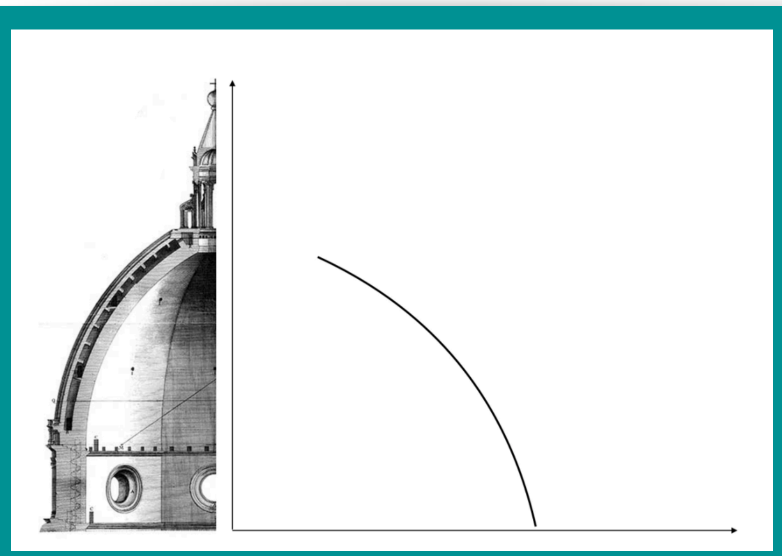
- Conformal field theory and conformal perturbation theory *vs.* Monte Carlo simulations of lattice gauge theories
- Lattice simulation of topological objects in statistical models
- Free energies from non-equilibrium Markov-chain Monte Carlo & machine learning for lattice field theory
- Strong dynamics with matter fields in multiple representations: lattice simulation of SU(4) lattice gauge theory for new physics beyond the Standard Model

## SIM *(M. P. Lombardo)*

*r.n. V. Greco*

SIM

*Research Topics*



Critical and pseudocritical behaviour in QCD

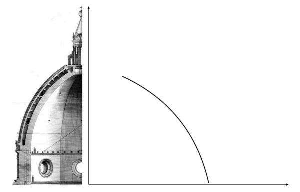
Phenomenology of the Quark Gluon Plasma

QCD axions and topology of strong matter

Dense matter: methods and models

Machine Learning for phase transitions

Compute grants*during the past three years



2022 – 2025 UK STFC DIRAC PPTM303 - Extreme QCD: Quantifying the QCD Phase Diagram III
2019 – 2021 ISCRA High Performance Computing Allocation PCHSHT – Patterns of chiral symmetry at high temperatures
2016–2019 PRACE High Performance Computing Time Allocation – Extreme QCD, quantifying the QCD Phase Diagram

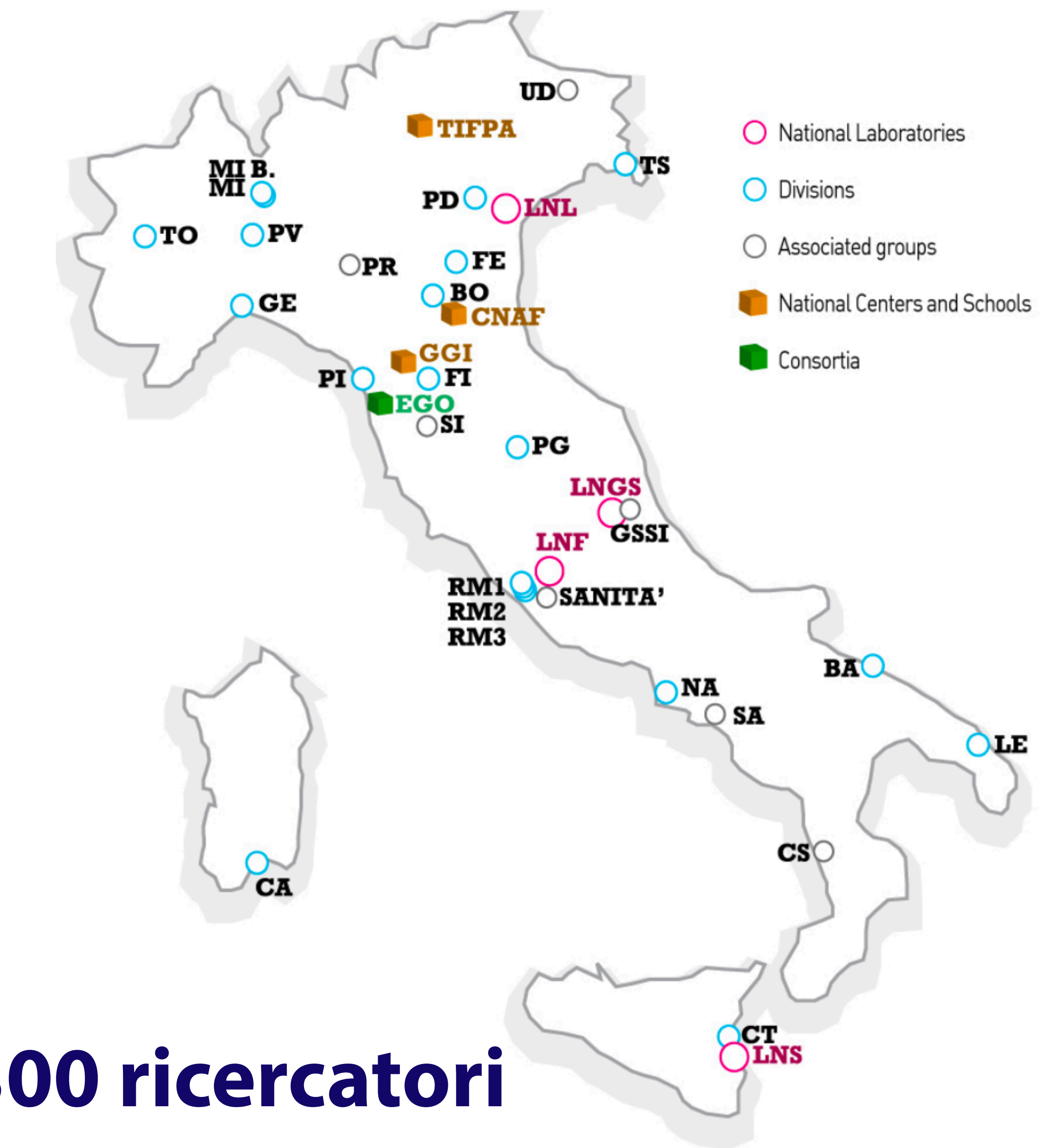
**M.P. Lombardo is excluded from European compute grants as chair of the EuroHPC panel on fundamental physics and universe, and member of the PRACE AC 2017—2022*

# NOT ONLY LATTICE QCD…

# HPC @ INFN

## Theoretical Physics projects that make use of HPC

- **Lattice QCD**
  - LQCD123 *(F. Sanfilippo)*
  - NPQCD *(M. D'Elia)*
  - QCDLAT *(L. Giusti)*
  - SFT *(M. Panero)*
  - SIM *(M.P. Lombardo)*
  - GAGRA *(M.Papinutto)*
- **Cosmology and Astroparticle Physics:**
  - INDARK *(M. Lattanzi)*
  - NEUMATT *(R. De Pietri)*
  - TEONGRAV *(B. Giacomazzo)*
- **Condensed matter:**
  - NEMESYS *(A. Sindona)*
- **Standard Model Phenomenology:**
  - QFTATCOL *(C. Carloni Calame)*
- **Nuclear Physics:**
  - MONSTRE *(N. Itaco)*
  - NUCSYS *(M. Viviani)*
- **Physics of the Complex Systems:**
  - BIOPHYS *(S. Morante)*
  - ENESMA *(C. Presilla)*
  - FIELDTURB *(G. Boffetta)*
- **Quantum Information:**
  - QUANTUM *(S. Montangero)*




**~300 ricercatori**

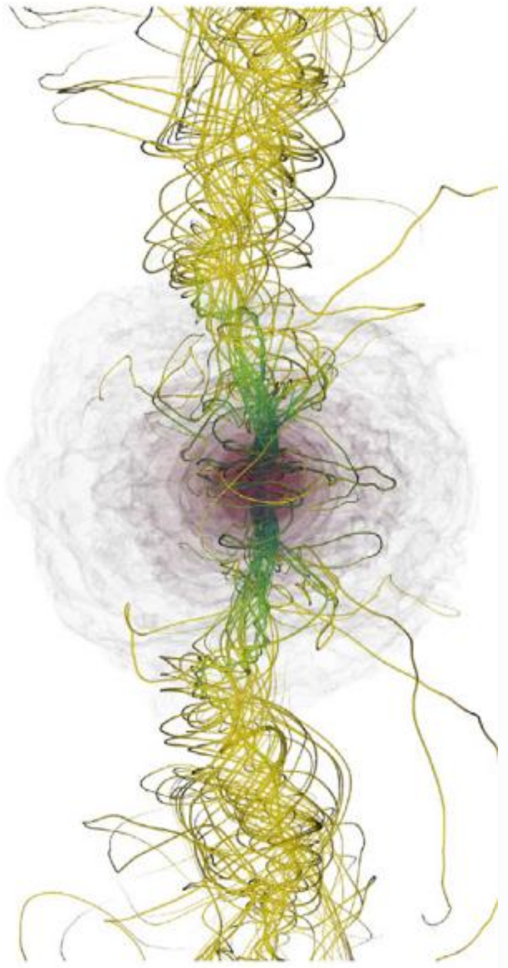
## Experimental Physics projects that make use of HPC

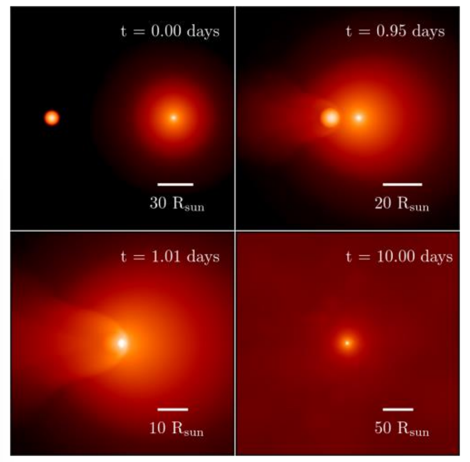
- **EUCLID** *(M. Tenti)*
- **LSPE** *(F. Piacentini)*
- **VIRGO** *(S. Mapelli)*
- **LHC** *(T. Boccali)*

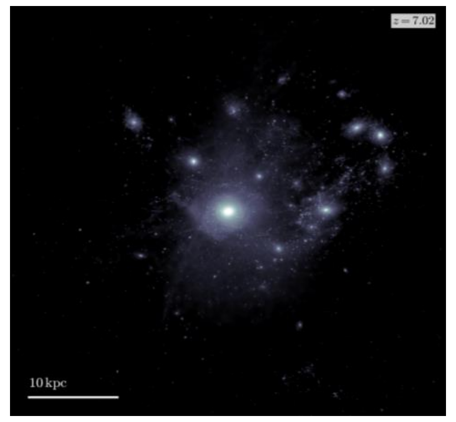
# COSMOLOGY AND ASTROPARTICLE PHYSICS

## TEONGRAV *(B. Giacomazzo)*

### Hydrodynamics and magnetohydrodynamics simulations using state of the art codes in both the Newtonian and the General Relativistic regime





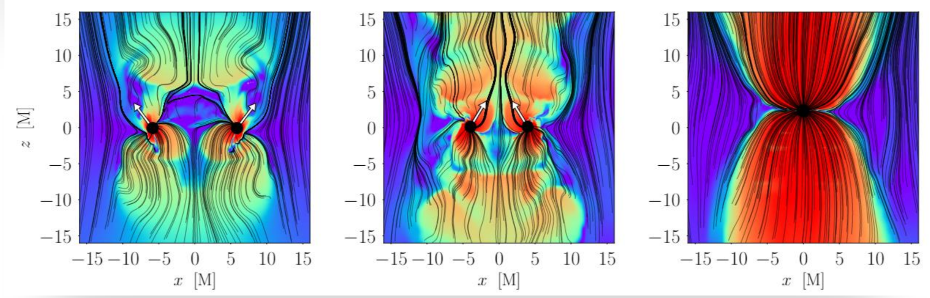

TEONGRAV

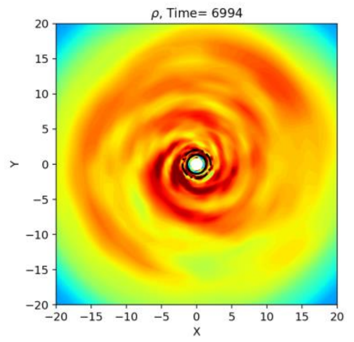
TEONGRAV members run simulations on several HPC clusters, including also Marconi A3, Marconi 100, and Galileo 100 at CINECA.

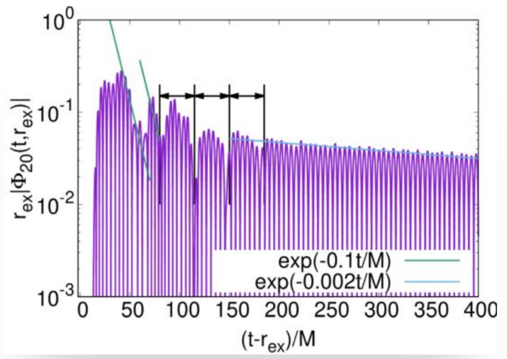
Projects includes both analysis of observational data and numerical simulations of compact objects.

In the field of numerical simulations of compact objects, TEONGRAV performs hydrodynamics and magnetohydrodynamics simulations using state of the art codes in both the Newtonian and the General Relativistic regimes. Main recent projects include:

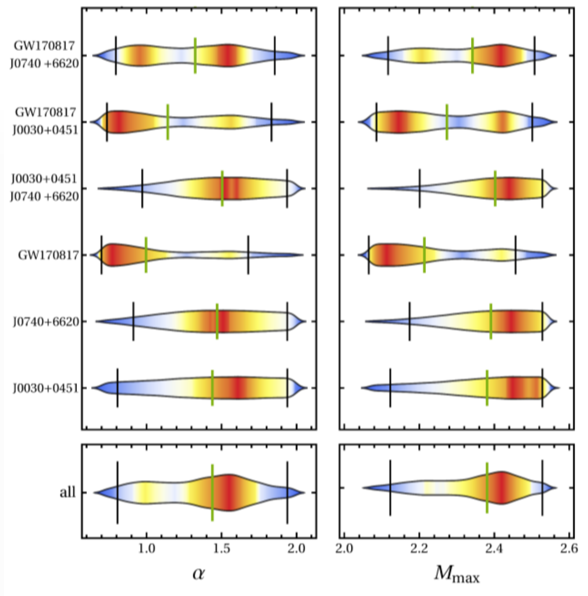
- Model the gravitational wave emission from horizonless, multicenter geometries within the "fuzzball" paradigm of string theory (Roma 1)
- Model gravitational and electromagnetic emission from neutron stars (Firenze, Milano-Bicocca, Padova, TIFPA, Trieste)
- Accretion disks around Kerr black holes (Firenze)
- Simulations of binaries neutron stars beyond General relativity (Trieste)
- Exploring the dynamics of massive black hole binaries embedded in circumbinary discs (Milano-Bicocca)
- Model electromagnetic counterparts of supermassive black hole mergers (Milano-Bicocca)
- Model dynamical evolution and formation of stellar-mass and supermassive black holes via N-body simulations (Milano-Bicocca, Padova)

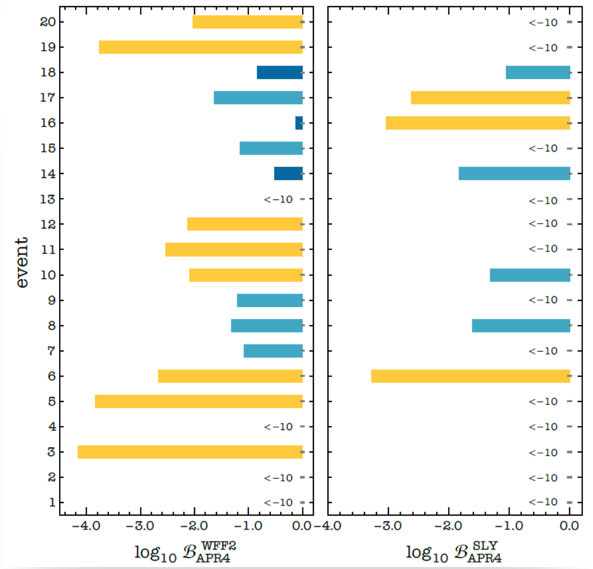







### Analysis of observational data and numerical simulations of compact objects

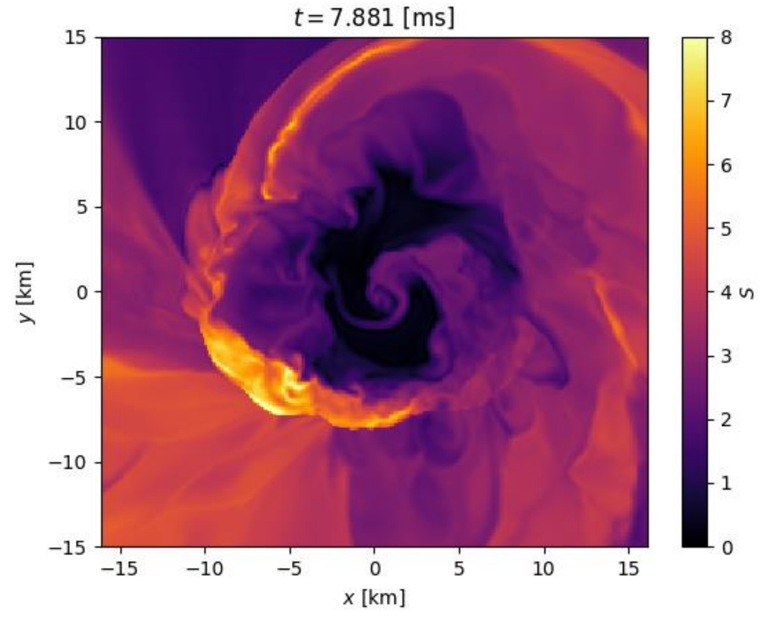




TEONGRAV

In the field of data analysis, main recent projects include:

- Develop efficient data analysis strategies which use gravitational-wave observations of binary neutron stars to test the nuclear equations of state of neutron star matter (Roma 1, GSSI).
- Exploit multimessenger observations to constrain fundamental properties of hadron interactions within the neutron star cores (Roma 1, GSSI).
- Inference of nuclear equation of state properties and nucleosynthesis yields from compact binary mergers (TIFPA)
- Machine learning techniques to analyze gravitational waves from black hole binaries (Milano-Bicocca)
- Model selection for detector characterization in Pulsar Timing Arrays (Milano-Bicocca)
- Inferring population distribution parameters using non-parametric methods (Milano-Bicocca)




2019: 2 ISCRA B ed 1 ISCRA C (totale 4.2 M core hours)
2020: 2 ISCRA B, 2 ISCRA C, 1 PRACE (totale 16.8 M core hours)
2021: 2 ISCRA C e 2 DECI (totale 4.4 M core hours)
2022: 4 ISCRA C (totale 0.4 M core hours)

# COSMOLOGY AND ASTROPARTICLE PHYSICS

**INDARK** *(M. Lattanzi)*

dark energy and matter, axions, neutrinos, modified gravity

Markov Chain Monte Carlo codes interfaced with Boltzmann codes

## ATTIVITÀ HPC IN INDARK

InDark è l'IS che si propone di studiare il modello cosmologico standard e le sue estensioni, e le connessioni con la fisica delle particelle. Si occupa di **inflazione**, **materia ed energia oscure**, **neutrini** e altre **relic cosmologiche leggere** (e.g. **assioni**), e **gravità modificata**.

A questo scopo, in InDark si utilizzano risorse HPC per:

- *Esplorazione dello spazio dei parametri di modelli cosmologici*
    - codici paralleli Markov Chain Monte Carlo interfacciati con codici Boltzmann.
    - applicazioni per es. alla stima dei parametri del modello cosmologico standard e delle sue estensioni, inclusi: proprietà dei neutrini, assioni e altre light relics; birifrangenza cosmica; storia di reionizzazione.
    - Inferenza "Likelihood-free" (i.e. basata su simulazioni) per stimare parametri di nongaussianità primordiali.
    - Applicazione a dati reali e a dati simulati di esperimenti futuri

- *Implementazione di algoritmi per la stima dello spettro da mappe di osservabili cosmologiche*
    - Test, validazione e produzione di codici paralleli per stime dello spettro di potenza e di statistiche di ordine più alto (es. bispettro).
    - Estrazione di informazione dalla polarizzazione del fondo cosmico di microonde, inclusa la ricerca di effetti di violazione di parità;
    - Studio di estimatori di nongaussianità primordiali dalla distribuzione di materia, validati su simulazioni N-body.

- **EuKEy: 33333 Standard Hours**
- **EuNuComp: 32000 Standard Hours**
- **DZSH: 750000 Standard Hours**
- **DZS: 50000 Standard Hours**

# COSMOLOGY AND ASTROPARTICLE PHYSICS

**NEUMATT** *(R. De Pietri)*
*r.n. A. Drago*

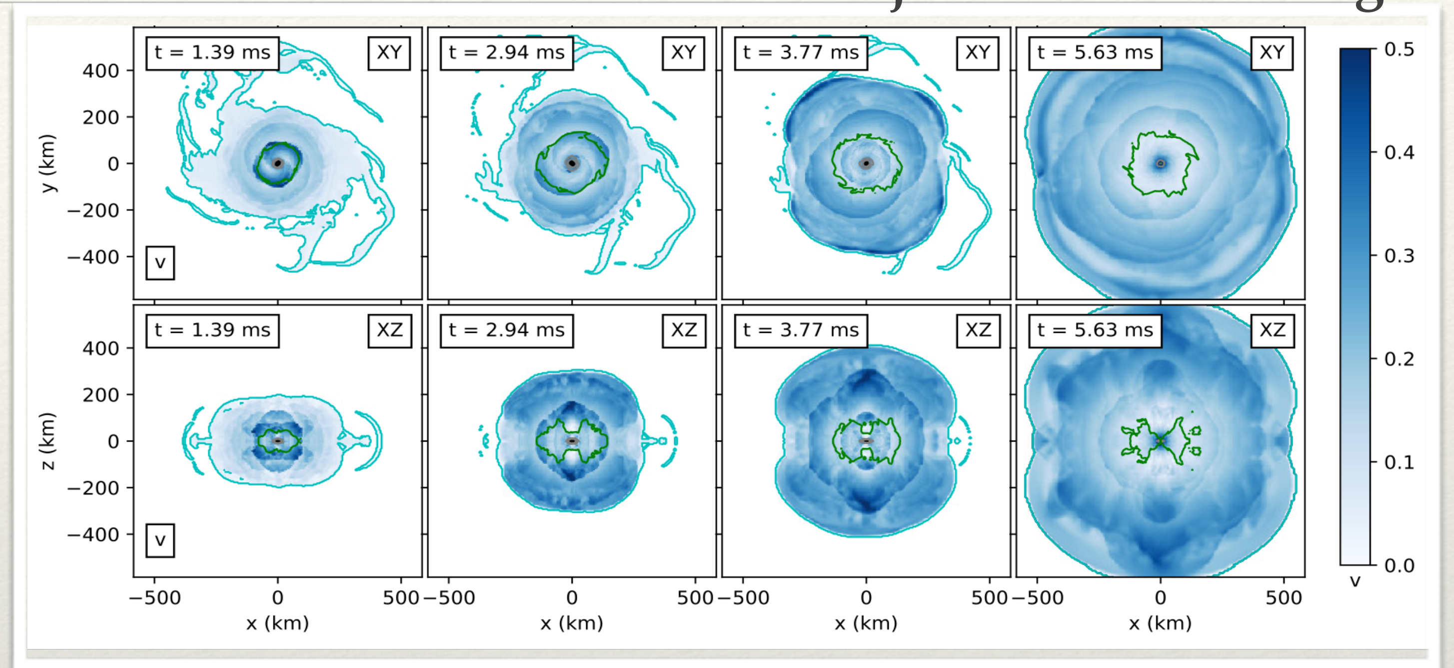
Gravitational wave signals from the merge of binary neutron stars

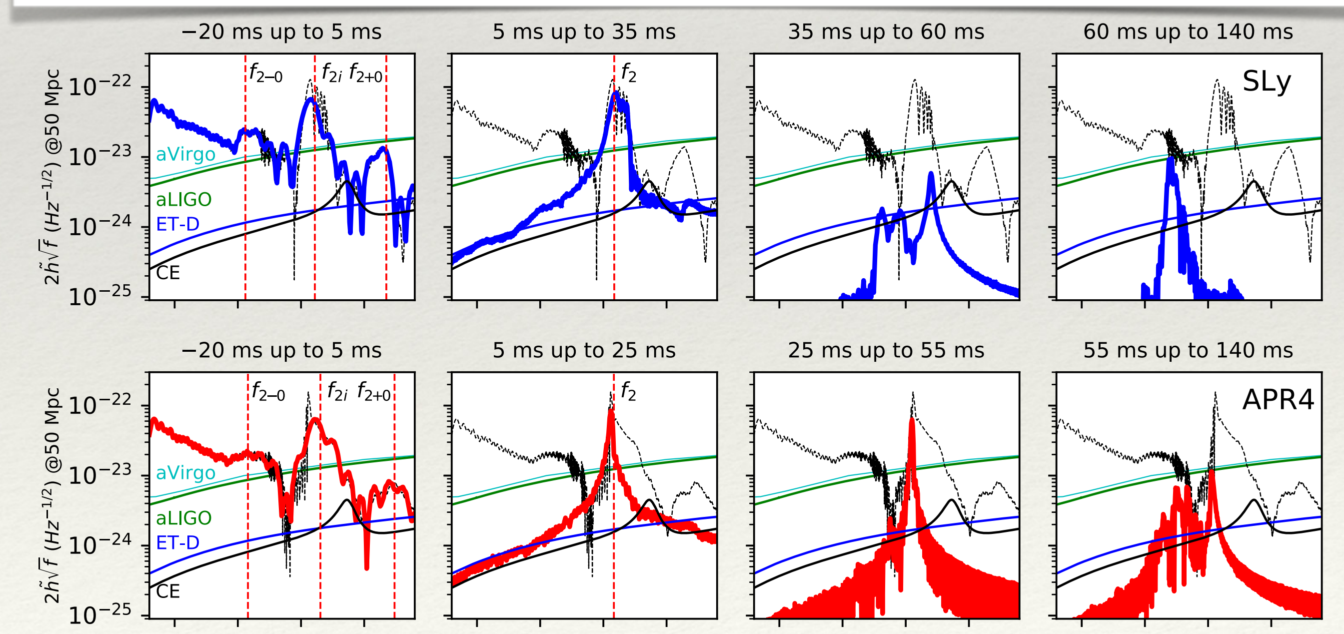
Full 3d-simulation of Einstein equation coupled to the matter of the merger

## NEUtron star MATTer - Computing Activity

- National Coordinator : **Alessandro Drago** (Univ. Ferrara)
  **INFN-CT**: Fiorella Burgio, Antonino Del Popolo, Hans-Josef Schulze, Isaac Vidaña **INFN-FE**: Michal Bejger, Roberto De Pietri, Alessandro Drago, Alessandra Feo, Andrea Lavagno, Giuseppe. **INFN-LNGS**: Massimo Mannarelli, Francesco Vissani, Giulia Pagliaroli. **INFN-MI**: Pierre Pizzochero. **INFN-PI**: Ignazio Bombaci, Domenico Logoteta
- **Main topic: GRAVITATIONAL WAVE SIGNAL FROM THE MERGE OF BINARY NEUTRON STARS**
- **New research in progress on the R-mode excitation of Neutron Stars as Gravitational Waves-source.**
- **Full 3D-simulation of Einstein Equation coupled to matter of the merger. Post-merger signal + study of the the ejected matter. Equation of State effect on the signal.**
- Recent works: ApJ 881 122 (2019), Phys. Rev. D 101, 064052 (2020) + PhD. + MS.Th + work in preparation.

Matter Eject after BNS-Merger




post-merger GWfrequency is changing with time….

# COLLIDER PHENOMENOLOGY

## QFTATCOLLIDERS (C. Carloni Calame)

*r.n. G.P. Vacca*

**Developing techniques for high-precision computations in Quantum Field Theory and to apply them to particle-physics phenomenology at present and future colliders**

### QFT@Colliders [BO, CS, FI, MIB, PV]

- Application of Quantum Fiedl Theory to phenomenology of present and future hadron and lepton colliders
- Development of Monte Carlo event generators, for meaningful comparison of Theory predictions vs Experimental measurements
- Simulation of Standard Model and BSM processes, both for backgrounds and signal
- Steadily increasing complexity in theory predictions: higher-order radiative corrections (NLO, NNLO, . . . ), both in QCD and EW theory, to processes with more and more external particles
- CPU intensive computer codes due to multi-loop matrix elements evaluation, Monte Carlo integration and event generation, highly parallelizable

✓ QFT@Colliders gets typically 0.4 Mcorehours per year on Marconi under INFN-Cineca HPC agreement

✓ MIB won 10 ISCRA C grants (2018-20), for a total of 0.25 Mch on Marconi, 0.22 Mch on Galileo and 23 Kch on Marconi100

✓ Furthermore, under a UNIMIB-CINECA agreement, $\simeq$ 2 Mch (effective) on Marconi A3 (2019-22).

HPC for CSN4 1 / 3

### QFT@Colliders [BO, CS, FI, MIB, PV]

- A few examples of CPU intensive phenomenological study

S. Catani *et al.*, JHEP **08** (2020) 08, 027 [FI]
"Top-quark pair hadroproduction at NNLO: differential predictions with the $\overline{MS}$ mass"

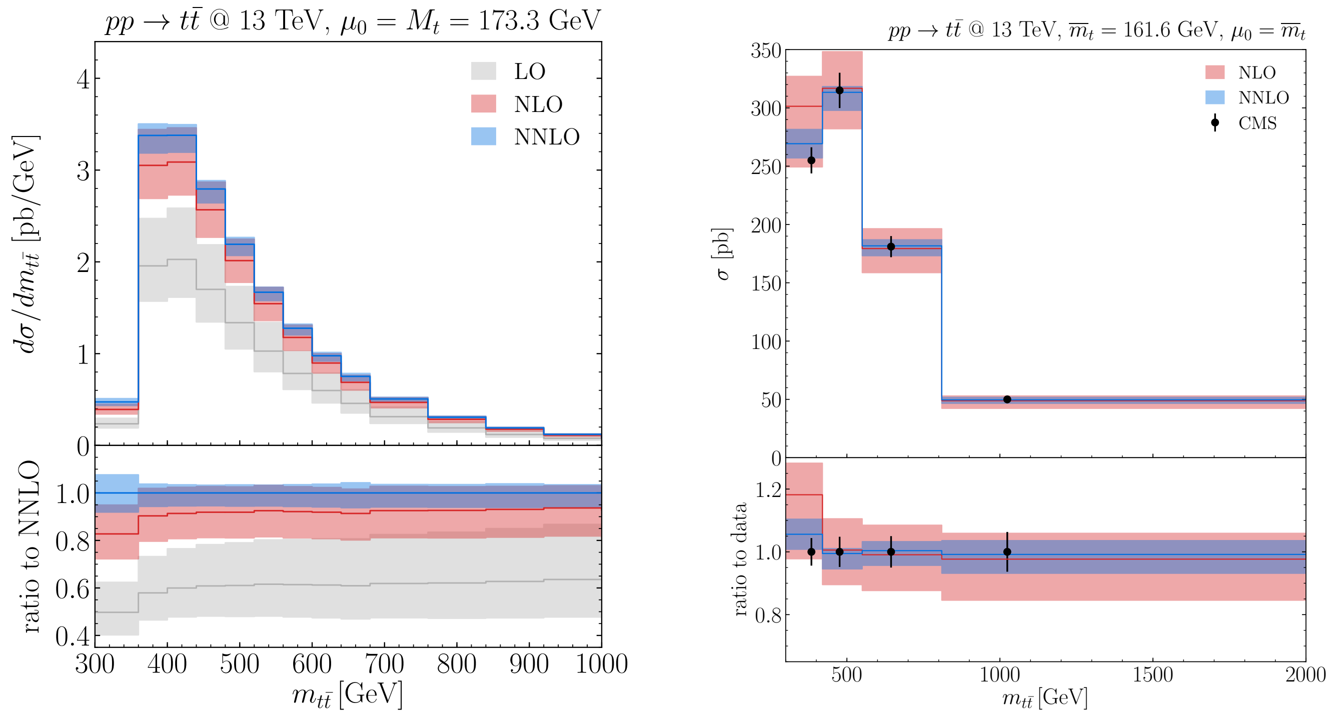



Figure: $m_{t\bar{t}}$ at different accuracies. NNLO greatly improves agreement with CMS data

HPC for CSN4 2 / 3

### QFT@Colliders [BO, CS, FI, MIB, PV]

S. Alioli, *et al.*, Phys. Rev. D **104** (2021) no.9, 094020 [MIB]
"Matching NNLO predictions to parton showers using N3LL color-singlet transverse momentum resummation in GENEVA"
S. Alioli, *et al.*, Phys. Lett. B **818** (2021), 136380 [MIB]
"Next-to-next-to-leading order event generation for $Z$ boson pair production matched to parton shower"

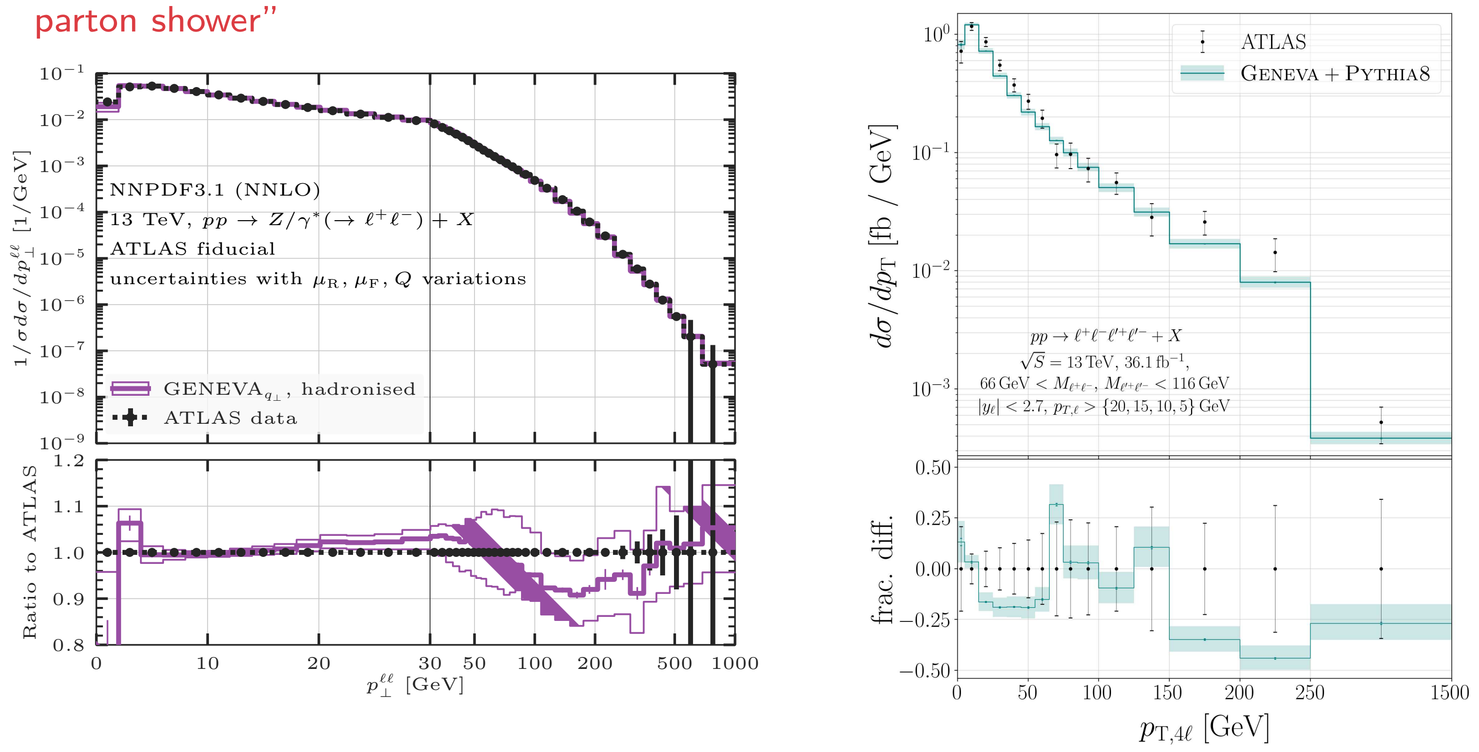



Figure: Matching NNLO to Parton Shower for single and double $Z$ production vs ATLAS data

HPC for CSN4 3 / 3

# NUCLEAR PHYSICS

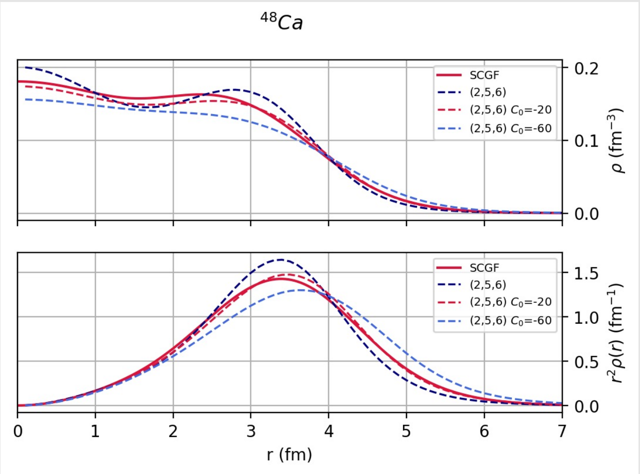
## MONSTRE *(N. Itaco)*

*r.n. E. Vigezzi*

**Integrated framework for the physics of atomic nuclei, nuclear reactions, and strongly interacting matter.**

Iniziativa Specifica MONSTRE
MOdeling Nuclear STructure and REactions

- Bologna
- Catania
- Lecce
- LNS
- Milano
- Napoli
- Padova
- TIFPA - Trento




**Quadro unificato per lo studio dei nuclei atomici, delle reazioni nucleari e della materia fortemente interagente**

**Keywords**

- Struttura Nucleare
- Reazioni Nucleari
- Metodi a Molti-Corpi
- Funzionali Densità

```
1) IscraC:
A three-body chiral interaction for nuclear structure calculations of
heavy nuclei
Acronym: Ch3B
Code: HP10C8TBT0
Validity:6/08/2019-6/12/2020
Budget: 245.000 local hours su Marconi A2 + 8100 local h su Marconi100

2)IscraB:
Calculation of the Nuclear matrix element of Neutrinoless double beta
decay using realistic shell model approach
Acroym: NLDBD
Code: HP10B51E4M
Validity  9/10/ 2019 to  9/03/2021
Budget: 750.000 su Galileo + 45000 su M100+875.000 su Marconi A2

3)Prace_icei
Neutrinoless double beta decay of 100Mo
08-10-2020: creazione progetto al 22/10 /2021
Budget: 1.6M local hours su Marconi100

4)IscraC:
Quenching effect of two-body currents on the axial vector constant g_a
Acronym: QTBGA
Thursday, 10 March, 2022 to Saturday, 10 December, 2022
Budget 100.000 local hours su G100
```

## MONSTRE & HPC

**Large Scale Shell-Model Calculations**

- **Thick-Restart Lanczos method** - OpenMP-MPI hybrid (dim $10^{11}$)
- Elementi di matrice di interesse per esperimenti con sonde elettrodeboli (Neutrinoless **double-beta decay**)

**Funzionali dell'energia**

- Eq. di stato della materia nucleare

**Calcoli *ab initio***

- Quantum Monte Carlo
- Machine Learning

"Quantum Computing applied to Artificial Intelligence" nell'ambito del programma PON R&I 2014-2020

# NUCLEAR PHYSICS

## NUCSYS *(M. Viviani)*

*r.n. A. Kievsky*

**Strongly correlated nuclear system**

### I.S. nucsys: study of dd fusion

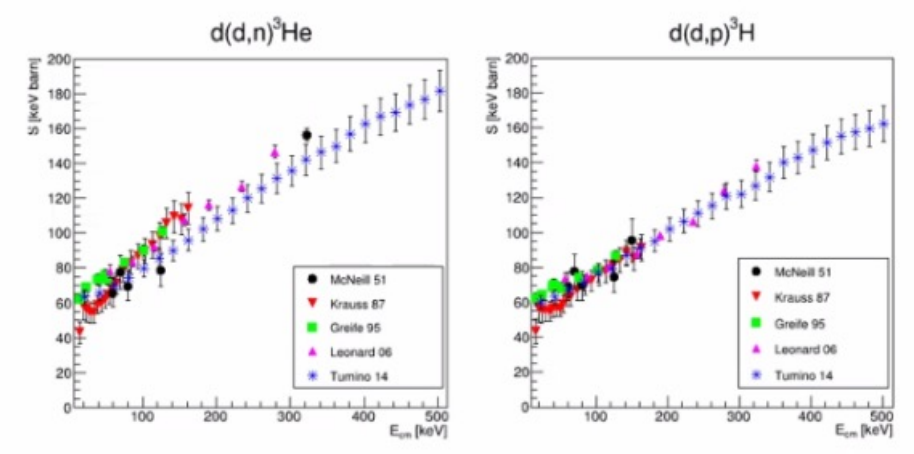
Theoretical study of the d(d,p) H & d(d,n) He reactions

Interest: 1) BBN primordial deuteron abundance 2) fusion reactors

**Astrophysical factor for d(d,p) H & d(d,n) He reactions**

Problem:

- No ab initio calculations
- Large uncertainties from experiments [Yeh, Olive, & Fields, 2021]
- This uncertainty affects the output of BBN codes




**Rates of the reactions d(d,p) H & d(d,n) He with polarized fuel**

Interest:

- For d+ He reactors, the possibility to suppress the production of neutron from d(d,n) He **(Quintic suppression factor)**
- The possibility to control the direction of emission of neutrons (products emitted preferably in a direction)

→"Lean neutron reactors" reduction of the cost of the walls, more safety, less induced radioactivity, etc.

**Quintic suppression factor = σ /σ** ratio between the fusion cross section with polarized deuterons and the unpolarized cross section

### I.S. nucsys: study of dd fusion

Method of calculation: expansion of the scattering wave functions in a basis
Problem to be solved: linear system M X = T(E)
M=matrix nxn (independent on energy E), T=known vectors, X=solution vector

**Calculation of M & T**
Tipically n=**300,000**

- 5-dimensional integration
- OpenMP code

**Solution of the linear system (Lanczos)**

- OpenMP code

Memory intensive calculation: work with 1 node only

- run for different J , energies, interactions,…

- a typical calculation takes 5,000 core hours on 1 Marconi & Galileo100 (48 cores)

**NEXT: implementation using GPUs, extension up to A=6**

**Theoretical uncertainty**

- **Numerical integration, convergence:** well under control
- **Dynamical input**: we start from a given V= NN+3N interaction, but V is not exactly known

Approach used so far

- Perform the calculations using V derived from chiral Perturbation Theory (ChPT) & vary the cutoff Λ used to regularize the high momentum tail [Λ=500 - 600 MeV] (rough estimate of the theoretical uncertainty coming from the incomplete knowledge of the dynamical input)

**NEXT: calculation with V derived from different orders of ChPT & estimation of the theoretical uncertainties using Bayesian method derived for that purpose.**

# PHYSICS OF THE COMPLEX SYSTEMS

## FIELDTURB *(G. Boffetta)*

- Complex fluids and active matter
- Turbulence and scaling
- Out of equilibrium systems
- Machine learning with applications to complex flows

Alessandra Lanotte, Unita' Lecce
2019 Project EU-PRACE 19th Call
SPECTRA Universality of Kolmogorov spectrum in non ideal turbulent flows
56 M core-hours Marconi KNL (Cineca)

Luca Biferale, Unita' di Roma 2
2019 PRA17_4374
TURB-ROT - Inverse and direct cascades in rotating turbulent flows
60 M core-hours Marconi 2 (Cineca)

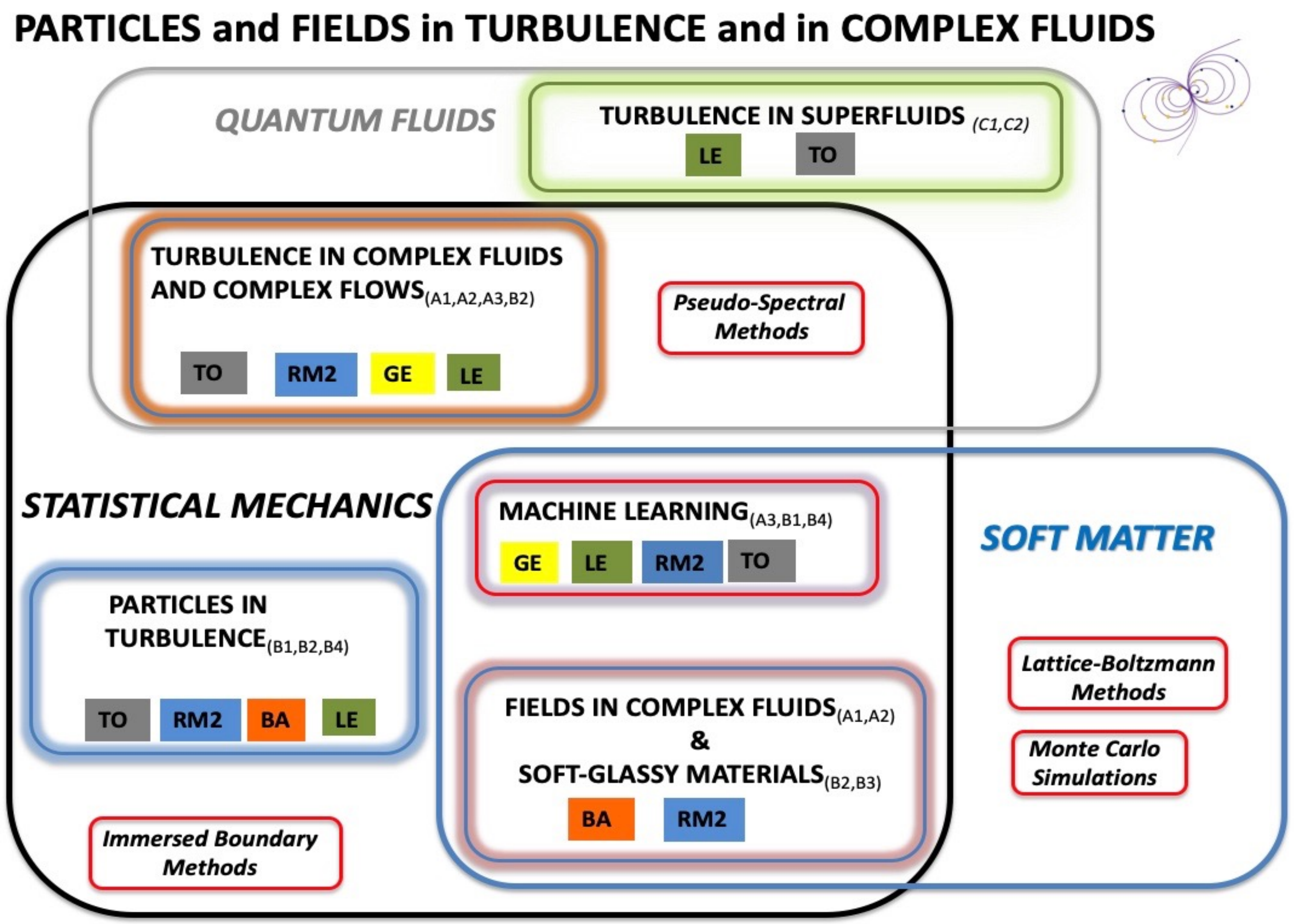
Guido Boffetta, Unita' di Torino
2019 Iscra B
Pourun - Turbulent convection in porous media
4 M core-hours su Marconi KNL

Guido Boffetta, Unita' di Torino
2020 Iscra Covid
TurboPuf - Transport of droplets by turbulent multiphase puff
2 M core-hours su Galileo

Stefano Musacchio, Unita' di Torino
2022 EuroHPC proposal
Anisotropy in turbulent emulsions
richieste 3.58 M core-hours su MeluXina (under revision)

## FIELDTURB 2021 - 2024

National Coordinator: Guido Boffetta (Univ. Torino)




5 Units
Torino
Genova
RM2
Bari
Lecce

Keywords : Turbulence, Complex fluids, Active matter, Out-of-equilibrium statistical mechanics, Machine learning

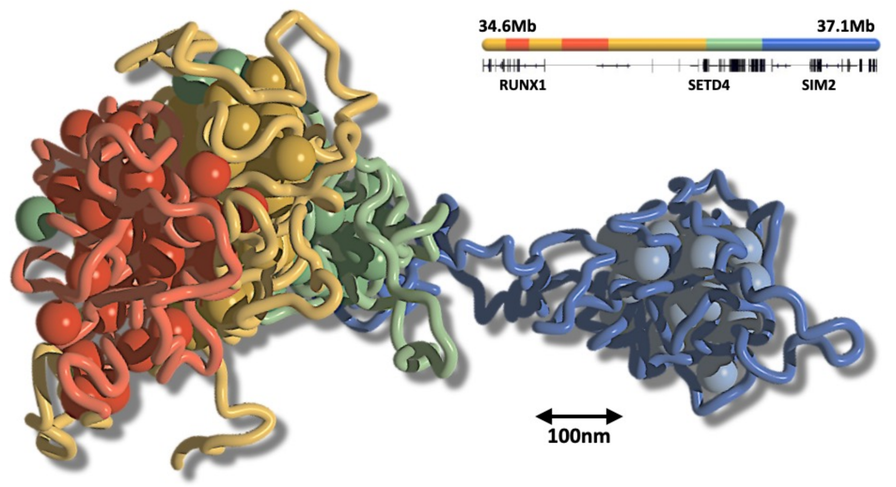
# PHYSICS OF THE COMPLEX SYSTEMS

## BIOPHYS *(S. Morante)*
*r.n. M. Nicodemi*

**Modelling and discovering emergent properties of biological systems by using innovative methods and ideas coming from theoretical physics**

Investigation of the three-dimensional structure of the mammalian genome and its links with gene regulation at the single-molecule level by use of extensive Molecular Dynamics computer simulations.

Napoli



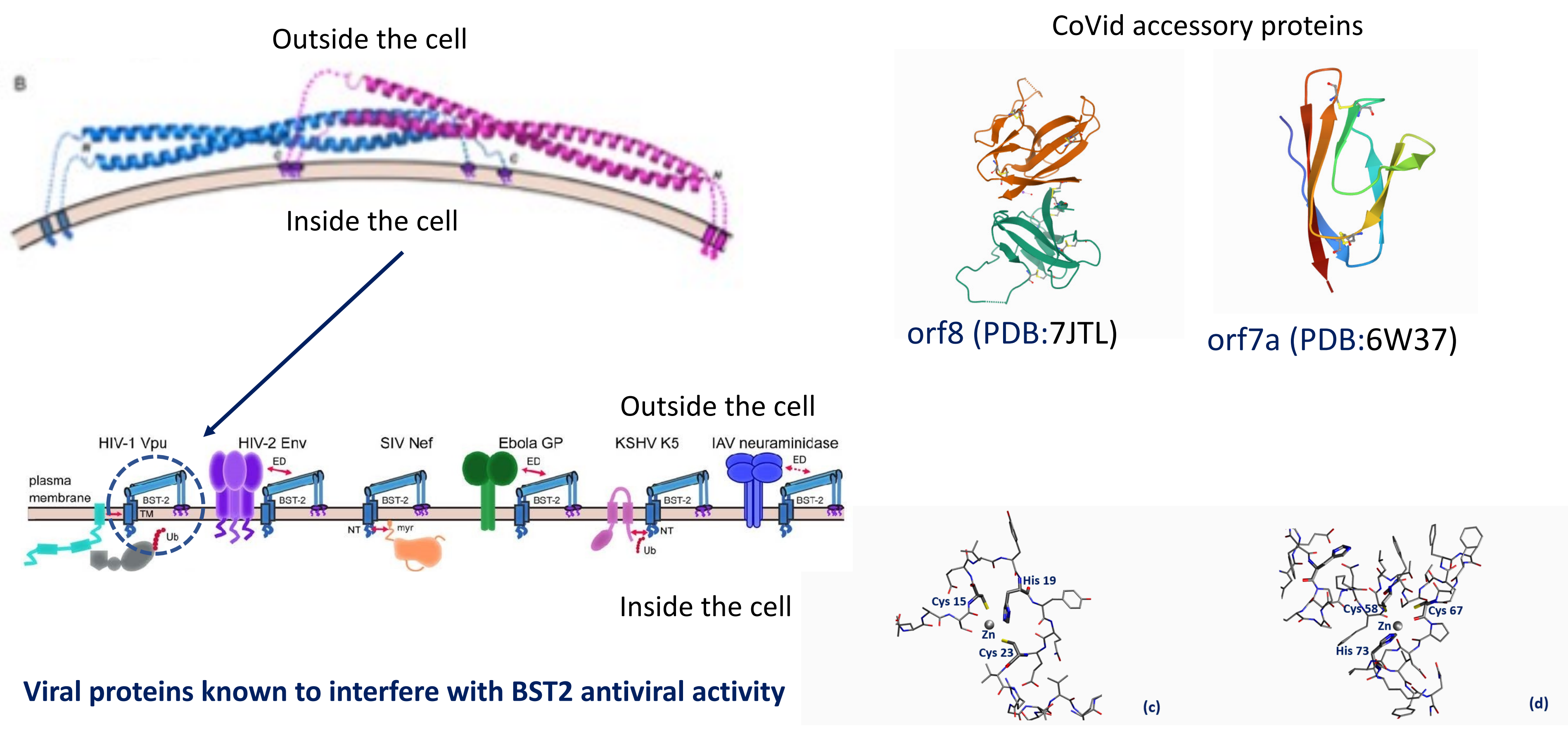

DNA Folding

Three-dimensional structure of the mammalian genome and its links with gene regulation at the single-molecule level

Structural properties of proteins and protein assemblies (Fig.2 Covid2-orf7 and orf8, in interaction with BST2)

Viral proteins may forbid BST2 antiviral action through Zn-mediated disulfide bond disruption

Roma2




Study of the structural properties of proteins and protein assemblies in the presence and in the absence of metal ions by using several computational techniques: classical and ab-initio Molecular Dynamics, Monte Carlo and enhanced sampling by molecular dynamics algorithms. The most interesting systems we recently studied are:

- CoVid2 orf7 and orf8 accessory proteins, alone and in interaction with BST2 with the latter being a protein of the human immune system (Fig.2: covid+bst2;)
- Frataxin (FXN), a protein involved in iron transportation, whose malfunctioning is often related to tumor development (Fig.3: FXN)

**ISCRA approved Projects within the IS:**

- 4 IscraC projects on Marconi 100 for a total of 128 k core-hours;
- 2 IscraC projects on Marconi 100 for a total of 95 k core-hours
- Iscra B on Marconi 100 of 1.6 M core-hours
- ISCRA-HP10CCZ4KN
- ISCRA-HP10CCZ4KN
- ISCRA C 20’ of quantum computing time on the D-WAVE quantum annealer
- ISCRA C project 30,000 hours on CiNECA

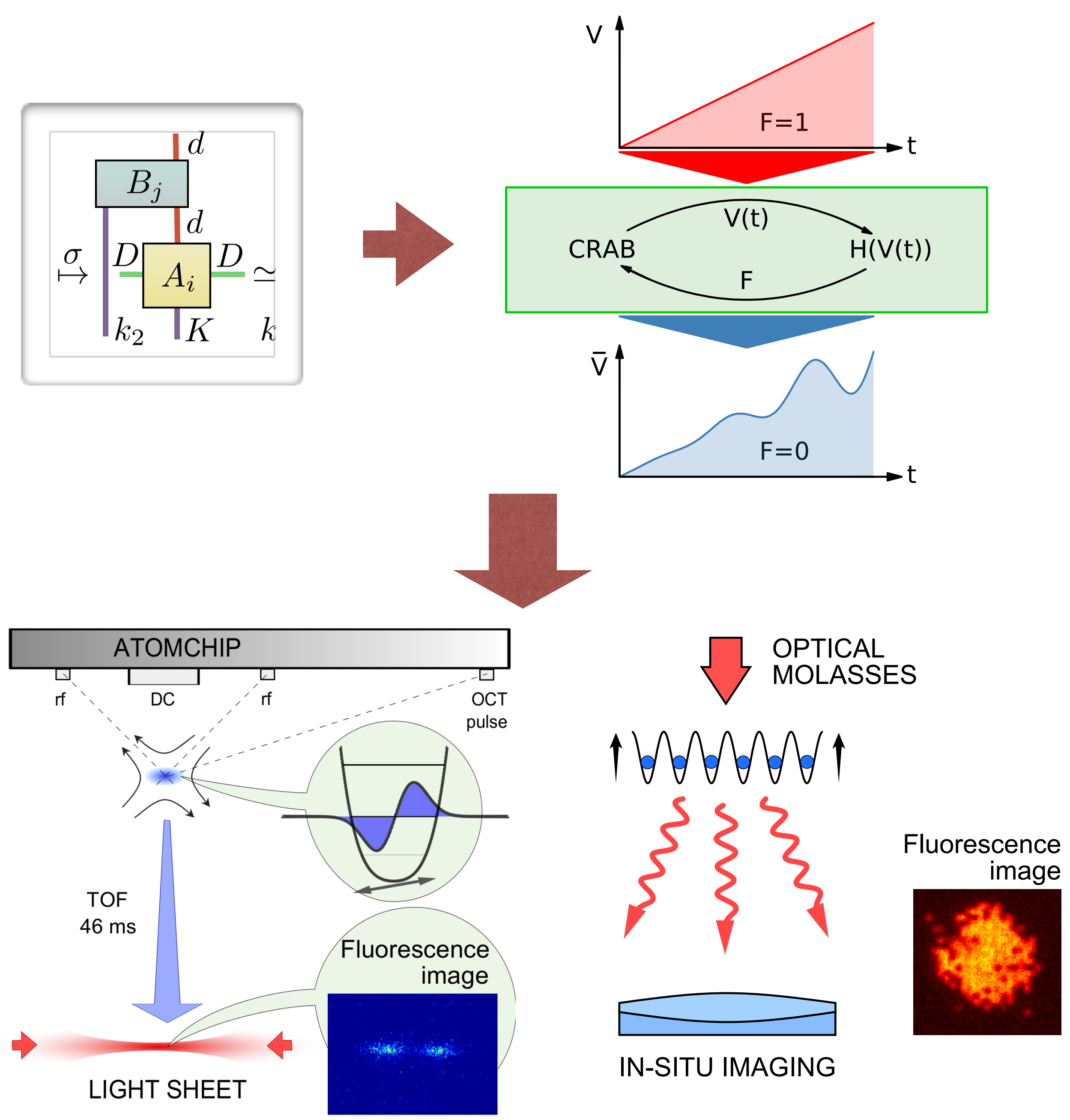
# QUANTUM INFORMATION

## QUANTUM (S. Montangero)

*r.n. P. Facchi*

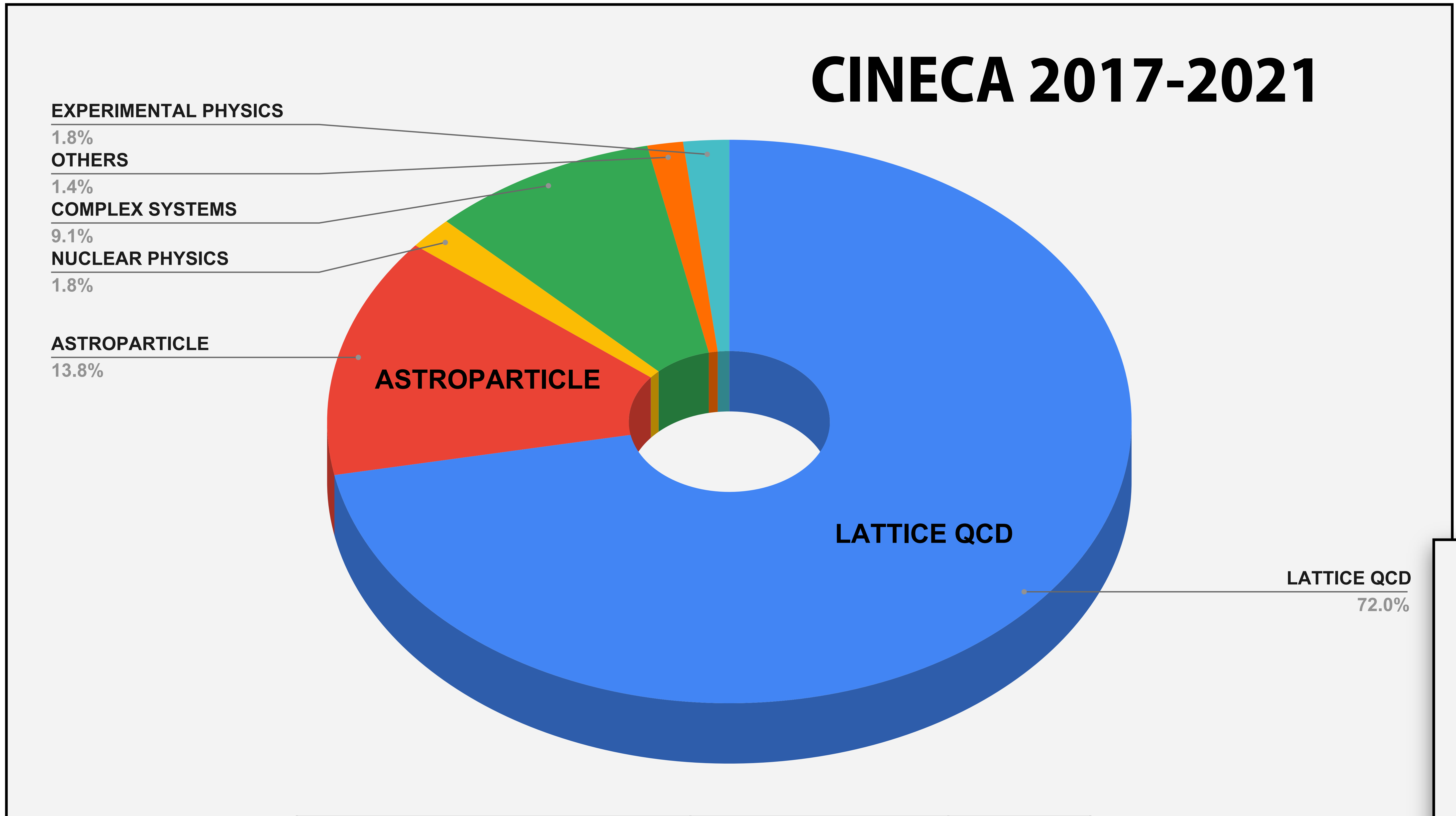
**Entanglement and other Quantum Correlations, Quantum Simulation, and Quantum Control**

### S. MONTANGERO'S GROUP RESEARCH LINES



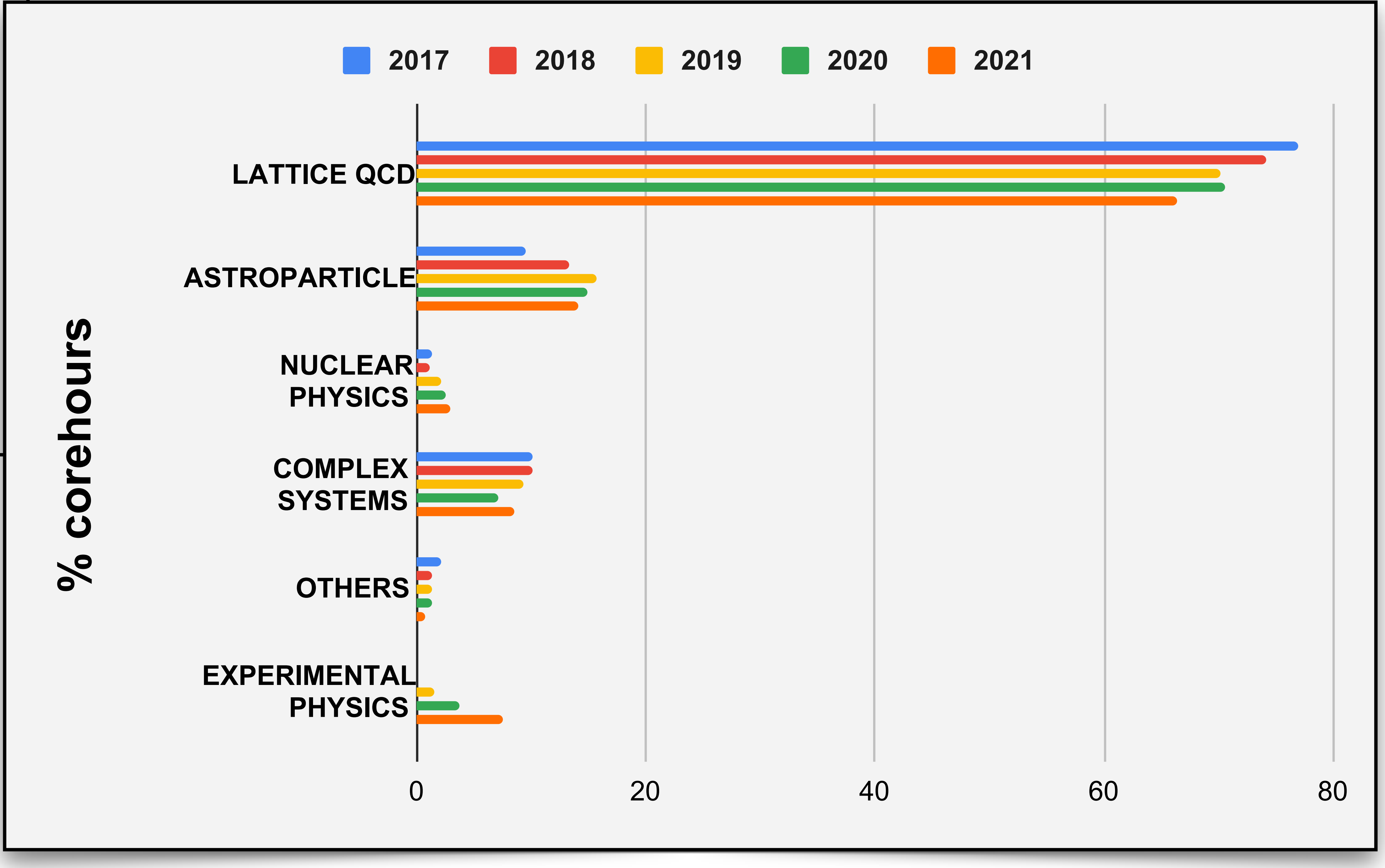

- Development of efficient (classical and quantum) simulation and control techniques
- Simulation of interesting physics
- Define and probe fundamental limits given by energy, time and information constrains
- Experimental verification of theoretical optimal protocols

# HPC COMPUTING RESOURCES 2017-2021




| AREA | corehours | % |
|---|---|---|
| LATTICE QCD | 687,787,117 | 72.0 |
| ASTROPARTICLE | 131,826,951 | 13.8 |
| NUCLEAR PHYSICS | 17,546,676 | 1.8 |
| COMPLEX SYSTEMS | 87,396,389 | 9.1 |
| OTHERS | 13,724,017 | 1.4 |
| EXPERIMENTAL PHYSICS | 17,596,432 | 1.8 |
| *TOTAL* | *955,877,582* | *100* |

| %corehours | 2017 | 2018 | 2019 | 2020 | 2021 |
|---|---|---|---|---|---|
| LATTICE QCD | 76.97 | 74.09 | 70.06 | 70.62 | 66.31 |
| ASTROPARTICLE | 9.49 | 13.34 | 15.64 | 14.80 | 14.06 |
| NUCLEAR PHYSICS | 1.24 | 1.05 | 2.17 | 2.45 | 2.86 |
| COMPLEX SYSTEMS | 10.09 | 10.10 | 9.25 | 7.10 | 8.51 |
| OTHERS | 2.21 | 1.43 | 1.35 | 1.28 | 0.80 |
| EXPERIMENTAL PHYSICS | | | 1.53 | 3.75 | 7.46 |



# OSSERVAZIONI CONCLUSIVE

- **La comunità di Fisica Teorica INFN nel corso degli ultimi 30 anni ha dato contributi fondamentali allo sviluppo del calcolo HPC. Il calcolo HPC é diventato di interesse strategico per tutta la comunità INFN (e anche per la comunità scientifica nazionale: PNRR).**

- **Molti progetti di ricerca in Fisica Teorica Computazionale (Lattice QCD, HEP, Astroparticle, Nuclear Phyisics, Complex systems) con un grande numero di ricercatori coinvolti.**

- **Il problema della transizione alle GPU —>** modificare e ottimizzare i codici esistenti

  *Esempio: Lattice QCD*

  - I codici per LQCD sono stati scritti per girare su computer basati su CPU: data le notevoli dimensioni dei codici, la transizione alle GPU è onerosa: non esiste una corrispondenza "uno-a-uno" fra un codice CPU e un codice GPU.
  - Scrivere codici LQCD richiede grande "man power": come tenere conto di possibili evoluzioni delle architetture di calcolo?

- **Il problema della sostenibilità degli sforzi per modernizzare e adeguare i codici alla evoluzione dell'hardware (impegno di considerevoli risorse umane)**

  - **Un programma adeguato di formazione e reclutamento è cruciale per creare le competenze necessarie per un utilizzo efficiente delle presenti e future risorse di calcolo (GPUs,…), e anche per la ottimizzazione e lo sviluppo di nuovi algoritmi (—> Centro di Calcolo Scientifico Nazionale (PNRR)).**

# BACKUP SLIDES

# Le risorse di calcolo

## Andamento storico (2012-2021)

| RISORSE INFN SULLE MACCHINE CINECA A PARTIRE DA SETTEMBRE 2012 (Mcorehours) | | | | | | |
|---|---|---|---|---|---|---|
| | FERMI | GALILEO | MARCONI (A1) | MARCONI (A2) | MARCONI (A3) | MARCONI100 |
| Set 2012 - Dic 2013 | 115 | | | | | |
| 2014 | 110 | | | | | |
| 2015 | 100 | 15 | | | | |
| 2016 | 100 | 15 | | | | |
| 2017 | | 15 | 18 | 120 | | |
| 2018 | | | 9 | 120 | 164 | |
| 2019 | | | | 120 | 164 | |
| 2020 | | | | | 164 | 10 |
| 2021 | | | | | 110 | 21 |

| 2018 | ASSEGNAZIONE (Mcorehours) | CONSUMO (Mcorehours) | CONSUMO/ASSEGNAZIONE (%) |
|---|---|---|---|
| MARCONI (A1) | 9.00 | 4.90 | 54.44% |
| MARCONI (A2) | 120.00 | 119.00 | 99.17% |
| MARCONI (A3) | 164.00 | 141.00 | 85.98% |

| 2019 | ASSEGNAZIONE (Mcorehours) | CONSUMO (Mcorehours) | CONSUMO/ASSEGNAZIONE (%) |
|---|---|---|---|
| MARCONI (A2) | 120.00 | 119.20 | 99.33% |
| MARCONI (A3) | 166.10 | 162.80 | 98.01% |

| 2020 | ASSEGNAZIONE (Mcorehours) | CONSUMO (Mcorehours) | CONSUMO/ASSEGNAZIONE (%) |
|---|---|---|---|
| MARCONI (A3) | 169.00 | 163.00 | 96.45% |
| MARCONI100 | 10.11 | 11.93 | 117.98% |

| 2021 | ASSEGNAZIONE (Mcorehours) | CONSUMO (Mcorehours) | CONSUMO/ASSEGNAZIONE (%) |
|---|---|---|---|
| MARCONI (A3) | 102.25 | 73.25 | 71.64% |
| MARCONI100 | 20.70 | 14.50 | 70.05% |

## Le macchine al CINECA (2012-…)

| | processor | #cores/ node | #accelerators/ node | #nodes | #cores | (peak perf)/node [GFlop/s] | (peak perf)/core [GFlop/s] | peak performance [PFlop/s] | start date | end date |
|---|---|---|---|---|---|---|---|---|---|---|
| FERMI | IBM PowerA2 | 16 | | 10,240 | 163,840 | 204.8 | 12.8 | 2.1 | 01-Sep-2012 | 18-Jul-2016 |
| GALILEO | Intel Haswell | 16 | | 516 | 8,256 | 1,170.0 | 73.1 | 0.6 | 01-Feb-0205 | 20-Nov-2017 |
| MARCONI-A1 (Broadwell) | Broadwell | 36 | | 1,512 | 54,432 | 1,300.0 | 36.1 | 2.0 | 04-Jul-2016 | 26-Sep-2018 |
| MARCONI-A2 (KNL) | Knights Landing (KNL) | 68 | | 3,600 | 244,800 | 3,000.0 | 44.1 | 10.8 | 04-Jan-2017 | 01-Jan-2020 |
| MARCONI-A3 (SKL) | Skylake | 48 | | 3,188 | 153,024 | 3,200.0 | 66.7 | 10.2 | 07-Aug-2017 | |
| MARCONI100 | IBM Power AC922 | 32 | 4 nVidia V100 | 980 | 31,360 | 32,000.0 | 1,000.0 | 31.4 | 04-May-2020 | |
| GALILEO100 | Intel Xeon Platinum | 48 | 2 V100 (su 36 nodi) | 554 | 26,592 | 3,530.0 | 73.5 | 2.0 | 15-Oct-2021 | |

# Le risorse di calcolo

## Le risorse computazionali oltre l'Accordo CINECA-INFN *(e.g. periodo 2017-2019)*

- agreement CINECA-INFN dal 2012 parzialmente finanziato da:
  - progetto premiale SUMA (0.5 Meuro: GALILEO)
  - progetto HPC_HTC (CIPE) (1.5 Meuro: MARCONI-SKL)
- PRACE — Partnership for Advanced Computing in Europe (PRACE)
- Italian SuperComputing Resource Allocation - ISCRA

| | # progetti | corehours |
|---|---|---|
| CINECA-INFN AGREEMENT (2017-2019) | | *730,000,000* |
| ISCRA-C | 45 | 20,615,000 |
| ISCRA-B | 40 | 205,440,950 |
| PRACE | 30 | 925,928,640 |
| ALTRE RISORSE INTERNAZIONALI | 11 | 367,000,000 |
| *TOTALE* | | *1,518,984,590* |
| *GRAN TOTALE* | | *2,248,984,590* |
| | | |
| Lavori pubblicati (con uso di risorse HPC) | *315* | |

- **Moltiplicatore per accesso a risorse ISCRA e PRACE: 2,250,000,000/730,000,000 = 3**

# Le risorse di calcolo HPC

*(in via di approvazione)*

- **Accordo Quadro CINECA-INFN 2022-2026**
- **Accordo Attuativo dell’Accordo Quadro CINECA-INFN**

- **MARCONI-A3**
- **MARCONI100**
- **GALILEO100**


| | CPU (mhz,core, ...) | Total cores / Total Nodes | Memory per node | Accelerator |
|---|---|---|---|---|
| **MARCONI-A3** | Intel SkyLake<br>2x Intel Xeon 8160<br>@2.1GHz<br>24 cores each | 48*3216 / 3216 | 192 GB | - |
| **MARCONI100** | IBM Power9 AC922<br>@3.1GHz<br>32 cores HT 4 each | 32*980 / 980 | 256 GB | 4x NVIDIA Volta<br>V100 GPUs per node,<br>NVlink 2.0 16 GB |
| **GALILEO100** | 2 x Intel CascadeLake 8260<br>@2.4 GHz<br>24 cores each, | 48*554 / 554 | 384 GB<br>3.0 TB | 34 nodes with 2x NVIDIA<br>V100 per node, PCIe3 |

## LEONARDO

**Sustained performance: 249.4 PFlop/s**
**Peak performance: 322.6 PFlop/s**


### Specifiche tecniche

Il supercomputer Leonardo è costituito da 3 parti:

- La prima, chiamata Booster, è formata da oltre 3.000 nodi basati sui sistemi a raffreddamento diretto a liquido BullSequana XH2000, che integrano una CPU Intel Xeon SP di terza generazione e quattro GPU Nvidia Ampère A100, per un totale di quasi 14.000 acceleratori;
- La seconda, chiamata Data Centric Partition, è formata da oltre 1.500 nodi basati sugli stessi BullSequana XH2000, ma che ospitano processori Intel Xeon di generazione futura.
- L'intero sistema è collegato ad un terzo modulo di servizio e visualizzazione, ed ad un'area di archiviazione multi-tier ad alte performance, con una capienza aggregata di olte 100 PetaByte, basata sui prodotti DDN. Tutte le parti del sistema comunicano tra di loro grazie un'interconnessione a bassa latenza InfiniBand HDR a 200Gb/s per collegamento, allocata su tecnologia Nvidia Networking.

I processori Intel Xeon di generazione futura sono ottimizzati per eseguire carichi di lavoro computazionalmente intensi in sistemi di calcolo ad alte prestazioni consentendo computing con avanzate capacità di accelerazione AI integrate.

- Più di 136 BullSequana XH2000 rack di raffreddamento diretto a liquido
- 250 PFLOPs HPL Linpack Performance (Rmax) aggregata
- 3+PB RAM
- 10 ExaFLOPs di prestazioni FP16 AI
- 3456 server equipaggiati con Intel Xeon Ice Lake e GPU con architettura Nvidia Ampère
- 1536 server con processori Intel Xeon SP di prossima generazione
- 5PB di storage ad alte prestazioni
- 100PB di storage a grande capacità
- Larghezza di banda di interconnessione minima di 200Gb/s per singolo link InfiniBand HDR
- 9MW di Potenza elettrica aggregate
- Oltre 140 km di cablaggi in fibra ottica

# Le risorse di calcolo HPC

- **Accordo Quadro CINECA-INFN 2022-2026**

ACCORDO QUADRO DI COLLABORAZIONE PER LO SVOLGIMENTO DI ATTIVITÀ DI RICERCA E SVILUPPO NEL SETTORE DEL CALCOLO SCIENTIFICO AD ALTE PRESTAZIONI (HPC) IN AMBITO DI FISICA DELLE ALTE ENERGIE, FISICA ASTROPARTICELLARE, FISICA NUCLEARE

**Art. 2 – Oggetto e finalità dell'Accordo**

Con il presente Accordo Quadro, le Parti instaurano una collaborazione rivolta allo

- sviluppo e sperimentazione di sistemi di calcolo ad alte prestazioni e ad alta capacità;
- sviluppo di algoritmi e applicazioni relative all'ambito della modellazione e della simulazione numerica e dell'analisi dei dati in aree di interesse della fisica fondamentale, in particolare utilizzando architetture innovative dei processori, delle reti d'interconnessione e delle strutture di input-output;

(in via di approvazione)

- **Accordo Attuativo dell'Accordo Quadro CINECA-INFN**

**ACCORDO ATTUATIVO DELL'ACCORDO QUADRO DI COLLABORAZIONE PER LO SVOLGIMENTO DI ATTIVITÀ DI RICERCA E SVILUPPO NEL SETTORE DEL CALCOLO SCIENTIFICO AD ALTE PRESTAZIONI (HPC) IN AMBITO DI FISICA DELLE ALTE ENERGIE, FISICA ASTROPARTICELLARE, FISICA NUCLEARE**

- **MARCONI-A3:** 60 Mcorehours/anno fino a dismissione
- **MARCONI100:** 60 Mcorehours/anno fino a dismissione
- **GALILEO100:** 6 Mcorehours/anno fino a dismissione
- **LEONARDO**

| PARTIZIONE | 2023 | 2024 | 2025 | 2026 |
|---|---|---|---|---|
| General Purpose (CPU) | 165 nodi | 300 nodi | 300 nodi | 300 nodi |
| Booster (GPU) | 3 Mnodehours | 3 Mnodehours | 3 Mnodehours | 3 Mnodehours |

su 1536 nodi *Intel Sapphire Rapids (48 cores)*

su 3456 nodi *Intel Ice-Lake (32 cores)*

# Le risorse di calcolo HPC

## ISCRA: Italian SuperComputing Resource Allocation

CINECA, through the **Italian SuperComputing Resource Allocation - ISCRA**, releases Call for Proposals.

**CINECA**, the Italian most powerful HPC center, twice a year **will directly award in excess of 100 millions core hours**, to ensure an adequate supply to scientists and engineers for HPC-related research.

CINECA infrastructure offers different HPC resources to its users. The available resources are divided in three categories:

- The TIER-0, top level computing resources, which is the new **MARCONI100** machine and can be accessed trough class B and C projects.
- The TIER-1 level, is **GALILEO100** (BROADWELL) and can be accessed trough class C and B projects.
  The Big Data resources and new state-of-the-art public CLOUD.
  The data infrastructure is available for data analysis, visualization, post-processing, bio-informatics applications.
  The **CLOUD** infrastructure integrates and completes the HPC ecosystem, providing a tightly-integrated infrastructure that covers both high performance and high flexible computing. The flexibility of the CLOUD will better adapt to the diversity of user workloads, while still providing high-end computing power.
- The DGX resources:
  Available through ISCRA-C: these projects aim to support researchers in the domain of Machine Learning and Artificial Intelligence and their applications.
- The Quantum Computing Resources.
  Available through ISCRA-C, CINECA makes quantum computing resources of various kinds available to its users. It will be possible to request machine time on our Tier-0 system to emulate complex quantum circuits (both general purpose and special purpose type) and directly request quantum computing resources (currently of quantum annealing type).

**Class B** projects are received twice a year. They go under peer-review evaulation and a 3 month delay is expected before your project gets access to HPC resources. For each user it is allowed to have only one class B project each 6 months as Project Investigator.

**Class C** projects are received through continuous submission and reviewed once per month. An average period of about 15 days is required for activating the project. For each user it is allowed to have only one class C project each 6 months as Project Investigator.

# Le risorse di calcolo HPC

**PRACE, EuroHPC JU (Joint Undertaking)**

PRACE PARTNERSHIP FOR ADVANCED COMPUTING IN EUROPE

- International, not-for-profit
- 25 member countries - pan-European supercomputing infrastructure enabled by 5 Hosting Members
  - BSC (Spain), CINECA (Italy), ETH/CSCS (Switzerland), GSC (Germany), GENCI (France)
- Access on basis of peer-reviewed (open) science & industry proposals
- Additionally, schools, workshops, PRACE IP …

- Enable high-impact scientific & engineering discovery and R&D.
- Tier-0 computing and data management resources and services through **competitive peer review.**
- Training & education via schools, workshops, seminars.
- Enabled by 5 Hosting Centres.
- **No procurement, no technology development.**

EuroHPC Joint Undertaking

- Based on 2 EU Council Regulations (2018 & 2021)

Objectives

- Build and operate a world class integrated HPC and data infrastructure
- Enable member states to improve HPC competency
- Foster HPC skills, education and training
- Develop HPC core technology
  - *European Processor Initiative (EPI)*
  - *Energy efficient HPC*
  - *Quantum Computing*

## In 2021 EuroHPC planned resources and timelines

**Infrastructure and Operations**

- 5 x petascale machines @ 15-30 petaflops. In operation by Q1 2021. Bulgaria, Czech Republic, Luxembourg, Portugal, Slovenia.
- 3 x pre-exascale machines. In operation Q2/3 2021:
  - CSC - Finland *Cray: 375PF sustained, 552PF peak; GPU, x86, data analytics, cloud container partitions*
  - Cineca - Italy *ATOS-Bull Sequana 249PF sustained, CPU-GPU, DDR5 & local NVM for data analysis*
  - BSC - Spain
- 2 x exascale in operation by 2022-2023. In coordination with EPI (European-based technology) for at least one machine?
- Data I/O, management, storage and security federation for impact: GEANT, EOSC etc

## Access

There is an access policy at https://eurohpc-ju.europa.eu/access-our-supercomputers

*Talk S. Ryan @ GGI Mini Workshop "Phase transitions in particle physics"*